Planetary Systems

The study of planetary systems around stars other than the Sun is going through a genuine scientific revolution. While the first exoplanet was discovered less than 3 decades ago, we now know they are ubiquitous, and have found the first rocky worlds that could have climates similar to Earth. In the meantime, the planet formation process is studied in ever increasing detail around newly born stars, showing us how the solar system, 4.5 billion years ago, may have come into existence. In this chapter, we identify clear pathways to the exciting future of this field of research, each with their own observational, computational, and technical challenges.

How did Earth come into existence?
How special is Earth within all the possible worlds?
What are the necessary conditions for life to emerge and thrive?
What is the fate of the Solar System?
Are we alone...?

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, in contrast to stars, do barely emit their own light so that detecting them in the glare of their host star's light is 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 4000+ 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 the parameter spaces 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 disc to explain the observations. For the last decade, the very early stages of planet formation have 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 characterized, which has lead to great successes using both space-based (Hubble Space Telescope/USA+ESA, Spitzer/USA) 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 characterizing 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 optimized for red dwarfs have led to an explosion of detections of warm-to-temperate terrestrial worlds such as Proxima b (the nearest exoplanet 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 in four routes, each guided by overarching questions, both from the current and prospective points of view.

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?

1 Status of the field

1.1 Planet formation

Planets form in protoplanetary discs around young, accreting stars (see Star-Formation Chapter). These discs 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 disc evolution itself is controlled by the gas.

Figure 1 summarizes 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 disc 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 disc 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 disc 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 in particular 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 Mearth), 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 disc, the PDS 70 system, in which direct observational evidence has been found of forming planets in the large disc cavity. The presence of material accreting from the disc to the forming planets, the so-called “circumplanetary disc” 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 discs have been recently renamed "planet-forming" or "planet-hosting" discs, as observations have revealed indirect signatures of already formed planets embedded in the disc. 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 discs 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 disc 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 disc's upper layers. Furthermore, detailed observations of simple molecules, such as CO, have revealed perturbations of the typical Keplerian disc rotation, which would be due to the presence of massive protoplanets in the disc. Finally, recent studies of the disc molecular content, focusing on molecules slightly more complex than CO such as e.g. simple hydrocarbons, have started to link the chemical properties of the disc gas with the composition of the atmosphere of gaseous exoplanets.

