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THE ASTRONET SCIENCE VISION & INFRASTRUCTURE
ROADMAP 2022-2035

A STRATEGIC PLAN FOR EUROPEAN ASTRONOMY

Executive Summary

Index

Introduction

Key Recommendations Summary

Cover image (in band):

The cosmic web
Credit: Mansfield & Diemer

Pillars of Creation
(JWST/MIRI Image)

Credit: NASA, ESA, CSA, STScI; Joseph DePasquale (STScI), Alyssa Pagan (STScI)

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 optical 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.

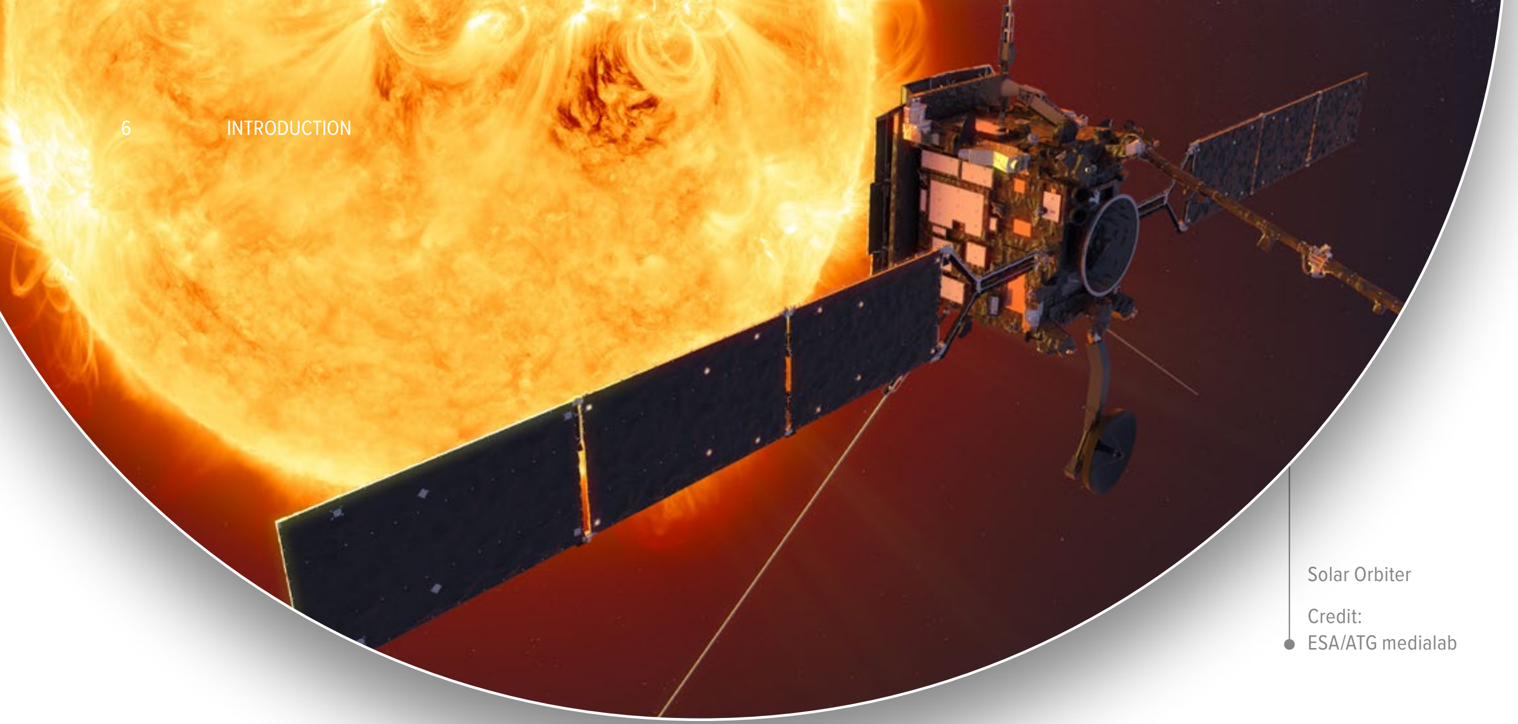
The recommendations of the ASTRONET Roadmap are far-reaching and ambitious. The current global context with war in Ukraine, inflation, and the post-pandemic society changes will make their implementation a challenge, but it also highlights the strategic importance of science, education, and international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



