SUMMARY

"Planetary Exploration, Horizon 2061" is a long-term foresight exercise initially proposed by the Air and Space Academy and led by scientists, engineers and technology experts heavily involved in planetary sciences and in the space exploration of the Solar System. Its ultimate objective is to draw up to the 2061 horizon a long-term picture of the four pillars of planetary exploration:

(1) our major scientific questions on planetary systems;

(2) the different types of space missions that we need to fly to address these questions;

(3) the key technologies we need to master to make these missions flyable;

(4) the ground-based and space-based infrastructures needed in support of these missions.

The year 2061 corresponds to the return of Halley's comet into the inner Solar System and to the centennial of the first human space flight and of President Kennedy's Moon initiative. It symbolically represents our intention to encompass both robotic and human exploration in the same perspective. Its distant horizon, located well beyond the usual horizons of the planning exercises of space agencies, avoids any possible confusion with them and is intended to « free the imaginations » : imaginations of planetary scientists, who are invited to formulate what they think are the most relevant and important scientific questions independently of the a priori technical feasibility of answering them ; imaginations of engineers and technology experts, who are invited to contribute to the exercise by looking for innovative technical solutions that will make it possible to fly the challenging space missions that will allow us to address these questions.

Four main objectives can be reached via this dialogue between scientists and engineers:

(1) Identify the technologies and infrastructures that will be needed to address our major scientific questions;

(2) provide a broad spectrum of notional space missions of diverse sizes and complexity levels all contributing to address these questions;

(3) inspire coordination and collaborations between the different players of planetary exploration to better meet technology challenges, stimulate complementary and synergies between individual missions and increase the overall science return of space exploration;

(4) share with the public and public/private leaders the major scientific questions and technological challenges of planetary exploration.

The « Horizon 2061 » exercise involves three successive steps designed to progressively build the four pillars. Its third step, the « Horizon 2061 synthesis workshop », will be hosted by the Institut Aéronautique et Spatial (IAS) in Toulouse from September 11th to 13th, 2019. Its tentative conclusions will be presented for discussion at the joint EPSC-DPS meeting in Geneva (September 15th to 20th, 2019), and later for discussion and final approval at the COSPAR General Assembly (Sydney, August 15th to 23rd, 2020).

Origin, context and motivations

The "Planetary Exploration, Horizon 2061" exercise was born from an initiative of the Air and Space Academy whose "GT 2061" working group was tasked to draw via a dialogue with the science and technology communities a long-term picture of the four pillars of planetary exploration at the 2061 horizon:

Pillar (1): our major scientific questions on planetary systems;

Pillar (2): the different types of space missions that we need to fly to address these questions;

Pillar (3): the key technologies we need to master to make these missions flyable;

Pillar (4): the ground-based and space-based infrastructures needed in support to these missions.

The choice of the year 2061, corresponding to the return of Halley's comet into the inner Solar System and to the centennial of the first human space flight and of President Kennedy's Moon initiative, symbolically represents our intention to encompass both robotic and human exploration in the same perspective. Its distant horizon, located well beyond the usual horizons of the planning exercises of space agencies and of their standing committees, which generally address shorter time scales, avoids any possible confusion with them and is intended to trigger a joint foresight thinking of the scientific and technology communities of planetary exploration that will « free the imaginations »:

- of the planetary scientists, who are invited to formulate what they think are the most relevant and important scientific questions independently of the a priori technical feasibility of answering them;
- of the engineers and technology experts, who are invited to explore innovative technical solutions that will make it possible to fly by 2061 the challenging space missions that will allow us to address these questions.

To build these four pillars, we follow the classical method used to design science-driven space missions, e.g. we write a "Science Traceability Matrix" (STM) by which each science question and measurement objective can be translated into requirements on the scientific investigations and instruments needed, on the mission profile and on characteristics of the platforms to be flown. But in the case of Horizon 2061, we are going to write the STM, not of a single space mission, but of a "set of representative missions" whose combined science return will make it possible, by 2061, to address as comprehensively as possible six "key science questions" of planetary sciences. As one can realize, *such a perspective is by essence international*.