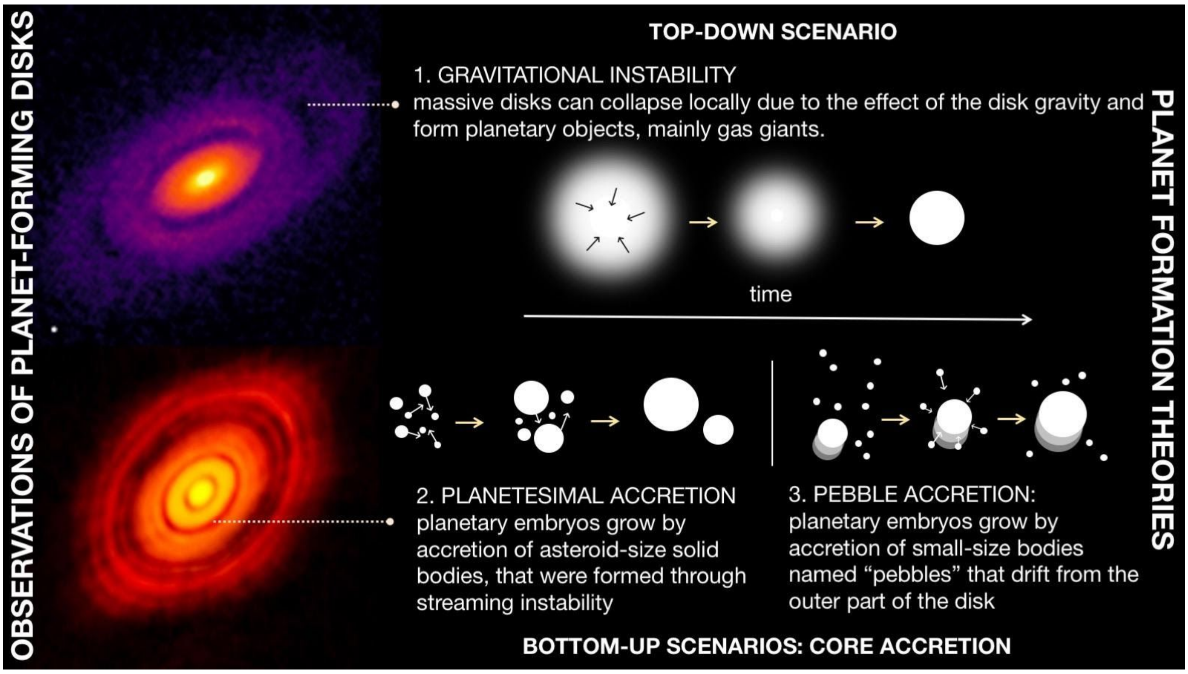

Fig. 1: Schematic overview of the main planet formation pathways

Another angle from which planet-forming discs have been studied is by studying the dust components. The composition of these dust particles can be assessed by telescopic observations in distant planet-forming discs and, by analogy, by analysis of dust from the Solar protoplanetary disc. 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 ultracarbonaceous 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 discs (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. Observations with the future JWST of distant planet-forming disks will help understanding these mineral distributions in discs. 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 Protoplanetary disc.

Finally, planets that we observe today are not only the result of isolated planet formation, as external processes (e.g., photoevaporation, strong interstellar UV radiation, and stellar encounters) may strongly affect disc 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 disc 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, disc-planet interplay and host star interactions. The next section gives an overview of the present status of exoplanetary demographics, highlighting the most recent discoveries in terms of planetary properties.

1.2 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 the 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 favorable 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.

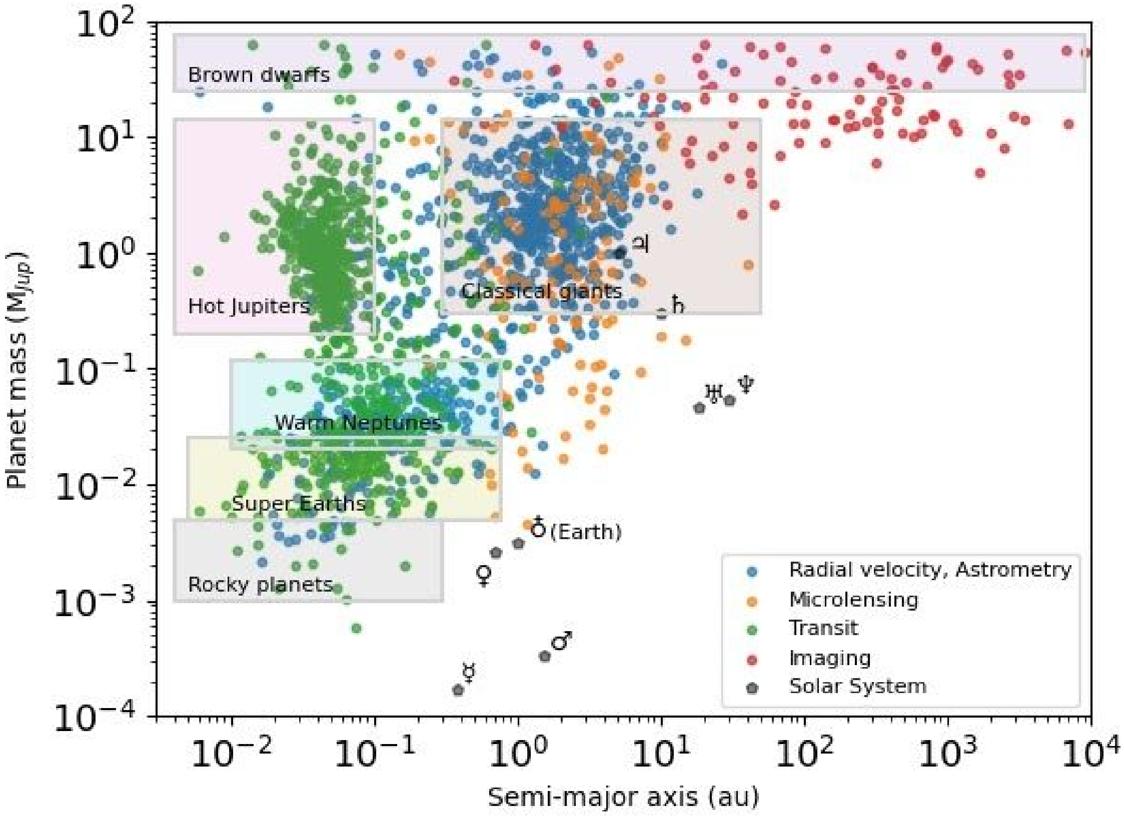

Figure 2: Exoplanets (and brown dwarf companions) discoveries considering the different planet hunting techniques (from http://exoplanet.eu). The exoplanets masses are reported as a function of their distances (with minimum masses for the radial velocity method). The different categories of exoplanets 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.