Solar Orbiter

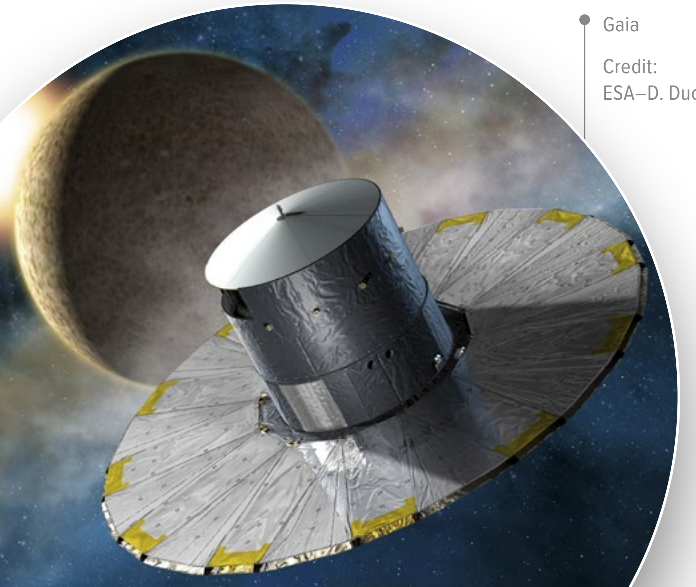
Credit: ESA/ATG medialab

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.

Gaia

Credit: ESA–D. Ducros



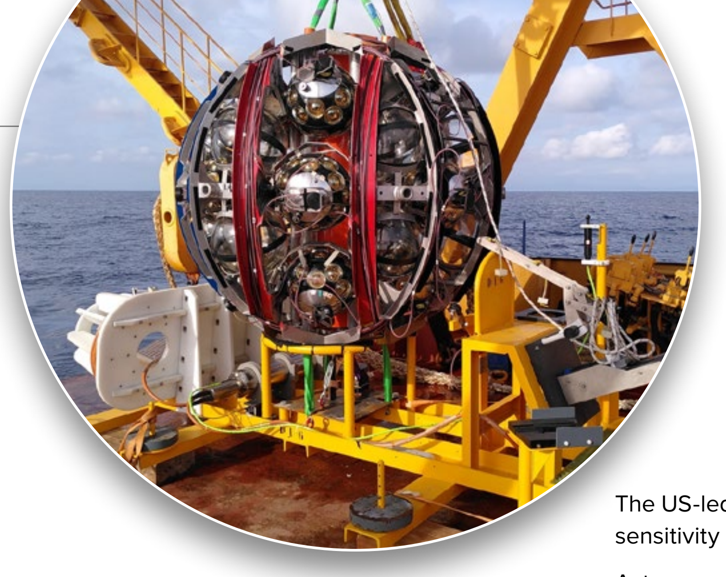
In space, the **HST**, still up and running after more than 30 years in orbit, is now complemented by the 6.5 m diameter **JWST** and its four instruments, NIRCam, NIRSpec, MIRI and FGS/NIRISS. Observations of the X-ray and high energy Universe are currently possible with ESA's **XMM-Newton** and NASA's **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.

KM3NeT
The next generation neutrino telescopes

Credit: km3net.org



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.

