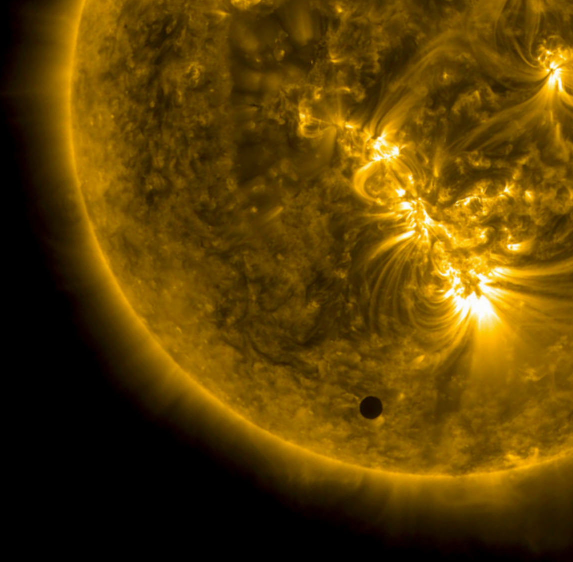
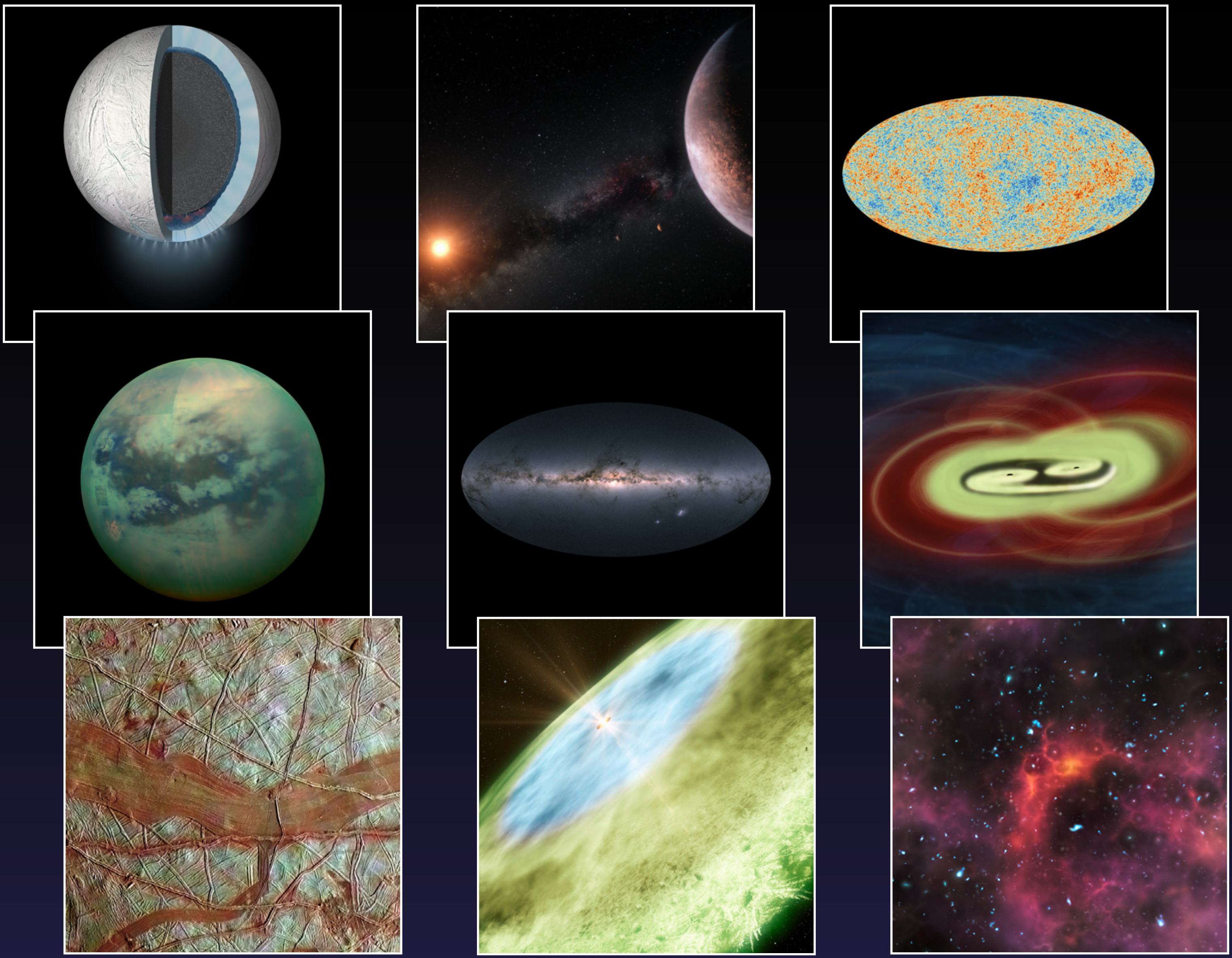
Voyage 2050

Final recommendations from the Voyage 2050 Senior Committee





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May 2021

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Executive summary

In 2018, the Director of Science established a Senior Committee of scientists, chaired by Linda Tacconi (Max Planck Institute for Extraterrestrial Physics, Garching, Germany) and co-chaired by Christopher Arridge (Lancaster University, UK) to develop a plan, Voyage 2050, to follow Cosmic Vision and establish ESA's Space Science Programme up to 2050. In this report, the committee summarizes its recommendations to ESA and the process that led to these recommendations. The Voyage 2050 Senior Committee members were tasked with:

1. Making a clear recommendation on science themes for the next three Large missions following *JUICE*, *ATHENA* and *LISA*. This has a significant impact on the Programme due to the technology developments often required for Large missions and the associated financial investments. We present these recommendations in Section 2 of this report.
2. Providing a list of possible science themes that could be addressed through Medium missions. The list we provide is neither exhaustive nor prescriptive but provides a clear demonstration of the health of European Space Science and the excellent science that can be achieved through the Medium mission Programme. We also highlight specific themes that are beyond the reach of the Large mission Programme but may be carried out through international collaboration with ESA as a minor partner, in the spirit of missions such as the *Hubble Space Telescope* and *Cassini-Huygens*. Our recommendations are presented in Section 3.
3. Recommending long-term technology development that would lead to breakthrough science from ESA Space Science missions in the future, beyond Voyage 2050, and create and enable a path for the far future to ensure agility and reach of the Programme. Our recommendations are presented in Section 4.

The task set by the ESA Director of Science for the Large missions was to make recommendations to ESA and the Science Programme Committee of three science areas where such missions could achieve breakthrough advances in the period 2035 to 2050. It is particularly important to emphasise that this is a choice of *science area* and not of specific missions. The missions will be chosen in due course when ESA issues calls for mission proposals to address in turn each of the science goals recommended by the Senior Committee in this report. For these three Large mission science themes for Voyage 2050, we recommend, moving out from the Solar System to the edge of the visible Universe:

- **Moons of the Giant Planets**. Exploring the issues of habitability of ocean worlds, searching for biosignatures, and studying the connection of moon interiors, near-surface environments, and the implications for the exchange of mass and energy into the overall moon-planet system. This theme follows the breakthrough science from *Cassini-Huygens* and expected scientific return from *JUICE* in Cosmic Vision.
- **From Temperate Exoplanets to the Milky Way**. Our Milky Way contains hundreds of millions of stars and planets along with dark matter and interstellar matter but our understanding of this ecosystem, a stepping-stone for understanding the workings of galaxies in general, is limited. At the same time, a mission specifically focusing on the *Characterisation of Temperate Exoplanets* would be transformational and of great interest to scientists and to the public alike. The Senior Committee

considers a mission on the Characterisation of Temperate Exoplanets to have a higher scientific priority. However, since an informed down-selection is not currently possible with the available information, the committee specifically recommends that a study be carried out before selection. Should it be determined that this is not feasible, the Senior Committee recommends rather a focus on the *Galactic Ecosystem with Astrometry in the Near-infrared.*

- **New Physical Probes of the Early Universe.** How did the Universe begin? How did the first cosmic structures and black holes form and evolve? These are outstanding questions in fundamental physics and astrophysics, and we now have new astronomical messengers that can address them. Our recommendation is for a Large mission deploying gravitational wave detectors or precision microwave spectrometers to explore the early Universe at large redshifts. This theme follows the breakthrough science from *Planck* and the expected scientific return from *LISA*.

Ideas for Medium mission themes in the Voyage 2050 timeframe are described in Section 3, and Section 4 summarizes three recommendations on technology developments for missions beyond Voyage 2050.

All of these recommendations were developed with significant and overwhelming involvement from the community. A Call for White Papers yielded almost 100 ideas for scientific themes that had to be evaluated and assimilated into the three Large mission themes described in this report. To assist the Senior Committee and further involve the community, a set of Topical Teams was established through an open Call. It was extremely challenging for the Senior Committee to reduce these scientific ideas into three themes, especially under conditions of a global pandemic. The Senior Committee could not have completed its work without the contributions from these Topical Teams.

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1 Introduction

1.1 A Vision for Voyage 2050

In late 2018 the Director of Science tasked a team of 13 scientists, the Voyage 2050 Senior Committee, to lead the definition of a new long-term plan that will set the European priorities in space science for the couple of decades following the end of the current planning cycle Cosmic Vision. The members of the Senior Committee are listed in Appendix B.

The Director of Science requested the Senior Committee to make a three-tiered recommendation. The first, and the one with the strongest impact on the Programme, was to provide a clear recommendation about the scientific themes that shall be addressed by the three Large missions following *Athena* and *LISA*. This is in line with the long-term planning being by its nature mainly concerned with the Programme's Large missions. Large missions require significant technology development, which often takes a number of years. While these developments require significant resources (certainly from ESA, and often also from Member States), they are best carried out well in advance of the actual mission development activities being started. To justify the significant investments required to carry out these technology developments and avoid nugatory spending it is thus necessary to decide well in advance which Large missions the Programme will implement, hence the request to provide a clear and prescriptive recommendation in this sense. Depending on the outcomes of the recommendations in Sections 2 and 3 of this report, the Director of Science will likely discuss with Member States the early start of technical and scientific studies, as well as potential technology developments necessary to enable the implementation of ambitious missions some fifteen years from now.

The second request was to provide a list of possible science themes that could be addressed through Medium missions. This list in Section 3 is neither exhaustive nor prescriptive, and Medium missions will continue to be selected following open Calls for Missions issued periodically. The purpose of the recommendation is multifarious: it will provide evidence to both the Director of Science and the Science Programme Committee that Medium missions will continue to be a good investment for the future Programme. It will also provide the Executive with possible areas where modest technology developments might enable future Medium missions.

The third and final request concerned long-term technology development strategies: a number of ideas presented in the White Papers would be feasible, and would provide break-through science to the ESA community, if certain specific technologies would be available. In some cases, this simply concerns the availability of this technology, in some other cases it concerns availability in Europe. Either way, an ESA-led technology effort (likely with Member States' involvement) could enable the implementation of such ideas in the future (likely in the next planning cycle). Thus, in parallel with the implementation of the ideas selected for the current cycle, this recommendation will guide the Programme in starting now to create and enable a path for the further future.

1.2 Organisational Process of Voyage 2050

The process began with the appointment of the chair of the Senior Committee, Linda Tacconi (Max Planck Institute for Extraterrestrial Physics, Garching, Germany) and co-chair Christopher Arridge (Lancaster University, UK) followed by a selection process to define the rest of the Senior Committee membership. In selecting the committee, particular attention was paid to the scientific breadth and expertise, gender and geographic diversity of the members and the distribution of Member States represented in the committee. This committee was established in December 2018 and the first Senior Committee meeting was held in February 2019 at the European Space Research and Technology Centre (ESTEC), The Netherlands to establish the working procedures. Figure 1 illustrates the timeline of Voyage 2050 from the establishment of the Senior Committee to the delivery of this report. Our processes are described in more detail in Appendix A.

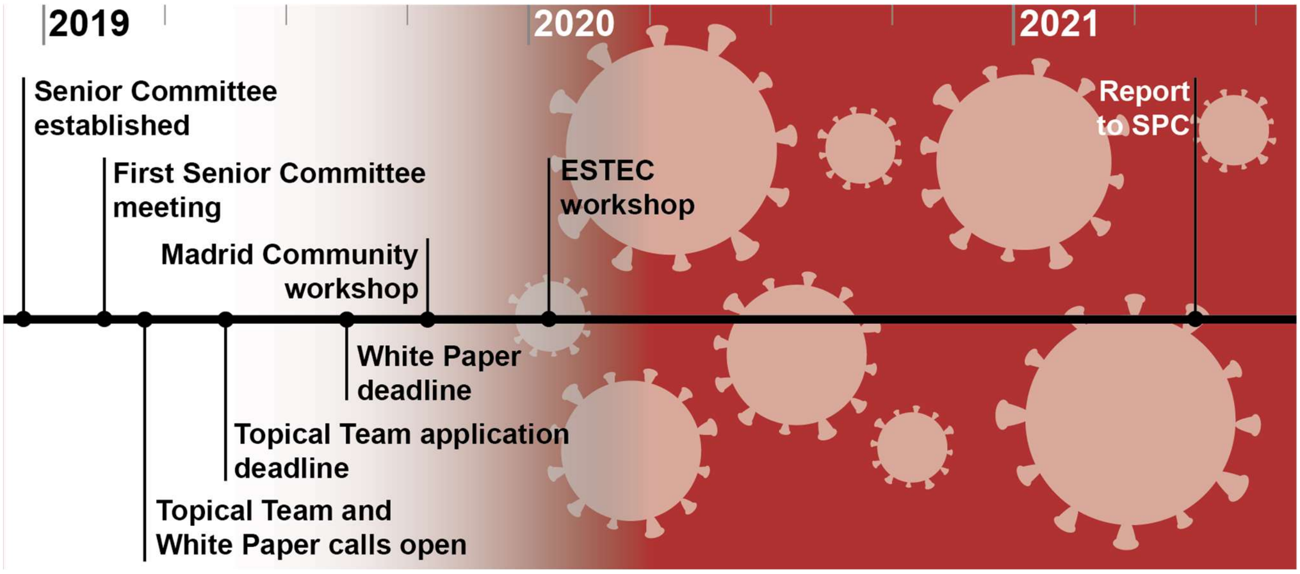

Figure 1: Timeline for Voyage 2050

As main ESA liaison for Voyage 2050, Fabio Favata attended the Senior Committee meetings, bringing in important aspects from the ESA perspective and answering the many questions of the committee. Karen O'Flaherty cheerfully and efficiently arranged the meetings, and assisted the Senior Committee on many different levels. The work of the Senior Committee was also overseen by three observers from the ESA advisory structure: Stefano Vitale (the 2017-2020 chair of the Science Programme Committee), Martin Hewitson (the 2020-2022 chair of the Space Science Advisory Committee), and John Zarnecki (the 2017-2019 chair of the Space Science Advisory Committee). All three participated actively in the discussions, but did not take part in the voting on the recommendations.

Such an ambitious undertaking as Voyage 2050, which affects European space science for decades, is best implemented based on an open consultation of the broad scientific community interested in Space Science. As a first step, the community was invited to submit White Papers to present their ideas for the science themes that the Science Programme should address following the launch of *Athena* and *LISA*. To ensure a fair process it was decided that no member of the Senior Committee should participate as lead authors or co-authors of any of the White Papers. The next step was to issue a Call for Membership of Topical Teams to ensure the broadest possible peer support and involvement, and to make available to the Senior Committee the broadest possible scientific expertise to analyse the White Papers. This call gave the possibility to any scientist working in Europe, with a strong preference for early career scientists, to participate in the process and inform the recommendations of the Senior Committee. Topical Team members were allowed to co-author White Papers, but they were not allowed to lead any of them, and removed themselves from any discussion of White Papers in which they were involved.

The Senior Committee selected Topical Team members by a scoring process which included deliberate checking for evidence of scoring biases. Keywords were used to broadly group candidates into topic areas and to check the appropriate balance of expertise from the relatively fine-grained keywords (see Appendix E). The final Topical Team selections were also examined for evidence of bias. The Senior Committee decided on five Topical Teams to cover the expected scientific breadth of the White Papers. The teams were selected to be broad and at a wide range of career states to facilitate discussion and interaction. The scientific scopes of the Topical Teams are briefly described in the sub-sections below and their membership is detailed in Appendix C. In their evaluations each Topical Team implicitly considered the state of the art, and current and future missions. Figures 2 and 3 highlight the ESA missions that formed part of this state of the art.

1.2.1 Topical Team 1: Solar and Space Plasma Physics

The Sun, the heliosphere and planetary magnetospheres are natural laboratories for studying space plasma physics. They are host to a wide range of plasma physics conditions but are near enough to allow for a detailed investigation using both remote and *in situ* measurements; plasma regimes within our reach range from the very low-beta solar corona and auroral regions, where the magnetic field controls much of the plasma behavior, to the high-beta plasma sheet and magnetosheaths where the plasma is in control. Solar System missions such as *SOHO*, *Cluster*, *Mars Express*, *Rosetta*, *Hinode* and *Solar Orbiter* (Figure 2) have provided, and will continue to provide information and ground-breaking studies of the workings of space plasmas in various environments, alongside remote observatories studying planetary aurorae such as the *Hubble Space Telescope* and *XMM Newton* (Figure 3). Knowledge of the fundamentals of solar and space plasma physics processes in a wide range of environments has obvious implications for our understanding of how these processes operate in the wider astrophysical context as well as for planetary and stellar evolution. In addition, the study of the heliosphere has strong societal implications that stem from the effects that the complex chain of plasma processes in the Sun-Earth relationship has on determining possibly detrimental conditions for life and technologies on and near Earth.