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;

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, 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, the Kepler, K2, and TESS 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.

1.3 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, characterizing 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 section 1.4).

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 utilizes transits and eclipses. If the orbit is fortuitously orientated, 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 characterize 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.

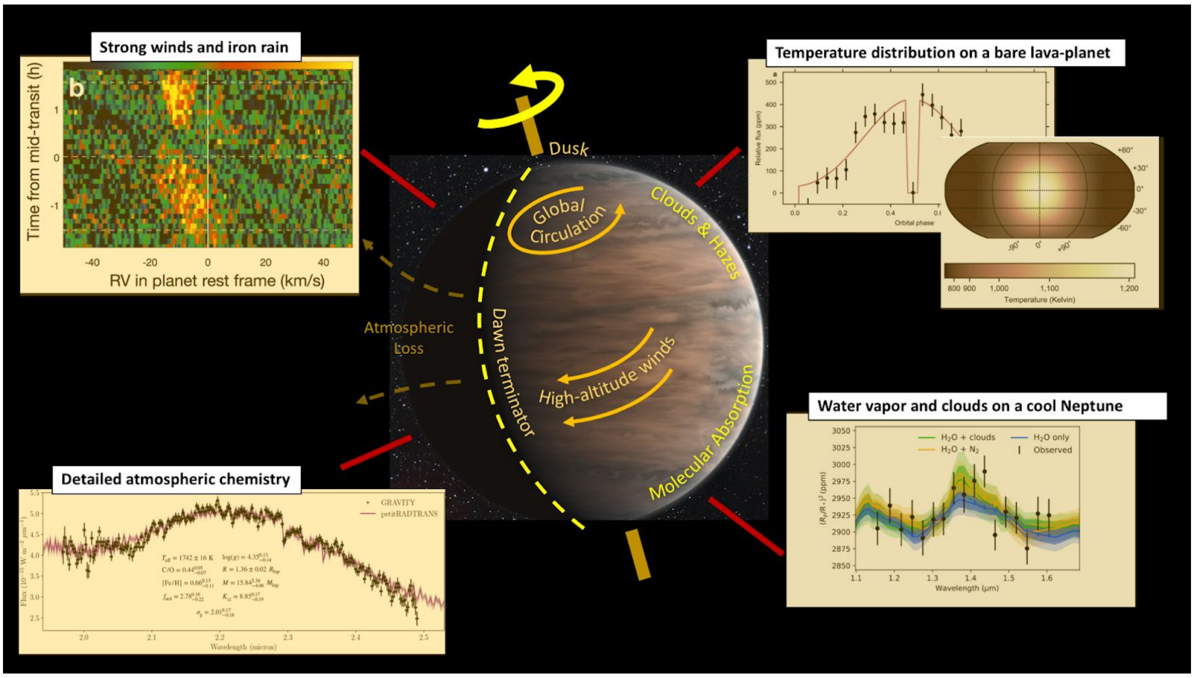

Fig 3: Schematic overview of different types of observations of exoplanet atmospheres [credits: Ehrenreich et al.; Kreidberg et al.;Tsiaras et al.; Nowak - GRAVITY Collaboration]

1.4 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 discs. 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.