ALMA (ESO/NAOJ/NRAO)

Credit: W. Garnier

ASTRONET and the Science Vision and Infrastructure Roadmap

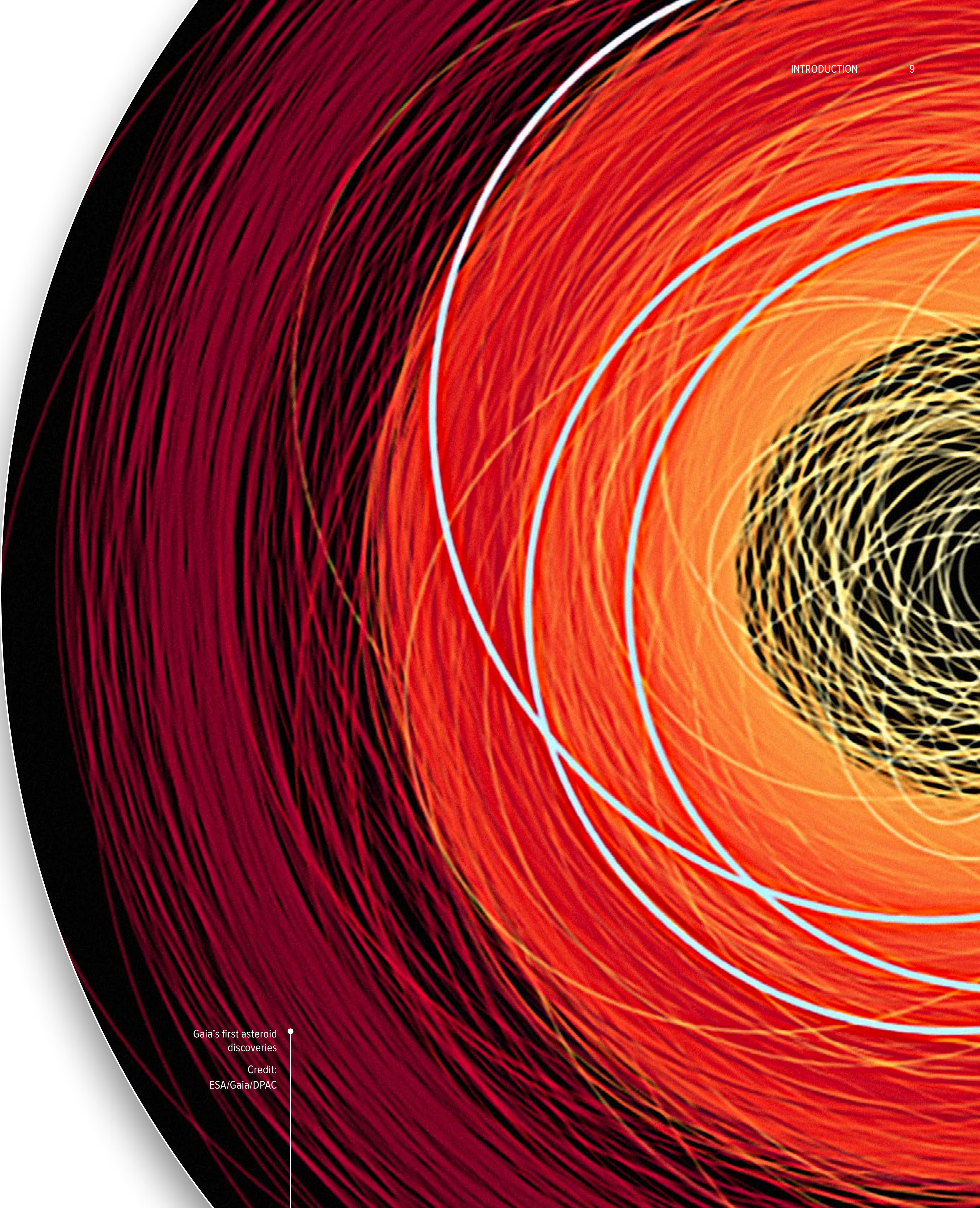
ASTRONET is a group of European funding agencies, community representatives and infrastructures working together as a forum for coordination for all aspects of European Astronomy.

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**



Gaia's first asteroid discoveries

Credit: ESA/Gaia/DPAC

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.

SKA-Mid - wide angle artist impression

Credit: SKAO

SKA-Low - wide angle artist impression

Credit: SKAO

ELT in construction
at Cerro Armazones, Chile

Credit:
ESO/ S. Lowery

KEY RECOMMENDATIONS SUMMARY

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.