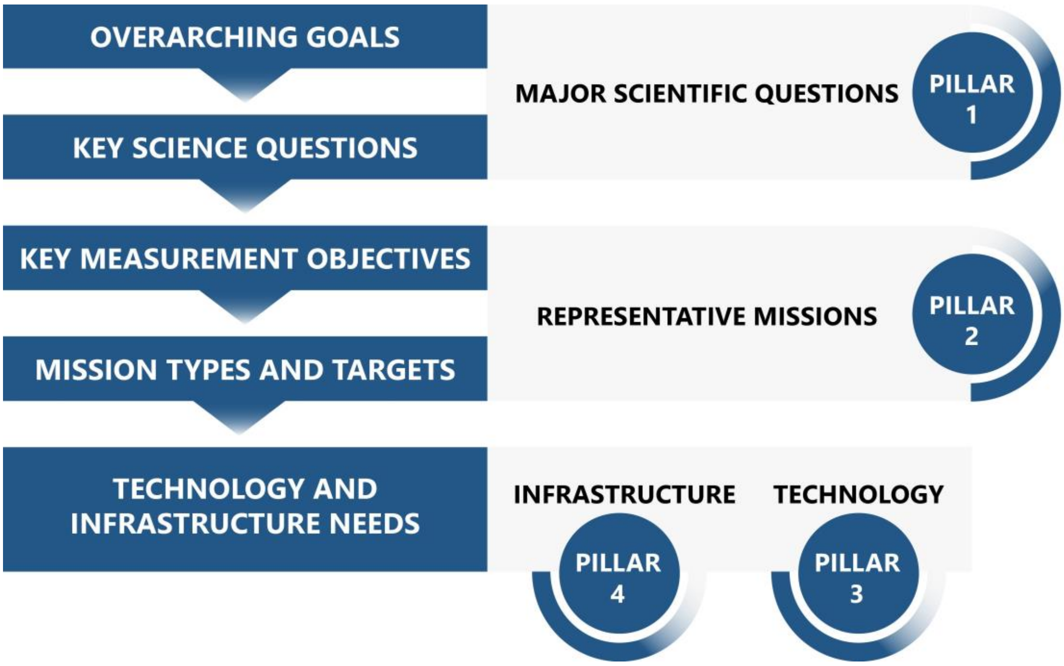

Figure 1:

To build the four "pillars" of planetary exploration, the Horizon 2061 exercise progressively fill the successive columns, from left (overarching goal) to right (technical requirements) of a set of representative missions whose combined science return will make it possible to address six "key science questions" of planetary sciences by 2061.

Understanding Planetary Systems: from science questions to mission types and destinations.

We have chosen to place our Horizon 2061 exercise in the very important context of the current emergence of a unifying paradigm of planetary sciences: the concept of « planetary systems, a class of astrophysical objects which covers and links together the solar system, giant planets systems and extrasolar planetary systems. It is a “hard fact” that the solar system and its giant planets systems (5 “realizations” of planetary systems within our own) on one hand and extrasolar planetary systems on the other hand can be observed by different techniques and with important differences in measurement resolutions: whereas remote sensing using the variety of techniques of astronomy applies to all systems, only the solar system, in the XXIst century, is accessible to the powerful approaches of in situ investigations. Despite this importance difference in their accessibility to our observations, there is no doubt that they form *one class of astrophysical objects*, as illustrated by the “cartoon” of Figure 2. Studying them together in a comparative approach, from their formation in circumstellar disks to the potential emergence of habitable worlds and of life within them, will be a considerable source of new scientific insight, in the same way as what happened to Solar and stellar physics when they were finally considered as two different entries to the same scientific discipline.