1.2.2 Topical Team 2: Planetary Science

Our Solar System is made of very diverse objects in term of e.g. size, chemistry, origins and evolution, or dynamics. After the pioneering phase of exploration in almost all places of the Solar System from Mercury to the Kuiper belt, using flyby and orbital missions, planetary science is now aiming at exploring each object in all its complexity, for example through missions such as *Mars Express*, *Cassini-Huygens*, *BepiColombo* and looking forward to *JUICE*. These missions aim to examine these bodies as planetary objects in their own right, but also as a key element of broader themes, such as the origin and evolution of terrestrial planets, climate evolution on terrestrial worlds, gas or ice giant systems, and the origins of the Solar System. This era of fully interdisciplinary planetary science requires i) the use of orbiters to remotely investigate surface characteristics, characterise their space environments *in situ*, and characterise the geophysics of their interiors, and how these elements evolve in time, ii) probes, landers or rovers to characterise their surfaces and near-surface environments *in situ*, and finally iii) spacecraft to return surface and subsurface samples to Earth.

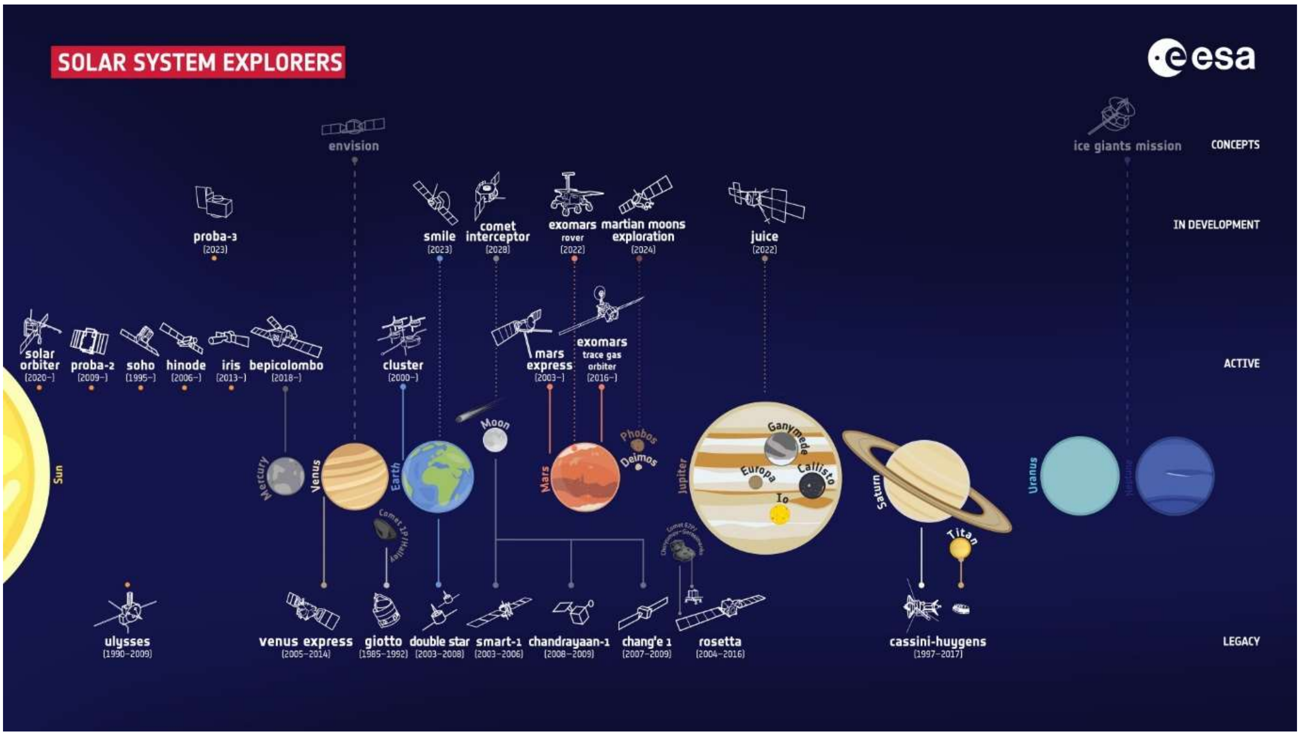

Figure 2: Illustration of ESA missions exploring the Sun, planets and Solar System (Credit: ESA).

1.2.3 Topical Team 3: Galaxy, Star and Planet Formation and Evolution; Astrochemistry and the ISM

This Topical Team covered many different areas of Astrophysics, from the formation and characterisation of stars, planets and the interstellar medium (ISM) in our Galaxy, to the formation and evolution of galaxies like our own to the most distant systems in the Universe. To tackle the many open, rather fundamental, questions addressed in this very diverse set of science topics we need to access multiple wavelengths from the X-rays to the radio wavelengths through space missions using a variety of observational techniques that include photometry and spectroscopy, for example *Herschel* and the *Hubble Space Telescope*, and as well as astrometry, for example, *Gaia*, and interferometry.

1.2.4 Topical Team 4: The Extreme Universe, including Gravitational Waves, Black Holes, and Compact Objects

The physics of extreme conditions, which spans strong gravitational and electromagnetic fields, highly energetic particles and photons, and matter at ultra-high densities and pressure, has always been a major source of fundamental discoveries. Neutron stars, black holes, the X-ray background, and gravitational waves have each been the subject of Nobel prizes in the last 50 years, and space missions are key to reaching these targets, for example *XMM Newton*, the *Hubble Space Telescope, Athena* and *LISA*. Compared to the Cosmic Vision Programme, probably the most significant development in this topical area has been the opening up of the gravitational-wave window and its related multi-messenger astrophysics.

1.2.5 Topical Team 5: Cosmology, Astroparticle Physics and Fundamental Physics

What is the Universe made of? How did the Universe begin and evolve? What are the fundamental laws of nature? This Topical Team distilled these three fundamental questions about the Universe into three distinct themes: (1) The Origin and Evolution of Cosmic Structure; (2) Astroparticle Physics and Dark Matter; and (3) The Foundation of Quantum Mechanics and General Relativity. While these topics are amongst the most central in our current understanding of physics, there is at present no overarching theory that provides a common understanding of the current data. Space platforms, for example *Planck*, offer certain advantages in the exploration of these issues by experimental means: low ambient noise, long path lengths of free fall in 3D and easily variable gravitational environment, but for some experiments the mass required exceeds normal launch capacities. Each of these three themes has the possibility to provide breakthroughs over the coming decades and could form a highlight in ESA's Voyage 2050 Programme.

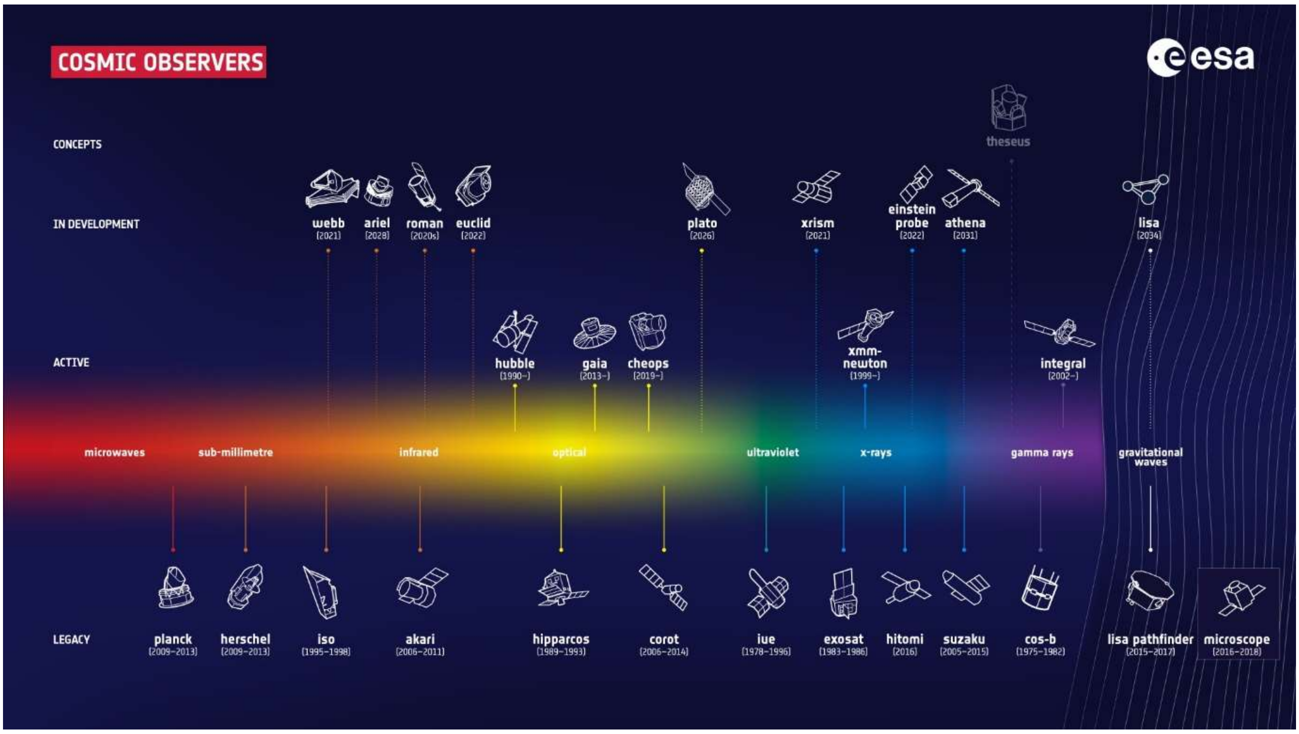

Figure 3: Illustration showing ESA missions exploring the Universe in various windows of the electromagnetic spectrum and in gravitational waves (Credit: ESA).

1.3 Decision making process

A community workshop was held in Madrid in October 2019 where a broad selection of authors were invited to present their White Papers. It was emphasized that the invitations to present were not any form of pre-selection but to highlight the range of scientific ideas. The Topical Teams started their work at the Madrid workshop and continued through the autumn and winter of 2019/2020, including a workshop at ESTEC in January 2020 and concluded with their final reports to the Senior Committee in February 2020, as COVID-19 began to take hold world-wide. At ESTEC the Topical Teams and Senior Committee were able to discuss feasibility of various mission ideas with ESA engineers. Through the COVID-19 pandemic the Senior Committee continued working via regular videoconferences.

The Senior Committee allocated White Papers to the Topical Teams. Some White Papers were evaluated by multiple Topical Teams where the scientific themes overlapped and to ensure that White Papers did not slip between artificial boundaries. Topical Teams were asked to:

- Evaluate each White Paper on its scientific merits.
- Synthesise White Papers into potential Large mission themes.
- Establish a list of White Papers that could be addressed with Medium missions.
- Identify any scientific areas that were compelling but not represented in the White Paper submissions.

The Large mission theme selection was the focus of the Senior Committee. The Topical Team leads, drawn from the Senior Committee, presented these syntheses to the Senior Committee. This resulted in a set of 14 potential Large mission themes that were all scientifically compelling and which posed a formidable challenge to down-select to three final themes. Themes were considered along four axes:

- Scientific excellence – is the scientific theme likely to lead to a scientific breakthrough?
- Is there a significant risk that much of the science would be done by other space missions or ground-based facilities in the Voyage 2050 timeframe?
- Is the required technology development considered feasible?
- Is there at least one foreseeable mission concept that could address the theme and fit within a Large mission envelope?

In-depth discussions and debates in many remote meetings throughout 2020 and early 2021, followed by anonymous voting and down-selection led to the consensus on the themes presented in Section 2. The Senior Committee emphasises that we strove for and achieved consensus at every step of the way to these recommendations.

Themes for Medium missions were also considered by Topical Teams. These emerged organically from a consideration of the Medium theme White Papers, from Large mission themes that could be de-scoped, and from themes that could only be achieved through opportunities to collaborate as a minor partner with other space agencies, e.g., following models such as the *Hubble Space Telescope (HST)*, *James Webb Space Telescope (JWST)*, and *Cassini-Huygens*. Medium mission themes were discussed as well at Senior Committee meetings. Similarly, specific technology developments also emerged organically from the Large and Medium mission process and were discussed and approved by the Senior Committee.

2 Recommendations for Large Mission Scientific Themes

The three recommendations detailed below are the results of the months of remote discussions following the procedures as outlined in Section 1.3. To flow-down from the 14 themes passed on from the Topical Teams to our final recommendations, the Senior Committee applied a set of basic questions and considerations to guide and focus our deliberations:

- Scientific excellence – is the scientific theme likely to lead to a scientific breakthrough?
- Is there a significant risk that much of the science would be done by other space missions or ground-based facilities in the Voyage 2050 timeframe?
- Is the required technology development considered feasible?
- Is there at least one foreseeable mission concept that could address the theme and fit within a Large mission envelope?

The recommendations below span nearly the full range of science breadth of the Programme, from the Solar System to the earliest phases of the Universe. Each recommendation is self-contained, with the necessary scientific background, short descriptions of potential mission concepts and likely science outcomes. These recommendations are for Large missions **scientific themes**, hence our recommendation focuses on the science and as a consequence any mission concepts we discuss are only schematic. In the process of evaluating the White Papers and forming opinions on the feasibility of proposed missions the Senior Committee assumed that every mission proposal under consideration by ESA for inclusion in the Voyage 2050 Programme would undergo substantial study to determine the technical feasibility, required technology developments, science outcomes, estimated resources and preliminary timeline. The outcomes of such mission studies would guide the final recommendations for actual Large missions to the Science Programme Committee.

2.1 Moons of the Giant Planets

Following the discovery of the Galilean moons at Jupiter in 1610 by Galileo, science interest in giant planet systems remained moderate for three and a half centuries. However, after the first close-up observations by the *Pioneer* and *Voyager* missions in the 1970s and early 1980s, and the surprising discovery of the complexity of giant planet systems, including the extreme diversity of their moons, scientific interest grew high enough to motivate dedicated space missions. Indeed, for both the giant planets and their moons, questions were raised about their origins, their interior structures, and the formation and evolution of the exospheres and atmospheres. Scientists acknowledged that they had to be considered as complex systems in their own right, especially regarding the coupling processes associated to gravitational and electromagnetic interactions and their complex and dynamic plasma, gas and dust environments.

Detailed exploration requires orbiting space missions and Figure 4 shows a sketch of the giant planets and their missions to date. *Galileo* orbiting Jupiter from 1995 to 2003 achieved this, as did *Cassini* orbiting Saturn from 2004 to 2017, which included the *Huygens* probe that landed on Saturn's largest moon, Titan, in January 2005. Among the many discoveries of that exploration phase, the most surprising outcomes were the discoveries of deep oceans or water layers below the outer icy shells of Europa, Ganymede and possibly Callisto at Jupiter, and Enceladus and Titan at Saturn. Over those two decades, exoplanets were also discovered, and a few water worlds were identified around other stars, as giant replicas of the icy moons of the Solar System.

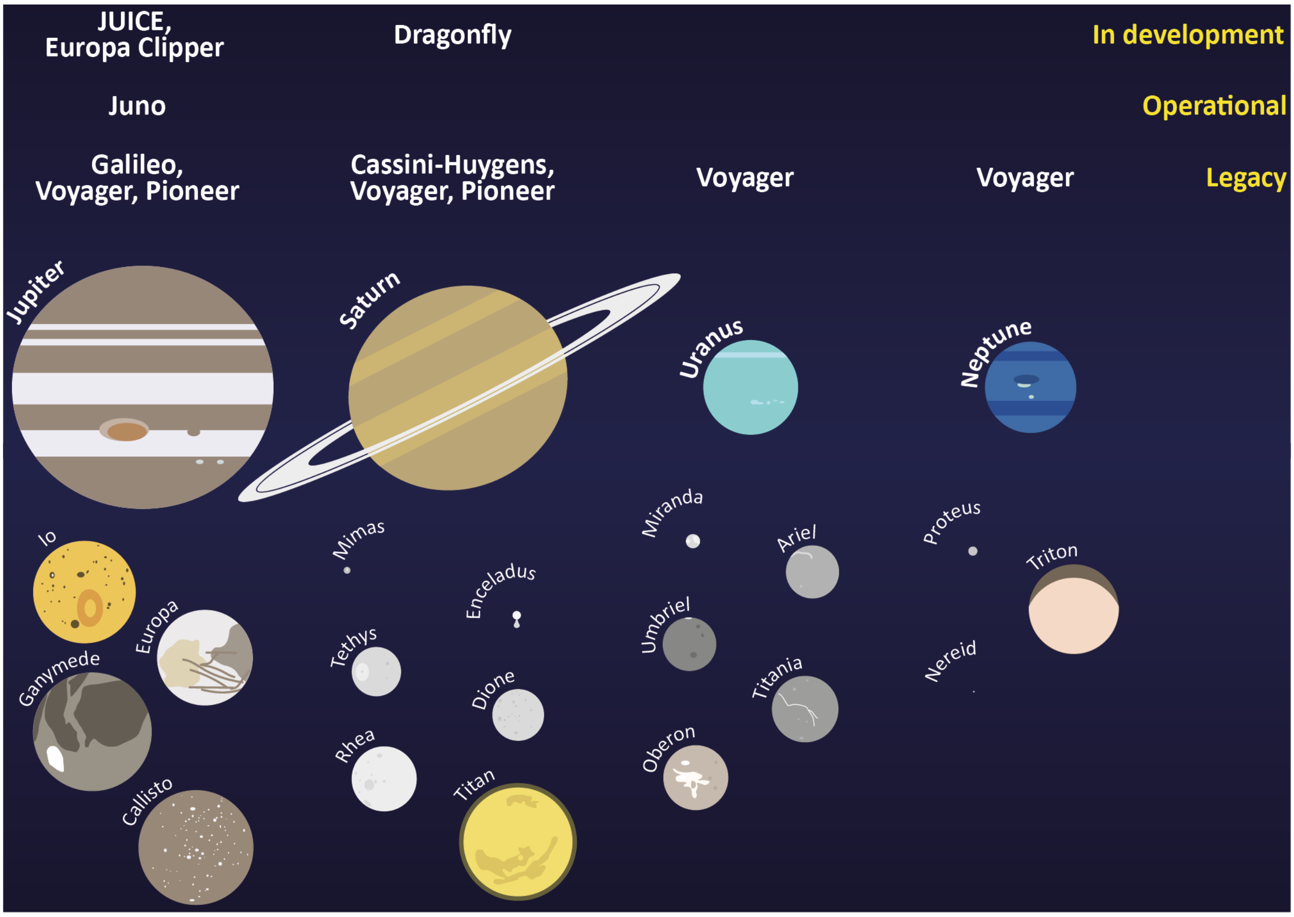

Figure 4: Sketch of the moons at giant planets with legacy, operational and in development missions.