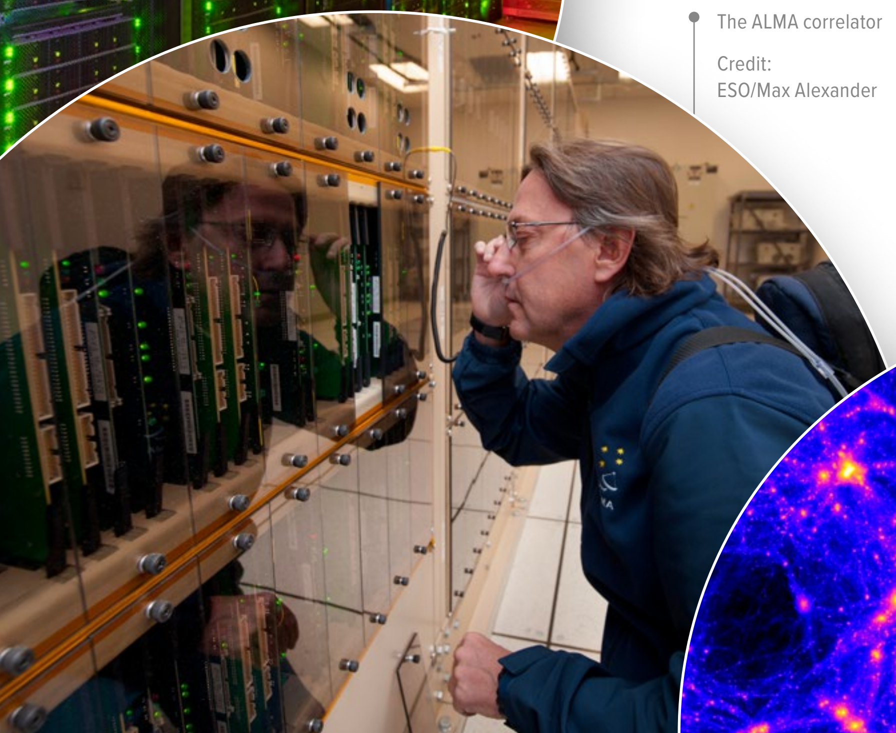
This situation will be exacerbated in the next decade by the commissioning of facilities such as Euclid, the Square Kilometre Array (SKA) and the Vera Rubin Observatory (VRO), making it ever more urgent to include computing and data requirements at the core of our strategic planning.

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.

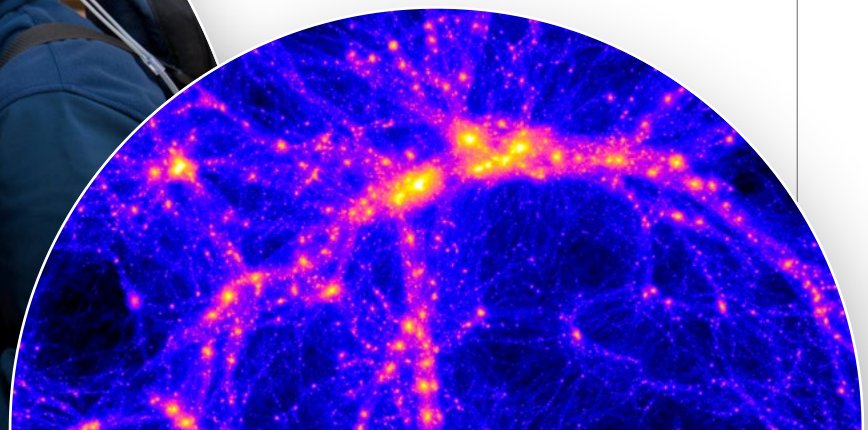
DiRAC Supercomputer

Credit: icc.dur.ac.uk



The ALMA correlator

Credit: ESO/Max Alexander



The Eagle Project

Credit: icc.dur.ac.uk

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.