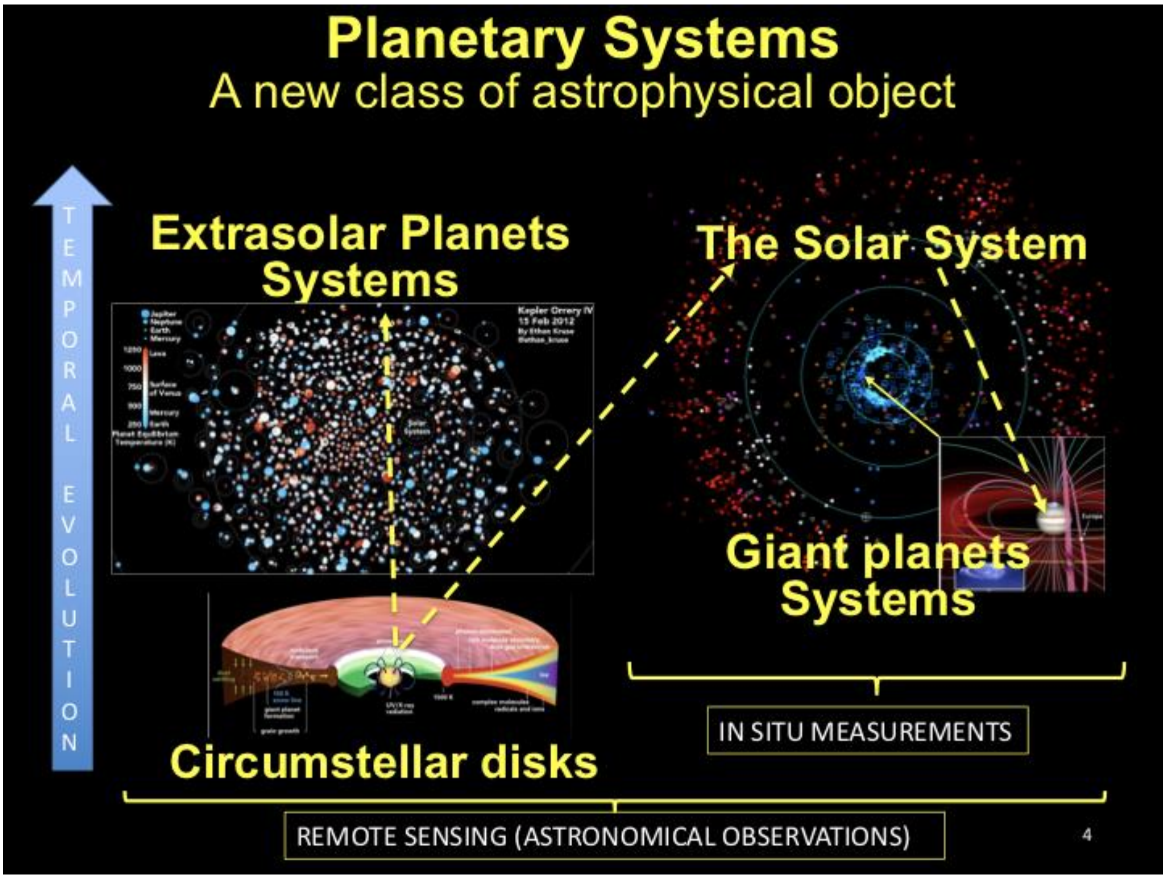

Figure 2: by studying Planetary Systems as a “new class” of astrophysical objects, in the perspective of their evolution, from their formation inside circumstellar disks to the possible emergence of habitable worlds within them, one can bridge the “observational gap” currently existing between disks, solar system objects and exoplanets and take advantage of considerable synergies to better address our “key questions” about them.

This is the challenge we propose for the development of our Horizon 2061 scientific foresight exercise: reach a more comprehensive understanding of how and under which conditions the formation and evolution of planetary systems can lead to the emergence of life, a question which we can formulate as our "overarching goal":

Study the formation and evolution processes leading to the growth of complexity, and ultimately to the possible emergence of life, through the diversity of planetary systems:

(1) the growth of molecular complexity, from the Interstellar medium (ISM) to planetary and moons environments;

(2) the growth of planetary environments complexity, and the conditions under which their evolutionary paths may lead them to become "habitable".

Developing this general goal into more specific questions addressing the different sequences of evolution of planetary systems and their coupling processes, we come up with the six "key science questions" presented in Figure 3.

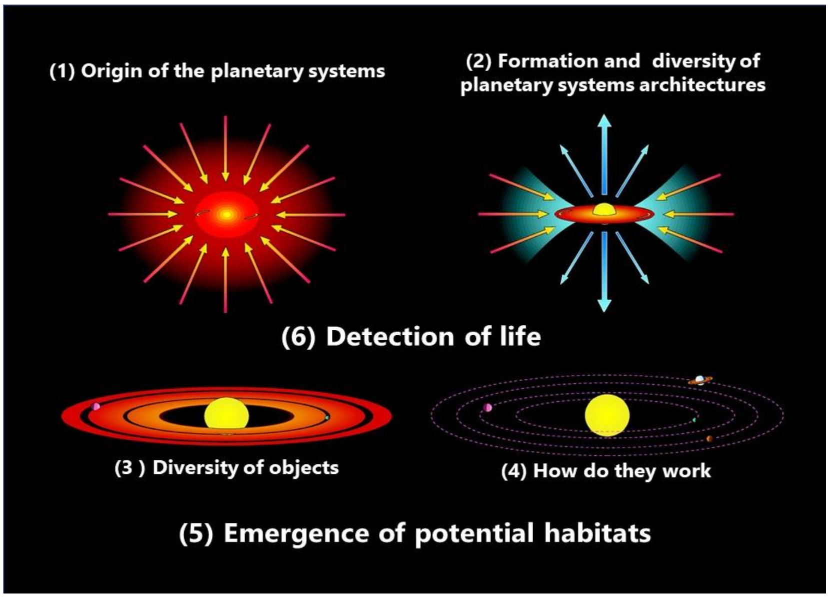

Figure3:
Six key science questions about planetary systems

Our chosen overarching goal is consistent with the current emergence of a unifying paradigm of planetary sciences: the concept of « planetary systems, a class of astrophysical objects which covers and links together the solar system, giant planets systems and extrasolar planetary systems in the quest for common answers to the major scientific questions just mentioned.

In this approach, our foresight analysis of the major scientific questions and of the types of space missions to solar system destinations needed to address them that can be placed in the broader context of the scientific exploration of the fascinating worlds of extra-solar planetary systems.

Then, starting from our six **major scientific questions** (figure 3), our Horizon 2061 foresight first identifies for each question the **key observations** that need to be performed and the destinations in the solar system where these measurements must be performed, and then the **types of space missions** that will need to be flown to these destinations by 2061 to perform these observations (figure 4).