Galileo and *Cassini*, in spite of the outstanding scientific success, left a large number of fascinating open questions. Being able to solve these “cold cases” requires a new phase of exploration. One of the most striking questions is the existence of deep habitats in outer Solar System moons (in particular Enceladus and Europa), similar to the black smokers in mid-ocean ridges that were discovered on Earth in the late 1970s. The preliminary indications of hydrothermal vents on the ocean floor of Enceladus, suggested by the Cassini measurement of H_2, is a striking example of the need to investigate the habitability potential of those moons. In the context of Cosmic Vision, this characterisation will begin with the JUICE mission, which will further study the Jupiter system in all its complexity, and then explore Ganymede as a planetary object and a possible habitat. JUICE will be the first orbiter of an icy moon. In the meantime, ESA will also play an important role in the international landscape of more focused missions such as NASA’s *Europa Clipper* and *Dragonfly*, bound for Europa and Titan respectively.

Each moon is unique, and poses intriguing questions that connect interior compositions and structures with exterior environments in ways that can be investigated with existing technology. Ganymede and Callisto, the first and third largest moons of the Solar System, possess very complex interiors, possibly including a deep water-rich liquid layer, still largely uncharacterised in terms of structure and dynamics. The *JUICE* mission will explore both moons. Titan is particularly exciting because it is the only object in our Solar System with two extensive layers of liquid (a subsurface salty ocean and hydrocarbon seas at the surface) possibly connected through cryovolcanism. The details and implications of this connection remain unclear. Europa and Enceladus are extremely attractive because they allow us to look into their inner liquid reservoirs through the material ejected in the form of plumes. As for Io, not only is it the most extreme volcanic world of the Solar System, but also a key element of the complex Jovian magnetospheric system.

All the moons of Saturn and Jupiter are part of a complex planetary system that requires continued in-depth exploration, going beyond past and ongoing missions. The moons comprise coupled layers, from the core to exosphere and a surrounding magnetosphere and neutral environment. They respond to the planetary system through gravitational and magnetospheric forcing, exchanging mass and energy in a complex and non-linear way. As an example, the surface of most of the moons are hit by energetic particles thus producing space weathering through sputtering, induced chemical reactions and desorption of surface molecules. This process is particularly effective for Europa, which is orbiting inside the strongest radiation belt in the Solar System. Material ejected from volcanic activity on Io can also be deposited on its surface. Ionized particles from the surface and atmosphere are then picked-up in the planet's magnetospheric flows. These planetary-moon plasma interactions are quite diverse. Ganymede, with its intrinsic magnetic field, forms its own mini-magnetosphere within that of Jupiter. The surface and atmosphere of Titan are also subject to large variability in the ambient plasma, magnetic field, and dust-plasma environment of the Saturnian magnetosphere as well as the solar wind. Enceladus's plume interacting with the plasma and magnetic field leads to the generation of a current system linking it with Saturn's ionosphere, producing an auroral spot similar to those at the Galilean satellites. Characterising these processes are important not only to understand the present-day conditions, but also to understand the origin and evolution of any potentially habitable environment.

Many of the satellites of the outer Solar System, including the smallest, contain organic material. However, the largest icy moons, and Enceladus, are of much greater relevance to astrobiological studies since they satisfy all of the prerequisites for habitability: liquid water, energy, complex chemistry, and relative stability. Crucial to the onset of complex chemical reactions is the contact of liquid water with silicates in the bodies' cores. The knowledge of the interior structure therefore plays an essential role in assessing how favourable the conditions are to the onset of a complex chemistry. In addition, the interior structure holds the key to unveiling the formation and evolution processes of the moons and the satellite systems, which have a large impact on their habitability potential.

The presence of a deep liquid reservoir in Ganymede, and possibly Callisto, combined with essential prerequisites such as energy from the interior and time stability, granted on such large bodies, makes the presence of the organic molecules highly probable based on the overall chemistry of the system. However, the putative habitable zones of those bodies are located below thick icy shells that prevent *in situ* investigations by any conceivable space mission. Even so, a lot of information can be gathered from suitably equipped orbiters or landers. Part of the *JUICE* mission is dedicated to this science question.

Titan sits in a special place among the Solar System bodies. It is the only satellite in the Solar System to have a substantial atmosphere and possesses a combination of complex hydrocarbons and organic molecules. The methane cycle, which can be compared with Earth's water cycle, is partly responsible for this abundance of organic-rich materials through the combination of nitrogen and methane, with precipitation and large surface seas and lakes of ethane and methane. Cryovolcanism could be the source of methane, explaining its abundance in the atmosphere in spite of the short photodissociation time. However, *Cassini* found little clear evidence of cryovolcanism, probably because its instruments lacked the required resolution. In spite of more than one hundred *Cassini* flybys, Titan hides a poorly known interior structure. The thickness and ammonia content of the internal ocean is highly uncertain. The presence of a high-pressure ice layer between the silicate core and the liquid water is still debated, and so is convection in the ice shell, whose thickness is uncertain.

On Enceladus, hydrothermal activity is so active that thermal plumes expel the inner liquid layers in the southern polar regions where the overlying ice shell is thinner. Organic molecules and salt-bearing dust grains were measured in these plumes. In this regard, the *Cassini* mission has shown that almost all the prerequisites for life are indeed present, with the caveat that the duration of the present state over a long time period is not yet demonstrated. This makes Enceladus most certainly a prime candidate for a future mission focused on astrobiology objectives outside Earth's biosphere. The tidally modulated, but continuous, flow of water from plumes makes for an easy access to the internal ocean, a unique characteristic among the icy moons of the Solar System.

Europa also displays all the prerequisites not only for habitability but also for a possible investigation of this habitable zone with direct measurements. The question of the direct access of the deep reservoir to the surface via cryovolcanic processes and/or plumes is still unresolved but should be addressed by the future *Europa Clipper* mission. In the far future, space missions could directly access the internal ocean.

A future mission should address the scientific challenges of the icy moons, in particular:

- The issue of the habitability of ocean worlds through characterisation of the interior structure and the subsurface oceans with instrumentation capable of carrying out a full tomography of the moons' interiors.
- The search for biosignatures and the identification of prebiotic chemistry at the surface, in the atmospheres and within the plumes of ocean worlds can be achieved with remote sensing and *in situ* instruments.
- The study of the connection of interior and the near-surface environments, and particularly how this connection may be driven by dynamical forcing, as well as the implications for the exchange of mass and energy in the overall moon-planet system (including the planet's magnetosphere).

The *JUICE* mission at Ganymede and *Europa Clipper* at Europa will address some of these challenges. In Voyage 2050, a dedicated mission to other icy moons, especially Titan or Enceladus in the Saturnian system or a new mission in the Jovian system focused on key aspects of the Europa and/or Io science will be critical for further progress. Technological maturity is not expected to be a major challenge for an orbiting spacecraft (using heritage from *JUICE*). Technology developments on higher efficiency solar cells have been ongoing at ESA making a solar-powered mission in the Saturnian system not only feasible but also operationally flexible and capable of hosting advanced instrumentation. Surface elements, although of the utmost scientific interest, present critical technological challenges. Instrument development for such missions is strongly encouraged to achieve and boost the scientific return, for example in the characterisation of complex chemicals.

2.1.1 Recommendation

The Voyage 2050 Senior Committee recommends that ESA pursue efforts leading to exploration of the outer Solar System by considering a “Moons of the Giant Planets” theme that will continue and extend the characterisation era in Voyage 2050. An ESA mission to the moons of the giant planets will build on the agency’s expertise for exploration of the outer Solar System after *Cassini-Huygens* and (the soon to fly) *JUICE*. One possible profile for an ESA-led Large mission would involve obtaining a global perspective on these moons via a spacecraft, or a possible dual-spacecraft mission in a mother-daughter configuration, performing multiple flybys and/or orbit insertions. Alternatively, a mission profile might include a significant *in situ* element to characterise the local surface and subsurface environments, for example via a lander, drones or sample return.

2.2 From Temperate Exoplanets to the Milky Way

As well as our own Solar System, the Milky Way contains hundreds of millions of stars and planets, dark matter, and interstellar matter. Our current understanding of the workings of the galactic “ecosystem” is limited. For example, we do not know how galaxies like the Milky Way form their stars and although it is likely to be linked to global dynamical processes, we simply do not understand how. We know now that the majority of stars in the Milky Way host planetary systems, but we have no idea how many of these planets have temperate surface conditions and could potentially host life. These exciting and rather fundamental questions are notoriously difficult to address. Yet the technological and scientific developments of the past and coming decade place ESA in a unique position to answer these crucial questions in the context of Voyage 2050.

Within this area, the Senior Committee has identified two scientific themes of particular interest – the “Characterisation of Temperate Exoplanets” and the “Galactic Ecosystem with Astrometry in the Near-infrared”. Both themes are appealing and compelling, however, the committee considers the “Characterisation of Temperate Exoplanets” as having the highest scientific priority, although an informed down-selection does not seem to be currently possible with the available information. We thus recommend further study of its technical feasibility, as we outline after the description of the two aforementioned themes.

2.2.1 Characterisation of the Atmosphere of Temperate Exoplanets

Answering the question of the existence and distribution of life elsewhere in the Universe has been an important driver for the exploration of other worlds, both in and outside of our Solar System. Since the emergence of the field of exoplanets in the mid-1990s, the scientific community has embarked on this long-term quest with an approach complementary to what has been done in the Solar System.

This is, however, an ambitious quest and many steps have been, and will be necessary before we can truly establish the existence of life outside of the Solar System. Yet, since the implementation of the Cosmic Vision Programme, exoplanet research has enabled several paradigm-shifting discoveries making the field mature enough to tackle these big questions in the Voyage 2050 timeframe. Indeed, the last 25 years have shown us that exoplanets in general, and terrestrial planets in particular, are ubiquitous. Many have been found around nearby stars of all types. Figure 5 is an illustration of a temperate exoplanet that was found orbiting the ultra-cool red dwarf star TRAPPIST-1 which has recently been found to host seven temperate exoplanets and is only 40 light years from Earth. These planets are extremely diverse, with many of them still defying our understanding of planet formation and evolution. We are starting to have the technical ability to characterise terrestrial planets and their atmospheres through various observational means.

Figure 5: Illustration of a temperate exoplanet orbiting the ultra-cool red dwarf star TRAPPIST-1 (Credit: ESA/M. Kornmesser).

The exploration of the diversity of planets and planetary atmospheres, which far exceeds the diversity found in the Solar System, is thus the natural way forward for exoplanet research, and the *CHEOPS*, *JWST*, and *Ariel* missions are the next big steps in that direction. Altogether, these missions will achieve the first census of the diversity of warm to hot exoplanet atmospheres by observing several hundreds of objects. Yet, because of inherent limitations of the main methods used for these observations (e.g., transit spectroscopy), the information provided by these missions will still be very limited when it comes to small terrestrial planets that are cold enough to potentially harbour surface liquid water. This is particularly true if the aim is to capture thermally emitted photons to probe regions near the surface. Observing these planets is very challenging but crucial to understand whether planets harbouring habitable surface conditions are common in the Universe.

As mentioned by several White Papers reviewed in building this recommendation, being able to detect infrared light directly emitted by those atmospheres will be key in understanding the chemical and physical diversity of these temperate worlds and whether they harbour truly habitable surface conditions. The mid-infrared offers unique capabilities that cannot be matched by observations in the optical and near-infrared as envisioned by mission concepts currently under study by other agencies. Measuring mid-infrared thermal emission enables precise measurements of two critical bulk parameters essential to infer the habitability conditions of a planet: its radius and the temperature of its atmosphere. The radius, combined with some knowledge of the mass, yields the density and can tell us whether or not a planet is truly rocky. The temperature structure of its atmosphere is critical to know whether it can host liquid water at its surface. In addition, the mid-infrared window contains signatures of a wealth of key molecules – water, ozone, methane, carbon monoxide, carbon dioxide, nitrous oxide, among others – that, measured together, inform us about the state and history of the atmosphere.

With such a concept, we will be able to test our understanding of the necessary conditions for a planet to develop a habitable climate. Indeed, the current theoretical limits on the maximum planetary size and insolation (among other parameters) compatible with a habitable surface environment are strongly model-dependent. To constrain these limits, we thus need to observe a sample of temperate planets with varying size and insolation, including planets that are bigger and receive more insolation than what we think is theoretically possible. Understanding this diversity, even among temperate planets, will be important for putting any peculiar features we observe into context. Finally, the measurement of peculiar abundances of some chemical species that are difficult to explain by abiotic processes could also give us some evidence for potential bioactivity on some of these planets.

Therefore, launching a Large mission enabling the characterisation of the atmosphere of temperate exoplanets in the mid-infrared should be a top priority for ESA within the Voyage 2050 timeframe. This would give ESA and the European community the opportunity to solidify its leadership in the field of exoplanets, which started with the first detection of an exoplanet from the ground and the first detection of a terrestrial planet from space by the *CoRoT* mission. Being the first to measure a spectrum of the direct thermal emission of a *temperate* exoplanet in the mid infrared would be an outstanding breakthrough that could lead to yet again another paradigm-shifting discovery. Indeed, discovering any hint of life on an alien world and understanding the conditions for its emergence would have a transformative impact not only on the scientific community but also on society as a whole.

2.2.2 The Galactic Ecosystem with Astrometry in the Near-infrared

Our lack of understanding of star formation and its coupling to processes that take place on galactic scales (dynamics, feedback, mergers) has hampered progress in the field of galaxy formation and evolution for decades. The strong coupling that exists between the smallest (sub-parsec) scales, and the largest scales (those of galaxies and their environment, hundreds of kilo-parsecs), results in a highly complex problem that has been difficult to tackle. Since star formation occurs in galactic discs, a powerful approach is to study in great detail a specific example: the disc of our own Galaxy. This is the only system in the Universe where we can accurately observe the dynamics of the stars, of the star forming regions and youngest open clusters and associations, in deeply obscured regions. By measuring the motions of stars where they are currently forming with space astrometry, the interaction between the dynamics of the Milky Way and its link to star formation can finally be disentangled.

Space astrometry has become a major field in astrophysics with clear and strong European leadership. The *Gaia* mission is revolutionizing a large variety of research fields, including addressing aspects of the Milky Way's formation and structure, the physics of its stellar populations and many other important questions. Figure 6 shows a map of stars in the Milky Way and nearby galaxies as observed by Gaia – revealing almost 1.7 billion stars. Yet, our understanding of the Milky Way will remain incomplete and limited because *Gaia* is not able to penetrate the dust obscured regions where stars are forming, nor the inner regions of the

Galaxy, which contain the imprints of the very early stages of its formation. It is the dust-obscured regions where stars are forming through poorly understood mechanisms that are expected to be in part driven by the dynamics (on still unknown scales) of the galactic system. For example, *Gaia* has recently revealed mysterious dynamically coherent chains of star forming regions whose origin is not understood at all. A plausibly related phenomenon are the spiral arms commonly seen in galaxies like our own, which perhaps are induced by accreting galaxies, whose impact *Gaia* has shown to be much more important than previously thought. Mapping the motions of stars over large regions of the Galaxy are the way to answer these questions in which different phenomena on a variety of scales play a role simultaneously. The Galactic disc is also where we expect planets to abound, and astrometric study would allow a demographic census of the planetary systems.

