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A STRATEGIC PLAN FOR EUROPEAN ASTRONOMY

THE ASTRONET SCIENCE VISION & INFRASTRUCTURE

ROADMAP 2022-2035

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Wolf-Rayet 124 (JWST/MIRI Image)

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EXECUTIVE SUMMARY
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INTRODUCTION

An integrated roadmap for European Astronomy

Astronomy has entered the era of 'Big Science, Big Data'. Major current and upcoming facilities (priorities of the previous ASTRONET Roadmap) provide astronomical data at rates never seen before, across the entire electromagnetic spectrum and beyond.

This rich landscape offers immediate opportunities to explore fundamental questions relating to the origins of our solar system, planets, stars, galaxies, and the entire Universe. It also presents the challenge of strategically allocating resources to exploit data from current and upcoming facilities (both small and large), develop computing and theory infrastructures, while also laying the groundwork required to take the next big steps that will consolidate and strengthen Europe's position at the forefront of all areas of Astronomy research. Reproducibility and open science have become vital, with the ever-increasing volume and complexity of astronomical data and simulations. Questions of sustainability and development must also be an integrated part of this planning, including issues around the impact of Astronomy research on our planet, the recruitment, training and nurturing of a broad and inclusive workforce, and the use of Astronomy as a vehicle for science education.

Extraordinary progress has been achieved across all areas of Astronomy research over the past decade, in large part the result of strong international collaborations and of the work of European intergovernmental organisations ESO and ESA. There are dramatic results in many areas, with highlights including the identification and characterisation of thousands of exoplanets, the detection of gravitational waves from coalescing compact objects and the identification of their electromagnetic counterpart, imaging of the material orbiting the black hole at the centre of the Milky Way and of M87, and detailed investigation of the structure and history of the Milky Way through massive surveys from space and the ground.

Together with the observation of extrasolar systems, the exploration of the Solar system by probes and robots has led to new insights into its formation and evolution. But impressive results have emerged in many other areas where increased samples, higher precision and new discoveries, often enabled by new instruments and technologies, confront models and require revisions to our understanding. Simulations of increasing complexity, including higher dynamic range, resolution, and both physics and chemistry, while exploiting increases in computing power, are harnessed to interpret results, and sometimes to show vividly the outcomes of the research. Judging by the way astronomical results fill the science pages in many media, it is clear that Astronomy has a powerful draw, which in turn means that astronomers have a special responsibility for the dissemination of research and engagement with the public.

This Science Vision and Infrastructure Roadmap provides an overview of the current status of European Astronomy, in terms of its research activities and facilities, and presents to funding agencies recommendations for the next decade, based on the priorities of the community. The Roadmap aims to be inclusive and representative of all communities undertaking astronomical research within Europe.

It considers observational facilities on the ground, in the stratosphere, and in space, covering gamma-ray to radio wavelengths, as well as subatomic particles and gravitational waves. It also includes exploration and in situ investigation of solar system bodies and the interplanetary medium.

The Roadmap also encompasses theory, computing, laboratory studies, and technology development, while considering the societal aspects and ethical implications of Astronomy research.

The recommendations of the ASTRONET Roadmap are far-reaching and ambitious. The current global context with war in Ukraine, inflation, and the post-pandemic society changes will make their implementation a challenge, but it also highlights the strategic importance of science, education, and international collaborations.

Scientific priorities

The strategic Roadmap for the next decade of European Astronomy is based on the scientific aspirations of the community to answer fundamental questions about our Universe, the most pressing being:

What is the nature of dark matter and dark energy?

Are there deviations from the standard theories and models (general relativity, cosmological model, standard model of particle physics)?

What are the properties of the cosmic microwave background, first stars, galaxies and black holes in the Universe?

How do galaxies form and evolve, and how does the Milky Way fit in this context?

What are the progenitors of astronomical transients?

What physical and chemical processes control stellar evolution at all stages, from formation to death, and how?

What are the necessary conditions for life to emerge and thrive? Are we alone?

How do planets and planetary systems form and evolve?

What is the impact of the Sun on the heliosphere and on planetary environments?

What are/were the characteristics and habitability of various sites in the solar system, such as Mars or Jupiter's icy moons?

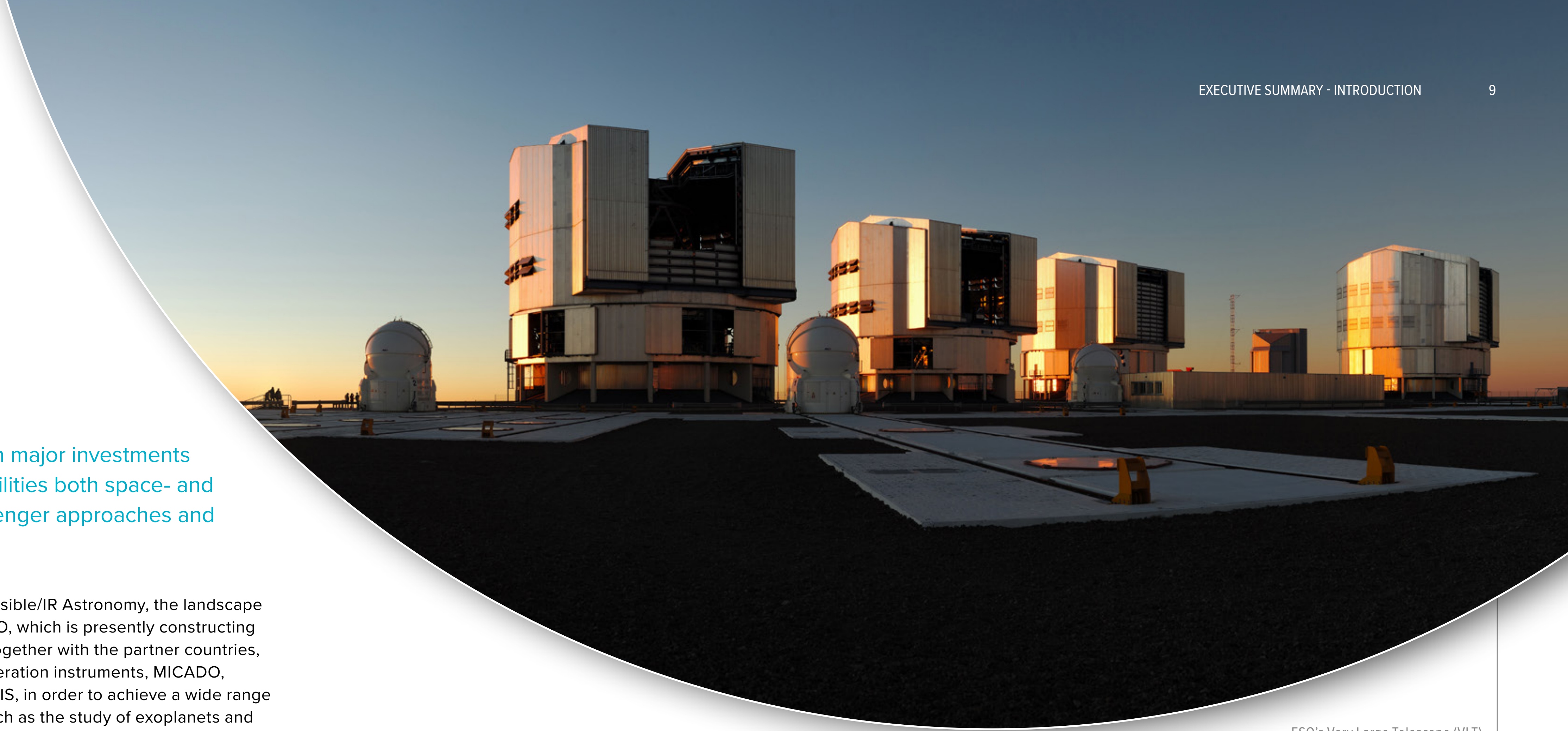
What is the origin of cosmic rays of all energies?

How can extreme astrophysical objects and processes probe new fundamental physics?

A general theme of the roadmap is the need for an integrated approach to decision-making if we are to achieve our scientific goals. This includes, for example, the necessity of planning for rapid response, small-scale facilities to complement large flagship observatories, to consider requirements for data processing, storage and dissemination at the stage of mission/facility planning, and to fund the computational and theoretical efforts that go hand-in-hand with breaking new observational grounds. While the strategic roadmap is shaped by science goals, its implementation must also respect the increasing desire of the European community to ensure Astronomy research is conducted in a sustainable and equitable manner that also fulfils our roles as educators and responsible citizens.

Overview of existing and upcoming observing facilities

In the coming decade, European Astronomy will capitalise on major investments from past decades that are delivering an important set of facilities both space- and ground-based, and spanning the whole range of multi-messenger approaches and electromagnetic wavelengths.



ESO's Very Large Telescope (VLT)

Credit:
ESO/F. Kamphues

In space, the **HST**, still up and running after more than 30 years in orbit, is now complemented by the 6.5 m diameter **JWST** and its four instruments, NIRCam, NIRSpec, MIRI and FGS/NIRISS. Observations of the X-ray and high energy Universe are currently possible with ESA's **XMM-Newton** and NASA's **Chandra** observatories, and with the ESA/NASA/Roscosmos **INTEGRAL** mission. The ESA programmes are continuing to develop at full pace. **Gaia** is delivering its impressive results on the content and history of our Galaxy, **Bepi Colombo** is on its way to Mercury, and **Solar Orbiter** is investigating physical processes at the solar surface and in the heliosphere.

Within the period 2023-2026, ESA is expected to launch further missions belonging to its Cosmic Vision programme: **Euclid**, to study the geometry of the Universe, as well as dark matter and dark energy; **PLATO**, for detecting and characterising exoplanets down to Earth sizes and in the habitable zone, while studying the internal structure of their host stars, and **JUICE** to explore the Jovian system.

These will be followed by other missions, such as **ARIEL**, to be launched in the late 2020s together with **Comet Interceptor**, then **EnVision**, in the early 2030s. Building on the success of the ESA **Mars Express** and **ExoMars Orbiter**, Europe is also confirming its long tradition of involvement in the exploration of solar system bodies, for example through its participation in the two rovers currently present on the surface of Mars: **Curiosity** (MSL mission) and **Perseverance** (Mars 2020 mission). It is also taking part in the NASA-led Moon exploration programme **Artemis**. Other missions, led by space agencies outside Europe, complete this landscape. These include the NASA missions **TESS**, studying habitable exoplanets orbiting very cool stars, and the **Nancy Grace Roman Telescope**, aimed at following up on Euclid to study dark matter and dark energy.

On the ground, in visible/IR Astronomy, the landscape is dominated by ESO, which is presently constructing the 39m **ELT** and, together with the partner countries, its suite of first generation instruments, MICADO, HARMONI and METIS, in order to achieve a wide range of science goals such as the study of exoplanets and protoplanetary disks, and the observation of individual stars in distant galaxies. ESO facilities also include the **VLT(I)** and some other telescopes at Paranal and La Silla, equipped with an impressive set of instruments for wide-field imaging, spectroscopy, and high angular resolution observations.

A counterpart in the Northern hemisphere is provided by the Roque de los Muchachos Observatory in the Canary islands, hosting the 10m-class **GTC**, as well as a suite of 4m- and 2m-class telescopes and smaller facilities. Other nationally-funded facilities provide essential complementarity to these pan-European observatories, including telescopes of the 4m- to 2m-class, the scientific use of many of which is coordinated by the Horizon 2020 Opticon RadioNet Pilot programme (ORP), whose efforts also include facilities at submillimetre and radio wavelengths.

The visible/IR landscape is completed by existing and upcoming facilities elsewhere in the world, including the **Vera Rubin Observatory**, the US-led plans for the **TMT** and construction of the **GMT**, and in the field of solar research, the **DKIST**.

In the mm/submm domain, the **ALMA** and **NOEMA** interferometers provide an exquisite sensitivity and angular resolution, while the **IRAM 30m** antenna is being upgraded. The international landscape at these wavelengths also includes the **JCMT**, **APEX** and **LMT**, as well as their crucial contribution to the world-wide collaboration operating the **EHT**.

The US-led **CMB-S4** will pave the way to high sensitivity CMB polarisation measurements.

Astronomy in the cm/m wave bands is presently relying heavily on **LOFAR** and **LOFAR2/NenuFAR**, and will later be revolutionised by **SKA** presently being constructed by the SKAO in South Africa (SKA1-mid) and Australia (SKA1-low), which, after its precursors such as **MeerKAT** and **ASKAP**, will undoubtedly dominate the field for many decades to come. The US-led **ngVLA** will complete the landscape at these radio wavelengths. Radio very long baseline interferometry provides the highest angular resolution imaging in Astronomy, and among all the VLBI networks, **EVN/JIVE** is the most sensitive. It delivers a wide range of excellent science and will remain the premier VLBI instrument during the SKA1 era. Large single-dish radio telescopes such as **FAST** and the **GBT**, as well as a range of other national facilities, offer complementary capabilities.

High energy astrophysics is developing at a rapid pace, with the upcoming construction of **CTA**, based on the heritage of pioneering projects such as **MAGIC**, **H.E.S.S.** and **VERITAS**, and will enable the study of the Universe in the gamma-ray domain.

Finally, multi-messenger Astronomy is opening up new windows on the Universe and is bound to play a major role in the next decades. Gravitational wave detectors such as **LIGO**, **VIRGO** and **KAGRA** are paving the way, while in the field of neutrino Astronomy, precursors such as Antares have built an important heritage over which new projects such as **IceCube** and **KM3NeT** are now developing.

This overview, while showing the impressive progress made in the past decade to provide efficient and versatile instruments, points to some important shortcomings, in particular in the ultraviolet and in the far infrared, where the community should direct some of its future efforts.

ASTRONET and the Science Vision and Infrastructure Roadmap

ASTRONET is a group of European funding agencies, community representatives and infrastructures working together as a forum for coordination for all aspects of European Astronomy.

Formed in the early 2000s with EU funding, it was responsible for the first European Science Vision and Infrastructure Roadmaps (2007/8) and their revisions (2013/14). It currently includes representatives from Austria, Belgium, the Czech Republic, Denmark, France, Germany, Ireland, Italy, Lithuania, the Netherlands, Poland, Portugal, Spain, Sweden, Switzerland, the UK and ESO. The European Astronomical Society (EAS), the European Space Agency (ESA) and the SKAO are also observers, and it has connections to independent research consortia such as the AstroParticle Physics European Consortium (APPEC), the Opticon Radionet Pilot (ORP) and Europlanet.

Since 2016, at the EU’s request, ASTRONET has been funded by the member agencies, with the delivery of a new Science Vision and Infrastructure Roadmap (this document) as its prime focus. For this current exercise, the ASTRONET Board appointed eight panels. Six of these panels are science-based, with the other two cutting across all science areas and looking at computing resources and societal impacts, respectively. Each panel was tasked with producing a report describing the current state-of-the-art research and facilities in their respective areas, assessing key questions and challenges, and making recommendations for the next decade.

The eight panels, each composed of 5-16 members (appointed for scientific expertise, as well as geographical and career stage balance), are:

Computing; big data, HPC and data infrastructure

Origin and evolution of the Universe

Formation and evolution of galaxies

Formation and evolution of stars

Formation and evolution of planetary systems

The solar system and the conditions for life

Extreme Astrophysics

Astronomy and society

The Editorial Board of the ASTRONET Roadmap was created in Autumn 2021, upon completion of the Panel reports, in order to establish overall priorities and formulate a list of recommendations, balancing scientific priorities, the current and upcoming landscape of both European and International research infrastructures, and overarching requirements relating to the desire of the community to move towards a model of sustainable, equitable and open science.

In order to prioritise observing facilities, the Editorial Board considered all the facilities reported in the Panel reports and assessed them for scientific impact, level of support across the European astronomical community, scale of European involvement, and uniqueness.

The following criteria were applied to decide which facilities were under consideration for the exercise:

- Only facilities where major funding decisions are still pending are considered for recommendation in the new Roadmap. In particular facilities currently under construction such as SKA1, or first generation instruments of the ELT are not.
- Facilities with first light expected by ~2035 were considered for immediate prioritisation, with those beyond that horizon instead included in the long-term vision section of the Roadmap.
- Facilities for which medium- to large-scale investment is required, defined for ground-based facilities as a European contribution to development and construction >€50M, and for space-based facilities following ESA’s definition of F-, M- and L-class missions as well as significant contributions to missions led by other space agencies.

After this exercise, the Editorial Board established priorities in eight different areas:

- Computing and data management
- New ground-based facilities
- New instruments and facilities upgrades
- Space-based facilities
- Laboratory astrophysics
- Technology development for facilities beyond 2035
- Sustainability and accessibility
- Training, education, and public engagement

The key recommendations in each of these areas are summarised in the remainder of this Executive Summary.

While the recommendations focus on major observing facilities and computation requirements, it is essential to remember that cutting-edge research relies on the interplay of instruments both large and small, across multiple wavelengths and messengers, as well as theoretical, numerical and laboratory investigations.

The ecosystem of European infrastructures needs to be balanced and synergised, in order to deliver the best science.

ELT under construction
at Cerro Armazones, Chile

Credit:
ESO/ S. Lowery

EXECUTIVE SUMMARY
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KEY RECOMMENDATIONS

1 Computing and data management

Astronomy is a data-intensive endeavour, and increasingly so with every new facility that comes online. The 2008 ASTRONET Roadmap already pointed out gaps in the funding and development of the necessary infrastructure to process, manage and make available the vast amounts of data, be they generated by telescopes, theoretical models, numerical simulations, or laboratory experiments.

This situation will be exacerbated in the next decade by the commissioning of facilities such as Euclid, the Square Kilometre Array (SKA) and the Vera Rubin Observatory (VRO), making it ever more urgent to include computing and data requirements at the core of our strategic planning.

Key recommendations are:

- Mission and facility planning should integrate plans for the production of science-ready data products and analysis tools, and for these initiatives to be funded for the long-term preservation and exploitation of the scientific data.
- A “tiered” approach for Data Infrastructure should be adopted and developed, for all types of data pertaining to astrophysics, including models, simulations and mocks, and where beneficial to connect with similar frameworks developed for other disciplines of science.
- The community should work towards a fully collaborative, open and synergistic view of the Astronomy-computing ecosystem, including data, software, analysis, simulations and modelling. Data and software storage/sharing facilities, archives, and cloud computing platforms are all facets of this integrated framework requiring funding.

2 Ground-based facilities

Completion of the construction and commissioning of the ESO Extremely Large Telescope (ELT) and its first generation instruments, as well as that of the Square Kilometre Array (SKA) Phase 1 and its Regional Centres are of key strategic importance. Amongst new ground-based infrastructure projects requiring major funding decisions, three emerge as priorities; two of those (CTA, EST) have unique capabilities and receive strong support from their respective communities, with the third (wide-field spectroscopic facility for a 8-10m class telescope) being a more general facility with applications from planetary systems to cosmology.

- First, the **Cherenkov Telescope Array (CTA)** is an array of telescopes located across two sites on both hemispheres to detect very high energy gamma rays from black holes and other extreme phenomena. As the first true large-scale observatory targeting these energies, it is expected to lead to breakthroughs in our understanding of the origins and production of non-thermal particles in the Universe. The construction of CTA is expected to start soon and the recommendation is to bring it to completion in a timely fashion.

The other two recommendations correspond to two additional, equally ranked, priorities:

- The **European Solar Telescope (EST)**, a 4m solar telescope to be built in the Canary Islands with first light expected by 2030. The EST will significantly increase our understanding of the solar magnetic field and its relations with the heliosphere and the Earth. Its completion and scientific exploitation in synergy with the US-based DKIST is a priority.
- A **general-purpose, wide-field, high multiplex spectroscopic facility**, for a telescope of the 8-10m class. Such a facility will enable a broad range of science investigations and help capitalise on other large investments by providing follow-up capabilities for facilities such as JWST, VRO and Euclid.

3 New instruments and facilities upgrades

Europe operates many astronomical facilities that will continue to do cutting edge science in the coming decade, both via existing functionality and continued upgrades to their capabilities. It is important to strengthen the ability of these successful facilities to secure the funding needed to continue their excellent scientific work, especially in a landscape of increased operations costs.

Across all science areas, there is a strong desire of the community to invest in upgrades and extensions to many of the flagship European facilities.

The following projects were seen as particularly important, for their broad scientific appeal:

- An upgrade of the **Atacama Large Millimeter/submillimeter Array (ALMA)**, as explored for example in the ALMA 2030 Vision, and including extending the frequency coverage with Band 1 and 2 receivers, longer baselines, wider bandwidths, and improved VLBI capabilities.
- The **Very Large Telescope (VLT)** and the **VLT-Interferometer (VLTI)** will remain the workhorse of European ground-based optical Astronomy even in the era of the ELT, and should therefore continue being supported and new instruments developed. Particular priorities for the community are the **BlueMUSE** integral field spectrograph, as well as high-contrast, **high angular resolution instrumentation** for e.g., exoplanetary system observations.
- While the ESO **Extremely Large Telescope (ELT)** and its first generation of instruments will see first light by the end of this decade, the immediate funding and development of second-generation instruments **ANDES** and **MOSAIC** is recommended.

ALMA (ESO/NAOJ/NRAO)

Credit:
W. Garnier

4 Space-based facilities

The major European space-based missions are coordinated by ESA, who has just completed its own scientific perspective exercise Voyage 2050, and is also currently defining its programme for human and robotic exploration, Terrae Novae 2030+, mainly targeting the Moon and Mars. The Panels of the ASTRONET Roadmap independently assessed the priorities of their respective scientific communities, with broad support emerging for the key facilities.

Concerning the previous and still ongoing ESA programme, Cosmic Vision, the following facilities, with first light expected before or by 2035, will play key scientific roles and should have their funding, development, launch and operations secured or, if not possible, alternative solutions to ensure an equivalent scientific return should be identified and implemented:

- The two future ESA L-class missions, **Athena** and **LISA**, are presently undergoing new studies, with the goal of cutting their costs down to 1.3 billion euros each. At the current stage of this ongoing exercise, the target is a cost reduction of about 30% for Athena and 10% for LISA. Acknowledging this budgetary context, it is recommended that both missions are adopted and developed in the best possible timeframe, preserving their initially-planned scientific return.
- The **ExoMars** mission was a priority of the astronomical community but it has been put in severe jeopardy by the geopolitical situation. Alternative scenarios to the cooperation with the Russian Roscosmos agency were studied, and the 2022 ESA ministerial council decided that a European lander would be developed to deliver the Rosalind Franklin rover to the surface of Mars. The exploration of Mars remains of major interest to the European scientific community, and the rapid implementation of this new strategy therefore a priority to preserve the scientific goals of the mission and minimise additional delays.

5 Laboratory astrophysics

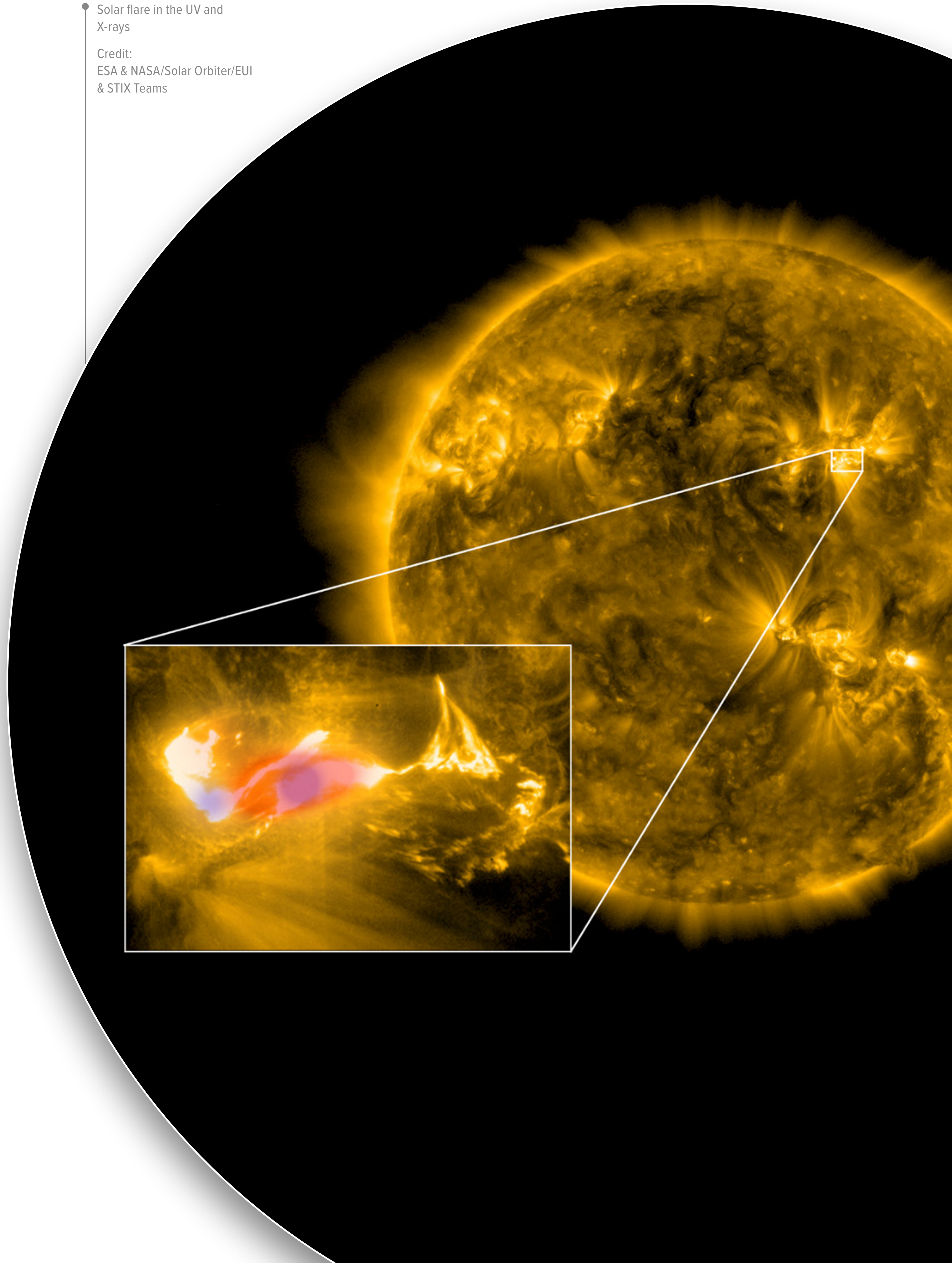
In addition to observational facilities, calculations and laboratory measurements of fundamental parameters such as equations of state and high-precision atomic and molecular line lists are required.

Laboratory experiments are essential to interpret astronomical data, both at the scale of individual astrophysical and astrochemical laboratories and in large facilities such as medium to high energy ion accelerators (GANIL, GSI, CERN) and synchrotron beamlines (e.g. SOLEIL, ESRF, DESY). This connection goes both ways; astronomical observations are also used to interpret laboratory data, providing a powerful synergy.

Laboratory astrophysics facilities necessary to underpin the physical understanding of observations must proceed hand-in-hand with observational facilities. While large observational facilities are often funded from major infrastructure grants, this complementarity is vitally important to the successful interpretation of many fundamental phenomena, such as (exo)planetary atmospheres, comets, supernovae, kilonovae, and their remnants, the evolution of the Milky Way and other galaxies.

It is therefore recommended that:

- Laboratories and archives are supported to effectively produce, archive, and provide fundamental data on atoms, molecules, and optical properties of solids for astrophysical and astrochemical purposes.
- Individual laboratories are supported to tackle investigations of both meteoritic samples and space-mission sample return materials.



Solar flare in the UV and X-rays

Credit:
ESA & NASA/Solar Orbiter/EUI & STIX Teams

6 Science and technology roadmap for facilities beyond 2035

Current and upcoming facilities will open up exciting opportunities for discovery. Examples of areas of future science discovery and some of the key facilities required are:

- **The origins of the Universe, inflation, and the emergence of cosmic structure:** Fundamental questions at the intersection of astrophysics, cosmology and fundamental physics, building on the success of current/upcoming experiments will require next-generation CMB experiments, the exploration of the transient sky, and large imaging and spectroscopic surveys.
- **New tests of physics in extreme conditions:** New technologies including third generation gravitational wave detectors such as the Einstein Telescope as well as improvements in neutrino and cosmic-ray capabilities will greatly enhance possibilities in multi-messenger Astronomy. Such facilities also offer new routes to study physics in strong gravity, the nature of dense matter, and the acceleration of cosmic particles.
- **The first stars, galaxies, and the epoch of reionisation:** To fully capitalise on the discoveries that JWST will enable, we will need the capabilities of SKA2 and new far-infrared/submillimeter facilities to characterise the interstellar medium, stellar populations and black holes of the first galaxies, and their impact on the intergalactic medium.
- **The formation of planets, stars and galaxies:** Understanding the assembly of planets, stars and galaxies requires information across the entire electro-magnetic spectrum, with a particular need in the next decades for new far-infrared and UV space telescopes, astrometric missions (e.g. GaiaNIR), and high-resolution, wide-field spectroscopic capabilities.
- **The origins of our Solar System and the characterisation of other worlds:** Future priorities include in situ observations of new worlds within our Solar System, especially the moons of the gas giants (as prioritised in ESA's Voyage 2050), and sample returns to Earth. The continued characterisation of exoplanet systems will require direct-imaging capabilities (e.g. ELT-PCS), and FIR/optical/UV spectroscopic capabilities to characterise atmospheres, or even infrared space-based interferometry (e.g. LIFE).

These long-term scientific ambitions can however only be met if crucial technological developments are anticipated and carefully planned well in advance. Most of the technologies that will be needed for the next generation of facilities are cutting-edge, and their emergence and maturation usually require a decade or more. The following technologies are priorities that need development now, if we are to build the facilities seen as priorities by the European Astronomy community for the next decades.

- **Receiver technology and dish development for Radio Astronomy:** While SKA Phase 1 will already open exciting opportunities, many of the scientific aspirations of the European community rely on SKA reaching its full power via Phase 2 construction. This requires significant technological progress in some key areas, including receiver technology especially at high frequencies, backend data handling, and progress in antenna manufacturing and installation.
- **Cryogenics and detector technology for far-infrared space telescope:** Among the major needs of the community in the mid- and long-term is a next generation far-infrared, large-collecting-area space telescope. Such a facility will require the development of improved cooling systems for both the telescope and its instruments, and detectors allowing for significant improvement in sensitivity and resolution over predecessors Spitzer and Herschel.
- **Space-qualified UV-optimised optical elements and detectors:** Access to the ultraviolet (UV) range is of utmost importance for the future of Astronomy. Anticipating the retirement of the Hubble Space Telescope and its UV instrumentation (STIS, COS), the 2020 US Decadal Survey has identified as one of its highest priorities a large collecting area space telescope covering the electromagnetic spectrum from the UV to the IR. The development of this future major facility, to which Europe will very certainly participate, requires in particular significant UV-related technological progress, necessary to optimise the space-qualified optical elements of this instrument in the UV (mirrors, gratings, etc.), as well as UV detectors and polarisation optics.
- **High-contrast imaging systems for exoplanet observations:** The Planetary Camera and Spectrograph (PCS) for the ELT will be dedicated to detecting and characterising nearby Neptune- and Earth-sized exoplanets. Achieving such a spectacular ambition requires a combination of eXtreme Adaptive Optics (XAO), coronagraphy and spectroscopy, all of which require technologies that can benefit from the strong heritage of today's instruments (e.g., SPHERE), but need to be pushed much beyond current capabilities.
- **Optical / infrared interferometry technologies:** The VLTI has become a very powerful facility for milli-arcsec studies of AGNs, exoplanets and young disks, evolved stars, etc. Future studies for optical - infrared interferometry include the construction a new array (Nx10 3-4m and/or 8m telescopes) up to kilometric baselines in an ESO / international context and to develop new technologies such as using heterodyne receivers for a large number of apertures, fibered beam transport and delay compensation, compact and fibered off-axis telescopes, etc. New technologies need also to be developed as the current concepts of classical telescopes and delay lines indicate that expanding the number of apertures to 10 - 15, or even more, encounters a limitation for the implementation.
- **Space- and lunar-based radio technologies:** A new frontier is to place facilities on or around the Moon, where a very low frequency radio array could open up the last unexplored wavelength range in Astronomy. International space agencies are pushing towards the Moon, and Europe intends to play a leading role on the surface. A European lunar lander is being designed by ESA to allow a series of different missions with various options for its payloads being studied. On its European Large Logistic Lander, there is an opportunity to develop a lunar far-side version of for example LOFAR and/or NenuFAR.

7 Sustainability and accessibility

A strong priority of the European Astronomy community is to see questions of sustainability, ethics, equality and diversity considered as part of decision making processes. The key recommendations are:

- Astronomy projects should include environmental footprint assessments and reduction plans regarding construction and management of facilities, travel and computing, to follow (at the least) the European timeline towards carbon-neutrality.
- The research community should use its platform to support education and public engagement activities in climate science.
- Diversity and inclusion should be central to funding strategies and plans. Data collection efforts should be standardised with suitable metrics to make meaningful comparisons and take action.
- Space is an increasingly active commercial sector for many countries. Whilst this has potential benefits for Astronomy it also comes with challenges, for example around risks associated with positional awareness, optical and radio interference and sustainability. The Astronomy community needs to work with national and international regulatory and policy bodies and with industry to ensure the protection of the dark, radio-quiet skies for the benefit of both the research communities and the general public.

Children in Tanzania playing with Earthball

Credit: UNAWE

8 Training, education and public engagement

The structures dedicated to facilitating or conducting Astronomy research keep increasing within Europe. Astronomy research requires unique technological developments, data management systems and highly-skilled research staff. This can lead to opportunities for innovation and market development, can attract investments and contribute broadly to socio-economic development. Community based science and community engagement have hitherto mainly been one-way processes from astronomy towards the community. To foster a positive impact of Astronomy on Society, and vice versa, it is recommended to:

- Further develop joint R&D and training programmes (MSc, PhD and PostDoc level) in close cooperation with industry, including training for entrepreneurship and social innovation.
- Ensure there are adequate training and career paths for Astronomy researchers specialising in the areas of advanced instrumentation, computing and data science.
- Further expand the recognition and award of researchers to include education and public engagement in their career paths.
- Promote modern cutting-edge Astronomy research, with emphasis on Big Science and Big Data, artificial intelligence, as well as technology R&D as part of the national education curricula.
- Include Astronomy education and public engagement as an integral part of facility/mission/project planning, devoting at least 1-2% budgets for professional Astronomy education and public engagement activities.
- Adopt an equal and respectful mutual engagement with communities in locations where plans for astronomical facilities are being developed, in full respect of the land, people, culture and ecosystems.

Stars Shine for Everyone activity in Belgium

Credit: SSVI

Gas and star formation in NGC4303 from ALMA and VLT/MUSE

Credit:
ESO/ALMA (ESO/NAOJ/NRAO)/PHANGS

INTRODUCTION

1 European Astronomy research and facilities

Extraordinary progress has been achieved across all areas of Astronomy research over the past decade, drawing huge interest from the public and media as well as from the wider scientific community. As has been the case for centuries, most Astronomy breakthroughs are triggered by technological advancements, improvements in computing methods and capabilities, and new theoretical ideas. This is especially true now, in this era of 'Big Science, Big Data'. For example, our recent ability to use gravitational waves and high energy particles to probe the Universe, in combination with the full coverage of the electromagnetic spectrum, is enabling fundamental new discoveries in areas from stellar physics to cosmology.

In terms of its facilities, European Astronomy benefits from having strong international institutions such as ESA and ESO, to take the lead in large-scale space- and ground-based projects, respectively. These facilities are part of a larger landscape that includes international observatories, often joint ventures between European and overseas partners, as well as national and institutional facilities. Cutting-edge research relies on the interplay of instruments both large and small, across multiple wavelengths and messengers, as well as theoretical, numerical and laboratory investigations.

The strategic Roadmap for the next decade of European Astronomy is based on the scientific aspirations of the community to answer fundamental questions about our Universe, the most pressing being:

- **What is the nature of dark matter and dark energy?** The importance of understanding the nature of dark energy and matter has triggered the development of numerous large ground and space-based galaxy surveys. These large-scale surveys include gravitational waves, spectral distortions of the cosmic microwave background radiation, large-scale structure, and cross-correlations between various probes. In particular, cross-correlations between various multi-tracer and multi-messenger probes form a key ingredient of modern major surveys designed to constrain dark energy and its evolution, and the nature of dark matter.
- **Are there deviations from the standard theories and models (general relativity, cosmological model, standard model of particle physics)?** At the onset of the 2020s, so-called tension is regularly found in measurements of the standard-model parameters when compared between, for example, early Universe probes, and late Universe probes. To widen or repair these cracks in the current cosmological model, powerful new instruments are needed in the coming decade, to provide robust answers to these questions.
- **What are the properties of the first stars, galaxies and black holes in the Universe?** The first stars formed some 100 million years after the Big Bang, and only 500 million years later early galaxies were well established, some with supermassive black holes. Studying directly the transition from the "Dark ages" of the Universe to the era of stars and galaxies, and measuring the properties of these first objects is now beginning to be possible.
- **How do galaxies form and evolve, and how does the Milky Way fit in this context?** When, where and how galaxies can build their mass via dark matter and gas accretion, followed by star formation, shapes the properties of galaxies over time. The range of physical processes and scales involved is vast, making this question complex and relevant to studies from planet/star formation, to cosmology. Fitting our observations of the Milky Way and its assembly history in the more global picture of galaxy evolution is of significant importance in these efforts.
- **What are the progenitors of astronomical transients?** Transients, such as supernovae, fast radio bursts, and gamma ray bursts are routinely observed, but in many cases their exact progenitors are not well understood. Making the connection between stellar progenitors and these energetic events is crucial to better understand the late stages of stellar evolution, and to improve the use of transients to probe questions in cosmology and interstellar physics.
- **What physical and chemical processes control stellar evolution at all stages, from formation to death, and how?** Stars are the basic constituents of today's Universe and play a major role in its structural, physical and chemical evolution. It is therefore essential to understand them in detail, and in particular to describe the physical and chemical processes that control stellar evolution.
- **What are the necessary conditions for life to emerge and thrive? Are we alone?** The evolution of the Universe toward more and more chemical complexity, leading eventually to the emergence of life, has become a major question that scientists are now investigating rigorously. The combination of vigorous interdisciplinary theoretical and experimental approaches to this question, the identification of potential sites for harbouring life in the Universe, as well as a thorough search for traces of life outside Earth, are the basic elements of this endeavour.
- **How do planets and planetary systems form and evolve?** Studying planetary system formation and evolution is necessary to understand the origin of Earth and of the Solar System. This research area has seen a revolution in the past few years, with an impressive development of our investigation of exoplanetary systems, as well as tremendous progress in our understanding of protoplanetary disks, both to be continued.
- **What is the impact of the Sun on the heliosphere and on planetary environments?** Matter and energy input from the Sun into the interplanetary medium is shaping the heliosphere, with strong consequences on the Earth's and other planets' environments. Studying the whole range of processes at work constitutes an important field of research in itself, known as "space weather", which needs to be fully developed.
- **What are/were the characteristics and habitability of various sites in the solar system, such as Mars or Jupiter's icy moons?** The question of the origin of life on Earth and potentially elsewhere in the solar system has become a major subject of research in recent years, and led to a rapid development of astrobiology. Progress in this field must be pursued, in particular by more detailed investigations of potential sites of past or present life outside the Earth.
- **What is the origin of cosmic rays of all energies?** A comprehensive multi-messenger observational campaign is required to address his century-old mystery. New cosmic-ray detectors will improve our understanding of the observed population via better measurements of spectra and composition, including novel routes to cosmic-ray identification and characterisation.
- **How can extreme astrophysical objects and processes probe new fundamental physics?** Extreme conditions create the opportunity to probe new physics. Dark matter should cluster strongly around very massive objects. The interaction of dark matter with either those massive systems or with itself in regions of sufficient density can provide a route to finally identifying its nature. Annihilations or decays resulting in neutrinos can be probed, with heavy dark matter decays a possible candidate for the origin of some of the observed high energy neutrino flux. Minute differences in the speed of light as a function of energy, or between the speed of light and that of gravitational waves or neutrinos, are greatly amplified by the very long path lengths to extragalactic sources, providing exquisite probes of some quantum gravity models.

The Astronet Science Vision and Infrastructure Roadmap 2022-2035 is ambitious. It is a challenging plan in the current global situation with the war in Ukraine, inflation, the post-COVID-19 changes in society, etc. Nevertheless we think that science and education are all the more important in this context. A key element of the recommendations is the strong support to the European intergovernmental organisations ESO and ESA. Without ESO we would not have the VLT(I) and soon the ELT, as well as European participation in global organisations like ALMA. The same is true for ESA that allows us to have a stable and long term dynamic space science program (including the exploration program). And last-but-not-least, cooperation with the US and other international partners is essential together with an open science and open skies policy.

2 ASTRONET and its mission

ASTRONET is a group of European funding agencies, community representatives and infrastructures working together as a forum for coordination for all aspects of European Astronomy. Formed in the early 2000s with European Union funding as an ERA-net, it was responsible for the first European Science Vision and Infrastructure Roadmap (2007/8) and its revision (2014/15). It currently includes representatives from Austria, Belgium, the Czech Republic, Denmark, France, Germany, Ireland, Italy, Lithuania, the Netherlands, Poland, Portugal, Spain, Sweden, Switzerland, the UK and ESO. The SKAO, European Space Agency and European Astronomical Society are associates, and it has connections to independent research consortia such as the AstroParticle Physics European Consortium (APPEC) and the Opticon Radionet Pilot (ORP), formed from the previous Optical Infrared Coordination Network for Astronomy (OPTICON) and RadioNet and to funded EU programmes such as ESCAPE and AHEAD.

Since 2016, at the European Union's request, ASTRONET has been self-funded by its members and all work associated with it is either provided 'in-kind' by those members or at 'no cost' by the community it serves.

In the original Science Vision (ASTRONET, 2007/8) it was stated that 'Realising all the plans and dreams (of the science community) would require substantial investments by national and international funding agencies, with significant long-term commitments for operations'. That remains true today and, whilst huge progress has been made in the intervening years, a strong and comprehensive vision for the science, and roadmap for infrastructures, with strong community involvement, is still the essential foundation for planning and realisation. For this reason, the delivery of a new Science Vision and Infrastructure Roadmap (this document) has been ASTRONET's prime focus.

Following publication of this Roadmap, ASTRONET expects to take a lead, working with its partners and the community, in taking forward the recommendations of the report, developing an implementation plan and acting as a catalyst for European astronomy in its broadest definition. Included within that will be:

- enhanced connectivity with the European Commission to identify opportunities and promote awareness of the needs of astronomy;
- greater engagement with strategic bodies such as the European Strategy Forum on Research Infrastructures (ESFRI);
- enhanced collaboration with common strategic objectives in associated scientific areas and promotion of inter-disciplinary engagement, for example via colleagues in Particle Astrophysics, Geophysics and Public Engagement;
- improved connectivity with significant international strategic planning activities, such as the US Decadal Survey.

ASTRONET will also work to increase its membership (both full and associate) to ensure that its work is representative, inclusive and recognised.

3 2008 Roadmap and progress since

The previous Astronet Science Vision and the Infrastructure Roadmap were published respectively in 2007 and 2008. These were updated five years later, accounting for some important decisions and context changes that had taken place in the interval. We can assess today the progress accomplished 15 years after the 2007 Science Vision, often thanks to major science infrastructures that were available when the Science Vision was published or became so shortly after. Similarly, we can examine to what extent the objectives of the 2008 Infrastructure Roadmap were met.

3.1 Science vision

The 2007 Astronet Science Vision was organised around four areas that were labelled with general science questions, themselves further subdivided into more detailed subjects. In this section, these four main science questions are briefly recalled, and some of the progress made since then is indicated. The summary presented here is only illustrative and by no means complete; the reader is referred to the panel reports, which present in much more detail the current state of research and the progress made in the last decade, in particular thanks to space missions and ground-based infrastructures led by European institutions, or to which Europe has made important contributions.

3.1.1 Do we understand the extremes of the Universe?

This broad science question includes issues such as the early history of the Universe, dark matter and dark energy, supernovae and gamma-ray bursts, physics in strong gravity, black holes and neutron stars, super-energetic radiation and particles. The Planck mission, launched in 2009, provided exquisite measurements of the key cosmological parameters and validated the Lambda-CDM model on cosmological scales. These results are now being complemented by large ground-based spectroscopic surveys, just starting or about to start, many under European leadership (WEAVE, 4MOST, MOONS). Interferometric observations of stars and gas in the centre of our galaxy, in particular with the Gravity instrument at the VLTI and the Event Horizon Telescope (EHT), have demonstrated the presence of a supermassive black hole, have provided a precise measurement if its mass, and are bringing decisive confirmations of general relativity theory in conditions of extreme gravity. Such studies were rewarded by the 2020 Nobel Prize to Genzel, Ghez and Penrose.

The nature of gamma-ray bursts and other super-energetic processes in the Universe have been studied by pioneering ground-based gamma-ray Cherenkov telescopes, such as MAGIC or H.E.S.S., soon to be followed up by CTA, starting a new era of gamma-ray astronomy. At the same time, multi-messenger astronomy, including neutrino and gravitational wave detectors, has opened a new window on the Universe, enabling the study of extreme events, such as supernova explosions or coalescence of black holes and neutron stars. The first detections of gravitational waves by the LIGO and Virgo collaborations, acknowledged by the Nobel Prize to Weiss, Barish and Thorne in 2017, are paving the way for a new era of discovery with next-generation facilities.

3.1.2 How do galaxies form and evolve?

This general question involves many fundamental scientific issues, among which the emergence of the first stars, galaxies and black holes from the dark ages, the formation and evolution of large-scale structures, the cycle of stars, gas and dust in galaxies, as well as the formation and evolution of our own galaxy. All these areas have seen major progress, mostly thanks to an ensemble of large infrastructures in space and on the ground. The sub-millimetre interferometer ALMA, first commissioned in 2010, and the far-IR space mission Herschel (launched in 2009) allowed us to study molecular gas and dust content of galaxies spanning a whole range of redshifts, while the centimetre and metre SKA pathfinders, such as LOFAR, whose science exploitation started in 2012, provided the necessary tools to explore galaxies at all epochs in the radio domain. In conjunction with analytic work and large suites of cosmological simulations, a solid framework is emerging in which galaxy formation and evolution is regulated by the cycling of baryons in and out of galaxies, the efficiency of the star formation process and its quenching through a range of physical processes, as well as the interplay of galaxies with their surrounding circumgalactic and intergalactic media.

Deep optical/IR surveys with HST and ground-based facilities such as the VLT helped complete the picture, by revealing the structure and kinematics of galaxies, linking their properties with their large-scale cosmic environment, and showing the impact of supermassive black holes on their host galaxies. Almost simultaneously, the space mission Gaia started in 2013 to build a census of more than 1 billion stars in the Milky Way, providing a dynamic map of our Galaxy and revealing a large fraction of its past history, allowing us to place it in this global picture for galaxy assembly.

3.1.3 What is the origin and fate of stars and planetary systems?

The formation and evolution of stars and their planetary systems was yet another major question identified by the 2007 Science Vision, which in turn can be translated into more elementary questions, such as the formation of stars and stellar systems, the universality of the initial mass function, the cycle of matter through stars and interstellar medium, the probing and modelling of stellar interiors, the census of exoplanets in our neighbourhood, the formation and evolution of planets, the search for habitable sites outside the solar system.

Here again, most of the progress in these areas can be attributed to some important space and ground infrastructures. In the field of star and planet formation, ALMA/NOEMA and Herschel, as well as high angular resolution instruments in the infrared, allowed us to study the physics and chemistry of protostellar and protoplanetary disks and to follow the early evolution of stellar systems.

Tremendous progress has been made in the detection and characterization of exoplanets, a field initiated by the discovery in 1995 of the first close-in gas giant orbiting 51 Peg by Mayor and Queloz, for which they obtained the 2019 Nobel Prize in Physics, then vigorously developed both from the ground with radial velocity surveys and from space with missions such as CoRoT, Kepler, CHEOPS and TESS, searching for exoplanetary transits. These efforts have led to a wealth of information about exoplanetary systems, their universality and their diversity.

3.1.4 How do we fit in?

This general and somewhat philosophical question was related to the processes in the Sun and Solar System, as well as to the origin of life on Earth and possibly elsewhere in the Solar System. As for the other three major questions, it was decomposed in a set of more focused topics, such as the physical processes in the Sun, at its surface, and in the heliosphere, the solar variability on all scales, and its impact on life on Earth, the formation, evolution and dynamical history of the Solar System, or the search for life beyond the Earth.

This field made very significant progress in the last one or two decades. Space missions such as CLUSTER, Hinode, STEREO, SoHo, SDO, now completed by Parker Solar Probe and Solar Orbiter, have provided and are providing a wealth of information on the Sun, its atmosphere and wind, and on how physical processes in the heliosphere impact the Earth, giving rise to a new branch of astrophysics known as space weather.

The exploration of the Solar System has also been a very active area. Missions such as Cassini/Huygens to Saturn and Titan, or, concerning the exploration of Mars, MSL and its rover Curiosity and Mars 2020 with Perseverance, or else Rosetta to the Tchourioumov-Guerassimenko comet, have all contributed to improve our understanding of these various Solar System bodies and brought their pieces to the puzzle of the origin of life and its past or present existence outside Earth. In particular, sample-return missions from the Moon, such as Apollo (US), Chang'e (China) and from asteroids, such as Hayabusa and Hayabusa2 (Japan), or OSIRIS-REx (US) have brought back to Earth several kilograms of extraterrestrial material for direct analysis, in order to determine the basic composition and geological history of various Solar System bodies, but also to identify the possible presence of building blocks of life outside the Earth. Further sample-return missions are planned in the near future, in particular the NASA-ESA Mars sample-return mission, whose first segment is the Perseverance rover presently exploring the surface of our neighbour planet. Other projects include the Japanese MMX mission to Phobos, the Chinese Chang'e 6 mission to the Moon, or the Russian projects Luna-Glob (Moon) and Mars-Grunt (Mars).

3.2 Infrastructures

In terms of research infrastructures, the 2008 roadmap had identified some major priorities, divided into ground-based and space infrastructures, each section being organised in three categories, large-, medium-, and small-scale. Significant progress in the development of these facilities has been made since this previous exercise, resulting in some major scientific results in all areas of astronomy.

However, as is inevitably the case with large projects, often involving complex technology and international consortia, some delays were experienced by many of these projects. It is instructive to recall the top priorities emerging from the Astronet 2008 roadmap, together with their foreseen timescales, to be compared with today's situation.

3.2.1 Ground-based, large scale (≥ 400 M€)

This category concerns very ambitious projects, which tend to be much more complex than those of previous decades. This trend is not unexpected, considering that further progress in astrophysics most often requires huge steps to be taken in the instrumentation in terms of information carriers, spectral range, resolution (spatial, spectra, temporal) and sensitivity. As a result, new generation major infrastructures are usually at least significantly above those of previous generations, both in terms of cost and organisational complexity. It is therefore not a surprise that projects in this category have slowed down advances with respect to the 2008 expectations. Astronomy has become Big Science.

Two equally high priorities were identified by the 2008 Astronet roadmap in this category, and still today constitute major flagships of European ground-based astronomy for the foreseeable future.

The ESO Extremely Large Telescope (ELT), called the E-ELT in 2008, was planned to be a 42m optical and infrared segmented telescope, able to accommodate six focal stations. At the time of writing the 2008 roadmap, the decision for the construction of the E-ELT was foreseen to be taken in 2010. In reality, following some difficulties in welcoming new ESO members or attracting new partners and the budgetary tensions that resulted, the decision was finally taken in December 2014 for the construction of a 39m telescope, with three first-light instruments (MICADO, HARMONI, METIS) and a multi-conjugate adaptive optics relay (MORFEO). First-light of the ELT, equipped with its initial suite of instruments, is currently planned at the end of the 2020s.

The Square Kilometre Array (SKA) aperture synthesis radio telescope was expected to cover the band 70 MHz – 25 GHz. At the time of the 2008 roadmap writing, the SKA deployment was planned to come in 3 successive phases of increasing completeness, with phase 1 covering 15-20% of the total collecting area and restricted to mid-band frequencies, phase 2 corresponding to the full collecting area, up to 10 GHz, and phase 3 extending the coverage to the full frequency band. According to the 2008 Astronet roadmap, the decision for the launch of phase 1 was supposed to occur in 2012, and that for phases 2 and 3 in 2016. Following these initial estimates, the SKA project has tackled challenges and delays, including in setting up an international governing organisation on which it is based. As a result, the SKA-Organisation, designed to establish the organisational, design and funding basis of this world-wide project, became the SKA-Observatory in 2019. The actual decision to launch the construction of phase 1 was taken in 2021, the construction itself being expected to take up to 5 years. The actual SKA phase 1, after a major redesigning exercise, is now planned to cover both low- and mid-band frequencies, and to represent 10% of the targeted full collecting area. It will be deployed on two separate sites: SKA1-LOW, covering the 50 – 350 MHz band, in the Murchison desert in western Australia; and SKA1-MID, working in the 350 MHz – 15 GHz band, in the Karoo desert in South Africa. No date is announced at this time for the decision-making process concerning a phase 2, which will probably not be deployed before the mid-2030s.

3.2.2 Ground-based, medium scale (50 - 400 M€)

Three facilities were recommended and ranked in this category. The development of all three of them progressed during the years following the Astronet 2008 Roadmap, but at different paces. Their degree of advancement in 2022 depends more on the difficulties encountered, either technical, budgetary or organisational, than on their rank in the previous Astronet Roadmap.

The top priority in the medium-scale category was the European Solar Telescope (EST), a 4.2m solar telescope, equipped with adaptive optics, to be installed in the Canary Islands. The EST was recommended in 2008 to be introduced in the European Strategy Forum on Research Infrastructures (ESFRI) roadmap and implemented as early as possible. It finally entered the ESFRI roadmap in 2016, and its preparatory phase (Pre-EST) started in 2017. An interim legal figure for EST has been approved, and will be signed into implementation shortly. The telescope is scheduled for PDR in mid 2023 and the project expects to request the construction permit by the end of 2023, so that if the ERIC is in place construction could start in the second half of 2024.

The second priority in this category was the Cherenkov Telescope Array (CTA), a high energy astronomy observatory, designed to detect gamma-rays at energies between a few tens of GeV and 300 TeV. The CTA will be deployed on two sites (North and South), and composed of three types of telescope: large-size telescopes (LST, diameter 20m, low-energy range), medium-size telescopes (MST, diameter 10m, medium-energy range), and small-size telescopes (SST, diameter 4m, high-energy range). The recommendation of the Astronet 2008 roadmap as to the schedule of this facility was not very precise, simply quoting a timescale around 2015 for its construction. The CTA entered the ESFRI roadmap in 2008, with an expected first-light in 2024. However, the initial study and prototyping phase was longer than expected, and the cost book and scientific & technical description of the observatory was approved by the Board of Governmental Representatives in June 2021 only, to be followed by the establishment of an ERIC, after which the construction will take at least 5 years.

A third priority was the KM3NeT facility, a neutrino Cherenkov detector involving a 1 km^3 volume of water in the Mediterranean Sea. The Astronet 2008 roadmap did not indicate any timeline for this facility, whose phased development actually started in 2015, with its first phase having started operations in 2022.

3.2.3 Ground-based, small scale (≤ 50 M€)

The major priority in this third category was the development of wide-field, highly multiplexed spectrographs, in particular to be placed on existing 8-10m class telescopes. This kind of instrument is meant to provide massive spectroscopic surveys at a speed compatible with the new generation wide-field imagers, such as the Vera Rubin Observatory. The Astronet 2008 roadmap recommended the implementation of such facilities for the 2015 – 2020 timeframe. This recommendation triggered the development of instruments such as MOONS on the VLT, 4MOST on 4m-class VISTA, WEAVE on 4m-class WHT.

3.2.4 Space-based, large scale

The Astronet 2008 roadmap first listed in this category the proposals submitted to the "L" mission component of the ESA Cosmic Vision program. The landscape in 2022 is of course simplified by the selections made by ESA, but needs to be completed with the missions that were or will be flown by other agencies (see Sections "Current and upcoming facilities" and "The future roadmap: beyond 2035").

In the field of planetary sciences, JUICE was selected as L1 (replacing the initial LAPLACE proposal). It is an observation and in-situ exploration mission to Jupiter and its icy moons, to be launched in 2023 for an arrival on site around 2030.

In high-energy astrophysics, the X-ray observatory Athena was selected as one of the next large missions of the Cosmic Vision programme (replacing the XEUS/IXO proposals), while the gravitational wave space observatory LISA, was also selected as a future large mission of that programme. The 2008 ASTRONET Roadmap identified both Athena and LISA as the top two priorities in the category of large-scale space-based facilities. Both missions are supposed to be launched in the 2034-2037 timeframe. However, due to recent financial difficulties, ESA decided on a new budget cap to both missions. Athena and LISA are presently being studied within this new programmatic constraint.

The L1 proposal TANDEM, a mission to Titan and Enceladus, also appeared in the 2008 Astronet roadmap, but was not selected by ESA.

Also not selected were the following three proposals, judged too challenging although scientifically highly rewarding, so that they were to be considered for the longer-term future: DARWIN (interferometric mission for the study of exoplanets and search for life), FIRI (free-flying ensemble of 3 space telescopes operating at far infrared wavelengths), and PHOIBOS (mission to study the inner heliospheric regions down to 3 solar radii).

The 2008 roadmap also included the ExoMars missions (ExoMars 2016 and 2018, both included in the ESA Exploration program) as third priority (after Athena/LISA and JUICE). These missions are developed within a collaboration between ESA and the Russian space agency Roscosmos. The first one was launched in 2016 as expected, and included an orbiter and a landing demonstrator. The orbiter has been working well since its orbit injection, while the landing demonstrator failed. The second mission is ready to go and was supposed to be launched in 2022, but is now severely delayed due to the Ukrainian-Russian war.

3.2.5 Space-based, medium scale

In this category, the 2008 Astronet Roadmap discussed all proposals to the "M" mission component of the ESA Cosmic Vision 2015-2025 program, and established a priority list. From these missions, the top three Roadmap priorities, all ultimately adopted by ESA, were:

- Gaia, a full-sky astrometry mission, which had been selected earlier, was launched in 2013, and since then has been successfully producing data which are delivered to the community as successive data releases.
- Solar Orbiter, a solar and heliospheric observatory, selected as M1 within the Cosmic Vision program, was launched in 2020, and started its routine science operations in November 2021.
- Euclid, a mission to map the geometry of the Universe, selected as M2, will be launched in 2023 by a Falcon 9 rocket, a decision recently made by ESA after the initial launch plan by a Soyuz from Kourou in French Guiana became impossible as a consequence of the Ukrainian-Russian war.

In the next level of priority, the 2008 Roadmap identified the M-class missions Cross-scale, Simbol-X, PLATO, SPICA, and Marco Polo. Of these five, only PLATO, a mission to detect and characterise exoplanets and study their host stars via asteroseismology, was selected as M3, and is expected to be launched in 2026.

ESA has since then continued the definition of the M-class segment of its Cosmic Vision programme, with the selection of ARIEL, a mission to characterise the atmospheres of close-in exoplanets, and of EnVision, a mission to explore the atmosphere and ground of Venus. It is currently in the selection process of another M-class mission (M7), whereas the M6 slot was cancelled, as well as of an F-class mission (F2). At the time of writing this report, there remain 5 candidate missions to the M7 slot, soon to undergo a phase-0 study, in the fields of high energy astrophysics, stellar physics, plasma physics, and planetology, while a mission in the field of cosmology was selected for the F2 slot.

4 Methodology of the current exercise

Whilst other roadmapping exercises (e.g. Decadal Survey, Voyage 2050) have invited white papers to provide the appropriate background from the community for their reports, ASTRONET decided that this could be achieved via a combination of expert panels and community consultation. This approach mirrors that adopted for the original ASTRONET Science Vision. The remits of the panels were derived from the key science questions, again, based upon those outlined before, since these were considered to cover all aspects of the mission for astronomy.

However, in consultation with the community and colleagues in Particle Astrophysics, an additional panel was added to cover Extreme Astrophysics and to ensure there were no gaps between the coverage of ASTRONET and its sister organisation, APPEC. It was recognised at an early stage that more than one cross-cutting panel would be required to address areas that would affect most, if not all, of the science drivers. Accordingly, two panels were included to look at computing resources and Astronomy and society. The Panels are:

A. Computing; big data, HPC and data infrastructure

B. Origin and evolution of the Universe

C. Formation and evolution of galaxies

D. Formation and evolution of stars

E. Formation and evolution of planetary systems

F. The solar system and the conditions for life

G. Extreme astrophysics

H. Astronomy and society

Panel membership was proposed initially by the members of the ASTRONET Board, with a view to ensure the panels were representative in career stage, gender, science coverage and geographical spread. The membership represents the best that could be achieved for an exercise that did not offer remuneration, came at a time when the Covid pandemic was beginning to have a severe effect and required considerable commitment from all that accepted the invitation. Once panels had self-selected chairs, additional members were added by ASTRONET on request and where coverage was considered inadequate. Each panel was composed of between 8 and 12 members, including the chair (see Appendix A for panels membership).

Each panel was tasked with producing a concise report describing the current state-of-the-art research and facilities in their respective areas (where relevant), assessing key questions and challenges and making recommendations for the next decade. The reports constitute the basis for the key recommendations presented in this Roadmap. In the event, the pandemic had a severe effect on the ability of the community to deliver to schedule. Adding the required work to the demands of lockdowns, family and health issues, remote teaching etc. meant that over a year was lost compared to the original plan. One consequence of this delay is that some parts of the reports were written up to 2 years before completion of this Roadmap, and in spite of efforts to update them with recent developments, some aspects of them may be slightly outdated. Nevertheless, the immense effort and dedication of the panels and their chairs demands high praise.

The first drafts of most reports were presented to a webinar attended by over 400 researchers and hosted by the European Astronomical Society (EAS) in June 2021. The drafts were subsequently made available to the community via the ASTRONET web pages and advertised via a variety of national mailing lists. Once the remainder of the reports were available, a second consultation period was held between June and August 2022. The Editors presented the status of the report to the EAS meeting in Valencia in July 2022. Several updates on the Roadmap process were provided to the APPEC GA, the European Planetary Society and within ASTRONET member organisations, as well as to the ASTRONET Board.

Considerable efforts to appoint a lead Editor at the start of the report process failed (none of those approached were able to provide the required commitment - though all welcomed the opportunity). Accordingly, an Editorial Board was created by the ASTRONET Executive in Autumn 2021, upon completion of the panel reports (see Appendix A for Board membership). The role of the Editorial Board was to establish overall priorities and formulate a list of recommendations, balancing scientific priorities, the current and upcoming landscape of both European and International research infrastructures, and overarching requirements relating to the desire of the community to move towards a model of sustainable, equitable and open science.

In order to prioritise observing facilities, the Editorial Board considered all the facilities reported in the Panel reports and assessed them for scientific impact, level of support across the European astronomical community, scale of European involvement, and uniqueness. The following criteria were applied to decide which facilities were under consideration for the exercise:

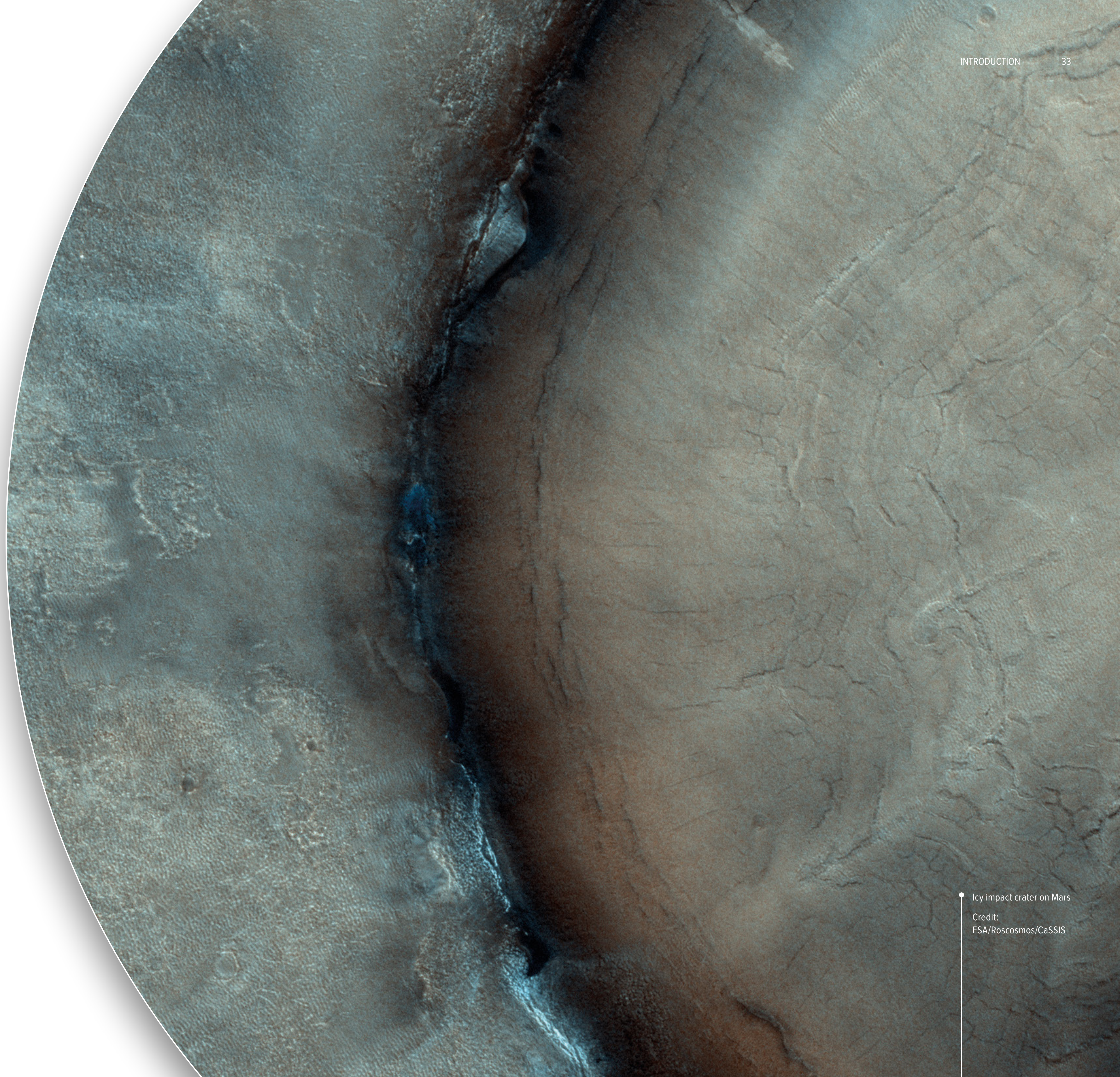
- Only facilities where major funding decisions for their construction still pend (rather than decisions about further running / exploitation costs / data centres) are considered for recommendation in the new Roadmap. In particular, facilities currently under construction such as SKA1, or first generation instruments of the ELT, are not.
- Facilities with first light expected by ~2035 were considered for immediate prioritisation, with those beyond that horizon instead included in the long-term vision section of the Roadmap.
- Facilities for which medium- to large-scale investment is required, defined for ground-based facilities as a European contribution to development and construction >€50M, and for space-based facilities following ESA's definition of F-, M- and L-class missions as well as significant contributions to missions led by other space agencies.

In making recommendations for new facilities, the assumption was made that currently-running or upcoming facilities (those with already secured construction funds) and their instruments would remain supported with sufficient budgets to ensure their continued operations on the timescale to 2035. These facilities form the baseline used to assess new projects.

After this exercise, the Editorial Board established priorities in eight different areas:

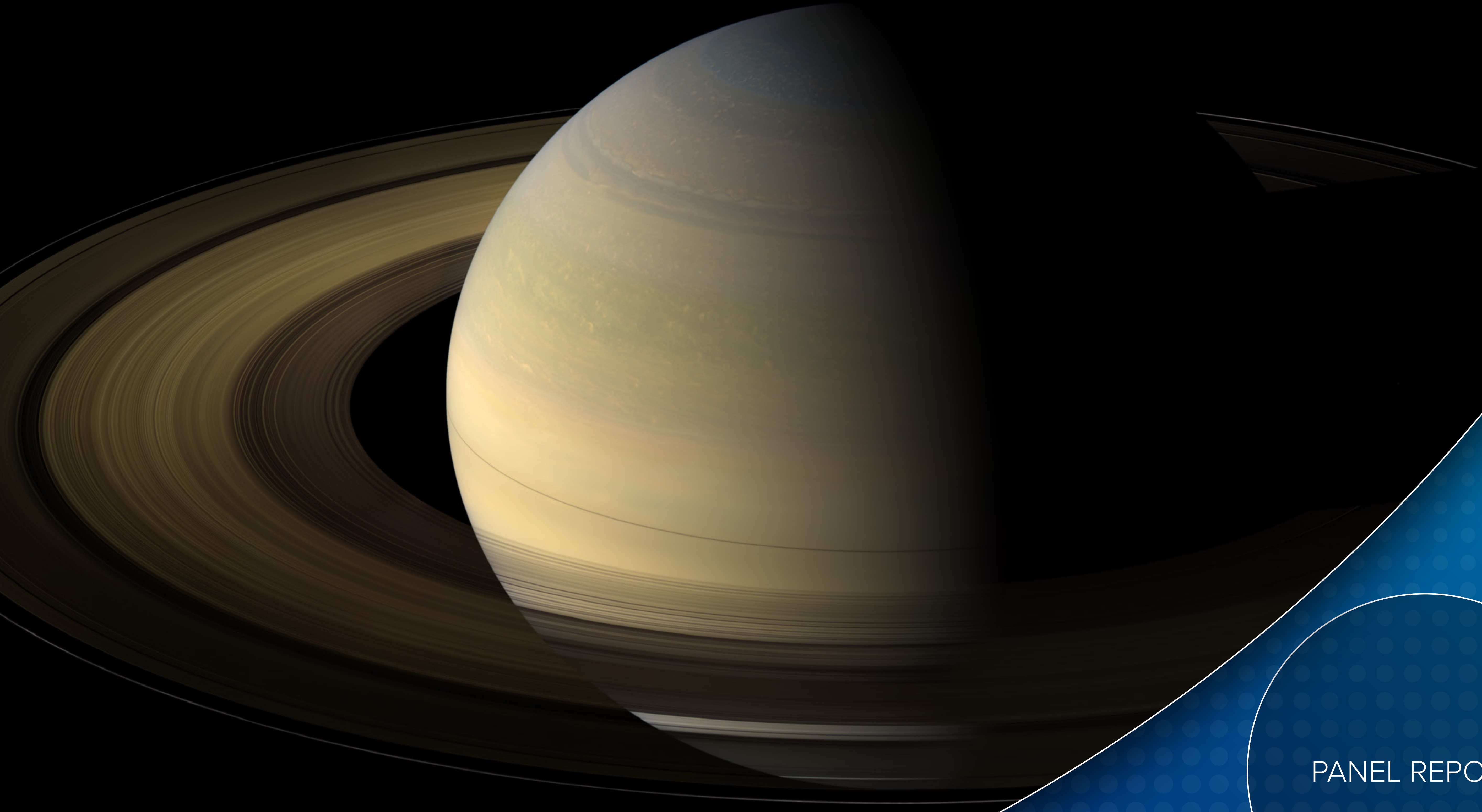
- **Computing and data management**
- **New ground-based facilities**
- **New instruments and facilities upgrades**
- **Space-based facilities**
- **Laboratory astrophysics**
- **Technology development for facilities beyond 2035**
- **Sustainability and accessibility**
- **Training, education, and public engagement**

The recommendations and priorities are summarised in the Executive Summary, and presented in full in the Roadmap section. While the recommendations focus on major observing facilities and computation requirements, it is essential to remember that cutting-edge research relies on the interplay of instruments both large and small, across multiple wavelengths and messengers, as well as theoretical, numerical and laboratory investigations. The ecosystem of European infrastructures needs to be balanced and synergised, in order to deliver the best science.



Icy impact crater on Mars

Credit: ESA/Roscosmos/CaSSIS



Saturn at equinox from Cassini

Credit:
NASA/JPL/Space Science Institute

PANEL REPORTS

A

Computing; big data, HPC and data infrastructure

Top Level Key recommendations

Key 1:

[People] we recommend developing and investing in a professional software engineering / computational skills base in Astronomy. This has many implications and requirements, including career development with clear progression pathways in academia and improving the diversity of the workforce. Such careers have to be promoted and considered as an integral part of our science/research portfolio. Traditional metrics for academic performance are often inappropriate for measuring the impact and usefulness of computationally focussed outputs. New assessment criteria, for example based on industrial models, should be adopted by the astronomy community to give proper credit to essential contributions that technicians and software engineers provide.

Key 2:

[Data, Open, Archive, User-to-Data] we recommend that missions and facilities plan an integrated approach for data products and software tools: their design, delivery, maintenance and development should be sufficiently planned for and resourced already at the onset and for the lifetime of the mission/facility. We recommend that initiatives be supported for the long term preservation and scientific use of data.

Key 3:

[Data, Archive, User-to-Data, Open, Green] we recommend to adopt and further develop a “Tiered” approach for Data Infrastructure, for all types of data pertaining to astrophysics, including models, simulations and mocks, and where beneficial to connect with similar frameworks developed for other disciplines of science. A `Tiered’ Distributed Analysis model maximises the transformation of science data to scientific results, organising and sharing expertise to benefit from economies of scale, with attention given to preventing the exclusion of individual communities, as well as monitoring and minimising the environmental cost.

Key 4 :

[Open, User-to-Data, People, Green] we recommend embracing a fully collaborative, open and synergistic view when it comes to the astronomy-computing ecosystem, encompassing data, software, processing, analysing and modelling. The community should implement and support official mechanisms to monitor, acknowledge and reward behaviours that model this ambition.

Open science, data and software sharing, archives, cloud computing, platforms and service infrastructure represent various facets of an integrated view of computing in astronomy: this should be acknowledged and acted upon.

Key 5:

[Green] We recommend that ASTRONET produces or commissions a biennial quantitative report to assess the carbon footprint of computing in Astronomy. The initial review should define clear measurable metrics against which progress can be evaluated. We further recommend that ASTRONET strongly encourages the use of efficient programming languages and computational architectures for intensive computations, the training of its scientists and developers in this regard, and strives to ensure that all computation performed is strictly required to achieve the desired science goals - all with the aim of minimising the environmental cost.

Key 6:

We recommend that ASTRONET develop specific actions to coordinate cross-cutting activities. Transparent mechanisms should be defined and implemented to monitor and report on the progress pertaining to computing in Astronomy. This may involve the implementation of dedicated polls and studies, coordinated working groups reaching out to research groups and centres, communities, national and transnational entities, leading to an exposed and clear mandate for technology and solution watches.

The implementation of such recommendations requires an update of our research crediting and promoting system, as well as a more collaborative and ordered set of resources (e.g., funding agencies, grants, computing centres).

Keywords in brackets refer to specific sections of this document:

- [Open] = The paradigm change: Open Science, Data and Software sharing
- [Data] = Mission / Facility data processing
- [Archive] = Archives for data and software
- [User-to-Data] = The next generation tools: Cloud computing, Platforms, Collaborative frameworks
- [Green] =Green Data Infrastructures, Reducing the Carbon Footprint
- [People] = Training, Careers, People

General Introduction

The wide and diverse range of astrophysics research in this roadmap leads to cross-cutting requirements for data handling techniques, software, simulations and computing. Astrophysics research has already become a data-intensive endeavour, and the future large, complex and inter-dependent data sets that will be generated by observatories, space missions, mock experiments, theoretical model simulations and numerical simulations require new tools and approaches for doing science.

Scientific questions are driving the need for surveys that e.g., cover large regions of the sky, obtain deeper exposures or include multi-frequency/messenger coverage. The sheer data volumes from such experiments will increase at a high rate with a number of projects/facilities expected to have annual data production of the order of petabytes, and hundreds of petabytes for the extreme example of SKA. The archives of the future large data producing telescopes and missions will dwarf the existing ones in terms of volume and complexity.

We have also entered the era of multi-messenger astronomy. Going beyond the often-quoted advent of gravitational wave science or the synergy with astroparticle physics experiments, the trend is towards the need to combine data from observations across the electromagnetic spectrum and beyond. This is in addition to the transient object searches of time domain astronomy, leading to high flux event streams where rapid detection, classification and follow-up observations bring new challenges for computing and analysis.

Dedicated simulations, either conducted as numerical experiments or modelling efforts, also reach levels of complexity and volumes which call for an updated assessment of how we run them, process them, and share and distribute their outputs and associated data products. This is all the more true when auxiliary products and models (e.g., mock simulations, various realisations of the same datasets), themselves challenging to produce and store, must be associated with those primary simulation datasets.

We can expect users to interact with data from diverse sources. The need to jointly analyse datasets from a variety of instruments/facilities with different characteristics, as well as to connect the observational and simulation/modelling landscapes further motivates the development of flexible and transparent frameworks where the focus shifts from data towards the applied expertise and tools. This is sometimes reinforced by the paradigm shift pertaining to sharing information and the push for “Open Science”, often emphasised by national and European funding agencies and organisations. The added value will come from the access to expertise, supported by media and tools that alleviate the difficulty of dealing with varied datasets.

This motivates new ways to deal with data, using e.g., science analysis platforms that enable a “bringing computing to the data” paradigm. We further need to look at the technical resources, infrastructures, identify potential obstacles and challenges (e.g., the scaling and access to fast network connections). Most importantly, we need to scrutinise the existence and access to relevant expertise.

The technologies that will enable cross-cutting activities related to data and computing are evolving extremely rapidly. Astronomy, and indeed all scientific domains, will benefit greatly from increases in network speed, access to large volume data storage, fast computing as well as from the adoption and application of machine learning, informatics and the rise of data science as a discipline. Many fields face common challenges which at some level can be addressed by initiatives and developments such as the European Grid Initiative (EGI), and European Partnerships for the European Open Science Cloud (EOSC) and for High Performance Computing. There are also benefits that will come from widespread use of common tools and methodologies, such as collaborative development tools (e.g. Gitlab), sharable notebooks and workflows (e.g. via JupyterHubs), and building on ground-up developments such as astropy. From the individual researcher, up to the largest projects, the cross-cutting technologies that will influence the next decade will involve the wider context of computing and data infrastructures for science in general.

This document aims to provide a few principles and key points that are designed to support a pragmatic approach to address such challenges. It emphasises the need to actively monitor the ongoing and future technology and paradigm changes associated with computing in astronomy. It requires acting immediately and globally, with close coordination between missions, facilities, funding agencies, and key actors in the astronomical community. These challenges are not specific to computing in astronomy, are shared by other sciences, and must sometimes be viewed at the societal level. We thus need to coordinate such an upgrade of our services and infrastructures with other disciplines, building on the robust baseline and specifications we have deployed over the last decades, while making use of the quite unique vantage point and attractiveness of astronomy.

Finally, we should acknowledge that many of the proposals made here come with an apparent cost. However, investment in data brings added value to the wider astronomical community, and can help reduce waste in other areas, for instance, in removing costs associated with inefficient access to high quality science ready data products. As a community we need to provide a clear sense of direction and make choices, to support the investments in people, computing infrastructure etc, that we recommend. Given how vital the contribution of computing is to modern astronomy and astrophysics, it is a science-driven necessary cost and must be treated as a top priority item, in contrast with what has so often been done in the past. This is a prerequisite for high quality and shared science. We should also consider that implementing the coordination advocated in the present document would partly address the existing resource (software, hardware, possibly staff) fragmentation, which in turn would boost efficiency and create potential cost margins.

[OPEN] The paradigm change: Open Science, Data and Software sharing

Key Points

- Open-1: The Astrophysics community should be encouraged to engage with, and participate in, EOSC and other European or national Open Science initiatives, to benefit from them, and to ensure that astronomy requirements and feedback are taken into account.
- Open-2: Promoting and adopting principles of FAIR, Open data and open-source software should become the default requirement for all of Astronomy within the next decade. This should commit the research community at large, as well as all the associated actors: research institutes, national and transnational organisations, missions and observatories. Doing so will be essential to fully exploit the capabilities of next-generation facilities, maximise the impact of scientists' research, and build up a virtuous and inclusive environment that promotes the development of tools.
- Open-3: Encourage community development of software, supported by long-term funding, and provide proper credit to such efforts (see Open-4).
- Open-4: The current framework for reward and recognition in astronomy research is outdated and requires radical changes to acknowledge the increasing contribution of software developers, data scientists and data stewards to the scientific yield of our facilities and instruments.
- Open-5: Given the potential costs associated with making Big data sets, simulations sets, and software Open and compliant with the FAIR principles, it is crucial that that community establishes whether complete access is useful in all cases. Where the choice is made not to make particular datasets FAIR, this should be done because of an untenably high cost-benefit ratio for the whole astronomy community and not to e.g., artificially increase the journal article output of those who do have full access.

Open Science and Open Data are central to the Strategic Research and Innovation Agenda of the European Open Science Cloud (EOSC), which is now entering its 10-year implementation phase following the creation of the EOSC Association. EOSC will "enable a trusted, virtual, federated environment in Europe to store, share and re-use research data across borders and scientific disciplines" based on the precept that all data artefacts should be Findable, Accessible, Interoperable and Reusable[1] (FAIR).

It is incumbent upon the astronomy and astrophysics communities within Europe to ensure that they continue working towards the adoption of FAIR principles by defining sets of common metadata standards and agreed procedures to enable widespread data sharing. Substantial progress has already been achieved with the astronomical Virtual Observatory (VO), which is a framework for FAIR astronomy data based on common internationally agreed interoperability standards. Since 2002, the International Virtual Observatory Alliance (IVOA) has advised and overseen development of the VO with support from numerous aligned national initiatives. The VO is now a mature framework that is used by astronomers around the World. It is embedded in major astronomy archives and data centres including ESA, ESO and CDS, and is integrated into a large number of tools, online services and software frameworks.

The usefulness and scientific yield of Open and FAIR astrophysical data is substantially reduced without the knowledge, expertise and appropriate software to process and analyse them. An outstanding challenge for the astronomy community in the coming decade is to build on the success of VO by defining common strategies for sharing software, its documentation and contextual metadata about its intended execution environment. One example of ongoing work to address this challenge is the ESCAPE Open Software and Services Repository (OSSR). The OSSR prototype aims to provide "a sustainable open-access repository to share scientific software and services to the science community and enable open science", but it is still to be seen whether such activities will lead to a relevant milestone and concrete adoption and usage from the research community. Existing technologies and paradigms including unit testing, version control, continuous integration and deployment and containerisation can undoubtedly be applied in the context of astronomy, but best practises for how and when to use them remain to be established.

It is widely accepted that the construction and maintenance costs of modern astrophysical observatories make large-scale collaboration between scientists, institutes and national governments essential. A fact that seems less well recognised is that similarly collaborative activity will be required to effectively exploit datasets with the diversity, size and complexity that these new observatories will provide. Computing centres and coordinated calls for computing time are increasingly requesting that research programmes (publish and) share the outcome of the simulations they conduct. Those models and astrophysical simulations often need to be associated with specific datasets to enable their interpretation. This is a challenging task in itself, even prior to any consideration regarding a broader sharing effort. While the associated efforts and cost need to be acknowledged and addressed, effective data and software sharing demonstrably enhances the productivity of astronomers, expands the scale and scope of the projects they can undertake and improves the quality of the results they produce. Sharing of software and data, with appropriate credit, also increases the impact by allowing others to build on past effort and previous investments.

There is a general need to more strongly incentivise astronomers to embrace principles for data and software sharing. Achieving this will likely require us to reconsider our funding and recognition systems that predominantly measure success and productivity according to the numbers of refereed journal articles that researchers produce. This system naturally discourages sharing of data and software because astronomers will be reluctant to release data until they have extracted and published any scientific insights they contain. While we must acknowledge the relevance and usefulness of established proprietary times when it comes to acquiring data and motivating its timely analysis, it is important to realise that further disincentives may persist unless we improve mechanisms to recognise data and software as legitimate scientific products in their own right. We must establish channels to accept and promote articles that emphasise software or data that are not systematically attached to a scientific interpretation[2]. At the same time, the community must find ways to recognise and reward the substantial contribution made by technicians and software engineers whose work is essential but is not readily publishable in any form. Industrial models for performance assessment and career progression may be appropriate for this purpose and should be seriously considered.

If the incredible potential of forthcoming astrophysical observatories is to be realised, this instinct for proprietary software and closed datasets cannot survive the next decade. The astronomy community must establish new mechanisms that actively encourage collaboration and reward activities like Open software development and Open data stewardship as essential activities within astrophysical research. The technologies required to provide recognition and reward for these activities and the digital assets they produce already exist. Web-based utilities like Zenodo provide a citable Digital Object Identifier (DOI) that can be associated with datasets or software products. Journals dedicated for the publication and exposure of software are emerging (e.g., Journal of Open Source Software - JOSS - https://joss.theoj.org/). While numerous digital assets related to astronomy now have DOIs associated with them, the practice of citing these identifiers is yet to become widespread. Instead, citations for software or data are often attributed to articles describing science results they were used to derive. This is doubly damaging because it implicitly diminishes the perceived importance of the software or data product and denies a second citation to the relevant software developer or data steward.

We also need to clearly state that DOIs, by themselves, have little value if the associated content is not properly curated and/or reviewed. There is therefore a need to associate a process with sufficient capacity to acknowledge, deal with and review the incoming flow of shared data and software products.[3]

When the Open community-led software development paradigm is followed, the rewards can be substantial. A compelling example is provided by the astropy project, which has revolutionised the way that astrophysical analysis software is designed, developed, extended and delivered. It has undoubtedly enhanced the productivity of astronomy researchers around the World. The collaborative development effort exemplified by the astropy project , which includes experts and research groups from all corners of the community, as well as engaged and exposed (scientific and engineering) staff from missions or observatories, helps to alleviate the burden on individual astronomers who can help to develop, extend or improve small subsets of the overall framework. Moreover, the widespread usage of astropy, in conjunction with well developed methodologies for unit testing, helps to ensure robust software by allowing astronomers to find and report bugs that might have gone unnoticed in a closed-source project. While we need to fully acknowledge both the short and long term direct costs and commitments such efforts entail (i.e., in terms of personnel), the overall gain in reach and agility are huge benefits shared by the community. We further need again to monitor where the credit for such achievements go, and properly promote the developers and actors who made it possible.

It should be clearly acknowledged that this voluntary model for scientific software development also has drawbacks. Contributors to community-maintained software packages are predominantly early-career researchers who often find themselves without time to maintain their involvement when their careers shift or progress. The loss of experienced developers and their expertise can leave substantial sections of the code without a knowledgeable maintainer and may impact the ultimate longevity of a software package. These statements are not limited to the astropy package - they apply to a whole ecosystem of widely used, freely contributed and scientifically useful software products.

Notable examples include Numpy, Scipy, Matplotlib, Jupyter but there are many more. The community should consider new funding mechanisms that allow skilled developers to maintain long-term involvement with particular software packages and frameworks. Prolific users of scientific software should consider assigning members of their in-house pools of software engineers as contributors to community-developed software as an in-kind contribution.

We further need to acknowledge the fact that FAIR principles represent a very high standard to reach. Despite the obvious advantages and rewards that come when data and software are widely shared, it can be technically challenging and costly on many fronts (e.g., staffing, expertise, funding). There may be cases when the significant cost of adopting FAIR principles is not sustainable or even desirable if the cost/benefit ratio is deemed to be too high. Notable examples of when this may be true include the petabyte scale raw data produced by next-generation facilities and the equally large data sets produced by current simulations. While these data must certainly be retained for as long as possible, making these genuinely Big datasets fully accessible implies sophisticated technological solutions for cataloguing and retrieval, as well as substantial networking resources to enable their transfer around the World. It is also unclear whether access to these raw data is actually useful to the vast majority of the research community. The computational resources required to process these data into science-ready products are not available to most astronomers, so it is very likely that providing access to smaller volumes of partially or completely reduced data is both more tractable and more desirable. Another plausible solution involves implementing access protocols via dedicated analysis services. Such services should implement software frameworks that deliver the required data products directly and deploy those frameworks via an associated service that provides a manageable interface to the Big data. Later in this document (see the [Archives] and [Data-to-User] Sections) we briefly discuss modes of analysis that can be applied when even the reduced data products are too large to be analysed locally.