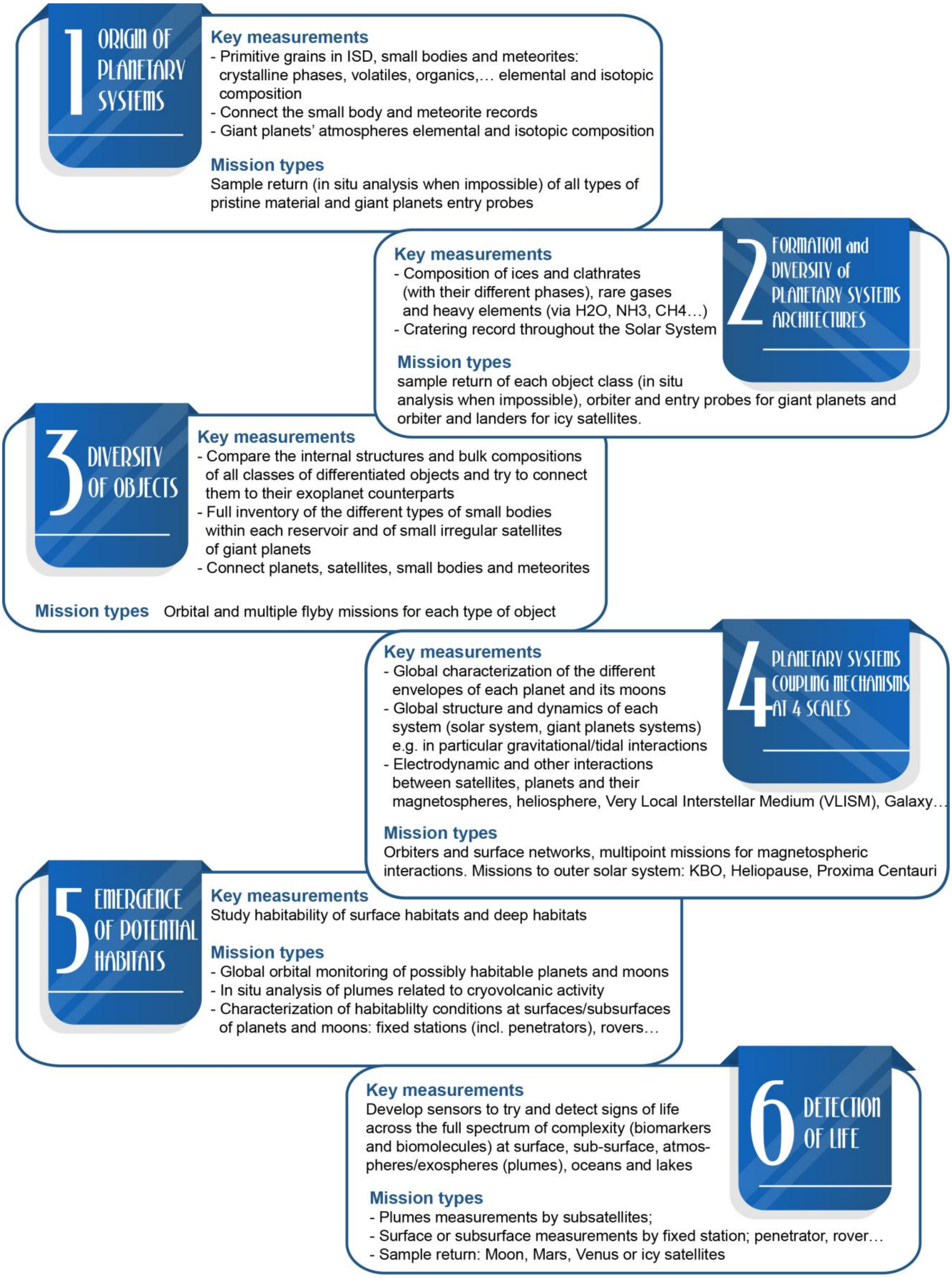

Figure 4: relationships between the six key science questions, key measurements and mission types in the Horizon 2061 exercise.

This analysis shows the large diversity of the destinations of our types of missions and its broad spatial spread towards deep space, from the Earth-Moon system up to the local interstellar medium beyond the heliopause, illustrated in Figure 5. By 2061, all the outer boundaries, or "frontiers", of exploration should have moved dramatically outwards: *human exploration* might have reached Mars and perhaps the main asteroid belt; *sample return* missions should have reached, beyond the asteroid belt, the Trojan asteroids on the orbit of Jupiter and the icy moons of Jupiter and Saturn; *robotic exploration* should have reached the very local interstellar medium, well beyond the outer shock of the heliosphere, thus opening the very-long-term perspective of a new era: the onset of interstellar travel towards the closest stars and their planetary systems; and finally, the development of new giant telescopes on Earth or in orbit will provide unprecedented access to solar system small bodies, resolving them, spatially and/or spectrally, up to the distance of the Kuiper belt.