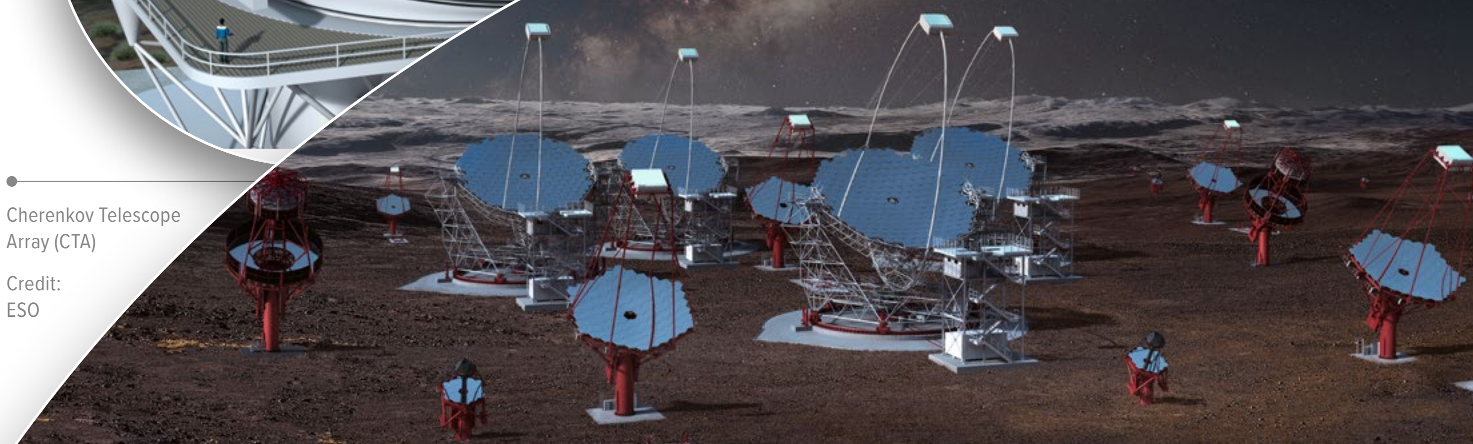
- First, the **Cherenkov Telescope Array (CTA)** is an array of telescopes located across two sites on both hemispheres to detect very high energy gamma rays from black holes and other extreme phenomena. As the first true large-scale observatory targeting these energies, it is expected to lead to breakthroughs 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.

European Solar Telescope (EST)

Credit: Gabriel Pérez (IAC)



Cherenkov Telescope Array (CTA)

Credit: ESO

ESO's Very Large Telescope (VLT)

Credit: ESO / John Colosimo

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.

Space-based facilities

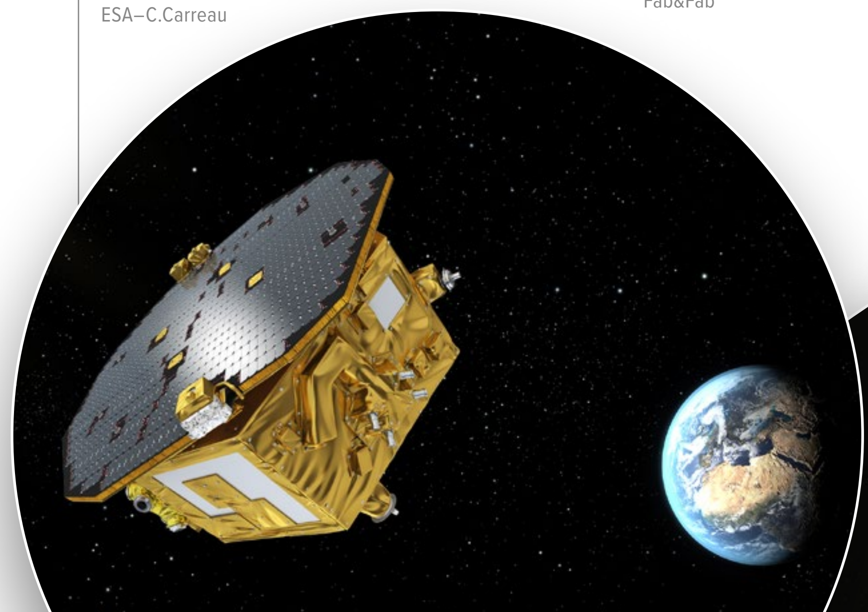
The major European space-based missions are coordinated by ESA, who has just completed its own scientific perspective exercise Voyage 2050, and is also currently defining its programme for human and robotic exploration, Terrae Novae 2030+, mainly targeting the Moon and Mars. The Panels of the ASTRONET 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.