[DATA] Mission / Facility Data Processing

Key Points

- Data-1: Data products and software tools should be recognised as an integral part of the design and development of the mission, instrument and/or facility, and the production of those adequately resourced as part of its development plan.
- Data-2: In that context, advanced data products and analysis tools should be considered as a key component at all phases of the development, operation and post operations lifecycles. Resources shall be available throughout the lifecycle to deliver the data products, with sufficient capability to ensure final product delivery (reflecting that final data sets can be large/complex).
- Data-3: in response to the increasing complexity of instruments, missions, facilities, and simulations being developed, and in order to best utilise expertise in data analysis, connecting the overall data processing development and operations with expert centres may be required. A tiered approach is highlighted where Tier 2 Data Processing Centres support the data processing needs of Tier 1 facilities, and provide a live and collaborative interface to Tier 3 instrument teams and the wider community, exploiting the use of standards in building these connections between facility-to-data-to-science.

The motivation for ground-based observational facilities and space missions[4] (hereafter 'missions' or 'facilities') to produce science-ready data products has grown very significantly over the last two decades. This has been driven by various factors, including the increasing complexity of modern datasets, the need to optimally imprint the know-how of instrument-builders and science experts into the delivered datasets, and the wish to maximise the scientific return and serve a broader community of scientists who should focus on scientific exploitation. With trends such as multi-messenger astronomy, and cross-fields fertilisation, the value of data is becoming more dependent on the availability of expertise and tools, rather than on its bare existence. In practice, "science-ready" data products and tools to address them now represent the key outputs of facilities and missions, and deserve further attention.

These new facilities increasingly involve the generation of larger and more complex data sets, where there is often a requirement to incorporate a range of external data sets to achieve the key science aims. For instance, the ESA M2 Euclid mission, with key aims to probe cosmology through galaxy shear and clustering measurements, requires data not only from the Euclid spacecraft (broadband optical imaging and near infrared spectroscopy) but also multi-band photometry from ground-based imaging surveys. Likewise the final science data goals from the ESA M3 PLATO mission require not only the onboard high cadence photometry, but also high resolution spectroscopy for the high priority targets that will be sourced from a dedicated ground based observational programme. Facilities such as ESO's 4MOST rely on the availability of associated ground and space based image survey data in order to construct their input target catalogues.

In parallel, the success of a mission is increasingly being measured not only in terms of delivery of the new mission or facility on time and on cost, but also on the scientific productivity of the mission through its operational and post operational phases in terms of science outputs, which should be focused on scientific discoveries and should encompass a wide range of impact measures (societal or economic impacts, including e.g., innovation, education, outreach).

Further, the ambition of the science goals of new missions (only the strongest science cases are successful) and complexity of the resulting instrumentation, mean that it is unrealistic for any new mission to provide only raw data to the community. Over the last few decades the release of so called Level 1 products (broadly data with instrumental signatures removed) has been seen as a minimum key deliverable from any mission or facility (e.g. the public SDSS sky survey releases). More recently though, and especially for large survey missions, there has been an increasing expectation of the delivery of Level 2 data products along with key extracted astrophysical parameters (e.g. in the case of spectroscopic surveys, Level 1 spectra and Level 2 catalogues with source measurements of key chemical abundances (Galactic) or redshifts (extragalactic). The generation of these layered data products in turn requires development of sophisticated processing chains, effective data management systems and significant hardware infrastructures.

The increasing trend towards delivery of advanced data products requires the corresponding development of software and tools which must be regarded as core elements in the deliverables for any new facility/instrument. The availability of both the data products and either the software and tools that generated the data products, or a fully documented description of the software is essential in ensuring the transparent, fair, direct and robust scientific exploitation of newly delivered data (see the [Open] Section). This software development must be resourced at a sufficient level to match the requirements on data delivery, and is a key factor in the total cost, covering development, operations, and post operations, of any new mission, facility or instrument.

In short, ensuring the timely delivery of these complex, quality assured science data products, delivered in well documented releases, is a demanding process that must be adequately resourced. Effective mission/facility science data releases is increasingly a requirement in ensuring that the science goals of the missions are met, that the facilities are scientifically productive, and that the wider astronomical community is able to exploit the mission and complementary science data from other missions/facilities for their science.

The Gaia model

Large projects (especially in the case of ESA missions) are able to devote sufficient resources to enable the construction of highly performant science pipelines to generate their science data products. For instance, the ESA Gaia mission planned from an early stage, a series of increasingly rich Data Releases through the lifetime of the project. The complexity and richness of the data products released by Gaia has increased with each new release. All Gaia data releases are fully quality assured and documented. The quality of these releases, and effective distribution to the community, through the ESA Gaia Archive and partner centres, underpins the huge range of scientific advances made by the community based on the Gaia data. The data analysis model adopted by Gaia, with the analysis chains being developed and operated by the Gaia Data Processing and Analysis Consortium (DPAC) is an example of a successful large astronomy data infrastructure, noting that the DPAC is constituted as a community funded organisation, with participation from ESA. The Gaia model reflects that the analysis of Gaia data is so complex that it could not be carried out in the wider community, rather a critical mass of expertise is concentrated in the DPAC, which then ensures a cost effective delivery of science ready data to the community which they are then able to scientifically exploit.

Towards the SKA

The new generations of radio telescopes (like LOFAR and SKA) produce prodigious amounts of very complex raw data which can not be permanently stored and provided to users at their original time and frequency resolution. Processing the data is challenging and ongoing development and experience often leads to valuable improvements in calibration and (image) data quality. SKA has adopted a tiered processing approach, with the Observatory delivering science quality data which has been sufficiently reduced in volume to be distributed to a global network of SKA regional centres (SRCs) that will take up further processing and analysis of the data by the scientific community. The SRCs will also host the (distributed) and globally accessible primary science archive - consisting of both the observatory data products and advanced data products created in the SRCs while the Observatory retains a (backup) copy of its observatory data products. The development and operation of the SRCs is also largely a community funded activity - outside the scope of the SKA Observatory.

As exemplified by ESA Gaia, large space-born missions often plan and devote sufficient resources to provide robust delivery and support for science data products. The picture and approach taken for new ground based facilities is more mixed. One the one hand, there are commendable and efficient engagements, including e.g., the European side of the ALMA observatory which has developed a network of expertise centres (the European ALMA Regional Centres, or European ARCs) connecting with the scientific community and "staffed (...) throughout the lifetime of a project, from proposal preparation to data analysis". On the other hand, new instruments that are added to major telescopes often have development budgets that do not cover longer term operations, and hence the data processing systems delivered for these new instruments are limited to basic pipelines, which are assumed to be run by the eventual users of the facility. This leads to an uneven situation when it comes to the maturity and readiness of the delivered software and tools, depending on parameters associated with the scientific focus of the instrument-builders, available expertise during the design and development of the mission, and the achieved balance (or tension) between key efforts to deliver a given instrumentation. For instance, ESO facility instruments typically are delivered with basic instrument pipelines that can be run by the user to reduce their raw observational data. There are very significant efforts and associated resources engaged in processing reduced data for the users. However, it almost unavoidably often depends on specific choices, and science data products are not generally available to the general astronomical community except for a given set of programmes. There are obvious exceptions, where the instrument is foreseen to be used in a larger 'survey' operation mode, and for which data products to be released publicly are planned from the start. Even in such cases, the resources available for the data analysis system development and operations may be limited.

In the development of new facilities with more modest budgets, there are opportunities to benefit from shared/common approaches. Complementary paths for the implementation of software and analysis systems could be coordinated between the mission/facility/observatory and the community. These should be planned as early as possible, certainly in the initial phases of the facility development. There is an opportunity to benefit from expertise in thematic processing centres in the development of pipelines and data infrastructures that meet the needs of science requirements generated by the new instrument teams. Coordinating a guided effort where deliverables are developed, promoted, and implemented via an integrated communication between the builders, the coordinators (e.g., an observatory or mission) and the scientific community will help ensure an improved common standard of data product delivery for all new instrumentation. A tiered approach encompassing identified centres of expertise for experimental and simulated data analysis represents an efficient route towards the development of robust, mission-specific, tools, as well as a more agile set of packages and frameworks. Those expertise centres can interact with the science teams of the projects that they are working with to ensure the analysis systems meet the project's science requirements, and can directly connect with the scientific community via exposed two-way communication and collaborative channels.

The critical ingredient for an efficient and functional structure is that this sense of direction is planned early, represents an integral part of the design and development of the facility, in close coordination with potential partners and with the scientific community.

[ARCHIVE] Archives for Data and Software

Key Points

- Archive-1: Pursue long-term investment in state-of-the-art archives for storage, exploration and exploitation of data associated with missions and facilities.
- Archive-2: Consider alternative storage solutions for data that require limited access.
- Archive-3: Keep data accessible and live where possible, facilitating and encouraging updates of methods/pipelines, metadata and associated usage examples.
- Archive-4: Consider direct access to on-the-fly user-tuned computation of data and models (e.g., IRFs), watching out for computational and environmental costs.
- Archive-5: Make development and preservation of software an integral part of astronomy portfolio (as it is for data), including efforts on the Open Science side (see Open-3), promoting associated achievements and careers (upgrading our crediting system, see Open-4), and appropriate long-term funding (including full-time tenure positions).
- Archive-6 Embed the existing and new data centres and archives, in a coordinated way, in the global interconnected, interoperable data-and-computing infrastructure described above.

The need for state-of-the-art archives does not need much justification any more, considering the heavy and successful usage made by the astronomical community, thanks to the implementation of transparent, efficient and accessible archival channels. The proportion of archival data in the overall scientific production has significantly increased over the years. Archives that provide effective access to their science data products, are increasingly used for archival research, which can in turn lead to the acquisition of new observational or simulation data to further the initial investigations. While the implementation, curation and expansion of archives is a demanding task, astronomy is one among a few privileged sciences where extensive archive services have developed steadily and robustly over the years. Beyond the associated efforts and resources, their implementation benefited from the data standardisation and tools offered by the maturation of the Virtual Observatory.

In the context of data preservation, archives are no longer just a way to store and access raw data. They increasingly expose advanced products and implement interactive and visualisation tools, advanced search services to optimise the user experience and their scientific content and objectives have significantly evolved over the last decade. Moreover, those centralised archives are no longer the only interface by which scientists can harvest and connect their datasets. The concept of data preservation is broadening in connection with the increased need for sharing and widespread distribution (see [Open] Section). All of these considerations imply that the preservation of data has become a multi-facetted challenge which calls for a coordinated, yet diverse set of approaches depending on the type and usage of data, i.e. raw, reduced, mock or simulated data. The following focuses on selected items within the broader picture, with interoperability, curation and documentation always being key requirements.

Raw data

In the coming decades, a few space and ground-based observatories will deliver raw and low-level data of unprecedented complexity and volume (at the petabyte/exabyte scale), while a good fraction of all raw data will have to be reprocessed multiple times. These datasets are expensive to acquire and potentially irreplaceable, so robust, backup (and possibly mirrored) data storage infrastructures are essential. Ideally, the HPC and HTC facilities that run associated reduction pipelines are co-located with

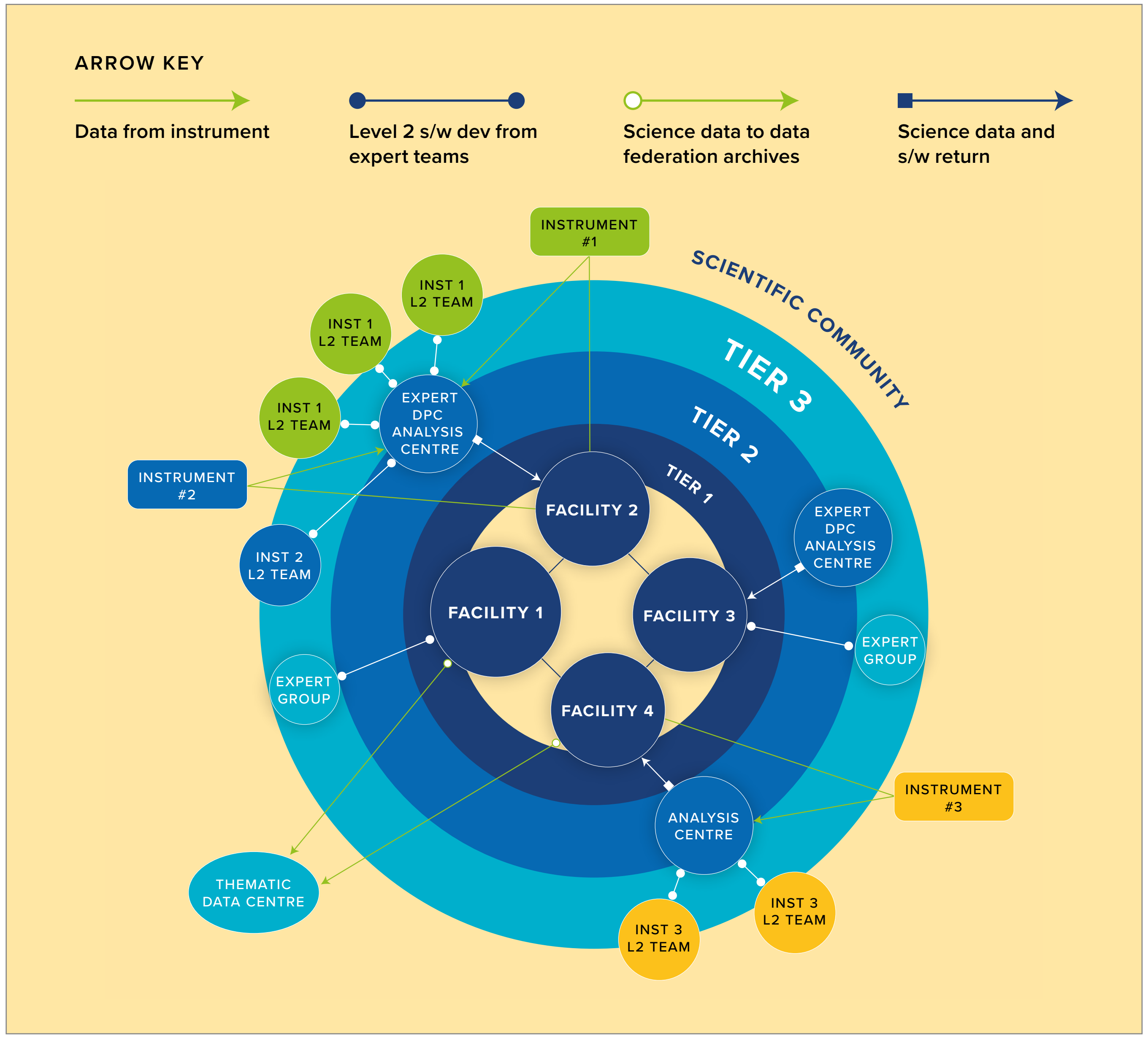


Figure 1

This diagram illustrates a tiered processing infrastructure model for the case of major astronomical facilities and survey instruments. Tier 1 facility operators such as ESO and SKA which are responsible for multiple data generating telescopes and their instrument suites, pass data from these to community provided Tier 2 expert data processing centres (DPC), which have critical expertise in specific techniques or wavelength domains (e.g. optical/near-IR, thermal-IR, radio, etc), including mocks and numerical simulations. Tier 2 centres connect directly with the scientific community and provide an interface to Tier 3 expert development teams and groups in the wider community who are responsible for the development of specialised processing chains that provide higher level value added science products. This is notwithstanding the need for Tier 1 facilities to directly connect and be embedded within the scientific community at large, providing an open collaborative channel. Such a layered and distributed approach will facilitate the inter-connection between (all level) data centres, facilities and the community.

the repositories for the data they process to avoid time-consuming network transfer.

It remains unclear whether universal access to these low-level data is feasible or even useful for all experiments and observatories. While this may sound like a provocative statement which could lead to restricted access to critical datasets, it is actually meant as a way to bring a fresh perspective on such data, already applied e.g., in the context of large-scale simulations, and to maximise the exploitation of existing scale-effective solutions. To provide usable open access to such large data volumes is technologically challenging and can be extremely costly, with corresponding requirements for network connectivity and bandwidth if processing close to the archive cannot be provided. Where possible and applicable, provision should be made for retrieval of data subsets, and technologies including data streaming should be considered to minimise local data storage requirements for the data users. For long term storage of low-level data with limited access, different technical solutions may be appropriate. If data are stored indefinitely then they must be curated, annotated with comprehensive metadata and potential hands-on usage tutorials to ensure that they remain interpretable.

Reduced Data

Open access to intermediate reduced data and post-analysis high-level data products is likely to be of a more direct utility for the astronomical community. Fortunately the volume of these data is (often but not always) expected to be much smaller than their low-level counterparts, and the technological challenges associated with publishing them are correspondingly reduced.

Online science analysis platforms are increasingly prevalent and such facilities plus other similar facilitating frameworks and services (including archives providing advanced services and tools) will likely become the most common means of accessing science-ready data. This is fortunate because the sheer volume of forthcoming datasets may make download and local storage of reduced data products impractical or unfeasible. Existing archives are also often not designed a priori to sustain an agile and flexible expansion towards new data products or frameworks. In principle high level data can be regenerated from their lower-level counterparts. However, the computational and environmental costs of doing so may be substantial, making redundant, mirrored storage cheaper and preferable in some cases. Data losses notwithstanding, revisions to data processing pipelines and improved instrument calibrations may necessitate regeneration of intermediate level data products and provision should be made for sufficient computational resources. To promote straightforward reproducibility of scientific results, retention of used data pipelines and processes (on top of the raw data) using appropriate versioning plus metadata may sometimes be desirable. Those requirements also have clear ties with the development of dedicated services and new frameworks to bring software (and the user) to data (as opposed to bringing data to the user, see the [User-to-data] Section of the present document).

Software

Software development entails substantial investment of time and intellectual effort, making tools for reduction and analysis almost as valuable as the data they process. For the processing and reduction software stacks associated with large observatories, industry-standard software development and preservation practises should be adopted. In particular, effective use of version control, robust unit testing and comprehensive documentation are essential to ensure stable code that is correctly applied. However, it is clearly not the whole story, as version control does not ensure that software is preserved and exposed appropriately or serves its purpose.

The specific requirements of different science communities within astronomy result in the majority of high-level analysis tools being developed as required by the astronomers themselves. Unfortunately, for many individual researchers who develop software, there is currently little incentive to perform time-intensive tasks like writing documentation or unit tests. Software development activity receives little recognition in the astronomy community, which can impact individuals' career progression if it reduces their publication and citation indices. Failure to adopt good practises for software development, albeit for pragmatic reasons, leads to adverse effects including non-reproducibility of results if software evolves without proper versioning, misuse of tools producing spurious results if code is not documented and duplication of effort if code is lost, difficult to adopt, or never published. These issues can be mitigated by providing proper recognition for software development activities and training early career researchers in development best practises.

Another way to alleviate the software development burden on individual researchers is to encourage open software development principles and procedures (see the [Open] Section). Community-developed open-source frameworks like astropy or the yt-project provide excellent examples of how collaborative software development can promote reliability, useability and utility for high-level analysis tools. Frameworks like astropy aim to provide comprehensive documentation with usage examples, which reduces the chance that misapplied software will generate spurious scientific results.

In some cases, preservation of software source code may not be sufficient. The context in which software executes may also affect the results it generates. Containerisation frameworks (like Docker and Singularity) enable preservation and restoration of software within defined runtime environments to help achieve reproducibility for data analyses. Containerisation also allows software to be straightforwardly deployed on cloud computation infrastructure and container runtime engines have been developed that run on HPC infrastructure (e.g. NERSC Shifter). And as any piece of software, containers need maintenance efforts to be planned and executed when relevant.

Using metadata to associate software with the data that it is designed to process can also prevent its misuse. And again, detailed usage examples as well as dedicated tutorials should help preserve the expertise that is possibly the hardest part to safeguard on long timescales.

Preservation of software is thus closely inter-connected with efforts on the Open Science side (as it is in the case of data). This should definitely be recognised as an integral part of the scientific portfolio, and supported by robust and long-term funding, as opposed to solely individual-project-based and time-limited efforts.

Instrument Response functions

Several instruments including CTA and KM3NeT will require large scale simulations to generate their instrument response functions (IRFs). These IRFs will likely evolve over the lifetime of the observatories and may change abruptly to reflect observing conditions or temporary reconfigurations of the instrument. Science analyses require IRFs that correspond to the epoch when the data were obtained, so it is important that all historical response functions are retained. If the simulated data that are used to generate the IRFs must be retained this could imply substantial storage requirements, increasing at a rate that depends on how regularly IRFs must be regenerated. In some cases it may be feasible to store only the reduced IRFs themselves and discard the raw simulation data, with corresponding storage cost savings. Emulators or trained deep learning models may provide a mechanism to compress simulation results without discarding them completely.

[USER-TO-DATA] The next Generation Tools: Cloud computing, Platforms, Collaborative frameworks

Key Points

- User-to-Data-1 Support researchers in addressing multi-source datasets, models and simulations, encourage the "bring the user to the data" cross-mission/ facility approach, with expert centres, missions and observatories as engaged facilitators.
- User-to-Data-2 Encourage and coordinate the development of open source research-oriented platforms and analysis/collaborative frameworks close to data. Promote and support coordination of the fragmented computing infrastructures in the framework of the Tiered data-and-computing infrastructure described above.
- User-to-Data 3 Monitor and address dependence and constraints associated with private providers (potential "vendor lock-in"), using mirroring, diversification and easy re-deployment of cloud computing services (e.g., encouraging the development and usage of framework standards).
- User-to-Data-4 Imprint such developments in the long-term planning of infrastructures, with associated long-term investments coordinated with the missions and facilities.
- User-to-Data-5 Encourage cross-disciplinary efforts in the platform building processes, and promote and facilitate careers with professional software engineering and computing skills.

The computing landscape is changing both from the view point of astronomers performing large-scale simulations and those analysing data from large-scale observational infrastructures. In the case of simulations, the current codes can scale up and take advantage of new computing paradigms, such as accelerator platforms, and HPC facilities can provide more CPU/GPU flops. As the size of the data from these simulations correspondingly grows, the analysis, transfer, and long-term storage of the data is becoming a severe computational bottleneck. Increasing amounts and resolution of the observational data, on the other hand, did not before pose a real HPC challenge, but nowadays it increasingly does: to manipulate the increasingly large data sets, memory and computing requirements bring this work to the realm of HPC computing. The challenges, goals, and the required infrastructure for both communities approach each other - the big data analysis and HPC computing borders are getting increasingly blurred. The current trend is computation becoming cheaper, but bandwidths of memory and data transfer are not growing at the same speed. Hence, any type of computation/data analysis tasks will become limited by these bandwidths, when the data sizes increase.

The implications of these trends are plentiful and important to be considered by the astronomical community itself, but also by the funding and mission-based agencies. Firstly, data at Petascale and beyond is too large to be "moved" around, hence users should be brought close to the data as opposed to the data being distributed (via downloads) to the users ("user-to-data" -policy). The increasing size of the data has the consequence that, even if it is hosted in an open access data storage facility, it would not be "open", as the capacity for downloading and utilising the data at local sites would be difficult if not impossible. It will also violate the principles of diversity, as some researchers from rich and therefore better-equipped institutes would have increased chances to exploit the data in comparison to researchers from poorer institutes. The policies for data access and the infrastructures built should better reflect the demands arising from large-scale data.

Instead of merely providing data access, the efforts should therefore concentrate on providing data analysis tools and resources on the site, where the data is stored. This necessarily means that in addition to the access, there should be HPC resources and additional software stack on site, which we refer to as “research-oriented platforms”, so that any user could have access to the data, have basic data analysis toolbox available to operate on the data on site, and furthermore to be able to contribute to the development of the tools on the software stack. The structure of the platform can be envisioned to follow the tiered structure discussed before: the HPC resource level would be the lowest, invisible, layer to the community user, the data, software, and cloud services level the layers above, whereto the user would have access depending on the engagement level desired.

For similar reasons, addressing multi-source datasets together with models (and simulations) synergistically requires dedicated services and development frameworks with an emphasis on both robustness and adaptability. A global need to share analysis tools and allow further developments close to the data is emerging. Such frameworks have been and are being developed and implemented in various scientific disciplines, including Astronomy. The ESA Datalabs promote the idea of “bringing the questions to the data”, while ESCAPE ESFRI Science Analysis Platform (ESAP) is meant as a “flexible science platform for the analysis of open access data available through EOSC”. Pangeo is another example of a more global collaborative ecosystem with the Earth science community. Implementing and promoting cloud computing and collaborative research platforms may first help alleviate obstacles associated with downloads Most importantly, it will be key to allow efficient and innovative science derived from multi-source, multi-messenger, big-scale, and complex datasets. They are a promising thread to follow when it comes to environmental costs (see [Green] Section). Last but not least, we need to admit that we cannot predict the future: completely new attractive and relevant technologies, protocols, or ways to conduct our research may emerge. It is critical that we keep a live update on the requirements encompassed by our activities, associated with a pro-active technology watch.

Many challenges lie ahead if we wish to establish such a new (and modern) way of doing research. To be successful, it requires a broad coordination of the main actors in the community, including the research institutes and organisations, missions and observatories, to engage into and connect to that scheme. It also requires even more dedicated efforts to develop codes as open-source community efforts, and efficient collection, cataloguing, and sharing of the developed algorithms and software. While platforms do exist, including a few dedicated to Astronomy (e.g. the Astrophysics Source Code Library, or ASCL), software is often deposited across various repositories that are either not well curated or exposed. Committing to these activities would enable them to focus on exposing and sharing their unique expertise at the service of science (Smith et al. 2020), to benefit from serving the Open science objective and FAIR principles. While open source frameworks should be encouraged, there may exist attractive technologies or services provided by the private sector: in such cases, the community at large needs to monitor, assess and address the potential risks associated with the dependence to such products (e.g., “vendor lock-in” in cloud computing). This calls for a diversification and easiness of deployment of cloud computing and platforms (possibly via established standards), as well as adaptable schemes for down-scaled datasets.

Some data transfers in between different sites are inevitably still required (and desirable). For this purpose, new tools exploiting, e.g. streaming software solutions, or better utilisation and further development of compression schemes, would be desirable. Obviously such work, constituting the design and implementation of complex and non-astronomical software, cannot always be done by the astronomical community alone. The same constraint applies to the build-up and maintenance of the research-oriented platforms; the thinking of building and funding only hardware is no longer meeting the requirements of infrastructures resulting in/dealing with massive amounts of data. For such infrastructures to be useful, considerable human resources should be funded alongside the hardware. This is not the current trend in the infrastructure funding schemes, and poses a major challenge for astronomical infrastructures in the future. Special care should finally be taken to ensure that all parties have sufficient and fast network connections, as to prevent the exclusion of less privileged regions and institutions.

The HPC paradigms are in constant change. For some time, the astrophysical community has been preparing for the paradigm change from CPU computing to GPU and hybrid platforms, currently taking place in HPC facilities all over the world. Such paradigm shifts are not at all trivial for the adaptation of the community’s codes; this problem is only to become more pronounced in the Exascale and quantum computers. Reacting to these changes has taken up and will take up a lot of resources and attention from the principal function of the researchers in our community: producing high-quality science. AI is bringing forward great potential for data analysis tasks, and the HPC centres are also conforming their hardware to adapt to the increasing need of such tasks. The constant change will force us to soon tackle other challenging paradigms, again requiring a lot of resources (and dedicated skills) to develop novel algorithms, and perhaps even going back to old paradigms such as field-programmable gate arrays.

In reaction to the increasing prevalence of petabyte and exabyte-scale datasets, the astronomy community has rapidly adopted new paradigms for Big Data analysis. Prominent among these are Deep Learning techniques (colloquially referred to as AI) that can be used to discover complex patterns and relationships within and between high-dimensional datasets. The rapid development of Deep Learning techniques during the last decade was primarily driven by commercial companies and facilitated by very large, labelled datasets and novel computational architectures - most notably GPUs. In astronomy, large collections of reliably labelled data are less common which has made training supervised Deep Learning models more challenging, notwithstanding some notable successes. Innovative approaches like the Galaxy Zoo citizen science project have been used to collect labels for millions of astronomical images and more recently, astronomers have begun to explore methods that can be used to compensate for limited or absent data labels. Domain-adaptation techniques have allowed highly realistic simulated data (with known ground-truth labels) to be used to train supervised Deep Learning models before fine-tuning with a small number of human-labelled real data. With increasingly large, high quality datasets, unsupervised and self-supervised techniques become increasingly feasible, and allow complex data representations to to be learned from unlabeled data. Deep Learning techniques will certainly be required to efficiently analyse data from next-generation surveys. The community needs to promote the skills and provide the computational resources (like GPUs and TPUs) that these techniques require.

The requirement is not only to produce code that can compile, run and scale up in the novel HPC platforms - the society has the demand of energy efficiency, and low carbon footprint (see the [Green] Section). Hence, we need to pay much more attention to producing optimal solutions of the data analysis and simulation tools. Plenty of know-how in ICT is similarly required in building the research-oriented platforms. Therefore, for both of these tasks, cross-disciplinary efforts in between astro- and ICT sectors would be strongly beneficial, and careers with professional software engineering / computing skills should be promoted and facilitated (see the [People] Section).

[GREEN] Green Data Infrastructures, Reducing the Carbon Footprint

Key Points

- Green-1 Quantifying, monitoring and exposing the carbon footprint of computing in astronomy should become a default for research institutes, organisations, computing centres (as part of a more global assessment of the impact of our research activities). We should implement a regular reporting exercise, coordinate the gathering of such data for the community, aim at clear objectives and specific recommendations.
- Green-2 The community at large should aim at minimising its energy consumption altogether while encouraging energy suppliers to invest in power generation capacity using carbon neutral sources.
- Green-3 Code optimisation should become a key both for the sake of efficiency and to minimise the environmental cost. Efforts should focus on the training of scientists and associated developers, promoting careers around code optimisation and adaptation.

It is high time that the astronomical community accepts that our activities, which form part of the everyday business of our scientific research, have a significant impact on our environment and contribute to the climate emergency that is the result of increased levels of greenhouse gases. Making the changes that form a meaningful contribution to addressing the issue come at a cost, both financially and in adaptations to the way we work, interact and collaborate. One side-effect of the Covid-19 pandemic has been the dramatic increase in working from home and reduction in travel, which have forced us to explore new ways of collaboration and have shown that at least some changes are possible. But we aren’t there yet.

The factors that contribute to the carbon footprint of our profession are diverse and have different relative weights. Those include (super)computing, travel, flights & commuting to work, the building and operation of our observatories, offices and facilities and should be addressed in their respective contexts (Burtscher et al. 2021).

Supercomputing as well as the distribution, archiving and retrieval associated with simulations and increasingly large data-sets from our observatories and space instruments play an ever increasing role in modern astronomy. It forms a significant component of our energy consumption. Whether these activities also contribute to the carbon footprint depends on the way in which power is generated. Traditional carbon-fuel is still widely used, and therefore the move to renewable and sustainable energy sources would contribute to lowering astronomy’s carbon footprint. The largest impact will be achieved if our activities lead directly to new or additional investments in power generation capacity using carbon neutral sources (e.g. wind, solar, tidal, geothermal). All institutes, universities and observatories are encouraged to continue their transition to non-fossil fuels and wherever possible ensure this also applies to the (super)computing centres, cloud providers, data centres as well as network providers that we work with. We should be mindful of the fact that the move towards a carbon-neutral future can have a negative impact on the fairness of access to computing resources. The move towards reuse of heat generated by computing and hot or warm water cooling also deserves to be pursued.

The astronomical community has, for many years, benefitted from the dependable and predictable increase in affordable and readily available computing (e.g., Moore's Law). This has coincided with a growing dependence on interpreted languages and little incentive to invest in optimisation and acceleration of codes. While many will benefit from the ease of using interpreted languages such as Python, the community needs to also maintain the skills in compiled languages.

We should keep in mind that compiled languages are still in use in the libraries and routines that are called from interpreted languages. There are many optimisers and transpilers available now that can be used to increase efficiency (e.g., numba, cupy) and users are encouraged to continue to contribute to valuable community resources such as astropy and numpy, while the emergence of new languages may ease the transition towards more efficient interpreted languages.

As new hardware solutions emerge, codes require demanding refactoring which is often challenging to deploy due to the lack of dedicated expertise, resources or a lack of awareness. Scientists should be trained in the general optimisation of codes both for the sake of efficiency and the gain in environmental cost. Such optimisations should also be incentivised by crediting such efforts as part of the research portfolio, and careers in general. The implementation will require this expertise to be deployed at the service of or within the scientific collaborations, which itself needs robust and long-term funding and acknowledgements from academia and funding agencies.

Providing specific recommendations goes admittedly well beyond the scope of the present report. We must acknowledge that we are still lacking the basic tools, processes and information to quantify the present state of affairs, establish concrete objectives, and report on our progress (Henderson et al. 2020 and Patterson et al. 2021, as illustrations). The above-mentioned focus on the global environmental cost of computing in Astronomy desperately needs to be reflected in concrete, quantified and controllable actions, within a more global framework addressing the impact of our research activities. This in turn requires proactive monitoring and regular reporting exercises fed by all intervening actors in a guided and transparent process.

[People] Training, Careers, People

Key Points

- People-1 Establish and promote metrics to encourage data scientists and data stewards, HPC and software experts to pursue careers within Astronomy, and exploit the attractiveness of astronomy to recruit and promote talented staff.
- People-2 Encourage multi-disciplinary collaborative programmes fostering long-term human resources pertaining to software, coding, ICT and HPC, favour mobility, value and pro-actively increase the diversity of the workforce.
- People-3 Promote the (computing/software/ICT) existing talent of those who are actually educated in an astronomical context, nurturing the combined motivation for and understanding of the field.
- People-4 Fully integrate professional software and computing engineering career paths within our research scheme/system and promote them as part of the "astronomy" world.

While software (and computing in general) is increasingly seen as a critical ingredient of e.g., new astronomical facilities, and more generally of scientific endeavours, the skills and work of the associated developers (engineers, scientists) are too often hidden behind project or facility fences, and are neither actively promoted nor even exposed. The engagement of missions towards Open Science (see [Open] Section) may partly help to resolve this unbalanced situation, but there is still a long way to go. More alarming is the fact that such a situation may be prolonged due to our established perspective towards computing and software, and becomes unsustainable in the face of the novel ways we are conducting scientific work. Given the increasing numerical challenges the astronomy community are facing, there is a dire need for professional and coordinated support in terms of computer scientists, software and hardware engineers, data stewards that combine both ICT and astronomy/astrophysics expertise.

In particular, multidisciplinary university studies and diplomas at the crossroad between astronomy and informatics should be fostered, including the definition of key specialisations for future astronomical computing. Careers for these new profiles, from HPC experts to data and software scientists, in astronomy, should be properly defined, made attractive, promoted and rewarded with dedicated career paths and metrics. They should be integrated at various levels of the tiered approach, within the research institutes, the data centres, computing facilities, missions and observatories and be part of multi-disciplinary teams with complementary skills. Such expertise should be active in community forums, and exposed in relevant committees, panels, jurys and executive authorities.

One effective path is to identify and promote the internal talent, already present within the astronomy research and education ecosystems, that has computing expertise. This approach may ease the challenges of securing long-term funding and career development when such experts can grow within a fixed ecosystem and their work is thus fully acknowledged as a part of the collaboration entity. While such a path may look attractive, it certainly cannot fill in the required expertise for the development, implementation and maintenance of professional computer-related efforts. Another complementary and possibly central approach is to connect with external computing experts, or create active trans-disciplinary bridges. While this requires a dedicated effort to share the relevant astrophysics-related research objectives, it does favour mobility and nurtures a diversity of perspectives, a key catalyst for creativity and scientific progress. More generally speaking, there is a critical need to increase the diversity of the workforce, better reflecting society in its richness. Building up the next generation of computing experts staff in Astronomy (and science) is a unique opportunity to fully embrace such a guiding principle.

Coordinated efforts should also be encouraged and supported to specifically address computing challenges in astronomy. This includes the development of multidisciplinary collaborative programmes and the mutualisation of ICT human resources on common European-level projects. For instance, adapting existing and widely used codes to new architectures in the upcoming exascale era so that it is efficient (see [Green] Section of the present document) would benefit the whole community and avoid sub-optimal duplication of efforts.

Long-term investments at all levels of astro-computing are thus highly desirable. Significant funding should be invested for computing-related FTEs in astronomy, not only for local and timely support on specific projects but also at the national and European level, within the facilities, the research institutes and academic world. Those careers should be pro-actively sponsored, recognised and rewarded as part of the astronomy portfolio, benefiting and committing to the appropriate exposure (e.g., conferences, panels, papers).

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[1] We emphasise that the "R" in FAIR stands for the principle of "reusability", not to be confused with "reproducibility".

[2] Note the recent advent of dedicated journals, e.g., the Royal Astronomical Society "Techniques and Instruments

[3] We do not address the potential move towards Open Access (for publications), for which many regimes (and associated business models) have been proposed and debated: it is an important and complex topic, but outside of the scope of the present document.

[4] We discuss astronomical observational facilities and missions to encompass major telescopes (space or ground based) and their associated instruments. We also include facilities that may be a telescope/instrument that is operated to carry out large scale surveys. For simplicity the words 'mission' or 'facilities' are used to refer to both space and ground based telescopes, instruments and large scale surveys. Current examples are e.g., Gaia, Euclid, PLATO, ESO-VLT, ESO-ELT, ESO-4MOST, SKA, CTA, and other astronomical infrastructures identified in the ESFRI roadmap. We note that large numerical simulations nowadays produce data of complexity comparable to observational data and thus can and should be treated as missions/facilities themselves.

B Origin and evolution of the Universe

Cosmology encompasses the study of the origin, the contents and the evolution of the Universe. In this Chapter, we provide a short status update of our understanding of the current standard cosmology and what are seen as the main science drivers in the coming two decades to test, improve, or even overhaul the cosmological model. We discuss observational probes, and new facilities that allow one to address key science questions, either through general-purpose instruments and telescopes but also through those optimally designed for a single purpose or to answer very specific questions. Besides these new instruments, future facilities also rely increasingly on computers and data science as well as on simulations to maximise their return. This chapter will not cover the study of gravitationally collapsed objects but rather focuses on larger scales. Similarly, high-energy processes and computational cosmology will be covered in other chapters.

Introduction

The standard paradigm of cosmology is exceptionally simple. It is fundamentally based on the general theory of relativity, which describes gravity on sub-horizon scales but also the expansion history of the Universe itself. The energy-density tensor in general relativity is determined by three components: in particular, those of ordinary baryonic matter, (non-baryonic) dark matter, and dark energy (or a cosmological constant). No conclusive deviations from general relativity have manifested themselves in observations on large scales, even though the nature of dark matter and dark energy remain unknown. General relativity is thus believed to describe the expansion of the Universe accurately, as well as gravity on scales much below that of the horizon scale of the Universe. Over the past two decades, a “standard model of cosmology” (see Fig. 1 for a sketch), usually denoted ΛCDM, has been developed with only six free parameters, which explains everything we observe on scales exceeding roughly one comoving Mpc. This model is geometrically flat, with significant contributions to the energy density from baryons, radiation, neutrinos, non-baryonic dark matter and negative-pressure dark energy, with additional parameters to describe the early distribution of energy-density fluctuations. Observations, obtained through general-purpose as well as specially-designed instruments, of directly calibrated distance measures (e.g., supernovae [SNae], strong lenses), large-scale structure, weak gravitational lensing, the cosmic microwave background, and baryonic acoustic oscillations, were all in agreement with this model within their specified uncertainties, at least until recently. On smaller scales, complex astrophysics (e.g., baryonic physics, chemical, radiative and kinetic feedback) is thought to confound simple interpretation. At the onset of the 2020s, this simple but incomplete picture is starting to show cracks, and so-called tension is regularly found in measurements of the standard-model parameters when compared between, for example, early Universe probes (e.g., cosmic microwave background [CMB], baryon acoustic observations [BAO]) and late Universe probes (e.g., large-scale structure [LSS], SNae and weak/strong gravitational lensing). These most recent observations probe increasingly larger volumes of the Universe (both in sky coverage and in redshift space) with increasingly more sensitive instruments, sometimes specifically designed for one purpose only, reducing the statistical (and, we hope, systematic) errors sufficiently to highlight any discrepancy. This tension is now exceeding levels of 4-5σ significance (Fig. 2), despite a concerted effort to search for systematic errors in the data, analyses and interpretation. We have thus reached a point where the foundations of the cosmological model need further scrutiny. Researchers have thus started questioning General Relativity (i.e. gravity) itself, further probing the still-unknown nature of dark matter and dark energy (or whether it exists at all), and asking whether other energy-density components can contribute (e.g., early dark energy, more neutrino species). To widen or repair these cracks in the current cosmological model, powerful new instruments are needed in the coming decade, to provide robust answers to these questions. These instruments need to probe large(r) volumes and higher redshift regimes, explore upcoming new probes (e.g., 21-cm cosmology, gravitational waves), and be more sensitive and less prone to systematic errors, which are otherwise becoming increasingly subtle. Moreover, answers will likely not come from one instrument alone, but from complementary probes, even if only to confirm each other’s findings. Besides these instruments, high-performance computing and new data-analysis and data-science tools need to be developed, and are already becoming an integral part of the development of new instruments. The next decade in cosmology will therefore focus on trying to answer fundamental questions about the nature of our Universe, ranging from its energy-density components all the way the nature of gravity, and connect this to the standard model of particle physics, which is itself being scrutinised both in cosmology and in high-energy physics. In particular, we identify some key questions, listed below, that are likely to drive research in this field in the coming decade(s).

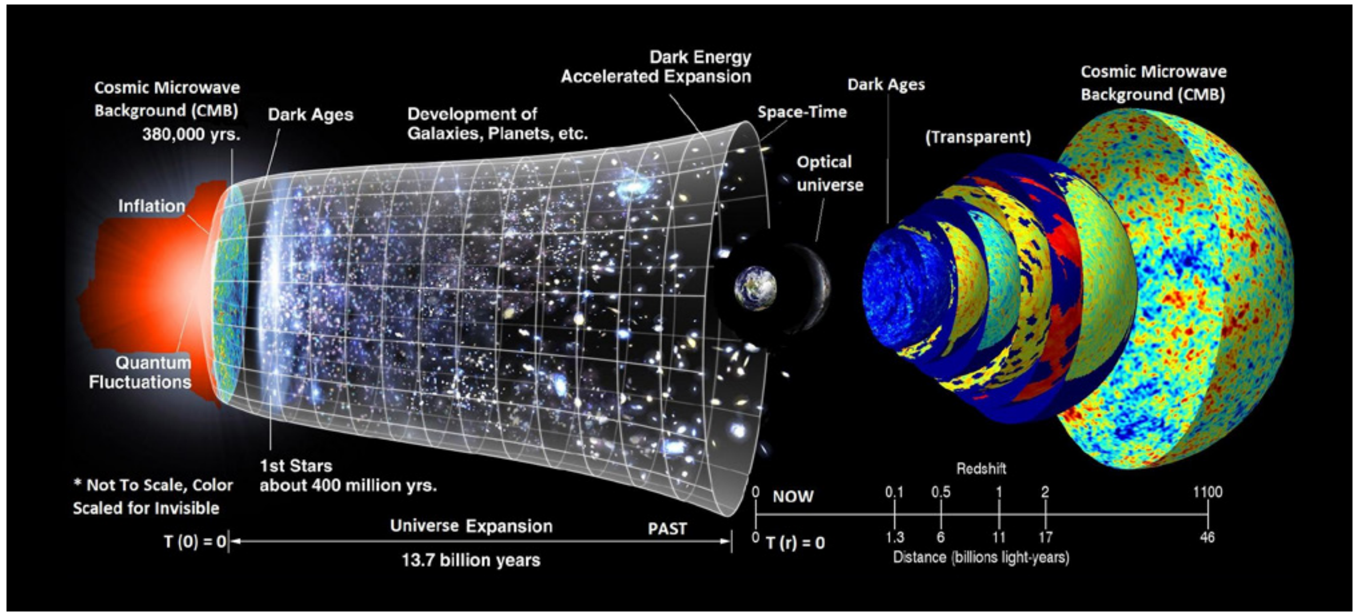

Figure 1

This graphic shows the evolution of the Universe, from the Big Bang to the present day.

Credit: NASA/WMAP team.

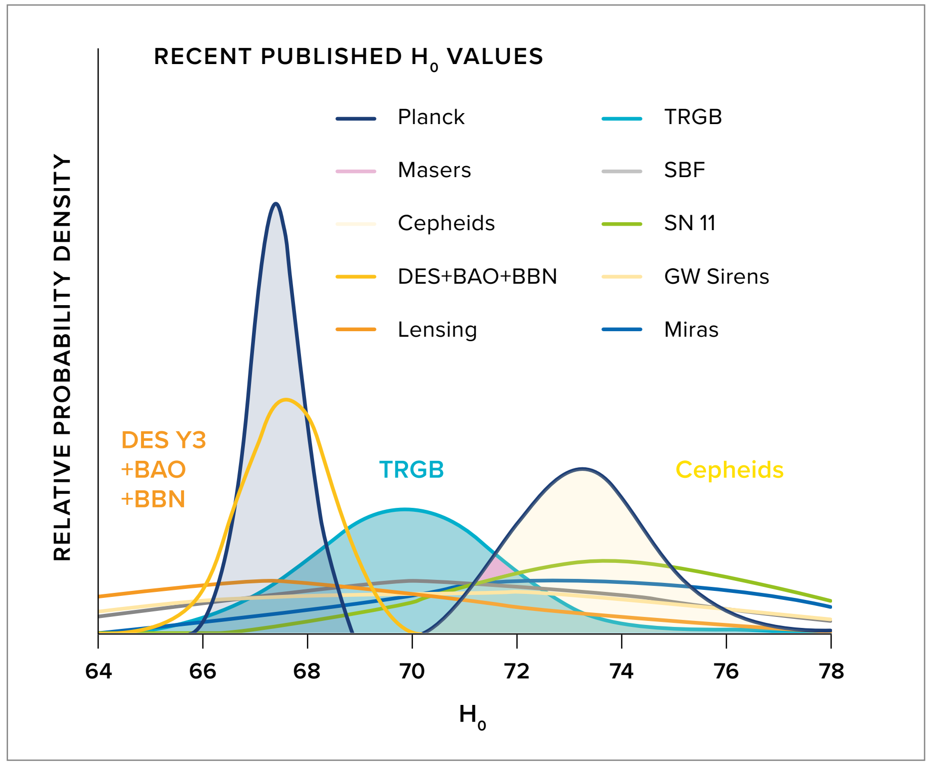

Figure 2

Relative probability density functions for several current methods for measuring H_0. The CMB (cosmic microwave background), BAO (baryon acoustic oscillations), strong lensing, and TRGB (tip of the red giant branch) methods currently yield lower values of H_0, while Cepheids yield the highest values. The uncertainties associated with H_0 measurements from gravitational wave sirens, strong lensing, Miras, masers, and SBF (surface brightness fluctuations) are currently significantly larger than the errors quoted for the TRGB and Cepheids.

Credit: Freedman, W.L., 2021, ApJ, 919, 16 (arXiv:2106.15656).

Key questions

- **Are there deviations from general relativity, and on what scales?**
- **Are there deviations from the standard model of particle physics?**
- **Are there deviations from the standard cosmological model?**
- **What is the nature of dark matter?**
- **What is the origin of the accelerated expansion?**
- **Can we identify specific observational signatures of inflation?**
- **What can gravitational waves observations reveal about dark energy, dark matter and modifications of gravity on cosmological scales?**

Research areas

We briefly summarise the current status and some open questions in cosmology, in chronological order of the Universe's expansion or in some cases being of importance to a number of eras.

Inflation & Reheating

Observations of the temperature and polarisation anisotropy of the CMB strongly support the idea that the early Universe underwent a period of inflation. Inflation is a phase of accelerated expansion which is supposed to take place at very high energy (i.e., at an early time), most likely between the Large Hadron Collider (LHC) scale, $\simeq 10^4$ GeV, and the Grand Unified Theory (GUT) scale, $\simeq 10^{16}$ GeV. Inflation allows us to understand several puzzles that plagued the pre-inflationary standard model and that could not be understood otherwise (e.g., the near-flatness of the spacetime manifold; the near-uniformity of the CMB). Without inflation, the standard model of cosmology would remain incomplete and highly unsatisfactory. The most spectacular achievement of inflation is that, combined with quantum mechanics, it provides a convincing mechanism for the origin of the cosmological fluctuations (the seeds of large-scale structures that will form later and which we see in the CMB anisotropies) and predicts that their spectrum should be almost scale-invariant and their distribution should be nearly that of a spatially isotropic Gaussian random field — all of which is fully consistent with the observations. Inflation offers a unique way to test experimentally an effect based on the interplay of general relativity and quantum mechanics. In order to produce a phase of inflation, one needs a situation where the matter content of the Universe is dominated by a fluid with negative pressure. In standard astrophysics, matter is usually modelled by gases with positive pressure. At very high energy, the correct description of matter is no longer fluid mechanics but field theory, the prototypical example being a scalar field. Quite remarkably, if the potential of this scalar field is sufficiently flat so that the field evolves slowly, then the corresponding pressure is negative. This is why it is believed that inflation is driven by one (or several) scalar field(s). However, the physical nature of the inflation and its relation to the standard model of particle physics and its extensions remain elusive. Another crucial aspect of the inflationary scenario is how it ends and how it is connected to the subsequent hot big bang phase. It is believed that, after the slow-roll period, the field reaches the bottom of its potential, oscillates, and decays into radiation. In this way, through this so-called reheating process, inflation is smoothly connected to a subsequent radiation-dominated epoch. It is also possible for a phase of parametric resonance and explosive particle production, called preheating, to occur before the thermalization phase. Both reheating and preheating may leave subtle traces in the distribution of matter at late times.

Key questions:

- Did inflation happen, and if so, what direct observational imprints do we see for its energy scale?
- Which quantum field(s) caused inflation and how is it related to particle physics, if at all?

From Reheating to Recombination

As the Universe cooled in the aftermath of inflation, it underwent a series of transitions as different interactions froze out: baryogenesis, when the amount of matter first exceeded that of antimatter; from quarks to nucleons; from nucleons to light nuclei (big-bang nucleosynthesis); and finally from ionised nuclei and free electrons to neutral atoms. Each of these transitions — and any others due to physics beyond the standard model of particle physics — has left its imprint in the present-day Universe. This last transition — recombination — directly generates the cosmic microwave background, as the Universe goes from being opaque to transparent to photons, and has become the most precise test of the cosmological model.

Key questions:

- What are the observational consequences of non-standard-model particle physics, in the CMB or other cosmological observables?
- What information about the inflationary model can we access?

Dark Ages, Cosmic Dawn & Epoch of Reionization

After recombination ($z \sim 1100$), the Universe became transparent to most radiation. Being mostly neutral and consisting of hydrogen and helium, with only a trace of electrons left, the Universe entered the so-called "Dark Ages", where no significant source of emission is known except for the redshifted 21-cm line of neutral hydrogen (designated the "21-cm signal" hereafter). Until $z \sim 200$, the spin temperature of the 21-cm hyperfine line is equal to that of the CMB, yielding no discernable 21-cm signal. The Universe appears genuinely dark. At $z \leq 200$, however, the spin and radiation temperatures decouple, and hydrogen becomes visible in absorption until about $z \sim 30$. During this period, the physics of the resulting 21-cm signal is well understood and based on linear perturbation theory. In addition, it is tightly coupled to the physical model that describes the CMB and later the BAO. The advantage of observing the 21-cm signal over the CMB is that the former is redshift-dependent and potentially contains many orders of magnitude more information since small scales are not suppressed, and independent information is obtained with redshift. Deviations from the standard cosmological model predictions of the 21-cm signal thus allow dark matter (e.g., through its power-spectrum and potentially through annihilation effects; see Fig. 7) and gravity to be probed on much smaller scales than with the CMB or BAO, and also whether other early contributions to the energy density exist (e.g., early forms of dark energy or other relativistic particles) that evolve with cosmic time. The Dark Ages are therefore an enormous and untapped reservoir of information. However, due to its very high redshift, space-based radio instruments will be needed that can observe at frequencies that do not penetrate the earth's ionosphere. Ideal locations for such instruments would be either in lunar orbit or on the lunar farside, where these instruments are also shielded from radio-frequency interference. In addition, using the faint radio light coming from neutral hydrogen, upcoming 21-cm surveys will enable the measurement of a complete time sequence of images from the onset of Cosmic Dawn, at $z \sim 30$, to the end of Reionization, at $z \sim 6$. In this case, the physics will be largely driven by complex astrophysical heating, cooling and radiative processes driven by the formation of stars, X-ray binaries and black holes. These eras will be more extensively discussed in the section on Galaxies and their formation, and can be probed through the 21-cm line, but also through emission from the first stars and black holes.

Key questions:

- When did the Dark Ages, Cosmic Dawn and Epoch of Reionization start and end and what physical processes drive them?
- Is there any evidence for deviations from the standard (cosmological) model during the Dark Ages?

The Formation of Large Scale Structure

As the initial density perturbations evolve across time under the effect of gravity, matter flows from underdense cosmic voids surrounded by sheet-like structures, the so-called walls, and then via filaments, marking the edges of the walls, into the nodes of the cosmic web. The late Universe, observationally dominated by the distribution of galaxies in these structures, gives a highly processed view of the primordial perturbations and their evolution and the interactions between different species of particles. This enables probes of our model — and extensions such as interacting dark matter and dark energy, new particle species, and non-Einstein gravity — in new physical situations. Those new situations require analytical or numerical predictions in highly nonlinear circumstances. In fact, in the early Universe, the density perturbations that characterise the distribution of the large-scale structure are very small, of the order of 10^{-5}. Therefore they can be described through the linear theory of cosmological perturbations, e.g., through the linearisation of Einstein's equations of gravity. These small initial anisotropies are imprinted in the CMB, i.e., in the temperature and polarisation of the photons interacting with matter in the initial plasma, which decouple at recombination. However, due to the gravitational instability, these small initial overdensities grow to form larger and larger structures in the Universe. At this stage, the linearised Einstein's equations are no longer able to describe the evolution of the Universe, which becomes highly nonlinear and describable only thanks to the use of numerical simulations (albeit usually using Newtonian gravity, adequate on scales between cosmological and black-hole horizons). These simulations allow us to understand and model structure formation, not only at large scales, where gravity plays the main role, but also at small scales, as galaxies within clusters, filaments and cosmic voids. The nonlinear evolution of structures in the Universe is characterised by different and intriguing aspects, which makes its description and interpretation much complicated, but at the same time even more fascinating. By means of the nonlinear evolution, not only overdensities merge together to form large virialised structures such as clusters of galaxies, but even underdense regions evolve by changing the depth and size of cosmic voids, i.e., the largest non-virialised structures in the Universe. Furthermore, the nonlinear evolution alters the position and height of BAO in the distribution of galaxies, i.e., of those acoustic peaks that we observe in the CMB at the linear level. This evolution depends on the constituents of the Universe, and on the physics that govern it. Thanks to nonlinear modelling of structure formation, it is possible to extract information from the statistics of data from the late Universe, such as the correlation of galaxies, or the abundance of clusters and cosmic voids, which, when combined with observations of the early Universe such as the CMB, allow us to quantify its constituents, their evolution, and to verify Einstein's general relativity.

Key questions:

- Is there evidence in structure formation for deviations from general relativity or the cold dark matter and dark energy paradigm?
- What is the exact connection between the formation of stars and galaxies and their dark matter halo?

Fundamental and New Physics

Astronomical data relevant for cosmology provide direct evidence for some physics beyond the standard model of particle physics: the matter-antimatter asymmetry, the presence of (nearly Gaussian) power-law fluctuations in the photon-matter mixture on scale larger than the horizon at recombination (when the Universe was 370,000 years old), the presence of a probably non-baryonic dark matter component dominating the matter budget of the Universe, the presence of a repulsive dark energy force, dominant at the largest scales of the Universe. The imprint of this new physics will have to be found in the matter distribution, through two main observables: the properties of the fluctuations of the cosmic microwave background, mostly tracing the distribution of matter at z ~

1000; and the distribution of galaxies (and possibly of baryons) at low redshift. Concerning the latter, both the density of the sampling and the volume coverage are critical. This has triggered development of several major facilities that will be put in operation in the coming decades (e.g., DESI and Vera Rubin Observatory as ground facilities, Euclid and Roman Space Telescope as space projects), and are calling for a new generation of yet more powerful instruments of the same type. Similarly, for what concerns CMB observations, ground based (e.g., Simons Observatory, CMB-S4) and satellites (e.g., LiteBIRD) will provide new polarised CMB data in the next decade. If early (i.e. high energy) physics is certainly a clue to some of the above puzzles, it has also been realised that our knowledge of gravitation at very large scales is very poor: the sign of the gravitational force at the scale of the Universe has only been known for twenty years!

Dark matter and Dark Energy

The interplay between high energy physics and cosmology can be traced back to the seminal works of Gamow. This connection has strengthened since then with two observational facts: the gravitationally normal matter in the Universe is dominated by a dark component which is likely to be composed of particles yet undetected in terrestrial experiments; and the evidence for an accelerated expansion of the Universe, meaning that gravitation, so well-studied since Galileo, is repulsive at cosmological scales. Despite continued attempts at laboratory and collider detection, until now only astronomical studies have provided direct information on these two dark components.

Testing GR at cosmological scales

The discovery of the accelerated nature of the expansion has considerably strengthened the importance of testing our theory of gravity at large scales: understanding the very nature of the origin of the accelerated expansion will come from accurate tests of GR at cosmological scales, with the goal of reaching accuracy similar to what has been achieved in Solar System tests. Even in the case of pure ΛCDM cosmology, this effort will remain essential.

Primordial power spectrum features

The standard ΛCDM cosmological model involves an inflationary era as an early phase. Specifically, two out of the six ΛCDM parameters are directly related to Inflation and completely define the power-law form (in Fourier space) of the primordial power spectrum of scalar perturbations. Any deviation from this power-law function can be linked to phenomena happening in the inflationary phase itself or during a hypothetical earlier one, where traces of quantum gravity effects might originate. Currently there are some very mild hints of such deviations, which however are not statistically significant. The situation might change when CMB polarisation data on large scales will be measured in the cosmic-variance limit or if, at longer time-scales, primordial CMB spectral distortions are observed. Moreover, in the less near future (~ 10–20 years from now) we could well be in a similar situation for the primordial spectrum of tensor perturbations (primordial gravitational waves) with the difference that even the detection of these modes, independent of the functional form of their power spectrum, would be an indication of a quantum gravity phenomenon by itself. The spectral characterisation of tensor modes could then add significant insight into this new physics.

Early dark energy models (H_0 tension)

The precision of cosmological observations has increased to the point that we have begun to see marked statistical tensions between different datasets. The clearest case is given by the value of the Hubble constant at present, H_0, which appears discrepant between early and late Universe observations, with a statistical significance between 4 and > 5σ depending on the data used. This might still be the consequence of systematic effects not properly taken into account during analysis or, more intriguingly, might be ascribed to new physics beyond the ΛCDM model. In the latter case, one of the most popular reconciliations of the discrepancy is represented by Early Dark Energy models, which introduce a new accelerated expansion phase well after inflation, but preceding the recombination era. The presence of a new field providing this acceleration might have other physical/cosmological consequences beyond the reduction of the observed tension. These would represent a benefit for the success of the model, as well as a falsifiable prediction, if these additional consequences could not be convincingly described in the standard scenario. Moreover, in the future (10+ years from now), the increase of the precision and of the wealth and quality of cosmological data might uncover new tensions similar to what we are presently facing with H_0.

Neutrinos, light relics, dark radiation, and more

The linear power spectrum of matter fluctuations results from the initial distribution of perturbations (believed to be set during the inflation period) and from their evolution during the early Universe, which depends on the precise contents and which in return can leave specific imprints. This is for instance how the most severe constraints on neutrino masses are obtained. Other "exotic" relics (axions, dark radiation, sterile neutrinos, coupled dark matter, etc.) may lead to specific signatures that can be looked for through measurements of the LSS distribution or through the CMB properties (the distribution of intensity and polarisation as well as any departures from a black body).

Key question:

- Is there any evidence in cosmology for deviations from general relativity, the standard cosmological model, or the standard model of particle physics?

Observational probes and signatures

The study of these different research domains requires a wide range of observational probes, some "traditional" and some more recent (e.g., gravitational waves). These probes drive the development of new instrumentation and enable some of the key questions posed in the Research Areas section to be addressed. Below we discuss these probes and identify some key facilities and instruments.

Gravitational Waves

Due to their weak interaction with matter, gravitational waves are an ideal probe of the physics of the earliest moments of the Universe. They freely propagate to us carrying unique information about their production processes, and enable us to explore epochs and energy scales inaccessible to electromagnetic observations and lying above the ones achievable with current particle colliders. During an inflationary phase, a stochastic gravitational wave background is produced by quantum fluctuations of the gravitational field. Quantum fluctuations in the spacetime geometry of the early Universe are expected during the primordial inflationary and reheating phases. They are amplified to cosmological scale and leave a background of relic primordial gravitational waves. Different mechanisms give rise to specific features in the primordial gravitational-wave power spectrum, whose detection should discriminate among inflationary models. Currently, the most promising way to detect primordial gravitational waves is the search for so-called B-modes in CMB polarisation anisotropies. Since gravitational waves are expected to affect the cosmic mass distribution by modifying the power spectrum of primordial scalar perturbations, the imprint of inflationary gravitational waves might also be found in the large-scale structure of the Universe. Ground-based gravitational-wave detectors, such as LIGO, Virgo and KAGRA, and the Pulsar Timing Array (PTA) search for stochastic backgrounds of astrophysical and cosmological origin. While the former arises from a superposition of a large number of unresolved astrophysical gravitational-wave sources, the gravitational-wave relics from the earliest cosmological epochs are a unique probe of the earliest moments after the big bang, able to test models of inflation and General Relativity at cosmological scales. The effectiveness of this search will enormously increase with the advent of the next generation of gravitational-wave ground-based (such as Einstein Telescope and Cosmic Explorer) and space-born (such as LISA) detectors which will reach unprecedented sensitivities and open the observations to lower frequencies, respectively. These instruments will have the capabilities to reveal new physics; particles beyond the standard model, high-temperature cosmological phase transitions, topological defects, inflation and reheating, extra spatial dimensions.

Gravitational waves from binary systems of compact objects can be used as "standard sirens" to measure cosmic distances and thus the expansion rate. The Einstein Telescope, Cosmic Explorer, and LISA, which will observe the Universe along its cosmic history, will enormously increase the number of detections, and locally improve the distance measurement precision. In addition to the possibility of solving the tension between the CMB and local Universe Hubble constant measurements, mapping standard sirens up to high redshift can also unveil the nature of dark energy. Gravitational-wave cosmography is expected to precisely measure cosmological parameters. The large number of binary compact object mergers expected to be detected by the next generation of gravitational-wave detectors (of order of 10^5 per year) also opens promising prospects for using them as a tracer of LSS, as, e.g., clustering measurements of gravitational-wave mergers in the luminosity distance space can be directly used as a tool for cosmology. Dark matter could be composed, at least in part, of primordial black holes. These could be seeded by fluctuations generated during the last stages of inflation, which then collapse in later epochs. Their mass distribution depends on the precise model of inflation and on the time when they collapsed. Increasing the number of black-hole merger detections and extending their observation to higher and higher distances will constrain their mass distribution (possibly identifying excesses of black holes in certain mass intervals) and their spatial distribution. Networks of the next generation of ground-based gravitational-wave detectors can detect populations of primordial black holes at redshifts so high (> 10) that black-holes from Pop-III stars could not have had the time to form and merge yet. The firm identification of primordial black-holes might thereby revolutionise our understanding of the inflation and the early Universe. The redshifts explored by third generation of ground-based gravitational-wave detectors will enable to test deviations from general relativity at cosmological scales; for example, probing modified gravitational-wave propagation.

Key facilities:

Advanced Ligo, Advanced Virgo and Kagra, the next generation of ground-based detectors, Einstein Telescope and Cosmic Explorer, and the LISA space mission have emerged as key facilities that could transform the field of gravitational waves, covering a wider range of masses and redshifts that can be probed, and increasing sensitivity. Europe plays a leading role in the Advanced Virgo, and the development of the ground-based detector Einstein Telescope and the LISA space mission. The Einstein Telescope has been recently included in the European Strategy Forum on Research Infrastructures (ESFRI) Roadmap.

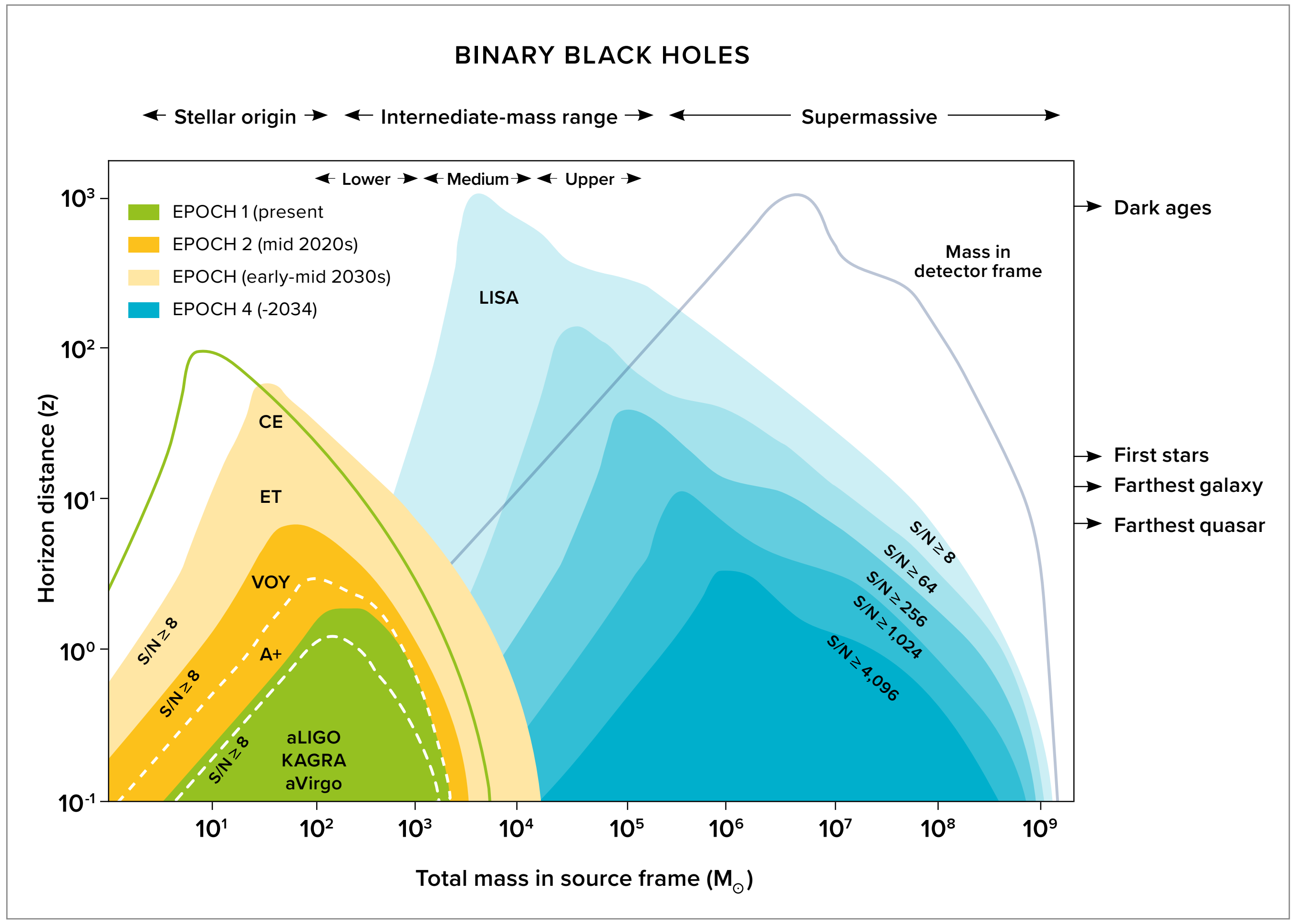

Figure 3

Cosmological reach to black hole binaries within the next 20 years of gravitational wave astronomy. The different coloured contours refer to the four epochs of gravitational wave detectors. The x-axis displays the total mass measured in the source frame. The total mass measured in the detector frame is heavier by (1+z) (as shown by dotted lines for LISA). We consider binaries with total mass in the IMBH range ($10^{2-5}M_\odot$). We divide IMBH binaries into three classes: (1) lower-range $10^{2-3}M_\odot$, (2) medium-range $10^{3-4}M_\odot$, and (3) upper-range $10^{4-5}M_\odot$ masses. The horizon distance (measured as the cosmological redshift for CDM cosmology) on the y-axis has been computed at the minimum threshold S/N=8 for binaries with two equal-sized, non-spinning black holes. For LISA, we show how the horizon radius depends on S/N.

Credit: Jani, K,, Shoemaker, D., Cutler, C., 2020, Nature Astronomy 4, 1.

Polarisation of the Cosmic Microwave Background Radiation

The linear polarisation of CMB anisotropies can be decomposed into a gradient-like (E-mode) and a curl-like (B-mode) component, which behave differently under a parity transformation. The great importance of the latter is due to the fact that primary B-modes can be attributed to tensor perturbations, i.e., primordial gravitational waves, as opposed to scalar (density) perturbations which source only E modes at linear order. Moreover, they can be directly linked to the energy scale of inflation. The observation of primary E-modes may represent the first detection ever of a (semi-classically calculated) quantum gravity phenomenon since, at least in the standard scenario, they are generated by a quantum effect in vacuum, i.e., the perturbations are directly coupled to quantum fluctuations of gravity. Unfortunately the amplitude of the tensor mode is not convincingly predicted by theory: most of the inflationary models allow for a large range of tensor modes amplitude and consequently tensor-to-scalar ratio, r (which is the parameter commonly used to provide constraints on primary B-modes). The observational difficulties are related to the exquisite control of systematic effects (both of astrophysical and instrumental origin) needed and to the capability to disentangle primary B-modes from astrophysical polarisation (i.e., foregrounds) and B-modes created by gravitational lensing from E-modes. Moreover, one has to check/control other new physics which might be able to produce B-modes: an example of the latter is cosmological birefringence, predicted by several extensions of standard electromagnetism involving parity violation. Many of these physical processes are probed by the various power spectra of the CMB temperature and polarisation, as well as that of the lensing potential that distorts the paths of CMB photons; see Figure 4 for the current status of CMB observations. Statistics beyond the two-point correlation function of CMB anisotropies probe non-Gaussian features which can provide further insights into the physics of inflation, and in particular of interactions of the quantum fields present during the inflationary epoch.

Key facilities:

The large ground-based observatories are mostly US-lead and include Simons Observatory (Simons foundation), South Pole Telescope and BICEP/Keck which will further evolve to CMB-S4 (DoE/NSF). They are paving the way to CMB high sensitivity polarisation measurements. Complementarity with a space mission such as LiteBIRD (JAXA+NASA+Europe) is essential to reach the next steps in CMB science in the next decade. With the LiteBIRD mission, selected by JAXA, Europe has a unique opportunity to consolidate its major role in the next generation of CMB space experiments capitalising on its successful leadership role in Planck. Together with involvement in US-lead experiments, European CMB ground-based (e.g. QUBIC, QUIJOTE, LSPE-strip) and balloon-borne experiments (e.g., LSPE-swipe, BISOU) are necessary and should be thought of as pathfinder for larger facilities.

Spectral Distortions of the Cosmic Microwave Background Radiation

In addition to the CMB anisotropies, the absolute CMB frequency spectrum is another key observable to probe the cosmological model. Since the measurements with COBE/FIRAS in 1992, the CMB spectrum is known to be extremely close to a perfect blackbody, with deviations in intensity I (proportional to temperature for a blackbody) limited to $\Delta I/I \sim 10^{-5}$. However, several standard and non-standard processes can lead to departures from a Planck spectrum. These so-called spectral distortions encode information about the thermal history of the Universe from the early stages until today. Spectral distortions from the primordial Universe, in particular to the chemical potential, μ, arise from cosmological recombination lines at $z \sim 10^3$ or energy injection caused by Silk damping of primordial perturbations. In addition to these expected "standard" signals, other distortions may arise from exotic processes related to the nature of dark matter and other components (dark matter annihilation and decay, primordial black holes, axions and dark matter interactions with standard particles). Furthermore, some inflationary models may be only distinguishable through their effects at ultra-small scales only constrainable by CMB spectral distortions (Fig. 5). After decoupling at $z \sim 10^3$, matter perturbations grew and evolved to form the first stars that eventually reionised the Universe. Galaxies assembled in clusters and filaments, and formed the cosmic web of LSS. CMB photon interactions with ionised gas during reionisation and in the LSS through inverse Compton scattering (also known as the thermal Sunyaev-Zel'dovich, tSZ, effect) generate a y-type distortion of order 10^{-6}. Measuring the y distortion will help in differentiating between reionisation scenarios, in measuring the absolute intensity of the extragalactic background radiation produced by dusty galaxies (the Cosmic Infrared Background, CIB), in providing intensity maps of the far-IR lines (such as [CII] and CO) of high-z galaxies, and finally in revealing the hot gas content and hidden baryons in the cosmic web, providing new constraints on galaxy cluster evolution and feedback processes. A significant improvement to the limits on μ-type distortion would allow us to rule out many particle physics and inflation models and to understand the structure formation model. In the next decade or two, future space missions including a Fourier Transform Spectrometer, covering frequencies from 30 GHz to 2-3 THz, should provide the most stringent limits on y and μ distortions, improving those obtained with COBE/FIRAS by several orders of magnitude.

Key facilities:

Complementary to CMB spatial fluctuations, several space missions such as PIXIE (NASA) and PRISTINE (ESA) were proposed to measure spectral distortions orders of magnitude smaller than COBE/FIRAS. The planned PIXIE instrument can engage European scientists in contributing to probe the spectral distortions. However, the full role of the European community in this area will be made real in the horizon 2035-2050 when instrumental concepts will be proposed for precise spectroscopic observations of the microwave sky, now part of the ESA's Voyage 2050 themes considered for ESA L-class missions.

Large-Scale Structure

The importance of understanding the nature of Dark Energy (DE) has triggered the development of numerous large ground-based, photometric and/or spectroscopic galaxy surveys. These large-scale surveys simultaneously offer the unique possibility of probing the cosmological framework and the dark sector. They also enable the exploration of the matter distribution from the smallest (Mpc) to the largest (hundreds of Mpc) scales, hence probing the formation and evolution of the large scale structure as it is modulated by non-gravitational physics.

Galaxy Clustering

Galaxy surveys allow us to construct large galaxy catalogues of unprecedentedly high quality with measured (spectroscopic or photometric) redshifts, providing a three-dimensional view of our Universe.

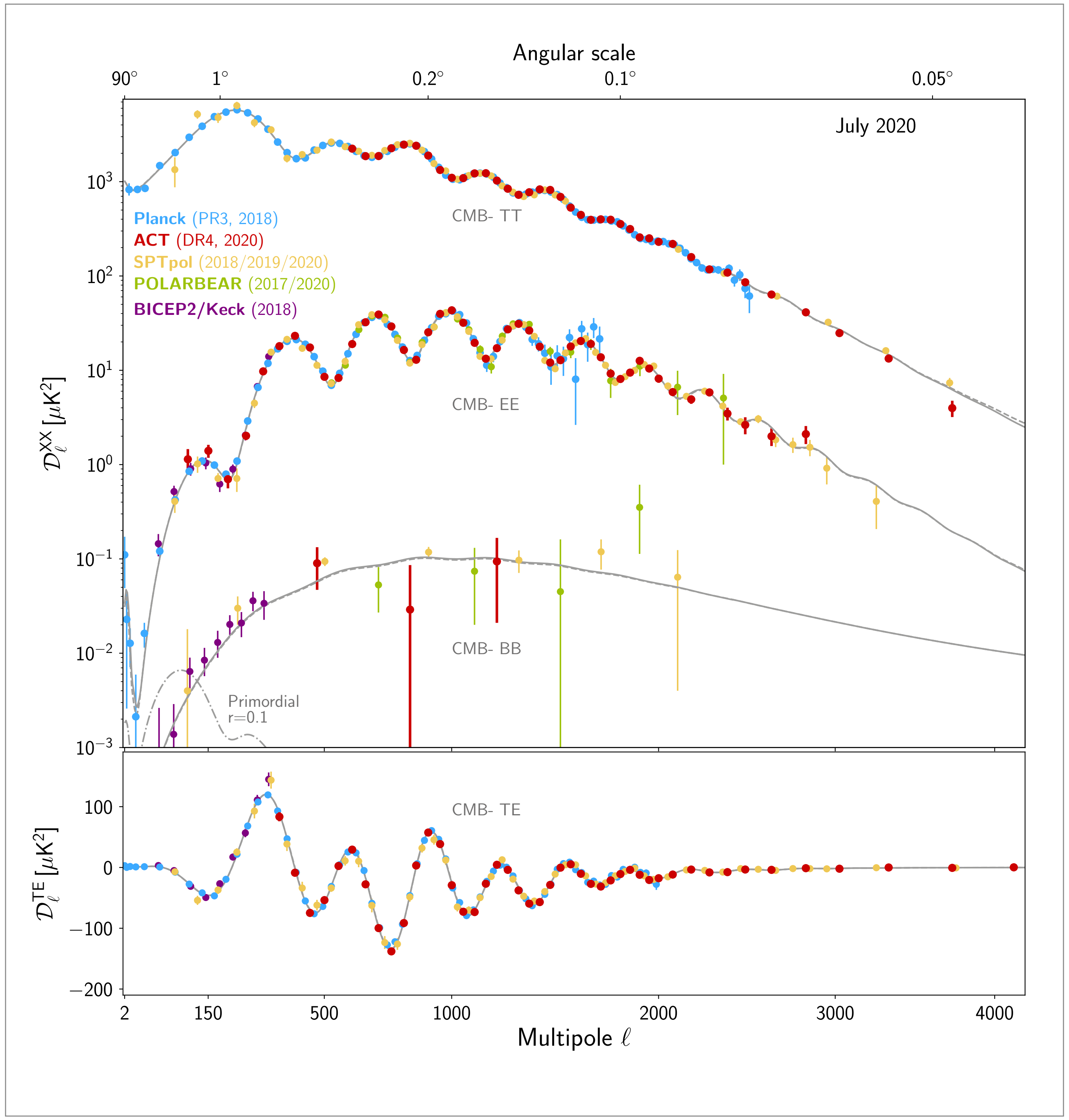

Figure 4

State of the art of CMB observations.

Credit: Choi, S.K., et al. 2020, JCAP, 2020, 45 (arXiv:2007.07289).

Probing and understanding the physical nature of dark energy will be achieved by measuring its effects on both the geometry/expansion of the Universe together with its dynamics. The imprints of these effects are thus observed through various LSS-based cosmological probes, all constructed from the precise characterisation of the spatial distribution of galaxies, i.e., luminous and biased tracers of dark matter. Galaxy clustering probes the fluctuations of the underlying dark matter density and velocity fields from the 3D positions of galaxies. It can be used to test the cosmological model in many ways: through geometrical probes consisting of the standard ruler, namely the BAO, and the Alcock-Paczynski effect; through dynamical probes, namely the growth factor from redshift-space distortions (RSD); and finally from the model-dependent cosmological information encoded in the full shape of the power spectrum, which, in addition to dark energy is also particularly sensitive to the neutrino mass through its effect on the growth of structure at small scales. The power spectrum can be accessed from the galaxy spatial distribution by computing the 2-point correlation function in real or harmonic space, the lowest-order statistics which couples different spatial regions. In this case, the data-model comparison probes the cosmological parameters but depends on physically relevant systematic effects such as the galaxy bias, describing how galaxies trace the dark matter field. Among the main large-scale galaxy surveys which have been able to greatly exploit the aforementioned probes there are WiggleZ, SDSS, BOSS, eBOSS and the currently operating DESI. On the theoretical side, characterising the non-linear evolution of the LSS is another key challenge requiring specific theoretical and methodological developments, as it directly induces mode coupling and scale-dependent bias on small scales (and even on very large scales in the presence of primordial non-Gaussianity). In this respect, given the non-Gaussian nature of the galaxy distribution, the measurement of higher order statistics, such as the bispectrum or three-point correlation function, provides crucial additional constraints on the model.

Intergalactic Medium

Another important and established probe of the cosmological large scale structure and its formation process is the intergalactic medium (IGM), the diffuse matter between galaxies and the principal repository of the baryons produced at the Big Bang epoch. Its most prominent manifestation is the Lyman-alpha forest, the pattern of absorption (scattering) features in the spectra of Quasi Stellar Objects (QSO) produced by the intervening neutral hydrogen along the line-of-sight. Its use as a cosmological and astrophysical probe has developed impressively in the last two decades thanks to the progress made along multiple lines. Firstly, high-resolution spectroscopic surveys (Keck/HIRES, UVES/VLT, etc.) deliver high quality data, producing rapidly growing databases. Secondly, cosmological structure formation codes implement increasing amounts of the relevant physical processes. Finally, more recently, the gain in statistical power achieved by low and medium resolution spectroscopic surveys (BOSS, eBOSS, DESI) has grown enormously, now permitting detailed probing of the cosmic web in 3D. These efforts are making possible the measurement of cosmic structures in an untested regime both in scales, from below the Mpc scale up to the BAO scales, and redshifts $z = [2–6]$, which are highly complementary to other cosmological probes. Moreover, BAO oscillations in the 3D flux correlation function have been used to measure the geometrical state of our Universe and provide tight constraints on new physics beyond the standard model. The 1D fluxpower offers among the tightest constraints on the cold dark matter coldness and other dark matter scenarios like warm dark matter, fuzzy/scalar dark matter and sterile neutrinos.

Galaxy Weak Lensing

Weak gravitational lensing describes the small deflections of photons by metric perturbations along their line of sight from their sources. It provides a direct and unbiased measurement of the total mass distribution. However, galaxy gravitational lensing requires high quality images since it is observed through the distortions of the galaxy shapes that correlate the ellipticities of pairs of galaxies, called the cosmic shear. Cosmic shear measurements as a function of source redshift can probe the impact of dark energy on the growth of structure and test gravitational explanations of cosmic acceleration. The control of systematic effects is one of the key challenges for this type of measurement. These effects include both the optical properties of galaxy images, as well as the measurement of their distribution along the line of sight from broad-band photometry. Cosmic shear is sensitive to the total amount of matter in the Universe, and to the amplitude and rate of growth of its fluctuations. It depends differently on the details of galaxy evolution than direct measurements of galaxy clustering and formation, especially through the presence of any systematic intrinsic alignments between galaxy images; as such it is a powerful and largely independent probe of the cosmological model, including the nature of dark matter and the underlying theory of gravity responsible for the clustering of matter. CFHTLenS, KiDS and DES are among the largest deep-imaging surveys exploiting galaxy weak lensing as a cosmological probe.

Galaxy Clusters

In addition to the aforementioned LSS-based probes, the use of clusters of galaxies as a cosmological probe has a long history, dating back to the discovery of dark matter in Coma in the 1930s, and remains an important complementary probe. Optical and X-ray surveys, such as SDSS, DES or ROSAT All Sky Survey, are the traditional ways by which clusters have been detected and studied. The recent and ongoing mm and submm CMB surveys (ACT, SPT, Planck)

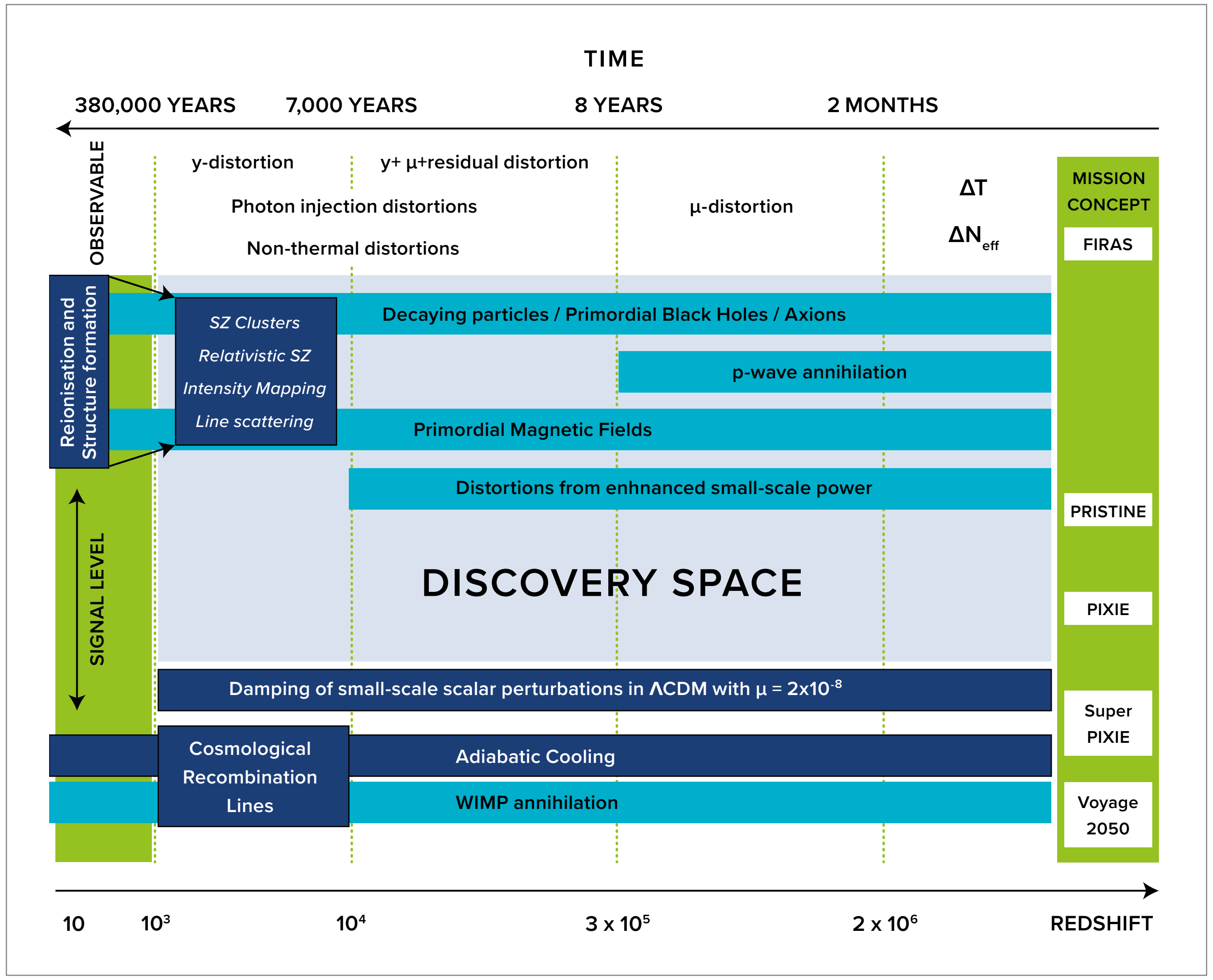

Figure 5

Science thresholds and mission concepts of increasing sensitivity for spectral distortions. Guaranteed sources of distortions and their expected signal levels are shown in dark blue, while non-standard processes with possible signal levels are presented in turquoise. Spectral distortions could open a new window to the pre-recombination Universe with a vast discovery space to new physics that is accessible on the path towards a detection and characterisation of the μ-distortion from the dissipation of small-scale acoustic modes set by inflation and the cosmological recombination radiation.