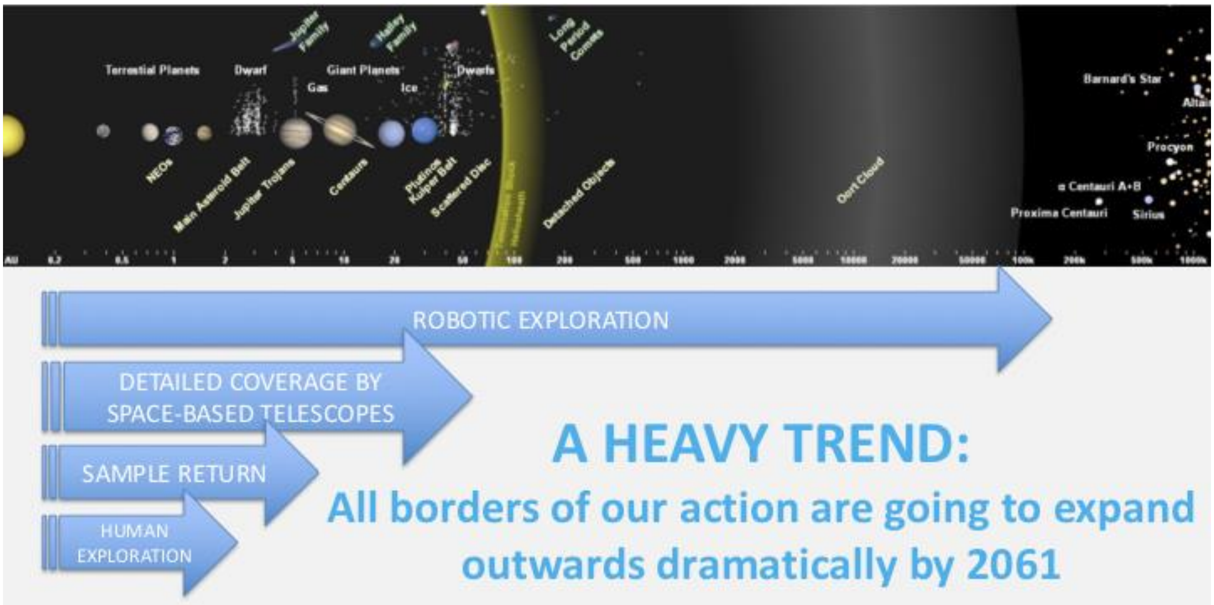

Figure 5: The outward expansion of the "frontiers" of our different ways of visiting and discovering the solar system should be one of the heavy trends of Humankind's exploration endeavours by 2061.

From representative missions to enabling technologies.

One can classify for convenience our broad range of destinations into the six **provinces** listed in table 1. Each of these provinces can be visited by several "representative **missions"** chosen for their requirements on enabling technologies and support infrastructures: this is the link we need to establish to build the last two pillars of our exercise.

Building on the presentations and exchanges of the Step 1 and 2 meetings in Bern and Lausanne, we have established a preliminary list of these "representative missions" and divided them into two sub-sets:

- 1. Missions that could/should reasonably be flown by 2040, using technologies that are or will be soon available either directly in the space activities sector, or in other domains from which they could be adapted to our needs;
- 2. An additional subset of missions that need to be flown during the following two decades (2041-2061) and will likely require novel technology developments and the design of infrastructures which will offer additional supporting capabilities and will enhance the overall science return of the exploration program, allowing better synergies between missions and stimulating international collaboration.

Then it is possible to connect each category of “representative missions” we have identified to the enabling technologies needed to fly these missions, based on the ouputs of the Lausanne workshop. With this additional link established, it was possible to draft figure 6, which summarizes the links between the representative missions that could be flown before or after 2040 and their enabling technologies.

