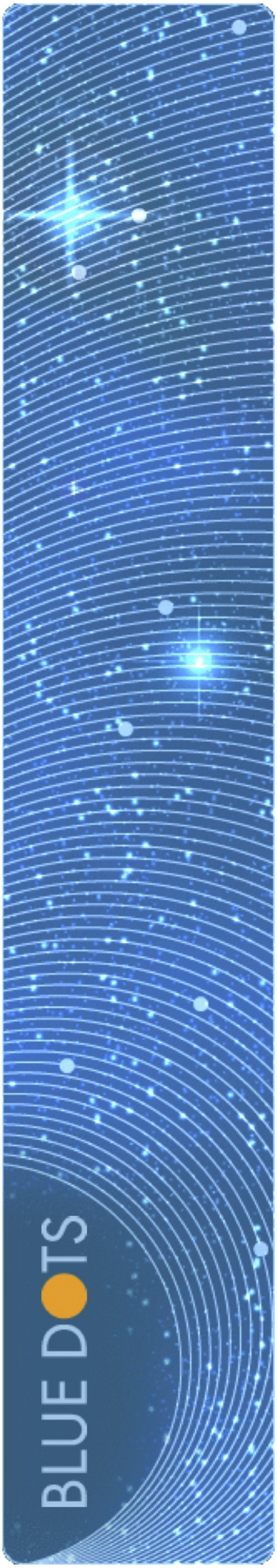

Blue Dots report

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1 Executive summary

This document presents the findings of the prospective exercize carried out in the frame of the Blue Dots activities.

Blue Dots was created in 2008 as a grassroot initiative to contribute towards building a community in Europe around the exoplanet theme, and to converge towards a strategy enabling a more coherent approach to Calls for Proposals in ground- and space-based projects, with the final goal of eventually characterizating habitable exoplanets to search for indices of biological activity. The scope of the initiative is science oriented and not restricted to a particular detection technique. The material produced by Blue Dots comes from the contribution of its participants (more than 180 scientists mostly located in Europe, with additional participation from the US, Japan, and India), and most notably its core team and Working Group coordinators. More information on this can be found on the website at `http://www.blue-dots.net`.

Blue Dots started working with white papers and also had strong interaction with the communauty through the concerned coordinators to identify the key science questions and assess the potential of related projects. This potential is graded for different categories of objects and along three steps: statistical information, identification of targets suitable for spectroscopic study, and spectroscopic characterization. The potential of each observational technique was then evaluated using the same grid in terms of detection and characterisation of several categories of objects, but also in terms of project horizon, cost and performance. A cross reading of the different grids allowed the identification of two strategies as parts of a possible roadmap:

- A systematic study involves the identification and characterisation of a complete sample of targets around nearby stars. This strategy is based on high accuracy astrometric obervation of nearby stars for identification of targets , and direct spectroscopy of their atmosphere using future generation of space telescopes and interferometers.
- A fast track approach focuses on the study of niche targets that happen to be comparatively more accessible for observations, recognizing that the sample is probably biased and not necessarily fully representative of its class. The associated observational strategy involves projects of a smaller scale to carry out similar science, and is based mainly on extreme radial velocimetry for identification (with statistical information also provided by transit and microlensing surveys), spectro photometry of planetary transits for characterization, and imaging using high performance coronagraphy on small telescopes.

The two strategies are complementary and should be pursued in parallel, with results from the fast track approach providing the data and impetus needed to define and move forward the larger projects that are required to carry out a systematic search for life in our galactic solar neighborhood.

The process and the associated outputs were discussed in September 2009 during the Conference "Pathways Towards Habitable Planets" organized by Blue Dots and other sponsors in Barcelona (`http://www.pathways2009.net`).

2 Introduction

One of the most important scientific challenges for the 21st century is the search of habitable worlds around other stars, and the characterization of their atmospheres with the goal of detecting signs of biological activity. This is a long-term, interdisciplinary endeavor, engaging astrophysicists, biologists, planetary scientists, and instrument scientists. Eventually, space missions will address those questions, however today progressing toward this goal with intermediate steps is necessary. The aim of this document is to provide a framework and some keys to help establish a consensus around a roadmap.

In our prospective exercize several underlying principles were applied. First, science questions should drive the roadmap – techniques should be seen as tools to address these questions. The main science themes related to Blue Dots are listed in Section 4 and the questions pertaining to the Blue Dots goal are detailed in Appendix A.

Then, specific projects should be introduced as late as possible in the process if convergence is to be sought. We chose to focus our attention on the potential of each technique for projects of different scales, rather than the merits of particular missions. The corresponding reviews are found in Appendix B. They are used to help us develop a synthetic picture of the situation (Section 5) from which, after analysis (Section 6), a roadmap can be derived (Section 7).

We also felt it was important to clearly identify the points of consensus and the matters of debate. Points of consensus provide an opportunity for the community to send out a common message. Scientific debates are obviously healthy and useful when they can be organized in a way to help clarify the issues. Four questions were identified as critical (or cornerstones) for the elaboration of a roadmap and we organized those debates, for each of which a synthetic summary appears in Appendix C.

Obviously no roadmap is carved in stone forever, and this is especially true with such a vibrant field as exoplanet science. It is likely to be revised every few years as the technology improves and new (possibly unexpected) results pour in. Blue Dots will continue to provide a forum and a framework to discuss these updates, keeping in mind the needs for diversity, open mindedness and flexibility as new elements appear.