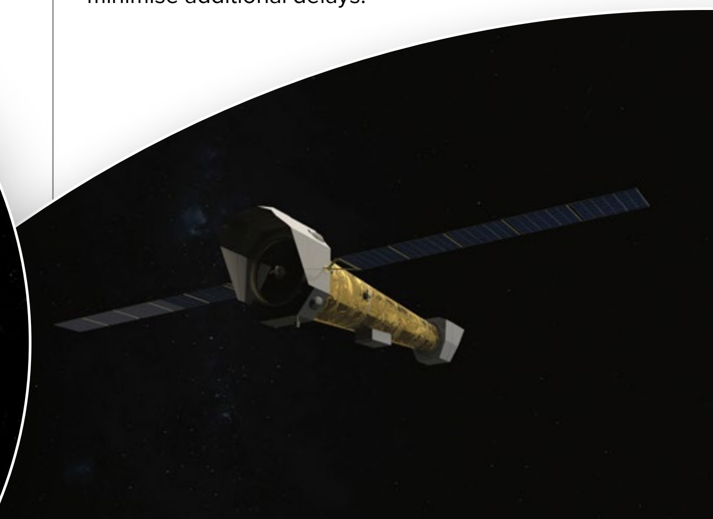
LISA Pathfinder

Credit: ESA–C.Carreau



Athena space observatory

Credit: IRAP/CNRS/UT3/CNES/ Fab&Fab



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.

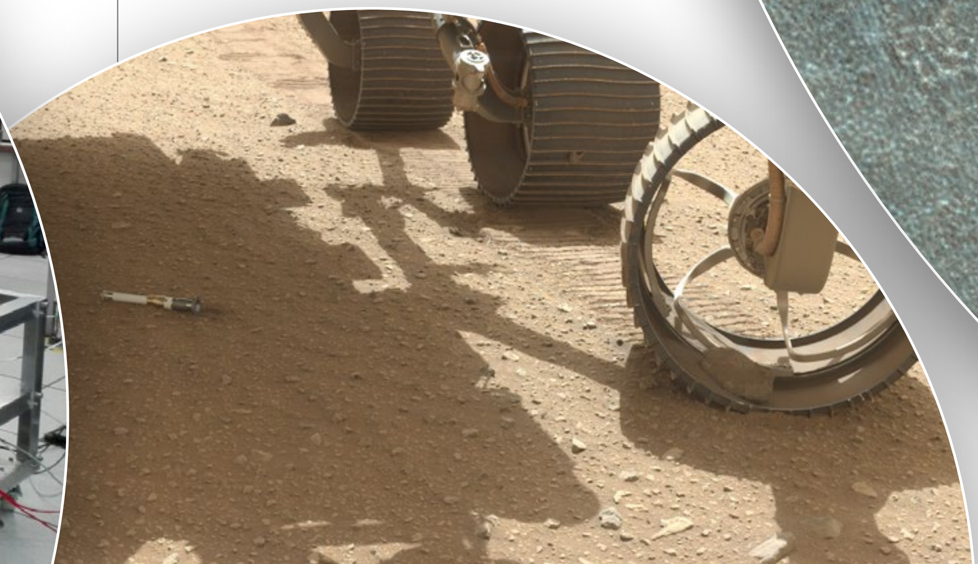
Laboratory astrophysics facilities necessary to underpin the physical understanding of observations must proceed hand-in-hand with observational facilities. While large observational facilities are often funded from major infrastructure grants, this complementarity is vitally important to the successful 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.