Credit: Voyage 2050 white paper from J. Chluba (Chluba, J. et al., 2021, Experimental Astronomy, 51, 1515).

are now releasing catalogues of hundreds of new groups and clusters of galaxies up to redshifts z ~ 2 detected via the tSZ effect. Clusters of galaxies trace the most massive halos lying in the nodes of the cosmic web, and are hence sensitive to the underlying cosmological model. Cluster number counts and spatial clustering (estimated via correlation functions or power spectra), mass fraction of hot intra-cluster gas, distances from joint X-ray and tSZ observations, tSZ power spectra, cluster bulk flows and kinetic SZ effect, etc., are among the many cosmological probes associated with clusters of galaxies. Although these probes have an obvious important potential, they pose specific problems. Clusters are highly non-linear objects, whose properties need to be validated by extensive numerical simulations and by detailed studies with facilities such as XMM-Newton or IRAM/NIKA2. Indeed, their use as cosmological probes relies on understanding systematic effects associated with the translation of observable quantities such as the X-ray luminosity, the richness or the tSZ "flux" into total mass. The recent and near future surveys in the optical and near-IR (e.g., Euclid), mm and sub-mm (e.g., CMB experiments), radio (e.g., LOFAR, SKA) and X-rays (e.g., SRG/eROSITA) will provide us with unprecedentedly large catalogues of clusters ranging from poor groups to massive clusters. These data will prove crucial to complete and confirm the cosmological constraints on the constituents of the Universe that will be drawn from cosmic shear and galaxy clustering.

Additional probes

A variety of complementary and novel probes stemming from observations of the cosmic web structure are proposed to further pin down the nature of dark energy. This emerging class of observables is gaining more and more interest and attention. Among the most popular new cosmic-web related probes are cosmic voids, filling the space between the sheets and filaments of matter. They can be used to probe cosmology through their counts, their correlations with CMB (via the integrated Sachs-Wolfe effect), weak lensing or galaxy distribution, their impact on the CMB deflection field, etc., to set constraints on the equation of state of dark energy and the neutrino mass. Furthermore, and in addition to the static distribution of mass and galaxies, the galaxy velocity field has long been proposed to constrain the growth rate of structure and hence the underlying cosmological model. This can be achieved by the direct measurement of velocity correlation functions/power spectra; pair-wise velocity statistics (which implicitly probe the correlation of density and velocity); or from the kinetic SZ effect.

Key facilities:

Future wide-field optical/IR imaging telescopes expected to have major impact in the field are Euclid, the Nancy Roman Space Telescope (RST, formerly WFIRST; NASA), and the Vera C. Rubin Observatory (Vera Rubin Observatory, formerly called LSST). By the end of the decade this will be complemented by radio observations with the SKA. Surveys in the mm and sub-mm such as Simons Observatory. Ground-based wide-field spectroscopic survey telescopes/instruments such as DESI, and Subaru-PFS, with a carefully designed survey strategy, will also play a major role in the coming decade. In the more distant future, new ideas have been put forwards for ambitious multi-spectroscopic ground facilities like MSE and MegaMapper, as well as space facilities like ATLAS and projects reviewed within Voyage 2050.

Hydrogen 21-cm Signal

Whereas the Epoch of Reionization and Cosmic Dawn can be observed at frequencies above ~ 50 MHz with ground-based radio-telescope such as LOFAR, NenuFAR, MWA, the uGMRT, HERA and the upcoming SKA, which will carry out the deepest observations ever undertaken of the diffuse neutral hydrogen gas in the $6 < z < 30$ range, the 21-cm signal from the Dark Ages is redshifted to frequencies that approach the ionospheric cut-off at 10 MHz, making it very hard if not impossible to observe from Earth. Further, human-made RFI signals contaminate the signal, excluding a large part of the observations domain in time and frequency. These difficulties motivate many space-based 21-cm signal missions, in particular, focusing on the lunar orbit and farside of the Moon. The 21-cm signal from the Dark Ages can be divided into two statistics, the globally averaged signal and the power spectrum. Both are extremely hard to measure due to foreground signals that are 5–6 orders of magnitude brighter. The global 21-cm signal, however, needs only a single well-designed receiver ([short] dipole or monopole) to measure, although integration times of about a year are required to reach enough signal-to-noise for detection at z ~ 40. To determine the 21-cm signal power spectrum, phase-arrays are needed with collecting areas of several to several tens of square kilometres. Although daunting, with new light-weight technologies, this could be feasible in space and on the lunar surface.

Key facilities:

Whereas first-generation instrument such as LOFAR, MWA and the GMRT, and their upgrades to second-generation instruments (LOFAR2.0, MWA2, uGMRT), play key roles in 21-cm Cosmology, the next-generation SKA and HERA are being designed or constructed already. Besides these next-generation instruments, a range of global signal instruments are being considered, such as the European initiatives REACH (ground-based) and NCLE (lunar L2), and ideas are being developed for lunar-based radio astronomy by ESA, NASA and CAS. Strong investment by Europe in both the SKA and space-based radio astronomy, as well as in smaller global 21-cm instruments, allow it to retain leadership in the field of 21-cm Cosmology.

Intensity Mapping

In many cases direct detection through imaging or spectroscopy of sources (e.g., via the high-redshift 21-cm line, FIR/X-ray, atomic [e.g., Lyα, Hα, Hβ, CII/III, NII], and molecular [e.g., CO] line emitters) is not feasible due to a (combined) lack of instrument sensitivity and/or resolution. In these contexts, intensity mapping (IM) — where many sources are within a resolution element of the instrument — can still yield information about these sources averaged over much larger volumes. It also allows for cross-correlations between various observational probes, in particular if redshift information is available in the case of line emission. One of the most intriguing cases is that of the cosmic infrared background, which has been coupled to, e.g., the formation of the first and second generation of stars. Similarly, at redshifts well within the Epoch of Reionization and beyond, the X-ray background places limits on high-redshift stellar remnants (e.g., HMXRBs and QSOs), and intensity mapping of molecular lines and atomic-line emitters are being considered an excellent complementary probe of sources of reionisation, anti-correlating with the redshifted 21-cm line of neutral hydrogen. At lower redshifts, the intensity mapping of the [CII] line with APEX/CONCERTO can probe galaxies in the range z ≥ 5.3. Intensity mapping of the redshifted 21-cm line can also be used to probe BAO over extremely large volumes. Most recently, around redshift one, significant correlations between 21-cm IM and the distribution of massive galaxies

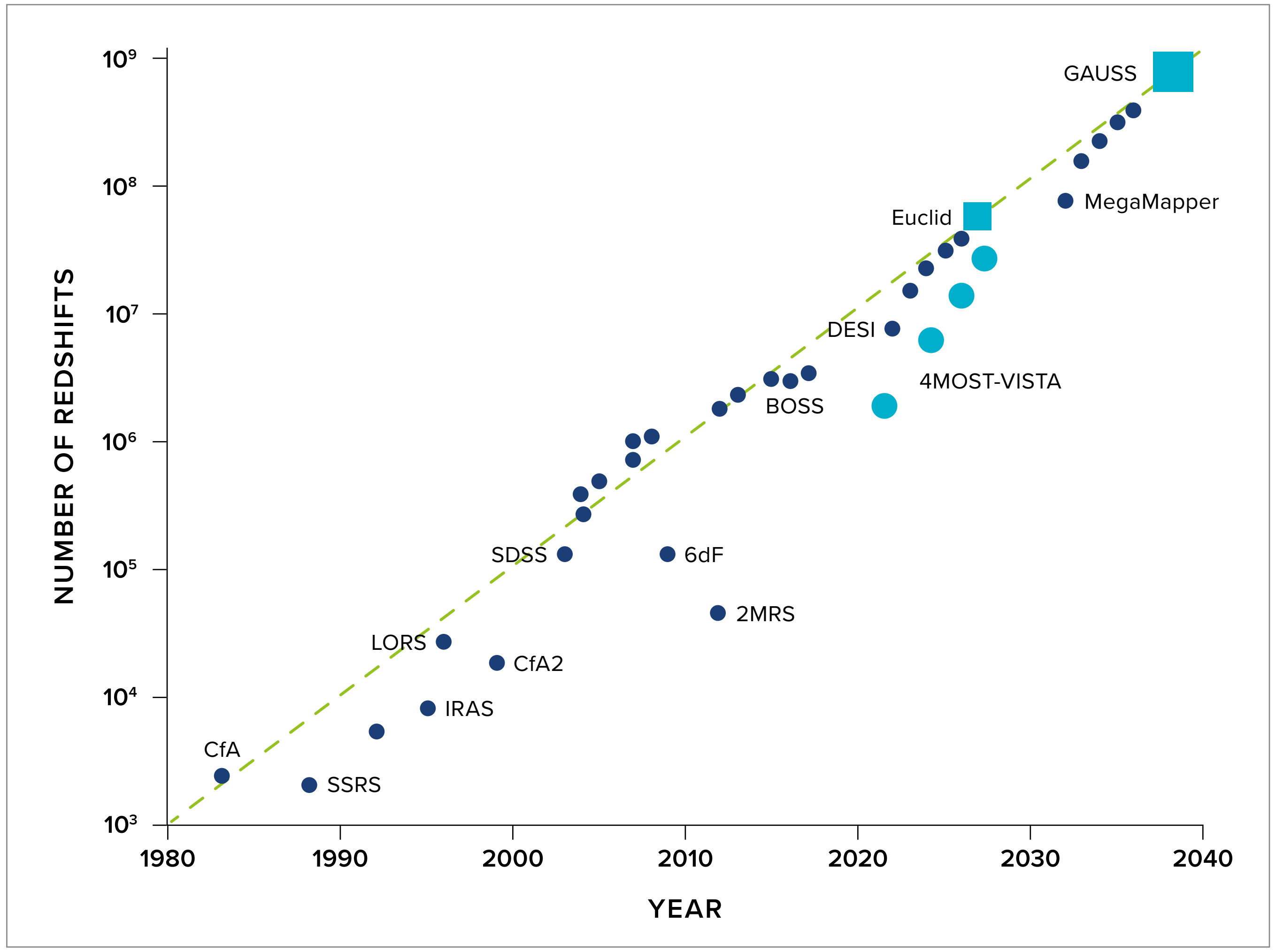

Figure 6

Summary of major redshift surveys that are dedicated to the studies of large scale structure.
The light blue symbols are for European projects.

Credit: figure adapted from Astro2020 APC White Paper, Schlegel D.J., et al. (arxiv:1907.11171).

have been found. In the next future, SKA Phase 1 will survey a total area of ~ 20,000 deg^2 from z = 0 to 3 over 1 - 2 years, with a sensitivity to the first BAO acoustic peak comparable to future nearly full sky galaxy surveys. The technique of IM is becoming increasingly important especially since it sometimes is the only way to detect a signal. Intensity mapping, however, requires very large volumes both spatially and in redshift to reduce sample variance and yield sufficient signal to noise, driving the development of many new instruments.

Key facilities:

Planned major facilities in this field are HIRAX, SphereX, CCAT, BINGO, most with European involvement. In addition to the intensity mapping of atomic and molecular line emitter by APEX/CONCERTO, only intensity mapping of the 21-cm signal up to z ~ 3 with the SKA-MID and low is currently foreseen.

Cross-correlations between various probes

The use of combinations of different probes has already led to tight constraints on the cosmological model. For instance, up to date constraints on dark energy are obtained by combining CMB data from Planck, the type Ia Hubble diagram of supernovae, and large-scale structure data from BAO. This is due to the fact that different probes usually constrain different combination of parameters, and are affected by different systematic effects, and hence the joint constraint can therefore be much stronger than any single one. Further, when two samples of data (corresponding to two distinct probes) overlap on the sky this can provide an additional data vector through the cross correlation of the two data sets. This new data vector can thereby provide qualitatively and quantitatively new information. This is well-illustrated by the historical fact that the cross-correlation between CMB temperature maps and galaxy catalogues can reveal the accelerated expansion, being able to isolate the Integrated Sachs-Wolfe effect. In addition, on the one hand, the cross-correlation between galaxy clustering and CMB lensing helps to improve the constraints on the dark energy equation of state and the structure growth rate. On the other hand, the cross-correlation between galaxy weak lensing and CMB lensing is a powerful tool to probe matter fluctuations at intermediate redshifts and to fix residual systematics.
This power of cross correlations is a key ingredient of modern major surveys designed for constraining Dark Energy: the 3 × 2-point statistics, comprising the shear-shear correlation, the galaxy-galaxy correlation and the galaxy-shear correlation offer an ultimate survey performance much higher than what would be obtained from the simple combination of the individual probes (i.e., the simple product of the likelihoods from shear-shear and photometric galaxy-galaxy correlations). Furthermore, in the case of upcoming surveys such as the Vera C. Rubin Observatory and Euclid, such cross-correlations will be much more powerful and constraining. Since these galaxy surveys will provide mostly full-sky weak lensing maps, it will be possible to take into account the cross-correlation of weak-lensing and photometric galaxy catalogues with spectroscopic surveys.
In particular, the spectroscopic and photometric galaxy distributions observed by Euclid will share the same sky area above redshifts z ~ 1. This will extend the current 3 × 2-point statistic to include the spectroscopic galaxy-shear correlation and the spectro-photo galaxy correlation, the latter presently used only for photometric redshift calibration. Including these cross-correlations in the data vector for likelihood analyses and cosmological parameter inference is the challenge to guarantee the full and accurate exploitation of forthcoming full-sky galaxy surveys. In addition, the “multi-tracers” technique will allow the removal of the dominant source of noise in some analyses. In this respect, it is worth stressing the importance of cross-correlating optical and radio galaxy surveys, such as Euclid and SKA. In fact, due to large signal contamination by foregrounds, up to now the detection of the HI intensity mapping power spectrum has happened only in cross-correlation with galaxy surveys. It has been shown that the cross-correlation of a Euclid-like spectroscopic survey with SKA HI intensity mapping may allow us to recover the BAO imprint in the full power spectrum, which otherwise, taken individually, is smeared out by the beam size of the radio survey. Such cross-correlations will also help in mitigating systematic effects such as miscalibration and intrinsic alignments, and to improve constraints on relativistic effects and primordial non-Gaussianity, which may affect very large scale clustering. Finally, a particular mention should be given to the advent of the so-called multimessenger cosmology. This does not refer only to the combination of measurements of the gravitational-wave luminosity distance, d_L^{GW}, with those obtained from CMB and galaxy survey data, to better constrain cosmological parameters, as e.g., H_0 and the dark energy equation of state (see Figure 8). Rather, especially for gravitational-wave observatories extending up to very high redshift, the expression “multimessenger cosmology” refers to the possibility of detecting and measuring the cross-correlation of d_L^{GW} and gravitational-wave stochastic backgrounds (modified by structures intervening between emission and observation) with galaxy clustering, galaxy shear, and CMB data. This will provide information of astrophysical and cosmological origin, e.g., about the physics of the early Universe, modifications of gravity, the nature of dark matter, and the evolution of dark energy.

Key facilities:

Cross-correlation between probes generally requires wide field surveys. Euclid and the SKA are prime examples of European-driven instruments that will have a long-lasting legacy value of their data products, similar to the success of SDSS or Planck, and allow cross-correlations with many other probes such as the SRG/eROSITA X-ray survey, or lead to follow-up observations, e.g., with ALMA. We also think that Europe should strengthen its position, where possible, in other efforts with the Vera Rubin Observatory, Roman Space Telescope, and James Webb Space Telescope, which will cover time-domain science, medium deep wide-field imaging, and ultra-deep optical/infrared imaging and spectroscopy.

General considerations on future facilities

To address the questions posed in the beginning of this chapter with the probes discussed above, a wide range of facilities are being rolled out or planned, some already having been discussed for decades and part of e.g., the ESFRI roadmap, and others only recently proposed in decadal reviews (e.g., the US decadal plan, ESA’s Voyage 2050, and other national strategic plans). Among them, within Europe, are a number of instruments regarded as of key importance to cosmology and will be discussed below.

Ground-based

Major ground-based facilities with European leadership in radio astronomy include the Square Kilometre Array, in optical and infrared astronomy the European Extremely Large Telescope (ELT), and in astro-particle physics the Cherenkov Telescope Array (CTA). A concerted effort is now also unfolding in the direction of gravitational waves, focusing on the continued operation and upgrading of the Advanced Virgo detector, and the development and building of the next generation infrastructure, the Einstein Telescope. In ground-based CMB observations, however, initiatives are currently limited in Europe and much of the initiative centres on the US with e.g., the Simons Observatory and the CMB-S4 initiative. Similarly, whereas Europe can play a leading role in 21-cm cosmology with the upcoming SKA, it does not lead in low/

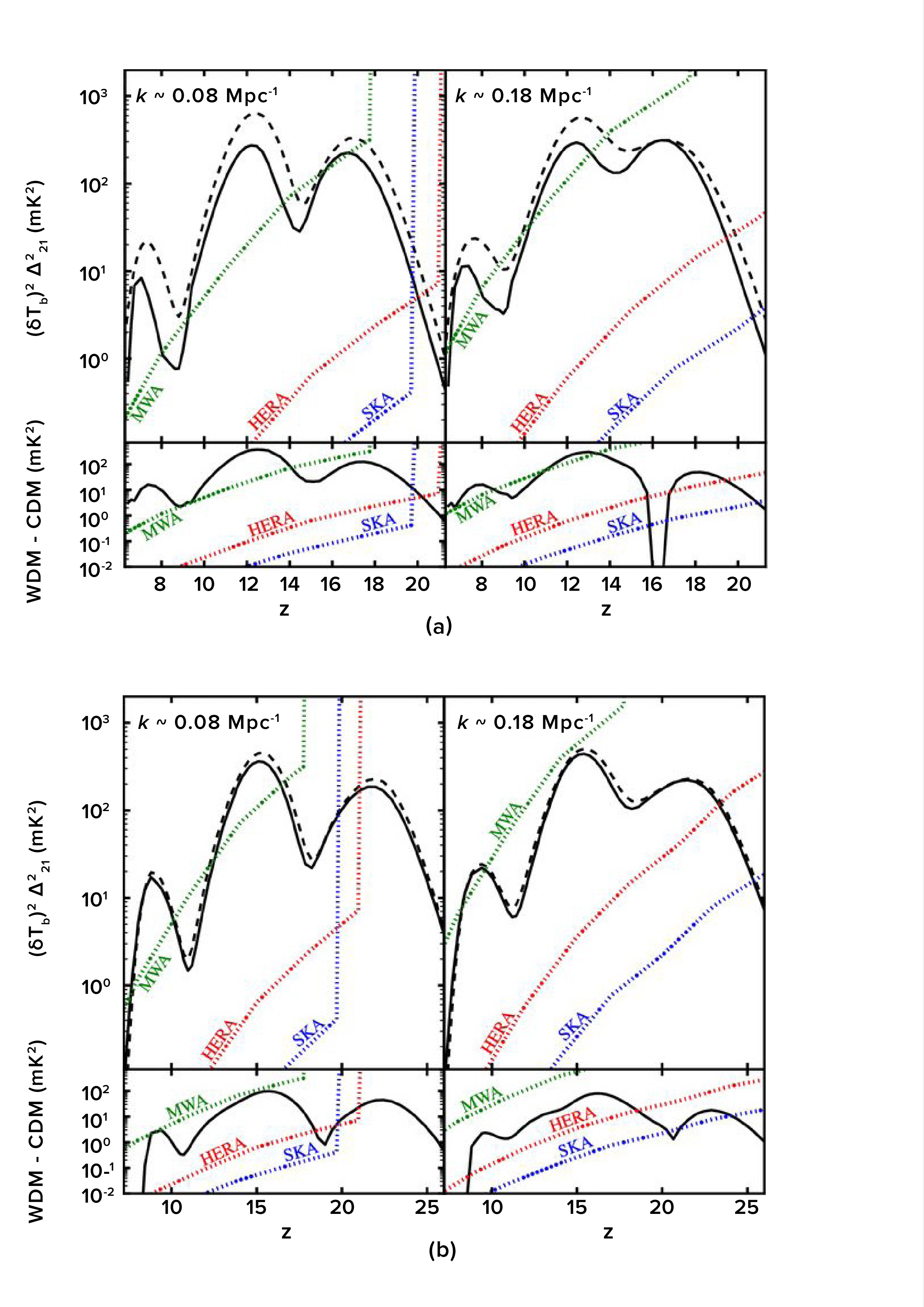

Figure 7

Evolution of the 21-cm power spectrum for WDM with (a) m_x = 2 keV and (b) m_x = 4 keV. The top panels show power spectra at k = 0.08, 0.18 Mpc^{-1} for the WDM (dashed) and the CDM model (solid). CDM models are chosen to reproduce the global 21-cm signal found for the respective WDM model. The bottom panels show the difference in the power spectrum between WDM and CDM models. Dotted curves show forecasts for the 1σ power spectrum thermal noise with 2000h of observation time. The dotted green, blue, and red curves are the forecasts for the MWA, SKA, and HERA, respectively.

Credit: Sitwell, M. et al. 2014, MNRAS 438, 2664.

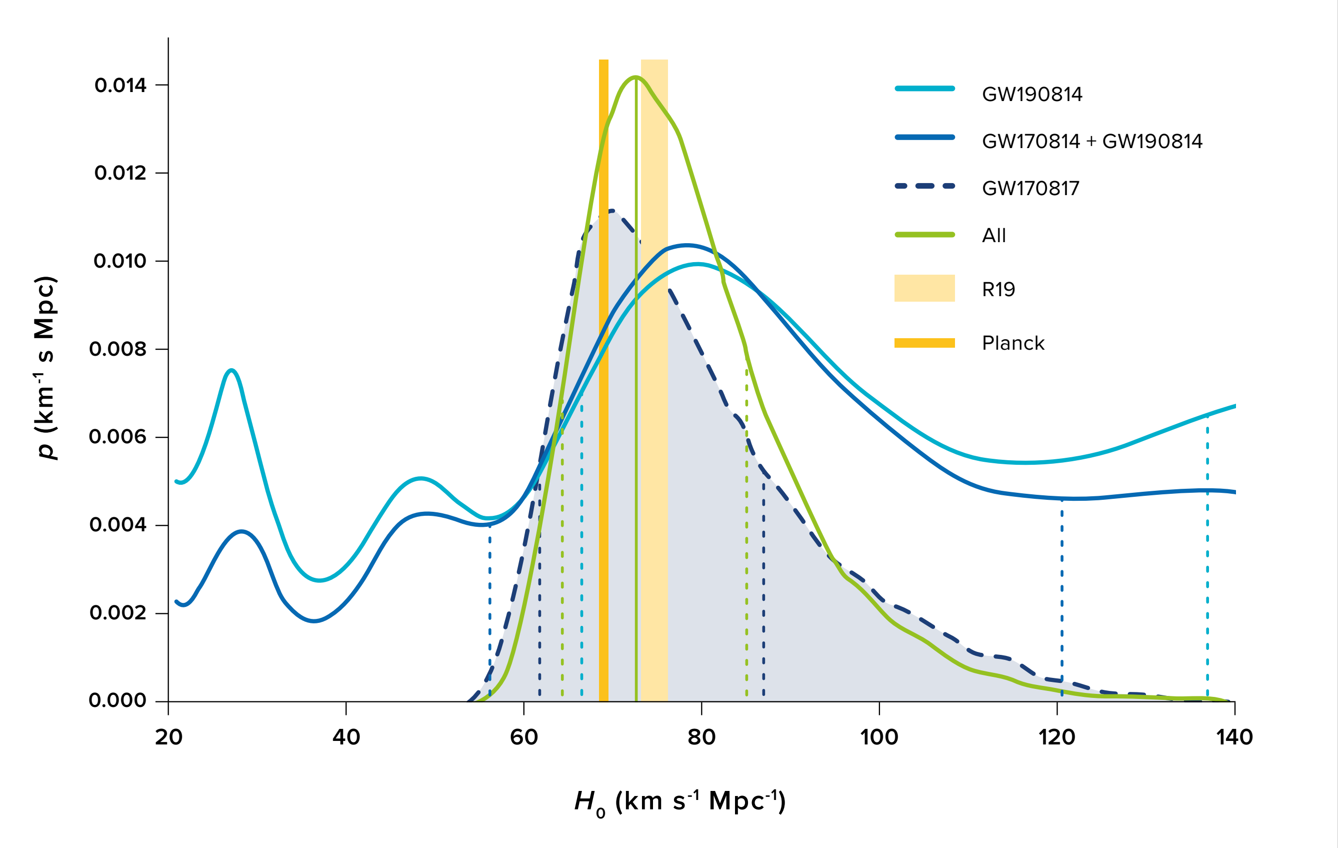

Figure 8

Hubble constant posterior distribution for GW190814 obtained by marginalising over ~ 1, 800 possible host galaxies from the Dark Energy Survey (DES) (light blue line). The dark blue curve represents the posterior obtained by the combination of GW190814 and GW170814 using DES galaxies. The maximum a posteriori and its 68% CI for the combined result is $H_0 = 78^{+57}_{-13}$ km s^{-1} Mpc^{-1} using a flat prior in the range [20, 140] km s^{-1} Mpc^{-1}. A combination of the two dark sirens, GW190814 and GW170814 with GW170817 is shown in green and gives $H_0 = 72.0^{+12}_{-8.2}$ km s^{-1} Mpc^{-1}. The addition of the dark sirens provides a ~ 18% improvement to the 68% CI from GW170817 alone. The maximum a posteriori is represented by the solid vertical line. The 68% CI of all PDFs is shown by the dashed lines. Constraints from Planck and ShoES at 1σ are shown in orange boxes.

Credit: Palmese, A., et al. 2020, ApJL, 900, L33 (arXiv:2006.14961).

medium-redshift ground-based Intensity Mapping arrays. The mapping of matter distribution on large scale through wide deep imaging and spectroscopic ground-based dedicated facilities remains US-led, like the MegaMapper, despite the interest of the European community in such facilities. In time-domain cosmology, Europe has an opportunity with the transient science in the radio domain with the SKA to complement the US-led Vera Rubin Observatory.

Space-based

Major space-based facilities with European leadership in the coming decade are undoubtedly SRG/e-Rosita, Euclid and Athena that will observe the optical/infrared and X-ray Universe. Besides these telescopes, the recent deselection of SPICA is a major blow to space-based infrared astronomy with European leadership. In the field of cosmology, many upcoming initiatives, such as the JWST and Roman Space Telescope have only a limited European contribution. However, with a strong European tradition in radio astronomy, new initiatives of space-based low-frequency radio astronomy are being put forward in Europe, but also in the US, China and India, with particular focus on the moon. For CMB studies, Europe is a major partner of the JAXA project LiteBIRD for the first detection of primordial gravitational waves. The future generation of CMB satellites will also target CMB spectral distortions (considered as one of the three themes for L-class missions in ESA's Voyage 2050). With LISA, Europe is clearly in a leading position for space-based gravitational wave science, complementing its drive to upgrade and develop new ground-based facilities.

Lunar-based

A new frontier being explored currently is to place facilities on or around the moon, where particular focus is being put on low-frequency radio astronomy. With NCLE in Lunar L2, as part of the Chang'e 4 mission, a pilot program is already in place. However, some other facilities (e.g., astroparticle physics and gravitational wave detection) could also benefit from a lunar environment without atmosphere and ionosphere and very low seismic noise. With ESA announcing a lunar observatory with low-frequency radio astronomy as one of its prime missions in the coming decade, on its European Large Logistics Lander, and the US and China both aiming to put (radio) facilities on the moon, this new frontier is not one that Europe can afford losing out on.

Maintaining, improving and strengthening advanced instruments

Besides new facilities (sometimes dedicated experiments with a single purpose), continuous operation and upgrading of existing facilities should occur. Prime examples are the operation of XMM-Newton by ESA and member states and continuous upgrades by ESO of its VLT (and in the future ELT) instruments. Similarly, upgrades of the LIGO and Virgo detectors are underway. New technologies are being developed to achieve a ten-fold increase in sensitivity for the Einstein Telescope and Cosmic Explorer, which are expected to be operative in the 2030s. SKA phase 2 can further increase the sensitivity and improve the spatial resolution of the SKA. New bands are continuously added to ALMA, where phase-array front-ends could enable a huge increase in survey speed. Besides these, we emphasise that smaller facilities (e.g., ING) play an important role in laying the groundwork for these massive facilities coming online in the future. To ensure feeding them with targets, small/medium-sized facilities remain essential.

Data Science

Data from ground-based and space-borne facilities are becoming increasingly complex and extensive in volume owing to the increasing sensitivity of the detectors and of the observed sky area. The specific data used to answer the fundamental cosmological questions about the origin and evolution of the Universe will be of very different types: images, catalogues of millions of galaxies; 2-D averaged pixels in “tomographic” slices, 3-D voxels, etc. Even the science-ready end products are often too large and too complex to inspect and analyse through human interaction. This situation has motivated intense interdisciplinary research and even dedicated institutes focused on applied mathematics, statistics, machine learning, or more generally data science in the field of cosmology and astronomy.
The objectives are here to develop novel algorithms and methods designed to handle, explore, analyse and combine the expected complex datasets. The broad idea of machine learning is therefore gaining immense momentum in the cosmological community. It includes both supervised and unsupervised methods targeting the search for rare targets, pattern recognition, classification, etc. Beyond its standard usage for data mining and component separation/classification, sophisticated approaches have been proposed to accelerate or even replace numerical simulations, to explore the likelihoods of models, and to even propose alternatives to theoretical models for the growth of structure!

Conclusions and General Notions

Whereas large-scale facilities by their very nature draw most attention, a careful balance between small, medium, large-scale instruments should be found, in a “wedding cake” approach where smaller and medium size instruments either lay the foundations for follow-up with larger facilities, or vice versa follow-up with the smaller instruments is done. Also complementary between space and ground facilities is important. We believe that European leadership and “independence” is crucial, although collaboration with other countries is seen as important and sometimes crucial. With Planck and Euclid, European research in cosmology has been put at the forefront of space based research. It is worth noticing that no similar ground based efforts have been performed (or foreseen) at the European level, either in the CMB or wide field spectro-imagery, over the last twenty years, a period over which the USA has consolidated the leadership in these areas. Besides building the next generation instruments themselves, it is crucial that such devices are connected to high-performance (but preferably green) computing facilities that operate state of the art data processing and analysis tools. This must come together. In addition, structuring and training the communities beyond individual projects, through instruments like Opticon or RadioNET should be promoted.

Key Notions:

- Cosmology and fundamental physics are expected to blend further in the future.
- Research fields in cosmology expected to grow rapidly are those related to gravitational- wave and 21-cm cosmology, each opening an entire new window on the Universe in the coming decades.
- Similarly, polarisation and spectral distortions of the CMB are new frontiers.
- The cross-correlation and combination of cosmological data-sets and wavelengths appear as an increasingly powerful probe of the cosmological model.
- Key future facilities with large European leadership roles in the field of cosmology are Euclid (ESA), Athena(ESA), SKA, the Advanced Virgo, LISA, and LiteBIRD (JAXA-lead with a large European involvement).
- Other facilities in which Europe is a partner, or should consider partnering with, are the JWST, the Roman Space Telescope, the Simons Observatory, CMB-S4, and the Vera Rubin Observatory, the MegaMapper.
- Investing in small/medium-size facilities and new instruments on existing platforms (e.g., WEAVE, 4MOST) should be thought of as pathfinder for ambitious wide field facilities like MSE.
- Noticeable large scale and longer term initiatives at the European level are developed to cover in the domains of gravitational waves (Einstein telescope), CMB (super-PIXIE, PRISTINE or PICO-like missions combining a spectrometer and an imager), X-rays and IR astronomy.
- New instrumentation should be accompanied by investments in data processing, analysis and data science to maximise the scientific return as soon as the facilities go online.

C

Formation and evolution of galaxies

Prior to the recombination event, matter and radiation were coupled in the hot, post big-bang plasma. Because of the large ratio of photons to baryons and pressure from Thompson scattering, matter was distributed evenly throughout the cosmos. Only non-interacting particles of dark matter (DM) were able to coalesce and form overdensities, which amassed to only one part in 100,000 by 400,000 years after the big bang (redshift, z, of 1100). The background radiation emitted at recombination remains the only observable signature of these early epochs, after which the universe entered the so-called ‘dark ages’, an epoch about which we currently have almost no empirical information.

During the dark ages, however, the framework for the large-scale structure of the universe began to assemble (Figure 1). Dark matter began collapsing and produced the first scaffolding of the cosmic web, while baryons were able to gravitationally follow this structure. With no metals, and all the hydrogen and helium residing in atomic form, this epoch is observable via low frequency radio signals. Structure formation proceeded largely unseen: the largest density fluctuations grew by around 10 orders of magnitude, until the first (probably exotic) stars ignited 100 million years later.

The formation, evolution, and end-points of the first (Population III) stars were likely peculiar in many ways: the absence of interstellar coolants and under-abundance of molecules will have made fragmentation, stellar initial mass distributions, and binarity fractions very different from those known in the more evolved universe. Differing stellar structure, rotation, and opacity will all affect the evolution timescales and emissivities. These early stellar photospheres produced the first ionising photons, and an ultraviolet (UV) radiation background that could reionize the universe and inhibit subsequent star-formation. The same stars also polluted pristine interstellar media with metals, and modified subsequent gas cooling and fragmentation, etc; their deaths are also believed to produce the first stellar mass black holes, thereby planting the seeds for luminous active galaxies seen at later epochs.

Galaxy formation continues as DM halos grow and merge; the accretion of baryonic matter from the cosmic web increases, and fuels star formation and early galaxy buildup until the first objects become visible at $z\sim10$. Black holes grow to attain ‘supermassive’ status, while others may have formed by alternative methods such as direct collapse, and produce the first quasars that are currently observed only shortly after the first galaxies. The mechanisms by which these early systems grew remain elusive, but soon-to-be commissioned telescopes will be charged with determining the properties of these galaxies, and with that the foundations for galaxy assembly. The first observable large-scale structure grows with the buildup of massive galaxies, which proceeds down to redshifts of about 2 (around 3 billion years post Big Bang), around which point the first virialized galaxy clusters emerge and the Milky Way experienced its last significant merging event, which formed the thick disk, delivered globular clusters, and polluted the stellar halo. The star formation rate (SFR) of the universe increases ten-fold since the earliest observable times, and individual objects become more luminous, massive, and physically larger. The assembling galaxies are very rich in gas that has been accreted from the intergalactic medium and settles to form massive disks. At the same time, galaxy scale winds are ubiquitous, and the complex interplay between gas inflows and outflows, occurring in the circumgalactic environment, regulate the ultimate efficiency of star formation. Scaling relations between fundamental galaxy properties become clear, with relatively tight sequences emerging between mass, star formation rates, and abundances of heavy elements and sizes. These relations remain in place, but shift in their loci, down to the present day universe; the processes underpinning our place in the cosmos were thus established at least 10 billion years ago, if not earlier.

Galaxy evolution changes fundamentally during the latter half of cosmic time. While galaxies continue to grow in size and mass, the total star formation rate per volume of the Universe decreases 10-fold. Over the same timeframe, the nodal points of the more diffuse large-scale structure/cosmic web condense to form galaxy clusters with masses $10^{13\text{-}15}$ solar masses (mass expressed in units of that of the Sun), and hot intracluster media, and play host to the most massive galaxies known. As mass overdensities grow and cosmic contrast increases, environmental processes contribute more: the complex interplay of environmental interactions and internal (‘secular’) processes induce morphological transitions, growing galaxy bulges/spheroids and quenching the formation of new stars in a process that begins in the most massive galaxies, and progresses downwards in mass. The majority of star formation shifts to Milky Way-like galaxies in intermediate density environments. Studies resolving the distribution of stars, hot and cold gas, dust and star-forming sites, in concert with active galactic nuclei and their surroundings, in nearby to high redshift galaxies can provide key insights into how these secular processes affect and modify the galaxy populations and uncover the underlying physics acting on these small scales.

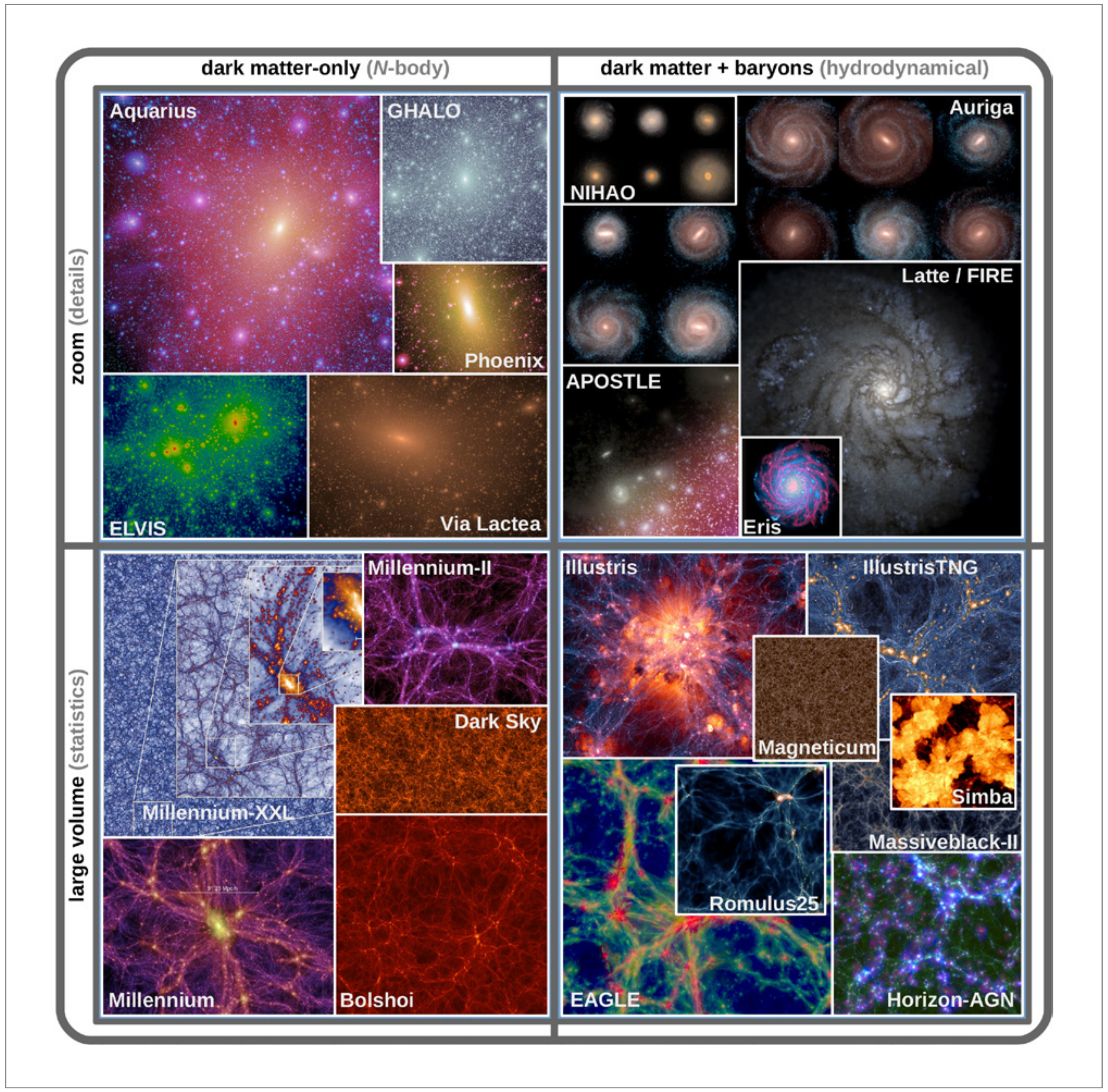

Figure 1

Visual overview of some recent structure and galaxy formation simulations. In the left and right panels, dark matter-only and dark matter+baryons simulations are shown, respectively. In top panels, zoom simulations are displayed that are able to resolve small scales. In bottom panels, the large volume simulations are visualised.

Credit: Vogelsberger et al. 2020, Nature Reviews Physics, 2, 42.

Our own galaxy, the Milky Way, plays a particular role in understanding the galaxy formation process. Unlike (most) other galaxies the Milky Way, its satellites, and, to some extent, other galaxies in the Local Group can be decomposed into individual stars, 3D positions and space motions of these stars can be determined as well as, via high-resolution spectroscopy, individual elements and potentially even ages. Such a decomposition into different formation epochs, sometimes also dubbed as “Galactic Archaeology” or “Near Field Cosmology”, allows to decipher its structure and formation history, eventually in a fully spatially resolved manner. The capability to disentangle the formation history of an individual object perfectly complements the traditional extragalactic approach that primarily aims to conclude on the formation history of galaxies by investigating populations of galaxies at different epochs. A detailed understanding of the peculiarity or generality of the Local Group environment for the galaxy formation process is, however, a prerequisite to exploit the synergies between both approaches towards a coherent understanding of the evolution of galaxies.

Future scientific research will proceed both through observations with increasingly sensitive and dedicated instruments, and through the construction of increasingly sophisticated theoretical ab-initio models and simulations that contain all the physics of galaxies and are able to reproduce deep observations and predict new ones (Figures 1 & 2). The interplay between models and observations produces an advance in the knowledge of galaxy formation and evolution from the dark-ages to the present-day universe.

The First Galaxies and the Epoch of Reionization

Soon after its inception in the hot big bang, the Universe probably underwent a period of exponential expansion called inflation, that was responsible for generating the (nearly) scale-invariant primordial density perturbations that form the seeds of all the large-scale structures we see today. After inflation, as the Universe expanded and cooled, roughly 400,000 years after the Big Bang, it became cool enough that electrons and protons could combine to form neutral hydrogen atoms - this is known as the "epoch of recombination". It is at this point that matter and radiation decoupled from each other, giving rise to the Cosmic Microwave Background (CMB) discussed in the previous section (Origin and Evolution of the Universe). Indeed, the CMB has been crucial in inferring the two key cosmic constituents that shape the formation and evolution of galaxies: dark matter (representing about 86% of all matter) that forms the cosmic scaffolding within which galaxies form and baryons (normal matter; comprising 14% of all matter) that interact with radiation to make up the "visible" Universe. Immediately after the recombination epoch, the Universe entered a phase called the "Dark Ages", where no significant radiation sources existed, nor observations can currently probe. At this time, the small inhomogeneities in the dark matter density field present during the recombination epoch grew via gravitational instability giving rise to collapsed haloes. In what is now understood to be the second stage of galaxy formation, diffuse (neutral) hydrogen and helium gas was accreted by these halos from the Intergalactic Medium (IGM), and started cooling via gas-dynamical processes. If the mass of the halo is high enough, the gas would be able to dissipate its energy, cool via atomic or molecular hydrogen transitions and fragment within the halo, giving rise to conditions appropriate for the condensation of gas to form the first stars. The cosmic dark ages end and the era of "cosmic dawn" begins with the formation of the first stars a few hundred million years after the Big Bang.

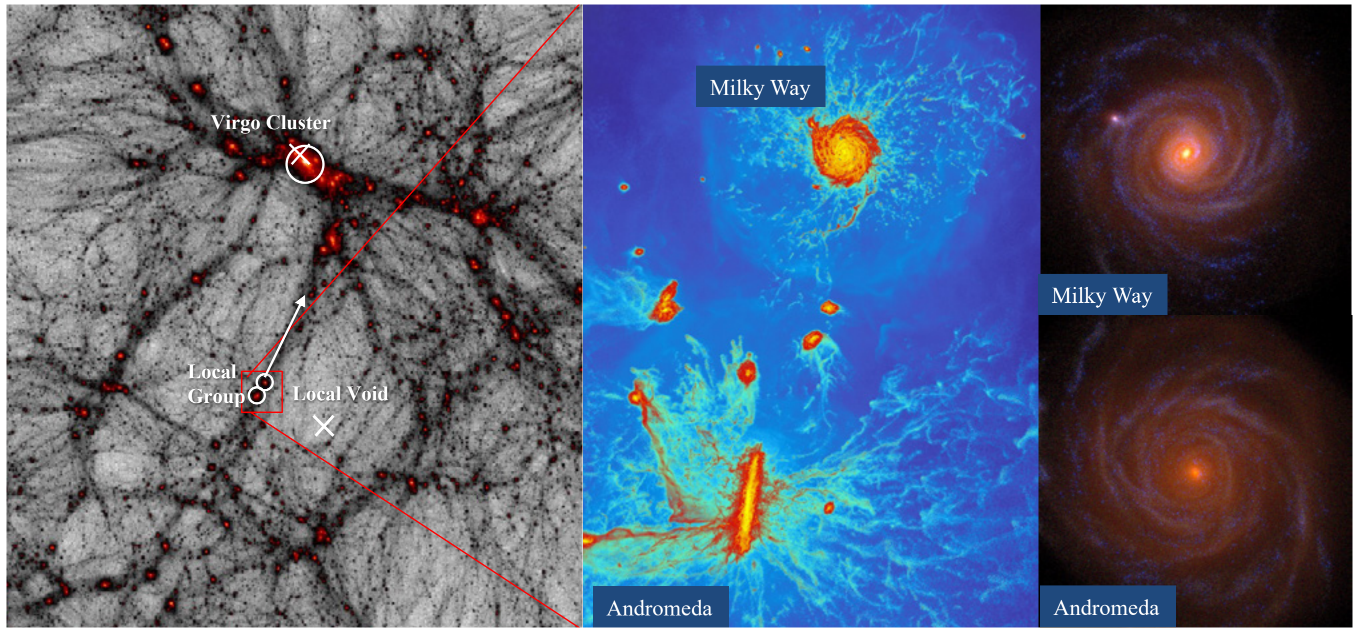

Figure 2

The Local Group as embedded into the cosmic web.

Credit: Libeskind et al. 2020, MNRAS 498, 2968.

The formation of the first stars irreversibly changed the Universe and all subsequent galaxy formation in two key ways: Firstly, PopIII stars in the mass range of 140-260 solar masses probably explode as highly energetic Pair Instability Supernovae (PISN), yielding copious amounts of metals and starting the "metal age" of the Universe. Secondly, the first population of luminous stars and galaxies generated hydrogen (and helium) ionising photons, starting the "epoch of (hydrogen and helium) reionization". A fraction of the ionising energy produced by these sources was also responsible for heating the IGM, which resulted in gas being (photo-) evaporated from low-mass halos, and the inhibition of their star formation. The Epoch of reionization (EoR) is therefore of immense importance in the study of structure formation because, on the one hand, it is a direct consequence of the formation of first structures and luminous sources while, on the other, it affects all subsequent structure formation. However, due to a number of interlinked complex problems - including the gas masses and star formation rates of early galaxies, the fraction of ionising photons that could escape out of the galactic environment and contribute to reionization (escape fraction) and the impact of reionization on galaxy formation - the history, sources and progress of reionization remain compelling open questions.

The last few years have seen a golden era for the search of galaxies lying within the EoR. This has been made possible by a combination of state-of-the-art facilities such as the Hubble Space Telescope (HST) and 8-10 metre diameter ground based telescopes (e.g. the ESO Very Large Telescope, VLT) and the power of cosmic gravitational lensing (that magnifies the light from distant objects). These have been used to detect sources at redshifts as high as $z\sim11$ (only half a billion years after the Big Bang) and galaxies three orders of magnitude less luminous than the Milky Way at $z\sim7$ (800 million years post-Big Bang). In addition, quasars, powered by accretion onto supermassive black holes (SMBH) are found to be in place well within the first billion years. Dust and metals have been identified in some of these systems with ALMA. Finally, some of the most distant objects are Gamma Ray Bursts that confirm star formation was already well under way at those early epochs, and further encouraging deeper galaxy searches. These data sets will soon be supplemented by those from cutting-edge facilities in the coming decade by forthcoming optical/IR observatories (JWST, Euclid, VRO, ELT, Nancy Grace Roman Space Telescope), and low frequency radio facilities (SKA and HERA), as well as gravitational wave telescopes (LISA, Einstein telescope) to build a panchromatic and multimessenger picture of galaxy formation. This observational progress has naturally given rise to a plethora of theoretical models, ranging from analytic calculations to semi-analytic models to numerical simulations. We now discuss the key open questions in the field of early galaxy formation.

Key open questions

1. How did galaxies obtain their gas?

According to the current standard theoretical paradigm, early galaxies accrete most of their gas from the IGM through filamentary streams along the cosmic web. The accretion results in a complicated mix of hot (shock-heated) and cold gas (that avoids the virial shock) that may penetrate deep into halos and fuel galaxy disks. This medium is further stirred and heated by supernova explosions and photoionization, resulting in a multiphase gaseous mixture that remains poorly understood. From the theoretical perspective, realistic and improved implementations are needed for feedback and mixing, all performed in cosmological setting simulations (see Fig. 1, i.e. Illustris, EAGLE, Hestia). Observationally, the challenge is to overcome the small solid angle of cold flow, requiring massively multiplexed spectroscopic surveys (e.g. with VLT/MOONS, CFHT/MSE), high resolution spectrographs (e.g. CUBES and ELT/ANDES+MOSAIC), and mapping the gas in emission with sensitive integral field spectrographs (e.g. VLT/MUSE+BlueMUSE), and with deep targeted spectroscopy at 21cm with stacking techniques (e.g. with SKA1-Low).

2. What are the properties of the first stars?

While simulations have made major progress on the fragmentation of metal-free gas, the formation mass of a PopIII star, as well as their initial mass function (IMF) remain challenging open questions. The answer depends on solutions to poorly understood processes such as the turbulence of halo gas, magnetic fields, and gas bulk motions that remain to be consistently implemented in simulations. Depending upon their formation epochs, both JWST and ELT are likely to detect the signatures of PopIII star formation either with ultraviolet emission lines or photometrically, especially when leveraging the boost of gravitational lensing. Extremely luminous supernovae may be expected from PopIII stars, and can be detected at early times: deep, wide-field multi-epoch imaging will ultimately provide the requisite time-series to detect these SNe (ESA's Euclid mission, WFIRST and the LSST survey, combined with spectral followup). Finally, intensity mapping techniques - the cumulative fluctuations produced by individually undetectable sources - may be employed by a future space-based ultraviolet observatory to hunt for PopIII star formation at $z=10-20$ using multiple lines (e.g. HeII-CO or HeII-21cm). In the local universe, "stellar archaeology" methods will continue to capitalize on metallicity measurements, together with updated calculations of the yields from the first stars, that reflect the conditions of primeval star formation in observations that are fed by ESA/Gaia among other surveys, and followed up with 4MOST, MOONS, WEAVE, MSE, then ELT spectrographs.

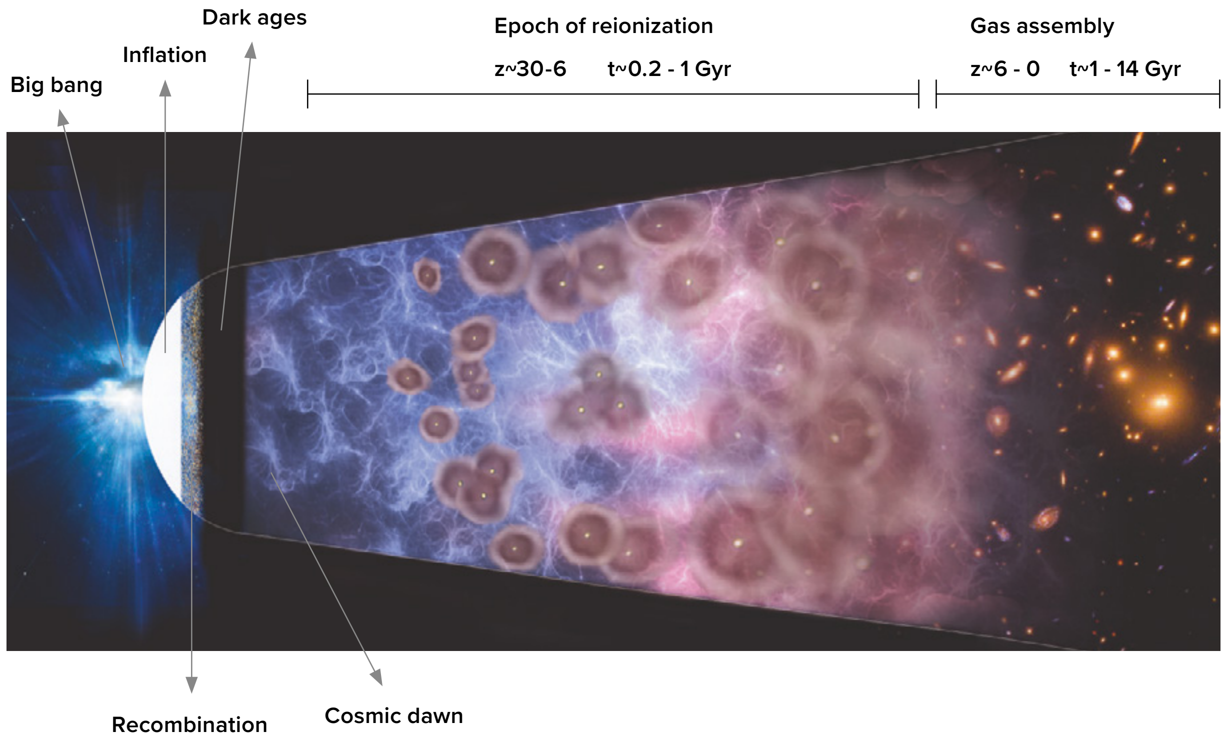

Figure 3

A timeline of the key cosmic epochs, with time increasing in the x-direction and space represented on y. The big bang is represented at the far left, followed by inflation and then a period of 'dark ages'. Reionization is illustrated by the bubbles through the bulk of the diagram, before galaxies emerge at the far right.

3. What were the physical properties of early galaxies?

While the general evolution of cosmic star formation is relatively clear, the gas content and conditions of the first galaxies remain open questions. Cosmological simulations of galaxies (see Fig. 1) are able to map out the gas masses and temperatures, but current zoom simulations need to be expanded to the full cosmological setting to understand the populations. Direct observations are crucial. They must target molecular and atomic emission lines and sub-millimeter continuum emission. To capture the diversity in galaxy populations current interferometers need upgrading (ALMA as foreseen in the ALMA2030 roadmap, PdBI/NOEMA) and new facilities built (e.g SKA mid frequency array, ngVLA, AtLAST) to measure the spatial distribution critical for understanding what regulates the star formation efficiency. It is vital to push the observations to the lowest possible masses (10^{8-9} solar masses) to build dynamic range in scaling relations and search for turnover in the luminosity function, which will be critical to understand the build-up of massive galaxies seen today (see next section).

The metal content of early galaxies remains another challenging open question that has been the focus of many theoretical models. How and when metallicity relations - linking key galaxy observables (e.g stellar mass) - emerged remain open questions although combinations of ALMA, JWST, and ELT data to target molecular, atomic, and ionized gas phases, will extend fundamental metallicity relations from intermediate redshifts to these very early epochs.

Finally, explaining the high observed dust-to-stellar mass ratios (~0.2%) of some high-z galaxies requires most of the dust be grown by accretion in the ISM, on timescales far shorter than that required by evolved intermediate mass (e.g. AGB) stars, which require at least several 10^8 years to start ejecting enriched material. Grain growth by accretion in the ISM is very inefficient, but the key dust sources, masses and their impact on the observability remain open questions. Again, upgraded and new submm telescopes (e.g. ALMA, AtLAST), and future space-based infrared missions (with design concepts similar to ESA's cancelled SPICA mission or a far infra-red probe-class mission as suggested by the US decadal survey), will be invaluable in measuring the dust masses of low-mass early galaxies in the coming decade.

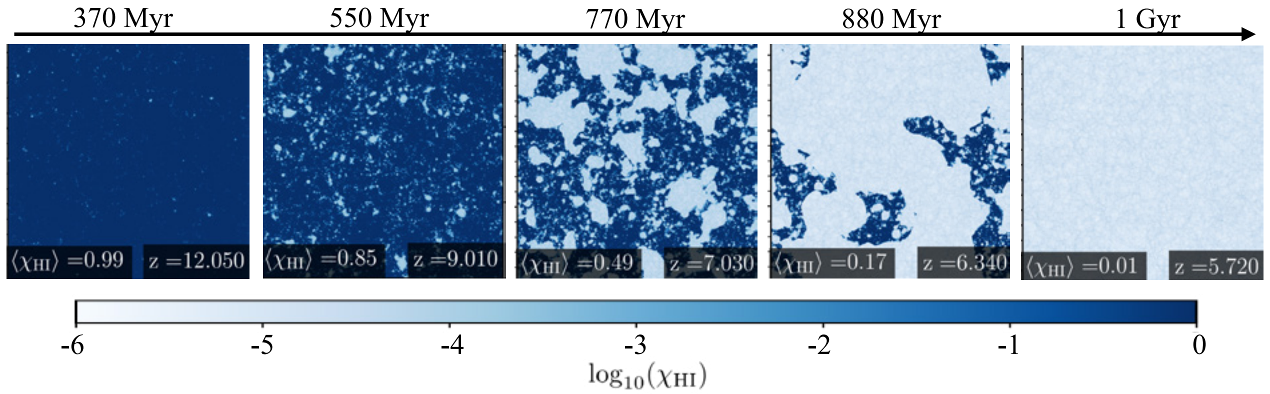

Figure 4.

A numerical simulation of how reionization proceeds through time. The numbers above the arrow show the age of the Universe; dark blue colours show neutral hydrogen while lighter blue colours show ionized regions. As shown, starting off filled with neutral hydrogen, the Universe is slowly reionized within the first billion years by (mostly) star formation. The exact shapes and distribution of the ionized regions depend on the sources and their distribution as discussed in the text. The colour bar shows the fraction of hydrogen that is neutral.

Credit: Hutter et al. 2021, MNRAS, 503, 3698.

4. Which sources caused reionization and how did it impact galaxy formation?

Only a fraction of the ionising photons produced in a galaxy escape and contribute to reionization. This 'escape fraction', which is a function of the gas/dust distribution and line of sight effects, remains a major unknown for reionizing galaxies, with both theory and observation finding widely-ranging values. Forthcoming observations, with JWST and ELT will identify strong ionising photon leakers up to z~9 through a variety of indirect methods. This escape fraction, as well as the production efficiency of ionising photons, will be crucial in determining the relative contribution of galaxies to reionization. In addition the contribution of more exotic sources remains entirely open: secondary ionizations from black hole activity could allow significant reionization contributions from low mass black holes. Large-scale surveys with optical (Euclid, LSST), X-ray (Athena), and radio telescopes (upgraded LOFAR, SKA) will be invaluable in pinning-down high-redshift AGN number densities to shed more light on this issue. Gravitational lenses acting as cosmic telescopes allow us to probe the scales and luminosity regimes of individual star clusters, and determine their direct contribution to reionization and feedback. Current observations (e.g. with VLT/MUSE) hint at what future extreme adaptive optics facilities at ELT will do in blank fields, whilst similar facilities (MAVIS, MICADO, HARMONI) may allow us to definitely probe sub-kpc scales close to the reionization epoch, revealing the true morphology of reionizing galaxies.

Further complicating the issue, the rising UV background could slow the progress of reionization by photo-evaporating gas from low-mass halos. The impact of this heating critically depends on the emissivity of reionization sources, the strength of the heating background, and the redshift distribution of sources, so the impact on star formation remains unknown. Self-consistently coupling galaxy formation and reionization on large-scales with high-resolution is the key goal of ongoing theoretical models (Bluetides, Dragons, Astraeus, Sphinx), which will be informed by the same optical, X-ray, and radio facilities mentioned above.

5. What was the topology and history of reionization?

The past decade has witnessed the emergence of a concordance picture in which reionization was effectively complete within the first billion years. Despite major observational progress near the end of the EoR, details of both the history and topology (e.g. whether it progressed outwards from galaxies - 'inside out' - or the reverse; Figure 4) remain poorly understood. This is because EoR progression depends upon the space- and time-dependent density of the IGM as well as the astrophysical sources described under point #4. A huge theoretical effort has been dedicated to answering these questions using high-resolution, large-scale models with some now close to the resolution and volume limits required (e.g. Bluetides, Astraeus, Sphinx).

In the next decades, forthcoming radio observatories (e.g. SKA1-Low and HERA) will map out the reionization topology using the 21cm emission of neutral hydrogen. However, confirming the high-redshift nature of this emission, connecting the IGM phase with galaxies, and inferring how the reionization topology evolves with time, will require cross-correlating 21cm signals with independent galaxy data. A high-priority challenge will be to identify surveys that – combined with SKA – will maximise the synergy and information content: Lyman break and Lyman alpha surveys with Vera Rubin Observatory, JWST, MSE and Euclid will provide the most promising opportunities.

6. What is the state of intergalactic gas?

The last few years have seen impressive progress in detecting high redshift quasars, with over 200 now known at $z>6$ by deep, wide-field optical and NIR imaging. These observations have yielded insight into the buildup of the first SMBHs, but furthermore provide many background objects for studying the IGM. Absorption studies approaching the EoR play a vital role to direct searches for the reionisation sources, since the interplay between galaxies and the surrounding gas determines the evolution and morphology of the reionisation epoch, and are used to constrain the UV background and IGM temperature, and buildup of heavy elements.

In the future a raft of new facilities will help shed much needed observational light on these issues. The Vera Rubin Observatory, Nancy Grace Roman Space Telescope and Euclid will add further to this data set, while high resolution spectroscopy with ELT will enable spectroscopic follow-up of quasars that are currently too faint to feasibly observe. These developments will revolutionise our understanding of the high redshift Universe. A similar advance in the theoretical modelling of quasar absorption systems at high redshift is also required to explain and interpret both current developments in the field as well as future data. A key goal in this area will be coupling radiative transfer to high resolution hydrodynamical simulations with a dynamic range capable of resolving the small scale structure of the IGM and CGM.

Galaxy Evolution and Buildup

The evolution of galaxies cannot be separated from structure in the Universe in the form of (mostly) virialized dark matter (DM) halos. The multifaceted challenge of understanding galaxy evolution comes down to understanding how matter cools and assembles near the centers of halos, how star formation is started, proceeds, and is influenced by feedback and radiation. A further vital constituent of this is understanding how the supermassive black holes (SMBHs), which reside in the centres of most galaxies, grow and evolve together with their hosts.

These SMBHs range in mass from 10^6 up to even 10^{10} solar masses, and the processes that link them to the masses of the bulges of the galaxies are still largely debated. The combination of these processes gives rise to a remarkably diverse galaxy population that nonetheless shows great regularity in its properties as evidenced by mass scaling relations and a multitude of correlations over a wide array of properties.

State-of-the-art hydrodynamical simulations and semi-analytical models capture this diversity quite accurately, but the physical models that describe all processes (with the exception of gravity) are prescriptions that work ‘in practice’ and not ab initio physical calculations. At the same time, empirical models, using the DM halo mass distribution as a starting point, seem to give a reasonably good description of how the occupation of halos by galaxies evolves over time, in particular in terms of the stellar-to-halo mass ratio.

This success is enabled by the now accurate and precise measurements of the evolution of the star formation activity and the mass function of galaxies across cosmic time (Fig. 5).

A central tenet is that most of the ordinary, non-dark matter (usually referred to as baryonic matter) is not in the form of stars and does not even reside inside galaxies.

Therefore, understanding galaxy evolution comes down to understanding the entire ‘baryon cycle’ (Fig. 6), i.e., how material cycles through different phases and locations from cool/cold gas and dust within galaxies to material outside galaxies in the inter- and circumgalactic medium (CGM). This baryon cycle is key to understanding fueling and regulation of star formation and accretion processes within the context of galaxy evolution.

The processes that govern this cycle determine how much fuel for star formation is available at any point, and act as a backdrop for understanding the star formation process, and the growth of galaxies and SMBHs.

According to both hydrodynamical simulations and observations, the rate of star formation is to first order predicted, at all cosmic times, by the amount of cold, dense gas available. But how efficiently and where exactly stars form is only understood more crudely, and limited by observational resolution on the one hand and the fidelity of even the most recent state-of-the-art hydrodynamical simulations on the other.

Another key challenge for galaxy formation models has been to explain the inferred low star formation efficiency (the conversion of gas mass into stellar mass) in galaxies and dark matter halos. Indeed, a key prediction of ΛCDM cosmology is the halo mass function, which is known to diverge from the observed stellar mass function of galaxies at both low and high masses: the deviation suggests that the star formation efficiency must drop in these two different regimes. To reconcile theory with observations, state-of-the-art models and simulations require the inclusion of feedback from various astrophysical processes. Essentially all models need to invoke feedback from supernovae in low-mass galaxies and, at high masses, feedback from an accreting SMBH in the nucleus. The energy injection into the halo in the form of jets and outflows is expected to offset cooling and thereby prevent the replenishment of the galaxies’ cold gas reservoir, thereby inhibiting the star-formation process. This mechanism must act efficiently, as many present-day massive galaxies have been largely devoid of star formation for half the age of the Universe. The only way for these galaxies to grow is through merging and the accretion of satellite galaxies, adding to their stellar mass budget and altering their dynamical structure over certain mass ranges. It is likely that gas flows also impact the evolution of the SMBH: the accretion rate can vary from low accretion states (low Eddington rates; ‘radio mode’) to high Eddington rates (‘quasar mode’). The launching mechanisms for AGN outflows are linked to the mass accretion rate, and include: radiation- or thermal pressure, cosmic rays, or magnetic forces, energy-driven vs momentum-driven. AGN feedback manifests itself as powerful (or weak) radio jets (=radio mode), wide-angle winds (=quasar mode) or a combination of the two, and the outflows are often multi-phase and consist of cool phases of neutral (atomic and/or molecular) gas and a hot ionized gas. Also more detailed properties of the SMBHs, such as its spin, impact feedback processes and hence the co-evolution of the host galaxy and central SMBH.

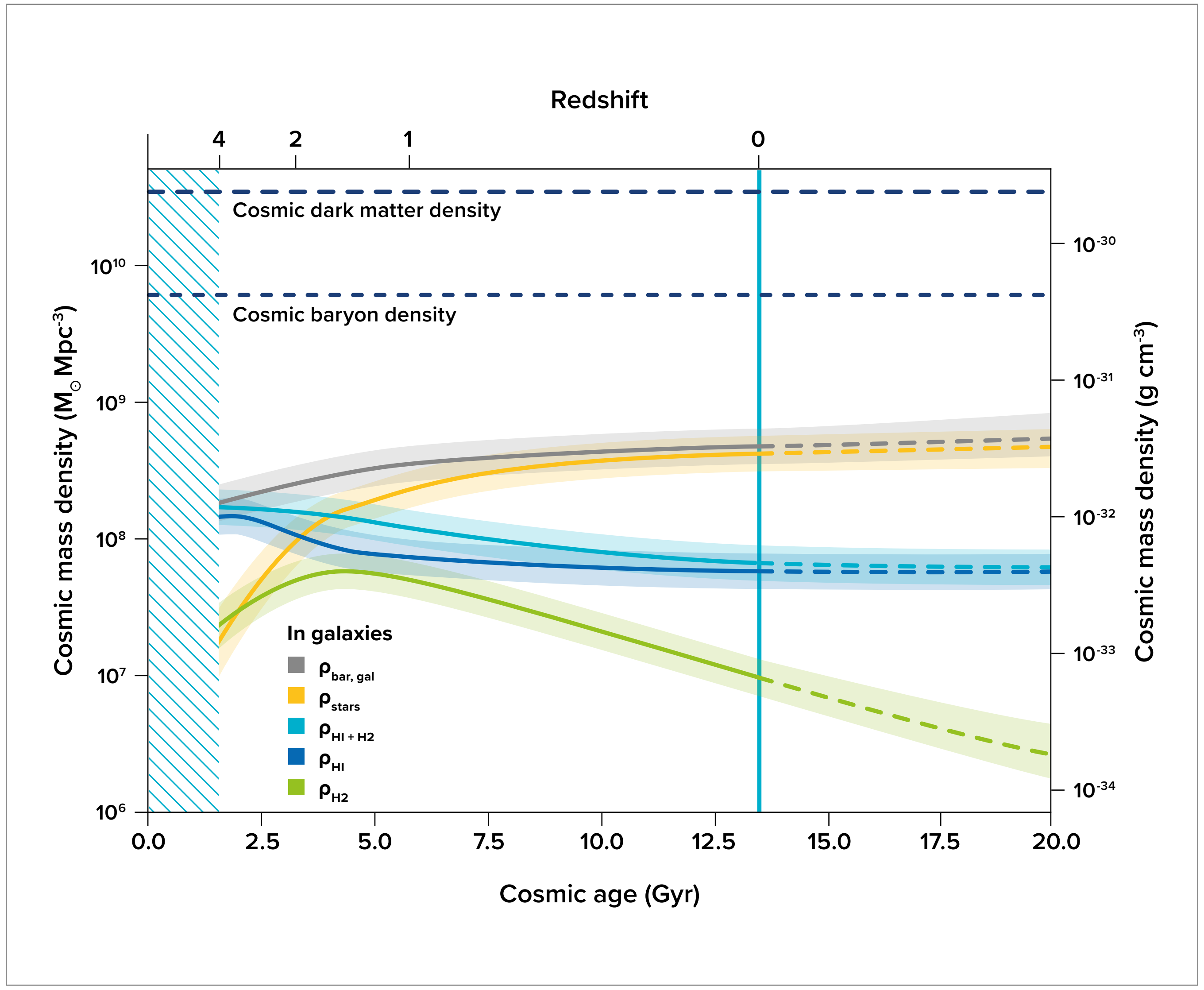

Figure 5

The cosmic evolution of baryonic mass densities with time (lower abscissa), while redshift is given above; cosmic time increases from left to right. Densities become dominated by stars around redshift 2, as the molecular gas (which converts to stars) proceeds to fall. The vertical line marks the present age.

Credit: Walter et al. 2020, Astrophysical Journal, 902, 111.

The regularity of the formation process of massive galaxies, and the imprint of the various evolutionary stages (fast initial growth, steady star formation, quiescence), are evidenced by the tight, empirical correlations that have proved to be a powerful tool to understand galaxy evolution. Dynamical scaling relations such as the Fundamental Plane and the Tully-Fisher relation connect the total mass (set by the halo) with the baryonic mass (set by the integral of cooling/star formation and outflows), and the close connection between galaxy structure and age serves as a strong constraint on any galaxy formation model.

In summary, a very solid framework -- based on excellent observations of galaxies across cosmic time -- exists to describe the broad picture of the evolution of galaxies. However, there are many elementary parts missing from our understanding of galaxies and their cosmic evolution. Our current models provide a good basis, yet are still not sufficiently realistic to fully explain either the regularity, or the rich detail of galaxy properties as revealed by observation. Advances require the combination of panchromatic datasets from state-of-the-art observational infrastructures with simulation to constrain and validate our physical understanding. To advance these areas a number of key questions should be addressed.

Key open questions

In order to make progress the following key questions need to be addressed:

1. What DM halo properties (besides mass) determine the properties of a galaxy?

Most current empirical models have focussed on reconstructing the stellar-to-halo mass relation and its evolution, but mass is far from being the only quantity that determines the fate of the galaxy. The formation epoch, concentration, angular momentum, merger history and large-scale environment must play crucial roles, which must be understood if we aim to explain the diversity of properties, even at fixed halo mass. Furthermore, it is possible that the baryon fraction, which is often set to the cosmological value, is not actually constant with halo mass and time, complicating the interpretation of existing mass relations and galaxy evolution in general.

2. What is the state of the gaseous halos that surround galaxies?

Observations and high-resolution simulations have shown that the properties of the large (200-300 kpc), diffuse reservoir of CGM gas are far more complicated than a quasi-static, homogeneous hot atmosphere of classical theory. The recent idea that a large amount of relatively cool material exists in small clouds or so-called cloudlets in a pervading medium of hotter and less dense gas is a major observational puzzle, with no firm theoretical understanding of the origin of such cloudlets. Cold gas in the CGM will also modulate halo cooling, fuel later star formation, and in turn affect future feedback to the halo. Understanding both how the CGM influences galaxy evolution, and how galaxies themselves impact the CGM properties (e.g. via AGN jets, cosmic rays and magnetic fields, and outflows of energy and material) demands that we determine what observational signatures the CGM present: how we can extract maximum information from these observables.

3. How much material escapes from and cycles back to galaxies, and what drives these flows?

The enriched gas surrounding galaxies provides direct evidence for the importance of outflows, which are driven by stellar winds, supernovae, AGN, cosmic rays, etc. It has so far, however, been very challenging to generally quantify the amount of mass in these flows, how they evolve, and how enriched material cycles back onto the galaxy at later times. Yet understanding this feedback and the associated cycle determines the stellar mass of the galaxy and its chemical composition. It will be crucial to understand the flows of gas within galaxies as well, as this determines the degree of mixing, the composition of newly formed stars and the level of chemical enrichment of outflows. Moreover it remains unclear what the accelerants of the winds are: for example, in what proportion radiation pressure, stellar winds and SNe, AGN, cosmic rays etc. contribute to the mass outflow as a function of galaxy mass, star formation rate, dust content, etc. and how wind fluids couple to the bulk of the gas at small scales. This all imposes strong limitations onto our theoretical picture of wind and jet physics, how these phenomena should be implemented in computer simulations and ultimately how they influence galaxy evolution in general.

4. How do stars form out of dense, molecular gas?

There is a tight correlation between the amount of dense gas and the amount of star formation, for which the average efficiency is assumed to be constant. Combined with the outflows of gas described under point 3 above, this gives rise to the idea of self-regulation, where star formation drives out the gas needed for the process to continue. However, large variations in the star formation efficiency are observed within galaxies (see, for example Figure 7), which leads to large departures in morphology compared to what is expected for a constant efficiency (as is assumed in hydrodynamical simulations). This is closely related to understanding the conditions under which molecular gas is formed, clouds become self-gravitating, and star formation is initiated. This includes knowing the role played by cloud collisions, dynamical/orbital features, or turbulence, which have all been proposed to promote self-gravity. It is also important to understand how the metal enrichment of the ISM affects the efficiency of star formation across cosmic time as metals act as coolants and are fundamental in dust production, and hence shielding molecules from dissociating radiation. The interpretation of this variation in efficiency is currently under debate, and understanding this phenomenon is crucial for understanding the diversity in galaxy morphologies.

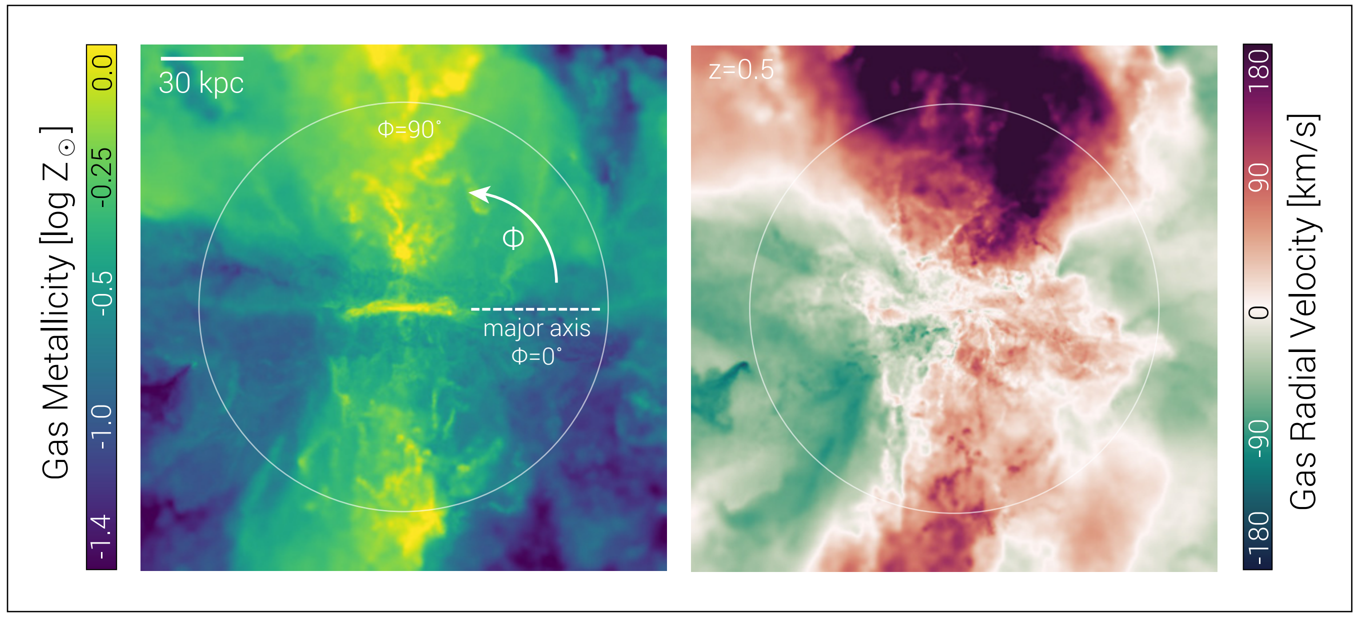

Figure 6

The baryon cycle is complex. Inflows and outflows interact. It all takes place in the CGM. The CGM is thus an interface regime/reservoir, which encodes both cosmic gas accretion (from the outside) and feedback (from the inside). It has a multitude of observable signatures, in both gas absorption and emission, particularly in the UV and X-ray.

Credit: Péroux et al. 2020, MNRAS, 499, 2462.

5. What determines the star-formation history of individual galaxies?

The tight relation between the star-formation rate and the stellar mass of galaxies -- the ‘main sequence’ -- holds for ~90% of the cosmic time and indicates that most stars form through steady-state processes rather than in violent episodes. However, this provides only the crudest picture of the formation history, and the observed scatter reflects the complicated star-formation history of individual galaxies. Simulations predict that galaxies undergo fluctuations in star formation on short time scales (0.2-2 Gyr) that could result from morphological compaction, accretion, cooling, star formation, and outflows. Longer term fluctuations (~10 Gyr), however, are thought to be driven by differences in initial halo mass. The current frontier is to compare the evolutionary history of individual galaxies with the paths predicted by simulations. This requires reconstructing the full star-formation history (SFH) of galaxies, which has proven extremely challenging: the integrated light is dominated by that of the youngest stars, the information derived for the underlying population is limited. Furthermore, the reconstruction of the SFH using UV-optical-NIR data is an ill conditioned problem because of degeneracies between age, metal content, and dust obscuration of stars and black hole growth. The problem is further exacerbated for the low-mass objects that dominate the galaxy population by numbers at mid-to-high-redshifts and this, together with the previous points, is subject to uncertainties in the opacity, emissivity, and composition of dust grains.

6. How does the structure of galaxies evolve?

Many of the morphological patterns we see today (disks, bars, bulges, etc; see Figure 7) began to emerge at least 10 billion years ago. At these early cosmic times, spheroidal galaxies, disks and bars were all less common (although disks have been found as early as z=4) and irregular galaxies were instead more prevalent, with their morphologies perhaps reflecting rapid gas accretion and fast growth. As these galaxies gain in mass, they are thought to `settle’ into disks that then remain stable for many orbital periods, and for massive galaxies a gradual loss of angular momentum possibly due to merging leads to a more spherical structure. This brief evolutionary story leaves many blank spaces, as we do not know how, along its evolutionary history, a galaxy moves through the various morphological stages, nor how this may vary with halo mass and local environment. Morphological and kinematic signatures such as rotation curves must be combined across cosmic time and assessed in concert with the star formation histories as well as gas contents.

7. What is the role of the environment and large scale structure in galaxy evolution?

Dark matter halos grow hierarchically by accretion of neighbouring substructures, meaning the most massive halos that play host to galaxy clusters form the latest and are less dynamically mature. Preferentially located at the nodes of the complex filamentary web, clusters are continually accreting dark matter halos containing individual galaxies or galaxy groups. It is well established that the properties of galaxies are correlated with the environment: massive clusters contain a higher (lower) fraction of ellipticals (star forming galaxies) than the field, and the Galaxy Stellar Mass Function shape depends on various environmental processes. Intra-cluster processes like ram-pressure stripping, strangulation, harassment, or tidal disruption can all quench star formation as galaxies orbit within the cluster, but it remains unclear how the final properties of galaxies relate both to these differences and to their initial conditions.

8. How do supermassive black holes evolve with their host galaxies?

Observations and simulations show there is a symbiotic relationship between a galaxy and its central SMBH, such that the mass of both components is closely related. Understanding how this coevolution works is one of the major challenges in galaxy evolution: the answers require studies of the in- and outflow properties, accretion states of the SMBH, and how these properties link to that of the host galaxies. Feedback may eject the interstellar gas from the entire galaxy – or just temporarily remove it from the nuclear region in a “fountain”. The fate of this outflowing gas is intimately linked with AGN feedback processes. Furthermore, powerful radio jets may heat the intergalactic medium, preventing galaxies from being replenished by cooling cluster gas. This way, feedback processes may regulate the gas content of the host galaxy and therefore both star formation and the growth of the black hole. (Suggestions of star formation occurring in the ejected gas also open possibilities of “positive” feedback processes that enable star formation).

In the present day Universe we are well past the “high noon” of galaxy growth that occurred at a redshift of z=1-3. Galaxy growth was more vigorous when the Universe was younger as there was more gas available, and interactions among galaxies were more frequent. Processes of feeding and feedback are therefore likely to change with redshift.

9. The physics of supermassive black holes (SMBHs)

How the first SMBHs were formed at the dawn of the universe is still shrouded in mystery, together with the role that the SMBHs play in the secular and transformational evolution of their host galaxies. Modelling and observing the first seeds for SMBHs is a key question for cosmology (see the previous sub-chapter on the first galaxies). Dense nuclear star clusters are present at the centres of all but the smallest galaxies and the largest ellipticals, where they have likely been dispersed by mergers of massive black holes. Nuclear star clusters might play an important role in the seeding and growth of massive black holes. How do SMBH interact with their surrounding nuclear star clusters? Are cusps of stellar mass black holes in nuclear clusters around SMBHs important sources for gravitational wave emission in extreme mass ratio inspiral events? To study the rise and development of the black holes involves detailed modelling of their physics and observations of their near environments and how they interact with their surroundings.

Requirements for future observations and theory

Observations across the electromagnetic spectrum give access to the properties of different components that make up galaxies from cold atomic to hot ionized gas, young star-forming sites, the underlying old stellar populations, and supermassive black holes residing at the centers of massive galaxies. In order to uncover and test the interplay of the different physical processes acting from very small scales (below 1 AU, i.e. formation of a single star) to very large scales (tens of megaparsecs, e.g. to encompass the overdensity range occupied by a massive protocluster), data probing these scales are essential. This requires combination of the knowledge gained from studies in the Milky Way, and its immediate neighbors with resolutions below 1-10pc, with results from surveys of nearby galaxies of 10-100pc which offer a several orders larger phase space of physical conditions in galaxies and variety between galaxies to obtain more self-consistent models for physical processes linked to, e.g., star formation, metal mixing, AGN etc. Studies of high redshift galaxies with a couple or few 100pc resolution provide the necessary information for testing these self-consistent models and studying the evolution of galaxies. Wherever possible European researchers should have continued access to a maximum of wavelength regions.

Concerning the integrated properties of galaxies, the requisite improved masses (stellar and total), SFR, and abundances will be delivered by analysis of spectra obtained with ELT (particularly integral field spectrograph HARMONI & MOSAIC) that may target either stellar absorption lines or nebular light. High angular resolution interferometry with ALMA (especially with the foreseen baseline extension), ngVLA, SKA, and its precursors (such as MeerKAT) will produce the same for the cold gas, as well as dust and continuum emission linked to star-formation processes and obscured nuclear regions. JWST and Euclid will provide both stellar photometry and attack the sub-galactic structure (down to star-cluster scales) and morphological evolution, in deep and wide field surveys, respectively, while the Vera Rubin Observatory will contribute integrated photometry. The combination of total masses and kinematics delivered by high-angular resolution, spectrally resolved data will provide the angular momenta required to thoroughly investigate morphological transformations and evolution. In dust embedded regions infrared, radio and mm techniques are also essential to study the rapid enshrouded growth. Key diagnostic tools are the far-infrared continuum and the fine structure lines of carbon, oxygen and nitrogen. In the distant universe they can be probed by JWST, while in more nearby galaxies a far-infrared mission, such as a replacement for SPICA or FIR probe-class mission.

Star-formation histories require high-quality spectra from the UV to NIR, that allow us to weigh the contribution of different evolutionary phases, including asymptotic giant and horizontal branches, that dominate the light at specific wavelengths. Spectroscopic surveys with DESI, 4MOST, WEAVE, MOONS, Subaru-PFS, or the Maunakea Spectroscopic Explorer will provide us with massive datasets of galaxy spectra from the NUV to the NIR, which will allow this type of studies, while ELT/HARMONI and MOSAIC will address similar issues for the faintest systems. Obtaining the merger history from observation will be even more challenging, but will be elucidated on by greatly improved SFHs and resolved abundance studies that will be derivable from the same telescopes, particularly with high angular resolution observations and machine learning techniques. At longer wavelengths, radio telescopes (SKA and its pathfinder facilities, ALMA, AtLAST) and far-infrared space missions will deliver key information.

In order to resolve the star formation process, observations of galaxies at resolutions of 100pc (see Fig. 7) and better are essential. Observatories like ALMA (complemented by AtLAST) probing both the bulk and dense molecular gas and dust, SKA (and its precursors) probing star formation activity and atomic gas, VLT (in the future ELT/HARMONI) and JWST probing ionized gas and stellar populations can provide the required multi-wavelength data to assess the key physical processes. Among the key missing observables are the FIR cooling lines and dust emission, for which there is no (sensitive) current or forthcoming facility to enable low-redshift science: future FIR space missions would be essential here. Similarly, simulations need to reach resolutions down to 10pc or below to self-consistently study the effects of star formation and stellar feedback and its impact on the (secular) evolution of the galaxy. A major step in this area will come with JWST and when the extremely large telescopes, such as the European ELT, the Giant Magellan Telescope (GMT), or the Thirty Meter Telescope (TMT) come to operation. The large collective areas and adaptive optics techniques will allow us to separate stars in more crowded conditions such as those in elliptical galaxies and the bulge of spirals and obtain color magnitude diagrams of their stars. They will similarly extend color-magnitude based analysis beyond the local group. The only observational technique that can spatially resolve evolving supernovae is Very Long Baseline Interferometry (VLBI). With resolutions counted in milliarcseconds (fractions of a pc in nearby galaxies), VLBI provides key information to stellar evolution in external galaxies.

To probe compact star formation and growing SMBHs in galaxy nuclei requires high angular resolution observations that can penetrate the, often large, columns of gas and dust in rapidly evolving regions. In terms of the population and demographics, the abundance of these objects will be securely established by Euclid, while the rate and background of gravitational wave events will be provided by LISA. Radio to sub-mm interferometry (e.g. ALMA, e-MERLIN, VLBI) will remain essential to probe these obscured regions, with the critical inclusion of APEX for phase and amplitude calibration, as well as to provide southern baselines and coverage of the uv-plane. JWST and VLTI/GRAVITY+ will be key instruments in the near-infrared. Gamma-ray telescope and CTA have excellent potential to understand the supermassive black hole in the core of the galaxy, a pevatron candidate, and to probe the global interactions between cosmic rays and gas, that lead to the production of galaxy winds, heating and enrichment of the CGM, and the loss of angular momentum. LOFAR2 will provide low energy measurements of the same high energy phenomena. The Event Horizon Telescope (EHT, vitally including ALMA+APEX) has provided the first ever “image” of the environment of an SMBH. ELT will be key in probing unobscured nuclear star formation and AGN. Origins and the proposed OASIS space telescopes target key diagnostic lines. X-ray missions such as XMM Newton and the upcoming Athena represent the brightest futures. Moreover it would be advantageous for XMM to continue operations throughout the 2020s and provide maximal overlap of X-ray and JWST operations and the early phases of Athena.

Concerning the wide range of circumgalactic observations, observations over the full electromagnetic spectrum are required. Hotter phases need to be probed in the X-ray, particularly with Athena that will see the CGM gas both in emission and absorption, and determine the location and amount of intergalactic baryons. Similar observations for the warmer phases at low-redshift must await a UV replacement for Hubble such as LUVOIR or HABEX; ELT will provide major breakthroughs in the CGM structure at mid-z, and the total baryon density of the universe may be fully pinned down using fast radio bursts (e.g. with ASKAP and CHIME). Galaxy cluster observations (e.g. with LOFAR) may provide a more complete view of the metal production via ICM measurements, although a number of uncertainties regarding the stellar initial mass function also need to be addressed.