3 Initial assumptions and consensus

3.1 Habitable niches

Our prejudice is to have the future detection of life as our final, perhaps far away, goal, with all necessary intermediate steps on this road. To reach this goal, we inevitably need some preconceptions on life, yet we do not want to be prisoners of a too restrictive definition of life. Nevertheless we accept to limit ourselves to life correlated to organic carbon chemistry developing in presence of liquid water at temperatures were complex molecules are stable. We also assumed that the primary low entropy energy source to build complex molecules is stellar photons (we leave other alternatives open for future studies). These two a priori assumptions allow us to define "habitable niches" on planets where there is liquid water and a sufficient stellar flux.

3.2 Potential targets

Assuming this definition of *habitability* as referring to the existence of liquid water on the planet surface, the goal of Blue Dots may be formulated as : *Characterizing a set of habitable planets comparable to Earth*. This characterization implies direct imaging and spectral analysis of the planetary light emission, absorption or scattering. Looking exclusively for Earth-like (same mass and G-type star) objects seems both too difficult and too restrictive, and a consensus ermerged on defining this set as made of objects with masses 1 to 10 terrestrial masses, with the parent stars of spectral types later than F.

Many aspects of exoplanet science currently deal with hot Jupiters or similar mass planets. On the other hand, the long term question clearly deals with Earths and super-Earths, and we shall focus on these. Yet, the continuation of observations and models for the larger masses is essential, as it will make more and more precise the continuity and differences along the mass spectrum, as well as stimulating new observational techniques.

3.3 A step by step approach

The way leading to the direct detection and characterization of planets is paved with many questions, either concerning the pre-required science or the associated observational strategy. As a starting point of this work, given the difficulty of the final goal we identify that a step by step approach is absolutely necessary.

A consensus emerged that the three main steps are (see Sec. 5.1.1) the statistical studies of the various planetary objects in order to get information about their abundance, the identification of potential targets (suitable for spectroscopic follow-up) and finally a spectroscopic analysis of these targets.

Different classes of planetary objects (see Sec. 5.1.2) provide another axis for the graduation for difficulty, as some types of planets are obviously easier to investigate than others.

Finally, while eventually one wants to carry out a systematic investigation that completely covers an unbiased sample, an earlier initial step can involve a fast track approach with focused studies on a (possibly biased) subset of that sample, that happens to provide a less challenging observational niche.

4 Science themes related to Blue Dots

We list below all what is required to know about the planet to ensure that it satisfies the habitable conditions. We include here all intermediate steps on planets without reference to life.

- *Stellar types and fraction of planets*
  How is the fraction of planets, particularly small planets, correlated to stellar type. Is the tendency of having small planets around small stars confirmed?

- *Architecture of planetary systems (including dust/debris disks)*
  Presently 80% of super-Earths are in multi-planet systems. Is this tendency confirmed? Are there "Trojan planets"? How often does early stellar winds blow off the gaseous part of the proto-planetary disc? [1].

- *Atmosphere and surface of planets*
  Can the species in atmospheres be very different from Solar System planets (sulfuric, nitrogen dominated, molecules, etc...)? Are there planets covered by a global ocean? Can one detect the liquid nature of portions of the surface?

- *Internal structure of planets*
  Are there ice-dominated, carbon-dominated, iron-dominated Earths and super-Earths?

- *Planet surroundings (moons, rings, magnetosphere)*
  Moons are important as potential abodes of life, rings have an important role as potential artifacts in the planet characterization, magnetospheres are important for the protection from strong stellar winds. How to detect these surroundings?

- *Habitability criteria*
  How is habitability related to the eccentricity of orbits or phase-locked orbits (thanks to their thermal inertia)? Investigate potential habitable moons ("Europa-like") outside the circumstellar habitable zone.

[1] According to Zuckerman, Forveille and Kastner 1995, this happens for 50% of young stars

5 Detecting and characterizing habitable planets

5.1 Axes of the discovery parameter space

5.1.1 Science potential levels

Following the lines of the step-by-step approach mentioned in the introduction (see Sect. 3.3), for a given class of objects we define the **science potential level** (SPL) of a technique by its capacity:

$*$	SPL1: to carry out a statistical study of objects in a given class;
$**$	SPL2: to designate targets in the solar neighborhood for spectroscopic follow up study;
$***$	SPL3: to carry out a spectroscopic characterization of the object.

5.1.2 Target classes

These classes are not meant to categorize objects according to their physical nature – they rather group objects of similar difficulty as far as detectability is concerned. The five classes identified are (by order of increasing detection difficulty):

1. **Hot giant planets**: these planets can be hot either because they are close to their host stars and highly irradiated, or because they are young;
2. **Other giant planets**: these planet include the warm and cold gaseous giants, down to Neptune size;
3. **Telluric planets out of the habitable zone** are the telluric planets (whatever their mass) which are either within, or outside, the habitable zone of their host star. These include hot irradiated planets and colder planets in the outer system. Hot young planets are also part of this category;
4. **Telluric planets in the habitable zone of M-type stars**: these might be Super-Earths or Earth twins;
5. **Telluric planets in the habitable zone of solar-type stars**: these might be Super-Earths or Earth twins.

5.1.3 Observing methods

The methods employed for detecting and characterizing exoplanets can be grouped in six large families, which are represented in the corresponding *Blue Dots* working groups:

- the **microlensing** method which consists in monitoring the photometry of distant stars in order to detect perturbations due to planets in microlensing events.
- the **transit** method which relies on measuring the relative change of the photometry and spectroscopy of the star due to a primary eclipse (the planet transiting in front of the stellar photosphere) or to a secondary eclipse (the planet disappearing behind the star).
- the **radial velocities** method (RV) which relies on measuring the Doppler shift of star spectra with high precision in order to detect the reflex motion due to the presence of one or several planets. This method also includes timing techniques.
- the **astrometry** method whether in narrow-angle or globally consists in measuring the relative position of stars in order to detect the reflex motion due to the presence of orbiting planets.