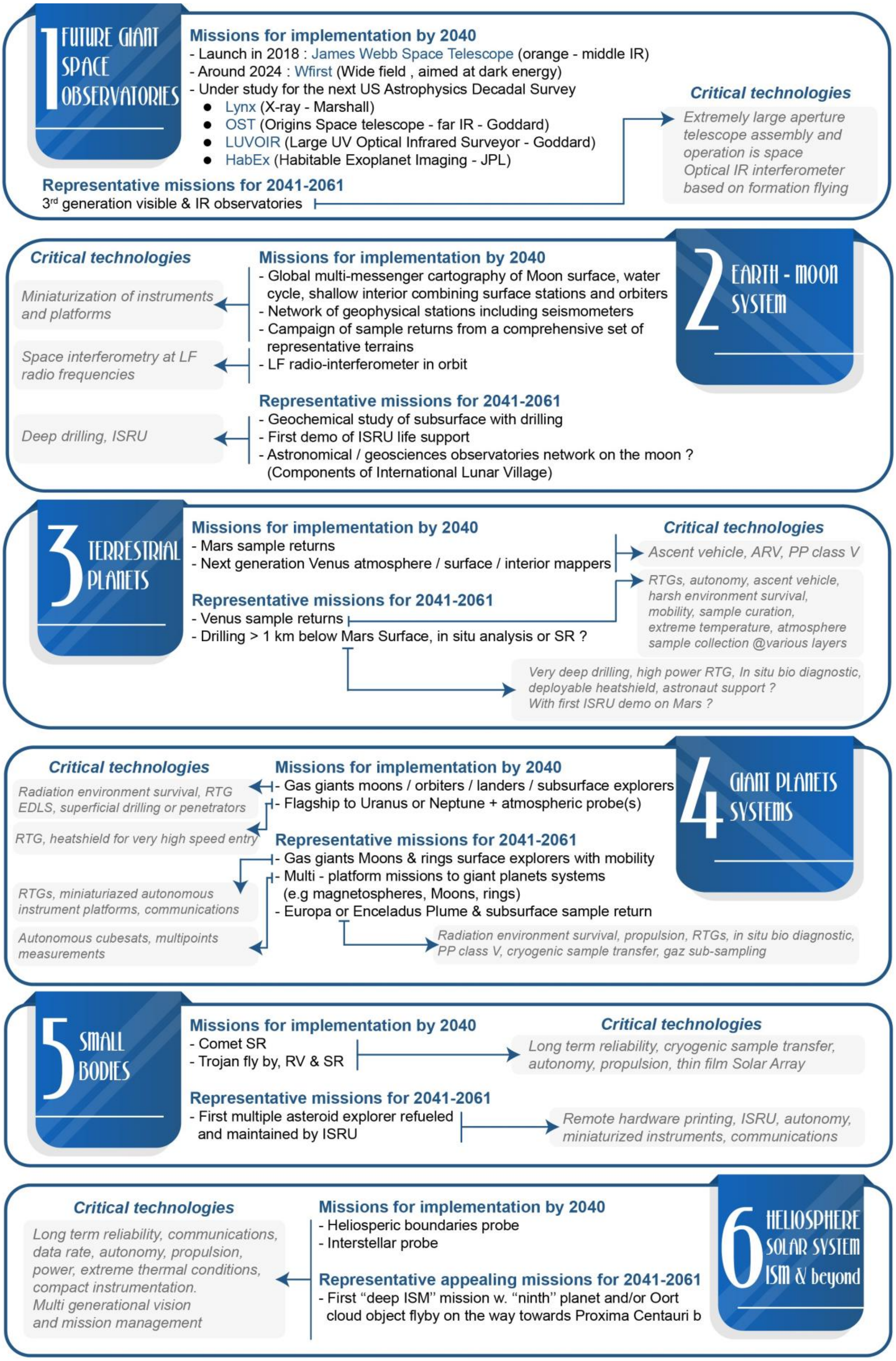

Figure 6: From representative missions to their enabling technologies

Critical technologies (pillar 3)

The **critical technologies** needed can be classified into six generic themes (Table 1) including critical technologies of dual use with manned space exploration.

Table 1: Six critical technological domains	
1. Science instrumentation	*4. Mission implementation- Overall system architectures*
2. Platform subsystems and enabling technologies	*5. Ground operations technologies and implementation*
3. System level technologies	*6. Advanced and breakthrough technologies*

1 Science Instrumentation

Remote sensing, In situ measurements, Seismometers

Life detection

In situ operations: Sample access (drilling, coring...) retrieval, selection/curation, encapsulation

Contamination control

Miniaturization, Printable instruments and electronics,

Sustainability in extreme environment

Autonomy (IA...) for operations, sample selection...

…

2 Platform subsystems and enabling technologies

Increased computer power, Data handling/data processing, Autonomy

Power, Energy storage,

Propulsion,

Structures, Thermal control

Communication, Navigation, Guidance and control,

Sustainability and performance in different severe environments (high radiation level, high or low temperature, high pressure, corrosive environment, adaptation to unknown events,)

…

3 System level technologies

Aerocapture, Aeroassistance, Entry, descent and landing

Mobility: Aerial, surface, subsurface

Hard landers and penetrators

In Situ Resource Utilization

Sample return (ascent, RV, orbital transfer...)

Intelligence in machines/Systems (IA,…)

…

4 Mission implementation- Overall system architectures

Multitarget missions, multi point measurements

Large S/C and collection of smallSats and probes, swarm of smallSats

Low cost and higher risk missions

Standardisation of S/C interface for flexible and collaborative missions

Large observatories based on Formation flying or on deployment of monolithic structures

…

5 Ground operations technologies and implementation

New technologies required for operations of outer solar system missions

Ground technologies related to the return of sample from space

Technologies and operations implementation aiming at cost reduction and efficiency improvement

…

6 Advanced and breakthrough technologies, *Technologies featuring low or very low TRL today, but large potential for science missions*

6.1 Advanced technologies for reducing the time of access to the outer solar system

Electric power generation (from radioisotope, nuclear reactor…)

High power electric propulsion, … other high efficiency, high thrust propulsion

…

6.2 Breakthrough technologies (*very low TRL today)* e.g.:

Beamed energy propulsion: Electric sail/solar photonic propulsion

Quantum technologies: Quantum communication, Sensing and measurement in space

Collaborative systems or devices: collaborative swarms of Picosat (few 100g) or femptosat (few g), Collaborative swarms of small mobile...

Mobility: Extreme terrain mobility, microgravity mobility

Damage tolerant materials

…

Shared infrastructures and facilities and international cooperative programs

While each mission, taken individually, requires enabling technologies and technical support equipments, considering all missions together in an international perspective makes it possible to create a considerable added value to an "international planetary exploration program:

- Some of the support equipments can be – and are – shared between different missions (e.g. DSN-type mission support);
- Some facilities, technical or scientific (data centers, extraterrestrial sample repositories, …) also serve much more than one mission, and facilitate "across-missions" science analysis;
- And finally, in some areas the best way of maximizing the science return from the exploration program is to define "international cooperative programs" within it: one of the best possible examples is given by the great perspectives offered by the upcoming phase of Lunar science exploration.