Resolving Interstellar Matter (ISM) and Stellar Populations in Local Galaxies

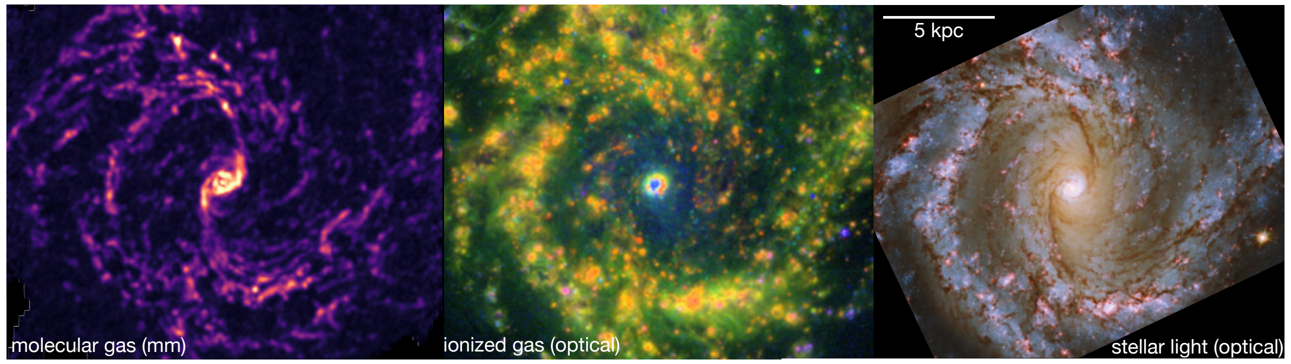

Figure 7

Resolving the components of a nearby galaxy at a resolution of about 100pc (from left to right): cold molecular gas as traced by its CO line emission (ALMA), ionised gas via its optical emission lines (IFU), and light from the young to old stellar populations (HST). Galaxies appear very different across these components and this high physical resolution reveals not only the intricate structures but also individual star-forming sites. Future instruments will enable such studies not only in the local universe and at higher redshift, but also extend high spatial resolution information to other wavelengths and thus more components (e.g. (hot) dust, atomic gas).

Credit: JAO/NRAO/NOAJ/ESO/NASA & J. Schmidt.

Colder components will be delivered by FIR/submm emission lines and 21cm absorption, e.g. with AtLAST and ALMA and SKA, respectively, which will produce robust gas contents of the universe beyond the cosmic noon. This is also a field in which future generations of simulation will make huge impacts, in understanding the out-of-equilibrium physics and dynamic nature of the CGM, with improved techniques for handling low-density gas, improved sub-grid physics constrained by detailed observation, and higher resolution over larger scales.

Built into the questions of where galaxies end, and what is their assembly and accretion history, is the demand for imaging that is optimized to detect the very lowest surface brightnesses. Reaching below 28 magnitudes per square arcsecond is a major observational challenge, but one that must be met in order to determine the ages and origin of the faintest halos of massive galaxies, tidal streams, truncations in the disk of dwarf galaxies, etc. Large-scale observational studies in this domain will be delivered by the LSST and Roman Space Telescope, while dedicated low surface brightness missions in the stable environment of space would be required to genuinely determine where galaxies end. Similar facilities will conduct a complete census of dwarf galaxies. Their demographics, dynamics/angular momenta, and distribution of central surface brightnesses all remain difficult to explain within the ΛCDM paradigm, making ΛCDM falsifiable with these surveys. Rubin, Roman, and Euclid will again deliver tremendous samples of dwarf galaxies across different environments, probing their bulk properties and fainter isophotal properties from the ground and detailed internal conditions from space. Distances will be delivered by high resolution colour magnitude analysis with AO-fed imaging and spectra on ELTs, and in concert strong astrophysical constraints on the nature of dark matter will come within reach.

Concerning the flows of gas within galaxies, large observational samples of metallicity gradients are required, spanning a large range of mass and redshift. These will be delivered as above by the combination of optical IFU (such as BlueMUSE, ionised gas), submm array (molecules, dust) and radio array (atomic and molecular gas) observations. The well-resolved kinematic observations, together with observational constraints on the recent SFH, will determine the impact of non-symmetric components (spiral arms, bars), and quantify the rates of gas inflow and outflow. Questions directly concerning the star-forming ISM will remain dominated by submm and radio frequencies and key diagnostic tools in the far-infrared. Multi-transition studies of molecular species across redshifts will be facilitated by ALMA, NOEMA, ngVLA and AtLAST, while the cold HI phase that is currently hard to connect to star formation will be probed in both emission and absorption by SKA and its pathfinder facilities; the high angular resolution interferometers will also deliver kinematic information across essentially all redshifts. Resolution will again be key, and cospatial metallicity estimates (e.g., from ELT/IFUs) will be vital for converting line intensities to molecular gas masses. In luminous dusty enshrouded galaxies far-IR metallicity tracers will be required, but no clear path to such facilities currently exists. Again the theoretical underpinning of this very multiscale process needs to be attacked using higher resolution of hydrodynamical simulations, that pay special attention to cooling and all the possible sources of feedback.

At the largest scales, surveys with WEAVE, 4MOST and MOONS will provide a better understanding of the different physical mechanisms acting in galaxy clusters and their environment. eRosita will detect the hot ICM of 50-100 thousand galaxy clusters, groups and filaments, and enable us to characterise the interactions between galaxies and this component in different environments. Transformational results shall be achieved by ESA's Athena & XMM Newton mission, that will determine abundances of different elements (Na, Al, C, Ne, Ca, Ni, etc) that, combined with galaxy abundances will allow to recover star formation histories in cluster galaxies, as well as study the importance of AGN and SN in producing outflows. After the incredible success of spectroscopic surveys (e.g. SDSS and VLT), it has become crucial to embark upon comparable environmental studies near the peak in cosmic star formation: near-infrared missions and instruments (MOONS, Euclid, Nancy Grace Roman Space Telescope) will determine the environmental dependence of galaxy properties, shedding light on the physical processes that determine it. Protocluster studies, in particular at $z>2$, will determine the role played by the first overdensities in shaping galaxy evolution, and how galaxies co-evolve with their hosting structures, which ranks among the most crucial issues to be tackled in the future with the new facilities.

The Milky Way and Local Group as a "reference organism" for galaxies

Local Group galaxies, and the Milky Way in particular, hold a special place in building our understanding of galaxy evolution. They are indeed the only galaxies where we are able to test with the highest degree of detail (spatial and age resolution), the processes that drive galaxy formation and evolution. Galactic Archaeology addresses this topic by studying the kinematics, chemical compositions and ages of stars, to shed light on the conditions in the Milky Way as it was assembled. Yet, the Galactic fossils are intrinsically difficult to obtain and analyse; they require both precise astrometry (for the parallaxes and proper motions) and spectroscopy (for abundances and radial velocities) of millions of stars, covering the major Galactic components (disk, halo, bulge, etc.).

Galactic Archaeology stands on the brink of a new era: exquisite position, parallax and proper motion measurements of more than a billion stars by ESA's Gaia satellite were released, allowing for the first time a census, in three dimensions, of the stellar content of our host galaxy and its closest neighbours (Magellanic Clouds and dwarf satellite galaxies). Gaia will continue to revolutionise the scene in the coming years, with more precise astrometric solutions and richer catalogues. In parallel, several very large spectroscopic survey facilities will become available, complementing Gaia with line-of-sight velocities, precise stellar parameters and chemical abundances. Asteroseismic missions such as CoRoT and Kepler have also revealed the extreme precision ages that can be reached for giant stars in the Milky Way, making these missions very relevant to the field of Galactic Archaeology.

In the past few years, Gaia (aided by the previous spectroscopic surveys such as RAVE, APOGEE, Gaia-ESO, GALAH) has already significantly changed our understanding of our home galaxy by revealing dozens of faint stellar streams. It identified the last major accretion event that made a significant fraction of what we today call the Milky-Way halo, and shed light on the impact of accretions on the Milky Way disk, which appears today dynamically young and out of equilibrium. A major finding of these last years has been that the Milky Way had a disk in place very early in its evolution (early enough to host some of the most metal-poor stars known), part of which was then heated into orbits that today make these stars appear as halo stars (in-situ formed halo stars).

The inner parts of the Milky Way, known as the Galactic bulge, hosts a large fraction of the mass (2/3 of that within 6 kpc), and has also been revealed in all its complexity in the past few years, thanks to the VVV NIR imaging and several dedicated spectroscopic surveys. Dominated by a bar that drives the global dynamics of the region, it hosts several populations, including a very old and metal-poor population (traced as RRLyr stars among others) with little rotation. The relation between populations identified in the bulge and other stellar populations such as the thick disk and inner halo, is still very poorly understood, and holds the key to many open questions on the early days of our Galaxy.

Embedded deep inside the Milky Way's bar/bulge there are separate stellar structures that mark the Galactic centre: the nuclear stellar disk, a one-billion solar mass rotating structure with a diameter of about 0.5 kpc, that is kinematically and chemically different from the surrounding bulge. The nuclear disk spatially overlaps with the central molecular zone, where ~10% of the Galaxy's molecular gas is concentrated. The central molecular zone is the most active star-forming region in the Galaxy, and it is a unique laboratory to test theories of star formation under extreme conditions. At the centre of the nuclear disk lies the much more compact nuclear star cluster with a radius of ~5pc and a total mass of $\sim 2.5\times 10^7\ M_\odot$, that is the densest stellar system that can be studied in detail in the local Universe. The four million solar mass black hole Sagittarius A* lies at the very centre of the nuclear cluster. Nuclear clusters and disks are common components of spiral galaxy nuclei. The Galactic Centre is a fundamental template to study the properties and interactions of these common

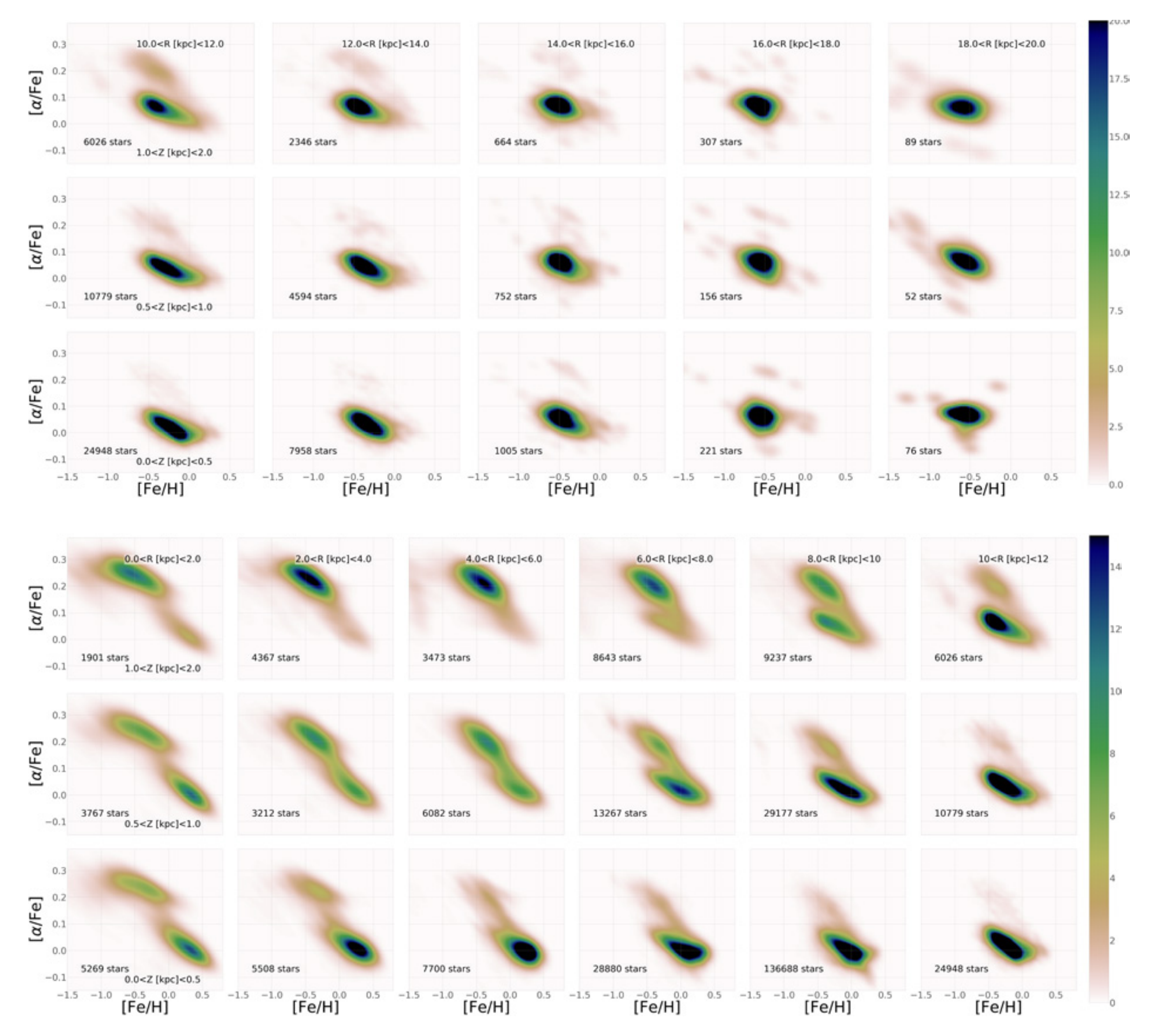

Figure 8

Chemical tomography of the Milky Way inner (top) and outer (bottom) disk. The [α/Fe] vs. [Fe/H] diagrams serve as a tracer of the chemical enrichment timescales of the various Milky Way regions, which are a consequence of the star formation history. The chemo-structural tomography of large parts of the Milky Way disk could be achieved by combining astrometric data from Gaia DR2 with spectroscopic data from SDSS/APOGEE DR16 and several photometric catalogs.

Credit: Queiroz, A. et al. 2020, A&A 638, A76.

building blocks of galaxy nuclei: it is the only galaxy nucleus in which we can observationally resolve its stars and study the physics of the interstellar medium down to the scale of forming stars. The Galactic Centre is also a key testbed to study high-energetic phenomena associated with Galactic outflows and to test general relativity in unexplored regimes.

Another area in which the study of the Milky Way and its satellites provide unrivalled fundamental information is that of dark matter (DM) distribution. Studies in external galaxies are hampered by degeneracies between the amount of dark matter and stars, while in the Milky Way, we can measure the full 6D kinematics of individual stars and thereby uniquely infer the detailed properties of our dark matter halo: its total mass and profile, but also sub-structures within, which have implications on the nature of DM. Dwarf galaxies are the most dark matter dominated systems we know of in the universe, and those around the MW and Andromeda allow us to explore the very smallest galactic mass and luminosity regimes. In the past decade, the number of known low-luminosity dwarf galaxies has been growing enormously, thanks to precision photometric surveys, bringing the census of low luminosity to well below $L<10^5\,L_{sun}$.

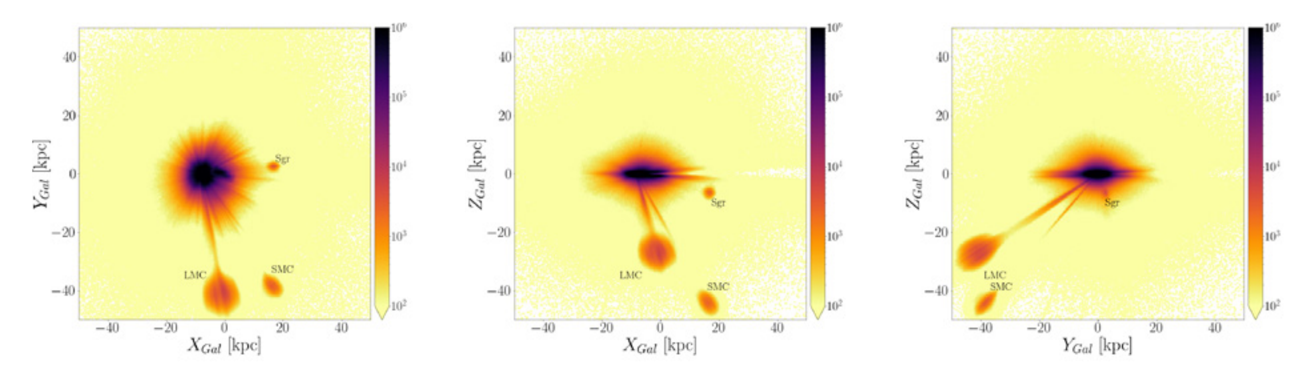

Figure 9

3D stellar density (from left to right XY, XZ and YZ) of the Milky Way and its most prominent satellites, the Magellanic Clouds and the Sagittarius dwarf galaxy as drawn from a combination of Gaia EDR3 with spectroscopic and photometric catalogues. Also the structure and orientation of the Galactic bar is clearly visible.

Credit: Anders et al. 2022, Astronomy & Astrophysics, 658, A91.

Among the challenges to the ΛCDM paradigm provided by galaxy observations, dwarf galaxies have provided rank among the most constraining: (i) despite a growing number of detected dwarf galaxies, their number is still lower than expected in DM simulations, (ii) dark matter profiles in dwarf galaxies have been explored extensively in the past 15 years, without resolving the controversy on their central DM profiles: cusped profile as predicted by ΛCDM, or a shallower cored profile? (iii) a number of satellites to the Milky Way, and Andromeda seem to be moving in a plane of satellites, and/or present coherent motions. While the first challenge could be due to the retro-action of galaxy evolution baryonic processes on the dark matter distribution, the second has been questioned by more precise 3D motions provided by Gaia for the MW satellites.

Key Questions

Research in this area is faced with a number of crucial open questions, which are organised as follows, from the larger scales to the smaller:

1. How does the Galaxy fit into the cosmological context?

What is the formation and evolution history of the Milky Way and its Local Group environment, with respect to its structure, kinematics and chemical abundances? Is the Milky Way typical of low-redshift spiral galaxies of comparable mass and environmental properties.

2. What is the underlying structure in the local group and its dark matter?

The distribution of satellites and streams of both the Milky Way halo and M31 group is preferentially sorted into a flattened plane, and emerging studies suggest the same is true for other galaxies. As simulations fail to explain this Planes of Satellites problem, which is based purely on gravitational effects, this may point towards a tension in the ΛCDM paradigm.

3. What is the Milky Way's accretion history and how was the halo assembled?

The MW has a high baryon fraction, but the reason is not currently clear. In relation to this we need to connect the star-formation history of the Galaxy, determine how star-formation was initiated in various components, and connect this to the composition of both hot and cold gas. The origin and distribution of the population of Milky Way halo stars remains only partially understood, where a substantial fraction of stars must have formed ex-situ (i.e. were delivered by satellites). For example, some stars must have been delivered by interactions with the Magellanic Clouds while others were accreted from dwarf galaxies. How these stars were delivered and how the interactions shape the halo structure remain largely open questions.

4. How much information is retained from the formation events?

That the MW has a complicated formation history has become apparent, and one obvious question becomes how much information concerning these individual events remains in (and can be extracted from) the present-day chemical and orbital information. Goals include the construction of the global structural and dynamical model, understanding radial migration within the disk, and to establish where the sun was born.

5. What are the abundance patterns of the first stars?

If the oldest stars in the Milky Way formed in a pristine environment, they will provide unique and vital tracers of the first stars and their formation. The most pressing questions are whether we can identify signatures that point towards Population III stars, and if we can determine the yields of the first supernova (and similar) explosions. These methods offer clear and direct connections to the questions raised in the first subsection of this chapter concerning the first galaxies and the epoch of reionization.

6. Our very local environment?

What do the Solar neighbourhood data tell us in terms of reference objects for surveys of larger volumes: masses, ages, chemical abundances, stellar multiplicity, etc.

Requirement for future observations and simulations

In the coming decade, tremendous progress is expected to be achieved in our understanding of the Milky Way formation and evolution, and the respective importance of processes that shaped this evolution. Gaia will continue to be the cornerstone mission for the field of Galactic archaeology for the next decade providing full 6d phase space information of stars in the Milky Way and its outskirts, as well as massive spectral and photometric information. Keeping the Gaia-DPAC analysis team operative until the full science content in the Gaia data has been extracted will be crucial, as there is no obvious successor of Gaia. The Vera Rubin Telescope and the Nancy Grace Roman Space Telescope will extend astrometric information to much fainter magnitudes, with expected precisions matching that of the faintest stars in the Gaia catalogue, enabling us to probe deeper in the luminosity function of the Galactic Halo and surroundings. An infrared sensitive astrometric space mission (GaiaNIR), as part of ESA's Voyage 2050 would extend the Gaia mission into the bulge and beyond and thus considerably enlarge the astrometrically charted volume of the Milky Way.

Spectroscopic information for large samples of stars will be a key ingredient to fully harvest the science potential provided by Gaia, providing line-of-sight velocities and full chemical characterization of stars too faint for the Gaia onboard spectrograph RVS. Large numbers as well as sufficiently high resolution and depth will be at essence. 4MOST, WEAVE and SDSS will be the core mission for this task to cover the Milky Way at large, with MOONS adding depth in selected areas. Integral Field Spectroscopy (e.g. BlueMUSE) will extend these studies into the bulge and allow to draw parallels to other galaxies in the Local Group. In the longer run, the development of the next generation of survey facilities, providing higher resolution (HRMOS) and/larger depth owing to more light collecting power (MSE, ESO spectroscopic facility).

ELT/MOSAIC will allow us to spectroscopically probe stellar populations in other Local Group galaxies and beyond, going further by targeting globular clusters for both abundances and dynamics. Similarly, ELT/ANDES will produce R~100,000, S/N>100 spectra of stars in the dwarf satellites of the Milky Way from which the chemical enrichment and star formation histories of these systems can be reconstructed all the way back to the enrichment by the first PopIII stars. In concert, interferometric data (GRAVITY+) will precision-anchor the stellar atmospheric parameters for reference stars. The combination of a large sample of spectra with machine learning methods trained on precision data will bear particular potential combining the benefits from the ELT/ANDES and multi-object spectrograph surveys worlds.

Finally, asteroseismology will be of high relevance as it allows age determination and tight constraints on surface gravities. This field will be dominated by space missions, TESS and, in the mid of the decade, PLATO will be the key players, on the longer run (as part of ESA's Voyage 2050) possibly HAYDN.

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[2] Astro2020 Decadal report:
https://www.nationalacademies.org/our-work/decadal-survey-on-astronomy-and-astrophysics-2020-astro2020

[3] The hunt of elusive intermediate mass black holes that bridge the mass range gap between stellar-mass and supermassive black holes is now beginning to provide tantalising initial results.

[4] Much of it may have been processed through a galaxy at some point, or may never have entered galaxy halos at all.

D Formation and evolution of stars

Stars have fascinated humanity since we first looked to the heavens. Beyond the constellations drawn out by past generations and their importance to guide travellers and ships for centuries, stars provide us with a unique chance to explore physical conditions that are impossible to forge on Earth. From their birth in dense molecular clouds to their compact remnants as white dwarfs, neutron stars and black holes (see also chapter on Extreme Astrophysics), they span a tremendous range in density and temperature. Their interiors are subject to instabilities and turbulence that make them powerful physics laboratories. Many stars are paired in binary (and higher multiple) systems, opening-up studies of new physics. In particular the binaries including neutron stars and black holes provide remarkable tests of theories of gravity through the timing of pulsars and the detection of bursts of gravitational waves.

Stars are at the heart of almost all astronomical structures. A large fraction are found to have planetary systems, and precise knowledge of the host stars is critical if we are to accurately characterise the planets. Populations of stars form the building blocks of galaxies. The energy feedback and chemical yield of entire stellar populations are fundamental drivers, and key tracers, of the evolution of galaxies (near and far) and of the Universe itself. Stars are an important tool to map the geometric and dynamical structures of galaxies, with their kinematics revealing the mass distribution that includes a dominating unseen ('dark matter') component. At larger distances, stars shape the integrated light and trace active star formation in galaxies, while also providing beacons to anchor the distance scale for cosmological studies.

Tremendous steps have been made over the past century in our understanding of stellar properties, enabled by new observational capabilities and detailed modelling (supported by the growth of computing power). We can now resolve their surfaces, probe their deepest interiors and characterise their evolution better than ever before.

The emergence of multi-messenger (e.g. LIGO-Virgo, KM3NeT) and 'big data' astrophysics (e.g. Gaia, VRO, LOFAR), combined with the recent or imminent arrival of unprecedented facilities in space (e.g. JWST) and on the ground (e.g. VRO, ELT, SKA, CTA), will provide exquisite new constraints on the properties of stars through all of their evolutionary stages. Multi-wavelength observations will allow astronomers to address fundamental questions in modern science, ranging from the nature of the once massive binary systems now detected regularly by the GW experiments, down to the seemingly innocuous low-mass stars that may harbour Earth-like planets. Only with strong observational constraints can we improve stellar models to better understand physical processes across a broad range of scales, from the factors influencing the appearance of our own Solar neighbourhood, back to conditions in the most extreme environments in
the early Universe.

Figure 1

Artist's concept of two neutron stars at the moment of collision, a catastrophic event probably producing short gamma-ray bursts.

Credit: Dana Berry / SkyWorks Digital, Inc.

Some of the key questions regarding the nature of stars and their impact on other areas of contemporary astronomy are presented below, including identification of some of the future facilities needed to address them. They are explored in three stages that stars navigate through their lives: formation and youth, their main-sequence lives and evolution, and their ultimate demise leading to the formation of compact remnants.

Stellar Birth & Youth

Stars spend most of their lifetime on the main sequence, but the physical processes at work during their childhood determine their properties, evolution and eventual fates. Stars form from the interstellar medium in dense molecular clouds. Over a process that lasts but a few million years, they inherit their mass and spin, build their planets, and fire-up their dynamos.

The step-change in studies of Galactic star-formation have been wide-area surveys in the near-IR (UKIRT, VISTA), optical (INT, VST, DECam, Gaia), and at longer wavelengths (Herschel, Spitzer) for an overarching picture of the gas and dust properties. These have been supported by studies of molecular clouds in the Galaxy and beyond (with e.g. IRAM- 30m, APEX, JCMT), revealing the filamentary nature of many structures. Molecular rotational lines trace kinematic components and map the signatures of dynamic chemistry, as well as revealing places where reduced shielding means that some gas is not detected in maps of carbon monoxide.

Key questions to progress the field include:

- How do molecular clumps fragment?
- What effect does the local magnetic field have on collapse?
- How do stars accrete material?
- What sets the upper mass limit of a star?
- Is the initial mass function (IMF) universal?
- What is the relationship of the IMF to the core mass function?
- What sets the initial multiplicity of stars, and how does this impact the IMF?
- How do young stars and their disks set the properties of nascent planetary systems and their early evolution?
- What chemical pathways are important in the production of complex organics?

Multi-wavelength observations of a multitude of star-forming environments (in terms of mass, density, metallicity, etc.) are required to tackle these questions, as outlined below.

Transforming interstellar gas into stellar embryos: challenges & future facilities

Large single-dish facilities (e.g. IRAM-30m, JCMT, LMT) are vital to trace the properties of the extended, low surface-brightness, dense filamentary structures where stars are forming under the combined effects of gravity, magnetic fields and turbulence (complementing mapping with the ALMA Compact Array). However, limited spatial resolution and mapping speed at mm/sub-mm wavelengths with the largest dishes is now motivating study of a large aperture antenna (AtLAST) equipped with highly multiplexed detectors with a large (>1 sq. degree) field and operating at high frequencies.

On smaller spatial scales, the development of ALMA and the JVLA has opened new horizons in tracing the dense, cold structures in the Milky Way and transforming many of the long-standing paradigms of star formation. ALMA's exquisite resolution and sensitivity at mm/sub-mm wavelengths makes it the facility of choice to investigate the close environments of protostars, tracing both the mass accretion processes and the locations where planets form. The planned ALMA upgrades (larger bandwidths, new receivers) will enhance its capabilities to hunt for chemical complexity and the physical interplay at work during the star and planet formation process, including stellar multiplicity.

In the coming years, ALMA and NOEMA will measure the core-mass function and gas dynamics in large samples across a range of environments, and in distant regions where single-dish facilities cannot resolve the characteristic core scales. Alongside this, JWST will obtain unprecedented observations of young stellar objects (YSOs) down to planetary mass objects in nearby star-formation regions and in lower-metallicity environments such as the Magellanic Clouds. Variability studies to probe the physics of accretion onto protostars have been significantly advanced with surveys from VISTA (VVV, VVVX), with contributions from other facilities such as JCMT and XMM-Newton. The future focus of such time-domain studies will be VRO/LSST (alongside ZTF in the north), complemented by e.g. X-ray studies of T Tauri stars, M dwarfs, and planet-hosting stars.

To understand the chemical content and physics of star-forming gas in the progenitor dense cores requires far-IR observations. Some of the most important gas coolants have transitions in the far-IR (and sub-mm), including lines from [CII], [NII], [OI] and [OIII], as well as transitions from warm molecular gas (H_2O, CO) that are inaccessible from the ground. In particular, far-IR spectroscopy is needed to address the dust properties and chemistry in dense structures and the interstellar medium (ISM), supported by investments in laboratory astrophysics to be sure that we can meaningfully interpret the observed features. Such observations require a large, sensitive far-IR space observatory (e.g. the Origins Space Telescope concept). Sensitive X-ray observations (XRISM, Athena), when coupled to models built from irradiation laboratory experiments (e.g. large facilities such as SOLEIL), will allow us to probe the crystallinity, composition and size of the dust in the relatively dense (10^{23}/cm^2) interstellar medium (ISM).

To directly compare the structures of the cores and gas, as well as the spatial distribution of YSOs (using statistical tools) we need to match the angular resolution from ALMA at IR wavelengths. This requires the angular resolution of the European Extremely Large Telescope (ELT) and its near-IR (MICADO) and mid-IR (METIS) instruments to probe, e.g., the pristine stellar mass function of heavily embedded star-forming regions for a key test of the IMF.

The full reward of ambitious future facilities will only be secured if also supported by significant computational efforts. For example, high-resolution MHD models to obtain predictions from the scales of molecular clouds down to stars and their protoplanetary disks. Only with such comprehensive models, for a range of initial conditions, can we describe the interleaving of different physical processes to determine stellar properties at birth. Future large datasets will also require analysis with data-mining tools and machine-learning techniques to track the fragmentation and evolution of cores, to feed into the theoretical framework within which to interpret the observations. The ISM is dynamic with enrichment from stellar winds and outflows, and evolving temperature, gas state and density, possibly mediated by magnetic fields. The interpretation of observations relies on time-dependent astrochemical models to reflect the evolutionary state of the regions under study.

Moreover, the analysis and interpretation also need to be supported by efforts to produce the required laboratory data. This is especially important and challenging regarding experiments to constrain dust emissivities and scattering, irradiation experiments in astrophysical ices to set-up the chemical complexity (from stellar environments down to planets), and laser experiments to study the physics occurring in shocks, which may be key to set the ionisation conditions around young stellar jets.

Role of magnetic fields: star-formation, young stars and their disks

The importance of magnetic fields in star formation and early stellar evolution remains unclear. The first complete map of magnetic fields in the Galactic environment came with Planck, but we have only recently had the sensitivity to magnetic fields on a variety of size scales. Facilities such as JCMT, SMA and ALMA have produced the first maps of magnetic fields threading from cloud scales down to individual protostellar cores, tracing the importance of magnetic support over orders of magnitude in density, temperature and pressure. These ground-breaking observations have revealed strong hints of a star-formation process where magnetic fields play a key dynamical role in transporting angular momentum from the core to the central star, hence potentially influencing the spin of new-born stars and therefore their internal structure. Moreover, recent interferometric observations of young stars with VLTI-GRAVITY have revealed the presence of accretion funnels, indicating that the strong stellar magnetic field disturbs the disk and controls accretion. It seems clear that magnetic fields play an important role at these small scales in reproducing the properties of both young stars (spin, multiplicity) and their protostellar disks (sizes, dust evolution). Polarised dust emission at thermal-IR and mm wavelengths and observations of scattered light at near-IR wavelengths (e.g., with VLT-SPHERE, VLTI-GRAVITY) have also provided new insights into dust properties, disk structure and evolution, and planet formation.

In the coming decade, current and future polarimetric facilities (e.g. SPIROU, NOEMA, ALMA, SKA) will be used to provide large surveys of the magnetic fields at disk and envelope scales. A critical gap in our ability to map the magnetic fields of these processes is where the dense medium mediates between the scales probed by these surveys and the Planck results. This can be filled by a sub-mm/far-IR large single-dish telescope probing magnetic fields at the typical scales of cores to clouds (e.g. the Origins and Millimetron concepts).

Despite great progress in the mapping of magnetic fields in star-forming structures in the last decade, a key question remains as of how to probe them in the deeply embedded, warm regions surrounding protostars, and in protoplanetary disks. Putting constraints on magnetic fields at disk and stellar-surface scales is key for example to set strong constraints on MHD models to extract angular momentum and regulate mass-accretion rates during star formation. Measuring the magnetic fields in disks is key to understanding disk-winds and their relationship to early stellar and planetary evolution. Mid-IR polarimetry on large telescopes could help make substantial progress in capturing magnetic fields at work in the warm dust around young stars, but there is no polarimetric capability on JWST-MIRI, nor planned for ELT-METIS. Another promising avenue to explore, yet still under-developed, would be to measure (proto-)stellar magnetic fields directly via the Zeeman effect in astrophysical molecules. Circular polarisation observations of spectral lines from the near-IR to the millimetre wavelengths can assess the nature and role of magnetic fields in disks and their host stars, allowing breakthroughs regarding their intertwined evolution through the magnetic field that threads them. Mid-IR polarimetry would also provide unique information on the size and shapes of the dust grains populating the youngest disks (from which protoplanets form), complementing JWST that will probe the ice composition by absorption spectroscopy at these scales.

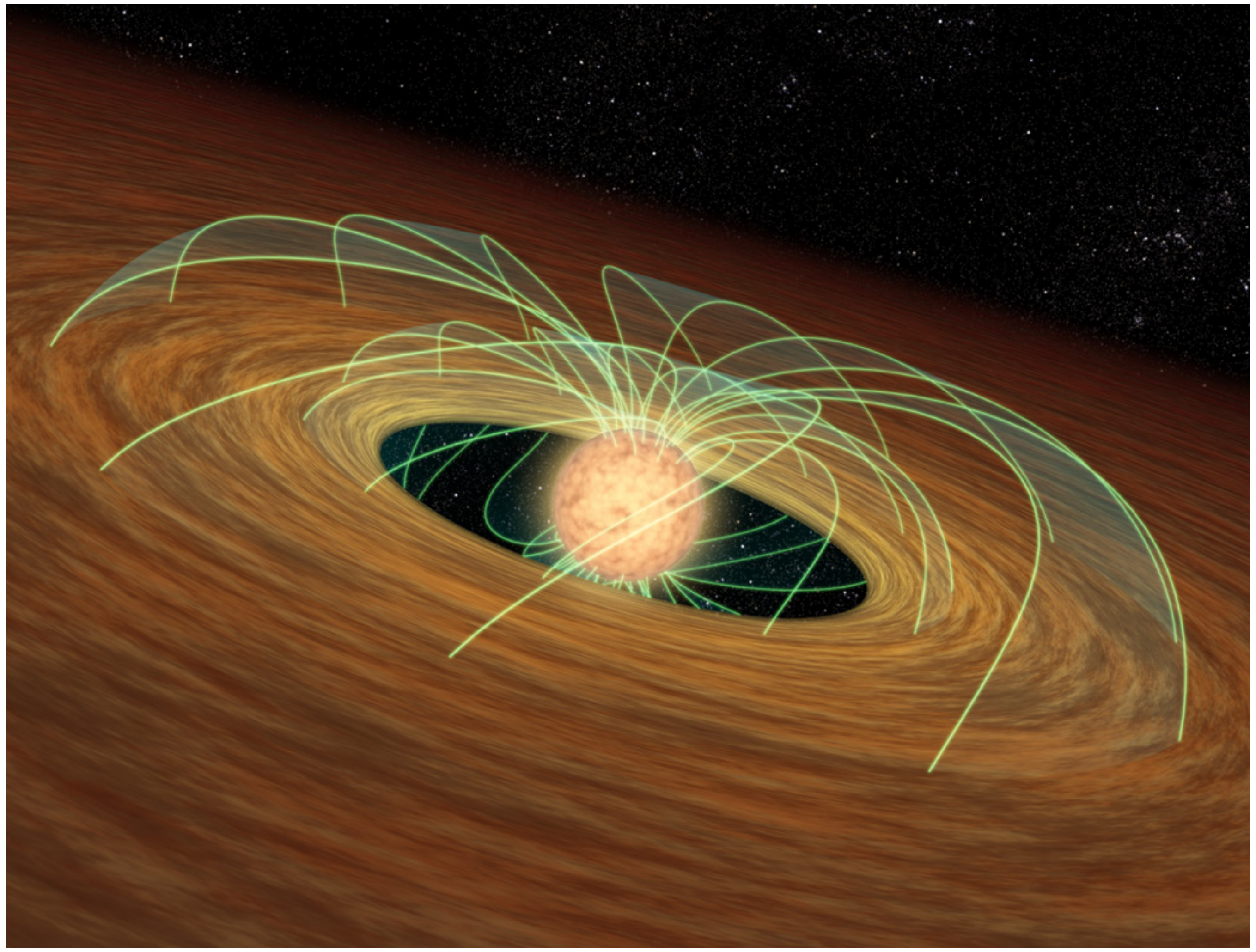

Figure 2

Artist's concept of a young star connected to its dusty planet-forming disk by magnetic field lines, potentially braking the star's rotation.

Credit: NASA/JPL-Caltech.

Star formation in the exoplanet context

Increasing observational evidence suggests that planet formation has already started as early as 1-2 Myr into the star-formation pathway, much earlier than previously thought. For example, disks around T-Tauri stars (and earlier evolutionary stages) observed with ALMA in different star-forming regions show structures suggestive of ready-formed Jupiter-like planets, and may have revealed dust reservoirs that are too small to form the observed population of exoplanets. The study of star-disk systems will be key to our understanding of early planet formation and evolution (see chapter on Formation and Evolution of Planetary Systems), as well as our understanding of the early evolution of pre-main sequence stars.

The chemical composition and orbits of planets are inherited from the properties of their parent protoplanetary disks, a focus for the coming decade will be large studies of young protostars and their circumstellar material. The chemistry, dust composition, and interaction of disks with their host stars will be scrutinised to assess how planets acquire their mass and composition. Facilities such as JWST, JVLA, ALMA ELT, SKA, VLTI (including GRAVITY+), the European VLBI Network (EVN) and the ngVLA will have complementary roles in characterising the star-disk system at the unprecedented scales needed to study exoplanets around main-sequence, solar-type stars in the Milky Way. Combined near-IR to mm observations of disk structures, such as spirals or rings, will allow constraints on the physical properties and chemical evolution of both the gas and dust. The large collecting area and time sensitivity of the next generation of X-ray spectroscopy (e.g. Athena) will allow us to observe the detailed atomic lines and probe the magnetic reconnection events between T-Tauri stars and their disks. This is the key to constraining the physico-chemical conditions in planet-hosting disks, as the X-ray ionisation and heating also has significant consequences on the stellar spin, the disk cosmochemistry, and potentially also on planet migration. Direct imaging of protoplanets at infrared and sub-mm wavelengths will become more common with high spatial resolution observations, with radio emission providing one useful diagnostic of star-planet interactions (e.g. LOFAR, SKA). However, most Earth-like planets may well form at smaller separations (<1au) from their host stars, making them difficult to detect (especially early on). For such systems, only interferometry or indirect signatures of planet-disk-star interactions in time-series observations may reveal their presence.

Another topical area is the study of brown dwarfs and planetary mass objects in Galactic star-forming regions to examine the boundaries and formation mechanisms of these different object classes (e.g., with IR surveys from the ground or space, such as VISTA, Euclid, and JWST, as well as LOFAR and SKA). For instance, dynamical evolution may lead to mass segregation and with precision photometry, astrometry and spectroscopy we can potentially estimate the number of planetary mass objects in interstellar space.

Stellar Evolution

Stars span a vast range in mass, from brown dwarfs (less than 0.1 MSun) with just enough hydrogen to begin nuclear fusion, to over 100 MSun, where they burn through their fuel in just a couple of million years. In the past decades we have studied the physical details of individual stars throughout the Milky Way, out into our neighbouring galaxies (such as the Magellanic Clouds) and even further out into the Local Group of galaxies.

Stars provide us with unique laboratories to address some of the biggest, unanswered questions in modern astrophysics, such as:

- What are the basic constituents of matter?
- What happens to matter in extreme conditions?
- What external factors influence the conditions required for life on planets?

Stellar evolution is a mature subject but there are significant gaps in our understanding that limit our interpretation of the latest observations. Given the broad scope of the topic, it is not possible to be comprehensive in this report; here we highlight four prominent areas of active research in the field that are driving the development of facilities in the coming decade and motivating those beyond.

Stellar atmospheres

The study of stellar atmospheres is required to determine the basic physical properties of stars, such as their temperatures, surface gravities, magnetic fields, radii and chemical composition. Such parameters are generally estimated from analysis of the spectral lines formed at various depths in the atmosphere. Observations at high signal-to-noise and high spectral resolution and from a diverse set of wavelength ranges are required to glean the maximum information from the cores and wings of spectral lines to calibrate stellar models, which can then be used at larger distances and to fainter magnitudes with less optimum observations.

At the same time, modern high-angular resolution techniques such as extreme adaptive optics or interferometry (e.g., at VLT and VLTI) allow astronomers to resolve the stellar surfaces of the largest stars, revealing the complex atmospheric structures of supergiants, as well as their strong and spectacular temporal dependency. Streamlining and further improving these advanced imaging techniques that are pioneered by Europe will allow us to expand existing studies beyond just a handful of objects, and to further time-dependent analyses. These will undoubtedly shed new light on the physical and dynamical properties of stellar surfaces, allowing important observational constraints at the interface between stellar interiors and stellar winds.

Another key goal for atmospheric models is to understand the complex vertical structure of the convective motions and their efficiency in producing the stellar spectra we observe. For instance, M-type dwarfs represent about 70% of the total Galactic population. High-resolution spectroscopy (e.g. ELT-ANDES) will provide robust constraints on 3D magneto-hydrodynamical models of their atmospheres, testing our understanding of convection, magnetism, and the mass-luminosity relation at different metallicities. High-quality spectroscopy will be similarly important for new insights into the impact of rotation, magnetic fields, and chemical enrichment at higher stellar masses.

The physics of stellar interiors

We still have a limited grasp of the fundamental mechanisms in stellar interiors (e.g., convection and transfer of angular momentum), and numerical simulations struggle to reproduce the physical conditions in these internal regions. For example, hydro-magnetic instabilities can appear that drive the system to a turbulent, possibly self-organised state that can account for many of the features we observe in stars, from winds to stellar cycles and flares. High-resolution, multi-dimensional simulations are needed to study these processes from first principles, to arrive at formulations that can be implemented in stellar evolution codes to then follow the full secular evolution of the stars.

Stars also provide us with unique laboratories to study the assembly of the elements by nucleosynthesis. By studying different populations of stars in the Milky Way and other galaxies we can learn about the temporal evolution of chemical abundances of key elements, both from spectroscopy and photometry (where the location of stars in colour-magnitude diagrams is influenced by their internal chemical profiles). Moreover, ongoing underground experiments (e.g., LUNA) are investigating critical nuclear reactions of astrophysical interest for stellar evolution and cosmic nucleosynthesis.

New facilities in the next decade will deliver unprecedented, high-quality datasets of stellar spectra (e.g., 4MOST, WEAVE, MOONS, MSE), magnitudes (e.g., LSST/VRO), and studies of stellar oscillations (e.g., TESS, PLATO). These data will potentially lead to fundamental changes in our prescriptions of how stars evolve, for instance:

- Which phenomena most influence surface and interior chemical composition?
- What is the interplay between radiation and convection in stellar interiors?
- How does material mix and diffuse inside stellar interiors and up to the surface?
- What are the evolutionary timescales across different masses, chemical compositions and evolutionary stages?

The challenge is to derive robust physical prescriptions that explain the observed properties, but analysis of such data is only as good as the available tools and models.

In this context, laboratory astrophysics is the bedrock of stellar research. There remain significant uncertainties in areas such as reaction rates, molecular physics, line opacities, precise wavelengths, PAH characteristics, and more. We also highlight the need for sustained investment in high-performance and high-throughput computing for theoretical models. Moreover, large-scale distributed computational resources (and cloud computing) have become essential to study and efficiently interpret the tremendous volume of data from the latest space and ground-based surveys.

In recent years the study of stellar evolution has been revolutionised by the extremely accurate and extensive data from the CoRoT and Kepler space missions. In particular Asteroseismology, namely the study of stellar oscillations, has led to the discovery of new avenues of research in our understanding of stellar interiors across the whole HR diagram. Ongoing and future missions such as TESS and PLATO will provide time series of unprecedented extent and precision on a large number of bright stars, on exoplanet-hosting stars, and on active stars, so that precise determinations of masses, radii and ages will finally enable us to constrain current theories of stars, planetary system formation and Galaxy Evolution.

Stellar winds and chemical enrichment

Stellar winds and outflows are a fundamental process through which stars contribute kinetic energy and chemically-processed material into the interstellar medium. There remains much to learn in our understanding of the mass-loss and winds from stars of all masses. High-resolution numerical simulations are being used to explore the complex physics involved in the dynamical evolution of stars, from low-and intermediate-mass stars on the red giant branch (RGB) and asymptotic giant branch (AGB), up to the physics and evolution of massive OB- and Wolf-Rayet type stars that ultimately explode as supernovae.

In massive stars there remains much to understand regarding the stratification and intensity of stellar winds, particularly at low metallicities. Only with a firm grasp of these properties can we correctly interpret the integrated-light observations of star-forming galaxies in the distant Universe. Multi-wavelength observations from X-rays (e.g. XMM-Newton, Athena) to radio (e.g. EVN) are required to characterise these outflows, with longer-wavelength studies, particularly important for studies in obscured Galactic clusters (e.g., ALMA, SKA, EVN).

Studies in the Magellanic Clouds provide us with a window into the lower-metallicity regime (e.g., the ULLYSES programme with HST) but a long-standing goal is for optical and ultraviolet spectroscopy of massive stars in more distant systems, that have closer to primordial abundances (e.g., Sextans A, Leo A, and beyond out to I Zw 18). Increased sensitivity with current facilities will be important to study such populations beyond 1 Mpc (e.g., BlueMUSE, CUBES) but ultimately an ambitious UV/visible space-borne capability is critically required to succeed the HST, such as the Large UV/Optical/IR Surveyor (LUVOIR) concept.

Less spectacular but equally important are the contributions from lower-mass RGB and (post-)AGB stars to the ISM. Improving our understanding of their mass loss and winds requires sensitive IR, millimetre and radio observations. Moreover, in the last stages of their lives, as nuclear fuel in their cores is depleted, many stars move into giant or supergiant phases with extended low-surface gravity envelopes and relatively cool surface temperatures. These conditions radically change the characteristics of the stars as the conditions become favourable for the formation of molecules, such as carbon or silicon monoxide, and the condensation of refractory elements into dust. The molecules and dust particles reflect the chemical composition of the stellar envelope and are ejected into the interstellar medium, enriching it in processed materials.

The detailed composition and physical properties of interstellar dust remain uncertain, but it appears that stardust is regenerated in the ISM and reflects the local element abundances. Beyond the properties of the dust itself, a detailed understanding of how dust evolves with the Universe is important in the context of how it affects circumstellar disks and the building blocks of planets. Its properties are also imprinted in interstellar extinction, which impacts nearly all astronomical observations. For instance, dust formed in supernova ejecta may be an important component of the infrared emission seen in high-redshift galaxies, and understanding its composition and how much material condenses into the solid phase at different stages of supernova evolution is the key to interpreting observations. Spectroscopic (and, where possible, spectropolarimetric) measurements of dust emission and absorption features to probe dust properties and their environmental dependence will exploit facilities such as Spitzer, JWST, VLT and ELT.

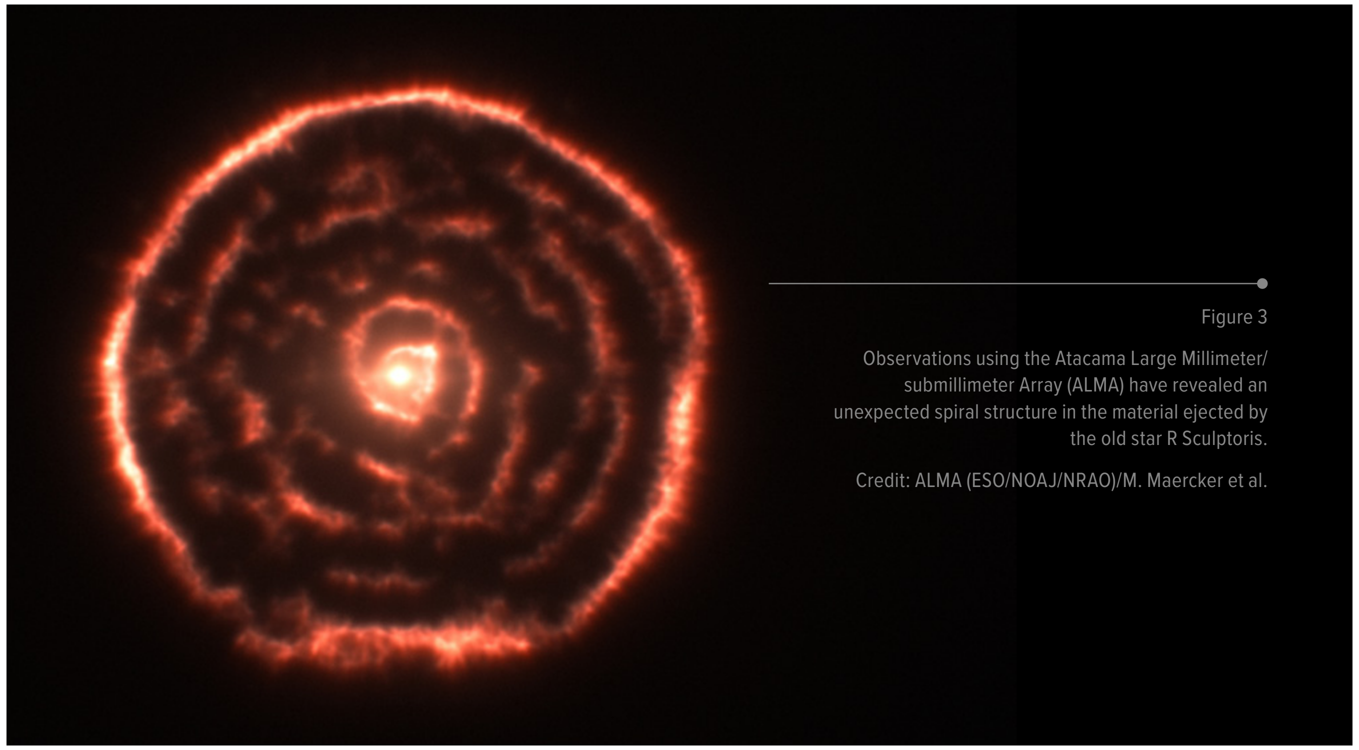

Figure 3

Observations using the Atacama Large Millimeter/submillimeter Array (ALMA) have revealed an unexpected spiral structure in the material ejected by the old star R Sculptoris.

Credit: ALMA (ESO/NOAJ/NRAO)/M. Maercker et al.

Multiplicity

Many low-mass stars, and the majority of stars at least as massive as our Sun, are paired with at least one other star in a binary or a higher-order multiple system. Their orbital properties are remnants of the pairing mechanism during formation and their early dynamical evolution. These multiple systems offer unique diagnostics to precisely measure some of the fundamental properties of stars, such as their masses and sizes. In addition, as a result of the secular expansion of stars as they age, stars in close binaries will exchange mass and angular momentum with their companions and may even merge. This dramatically alters the evolution of both stars, and the nature and properties of their end states. This leads to a plethora of complex physical processes that remain insufficiently understood but that dramatically impact the outcome of stellar models and the predicted properties of entire populations of stars across cosmic time. It is worth noting that while the majority of stars are in multiple systems, most of the studies of exoplanets and exoplanet formation (e.g. via disk studies) are being carried out in single systems, which are not generally representative of the whole population.

Large observational samples of pre-interaction, interacting, and post-interaction binaries across a broad range of mass, age and metallicity are required to map the initial conditions and study the physics of the interaction and characterise its outcome. Such strong observational constraints are needed to phenomenologically connect evolutionary stages within the binary evolution paradigm, as well as to guide the development of models and confront their predictions. Significant multi-epoch photometric, spectroscopic and astrometric observational efforts are needed to characterise their orbital, physical and surface abundance properties. Some of the data will be provided by missions such as Gaia, TESS and PLATO, but a similar-scale spectroscopic effort in the form of a large-aperture spectroscopic telescope is missing, especially if we are to push the metallicity barrier beyond that of the Milky Way. Interferometric observations (e.g. EVN, VLTI/GRAVITY+) will also be required to directly characterise stellar and substellar multiple systems in unprecedented detail.

Full integration of multi-messenger astrophysics in the constraints of single and binary evolution will be an important cornerstone of research in the coming decades. Alongside new observations, fundamental theoretical work is required to improve our understanding of the complex physics in binaries, to predict the evolution and final fates of entire populations of stars, and to investigate the interplay between stellar evolution and stellar dynamics in higher-order multiples (e.g. via detailed binary evolution models as well as population-synthesis models that include binary evolution and, possibly, stellar dynamics). At the same time, better predictions are needed regarding the formation channels of compact objects, and their contributions to the stochastic astrophysical background, to properly interpret the large number of GW signals that will be detected by the next generation of GW-interferometers both on (or under) the ground (e.g,. Einstein Telescope) and in space (e.g., LISA).

Stellar death

The evolution of stars depends primarily on their initial mass, and undergoes a major bifurcation around 8-10 solar masses. Stars with masses above this boundary will end their lives in core-collapse supernovae, leaving behind neutron stars and black holes; those with lower masses have a less violent destiny, and their cores will eventually become white dwarfs. Our understanding of these different classes of compact, extreme objects has grown considerably over the past decade from comprehensive multi-band study of the transient sky and the availability of GW interferometers. We now briefly expand on each of these topics in more detail (see also the chapter on Extreme Astrophysics).

White dwarfs

White dwarfs are Earth-sized stellar embers in which the pressure of degenerate electrons balances gravity. Because of their short lifetimes, most A/F-type stars formed throughout the history of the Galaxy have already evolved into white dwarfs. As such, white dwarfs play an important role across a variety of areas in astrophysics (including exoplanets, as discussed in the chapter on planetary systems).

Key questions include:

- What are the progenitors of type Ia supernovae?
- What is the Galactic low-frequency GW background?
- What is the ultimate fate of planetary systems orbiting stellar remnants?

Stellar evolution & fundamental physics

Homogeneous samples of white dwarfs with accurate physical parameters are essential to constrain and calibrate stellar evolution theory, e.g. mass loss on the asymptotic giant branch (important for the initial-to-final mass relation), internal rotation profiles and loss of angular momentum, and fundamental nuclear reaction rates, as well as having important implications for stellar population synthesis and galaxy evolution theory. Given their well-constrained cooling ages, white dwarfs can be used to estimate the age of the Galactic disk, open clusters and globular clusters, and can potentially trace variations in the Galactic star-formation rate.

Given their extreme densities, white dwarfs also provide excellent cosmic laboratories for the behaviour of matter under extreme conditions, including non-ideal plasma effects, first-order phase transitions, and detailed atomic physics in magnetic fields that are many orders of magnitude beyond capabilities on Earth.

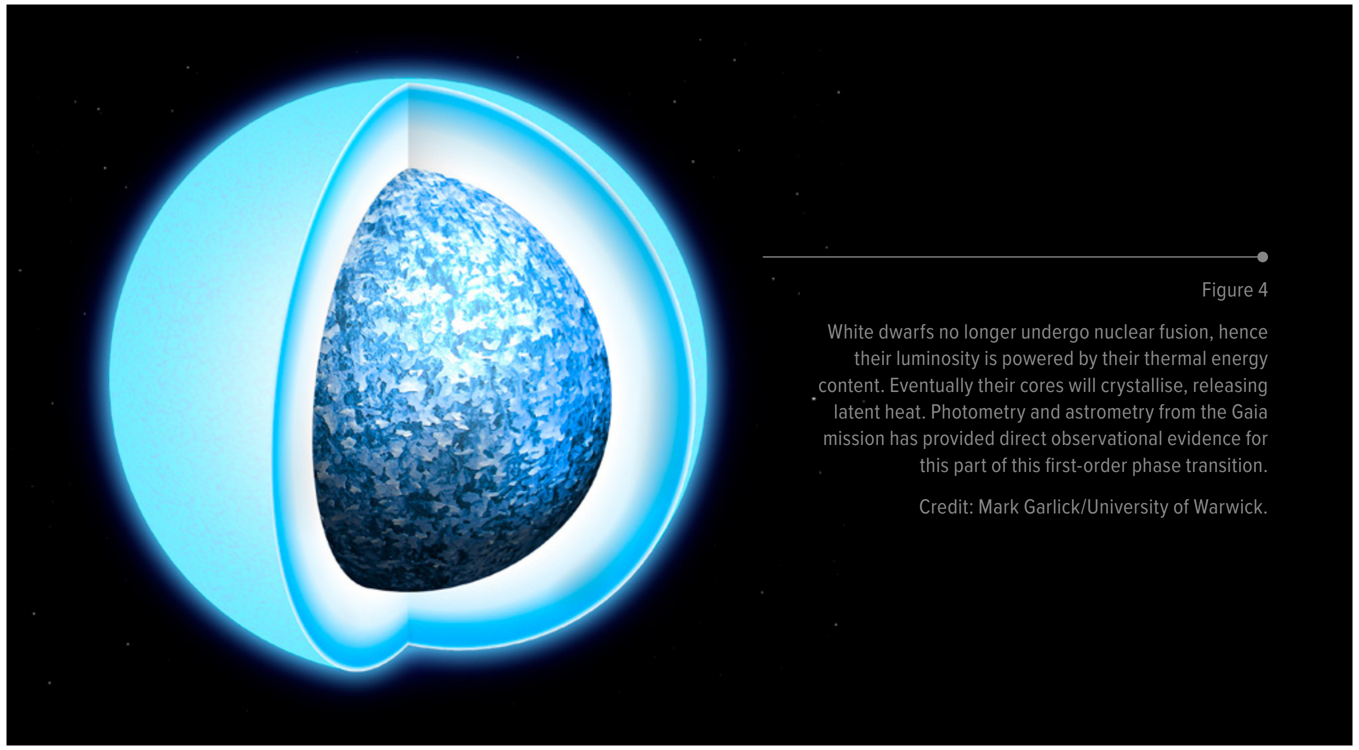

Figure 4

White dwarfs no longer undergo nuclear fusion, hence their luminosity is powered by their thermal energy content. Eventually their cores will crystallise, releasing latent heat. Photometry and astrometry from the Gaia mission has provided direct observational evidence for this part of this first-order phase transition.

Credit: Mark Garlick/University of Warwick.

White dwarfs in binaries: progenitors of SNIa & low-frequency GW sources

A significant fraction of local white dwarfs are members of binaries, providing a benchmark population to investigate complex interactions. White dwarf binaries are the progenitors of type Ia supernovae - the cosmic distance beacons that led to the discovery of dark energy – but the details of the evolutionary paths leading to these thermonuclear explosions are still poorly understood. Short-period double white dwarf binaries are powerful emitters of low-frequency GWs but we do not know their space density and period distribution very well, and such systems may well define the Galactic background level for the LISA mission. Finally, white dwarfs with precise cooling ages in wide binaries can also be used to calibrate main-sequence ages.

White dwarf science over the next decade

White dwarfs are intrinsically faint and difficult to distinguish from more distant main-sequence stars with similar colours. Most known white dwarfs were identified as ultraviolet-excess objects and are young (< 1 Gyr) and hot (T_{eff} > 10,000K), and are not representative of the Galactic population as a whole. Gaia DR2 and DR3 finally provided the parallaxes needed to break the degeneracy between nearby white dwarfs and background main-sequence stars, enabling assembly of the first unbiased all-sky magnitude-limited (G20) sample of 260,000 white dwarf candidates.

While the Gaia data are sufficient to identify white dwarfs with high confidence, follow-up spectroscopy is required to determine their physical properties (temperature, gravity, composition, magnetic-field strength, multiplicity) and derive their fundamental properties (mass, cooling age, progenitor mass). Multi-object spectroscopic surveys are key to this follow-up, e.g., ongoing surveys with SDSS-V and DESI and in the future with 4MOST, WEAVE, MSE. Multi-epoch spectroscopy is also critical to identify a large, representative sample of short-period double white dwarf binaries. This sample will both guide the development of accurate theoretical models of SN Ia progenitors, as well as establish a suite of calibration targets for the LISA mission.

Finally, pushing deeper than Gaia, VRO will identify several million white dwarfs, in particular extending the population of cooler and older white dwarfs to a larger volume that will provide new insights into the history of the Galactic star-formation rate.

Neutron stars

Neutron stars are born in the core-collapse supernovae of massive stars (~10 MSun), as well as via accretion-induced collapse and binary mergers. They are unique laboratories to study the most extreme phases of matter. We can probe the extremes of gravity and electromagnetism, and the strong and weak interactions in regimes that we have no prospect of exploring on Earth.

The neutron-star population is dominated by radio pulsars, but also includes several extreme and puzzling subclasses such as magnetars, X-ray dim isolated objects, accreting systems with a large variety of companion stars, and more. In excess of 3000 neutron stars are now known, mostly in the Milky Way, in different systems and environments: isolated or in binaries, in binaries containing two neutron stars, in the Galactic disk, in globular clusters, and in other nearby galaxies. Their extreme gravitational, rotational and magnetic energy are fuel for the diverse emissions from neutron stars, which encompass all multi-messenger tracers: electromagnetic waves, cosmic rays, neutrinos, and GWs. We therefore require a multidisciplinary effort that spans from particle and nuclear physics to astrophysics, from experiment to theory, and from the electromagnetic spectrum to GWs.

Outstanding questions on the nature of neutron stars include:

- What is the equation of state that relates the pressure and density in their interior?
- How do their strong magnetic fields form at birth? How are they ordered in a dipolar field component?
- What are the progenitor stars of the different neutron-star classes?
- In addition to those formed in core-collapse supernovae, which neutron stars are formed via accretion-induced collapse or binary merger?
- How do pulsar winds interact with the local environment to form powerful pulsar wind nebulae and accelerate particles up to TeV energies?
- How is their radio emission produced?
- How do they accrete material from companion stars and produce outflows?

Magnetars

This small group of X-ray (and sometimes also radio) pulsars are among the most puzzling neutron stars. Their strong X-ray emission is too luminous and variable to be fed by rotational energy alone (as in typical radio pulsars) and with no evidence for a companion star that could be contributing via accretion. They are the most strongly magnetised neutron stars known; their fields may form via a dynamo action in the fast-rotating proto-neutron star, via magnetorotational instabilities within the highly convective stellar core or, alternatively, these could be remnant fossil fields from a highly magnetic massive star progenitor (with field ~1 kG).

The emission from magnetars is thought to be powered by the decay and the instability of their strong magnetic fields. As well as persistent X-ray emission, magnetars emit peculiar flares and outbursts on several timescales (from fractions of a second to years) emitting large amounts of energy (10^{40} - 10^{46} erg; the most energetic Galactic events after supernova explosions). These flares are caused by large-scale rearrangements of their twisted magnetic field, either accompanied or triggered by neutron-star crust movements (similar to stellar quakes). These extreme neutron stars are believed to be strongly related to some of the transient objects discussed below, namely superluminous supernovae, gamma-ray bursts (GRBs) showing plateaus in their afterglows, and fast radio bursts.

Physics of accretion & fundamental physics

The accretion of matter from a companion star onto a neutron star (or a black hole) produces X-ray luminous systems that are observable at extragalactic distances in some cases. We know several thousand high- and low-mass X-ray binaries in the Milky Way, the Magellanic Clouds and beyond. Some of these binaries are spun-up to extremely short spin periods (of milliseconds) by the accretion. Understanding how such neutron stars are spun-up, and how fast they can rotate, gives direct constraints on the neutron star equation of state. The possibility of detecting continuous GWs from such systems also depends on the maximal spin that can be reached and the deformation of the neutron star. To address such topics we need high-sensitivity telescopes such as XMM-Newton, Chandra, and the significant gain in X-ray capabilities that Athena will provide. Alerts from all-sky monitors and high-cadence monitoring (e.g. Swift/XRT in X-rays, MeerKAT in the radio) are also critical.

Rotationally-powered pulsars (particularly those with millisecond periods) also provide us with exceptionally precise astronomical clocks that can serve as unique laboratories for tests of fundamental physics. For instance, the ‘pulsar timing array’ is a set of pulsars used as a Galactic-scale interferometer to look for GWs from binary supermassive black holes at the centre of galaxies, neatly complementing efforts from ground-based GW detectors (and LISA in the future), which are sensitive to other parts of the GW frequency spectrum. Pulsar-timing arrays depend on high-cadence measurements with radio telescopes such as Lovell, Nançay, Effelsberg, MeerKAT, GBT and FAST. These can also be combined into coherent arrays like LEAP, the Large European Array for Pulsars. Unveiling the total Galactic population of radio pulsars (anticipated to be in the tens of thousands of sources) will be significantly progressed by the SKA (and on the shorter term by MeerKAT and FAST). An exciting question here is whether we can find examples of sub-millisecond pulsars, which would provide even more exquisite constraints on neutron-star structure, or pulsar – black hole binary systems that would enable unprecedented tests of general relativity. At the same time, low-frequency pulsar searches (e.g., LOFAR) and targeted high-frequency searches (e.g. MeerKAT searches of the Galactic bulge and centre) can help us achieve a less biased view of the Galactic pulsar population. Discovery of a pulsar orbiting Sgr A* would provide both novel information about the Galactic population and unprecedented tests of general relativity.

Pulsar wind nebulae

Neutron stars lose the bulk of their rotational energy via pulsar winds. These are ultra-relativistic outflows of electrons and positrons for which we have few constraints at present. These winds impact the local environment and are eventually halted by the ISM (and the blast wave of the supernova remnant shock that earlier generated the pulsar) or by a more dramatic interaction with a close binary companion. These mechanisms yield different classes of nebulae, which can provide insights into the formation of their pulsars, the electrodynamics of the magnetised rotators, how the magnetospheres generate the wind, the acceleration of leptons up to very high energies (and their energy distribution), and how these impact on the surrounding ISM. Pulsars and their wind nebulae allow study of plasma-field interaction processes in conditions far beyond what is achievable in the lab. In this context, neutron stars and their environments will be the largest source class for next-generation facilities such as the CTA and SKA.

Stellar- and intermediate-mass black holes

Stars more massive than ~20 solar masses are thought to collapse to black holes when exhausting their nuclear fuel. In such massive objects not even the neutron degeneracy pressure and strong force that sustains neutron stars can counteract the gravitational forces and nothing can halt the collapse. This process is expected to give birth to one of the most intriguing astrophysical objects: a black hole.

Black hole theories flourished in the 1960s and the first astrophysical example of such an object (Cygnus X-1) was identified in 1971 from the observation of a large amount of X- rays from a star orbiting an invisible compact object. The X-rays are from gas stripped from the star and heated to high temperatures while spiralling onto the hidden object, which was later estimated to have a mass greater than five solar masses, thus ruling out a neutron star. Since the discovery of Cygnus X-1, several similar accreting but otherwise invisible objects (with masses between 5 and 20 solar masses) in binaries have been observed in the galaxy, which are considered as stellar-mass black holes. However, the limited number of detections over several decades leaves many questions:

- Are these objects really the black holes described by general relativity?
- How common are they, and how do they form?
- Do intermediate-mass black holes exist beyond the stellar mass range?
- Is there a mass gap between neutron stars and black holes (and within BHs)?

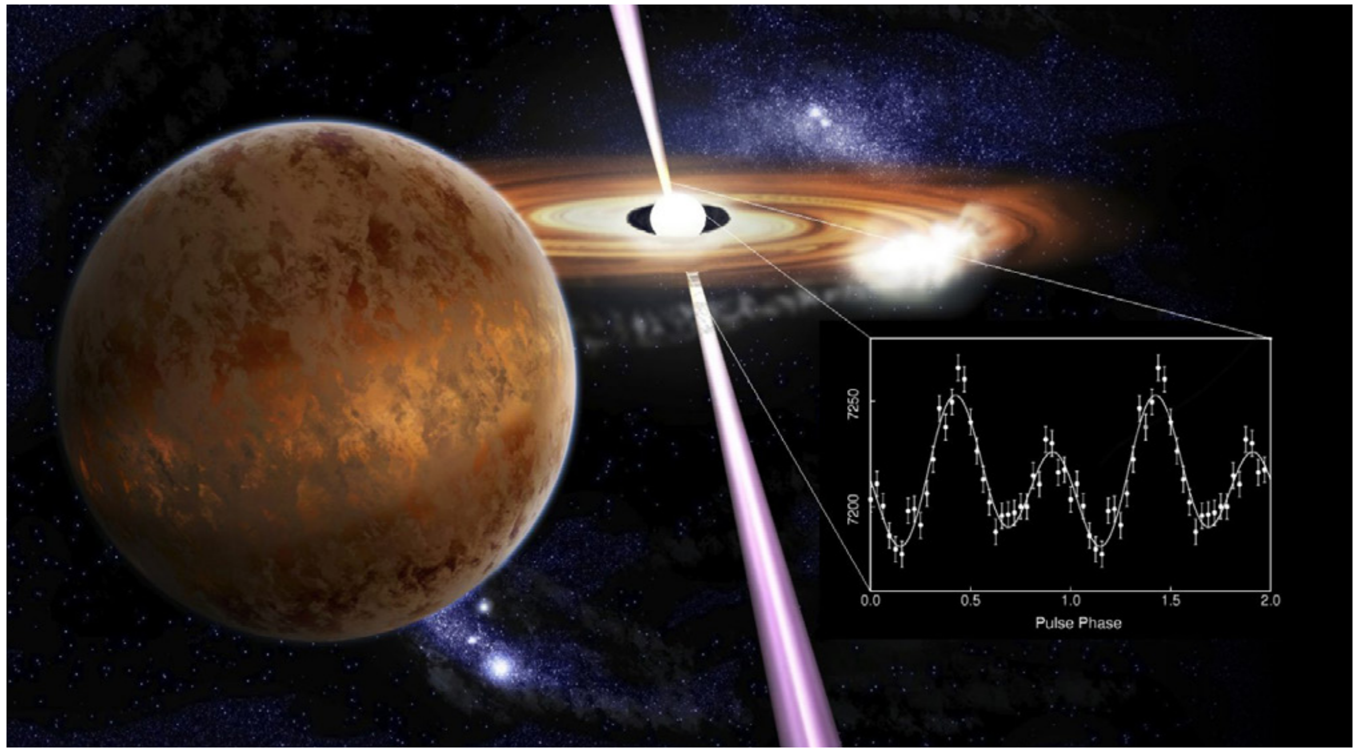

Figure 5

Artist's impression of PSR J1023+0038, a binary system composed of a neutron star that tears matter from a companion star with the formation of an accretion disk, and emits pulses of X-rays and visible light.

Credit: https://nathaliedegenaar.files.wordpress.com/

The pioneering GW results from LIGO and Virgo have finally provided some answers to these questions. Compact binaries of neutron stars or black holes emit gravitational distortions (ripples in spacetime) that can be detected by GW interferometers when they merge to form a bigger black hole. The detections of more than 50 merging compact binaries to date have transformed the field. Merging black holes are found to be quite common and span a wide range of masses. We have now detected black holes as massive as 160 solar masses, some of which challenge the standard proposed formation channels for such objects. Studies of the gravitational waveforms have allowed spectacular tests of general relativity in the strong-field regime, thus far confirming theoretical predictions.

It is still early days for the GW field, however. In the next few years the ground-based detector network (including LIGO, Virgo, LIGO-India, and KAGRA) will reach design sensitivities, detecting hundreds of such objects per year up to large cosmological distances. By the end of the 2030s, third-generation detectors (the Einstein Telescope in Europe and Cosmic Explorer in the US) will allow us to see black-hole binaries essentially everywhere in the Universe. This will allow us to reconstruct their origin in connection with stellar and binary evolution and, hopefully, to answer (some of) the questions outlined above. For example, detection of nearby binaries at high signal-to-noise will allow us to probe the ringing modes of the newly formed black holes, which carry the fingerprint of their geometrical structure, thus allowing tests of general relativity with unprecedented precision. The improved sensitivity of the new instruments will enable objects up to several thousand solar masses to be observed, testing the existence of intermediate-mass black holes. In short, our journey in the understanding of astrophysical black holes has just started and the future promises to be rich with new discoveries.

Stellar death and the transient extra-galactic sky

Our understanding of the violent and explosive Universe has been revolutionised in the last decade with the development of time domain sky surveys. Wide-field photographic sky surveys were replaced with multi-colour optical and near-infrared digital coverage of the whole sky. These surveys are now on repeat and have opened up the time domain for exploration. A series of wide-field surveys with 20cm to 2m telescopes covering most of the visible sky every few nights have discovered a remarkable diversity in how stars explode and die. Until 2010, our understanding of the transient sky was dominated by the normal supernova populations of type Ia from white dwarfs, type II from massive, hydrogen-rich supergiants and the type Ibc from massive stars that have been stripped of their hydrogen envelopes. GRBs were characterised into short and long varieties, with the long events securely associated with energetic supernovae, potentially from Wolf-Rayet stellar progenitors. The tremendously bright afterglows of GRBs (with some at $z > 6$) allow the high redshift Universe to be probed through absorption line systems and identification of their host galaxies.

The novel optical surveys and rapid, multi-wavelength follow-up have discovered super- luminous supernovae, which are 100 times more luminous than normal core-collapse supernovae and seem to be predominantly produced in very low metallicity galaxies (perhaps from ultra-massive stellar progenitors). Candidates for pair-instability supernovae have been discovered, along with very faint and fast transients that do not yet have an accepted explanation. The debate around the progenitor systems of type Ia supernovae (white dwarfs exploding due to a merger event or accretion from a companion) has widened to question whether the white dwarf really is of Chandrasekhar mass and how the wide diversity in thermonuclear explosions can be explained. Several transients with relativistic outflows, but no GRBs have been found and have been associated with prompt black hole formation. Moreover, in 2017, the first kilonova was found, resulting from the merger of two neutron stars that produced the strong gravitational-wave signal GW170817. This produced a short, faint GRB, non-thermal emission from the X-ray to radio and a kilonova powered by the radioactive decay of heavy elements.

The next decade will explore this rich discovery space, with a key facility being the Rubin Observatory that will start operations in 2023. Its Legacy Survey of Space and Time (LSST) will be the deepest, most precise, wide-band survey of the sky ever undertaken, and repeated observations and rapid analysis will produce a stream of transient alerts. LSST combined with CTA, LOFAR, EVN, SKA, the upgraded LIGO-Virgo-KAGRA network and ultimately Athena, will define the future of transient discoveries, and motivate significant optical/IR follow-up with telescopes of all sizes (from small-to-medium class telescopes up to the ELT) and at other wavelengths (e.g., HST, XMM-Newton, THESEUS concept).

In the coming years we will be able to use supernovae as precision cosmology probes to measure dark matter and dark energy parameters over a larger volume than previously possible. The physics and diversity of stellar explosions will be unveiled across a wide-range of redshifts and host galaxy environments. Indeed, the statistical samples of transient events with precision photometry will be unprecedented, and combining the LSST alerts with multi-wavelength and multi-messenger signals will be very powerful. For instance, radio and high-energy emission probes shock physics and how stellar progenitors evolved in the last few years of their lives, while also revealing relativistic jets.

Finding the electromagnetic counterparts to GWs will constrain the equation of state of nuclear matter in neutron stars, uncover the source of the heaviest elements and probe black hole and magnetar formation. Sources with both GWs and an electromagnetic signal can then be used for both cosmology (direct measurement of the Hubble constant) and fundamental physics (the equivalence principle, velocity of gravitational waves and modified gravity) with novel methods.

Following their discovery just over a decade ago, the physical origin(s) of fast radio bursts (FRBs) is also a very active topic in the study of astrophysical transients. They are seen to originate in other galaxies (some quite distant) but these incredibly luminous radio flashes are shorter than the blink of an eye and the underlying engine that could power them is still a mystery. There is increasing evidence that highly-magnetised neutron stars could be the sources, but many questions remain. For instance, repeating and apparently one-off FRBs have been discovered – are these produced by the same type of source? Giant flares from magnetars could explain the one-off events, but the periodic activity level of some repeating FRBs could indicate a binary orbit.

Regardless of their physical origins, FRBs have already been shown to be unique probes for extragalactic astrophysics and cosmology, as their observed radio waves undergo propagation effects due to the magnetic and ionised material they pass through. This allows us to detect the otherwise invisible gas and magnetic fields within and between galaxies. Wide-field radio telescopes like CHIME/FRB are now detecting multiple FRBs per day, and radio interferometers like the EVN, ASKAP, MeerKAT, and VLA are capable of providing the (milli-)arcsecond localisation that is needed to robustly associate them with a host galaxy.

Precision Stellar Physics

Our understanding of stellar physics and the accuracy with which we can model stars has now become a limiting factor in other fields. This arises because the computational models used to predict stellar properties as a function of time necessarily focus on limited aspects or have to simplify the relevant physics to obtain the required temporal resolution. These models are used to predict the observed properties of stars at different epochs and environments, to then study the properties of, e.g., exoplanets, galaxies, and the transient Universe. We briefly highlight two topical areas in this regard.

Interpretations of exoplanet observations

Missions such as TESS, CHEOPS, JWST and PLATO, together with the ELT, will push the limits of planet detection and characterisation. However, disentangling the planetary and stellar signals is often limited by our ability to accurately model the properties of the host star. The stellar component gives important context for the planetary studies, e.g. age estimates for the systems. Moreover, with the maturing of exoplanet atmosphere spectroscopy, comparing planetary atmospheric abundances with the surface composition of the host star is now a reality. This will provide powerful constraints on planet-formation models, but only assuming we are able to confidently recover a unique set of initial conditions from stellar and planetary models.

Observational cosmology

The tension between estimates of the Hubble constant (H_0) from the near and far Universe has survived intense scrutiny. The results can potentially be reconciled by invoking new physics in the standard (ΛCDM) cosmological model, but this extraordinary step would require remarkable trust in the measurements. Improving our knowledge of the stellar standard candles used in late-universe H_0 measurements, combined with better observations, will be critical to either reinforce or disprove the tension. A large sample of well-localised fast radio bursts can also help address this open problem.

Distances are notoriously difficult to estimate in astronomy, and stellar physics provides many useful distance indicators. Precision cosmography uses a distance ladder to measure distances up to the Hubble flow (where galaxy velocities are dominated by the cosmic expansion). The ladder's first rung and anchors are mostly based on stellar indicators such as eclipsing binaries, RR Lyrae, Cepheids, Miras, tip of the RGB, etc. Exquisite observations have led to distances with 1% or better statistical precision, but the underlying hypothesis of standard candles and their models need to be better than 1%. For instance, can all objects in a given class be reduced to a simple model? In other words, when calibrating a given distance indicator in the Milky Way, to what accuracy is this calibration valid in other galaxies (with e.g., different metallicities)? These effects require dedicated observational experiments and theoretical investigations.

These examples are not exhaustive, but they illustrate how observational advances can push stellar physics to be an ever more accurate tool. Data analysis and models that were designed and validated when the estimated precision was of order 10% cannot be readily applied to data with 1% precision. Future progress in this area will need to include:

- Strong connections between stellar physicists and the communities using their results.
- Careful calibration of the models used to derive stellar parameters (abundances, ages, masses, distances, etc) in future large surveys.
- Development of data-analysis techniques scalable to large surveys that also preserve the accuracy of the underlying models.

The Local Group as a laboratory for galaxy evolution

Resolved stellar populations are a powerful tool to study galaxy evolution. In particular, low-mass stars in galaxies are sufficiently long lived that they allow investigation of star-formation histories and evolution of their host systems over cosmic time. This 'galaxy archaeology' is an important complement to studies of (unresolved) galaxies at high redshift. The Milky Way provides us with an unrivalled opportunity to study the formation and history of a large spiral galaxy directly, and the vast dataset from the Gaia mission is now transforming our understanding of its structure and kinematics.

A vital complement to Gaia is ground-based spectroscopy to provide radial velocities (giving space velocities when combined with Gaia proper motions) and chemical abundances. The European astronomical community has invested significantly in new, high-multiplex facilities to provide the required spectroscopy (e.g., WEAVE, MOONS, 4MOST). When combined with the Gaia catalogues and precise ages from asteroseismology these will provide new insights into Galactic structure and its chemical evolution and past accretion history. A missing capability is the combination of high spectral resolution (R >40,000) combined with high multiplex (VLT-HRMOS), to provide detailed chemical abundances of a wide range of elements to fully disentangle the populations studied by Gaia.

Such Galactic archaeology requires determinations of stellar ages and chemical abundances to high precision to identify different stellar populations. To harness the full diagnostic power of the new spectroscopic surveys, as well as high-precision photometry from other facilities (e.g., VRO, TESS, PLATO), automatic reliable data analysis will be critical in the determination of fundamental parameters. Such analysis is also only as good as the stellar models available, reinforcing earlier comments on the continued need to improve our understanding of the internal structure and atmospheric properties of stars.

Within this topic, the identification of very low metallicity stars in the Galaxy provides a fascinating probe of early chemical enrichment. The lowest metallicity stars known display very weak absorption lines in their spectra, indicative of heavy element abundances much lower than the solar values, with iron abundances up to a million times lower in the most extreme examples. Models suggest these abundance patterns may reflect enrichment by a single supernova, providing a unique window into the early evolution of the Universe. To expand our understanding of these tantalising objects we need better sensitivity (e.g. CUBES) and larger samples (e.g., within the WEAVE and 4MOST surveys).

Looking to the future, key parts of the Milky Way (centre, plane) are inaccessible to the optical Gaia mission due to interstellar extinction. Future plans for the EVN could potentially use stellar masers to probe the dynamics of the inner Galaxy. Longer term, a near-IR mission similar to Gaia would provide the same precision astrometry and photometry to unlock the detailed dynamics and populations of these obscured regions (combined with near-IR spectroscopy from MOONS).

In parallel, we have already begun exploring the broad range of galaxies beyond the Milky Way, both in the Local Group (M31, M33, metal-poor dwarfs) and beyond. Such efforts are at the sensitivity limits of our capabilities, but new facilities such as the JWST and ELT will provide us with unrivalled insights into the stellar populations and histories of a diverse range of galaxies. For instance, the sensitivity and spatial resolution of the ELT-HARMONI spectrograph will provide spectroscopy of individual red-giant stars in galaxies at several Mpc, allowing evolved stellar populations to be investigated over a significantly greater range of physical conditions for the first time. Longer-term, a priority in galaxies at >1 Mpc is multi-object spectroscopy with the ELT in the visible (MOSAIC), to address the physical properties of massive stars, and the kinematics and chemical abundances of lower-mass evolved stars across the full spatial extent of their host systems.

Summary

Stellar astrophysics is a diverse and vibrant field, spanning studies of low-mass stars in the local neighbourhood, out to dramatic SNe and GRB explosions of high-mass stars at high redshift. It also underpins a broad swathe of studies in contemporary astronomy from exoplanets to the most distant galaxies at cosmic dawn.

Many of the large facilities under construction by European partners have been strongly influenced by cases from contemporary stellar astronomy. These include (but are not limited to) facilities such as the JWST, ELT, VRO, SKA and Athena, as well as new instruments on 4m telescopes (e.g., WEAVE, 4MOST), 8-10m telescopes (e.g., MOONS, CUBES), large interferometers (e.g., VLTI), and new, smaller observatories focussing on time-domain science (e.g. GOTO, BlackGEM).

The immediate priority of the community is to complete the construction of these exciting new facilities and instruments and then deliver on the broad range of stellar science that they will enable. Alongside this, there is a continued need for significant investment in theoretical models (and the relevant tools), laboratory astrophysics and machine-learning/data-mining techniques to be able to draw meaningful conclusions from the rich datasets ahead of us. We also need to continue to invest in existing facilities that have unique capabilities (e.g., ALMA, XMM-Newton, HST, Gaia, VLT/VLTI, GTC, WHT, TNG, LOFAR, EVN, LEAP) to ensure we have the multi-wavelength and multi-technique observations needed.

The large numbers of transient objects expected to be identified by facilities such as VRO and the GW observatories (and GR bursts etc.) will lead to increased demand for follow-up observations at all wavelengths, with both photometric and spectroscopic instruments. Effective follow-up will make use of the full range of telescope apertures; coordination to ensure optimum use of the available observing time will be a challenge.

Looking to the future there are exciting concepts in development that will provide important capabilities to address the topics outlined in this chapter. These include further development of 8-10m class telescopes (e.g., GRAVITY+, BlueMUSE, HRMOS), new spectroscopic survey facilities (e.g., wider European participation in a project such as MSE), a large single-dish sub-mm facility (e.g., AtLAST), and an ambitious new UV/visible/IR space observatory (LUVOIR).

These electromagnetic-oriented facilities, supported with the necessary theoretical and lab work, will allow Europe to keep its leadership in stellar astrophysics. At the same time, the existing bridges between EM, multi-messenger and GW astrophysics need to be strengthened, and even integrated, if we are to grasp the full nature of the evolution of stars and of their end products. In that context, efforts to secure the funding and start the construction of a next-generation, large-scale GW observatory under European leadership should be considered as an additional high priority goal for the decade to come.

E

Formation and evolution of planetary systems

The search for other worlds has been a major driver of astronomy and science throughout history. The first attempts for finding distant planetary systems coincided with the empirical realisation that our Sun was one among many others within a vast universe, which became a proven fact in the XIXth century. Planets emit very little light on their own, making their detection in the glare of their host star's light a fabulously challenging task that has only become possible in the last decades.

First clear evidence of exoplanets was found in the 1990s, including planets around pulsars and gas giants orbiting Sun-like stars. The discovery of 51 Peg by the Swiss Astronomers Michel Mayor and Didier Queloz in 1995 is considered the beginning of modern exoplanetary science, and it was recognised by the 2019 Nobel Prize in Physics. This milestone discovery was achieved using the radial velocity method, i.e., by observing the motion of a star (the Doppler effect) caused by a planet orbiting it. These initial discoveries were quickly followed by the first multi-planet systems (1998), and first planets in the Neptune mass regime in the early 2000s. The detection of the first potentially rocky planets (super-Earths), including many of them in compact multi-planet systems, were also found before 2010 using the same technique.

The other very successful technique is the transit method, which detects small dips in the stellar light due to a planet passing in front of the star. The first transiting planet was found using small telescopes from the ground in 2000 (HD 209458), and was followed by the birth of large ground-based surveys, which were mostly sensitive to close-in giant planets (hot Jupiters) and detected hundreds of them. Space-based photometry missions were also conceived in the early 2000s, and CNES/ESA CoRoT was the first mission to discover a rocky planet. Arguably the second revolution in exoplanet studies was prompted by the NASA mission Kepler (2009-2014), which brought the number of detected planet candidates from a few hundreds to the current 5000+ exoplanet candidates.

Steady technological advances in Adaptive Optics, high contrast imaging and infrared detectors, in which Europe played a leading role, enabled the first images of planetary mass companions (2004), which typically consist of young gas giants that are self luminous at infrared wavelengths due to latent heat from their formation. Other complementary techniques sensitive to other regions of parameter space also developed in the last two decades such as gravitational microlensing, which requires a coordinated network of small telescopes around the globe. Since 2014, the ESA mission Gaia has been collecting precise astrometric measurements and will have detected almost all Jupiter-like analogues (several thousands to tens of thousands) within 100 light-years from the Sun in its forthcoming final data release, expected in 2023.

Initial tensions between observed populations of exoplanets and planet formation concepts has led to intensive development of the main theories, namely the core accretion, and gravitational instability mechanisms. Both approaches underwent major revisions to incorporate new processes such as migration and turbulent mixing in the protoplanetary disk to explain the observations. For the last decade, the very early stages of planet formation have been and continue to be directly probed by ALMA (submm/radio wavelengths), and by using high contrast near infrared & optical imaging systems at 10m class telescopes, spearheaded by cutting edge instrumentation operating at the European Southern Observatory (ESO).