Methods	Planet classes				
	Hot Giant Planets (young or hot)	Other Giant Planets (same as in Solar System)	Telluric Planets (out of the habitable zone)	Telluric Planet in habitable zone around M-dwarfs	Telluric Planet in habitable zone around solar-type stars
Microlensing		★	★	★	★
Transits	★★★	☆☆	★★★	☆☆☆	★
Radial velocities	★★	★★	★★	★★	☆☆
Astrometry	★★	★★	★★		★★
V imaging / coronagraphy (SAI)	★★★	★★★	★★★	★★★	★★★
IR imaging / nulling (MAI)	★★★		★★★	★★★	★★★

Figure 1. Science potential levels ($*$: statistics, $**$: identification, $***$: spectral characterization) of each family of detection methods for different classes of exoplanets. A full symbol means that the capability exists under most circumstances while a hollow star means that the science potential level can be achieved only for specific targets (see Appendix B for details and examples of projects in each case). The scale of corresponding projects is color coded in green (existing facility), yellow (ground-based endeavor), orange (M-size space mission or budgetary equivalent), and red (L-size space mission or larger).

- the **single aperture imaging** (SAI) technique includes all types of coronagraphic methods on a single dish telescope, including external occulters as well as imaging techniques using Fresnel lenses, in order to separate the direct light of the planets from the stellar light which is usually hidden.
- the **multiple aperture imaging** (MAI) technique uses interferometric nulling, hypertelescopes, etc… in order to extract the direct light from the planet and to block the stellar light.

It is clearly understood that these methods are in many ways interrelated and complementary, in as much as observables obtained by one technique can often be interpreted only with the help of additional information from another technique. The reader is referred to Appendix B for more details on each methods and how they were evaluated.

5.1.4 Different scales of projects

Projects related to the different detection methods are listed and discussed in Appendix B. We recognize that those projects, which can be ground-based instruments or facilities, or space-borne missions, can be of different scales. These are symbolized by different color codes:

- **Green** code: existing, or already programmed efforts on an existing facility;
- **Yellow** code: projects which are not yet funded but whose effort is equivalent to that of a ground based instrument on an extremely large telescope ($\simeq$30 M€, 5-10 years);
- **Orange** code: projects whose effort is comparable to an ESA M-class mission ($\simeq$450 M€);
- **Red** code: flagship projects corresponding to an ESA L-class mission ($\simeq$650 M€, 10-15 years), or even larger projects (XL, $\geq$1 G€) carried out in worldwide collaboration where ESA's participation would be an L-size mission in itself, are color coded in red. A typical time frame for such projects is 20+ years.

5.2 Reading the grids

5.2.1 Methods vs. planet types (SPL)

Fig. 1 aims at providing a synthetic view of the potential of each family of detection methods for different classes of exoplanets.

		Project classes			
Methods	**SPL**	Existing	Ground-based	M-class in space	L-XL class in space
Microlensing	★	Giants		HZ telluric solar stars	
Transits	★★ / ☆☆☆	Close giants	Other giants	All other terrestrials	
Radial velocities	★★	Giant, close telluric	Habitable telluric		
Astrometry	★★	Giants		Telluric planets	Young + telluric in HZ
V imaging / coronagraphy (SAI)	★★★	Young giants	Far giants		Telluric planets in HZ
IR imaging / nulling (MAI)	★★★		Hot giants		All others

Figure 2. Timelines for various families of detection methods.

5.2.2 Timelines for the different detection families

Fig. 2 presents the progression in observation capacity for each family of methods, as a function of the increasing size of the projects.

5.3 Critical questions

Establishing the matrices detailed above led us to isolate the following questions, whose answer will have an impact on roadmaps:

1. Designating habitable planets for follow-up study: what are the relative parameter spaces of RV and astrometry?
2. Can we characterize habitable planets with transits?
3. Do we need to solve the exozodi question ? If yes, how to best solve it ?
4. How to consolidate efforts within the community and the related agencies?

These cornerstone questions are discussed in Appendix C.

6 Analysis

In the context of the goal of Blue Dots (spectroscopic characterization of telluric habitable exoplanets), a roadmap should be represented by the path of least effort from where we stand now (the green areas, upper left corner of the table in Fig. 1) to where we want to go (SPL3 in the last column, or in the last two columns if habitability is possible around M stars).

We should start by noting the successes of the discipline and recognizing that the green areas encompass some major achievements: spectroscopic characterization (SPL3) has already been achieved on some classes of exoplanets (hot close-in giants and young long periods giants) and a few telluric planets, albeit non habitable, have already been identified (SPL2). If one considers the youth of our field (the first exoplanets have been identified less than 15 years ago), this is quite remarkable indeed, and if the trends continue it would give all reasons to be optimistic for the future.

We should note also that there are "white holes" in the grids (not every method is relevant for every class of object). This means, and there is no surprise here, that the roadmap will necessarily have to rely on a portfolio of techniques in order achieve the Blue Dots goal. Likewise, the timelines table shows that no single method has relevant projects at all scale levels. So, while some techniques may run the show now, we should realize that other techniques need to be developed in order to take the relay when they are needed. It is difficult to justify demonstrators in the white areas by scientific output. "Least effort" in the roadmap means that a subsidiarity principle should apply: priority should be given, at each step towards the Blue Dots goal, to the method which enables to achieve it with the "greenest" color.