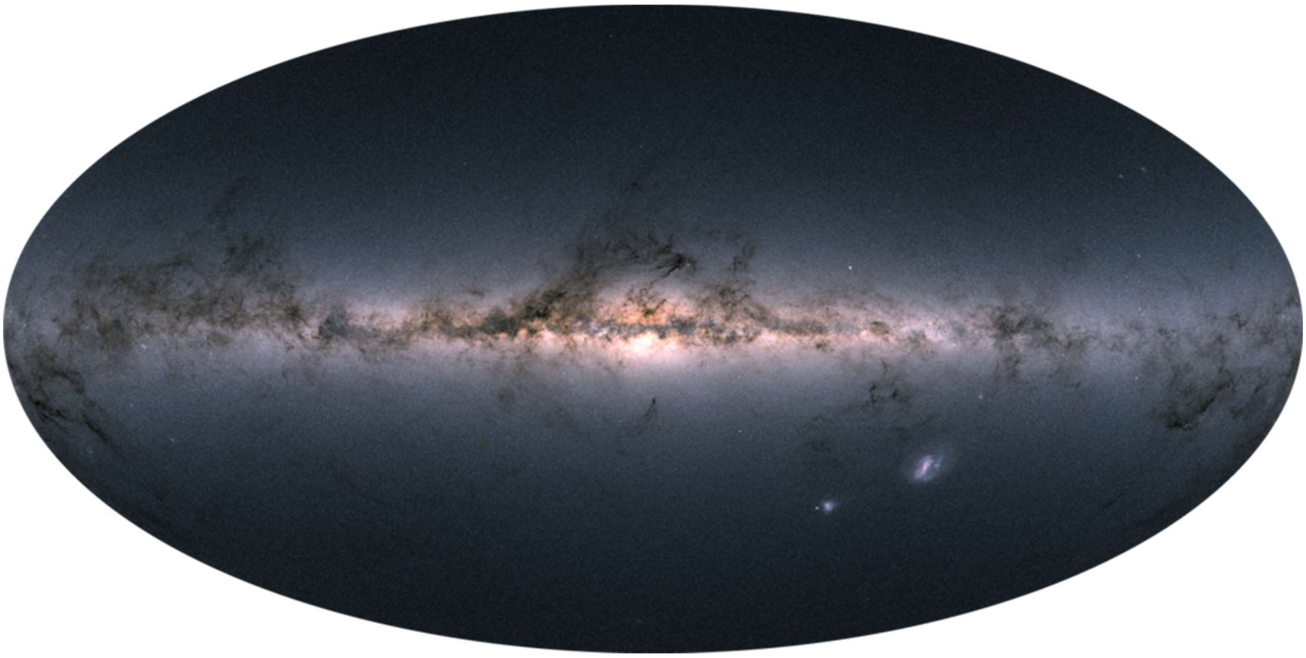

Figure 6: Measurements of almost 1.7 billion stars observed in the Milky Way and nearby galaxies from Gaia (Credit: ESA/Gaia/DPAC).

The dynamics and stellar content of the galactic bulge/bar is another region that is (and will remain) inaccessible in the coming decades. Studies thus far (and in the near future, with, for example, the JAXA mission *(nano)Jasmine*) have been typically very limited in scope (to small, less reddened regions); because of this, the link to the inner disc and other galactic components remains unknown. The very first mergers that have taken place in galactic history will have deposited stars in this region, and the very first stars formed in the Milky Way should have left their imprints there as well. Photometric and astrometric studies of these deeply dust enshrouded, very complex regions of the Galaxy, from a structural and dynamical point of view, are the only way forward. The impact of such a study goes beyond the Milky Way because it will contribute directly to understanding the physical processes that play a role in galaxies in general.

An all-sky astrometric catalogue complemented with photometry is an invaluable source of information for a wide range of astrophysics. The applications also include measuring the distribution of matter in the outskirts of the Milky Way, and in its satellites, crucial to determine the nature of the mysterious dark matter. The census of stars and planetary systems also serves to determine the star formation history and the initial mass function throughout the whole Galaxy. A global astrometric mission flying in the timeframe of Voyage 2050 will also extend and maintain the *celestial reference frame*, which is crucial for multiple space and on-ground astronomical facilities of the coming decades that need to maintain dense and accurate reference grids for their operation.

Based on all the above, it is clear that space astrometry beyond the end of the *Gaia* mission, with an extension of its capabilities to explore the Milky Way in regions currently unreachable for *Gaia*, particularly in the near infrared, should become a key theme in Voyage 2050. Such a mission will capitalize on the expertise developed since the *Hipparcos* mission at the end of the 1980s and continued with the current enormous success of *Gaia*, both of which demonstrate the undisputed and long-standing European leadership in the area.

2.2.3 Recommendation

In conclusion, the Senior Committee finds that the science themes focusing on the “Characterisation of Temperate Exoplanets” and the “Galactic Ecosystem with Astrometry in the Near-infrared” are both compelling and offer the potential for a high science return in the 2050 timeframe. The “Characterisation of Temperate Exoplanets” is considered as having the highest scientific priority, but an informed down-selection is currently not possible with the available information.

The committee recommends that ESA launch a detailed study involving the scientific community for the exoplanet theme to assess its likelihood of success and feasibility within the Large mission cost-cap. Specifically, such a study should assess what molecules could be detected, to what precision, and for how many targets. If it is found that at least 10 temperate exoplanets (within some reasonable bound of uncertainty) can be characterised and thus that a scientific breakthrough can be achieved in a feasible and affordable mission, then the committee recommends such a theme be selected for the third Large mission in the Voyage 2050 timeframe. If this is not the case, the committee instead recommends that ESA select the “Galactic Ecosystem with Astrometry in the Near-infrared” for a Large mission. The compelling nature of the astrometry theme is also highlighted by its inclusion in the Medium mission recommendations.

2.3 New Physical Probes of the Early Universe

How did the Universe begin? How did the first cosmic structures and black holes form and evolve? We now have new probes to answer these fundamental questions of physics. One is gravitational waves (GWs), which offer an entirely new and unobstructed view of the early Universe, because the waves travel through space unimpeded by scattering or absorption. The other probe is high-precision spectroscopy of the light of the fireball Universe, the cosmic microwave background (CMB) radiation.

Figure 7 illustrates the history of the Universe from the Big Bang to the present day. Many dramatic events occurred during the first half billion years of the Universe (redshift, $z > 8$). According to the current cosmological paradigm, there was a period of accelerated expansion of the Universe called “cosmic inflation” in a tiny fraction of a second, during which quantum vacuum fluctuations occurred. The enormous inflationary expansion stretched the wavelengths of these initial quantum vacuum fluctuations to astrophysical scales (an expansion so enormous that the size of an atomic nucleus became the size of the Solar System), and these fluctuations became the seeds for all structures seen in the Universe today—galaxies, stars, and planets, leading eventually to life. At the end of inflation, the Universe was heated as the energy that drove the accelerated expansion was converted into radiation. In this intensely hot Big Bang era, helium nuclei and trace amounts of other light elements were synthesized from the primordial protons and neutrons. The excess of matter over anti-matter and the origin of dark matter were also likely generated during this hot era. From that point, the Universe cooled down, reaching 3000 K after 400 000 years, whereupon protons and helium nuclei were combined with electrons to form neutral hydrogen and helium gas, which made the Universe finally transparent to photons. In the meantime, the small seed fluctuations that were generated during inflation grew gravitationally, eventually forming, within the first half billion years, the first stars, the first galaxies, and the first black holes.

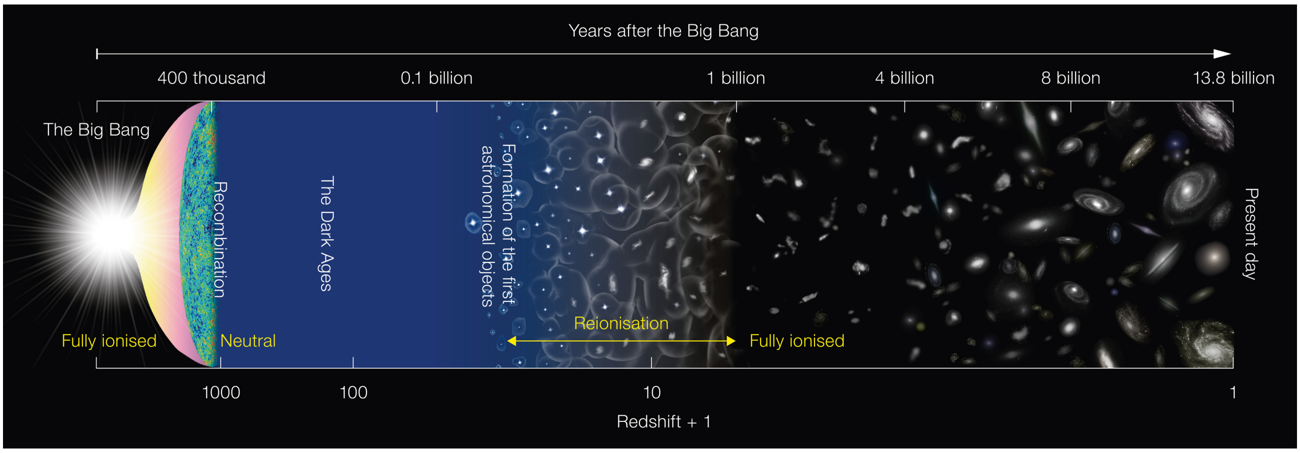

Figure 7: Illustration of the history of the Universe from the Big Bang to the present day (Credit: NAOJ).

Even though this story sounds remarkable, it is consistent with all the observational data we have at hand. Yet, we do not know precisely how inflation occurred or the physical mechanism by which the Universe became hot (“What powered the Big Bang?”). We have not seen directly how the Universe became transparent. We do not know what the dark matter is. Nor do we know how the initial cosmic structures grew or how and when the first black holes formed and evolved. How did monstrous supermassive black holes, weighing billions of solar masses, the hearts of quasars, come to exist less than a billion years after the Big Bang? How can we make serious progress on these outstanding questions, which range from fundamental physics to the nature of gravity, to the science of astrophysics?

2.3.1 New Opportunities for Exploring the Early Universe

Missions exploiting new probes, such as measuring the detailed spectrum of the CMB or observing GWs with high precision or in a new spectral window, can each answer many of these questions. Considerable advances have been, and are being, made in microwave instrumentation, enabling Fourier Transform Spectroscopy (FTS) to probe any injection of energy in the early Universe at $z > 10^3$, up to 100 000 times better than the FIRAS spectrograph on board NASA’s *COBE* satellite. The improvement by such a large factor promises a huge space for discovery. This science requires absolutely calibrated spectrographs, and cannot be done by the relatively calibrated radiometers of NASA’s *WMAP* or bolometers of ESA’s *Planck* satellite. Such a mission would not only detect the guaranteed signals of the standard paradigm of cosmology (thus providing an important test for our current understanding), but would also offer a discovery space for evidence of axion-like particles, annihilating dark matter particles, primordial magnetic fields as the origin of magnetic fields in the Universe, and primordial black holes. Considerable advances have also been made in GW laser interferometry and in gravity reference sensors. On the ground, this is attested to by the remarkable precision achieved by the *LIGO* and *Virgo* detectors in the deca-to-kilohertz GW bands, and in space, by the superlative performance of *LISA Pathfinder*, and the steady development of ESA's *LISA* mission, which will operate in the millihertz regime. Another approach that would shed a lot of light on the origin and growth of cosmic structures in the early Universe, say at $z > 8$, is to open up a totally new spectral window for GW astronomy, either in the decihertz or microhertz (notably from the sub-microhertz to millihertz or from millihertz to hertz). Depending on the chosen frequency band, such a mission will search for and characterise the elusive black-hole seeds, which bridge the gap between stellar mass and supermassive black holes, revealing how the first massive black holes assembled their mass and how high-redshift quasars emerged with their billion solar mass black holes. Such a mission would also seek evidence of a cosmological background in GWs, produced around the time of the Hot Big Bang by several physical phenomena, including quantum chromodynamics and electro-weak phase transitions with physics beyond the standard model, and topological defects such as fundamental and cosmic strings.

2.3.2 Precision Spectroscopy of the Fireball Universe

The spectrum of the CMB is near-perfect blackbody, which proved that the Universe was in a hot and dense state in the past. Yet, many of the events in the early Universe would have injected energy into the hot plasma, causing the CMB spectrum to deviate from a perfect blackbody. This so-called spectral distortion of the CMB offers a powerful new window into the physics of the early Universe. The *COBE*/*FIRAS* mission placed upper limits on the spectral distortion at the level of one part in 100 000. 30 years later, we can now push this limit by another factor of 100 000, reaching the level of 10^{-10}. This "precision spectroscopy of the fireball Universe" allows us to probe the energetics of the early Universe with unprecedented depth and helps us answer some of the fundamental questions on the origin and evolution of the early Universe. The recombination lines from the formation of hydrogen and helium atoms were imprinted on the CMB spectrum at the level of one part in a billion, and these offer the first direct observation of how the Universe became transparent. This is the underpinning for all the interpretation of the CMB data sets.

We now know that the initial fluctuations excited the propagation of sound waves in the early Universe plasma. These are seen clearly in the remarkable data sets of the CMB temperature and polarization anisotropies mapped by the *Planck* satellite, which led to the Nobel Prize in Physics being awarded to Jim Peebles in 2019. We also know that the sound waves damp on short wavelengths due to the viscosity of the plasma. This damping continues to much shorter wavelengths than measured by *Planck* and heats the CMB photons, distorting its spectrum at the level of one part in 100 million. The magnitude of this effect is proportional to the amplitude of the small-scale structure, which is inaccessible by any other known means and offers a powerful probe of the physics of inflation. Both of these effects – the recombination lines and the damping of sound waves – are the *guaranteed* signals of the current paradigm of cosmology; thus, the lack of detection would pose a serious challenge to the paradigm. In addition, the vast improvement in the sensitivity (100 000 times better than *COBE*/*FIRAS*) offers a huge space for discovery of new physics. Furthermore, annihilating dark matter particles would inject energy into the plasma, distorting the CMB spectrum in a characteristic way. The knowledge of the small-scale fluctuation has important implications for formation of primordial black holes, which may make up a fraction of dark matter and the GW signal seen by *LIGO*/*Virgo*. The presence of primordial magnetic fields in intergalactic space would alter the damping of sound waves in a magnetized plasma, making them visible to precision spectroscopy.

2.3.3 Adding Colour and Depth to the Gravitational Wave Sky

Gravitational waves are the cleanest astronomical messengers from the dark and deep Universe. They are produced by the coherent, bulk acceleration of huge amounts of mass, either in the form of matter or the mass-energy of warped space-time. The GW spectrum spans more than 20 orders of magnitude from femtohertz to megahertz. Observing different wavelengths allows us to probe black holes of different sizes (from stellar to billions of solar masses), at different times in their evolution, and how they interact with different astrophysical environments. Exploring different wavelengths also allows us to unveil different cataclysmic phenomena dominated by gravity, including the rapid changes of space-time throughout cosmic history. The *LIGO* and *Virgo* detectors have opened the frequency band from decahertz to kilohertz, observing the first binary black-hole merger, which was recognized with the Nobel Prize in Physics 2017, and several tens of compact-object collisions since then. ESA's *LISA* mission may provide the missing link between stellar-mass and supermassive black holes. The properties of such a population could be inferred with high precision during cosmic history out to $z \sim 10^2$. A mission concentrating on the microhertz range would offer the unique opportunity to understand how quasars, which are observed at high redshift ($z \sim 7$), have emerged, and whether the mass of the first massive black holes assembled through gas accretion or through mergers. Several hundreds of binary black holes with masses of hundreds of millions of solar masses would be observed hundreds of years before merger up to the dawn of galaxy formation ($z \sim 8$ to 10). Identifying electromagnetic signatures from those inspiraling massive black holes would offer unprecedented synergies in multi-messenger astronomy. Missions in the decihertz and microhertz frequency bands would also provide exquisite tests of General Relativity with black holes, could lead to the discovery of ultralight particles and primordial black holes, and would offer the possibility to observe the imprints of dark matter on the GW signals from extreme- and intermediate-mass black-hole inspirals.

Both decihertz and microhertz missions can peer back to the earliest moments of the Universe ($z \gg 10^3$) with a sensitivity to the stochastic GW background several orders of magnitude better than LISA, and more importantly, in a totally different frequency band. This greatly enhances the possibility of observing primordial signals from the time when the Universe transited from cosmic inflation to radiation, of probing how the particle physics landscape changed during cosmic evolution and for exploring the epoch from the end of inflation to Big Bang nucleosynthesis in which the Universe was dominated neither by vacuum energy nor by radiation or matter. In the same way that the opening of new frequency bands (X-rays, gamma rays, infrared light, and radio waves) have led to a radical reshaping of our understanding of the cosmos in electromagnetic astronomy, so we expect it to be with GW astronomy, with infrasounds or microsounds in the exploration and characterisation of the deep and dark Universe.

2.3.4 Recommendation

The Senior Committee recommend that ESA should develop a Large mission capable of deploying new instrumental techniques such as gravitational wave detectors or precision microwave spectrometers to explore the early Universe (say $z > 8$). Such a mission would shed light on outstanding questions in fundamental physics and astrophysics, such as how inflation occurred and the Universe became hot and then transparent, how the initial cosmic structures grew, how the first black holes formed and how supermassive black holes came to exist less than a billion years after the Big Bang.

While the focus of this Large mission is on the early Universe and the exciting new insights into the physics and astrophysics of that era, it is expected that the space observatories proposed to meet these objectives will also accomplish significant science at lower redshifts by the nature of their survey and new spectroscopic capabilities.

3 Potential Scientific Themes for Medium Missions

Medium missions are a key component of ESA's Science Programme and enable Europe to conduct relatively stand-alone missions that answer important scientific questions. Although there might be a perceived hierarchy where Large missions carry a higher scientific priority, some scientific questions can be comfortably addressed within a Medium mission envelope and lead to breakthrough science. Naturally, the cost cap limits the available launch vehicles and therefore, for example, the size of platform, diameter of telescope apertures, launch mass and what orbits or interplanetary targets may be reached by a Medium mission, and can also require compromises on payload, instrument resolution, sensitivity, or time resolution. By the design of the Programme, Medium missions are also limited to more mature technology.