The fate of planetary systems at the end of life of stars has also been investigated via radial velocity searches for red giant stars, and observation of stellar remnants such as white dwarfs. Spectroscopic studies of contaminated white dwarf atmospheres enable inferring the composition of rocky materials in planetary systems, and the 2015 milestone discovery of a disintegrating exo-asteroid orbiting a white dwarf has ushered in a new era of detections.

The conditions on some gas-giant exoplanets (both transiting and directly imaged) are such that their atmospheres can be detected and characterised, which has led to great successes using both space-based (Hubble Space Telescope/NASA+ESA, Spitzer/NASA) and ground-based telescopes (ESO/VLT, Gemini, Keck, Carmenes), leading to atomic, ionic, and molecular detections, inference of clouds and hazes, temperature structures, winds, spin-rotation and global circulation patterns. Due to the high contrast between the light coming from a planet and its host star, the challenge of characterising the atmosphere of small terrestrial planets is extreme for those orbiting Sun-like stars. However, the situation is much more favourable for small stars (so called red dwarfs). Searches optimised for red dwarfs have led to an explosion of detections of warm-to-temperate terrestrial worlds such as Proxima b, c and d (the nearest exoplanets to the Solar System) and the seven terrestrial worlds of TRAPPIST-1. The discoveries of both systems originated within Europe's astronomical ecosystem.

As the landscape of discovered planetary systems expands, new questions emerge and theories and sub-specialties keep developing every year. The number and variety of planetary systems, and the multidisciplinary nature of this science anticipates a bright future of discoveries. In this chapter, this exciting field is divided into four routes, each guided by overarching questions, both from the current and prospective points of view. These four questions are:

Planet Formation: How do planets and planetary systems form?

Discoveries & Demographics: What is the diversity of planets and planetary system architectures? How does the Solar System fit in?

Planet Characterization: What are planets made of? Can we understand the atmospheric and geological processes? Can we find evidence for biological activity?

Evolution and fate: What is the evolution and ultimate fate of planetary systems?

Status of the field

Planet formation

Planets form in protoplanetary disks around young, accreting stars (see chapter on Formation and Evolution of Stars). These disks are 99% composed of gas with the rest being solids. These solids are the seeds of planets, both terrestrial planets and the cores of gas giants, making them particularly important - even though disk evolution itself is controlled by the gas.

Figure 1 summarises the two main pathways for the formation of planetary systems that are currently extensively studied. First, the top-down scenario (gravitational instability) possibly occurs at early stages when the protoplanetary disk is massive and warm. This theory is well suited to explain the formation of massive giant planets at large distances from their host star, where they have been linked to spiral-like structures in the protoplanetary disk seen in sub-mm interferometric data. However, the formation of core-dominated planets has not been convincingly explained in this model. The second pathway, the bottom-up scenario (nucleated instability of core accretion model), is favoured for core-dominated planets, as well as gas giant planets close to their host star (up to ~20 AU), like those in our Solar System. It involves a number of distinct processes that turn initially sub-micron sized dust grains into bigger bodies, such as pebbles (centimetre in size), planetesimals (kilometre in size), and planetary embryos (~1000 km in size). Sub-micrometer sized grains first grow through mutual collisions (sticking) to pebbles at which point gas drag sets in and the pebbles start to drift with respect to disk gas towards the star, enhancing the growth rate. Planetesimals, and planetary embryos, are thought to form from pebbles by the streaming instability.

Once a planetary embryo has been formed, it can grow by continuous accretion of pebbles, or by accretion of planetesimals (or both). The importance of these two modes of accretion (pebbles or planetesimals) depends on the efficiency of the conversion of pebbles to planetesimals by the streaming instability. Along its growth, a planetary embryo accretes gas. If the embryo remains smaller than a few Earth masses, the amount of captured gas is very limited, and the planet is thought to become a terrestrial or super-Earth type planet. If the embryo can grow further by solid accretion (to a mass larger than ~10 M_{Earth}), the amount of captured gas suddenly largely increases, building a gas giant without the need of invoking gravitational instabilities. For planets in between, it is believed that the final outcome will look similar to ice giants in the solar system, although - despite the large effort put into solving this problem - the formation of this kind of planets is still not well understood. To date, however, there is only one circumstellar disk, the PDS 70 system, in which direct observational evidence has been found of forming planets in a large disk cavity. The presence of material accreting from the disk to the forming planets, the so-called "circumplanetary disk" has been observed at sub-mm infrared and optical wavelengths, setting constraints on the physics of accretion of giant planets and potential formation of exomoons.

Protoplanetary disks have been recently renamed "planet-forming" or "planet-hosting" disks, as observations have revealed indirect signatures of already formed planets embedded in the disk. Sub-mm interferometric observations of mm-sized dust emission have revealed a plethora of substructures, such as rings and gaps, as well as spirals, in basically all disks when observed at high enough angular resolution (see Fig. 1). Rings and gaps may be possibly carved by protoplanets or planetary cores formed according to the bottom-up scenario, while spirals may be a sign of disk gravitational instability, as in the top-down scenario. It is, however, also possible that these features result from other causes that are not related to planets, such as so-called dead zones, which are zones of reduced turbulence and little to no radial mass transport. Similar features are also found in scattered light images in the optical and infrared, which reveal the properties of smaller dust grains in the disk's upper layers. Furthermore, detailed observations of simple molecules, such as CO, have revealed perturbations of the typical Keplerian disk rotation, which would be due to the presence of massive protoplanets in the disk. Finally, recent studies of the disk molecular content, focusing on molecules more complex than CO such as e.g. simple hydrocarbons, have started to link the chemical properties of the disk gas with the composition of the atmosphere of gaseous exoplanets.

Another angle from which planet-forming disks are investigated is by studying the dust components. The composition of these dust particles can be assessed by

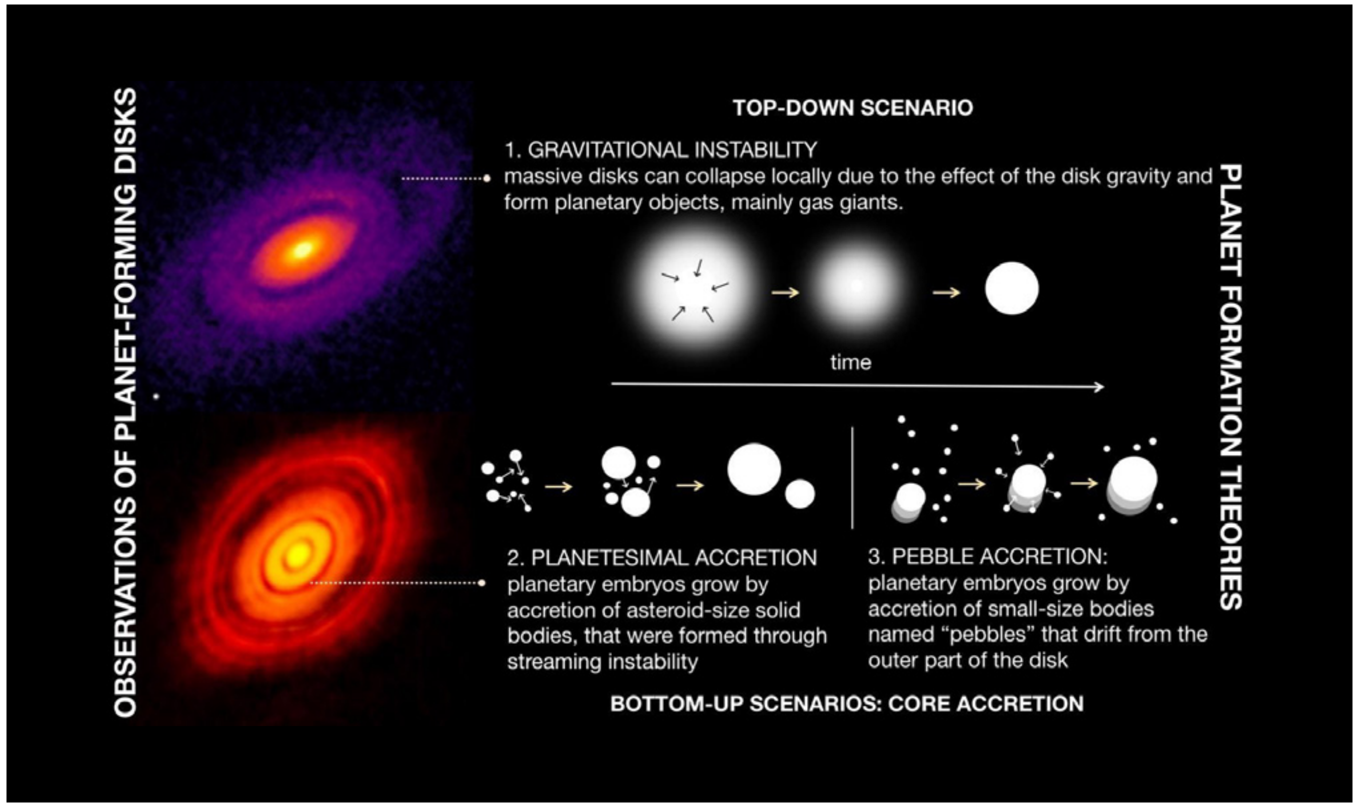

Figure 1

Schematic overview of the main planet formation pathways.

The two ALMA images are of Elias 2-27 (upper image, Andrews et al. 2018, ApJ 869, L41) and HL Tau (lower image, ALMA partnership, 2015, ApJL 808, L3)

observations in distant planet-forming disks and, by analogy, by analysis of dust from the Solar protoplanetary disk. Examining interplanetary dust collected on Earth that has not (or minimally) been altered since its formation provides important information for the formation of planetary systems. In particular, some interplanetary dust particles collected on Earth have a very probable cometary origin: the chondritic-porous interplanetary dust particles (CP-IDPs) collected in the stratosphere and the ultra carbonaceous Antarctic micrometeorites (UCAMMs) recovered from Antarctic snow. Information gathered from CP-IDPs and UCAMMs suggests that building blocks of dust are made of amorphous silicates dubbed as “GEMS” (Glass with Embedded Metals and Sulfides). Whether GEMS were directly inherited from the presolar cloud that formed the solar system, or formed early in the solar nebula, is still debated. Remote sensing observations of dust particles in distant planet-forming disks (Spitzer, MIDI-VLTI), suggest that the relative abundance of the dominant minerals in the dust (olivine-pyroxene-amorphous silicate) change as a function of the distance from the central star. These mineralogical gradients are not well constrained nor understood, but could influence the final composition of planets in stellar systems. Analyses from CP-IDPs and UCAMMs suggest a predominance of amorphous minerals and crystalline pyroxenes in the outer regions of the solar protoplanetary disk. Analyses of cometary dust (e.g. returned by the Stardust space mission) also suggest early and large-scale dust mixing mechanisms between the inner and the outer regions of the Solar planet-forming disk. Observations with JWST of distant planet-forming disks will help understanding these mineral distributions. Laboratory equipment such as sophisticated high-vacuum facilities coupled to particle physics and laser diagnostics are also complementary to astronomical observations, for instance to investigate the role of grain surfaces in astrophysical conditions to promote molecular complexity from interstellar dark clouds to planet-forming disks. Laboratory spectroscopic studies of stable and reactive molecules and molecular ions, laboratory kinetic and dynamics studies over an extended range of temperature conditions also allow to constrain the chemical mechanisms at work in the planet-forming disks.

Finally, planets that we observe today may not only be the result of isolated planet formation, as external processes (e.g., photoevaporation, strong interstellar UV radiation, and stellar encounters) may strongly affect disk evolution. At the same time, the long term evolution of the planetary system is crucial for setting the properties of planets observed today. Work in the last two decades, in particular in the framework of the Nice and Grand Tack models, has shown that the solar system likely suffered from strong dynamical rearrangement after its formation, including migration within the protoplanetary disk and gravitational scattering during and after its dissipation. Whether these models are correct or not is still debated, but it seems clear that migration, scattering and tidal interactions are prevalent, important processes in extrasolar systems.

Understanding the present demographics and properties of planets (inside or outside the Solar System) at different levels (composition, habitability, etc...) also requires the understanding of planet formation and evolution at the level of multi-planetary systems (as opposed to single planet level), incorporating the effects of multiple planets, disk-planet interplay and host star interactions, which may cause significant planetary evolution even after the dispersal of the protoplanetary disk through atmospheric erosion by high-energy (X-ray to UV) photons or energetic particles (stellar wind, flares) from the host star. The next section gives an overview of the present status of exoplanetary demographics, highlighting the most recent discoveries in terms of planetary properties.

Exoplanet Discoveries and Demographics

The observed orbital and physical properties of known exoplanetary systems (see Figure 2) underline the astonishing variety of outcomes of planet formation and evolution processes. Studying trends and correlations in exoplanet population statistics, i.e. exoplanet demographics, is key to the development of observationally-constrained formation and evolution models. Exoplanet demographics is allowing us today to begin addressing key open questions in exoplanetary sciences, such as: What is the dependence of exoplanet formation on the natal environment and host star? What are the mechanisms and timescales for planet formation and migration? What drives the evolution and diversity in the resulting exoplanet systems? How do we classify subpopulations of planets, such as super-Earths and warm Neptunes? How are planetary properties related in the same system? Which are the favourable conditions and architectures for the formation of telluric planets capable of sustaining life?

The discovery of thousands of exoplanets in the past quarter century has been achieved thanks to a portfolio of observational techniques (both from the ground and in space, at visible and near-infrared wavelengths) that unveil their presence based on 1) the gravitational pull on the parent stars along the line-of-sight or in the plane of the sky, i.e. radial velocity, and astrometry, 2) transits that thanks to the peculiar system geometry create periodic drops in apparent stellar flux, 3) gravitational light deflection effects through microlensing, and 4) direct imaging - angularly resolving photons emitted by the planets.

The multitude of discoveries over the past two decades suggest that:

a) Most stars have planets. Particularly abundant are planets with masses and radii between that of the Earth and Neptune. These super-Earths and sub-Neptunes have no counterpart in our Solar System;

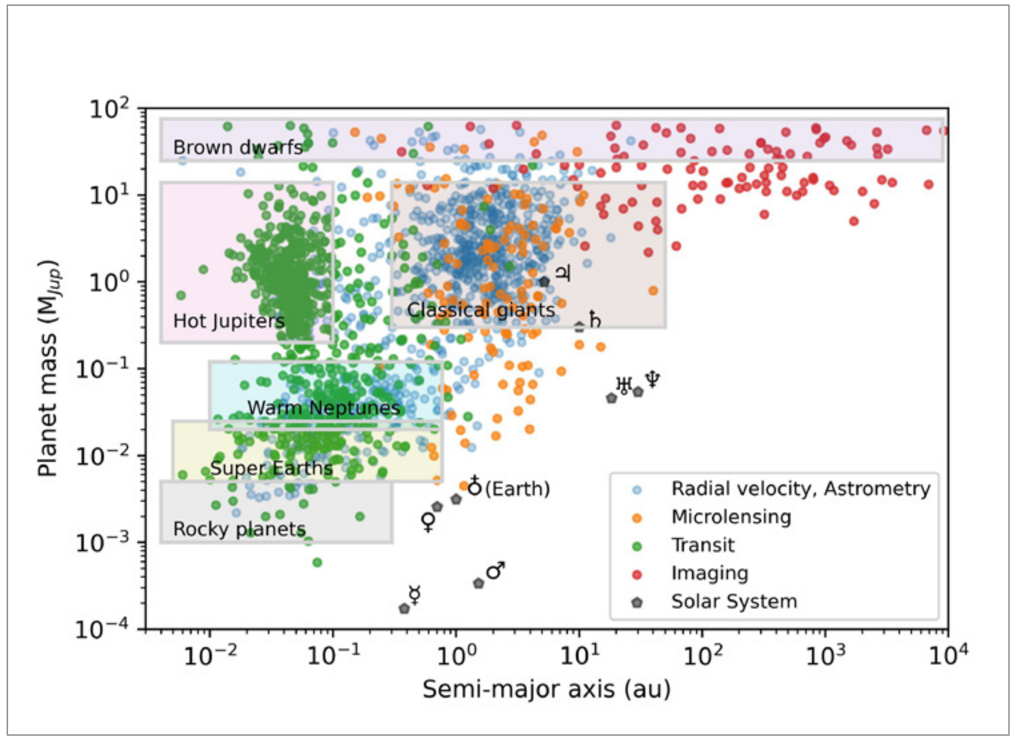

Figure 2

Exoplanets (and brown dwarf companions) discoveries considering the different planet hunting techniques (from http://exoplanet.eu). The exoplanets masses are reported as a function of their distances (with minimum masses for the radial velocity method). The different categories of exoplanets are reported including the rocky planets, super-Earths, warm Neptunes, Hot Jupiter and classical giants. The brown dwarf companions are also reported as both populations probably overlap although a typical limit at 20 - 30 Jupiter masses is generally adopted given the observed companion mass distribution to stars.

b) Gas giants are found both on very short-period orbits (hot Jupiters) as well at distances of hundreds of au;

c) Multiple-planet systems are common, particularly those in dynamically packed configurations of close-in, small planets;

d) Occurrence rates of planets of different mass and radius correlate with the properties of the parent stars (mass, chemical composition).

e) The size distribution of strongly irradiated, small planets is bimodal and shows a gap in radius, potentially sculpted by evaporation processes;

Great progress has been made in our understanding of planetary systems in close orbits (<5 au) with radial velocity programs, transit surveys, and microlensing surveys, and at larger orbital separations (>10 au) with direct imaging surveys. Nevertheless, significant progress is still required to obtain a complete picture of the formation, evolution and diversity of exoplanetary systems. Our current vision of the exoplanet demographics is largely incomplete given the limited sensitivity of today's observing techniques. For instance, only very poor knowledge exists on the occurrence of Solar-System analogs (i.e. architectures with inner rocky planets in the stellar temperate zone, outer giant companions, asteroid belts, and cometary reservoirs; see Figure 2). Fortunately, the tide is about to turn. Convergent measurements from space- and ground-based observational programs (both existing and coming online in the next decade) will sample the full planet parameter space, providing a robust foundation to guide the important planet formation and evolution topics.

Exoplanet Characterization

The discoveries of numerous exoplanets provide unique opportunities to learn more about these distant worlds. What are the bulk compositions of exoplanets, and can we link them to their formation and evolution? Do they have atmospheres, and if so, what gases are present? Are they water-rich or water-poor? What are their climates like? Which aspects of their atmospheric physics and chemistry do and don't we understand, and can we possibly connect them to geological processes? How common are temperate rocky planets, like Earth? In what ways are they similar to our home planet? Could they be habitable? Do we see any signs of extraterrestrial biological activity? Are we alone? Although humanity is far from being able to visit these distant worlds, characterising exoplanets will put ourselves, the Earth, and the Solar System in context of other planetary systems in the Milky Way.

Characterisation of the bulk properties of planets can be performed by combining mass and radius measurements to derive their bulk densities. Such measurements have now been performed for a number of planets, and we have discovered that diversity is, here also, the rule, with possibly very different bulk composition for planets of similar mass. Planet compositions can also be probed by measuring the composition of planetary remnants accreted by white dwarfs (see below section on Late-stage evolution and fate of planetary systems).

Atmospheric characterization requires detecting light from the planets themselves. This light has to be filtered out from that of the thousands, millions, or even billions of times brighter light from the star. Two families of techniques can achieve this: The first technique utilises transits and eclipses. If the orbit is fortuitously oriented, an exoplanet moves repeatedly in front of its host star. While part of the starlight is blocked by the planet, a small amount filters through the planet's atmosphere leaving an imprint of absorption and scattering processes – which can reveal a lot about the atmospheric conditions. Half an orbit later, the planet is eclipsed by the star, allowing the measurement of reflected light and/or intrinsic thermal emission - which can also be observed to change during the rest of the orbit when varying parts of a planet's day- and nightside rotate into view (the so-called phase curve). These techniques work best for warm, close-in planets, such as hot Jupiters. The second family of techniques involves high-contrast imaging or interferometry, where the planet is angularly separated from the much brighter host star. This works best for young planets, which are still warm from their formation processes, on wide orbits.

In particular for hot Jupiters and young gas giants, we can now characterise many aspects of atmospheres and planet internal structure (Fig. 3). From their densities, it is clear that they consist largely of hydrogen/helium gas with possibly small rocky cores, with the hottest and most close-in planets appearing extra puffed up. As expected from chemical models, their spectra are dominated by molecular species such as water, methane, and carbon monoxide, while some of the hottest planets show traces of iron and other metals. Others exhibit enigmatic, evaporating atmospheres of hydrogen and helium gas. The somewhat cooler planets increasingly show evidence for clouds and hazes – sometimes partially masking other atmospheric species. Careful monitoring of the spectra of both hot Jupiters and young gas giants reveal fascinating atmospheric features, such as day to night-side temperature variations, changes in cloud coverage, atmospheric winds and planet spin.

Atmospheric characterization of significantly smaller and cooler planets is still largely outside the realm of current instrumentation, but their mean densities suggest a very heterogeneous population ranging from gas-dominated mini-Neptunes, to possibly water-worlds and planets with a largely rocky composition, but unique solutions in composition for individual planets are not yet possible. It is clear that the planets in our own Solar System just form a small subset of the wildly diverse exoplanet population in the Milky Way and beyond.

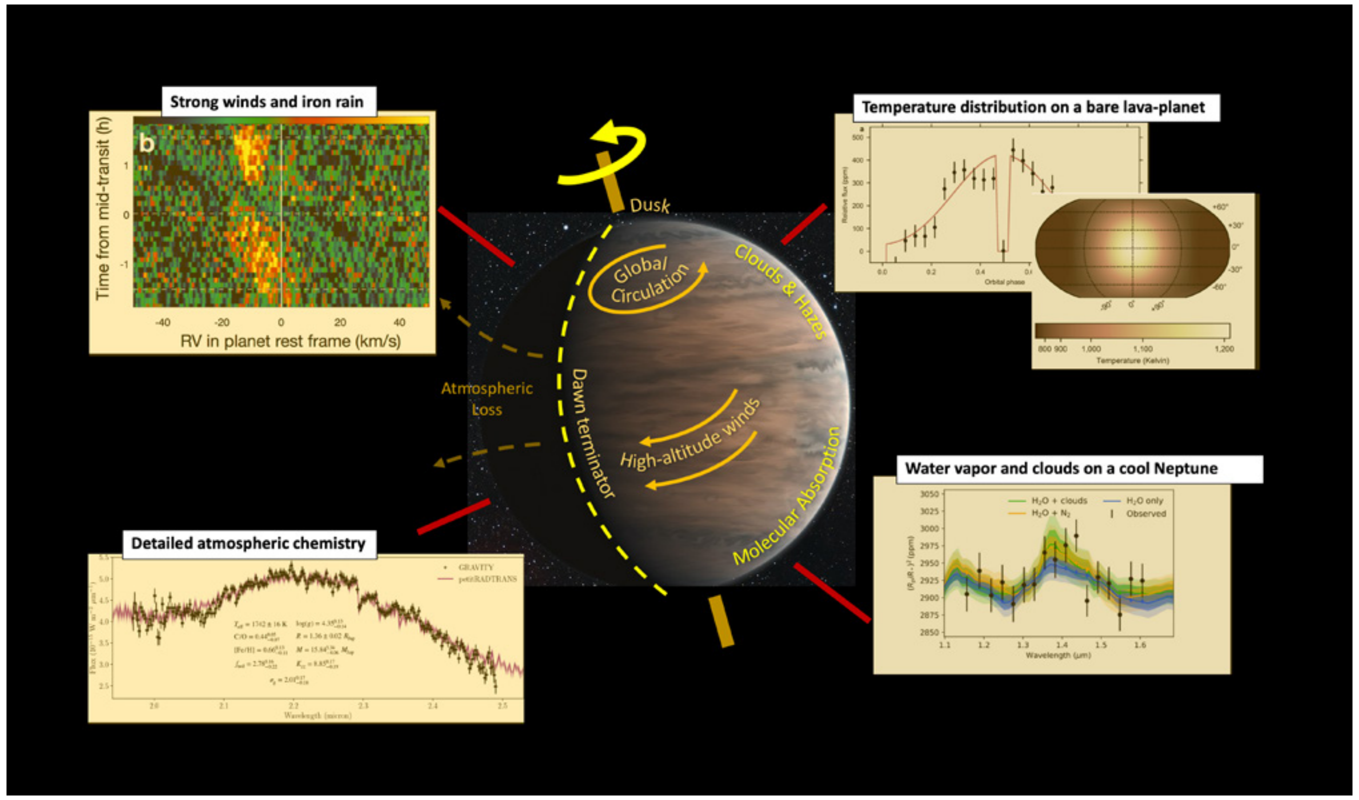

Figure 3

Schematic overview of different types of observations of exoplanet atmospheres.

Credits: Ehrenreich et al.; Kreidberg et al.;Tsiaras et al.; Nowak - GRAVITY Collaboration.

Late-stage evolution and fate of planetary systems

Another interesting aspect of planetary systems is their late stage evolution and fate (Figure 4). When a star evolves off of the main sequence after exhausting its core hydrogen and becomes a giant, it will expand by a factor of hundreds, eject half of its mass, and increase its luminosity by a thousand-fold. This violent environment inflates gaseous planets, spins up asteroids to destruction, and enlarges debris disks. Over 100 planets have so far been discovered around sub-giant and giant stars with the Doppler radial velocity technique. The architectures of these systems reveal aspects about tidal dynamics between the giant stars and planets and help link planet formation demographics to host stellar mass.

Subsequent to shedding its outer layers, a giant star will become a dense remnant known as a white dwarf. Enough of the surviving planetary debris will be perturbed onto the star such that this debris is detectable in 25-50% of all observable white dwarfs. Because of the unique properties of white dwarf atmospheres, the chemical composition of the planetary debris can be discerned; so far, 22 different chemical elements have been detected. These measurements reveal that these exoplanetary bodies are primarily dry and rocky, although they are occasionally able to sequester water ice. The relative abundances of elements are used to quantify the extent of the differentiation in the debris progenitors according to crustal, mantle and core mass fractions.

These exclusive insights into exoplanetary chemistry are accompanied by photometric transit observations of minor planets breaking up around at least 7 different white dwarfs, spectroscopic detections of a planetary core orbiting SDSS J1228+1040, an ice giant planet evaporating around WD J0914+1914, a giant planet transiting WD 1856+534, and a microlensing discovery of a Jupiter analog orbiting white dwarf MOA-2010-BLG-477L. Further, infrared excesses on spectral energy distributions have revealed the presence of over 60 dusty disks orbiting white dwarfs; 20% of these have detectable gas, and link the destruction of asteroids to the deposition of debris onto these stars. Variability in these planetary debris disks on yearly and decadal timescales indicate ongoing dynamical activity which has yet to be explained by theoretical and numerical modelling efforts.

The coming decade

Planet formation

Demonstrating which features of protoplanetary disks trace ongoing planet formation, where and how planets grow, and their early evolution, will be the most important goals during the next decade. Specifically, these tasks range from the relevance of snow lines for planetesimal growth to the origin of spirals and gaps, i.e., identifying those disk features that unambiguously signal planet formation, from the discovery and characterization of the youngest planets that are still embedded in their natal disk, to the planetary accretion history.

ALMA is playing a transformational role in this context, and it is expected to continue producing breakthroughs in the coming decade. The dust and gas composition of protoplanetary disks needs to be better characterised to probe the conditions in which planets form and their early evolution, in addition to better match the endpoint of stellar formation. Particularly relevant will be a better understanding of the disk size distribution, both in disk height and disk radius, which requires high-spatial resolution observations over a range of wavelengths. Pioneered by HST observations, it is expected that the James Webb Space Telescope (JWST) and ground-based facilities such as SPHERE, MUSE, ERIS, and possibly MAVIS at ESO with their extreme Adaptive Optics (AO) systems and complementary wavelength ranges continue to deliver the much needed results for the dust composition of protoplanetary disks.

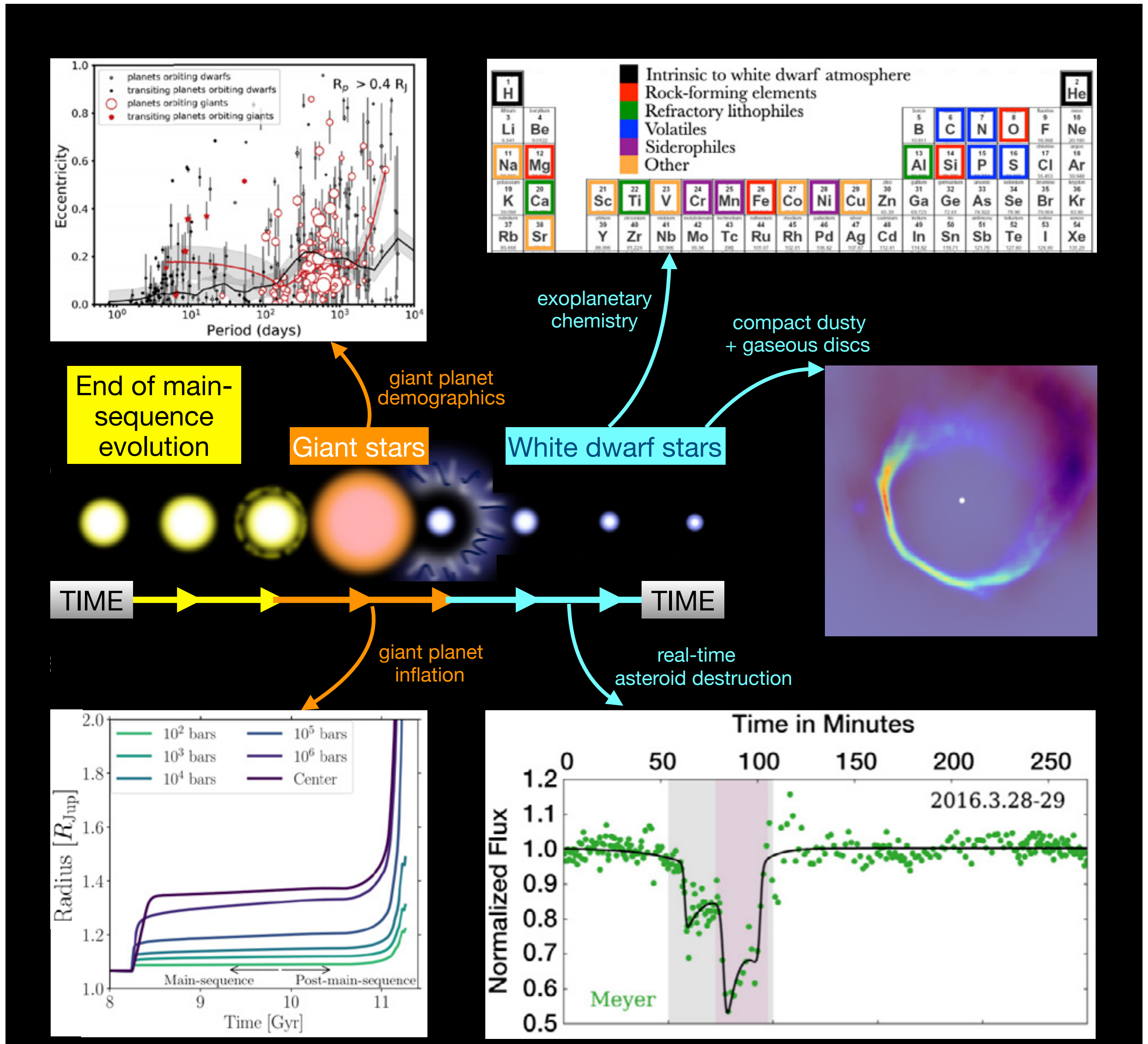

Image credits: Grunblatt et al. 2018, ApJL, 861, L5; Komacek et al. 2020, ApJ, 893, 36; Xu et al. 2019, AJ, 157, 255; Christopher Manser, PhD Thesis p. 145

Figure 4

Late stage evolution and fate of planetary systems.

Deep gas observations of disks with ALMA, will allow us to probe the radial extent of the gaseous disks, which is the fundamental parameter for constraining disk evolution theories. Characterization of dust from the outer regions of the solar protoplanetary disk can be achieved through laboratory analyses of primitive dust collected in the stratosphere and in Antarctica. Space missions like Comet-Interceptor will also bring more constraints on the composition of cometary dust.

Probing the chemistry within protoplanetary disks will be tackled by combined efforts with ALMA and the JWST (MIRI). With complementary measurements of the host star's high energy radiation field (XMM-Newton, Chandra, and HST UV observations), we can probe an unprecedented range of physical conditions to build a coherent census of abundance gradients or peaks, which can then be compared to the ever growing library of exoplanet compositions. Such studies will also allow us to understand whether the disk chemistry is inherited from the parent cloud or if it was reset when the disk formed, and which are the different implications for planet formation.

Ground-based observatories are now reaching spatial scales that allow us to probe disk substructure at scales of a few AU around fainter stars. In the coming decade, facilities such as ESO SPHERE (upgraded), GRAVITY+, MATISSE, MUSE and ERIS will follow the (orbital motion of) disk features, which is key to understanding where they originate in the disk, i.e., if they, and under which conditions, trace ongoing planet formation. When combined with ALMA data, the vertical structure of spirals may be studied to improve our understanding of the conditions in which planets form. Furthermore, high-spectral resolution ALMA gas observations will allow the detection of perturbations of the disk Keplerian rotation that would hint to the presence of embedded planets.

With the first accreting planet having been discovered in a rather evolved architecture, the coming decade will see an intensive hunt for the youngest gas-giant planets, which are still embedded in their disk. ESO's MUSE and ERIS, with their ability to spatially and spectrally resolve such young planets, will be work horses for this direct search and characterization, but other methods like transit (TESS, VRO), astrometry (Gaia), radial velocity (ESO CRIRES+, NIRPS), may play an important role too, if the impact of stellar activity and circumstellar environment can be overcome. Such observational endeavours are important to explore the early phases of planetary formation and evolution of giant planets, their interaction with their environment (host star, disk, and other forming planets) leading to the exoplanet demographics which is observed or which will be observed in more evolved systems.

The ELT will image and spectrally characterise the inner disk planetary regions, thanks to MICADO, HARMONI and METIS. METIS in particular will revolutionise the field of planet formation thanks to its excellent angular and spectral resolution at mid-infrared wavelengths. "Planetary regions" at radii smaller than 30 AU for disks in the closest star-forming regions (around 150 pc) will be directly imaged allowing us to characterise the composition and the spatial and kinematic distribution of gas and dust in the planet-forming zone, but also directly image the formation of giant planets. Furthermore, the mid-infrared also enables the study of solid state features of different materials, which will inform us about the chemical origin of planets.

Additionally, laboratory experiments are essential to understand and interpret astronomical observations of gas and dust. Such experiments can probe the microphysics of how particles stick together under the different conditions encountered in protoplanetary disks (i.e., how ice mantels affect stickiness, what collision velocities are tolerable), the formation and evolution of dust in the radiative environment of planet-forming disks, chemical reactions in the gas phase and between gas and dust, the behaviour of dust-ice mixtures when they sublimate (reminiscent of what happens when drifting pebbles cross the iceline), the optical properties (including polarimetry) of dust-ice mixture, etc. These experiments are performed both in individual laboratories (e.g. plasma chamber, irradiation platforms) and in large facilities such as synchrotron beamlines (e.g., SOLEIL, ESRF, DESY) and medium to high energy ion accelerators (GANIL, GSI, CERN).

A large effort aiming at developing 3D numerical simulations considering not only hydrodynamics, but also gas-solid interactions at various scales, the role of magnetic fields, etc., is also required. These simulations are mandatory in order to transform astronomical observations and laboratory experiments into an understanding of the physics of protoplanetary disks, the natal environment of planetary systems. The observations discussed in this section, combined with relevant numerical models, are expected to provide solid grounds for planetary system formation models in the frameworks of the pathways described in Fig. 1.

Planet discoveries and demographics

Two main research lines at the frontier of exoplanet discovery are expected to see dramatic improvements over the next decade: 1) a systematic exploration of the young/old giant planet demographics at all separations, and 2) the search for true Earth analogs and Solar System-like architectures.

Historic RV surveys (with e.g., ANDES, HARPS, HARPS-N) of thousands of bright main-sequence dwarfs in the Solar neighbourhood will reach up to >30 years of data collection, achieving sensitivity for gas giants at Saturn-like distances (at about 10 AU). Inferences on the occurrence rates of giant planetary companions on 3-20 AU orbits (beyond the snowline, where the bulk of planet formation is expected to happen) will be put on solid statistical grounds combining ground-based Doppler spectroscopy with high-precision space-based global astrometry from ESA's Gaia mission (particularly in the case of a full mission extension thus reaching 10-yr duration). Gaia will achieve a sensitivity down to Jupiter-mass planets in a regime up to 10 AU around possibly 10^6 stars (and even Saturn-mass planets for the closest systems). At the same time, the new instrumental upgrades of planet imagers (ERIS, SPHERE at VLT) and interferometers (GRAVITY+ at VLTI), followed by the first generation of high-contrast imaging instruments on the European ELT (HARMONI, MICADO, and METIS) will enable surveys that are sensitive to similar separations, and their improved sensitivity will probe the population of young Jupiters around young, nearby stars. The overlap between the techniques will be extremely powerful to constrain the physical properties of young, giant planets (mass, luminosity, orbital properties, atmospheres - see below paragraph on Exoplanet Characterisation).

Space-based observations with JWST with NIRCAM/NIRISS/MIRI, although limited in spatial resolution, will push current sensitivities further down to young Saturn-mass planets in the outer region of young, planetary systems beyond 20-40 AU. For the nearest (< 10pc) M dwarfs, JWST/MIRI and ELT/METIS might actually even image (and characterise) a handful of cold (<500K) giant planets and even a few telluric planets owing to the favourable star/planet contrast in mid-infrared wavelengths. Our understanding of the cold giant planet population (in terms of compositional diversity) might come from detections of long-period transiting companions based on data from the CHEOPS, PLATO, and extended TESS missions. This will be complemented with the advent of the NGRST telescope, and its coronagraphic imaging capabilities to explore the properties of giant planets in reflected light, offering a path forward to future technologies for more ambitious space missions like LUVOIR or Habex (see below). The synergy offered by the data combination coming from multiple techniques will become inexorable for a systematic investigation of the global giant planet demographics at all separations around stars of all spectral types, ages, and chemical compositions, bringing in additional knowledge on the correlation between planetary internal structures inside multi-planetary systems. This will offer the incredible opportunity to constrain today's theories of formation and evolution of giant planets, and explore their role in shaping planetary architectures including the ones favourable for the formation of telluric planets able to sustain life.

The suite of new-generation radial velocity instruments for precision (~1 m/s) measurements at near-infrared wavelengths (e.g., SPIROU, NIRPS, CARMENES) and extreme precision (10-20 cm/s or better) in the visible (e.g, ESPRESSO, EXPRES, HARPS3) now starting, and coming online in the next few years, will push the exploration of the demographics of low-mass planets (super-Earths and sub-Neptunes) away from the regime of strongly irradiated systems into that of intermediate separations. In particular, near-infrared radial velocities will allow completing the census of temperate rocky planets around nearby M dwarfs. Temperate, low-mass super-Earths and sub-Neptunes will be uncovered by extreme precision radial velocities around the nearest G and K dwarfs, out to separations of ~1 AU. Towards the end of the decade, the PLATO mission will identify transiting Earth-radius planetary candidates in the temperate zone of bright solar-type and solar-like stars, and determine system ages, amenable for dynamical mass determination by radial velocity. All the low-mass planet systems in the solar neighbourhood discovered by the new generation of radial velocity programs will have been screened for outer giant planets by Gaia astrometry, VLT/ELT ground-based planet imagers, and space missions like JWST and NGRST. The NGRST microlensing survey is for instance expected to carry out the systematic exploration of the demographics of Earth-mass planets beyond typically 1 AU in the galaxy complementing transiting space missions TESS & PLATO, and the extreme precision radial velocities surveys. We can therefore expect that by the end of the decade a more meaningful statement on the prevalence of Solar-System like architectures will be made, as a crucial piece of observational evidence for comparison with theoretical modelling.

In parallel to the observational effort, theoretical work is required in order to advance the modelling of the main physical processes at work in planet formation. Comparing results of future generation planet formation models with populations of planets in all parts of the parameter space will allow disentangling the contribution of the different planet formation pathways outlined in Fig. 1.

Exoplanet characterisation

The field has been eagerly awaiting the launch of the JWST. With more than six times the collecting area of the HST, its significantly larger wavelength coverage including the thermal infrared, and its stable location at Lagrange Point 2, it will revolutionise transit and eclipse spectroscopy. For the first time, exoplanet atmospheres will be studied over a wide range of mass, temperature, and composition. JWST with NIRISS, NIRSpec and MIRI, will investigate the enigmatically diverse class of super-Earths and mini-Neptunes to provide the important clues required to understand their formation and evolution. Moreover, for the most favourable systems around the smallest nearby dwarf stars, atmospheric studies can be pushed even to temperate rocky planets – in particular those around TRAPPIST-1 – to reveal whether they have atmospheres, and if so, what they are primarily made of. This is a first step towards assessing their habitability. In addition, evidence of star-planet interactions and planet magnetic fields – another important ingredient of planet habitability – may come from low-frequency radio telescopes such as LOFAR, SKA and others or from X-ray to UV observations (e.g., XMM-Newton, HST). To acquire a true understanding of atmospheric physics and chemistry, including potential biomarkers, and links to formation and evolution, it is also vital to study large samples of exoplanets under varying conditions, which includes the (high-energy) radiation environment that the planets experience. Such large samples are crucial to extract statistical trends – ESA's ARIEL mission will conduct such studies for gaseous planets.

While transit and eclipse spectroscopy is most accessible for planets in close-in orbits, high-contrast imaging relies on the apparent separation between a planet and its host star, with observational limits governed by telescope diameter and the wavelength of light. An additional challenge is that planet light needs to be recovered from the glare of the much brighter starlight, and that ground-based telescopes need to compensate for turbulence in the Earth atmosphere to reach their theoretical limits. While technically very demanding, the rewards are high. With its diameter of 39 metres, the reach of the ELT will be unprecedented and unrivalled. Its first generation instruments (MICADO, HARMONI and METIS) will offer the opportunity of a systematic characterization of the physics of young, giant planets located down to the snowline (~2 AU). In addition to their atmospheric properties (temperature, composition, clouds, accretion rate, etc.), the synergy with indirect techniques such as astrometry with Gaia and RV will allow to explore the mass - luminosity relation, and further constrain their processes of formation (See Planet-Formation Section). At mid-infrared wavelengths, METIS will have the sensitivity to image our nearest neighbour Proxima Centauri b, in addition to other nearby planets, and study its atmosphere. With a temperature between that of Earth and Mars, does it have liquid water on its surface? Is it anything like Earth? While METIS probes planet thermal emission, ELT's second-generation spectrograph ANDES will target starlight reflected off the planet atmospheres, e.g. studying the habitability of planets such as Proxima b (and d), and find out whether it has oxygen in its atmosphere – a possible sign of biological activity, although this will only be possible for a few of the most nearby systems. The search for life on worlds like Proxima b and d are closely linked to similar searches in our Solar System, such as on Mars, Venus, or the icy moons of Jupiter and Saturn.

While with JWST, ARIEL and ELT, the main observational roadmap for exoplanet characterization in the coming decade is evident, the need for further theoretical endeavours and technical instrumentation developments is equally clear. A modelling framework is needed to further understand the links between upper atmospheres and the conditions deep down, on the planet surface and in the planetary interior, the applicability of potential biomarkers, the role of clouds in lower atmospheric conditions, and the links between a planet's formation and evolution and its current state – to name a few. In addition, calculations and laboratory measurements of fundamental parameters such as equations of state and high-precision molecular line lists are required.

Further developments of adaptive optics techniques to compensate for Earth-atmospheric turbulence is vital, in addition to coronagraphs to optimally suppress starlight. Also, further interferometric developments as proposed with GRAVITY+ will be a path forward to push this technique. Methods to combine high-dispersion spectroscopy with high-contrast imaging to further filter out starlight, have great prospects, and require testing of instruments such as ERIS, HiRISE (SPHERE/CRIRES+ coupling), RISTRETTO and possibly a SPHERE upgrade. For ground-based characterization, this ultimately has to lead to an ELT instrument with extreme adaptive optics capabilities in optical and near-infrared light (PCS) that can study a small sample of Earth-like planets and their system environments in the solar neighbourhood.

Equally important for the long-term future of exoplanet characterization is the development of space-based high-contrast imaging. Free of atmospheric turbulence and thermal backgrounds, space telescopes can provide the next step (see below). NASA's NGRST with its coronagraphic instrument is an important stepping stone in this regard.

The characterization of surface conditions (which govern habitability) will likely be only attainable via indirect means, as only the upper atmosphere will be observable in the foreseeable future. A strong theoretical effort is therefore required in order to link the upper atmosphere properties with bulk chemical composition and surface temperature and pressure of low-mass extrasolar planets.

Late-stage evolution and fate of planetary systems

In the coming decade, there will be an exponential increase in our understanding of white dwarf planetary systems, while the census of giant planets around subgiant and giant stars will continue to grow steadily.

The ongoing TESS mission has already proven its ability to both discover planets orbiting giant stars through transit photometry and also refine the age, mass and radius of the stellar host through asteroseismology. This important combination reduces the uncertainty in the observed planet parameters and allows for accurate predictions of the fate of the planet. The legacy of TESS will last throughout the next decade partly due to follow-up of targets of interest by ground-based Doppler radial velocity campaigns. After 2027, the PLATO mission will supplement this yield.

By representing the intermediate phase between the more heavily observed main-sequence and white dwarf planetary systems, giant star planetary systems provide the crucial link.

Throughout a giant star's violent evolution, theoretical and numerical modelling of all aspects of these systems -- dust, asteroids, moons, comets, planets -- will inform both the past and future, providing key insights into planetary system formation and fate.

For white dwarf planetary systems, there will be critical advances in all three aspects of (i) exoplanetary chemistry, (ii) dust and gas disks, and (iii) planet discoveries. In 2018, Gaia-DR2 increased the entire population of known white dwarfs by a factor of 8 to about 260,000. From this sample, on the order of 10,000 white dwarfs with atmospheric planetary remnants will be suitable for low-resolution spectroscopic study in the next decade with the wide-area multi-object spectroscopic surveys WEAVE, DESI, 4MOST and SDSS-V. The resulting spectra will yield exoplanetary chemistry on an unprecedentedly large scale, allowing us to quantify the prevalence of differentiation, water retention, core formation and post-nebula volatilisation of exoplanetary bodies. The new statistical insight into exoplanetary bulk abundance will be at a level equal to or exceeding that attained for current solar system meteorite analyses, particularly when supplemented with observations from the CUBES spectrograph on the VLT, which will increase the sensitivity over existing ground-based instruments by at least an order of magnitude.

Although the chemistry of planetary debris in white dwarf atmospheres is well-characterised, mineralogy data in the surrounding 60 known dust and gas disks is sparse, primarily being limited to the close and bright G29-38 planetary system. JWST will significantly improve this situation, allowing for the fitting of synthetic spectra for dusty components of multiple debris disks. This data can then be combined with the known atomic atmospheric abundances measured with HST to further refine exoplanetary chemistry and constrain disk lifetimes. Over the next decade the total number of known disks is expected to double or triple due to the launch of Euclid, which will be sensitive to weak infrared excesses.

So far, each new discovery of a minor or major planet orbiting and/or disintegrating around a white dwarf has been surprising and exciting, showcasing a startling demographic variation. The rate and type of these discoveries, while unpredictable, will likely accelerate over the coming decade with continued monitoring from TESS and ZTF and the introduction of Gaia-DR4, VRO and PLATO. The clearest prediction is that Gaia-DR4 will astrometrically discover at least one dozen giant planets orbiting white dwarfs, tripling the known population overnight.

Observations of white dwarf planetary systems have accelerated past theoretical endeavours to explain and make future predictions for these systems. Modelling often requires a multi-faceted approach, calling for interdisciplinary efforts. In particular, asteroid and cometary dynamics and chemistry must be modelled at a high, solar system-level of detail. Gas and dust disk physics predominantly takes place within a distance of one Solar radius, representing a compact scale which is unusual in planetary science. Modelling the dynamical history of a planetary system from formation in a protoplanetary disk requires knowledge of stellar evolution, as does modelling the atmosphere of a white dwarf. Overall, the stream of unexpected discoveries and the rapid pace of observations facilitates novel theoretical investigations and necessitates fresh ideas. Some modelling, with regard to, for example, population synthesis, asteroid destruction and atmospheric mixing, will require high performance computing simulations. However, this subject area still accommodates purely analytical investigations and blue skies theory.

Long-term outlook

The study of other planetary systems will be an exciting and vibrant research discipline for decades to come. On long timescales, we clearly identify a number of areas that require significant technical developments and investments to keep Europe at the forefront of this field.

The foremost ingredients for planet-formation theories are the fundamental properties of proto-planetary disks. In particular, reliable disk mass measurements are crucial. By far, the most promising mass tracer is hydrogen deuteride (HD), the less abundant isotopologue of molecular hydrogen. Such a molecule was detected in a few bright disks by ESA's Herschel Space Telescope, and no other current facility is able to carry out such observations, nor to extend the sample. In this context, with SPICA being cancelled, a high spectral-resolution infrared space mission will be essential to measure HD-based disk masses in a large sample of disks, i.e., increase the sample size by an order of magnitude to be compared with the known population of exoplanets. Such a mission will also allow us to determine the water budget, in gas and ice, in planet-forming disks.

In addition, a cryogenic comet sample return mission would greatly increase our knowledge on the composition of the building blocks used for planet formation.

Laboratory experiments will always be needed to interpret astronomical observations, both at the scale of individual laboratories and in large facilities such as medium to high energy ion accelerators (GANIL, GSI, CERN) and synchrotron beamlines (e.g., SOLEIL, ESRF, DESY).

Future long-term projects aimed at discovering new planetary systems will aim at: 1) expanding exoplanet demographics for giant and telluric planets at all separations around stars of different spectral types, ages, chemical compositions and environments, 2) exploring the statistical diversity of their physical properties in terms of atmospheres, composition, structures, orbital distribution, architecture, stellar properties, correlations between all these properties, and ultimately favourable conditions to host life, 3) taking advantage of the identification of the most interesting planetary systems discovered to target the most promising exoplanets for the search for biosignatures.

In the perspective of upcoming studies and surveys from space missions like JWST and NGRST, complemented by ground-based observations with the ELTs, our vision of the demographics of giant planets around stars of various masses, ages, and environments will be rich and almost complete by 2035. The nearest Sun-like and low-mass stars will become the ultimate 'laboratories' to explore the demographics of telluric planets located in the temperate zone where life might exist. The largest across-technique efforts will be concentrated on this sample in order to provide the best targets for atmospheric characterization and identification of complex biological activity. The transiting temperate rocky planet candidates identified by PLATO around bright Sun-like stars will be confirmed and their bulk compositions constrained through multi-year extreme precision radial velocity campaigns. As a result, the tightest constraints will be placed on the occurrence rate of true Earth analogs. In our direct vicinity, decade-long campaigns will provide us with potential habitable worlds, although the challenging problem of efficiently disentangling the tiny Doppler signal (9 cm/s) of an Earth-like planet on a solar-type star from radial velocity variations due to stellar surface activity (typically >1 order magnitude larger) might prove difficult to overcome. A viable alternative option might come from a dedicated high precision astrometric space mission (Theia concept), less impacted by stellar activity. Ultimately, the future generation of high-contrast imaging devices on the ELTs (e.g., PCS), and the ambitious monolithic and interferometric solutions in the visible and thermal infrared proposed in space (e.g., LUVOIR, HabEx, and LIFE - see below), will systematically explore the demographics and the physical diversity of temperate rocky planets, revolutionise our understanding of planet habitability when combined with improvements in the host star's (high-energy) spectral energy distribution (e.g., ESA's next X-ray mission Athena), and ultimately discover the first indication of the presence of life on other worlds .

The cost reduction in the access to space is enabling more locally organised experiments. These often involve national agencies, the private sector and are often supported by ESA. These partially address many of the science cases discussed earlier, they can complement larger efforts, and they drive the development of space capabilities in the European context. Examples are the BRITE (Austria) and Twinkle (UK, and others), and several other initiatives are developing using, for example, CUBESAT standard technologies.

In the context of the late-stage evolution of planetary systems, HST is currently providing the last space-based high-resolution ultraviolet observations of white dwarf atmospheres until the potential launch of a LUVOIR/HabEx type mission in the 2040s. Such a mission will allow for even deeper probes of exoplanetary chemistry, allowing us to greatly increase the number of known white dwarfs with over a dozen different planetary metals in their photospheres. By the 2030s, the census of major planets orbiting single white dwarfs will have increased by a factor of ten to hundred. However, there are currently no plans to target circumbinary planets orbiting double white dwarfs. LISA, slated for launch in >2034, will fill this gap. By using gravitational waves, LISA could potentially discover hundreds of these planets throughout the Milky Way. Such discoveries will substantially increase the known white dwarf giant planet population, and for the first time, probe white dwarf planetary systems outside of the Solar Neighbourhood.

JWST and ELT will start with the exciting exploration of planet atmospheres in the solar neighbourhood. With PCS, the ELT will probe rocky planets in the habitable zones of nearby red dwarf stars in reflected light. However, true Earth analogs orbiting Sun-like stars will be out of reach until the next decade, at least around the nearest stars. Their planet-star contrasts in reflected light are simply too high, requiring a large high-contrast imaging mission from space.

A mid-infrared space interferometric mission, such as LIFE, will probe the thermal emission spectra of rocky planets around all sorts of host stars. NASA has concluded its first two studies, the LUVOIR and HabEx concepts, of what a high-contrast imaging mission could entail and these concepts have been given a high priority in the Astro2020 decadal survey. ESA's plans in these directions are also acknowledged as one of the milestones within ESA Voyage 2050, with a possible large space mission addressing the characterisation of Earth-like planets. Tens of true Earth analogs and their planetary environments (including life indicators) could be studied in high contrast instruments in the thermal infrared with a space-based interferometry mission (as in the LIFE concept), and also via reflected light (possibly through collaboration with NASA missions).

The European planetary-systems community is united in its view that significant investments in technical developments are required now as a necessary precursor, such that in a decade an informed decision can be taken on which route to take.

F

Solar system and the conditions for life

Heliospheric Plasmas, Solar Physics, and Space Weather

The Earth is embedded in the heliosphere, the bubble carved out in the interstellar medium by the solar wind. We are orbiting the Sun, in astronomical terms, at a close distance. This unique vantage point allows us to study astrophysical plasma processes in-situ, with spacecraft launched to the interplanetary medium. We can study the physics of the Sun, from dynamo-action, via the sources and variability of the solar wind outflow, to explosive energy release in the outer solar atmosphere, in great detail. Finally, an emerging field of research concerns the understanding of the chain or processes that controls the interaction of the solar wind with planets, their atmospheres and magnetospheres: a domain coined planetary Space Weather.

What does the heliosphere teach us about astrophysical plasma processes?

The Universe is filled with plasma and most remote-sensing signatures result from plasma processes that produce bulk plasma heating and/or radiation from charged particle acceleration. Plasma heating and acceleration occur through a range of plasma processes such as magnetic reconnection, turbulence, and shock waves. Because the solar system is within our reach, it is the only place where fundamental astrophysical processes can be studied in detail through the unique combination of remote-sensing and in-situ measurements. The Sun, from its deep interior to the corona, the planetary magnetospheres, and more generally the interplanetary medium are pristine natural laboratories for studying plasma processes.

Understanding fundamental plasma processes

A fundamental property of plasmas is that their dynamics are driven by complex processes that couple to each other through different spatial and temporal scales. These scales are typically associated with large-scale structures, on the one hand, where energy is being injected and which can often be described through a fluid description (e.g. magnetohydrodynamics), and on the other hand with the kinetic scales associated with ions and electrons, where energy dissipation actually occurs. In order to comprehensively study plasma processes and associated energy conversion, dissipation and particle energization, observations have to cover multiple scales at the same time. This strategy has been used in the past using measurements from multi-spacecraft constellations with different inter-spacecraft separations, with in particular the Cluster and MMS (Magnetospheric Multiscale) missions sampling plasmas respectively at separations close to the ion and electron scales.

However, a major qualitative jump in understanding the fundamentals of astrophysical plasma processes requires probing the dynamics of the plasma at all relevant scales at the same time. This is because the workings of all processes involve intricate, inextricable couplings between all these scales. It has been shown that, in order to fully cover the characteristic plasma scales in 3D space, at least 7 properly instrumented spacecraft with appropriate inter-spacecraft distances are required. Europe has a strong heritage in this field, from the Cluster era, and thus would be in a prime position for leading such a next generation space mission.

Exploring the outer heliosphere

Near-Earth plasmas only cover a limited range of astrophysical properties. The exploration of the outer regions of the heliosphere, of the boundaries that separate the solar system from the interstellar medium, and of the interstellar medium itself, are therefore an obvious next step. Such studies are crucial to understand the properties and dynamics of our home, the Solar System, and how it interacts with its surrounding environment. The dynamics of this system can also be contrasted with the interactions of other known planetary systems, and constitutes the best prototype from which we may extrapolate on the nature of other “astrospheres”. Exploring the confines of our Solar System requires a dedicated space mission, an interstellar probe. A strong push for such an endeavour is currently being made in the USA and China, and proposals for contributing to these ambitious missions have been made within Europe to ESA and national space agencies. There is no doubt that this next step has to be taken, and we believe that it is the right time to shape such missions and have them fly in the next few decades.

How does the solar magnetic field drive solar variability at all scales?

The magnetic field is the driver of solar variability at all scales. It links and provides the energy for all plasma processes, while it originates from the dynamo process involving convection and rotation. Due to this dynamo process, the solar magnetic field is continuously reconfigured, generated and destroyed on timescales from seconds to decades, and fills the whole heliosphere. Understanding the solar dynamo inside the Sun, the effects of the magnetic fields on the solar atmosphere, and finally the resulting consequences of the magnetic field variability on the whole heliosphere remains a challenge for solar (and in the broader context stellar) and heliospheric physics. Indeed, the plasma physics behaviour in the heliosphere is determined by long-term Space Weather and intermittent solar storms, which are notoriously hard to predict. The major open questions in solar physics remain the precise workings of the solar dynamo, how the magnetic field heats the outer solar atmosphere, and how it drives solar flares, coronal mass ejections and associated events.

Dynamo

Even if a lot of progress has been achieved this last decade on the way the solar dynamo works, e.g., through the achievement of sophisticated numerical simulations, a 3D view of the processes is still missing. In particular, getting a polar view of the magnetic field and flows will be a great achievement to better constrain dynamo models. Some first constraints of this type will be obtained with Solar Orbiter. In the long-term planning, a mission focusing on a view of the solar poles from high helio- latitudes (above 70°) has been proposed to study the interior of the solar polar regions in order to uncover the key role of magnetic flux transport in the solar cycle.

From the ground, full disk observations of surface oscillations and magnetic fields are needed to further constrain dynamo modelling and serve as boundary conditions for Space Weather forecasting. Such continuous observations can be carried out either in space by a single observatory (such as SDO/HMI) or on the ground in the form of a network of observatories (such as GONG). In the case of a ground-based network, the telescopes need to be geographically distributed such that gaps from the night time, bad weather and instrumental interruptions are minimised. Ideally the individual observatories are equipped with nearly-identical observing instruments to ease the data merging and analysis. The success of this strategy is that small-aperture telescopes with a large field-of-view provide important observations of the Sun, and can be operated for a long time.

GONG is currently providing solar magnetic field measurements since the 90s. However, addressing the questions of solar physics and Space Weather research requires higher spatial and temporal resolution and an improved spectral coverage, and thus the outdated technology of GONG is to be replaced in the coming decades with a state-of-the-art ground-based network. The importance of such a new global network was already pointed out by the ASTRONET Roadmap 2008 and has gained in relevance since then.

High-resolution observations

The driver of solar activity is the magnetic field. Measuring the magnetic field is a difficult task, because the polarisation signals from which the field is determined are generally weak, and thus require high signal-to-noise ratio observations, which is daunting to do while simultaneously observing at diffraction-limited resolution and at a time cadence that freezes the time evolution of the atmospheric plasma.

A major goal for solar physics in the coming decade is to routinely measure the magnetic field simultaneously at multiple heights in the solar photosphere and chromosphere at the highest spatial and temporal resolution. This requires telescopes with a larger aperture than the current 1-m class telescopes, such as the German GREGOR telescope and the Swedish 1-m Solar Telescope. The American Daniel K. Inouye Solar Telescope (DKIST), which is starting its science operations in 2021, has an aperture of 4 m, which is a major step forward in light-collecting area to reach high polarimetric sensitivity and spatial resolution (to probe the smallest possible spatial scales).

A 4-m class ground-based solar telescope in Europe to complement DKIST is of the highest priority for European solar physics. This has been recognized for a long time, and plans for the European Solar Telescope are at an advanced stage. The telescope is scheduled for PDR in mid-2023 and the project expects to request the construction permit by the end of 2023, so that if the ERIC is in place construction could start in the second half of 2024. EST’s optical design facilitates extreme polarimetric sensitivity and precision, and is designed with maximum throughput in mind to be able to obtain the highest signal-to-noise at fixed spatial and temporal resolution. Its planned instrument suite will consist of several integral-field spectropolarimeters, an instrument-development field where Europe is currently leading.

Together with the American DKIST, EST will fill a gap that is not covered by any other existing or upcoming instrument: it will be able to examine magnetic coupling in the solar atmosphere from the deepest layers of the photosphere to the highest layers of the chromosphere. This allows to uncover the thermal, dynamic and magnetic properties of the sun’s plasma at high spatial and temporal resolution. According to the 2013 Science Vision update by ASTRONET, the EST is the infrastructure to meet these requirements. EST was included in the ESFRI (European Strategy Forum for Research Infrastructures) Roadmap in 2015, and preparations have started for construction of the European Solar Telescope (EST, with 4m aperture) on the Canary Islands, Spain. The project now requires the strongest support in order to realise its construction.

Another challenge in the field is to measure the magnetic field in the corona. This can be done from space by measuring polarisation at EUV wavelengths. Such measurements of the coronal magnetic field could be complemented by ground-based observations from EST to build a complete 3D picture of the magnetic field from the visible solar surface to the corona. Radio observations could also provide quantitative values of the chromospheric and coronal magnetic field through future circular polarisation measurements with ALMA of the millimetre emission from active regions. In the microwave domain, quantitative magnetic field measurements in the low corona can be obtained from gyroresonance/gyrosynchrotron emissions and future observations with SKA could provide crucial contributions in this area with its unprecedented image quality and dynamic range.

The American DKIST telescope has a capability to measure coronal fields from the ground using spectral lines in the IR, owing to its off-axis design that leads to low straylight contamination from the solar disk. However, DKIST can only do this off-limb, and the method suffers from line-of-sight integration effects. Another way forward is to measure intensity and Doppler-shift oscillations caused by localised, high-frequency coronal waves, that allow access to the coronal magnetic field information through coronal seismology. Both these measurements of the coronal magnetic field are to be complemented with numerical simulations, to study the magnetic field evolution in less accessible parts of the solar atmosphere. The combination of the simulations with forward modelling helps to more precisely constrain the solar atmospheric magnetic field.

A particularly powerful approach to probe both various heights in the atmosphere and different physical parameters is to combine simultaneous observations from multiple observatories to increase coverage of the spectrum. Combinations of observations with for example ALMA, optical ground- based telescopes and space-based (E)UV telescopes such as SDO/AIA, IRIS, and Hinode are now common. New ground-based observations in the radio domain such as the ones provided by LOFAR will lead, for example, to new insights into the fundamental physics of the solar corona through a combination of spectroscopic measurements and high-resolution imaging of solar radio bursts.

Future solar ground and space-based observatories should carefully consider synergies. In the coming decade, such synergies will be achieved through the combination of observations from Solar Orbiter and other space missions and ground –based observations, thus providing a stereoscopic vision of the different phenomena.

What is the impact of the Sun on the heliosphere and on planetary environments?

Multi point observations in the inner heliosphere

The coming decade will see a fleet of spacecrafts flying in the inner heliosphere (Solar Orbiter, Parker Solar Probe, BepiColombo) providing measurements of the solar wind, of its perturbations such as coronal mass ejections (CMEs), and of solar energetic particles (SEPs) at different distances from the Sun and different longitudes. This will bring a better understanding on the origin of solar transients, their variability and propagation in the heliosphere, as well as on the source, characteristics and propagation of SEPs in the inner heliosphere.

Observations from ground-based radio-observatories such as LOFAR should also provide in the near-future crucial remote-sensing measurements of the solar wind parameters and even of magnetic field in interplanetary coronal magnetic ejections. These measurements will complement satellite measurements and will strongly contribute to an improved understanding of the evolution of the solar wind and coronal mass ejections through the inner heliosphere and to better constrained space weather models.

In order to increase our understanding of the physics of the Sun and the heliosphere, there would be a strong advantage to be had from a new space mission located at the Lagrange point 5 (L5). Such a scientific mission needs to be considered thoroughly in the space plasma and solar physics communities in Europe. The L5 point is interesting because it offers a side view of the Sun-Earth line. This allows us to measure the speed of CMEs impinging on Earth with higher accuracy. Furthermore, stereoscopic and coronographic views of CMEs combined with numerical simulations of their propagation would permit a better forecast of the propagation of solar storms to Earth. Such a mission would also allow an early view of the Sun's surface and its sunspots, which are the sources of flares and CMEs. As the Sun rotates towards the Earth, the detection and prediction of these events is improved. Multi-point in situ measurements from L1 and L5 will provide essential insight into the nature of SEP events. This should be complemented with numerical simulations of their generation and propagation in the heliosphere.

Planetary environments, Space Weather and Space Climate

Understanding how the solar wind interacts with a planet is critical to determine the properties of the near-planet environment, and in turn to determine its habitability. This is because this interaction controls, among many other factors, atmospheric escape (such as Mars' dehydration over time), energy dissipation (such as auroral processes and radio signal absorption), or the shielding of harmful radiations from the surface. The solar wind interaction with planets first occurs at high altitude with their magnetospheres and upper atmospheres. In particular, for planets with an atmosphere (i.e., all except Mercury), the ultimate region where the energy of the solar wind is dissipated is the ionosphere (the solar photoionized part of the upper atmosphere). This is common for all planets, moons and comets that have surrounding gas. In the case of Mercury and other bodies with no atmosphere (including the moon), the energy of the solar wind is ultimately dissipated at the surface of the planet.

Understanding the chain of processes that control Space Weather and Space Climate at planets, i.e. the impact of the solar wind on the planets near-environment on various time scales, is essential to accurately forecast and thus prevent hazardous situations for spacecraft and humans.

It is now understood that solar storms impacting Earth can severely damage electronics onboard spacecraft, threaten the lives of astronauts, inflict strong damage in power lines and transformers on the ground, sometimes leading to electrical blackouts. Numerous national monitoring schemes have been put in place for Space Weather forecasting on Earth. Although large efforts have been made in the last few decades, we need significantly more efforts in terms of theory and numerical modelling, to increase our understanding of the full chain of processes, as well as much more real-time (in situ as well as remote-sensing) data, to propose truly accurate space-weather warning services in the future. Space Weather is not unique to Earth! It will very soon become a necessary service at other planets where robotic exploration is significantly rising, especially at Mars on the eve of its human exploration.

A main goal to accomplish in the next few decades is to be able to forecast accurate upper atmospheric responses to Space Weather events at least for terrestrial planets, although it would be desirable to have some level of monitoring at giant planets as well. At Earth, accurate and real-time data are mandatory, and at the terrestrial planets (particularly at Mars) a continuous solar wind monitoring platform to provide timely and accurate Space Weather information is also essential (but not available so far). Accurate forecasts are only possible if sufficient and appropriate data both upstream in the solar wind and in-situ at the magnetosphere and ionosphere-thermosphere levels are continuously available.

In addition to upstream solar wind monitors, we need multi-spacecraft observations of the coupling between the many layers of planetary environments (magnetosphere – ionosphere -thermosphere) in the solar system, which would give us a more complete picture of plasma processes and their importance in driving Space Weather. At the moment, multi-spacecraft plasma missions are only available near Earth with missions such as Cluster, THEMIS, Swarm, and MMS. At Mars, prototype multi-spacecraft studies have been completed using initially independent missions (Mars Express, Mars Global Surveyor, Rosetta and MAVEN (Mars Atmosphere and Volatile EvolutioN)), and in the coming years Bepi Colombo will perform coordinated observations at Mercury with two spacecraft. Nevertheless, dedicated multi-spacecraft studies with high temporal resolution, capable of making simultaneous and coordinated observations of the different plasma regions and their coupling on both day and night sides (i.e. solar wind, magnetosphere, ionosphere, and atmosphere), would enable the much-needed understanding and forecast ability of upper atmospheric and magnetospheric conditions.

Increasing our knowledge of the solar wind impacts on planetary plasma environments is a key to future planetary science and exploration, which has notable implications beyond the solar system. A better understanding of the solar wind interaction with planets in our solar systems is a required stepping-stone to understanding Space Weather and Space Climate impacts at other astrophysical systems beyond reach, and in the first place Exoplanetary systems, for which much fewer observations are available.

Solar impact on planetary environments is not limited to solar wind nor to energetic particles. The variability of solar total (i.e. integrated over the entire spectrum, TSI) and spectrally-resolved (SSI) irradiance is among the main uncertainties hindering reliable assessment of the solar influence on Earth's climate, as pointed out by the Intergovernmental Panel on Climate Change (IPCC) reports. Furthermore, understanding solar irradiance variability is key to understanding the variability of other Sun-like stars as well as their impact on exo-planets and their detectability. Key open questions are the magnitude of irradiance changes on time scales longer than the solar cycle and the spectral distribution of this variability, most critically the amplitude of the SSI variability in the UV and the phase of the variability in the visible range. One critical aspect is the continuity of TSI and SSI measurements. Past experience teaches us that having just one single operating TSI experiment at a time often brought the continuity of the TSI record into danger and is the main reason for the currently existing significant uncertainties in the amplitude of the variability on time scales longer than the lifetime of a single mission. The over 20-year long (since 1996) record from VIRGO on SoHO became a crucial bone of the current TSI record covering more than 40 years. The shorter (2010-2014) record from PREMOS on PICARD has contributed to resolving the discrepancy in the absolute calibration between the SORCE/TIM measurements and all earlier experiments. Since then, no other European experiment regularly monitoring the solar irradiance variability was operating. The only currently operating experiment is TSIS-1 on ISS to be succeeded by TSIS-2, both led by LASP, USA, cannot guarantee the continuity and reliable cross-calibration of the record. Radiometers measuring TSI are usually light-weight and comparatively low-cost experiments that can be placed on many space-based platforms. Therefore, including a radiometer on a suitable future mission would be beneficial. The existing spectral irradiance record is even more uncertain, being patchy in both temporal and spectral coverage and partly with huge uncertainties. At the same time, UV irradiance is of special interest for Earth as it controls the chemistry of the terrestrial atmosphere, which urgently calls for long-term monitoring of the irradiance variability in the UV and visible.

The early history of the solar system

The origin and formation of the solar system encompasses complex processes that can be divided in a number of steps whose understanding has benefited from the recent discovery of a large number of protoplanetary disks and extrasolar planets. Observations, simulations and theory have to go hand-in-hand in order to identify the main formation and evolution paths of exoplanetary systems, as well as to understand the formation of rare systems like our own.

Key questions concern the physical state of the circumstellar disk at the onset of the formation of the planets of the Solar System such as its temperature profile (which determines the location of the snow line beyond which icy dust can condense and form the core of giant planets), as well as the dust and gas density distributions (which influence the planetesimal formation process).

The advances in understanding phenomena such as dust particle accretion, the potential pebble concentration processes and their role on the fast formation of the giant planets as well as the early-stage planetary migrations, have provided explanations for some peculiar characteristic features of our Solar System (e.g., the existence of Jupiter Trojans and the dynamical structure of the Kuiper Belt). In the next decade, it is expected that additional theoretical work, mostly based on numerical simulations, will shed new light on the kind of instabilities present in a circumstellar disk. Understanding the pebble accumulation process will help to develop a coherent model of planetesimal formation that is able to predict their initial size distribution and composition at different radial distances.

Dynamical properties of small body populations and families

Wide-field, high-sensitivity sky surveys have allowed the cataloguing of a very large number of asteroids and comets which is pushing forward our ability to reconstruct the collisional history of the Main Asteroid Belt through a refined classification in asteroid families. For comets, the history of the Oort Cloud through models and simulation on a grander scale, has led to a better knowledge of the influence of stellar encounters and of the galactic tide. Understanding the dynamics of the trans-neptunian region needs deeper surveys which will also ascertain the existence of any further planet in a large heliocentric orbit. Aiming to a deeper understanding of the dynamical evolution of the small solar system bodies has strong implications not only for the planning of exploration missions, but also for properly addressing the associated data analysis for either science or applications.

A striking example is represented by the Near-Earth Object (NEO) population, which will greatly profit from the dynamical models, based on the extremely precise GAIA astrometry. This will allow the study of finer and finer dynamical perturbations and will push forward the horizons of predictability for objects in chaotic orbits. This, in its turn, will greatly support the Planetary Defence initiatives started at worldwide level (notably in the US and in Europe) for protecting our planet from the impact hazard by providing impact monitoring services directed to a large spectrum of stakeholders ranging from civil protection agencies to the citizens. The harvesting of extraterrestrial resources relies also on the accessibility of the small bodies of the solar system.

Study of the non-gravitational forces

The small body populations represent an important constraint in the validation of the models for the evolution of the Solar System. The non-gravitational perturbations play a paramount role in determining their dynamical history that led to the presently observed situation. The high precision astrometry coming from ground-based surveys, coupled with the lengthening of the observed arcs, has allowed the detection of the tiny non-gravitational forces affecting the motion of small asteroids passing close to our planet. The development of the associated theoretical modelling has, in turn, led to a better understanding of the long-term evolution of these bodies, unveiling in detail the role of mean motion and secular resonances in shaping the dynamical paths followed.

In particular, the Yarkowsky and the Yarkovsky-O'Keefe-Radzievskii-Paddack (YORP) effect influence the orbital and rotational evolution of a small body close to the Sun, respectively. Moreover, the coupling between the two mentioned effects can enhance or hinder the efficiency of the mobility of a small body through the Solar System. Beyond the orbital evolution of the bodies, the non-gravitational perturbations are also responsible for sculpting the size distribution of the small body populations closer to the Sun (NEAs and Main Belt). The YORP effect is responsible for the rotational disruption of small bodies possibly down to a limiting size representing the building blocks of the observed rubble pile objects.

Therefore, enhanced theoretical models and numerical simulations of the small bodies evolution (including the transient populations of the Centaurs) coupled with extended large observation campaigns of small Main Belt objects (more affected by the non gravitational perturbations) shall help in refining the theoretical models of the evolution of the small bodies in the region both in terms of orbital distribution (e.g., asteroid families evolution and dating) and in terms of size distribution.

Small bodies of the Solar System

Small bodies are the remnants of the early stages of formation of our solar system. They are the building blocks from which planets were created, and therefore contain information on the materials and conditions prevailing in the solar nebula during its early stages. Small bodies are rocky and/or icy objects, usually ranging in size from a few metres to 1 - 2 thousand kilometres. Their physical nature, distribution, formation, and evolution are fundamental to understand how the solar system formed and evolved and ultimately, how planetary systems are formed and evolve in other stars.

Small bodies of the Solar System populate three main fossil structures that characterise our star: the main asteroid belt (MB). the trans-Neptunian belt (TNB, also known as Kuiper belt), and the Oort Cloud. The main concentration of asteroids (currently 800,000 are known) is located in the main belt, a ring- shaped region located between the orbits of Mars and Jupiter at a distance of 2.0 - 3.5 au where we can find mainly bright asteroids composed of silicates and metal and dark (primitive-class) asteroids with a high content of carbon compounds and hydrated minerals. Beyond the orbit of Neptune (30 au) and up to 48 au we find the second ring-shaped concentration of objects (currently 2500 known), the Kuiper Belt. The trans-Neptunian objects (TNOs) are composed largely of ices, such as water, methane, or nitrogen mixed with silicates and refractory non-volatile species and its most famous member is Pluto. The third, outermost, and largest concentration of icy-bodies is the Oort Cloud. It starts as a disk-shaped structure at its innermost region (a few hundred au) and becomes spherical as we move outwards, extending up to 50,000 – 200,000 au.

Similar belts of rocky and icy-bodies have been detected around other stars in the form of debris disks. In fact, the most recent studies refer to a two-component temperature debris disk, where a combination of two blackbodies at different temperatures is sufficient to reproduce the entire spectral energy distribution from the mid-infrared to millimetre wavelengths. In this scenario, the disk will be a combination of a trans-Neptunian belt analogue and an asteroid belt analogue closer to the star. Such belts have been marginally resolved for some exo-solar systems, such as Epsilon Eri and HD 107146.

There are also other populations, such as NEAs, comets and Centaurs, Jupiter's Trojans (JT) and Hildas. NEAs are objects that move into the terrestrial planet region in dynamically unstable orbits with short lifetimes, needing to be replenished by the inner zone of the main belt. Comets and Centaurs are icy- objects scattered from the trans Neptunian belt and the Oort Cloud. Centaurs orbits are in the region of the Giant Planets, while comets move in very elliptical orbits that can cross the terrestrial planet region. When close to the Sun, comets sublimate ices and present the well known coma and tails which are also observed in some Centaurs and a very few main belt asteroids. Cybeles, Hildas and Trojans are the three main stable populations immediately outside the Main Belt, and their origin is under debate. Their origin can be in situ or TNB objects scattered in the early stages of the Solar System and captured in their present orbits.

The proximity of NEAs makes them ideal candidates for exploration with spacecrafts, in addition to being a source of material resources that in a not too distant future may be exploited through asteroid mining or In-situ Resource Utilisation (ISRU) for the production of fuels, drinking water, habitats, and communications devices. In addition, they constitute impact hazards. In particular, NEAs that approach less than 20 times the Earth-Moon distance and whose diameter is greater than 140 metres are called potentially dangerous, or PHAs because of their catastrophic global effect in case of collision. Smaller objects (with diameters of a few metres) can produce catastrophic local effects too. Discovery, orbit follow-up (in particular of PHAs and small virtual impactors), physical characterization (including Earth- based observation and space mission), and dynamical studies are crucial to understand the nature of asteroids and its relation with the evolution of life on Earth as well as to develop an effective strategy for Planetary Defense and for future space exploitation. Therefore, dedicated Earth-based telescopes, Space telescopes to look for PHAs in regions not observable from Earth, and missions like DART and HERA are a priority.

Cometary science has been revolutionised by ESA's Rosetta mission. It showed that the composition of comet 67P/Churyumov-Gerasimenko is rich in organics and has an isotopic water ratio which is different from that on Earth. The Rosetta mission also revealed that its nucleus structure is stratified and surface morphology is controlled by seasonal activity, with starkly contrasting areas dominated by erosion via sublimation and by fall back. The comet's inner coma was also shown to be highly dynamic, changing in time and space. However, Rosetta also raised important new questions that need to be tackled in the next decades. Some of these questions relate to: 1.) the primordial properties that reflect the process of comet formation; 2.) the evolutionary features and their control of cometary activity; 3.) the differences in composition seen in the coma and how the solar wind interacts with it; 4.) the nucleus evolution and changes on the surface driven by insolation weathering which leads to pervasive fracturing, fragmentation, and mass wasting, such as collapsing cliffs; 5.) non-gravitational forces, which develop as activity-induced torques and affect the rotational parameters of comets; etc.

The bulk of our knowledge of the ice composition of comets comes from studying the gas of their coma. Detailed compositional measurements are only possible in situ and provide crucial information on the provenance of cometary material. The two distinct D/H ratios in the water of 67P, derived from HDO/H_2O and D_2O/HDO, suggest a cold-temperature origin of the ices in the Interstellar medium (ISM). The D/H ratio of a less evolved object may give some insight into outgassing-related fractionation processes, which will help in interpreting differences or similarities between remote and in situ D/H measurements. Pre-solar signatures have been observed in the isotopes of 67P's volatiles while similar bulk abundances of the volatile molecules were observed at comet C/1995 O1 Hale-Bopp and in objects in the ISM. One of the surprising results of Rosetta was the abundant molecular oxygen observed in the coma. Circumstantial evidence for O_2 was also found in comet 1P/Halley. Several formation mechanisms have been discussed, from radiation of water ice and cold temperature chemistry in the ISM to various in situ formation mechanisms. However, the formation of molecular oxygen remains a key open question that spans several research fields. It is obvious that processes in the interior, subsurface, surface and gas, as well as the dust envelope of a comet need to be analysed in a multi/interdisciplinary approach. Europe is in a privileged position to lead these studies.

The link between primitive-class asteroids and carbonaceous chondrite meteorites has undoubtedly been determined: they are the parent bodies of this kind of meteorites that have a high content of complex organics molecules (including amino acids). Compositional and dynamical studies of primitive asteroids are crucial to determine the abundance of these materials in the Solar System and its role in the development of life on Earth. Observations in the near-infrared regions that are very difficult from Earth are needed to study ices and organics. The capabilities of JWST in the 3-8 µm region offer a unique opportunity for a big step forward in this field.

The physical properties and dynamical links among TNOs are still poorly understood as we need larger facilities to study these objects whose orbit is too far from Earth. A new window of opportunity will be opened / has been opened by the new generation of giant telescopes and, in particular, the JWST. Additionally, the study of TNOs in extreme orbits and its possible link with the existence of a planet at ~100 au (and its search) has been of high interest to the community.

The previously used distinction between asteroids (inactive) and comets (active objects) disappeared over the last decade as there are clearly comet-asteroid transitional bodies called active asteroids (ACOs). Several objects have been discovered with a motion that resemble that of asteroids and show cometary behaviour (active asteroids, AAs), while the motion of other objects are similar to comets but don't show cometary-like activity (asteroids in cometary orbits, ACOs). More research is required to understand the mechanism that ejects dust in AAs and why ACOs do not sublimate ices like comets.

Over the last years, large surveys like SMASS and WISE allowed us to map the compositional distribution of the MB. The combination with dynamical simulations and laboratory studies allowed a much better understanding of the collisional evolution of the MB, the formation of collisional families and the number, size and composition of their parent bodies that populated the early solar system.

The compositional distribution of the asteroid belt and its parent bodies is of fundamental importance to understand the origin of the solar system.

In the first two years of operation of the Vera Rubin Observatory (VRO), the number of minor bodies will increase by a factor of ten or more. This will have a high impact on the study of the currently known populations providing astrometry and colour photometry (i.e., composition), in particular of their smaller members. It is expected that VRO will discover new types of bodies that, not surprisingly, will create a revolution in the field similar to the one created by the surveys in the 1990s.

Interstellar planetesimals

The planetesimal population of the young solar system was initially very numerous but the majority of the objects ended up ejected due to gravitational perturbations by the planets and other external perturbers. Numerical simulations indicate that many other planetary systems would have experienced a similar evolution, yielding to an interstellar space filled with ejected planetesimals. In this scenario, 1I/'Oumuamua discovered by PanSTARRS is the first interstellar interloper with no evidence of outgassing. The second object discovered so far is 2I/Borisov with an unquestionable cometary composition, reassuring us that a population of icy interstellar planetesimals exists.

Numerical simulations of the number of interstellar planetesimals that can be trapped in these environments indicate that many of them will be incorporated to each star- and planet-forming disk. The interest of these trapped planetesimals is that they could have sizes large enough to rapidly grow into larger bodies via the direct accretion of the sub-cm sized dust grains in the protoplanetary disk. This may happen before the planetesimals drift toward the star due to gas drag, overcoming the metre-size barrier that challenges the growth of cm-sized pebbles into km-sized objects. This is an unsolved problem in planet formation theories. Trapping of interstellar bodies in these environments should be considered in future planet formation models and at the same time require a better characterization of the population of interstellar planetesimals, particularly its background density, size, and velocity distributions.

Exploration of terrestrial planets

The last decades have been characterised by a growing worldwide interest and investment in space economy that provided a boost to scientific space exploration programmes. The amount of data retrieved is enormous and will exponentially increase in the years to come. Of particular relevance for the future will be the integration of data from different missions to favour comparative planetology. In this perspective any kind of data interpretation needs to be carried out in the light of experimental analysis, modelling and analogue studies both in situ and in the laboratory.

Mercury

Mercury, explored by Mariner 10 in the 1970s and more recently by MESSENGER (2008-2015), is an enigmatic small planet with a remarkably large metallic core, a magnetic field, a volcanically dominated surface and numerous evidence of volatile rich materials at its surface. All these peculiar characters pose numerous issues on where and how Mercury formed and evolved, which is in its turn strictly related to the solar system evolution in terms of planetary accretion and differentiation, orbital migration and collisional history. The coupling of a high metal/silica ratio and a volatile rich composition are severe constraints on any formation theory of planet Mercury either being related to orderly processes by early accretion from the protoplanetary disk or to chaotic later collisional events. In the meantime the long lived effusive and explosive volcanism and the significant radius contraction by cooling, raise issues on the way magmatism and tectonism coexists on a small terrestrial body which experienced important collisional events that formed large basin structures. On the one hand, the Mercurian harsh environment provides unparalleled opportunities to investigate unique magnetosphere and exosphere interactions with the solar wind, radiation and interplanetary dust as well as of exploring the surface materials behaviour under high diurnal thermal variations. It will also allow studies of the enhanced space weathering, sputtering and regolith production due to faster collisional speeds. On the other hand, its high orbital axis inclination allows extensive permanently shadowed areas in the polar region where water ice and organic volatiles storage is maintained at stable cryogenic temperatures even on this warm planet close to the Sun. All these peculiar aspects make Mercury the ideal planet for answering key questions of planetary sciences. In addition, the close proximity of Mercury to the Sun, whose mass causes distortion in space-time, enables testing of Einstein's theory of General Relativity. The ESA-JAXA BepiColombo mission, launched in 2018, has the aim of solving these open issues providing simultaneous measurements from two spacecraft from December 2025 onwards.

Venus

At the early stage of space exploration, Venus was the most visited planet, but after the last US mission Magellan in 1994, it became a forgotten planet for many years until the launch of the ESA Venus Express mission in 2005 and, soon afterwards, the JAXA mission Akatsuki. Despite Earth and Venus having a similar size and bulk composition, they show a dramatic difference in environment, being the CO_2 dominated Venus atmosphere able to reach an average temperature of 470° C and a pressure of 90 atm at the planet surface. In this framework a key aspect to be addressed is to understand Venus' early evolution, potential habitability and how much of the geologic history is preserved on its surface, considering also the present-day coupling between the surface and atmosphere.

The relatively young surface of Venus implies that the planet is geologically active, but it does not show any evidence of plate tectonics. However, the current geodynamical regime, surface chemistry and mineralogy, interior and thermal evolution remain poorly understood and consequently Venus' geological history remains enigmatic. Venus could have maintained a habitable environment with liquid water oceans for billions of years, a significantly longer period than Mars, and detectable signatures of this ancient epoch could await discovery by new missions.

In conclusion Venus has all the ingredients for a habitable planet (geologic activity, a massive secondary atmosphere, possible past surface water, possibly a past dynamo, similar size and gravity as the Earth). But despite it all, something happened during its planetary evolution that made Venus a hell and its surface the most unhabitable site in the solar system. Future missions will have to address when and why Venus and Earth's evolutionary paths diverged, if Venus ever hosted habitable conditions or even past signs of life, or if the Earth could follow the same destiny as Venus in the future.