Applying this principle leads to the conclusion that :

- SPL1 has been undertaken some years ago and results esentially from RV and microlensing surveys. The statistics of giants is quite known within a few AUs (typically < 4) and the frequency of Super Earths is being investigated at short periods. Microlensing yields the statistics in the bulb down to a few Earth masses for separation of a few AU (0.5-5). There is clearly a need to extend this knowledge to longer periods (beyond the snow line) and to lower masses: this can be achieved by pushing radial velocity and direct imaging surveys.
- SPL2 on habitable exoplanets should be carried out preferably from the ground (yellow) by radial velocity. This is contingent to the acceptation that RV techniques are indeed capable to identify telluric habitable exoplanets (first cornerstone question, see discussion in Appendix C.1). However, an exhaustive approach should involve at some stage an astrometric mission to be more resiliant with respect to the stellar parameters and to identify Earth masses around the nearby stars to be eventually characterized spectroscopically.
- Spectral characterization of telluric planets will certainly require space missions for two main reasons. First, the Earth atmosphere will make difficult (at low resolution) the analysis of other telluric planet atmospheres. Second, performance (stability, contrast) can be met more easily from space. In any case ground based telescopes and in particular ELTs will certainly contribute to this study but at a more modest level. That being said, SPL3 of close-in telluric planets around M stars should be attempted by transit photometry if it is indeed possible (second cornerstone question, see discussion in Appendix C.2). Similarly, direct imaging at short wavelenghts could potentially achieve spectral characterization of telluric planets but for brighter/closer stars and larger separations (around 1-2 AU).

If one of these goals in the last item is achievable, this means that the goal of Blue Dots, at least in a selected sample of targets, can be achieved with a medium term (orange) project.

If not, and in any case for the solar type stars and Earth masses, spectroscopic characterization will require a flagship mission (red) which will involve either an infrared interferometer, or an imager in the visible (and obviously preferentially both). It is not possible at this stage to prioritize these two options but we can work on collecting the elements that will help make the decision:

- Pursue the study of the exozodi issue (see discussion of this cornerstone question in Appendix C.3) to see how it impacts the detectability of habitable exoplanets in both cases ;
- Comparative system study for the two concepts in order to be able to compare performances/costs with an equivalent maturity level ;
- Pursue the identification of biomarkers and assess their detectability both in the infrared and the visible/near IR range.

7 Conclusion

After 15 years of discoveries following the announcement of 51 Pegasi b in 1995, exoplanet science has evolved into a rapidly evolving and dynamic discipline. Arguably, one of the long-term objectives of this field of research is to seek the answer to the old question of *Is there life elsewhere in the Universe?*.

Exoplanet science has its foundations laid on the discoveries made in the last decade, namely over more than 400 stars with planets, including systems with several planets. These observations are complemented by an increasingly large amount of theoretical work, going from fundamental biology and biochemistry to the geophysical and chemical analysis of conditions on primitive Earth, from celestial to fluid mechanics, in order to establish boundary conditions for the apparition and sustainability of life. Exoplanet science is thus an interdisciplinary field and currently living an exponential learning curve, where the parameters used in modelisations to describe and understand the observations are enriched and modified on short periods of time – namely a few years.

Consequently, observational techniques are extremely diverse and are subject to intense creativity. Whether they involve ground- or space-based instruments, the levels of difficulty, hence of instrument sophistication, cost and implementation, are great. Hence, establishing observational strategies has to be done for a long period ahead, such as 10 to 15 years, while the field itself changes much faster. The mismatch of this time constant with the previous one offers a challenge for planning, to be taken seriously.

For super-Earths and Earth-like planets, three successive steps have been identified as a pathway to the realization of the Blue Dots goal:

- Step 1 (statistics): It is necessary to obtain a good measurement of the statistical occurence of terrestrial planets.
- Step 2 (target identification): A reasonable number of potential targets for spectroscopic analysis must be identified.
- Step 3 (characterization): Only after Steps 1 & 2 are complete comes the detailed characterization. This will require the determination of the physical and chemical conditions on the surface (solid, or solid/liquid, or liquid) and in the atmosphere. It also requires to obtain extensive information on the system as a whole: star, age, other planets, residual disk, etc.

To reach the ultimate goal above, at least one complex and costly space mission (flagship) will be needed. Planning for it requires more maturation of the field, as today many unknowns remain to be explored and clarified. Space is absolutely necessary to achieve this clarification task, which ought to be pursued in the decade 2010-2020. A number of new mission concepts and designs, in the cost range 0.5 to 1 G€, have already been put forward. In the meantime, Step 1 is well underway by means of ground-based radial velocity surveys (e.g., ESO/HARPS) and with missions such as COROT and KEPLER. This will be further extended if missions such as PLATO and/or EUCLID are approved, the latter potentially providing a broad statistical picture from microlensing events, and if ground-based projects are carried forward (e.g. VLT/ESPRESSO, E-ELT/CODEX,EXAO,VLTI/PRIMA).

The efforts on Step 2 are less advanced but well defined, the main focus being near-IR radial velocities of nearby stars (mostly M-type) and an astrometry mission (such as the proposed SIM-LITE), which could identify a complete set of reasonably close targets (distance ca. 10 pc). The successful completion of such projects will largely fulfill Step 2. Thus, besides pushing the ground-based efforts, an obvious conclusion seems to be a recommendation for the NASA mission SIM-LITE, with some minority participation from ESA.