A past example of an ESA mission that fits comfortably within the Medium mission envelope is *Mars Express*, and its sister mission *Venus Express*, both of which have led to breakthrough science at these planets. For example, *Mars Express* discovered subsurface deposits of water, hydrated minerals that are evidence of liquid water, localised aurorae, and identification of recent glacial landforms helping us to begin to unravel the climatic history of Mars. *Venus Express* has returned the first indirect evidence of ongoing volcanic activity on Venus. *Ariel*, ESA's fourth Medium mission is dedicated to characterising the chemistry and thermal structure of hundreds of transiting exoplanets to move beyond the detection of exoplanets to their characterisation as planetary bodies.

Medium missions also provide a route for Europe's participation in missions with international partners. The *Huygens* probe, whose cost of M€ 360 was of the order of a Medium mission, is a clear example of ESA participating as a minor partner. *Huygens* was the first landing of a spacecraft on the natural satellite of another planet and was able to answer questions about the origin of Titan's atmosphere, the thickest atmosphere of any moon in the Solar System and the only other body apart from Earth that has a thick nitrogen atmosphere, by examining isotopic ratios. It also provided part of the evidence for Titan's subsurface oceans via the identification of Schumann resonances in the atmosphere. ESA's participation in the *James Webb Space Telescope* is a prime example of where a Medium level participation will result in an enormous scientific return for ESA Member State scientists over a wide range of science themes.

Within Voyage 2050, there are many examples where scientific themes can be completely encapsulated within a Medium class mission. For example, and without indicating a priority, much work can be done on the foundations of quantum mechanics and general relativity by testing the equivalence principle and probing the structure of space-time. Another example from our recommendation is to probe the intergalactic medium in absorption, which will search for missing baryonic matter and examine the gas cycle in and around galaxies, exploring the role of the galactic environment on star formation. A Large mission would enable a mission to probe the intergalactic medium in emission and would reach a larger fraction of the hidden baryonic matter, but a Medium mission on this theme would still yield breakthrough science in this area.

Below we list science themes for Medium missions that arose from discussions within the Topical Teams and the Senior Committee. This list is separated into 14 themes that could be led by ESA within a typical Medium mission envelope and four themes where ESA could participate at the Medium mission level in other agencies' large missions. The list spans the full breadth of the ESA Science Programme, and demonstrates that the community has more than enough excellent ideas to fill as many Medium calls as could realistically fit into ESA's financial envelope. The list below is ordered roughly by Topical Team, and does not represent a scientific priority. In summary, Medium missions will continue to play an important role in ESA's Science Programme and can achieve breakthrough science with relatively modest envelopes.

3.1 ESA Led Medium Mission Themes

3.1.1 Magnetospheric Systems

Magnetospheric systems are ubiquitous in (exo)planetary systems. While there has been major progress regarding local physical processes, a magnetospheric system is more than the sum of its parts. Important questions such as "How is energy and matter transported in this system?" still need to be answered by studying entire magnetospheres as complex systems. This theme covers much of "the science behind space weather" and it thus has also a strong societal impact in terms of Earth's magnetosphere, and may become relevant to Mars' environment in the Voyage 2050 era in relation to astronaut safety and the protection of space infrastructure in Mars orbit.

A system-level approach combines multiple remote and *in situ* observations to understand how the interactions between neutrals, charged particles, and electromagnetic fields operate together to form the coupled magnetosphere-ionosphere-atmosphere-subsurface systems. The terrestrial magnetosphere is naturally most accessible for addressing this theme in a complete way. With the *SMILE* mission, it is expected that a new observational technique will become available for imaging dayside magnetospheric boundaries. Combining all the different images of aurora, energetic particle environment, and other boundaries are a new way to study global solar-terrestrial interaction. Another approach is a constellation at the magnetosphere-system level or constellation along targeted magnetic field lines to study energy transfer and partitioning in the coupled magnetosphere-ionosphere system. Plasma and field instrument packages on board probes to planetary objects such as Mars, Jupiter, and comets enable the study of different types of magnetospheric interaction, including interactions with induced magnetospheres. It further addresses fundamental questions of planetary evolution such as atmospheric escape over geological time scales.

International partners would enable a more comprehensive mission of any of the magnetosphere systems and mission ideas such as magnetospheric constellations, imagers, and planetary plasma probes are expected to be proposed to the next US Solar and Space Physics Decadal Survey.

3.1.2 Plasma Cross-scale Coupling

Wherever in the Universe a time-varying magnetic field in a plasma exists, there is also plasma energization. The key difficulty in understanding the plasma energization lies in the two-way nature of the intrinsic multi-scale physics of plasmas: processes on the large scales affect the small-scale physics and processes on the small scales affect the large-scale evolution of plasmas. The importance of understanding the multi-scale processes of plasma is expected to become a coherent theme of the plasma Universe in the Voyage 2050 era.

Multi-scale constellation missions in the near-Earth space and solar wind with dedicated plasma and field measurements to cover simultaneously different spatial and temporal scales is the next logical step after the successful *Cluster* and *Magnetospheric Multiscale (MMS)* missions. It will provide new insight into how the energization regions form and evolve that can be answered only by direct *in situ* measurement. Such knowledge allows a major step forward in our understanding of the fundamental plasma processes, such as shocks, turbulence, and magnetic reconnection, which are known to take place in many plasma environments throughout the Solar System as well as around compact objects and up to the largest structures in the Universe.

The required numbers and types of spacecraft depend on target observation regions and interested range of the spatial/temporal-scales, i.e. electron/ion kinetic/fluid scales and can construct a competitive mission within a Medium mission cost cap. Due to the growing interests on plasma cross-scale science from the international *in situ* plasma community, such as China, Japan and US, considering partnership is an effective approach for a realization of a further extensive plasma observatory mission, as has already been carried out by ESA with *Double Star*, and will be carried out with *SMILE*. A multi-point mission with interest in cross-scale science is expected to be proposed to the next US Solar and Space Physics Decadal Survey for consideration.

3.1.3 Solar Magnetic Fields

The magnetic field of the Sun dominates the total energy in the outer atmospheric layers, from the chromosphere and upward into the corona, and controls the phenomena that we observe there. Despite much progress over the last decades, determining the magnetic field in the outer atmosphere through polarimetry remains a significant challenge, as opposed to the field in the photosphere, which is routinely measured. Consequently, the study of the magnetic coupling and energy transport in the atmosphere, outer atmospheric heating, flares, and particle acceleration has so far relied only on indirect markers of the main driving cause of these phenomena.

Measuring polarization from space has several unique advantages compared to ground-based telescopes. Firstly, the lack of atmospheric distortions caused by Earth's atmosphere allows for continuous, constant and high-quality data from a large field-of-view, as evidenced by the success of photospheric magnetic field measurements by the SOT instrument on board *Hinode*. Secondly, space allows access to (E)UV diagnostics. Thirdly, space allows for highly efficient coronagraphs for studying the magnetic field in the extended corona.

A Medium mission focusing on a comprehensive determination of solar magnetic fields, from photosphere to corona, would deliver the data needed to distinguish the relative importance of, or even confirm or rule out, the various proposed mechanisms that aim to explain coupling, heating, destabilization, and particle acceleration in the solar atmosphere. Some example implementations are: A UV to IR telescope that focusses on the magnetic field in the chromosphere; an extreme-UV to IR coronagraph to study the large-scale magnetic field in the corona as seen off-limb; and an extreme-UV imaging polarimeter to measure the magnetic field direction in the corona as seen on disc.

3.1.4 Solar Particle Acceleration

A variety of active solar phenomena (e.g. flares, CMEs, nanoflares and jets) result in the acceleration of particles – both ions and electrons – to a wide range of energies. The acceleration mechanisms found in the solar atmosphere are most likely found in astrophysical sources throughout the Universe and, closer to home, the energetic particles generated by flares and CMEs can have a major impact on human systems as part of what we call space weather. Whilst a number of spacecraft have detected signatures of such acceleration using X-ray and gamma-ray instrumentation, limited wavelength ranges and imaging capabilities have resulted in limited understanding of the acceleration processes – in particular for the lower energy events and for ion acceleration.

Major questions that remain unanswered are: Which fraction of flare energy is given to energetic particles? What are the processes responsible for ion acceleration, and how do they differ from electron acceleration? How and where are the most energetic particles accelerated on the Sun?

RHESSI has started to reveal how the physics of particle acceleration can be explored using imaging spectroscopy. An ESA-led Medium mission with dedicated X-ray and gamma-ray imagers, spectrographs and polarimeters would allow for a determination of the energy distribution of accelerated electron and protons and precise localization of the acceleration sites as well as providing the direction and angular distribution of the accelerated electrons.

3.1.5 Solar Polar Science

The poles of the Sun have never been imaged directly. To fully understand some very basic solar properties a polar view is necessary. Polar observations are critical to investigating the operation of the solar magnetic dynamo, including why the magnetic field reverses every 11 years, as well as studies of the global mass-loss and radiation output of the Sun, and the generation of the fast solar wind. Observations of the polar magnetic field, solar oscillations and the sites from which the fast solar wind originates, from an orbital inclination on the order of 60 degrees to the ecliptic, have a significantly reduced geometrical foreshortening compared to ecliptic plane or even *Solar Orbiter* vantage points. Indeed, *Solar Orbiter* will provide the first glimpses of the polar regions, as a pathfinder to a dedicated polar mission. From a polar-orbiting platform, the heliospheric current sheet and the other steady and transient plasma and field structures that surround the Sun, roughly in its equatorial plane, can be properly observed circumventing the typical line-of-sight projections from observations in the ecliptic that currently hinder further progress. Measurements of the total solar irradiance and activity from the range of latitudes afforded by a polar mission will also help in interpreting observations of Sun-like stars.

3.1.6 Venus Geology and Geophysics

Although Venus has been visited by several orbiters, few landers, and even by aerostats, our knowledge of the planet's geology and interior structure is poor as compared to the other terrestrial planets and the Moon. Why Venus took an evolutionary path so different from the one of its twin planet (our Earth) is far from understood. Some myths regarding Venus, such as i) its lack of geologic activity, ii) the absence of water in its mantle, and iii) the missing plate boundaries, are all challenged today. New evidence for a geologically active planet has emerged from observations of variable SO_2 content recorded by *Venus Express* and hints of recent volcanism. Although Venus' atmosphere is dry, a dry atmosphere and crust/lithosphere do not imply a dry mantle. Volatiles such as water are mostly carried by planetesimals, not comets, so Venus' mantle may contain large quantities of water. It may well be that major plate boundaries/shear zones are simply invisible in the available data since deformed tectonic features on Venus are difficult to interpret as a consequence of the missing link to mantle processes.

The characterisation of the surface processes, past and ongoing, is therefore quite important for planetary science. Global mapping of the surface at a level of detail far superior to *Magellan's* is highly desirable, but it would provide only an incomplete picture if not accompanied by a precise determination of the internal structure. The core size and physical state, as well as the mantle viscosity and the crust-mantle interaction are essential to decipher its geological evolution, and understand the mystery of why Venus lacks a dynamo. Venus' moment of inertia, k_2 Love number and tidal phase lag are key measurements that a Medium mission to Venus must carry out to a sufficient precision to constrain the interior structure, tackling with the right data sets the adverse effects of the large thermal tides and the recently discovered irregularities of the rotation rate.

3.1.7 High Precision Astrometry

Astrometry has significantly contributed to our understanding of the Universe, from the smallest scales of planetoids in the Solar System to very distant quasars. ESA has a history of precision astrometry, beginning with the breakthrough mission *Hipparcos*, and we are currently experiencing major breakthroughs particularly in Galactic astronomy thanks to the global astrometric ESA space mission, *Gaia*. This mission is impacting the extent of our knowledge in many fields of astrophysics, ranging from exoplanets and star formation, to the formation and evolution of the Milky Way itself as well as in fundamental physics. The next steps in space astrometry could be either to improve by one order of magnitude the relative astrometric accuracy, or to extend global astrometry to a different wavelength domain, i.e. the near-IR.

High precision relative astrometry at the level of sub-µas can probe dark matter in galactic environments and the detection and full characterisation of the orbital architecture of exoplanetary systems with habitable planets orbiting the nearest stars to the Sun. Substantial technology developments in a number of critical areas would be needed in order to reach the highest required precision of 0.2 µas.

Global astrometry in the near IR as described in Section 2.2.2 would have a much broader impact as it would tackle various aspects of the above questions, as well as additional important open questions regarding the whole Milky Way ecosystem. Such a mission, which is of Large class given its scientific breadth, will be difficult to scale down to fit the Medium mission cost cap given the technological developments required for the near-IR detectors. However, all of its science objectives could be achieved with a Medium mission led by ESA with a substantial contribution from other partners. Among other possibilities, the US could contribute with the near-IR detector following a similar scheme as in the *Euclid* mission.

3.1.8 High Precision Asteroseismology

Asteroseismology is one of the most powerful tools for probing the structure of stars. It uses the variability of the light from the star produced by its pulsation modes to constrain the interiors of stars. Its final aim is to determine the physical properties and the internal structure of stars, such as how temperature, pressure, density, speed of sound, and chemical composition vary with radius. In the last decade, the research field of asteroseismology has experienced a revolution with the operation of several space missions whose main aim has been the detection of exoplanets, for example *Kepler*.

A Medium mission designed to carry out pure asteroseismology would characterise stars in a wider range of (relatively homogeneous) stellar environments such as dwarf galaxies or the Galactic bulge, as well as Red Giant Branch stars that are relatively close to the Sun. Such missions would provide key information on stellar physics that would allow testing of stellar evolution models, especially when 2-D and 3-D modelling become widely implemented. Furthermore, and in combination with *Gaia* and large ground-based spectroscopic surveys, they would provide new insights into the star formation history and different phases of the assembly of the Milky Way.

3.1.9 The Role of the Multiphase ISM in Star Formation and Galaxy Evolution

Understanding how star formation proceeds in galaxies remains one of the major goals in the theory of galaxy evolution. Observations of the interstellar medium (ISM) are key to deciphering the physical processes regulating star formation in galaxies. The physical processes that transform the overall galactic gas content, such as gas accretion and outflows, regulate star formation in typical nearby galaxies. The accreted gas from the outer regions in the form of ionized or partially ionized gas becomes neutral, cools, and increases its density as it is transported to the galactic inner regions, where it becomes molecular and forms stars, which themselves produce outflows that return material to the ISM. Studying the multiphase structure of the ISM and its evolution will reveal the underlying physical phenomena that set star formation rates and efficiencies.

The far-infrared is rich in atomic, ionized, and molecular spectral lines that can directly constrain the physical properties of the different ISM phases and reveal the physical conditions at the transitions between the warm ionized medium, the cold neutral medium, and the self-gravitating cores. The ability of previous far-infrared missions to disentangle the physical properties and the kinematics of the multi-phase ISM has been hampered by their poor spectral resolution and limited spectroscopic mapping capabilities. Far-IR missions with 2-meter class telescopes equipped with multi-beam heterodyne arrays and high resolution ($> 10^6$) spectrometers, can provide large-scale 3D-maps of velocity resolved lines of the dominant gas coolants (e.g. OI, CI, CII, and NII) in our Galaxy and nearby galaxies. The combination of these large-scale maps of key spectral lines will fully characterise the multiphase ISM contributing to a better understanding of the processes that govern star formation in galaxies.

3.1.10 Probing the Violent and Explosive Universe at High Energies: Accretion by Compact Objects and Astroparticle Physics

The physics of accretion, acceleration and high-energy particles involves phenomena of great relevance to fundamental physics and in understanding how the Universe was born and how it evolves. Furthermore, multi-messenger astronomy calls for an enhanced synergy between electromagnetic and gravitational wave events. Space-based X-ray and gamma-ray detectors, with improved capabilities with respect to the current generation, such as high-sensitivity, large field-of-view detectors, and/or sensitive keV–MeV spectropolarimetry based on new technologies, will allow us to detect and investigate the most extreme and violent physical phenomena in the Universe and provide a powerful and fundamental synergy with gravitational wave astronomy. Unresolved questions related to explosive nucleosynthesis in stellar explosions, the origin of cosmic rays, accretion and ejection mechanisms in stellar and supermassive black holes and neutron stars, could be solved with missions with these capabilities, as well as boosting the discovery rate of known and unknown rare classes of transient sources throughout the Universe.

3.1.11 Space (Radio) Interferometry with Ground-based Telescopes for Probing the Physics of Black Holes.

The first images of the close environments of a black hole obtained in recent years with the *Event Horizon Telescope's* observations of the nucleus of M87 offered the first glimpse of the power of long baseline, high frequency radio interferometry to deliver remarkable images close to the event horizon. Significantly improving the angular resolution now requires space-based dishes and receivers, since the atmosphere prevents a move to higher frequencies and the existing baselines cover most of the Earth's diameter. Space radio interferometry would increase the length of available baselines significantly, allowing image quality improvements of factors of at least several over what is currently possible, providing better images of the supermassive black holes at the heart of the Milky Way and M87, and enabling imaging of the black hole nuclei of several other nearby massive galaxies.

3.1.12 Mapping the Cosmic Structure in Dark Matter, Missing Baryons, and Atomic and Molecular Lines

The progress in our understanding of cosmology, such as the physical nature of dark matter and dark energy and the formation and evolution of structure formation in the Universe, has been driven mainly by mapping observations of the large-scale distribution of matter. This mapping has traditionally been done by measuring locations of galaxies in the optical and near infrared bands. The *Euclid* mission will use optical and near-infrared cameras and spectrographs to map the distribution of galaxies out to a redshift, z, of two.