Mars

Mars is the most widely explored extra-terrestrial planet in the Solar System. Its surface shows clear evidence of an early stage environment very similar to the terrestrial one, with a complex system of flowing liquid water in the form of rivers, lakes and seas. Under similar conditions, the Earth assisted the emergence of life. Although the geological records of that early period are lost on Earth due to crustal recycling related to plate tectonics, they are well preserved and still accessible on Mars. On those records, it is also possible to unveil the climate changes that brought the planet from a warm and wet past, dominated by the formation and deposition of hydrated minerals, to the present cold arid desert through an intermediate stage characterised by evaporite precipitation. The main climate transition is thought to have taken place between the Noachian and the Hesperina at around 3.5 Gyr ago and the possible driving causes are still to be unveiled. In the present era, only a fraction of the water from the very early stages has been detected. It can be found in the form of ice or embedded in the structure of water-bearing materials. There is also good evidence of active ground water systems that occasionally interact with the surface. Polar caps hide systems of subglacial saltwater lakes and should record the recent Martian climate variability which is thought to be paced by orbital forcing. However, the way how orbital parameters affect the climate on Mars is still to be understood. An important aspect to investigate is therefore the feedback of atmospheric dust on the characteristics and circulation of the atmosphere and on the past and present climate, habitability and geologic history. Today Mars is still a dynamical world and is a key target of future explorations that will help to understand the formation and evolution of inner planets, the path that leads a planet to be habitable and the processes that determine the emergence and the destiny of life. Moreover, the study of Martian satellites will provide important information on the formation processes of terrestrial planets' satellites. In particular, recent studies suggest that Phobos and Deimos could represent the present state of a dynamical and evolving process following a giant impact on Mars. This should be studied and compared with the Earth-Moon system origin and evolution. Europe has been developing the ESA-Roscosmos ExoMars programme. It includes two missions: the Trace Gas Orbiter, orbiting Mars since October 2016 to monitor atmospheric trace gases including methane, and a rover and a Surface Platform which was planned to be launched in the late summer of 2022, but was interrupted after Russia's invasion of Ukraine in February that year. The programme, which addresses astrobiological, surface, near-surface and atmospheric studies, needs to be redefined in the context of the new geopolitical situation. Next frontier will include the very ambitious Mars Sample Return program, in which Europe is deeply involved, and the preparation for human exploration. This last step would still require filling some knowledge gaps on the planet that could be covered through some additional dedicated explorations.

Moon

Besides being a privileged base for observations of the universe and the future exploration of the Solar System, the Moon itself is an interesting target from a scientific point of view. Indeed, several scientific missions have been and operate to date on the Moon with orbiters, landers and rovers exploring the lunar environment and many others are in preparation. The major open scientific questions about the Moon cover planetary science with special emphasis on: 1.) an in-depth study of the surface, subsurface layering and voids, and interior; 2.) the dust dynamics and the plasma environment; 3.) the calibration of methods for absolute chronological dating of planetary surface; 4.) the origin and accumulation mechanisms of volatiles and water on the Moon; 5.) the In Situ Resource Utilisation materials for sustainability of human settlements and potential exploitation; 6.) the physiology, survivability, and habitability in Space; and 7.) the origin of the Earth-Moon system. Furthermore, the implementation of Radio, Optical, Infrared and Cosmic ray astronomy from the Moon is of great importance. The path for human exploration to Mars includes the development of several space missions with growing complexity that will eventually bring a return of astronauts to the Moon. The NASA Artemis program, which will land the first woman and the next man on the lunar surface by 2025, the ESA projects under study (the Cislunar Transfer Vehicle and the European Large Logistic Lander), and the articulated Lunar Exploration program from China, Russia and other countries make the Moon closer than ever before.

Jupiter, (Saturn), Neptune and Uranus: planets and their systems

The Jovian and Saturnian systems

Our knowledge of the large gas giants has enormously grown over the last decades. The Cassini-Huygens mission (NASA-ESA-ASI) scrutinised the Saturnian system (planet, rings and satellites) to an unprecedented level. The discoveries are almost endless, below we mention a few of them: 1.) The first view ever of Titan's surface reveals a landscape similar to a river bed on the Earth at the Huygens probe landing site; 2.) The icy plumes on Enceladus contain water and other molecules likely coming from an ocean beneath the surface; 3.) An active and dynamic ring system; 4.) Titan reveals an Earth-like world with methane and ethane rain, rivers, lakes and seas responding to seasons; 5.) An extremely dynamic atmosphere on Saturn is developing massive storms and a jet stream with hexagon shape at the both poles with giant hurricanes; 6.) Dual bright-dark surface spots on the moon Iapetus due to a combined effect of the body's long rotation and swept up reddish dust along the orbit; etc.

The scientific community is lacking knowledge of the Jovian system compared to what was achieved with the Cassini-Huygens mission at Saturn. The Galileo mission changed the way we look at our solar system, and it witnessed the impact of the comet Shoemaker-Levy 9 with the planet. The mission lasted for 14 years, discovering an intense radiation belt above Jupiter's cloud tops, helium in about the same concentration as the Sun, extensive and rapid resurfacing of the moon Io because of volcanism and a magnetic field at Ganymede. The mission ended when the probe carried by the orbiter plunged into the planet's atmosphere to measure the water (and other molecular and atomic species) abundance in deep layers to be compared with the solar values. This shed light on the origin and evolution of the planet and processes in the early solar system. On the other hand, the Juno mission was exclusively devoted to study the atmosphere (storms, lightning, weather, water abundance four times higher than solar values) and its interior (displacement of huge masses induced by weather processes, strong magnetic field also displaces with respect to the north pole). Key aspects of the planet itself and crucial questions related to the habitability of the icy satellites such as Europa, Ganymede and Callisto remain unsolved to date. To remediate this, ESA will launch the JUICE mission in 2023. The mission is conceived to characterise the potential habitable worlds of Ganymede, Europa and Callisto (hosting pre-requisites were already established by the NASA missions Voyager and Galileo). Juice will provide a complete spatio- temporal characterisation of the giant, rotating magnetosphere, and of the meteorology, chemistry and structure of Jupiter's gaseous atmosphere. It will also allow to study the coupling processes inside the Jupiter system, with emphasis on the two key coupling processes within that system: gravitational coupling, which ties together Jupiter and its satellite system, and electrodynamic interactions which couple Jupiter and its satellites to its atmosphere, magnetosphere and magnetic disk.

By investigating Jupiter, its moons and the Jovian system in all its complexity JUICE will address many more goals than the NASA Juno mission, whose focus is on the giant planet. In the study of the giant planet itself, JUICE will give new insights due to broader spectral range, its emphasis on global mapping, the long temporal baseline offering the opportunity to study spatial/temporal variability, the even dayside and night side coverage, and its focus on sounding of the stratosphere and thermosphere. In addition, JUICE will provide much more, by achieving a full exploration of Ganymede, with very focused investigations of Europa and Callisto, by exploring new regions of the magnetosphere never reached by any other spacecraft, and by assessing the coupling processes of the entire system. The recent geological activity in some of the Jovian moons is revealed as diverse tectonic and cryo magmatic structures as well as features resulting from the atmosphere dynamics, if present. The scientific interest on these icy moons has increased in the planetary community since evidence of deep habitable environments was discovered. Indeed, some of the satellites of the giant planets are now called "ocean worlds", because liquid water layers characterise their interiors, making them important targets for astrobiology studies. In a broader perspective, the search for primordial life forms in the "ocean worlds" necessarily passes through the Jupiter and Saturn systems. Although their distance from the Earth imposes a minimum cruise times of several years for a spacecraft, and for Saturn there is a need for onboard radioisotope thermoelectric generators (RTGs), the long-term vision foresees to return to Enceladus, Europa and Titan through a series of missions that can ultimately shed light on the actual presence of elementary life forms in the watery environments of those worlds.

Icy giants: Uranus and Neptune

The ice giants Uranus and Neptune and their satellite systems remain to date largely unexplored. Most of our understanding of these worlds relies on data provided by the brief visits of the Voyager 2 mission more than 30 years ago. The very existence of these planets poses a conundrum when considered in a broader context of the known family of planets in our Galaxy. Their limited gaseous envelopes have long been interpreted as an indication that their formation occurred close to the dissipation of the solar nebula, which prevented them from accreting larger quantities of nebular gas like Jupiter and Saturn. However, such a limited temporal window for their formation is at odds with the large abundance of planets similar to Uranus and Neptune among the discovered exoplanetary population. The exploration of Uranus and Neptune is therefore a critical step to understand their origins and shed light on the formation process on one of the most abundant classes of planets in our Galaxy. Moreover, while the two planets are considered members of the same planetary class based on their shared characteristics, each of them is unique in many respects. The limited internal heat flux of Uranus results in a sluggish atmosphere, while Neptune's atmosphere is extremely dynamic and characterised by powerful winds. Both ice giants have complex magnetic field configurations, but the large obliquity of Uranus allows for unique interactions with the solar wind. Neptune's satellite system has been completely reshaped by the capture of Triton, a geologically active former trans-neptunian object, while Uranus may be host to a primordial satellite system that, however, shows evidence of a violent past. The exploration of these planets and their satellites would therefore allow us to address scientific questions over a number of disciplinary domains in both planetary and exoplanetary sciences.

The key importance of Uranus and Neptune to advance our understanding of the evolution of our own and other planetary systems has been highlighted over the last 10 years by the rapidly growing number of mission proposals and white papers submitted by the European and international communities. In addition there is a vast amount of international studies performed by space agencies to assess the feasibility of the different proposed mission scenarios (NASA Pre-Decadal Ice Giants Study 2017; ESA CDF Ice Giants Study 2019; ESA EPIG CDF Study 2019, ESA White Papers Voyage 2050, Planetary Science and Astrobiology Decadal Survey 2023-2032). Independent from the different scientific goals of the proposed mission scenarios, all studies agree that a mission to the ice giants is the logical next step in the exploration of the outer Solar System. Two additional elements of consensus are present among all studies performed up to date. First, to address the most fundamental science questions concerning the origins and nature of Uranus and Neptune, the ideal mission scenario for the exploration of one of these two planets should combine an orbiter with an atmospheric probe for in situ measurements. Second, due to the unique characteristics of each of these two planets and their satellite systems, the comparative exploration of both ice giants is critical to understand which characteristics are primordial and shared by ice giants and which are the result of their different and individual histories. Comparative exploration using twin or dual spacecrafts has been assessed as feasible in the framework of a single mission by both ESA and NASA, at the cost of not being able to accommodate an atmospheric probe in the mission scenario. As a result, achieving a full and detailed characterisation of both planets and their satellite systems within the next two decades requires international collaborations between leading space agencies.

However, although these two planets contain many clues to understanding the evolution of the solar system, Uranus and Neptune remain poorly investigated. There are striking differences between these two planets, and also between them and the other two massive planets. They represent a class of planets that is not well understood, and which is fundamentally different from the gas giants (Jupiter and Saturn) and the terrestrial planets. Ice giants are, by mass, about 65% water and other so-called “ices,” such as methane and ammonia. In spite of the “ice” name, these species are thought to exist primarily in a massive, supercritical liquid water ocean. No current model for their interior structure, including the nature of the planetary dynamo, is consistent with all observations.

The elemental composition of the atmosphere of Uranus and Neptune has to be ascertained as it can shed light on early processes in the solar system. It is still under debate if the core accretion or the gravity instability model explains the interiors of the giant planets. The available measurements of Jupiter, the few ones of Saturn and virtually none of Uranus and Neptune are not conclusive. Something similar is the case for our knowledge of composition of the atmospheric elements, which is crucial to determine the abundances of carbon, oxygen, nitrogen and noble gases (He, Ne, Ar, Kr and Xe) and their corresponding isotopes.

The wind regime in Uranus and Neptune is dramatically different from the one on Jupiter and Saturn. The icy planets have broad retrograde equatorial jets and nearly symmetric prograde jets at high latitude. The origin of this pattern is unknown and none of the current models is able to explain this. Both planets have satellites whose surface is strikingly new. Whereas Triton (a Kuiper Belt Object captured by Neptune) shows cryovolcanic activity, the reason why Ariel and Miranda (natural satellites of Uranus) possess new surfaces is an open question. Furthermore, Ariel and Miranda could host potential subsurface oceans (in addition to the Jovian and Saturnian satellites).

Characterising the structures and temporal changes in the rings, the interior and surface composition of the satellites, the atmosphere of Triton, the solar wind-magnetosphere-ionosphere interactions, etc., are also by themselves key science topics in the exploration of the outer solar system. In situ investigations of the Uranus and Neptune systems must represent a milestone for Europe when aiming for the understanding of the solar system as a whole and in context with other exo-planetary systems discovered in our Galaxy.

Astrobiology, linking the Solar System to Exoplanets

Astrobiology is the study of the origin of life on Earth and the potential for life elsewhere. Astrobiology also includes the search for extraterrestrial life. In this search there are several key questions that need to be resolved to ensure an unambiguous detection:

- How do we define what we are searching for?
- Where should we look for life in the solar system?
- How do we correctly interpret our findings?
- How can we extend our search to exoplanets?

To define what we are searching for we need to look here on Earth, as Earth is the only place currently known to harbour life. The first step is to study the Earth as an exoplanet through field work and laboratory research. Biosignatures include biologically produced gases in the atmosphere and reflection signatures, but also mineralogy only produced through or in the presence of life and organic remnants in a planet’s surface and subsurface materials. Earth is the best place to grasp the full breadth of potential biosignatures. In addition, dedicated space instrumentation shall allow us to observe the Earth-as-an-exoplanet, compressing all our reflected and emitted light into a single “dot” (to paraphrase Carl Sagan), and test our retrieval methods for atmospheric and surface properties, the presence of continents and liquid-water oceans, vegetation, a large range of other biomarkers and technosignatures. Future missions to land on or orbit the Moon (except landing on the far side) constitute an ideal platform for such observations, as the Earth is always up in the lunar firmament, and is being illuminated by our star at all phase angles within a month. Also, e.g., the ISS and deep-space missions could and should be used to obtain crucial benchmark data of our living planet. Strong links between astronomers, Earth scientists and biologists are necessary and many have already been established. It is important to keep fostering these collaborations.

The currently most promising locations within our Solar System to study the possibility for life and its potential presence are Mars, Enceladus, Europa, Venus, and Titan. Each of these bodies has its own niches and, in addition, Venus and Mars represent cases at the extremes of the canonical habitable zone, both with possible past life. Mars missions studying the potential for extinct life should focus on locations where water used to be present. For extant life, caves, subsurface water bodies, and locations with current water activity have been identified as the most targeted locations. Enceladus and Europa, the icy moons with large oceans under a thick ice crust, have an outer surface very hostile to life. The moons’ rocky surfaces underneath the oceans may, however, support similar conditions as Earth’s current or early oceans. In the near future the compositions of these oceans can be studied through analysing the plumes and geysers erupting through the ice crusts. First steps have already been made by the Cassini mission, investigating Enceladus’ plumes. Near-future missions should continue to focus on analysing the composition of the plumes. In the meantime, preparatory studies should be carried out on the potential for probing the ice crust and the oceans below. Recent findings, combining findings on terrestrial microbes with observations of the Venusian atmosphere have once again spiked interest in the potential for life in the clouds of Venus. Before we can make any assumptions on observations of compounds in Venus’ atmosphere, a dedicated Venusian clouds mission shall ensure a much better insight in the chemical and physical conditions of and processes playing a role in these clouds. Titan will be visited soon by DragonFly that will already put some additional constraints on the potential for life in its liquid hydrocarbon lakes.

Now that we have identified how to define what we are searching for and where to search in our solar system, the next big step to take is to correctly interpret our findings. Life produces many signals that individually may hint towards life, but may also have many other origins. We need to avoid misconceptions that can easily arise through the multidisciplinary approach of the search for extraterrestrial life, potentially leading to false claims of life detection, and to pave the way for optimal interpretation of (near)- future findings, and to eventually identify extraterrestrial life. We therefore need an overarching unambiguous interpretation of terrestrial data and data that we will receive in the next few years with upcoming Solar System missions and exoplanet detection and characterization missions, an interpretation that will be accepted by all scientific disciplines. For this we need to develop a common language and classification of biosignatures that is agreed upon by all participating disciplines.

The solar system is only one of very many planetary systems that we can observe. By merging the fields of planetary science and exoplanetary astronomy (see Panel Report E) we can extend our search for life to exoplanets. Most notably in the form of “comparative planetology”, putting new exoplanetary discoveries in the context of the solar system as a whole, and also specific solar-system planets. The solar system seems to be an atypical case, even among the already huge diversity of exoplanetary systems currently accessible to detections. And of course, the solar system hosts the only planet currently known to harbour life. However, and rather thanks to our privileged position to observe this particular planetary system from within in great detail, solar-system studies remain of vital importance for exoplanetary astronomy and the search for life.

First, indirect exoplanet detection approaches (both the radial velocity and transit methods) are now fundamentally limited by stellar activity that can mimic or obfuscate the signals of the presence of exoplanets in starlight. Studying and understanding the Sun-as-a-star is therefore crucial to mitigate these effects and discover small, rocky exoplanets on long orbits around Sun-like stars that can potentially harbour life. Second, observations of solar-system planets can prepare us for future observations of exoplanets, whether they are fully comparable or not. Third, conditions for life may also be present elsewhere in the solar system, for instance in subsurface water oceans of icy moons like Europa and Enceladus, and possibly also in Titan’s liquid hydrocarbon lakes. This would greatly expand the available search space for life in exoplanetary systems. Dedicated observations of and missions to those moons should inform the observational strategies of exomoons and associated exorings.

More generally, solar-system studies and exoplanetary research are converging to address fundamental questions about habitability, the origin and evolution of life, and how diverse and widespread life could be. Observations of young and mature exoplanetary systems will soon probe AU-scales, and thus provide essential insights into the formation of our own planetary system, and the conditions and ingredients for (early) life on at least one of its planets. Vice versa, understanding the conditions for (possible) life in all unlikely places on Earth and elsewhere in the solar system is crucial to prepare us for the search for life on exoplanets and/or exomoons. In particular, we need to understand (through observations, lab experiments and simulations) to what extent harsh environments (e.g., due to stellar flares and space “climate”) can be ruled out for life, and which stabilising factors (shepherding planets, stabilising moons, planetary magnetic fields, atmospheric absorption, etc.) provide sufficient comfort for life to evolve.

Most importantly, being able to ask relevant questions about the possibility of extraterrestrial life in the solar system and/or beyond demands a fundamentally interdisciplinary approach. This research does not only bring together astronomers and planetary scientists, but also Earth scientists (climate/atmospheric scientists, geoscientists, etc.), chemists, biologists, ecologists, (applied) physicists, engineers, etc. It is therefore crucial to form new interdisciplinary research and educational structures to learn each others’ languages and to learn how to ask really relevant questions that address all pertinent aspects. Moreover, the possibility of detecting first signs of extraterrestrial life demands an intimate collaboration and public engagement with scholars in the humanities, philosophers, artists, and indeed society-at-large, to instil the significance of such a ground-breaking discovery in the broadest possible sense for all of humankind.

G Extreme astrophysics

Astrophysics at the Extreme

Many astrophysical systems attain extremes of physical parameters that exceed those of everyday life and any Earth-bound experiment. The most exotic of these conditions commonly exist within and around compact objects – white dwarfs, neutron stars, and black holes (Figure 1). The compactness of these objects naturally creates extremes of density and strong gravitational fields. At the same time, this strong gravity yields a raft of other physical processes related to the infall, accretion and outflow of material. These systems then provide a route to probing extremes of gravity, density, energy, temperature, velocity and magnetic field (Figure 2).

The emission from such objects is often luminous and non-thermal: spanning from the longest-wavelength radio waves to the highest-energy gamma-rays. Extreme astrophysics was transformed by the multi-wavelength revolution that swept through astronomy in the second half of the twentieth century, starting with the identification of radio-loud Active Galactic Nuclei (AGN) and quasars. The serendipitous discoveries of pulsars, X-ray emission from black hole X-ray binaries and gamma-ray bursts all happened thanks to our ability to probe across the electromagnetic spectrum and time domain. New objects, such as fast radio bursts (FRBs), that test our understanding, continue to be identified as our observing capabilities improve. Future gains come from multiple directions. Our current capabilities will expand via wide-field, multi-wavelength surveys with depths matching those currently only attainable by premier narrow field observatories (e.g., VRO, Euclid, MeerKAT). Alternatively, smaller facilities with a cadence or field-of-view that allow a wider parameter space to be explored can identify some of the rarest but astrophysically insightful sources including rare supernovae, fast radio bursts, gamma-ray bursts, stellar mergers, tidal disruption events, extreme AGN variability (e.g. wide-field fast optical surveys, CHIME, eROSITA). These surveys will find many new objects for intensive follow-up with dedicated facilities (e.g. XMM-Newton, Swift, VLT, Chandra, JVLA, EVN). Simultaneously, the next generation of flagship facilities will push far deeper into the physical conditions within individual systems, providing stringent tests of our current understanding of extreme astrophysics (e.g., Athena, IXPE, SVOM, ELT, SKA, EHT, CTA).

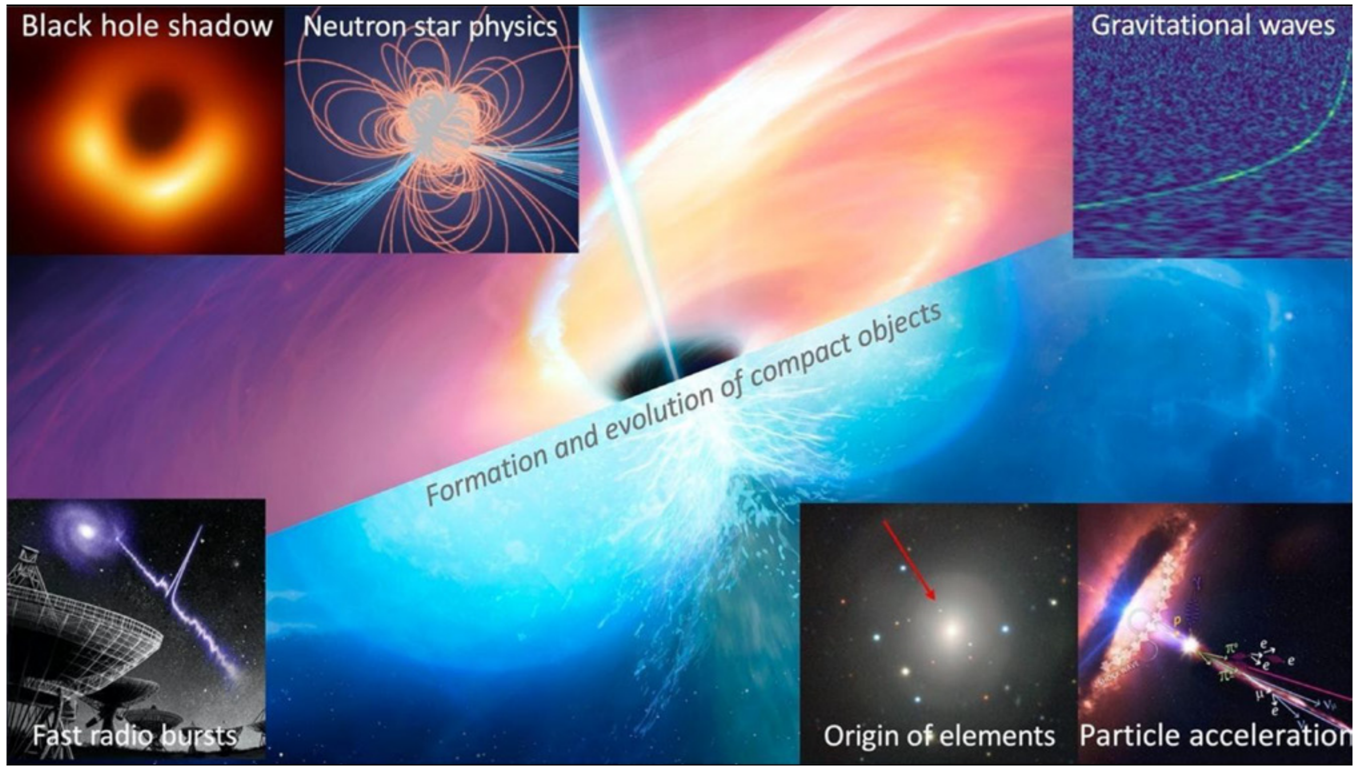

Figure 1

Core questions and tools for extreme astrophysics. A central theme is the use of compact objects to access physical conditions beyond those attainable anywhere else in the Universe, and to use these to address a range of questions in contemporary physics and astronomy.

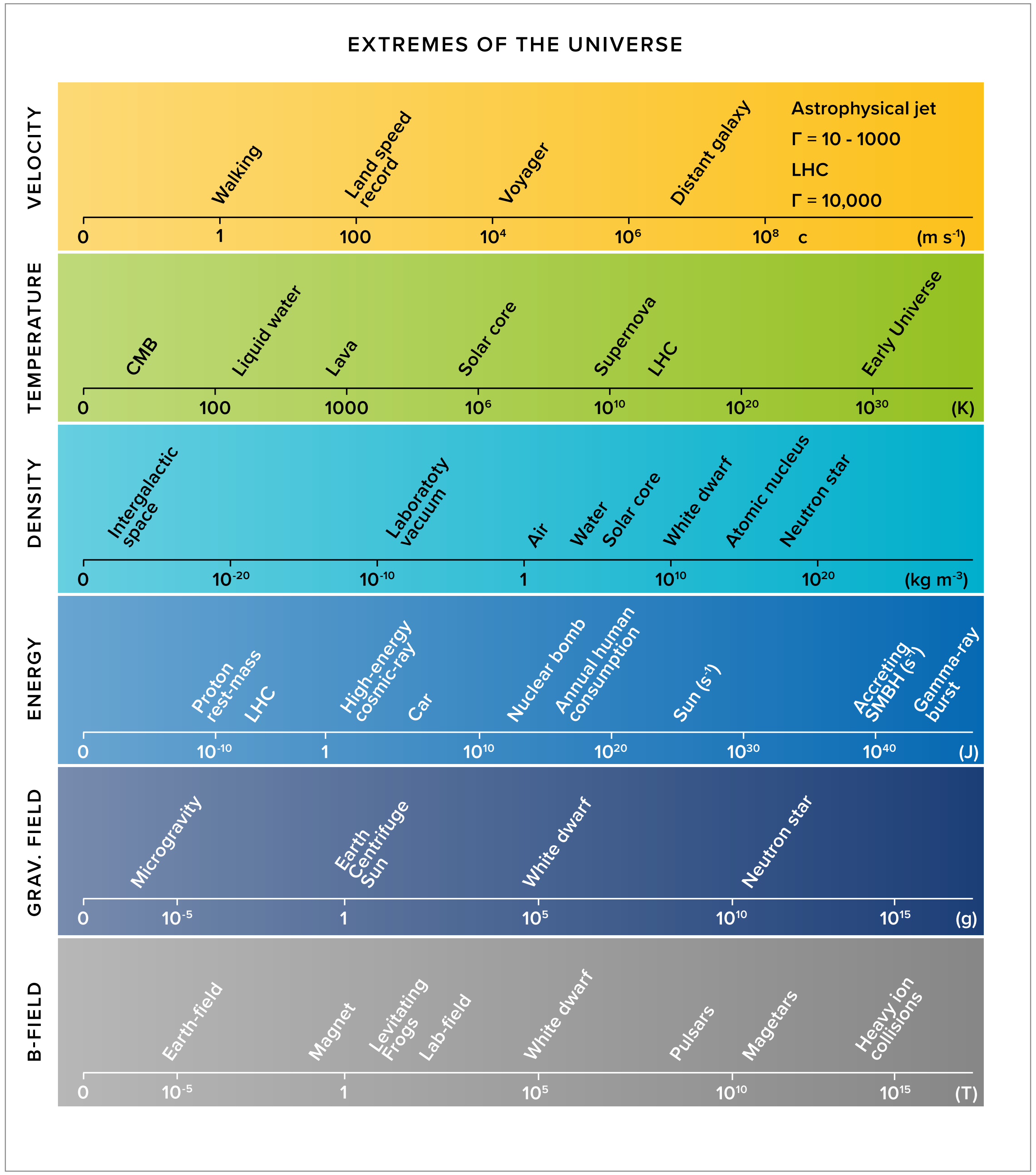

Figure 2

The extremes of the Universe. The figure shows the range of physical parameters (velocity, temperature, density, energy, gravitational and magnetic field) that can be found in Earth-bound locations, and in different astrophysical conditions. Conditions in and around compact objects are far more extreme than everyday experience and often lie beyond the reaches of Earth-bound experiments. Hence, these systems provide powerful laboratories to test physics and astrophysics to its limits.

While physical conditions at their most extreme exist in many systems, they are sometimes hidden from observations using electromagnetic radiation. Here, new techniques and messengers offer a route to the understanding of highly complex and astrophysically rich systems (Figure 3). Gravitational waves provide a means of directly probing the behaviour of mass; at the same time, the generation of neutrinos in core-collapse supernovae offer direct real-time insight into the physical processes at play in merging or collapsing stars.

Thirty years on from the first multi-messenger signal – identifying neutrinos from SN 1987A – we have finally succeeded in observing light in tandem with both gravitational waves, and likely high-energy neutrinos. Gravitational waves and neutrinos become powerful probes of extreme phenomena, especially if paired with more traditional electromagnetic observations.

The capabilities of gravitational wave detectors are rapidly improving: gains in sensitivity of several orders of magnitude and new energy/frequency windows are opening with upgrades to ground-based detectors (e.g. LIGO/VIRGO/KAGRA) and new ground- and space-based facilities (e.g., LISA, ET). A new generation of neutrino detectors is offering similarly enhanced prospects (IceCube, Antares/KM3NeT, Baikal-GVD).

These improved capabilities will expand this work from single-source detection to samples of tens to hundreds of objects. With such samples, we have an unprecedented opportunity to make decisive progress towards addressing the many issues that such observations can impact, from the equation of state of neutron stars, to the origin of heavy elements, the growth and merger history of black holes and the very limits of general relativity.

Extreme conditions also create the opportunity to probe new physics. Dark matter should cluster strongly around very massive objects. The interaction of dark matter with either those massive systems or with itself in regions of sufficient density can provide a route to finally identifying its nature. Annihilations or decays resulting in neutrinos can be probed, with heavy dark matter decays a possible candidate for the origin of some of the observed high energy neutrino flux. Minute differences in the speed of light as a function of energy, or between the speed of light and that of gravitational waves or neutrinos, are greatly amplified by the very long path lengths to extragalactic sources, providing exquisite probes of some quantum gravity models (by so-called Lorentz factor violation).

The next decade offers the opportunity to consolidate the gains of the past years and use new facilities and capabilities to make decisive progress towards answering the many questions that remain open. The nature of the emission from extreme physical systems often requires combining data and observations from many sources. In most cases, answering fundamental questions about their nature requires state-of-the-art facilities, but interpreting the results requires more routine observations in tandem. Therefore, this science is best achieved by employing a broad portfolio of multi-wavelength and multi-messenger facilities that can operate both alone or in concert. Such an endeavour benefits from the highly collaborative nature of the high-energy astrophysics scientific community that is accustomed to managing and running large international collaborations, necessitated by the very complex nature of their experiments and observatories.

This chapter outlines the core scientific questions that this field will face in the next decade, and possible routes to tackling them.

What is the nature of matter at nuclear densities?

The central densities of neutron stars exceed the density in atomic nuclei. As such, testing the properties of their interiors provides quite possibly the only realistic route to test fundamental physical theories in the most extreme regimes of supranuclear density and high magnetic fields. This includes regimes where collective and quantum effects become important. The goal of such studies would be the determination of matter’s equation of state (EoS) at extreme densities, which cannot be derived from first principles. Neutron stars provide a natural target for these studies. The simplest approach to distinguish between possible theoretical EoS is to pin down the mass-radius relation of neutron stars (e.g., Figure 4).

Progress towards this goal is being made from several directions. For example, high time resolution X-ray observations (e.g., the NICER instrument on-board the International Space Station) can create maps of neutron star surfaces and directly measure their radii. Future endeavours will build upon this capability to enlarge the sample of neutron stars for which such measurements can be made, and will provide a higher signal to noise within the existing samples. Likewise, timing observations of radio pulsars continue to provide high-precision mass measurements, which in some cases push the limits of what is possible for most proposed equations of state. Indeed, millisecond pulsars are often found to have larger masses than the canonical 1.4 solar masses, likely (in part) because they have accreted from a stellar companion. The discovery of ultra-fast-spinning millisecond pulsars (well beyond the current record of 716 Hz) could also help constrain the maximum radii of neutron stars.

A more precise approach would be to study proper oscillation modes of NSs. Frequencies of those modes and their damping time would serve detailed information about internal structure of NS and so potentially provide very tight constraints on EoS. Quasi-periodic oscillations (QPO) have been seen in the emission of isolated NSs, e.g. following magnetar bursts. To unambiguously identify such QPOs as manifestations on NSs oscillations, rather than magnetospheric modes, and reliably estimate their damping times further development of theoretical models of NS magnetospheres is needed.

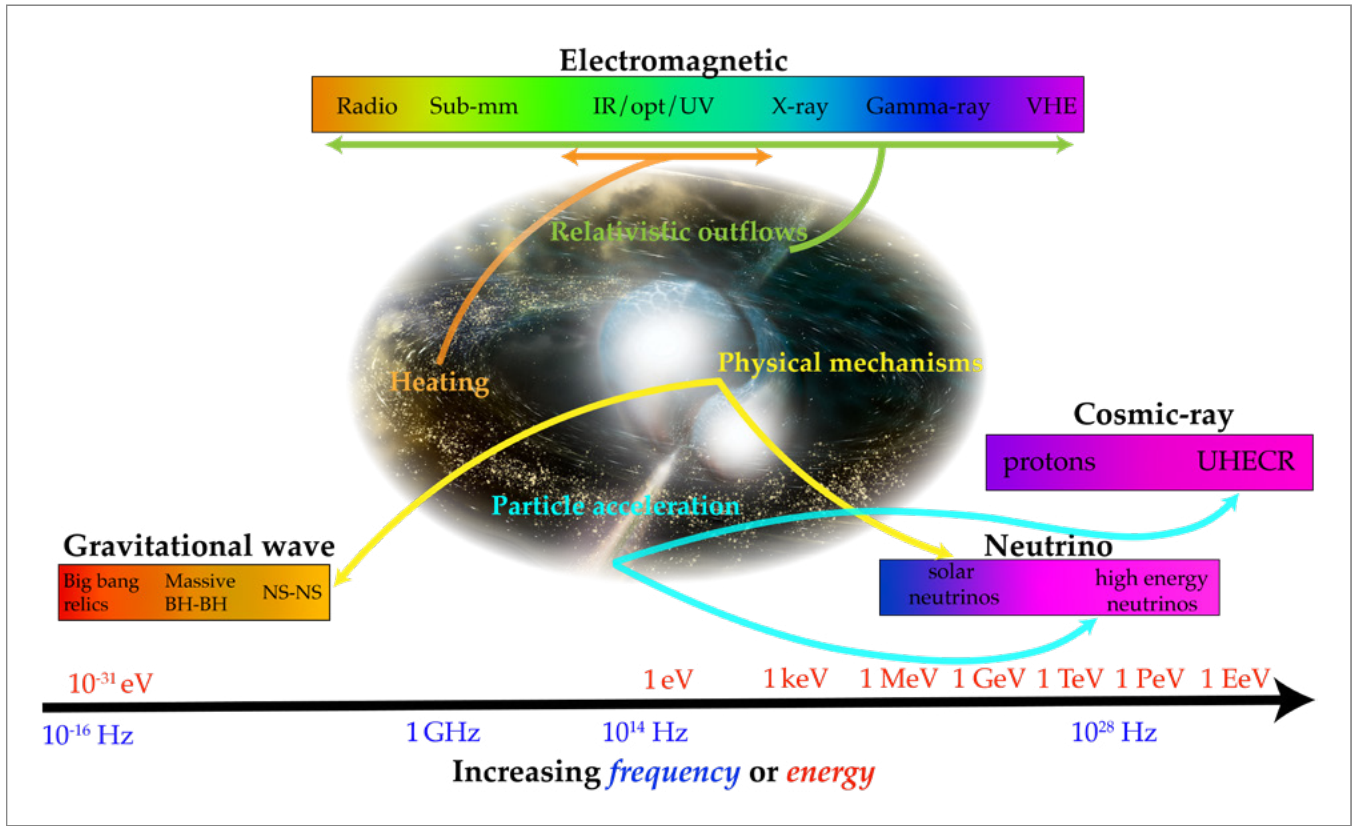

Figure 3

The spectrum of astrophysical messengers. In addition to multi-wavelength observations that probe the generation and dissipation of energy within extreme events, the addition of non-photonic information in the form of gravitational waves, neutrinos or cosmic-rays enables a far more complete picture of the physics in a given event. The figure shows a binary neutron star merger, but many systems will generate detectable multi-messenger signals in the next 10-15 years. Gravitational waves and neutrinos carry information from regions inaccessible to electromagnetic observations at any wavelength.

Central image credit: NSF/LIGO/Sonoma State University/A. Simonnet

In addition to studying the emission from isolated neutron stars or millisecond pulsars, studying the motion of matter around accreting neutron stars in binary systems via high time-resolution studies of the quasi-periodic modulation in the X-ray/Optical-UV flux can help constrain the EoS of neutron stars. This is because orbits in the vicinity of the compact object are strongly sensitive to the space-time properties, which in turn strongly depend on the mass, spin, radius and internal structure (in the case of neutron stars) of the collapsed object.

Investigations of the EoS is also supported by Earth-based high-energy measurements at accelerator facilities (CERN LHC, FCC, BNL RHIC, GSI FAIR, NICA). Present and future giant experiments (e.g., ALICE, STAR, CBM) connected to the heavy-ion colliders can complement the sky-based EoS-exploration by probing the hot version of the superdense matter of neutron stars. Matter, which existed in the early Universe microseconds after the Big Bang, can be re-created in microscopic droplets in Little Bangs to explore the phase structure of the strongly interacting nuclear matter. This can further constrain our celestial knowledge on neutron star matter, strange quark and hybrid states, or phases slightly before neutron stars merge to form a black hole.

Gravitational waves offer multiple alternative routes to the measurement of the neutron star equation of state. In a binary merger involving a neutron star, the strong interaction between the coalescing objects creates a tidal deformation, which changes the shape of the neutron star. That in turn imprints specific signatures in the resulting gravitational wave signal. To date, only upper limits on the neutron star deformability are available, the most striking coming from the source GW170817. Such constraints, while extremely valuable, only rule out extrema in plausible mass-radius relations. The determination of the nature of the remnant following the merger provides the test of the equation of state at the highest mass end. Discriminating whether a (possibly short-lived) neutron star, or a black hole is formed is possible through a range of observations. For example the gravitational-wave ring-down can give a direct measurement. Alternatively, energy injection from a neutron star can dramatically change the appearance of the electromagnetic counterpart, even if it is only active for milliseconds before collapse. Future progress in this field requires the identification of many more mergers that span the true astrophysical range of properties (e.g., masses, mass ratios, spins). The planned upgrades to the LIGO, VIRGO and KAGRA interferometers will provide this possibility with an expected source identification rate an order of magnitude larger than in previous observing runs, while in the future new interferometers such as the ET will bring a leap forward in sensitivity of several orders of magnitude. As sensitivity further increases, asymmetries in Galactic neutron stars may become apparent in the gravitational wave signals. Finally, specific variability patterns in the X-ray light curves of short GRB afterglows may point to the existence of a solid crust in the neutron star-merging remnant. They could be routinely detected by a large-area X-ray observatory such as Athena if identified by a suitable GRB detecting mission.

Key current facilities:

Chandra, eROSITA, ground based 4-8 m telescopes, HESS, JVLA, LIGO/VIRGO/KAGRA, LOFAR, MAGIC, MeerKAT, neutrino detectors, NICER, Swift, XMM-Newton

Facilities in development:

Athena, CTA, ELT, eXTP, SKA

Where are the heavy elements made?

It is now more than 50 years since a series of seminal papers pinpointed the physical pathways that create the heaviest elements. They are based on “neutron capture” processes, whereby seed nuclei capture neutrons and subsequently undergo a beta-decay to move up the periodic table. The origin of slow captures is now reasonably well understood. However, identifying sites for the so-called rapid capture, or r-process, remains a challenge, although this route produces almost half the elements heavier than iron and virtually all the elements heavier than gold.

Recent progress from the abundances of metal-poor stars in the Galactic halo, the presence of r-process material in dwarf galaxies, and even the replenishment of radioactive plutonium in sea sediment, have demonstrated that normal supernovae are not major r-process factories. This suggests that this material is generated by rare events (one per Galaxy per 10^5 - 10^7 years) with relatively high yields (0.01-1 solar masses). The most promising sites for this production are in unusual supernovae or merging binary neutron stars. In supernovae, the necessary conditions may arise in so-called magnetohydrodynamic (MHD) supernovae or in the accretion disks surrounding nascent black holes in engine driven supernovae, such as those accompanying long-duration gamma-ray bursts. Merging neutron star binaries also create neutron-rich environments. They eject perhaps 0.1 Solar masses of material in tidal tails during the merger, and more mass is propelled in a polar direction by a disk-wind following the merger.

Identifying a kilonova as the multi-messenger counterpart of the gravitational wave detected binary neutron star merger, GW170817, provided the first unambiguous evidence for the site of r-process material (Figure 5). Furthermore, the bulk properties of the counterpart matched the expected theory of heavy element production closely. Here, the complex electron structures in the heaviest elements (e.g. the lanthanides and actinides) blanket optical radiation, yielding a short-lived transient that rapidly transitions from blue to red.

However, while the identification of the kilonova in GW170817 provided evidence for the r-process, we do not know if merging neutron stars produce some, most, or all of the r-process material. Progress in the coming years will require the honing of merger rates, detailed studies of supernovae and kilonovae and improvements in our theoretical understanding and modelling capabilities. Such improvements should arise due to the increase in capability of gravitational wave detectors to locate and localise many more mergers, combined with ground- and space-based follow-up observations. Short GRBs may provide an additional route to this diagnostic, and JWST can study their kilonovae, potentially out to z~1. Finally, we must also determine the contribution (if any) of supernovae to the r-process. However, the expected signals are complex to predict, and so a robust observational effort must also be paired with investment in the modelling necessary to predict the signatures that may be visible and to extract meaningful outputs (e.g. yields) from observations.

Key current facilities:

Chandra, HST, JWST, LIGO/VIRGO/KAGRA, Swift, VLT, Wide-field optical/IR facilities, XMM-Newton

Facilities in development:

Athena, ET, New wide-field facilities, VRO, SVOM

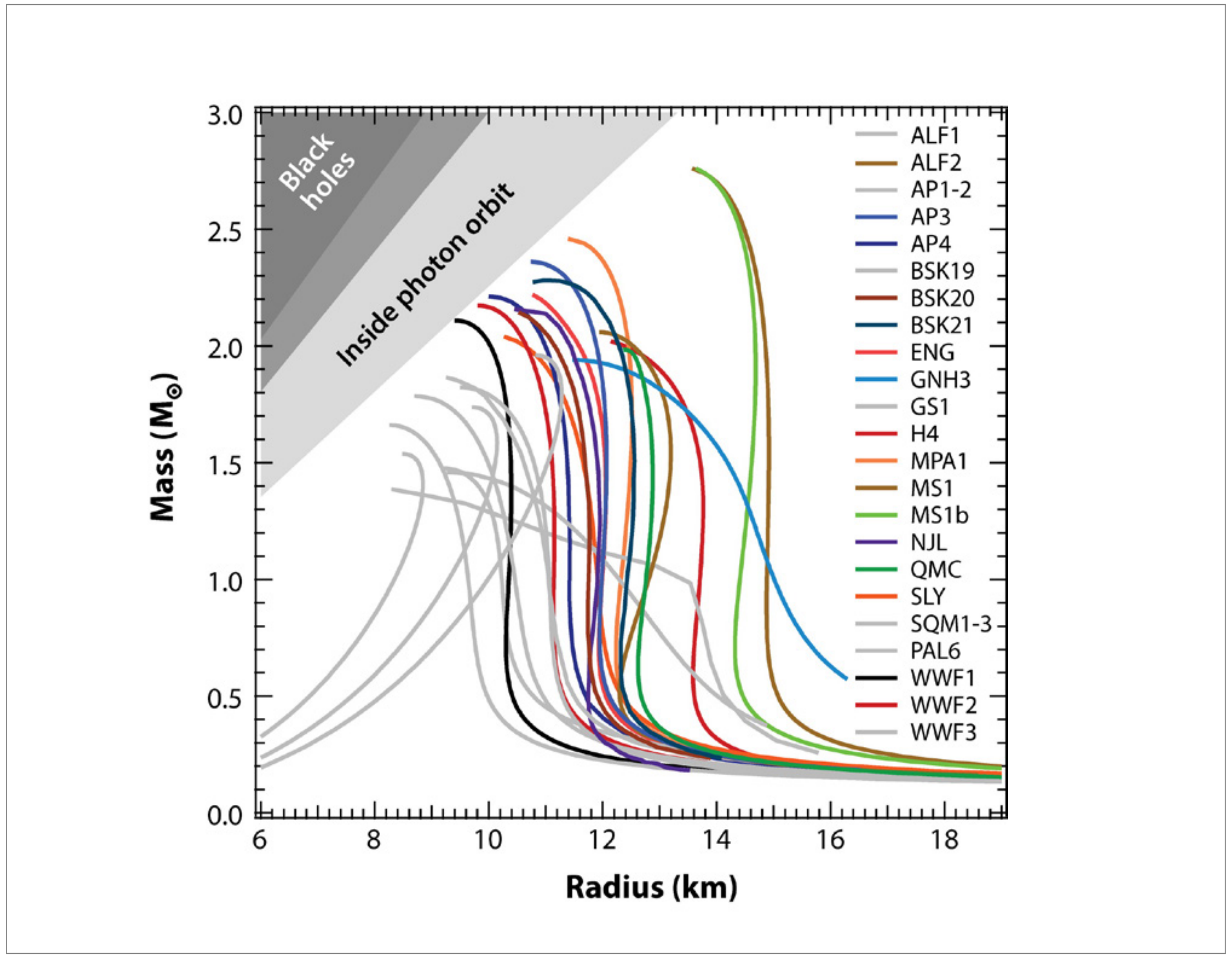

Figure 4

Proposed variants on the neutron star mass-radius relation. Our inability to write down the equation of state of dense matter from first principles leads to a number of plausible mass-radius relations form neutron stars. These predict radii for a given mass that differ by a factor >2 in some cases (or densities that vary by an order of magnitude). Hence, direct measurements of multiple neutron star masses and radii from a raft of current and upcoming observations can narrow the range of plausible models, in turn informing our knowledge about the behaviour of matter at the highest densities possible.

Credit: Özel & Freire, 2016, Annual Review of Astronomy and Astrophysics, 54, 401

How do compact objects produce energy and accelerate particles at all scales?

Compact objects (from white dwarfs to AGN) are powerful astrophysical engines: strong gravity accelerates infalling matter converting the gravitational energy into radiative and mechanical energy via accretion. Rapid rotation and strong magnetic fields are the roots of extreme physical processes, such as the formation of accretion disks, fast collimated jets, and powerful winds. The understanding of these processes is crucial to test the very edges of our physical understanding of the Universe. Probing these phenomena requires state-of-the-art observations to capture the most extreme radiation, as well as non-photonic messengers such as gravitational waves, neutrinos and high energy cosmic-rays. A complete interpretation frequently requires confronting these observations with complex numerical models (like General Relativistic Magneto-HydroDynamics; GRMHD) that attempt to capture the full complexities of the physical systems.

The majority of discrete sources observed outside the UV/Optical/IR window emit radiation that is not thermal. In many (but by no means all) cases, the energy for that emission ultimately arises from power formed via the accretion of material onto some central compact object. The resulting radiation comes from a raft of non-thermal (and occasionally extreme thermal) processes, including the generation of synchrotron shocks, Bremsstrahlung radiation, and inverse

Compton scattering. The radiation is generated at differing locations, including the innermost regions of accretion disks (emitting mostly in the X-rays) where strong gravity becomes paramount. A large fraction of the emission from accreting objects arises further out in the accretion disks, in thin and diffuse material around them, and even in outflowing material. Our picture of the accretion geometry on different scales comes from piecing together multi-wavelength, time-resolved and polarimetric observations to create a coherent physical model. In turn, this allows us to both follow the accretion of material and use these observations to infer the fundamental properties of the compact objects, such as their mass and spin, which in the case of a black hole fully characterise the space-time around it. The innermost regions surrounding the event horizon remained unresolved until the first images of the black holes "shadows" in M87 and Sgr A* by EHT were published. X-ray interferometry has the potentiality to extend such a sharp view to the highly-energetic phenomena occurring in the innermost regions of the accretion disk and the hot corona in accreting black hole systems, or unveil the history of activity in recurrent active supermassive black holes. X-ray interferometry was identified by the European Space Agency in the framework of its recent "Voyage 2050" exercise as a key space technology enabling innovative science, for which a detailed plan of action will be defined in the near future in collaboration with the European science community.

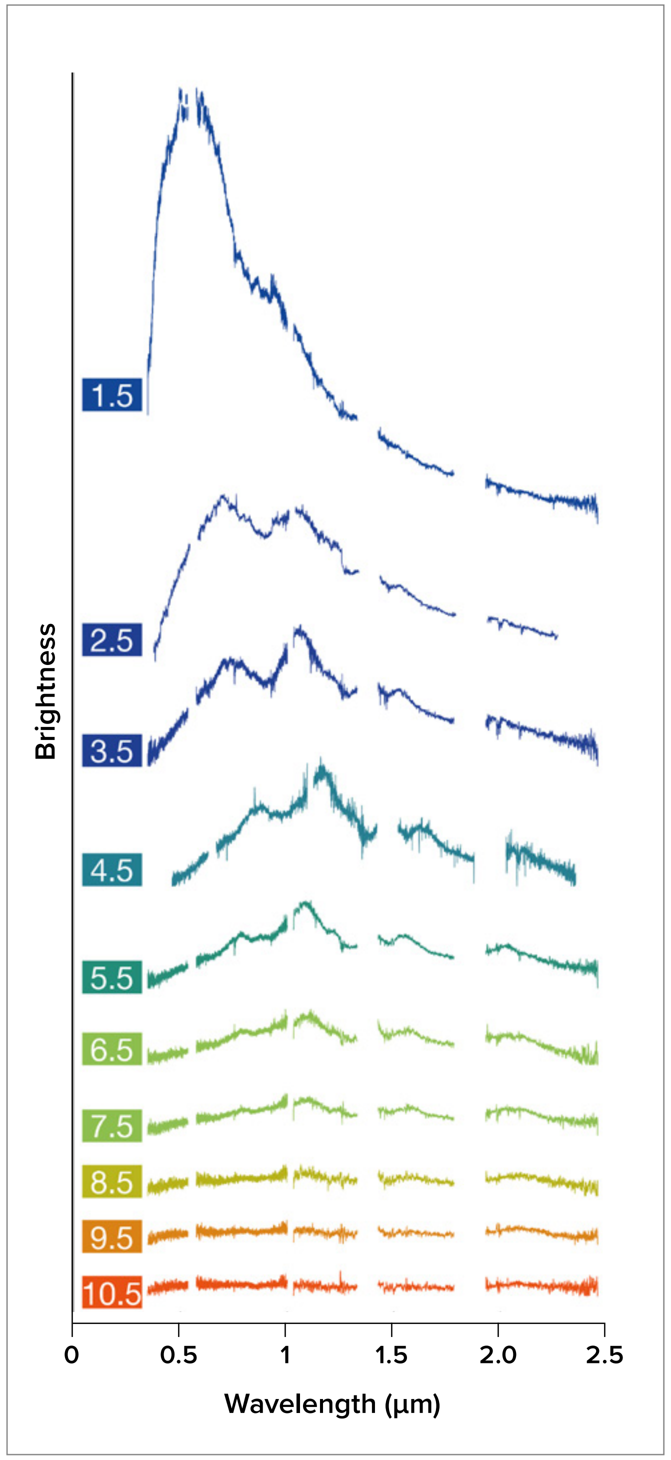

Figure 5

The VLT/X-shooter spectral series of the electromagnetic counterpart of the binary neutron star merger GW170817. This shows the first spectral sequence of a so-called kilonova. The striking feature is the development of broad IR features created by the synthesis of very heavy elements.

Credit S. Smartt, E. Pian and ESO.

One crucial area in understanding accretion is how it proceeds at rates substantially higher than the Eddington limit. The vast majority of sources observed accrete below this limit, but some appear to exceed it, sometimes even by orders of magnitude. While this may sometimes be the result of a geometric effect (e.g. beaming), which reduces the isotropic luminosity, such high rates are inevitable in other cases. Indeed, super-Eddington accretion may be needed to explain the growth of the most massive black holes in the early Universe. Observations that could test the super-Eddington regime can be made by ascertaining the nature of many so-called ultra-luminous X-ray sources, studying accretion processes following the tidal disruption of stars by supermassive black holes, by identifying the frequency of quasars associated with very massive black holes in the early Universe, and even by studying the evolution of material falling into the central compact object in supernovae, gamma-ray bursts or compact object mergers. Particular insight is possible in studying systems, at all masses, which vary on human timescales between the different regimes and so directly probe different accretion modes around the same compact objects (e.g. tidal disruption events, changing look AGN, GRBs).

Accretion is frequently accompanied by outflows, most prominently in the form of jets, which are seen in accreting systems from white dwarfs and protostars through to neutron stars, stellar-mass black holes and supermassive black holes. The ubiquity of the jets, their acceleration mechanism as well as composition, structure, and role in the acceleration of the highest energy particles are all open issues in the field that need answering. Furthermore, different types of jetted systems enable the jet ejection mechanism to be studied by following different approaches. We can observe from large extended jets around AGN that can be resolved, in some cases down to the inner accretion disk that launches the jet (e.g., in M87, Figure 6) to the (mostly) unresolved jets associated with gamma-ray bursts. Studies of these jets may be time-resolved, photometric, spectroscopic or polarimetric and can span a large energy range, from radio to the very high energy gamma-rays. Several AGN and GRBs have been detected with Cherenkov detectors, and we expect many more such detections in the years to come. In addition, we now have an increasing number of indications of potential associations of very high energetic neutrinos with blazars. Jets in blazars are also a primary target of future X-ray polarimetry explorations by determining their geometry and the emission mechanism.

In addition to jets, which are highly collimated and often reach relativistic velocities, different types of winds are common around compact objects. While being perhaps less spectacular than the violent radio jets, these outflows can carry a very significant amount of energy and, most notably, mass. Disk-winds may carry away enough mass from the accretion disk around stellar mass black holes and neutron stars to temporarily stop accretion thus ending their active phases, and may be responsible for a considerable fraction of the intermediate-mass r-process elements in merging neutron stars. Pulsar wind nebulae provide a dramatic example of outflows around neutron stars, and may play important roles in particle acceleration, with particular relevance for the so-called positron excess observed by several orbiting experiments. Future observations, including those with X-ray polarimetry, should add insight into their role as accelerators. Around supermassive black holes, sub-relativistic winds are thought to have a major role in the AGN feedback together with jets, and to significantly impact the evolution of galaxies. A key role in the study of feedback by sub-relativistic AGN outflows will be offered by high-resolution X-ray spectroscopy by, e.g., X-ray micro-calorimeters. They will enable the whole structure (in dynamics and ionisation parameter spaces) of the outflow to be studied, accurately determining the energy and mass loading and therefore estimating precisely their contribution to AGN feedback, even at high redshift.

Of particular interest is the supermassive black hole in the centre of the Galaxy itself. Here the fundamental parameters can be inferred with unprecedented accuracy. This supermassive Black Hole shows very little in terms of jet activity. It could be starving, or possibly its lack of activity could be linked to its spin properties, but a critical question remains in ascertaining if jets are powered solely by accretion or also via tapping the spin. The combination of IR stellar astrometry (or the detection of pulsars orbiting SgrA*) with millimetre VLBI imaging could provide unique results here. The dense reflecting nebulae surrounding SgrA* can also be investigated through X-ray polarimetry to provide a 3-D tomography of the nuclear environment, while unveiling the activity history of our own black holes in the last few hundreds years.

While accretion powers the visible emission of many compact objects, there are others where it does not. The emission from isolated neutron stars arises from the rotation of the neutron star itself and the interaction of the neutron star and its crust with the powerful magnetic fields. Although the "persistent" emission from such systems is generally reasonably well explained, we still have far poorer understanding of outbursts, especially from systems with extreme magnetic fields – the so-called magnetars. Indeed, although we have studied only ~30 magnetars within our own Milky Way, they have been invoked with some success as engines powering many transient extragalactic astrophysical systems, including GRBs, luminous supernovae and fast radio bursts.

Emission of isolated neutron stars (NS) - pulsars and magnetars - is not powered by accretion, but by their macroscopic electromagnetic fields. Practically all the emission we receive from isolated NSs is generated in their magnetospheres. Physical processes in magnetospheres of isolated NSs include acceleration of particles to ultrahigh energies, creation of electron-positron pairs, and complex physics of high-energy astrophysical plasma in strong magnetic and electric fields, all of which can not be directly studied in Earth-based laboratories. GR effects also seem to play an important, if not crucial, role in pulsar emission mechanisms. Hence, isolated NSs can be considered as natural testing beds for quantum electrodynamics and plasma physics in regimes of ultra strong electromagnetic and strong gravitational fields. Although thanks to advances in computational methods a remarkable progress has been achieved in this field in the past two decades, reliable quantitative models of NS magnetospheres are still missing. Additional theoretical efforts are required in this field.

From an observational point of view, X- and gamma-polarimeters can provide crucial information about physical processes in NS magnetospheres, as emission is expected to be highly polarised along magnetic field lines. Polarisation information would be the only practical way to experimentally infer spatial localization of emission regions in NS magnetospheres because of their small sizes. Inner parts of NS magnetospheres are not transparent to gamma-rays above several tens of MeV, therefore, new generation of MeV gamma-telescopes with enough sensitivity and spectral resolution to observe emission from pulsars and magnetars could provide a crucial direct information about physical processes close to NS surface where particle acceleration is expected to happen. Important information about the mysterious pulsar/magnetar coherent radio emission mechanism(s) can be obtained with current and next generation radio telescopes, such as SKA, which, on one hand thanks to wider field of view should find more radio emitting NS with potentially helpful peculiar properties, on the other hand, thanks to higher sensitivity could study properties of coherent radio emission on much smaller temporal scales for a large number of objects.

Key current facilities:

Chandra, eROSITA, EVN, ground-based 2-8 m telescopes, HESS, HST, IceCube, JVLA, KM3NeT, LIGO/VIRGO/KAGRA, LOFAR, MAGIC, MeerKAT, NICER, Swift, Wide-field optical/IR facilities, XMM-Newton.

Facilities in development:

Athena, CTA, ET, eXTP, LISA, New wide-field searches, SKA, SVOM, XRISM.

What is the origin of cosmic rays of all energies?

The origin of cosmic rays of all energies, from sub-GeV to >100 EeV, is a century-old mystery still waiting for an answer. The wealth of high precision data collected in the last decade has helped to clarify many aspects, providing exquisite measurements of features in the cosmic-ray energy spectrum and a determination of cosmic-ray composition into protons, nuclei, electrons, positrons and anti-protons. At the same time, this complexity raises more questions.

For example, it remains unclear which Galactic sources create the so-called PeVatrons, able to accelerate protons up to PeV energies. Can all these particles originate from supernova remnants, or do additional accelerators exist? The recent detection of VHE gamma-rays from a Galactic nova is a potentially important indicator in this regard. Also very exciting is the very recent discovery of sources emitting >100 TeV photons and the possible association of at least one of these with the Young Massive Star Cluster in Cygnus, already known to be a cosmic ray source at lower energies. In the next few years, sensitive searches of the Galactic plane with CTA should provide a complete census of young supernova remnants and other persistent accelerators. Further measurements and associations of high energy neutrinos with cosmic sources will independently probe the underlying nature of the acceleration processes and clearly discriminate between leptonic and hadronic scenarios.

Cosmic-rays are deflected by the large-scale Galactic magnetic field and by more complex magnetic structures (i.e. both smooth and chaotic fields exist). Propagation through the Galaxy affects the cosmic ray spectrum and composition. In order to derive their properties at injection, from what we measure at Earth (Figure 7), propagation must be properly understood and modelled. Better models of cosmic-ray propagation, ideally directly informed by the large- and small-scale structure of the Milky Way's magnetic field will significantly aid this endeavour. Cosmic-rays have also been recognized to have a relevant role in galactic dynamics, being likely an essential agent for the launching of galactic winds, which in turn expel gas, with an impact on star formation and on the enrichment of the intergalactic medium. This complex chain of dynamical relations is far from understood and requires dedicated theoretical and observational efforts.

The formation of halos of TeV emission around energetic pulsars due to electron escape is an expected consequence of the particle acceleration process, although the data suggest particle transport is much slower than expected. This phenomenon has been detected in a small number of objects, and hence their role in the diffusion of energetic particles in the Galaxy is still to be assessed. Future detections of diffusive halos will help to place constraints on the models.

Several experiments have identified a so-called positron excess in which the local (i.e. around Earth) number of positrons observed is significantly higher than models predict. An exotic prospect is that these positrons arise from the annihilation of Weakly Interacting Massive Particles (WIMPs). Such a result would be of critical importance but is also highly controversial. The most accredited alternative prospect is that pulsars and pulsar wind nebulae accelerate these positrons, which could be indicated by the presence of TeV halos mentioned above. However, the crucial distinction between these possibilities remains to be made. This work requires a census of likely acceleration sites and the measurement of the positron energy spectrum beyond its current limits.

Finally, we still have to confirm the origin of the very highest-energy particles in the Universe. While rare, these highest-energy cosmic rays have macroscopic energies, yet their origin remains a mystery. Do they arise from stellar-scale objects such as newborn magnetars, from acceleration in AGN jets, from jets formed via the tidal disruptions of stars?

These disparate issues require a comprehensive multi-messenger observational campaign to address them. New cosmic-ray detectors improve our understanding of the observed population via better measurements of spectra and composition, including novel routes to cosmic-ray identification and characterisation (e.g. via radio antennae). However, identifying the sites of acceleration is challenging because of the deflections the cosmic rays encounter.

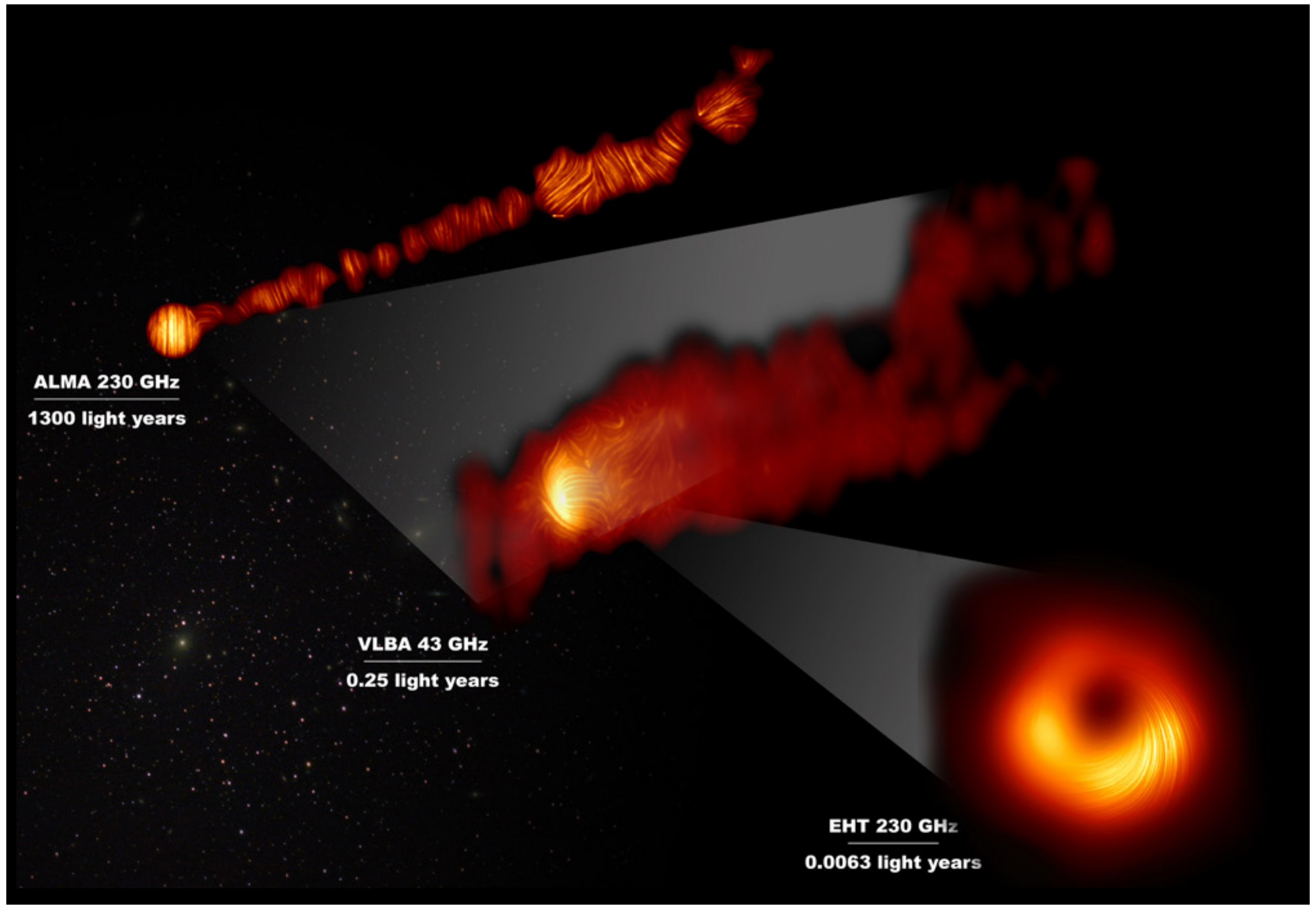

Figure 6

Radio signatures of accretion across length scales. The jet of M87 observed with ALMA, Very Long Baseline Interferometry and EHT. The first image demonstrates the scale of the jet, while the second focuses on its base. The final image from the EHT shows the black hole shadow, and the (highly lensed) accretion disk in polarised light.

Credit: EHT Collaboration.

Photons and neutrinos do not suffer from these effects, yet VHE photons and neutrino emission should accompany cosmic-ray acceleration. Indeed, even these still rare techniques can be paired with detailed electromagnetic studies from the radio to gamma-ray to characterise the sites of acceleration, for example by searching for changes in jet structure during VHE or neutrino outbursts. The identification of individual sites and of the nature of acceleration within them can thus be done via these observations from pulsars, Galactic supernova remnants, gamma-ray bursts, star-forming regions and AGN.

Key current facilities:

AMS-02, Chandra, HESS, IceCube, KM3NeT, LOFAR, MAGIC, Pierre Auger, XMM-Newton.

Facilities in development:

ASTRI, Athena, CTA, GCOS, GRAND, POEMMA, SKA.

How do compact objects form and evolve?

The formation and evolution of compact objects through collapse, accretion, mergers and spin-down provides a myriad of signatures, potentially allowing us to probe the first stars or build intermediate and supermassive black holes. Various astrophysical channels create compact objects. The standard route is that stellar core-collapse makes neutron stars or black holes. Alternative channels involve accretion induced collapse, stellar mergers and dynamical interactions.

The details of the formation channels are primarily in the realm of understanding stellar evolution. However, compact objects form in a large variety of physical conditions. Following their formation, they evolve significantly; a few fade from view, with isolated white dwarfs gradually cooling, and individual neutron stars cooling and spinning down depending on the spin rate and magnetic field. Other compact objects grow significantly through accretion from the interstellar medium or through a binary companion.

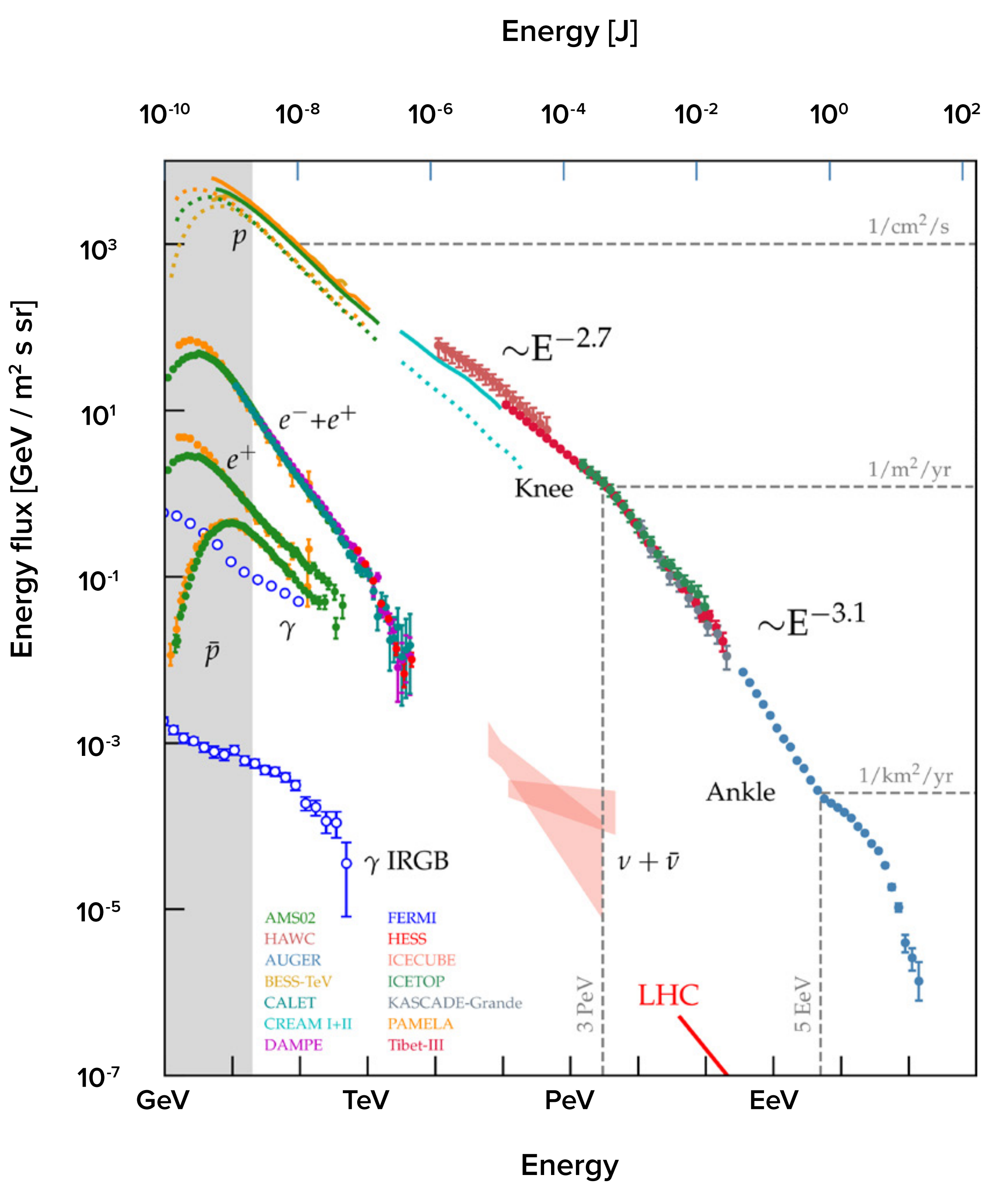

Figure 7

Cosmic-ray energy spectrum. The spectrum, measured from multiple sources shows a complex morphology and is shaped by both intrinsic processes (e.g. the composition of the rays and their spectrum upon acceleration) and their propagation through the interstellar and sometimes intergalactic medium. Future work will improve the measurements of the spectrum, in particular at the highest energy end, determine the composition of the rays, and pinpoint the various physical sites in which acceleration may occur.

Credit: https://zenodo.org/record/2360277#.YV15x2YzZ-U.

At higher masses, black holes can disrupt and accrete individual stars through tidal disruption events, extreme mass ratio inspiral, or direct capture. Those events should be crucial in growing black holes from stellar-masses up to millions of solar masses. The nature of the first 'seed' black holes initiating this process in the early universe remains unclear; they might be the remnants of the first generation of stars or intermediate-mass objects generated by direct collapse events or even remnants of primordial origin.

Indeed the intermediate-mass black holes, whose existence must be essential for black holes to transition from stellar to supermassive, have proven to be stubbornly tricky to detect. The recent discovery of black hole merging events by ground-based gravitational wave interferometric arrays (Figure 8) may have started filling the gap, and some tidal disruption events also appear to arise from black holes with intermediate masses.

Much insight into the formation and evolution of black holes comes from multi-wavelength studies of their properties. This includes the details of their formation in supernovae and gamma-ray bursts, where open questions remain about the neutron star vs. black hole nature of the central engine. Measurements of accretion flows around stellar-mass and supermassive black holes with radio and X-ray spectroscopy and polarimetry, to the direct dissection of the kinematic properties of accretion disks via tomography, enable their growth to be measured.

Future progress is predicated on a raft of new endeavours, and this is a field where the multi-wavelength and multi-messenger elements are crucial. New wide-field capability across the electromagnetic spectrum are vital to identify rare events, and the counterparts of gravitational wave of neutrino signals. For example, the merger history of black holes and their growth (e.g. Figure 8) can be well characterised via gravitational-wave observations.

Indeed LISA and ET will see merging supermassive and stellar-mass black holes everywhere in the Universe, allowing a detailed description of their formation and evolution along the cosmic history. Understanding the formation of compact objects requires us to identify the sources that make them, pinpoint the nature of the compact objects formed and study them in detail. In principle, this should also be done across cosmic time.

Widefield surveys will identify ever more transient sources. From highly complete local searches that will map the parameter space for compact object formation to deep searches with Rubin, Euclid and even JWST that may pinpoint the collapse of the first stars. The signatures of the most extreme explosive events are perhaps most readily identified outside the optical window, with gamma-ray bursts identifying extreme stellar death across cosmic history.

Indeed, searches for high-z GRBs perhaps offer the most promising route of directly detecting the first stars, or at least their demise. Their initial identification requires a dedicated mission with good localisation (especially for finding likely faint high-z GRBs). Once found, the next generation of ground and space-based facilities (e.g. ELT, JWST and ultimately Athena) can perform accurate optical/IR and X-ray spectroscopy of the interstellar and intergalactic medium beyond z~7, probing the metallicity evolution down to the Epoch of Reionization in galaxies fainter than the sensitivity limit of galaxy surveys such as those performed by JWST.

These new sources should also greatly increase the number of identified tidal disruption events, in which the strong gravity of a black hole shreds and subsequently accretes another star, from white dwarf disruptions around intermediate mass black holes through to main sequence and giant disruptions. In addition to providing insight into accretion these systems also probe the demographics of the vast majority of black holes which are otherwise dormant.

Finally, it is also critical to understand how other, perhaps new, transient signatures fit into this remit. Fast Radio Bursts are a prime example. It appears near-certain that they are created by neutron stars, but are they made at the point of formation, soon thereafter, or for a prolonged period? Since some fast radio bursts are known to repeat, at least these sources must be associated with a more stable form of energy, like the magnetic decay of a magnetar or the relativistic shocks from the jet of an accreting source. Wide-field radio telescopes (e.g. CHIME) are opening this discovery space, and interferometers are localising the host galaxies of fast radio bursts. Similar questions revolve around the nature of Fast X-ray Transients identified by Chandra, XMM-Newton and Swift, which may represent exotic signatures of supernova shock breakout, or perhaps even near-isotropic signals of the mergers of binary neutron stars.

Key current facilities:

Chandra, CHIME, ground-based 2-8 m telescopes, HESS, HST, IceCube, JVLA, KM3NeT, LOFAR, MeerKAT, Swift, VERITAS, Wide-field optical/IR searches, XMM-Newton.

Facilities in development:

Athena, CTA, ET, GCOS, GRAND, JWST, LISA, New wide-field optical/IR searches, POEMMA, SKA, SVOM, VRO/LSST.

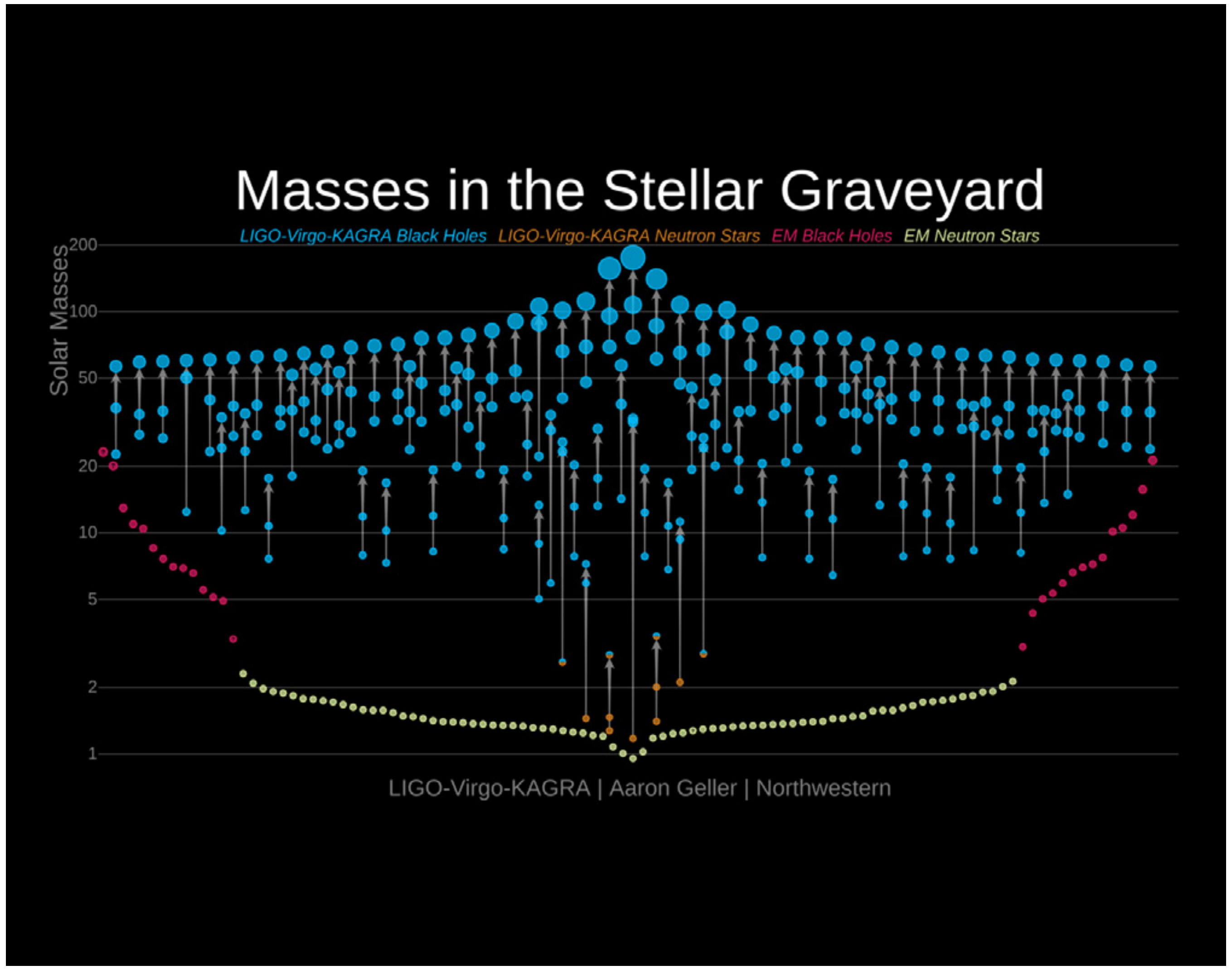

Figure 8

The masses of known neutron stars and black holes. Once formed their mass and spin can increase via mergers and accretion. A central aim of future work is to understand how each set of objects form (and at which masses), and their evolution.

To what precision can general relativity describe gravity?

Gravitational waves and the imaging of a supermassive black-hole shadow provide new opportunities to test gravity. Progress will follow through the detection of many gravitational-wave mergers and the expansion of the gravitational-wave frequency regime. Radio interferometry revealed the shadow of the Galactic Centre black hole and enable further GR tests via time-resolved observations. Finally, precision observations of Galactic compact binaries provide additional novel tests. A premier example are the high-precision tests of general relativity that can be done via timing observations of radio pulsars in binary (or even triple) stellar systems with current and next generation facilities.

General relativity has, to date, provided a remarkable and robust set of predictions that have passed essentially every critical test posed and made several crucial predictions, from readily-measured gravitational redshift to the recent first discoveries of gravitational waves. However, while powerful, it is also complex. Few analytical solutions exist, and complex interactions in dynamic space-time, such as the final mergers of compact objects, or the flow of matter around supermassive black holes, must be calculated numerically. Furthermore, its incompatibility with quantum mechanics has led to the decades-long search for a theory of quantum gravity. While many suggestions exist for the directions of this theory, few observational tests can critically distinguish between them. Observations of black holes and their interactions across the mass scale can provide new critical tests of general relativity and place meaningful constraints on variations from it.

While the measurements of a black hole shadow, spectacularly demonstrated by EHT images of the core of M87 and Sgr A*, provide a route to measuring the black hole mass, such an estimate is weakly dependent on the black hole spin. The next goal is to build time-resolved and higher angular-resolution observations of the supermassive black holes in M87 and Sgr A*. Combined with multi-wavelength monitoring of the accretion flows and the orbits of individual stars around Sgr A* (e.g. with VLTI/GRAVITY), it will be possible to make direct tests of the applicability of the Kerr metric. The objective is to resolve the (steady) signatures of the lensing in the gravitational metric from the (variable) emission of the accretion flow and jet. This work requires the creation of a more robust EHT array with improved UV-plane coverage, longer exposures and the ability to observe at higher and/or multiple frequencies. An interesting option is VLBI with space-based millimetre telescopes to reach the ultimate resolution.

Many of the most stringent tests of GR in the strong dynamical regime will come from gravitational-wave observations. Several tests have already been performed by verifying the consistency of the chirp signals measured by LIGO and Virgo with those predicted from relativity. The high signal to noise observations of LISA and ET will enable unprecedented tests of GR. Extreme mass ratio inspirals observed by LISA will allow a precise mapping of massive black hole spacetime geometry, while the frequency evolution of stellar and massive black hole binaries during the so-called ring-down phase after the merger observed by LISA and ET will provide decisive tests of the no-hair theorem. Further, measurements of the combined masses of the pre-and post-merger black holes will test the so-called area theorem, which states that the area of a black hole horizon can never shrink.

The possible concurrent scientific operations of Athena and LISA may open a new, exciting discovery space: the identification of the electromagnetic counterparts of supermassive black hole merging events detected by LISA days to weeks prior to coalescence. This may be possible (even if challenging!) during the inspiraling phase - through follow-up Athena campaigns of the error box of the gravitational wave signal, whose size rapidly improves down to degrees accuracy a few days prior to the merging event. At and after merging, when the position of the GW event will be known at an accuracy compatible with the small field of view of the Athena micro-calorimeter, for the best signal-to-noise events. Such observations may provide unique insights into the behaviour of matter in the time-space fabric stirred by the orbiting black hole merging pair, as well as on the onset of the accretion disk, corona, and jet in newly formed AGN (a complementary channel to TDEs).

Ultimately, deviations from the predictions of General relativity may become visible thanks to these observations in combination with the effects predicted by either alternative theories of gravity alone, or by quantum gravity models, such as dispersion in the speed of light with photon energy. Such effects may be tested with discrete events such as AGN flares and GRBs identified across many decades of photon energy from optical to VHE energies (SVOM + Fermi + CTA). It may also be possible to observe deviations in the velocities of the wave in the gravitational wave regime, either directly compared to the speed of light inferred via EM observations or perhaps due to variations in the speed of gravitational waves as a function of wave frequency or polarisation state. High signal-to-noise observations of gravitational wave sources from LIGO/VIRGO/KAGRA, as well as LISA and Cosmic Explorer/Einstein Telescope on longer time-scales, may detect such signatures.

Key current facilities:

Chandra, eROSITA, LIGO/VIRGO/KAGRA, LOFAR, neutrino detectors, NICER, Swift, VLBI/EHT, XMM-Newton.

Facilities in development:

Athena, CTA, expanded EHT, eXTP, SKA, SVOM.

What new fundamental physics can be probed with extreme astrophysical objects?

In addition to being probes of multiple astrophysical processes, the conditions that exist around compact objects can lead to solid constraints on several critical questions in physics. One of the foremost of these questions relates to the origin of dark matter. While creating ~23% of the mass of the Universe, increasing evidence exists that it is not formed from traditional baryonic material.

Various possibilities for the origin of dark matter exist. Those currently in vogue include sterile neutrinos, whose presence may explain the apparent Hubble constant tension, ultra-light bosons (such as axions), primordial black holes, and Weakly Interacting Massive Particles (WIMPs). Each of these possibilities has a direct route to identification. For example, sterile neutrinos should cluster around compact objects (e.g. black holes) to a degree that should make detectable changes to their orbits of surrounding material; axions should tap the rotational energy of black holes to slow their spin. Unless they continuously accrete angular momentum, there should be few rapidly spinning black holes in an axion dominated Universe. Robust spin measurements of black holes across the mass range have the potential to constrain this possibility. Primordial black holes should exist in mass ranges notionally inaccessible to astrophysical production mechanisms. Perhaps most notably and relevant for the next decade is the exploration of the sub-solar mass regime. The unambiguous detection of a sub-solar mass binary black hole merger would offer strong support for the presence of such black holes.

Alternatively, dark matter may exist as more massive, Weakly Interacting Massive Particles (WIMPS), where astrophysical observations can offer constraints complementary to those obtained via ground-based deep detectors or accelerators. Many models posit that self-annihilation is possible for these particles; promising annihilation may produce detectable gamma-ray and neutrino emission that directly links to the dark matter particle mass. Observations with Fermi and ground-based Cherenkov detectors have placed some constraints on such annihilation towards the Galactic centre and dwarf galaxies, and order of magnitudes improvements or direct detections will be possible with CTA and the next generation neutrino telescopes.

Finally, a further, fundamental, question arises about the nature of black holes. While these are the astrophysically simplest explanation for many objects (and are perhaps the most likely to be correct) there are alternative possibilities. These so-called black hole mimickers include dark matter stars, boson stars, gravastars, and many other exotic objects. The majority of these are indistinguishable from black holes to most observations, as they cannot violate existing observational constraints. However, they may well result in different interactions, either directly via gravity (e.g. to gravitational wave observations) or with their surroundings (e.g. via EM observations of the persistent or transient emission from sources that contain putative black holes).

Key current facilities:

Chandra, Fermi, HESS, IceCube, KM3NeT, LIGO/VIRGO/KAGRA, MAGIC, Swift, VLBI/EHT, XMM-Newton.

Facilities in development:

Athena, CTA, ET, expanded EHT, GCOS, GRAND, LISA, POEMMA.

Summary

Astrophysical systems can achieve physical conditions in which rare and unusual manifestations of physics become apparent, and where our current physical theories can be tested to breaking point. Their study can provide insight into central questions in both contemporary astronomy and fundamental physics that cannot be obtained elsewhere. The field has undergone significant growth in the past decades with growth from both within the astronomical community, and from the addition of researchers from outside its traditional boundaries. Continued progress requires both large, headline facilities such as Athena, LISA, the ELT, SKA, CTA, global VLBI arrays and ET as well as a raft of smaller, cheaper and more specialised initiatives. Indeed, it would be extremely valuable to ensure that where flagship facilities require scientific input from the smaller initiatives, these are suitably considered in roadmaps, including possible funding. Through ensuring the necessary resources continue to be available there is a high confidence that the science questions outlined in this chapter can be realised.

H

Astronomy and society

Introduction

The universe is larger and more diverse, dynamic, and enigmatic than our ancestors could have imagined when they first gazed at the stars. The captivating and mysterious nature of the universe makes astronomy fascinating to the public and a fertile ground for the imagination of young and old minds alike. Astronomy is integrated in society in a multitude/myriad of ways.

The astronomy structures dedicated to facilitating or conducting research continue to increase with Europe (e.g., ESO, JIVE, SKA). Astronomy research requires unique technological developments, data management systems and highly skilled research staff. This research can lead to opportunities for innovation and market development, can attract investments and contribute broadly to socio-economic development.

This section explores relevant societal aspects of astronomy within the European context.

Social and cultural relevance of astronomy

Astronomy has always had a significant impact on our world, with the power to inspire and unite people from a variety of different cultures and across all age groups. Early civilisations studied celestial objects to measure time, mark the seasons, and navigate across vast oceans. Now, as our understanding of the world progresses, we find ourselves and our view of the world even more entwined with the Universe. The discovery that the basic elements that we find in stars, the gas and dust around them, are the same elements that make up our bodies has further deepened the connection between us and the cosmos. Astronomy also helps us to broaden our perspectives and to think on grander scales. Our connection to the cosmos and the awe it inspires, is perhaps the reason that the beautiful images astronomy provides us with are so popular in today’s culture.