To advance towards Step 3, where spectroscopy is mandatory, the study of transit (primary and/or secondary) and off-transit observations from space on already defined targets is likely to be the best option. Such mission should account for the following points:

- Broad spectral coverage (0.5 to 20 μm or even more) will be necessary to remove ambiguities in the interpretation of spectra, as already shown by simulations.
- Even the JWST may not be sufficient to achieve this, because of its limitations in observing time dedicated to exoplanet programs, operational pointing constraints and possibly an insufficient S/N ratio over this broad spectral range.
- Step 3 has already been achieved on massive planets, and one can be confident that it will soon extend to objects of smaller masses in the habitable zone for some targets. The feasibility of such mission is already established. The comparison with models becomes straightforward and highly conclusive.

While spectroscopy remains the main tool to achieve characterization, one should not underestimate the rapid progress made by coronographic and interferometric imaging techniques, making them capable to contribute to Step 3. For this reason some proposed missions (such as SPICA and a possible NASA Probe mission) have a chance to demonstrate the concepts. Nevertheless, this path requires the clarification of the issue of exozodi emissions, to establish whether and in which cases such emissions would present insuperable obstacles to full characterization. Double blind studies may provide a precious support for mission planning and data analysis. In any case, JWST will also contribute significantly to the progress in this field.

Once these three steps are mastered, a flagship mission, possibly with global resources worldwide (see a discussion of this critical question in Appendix C.4), in the decade 2020-2030 will follow naturally: the exoplanet community will be sufficiently knowledgeable to devise the best technological approach, to plan a sound observing program and to optimally exploit the data, especially spectroscopy.

The question *Is there life elsewhere in the Universe?* may or may not find an answer during the next decades, and nobody is able to predict the outcome of the quest. But one can agree on the fact that many inhabitants of the Earth, many cultures are supporting this quest, as a fundamental one for the representation of the place of Mankind in the Universe.

Appendix A: Key science questions and their rationale

The aim of this section is to identify the key scientific questions which pave the way to the resolution of the Blue Dots objective. For each of those questions, a short rationale is provided to explain the relevance to the Blue Dots theme, and the information needed (observables etc...) to address the question is presented.

The structure of this section matches the organization of the astrophysical themes Working Groups of Blue Dots (see `http://www.blue-dots.net`).

A.1 Targets and their Environments

1. **What are the physical properties (including mass and age) of the target stars?**
   This requires the determination of the fundamental stellar properties such as the mass, radius, chemical composition, and age. The possible techniques to obtain this information are the use of accurate calibrations of mass and radius, stellar evolution models and asteroseismology.

2. **What are the radiative properties (light and particles, T_{eff}, L_{bol}) of the target stars?**
   The overall radiative properties are the effective temperature and the luminosity, although a detailed spectral energy distribution covering from high (X-rays) to low energies (IR, radio) is essential. Spectroscopy is required to characterize the radiation field. Particle emissions in the form of stellar wind are also a requirement to fully describe the stellar radiation. Related to this, it is important to characterize the magnetic properties of the star (including flares and mass ejections) since they are basic to understand star-planet interactions.

3. **What is the time-variation of such emissions ?**
   The stellar emissions need to be characterized also in their time variation. This is especially relevant to the high-energy and particle components. The characterization must include all timescales, including those of minutes and hours (micro-variability, flares), days (spot modulations), years (spot cycles), centuries (Maunder-like minima) and Gyr (rotational spin down). The targets themselves can be used to investigate the short timescales, but the long-term changes can only be determined using stellar ensembles or stellar proxies to reconstruct the overall history.

4. **What are the characteristics of the stellar immediate surroundings (i.e., zodiacal dust, companion stars, brown dwarfs or giant planets)?**
   The properties of the stellar surroundings include the zodiacal dust (parametrized as the surface brightness vs. wavelength) and the multiplicity. The latter comprises stellar and brown dwarf companions, but also the presence of Jupiter-size planets, which may influence the presence of telluric planets.

5. **What are the stellar properties (mass, chemical composition) influencing the existence of telluric planets?**
   This question boils down to determining η_{Earth} (M,Z). That is, the fraction of stars with telluric planets as a function of stellar mass and chemical composition. This question is essential to decide what stellar types are the optimum targets for detailed searches. The correlation with parameters such as multiplicity and age must also be investigated. Additionally, putting our own Sun in context is highly relevant. Questions such as the comparison between the Sun and

other solar-like stars or the existence of chemical abundance patterns may provide important clues on the process of planet formation. In the latter case, it is important to compare the abundances of biogenic elements (C,N,O,P,S) in the Sun to those measured in other solar like stars.

6. **What is the census of telluric planets in the solar neighborhood?**
   A survey of the solar neighborhood should be conducted to uncover the presence of telluric planets and especially those in the habitable zones of their parent stars.

7. **What are the properties of stars and their circumstellar environments (disks, outflows) in which planets are actually forming? What are the earliest stages when this happens, and what environments are conducive to planet formation?**
   A survey of disk-surrounded classical T Tauri stars and disk-less weak-lined T Tauri stars in the nearest star-forming regions should be conducted. The presence of planets may be evidenced by disk properties (gaps, etc), but radial velocity measurements may be more reliable.

A.2 Formation and Evolution of Planetary Systems

1. **How is planet formation connected to the physical properties and temporal evolution of the host star and the circumstellar disk?**
   Current exoplanet samples show that the probability of finding a giant planet around a solar-type star is much higher if the stellar photosphere is rich in heavy elements. For earlier type stars (A-stars) and less massive planets (super-Earths), the metallicity correlation appears much weaker. Large samples of exoplanets, going to lower planet masses than today and sampling both early and late type stars, will be needed to get better statistics of how the metallicity dependence changes with host star and planet mass, thus giving important constraints on planet formation theories. The circumstellar gas disk furthermore leads to the migration of planets. Photoevaporation by stellar UV or X-rays can play a deciding role in stopping migration and parking planets in their final orbits. Removal of gas can also trigger planetesimal formation, leading to a late burst of planet formation and/or to the creation of planetesimal belts. Searching for planets around young stars (1-100 Myr) will allow such scenarios to be investigated observationally.