In recent years, new methods have emerged for mapping the large-scale structure of the Universe using detectors in microwave bands. Using the cosmic microwave background (CMB) as a ‘backlight’, we can map all the mass in the Universe, including dark matter, via deflection of the path of CMB photons by gravitational lensing of the intervening matter. Scattering of CMB photons by electrons in ionized gas enables us to map the distribution of diffuse baryons in the cosmic web. This technique offers the powerful new observational probe of the “missing baryons”, which is too diffuse to emit X-ray photons detectable by the existing or planned missions. In addition, scattering by hot gas distorts the blackbody spectrum of the CMB, which enables new measurements of the temperature of gas without X-ray spectroscopy. A Medium mission with a modest size telescope and a large focal plane containing microwave sensors at multiple frequencies, that cannot be observed from the ground, this “CMB as a backlight” technique offers an entirely new census of the matter in the Universe – both dark and diffuse matter – that is difficult to observe by other means.

The other new technique, called “line intensity mapping”, allows for mapping the cosmic structure in 3D. Unlike the traditional method used by *Euclid*, for which we measure the distribution of resolved galaxies, the key idea for the intensity mapping is that we do not resolve individual sources of light, but we use all photons as tracers of the underlying matter distribution. This “no photons left behind” philosophy enables a new methodology for mapping the Universe. Various atomic and molecular transitions, such as carbon lines and carbon monoxide lines, can be used to map the cosmic structure in a wide range of redshifts up to the epoch of reionization, $z{\sim}8$ (see Figure 7). This new method is enabled by the development of on-chip low-resolution spectroscopy, which can be deployed in a Medium mission in the Voyage 2050 timescale. Space offers the access to frequencies (thus redshifts) that cannot be observed from the ground, as well as to an all-sky survey with the exquisite control of calibrations that is not available for ground-based observations.

Both Medium missions have a potential to transform our understanding of the cosmic structure formation in the previously explored range of redshifts and parameter space. It may be possible to implement these two techniques into a single Medium mission.

3.1.13 Probing the Large Scale IGM in the Local Universe through Absorption Lines in the UV and X-rays

Current theories of structure formation predict the existence of intricate filaments connecting galaxies known as the 'cosmic web'. A large fraction of the baryons are not in stars but in the warm/hot, diffuse intergalactic medium (IGM) that fills extended galaxy halos, galaxy groups, galaxy clusters, and the cosmic web. Galaxies accrete matter from the intergalactic medium and enrich it with metals by blowing winds out into space. Galaxy formation and evolution is therefore believed to be affected by the intergalactic medium, and vice-versa.

The warm and hot intergalactic medium are observable in UV and in X-rays. Missions in the soft X-rays and in the UV with moderate effective area telescopes have the potential to probe the diffuse gas of the intergalactic medium and of the cosmic web. To this end, challenging UV wide-field ($1\ \mathrm{arcmin}^2$) spectroscopic imaging capabilities with spectral resolutions of 2000–4000 or large effective area ($1000\ \mathrm{cm}^2$) X-ray spectrographs with spectral resolutions of about 10 000, need to be developed. These will also provide important information on the gas cycle in and around galaxies and on the role of the galactic environment in quenching star formation. An ESA contribution to a future major NASA X-ray mission such as the proposed *Lynx* mission concept would also achieve many of these scientific goals.

3.1.14 Quantum Mechanics and General Relativity

Despite extensive testing of the fundamental theories of quantum mechanics and general relativity, no violations have yet been observed of their predictions in experimental situations. However, the search for an overarching theory which is applicable in both regimes and which can be verified experimentally has so far failed. This situation leaves us unable to describe the force of gravity in quantum terms and many processes in the very early Universe lack a theoretical foundation. The incompatibility of these two, well-tested, fundamental theories is a fundamental obstacle to the further understanding of our Universe.

Space provides many attractive aspects for experiments exploring quantum mechanics or general relativity in an effort to further our understanding of this problem. Test particles can be observed in three-dimensional free motion, observations can be made undisturbed over long distances and long times, the gravitational potential in which the experiment takes place can be varied by orbital position and local noise sources can be much reduced compared to ground-based experiments. For many experiments in this area of science, the instrumentation is not large and can be contained within the envelope of a Medium mission. Given the commonality of platform requirements between many of these experiments it is possible to envisage single Medium missions carrying multiple, separate instruments examining different aspects of the problem.

In the absence of a widely agreed overarching theory, precision tests of quantum mechanics and general relativity separately provides a route for progress by experimentally disproving alternative theories or by limiting the parameter space in which they can exist. These precision tests require technology at the very limit of current sensitivity and sophistication, in some cases using cold atom technology in other cases using highly optimised classical mechanics and optics with quantum sensors. In all cases, the instrumental performance will require programmes of ground-based demonstration and space readiness development as for other disciplines.

The following topics were discussed by the Topical Team as representing possible experiments in this area of fundamental physics:

- Tests of quantum mechanical wave function collapse for different mass test particles.
- Tests of the Equivalence Principle.
- Tests of quantum coherence over large distances.
- Tests of gravitational redshift.
- Improved measurements of the PPN parameters.

As the theoretical efforts to resolve this fundamental problem develop, it may transpire that new and completely unexpected ideas for decisive experimental tests in space will emerge. It is easily possible that these will fit within the framework of a Medium mission and therefore benefit from the frequent opportunities for new mission ideas within the Voyage 2050 Programme.

3.2 ESA Medium Contributions to International Missions

3.2.1 Contribution to a Mission to the Ice Giants

The planetary systems at Uranus and Neptune, comprising the planet's interiors and atmospheres and their planetary magnetospheres, rings and moons are complex interconnected systems yet they remain largely unexplored. Despite their similarities in terms of mass, radius, insolation and atmospheric composition, Uranus and Neptune have significant differences concerning their tilt axis, their internal flux, and their rings and moons. This implies different evolutions, potentially because of early giant impacts. The only flybys of these planets and planetary systems, by *Voyager 2* in 1986 and 1989, respectively, returned very important measurements, but constitute only glimpses of what needs to be uncovered. A mission towards Uranus and/or Neptune is a necessary step in the exploration of the Solar System, filling the current, huge, knowledge gap, and allowing a thorough understanding of these planets and, ultimately, the formation/evolution of the Solar System and other exoplanetary systems.

An orbiter, around Uranus or Neptune, with the appropriate instrumentation for performing a detailed characterisation of the atmosphere, interior, magnetosphere, moons and rings, exceeds the envelope of a Large mission. A partnership with another agency is an absolute necessity. One possibility would be a Medium class contribution in a mission led by an international partner. It could for instance consist of an atmospheric entry probe, a Triton lander, or some key instrumentation. The partnership for the *Cassini-Huygens* mission, for which ESA provided the *Huygens* probe, had a major impact for the whole European planetary science community, certainly as high as (or higher than) the impact of an ESA-led Medium mission. The joint ESA-JAXA *BepiColombo* mission *en route* for Mercury is another example of a fruitful and successful collaboration. A similar impact is foreseen for an icy giant orbiter.

As stated already in 2012 when defining the L2 and L3 Large missions within Cosmic Vision, it is foreseen that "*The whole planetology community would be involved in the various aspects of this mission, including physics* *of the interior, atmospheric and surface sciences, plasmas physics and dynamics*"[1]. In view of its importance, it is strongly recommended that every effort is made to pursue this theme in order to set up a cooperation scheme on a future mission to the Ice Giants.

3.2.2 Contributions to the NASA LUVOIR, Origins, HABEX, or Lynx Concepts

The next generation of large space observatories – all of which are well beyond the financial envelope of an ESA Large mission – will tackle a wide range of very important open problems in astrophysics. This is why contributions at the level of an ESA Medium mission to such a large-size space telescope are of great significance and value to the ESA programme in the time frame of Voyage 2050. Four mission concepts for large space observatories are currently being considered as part of the Astrophysics Decadal Survey in the USA, involving large X-ray, UV, optical or infrared telescopes. A contribution to the observatory concept that will emerge from the decadal survey could follow a similar scheme to the ESA/NASA collaboration in *HST* and *JWST*, and consist of a combination of an ESA contribution and/or nationally funded instruments.

A contribution to *LUVOIR* will offer a unique opportunity for the community to have access to the UV, a crucial wavelength range that will not be accessible after *HST* is decommissioned. Instrumentation in UV provided by the ESA Member States will allow the study of galaxy evolution, interstellar medium, star formation and stellar evolution, exoplanets atmospheres and Solar System objects. In the visible, mid and far-IR, a contribution to *Origins* and *HabEx* would provide access to a large space facility to study the formation of galaxies, stars and planetary systems as well as the characterisation of exoplanet atmospheres. A contribution to *Lynx* would offer access to very high spectral resolution X-ray instrumentation with large effective area and exquisite spatial resolution over a large field of view, offering substantial improvements over what ESA *Athena* will provide in these areas.

3.2.3 Contribution to NASA Interstellar Probe concepts

The stellar-interstellar interaction remains largely unknown, even in our heliosphere, because the boundary between these regions hosts a complex interaction with highly variable and turbulent mixture of plasmas, neutrals, and dust with variable background radiation. The only missions to have probed this region *in situ* are *Voyager 1* and *Voyager 2*, currently 153 and $127\ \mathrm{AU}$ from the Sun respectively. The boundary has also been probed remotely in energetic neutral atoms by the *Interstellar Boundary Explorer (IBEX)* and *Cassini*.

A dedicated Interstellar Probe equipped with appropriate instruments would for the first time truly unveil the properties of the interstellar medium and the nature of its interactions with the heliosphere, which shapes our Solar System. The exploration of the interstellar medium with an Interstellar Probe travelling up to $\sim 200\ \mathrm{AU}$ represents a very compelling science case with a unique *in situ* observatory and a high potential for discoveries to answer unsolved questions on the local interstellar medium and more generally on the formation of astrospheres.

The great challenge for a mission to the interstellar medium is the requirement to reach $200\ \mathrm{AU}$ as fast as possible and ideally within 25-30 years. The necessary power source for this challenging mission requires ESA to cooperate with other agencies. An Interstellar Probe concept is under preparation to be proposed to

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[1] **Report of the Senior Survey Committee on the Selection of the Science Themes for the L2 and L3 Launch Opportunities in the Cosmic Vision Programme** (October 2013) p17. Available at **http://sci.esa.int/ssc_report**.

the next US Solar and Space Physics Decadal Survey for consideration. If this concept is selected, a contribution from ESA bringing the European expertise in both remote and *in situ* observation is of significance for the international space plasma community, as exemplified by the successful joint ESA-NASA missions in solar and heliospheric physics: *SOHO*, *Ulysses* and *Solar Orbiter*.

3.2.4 Contributions to Missions Focused on Origins of the Solar System

The key to understanding the composition of the material from which the Solar System formed is to identify bodies that have been relatively unaltered since their formation. The ultimate objective of this theme is therefore to return samples of pristine cometary material to the Earth for the first time. A comet sample return mission is the next step for Solar System small body exploration, with far wider implications for planetary science and astronomy. It is also a natural next step for ESA, following its lead in flyby (*Giotto*), rendezvous and landing (*Rosetta*), and fast rendezvous (*Comet Interceptor*) cometary missions. Samples of dust from a comet's coma were obtained by the *Stardust* mission and returned to Earth in 2006 but were significantly modified by the space environment and capture into aerogel. A pristine sample must be obtained by drilling to extract a core from 1m below the surface, or alternatively a core from a large surface boulder, and must not be mechanically or thermally altered in the process. A mass of at least 1 kg, and preferably around 10kg is thought to be required. While solution of the technological challenges can be envisaged for a mission to collect cryogenic sub-surface samples from a comet in the time-frame of Voyage 2050 (see Section 4.3), the budget is most likely to be well in excess of that of a Large mission. Descoping to an *in situ* mission would however change the focus to understanding of cometary processes and evolution, and could not achieve the primary objectives of this theme. The ability to select, prepare and analyse micro-samples using state-of-the-art instruments, unconstrained by mass and power considerations, to repeat and evolve experiments based on the results obtained, and to retain legacy samples for future advances, far exceed the capabilities of *in situ* missions, even anticipating advances in instrumentation in the next decade.

An alternative way to investigate origins is through *in situ* exploration of giant planet atmospheres. The gas giants, Jupiter and Saturn, are believed to have formed rapidly to capture their hydrogen and helium envelopes, trapping pristine material from the epoch of Solar System formation. Measuring their heavy elements, noble gas and isotope abundances will reveal the physico-chemical conditions of the interstellar medium in the location and epoch of Solar System formation, the processes that led to formation of planetesimals, the delivery of heavy elements to the giant planets atmospheres and would help decipher evidence of possible giant planet migration. *In situ* measurements at Saturn especially, would complement *Galileo's* past science investigation at Jupiter and reveal key information pertaining to the solar nebula chemical, thermal and dynamical evolution. An ESA *in situ* probe reaching 10 bars, to one of the gas giants, could be envisioned as a Medium class contribution to a joint mission with an international partner.

4 Technology Development Recommendations

In discussing the Large mission themes, the Senior Committee identified several areas where the science return would be outstanding, but the technology would not reach maturity by the timeframe of Voyage 2050. This list describes those areas where the Senior Committee recommends ESA to invest in technology development soon, so that missions addressing these themes could become a reality in the second half of this century.

4.1 Cold Atom Interferometry

4.1.1 A Development Programme for European Cold Atoms in Space

Europe has considerable strengths in cold atom science and funded terrestrial programmes are already running in Germany, France, Italy and the UK. These programmes aim at both fundamental science and terrestrial applications but do not target space applications. Nevertheless, these programmes aim to reduce the size, mass and power requirements, developments which also facilitate use in space. Two requirements must be met to enable cold atom technology to be realistically considered for space science missions: (1) the technology must already be at Technology Readiness Level (TRL) 5 or 6 (see Definitions of Technology Readiness Level), and (2) the demonstrated performance must be superior to that of classical technologies. Since the performance of cold atom technologies in atomic clocks vastly exceeds classical techniques it is reasonable to start with a space qualification programme for an atomic clock, a programme that will also qualify 60-70% of the subsystems needed for atom interferometry when that technique demonstrates its competitiveness. A possible programme is outlined below.

1. The programme should choose an atomic species at the outset and strontium is recommended here. This is despite European expertise using rubidium because many of the current ground-based projects (*AION*, *MAGIS*) use strontium and so their technical developments and lessons learnt, will allow on-ground tests of performance, meeting one of the serious requirements outlined above.
2. It is proposed to base the programme on the development of an atomic clock for eventual flight either on a free flying satellite, or on the *ISS*, with science goals similar to *STE-QUEST*. The objective would be to develop all subsystems to a level of TRL 6 before a choice on flight profile is made. Close coordination with any relevant programmes in the Directorate of Technology, Engineering and Quality or the Directorate of Human and Robotic Exploration would be mandatory but the science aims should remain under the authority of the Science Directorate.
3. The programme could follow a logical pattern: definition of science requirements, system design of payload and platform to meet science requirements, audit of subsystem technology readiness, space qualification of lowest TRL subsystems, identification and evaluation of subsystem suppliers, project review of updated technical readiness, review of flight opportunities (*ISS* , Free flyer-Small, Fast, or Medium mission), and response to Science Directorate Call for Proposals. During all these stages, keeping track of the evolving performance of ground-based experiments would be required.
4. This programme would only require a modest investment to start with, growing as the various targets are delivered and confidence in the performance increases.

4.1.2 Potential Science Outcomes

A successful programme following principles similar to those outlined above might deliver: gravitational wave detectors in new wavebands and potentially with fewer space components, detectors for dark matter candidates, sensitive clock tests of general relativity, tests of wave function collapse in quantum mechanics, better definition of some planetary interiors, and new navigation and attitude control systems for Solar System exploration.

4.2 X-rays in High Resolution

4.2.1 Enabling X-ray Interferometry for the Future

X-ray wavelengths are a thousand times shorter than optical/near-infrared (NIR) wavelengths. This means that an X-ray interferometer (XRI) on a single spacecraft can achieve angular resolution better than any current optical/NIR interferometer. Extreme physics is often related to high density and compact objects, i.e. small scales. High angular resolution enables direct imaging of physics at the extremes: black holes, accretion onto compact objects, and compact binaries.

It was thought originally that formation flying would be required to achieve XRI due to the long focal lengths. However, the development of a ‘telephoto’ mirror arrangement means that a 1–2m baseline XRI can be achieved in a single-spacecraft design. To date X-ray fringes have been demonstrated in the lab over very small baselines (1mm). Developing this to baselines a thousand times longer will require a European XRI testbed where the accuracy of surface flatness, location and orientation, as well as exquisite thermo-mechanical control can be developed. Such a testbed could start from the experimental work of Cash et al.[2] two decades ago and develop to include the telephoto design in the optical layout. A sufficiently small and brilliant X-ray source also needs to be realized with either a synchrotron source or the telephoto set-up in reverse to set up close-to-parallel light-rays.

Following a successful ground testbed, a space demonstration on a small satellite, demonstrating 1 mas angular resolution at high TRL, might be considered. Interesting science is achievable at this resolution: stellar coronae and outflows in nearby Active Galactic Nuclei can just be resolved, and differential astrometry of bright sources could provide µas-scale information for certain cases. Ultimately, the combination of X-ray interferometry and highly advanced thermo-mechanical control techniques may have broader applications and benefits outside of XRI.

4.2.2 Potential Science Outcomes

The main science case for this technology is high-resolution imaging of the close vicinity of black holes: measurement of black hole mass and spin and testing of space-time geometry by directly imaging emitting gas and testing accretion physics by directly measuring gas streams (resolved images and spectra). The scientific and public impact of this science is enormous, as recently demonstrated with the *Event Horizon*

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[2] Cash, Shipley, Osterman and Joy (2000) **Laboratory detection of X-ray fringes with a grazing-incidence interferometer.** Nature 407, 160-162, doi: 10.1038/35025009.