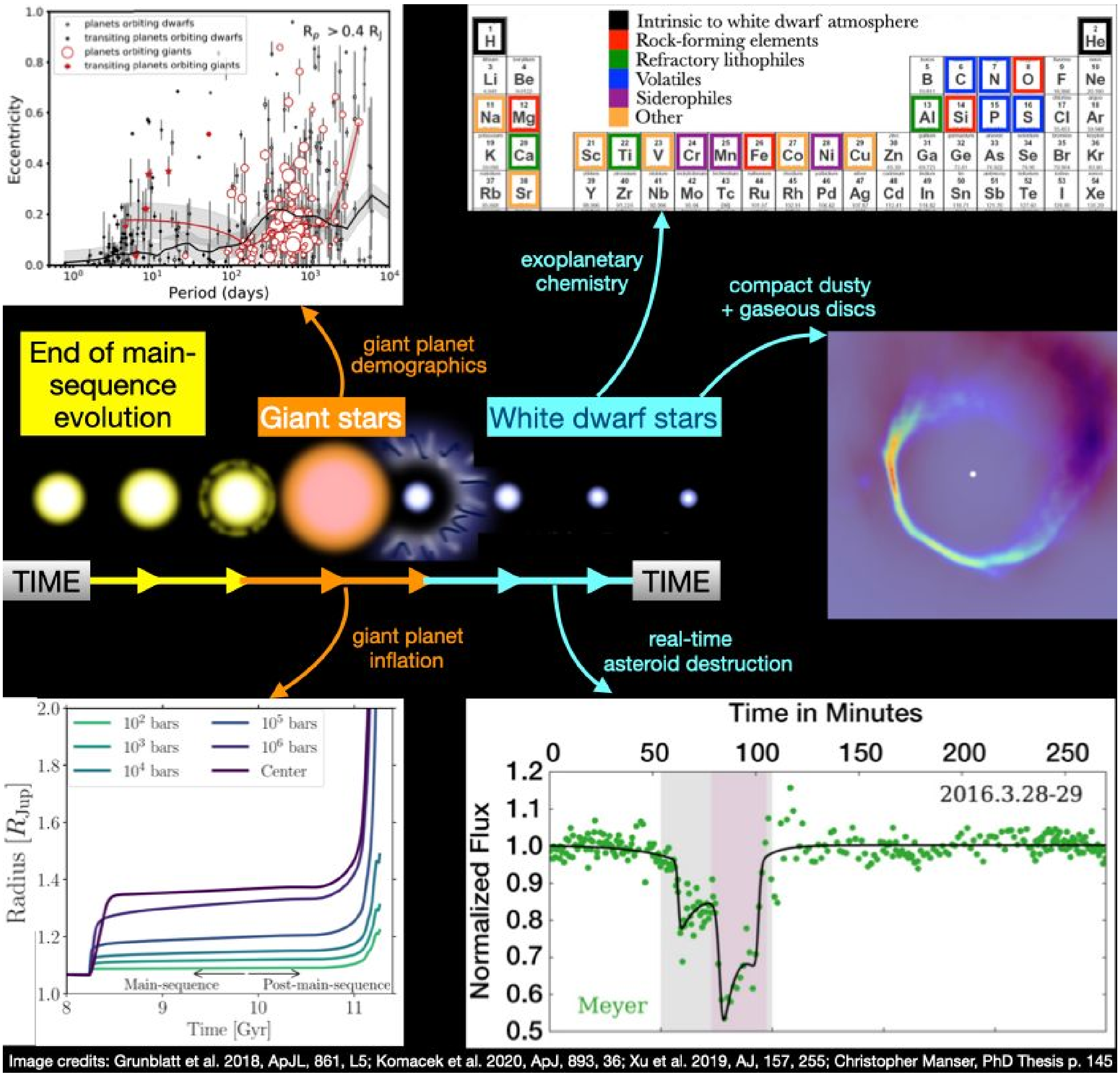

Image credits: Grunblatt et al. 2018, ApJL, 861, L5; Komacek et al. 2020, ApJ, 893, 36; Xu et al. 2019, AJ, 157, 255; Christopher Manser, PhD Thesis p. 145

Fig 4: Late stage evolution and fate of planetary systems

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 white dwarfs WD 1145+017 and ZTF J0139+5245, spectroscopic detections of a planetary core orbiting SDSS J1228+1040, an ice giant planet evaporating around WD J0914+1914, and a giant planet transiting WD 1856+534. Further, infrared excesses on spectral energy distributions have revealed the presence of over 60 dusty discs 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 discs on yearly and decadal timescales indicate ongoing dynamical activity which has yet to be explained by theoretical and numerical modelling efforts.

2. The coming decade

2.1 Planet formation

Demonstrating which features of protoplanetary discs 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 disc features that unambiguously signal planet formation, from the discovery and characterization of the youngest planets that are still embedded in their natal disc, to the planetary accretion history.

ALMA has recently played 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 discs needs to be better characterized 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 disc size distribution, both in disc height and disc 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 discs. Deep gas observations of discs with ALMA, will allow to probe the radial extent of the gaseous discs, which is the fundamental parameter for constraining disc evolution theories. Characterization of dust from the outer regions of the solar protoplanetary disc can be achieved through laboratory analyses of primitive dust collected in the stratosphere and in Antarctica. Spatial missions like Comet-Interceptor will also bring more constraints on the composition of cometary dust.

Probing the chemistry within protoplanetary discs will be tackled by combined efforts with ALMA and the JWST (MIRI). In combination, 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.