2. **What role does the stellar birth environment play for planet formation?**
   Several exoplanets are known to orbit the primary component of binary systems. The planet formation process will be heavily influenced by a binary star orbiting at a few AU, pumping up eccentricities of protoplanets and planetesimals. The presence of O and B stars in the vicinity of a young star can influence planet formation through photoevaporation, while supernovae and stellar outflows can lead to the injection of radioactive isotopes, such as ^{26}Al believed to be responsible for melting iron meteorite parent bodies, into the circumstellar disk. Searching for planets around young stars in various environments (low-mass vs. high-mass star forming regions, clusters) could give information about the universality of how the early solar system evolved.

3. **What is the predominant mode of giant planet formation?**
   The two most popular theories of giant planet formation are a) the core accretion scenario, in which a 10 Earth mass solid core attracts gas from the protoplanetary disk, and b) the gravitational instability scenario, in which giant planets form through a gravitational instability in the gas disk. The core accretion scenario is currently favored, but it is a slow process and struggles to explain giant planet formation during the gaseous disk phase. Disk instability, on the other hand, is rapid, but requires massive disks and very efficient cooling. The directly imaged planets around Fomalhaut and HR 8799, orbiting several ten AU from their host stars, are

challenging to explain by the standard core accretion scenario. Direct imaging of giant planets in wide orbits (several ten AU) and around young stars still surrounded by a protoplanetary disk, will give further input to determine the predominant mode of giant planet formation, and to extend and improve models of how gas giants and ice giants form.

4. **Is there a correlation between the existence and location of planetesimal belts and the existence of planets?**
Observationally detectable debris disks arise from the collisional cascade of (super-)km-sized planetesimals. The current exoplanet population shows little or no correlation with the presence of planetesimal belts. Nevertheless the first directly imaged planets (orbiting Fomalhaut and HR 8799) were found around stars with outer debris disks. The first step to forming giant planets is the formation of km-size planetesimals. Direct imaging of planets around young stars will be able to shed further light on any connection between planetesimal belts and the presence of giant planets.

5. **What can observations of exoplanets tell us about planet migration?**
Planets can migrate both towards and away from the star, due to gravitational interaction with gas and planetesimals. Observations of systems containing multiple giant planets, combined with dynamical models of planet-disk interaction and planet-planet scattering, will give us important knowledge of what role planet migration plays in the observed orbital architecture.

6. **What is the "typical" planetary architecture, and what range is realized in nature?**
Planet-planet scattering is believed to be the dominant driver of orbital evolution after the dispersal of the protoplanetary disk. The current exo-planet sample shows planetary systems that are very different from our solar system, with planet orbits displaying high eccentricities and inclinations. However, this may be a bias, because the radial velocity technique favors massive planets close to their host stars. Future investigations of giant exoplanets further than 3-5 AU from their host stars will shed light on whether the solar system orbital architecture is typical and on potential criteria for the long-term stability of planetary systems, with consequences for the presence and habitability of unseen terrestrial planets.

7. **What is the correlation of the presence of telluric planets with existence of super-Earths and gas giants?**
Giant planets migrate radially and interact gravitationally. The fate of low mass planets in such evolving systems is not clear. Searching for low mass exoplanets in systems where several giant exoplanets are known can give important information about where to find potentially habitable terrestrial planets.

8. **What range of terrestrial planet compositions is produced through the processes of planet formation?**
Delivery of elements to terrestrial planets, including the water crucial for life, depends strongly on the composition and presence of planetesimal belts (such as the asteroid belt) and the gravitational perturbation by giant planets. Discovery of systems containing both giant exoplanets and warm planetesimal belts would allow theoretical investigations of the type and quantity of elements delivered to unseen terrestrial planets.

9. **What are the properties of potentially existing free-floating Earth-mass objects?**
Free-floating exoplanets, particularly those lighter than gas giants, may originate from the gravitational perturbations in young binary star systems with planetary companions around each binary component. In a variety of cases, these perturbations can lead to ejections from the system and release of low-mass exoplanets into the interstellar space. If sufficiently frequent (e.g. in the inner Galaxy) they can be detected by gravitational microlensing events of short duration (days) towards bright stars in the Galactic Bulge. In addition, the recently

launched all-sky mid-infrared sky survey satellite WISE has the potential to discover free-floating youngish giant planets which emit cooling radiation at mid-IR wavelength from gravitational contraction. Candidates may also be followed up with JWST.

A.3 Habitability Criteria

Habitability of a terrestrial planet is closely connected to the open question of whether life could have originated and evolved on a planet beyond Earth. However, one should keep in mind that the origin and evolution of life is connected to habitability, but that the reverse is not automatically true. Although necessary conditions for the emergence, survival and evolution of life are still unknown, two main requirements are widely accepted as an unavoidable necessity:

1. long-time stability of planetary atmospheres
2. liquid water over geological timescales

The presence of liquid water, far from being a sufficient requisite for biology, allows the identification of potential extraterrestrial habitats or, more rigorously, to exclude dry environments, where the presence of life forms as we know them may be ruled out.