Telescope image of the shadow of a black hole. Additional science includes imaging of stellar coronae and exoplanet shadows, and resolving X-ray binary orbital scales.

4.3 Developments for future Planetary Missions

Two common themes have emerged from the analysis of the submitted White Papers in planetary science, namely the need for better power sources to enable the exploration of the outer Solar System, and the huge benefits to be derived from sample return missions from planets and small bodies. Both of these developments pose problems for the current ESA Science Programme but it was evident to the Senior Committee that overcoming those challenges will release a number of science areas for future important planetary missions having large scientific and public appeal.

For terrestrial planets, sample return provides a unique way to gather knowledge about the geological processes that shaped planetary surfaces. For comets, sample return would provide crucial information on rock, ices and organics formed in the earliest stages of Solar System formation or even pre-dating it. The scientific relevance of bringing back to Earth samples of pristine cometary material, collected without alteration and stored at cryogenic temperatures clashes with the technological difficulty of collecting and storing without contamination ice cores of sufficient mass (1 kg minimum). Returned samples allow the application of advanced analytical techniques, only possible in terrestrial laboratories that address fundamental questions on the origin and evolution of our Solar System, interstellar material from which it and other planetary systems formed, and the origin of that material in the late stages of stellar evolution. *In situ* analysis, even if carried out with the most advanced instrumentation that can be reasonably hosted on a space probe could only give partial if not ambiguous answers. Given the undisputed relevance of a comet sample return mission, advances in the technology of collecting and storing cryogenic samples of cometary ices is highly recommended in view of future missions.

4.4 Propulsion for Reaching High-Heliographic Latitudes

A White Paper in Solar System sciences proposed reaching solar polar orbits to investigate the solar polar region. The required orbit may reachable by using electric ion propulsion or solar sails. A solar sail option would require a significantly larger sail than has been flown so far, and requires technology development and testing.

5 Summary and Closing Remarks

The recommendations made here by the Senior Committee are the result of a significant community effort, projecting forward the likely development of space science and technology a decade or more in the future. The Senior Committee, together with five Topical Teams, has analysed the enormous body of outstanding science brought forth by the community in the form of almost 100 White Papers. The Senior Committee has arrived at the recommendations through consensus, after lively and productive debate. The analysis has identified new technologies that are emerging and gaps in which developments will be necessary to achieve the better understanding of our Universe that is the ultimate goal.

In a number of cases, the Senior Committee was restricted in its recommendations by the limitations of the Programme. The restriction of ESA missions to non-nuclear sources of power severely limits the ability of the ESA Science Programme to address important scientific goals in more distant and dimly-lit regions of the Solar System, for example beyond Saturn and near the poles of planetary bodies. The Senior Committee is aware of technology developments within Europe and wish to clearly highlight that the lack of our ability to utilise such power and heat sources on future missions will continue to limit the capacity of ESA's Science Programme. Secondly, the task of the Senior Committee was to identify and recommend themes at the very forefront of Space Science. Many of the scientific themes we identified would have led to breakthrough science but were beyond the envelope of a Large mission. If ESA wishes to remain competitive on the world stage of Space Science beyond Voyage 2050 then we encourage the Science Programme Committee and ESA Member States to consider a modest increase to the Large mission cost envelope.

The ESA Science Programme has achieved many, high quality scientific advances over the past decades and the format of Large, Medium and Small missions has been effective in distributing resources among the various scientifically determined goals. The Senior Committee believes that the recommendations presented in this document will help continue the success of this programme.

Appendix A Organisation of Voyage 2050

1. Process

The process began with the appointment of the chair of the Senior Committee, Linda Tacconi (Max Planck Institute for Extraterrestrial Physics, Garching, Germany) and co-chair Christopher Arridge (Lancaster University, UK) followed by a selection process to define the rest of the Senior Committee membership. In selecting the committee, particular attention was paid to the scientific breadth and expertise, gender and geographic diversity of the members and the distribution of Member States represented in the committee. This committee was established in December 2018 and the first Senior Committee meeting was held in February 2019 at the European Space Research and Technology Centre (ESTEC), The Netherlands to establish the working procedures.

Such an ambitious undertaking as Voyage 2050, which affects European space science for decades, can only be implemented based on an open consultation of the broad scientific community interested in Space Science, and ideally involves as many members of the scientific community as possible. In this spirit, the Senior Committee decided on a two-pronged approach. The first was to issue a Call for White Papers, through which the community was invited to submit their ideas for the science themes that the Science Programme should address following the launch of *Athena* and *LISA*. The second was to issue a Call for Membership of Topical Teams to ensure the broadest possible peer support and involvement, and to make available to the Senior Committee the broadest possible scientific expertise to analyse the White Papers. This call gave the possibility to any scientist working in Europe, with a strong preference for early career scientists, to participate in the process and inform the recommendations of the Senior Committee. The table below highlights important dates in the Voyage 2050 timeline. It was decided at the first Senior Committee meeting that no Senior Committee member should lead or participate in any White Paper and that Topical Team members may participate in White Papers, but should not lead, and should recuse themselves during any discussions of White Papers for which they are co-authors.

December 2018	Senior Committee Established
February 2019	First Senior Committee meeting
4th March 2019	Issue of Calls for White Papers and Membership of Topical Teams
6th May 2019	Topical Team application deadline
5th August 2019	White Paper deadline
October 2019	Madrid Community workshop
January 2020	ESTEC workshop for Senior Committee and Topical Teams
February 2020	Deadline for Topical Team reports for the Senior Committee
Spring 2020	Face-to-face Senior Committee meeting cancelled due to COVID-19 pandemic
Autumn/Winter 2020	Initial planned deadline for submission of this report
May 2021	Revised deadline to account for delays due to COVID-19 pandemic

Topical Teams were set up during the summer of 2019 leading up to a workshop in Madrid in October 2019, where a broad selection of authors were invited to present their White Papers. It was emphasised that the invitations to present were not any form of pre-selection but deliberately chosen to highlight the range of scientific ideas. The Topical Teams started their work at the Madrid workshop and continued through the autumn and winter of 2019/2020, including a workshop at ESTEC in January 2020 and concluding with their final reports to the Senior Committee in February 2020, as COVID-19 began to take hold world-wide. A planned face-to-face meeting of the Senior Committee early in the spring of 2020 was cancelled due to travel restrictions and health and safety concerns. The Senior Committee continued working via regular videoconferences throughout the rest of the 2020 and early 2021. Although the Senior Committee was able to complete the three sets of recommendations working via videoconference during the COVID-19 pandemic, the committee could not maintain the original, ambitious schedule for the process with this mode of working.

2. Topical Team selection

The Call for Topical Teams requested a brief two-page curriculum vitae (CV) and two-page motivational statement from each candidate, where the motivational statement provided the opportunity for candidates to explain why they considered themselves suited for membership of a Topical Team. Early career scientists were specifically encouraged to apply. The Call specifically requested that the motivational statement discuss notable achievements such as science policy experience, significant publications, development of scientific instruments, etc. In addition, candidates were invited to select from a set of scientific expertise keywords (reproduced in Appendix E) developed by the Senior Committee. These keywords assisted the Senior Committee in allocating candidates to individual Topical Teams and in assessing the expertise balance within these teams. Candidates could also include additional keywords if their expertise was not included in the default list. ESA and the Senior Committee received an overwhelming response to this Call with 218 scientists from 18 Member States submitting an application. ESA resources for about 50 Topical Team members were available, leading to an oversubscription factor of more than four.

To select the final Topical Team members, each application was scored (on a scale 1-5) by (typically) three Senior Committee members with appropriate expertise in the field of the candidate. Disparities between scores were highlighted by calculating the range in the scores among the three Senior Committee members and disparities investigated through discussion or additional scoring from a fourth committee member. At this point scores were analysed to search for evidence of scoring biases by country, gender, age, and years since PhD and years in the field. Figure 8 shows the mean scores separated by gender and career stage. No evidence of significant bias in gender or country was identified but there was some evidence of an upward trend in mean score with age and career stage. However, this did not give the Senior Committee significant cause for concern.

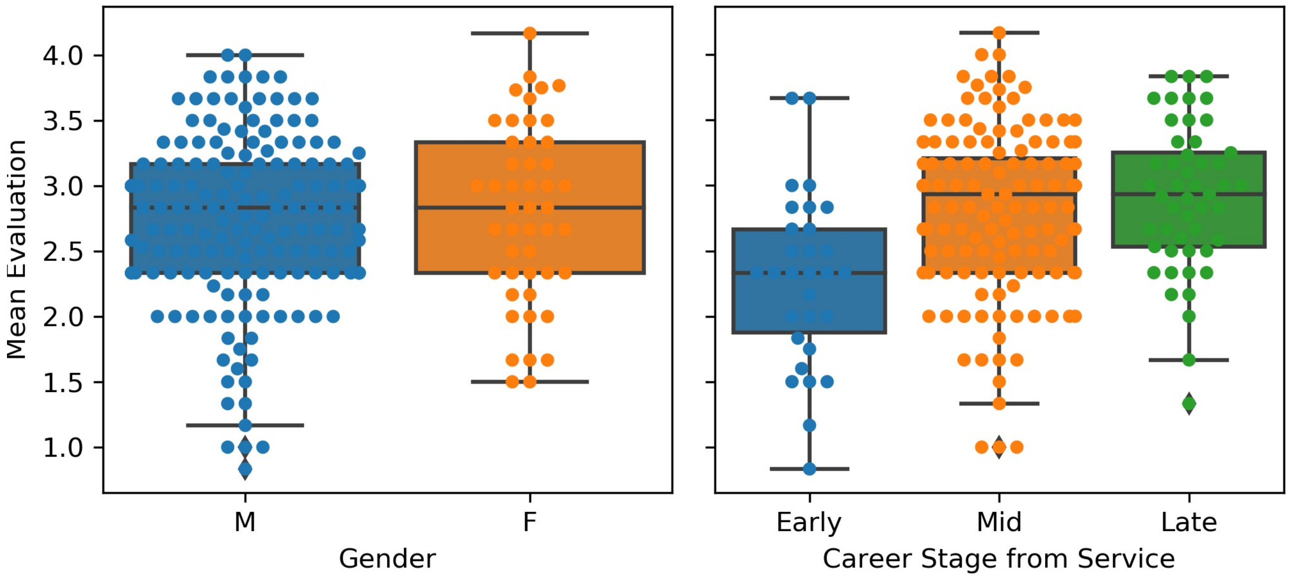

Figure 8: Mean Topical Team application evaluations with gender (left) and career stage (right). The overlaid box-and-whisker plots highlight the median and lower/upper quartiles of the mean evaluations plus the range. Early career was defined as less than 10 years in the field (from start of PhD studies where relevant), mid career was defined as 10 to 25 years in the field, and late career was more than 25 years.

The Senior Committee used these mean scores to generate a short-list of candidates. Keywords were then used to perform preliminary selections to cover the range of expertise required to assess the White Papers. This was carried out in two Senior Committee breakout groups – one in heliophysics/planetary science and one in astrophysics/cosmology/fundamental physics. With a draft Topical Team pool selection, the keywords were used to broadly group candidates into Heliophysics, Planetary Science, Astrophysics, Exoplanets and Fundamental Physics to check the appropriate balance of expertise from the relatively fine-grained keyword self-categorisation. These final Topical Team selections were examined for evidence of bias in gender, career stage and country to search for evidence of leaky pipelines. Our findings were that 1) proportions of Topical Team members from larger Member State countries decreased during the selection process in favour of smaller Member States; 2) our gender balance improved following selection (the proportion of selected female Topical Team members was larger than the applicant pool); and 3) the proportion of mid-career scientists decreased at the expense of the proportion of early career scientists (less than 10 years since PhD/starting in the field).

The Senior Committee decided on five Topical Teams:

1. Solar and Space Plasma Physics
2. Planetary Science
3. Galaxy, Star and Planet Formation and Evolution; Astrochemistry and the ISM
4. The Extreme Universe, including Gravitational Waves, Black Holes, and Compact Objects
5. Cosmology, Astroparticle Physics and Fundamental Physics

See Appendix C for the membership of each Topical Team and Section 1.2 for a detailed description of the scientific breadth of each Topical Team.

The Topical Teams were deliberately broadly defined to facilitate discussion and interaction. For example, the Senior Committee considered splitting the Planetary Science team into two, although it was one of the teams with the most White Papers. Similarly, we considered a separate Topical Team to consider exoplanets, or placing exoplanets within the Planetary Science Topical Team, however a pragmatic choice was made based on the methods used to study exoplanets.

Appendix B Membership of the Senior Committee

Linda Tacconi (Chair) Max Planck Institute for Extraterrestrial Physics, Garching, Germany		**Christopher Arridge** (Co-Chair) Lancaster University, United Kingdom
Alessandra Buonanno Max Planck Institute for Gravitational Physics, Potsdam, Germany	**Mike Cruise** Retired, United Kingdom	**Olivier Grasset** University of Nantes, France
Amina Helmi University of Groningen, The Netherlands	**Luciano Iess** Sapienza University of Rome, Italy	**Eiichiro Komatsu** Max Planck Institute for Astrophysics, Garching, Germany
Jérémy Leconte CNRS/Bordeaux University, France	**Jorrit Leenaarts** Stockholm University, Sweden	**Jesús Martín-Pintado** Spanish Astrobiology Center (CAB), Madrid, Spain
Rumi Nakamura Space Research Institute, Austrian Academy of Sciences, Austria	**Darach Watson** University of Copenhagen Denmark	

Appendix C Membership of Topical Teams

1. Topical Team 1: Solar and Space Plasma Physics

Co-Chairs	
Jorrit Leenaarts Stockholm University Sweden	**Rumi Nakamura** Space Research Institute, Austrian Academy of Sciences Austria

Members		
Johan De Keyser Royal Belgian Institute for Space Aeronomy Belgium	**Ineke De Moortel** University of St Andrews United Kingdom	**Lyndsay Fletcher** University of Glasgow United Kingdom
Dominique Fontaine CNRS - Laboratoire de Physique des Plasmas France	**Richard Harrison** Rutherford Appleton Laboratory United Kingdom	**Benoit Lavraud** Institut de Recherche en Astrophysique et Planétologie France
Hans Nilsson Swedish Institute of Space Physics Sweden	**Jan Soucek** Institute of Atmospheric Physics, Czech Academy of Sciences Czech Republic	**Francesco Valentini** University of Calabria Italy
Tom van Doorsselaere KU Leuven Belgium		

2. Topical Team 2: Planetary Science

Co-Chairs	
Olivier Grasset University of Nantes France	**Luciano Iess** Sapienza University of Rome Italy

Members		
Feargus Abernethy The Open University United Kingdom	**Benjamin Charnay** LESIA, Observatoire de Paris France	**Mohamed Ramy El-Maarry** Birkbeck, University of London United Kingdom
Jessica Flahaut CNRS - Centre de Recherches Pétrographiques et Géochimiques France	**Caroline Freissinet** LATMOS (Laboratoire Atmosphères, Milieux, Observations Spatiales) France	**Antonio García Muñoz** Technische Universität Berlin Germany
Antonio Genova Sapienza University of Rome Italy	**Simon F. Green** The Open University United Kingdom	**Benoit Langlais** Laboratoire de Planétologie et Géodynamique France
Matteo Massironi Università degli Studi di Padova Italy	**Alessandro Mura** Institute for Space Astrophysics and Planetology National Institute for Astrophysics, Rome Italy	**Gabriel Tobie** LPG, CNRS University of Nantes France
Josep M. Trigo-Rodriguez Institute of Space Sciences (CSIC/IEEC) Spain		

3. Topical Team 3: Galaxy, Star and Planet Formation and Evolution; Astrochemistry and the ISM

Co-Chairs		
Amina Helmi University of Groningen The Netherlands	**Jérémy Leconte** CNRS/Bordeaux University France	**Jesús Martín-Pintado** Spanish Astrobiology Center (CAB), Madrid Spain
Members		
Lars A. Buchhave DTU Space, National Space Institute Technical University of Denmark	**Karina Caputi** Kapteyn Astronomical Institute University of Groningen The Netherlands	**Heather Cegla** University of Geneva Switzerland
Elodie Choquet Laboratoire d'Astrophysique de Marseille (LAM) France	**Lucas Labadie** University of Cologne Germany	**Xavier Luri** Institut de Ciencies del Cosmos - Universitat de Barcelona Spain
Stephane Mathis CEA/DRF/IRFU/Department of Astrophysics - AIM Laboratory France	**Andreas Quirrenbach** Landessternwarte, Zentrum für Astronomie der Universität Heidelberg Germany	**Alexandre Santerne** Aix-Marseille University / Laboratoire d'Astrophysique de Marseille France
Antonella Vallenari Padova Astronomical Observatory Italy	**Floris van der Tak** SRON / University of Groningen The Netherlands	**Lingyu Wang** SRON Netherlands Institute for Space Research The Netherlands

4. Topical Team 4: The Extreme Universe, including Gravitational Waves, Black Holes, and Compact Objects

Co-Chairs	
Alessandra Buonanno Max Planck Institute for Gravitational Physics Germany	**Darach Watson** University of Copenhagen Denmark

Members		
Alessandra De Rosa National Institute for Astrophysics - Institute for Space Astrophysics and Planetology Italy	**Jonathan Gair** Max-Planck-Institut fur Gravitationsphysik (Albert Einstein Institut) Germany	**Davide Gerosa** University of Birmingham United Kingdom
Rubina Kotak University of Turku Finland	**Elisabeta Lusso** University of Firenze & INAF-Arcetri Italy	**Gijs Nelemans** Radboud University The Netherlands
Antoine Petiteau APC - Université Paris Diderot France	**William J. Weber** University of Trento Italy	