Ground-based observatories are now reaching spatial scales that allow us to probe disc substructure at scales of a few au around fainter stars. In the coming decade, facilities such as ESO SPHERE(+), MUSE and ERIS will follow the (orbital motion) of disc features, which is key to understanding where they originate in the disc, 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 disc 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 disc. 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), astrometry (Gaia), radial velocity (ESO CRIRES+, NIRPS), may play an important role too, if the impact of the stellar activity and the 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 (disc and other forming planets) leading to the exoplanet demographics observed or that will be observed in more evolved systems (see sections 1.2 and 2.2).

The ELT will offer the possibility to image and spectrally characterise the inner disc planetary regions, thanks to MICADO, HARMONI and METIS. METIS in particular will revolutionize 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 discs in the closest star-forming regions (around 150 pc) will be directly imaged allowing us to characterize 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 allows 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. Such experiments can probe the microphysics of how particles stick together under the different conditions encountered in protoplanetary discs (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 discs, chemical reactions in the gas phase and between gas and dust, the behavior 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 roles 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.

2.2 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. HIRES, HARPS, HARPS-N) of thousands of bright main-sequence dwarfs in the Solar neighborhood 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 if it will achieve 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 section 2.3).

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 favorable 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 mission. 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 and 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, age, and chemical composition, 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 favorable for the formation of telluric planets able to sustain life.

The suite of next-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 might 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 neighborhood 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 modeling.

In parallel to the observational effort, theoretical work is required in order to advance the modelisation 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.

2.3 Exoplanet characterisation

The field is 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 revolutionize transit and eclipse spectroscopy. For the first time, exoplanet atmospheres will be studied over a wide range of mass, temperature, and composition. JWST 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, low-frequency radio telescopes such as LOFAR and SKA may reveal further evidence of star-planet interactions and planet magnetic fields – another important ingredient of planet habitability. To acquire a true understanding of atmospheric physics and chemistry, and links to formation and evolution, it is also vital to study large samples of exoplanets under varying conditions 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 meters, the reach of the ELT will be unprecedented and unrivalled. Its first light 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...), the synergy with indirect techniques such as astrometry with Gaia and RV will allow to explore the mass - luminosity, and further constraints their processes of formation (See Planet-Formation Section). At mid-infrared wavelengths, METIS will have the sensitivity to image our nearest neighbor 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 HIRES will target starlight reflected off the planet atmospheres, e.g. studying the habitability of planets such as Proxima b, 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 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 endeavors 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 needs to be thoroughly explored, 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

SPHERE+. 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 neighborhood.

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.

2.4 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 sub-giant and giant stars will continue to grow steadily.

The ongoing TESS mission has already proven its unique 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 discs, 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-characterized, mineralogy data in the surrounding 60 known dust and gas discs 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 discs. This data can then be combined with the known atomic atmospheric abundances measured with HST to further refine exoplanetary chemistry and constrain disc lifetimes. Over the next decade the total number of known discs 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, LSST 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, allowing 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 disc 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 disc 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.

3. 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 ingredient for planet-formation theories are the fundamental properties of proto-planetary discs. In particular, reliable disc 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 discs 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 disc masses in a large sample of discs, i.e., increase the sample size by an order of magnitude to be compared with the known population of exoplanets. In addition, a cryogenic comet sample return mission such as AMBITION, proposed as a white paper to ESA, 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 observation, 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 separation around stars of different spectral type, age, chemical composition and environment, 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 favorable 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, NGRST, or a new global astrometry mission with Gaia-like precision, complemented by ground-based observations with the ELTs, our vision of the demographics of giant planets around stars of various masses, ages, environment 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 the 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., HIRES and 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, revolutionize our understanding of planet habitability, and ultimately discover the first indication of the presence of life on other worlds .

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 LUVOIR in the late 2030s. LUVOIR 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 neighborhood. 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 are simply too high, requiring a large high-contrast imaging mission from space. NASA has concluded its first two studies, the LUVOIR and HabEx concepts, of what such a mission could entail. ESA's plans in these directions are currently under consideration as part of the Voyage 2050 process. Tens of true Earth analogs and their planetary environments could be studied in reflected light (including life indicators), delivering a census of biological activity in our part of the Milky Way. In addition, a different concept, infrared space-based interferometry (LIFE Mission) is being proposed. This exciting space mission would probe the thermal emission of planets at ultra-high resolution – inaccessible with conventional telescopes.

The European exoplanet 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.