Sagan et al. (1993) analyzed a spectrum of the Earth taken by the Galileo probe, searching for signatures of life and concluded that the large amount of O_2 and the simultaneous presence of CH_4 traces are strongly suggestive of biology. To characterize a planet‘s atmosphere and its potential habitability, one can look for absorption features in the emergent and transmission spectrum of the planet. The spectrum of the planet can contain signatures of atmospheric species, what creates its spectral fingerprint. On Earth, some atmospheric species exhibiting noticeable spectral features in the planet‘s spectrum result directly or indirectly from biological activity: the main ones are O_2, O_3, CH_4, and N_2O. CO_2 and H_2O are in addition important as greenhouse gases in a planetary atmosphere and potential sources for high O_2 concentration from photosynthesis.

The presence or absence of these spectral features (detected individually or collectively) will therefore indicate similarities or differences with the atmospheres of terrestrial planets, and their astrobiological relevance.

The relevant key questions are:

- *What could constitute a (remotely detectable) biosignature under what conditions?*

  Biosignatures mean detectable atmospheric gas species, or a set of species, the presence of which at significant abundance strongly suggests a biological origin. This is the case for the couple $CH_4 + O_2$ or N_2O. If we base the search for signs of life on the assumption that extraterrestrial life shares fundamental characteristics with life on Earth, in that it requires liquid water as a solvent and has a carbon-based chemistry, it is justified to assume that extraterrestrial life on Earth-like habitats may use more or less similar input and output gases as life on Earth, that it exists far from thermodynamic equilibrium, and that it has analogs to bacteria, plants, and animals on Earth, although their spectral signatures can change significantly during geological timescales. Oxygen in high abundance is a promising bio-indicator, especially in combination with a reducing gas. A detectable concentration of O_2 and/or O_3 and of a reduced gas like CH_4 can be considered as a signature of biological activity that can be detected by a low-resolution spectrograph.

- *Conditions under which other biosignatures can form, e.g. methane biosignature and the limits of methanogens?*

CH_4 is not readily identified using low-resolution spectroscopy for present-day earth, but the methane feature in the IR should be detectable at higher abundances, provided that the spectrum contains the whole band and a high enough signal to noise ratio. Depending on the degree of oxidation of a planet's crust and upper mantle non-biological mechanisms can also produce large amounts of CH_4 under certain circumstances. N_2O is another biomarker on Earth, detectable at 17.0 and 7.8 μm with high resolution. There are other molecules that may act as biomarkers, e.g., the manufactured chloro-fluorocarbons (CCl_2F_2 and CCl_3F) in our current atmosphere in the thermal infrared waveband, but their abundances are too low to be observed spectroscopically at low resolution.

- *Minimum physical & chemical requirements to create a habitable environment?*

  - Early environments impact on evolution of life?

    The early atmospheres of terrestrial planets consist most likely of a reducing mixture of H_2, H_2S, CH_4, NH_3, CO_2, H_2O and rare gases. A comparison of the abundances of these rare gases is still present in present Earth's atmosphere, where the cosmic abundances of these gases indicate that Earth must have lost its primordial atmosphere through escape by the early active Sun/star and a strong solar/stellar wind as well as by impact erosion. The primordial atmosphere was replaced by a secondary slightly reducing neutral atmosphere of CO_2, H_2O, and H_2S (with minor amounts of other gases such as CH_4, CO, N_2) produced mainly by volcanic out-gassing, and volatiles imported via comets, meteorites and micrometeorites. Thus, the characterization of early terrestrial planet atmospheres orbiting young host stars will help us to connect the evolution of early planets environments to the conditions that life evolved at early Earth and possibly other planets.

  - Extreme physical and chemical limits for life in general?

    The basic habitability requirements for life as we know it are constrained by the following main factors: a certain time span where a planet can accumulate enough building blocks of life, liquid water which is in contact with these building blocks, external and internal environmental conditions that allow liquid water to exist, on the planet over a time span which is long enough that allows life to evolve. On Earth limits for life are related to temperature (0 - 113 degrees Celsius), surface pressure (>100 MPa), acidity (pH >12), UV radiation (on early Earth 200-400 nm range of the 25% less luminous Sun reached the surface), some organisms can tolerate pure CO_2 atmospheres and high N_2 contents should not prevent life, liquid water on the surface liquid water should be present but some halophilic organisms live also in high NaCl concentrations. A well designed mission for the characterization and search for signatures of life in planetary atmospheres can address the questions if life may evolve on exoplanets even under more extreme physical and chemical environments.

  - Limits of photosynthesis?

    The detection or non-detection of biomarkers on exoplanets orbiting cool stars with low UV fluxes will enhance our understanding on the limitations of photosynthesis.

  - Super-Earth environments and life?

    Active plate tectonics seems to be a crucial process in the evolution of life and the development of multi-cellular life on a planet surface. On super-Earths the kinematic energy of the mantel convection cells should be higher than on Earth-size planets. Plate velocities should be faster and orogenesis much heavier, resulting in higher mountains and more volcanic activity. However, plate tectonics and related habitability on super-Earths should depend on several factors, like the initial water contents, the forming of cratons and the distribution of convection cells. A careful characterization of such planets will show if these factors are individual for each planet or not.

– Influence of stellar activity on an atmosphere?