5. Topical Team 5: Cosmology, Astroparticle Physics and Fundamental Physics

Co-Chairs		
Mike Cruise University of Birmingham United Kingdom	**Martin Hewitson** Max-Planck Institute for Gravitational Physics Germany	**Eiichiro Komatsu** Max Planck Institute for Astrophysics Germany
Members		
Paolo de Bernardis Sapienza Università di Roma Italy	**Claudia de Rham** Imperial College London United Kingdom	**Stefano Ettori** Osservatorio Astronomico di Bologna Italy
Alejandro Ibarra Technischen Universität München Germany	**Paolo Natoli** University of Ferrara Italy	**Dennis Schlippert** Leibniz Universität Hannover Germany
Thomas Sotiriou University of Nottingham United Kingdom		

Appendix D Titles of all White Papers

White Paper Title	Lead Author	Lead Author Institute
Enabling the sustainable space era by developing the infrastructure for a space economy	Anglada Escude, Guillem	Institute de Ciencies de l'Espai - Consejo Superior de Investigaciones Cientificas, Spain
The Search for Living Worlds and the Connection to Our Cosmic Origins	Barstow, Martin	University of Leicester, United Kingdom
Quantum Technologies in Space	Bassi, Angelo	University of Trieste, Italy
A Space Mission to Map the Entire Observable Universe using the CMB as a Backlight	Basu, Kaustuv	Argelander-Institut fur Astronomie, Germany
High Precision Particle Astrophysics as a New Window on the Universe with an Antimatter Large Acceptance Detector In Orbit (ALADInO)	Battiston, Roberto	Dipartimento di Fisica, Università di Trento, Italy
The local dark sector. Probing gravitation's low-acceleration frontier and dark matter in the Solar System neighborhood	Bergé, Joel	ONERA, France
The Missing Link in Gravitational-wave Astronomy: Discoveries waiting in the decihertz range	Berry, Christopher	Center for Interdisciplinary Exploration and Research in Astrophysics, Northwestern University, United States of America
Exploring the nearest habitable exoplanets	Bertaux, Jean-Loup	LATMOS/CNRS/UVSQ/IPSL, France
Joint Europa Mission (JEM) A MULTISCALE, MULTI-PLATFORM MISSION TO CHARACTERIZE EUROPA'S HABITABILITY AND SEARCH FOR EXTANT LIFE	Blanc, Michel	IRAP, CNRS-Université Toulouse III-Paul Sabatier, France
Gravitation And the Universe from large Scale-Structures	Blanchard, Alain	IRAP, France

The GAUSS mission concept **Mapping the cosmic web up to the reionization era**		
AMBITION - Comet Nucleus Cryogenic Sample Return	Bockelée-Morvan, Dominique	LESIA, Observatoire de Paris, France
Exploring Solar-Terrestrial Interactions via Multiple Observers	Branduardi-Raymont, Graziella	Mullard Space Science Laboratory - University College London, United Kingdom
AEDGE: Atomic Experiment for Dark Matter and Gravity Exploration	Buchmueller, Oliver	Imperial College London, United Kingdom
GrailQuest: hunting for Atoms of Space and Time hidden in the wrinkle of Space-Time	Burderi, Luciano	University of Cagliari, Italy
Space Project for Astrophysical and Cosmological Exploration (SPACE)	Burgarella, Denis	Laboratoire d'Astrophysique de Marseille, France
White Paper on the case for Landed Mercury Exploration within the Voyage 2050 long-term plan in the ESA Science Program	Byrne, Paul	North Carolina State University, United States of America
Probing the Nature of Black Holes: Deep in the mHz Gravitational-Wave	Cardoso, Vitor	University of Lisbon, Portugal
UV Exploration of the solar system	Chaufray, Jean-Yves	LATMOS, CNRS, France
New Horizons in Cosmology with Spectral Distortions of the Cosmic Microwave Background	Chluba, Jens	JBCA, The University of Manchester, United Kingdom
Enceladus as a potential oasis for life: Science goals and investigations for future explorations	Choblet, Gaël	LPG, CNRS/Nantes University, France
Gamma-ray Astrophysics in the MeV Range: The ASTROGAM Concept and Beyond	De Angelis, Alessandro	INFN Padova and University of Padova, Italy

Microwave Spectro-Polarimetry of Matter and Radiation across Space and Time	Delabrouille, Jacques	Laboratoire APC, CNRS/IN2P3 & DAp, CEA/IRFU, France
High angular resolution gravitational wave astronomy	Dvorkin, Irina	Max Planck Institute for Gravitational Physics (Albert Einstein Institute), Germany
HiRISE - High Resolution Imaging and Spectroscopy Explorer **Ultrahigh resolution, interferometric and external occulting coronagraphic science: Great leap in solar physics**	Erdelyi, Robertus	Univ of Sheffield, United Kingdom
CHRONOS **A NIR Spectroscopic Galaxy Survey: From the formation of galaxies to the peak of activity**	Ferreras, Ignacio	IAC / UCL, Spain
Ice Giant Systems: Scientific Potential of Missions to Uranus and Neptune	Fletcher, Leigh	University of Leicester, United Kingdom
Understanding the origin of the positron annihilation line and the physics of the supernova explosions	Frontera, Filippo	University of Ferrara, Physics and Earth Sciences Department, Ferrara, Italy
Massive Stars in Extremely Metal-Poor Galaxies: a Window into the Past	Garcia, Miriam	Centro de Astrobiología (CSIC-INTA), Spain
CLOSING GAPS TO OUR ORIGINS **EUVO: THE UV WINDOW INTO THE UNIVERSE**	Gomez de Castro, Ana I.	Universidad Complutense de Madrid, Spain
Cometary Plasma Science	Götz, Charlotte	TU Braunschweig, Germany
The Changing Climate of Mars	Grady, Monica	The Open University, United Kingdom
A Deep Study of the High-Energy Transient Sky	Guidorzi, Cristiano	University of Ferrara, Italy
Uranus and Neptune are key to understand planets with hydrogen atmospheres	Guillot, Tristan	Observatoire de la Cote d'Azur, France

TeraHertz Exploration and Zooming-in for Astrophysics (THEZA)	Gurvits, Leonid	Joint Institute for VLBI ERIC and Delft University of Technology, The Netherlands
A journey to the polar regions of a star: Exploring the solar poles and the heliosphere from high helio-latitude	Harra, Louise	PMOD/WRC and ETH-Zürich, Switzerland
All-Sky Visible and Near Infrared Space Astrometry	Hobbs, David	Lund Observatory , Sweden
Precise Astrometry: Earth Analogs and Beyond	Horzempa, Philip	LeMoyne College, United States of America
The need for a multi-purpose, optical-NIR space facility after HST and JWST - The case for an ESA-led HabEx Workhorse Camera	Jahnke, Knud	Max Planck Institute for Astronomy, Germany
Occulter to Earth: Prospects for studying Earth-like planets with the E-ELT and a space-based occulter	Janson, Markus	Stockholm University, Sweden
Autonomous Lunar Geophysical Experiment Package (ALGEP)	Kawamura, Taichi	Institut de Physique du Globe de Paris, France
Peering into the Dark (Ages) with Low-Frequency Space Interferometers	Koopmans, Leon	Kapteyn Astronomical Institute, The Netherlands
In situ studies of the solar corona after Parker Solar Probe and Solar Orbiter	Krasnosselskikh, Vladimir	LPC2E/CNRS-University of Orleans-CNES, France
Lunar or space-based hypertelescope for direct high-resolution imaging	Labeyrie, Antoine	College de France and observatoire de la Cote d'Azur, France
LUNES: LUNar tErahertz teleScope Expanding the electromagnetic window	Lampin, Jean-Francois	IEMN-CNRS, France
PHEMTO: the Polarimetric High Energy Modular Telescope Observatory	Laurent, Philippe	CEA/DRF/IRFU/DAp, France
A complete census of the gas phases in and around galaxies: far-UV spectropolarimetry as a prime tool for understanding galaxy evolution and star formation	Lebouteiller, Vianney	AIM, CEA, CNRS, Université Paris-Saclay, Université Paris Diderot, Sorbonne Paris Cité, France

Bringing high spatial resolution to the Far-infrared - A giant leap for astrophysics	Linz, Hendrik	Max Planck Institute for Astronomy Heidelberg, Germany
Faint objects in motion: the new frontier of high precision astrometry	Malbet, Fabien	IPAG / Université Grenoble Alpes, France
Solar Particle Acceleration, Radiation & Kinetics (SPARK)	Matthews, Sarah	UCL Mullard Space Science Laboratory, United Kingdom
"The Grand European Heliospheric Observatory": An integrated ESA approach to challenges in Solar and Solar-Terrestrial physics.	McCrea, Ian	Rutherford Appleton Laboratory, United Kingdom
Chronos **Take the pulse of our Galactic neighbourhood** **After Gaia: time domain information, masses and ages for stars**	Michel, Eric	Observatoire de Paris - LESIA, France
HAYDN **High-precision AsteroseismologY of DeNse stellar fields**	Miglio, Andrea	School of Physics and Astronomy, University of Birmingham, United Kingdom
Exploration of Enceladus and Titan: Investigating ocean worlds' evolution and habitability in the Saturn System	Mitri, Giuseppe	International Research School of Planetary Sciences, Dipartimento di Ingegneria e Geologia, Università d'Annunzio, Italy
Stellar Physics with High-Resolution UV Spectropolarimetry	Morin, Julien	LUPM (Université de Montpellier & CNRS), France
In Situ Exploration of the Giant Planets	Mousis, Olivier	Aix-Marseille Université, France
The Voyage of Metals in the Universe from Cosmological to Planetary Scales: the need for a Very High-Resolution, High Throughput Soft X-ray Spectrometer	Nicastro, Fabrizio	INAF - Osservatorio Astronomico di Roma, Italy

Planetary Polar Explorer: The Case for a Next-Generation Remote Sensing Mission to Low Mars Orbit	Oberst, Jürgen	German Aerospace Center (DLR), Institute of Planetary Research, Germany
CASPER: A mission to study the time-dependent evolution of the magnetic solar chromosphere and transition regions	Orozco Suárez, David	Instituto de Astrofísica de Andalucía - Consejo Superior de Investigaciones Científicas, Spain
Magnetic Imaging of the Outer Solar Atmosphere (MImOSA) Unlocking the driver of the dynamics in the upper solar atmosphere	Peter, Hardi	Max Planck Institute for Solar System Research, Germany
EarthFinder: A NASA Probe Mission Concept	Plavchan, Peter	George Mason University, United States of America
Searching for (bio)chemical complexity in icy satellites, with a focus on Europa	Prieto-Ballesteros, Olga	Centro de Astrobiología (CSIC-INTA), Spain
Atmospheric characterization of terrestrial exoplanets in the mid-infared: biosignatures, habitability & diversity	Quanz, Sascha	ETH Zurich - Department of Physics, Switzerland
What are the fundamental modes of energy transfer and partitioning in the coupled Magnetosphere-Ionosphere system?	Rae, Jonathan	MSSL/UCL, United Kingdom
Particle Energization in Space Plasmas: Towards a Multi-Point, Multi-Scale Plasma Observatory	Retino, Alessandro	Laboratoire de Physique des Plasmas - Centre National de la Recherche Scientifique, France
The Far Infrared Spectroscopic Surveyor	Rigopoulou, Dimitra	University of Oxford, United Kingdom
Science goals and mission concepts for a future orbital and in situ exploration of Titan	Rodriguez, Sebastien	Institut de physique du globe de Paris, France
Spectropolarimetry as a Tool for Understanding the Diversity of Planetary Atmospheres	Rossi, Loïc	LATMOS, France

The in-situ exploration of Jupiter's radiation belts	Roussos, Elias	Max Planck Institute for Solar System Research, Germany
ESA's Voyage 2050 Long-term Plan for Education and Public Engagement	Russo, Pedro	Leiden Observatory, Leiden University, The Netherlands
Mars' plasma system. Scientific potential of coordinated multi-point missions: 'The next generation'	Sanchez-Cano, Beatriz	University of Leicester, United Kingdom
AMS-100: The Next Generation Magnetic Spectrometer in Space - An International Science Platform for Physics and Astrophysics at Lagrange Point 2	Schael, Stefan	RWTH Aachen University, Germany
Quantum Correlations at Earth-Moon Distance	Schneider, Jean	Observatoire de Paris, France
OWL-MOON: Very high resolution spectro-polarimetric interferometry and imaging from the Moon: exoplanets to cosmology	Schneider, Jean	Observatoire de Paris, France
Coronal Magnetism Explorer: ESA Solar Physics Mission White Paper	Scullion, Eamon	Northumbria University Newcastle upon Tyne, United Kingdom
Unveiling the Gravitational Universe at µ-Hz Frequencies	Sesana, Alberto	Università degli Studi di Milano-Bicocca, Italy
GAUSS **Genesis of Asteroids and EvolUtion of the Solar System - A Sample Return Mission to Ceres**	Shi, Xian	Max Planck Institute for Solar System Research, Germany
Mapping Large-Scale-Structure Evolution over Cosmic Times	Silva, Marta	Institute of Theoretical Astrophysics, University of Oslo, Norway
Voyage through the Hidden Physics of the Cosmic Web	Simionescu, Aurora	SRON Netherlands Institute for Space Research, The Netherlands

Detecting life outside our solar system with a large high-contrast-imaging mission	Snellen, Ignas	Leiden Observatory, Leiden University, The Netherlands
A Polarized View of the Hot and Violent Universe	Soffitta, Paolo	INAF - Istituto di Astrofisica e Planetologia Spaziali, Italy
The Quest for Life Leads Underground: Exploring Modern-Day Subsurface Habitability & Extant Life on Mars	Stamenkovic, Vlada	Jet Propulsion Laboratory, United States of America
Enceladus and Titan: Emerging Worlds of the Solar System	Sulaiman, Ali	University of Iowa, United States of America
Detecting the Gravito-magnetic field of the Dark Halo of the Milky Way (LaDaHaD)	Tartaglia, Angelo	INAF-OATo, Italy
A Comprehensive Investigation of the Galilean Moon, Io, by Tracing Mass and Energy Flows	Thomas, Nicolas	University of Bern, Switzerland
Mars and the Science Programme: The case for Mars Polar Science	Thomas, Nicolas	University of Bern, Switzerland
The high energy universe at ultra-high resolution: the power and promise of X-ray interferometry	Uttley, Phil	University of Amsterdam, The Netherlands
Venus Sample Return Mission Revisited	Valentian, Dominique	ITG, France
Sample return of primitive matter from the outer Solar System	Vernazza, Pierre	Laboratoire d'Astrophysique de Marseille, France
A Case for Electron-Astrophysics	Verscharen, Daniel	MSSL, University College London, United Kingdom
Origins Space Telescope: From First Light to Life (Mission of Opportunity)	Wiedner, Martina	Sorbonne Université, Observatoire de Paris, Université PSL, CNRS, France
Venus: Key to understanding the evolution of terrestrial planets	Wilson, Colin	Oxford University, United Kingdom

In-situ Investigations of the Local Interstellar Medium	Wimmer-Schweingruber, Robert F.	Institute of Experimental and Applied Physics, University of Kiel , Germany
Exploring the Foundations of the Physical Universe with Space Tests of the Equivalence Principle	Wolf, Peter	Observatoire de Paris, Université PSL, CNRS, Sorbonne Université, LNE, France
Plasma-neutral gas interactions in various space environments	Yamauchi, Masatoshi	Swedish Institute of Space Physics, Kiruna office, Sweden
Unveiling the faint ultraviolet Universe	Zanella, Anita	European Southern Observatory, Germany

Appendix E Keywords for Topical Teams

This list of keywords was developed by the Senior Committee and applicants for Topical Team membership were asked to select keywords that described their subject specialism.

active galaxies	gravitation and General Relativity	primitive bodies
astrobiology	gravity	protoplanetary disks
astrochemistry	heliophysics	Quantum Mechanics and microphysics
atmospheres	intergalactic medium	small solar system bodies
black holes	intermediate and giant planets	solar dynamics
beyond the Standard Model	interstellar matter	solar physics
biomarkers	ionosphere	solar system
CHON cycles	large-scale structure	solar wind
compacts objects	magnetosphere	space environments
cosmic microwave background	magnetospheric physics	space plasma physics
cosmic dust	Milky Way	space weather research
dark ages	non-thermal processes	spacetime, inertia and the vacuum
dark energy	origins	star formation
dark matter	planet formation	star-planet interactions
dark universe	planetary evolution	stars
exobiology	planetary interiors	surface interaction
exoplanets	planetary resurfacing	terrestrial planets
galactic structure	planetary rings	Titan
galactic dynamics	planetary science	waves and particles
galaxy clusters	planetary surfaces	weakly interacting particles
galaxy formation and evolution	plasma physics	

Appendix F Definitions of Technology Readiness Level

References to Technology Readiness Level (TRL) in this response follow the ISO 16290 definition as used by ESA.

TRL	Description
1	Basic principles observed and reported
2	Technology concept and/or application formulated
3	Analytical and experimental critical function and/or characteristic proof-of-concept
4	Component and/or breadboard functional verification in laboratory environment
5	Component and/or breadboard critical function verification in relevant environment
6	Model demonstrating the critical functions of the element in a relevant environment
7	Model demonstrating the element performance for the operational environment
8	Actual system completed and accepted for flight ("flight qualified")
9	Actual system "flight proven" through successful mission operations