The technological impact of astronomy

Astronomy and related fields are at the forefront of science and technology; answering fundamental questions, pushing engineers to new levels and driving innovation. Astronomy has been an important driver for the development of advanced technology, such as the most sensitive detectors of light and radio waves and the fastest computers. The need to study the faintest objects requires sophisticated electronics and extreme-precision adaptive optics as well as state-of-the-art engineering. Modern telescopes are among the most advanced machines ever built and are outstanding educational vehicles for introducing the latest complex technology. Among those, the LIGO and Virgo gravitational wave observatories are an example of the most precise laser interferometer ever built by humankind. A 40-year long endeavour that pushed the laser and precise measurement technology to a never imagined before level.

Astronomers are also trained data scientists with elaborate skills in data analysis and coding: 21st-century skills that are transferable to many societally relevant applications (see next section). Although blue-skies research like astronomy rarely contributes directly to tangible outcomes on a short timescale, there is a wealth of examples of day-to-day technologies that were initially developed by astronomy research (e.g., Rosenberg et al. 2014). The fruits of scientific and technological development in astronomy have become essential to our day-to-day life, with applications being integrated in many devices that play a vital role in society such as personal computers, communication satellites, mobile phones, digital cameras, GPS, solar panels, Magnetic Resonance Imaging (MRI) scanners and more recently ventilators during the global pandemic. Due to this cutting-edge technology and the international nature of astronomy research, astronomy is synergetic to the UN Roadmap for Digital Cooperation.

A bridge between astronomical computing and society

As astronomers we now routinely collect, store, manage and analyse petabyte-scale datasets. The computational challenges faced by the astronomy community are substantial, but it is not in our remit to develop all the computational tools that we need to address them. Limited resources often mean that we must rely on industry-developed solutions and adapt them to our needs. However, the multi-disciplinary, data intensive nature of our research means that astronomers are often also skilled programmers and data scientists. This lets us re-deploy industrial tools in new and innovative ways and discover best practices that we can share with other scientific domains. At the same time, we are able to develop new tools which can be shared to other domains (e.g. life sciences) and/or returned for industrial use.

As a subject, astronomy enjoys substantial public interest and support. Our discoveries are often spectacular, visually appealing and even awe-inspiring. As such, we can provide inspiring use cases for modern computational technologies like machine learning that are in stark contrast to more troubling applications like widespread facial recognition and behavioural prediction.

As astronomers, we are privileged that society is willing to support and fund our research activities. This means that we have the opportunity and the responsibility to reduce our environmental footprint by minimising the energy used for our data intensive tasks. To do this we will need to make changes to the way we work by minimising our data transfer rates, adopting modern remote computing paradigms and writing more efficient analysis tools. If we can channel our innovative mindsets into making astronomy greener, we have the opportunity to lead other scientific communities and wider society in the same direction.

The Universe as an Open Lab

The Universe provides a unique laboratory for studying extreme conditions that are inaccessible on Earth. Stars and galaxies are environments that have produced the chemical elements around us and formed organic molecules, the building blocks of life. During the last century astronomical /astrophysical studies have led to new discoveries in physics, chemistry and biology and to the creation of the new sciences of astroparticle physics, astrostatistics, astrochemistry and astrobiology. Because of its interdisciplinary approach, astronomy is also an excellent tool for education in STEM fields. Astronomy is also at the forefront of the Open Science movement: Open access to raw research data is the standard in astronomy. This is supported because it promotes productivity and competitiveness. Many scripts, libraries, codes and programming tools are open source, so everyone can use them and contribute to improving these tools. Scientific articles are available as open-access on arXiv, making the science more inclusive to all scientists and the general public. Open science is extremely relevant to a data-intensive science like astronomy and even though many open science practices and tools are already present, every astronomer needs to be trained in these skills for it to become the norm (Norman et al. 2019).

A gateway to the learning and appreciation of science in general

One of the most important societal functions of modern astronomy is as a “gateway science” for education in the broadest sense (Salimpour et al. 2020). Since it is one of the most approachable sciences, and one that consistently fascinates young people, astronomy is an excellent vehicle for introducing science and technology to children (Schreiner and Sjøberg 2010). The accessibility of the sky, the beauty of cosmic objects and the immensity of the Universe are inspirational and provide a perspective that encourages inclusiveness and tolerance. The excitement of astronomy has stimulated large numbers of young people to choose a career in STEM fields, thereby contributing to development of the “knowledge economy” of many countries. Astronomy also interfaces with other cultural fields and it is a source of inspiration for the visual arts, literature, philosophy and many others (e.g., Valls-Gabaud & Boksenberg, 2009).

A bridge between science and citizenship

Astronomy has a strong presence in public engagement (e.g., IAU100) and citizen science (e.g., the Zooniverse) to promote the science methodologies (e.g., Marshall et al. 2015) and more broadly key skills such as critical thinking and multiperspectivity, which are fundamental today as learners are living in increasingly diverse societies. By fostering a deep appreciation for our planet, Astronomy also provides a powerful means to raise awareness around issues of sustainability and responsible engagement to preserve life on Earth (e.g., Astronomers for Planet Earth, an international initiative to tackle Climate Change).

Technology Transfer / Industry Relations

Space is an increasingly active commercial sector for many countries, and scientific breakthroughs in Astronomy are to a large extent driven by technological advances, which, in turn, are often enabled by close collaborations between astronomers and industrial partners. Through spin-in, new technology that is developed for e.g., commercial applications can inspire radically innovative astronomical instruments (e.g., developments in the telecom industry leading to fibre-based or photonics-based instruments, the application of liquid-crystal technologies that have been developed for displays, high-volume internet and computing capabilities that enable huge radio telescopes, etc.). However, there are likely as many good examples of spin-off: technology that was originally specifically developed for astronomy that has applications elsewhere. The example that astronomers always like to emphasise (and claim) concerns the invention of WiFi, and several other success stories have been collected (Downer et al. 2019).

This does not merely pertain to high-tech hardware solutions, but the current big data / artificial intelligence revolution also certainly prominently features astronomers in starring roles. Besides some case studies, there is no complete overview of the impact of astronomical technology development on our society, both in terms of quantitative return on investment for the economy, as well as in terms of qualitatively improving life on Earth. With the ambitions laid out in this roadmap with respect to both hardware and software projects, the collaborations between astronomy and industry are likely to be intensified and enhanced, and it seems more than opportune to study the results of these developments at different levels and timescales.

The OECD provides a framework for assessing the impact of investments in science and technology, and for the "space industry" it is estimated that every Euro invested into advanced new infrastructure gets multiplied several times in terms of economic benefits (OECD, 2019). More importantly, the much broader range of socioeconomic benefits capture the true impact of investments, which is probably even more appropriate for specifically astronomy. A range of impacts of technology development for astronomy was compiled by Rosenberg et al. (2014) but this Astronet roadmap presents a unique opportunity to implement this for a range of different projects. This will not only provide ammunition to better justify the "commercial" case for astronomy, but, in conjunction with the other subsections of this chapter, will demonstrate how astronomy contributes to building a better world.

To further enhance the potential of (socio)economic impact, it is recommended for large projects and long-term collaborations between astronomy and industry to establish and communicate joint R&D agendas. Furthermore, educational (BSc/Msc) and research (PhD/post-doc) programs at universities and research institutes can already intimately connect to (local) industry in the form of internships, dedicated courses, or entire joint (interdisciplinary) programs on astronomy-themed advanced instrumentation and/or data science. Because, in the end, a major spin-off from astronomy is of course in the form of human capital of highly trained academics that go into industry.

Intensive joint educational and research programs are already existing and emerging, and while there is not yet any cause for major concern, we emphasise that academic freedom and independence needs to be guaranteed at all times when collaborating with industry, to prevent any conflicts of interest. Ethical issues pertaining to for instance companies that also operate in the defence industry always need to be openly discussed upfront.

Finally, having said all this, we need to continue making strong cases for investments in fundamental science, just for the sake of fundamental science.

Recommendations

- Further develop joint R&D and training programmes (MSc, PhD and PostDoc level) in close cooperation with industry including training for entrepreneurship and social innovation.
- Ensure there are adequate training and career paths for astronomy researchers specialising in the areas of advanced instrumentation, computing, and data science.

Astronomy Education

The way in which astronomy education projects are designed and executed have the potential to reshape the experience of astronomy learners and alter the astronomy education ecosystem.

Astronomy's presence in many European educational curricula is irregular. Some countries have astronomy subjects at many different levels, and other countries have only few mentions in the natural sciences curriculum. The EC-funded project, Space Awareness (2019) did a preliminary assessment of the European curriculum, and Salimpour et al. (2018) reviewed the astronomy presence in the curricula of the countries in the OECD. They noted that astronomy-related content was prevalent across the 52 curricula of the European and OECD countries. Content topics relating to basic astronomy such as telescopes and optics were the most prevalent, while topics related to cosmology and current research in astronomy were less common; material related to robotic telescopes was absent, probably due to the limited content- knowledge of curriculum developers, policymakers, and even teachers. Astronomers can and should engage with curriculum developers to bring modern cutting-edge astronomy research with emphasis of Big Science and Big Data to the national curricula.

Another important practice is to work with educational textbook publishers, as has been done e.g., with the Space Scoop text in English-language books (Reynolds 2014), South African textbooks, and Dutch Physics textbooks. Astronomers can work closely with textbook publishers to foster the use of more astronomy resources in educational material across different school subjects, especially by reviewing and developing the content of specific textbooks. In these ways, a much wider reach of astronomy content in textbooks and related materials can be realised.

Global Citizenship Education: Learning Through Perspective

The cosmic perspective that astronomy provides makes it an important tool for Global Citizenship Education (GSED), UNESCO's educational approach to tackle global issues that threaten peace and sustainability (UNESCO 2014). GSED empowers learners of all ages to assume active local and global roles to build more peaceful, tolerant, inclusive, and secure societies. For example, teaching the "Pale Blue Dot" concept from Carl Sagan can function on several levels:

- Cognitive: "I wanted to be a scientist from my earliest school days. The crystallising moment came when I first caught on that stars are mighty suns, and how staggeringly far away they must be to appear to us as mere points of light" (Sagan 1994a).
- Socio-emotional: "Fanatical ethnic or national chauvinisms are a little difficult to maintain when we see our planet as a fragile blue crescent fading to become an inconspicuous point of light against the bastion and citadel of the stars" (Sagan 1980).
- Behavioural: "Look again at that dot. That's here. That's home. That's us … To me, it underscores our responsibility to deal more kindly with one another, and to preserve and appreciate and cherish the pale blue dot" (Sagan 1994b,).

Several European educational programs use this approach, including Universe Awareness (UNAWE) and the Big History Project. UNAWE is a global science education program using the beauty and grandeur of the universe to encourage young children (4 to 10 years old), particularly those from an underprivileged background, to have an interest in science and technology and foster their sense of global citizenship. There is evidence that using astronomy as an intervention contributes to the motivation, science knowledge, science skills development, and intercultural awareness in these learners (Kimble 2013).

Big History is an educational and storytelling approach to recount the "history" of the universe over time through a diverse range of disciplines including physics, chemistry, biology, anthropology, and archaeology. Thus, traditional human history is reconciled with environmental geography and natural history (Simon et al. 2015). In the past decade, this approach has received more attention and funding (Sorking 2014) as well as a complete teaching website. The Big History Project was developed using evidence showing that students using this approach have made gains in reading, writing, and content knowledge (Big History Project 2015).

Beyond Science Literacy: Science Capital

Bucchi & Trench (2014) have asked for a move from the "teach them the simple facts" an approach that teaches the simple facts to a "capital-based" approach to science literacy. Science capital, a concept introduced by the ASPIRES UK policy report (Archer 2013), represents the sum of all science-related knowledge, attitudes, experiences, and resources that individuals build up throughout their life. This includes what science they learn and know from all different types of learning environments (formal or informal), what they think about science, the people they know who understand science, and the day-to-day engagement they have with science (Archer et al. 2015). Capital can be created through lifelong diverse learning opportunities for children, adolescents, and adults within a robust, community-wide system for science education (Falk et al. 2015). This perspective of an educational ecosystem encourages the building of partnerships that can support the STEM learning of young people across multiple settings (Schatz & Dierking 1998). This translates to developing opportunities for learners to participate in the astronomy enterprise, including collecting and analysing astronomy research data (Roth & Barton 2004).

An understanding of "science capital" offers the practitioner or project designer a powerful conceptual lens to identify interventions which can address disparities in science engagement and participation (DeWitt et al. 2016). For example, cultivating a "growth mindset" to improve skills and suppress self-criticism (Dweck 2016) in adolescents can aid their science achievement and appreciation. This approach has been effective in art-science programs that emphasise a creative cycle of design experimentation, prototyping, evaluation, and redesign (Conner et al. 2017, Tsurusaki et al. 2017). Recent research using online interventions that teach students that intellectual abilities can be developed have proven effective in improving grades in lower-achieving students, even though the intervention lasted less than one hour (Yeager et al. 2019)!

A science capital approach can also encourage schools to become less isolated in their communities. Because of the diverse subject linkages described by Miley (2009), astronomy can help schools shift towards "Open Schooling" (Hazelkorn et al. 2015), decreasing the isolation of schools and encouraging creativity, entrepreneurship, and innovation as the schools collaborate with businesses and the larger society. The astronomy enterprise naturally engages with these different stakeholders and can create new partnerships among teachers, students, researchers, innovators, industry professionals, and other stakeholders in science-related fields.

Recommendations

- Further expand the recognition and award of researchers to include education and public engagement in their career paths.
- Promote modern cutting-edge astronomy research, with emphasis of Big Science and Big Data, artificial intelligence, as well as technology R&D as part of the national education curricula.

Public Engagement with Astronomy

Community based science and community engagement have hitherto mainly been one-way processes from astronomy towards the community. However engagement is a two-way communication process. This is important and we should change our mindset. In particular how we approach the land, people and ecosystems that inhabit it, how we develop responsible relationships with indigenous peoples, and how we approach the governance of our projects. In addition, part of the public is interested in hearing the beautiful results of astronomy, but we have to engage other publics. An example of this changing perspective is that professional astronomers are more and more appreciating that amateur astronomers can make valuable contributions to their research and, vice versa such 'Pro-Amateur' collaborations also involve professional astronomers doing follow-up observations based on discoveries made by amateurs.

“Scientists, keep an open line of communication with the public” (Monteiro, 2020), this call for action from the editor of Nature Medicine in October 2020 comes at a time where our society still struggles with a global pandemic, fights for social justice and surfers from climate change. Scientists need to have open communication with the public and engage fellow citizens with research activities. Public engagement with science is not any longer a nice-to-have, it is a must-to-have in research.

“Public engagement”, “science communication”, and “education and public outreach” are blanket terms covering communication aspects about scientific research to those members of the public who are neither professionals nor specialists in the relevant field. These terms describe the myriad ways in which the scientific community can share its activities and scientific benefits with the wider society. Lewenstein (2015) categorises public engagement under two main aspects: “engagement” as a learning activity and “engagement” as public participation in science, see Table 1. Both have in common that academics and physics-related communities, such as educators, reach out to individuals and society-at-large and engage them with science. Engagement is, by definition, a two-way communication process, involving both listening and interaction, with the goal of generating mutual benefit.

Table 1 - Overview of the main categories of public engagement initiatives with astronomy (based on Bell et al. 2009)

Category	Characteristics	Examples of public engagement activities
Developing interest in science	Experience excitement, interest, and motivation to learn about science.	• Exhibits (e.g., IAU’s Above & Beyond) • Media: TV news, newspapers, magazines, etc. • Social media
Understanding (some) science	Understand concepts, explanations, arguments, models, and facts related to science. Manipulate, test, explore, predict, question, observe, and make sense of science.	• Public talks • Documentaries (e.g., Cosmos) • Popular-science books and magazines (e.g., Stephen Hawking’s seminal book: Brief History of Time (Hawking, 2009)) • Workshops and hands-on exhibitions (e.g., ESA’s ESERO) • Public Websites (e.g., ESA, ESO, SKA)
Using scientific reasoning and reflecting on science	Reflect on science as a way of knowing; on processes, concepts, and institutions of science; and on their own process of learning about phenomena.	• Community and dialogue initiatives (e.g., Civic Science)
Participating in the science enterprise	Public participates in scientific activities and learning practices with others, using scientific language and tools Public identifies as people who know about, use, and sometimes contribute to science. Public actively participates in research debates. Public co-design and/or co-implement research questions, projects. Public actively participates in funding research projects.	• Citizen-science projects (e.g., Zooniverse / Galaxy Zoo[1])

“Science communication” and “education and public outreach” are blanket terms covering anything to do with public engagement with science, from its aims to its methodology. Public engagement is, however, an essential tool to build, keep and strengthen public support for research. Indeed, the trend for evidence-based public policy increasingly relies on access to a wide variety of specialists, many based in universities.

Public engagement is an endeavour that takes many forms, ranging from education programmes to citizen-science projects and science festivals. These help researchers disseminate the societal benefits of their work while keeping abreast of public concerns and expectations. Public engagement activities provide a platform for researchers to discuss their projects and objectives with the wider public. For optimal benefits these actions must be practical, innovative, research-based, educational, and feeding each other with ideas, opportunities for research studies, and even financial resources.

Public engagement helps maximise the flow of knowledge and cooperation between astronomy communities and society, giving researchers the potential to create an impact through learning and innovation. Strategic investment in public engagement helps to maximise this potential by focusing attention and support on how research enriches the lives of people. It also contributes to social inclusion and social responsibility and allows researchers to better respond to local and global social issues with appropriate effective support to people (Robinson et al. 2012). Building trust and mutual understanding is critical to a healthy higher education and research system (Oreskes 2019), especially at a time when deference to authority and professional expertise is decreasing.

Moreover, the Internet has fostered many astronomy citizen-science projects where the public gets involved in data collection, analysis, or reporting. The low-level access to the scientific process is one key advantage of such projects and the large collaborations generated allow widespread research leading to discoveries that single scientists could hardly achieve on their own (Cavalier et al. 2020).

We believe that European astronomy institutions need to provide long-term support to retain the necessary skills, experience, and resources to facilitate communication efforts. It should not add to the existing pressure for publishing and being competitive but be part of the job profile of responsible scientists (Bubela et al. 2009).
We argue that research institutions should not rely on institutionalised science communication to avoid a trench to growth between scientists and communicators.

We do, however, endorse open and public spaces, where innovative science communication can take place. Such ”Idea Colliders” (Gorman, 2020), have the chance to supersede traditional science museums and promote critical scientific thinking and decision making. These spaces can trigger debates in an interdisciplinary setting involving scientists and citizens from diverse disciplines, including those from the cultural, political or business sectors.

We find ourselves in challenging times. Modern challenges are complex, broad, global, and deeply rooted in societal dimensions. Our roles and responsibilities as astronomers are changing at the same speed as the environment changes – an environment that we have described and tried to understand for decades. The knowledge we gained in that process should help for fast progress in preserving our environment and nature but can no longer remain the exclusive property of specialised research fields. Open communication among scientists, across disciplines, and with society (Public Engagement) is crucial on our way towards the future. While these communication efforts are key to meeting global challenges, their success depends naturally on a functioning science-society relationship: a challenging task in a rather unstable world, politically, socially and economically.

Present times demand a culture in society that appreciates (Burns et al., 2003) and trusts (Oreskes, 2019) science; understands the scientific process as a probabilistic approach and the concept of uncertainty in the interpretation of scientific results (Nichols, 2017), differentiates between scientific uncertainties and low-quality or doubtful science (Freudenburg, 2008), disregard the negative connotations of the term “uncertainty”; makes scientifically motivated decisions and seeks a dialogue with researchers.

Recommendations

- Adopt an equal and respectful mutual engagement with communities in locations where plans for astronomical facilities are being developed, in full respect of the land, people, culture and ecosystems.
- Include Astronomy education and public engagement as an integral part of facility/mission/project planning. Previous reports (e.g., Astronet Roadmap, 2007) and guides for science communicators (e.g., Christensen, 2007), recommend devoting at least 1-2% budgets for professional Astronomy education and public engagement activities.

Astronomy for Sustainable Development

Astronomy is an innovative and cost-effective tool for furthering sustainable global development because of its technological, scientific, educational and cultural dimensions. The role of scientific knowledge remains central to sustainable development (OECD 2020). However, research fields, like astronomy, must be conceptualised broadly to include not just natural and technical sciences, but also knowledge from the social sciences, arts and humanities as well as practical and non-technical knowledge, and experience (Schneider 2019). We need to learn to re-adjust and re-balance the interactions between these disciplines to increase the contribution of astronomy to sustainable development (ISC-UNDP 2020).

The European astronomical community needs to harness the skills, infrastructure and knowledge of astronomy to benefit society at large by:

- Strengthening collaborative networks to coordinate SDGs-related research and practice efforts across Europe and internationally. The European community needs to facilitate collaboration among the global network of researchers and development professionals, educators, communicators, policymakers and industry representatives and share European expertise and knowledge with the broader community. This ensures smaller European groups and initiatives can participate in a research-practice network, where experiences and different perspectives regarding this topic can be shared.
- Consolidating and stimulating SDG-targeted actions in society through astronomy at European and international levels, namely through the IAU European Regional Office of Astronomy for Development (E-ROAD). The E-ROAD needs to facilitate transdisciplinary collaborations to address SDG-related challenges within the field of astronomy. And further the development and implementation of innovative practices and actions of sustainable development within the astronomy community. For example, by using the cosmic perspective as a tool for fostering respect for cultural diversity and climate education, building on educational concepts such as Global Citizenship Education (GCED) and Education for Sustainable Development (ESD), and learning tools such as “the Pale Blue Dot” inspirational picture and respective educational programme.These approaches have been highlighted by the work of Attenborough (2020), Horvat (2019) or Zaki (2019), the recent UN75+ Dialogue on Astronomy - a Unique Educational Tool for furthering the SDGs and Stimulating a Global Perspective and align with UNESCOs educational approach, (SDG 4.7 and SDG 13.3).

Efforts to integrate the SDGs in astronomy research and practice have already begun across astronomy (Alves-Brito et al. 2019). Some specific SDGs that astronomy can directly contribute and tackle are summarised below.

Climate Action

Environmental sustainability of the astronomy practice, following the research and recommendations from several publications (Stevens et al. 2020; The climate issue 2020; Williamson et al. 2019) organisations such as UNESCO, and communities such as Scientists for Future and Astronomers for Planet Earth (SDGs 12 and 13), in accordance with the European Green Deal.

Threats to Dark and Quiet Skies (SDG 11): through the IAU, the astronomy community has been working closely with UNESCO to safeguard astronomy-relevant world’s cultural and natural heritage, from historical sites to the dark (and radio-quiet) skies. The European astronomical community needs to address the rising light pollution, including the emerging threat of increasing numbers of satellite constellations to astronomy research. (SDG 11.4 Strengthen efforts to protect and safeguard the world’s cultural and natural heritage; for example Serjeant et al. 2020 and Rawls et al. 2020).

Gender equality

While progress has been made in recent years, significant gender imbalance still exists within astronomy as a profession. Following the IAU’s initiatives to formalise individual efforts to boost women in astronomy, Astro4SDGs will work towards gender equality and the empowerment of women within the astronomy community. The European astronomical community needs to develop specific training to researchers and advocate for equity and inclusion in STI fields. The activities will be based on the recommendations and plans developed by Horizon 2020’s project Supera and ASTROMOVES and the IAU, which are in line with the European Union’s policies on Inclusive Societies. (SDGs: 5: Gender Equality and 10: Reduced Inequalities).

Inclusion

There is a significant imbalance in the inclusion of underrepresented and vulnerable groups (persons with (dis) abilities and persons with racial, ethnic, religious, LGBTQI+ backgrounds). The European astronomical community needs to be inclusive by training researchers and advocating for diversity and equality in STEM. Institutions will better understand how to create structures that support and nurture talent from minority groups, developing appropriate policies and procedures within their faculties to facilitate recruitment and retention of talent from these groups in astronomy. This could follow some of the work done by international research organisations such as the US-based Association of Universities for Research in Astronomy and Berkeley’s Division of Equity & Inclusion (SDG 10: Reduced Inequalities).

Recommendations

- Astronomy projects should include environmental footprint assessments and reduction plans regarding construction and management of facilities, travel and computing, to follow (at the least) the European timeline towards carbon-neutrality.
- The research community should use its platform to support education and public engagement activities in climate science.
- Diversity and inclusion should be central to funding strategies and plans. Data collection efforts should be standardised with suitable metrics to make meaningful comparisons and take action.
- Space is an increasingly active commercial sector for many countries. Whilst this has potential benefits for Astronomy it also comes with challenges, for example around risks associated with positional awareness, optical and radio interference and sustainability. The Astronomy community needs to work with national and international regulatory and policy bodies and with industry to ensure the protection of the dark, radio-quiet skies for the benefit of both the research communities and the general public.

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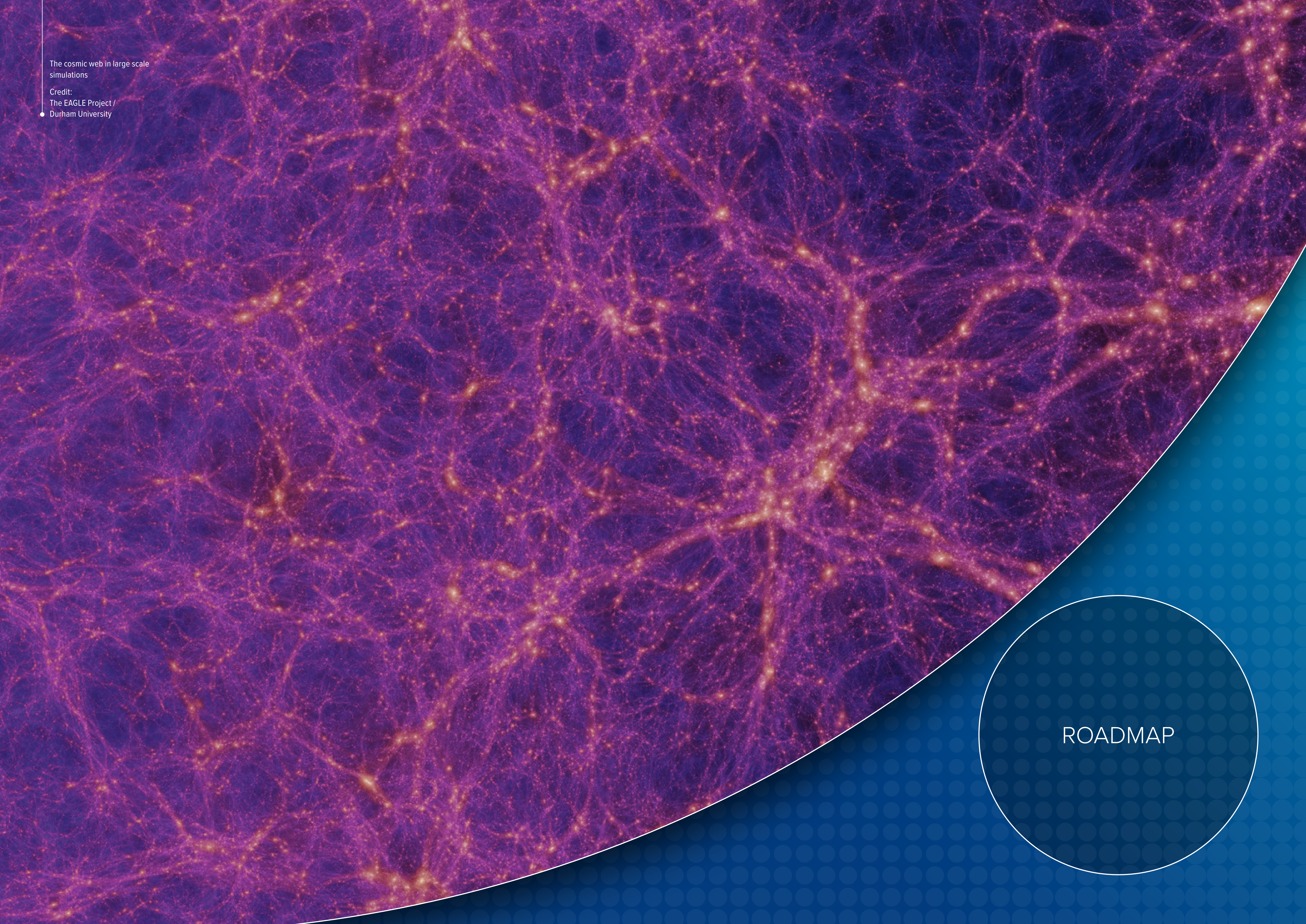


The cosmic web in large scale simulations

Credit:
The EAGLE Project /
Durham University

ROADMAP

1

Overview of current and upcoming facilities

In the coming decades, astronomers from Europe and elsewhere will have access to a set of facilities, either new or coming up. These facilities, both space- and ground-based, span the whole range of observational and multi-messenger techniques and wavelength bands, and provide or will provide the community with exquisite tools to study all types of astronomical objects. The most important of these facilities are listed below, with the list being restricted to instruments either already in operation or planned to be in operation before 2028, without requiring further major political or budgetary decisions. The lists of facilities below include both those with a strong European contribution and full access to European astronomers, and those where such contribution is small or even absent, but still considered as essential in the global world-wide context of astronomy.

ESFRI has recently published its 2021 strategy report on research infrastructures. This document, while dealing with a perimeter including all branches of science, therefore much wider than the present report, includes an analysis of the landscape in all areas of research, among which astronomy can be found within the general field of physical sciences and engineering (see p. 89-103). The landscape considered for astronomy by the ESFRI report focuses on the largest infrastructures, which are included in the more complete list presented below.

1.1 Space-based facilities

1.1.1 The ESA Science programs

The successive science programs of the European Space Agency, Horizon 2000, Horizon 2000+ and Cosmic Vision, have been the backbone of European space astronomy, resulting today in an impressive fleet of satellites and probes. The most important of these space-based facilities are listed below.

XMM-Newton and INTEGRAL

In 1999, both ESA and NASA launched X-Ray space observatories, XMM-Newton and Chandra, which are both still in operation.

XMM-Newton is a cornerstone of the ESA Horizon 2000 science programme, and includes three types of instruments: EPIC, the European Photon Imaging Camera, with a field of 30 arcmin; RGS, the Reflection Grating Spectrometers, providing spectroscopy of the detected targets; and OM, the Optical Monitor, providing simultaneous visible/UV observation of the detected sources.

The NASA flagship-class satellite Chandra is based on roughly the same principle, and includes several instruments: ACIS, the Advanced CCD Imaging Spectrometer, providing both images and spectra of the observed targets; and HRC, the High Resolution Camera. In addition to these two main instruments, Chandra also features two additional grating spectrometers, LETG and HETG, which can be used in conjunction with the main instruments.

These two missions were complemented by the launch in 2002 of INTEGRAL, a joint ESA/NASA/Roscosmos mission, providing imaging and spectrometric capabilities in the Gamma-ray domain.

Mars Express

The ESA Mars Express mission was launched in 2003, consisting of two segments: an orbiter hosting a suite of half-a-dozen instruments studying the Martian atmosphere and ground, and a lander, Beagle-2, which unfortunately failed. The Mars Express orbiter is still in operation.

Gaia

The ESA astrometric Gaia mission, launched in 2013, has been surveying the whole sky since then and is providing data on fundamental properties such as positions, proper motions, photometry, spectral types, temperatures, chemical compositions, etc. for up to 1.5 billion stars and other celestial sources, contributing to advances in almost all fields of astronomy. The data are processed globally, and released to the world-wide community in successive batches. The third Gaia data release (Gaia DR3) occurred in June 2022. At least one further release, Gaia DR4, is foreseen, and possibly more data releases will occur later if the mission is extended beyond its current termination date.

Bepi Colombo

Bepi Colombo is an ESA-JAXA mission to Mercury, launched in 2018 and composed of two complementary orbiters: MPO, whose objectives are the study of the internal structure and the surface of the planet, as well as its exosphere; and MMO, which aims at studying the magnetic field of the planet, as well as particles and waves in its immediate surrounding. Bepi Colombo will reach Mercury in 2025 and its routine operations will start in 2026.

CHEOPS

CHEOPS (CHaracterizing ExOPlanets Satellite) is the first S-type mission of the ESA Cosmic Vision program, developed jointly between ESA and Bern University in Switzerland. Its main objective is to search for exoplanet transits photometrically, around stars already known to host planets thanks to their radial velocity (RV) curves. The combination of RV and photometric curves enables the measurement of both the mass and the radius of the planet, hence its mean density. CHEOPS was launched in 2019 and has been operating nominally since then.

Solar Orbiter

Solar Orbiter is an ESA mission (Cosmic Vision M1) to study the Sun and the Heliosphere, with the particularity of approaching our star down to short distances and providing close-up images and in-situ measurements, including of the polar regions. More precisely, Solar Orbiter's objectives are to study physical processes at the origin of the solar wind, of the solar and heliospheric magnetic fields, of energetic solar particles, as well as of various interplanetary perturbations travelling across the solar system. Launched in February 2020, it started some of its routine scientific operations in November 2021. Solar Orbiter is equipped with a suite of 10 instruments, including imagers and spectrographs in all wavelength ranges from X-rays to visible, as well as in-situ instruments for characterising magnetic field, energetic particles, and plasma.

Euclid

The ESA Euclid mission (Cosmic Vision M2) will study the geometry of the Universe and its dark matter and dark energy components. It will do so by measuring the redshifts and shapes of galaxies and clusters of galaxies out to $z \sim 2$, i.e. with a look-back time of ~ 10 Gyrs, therefore including the period during which acceleration of the expansion of the Universe occurred. The mission features a 1.2m diameter telescope and includes two instruments: a wide-field visible imager (VIS), operating in the 550 - 920 nm wavelength range, over a field-of-view of 0.8 x 0.7 deg^2, and at an angular resolution of 0.2 arcsec; and an infrared spectro-imager (NISP), working in the 920 - 2000 nm wavelength range, on the same field-of-view as VIS, with an angular resolution of 0.3 arcsec. The resolving power of its spectroscopic mode is R=250. Thanks to NISP, Euclid will be capable for example of measuring photometric redshifts for at least a billion galaxies, and to determine more precise redshifts for a million of them, using slitless spectroscopy, placing strong constraints on baryon acoustic oscillations. The VIS instrument will be used in particular to study the repartition and deformation of galaxies, and constrain the distribution of dark matter in the universe. Euclid will be launched in 2023 by a Falcon 9 rocket, as an alternative to the initial launch plan by a Soyuz from Kourou in French Guiana, which became impossible as a consequence of the Ukrainian-Russian war.

PLATO

PLATO (PLAnetary Transits and Oscillations of stars) is the ESA Cosmic Vision M3 mission, planned for launch in 2026. It will survey large areas of the sky in ultra-high precision, long duration photometric monitoring in the visible, in search for transiting exoplanets while studying in detail their host stars, in particular their internal structure, via asteroseismology. The payload is composed of 26 cameras covering a very wide field-of-view and simultaneously monitoring large numbers of bright and nearby stars. PLATO is designed to detect all kinds of exoplanets, including Earth-like planets in the habitable zone of solar-type stars, and to characterise them by measuring their radius, their mass derived from RV curves obtained as follow-up from the ground, and their age thanks to asteroseismic studies of their host stars.

JUICE

The JUpiter ICy moons Explorer is the first large-class mission in ESA's Cosmic Vision program. Planned for launch in 2023 and orbit insertion in 2030, its scientific goal is to perform detailed studies of Jupiter and three of its satellites, Ganymede, Callisto and Europa, with a particular emphasis on their inter-relations as well as the characterization of the internal oceans on the three studied moons, in particular as potential habitable environments. JUICE's science payload includes 10 instruments, providing both in situ measurements of Jupiter's atmosphere and plasma environment, and remote observations, such as imaging and spectro-imaging from UV to submm, laser altimetry, radar sounding, radio science experiments, for the study of Jupiter and its moons.

ARIEL and Comet Interceptor

The Atmospheric Remote-sensing Infrared Exoplanet Large-survey mission (ARIEL) will be the fourth M-class mission (M4) of the ESA Cosmic Vision program, to be launched around 2029. Its science goals are focused on the study of the atmospheres of a sample of several hundred exoplanets with various masses and sizes, on close-in orbits around their host stars. ARIEL will feature a 1.19 x 0.73m telescope, feeding two instruments providing both photometric and spectroscopic capabilities up to 7.8 μm. ARIEL will be launched together with Comet Interceptor, a mission to visit a pristine comet or an interstellar object.

Further ESA Cosmic Vision missions

ESA is also planning other future missions, some of which have been selected but, unlike those listed above, not yet fully adopted, that is to say whose national agency contributions have not yet been fully committed.

Among these, ESA has recently selected the fifth mission of its Comic Vision program (M5), EnVision, which will explore Venus, from its inner core to its upper atmosphere, and should be launched in the early 2030's. Following the cancellation of the M6 window, the selection process of M7 is now on its way.

Two further L-class missions, Athena and LISA, are part of the ESA Cosmic Vision program, both to be launched in the 2034-2037 timeframe. Both missions are further commented on in the Facilities prioritisation chapter.

1.1.2 Partnerships between ESA and other space agencies

Hubble Space Telescope

The 2.4m NASA-led HST is still in operation 32 years after its launch, and expected to remain so until around 2030. With its current and ultimate suite of instruments: NICMOS (Near Infrared Camera and Multi-Object Spectrometer), ACS (Advanced Camera for Surveys), WFC3 (Wide Field Camera 3), STIS (Space Telescope Imaging Spectrograph) and COS (Cosmic Origins Spectrograph), HST is a versatile observatory which is intensively used by astronomers from all around the world. It is being succeeded by JWST, the instruments of which will operate only in the near and mid infrared, but remains at this time the only facility providing imaging and spectroscopic capabilities in the ultraviolet. The science objectives of HST encompass all areas of astrophysics, from the study of solar system objects to that of stars, interstellar medium, extragalactic science and cosmology.

James Webb Space Telescope

The JWST, launched on Dec 25, 2021, and its four instruments have now entered full operation. This 6.5m telescope, working at infrared wavelengths, features four complementary instruments:

- NIRCam, a near-infrared imaging camera, working from 0.6 to 5 µm, and equipped with coronagraphs;
- NIRSpec, a near-infrared spectrograph in the 0.6 to 5 µm range, capable of recording up to 100 simultaneous spectra;
- MIRI, a mid-infrared imager and spectrograph, working from 5 to 28 µm, also featuring a high-performance coronagraph;
- FGS/NIRISS, a fine-guiding system and slitless spectrograph, working from 0.8 to 5 µm, providing fine guidance to the whole telescope while recording spectra.

As HST, JWST is a versatile observatory-type facility, but among its many science objectives, one finds the detailed study of nearby exoplanets, the observation of primordial galaxies, and the evolution of the Universe since the dark ages.

ExoMars

As part of the ESA Exploration program, ExoMars was developed in cooperation with the Russian space agency Roscosmos. Its science objectives are the study of Mars' atmosphere, surface and subsurface structure and composition, in search for possible traces of present or past life. It is composed of two complementary missions. The first one was launched in 2016 and consisted of two components: an orbiter, Trace Gas Orbiter, measuring methane and other rare gases in the Martian atmosphere in view of determining their origin, possibly biotic, and a landing demonstrator, Schiaparelli. Trace Gas Orbiter has been fully operational since its Martian orbit injection, but the landing of Schiaparelli failed. The second mission, composed of a landing platform and a rover, was fully ready to launch in 2022 when Russia's invasion of Ukraine started in February, with the consequence that ESA had to interrupt its cooperation with Roscosmos, therefore suspending the mission sine die. An alternative solution was identified to the strong ESA-Roscosmos cooperation on which this mission was built, resulting in the decision by the 2022 ESA ministerial council to develop a European lander and still deliver the rover to the surface of Mars, although with a significant delay compared to the initial plan.

Other ESA partnership missions

ESA, as well as European national agencies, are also partners of other space mission projects, primarily led by other agencies, including, but not restricted to, the following ones.

Solar-C, a successor to the very successful Solar-B (Hinode) satellite, is a JAXA-led mission to investigate the energetics and dynamics of the solar atmosphere based on high spatial resolution, high throughput, high cadence spectroscopic and imaging observations. It is being developed in the framework of a partnership with ESA and NASA. In its full version, the mission includes an ultraviolet, visible, and infrared telescope for spectropolarimetry of the photosphere and chromosphere, an X-ray or extreme-ultraviolet imaging telescope observing the corona at high spatial resolution, and an extreme ultraviolet spectroscopic telescope with high resolution and effective area. The extreme ultraviolet telescope was judged of highest priority, and a smaller mission involving only that component is being studied, and could possibly be launched first, in the 2025 timeframe.

The LiteBIRD mission aims to detect the pattern of CMB polarisation (B-modes) imprinted by primordial gravitational waves in very early phases of the Universe's history. It will do so by observing the whole sky with a set of millimetric, polarisation-sensitive telescopes, illuminating an array of several thousand superconducting polarimetric detectors. LiteBIRD is being developed by a consortium led by JAXA and involving ESA, CNES and CSA. It is expected to be launched in the late 2020's.

XRISM is an X-ray satellite developed by JAXA, in partnership with several other agencies including ESA and NASA, to be launched in 2023. It will in principle bridge the gap in X-ray astronomy between the ageing XMM-Newton satellite and Athena. It will include two instruments working in the soft X-ray range, Resolve, an X-ray micro-calorimeter, and Xtend, an X-ray CCD camera.

Dragonfly is a lander and rotocraft mission to Titan, whose objectives are to sample materials and determine composition in different regions at the surface of that satellite of Saturn. One of its main goals is to characterise Titan's habitability and to search for possible chemical signatures indicating water- or hydrocarbon-based life. Dragonfly is primarily funded and developed by NASA, in a partnership involving several other agencies, including JAXA, CNES and DLR. It is supposed to be launched around 2027.

1.1.3 Other important space missions

Below are additional space missions, with no significant European contribution to their development, but still having an important place in the general landscape of today's and tomorrow's astronomy from space.

TESS

The Transiting Exoplanet Survey Satellite (TESS) is a NASA Explorer mission launched in 2018, surveying about 200,000 bright and nearby stars in the whole sky in search of transiting exoplanets down to Earth size, in close-in orbit. TESS is also providing information on the exoplanet host stars, including asteroseismic data on some of them. TESS's open data policy and guest investigator program enable European scientists to exploit the produced light curves and conduct their own science projects.

Nancy Grace Roman Telescope

The Nancy Grace Roman Telescope, also called Roman Space Telescope and formerly known as WFIRST, is a NASA visible and infrared space observatory with a 2.4m diameter telescope and two main focal instruments: a wide-field camera providing imaging and spectroscopic capabilities in the 0.5 – 2.8 µm range; and a coronagraphic instrument for high contrast imaging and spectroscopy working in the visible. The science objectives of the Nancy Grace Roman Telescope include the study of dark matter and dark energy, in the wake of the ESA mission Euclid, as well as a complete census of exoplanets in the solar neighbourhood and the detailed investigation of some of them, via direct imaging. It is planned for launch in the 2027 timeframe. The data acquired by the Roman Space Telescope will have no proprietary period, and the mission will also include an important guest observer program, both characteristics giving possibilities of access to European astronomers.

1.2 Ground-based facilities

1.2.1 Visible/Near infrared

ELT and its instruments

The development of the Extremely Large Telescope (ELT) is well on its way, with a first light expected for 2027. It will come with three first generation instruments, presenting complementary characteristics.

- **MICADO**
  The "Multi-AO Imaging Camera for Deep Observations" is designed to provide very high-resolution and high-contrast images, as well as spectroscopic capabilities, in the near-infrared. Its main science drivers are the direct imaging and spectroscopic observations of exoplanets, high angular resolution studies of the galactic centre, and the resolution of individual stars in nearby galaxies. Working in the wavelength range from 0.8 to 2.4 µm, it will provide a spatial sampling down to 1.8 milli-arcsec per pixel in imaging mode, and spectral resolving power up to 20,000. It will also feature a high-performance coronagraphic mode, optimised for direct observation of exoplanets. MICADO will use its own Single-Conjugate Adaptive Optics (SCAO) capabilities, but will also be able to be coupled to MORFEO, the Multi-conjugate Adaptive Optics RelaY of the ELT, providing high-performance adaptive optics correction over large fields of view, hence giving the possibility to reach exceptionally high-quality images.
- **HARMONI**
  The "High Angular Resolution Monolithic Optical and Near-infrared Integral field spectrograph" will offer 3D spectroscopic capabilities, providing spectra, at resolving powers between 3,000 and 18,000, for every pixel of its integral field unit, down to a spatial scale of 4 milli-arcsec per pixel. It will work in the wavelength range from 0.47 to 2.45 µm. HARMONI will be equipped with adaptive optics, both SCAO and Laser Tomography Adaptive Optics (LTAO). Its main science drivers are the investigation of the physics of distant galaxies, stellar populations in other galaxies, the study of the interaction of central black holes with their host galaxies, as well as the detailed characterization of giant exoplanets.
- **METIS**
  The "Mid-infrared ELT Imager and Spectrograph" is another 1st-light instrument of the ELT. This cryogenic instrument will work in the thermal infrared domain, from 3 to 13.5 µm. It will be composed of two separate units, one for imaging, also providing low-resolution slit spectroscopy; and the other one for high-resolution, integral-field spectroscopy. The spectroscopic capabilities attached to the imager will provide resolving powers up to about 1,000, while the integral-field, high-

resolution spectrograph will offer resolving powers up to 100,000. In all observing modes, there will be the possibility to use a high-performance coronagraph. METIS will use its own SCAO system. Its main science drivers are the formation and evolution of planets and exoplanets, in particular by the observation of protoplanetary disks, of exoplanets and of various solar system bodies, as well as stellar formation and evolution, by the observation of stars in all phases of their lives, from protostars to evolved stars and their circumstellar environments, as well as of brown dwarfs. It will also allow us to study galaxies, in particular their centres and the black hole they usually host, including our own galaxy and its central black hole.

VLT and other ESO telescopes

The VLT has been operated by ESO at Cerro Paranal, Chile, since 1998. It is composed of four 8.2m telescopes, that can be used either separately with various suites of focal instruments, or together at the interferometric recombining laboratory of the VLTI, a unique facility in the world. The VLT, with the additional 4m class telescopes operated by ESO (NTT, 3.6m and VISTA) provide European astronomers with top-level, highly-versatile instrumentation, and is arguably the most productive ground-based optical/IR facility in the world. Some of the major recent instruments, currently offered or soon to be offered to the community, are briefly described below, organised by observing modes.

- **Spectroscopic instruments**
  UVES is one of the high-resolution optical spectrographs of the VLT. It features two arms (UV-blue and visual-red) with cross-dispersed echelle spectrographs, that can be used separately or simultaneously, and together give access to the wavelength range from 300 to 1100 nm, at a resolving power up to 80,000 in the blue arm and 110,000 in the red arm. The red arm can also be fed with a set of 8 fibres from the FLAMES fibre positioner, giving the option of multi-object spectroscopy at a resolving power of 47,000. UVES was commissioned in 2000 and has been operating satisfactorily since then.

  ESPRESSO is an ultra-stable, high-resolution, fibre spectrograph, that can be fed with light from either one unit of the VLT, or from up to the four of them. It is installed at the combined incoherent Coudé focus of the VLT and provides a full coverage of the 380-788 nm wavelength range at a resolving power up to 190,000. These characteristics, coupled to an exquisite stabilisation, allow ESPRESSO to reach a radial velocity precision as good as 10 cm/s, sufficient to detect Earth-mass exoplanets. ESPRESSO was opened to the community in 2018.

  CUBES is a forthcoming U-band Cassegrain spectrograph. It will provide very high overall efficiency (≥ 40-50%) in the 300-400 nm wavelength band, at 20,000 resolution. The wavelength band will be covered by two separate spectrographs, simultaneously illuminated by a dichroic plate. CUBES has been recently approved as a 3rd generation instrument at the VLT, and detailed design and construction activities have started. The instrument is expected to be on the telescope in the 2028 timeframe.

  NIRPS and HARPS, on the ESO 3.6m telescope, are two high-efficiency, highly-stable spectrographs, optimised for radial velocity measurements and the detection of exoplanets. HARPS works in the visible from 378 to 691 nm, while NIRPS covers the infrared domain from 0.95 to 1.8 µm. Both spectrographs provide spectral resolving power above 100,000. HARPS was commissioned in 2003, while NIRPS saw first light in 2022.

- **Multi-object and IFU spectroscopic facilities**
  XShooter is a medium resolution UVB-VIS-NIR spectrograph with three arms, mounted on one the VLT units, offering a total wavelength coverage from 300 to 2480 nm. Spectral resolutions range from 3,000 up to 18,000. Both slit and IFU spectroscopy modes are possible. XShooter was commissioned in 2009.

  MOONS is a fibre-fed multi-object spectrograph on the VLT. It provides a total wavelength coverage from 0.6 to 1.6 µm, for about 1,000 fibres, at spectral resolutions of 4,000 – 6,000 (medium-resolution mode) and up to 20,000 in its high-resolution mode. Its first light is planned for 2023.

  4MOST is a wide-field, very high-multiplex fibre-fed spectrograph, mounted at the focus of the VISTA 4m telescope. It provides 2,400 simultaneous spectra in its 4 square degree field, divided into 1,600 low resolution (R=4000-7800) spectra covering the wavelength range from 370 to 950 nm, and 800 high resolution (R=18,500) spectra in the wavelength range from 392 to 679 nm. Its operation, consisting mostly in surveys of the whole accessible sky, is expected to start in 2024.

  SoXS (Son of X-Shooter), installed on the NTT at La Silla, has characteristics approaching those of X-Shooter, the UVB-VIS-NIR medium resolution spectrograph mounted on the VLT. It provides both slit and IFU spectroscopy, with a total wavelength coverage from 350 to 2000 nm, at a spectral resolution of about 4,500. SoXS is planned to arrive at the telescope in 2023.

- **High angular resolution instruments and interferometry**
  SPHERE is an extreme adaptive optics and coronagraphic instrument installed on the VLT. It provides imaging, spectroscopic and polarimetric capabilities, with the highest image quality and contrast performances. Several modes of observation are offered: imaging, dual-band imaging, differential-polarimetric imaging, low- and medium-resolution long-slit spectroscopy, low-resolution integral-field spectroscopy. The covered wavelength range is from 0.95 up to 2.32 µm, depending on the observing mode. SPHERE was commissioned in 2014.

  ERIS is an upcoming new generation adaptive optics imager and spectrograph. It will cover the J, H, K bands in integral-field spectroscopic mode, and up to the M band in imaging and long-slit spectroscopy modes. ERIS is beginning science operations in 2023.

  MAVIS will be a powerful adaptive optics imager and spectrograph working in the visible. It will use MCAO to provide diffraction-limited images over its full 30 arcsec field. In its spectroscopic mode, MAVIS will offer a range of resolving powers between 6,000 and 15,000. It is expected to see first light on the VLT in 2028.

  GRAVITY is an interferometric K band instrument, working at VLTI, delivering spectrally dispersed (at R = 22, 500 or 4000) interference fringes. It is capable of combining the four 8.2m UTs of the VLT, as well as the four 1.8m ATs. The interferometer offers two modes of operation: single-field mode, in which an on-axis source is observed; and dual-field mode, in which the phase of a primary source can be calibrated to a secondary one, enabling a very precise measurement of their angular separation. First light of GRAVITY was obtained in 2016. Among the science programs of this instrument are the groundbreaking results on Sgr A* black hole, that led to the 2020 Nobel prize to Genzel, Ghez and Penrose. GRAVITY is presently being upgraded into GRAVITY+, in terms of sensitivity, contrast, off-axis fringe tracking, and use of laser guide stars for the adaptive optics. When upgraded, it will for example enable milliarcsec interferometric imaging of extragalactic objects, as well as produce high-quality exoplanet spectra and orbits, and give access to targets as faint as K=22 mag.

  MATISSE is the second interferometric instrument of the VLTI, operating in the L, M and N bands. As GRAVITY, it can combine either the four UTs of the VLT, or the four ATs. MATISSE operates in spectro-imaging mode, providing resolving powers ranging from 30 to about 1000. MATISSE saw its first light in 2018.

Facilities at the Roque de los Muchachos Observatory

The Observatorio del Roque de los Muchachos (ORM), on the island of La Palma in the Canary Islands, has been operated since the mid 1980s. It hosts a long list of telescopes, funded and operated by various European countries, also with participation of non European ones. The largest telescopes present at ORM are the following.

The Gran Telescopio Canarias (GranTeCan, or GTC) is the largest facility of the ORM. This 10.4m diameter telescope, presently the largest single aperture telescope in the world, started its scientific operations in 2009. It is funded by institutions in Spain and Mexico, with the help of the University of Florida. It is equipped with three focal instruments: MEGARA, an optical integral-field and multi-object spectrograph, working between 0.365 and 1 µm at a spectral resolution between 6,000 and 20,000; CanariCam, a diffraction-limited mid-infrared imager, also offering spectroscopic, coronagraphic and polarimetric capabilities, in the 7.5 - 25 µm wavelength range; and OSIRIS, an imager and low resolution spectrograph covering the 0.365 - 1.05 µm wavelength band.

The William Herschel Telescope (WHT), a 4.2m telescope, operated since 1987 and funded by the UK, the Netherlands and Spain, hosts a wide range of instruments, among which: ACAM, an optical imager and low-resolution spectrograph; ISIS, a medium-resolution (R=1,800-20,000) long-slit, dual-beam optical spectrograph; LIRIS, a long-slit intermediate-resolution (R=700-2,500) near-infrared spectrograph and spectropolarimeter; and WEAVE, a multi-object and integral-field fibre-fed optical spectrograph, capable of observing up to 1000 targets simultaneously, at both low-resolution (R up to 5,000) and high-resolution (R up to 20,000). WEAVE is expected to be fully operational in 2023.

The Telescopio Nazionale Galileo (TNG), a 3.6m telescope, funded by Italy, saw its first light in 1998. It is equipped with a suite of five instruments: HARPS-N, northern counterpart of the HARPS spectrograph of ESO-La SIlla, a highly-stable, high-resolution, fibre-fed spectrograph dedicated to the search for exoplanets; DOLoRes, an imager and low-resolution spectrograph in the visible; NICS, its counterpart in the near-infrared; GIANO, a high-resolution echelle spectrograph working in the near infrared; and SiFAP2, an extremely fast visible photometer.

In addition to these three major telescopes, the ORM also hosts a suite of smaller facilities, such as the Isaac Newton Telescope, the Nordic Optical Telescope, several solar telescopes, gamma-ray Cherenkov telescopes, as well as several smaller facilities and experiments.

Other major ground-based visible/IR facilities

- **Vera Rubin Observatory**
  The Vera Rubin Observatory (VRO), previously known as LSST, is a US-led facility which will operate the 8.4m Simonyi Survey telescope, featuring a wide-field imager capable of surveying the whole accessible sky every three nights and of exploring the variability of various kinds of astronomical objects. It is expected to start its scientific operation in 2024. The Vera Rubin Observatory was fully funded by US public institutions and private donors. Its data policy is somewhat restricted for today's standards, US and Chilean astronomers, as well as other researchers having

participated in the development, including Europeans, being the only scientists entitled to become users of the facility and be granted full access to the data. However, other astronomers may obtain the status of international members and gain access to the data, under specific agreements between their institutions and NSF or DOE.

- **TMT and GMT**
  The US decadal survey for the 2020s has defined as its highest priority for ground-based facilities an Extremely Large Telescope Program, including two potential major facilities: the Giant Magellan Telescope (24.5m diameter, GMT), and the Thirty Meter Telescope (30m diameter, TMT). Both facilities are designed to address similar scientific questions as the ESO ELT, with somewhat complementary focal instrumentation, providing important synergistic capabilities. In particular, the larger unvignetted field-of-view of both GMT and TMT compared to ELT would make them more suited for large surveys. However, both GMT and TMT projects are currently facing difficulties for raising some necessary additional contributions, or for securing the access to the selected sites. It is not clear at this time whether both or only one of these telescopes will eventually be built.
- **SALT**
  The Southern African Large Telescope is a 10m-class optical telescope located near Sutherland (South Africa), operated by a consortium involving South Africa together with partners in Germany, Poland, the United States, the United Kingdom and New Zealand. It was commissioned in 2005. The SALT is equipped with three main instruments: a high-speed optical imager (SALTICAM), capable of recording images in the 320-900 nm wavelength range at a rate of 10 Hz and over a field-of-view of 10 x 10 arcmin; the Robert Stobie Spectrograph and spectropolarimeter (RSS), offering spectral resolution up to 10,000 in the visible (320 to 900 nm) and the near IR (up to 1.7 µm), with the capacity of simultaneously observing up to 100 objects; a fibre-fed high resolution spectrograph (HRS), with resolving power up to 80,000 and spectral range from 370-560 nm (blue) and 560-870 nm (red).

1.2.2 Sub-mm and mm

ALMA

The ALMA (Atacama Large Millimeter/submillimeter Array) construction was finished in 2014 and is approaching completion of its originally envisaged capabilities in the next few years. The development priorities between now and 2030 are: (1) to broaden the receiver IF bandwidth by at least a factor of two - the current ALMA digital processing signal and correlator can only handle 16 GHz of bandwidth (8 GHz per polarisation), and (2) to upgrade the associated electronics and correlator. These developments will advance a wide range of scientific studies by significantly reducing the time required for blind redshift surveys, spectral scans, and deep continuum surveys. In order of scientific priority, receiver upgrades are recommended for intermediate (200-425 GHz), low (< 200 GHz), and high (> 425 GHz) frequencies.

NOEMA

NOEMA (NOrthern Extended Millimetre Array), is the most powerful millimetre radio interferometer of the Northern Hemisphere, and constitutes the best available Northern counterpart of ALMA, providing very useful synergetic capabilities, despite performance (sensitivity, resolution, ...) remaining somewhat below that of ALMA. It is the successor to the Plateau de Bure observatory located at an altitude of 2550m in the French Alps. NOEMA has doubled the number of 15m antennas of its predecessor from six to twelve, and the longest baseline will be 1.7 kilometres . Currently the extensions of the antenna tracks to 2000m are being completed. The antennas are equipped with four receiver bands, observing in dual polarisation and two sidebands in the 3mm, 2mm and 1.3mm atmospheric windows. A wide-band correlator can now process a total instantaneous bandwidth of ~ 31 GHz for up to twelve antennas (two polarisations in each of the two available sidebands).

EHT

The Event Horizon Telescope (EHT) is an international collaboration that has formed to continue the steady long-term progress on improving the capability of Very Long Baseline Interferometry (VLBI) at mm wavelengths. This technique of linking radio dishes across the globe to create an Earth-sized interferometer, has been used to measure the size of the emission regions of the two supermassive black holes (SMBHs) with the largest apparent event horizons: SgrA* at the centre of the Milky Way and the SMBH of M87, the massive elliptical galaxy at the centre of the Virgo cluster. Over the coming years, the international EHT team will mount observing campaigns of increasing resolving power and sensitivity by linking additional millimetre telescopes in the network. A major goal of the EHT collaboration is to make videos of Sgr A* and of the M87 SMBH as the material around them moves and changes over time.

IRAM 30m

Various developments of the IRAM 30m millimetre telescope on Pico Veleta are currently taking place. The drive system controlling the movements will be replaced by a more performant and modern system which will allow precise and fast source tracking even under relatively high wind conditions. The surface of the telescope will be upgraded to allow higher efficiency in the short millimetre range.

The frontend and backend system developments include : (1) wider IF/RF bandwidths while keeping sensitivities close to quantum limit, and (2) large multibeam dual polarisation heterodyne arrays with an IF bandwidth of at least 8 GHz and 2 sideband mixers. Designs currently under consideration are an 7x7 pixel array covering 200-280 GHz with an instantaneous bandwidth of 32 GHz /pixel, and a 3 mm multi-beam (5x5 pixels) system covering 70-116 GHz with an instantaneous bandwidth of 32 GHz/pixel. The continuum NIKA-2 camera, operating simultaneously at 1 and 2mm, was commissioned in 2017, with its polarimetry capabilities likely to be offered to observers starting in 2023.

JCMT and APEX

The two largest single-dish submm telescopes, with 15 and 12m reflectors, respectively, are the James Clerk Maxwell Telescope (JCMT) and the Atacama PathFinder EXperiment (APEX). Both facilities are the result of strong European institutional collaborations. The JCMT was run until 2015 by the Netherlands, the UK and Canada, at which point operations were taken over by the East Asian Observatories (EAO) – the UK remains the only European partner with access to the JCMT. Current instrumentation at the JCMT includes the SCUBA-2 bolometer camera and the POL-2 instrument, which together provide imaging and polarimetric capabilities at both 450 and 850µm. Spectral line heterodyne receivers include the HARP 350 GHz 16 pixel receiver, and the newly commissioned Namakanui single-pixel receiver operating at 230 and 345 GHz.

APEX is the product of a partnership between the Max-Planck-Institut für Radioastronomie (MPIfR), the Onsala Space Observatory (OSO) and the European Southern Observatory (ESO), and saw first light in 2005. Recent upgrades of the telescope surface, subreflector and instrumentation have increased the sensitivity and image quality of the facility. Key instruments at APEX include the new nFLASH single pixel, dual polarisation, dual sideband heterodyne receiver operating at 230 and 460 GHz, and the A-MKID camera, currently in the final stages of commissioning, that will be capable of imaging the full 15 x 15 arcmin FOV of the telescope at 870 and 350 µm simultaneously. Science operations with APEX are currently funded until 2025.

Other mm/sub-mm single dish telescopes

The largest single-dish mm telescope, at 50m in diameter, is the Large Millimeter Telescope (LMT). It operates over the wavelength band of 0.85 – 4mm and hosts a combination of continuum cameras and heterodyne spectrographs. Of particular note is the upcoming TolTEC camera, which will operate in 3 bands simultaneously (1.1, 1.4 and 2.0 mm), with polarimetric capabilities. The LMT is a collaboration between Mexico and the USA, with no direct European involvement.

Finally, the Fred Young Submillimeter Telescope (FYST, formerly CCAT-prime) is a project led by a consortium of universities in the US, Canada, and Germany to build and operate a 6-meter submillimeter telescope with a surface accuracy of 10µm located on Cerro Chajnantor at an altitude of 5612m. FYST will study star and galaxy formation, and cosmology (including CMB and EoR studies). It will have two instruments, Prime-Cam, a high-throughput direct detection instrument using MKIDs that fills the diameter about half of the FOV with 7 modules consisting of arrays of broadband polarimeters (290-900 GHz) and spectrometers (210-420 GHz). The second instrument will be CHAI which is an 8 x 8 heterodyne array instrument operating at 455-495 GHz and 800-820 GHz. Construction has started and early science is currently planned for late 2024.

1.2.3 cm and m radio telescopes

SKA and its precursors MeerKAT and ASKAP

The SKA construction started in 2021. It will be built in two phases: the first phase SKA1 (2021-2029) will build 10% of the SKA, the second phase SKA2 will complete the full SKA. This phased construction of the telescope will mean that the SKA can start operating and producing valuable science before overall construction is completed. The start of Observatory and Science commissioning is planned for 2024. Routine science observations of SKA1 are expected to start in 2029. The SKA1 will consist of SKA1-low: 131,072 antennas in Western Australia covering 50 – 350 MHz and SKA1-mid: 197 dishes in South Africa, including 64 existing MeerKAT dishes, covering the frequency range 350 MHz - 15 GHz. The final SKA telescope will have the full 1 km^2 collecting area at low and mid-band frequencies, the latter extended to 25 GHz, will be an order of magnitude (or more) more sensitive than SKA1 and have 100-10,000 x the survey speed of SKA1.

At this moment SKA2 lies beyond the current planning assumptions of the project as work is focused on delivering the first phase of the SKA as defined above, with the possibility of a later extension to deliver the full SKA vision. However, detailed design of SKA2 should start around 2025 and incorporate new wide-field technologies (aperture arrays up to 1 GHz, phased array feeds at higher frequencies) to allow a start of full SKA science operations in 2035. SKA2 will consist of SKA2-low: a major expansion of SKA1-low

across Western Australia and SKA2-mid: extension of SKA1-mid to 2000 dishes across 3500 km of Southern Africa.
In parallel, technology development and an engineering design phase study as well as a site study should start for the implementation of high frequencies, SKA-high, operating to 25 GHz and preferably 50 GHz.

MeerKAT is the mid-frequency SKA precursor under construction in South Africa's Karoo Desert. When complete, that array will contain 64 dish antennas, each 13.5m diameter. Eventually MeerKAT will be integrated into the SKA's mid-frequency infrastructure and will provide both wide-view and high-resolution images.

ASKAP is a high-speed survey instrument consisting of 36 dishes, each 12m in size, in the Murchison Radio-astronomy Observatory (MRO) in Western Australia. Development and construction of the pathfinder, led by CSIRO, was completed at the end of 2012 and, during its recent commissioning, it has been producing early science and verification of its rapid survey speed through the Boolardy Engineering Test Array (BETA). ASKAP boasts leading-edge technology, including Phased Array Feeds (PAFs), which will be responsible for giving the SKA mid-high frequency component an extremely wide field of view and rapid survey speed.

MeerKAT and ASKAP will provide crucial design, assembly and deployment guidance for the SKA. In addition, both are also world-leading telescopes in their own right and will eventually complement SKA observations.

LOFAR, LOFAR 2.0 and NenuFAR

The International LOFAR Telescope has been running since 2012, using transformational technologies and novel software approaches to deliver unique data to the community with increasing observing efficiency approaching 70%. Efforts are ongoing to upgrade the current system to a new version: LOFAR 2.0. This will enhance the imaging capabilities of the system at Low Band Antennas frequencies and provide a crucial data set for astronomy. Many of the scientific deliverables of LOFAR 2.0 will come from a 10 to 90 MHz all-northern- sky survey, which will be over 100 times more sensitive (reaching 1σ sensitivities of 1 mJy/beam at 60 MHz and 5 mJy/beam at 30 MHz) and will have a more than 5× higher resolution (15” at 60 MHz) compared to any previous or planned survey at these low frequencies. The new system will address a broad range of scientific topics, such as (i) the formation and evolution of the earliest massive galaxies, black holes, and protoclusters, (ii) the nature of galaxy clusters and the steep-spectrum sources therein, including the influence of magnetic fields, shocks and turbulence, (iii) the Milky Way galaxy, including the topology of its magnetic field, (iv) exoplanets and their magnetospheric properties, (v) the composition of high-energy cosmic rays, and (vi) the structure and properties of the ionosphere. With an angular resolution over 10× higher than the proposed low-frequency array for the SKA, SKA1-LOW, and also accessing the largely unexplored spectral window below 50 MHz, LOFAR 2.0 will continue to be a unique instrument through the next two decades.

The LOFAR imaging capabilities at sub-arcsecond resolutions will be further enhanced by the dramatic advances in software and pipelines that exploit the international baselines, and the future inclusion of NenuFAR (New Extension in Nançay Upgrading LOFAR) in Sologne, France, providing a LOFAR “super station”, allowing NenuFAR + LOFAR to make radio images of the sky at resolution ≤1 arcsecond.

VLA

Three major initiatives are underway at the VLA. The first is the VLA Sky Survey (VLASS), which is the highest resolution survey ever undertaken of the radio sky. The survey is being conducted at a frequency of 3 GHz in the B-configuration, giving an angular resolution of 2.5 arcseconds. The survey began in September 2017 and will be carried out in three epochs over seven years. It will use ~5500 hours of VLA observing time. The survey will identify numerous sources worthy of follow-up with VLBI observations. The second initiative is a programme to improve the 40+ year old infrastructure at the VLA site. The third initiative is the development of a scientific and technical concept for a next generation VLA (ngVLA) from the US Astro2020 Decadal Survey. The ngVLA is envisioned to have 10 times the sensitivity and 10 times the angular resolution of the VLA. It will be located in the southwest US, centred on the present location of the VLA, and operate over a frequency range of 1.2-116 GHz. The ngVLA concept includes a long baseline component (~1000 km), and incorporates transformative technology relevant to VLBI, such as LO and time distribution, wideband feeds, and economic cryogenic systems. A detailed design and development phase is envisioned between now and 2024 followed by a construction phase in 2025-2034.

EVN/JIVE

Anticipated technical upgrades to all aspects of the EVN's telescope and correlator facilities between now and 2030 are expected to revolutionise the EVN's technical capabilities. New receiver developments will furnish low-noise systems that incorporate large instantaneous bandwidths and/or simultaneous multi-band capability. By facilitating simultaneous observations of multiple lines, similar increases in sensitivity can be realised for spectral line observations. Future EVN technical upgrades will support observing modes that allow joint observations with the SKA1-mid telescope. This will allow SKA1-mid used as a phased array to be used as an element of EVN/global-VLBI yielding a sensitivity improvement >2 to VLBI. The overall increase in sensitivity compared to the current VLBI is expected to be larger than a factor of eight. These improvements will open a whole new set of scientific opportunities that can benefit from the exquisite spatial and spectral resolution of VLBI.

As the community prepares for the era of SKA science operations, the way in which the European radio astronomy facilities collaborate and organise themselves is likely to change as well. The transition of JIVE into an ERIC in 2014 is an example of that process. For the EVN a more centralised approach, in which JIVE plays an increasingly prominent role, is likely to emerge. In the future, close engagement with the SKA, its regional centres and other complementary telescopes, such as the International LOFAR Telescope, will be mandatory. Within this decade extending the application of SKA technologies to VLBI can also be expected.
The e-EVN/JIVE was a SKA pathfinder, and crucial SKA technologies (such as real-time data transport and correlation over 1000s of kilometres, as well as central distribution of highly accurate time and frequency signals) have already been developed.

Single dish radio telescopes

The radio astronomy landscape also comprises several large single-dish telescopes, offering complementary scientific opportunities. Until 2016, the largest single-dish telescope in the world was the 305m-diameter Arecibo telescope, when it was superseded by the Five-hundred-meter Aperture Spherical Telescope (FAST) in Guizhou province, China. Both facilities share a similar fixed aperture design. The largest fully steerable radio telescopes currently have reflectors of 60-100m in diameter and include the Green Bank Telescope (USA), Parkes (Australia), as well as the Effelsberg (Germany), Lovell (UK), Nançay (France) and the Sardinia (Italy) radio telescopes. These single-dish radio facilities are particularly important for the study of pulsars and other radio transients, and for the mapping of atomic hydrogen, via the 21cm line, in and around the Milky Way and other galaxies of the nearby Universe.

The HI 21cm line is also a promising probe of the epoch of reionisation (EoR), and one of the key science drivers of facilities such as SKA and LOFAR. Complementary to these mapping efforts, the global 21cm signal from the EoR should also be detectable from much smaller experiments; recent examples include EDGES and SARAS.

A commonality of all the single dish radio telescopes is that they offer rapid mapping speeds, excellent sensitivity to extended emission, exquisite time and frequency resolution, and the rapid response to develop and test new technologies. They also add to the sensitivity of VLBI networks.

1.2.4 High energy astrophysics

CTA

The Cherenkov Telescope Array (CTA) is the major upcoming facility in the high energy astrophysics category, building on the heritage of pioneering projects that are described below. It is designed to detect gamma-rays hitting the Earth's upper atmosphere through the showers of particles they release by the Cherenkov effect. It will be sensitive to gamma-rays at energies from about 20 GeV up to 300 TeV. CTA will be deployed on two sites, in the Northern hemisphere in La Palma on the Canary Islands, and in the South in Chile. It will be composed of about 100 telescopes, falling in three complementary categories: large-size telescopes (LST, diameter 20m, low-energy range), medium-size telescopes (MST, diameter 10m, medium-energy range), and small-size telescopes (SST, diameter 4m, high-energy range). The CTA consortium involves 13 countries, mostly European but also from four out of the five continents. In its current schedule, CTA should be commissioned in the 2027-2028 timeframe. Its construction and timely delivery to the community is one of the recommendations of the present report.

MAGIC

The Florian Goebel MAGIC Telescopes are a set of two Cherenkov 17m diameter telescopes, installed at the Roque de los Muchachos observatory on La Palma. MAGIC is operated by an international consortium involving over 20 institutions, mostly in Europe. It is sensitive to gamma-rays in the 25 GeV – 30 TeV energy range. It has been operated in its full configuration since 2009.

H.E.S.S.

The High Energy Stereoscopic System (H.E.S.S.) is a set of five Cherenkov telescopes, installed near the Gamsberg mountain in Namibia. Four telescopes have a diameter of 12m, while the diameter of the fifth one is 28m. H.E.S.S. is sensitive to gamma-rays in the energy range from 30 GeV to 100 TeV. It was commissioned in its final 5-telescope configuration in 2012, and is presently the largest Cherenkov telescope array in the world. It is operated by a vast collaboration of about 40 scientific institutions in 13 different countries, in majority European.

VERITAS

The Very Energetic Radiation Imaging Telescope Array System (VERITAS) is a set of four 12m diameter Cherenkov telescopes, installed in Southern Arizona, and operated by a consortium involving institutions in the US, Canada and Germany. It is sensitive to gamma-rays in the energy range from 50 GeV to 50 TeV. VERITAS was first commissioned in 2007, then upgraded with new detectors in 2012.

1.2.5 Multi-messenger astronomy

Gravitational wave detectors

LIGO/VIRGO/KAGRA is a vast international collaboration, regrouping three very high-precision laser km-scale interferometers capable of detecting the passage across the Earth of gravitational waves produced by distant extreme gravitational events, such as black hole or neutron star mergers, or supernovae. LIGO is a set of two interferometers situated in the US, operated since 2015 by an international consortium led by Caltech and MIT; VIRGO, a European interferometric facility located in Italy, became operational in 2017, joining LIGO in world-wide observational campaigns. Together, LIGO and VIRGO have detected more than 50 gravitational-wave events from mergers of binary black holes and neutron stars, opening up a new window on the Universe. Finally, the Japanese interferometer KAGRA joined the collaboration in 2020, and will participate in further observational campaigns. Both LIGO and VIRGO are presently being upgraded into “Advanced LIGO” and “Advanced VIRGO”, constituting the second generation of gravitational wave detectors.

Neutrino detectors

Currently three neutrino detectors are in operation, IceCube, KM3NeT, and Baikal GVD. The goals of all three detectors are alike as all will collect cosmic and atmospheric neutrinos. All three detectors with comparable volumes at different geographical locations are vital at this moment to do any statistics of the low-number of observed cosmic neutrino events. All will also target hints for dark matter and other ‘exotics’ (magnetic monopole, neutrino decay, etc.). Tentative plans for neutrino detectors at other geographical locations include e.g., P-ONE and TRIDENT. Together, IceCube and KM3NeT (see below) will view the full sky and form a global neutrino observatory.

- **IceCube**
  IceCube (IceCube Neutrino Observatory) is developed by a large international team led by the University of Wisconsin-Madison, USA. It is a cubic-kilometre particle detector made of Antarctic ice and located near the Amundsen-Scott South Pole Station, buried beneath the surface, extending to a depth of about 2,500 metres. A total of 5,160 digital optical modules are buried in the ice and IceCube Full-scale observations began after its completion in 2011. It is optimised for the detection of diffuse high energy cosmic neutrinos. In 2012 two cosmic neutrino events were detected for the first time. In 2018, a neutrino event was used for the first time to identify an extragalactic blazar source emitting strong gamma rays and neutrinos.

  The IceCube Upgrade construction will start in 2024/2025 by adding 700 new high-performance detectors in the ice around the central area of IceCube. This will improve the calibration and allow detection of GeV neutrino events. In the plans for a future IceCube-Gen2 the amount of photodetectors would be doubled. The detection volume would be roughly eight times larger, increasing neutrino point source sensitivity by more than five times. The goal is to enable the identification of even more cosmic neutrino sources.

- **KM3NeT**
  KM3NeT (the cubic Kilometre Neutrino Telescope) is a European research infrastructure housing the next generation neutrino telescopes aiming at a better understanding of the workings of high-energy objects in our Universe. Following the successful deployment and operation of a series of prototypes, the construction of the first phase of the KM3NeT research infrastructure started in 2015 with two instruments focusing on two major scientific goals: 1.) the discovery and observation of high-energy neutrino sources in the Universe, and 2.) the determination of the relative masses of the neutrinos, referred to as the neutrino mass hierarchy. The ARCA (Astroparticle Research with Cosmics in the Abyss) neutrino telescope anchored at a depth of about 3500 m in the Mediterranean Sea 100 km south-east of Sicily, Italy, is dedicated to the search for very high-energy cosmic neutrinos. The ORCA (Oscillation Research with Cosmics in the Abyss) detector at about 40 km off-shore Toulon, France, is a particle physics experiment optimised for the study of the neutrino particles themselves by studying neutrinos created by cosmic rays in the Earth’s atmosphere.

  The construction of ARCA – with in its first phase 24 detection units – started in December 2015. In each unit 31 photomultiplier tubes have been arranged to look in all directions for the faint light emitted by particles passing by. Since October 2021, ARCA has been operational with eight detection units. The first phase ARCA telescope with a detection volume of about 0.1 cubic kilometre will provide a sound demonstration of the KM3NeT technology of cosmic neutrino detection. In KM3NeT 2.0, the detector of the ARCA telescope will comprise 230 detection units resulting in an instrumented volume of about 1 cubic kilometre – slightly larger than that of the IceCube neutrino telescope. A potential expansion beyond that would be to reach an instrumented volume of several cubic kilometres. Construction of ARCA will proceed in phases adapted to the available funding. Currently, the implementation of the full configuration of KM3NeT 2.0 and beyond is partially funded.

2 Integrated roadmap for 2020-2035

A general theme of the Roadmap is the need for an integrated approach to decision making, if we are to achieve our scientific goals. This includes, for example, the necessity of planning for a broad range of facilities to complement Europe’s very large flagship observatories. While no small-scale facilities are explicitly part of the Roadmap recommendations, their importance as part of the ecosystem of European facilities should not be underestimated. Small facilities are often more flexible, able to respond quickly to targets of opportunity (e.g., transient events), to allocate significant observing time to single projects, and can be optimised to perform specialised observations. In addition, such facilities often offer the best opportunities for the training of early-career researchers, as well as important public engagement opportunities.

Adopting a global approach also means to consider requirements for data processing, storage and dissemination at the stage of mission/facility planning, and to fund the computational, laboratory and theoretical efforts that go hand-in-hand with breaking new observational grounds. While the strategic roadmap is shaped by science goals, its implementation must also respect the increasing desire of the European community to ensure Astronomy research is conducted in a sustainable and equitable manner that also fulfils our roles as educators and responsible citizens.

The recommendations in the eight categories that follow, from ground- and space-based facilities, to computing, and human aspects, should be considered as an ensemble. New observatories should for example have questions of data access, sustainability, and training built in right from the onset. An example of good practice is AtLAST, a proposed 50m-class submillimeter telescope to be fully powered by renewable energies, which has embedded questions of energy production and storage in the design of the observatory from the earliest stages of planning.

2.1 Facilities prioritisation

2.1.1 Ground-based, new facilities

Completion of the construction and commissioning of the ESO Extremely Large Telescope (ELT) and its first generation instruments, as well as that of the Square Kilometre Array (SKA) Phase 1 and its Regional Centres are of key strategic importance. Amongst new ground-based infrastructure projects, three clearly emerge from the facilities prioritisation exercise. In this category, the highest priority facility is the Cherenkov Telescope Array, due to the expected science breakthroughs it will trigger, and for its potential to open up the high energy gamma ray spectral window to the broader Astrophysics community. This is followed by two other, equally-ranked priorities: the European Solar telescope, and a general-purpose wide-field optical spectroscopic facility on a 10m-class telescope. These facilities were also priorities in the 2008 ASTRONET Roadmap, and have emerged again independently in the current exercise.

Cherenkov Telescope Array

The Cherenkov Telescope Array (CTA) is the next-generation, European-led, imaging atmospheric Cherenkov facility. It will be composed of arrays of optical telescopes to detect radiation produced in the upper atmosphere by high energy gamma-rays produced by black holes, neutron stars and a wide range of extreme phenomena. The CTA Observatory (CTAO) will be the first true large-scale observatory targeting these energies, and will lead to breakthroughs in our understanding of the origins and production of gamma rays, with implications for both astrophysics and fundamental physics.

CTA will represent a major step-change in capabilities and sensitivity compared to current state-of-the-art atmospheric facilities H.E.S.S., MAGIC, and VERITAS. The observatory will comprise two arrays, on La Palma in the Canary Islands and on Paranal in Chile, each made up of telescopes of different sizes in order to probe a wide energy range (from 20 GeV to at least 300 TeV). The lower energy sub-arrays, which will explore new scientific territory and could bridge the gap to space-based gamma-ray astronomy, are more of a technological challenge, requiring larger telescopes equipped with high quantum efficiency focal plane detectors. The high energy sub-array will have a significantly larger detection area than current facilities, and with the improvement in background rejection compared to the most sensitive current telescopes, it will increase number counts by at least an order of magnitude, allowing meaningful source population studies.

The current initial phase (“Alpha”) plan produced by CTAO is for the Northern site on La Palma to be focused on extragalactic sources with 4 Large-Sized Telescopes and 9 Medium-Sized Telescopes in order to operate in the 20 GeV

– 5 TeV energy range. The Southern site, with its optimal view of Sagittarius A*, will initially focus on Galactic sources and operate at energies of 150 GeV to 300 TeV through a combination of 14 Medium- and 37 Small-Sized Telescopes. The longer-term plan is to increase the size of both arrays, involving the addition of all three classes of telescopes.

Prototype telescopes have been built and are undergoing commissioning on the La Palma site, with the Southern hemisphere array to begin construction later, once necessary infrastructure work has taken place. The recommendation is to secure the funding necessary so that this initial construction phase is completed by the target date of 2028.

European Solar Telescope

The European Solar Telescope (EST) is a 4m solar telescope to be built in the Canary Islands, with first light expected by 2030. The EST will significantly increase our understanding of the solar magnetic field and its relations with the heliosphere and the Earth.

The EST was the top recommendation in the medium-scale facilities category of the 2008 ASTRONET Roadmap – see Progress since Previous Roadmap. The international landscape has changed significantly in the intervening years, but the EST remains a high priority. In particular, the Daniel K. Inouye Solar Telescope (DKIST), a US-led 4m telescope, commenced its full scientific operation in February 2022. DKIST is equipped with adaptive optics, and designed to provide diffraction limited, very high angular resolution observations of the solar atmosphere, both in broadband imaging and spectro-polarimetry. While DKIST is designed to fight straylight by its off-axis configuration, optimising the observation of the corona, EST is a polarisation-free on-axis telescope that will deliver very high spectropolarimetric accuracy. These distinctions make the science applications of both facilities highly complementary. The completion and scientific exploitation of EST, in synergy with DKIST, is therefore a priority. This Roadmap's recommendation is to ensure EST reaches first light on the shortest possible timescale to maximise these synergies and help the European Solar physics community maintain their worldwide leadership.

Wide-field, high multiplex spectroscopic facility

Large-scale optical spectroscopic surveys are crucial to address a broad range of questions about the large-scale structure of the Universe and the nature of dark energy, the star formation histories of galaxies, and the structure and formation of the Milky Way and the Local Group, to list a few. Ensuring the access of the European astronomical community to a general-purpose, wide-field, high multiplex spectroscopic facility, behind a telescope of the 8-10m class is therefore a high priority. Such a facility will enable a broad range of science investigations and help capitalise on other large investments by providing follow-up capabilities for facilities such as JWST, VRO, Euclid, and SKA.

Several new dedicated spectroscopic survey facilities are beginning operations (or are expected in the first half of the 2020s). The Dark Energy Spectroscopic Instrument (DESI) began full survey operations in 2021 on the 4m Mayall telescope at Kitt Peak National Observatory, aiming to obtain spectra of 30 million galaxies and quasars up to z~2, in order to construct a 3D map of the Universe and constrain the equation of state of dark energy, with additional Galactic and extragalactic science applications. WEAVE on the 4m William Herschel Telescope started commissioning of the LIFU mode in 2022. In its Multiple Object Spectrograph (MOS) mode, it will allow for up to 1000 spectra to be simultaneously taken over a 2 deg^2 field of view. Several key surveys are planned, many of which aim to follow-up targets from key facilities, in particular Gaia, LOFAR and Apertif on the Westerbork Synthesis Radio Telescope. On the horizon is also the 4MOST instrument for the 4m VISTA telescope, which will allow for spectra of ~2400 objects distributed over an hexagonal field-of-view of 4.2 deg^2 to be observed at once. The 4MOST consortium consists of 15 institutes mostly from Europe, but the involvement of ESO allows for broader European community involvement in key surveys.

The combination of DESI, WEAVE and 4MOST will offer wide scale spectroscopic coverage over both sky hemispheres. Breakthroughs will come from the size of the samples produced, and the ability to follow-up key imaging surveys, but the size of the respective telescopes, all 4m in size, limits the depth of the observations. Planning for a wide-field, high multiplex spectroscopic instrument to be installed on a 8-10m class telescope is now crucial. Current plans on this front include MOONS, the new multi-object spectrograph being built for the VLT; while benefiting from the greater sensitivity offered by the 8m mirror, it is however limited by the 25 arcmin diameter field of view. On the 8m Subaru Telescope, the Prime Focus Spectrograph is planned to simultaneously target 2400 astronomical objects inside a 1.3 degree field of view. The most ambitious facility currently planned is the Maunakea Spectroscopic Explorer (MSE), a 11.25m telescope with the ability to observe 4000 astronomical objects at once over 1.5 deg^2. The project is currently in its design phase, led by the current Canada-France-Hawaii Telescope partnership, with full science operations nominally starting in 2029-2030.

The recommendation of this roadmap is for the European community to secure access to a wide-field optical spectroscopic facility on a 10m-class telescope. Possibilities include seeking increased European involvement in the MSE project, and/or planning for a separate, European-led facility, most likely under the auspices of ESO. The latter option would present the strong benefit of opening the Southern sky to deep, wide-field, high multiplex spectroscopic surveys. ASTRONET should set up a working group to explore all possibilities and develop a plan.

2.1.2 Ground based, upgrades and new instruments

Europe operates many astronomical facilities that will continue to do cutting edge science in the coming decade, both via existing functionality and continued upgrades to their capabilities. It is important to strengthen the ability of these successful facilities to secure the funding needed to continue their excellent scientific work, especially in a landscape of increased operations costs. Across all science areas, there is a strong desire of the community to invest in upgrades and extensions to many of the flagship European facilities. The following projects were seen as particularly important, for their broad scientific appeal.

ALMA upgrade

The Atacama Large Millimeter/submillimeter Array (ALMA) is a unique facility that has been producing groundbreaking science across a very wide range of science areas, from the imaging of protoplanetary disks as they have never seen before, to the discovery and redshift confirmation of some of the most distant galaxies in the Universe. The sensitivity and spatial resolution of ALMA over the entire currently-available frequency range of 84 to 950 GHz is unrivalled. The only future facility that would reach better resolution is the ngVLA, but only at the lowest frequencies (up to 116 GHz). There are no new major interferometers operating at submillimeter wavelengths anywhere on the horizon, making the upgrade of ALMA a high priority, in order to sustain the current pace of discovery into the coming decades.

On a short timescale, ALMA will be upgraded with Band 1 and 2 receivers, completing the intended coverage of frequency space down to 35GHz. Of particular note are the Band 2 receivers; with a wide bandwidth of 67-116GHz, and improved sensitivity, they represent a first step towards the kind of overall upgrade of the facility that will improve the scientific throughput by both opening up new parameter space, and increasing the speed of observation.

Across almost all science areas surveyed as part of this Roadmap's consultation process, a significant upgrade of ALMA was seen as a priority, and therefore constitutes one of the key recommendations of this report. There are two key areas where upgrades could trigger a sizeable scientific gain: (1) increasing the speed and efficiency of observations with larger bandwidths and more sensitive receivers, and (2) opening up new discovery space, especially in the field of solar physics, by increasing the maximum baselines beyond the currently planned 16km limit. Multi-beam receivers are also an avenue worth exploring to increase both sensitivity and mapping speed, but there are engineering limitations due to the current antenna design.

Such an upgrade to ALMA is a high priority to continue our exploration of the physics and chemistry of planet and star formation, and to match the increase in sensitivity and resolution that the ngVLA and SKA will produce at lower frequencies.