These three types of facilities and activities shared and coordinated at the international level "across missions" will not only save resources and maximize the fruit of investments, but will also produce a very significant additional science return. They can be broadly classified in the six categories listed in table 2.

In this approach, the sum of all missions will produce much more science return than would be the sum of the science return from each mission taken individually: an in-depth analysis of this exciting perspective will be our approach to build the “fourth pillar” of our Horizon 2061 exercise. The different types of infrastructures and services can be classified into six categories, as summarized in Table 2.

Table 2: Six categories of support infrastructures	
1. Solar system space weather	*4. Overall capabilities, developed for manned missions, for In-space manufacturing, assembly and/or deployment of large structures*
2. Solar system wide infrastructure for communications, navigation and scientific observations	*5. Nascent commercial space services (orbital transfer, in situ resources ...)*
3. Moon/Lunar platforms as laboratories and gateway	*6 Overall Ground/Space infrastructures for sample analysis, contamination control, sample curation, planetary and Earth protection*

1 Solar system space weather

Synergy with services for ground/ Earth environment and space services for manned flights (moon, then Mars and asteroids…)

Environmental characterization

2 Solar system wide infrastructure for communications and navigation

Ground and space infrastructure, Synergy with other space missions (DSN upgrade/advancement and beyond)

3 Moon/Lunar platforms as laboratories and gateway

Lunar orbital platform gateway to ease access to the solar system and safe return of samples from the solar system (critical operation or final testing before sending payload to farther destination, …)

Human aided sample retrieval/return from the Moon

…

4 Overall capabilities, developed for manned missions, for In-space manufacturing, assembly and/or deployment of large structures

In space (potentially on the Moon) manufacturing (3D, others), assembly or deployment of large structures for different types of observatories or other needs

Utilisation of material from in situ resources

…

5 Nascent commercial space services (orbital transfer, in situ resources ...)

Launch, orbital transfer, access to the Moon

Utilisation of resources from the Moon or asteroids

Mining services

…

6 Overall Ground/Space infrastructures for sample analysis, contamination control, sample curation, planetary and Earth protection

Ground and space laboratory network

Earth protection and planetary protection against contamination,

…

Horizon 2061: who, for whom, for what objectives

The "Horizon 2061" foresight exercise has been designed to be led by scientists and engineers covering diverse components of the science and technology communities of planetary exploration and fed by their ideas and inputs at each of its steps. Its three-step format makes it possible to collect new ideas from the diverse disciplines contributing to this activity domain and to stimulate interdisciplinary dialogues as a central source of its foresight. Thanks to these foundations, Horizon 2061 can aim to achieve four main objectives:

- 1. Identify the technologies and infrastructures that need to be developed to fly the space missions that will make it possible to address the major questions of the science of planetary systems in the long term;
- 2. Provide, free of programmatic constraints, a broad variety of notional space mission concepts that have the potential to contribute to the progress of our understanding of planetary systems, from « small missions » that could be implemented by some of the new actors of planetary exploration, to the most complex and expensive ones that cannot be implemented by a single space agency and require international collaboration;
- 3. Inspire coordination and collaborations between the different players of planetary exploration to meet the technology challenges, develop the needed infrastructures and implement the missions that will best serve the progress of knowledge;
- 4. Share with the public and public/private leaders the major scientific questions and technological challenges of planetary exploration for the decades to come.

We regard the international cooperation aspects of Horizon 2061 as of the utmost importance in its approach, in line with the official support it has received from COSPAR under the auspices of the Air and Space Academy.

Development scheme of the H2061 exercise and elaboration of its conclusions.

The Horizon 2061 exercise is being developed in three steps, e.g. three meetings of international experts designed to progressively build the four pillars of planetary exploration.

The first step has been a joint ISSI-Europlanet forum (ISSI, Bern, september 13th to 15th, 2016) which led to formulate the six **major scientific questions** (pillar 1), to identify the **key observations** and where to perform these observations and

initiated our exploration of the **critical technologies** needed.

The second step has been the community workshop "Technologies and Infrastructures for Planetary Exploration" hosted by the Ecole Polytechnique Fédérale de Lausanne (EPFL) from April 23rd to 25th, 2018, which laid the foundations of pillars 3 and 4 on the basis of a first inventory of the **mission types**.

The third step, devoted to the synthesis of the exercise, will be an international colloquium hosted by the Institut Aéronautique et Spatial, Toulouse, between September 11th and 13th, 2019. Its main organizers will be the Institut de Recherche en Astrophysique et Planétologie (IRAP) and the Observatoire Midi-Pyrénées (OMP). This colloquium, placed under the sponsorship of the Committee for Space Research (COSPAR), will complete the design of the four pillars and initiate the drafting of the final report, which will be edited and published under the auspices of COSPAR.

Proposed format of the Toulouse synthesis colloquium.