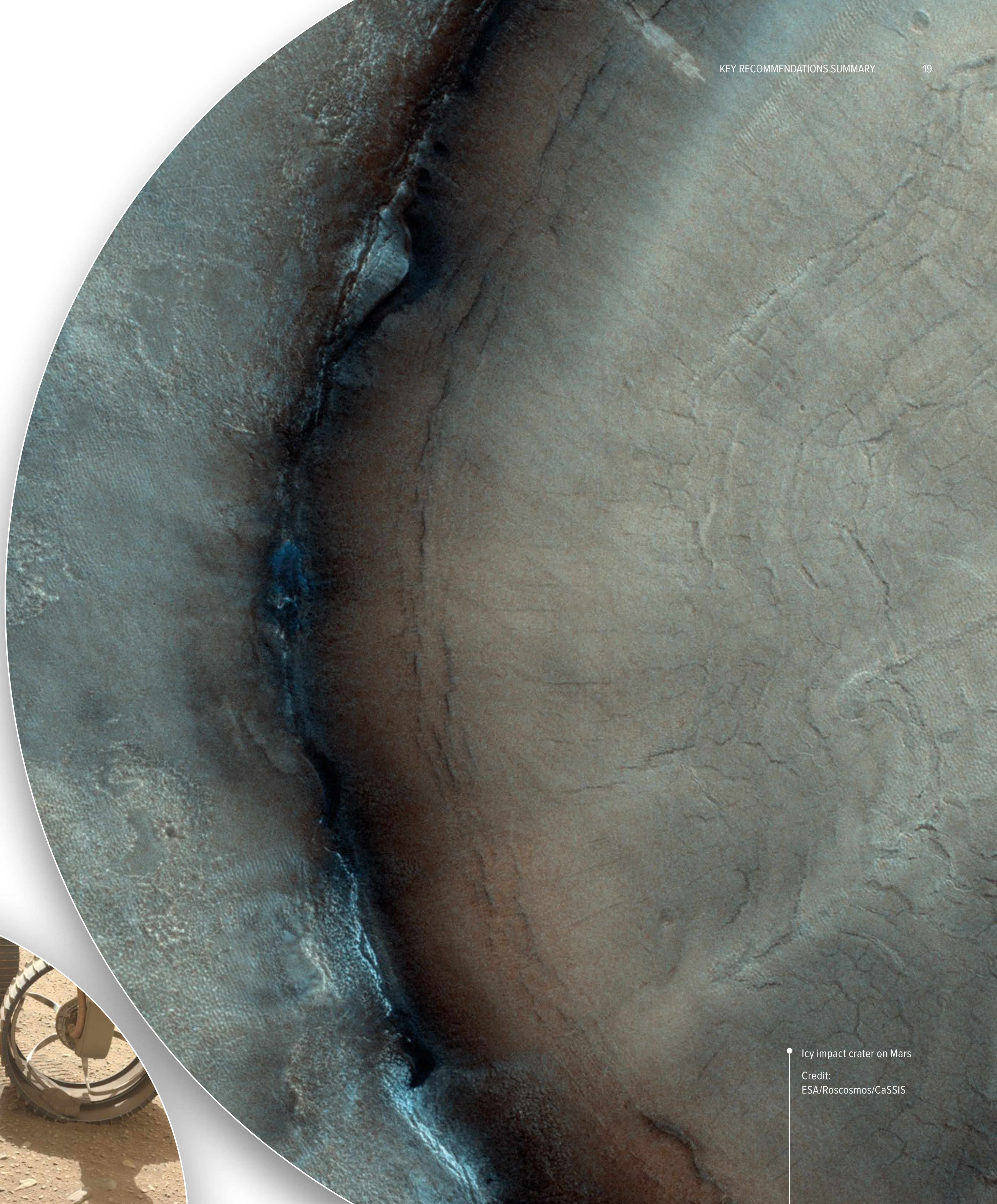
GACELA

Credit: Cernicharo et al.



Mars soil sample ready for return to Earth

Credit: NASA/JPL-Caltech/MSSS



Icy impact crater on Mars

Credit: ESA/Roscosmos/CaSSIS

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).

Exoplanet Beta Pictoris B

Credit:
Lawrence Livermore
National Laboratory

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.

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

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

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