New VLT instrumentation

Even after more than 20 years of operations, the Very Large Telescope (VLT) remains at the forefront of European (and worldwide) optical and near-infrared Astronomy. This position has been achieved and maintained up to the present day through an extensive and innovative instrument development programme (see Section 1.2.1 for an overview of current and upcoming VLT instrumentation). The recommendation of this report is that, even in the ELT era, VLT operations and instrument development efforts continue to be supported and strengthened. The ASTRONET science prioritisation exercise identifies two areas of instrumentation that receive particularly strong support from the research community:

- To follow-up on the successful MUSE instrument, BlueMUSE is a concept for a new seeing-limited, blue-optimised, large field of view, integral field spectroscopic instrument. With a wavelength range of 350-580nm and a 2 arcmin^2 field of view, it would offer new interesting scientific opportunities, such as the study at cosmic noon (z~2) of the structure of the Circumgalactic Medium (CGM) and, for the first time, the detection of the Intergalactic Medium (IGM) in emission. Other important applications include the study of very massive stars in the Milky Way and galaxies of the Local Group.
- Building on the success of the SPHERE instrument, there is strong support for a new high-contrast, high angular resolution instrument to push the capability of the VLT to perform exoplanetary system imaging to the limit of what can be achieved on a 8m-class telescope. Science breakthroughs would come from the ability to observe planets closer to their stars, to target lower mass planets, and to characterise their atmospheres in greater detail. In addition to immediate science gains, such an instrument would be an important stepping stone towards ELT instrumentation (see Section 2.3.3) by triggering crucial technological developments (e.g. sensitive wavefront sensors, extreme AO systems, high resolution spectroscopy up to R=100,000).

Second generation ELT instrumentation

Science operations on the ELT are expected to begin towards the end of the 2020s, with first generation instruments METIS, HARMONI and MICADO, alongside the MORFEO AO module (see Section 1.2.1). In 2021, ESO also gave permission for the agreements towards the development of the second-generation instruments ANDES and MOSAIC to be signed. These instruments are very important to increase the spectroscopic capabilities of the ELT. First, ANDES, a modular fibre-fed cross dispersed echelle spectrograph, will provide the highest spectral resolving power (R~100,000) of all first- and second-generation instruments in the optical and near infrared. Such spectral resolution is crucial to the characterisation of the atmospheres of exoplanets, and the study of the first generation of stars in the Universe. MOSAIC on the other hand will allow multiple object spectroscopy (MOS) over the widest possible field-of-view possible with the ELT. This will make MOSAIC particularly powerful to study the Interstellar Medium (ISM) of the first galaxies, the Epoch of Reionisation, and the ionisation state of the Intergalactic Medium (IGM) in the early Universe.

Both instruments, with the necessary capabilities to enable these science applications, are highly anticipated by the European scientific communities. The recommendation of this Roadmap is to ensure their rapid adoption, and progress towards first light on the shortest possible timescale, to ensure maximum synergy with other facilities such as JWST and SKA.

2.1.3 Space-based facilities

The panels of the ASTRONET Roadmap assessed the priorities of their respective scientific communities, with broad support emerging for the key facilities Athena, LISA and Mars exploration. These space-based facilities are described in the sections below.

Athena / LISA

Athena and LISA are the next two highly anticipated large-scale missions of ESA's Cosmic Vision programme, with expected launches in the 2034-2037 timeframe.

Athena is an X-ray space observatory, designed to study groups and clusters of galaxies, and investigate the physics of accretion onto compact objects. It will also detect the earliest supermassive black holes and study their impact on the evolution of galaxies and clusters of galaxies. Athena consists of a single, 1.4 m^2 X-ray telescope with a focal length of 12m, and an angular resolution of 5 arcsec on-axis, and featuring two instruments: a wide-field imager (WFI), offering excellent energy resolution, low noise, fast readout and high time resolution, over a field-of-view of 40' x 40'; and an X-ray Integral Field Unit (X-IFU), a cryogenic X-ray spectrometer, providing spatially-resolved X-ray spectroscopy with a spectral resolution of 2.5 eV up to 7 keV, over a field of view of 5 arcmin.

LISA will be the first space-based gravitational wave observatory and will consist of three spacecrafts about 2.5 million km apart. It will detect and study low frequency gravitational waves, and allow us to investigate their various sources in the whole universe. These include galactic compact binaries, consisting of white dwarfs, neutron stars or black holes; supermassive black hole mergers all the way back to their earliest formation; extreme mass ratio inspirals which consist of stellar compact objects orbiting massive black holes; intermediate mass black hole binaries. LISA is also expected to detect gravitational wave sources of the type already observed by LIGO/VIRGO, a few weeks or months before the merger, allowing to plan observing campaigns to identify their electromagnetic counterparts. In addition, LISA will be able to detect the stochastic gravitational wave background originating from the early universe, in particular during its inflation phase.

Both missions have been the subject of detailed studies, which pointed to important risks of rising costs. To tackle these, ESA has capped the cost at completion of each of the two missions to 1.3 billion euros. At the time of writing of this Roadmap, studies are ongoing with the aim of complying with this cost cap, with reductions of about 30% and 10% still to be achieved for Athena and LISA, respectively. Fully acknowledging this budgetary context, it is recommended that both missions are adopted and developed in the best possible timeframe, preserving their initially-planned scientific return.

Mars exploration

The exploration of Mars is a strong priority of the astronomical community. The main goals are to study Mars geology and climate, as well as to determine whether life was present on the planet in the past. Europe is currently involved in two complementary Mars exploration programs.

The first one is with NASA, and involves at this moment two rovers which are studying the Martian surface and collecting samples: Curiosity on Mars Science Laboratory, and Perseverance on Mars 2020. Both are operational and their scientific harvest is ongoing very successfully. These two missions will be followed in the years 2026-2028 by the NASA-led Mars Sample Return mission, of which ESA is a major contributor. Its main goal will be to return to Earth the soil and rock samples collected by Perseverance, for detailed chemical and physical laboratory analysis, including the search for past life signatures.

The second program is the ExoMars program, developed jointly by ESA and the Russian space agency (see Section 1.1.2). The first ExoMars probe was successfully launched in 2016 and its orbiter segment TGO is operating nominally, while its landing demonstrator failed. The second probe, with more ambitious objectives and in particular that of landing a full scientific platform and a rover, is now in jeopardy, due to the geopolitical situation. Alternative scenarios were studied, resulting in the decision by the 2022 ESA ministerial council to develop a European lander in order to deliver the Rosalind Franklin rover to the surface of Mars. This scenario will preserve the scientific goals of ExoMars, although with a significant delay.

In this context, given the importance of the complementarity of both programs and the probable long delay of the second ExoMars probe, it is necessary to reexamine and adapt the European strategy for the study of Mars.

2.2 Laboratory Astrophysics

The main goal of laboratory astrophysics is to perform experiments in the laboratory under conditions that as best possible reproduce aspects of astrophysical environments. This is done to complement and support astronomical observations through a combination of experiments, numerical simulations, and theory. Laboratory astrophysics is linked to modern observational techniques, from ground-based telescopes to space missions, including in-situ analysis of extra-terrestrial objects by interplanetary probes and sample return missions, and makes use of large-scale instruments of physics such as synchrotron radiation facilities, high energy lasers, and sophisticated analytical tools such at AFM, TEM and SEM microscopes, as well as high-precision isotope ratio measurements.

The aim of laboratory astrophysics is to characterise the basic properties of matter needed to model astronomical processes, provide the data necessary to interpret astrophysical observations and recreate in fully controlled conditions the large variety of environments in which matter exists. Laboratory astrophysics is therefore an essential component for all aspects of astronomical investigation.

Great ingenuity is often required, as most astrophysical settings do not occur naturally on Earth, to reproduce the relevant settings in the laboratory. It is, however, this endeavour of probing the properties of matter and deriving data that are directly useful for astrophysics which makes it possible for us to interpret and understand the universe as we observe it. Due to the complexity laboratory astrophysics involves scientists from many disciplines: astrophysicists, physicists, cosmochemists, geochemists, chemists, and biologists, who measure, calculate, or model the properties and processes involving nuclei, atoms, molecules, surfaces, fluids, and solids.

Laboratory astrophysics is a field which benefits greatly from the improved techniques within solid state and atomic physics. This development along with the greatly improved details in observational techniques over all wavelengths has created a strong demand for the best possible data for analysis of astronomical results and their interpretation. Examples are various aspects of; astrochemistry which studies chemical reactions under extreme conditions of temperature, density, and irradiation; plasma physics; spectroscopy; laboratory analyses of extraterrestrial samples (e.g. meteorites, IDPs and lunar samples); fluid dynamics, and magnetohydrodynamics.

Understanding astrophysical phenomena relies heavily on basic physical data of elements, nuclei, and fundamental particles, for example, in the form of atomic data such as line lists, nuclear cross-sections, and neutrino properties. All fundamental understanding of the key astrophysical processes in the interstellar medium and circumstellar environments is based on the understanding, provided from laboratory astrophysics, of the physical and chemical processes that generate and modify circumstellar and interstellar dust grains and molecules under different conditions.

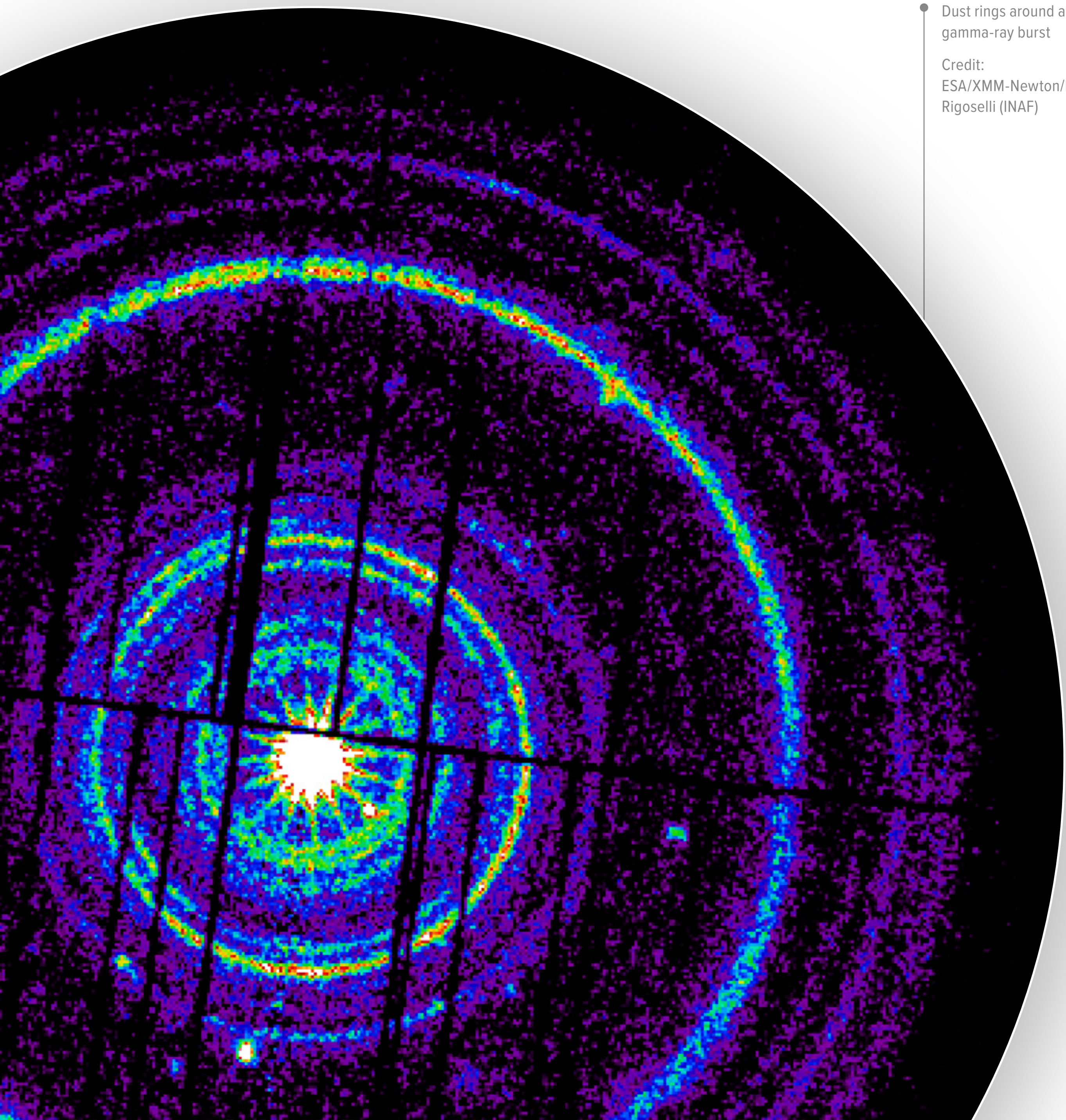
Nanometer- and micrometer-sized refractory dust grains play an important role for the thermal, dynamical and chemical conditions in many astrophysical environments, especially for the star and planet formation process and the late stages of stellar evolution. Dust particles determine the spectral appearance of protostars, as well as of evolved stars with circumstellar envelopes, and they also dominate extinction curves of galaxies.

The data obtained from the many different laboratory astrophysics experiments, for example, atomic and molecular spectra and optical properties of dust, are shared with the community through various online databases, such as the Database of Optical Constants (HJPDOC); Database of Aerosol Spectra for Cosmic Dust; Leiden Ice Database for Astrochemistry; The Cologne Database for Molecular Spectroscopy (CDMS); Databases of the Astrophysics & Astrochemistry Laboratory; High temperature molecular line lists for modelling exoplanet atmospheres (ExoMol); Atomic Database for Spectroscopic Diagnostics of Astrophysical Plasmas (CHIANTI) and the Astromaterial Acquisition and Curation Office.

The laboratory-based analyses of meteorites, fragments of asteroids located in the asteroid belt between Mars and Jupiter, allows the detailed reconstruction of the earliest history of the solar system, including the dynamics of material transport in the disk and the accretion and differentiation of the planets. These results are complementary to astrophysical studies and astronomical observations, such that combining the results from all three fields paves the way for understanding solar system evolution and planet formation in unprecedented depth.

Meteorite studies are strongly linked to space missions, especially through current and forthcoming sample return missions. The successful return of samples from asteroid Ryugu by JAXA's Hayabusa2 mission has established an important link between this asteroid and a specific group of carbonaceous chondrites, and the analyses of Ryugu samples has provided new key constraints on the original formation location of asteroids and potential links between asteroids and comets. The success of Hayabusa2 marks the beginning of an era of sample return missions, where ongoing missions include NASA's OsirisRex mission to asteroid Bennu (sample return in 2023), JAXA's MMX mission to Mars' moon Phobos (anticipated sample return in 2028), and the planned Mars sample return within the next two decades. These ongoing and future sample return missions will make the laboratory-based analyses of extraterrestrial samples an essential component in the broad field of laboratory astrophysics and astronomy.

Additionally, laboratory experiments are essential to understand and interpret astronomical observations of gas and dust. Such experiments can probe the microphysics of how particles stick together under the different conditions encountered in protoplanetary disks (i.e., how ice mantels affect stickiness, what collision velocities are tolerable), the formation and evolution of dust in the radiative environment of planet-forming disks, chemical reactions in the gas phase and between gas and dust, the behaviour of dust-ice mixtures when they sublimate (reminiscent of what happens when drifting pebbles cross the iceline), the optical properties (including polarimetry) of dust-ice mixture, etc. These experiments are performed both in individual laboratories (e.g. plasma chamber, irradiation platforms) and in large facilities such as synchrotron beamlines (e.g. SOLEIL, ESRF, DESY) and medium to high energy ion accelerators (GANIL, GSI, CERN).



Dust rings around a bright gamma-ray burst

Credit: ESA/XMM-Newton/M. Rigoselli (INAF)

2.3 Technology development

The facilities mentioned in the previous sections will constitute astronomy's workhorse in the coming decades, leading to major discoveries, and so will longer-term instrumentation development (see Section 3 of the Roadmap). Meeting these ambitious goals by successfully building these next generation facilities will require the development of crucial cutting-edge technologies, which must be anticipated and carefully planned in advance. Because the time-scale for the emergence and maturation of these new technologies can be as long as a decade or more, it is recommended that the following key technological developments are initiated and carried out in the best possible timeframe.

2.3.1 Receiver technology and dish development for radio astronomy

The Square Kilometre Array, in its phase 1 representing about 10% of the final targeted instrument, will be a unique facility providing us with exquisite sensitivity and spatial resolution at centimetre and metre wavelengths, opening exciting opportunities for the study of the Universe. Yet, it is only in its phase 2 configuration that SKA will reach its full power and become the unequalled radio astronomy facility for the rest of the century.

SKA phase 2 development will require significant technological progress in some key areas, including receiver technology, especially at high-frequencies, as well as backend data handling. The evolution from phase 1 to phase 2 will also involve the construction and deployment of hundreds of additional dishes, requiring significant progress in their manufacturing and installation.

These major technology developments will likely require many years, and we recommend to have them started as soon as possible.

2.3.2 Cryogenics and detector technology for far-infrared space telescopes

Among the major needed astronomical facilities for the mid- and long-term future, one finds a next generation far-infrared, large-collecting-area space telescope, as successor to Spitzer and Herschel. Key technological progress is needed for the design and development of such a space facility, the most important of which being:

- on the one hand the challenge of cooling down to very low temperatures such a large telescope and its focal instrumentation;
- and on the other hand, the development of new efficient detectors at far-infrared wavelengths.

These essential developments will require significant effort and time, and therefore the corresponding technological roadmap should be defined and started soon.

2.3.3 High contrast imaging en-route to ELT-PCS

The Planetary Camera and Spectrograph (PCS) for the ELT will be dedicated to detecting and characterising nearby exoplanets with sizes from sub-Neptune to Earth-size in the neighbourhood of the Sun. This goal is achieved by a combination of eXtreme Adaptive Optics (XAO), coronagraphy and spectroscopy. PCS will allow us not only to take images, but also to look for biosignatures such as molecular oxygen in the exoplanets' atmospheres.

To achieve its ambitious scientific goals, PCS must provide an imaging contrast of ~ 10^{-8} at 15 milliarcseconds angular separation from the star and 10^{-9} at 100 milliarcseconds and beyond. In addition, it must provide the spectroscopic capability to observe individual spectral lines due to molecules at optical and NIR wavelengths. The most promising approach for reaching these capabilities is a combination of XAO, coronagraphy and high-dispersion spectroscopy (HDS), which must each individually be pushed to the limit. A staged technology development program is being developed as a roadmap towards ELT-PCS. XAO is a key technology still requiring significant R&D, the same is true for the development of predictive control methods. These R&D activities will be followed by implementation and tests in the laboratory, and subsequently implementing a prototype followed by a pathfinder instrument designed to test and demonstrate the technology on sky. After the conclusion of these R&D activities at ESO and within the community, all major ingredients of PCS should be validated and lifted to a high enough level of technology readiness to enable the PCS to be on sky in the second half of the 2030's.

2.3.4 Space-qualified UV-optimised optical elements and detectors

Access to the ultraviolet (UV) range is of utmost importance for the future of astronomy. Imaging and spectroscopy in the UV is essential in a very broad range of astronomical studies. In the field of stellar physics, these include the study of hot stars, of young stellar objects, of white dwarfs, as well as that of magnetic activity of cool stars. Observations in the UV are also needed to study the interstellar medium, and UV astronomy is also essential in the field of galaxy evolution.

Anticipating the retirement of the Hubble Space Telescope and its UV instrumentation (STIS, COS), the 2020 US decadal survey has identified as one of its highest priorities a large collecting area space telescope covering the electromagnetic spectrum from the UV to the IR. The development of this future major facility, to which Europe will very certainly participate, requires in particular significant

UV-related technological progress, necessary to optimise the space-qualified optical elements of this instrument in the UV (mirrors, gratings, etc…), as well as UV detectors.

The development of UV spectropolarimetry will also be needed, calling for an important technological roadmap to design and manufacture space-qualified polarisation optics (retarders and analyzers) working in the UV.

2.3.5 Development of new optical / infrared interferometry technologies

The VLTI has become a very powerful facility for milli-arcsec studies of AGNs, exoplanets and young disks, evolved stars, etc. Future studies for optical - infrared interferometry include the construction a new array (Nx10 3-4m and/ or 8m telescopes) up to kilometric baselines in an ESO / international context and to develop new technologies such as using heterodyne receivers for a large number of apertures, fibered beam transport and delay compensation, compact and fibered off-axis telescopes, etc. New technologies need also to be developed as the current concepts of classical telescopes and delay lines indicate that expanding the number of apertures to 10 - 15, or even more, encounters a limitation for the implementation.

2.4 Computing and theory

Astronomical and astrophysical research has become a data-intensive endeavour over the last decades. The future large, complex, and inter-dependent data sets that will be generated by the observatories, space missions, mock experiments, theoretical model simulations and numerical simulations described in all the science panel reports of this roadmap require new tools and approaches for doing science.

Data from ground-based and space-borne facilities are becoming increasingly more complex and more extensive in volume owing to the increasing sensitivity of the detectors and/or of the observed sky area. Even the science-ready end products are often too large and too complex to inspect and analyse through human interaction. This situation has motivated intense interdisciplinary research and even dedicated institutes focused on applied mathematics, statistics, machine learning, or more generally data science in data intensive research areas of astronomy such as the Formation and Evolution of the Universe, the Formation and Evolution of Galaxies and the Formation and Evolution of Stars. The objectives are here to develop novel algorithms and methods designed to handle, explore, analyse and combine the expected complex datasets. The broad idea of machine learning is therefore gaining immense momentum in all branches of astronomy. It includes both supervised and unsupervised methods targeting the search for rare targets, pattern recognition, classification, etc. Beyond its standard usage for data mining and component separation/ classification, sophisticated approaches have been proposed to accelerate or even replace numerical simulations, to explore the likelihoods of models, and to even propose alternatives to theoretical models.

Therefore, computing is a top level priority of this Roadmap and it goes far beyond the need for sustained investments in high-performance and high-throughput computing for data analysis and theoretical models. Instead the computing keywords range from People (training, careers, people), Open (Open Science, Data and Software sharing), Data (mission/facility data processing), Archive (archives for data and software), User-to-data (next generation tools: cloud computing, platforms, collaborative frameworks), to Green (green data infrastructure, reducing the carbon footprint). The four key recommendations are:

1. Developing and investing in a professional software engineering / computational skills base in Astronomy. This has many implications and requirements, including career development with clear progression pathways in academia and improving the diversity of the workforce. Such careers have to be promoted and considered as an integral part of the science/research portfolio. New assessment criteria, for example based on industrial models, should be adopted by the Astronomy community to give proper credit to essential contributions that technicians and software engineers provide.

2. Missions and facilities have to plan an integrated approach for data products and software tools: their design, delivery, maintenance and development should be sufficiently planned for and resourced, from the onset and for the lifetime of the mission/facility. Initiatives should be supported for the long term preservation and scientific use of data.

3. To adopt and further develop a "Tiered" approach for Data Infrastructure, for all types of data pertaining to astrophysics, including models, simulations and mocks, and where beneficial to connect with similar frameworks developed for other disciplines of science. A `Tiered' Distributed Analysis model maximises the transformation of science data to scientific results, organising and sharing expertise to benefit from economies of scale, with attention given to preventing the exclusion of individual communities, as well as monitoring and minimising the environmental cost. Tier 1 are facility operators (e.g., ESO, ESA, SKA) which are responsible for multiple data generating telescopes and their instrument suites. They pass data from these to community-provided Tier 2 expert data processing centres which have critical expertise in specific techniques or wavelength domains (e.g., optical/ near-IR, thermal-IR, radio, etc.), including mocks and numerical simulations. On their turn Tier 2 centres provide a live and collaborative interface to Tier 3 instrument teams and the wider community, exploiting the use of standards in building these connections between facility-to-data-to-science.

4. Embracing a fully collaborative, open and synergistic view when it comes to the astronomy-computing ecosystem, encompassing data, software, processing, analysing and modelling. The community should implement and support official mechanisms to monitor, acknowledge and reward behaviours that model this ambition. Open science, data and software sharing, archives, cloud computing, platforms and service infrastructure represent various facets of an integrated view of computing in astronomy: this should be acknowledged and acted upon.

The implementation of these key recommendations requires an update of the research crediting and promoting system, as well as a more collaborative and ordered set of resources (e.g., funding agencies, computing centres). The implementation comes with an apparent cost. Given how vital the contribution of computing is to modern astronomy and astrophysics, it is a science-driven necessary cost and must be treated as a top priority item. It is a prerequisite for high quality and shared science in the Big Science, Big Data era. We strongly recommend that ASTRONET and the funding agencies acknowledge the key recommendations and put them into action.

2.5 Education, training and society

Astronomy has undergone dramatic changes over the last few decades, not only in the way we view the Universe but also in the way that research is being conducted. Astronomy entered the era of Big Science, Big Data, and consequently research is more often performed in large consortia of researchers covering all stages of a project: from the design and construction of new advanced instruments, to preparing, operating, processing, and analysing the data from large surveys and novel science instruments. There is a growing need for adequate training and career paths for Astronomy researchers specialised in areas of advanced instrumentation, computing, and data science.

The way in which astronomy education projects are designed and executed have the potential to reshape the experience of astronomy learners and alter the astronomy education ecosystem. At this moment the presence of astronomy in many European educational curricula is irregular. Content topics relating to basic astronomy such as telescopes and optics are the most prevalent. Topics related to cosmology and current research in astronomy are also found, but material related to robotic telescopes are nearly absent. There is a need for astronomers to engage with curriculum developers and educational textbook publishers to bring modern cutting-edge astronomy research with emphasis of Big Science and Big Data to the national curricula.

The structures dedicated to facilitating or conducting Astronomy research keep increasing within Europe. Astronomy research requires unique technological developments, data management systems and highly-skilled research staff. This can lead to opportunities for innovation and market development, can attract investments and contribute broadly to socio-economic development. Intensive joint educational and research programs between astronomy and industry already exist and many more are emerging. To further enhance the potential of (socio)economic impact, joint R&D agendas for large projects and long-term collaborations can be set up. Furthermore, educational (BSc/Msc) and research (PhD/post-doc) programs at universities and research institutes can already intimately connect to (local) industry in the form of internships, dedicated courses, or entire joint (interdisciplinary) programs on astronomy-themed advanced instrumentation and/or data science. Because, in the end, a major spin-off from astronomy is in the form of human capital of highly trained academics that go into industry.

Community based science and community engagement have hitherto mainly been one-way processes from astronomy towards the community. There is a growing awareness that a long term healthy and fruitful relation requires an equal and respectful two-way engagement.

The key recommendations of this report on the interrelation of astronomy and society are:

- Ensure there are adequate training and career paths for Astronomy researchers specialising in the areas of advanced instrumentation, computing and data science.
- Promote modern cutting-edge Astronomy research, with emphasis on Big Science and Big Data, artificial intelligence, as well as technology R&D as part of the national education curricula.
- Further expand the recognition and award of researchers to include education and public engagement in their career paths.
- Further develop joint R&D and training programmes (MSc, PhD and PostDoc level) in close cooperation with industry, including training for entrepreneurship and social innovation.
- Adopt an equal and respectful mutual engagement with communities in locations where plans for astronomical facilities are being developed, in full respect of the land, people, culture and ecosystems.
- Include Astronomy education and public engagement as an integral part of facility/mission/project planning, devoting at least 1-2% budgets for professional Astronomy education and public engagement activities.

3 The future roadmap: beyond 2035

Below we discuss the ingredients of the future roadmap, for the years 2035 and onwards. Preparation for many projects on these long timescales have already started, or should start soon, given the fact that the timelines towards operational readiness of Big Science facilities and/or the science readiness of complex instruments often require a lead time of 15+ yrs.

3.1 Ground-based facilities and instrumentation

The Big Science facilities ELT and SKA (SKA1, Phase 1) will be operational around 2030 and both facilities are expected to have a productive scientific lifetime of 50+ years. During this lifespan, upgrades and new generations of instruments will be deployed for both facilities. The Phased approach of the SKA will allow it to reach its full scientific capacities described as Phase 2. Similarly, second- and third-generation instruments for the ELT will be required so the facility can fulfil its most ambitious scientific goals, such as the imaging of Earth-like planets in the habitable zones of stars beyond the Sun with the ELT Planetary Camera and Spectrograph (PCS).

In the field of gravitational wave physics, the ambitious plan for the Einstein Telescope (ET) has entered its preparatory phase. A milestone has been the inclusion of the ET on the European Strategy Forum on Research Infrastructures (ESFRI) Roadmap 2021, where it is mentioned as one of the projects with a new level of ambition to develop globally unique, complex facilities for frontier science, with the highest value project ever on the Roadmap - EUR 1.9 billion.

Several other ambitious plans such as SKA Phase 2, future visible / IR interferometry, future ground based CMB facilities and instrumentation, are still in a study phase.

3.1.1 The ELT Planetary Camera and Spectrograph (PCS)

Shortly after the ELT's first light later this decade, its four first generation instruments will start to operate, while two second-generation instruments (ANDES and MOSAIC) are envisioned to be science-ready around 2035. The extreme AO imager and spectrograph PCS is the third generation ELT instrument dedicated to directly detecting and characterising nearby exoplanets and their atmospheres, with sizes from sub-Neptune to Earth-size in the neighbourhood of the Sun. In fact, the "Are we alone?" question has been one of the main scientific drivers for the construction of the ELT. This goal can only be achieved by a combination of eXtreme Adaptive Optics (XAO), coronagraphy and spectroscopy. PCS will allow not only to take images, but also to look for biosignatures in the exoplanets' atmospheres. In parallel to the R&D roadmap mentioned in Section 2.3, complementary activities are being carried out in the ESO community. For instance, the High-Resolution Imaging and Spectroscopy of Exoplanets instrument (HiRISE) is a VLT visitor instrument that will use single-mode fibres to feed the high-contrast PSF delivered by SPHERE to the upgraded CRyogenic high-resolution InfraRed Echelle Spectrograph (CRIRES+) thereby implementing and validating the general PCS concept. Similar ideas are also being pursued by e.g., ERIS, RISTRETTO and possibly a SPHERE upgrade. After the conclusion of the R&D activities at ESO and within the community, all major ingredients of PCS should be validated and lifted to a high enough level of technology readiness to enable the project to start construction.

A long-term, pan-European Roadmap for the ELT-PCS needs to be developed to tackle the involved technological complexity, effort and costs. The science-ready instrument will allow the observation of nearby rocky planets and maybe the discovery of an exoplanet that's truly habitable — or even already inhabited — in the second half of the 2030s. To achieve this ambition, technology development efforts need to be coordinated now.

3.1.2 The SKA Phase 2 (SKA2)

While SKA Phase 1 (197 radio dishes and 131,000 antennas) will already open exciting opportunities and breakthrough science, many of the scientific aspirations of the European astronomical community rely on SKA reaching its full capabilities in Phase 2 (2500 radio dishes, including an extension to higher frequencies and a million radio antennas). SKA2 will, for example, probe the Dark Ages from $z = 6$ to perhaps $z \sim 20 - 30$. It will use HI to make the 'billion galaxy' surveys needed to address key questions such as neutrino mass and sub-per-cent accuracy on the dark energy w parameter. It will make deep polarisation-sensitive 'all-southern-sky' surveys that will probe the origin of the magnetic field in the Universe, determining its role in the formation of structures from the cosmic web, through galaxies to stars. SKA2 will also be a critical instrument for understanding planet formation and astrobiology.

The SKA2 plans will transform the research scope of the SKA infrastructure, placing it among the great astronomical observatories and survey instruments of the future, and opening up new areas of discovery, many beyond the confines of conventional astronomy. The realisation of SKA2 requires approval of the project and a long term planning, starting with a detailed design study around 2025 to allow full SKA science operations in the second half of the 2030s.

3.1.3 The Einstein Telescope (ET)

The Einstein Telescope (ET) is a design concept for a European third-generation gravitational-wave (GW) detector, which will be 10 times more sensitive than the current advanced instruments of the second generation (e.g., Advanced VIRGO) by increasing the size of the interferometer from 3km arm length to 10km, and by implementing a series of new technologies. These include a cryogenic system to cool some of the main optics to 10 – 20K, new quantum technologies to reduce the fluctuations of the light, and a set of infrastructural and active noise-mitigation measures to reduce environmental perturbations. ET will be able to perceive gravitational-wave signals in much greater detail and detect previously invisible weaker waves for the first time. While today every few days a gravitational-wave signal is observed, ET will observe gravitational waves virtually continuously. The measurements will reveal new information about the extremely dense matter in neutron stars and about the distribution of observed events on cosmic time scales, and enable new cosmological studies.

With the inclusion of the ET on the ESFRI Roadmap 2021, the project has entered its preparatory phase. The formalisation of the ET collaboration took place in 2022. The preparatory phase towards implementation will further consist of a number of steps including the selection of the hosting site (expected around 2025), the acquisition of the land, the establishment of a legal entity, the organisation of the governance, the delivering of the operative Technical Design Report and the optimization of the site. Start of operations is expected in the second half of the 2030s.

3.1.4 Future visible / IR interferometry

A further increased sensitivity, image quality and angular resolution using visible and infrared interferometry can be reached in several ways. Below we list a few examples based on ongoing developments.

VLTI and beyond

Further improvement beyond the third generation of VLTI instruments would be building on the assets of the VLT: large pupils with the most comprehensive optical interferometric infrastructure. The ESO VLTI roadmap (Mérand 2018) focusses on: 1.) Increasing the sensitivity; 2.) High-contrast capability; 3.) Reaching shorter wavelengths. These capabilities would serve, in one way or the other, all science cases of VLTI, including AGNs, exoplanets and young disks, evolved stars, etc.

Possible pathways to reach this could be: 1) Improving the throughput (≥ 10%) with fibres and still better optics and systems; 2) Hybrid AT-UT combination for improved imaging; 3.) Adding more and larger ATs (3-4m) for improved imaging capabilities. In addition the baselines can be increased with additional telescopes off the summit connected with fibres.

The VLTI is optimised for operation in the infrared. Future studies for optical - infrared interferometry include the construction a new array next to Paranal or on Chajnantor (Nx10 3-4m telescopes) and to devote a fraction of the VLTI time to develop new technologies (heterodyne for large number of apertures, fibered beam transport and delay compensation, compact and fibered off-axis telescopes, etc.)

Some studies for the longer future, such as e.g., the Planet Formation Imager (PFI) study, are currently focussing around two main classes of optical arrays: 1) kilometric baselines with a small number of 8-m class telescopes and 2) a dense array of a large number of smaller telescopes over possibly kilometric baselines. New technologies need to be developed as the current concepts of classical telescopes and delay lines indicate that expanding the number of apertures to 10 - 15, or even more, encounters a limitation for the implementation.

Hypertelescope

The analysis of image formation in extended versions of Michelson's optical stellar interferometer has shown that resolved images of exoplanets are theoretically feasible, both from the ground and from space (e.g., Labeyrie 1996). Hypertelescopes are innovative extended versions of such optical stellar interferometers, incorporating many mirror segments for operating as a dilute giant telescope. Their dilute mosaic mirror and focal beam combiner with pupil densification produce direct high-resolution images with full luminosity and with the high resolution defined by the size of the meta-aperture. A hypertelescope concept with a diluted Arecibo-like optical array of small spherical apertures has been developed and tested in a southern Alpine valley over the last decade. The construction and alignment techniques and the required accuracy with fixed mirror segments at near-ground level and a cable-suspended movable focal camera have been demonstrated. Together with the development of its operating software a direct experiment with a high limiting magnitude was recently performed on sky. The technology is now mature for developing a pathfinder experiment that may lead to a diluted telescope of 70-120m, as post ELT facility, to image, and study planets in the most interior orbits of the nearest stars. A 70m baseline would provide the required resolution to image such a system. More work is needed to determine if a very high contrast (<10^{-7}) at 2-3 times smaller inner working angle than the ELT is feasible.

3.1.5 Future ground-based CMB facilities and instrumentation

In the coming decades several research fields in cosmology are expected to grow rapidly with the advent of new facilities that have been proposed and/or approved. For example gravitational-wave (e.g., LISA, ET) and 21-cm cosmology (e.g., SKA) will each open an entire new window on the Universe. Similarly, polarisation and spectral distortions of the CMB are new frontiers, including the search for so-called B-modes in CMB polarisation anisotropies to detect primordial gravitational waves. However, at this very moment no specific facility has been proposed.

The current plans for large ground-based observatories to study the CMB are mostly US-lead and include Simons Observatory and South Pole Telescope. These two facilities will further evolve to CMB-S4, an international project led by the US, supported by the Simons Foundation and the Heising-Simons Foundation. CMB-S4 will measure the CMB temperature and polarisation fluctuations to exquisite precision. The project currently includes 85 institutes from 13 countries. There is a growing wish of many European university groups to join CMB-S4 by providing additional telescopes to increase the sensitivity of the facility as well as by providing expertise in data processing and analysis. These efforts are paving the way to high sensitivity polarisation measurements with future space-based missions. Complementarity with a space mission such as LiteBIRD is essential to reach the next steps in CMB science in the next decade. Together with involvement in CMB-S4 experiments, European CMB ground-based (e.g., QUBIC, QUIJOTE, LSPE-strip) and balloon-borne experiments (e.g., LSPE-swipe, BISOU) play a role as pathfinder for larger facilities.

We recommend the funding agencies in ASTRONET and APPEC to join forces in establishing a European participation in CMB-S4.

3.2 Space-based facilities and instrumentation

In the current cycle of ESA's long-term planning for space science missions, Cosmic Vision 2015–2025, two future L-class missions will investigate some of the most extreme phenomena in the Universe, Athena, the Advanced Telescope for High-ENergy Astrophysics, and LISA, the Laser Interferometer Space Antenna. Currently in the study phase, both missions are scheduled for launch in the 2030s. Further ESA's L-class science missions for the timeframe 2035-2050 will focus on moons of the giant Solar System planets, temperate exoplanets or the galactic ecosystem, and new physical probes of the early Universe.

The ESA Voyage 2050 exercise was concluded by a first set of recommendations concerning the above topics and relevant to L-class missions in the 2050 timeframe:

- consider post-JUICE mission(s) to the moons of the giant planets, including multiple fly-bys and orbit insertions, in situ measurements of atmospheric, surface and subsurface environments, and possibly sample returns;
- launch a detailed study for the full characterisation of temperate exoplanets, including detection of molecules in their atmospheres;
- in case the above study concludes that the number of exoplanets that can be characterised this way is insufficient, plan for a near-infrared astrometric mission for studying the galactic ecosystem;
- consider the development of a mission devoted to the study of the universe at early stages of its evolution as well as to its exploration at lower redshifts, involving novel instrumental techniques such as gravitational wave detectors or high precision microwave spectrometers.

In parallel, medium missions will continue to be selected through future open 'Calls for missions'. These future M-class missions will potentially address major science questions in many areas, such as magnetospheric systems, plasma cross-scale coupling, solar magnetic fields and particle acceleration, solar polar science, high precision astrometry, high precision asteroseismology, star formation, galaxy evolution, accretion by compact objects, astroparticle physics, physics of black holes via space radio-interferometry, mapping of cosmic structure in dark matter, large scale structure of intergalactic medium, quantum mechanics and general relativity.

In the present roadmap, taking into account the very rich and open perspectives of the Voyage 2050 exercise for ESA programmes in the coming few decades, we identify on the one hand priorities similar to those in the Voyage 2050 document. On the other hand we identify a few complementary space-based observational concepts that could play a major role in advancing our understanding of the Universe and its constituents.

3.2.1 CMB large-scale polarisation

Europe has a unique opportunity to consolidate its major role in the next generation of CMB space experiments capitalising on its successful leadership role in Planck as well as obtaining leadership on some key technologies (e.g., KIDS). In the coming decade LiteBIRD, (JAXA-lead with a large European involvement) will be the key space facility for detecting the first primordial gravitational waves. Notable large-scale and longer-term CMB initiatives at the European level are super-PIXIE, PRISTINE or PICO-like missions combining a spectrometer and an imager, to target CMB spectral distortions (considered as one of the three themes for L-class mission in ESA's Voyage 2050).

We recommend to set-up a pan-European working group to define a long term CMB roadmap towards a next generation European CMB space mission focused on large scale polarisation and spectral distortions.

3.2.2 Toward a large multi-purpose UV/visible/IR space telescope

HST is currently the last space-based high-resolution ultraviolet facility. Increased sensitivity with current ground based facilities will be important for studying e.g., distant systems of massive stars that have closer to primordial abundances. But ultimately, an ambitious UV/visible space-borne capability is critically required to succeed the HST, such as the Large UV/Optical/IR Surveyor (LUVOIR) or the Habitable Exoplanet Observatory (HabEx) concept.

LUVOIR is a concept being developed by NASA with a contribution from several European groups for a highly capable, multi-wavelength space observatory with ambitious science goals. This mission would enable great leaps forward in a broad range of science, from the epoch of reionization, through galaxy formation and evolution, star and planet formation, to solar system remote sensing. LUVOIR also has the major goal of characterising a wide range of exoplanets, including those that might be habitable - or even inhabited.

HabEx is another UV/Visible/near IR follow up concept developed by NASA with an involvement of several European groups for a mission to directly image planetary systems around Sun-like stars. HabEx will be sensitive to all types of planets; however its main goal is, for the first time, to directly image Earth-like exoplanets, and characterise their atmospheric content. By measuring the spectra of these planets, HabEx will search for signatures of habitability such as water, and be sensitive to gases in the atmosphere possibly indicative of biological activity, such as oxygen or ozone.

The top recommendation of the US Astronomy and Astrophysics Decadal Survey (Astro2020) to NASA was to establish a new Great Observatories Mission and Technology Maturation programme that would conduct studies into the first half of the 2040s-launched telescopes, with a hybrid of LUVOIR and HabEx of diameter at least 6m, as the first major project.

This top-priority NASA project connects very well to the future priorities of many science panels of the Astronet Roadmap, the priorities in the "Technology development" section of this Roadmap "Space-qualified UV-optimised optical elements and detectors" as well as the L-class theme "From Temperate Exoplanets to the Milky Way" in ESA's long-term scientific plan Voyage 2050. The ESA medium-class missions provide another route for Europe's participation. We recommend to set-up a pan-European working group to establish a long term scientific and technological roadmap towards a key contribution to this ambitious mission.

3.2.3 Near-infrared astrometry

A follow up of Gaia in the 2040s will improve proper motions with fourteen times smaller errors than from Gaia alone and open up new science cases, such as long period exoplanets and accurate halo measurements. Adding NIR detectors would allow an all-sky astrometry and photometry of obscured regions like the Galactic centre and the spiral arms as well as observation of intrinsically red objects with almost diffraction limited resolution. A preliminary technical study has been performed after selection by ESA in a call for new ideas in 2017. The results of this study can be used in a potential future medium-class mission proposal within the Voyage 2050 programme.

3.2.4 Far Infrared astronomy from space

In order to resolve the star formation process, observations of galaxies at resolutions of 100pc and better are essential. Among the key missing observables are the FIR cooling lines and dust emission, for which there is no (sensitive) current or forthcoming facility to enable low-redshift science: future FIR space missions would be essential here to assess the key physical processes of star formation in low-redshift galaxies.

The foremost ingredient for planet-formation theories are the fundamental properties of proto-planetary disks. In particular, reliable disk mass measurements are crucial. By far, the most promising mass tracer is hydrogen deuteride (HD), the less abundant isotopologue of molecular hydrogen. Such a molecule was detected in a few bright disks by ESA's Herschel Space Telescope, and no other current facility is able to carry out such observations, nor to extend the sample. In this context, a high spectral-resolution infrared space mission will be essential to measure HD-based disk masses in a large sample of disks, i.e., increase the sample size by an order of magnitude to be compared with the known population of exoplanets. Such a mission will also allow to determine the water budget, in gas and ice, in planet-forming disks.

A future space-based infrared mission with design concept at least as ambitious as the cancelled SPICA mission, or a far infrared probe-class mission as suggested by the US decadal survey, will be invaluable in measuring the dust masses of low-mass early galaxies as well as masses of proto-planetary disks. We recommend to set up a working group to study the possibilities of a European contribution to a NASA Far-

Infrared mission – one of the second entrants in the US Astro 2020 decadal review – perhaps on the basis of key technology developed for e.g., Herschel, SPICA, SOFIA and stratospheric balloon experiments.

3.2.5 Characterising exoplanets via Nulling Interferometry in the mid-infrared

The Large Interferometer For Exoplanets (LIFE) is a proposed mission concept initiated in Europe with the goal to consolidate various efforts and define a roadmap that eventually leads to the launch of a large, space-based MIR nulling interferometer to investigate the atmospheric properties of a large sample of terrestrial, potentially habitable exoplanets. LIFE is based on the heritage of ESA/Darwin and NASA/TPF-I, and significant advances in our understanding of exoplanets and newly available technologies will be taken into account in the LIFE mission concept.

LIFE is currently in its first study phases. Main activities include: assessing the current status and maturity of key technologies required for the mission and drafting a technology development roadmap. The first step is whether the technology is reasonably achievable, followed by the development and deployment of a prototype in space. Large space projects require a lead time of about 20 years. There is an ambitious effort to push nulling interferometry from the drawing board to reality, and a proposal for a (pathfinder) LIFE mission may fit within the ESA Voyage 2050 programme.

3.2.6 Lunar-based optical and radio interferometry

A strong renewed interest for lunar exploration has arisen in the past years. One example of our efforts to return to the Moon is the Artemis program for robotic and human exploration of our satellite, led by NASA with strong contributions from ESA, JAXA and CSA. Its long-term ambition is to set up a permanent base camp on the lunar surface, and to operate a lunar orbital station, both seen as intermediate steps toward robotic and manned missions to Mars. While this program is not primarily science-driven, it can have significant scientific by-products and could for instance serve future endeavours such as those mentioned below.

A new frontier being explored currently is to place facilities on or around the Moon, where a very low frequency radio array can open up the last unexplored wavelength range in Astronomy. International space agencies are pushing towards the Moon, and Europe intends to play a leading role on the surface. A European lunar lander is being designed by ESA to allow a series of different missions with different options for its payloads being studied. On its European Large Logistic Lander, there is an opportunity to develop a lunar far-side version of e.g., LOFAR and/or NenuFAR.

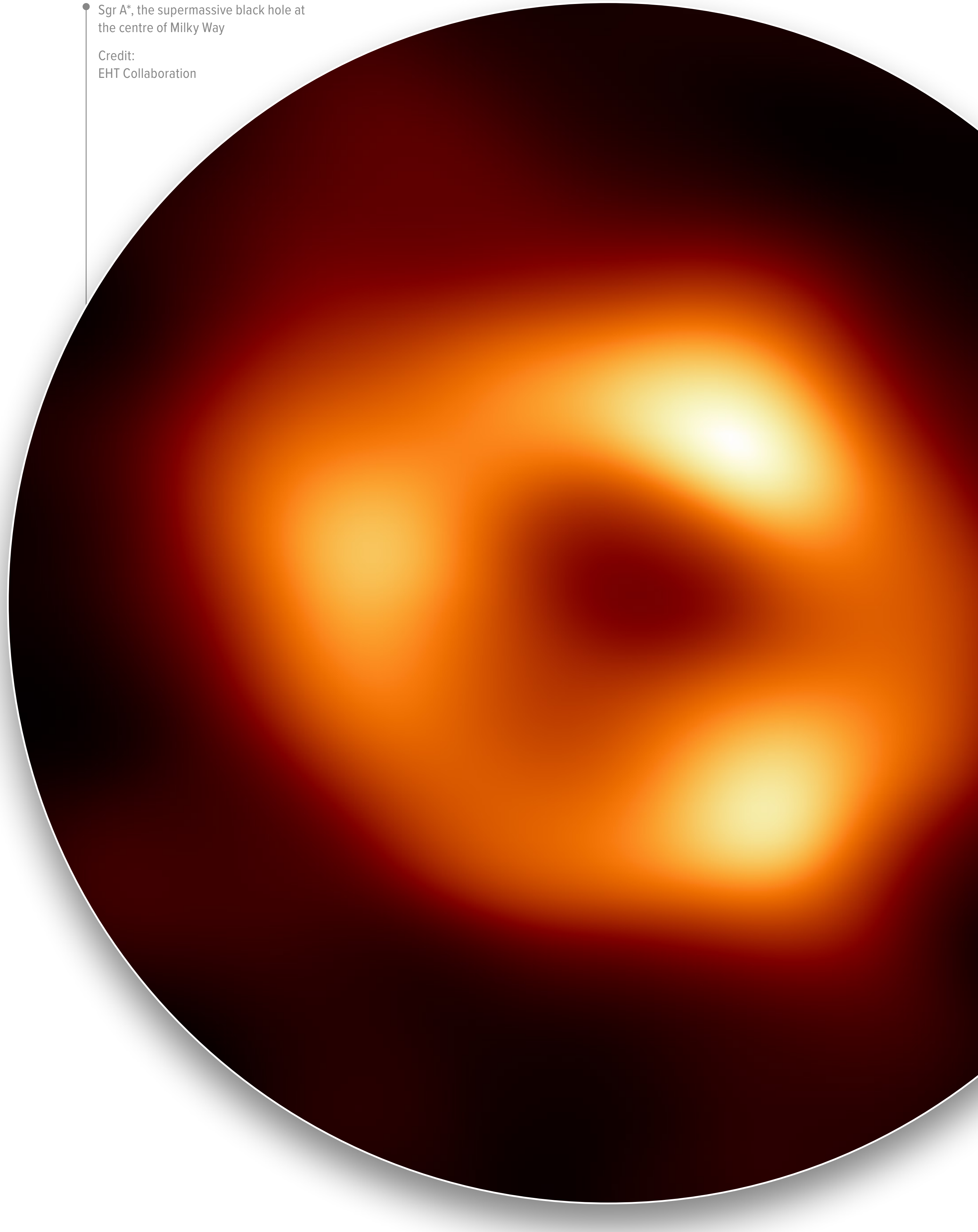
After a successful Hypertelescope pathfinder experiment and the construction of a telescope on the ground, a roadmap for space- and lunar-based optical interferometry for direct imaging at high resolution can be developed. For example, many small 0.5m mirrors can be sparsely arrayed in a lunar impact crater spanning 10–25 km, reaching an imaging resolution of the order of 100 nano-arcseconds. Imaging at this resolution has a wealth of (new) astrophysical applications, such as discovering potential indicators of life on nearby exoplanets by searching for seasonal spectroscopic variations.

3.2.7 Space exploration and science

Human spaceflight and space robotic exploration, developed in Europe in the framework of ESA's Terrae Novae Exploration programme, is largely motivated by political or economic considerations. It is above all a societal issue because it answers many basic human needs, ranging from the never ending desire to go where we have never gone before, to the more pragmatic race for the mining of resources that cannot be found on Earth.

Still, science has so far strongly benefited from space exploration and will continue to do so as manned and robotic exploration and exploitation of the Moon, Mars, and possibly asteroids, are further developed. Although these activities are not primarily science driven, they can and will have an important impact on future scientific progress and discoveries on the solar system and beyond. Examples of such potential synergies are numerous: establishment of astronomical facilities on the Moon's surface, including on its far side, completely free of human radio perturbations; search for past or present life on the surface or subsurface of Mars, including sample return to Earth; in situ analysis of asteroids or comets, witnesses of the history of solar system formation and evolution; and even boldly looking toward the more distant future, interstellar robotic probes for exploring the nearest exoplanets.

Conversely, it is clear that space exploration would not be possible without the tremendous progress that science has brought in our knowledge of physics, chemistry, astronomy and other science areas, as well as in our technological development. There is a strong cross-fertilisation of space exploration and astronomical research that must be acknowledged and which we must strive to further develop.



Sgr A*, the supermassive black hole at the centre of Milky Way

Credit:
EHT Collaboration

Appendix A: Panels membership

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- Claude Catala (Observatoire de Paris - PSL, France)
- Amelie Saintonge (University College London, UK)
- Ronald Stark (Leiden Observatory, Leiden University, The Netherlands)

Panel A: Computing; big data, HPC and data infrastructure

Chair: Eric Emsellem, co-Chair: Agnieszka Pollo

- Eric Emsellem (ESO / CRAL, Université de Lyon, France)
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The members of Panel A also acknowledge the very valuable contributions of Dominique Aubert, Frédéric Bournaud, Wolfram Freudling, Olivier Hainaut, Bob Mann, Marco Molinaro, Ralf Palsa, Felix Stoehr, Jean-Pierre Villote, John Swinbank.

Panel B: Origin and evolution of the Universe

Chair: Leon Koopmans; Co-Chair: Alain Blanchard

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- Alessandro Gruppuso (INAF, Italy)
- Alain Blanchard (IRAP, France)
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Panel C: Formation and evolution of galaxies

Chair: Matthew Hayes; Co-chair: Pratika Dayal

- Pratika Dayal (University of Groningen, Netherlands)
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Panel D: Formation and evolution of stars

Chair: Chris Evans

- Chris Evans (STSci, USA / UKATC, UK)
- Jason Hessels (University of Amsterdam & ASTRON, Netherlands)
- Alfio Maurizio Bonanno (INAF, Italy)
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- Sylvia Ekstrom (University of Geneva, Switzerland)
- Patrick Roche (University of Oxford, UK)
- Sana Hugues (Leuven University, Belgium)
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- Estelle Moraux (Université Grenoble Alpes, France)
- Alberto Sesana (University of Milano-Bicocca, Italy)
- Elena Maria Rossi (Leiden University, Netherlands)

Panel E: Formation and evolution of planetary systems

Chair: Ignas Snellen; Co-Chair: Alessandro Sozzetti

- Ignas Snellen (Leiden University, Netherlands)
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- Yann Alibert (Center for Space and Habitability, Universität Bern, Switzerland)
- Cecile Engrand (IJCLab, Université Paris-Saclay/CNRS, France)
- Christian Schneider (Universität Hamburg, Germany)

Panel F: Solar system and the conditions for life

Chair: Nicole Vilmer; Co-chair: Luisa Lara

- Nicole Vilmer (Observatoire Paris- PSL, France)
- Luisa Lara (Instituto de Astrofísica de Andalucía, Spain)
- Jes Jørgensen (University of Copenhagen, Denmark)
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- Inge Loes ten Kate (Utrecht University, Netherlands)
- Beatriz Sanchez - Cano (University of Leicester, UK)
- Matteo Massironi (Padua University, Italy)

Panel G: Extreme Astrophysics

Chair: Andrew Levan; Co-chairs: Nanda Rea, Jason Hessels

- Andrew Levan (Radboud University, Netherlands)
- Nanda Rea (Instituto de Ciencias del Espacio (ICE-CSIC, IEEC), Spain)
- Jason Hessels (University of Amsterdam & ASTRON, Netherlands)
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- Huib Jan van Langevelde (JIVE & Leiden University, Netherlands)
- Dorothea Samtleben (Nikhef Amsterdam & Leiden University, Netherlands)

Panel H: Astronomy and society

Chairs: Pedro Russo. Co-Chairs: Frans Snik, Inge Loes ten Kate

- Pedro Russo (Leiden University, Netherlands)
- Frans Snik (Leiden University, Netherlands)
- Inge Loes ten Kate (Utrecht University, Netherlands)
- Sara Lucatello (INAF, Italy)
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Appendix B: Acronyms and glossary

Term	Description
4MOST	4-metre Multi-Object Spectrograph for VISTA, ESO
AAs	Active Asteroids
AAT	Anglo-Australian Telescope, Australia
ACAM	Auxiliary-port CAMera, WHT, La Palma
ACIS	Advanced CCD Imaging Spectrometer
ACO	Asteroids in Cometary Orbits
ACS	Advanced Camera for Surveys, HST
ACT	Atacama Cosmology Telescope
AFM	Atomic Force Microscope
AGB	Asymptotic Giant Branch
AGN	Active Galactic Nucleus
AHEAD	Integrated Activities for the High Energy Astrophysics Domain - EC project
AI	Artificial Intelligence
Akatsuki	Venus Climate Orbiter mission, JAXA
ALICE	A Large Ion Collider Experiment, CERN
ALMA	Atacama Large Millimeter/submillimeter Array
A-MKID	Large Incoherent Submillimetre Camera, APEX
AMS-02	Alpha Magetic Spectrometer - on ISS
ANDES	ArmazoNes high Dispersion Echelle Spectograph for the ELT
Antares	Astronomy with a Neutrino Telescope and Abyss environmental RESearch
Apertif	Phased array feed for the Westerbork Synthesis Radio Telescope
AO	Adaptive Optics
APEX	Atacama Pathfinder Experiment Telescope
APOGEE	High resolution , near-IR spectroscope, Sloan telescope
APPEC	AstroParticle Physics European Consortium
ARC	ALMA Regional Centre
ARCA	Astroparticle and Oscillations Research with Cosmics in the Abyss, KM3NeT
Artemis	NASA Lunar Program
arXiv	free distribution service and an open-access archive for scholarly articles
ASCL	Astrophysics Source Code Library
ASI	Agenzia Spaziale Italiana, Italian Space Agency

Term	Description
ASKAP	Australian Square Kilometre Array Pathfinder
ASPIRES	UK Gov report on young people's career aspirations
ASTRAEUS	seminumerical rAdiative TranSfer coupling of galaxy formation and Reionization in N-body dArk mattEr simUlationS
ASTRI	Mini-Array of Cherenkov telescopes at the Observatorio del Teide, Tenerife
Astro4SDG	IAU programme in Sustainable Development Goals
ASTROMOVES	EU Horizon 2020 project on career decisions for Astrophysicists
Astropy	project to develop core package for Astronomy in Python
Athena	Advanced Telescope for High Energy Astrophysics, ESA
ATLAS	Astrophysics Telescope for Large Area Spectroscopy, NASA mission concept
AtLAST	Atacama Large Aperture Submillimetre Telescope
AT	Auxiliary Telescopes, VLT
AU	Astronomical Unit
BaiKal GVD	Baikal deep water neutrino telescope - Gigaton Volume Detector
BAO	Baryon Acoustic Oscillations
Beagle-2	ESA comet rendevous mission lander
BepiColombo	ESA mission to Mercury
BETA	Boolardy Engineering Test Array
BH	Black Hole
BICEP/Keck	US-led CMB facility on the South Pole
BINGO	Baryon Acoustic Oscillations from Integrated Neutral Gas Observations, Brazil
BISOU	Balloon Interferometer for Spectral Observations of the Universe
BlackGEM	wide-field array of optical telescopes, La Silla
BlueMUSE	Blue-optimised integral field spectrograph, ESO
BlueTides	Large volume cosmological hydrodynamic simulation project, from z=99 to z=8.0
B-mode	magnetic mode of polarisation
BNL	Brookhaven National Laboratory, US
BOSS	Baryon Oscillation Spectroscopic Survey, at the Sloan Telescope, Apache Point Observatory, US
BRITE-Austria	or TUGsat1. nanosatellite Bright star Target Explorer, led by Austria
CALTECH	California Institute of Technology

Term	Description
CanariCam	Mid-infrared (7.5 - 25 μm) imager, GTC La Palma
Carmenes	Radial Velocity instrument and survey, Calar Alto Observatory, Spain
CAS	Chinese Academy of Sciences
Cassini/ Huygens	NASA/ESA Saturn explorer mission
CCAT	Caltech Cornell Atacama Telescope, now Fred Young Submillimeter Telescope (FYST)
CCD	Charge Coupled Device
CDMS	Cologne Database for Molecular Spectroscopy
CDM	Cold Dark Matter
CDS	Strasbourg Astronomical Data Centre
CE	Cosmic Explorer
CERN	Conseil Européen pour la Recherche Nucléaire / European Council for Nuclear Research, Geneva, Switzerland
CFHTLenS	Canada France Hawaii Telescope lensing survey
CGM	Circumgalactic Medium
Chandra	Chandra X-ray Observatory, NASA mission
Chang'e	Lunar exploration mission, China
CHANTI	Atomic Database for Spectroscopy Diagnostics of Astrophysical Plasmas
CHEOPS	CHaracterizing ExOPlanets Satellite mission, ESA
CHIME	Canada Hydrogen Integral Mapping Experiment
CIB	Cosmic Infrared Background
Cislunar Transfer Vehicle	Transportation logistic space vehicle study, ESA
CLUSTER	Earth's magnetosphere study mission, ESA
CMB	Cosmic Microwave Background
CMB-S4	Proposed next-generation ground-based CMB experiment
CME	Coronal Mass Ejection
CNES	Centre National d'Études Spatiales, France
COBE/ FIRAS	Cosmic Background Explorer/Far Infra-Red Absolute Spectrophotometer, NASA
Comet Intercepter	ESA F-class cometary rendevous mission
CONCERTO	CarbON CII line in post-rEionisation and ReionisaTiOn epoch, instrument on APEX
CoRot	COnvection, ROtation and planetary Transits, mission, France
COS	Cosmic Origins Spectrograph
Cosmic Explorer	Next generation gravitational wave observatory concept, US
CP-IDPs	Chondritic Porous Interplanetary Dust Particles
CPU	Central Processing Unit

Term	Description
CRIRES+	Cryogenic high resolution Infrared Echelle Spectrograph, VLT
Cross-Scale	Plasma-coupling mission proposal to ESA, not selected
CSA	Canadian Space Agency
CSIRO	Commonwealth Scientific and Industrial Research Organisation, Australia
CTA	Cherenkov Telescope Array
CTAO	Cherenkov Telescope Array Observatory
CUBES	Cassegrain U-Band Efficient Spectrograph, VLT
cupy	open source Python array library
Curiosity	NASA Mars Rover programmes
DART	Double Asteroid Redirection Test, NASA
DARWIN	Proposed ESA exoplanet mission, not selected
DECam	Dark Energy Camera, Blanco Telescope
DE	Dark Energy
DES	Dark Energy Survey
DESI	Dark Energy Spectographic Instrument, Mayall Telescope, US
DESY	Deutsches Elektronen-Synchrotron
DKIRST	Daniel K Inouye Solar Telescope, Hawaii
DLR	German Aerospace Cente
DM	Dark Matter
DOE	Department of Energy, USA
DOI	Digital Object Identifier
DOLoRes	multi-object low-resolution optical spectrograph, TNG, La Palma
DPAC	Gaia Data Processing and Analysis Consortium
DPC	Data Processing Centre
DR#	Data Release #, Gaia
Dragons	Gemini Data Reduction Platform
EAO	East Asian Observatory, Hawaii
EAS	European Astronomical Society
eBOSS	extended BAO Spectroscopic Survey, Sloan
EC	European Commission
EDGES	Experiment to Detect the Global EoR Signature
EELT	European Extremely Large Telescope, now Extremely Large Telescope (ELT), ESO
Efflesberg	Effelsberg 100m Radio Telescope, Germany
EGI	European Grid Initiative
EHT	Event Horizon Telescope
ELT	Extremely Large Telescope
ELT-PCS	Extremely Large Telescope Planetary Camera and Spectrograph

Term	Description
e-MERLIN	enhanced Multi Element Remotely Linked Interferometer Network, UK
EnVision	Venus Orbiter, ESA mission
EoR	Epoch of Reionisation
EoS	Equation of State
EOSC	European Open Science Cloud
EPIC	European Photon Imaging Camera, XMM-Newton
E-ROAD	European Regional Office of Astronomy for Development, Leiden
ERIC	European Research Infrastructure Consortium
ERIS	Enhanced Resolution Imager and Spectrograph, ESO
E-mode	Electric mode of polarisation
e-ROSITA	X-ray Instrument on-board the Russian-German SRG mission
ESA	European Space Agency
ESAP	ESFRI Science Analysis Platform
ESCAPE	European Science Cluster for Astronomy & Particle physics ESFRI, EC
ESD	Education for Sustainable Development
ESFRI	European Strategy Forum on Research Infrastructures
ESO	European Southern Observatory
ESPRESSO	Echelle Spectrograph for Rocky Exoplanets and Stable Spectroscopic Observarions,VLT/VLTI, ESO
ESRF	European Synchrotron Radiation Facility
EST	European Solar Telescope
ET	Einstein Telescope
EU	European Union
Euclid	Cosmology survey mission, ESA
European Large Logistic Lander	also known as EL3, design study for a series of different Lunar missions, ESA
EUV	Extreme Ultra-Violet
EVN	European VLBI Network
ExoMars	ESA's MARS programme
ExoMol	data base of molecular line lists for exoplanet and other hot atmospheres
EXPRES	Extreme Precision Spectrograph, Lowell Observatory Discovery Telescope, US
eXTP	Extended x-ray timing and polarimetry mission, China with European participation
FAIR	Findable, Accessible, Interoperable, Reusable
FAST	Five-hundred-meter Aperture Spherical Telescope, China
F-class	Small ESA mission class ('fast', lower cost)
FAIR principles	data which meet the principles: Findable, Accessible, Interoperable, Reusable
FCC	Future Circular Collider
Fermi	Fermi Gamma-ray Space Telescope, NASA
FGS	Fine-Guiding System
FIR	Far-Infrared
FIRI	Far-Infrared Interferometer mission concept, ESA
FLAMES	Fibre Large Array Multi Element Spectrograph, ESO
FOV	Field Of View
FRB	Fast Radio Burst
FTE	Full Time Equivalent
FYST	Fred Young Submillimeter Telescope (formerly CCAT)
GA	General Assembly
Gaia	Global Astrometric Interferometer for Astrophysics mission, ESA
GaiaNIR	Gaia - Near-InfraRed mission concept
GALAH	GALactic Archaeology with HERMES, AAT survey
Galaxy Zoo	Crowd sourcing / citizen science public engagement programme
Galileo	space probe that studied Jupiter and its moons, NASA
GANIL	Grand Accélérateur National d'Ions Lourds
GCED	Global Citizenship Education - UNESCO programme
GCOS	Global Cosmic Ray Observatory
GBT	Green Bank Telescope, USA
Gemini	Twin 8 metre optical/infrared telescopes, Hawaii & Chile, US-led
GEMS	Glass with Embedded Metals and Sulphides
GIANO	IR cross-dispersed echelle spectrometer, TNG, La Palma
Gitlab	Open source software development platform
GMT	Giant Magellan Telescope, Chile, US-led
GMRT	Giant Metrewave Radio Telescope, India
GONG	Global Oscillation Network Group
GOTO	Gravitational-wave Optical Transient Observer telescope
GPS	Global Positioning Service
GPU	Graphics Processing Unit
GR	General Relativity
GRAND	Giant Radio Array for Neutrino Detection
GranTecCan /GTC	Gran Telescopia Canarias, La Palma
GRAVITY	Interferometric instrument operating in the K band (2.0 - 2.4 μm), VLTI, ESO
GRAVITY+	upgrade of GRAVITY and the VLTI
GRB	Gamma Ray Burst
GREGOR	Solar Telescope, Tenerife
GRMHD	General Relativistic Magneto-HydroDynamics
GSED	Global Citizenship Education - UNESCO programme
GSI	GSI Helmholtz Centre for Heavy Ion Research, Germany
GSI FAIR	Facility for Antiproton and Ion Research in Europe at GSI
GUT	Grand Unified Theory
GW	Gravitational Waves
HabEx	Habitable Exoplanet Observatory, now Habitable Worlds Observatory, NASA
HARMONI	High Angular Resolution Monolithic Optica and Near Infrared Integral field spectrograph, ELT, ESO
HARP	Heterodyne Array Receiver Program, array receiver with mixers, JCMT, EAO, Hawaii
HARPS	High Accuracy Radial Velocity Planet Searchers, ESO
HARPS-N	High Accuracy Radial velocity Planet Searcher for the Northern hemisphere, TNG, La Palma
HARPS3	HARPS instrument on the Isaac Newton Telescope, ING, La Palma
Hayabusa	Near-earth, asteroid sample return mission, JAXA, Japan
HAYDN	High-precision AsteroseismologY of DeNse stellar fields, ESA mission candidate
HD	Hydrogen Deuteride
HDS	High Dispersion Spectroscopy
HERA	Hydrogen Epoch Reionisation Array, South Africa, US-led
HERMES	four channel fibre-fed spectrograph with high resolution and multi-object capability, AAT, Australia
Herschel	Herschel Space Observatory, ESA
HESS	High Energy Stereoscopic System, Telescope, Namibia
HETG	High-Energy Transmission Grating
Hinode	Solar Observing Satellite, JAXA, Japan
HIRAX	Hydrogen Intensity and Real-time Analysis eXperiment, South Africa
HIRISE	High-Resolution Imaging and Spectography of Exoplanet Instruments
HJPDOC	Database of Optical Constants
HMXRB	High Mass X-Ray Binaries
HPC	High Performance Computing
HRC	High Resolution Camera
HR diagram	Hertzprung-Russell diagram, graph in which the absolute magnitudes of stars are plotted against their spectral type
HRMOS	High Resolution Multi Optic Spectrograph, ESO VLT concept
HRS	High Resolution Spectrograph
HST	Hubble Space Telescope
HTC	High Throughput Computing
Hypertelescope	Large optical interferometer concept for beyond the ELT
IAU	International Astronomical Union
IceCube	IceCube Neutrino Observator
ICT	Information and Communications Technology
IDP	Interplanetary Dust Particles
IFU	Integral Field Unit
IGM	Intergalactic Medium
IM	intensity mapping
IMBH	Intermediate Mass Black Holes
IMF	Initial Mass Function
ING	Isaac Newton Group of Telescopes, La Palma
INTEGRAL	International Gamma-Ray Astrophysical Laboratory, ESA space mission
INT	Isaac Newton Telescope, ING, La Palma
IPCC	Intergovernmental Panel on Climate Change
IR	InfraRed
IRAM	Institut de Radioastronomie Millimétrique
IRAM 30m	IRAM 30m millimetre telescope, Pico Veleta, Spain
IRAM/NiIKA2	New Iram Kid Array-2, instrument at IRAM 30m
IRF	Instrument Response Function
IRIS	Interface Region Imaging Spectrograph, NASA mission
ISIS	Intermediate-dispersion Spectrograph and Imaging System, WHT, La Palma
ISM	InterStellar Medium
ISRU	In-Situ Resource Utilisation
ISS	International Space Station
IVOA	International Virtual Observatory Alliance
IXPE	Imaging X-ray Polarimetry Explorer, NASA mission
IXO	International X-ray Observatory, NASA/ESA/JAXA study, elements are captured in Athena
JAXA	Japan Aerospace Exploration Agency
JCMT	James Clerk Maxwell Telescope
JIVE	Joint Institute for VLBI ERIC
JOSS	Journal of Open Source Software
JT	Jupiter's Trojans
JUICE	JUpiter ICy moons Explorer, ESA mission
Juno	space probe to orbit the planet Jupiter, NASA mission
Jupyter	free, open-source, interactive web tool known as a computational notebook
Jupyter/Hubs	multi-user web server for Jupyter notebooks
JWST	James Webb Space Telescope
KAGRA	Kamioka Gravitational Wave Detector

Term	Description
Keck/HIRES	High Resolution Echelle Spectrometer on the Keck Observatory, Hawaii
Kepler	Kepler Space telescope, exoplanet mission, Nasa
KiDS	Kilo-Degree Survey, VST, ESO
KIDS	Kinetic Inductance Detectors
KM3NeT	Cubic-Kilometre Neutrino Telescope
kpc	kiloparsecec, distance scale
L1, L2,...,L5	Lagrange points, positions in space where a small mass can orbit in a constant pattern
L-class	Large' class ESA mission category (e.g., JUICE)
Λ-CDM	Lambda cold dark matter, standard cosmological model
LAPLACE	Europa Jupiter System Mission, proposed NASA/ESA space mission, now JUICE
LASP	Laboratory for Atmospheric and Space Physics, USA
LEAP	Large European Array for Pulsars
LETG	Low Energy Transmission Grating
LHC	Large Hadron Collider
LIFE	Large Interferometer for Exoplanets
LIGO	Laser Interferometer Gravitational-Wave Observatory
LIRIS	Long-slit Intermediate Resolution Infrared Spectrograph, WHT, La Palma
LISA	Laser Interferometer Space Antenna, ESA
LiteBIRD	Lite (Light) satellite for the study of B-mode polarization and Inflation from CMB Radiation Detection, JAXA
LMT	Large Millimeter Telescope, Mexico
LOFAR	Low Frequency Array
Lovell	Lovell Telescope, Jodrell Bank, UK
LSPE	Large-Scale Polarization Explorer
LSPE-strip	Survey TeneRIfe Polarimeter, ground-based instrument for LSPE
LSPE-swipe	Short Wavelength Instrument for the Polarization Explorer, stratospheric balloon payload for LSPE
LSS	Large-Scale Structure
LSST	The Large Synoptic Survey Telescope, now Rubin Observatory, Chile
LSST survey	Rubin Observatory's Legacy Survey of Space and Time
LST	Large Sized Telescopes associated with the CTA
LTAO	Laser Tomography Adaptive Optics
LUNA	Laboratory for Underground Nuclear Astrophysics, Italy
Luna-Glob	Lunar lander mission, Roscosmos
LUVOIR	Large Ultraviolet Optical Infrared Surveyor, now Habitable Worlds Observatory, NASA
MAGIC	Major Atmospheric Gamma Imaging Cherenkov Telescopes
MAORY (now MOFEO)	Multi-Conjugate adaptive Optics RelaY for ELT

Term	Description
Marco Polo	Near-Earth Asteroid sample return, ESA mission concept (retired)
Mariner 10	first spacecraft to visit Mercury, NASA
Mars-Grunt	proposed robotic spacecraft sample return mission to Mars, Russia
MATISSE	Multi-Aperture mid-Infrared Spectroscopic Experiment, ESO VLTI
Matplotlib	Python visualizations tool library
MAVEN	Mars Atmosphere and Volatile EvolutioN, NASA mission
MAVIS	MCAO Assisted Visible Imager and Spectrograph, ESO VLT
MB	Main asteroid Belt
MCAO	Multi-Conjugate Adaptive Optics
M-Class	ESA 'medium' scale space mission (e.g., PLATO)
MeerKAT	Karoo Array Telescope, SKA precursor, South Africa
MegaMapper	Proposed massively multiplexed spectroscopic telescope facility
MEGARA	Multi-Espectrógrafo en GTC de Alta Resolución para Astronomía, GTC, La Palma
MESSENGER	Mercury Surface, Space Environment, Geochemistry and Ranging mission, NASA
METIS	Mid-Infrared ELT Imager and Spectrograph
MHD	Magneto-HydroDynamics
MICADO	Multi-adaptive optics Imaging Camera for Deep Observations, ELT
MIR	Mid-infrared
MIRI	Mid-Infrared Instrument, JWST
MIT	Massachusetts Institute of Technology
MKIDs	Microwave Kinetic Inductance Detectors,
MMO	Mercury Magnetospheric Orbiter, with MPO, satellites of BepiColombo, ESA mission
MMS	Magnetospheric Multiscale mission, NASA
MMX	Martian Moons eXploration mission, JAXA
MOONS	Multi-Object Optical and Near-infrared Spectrograph, ESO, VLT
MORFEO	Multi-conjugate adaptive Optics Relay For ELT Observations, ELT
MOS	Multi-Object Spectrograph
MOSAIC	Multi-Object Spectrograph for Astrophysics, Intergalactic-medium studies and Cosmology, ELT, ESO
Mpc	Megaparsec, distance scale
MPO	Mars Planetary Orbiter, with MMO, satellites of BepiColombo, ESA mission
MRI	Magnetic Resonance Imaging
MRO	Murchison Radio-astronomy Observatory
MSE	Mauna kea Spectroscopic Explorer
MSL	Mars Science Laboratory

Term	Description
MST	Medium-Sized Telescope of the CTA Observatory
MW	Milky Way
MWA	Murchison Wide field Array, Australia
Nançay	Nançay Radio Observatory, France
NAOJ	National Astronomical Observatory of Japan
NASA	National Aeronautics and Space Administration
NCLE	Netherlands-China Low-Frequency Explorer
NEAs	Near-Earth Asteroids
NenuFAR	New Extension in Nançay Upgrading LOFAR
NEO	Near-Earth Object
NERSC Shifter	software package that allows user-created images to run at the National Energy Research Scientific Computing Center, US
nFLASH	heterodyne instrument for APEX
NGRST	Nancy Grace Roman Space Telescope, NASA
ngVLA	Next Generation Very Large Array
NICA	Russian Laboratory of High Energy Physics collider complex
NICER	Neutron Star Interior Composition Explorer, payload on ISS
NICMOS	Near-Infrared Camera and Multi-Object Spectrometer, HST
NICS	Near Infrared Camera Spectrometer, TNG, La Palma
NIR	Near-InfraRed
NIRcam	Near Infrared Imaging Camera, JWST
NIRISS	Near-Infrared Imager and Slitless Spectrograph, JWST
NIRPS	Near-InfraRed Planet Searcher, ESO
NIRspec	Near Infrared Spectograph, JWST
NISP	Near Infrared Spectromer and Photometer
NOEMA	Northern Extended Millimetere Array, IRAM, France
NS	Neutron Star
NSF	National Science Foundation, US
NTT	New Technology Telescope, ESO
numba	open source Python and NumPy code compiler
NumPy	Numerical Python, Python library for working with arrays
OASIS	Orbiting Astronomical Satellite for Investigating Stellar Systems, NASA concept
OECD	Organisation for Economic Co-operation and Development
OM	Optical Monitor, XMM-Newton
OPTICON	Optical Infrared Coordination Network for Astronomy, now part of ORP
ORCA	Oscillation Research with Cosmics in the Abyss, KM3NeT
ORM	Observatorio del Roque de los Muchachos

Term	Description
ORP	Opticon RadioNet Pilot, EC network
OSIRIS	Optical System for Imaging and low-Intermediate-Resolution Integrated Spectroscopy, GTC, La Palma
OSIRIS-REx	Origins, Spectral Interpretation, Resource Identification, Security, Regolith Explorer, NASA asteroid mission
OSO	Onsala Space Observatory, Sweden
OSSR	Open Software and Services Repository
PAFs	Phased Array Feeds
PAH	Polycyclic Aromatic Hydrocarbon
Pangeo	Community platform for Big Data geoscience
PanSTARRS	Panoramic Survey Telescope and Rapid Response System, Hawaii
Parker Solar Probe	NASA solar mission
pc	parsec, distance scale
PCS	Planetary Camera and Spectograph, ESO ELT
PdBI	Plateau de Bure Interferometer, upgraded and renamed to NOEMA, France
PDS	Pico dos Dias survey, PDS 70b: first imaged protoplanet
Perserverance	NASA Mars Rover
PFI	Planet Formation Imager
PHA	Potentially Hazardous Asteroid or PHO (Object)
PHOIBOS	Probing Heliospheric Origins with an Inner Boundary Observing Spacecraft
PICARD/ PREMOS	PREcision Monitoring Sensor on the CNES solar-terrestrial microsatellite mission PICARD, France
PICO	Probe of Inflation and Cosmic Origins
Pierre Auger Observatory	international Cosmic Ray Observatory, Argentina
PISN	Pair Instability Supernovae
PIXIE	Primordial Inflation Explorer
Planck	ESA CMB mission
PLATO	PLAnetary Transits and Oscillations of stars, ESA
POEMMA	Probe of Extreme Multi-Messenger Astrophysics, NASA concept
POL-2	Linear polarimetry module for SCUBA-2, JCMT, EAO, Hawaii
P-ONE	Pacific Ocean Neutrino Experiment
PRISTINE	Polarized Radiation Interferometer for Spectral disTortions and INflation Exploration
PSF	Point Spread Function
PTA	Pulsar Timing Array
Python	object oriented, high-level general-purpose programming language
QPO	Quasi-Periodic Oscillations
QSO	Quasi-Stellar Objects
QUBIC	Q-U Bolometric Interferometer for Cosmology

Term	Description
QUIJOTE	Q-U-I JOint TEnerife CMB experiment
R&D	Research & Development
RadioNet	European Network for Radioastronomy, now part of ORP
RAS	Royal Astronomical Society
RAVE	Radial Velocity Experiment, AAO
REACH	Radio Experiment for the Analysis of Cosmic Hydrogen
RFI	Radio Frequency Interference
RGB	Red Giant Branch - branch of stars in HR-diagram
RGS	Reflection Grating Spectrometers
RHIC	Relativistic Heavy Ion Collider, Brookhaven, US
RISTRETTO	Proposed AO-fed spectrograph for exoplanets, ESO VLT
ROSAT	Röntgen SATellite, X-ray observatory
Roscosmos	Russian space agency
Rosetta	Asteroid rendevous mission, ESA
RR Lyrae	variable stars, standard candles for (extra)galactic distances
RSD	Redshift-Space Distortions
RST	Roman Space Telescope - see also NGRST, NASA
RTGs	Radioisotope Thermoelectric Generators
RV	Radial Velocity
RVS	Radial Velocity Spectrometer
SALT	South African Large Telescope
SALTICAM	SALT imaging and acquisition camera
SARAS	Shaped Antenna measurement of the background RAdio Spectrum, India
SCAO	Single-Conjugate Adaptive Optics
Schiaparelli	Failed entry, descent and landing MARS demonstrator, ESA
Scipy	open-source software for mathematics, science, and engineering
SCUBA-2	Submillimetre Common-User Bolometer Array, JCMT, EAO, Hawaii
SDG	Sustainable Development Goal
SDO/ AIA	Solar Dynamics Observatory/ Atmospheric Imaging Assembly, NASA mission
SDO / HMI	SDO / Helioseismic and Magnetic Imager, NASA
SDSS-V	fifth Sloan Digital Sky Survey
SEM	Scanning Electron Microscope
SEPs	Solar Energetic Particles
SFH	Star-Formation History
SFR	Star Formation Rate
SIFAP2	Silicon Fast Astronomical Photometer, TNG, La Palma
Simbol-X	Hard X-ray mission proposal
SKA	Square Kilometre Array
SMA	Submillimeter Array, Hawaii
SKAO	SKA Obervatory, intergovernmental organisation
SMASS	Small Main-belt Asteroid Spectroscopic Survey
SMBHs	Supermassive Black Holes
SN Ia	Type Ia supernova
SNe	SuperNovae
SOFIA	Stratospheric Observatory for Infrared Astronomy
SoHo	Solar and Heliospheric Observatory, ESA/NASA mission
Solar Orbiter	ESA Solar Mission
Solar-C	EUV High-throughput Spectroscopic Telescope, Solar Mission, JAXA-led
SOLEIL	Synchrotron radiation facility, Plateau de Saclay, France
SORCE / TIM	Solar Radiation and Climate Experiment / Total Irradiance Monitor, NASA
SoXS	Son of X-Shooter, NTT, ESO
SPHERE	Spectro-Polarimetric High-contrast Exoplanet REsearch instrument, VLT, ESO
Spherex	Spectro-Photometer for the History of the Universe, Epoch of Reionisation & Ices Explorer, NASA mission
Sphinx	Cosmological radiation-hydrodynamical simulations of reionization
SPICA	Space Infrared Telescope for Cosmology and Astrophysics, JAXA
SPIRou	SPectropolarimètre InfraROUge, NIR spectropolarimeter and high-precision velocimeter, CFHT, Hawaii
Spitzer	Spitzer Space Telescope, NASA Infrared telescope mission
SPT	South Pole Telescope
SRC	SKA Regional Centre
SRG	Spectr-Roentgen-Gamma, Russian/German mission - see e-ROSITA
SSI	Solar Spectral Irradiance
SST	Small-Sized Telescopes of CTA
STAR	Solenoidal Tracker at RHIC, experiment at the Relativistic Heavy Ion Collider (RHIC), Brookhaven National Laboratory, US
STEM	Science, Technology, Engineering and Mathematics
STEREO	Solar Terrestrial Relations Observatory, NASA mission
STI	Science, Technology and Innovation
STIS	Space Telescope Imaging Spectrograph, HST
Subaru-PFS	Subaru Prime Focus Spectrograph, spectrograph on the 8m optical-infrared Subaru Telescope, NAOJ, Hawaii
super-PIXIE	Enhanced version of PIXIE, concept
SVOM	Space-based multi-band astronomical Variable Objects Monitor, Franco-Chinese mission
Swarm	Earth Observation geomagnetic space constellation mission, ESA
Swift	Gamma-Ray Burst mission, NASA-led
SZ	Sunyaev-Zel'dovich Effect - CMB distortion
TANDEM	Titan and Enceladus mission
TDE	Tidal Disruption Event
TEM	Transmission Electron Microscopy
TESS	Transiting Exoplanets Survey Satellite, NASA
TGO	Trace Gas Orbiter, ExoMars Orbiter, ESA/Roscosmos mission
THEMIS	Time History of Events and Macroscale Interactions during Substorms, Earth magnetosphere mission, NASA
TMT	Thirty Meter Telescope
TNB	Trans-Neptunian Belt
TNG	Telescopia Nationale Galileo, La Palma
TNO	Trans-Neptunian Objects
ToITEC	Three-band imaging polarimeter for the Large Millimeter Telescope
TPF-I	Terrestrial Planet Finder - Interferometer
TPU	Tensor Processing Unit
Trace Gas Orbiter	see ExoMars
TRIDENT	The tRopIcal DEep-sea Neutrino Telescope
TSI	Total Solar Irradiance
TSIS	Total and Spectral solar Irradience Sensor
tSZ	thermal Sunyaev-Zel'dovich effect
Twinkle	Twinkle Space Mission, commercial exoplanet spectroscopy mission, UK
UCAMMs	Ultra-Carbonaceous Antarctic MicroMeteorites
uGMRT	upgraded GMRT
UKIRT	United Kingdom InfraRed Telescope, Hawaii
ULLYSES	UV Legacy Library of Young Stars as Essential Standards, programme with HST
UN	United Nations
UNAWE	Universe Awareness, programme to inspire every child with our wonderful cosmos
UNESCO	UN Educational, Scientific and Cultural Organisation
UTs	Unit Telescopes of ESO's VLT
UV	Ultra Violet
UVES	UV and Visual Echelle Spectrograph, VLT, ESO
VENUS Express	Venus exploration mission, ESA
VERITAS	Very Energetic Radiation Imaging Telescope Array System
VHE	Very High Energy
VIRGO	Virgo gravitational-wave detector, Italy
VIS	Visible InStrument
VISTA	Visible and Infrared Survey Telescope, ESO
VLA	Very Large Array, US
VLASS	VLA Sky Surveys
VLBI	Very Long Baseline Interferometry
VLT	Very Large Telescope, ESO
VLT- MUSE	Multi-Unit Spectroscopic Explorer, ESO VLT
VLT-HRMOS	Proposed High Resolution Multi-Object Spectrograph for ESO's VLT
VO	Virtual Observatory
Voyager	twin Voyager 1 and 2 spacecraft, NASA
VRO	Vera Rubin Observatory
VST	VLT Survey Telescope, ESO
VVV	VISTA Variables in the Via Lactea survey
VVVX	VVV eXtended Survey
WDM	Warm Dark Matter
WEAVE	WHT Enhanced Area Velocity Explorer, multi-object survey spectrograph for the WHT, La Palma
WFC3	Wide Field Camera 3, Hubble Space Telescope
WFI	Wide Field Imager
WFIRST	Wide Field Infrared Space Telescope mission concept, now NGRST, NASA
WHT	William Herschel Telescope, ING, La Palma
WiFi	Wireless Fidelity - wireless network protocols
WiggleZ	Dark Energy Survey, AAT, Australia
WIMPs	Weakly Interacting Massive Particles
WISE	Wide-field Infrared Survey Explorer, NASA mission
XAO	eXtreme Adaptive Optics
XEUS	X-ray Evolving Universe Spectroscopy, mission, now Athena, ESA
X-IFU	X-ray Integral Field Unit
XMM-Newton	X-ray Multi-Mirror Mission, ESA
XRISM	X-Ray Imaging and Spectroscopy Mission, JAXA
XRT	Swift's X-Ray Telescope, NASA
Xshooter	Multi-wavelength (300-2500 nm), medium resolution spectrograph, VLT, ESO
YORP effect	Yarkovsky-O'Keefe-Radzievskii-Paddock effect, physical phenomenon affecting the rotation rate and pole orientation of an asteroid
YSO	Young Stellar Object
yt-project	open source, community-developed astrophysical analysis and visualization toolkit
Zooniverse	Citizen science web portal
ZTF	Zwicky Transient Facility, camera on Samuel Oschin Telescope, Palomar Observatory, US

fwo Research Foundation Flanders Opening new horizons

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