The detailed program of the Toulouse synthesis colloquium, broadly inspired by the initial suggestions of the Air and Space Academy, will be defined by its Scientific Organizing committee (SOC).

Let us give a short preliminary description of it. Following a brief introduction which will present the objectives of the H2061 exercise and the results of its first two steps, session 1 will revisit the six **major scientific questions** and their related **key observations** and will present a first inventory of the different **types of missions** needed to perform these observations. Session 2, starting from this inventory, will focus on a small subset of these missions offering the most challenging technical requirements, e.g. those which will be seen as the best sources of inspiration for technology innovations. Its conclusions will connect us directly to session 3 on **critical technologies** and to session 4 on **shared infrastructures and facilities**. In conclusion, session 5 will discuss the **implementation schemes** for the most innovating missions and technical developments in the general context of « New Space », with a strong focus on the opportunities offered by international collaborations and public-private synergies. A provisional more detailed agenda of the Toulouse colloquium can be found in Annex 1.

All the information concerning Horizon 2061 and the Toulouse colloquium will be progressively posted on the Horizon 2061 website, currently under construction by the Local Organization Committee (LOC) of Horizon 2061 Toulouse 2019: http://horizon2061.cnrs.fr.

Proposed table of contents for the Horizon 2061 report.

The table of contents of the report on the findings and conclusions of our exercise, to be published under the auspices of COSPAR as a series of peer-reviewed thematic articles and/or a book of the COSPAR publications series, will follow closely the structure of the agenda of the Toulouse workshop. We will propose the following overall TOC to the examination of the Scientific Organization Committee (SOC):

Proposed title of the report:

Planetary exploration, Horizon 2061

From community vision to international perspectives

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Feed-back to the communities, discussion of the conclusions and validation of the report.

The provisional conclusions of the Horizon 2061 exercise formulated at the end of its synthesis colloquium will be presented for discussion over the following year to the communities of planetary sciences and exploration, in order to prepare for the discussion and validation of the report at the General Assembly of COSPAR in Sydney (August 15th to 23rd, 2019). To this end we will propose a session dedicated to Horizon 2061 for the joint EPSC-DPS meeting (Geneva, September 15th to 20th, 2019). The organization of similar sessions to the general assembly of IAF and AOGS is also desirable. Finally, we have also proposed to CNES, the French space agency, that the provisional conclusions of Horizon 2061 be presented to its « Séminaire de Prospective Spatiale » (SPS) in october 2019: this way Horizon 2061 could be fed by the ideas of the French space science community and contribute to its own foresight exercise.

ANNEX 1

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STEP 3: H2061 SYNTHESIS WORKSHOP

September 11-13, 2019, Institut Aéronautique et Spatial, Toulouse, France

September 11th, 2019 – morning		
08h45	Welcome; objectives of the workshop	
09h00	Setting the stage	Understanding Planetary Systems in the exoplanet era : 20 mn Magnetospheres, heliosphere, astrospheres : 20 mn
09h40	SESSION n°1 (Pillar 1) From Science questions to key measurements	3 talks : 3*20 • Origins of planetary systems and the Solar System • Formation and diversity of planetary systems architectures • Diversity of objects
10h40	Coffee Break	
11h00	SESSION n°1 From Science questions to key measurements	3 talks : 3*20 • How do planetary systems and their objects work – coupling mechanisms • Emergence of potential habitats • Search for life
12h00		• Additional contributions
12h45	Lunch break	

September 11th, 2019 – afternoon		
14h00	Session 2 (Pillar 2) From representative missions to key technical requirements	• Observing the Solar System from Earth and its orbits • Scientific investigations of the Earth-Moon system • Terrestrial planets • Small bodies
16h00	Coffee Break	
16h20	Session 2 (Pillar 2) cont'd	• Gas giants • Ice giants • Heliosphere, Solar System, ISM and beyond
17h20	Poster session 1	Science questions and mission scenarios
18h30	Horizon 2061 Icebreaker	(1 hour)

September 12th, 2019 - morning	
8h30	Session 3: foresight visions and programs from agencies and industry
10h30	Coffee break
10h50	Session 4: Enabling technologies (pillar 3) – first part
12h30	Lunch break

September 12th, 2019 - afternoon	
14h00	Session 4: Enabling technologies (pillar 3) – second part
14h45	Oral contributions
15h30	Round table – Missions and technologies
16h00	Coffee break
16h20	Poster session 2: Technologies and infrastructures for the future of planetary exploration
18h00	End of the day

September 13th, 2019 - morning	
8h30	Session 5: Infrastructures, services and collaborative programs (pillar 4)
10h30	Coffee break
10h45	Session 5 cont'd
12h00	Round table: Infrastructures and services for the future of planetary exploration
12h30	Lunch break

September 13th, 2019 - afternoon		
14h00	Session 6: Implementation Issues	2*20 mn talks Discussions / questions : 20 mn
15h00	Round table	30 mn
15h30	Coffee break	
16h00	Session 7: Conclusions and reporting	Final round table: Synthesis of each pillar by a rapporteur (10 minutes each) General discussion
17h15	Summary	
17h30	END OF MEETING	