  The stellar X-ray and EUV (XUV) radiation and the stellar plasma outflow (winds, CMEs) constitute a permanent forcing of the upper atmosphere of planets, thereby affecting the atmospheric evolution and the conditions for life to emerge. The effect of these forcing processes is to ionize, heat, chemically modify, expand (under extreme XUV conditions even above a magnetopause) and slowly erode the upper atmosphere throughout the lifetime of a planet. The closer the habitable zone of the planet is, the more efficient are these processes. Protection of the upper atmosphere of a planet against stellar XUV/EUV and plasma factors requires a strong intrinsic dipole magnetic field and IR-cooling molecules (e.g. CO_2, H_3^+) in the thermosphere of the affected planet. A combined and well coordinated characterization of planetary atmospheres and the environment of their host stars, for example by Energetic Neutral Atom (ENA) hydrogen cloud topology modelling and observations, will allow us to understand how important the star-planet connection is to the origin of life and habitability in general.

– Is there a minimum mass for plate tectonics and habitability on a planet?

  For terrestrial exoplanets the conclusion can be drawn that planets with masses less than Earth or Venus (e.g., Martian sized bodies) may lose their ability for plate tectonics, and related magnetic dynamo action very quickly. Furthermore lower mass planets may not have stable atmospheres during the active periods of their host star and may therefore lose their atmosphere and water inventories. Water-rich Earth-mass bodies should maintain the mantel convection cycle for a long time, thus forming dry continents and basins with water. The characterization of low mass exoplanets in orbits of different types of stars will allow us to proof this hypothesis.

A.4 Planetary Atmospheres and Surfaces

An aspect of exoplanetary science that is both high-impact and cutting-edge is the study of extrasolar planet atmospheres. The ultimate goal is to obtain a high-resolution spectrum of an Earth-like planet, and although such a goal remains lofty, the key intermediate steps towards this end are already being taken with current technology for planets which are more massive and warmer that our own Earth. The characterisation of exoplanet atmospheres with current telescopes can be tackled with two main approaches: low resolution spectroscopy from space, using SPITZER and HST, or the ground, and high resolution spectroscopy from the ground.

The key questions we want to address are:

1. **What are the physical characteristics of the atmospheres?**
   (composition, temperature and pressure profiles, haze, clouds, winds)
2. **What is the nature and composition of the surface?**
   (rocky, liquid, icy...)
3. **What is the time (and seasonal) variability of those features ?**
   (role of dynamics and photochemistry)
4. **What is the internal structure of those planets?**
5. **What are the key processes which govern the chemistry in those exotic atmospheres?**
6. **May some of the chemical disequilibria be caused by life?**

The information needed to address those questions can be provided by observations. In particular:

1. Bulk planetary composition and internal structure can be constrained by:
   (a) Planetary radius/mass relation;
   (b) Atmospheric composition, which allows us to distinguish a Neptune-like planet from terrestrial one. Traces of volcanic gases in the atmosphere may provide insight about the composition of the interior.
   (c) Gravity. Indirect estimate of the planet's gravity through, e.g. primary transit observations of the atmospheres.
2. Atmospheric composition:
   (a) Most abundant / with strongest signature molecules can be detected at low/medium spectral resolving power (e.g. H_2O, CO_2), from the UV to the IR, depending on the absorption properties of the molecular species.
   (b) To detect less abundant/weaker molecular signatures a spectral resolving power of ~ 100 or higher is needed (e.g. C_2H_2, HCN);
   (c) Most atoms and ions can be found in the UV-VIS-NIR (e.g. Na, K, H_3^+). Very high spectral resolution is needed to resolve the line (e.g. Na was detected with Hubble-STIS and ground-base observatories).
3. Chemistry:
   (a) To appreciate the elemental and molecular abundances, a combination of appropriate spectral resolving power (R) and wavelength coverage is desirable. The required R will mainly depend on the molecule/element, on the wavelength interval and atmospheric region we are probing.
   (b) To appreciate chemical gradients (spatial and temporal) we need to be able to resolve spatially the planet (e.g. observations at different planetary phases) and/or monitor the atmosphere with a cadence and integration time which are shorter than the specific chemical reaction rate.
4. Planetary temperature and thermal structure:
   (a) First order approximation of the planetary temperature can be calculated knowing the star temperature and the orbital parameters. This estimate is clearly not considering the contribution of the atmosphere: planetary albedo and atmospheric opacities are responsible for significant increase or decrease of the planetary temperature.
   (b) The IR is the best spectral interval to probe the thermal structure of a planetary atmosphere. Spectroscopic signatures of molecules absorbing in the planetary atmosphere may provide a way to sound the vertical thermal structure of the atmosphere. The higher the spectral resolution, the higher the altitude we can probe: with Spitzer and Hubble low resolution spectroscopy and photometry, we tipically sound the atmospheric region between the bar and millibar level.
   (c) Horizontal thermal gradients require the ability to probe the planet at different phases. Today this can be attempted by monitoring light curves of transiting and non transiting planets e.g. with band photometry with Spitzer.
   (d) Indirect constraints of the temperature can be obtained through molecular and elemental absorption properties depending on temperature, or measurements of the atmospheric scale height through transit measurements (provided other parameters such as gravity and atmospheric main components are known).
5. Atmospheric dynamics and variability:

(a) Atmospheric dynamics and temporal variability, can be monitored by repeated observations of the thermal structure of the atmospheres. The integration time of the observations needs to be shorter than the time scales of the dynamics.

6. Clouds/aerosols:

   (a) The presence of clouds and/or hazes in a planetary atmosphere deeply influences the radiation balance and the climate of a planet. The optical properties of clouds and hazes depend on the size, shape and distribution of the particles. Spectroscopic observations in the VIS and IR of the planetary atmosphere may provide constraints on those parameters.

   (b) Polarized light in the VIS may provide a key contribution to detect and characterize clouds and hazes.

   (c) Repeated observations are necessary to detect temporal variability, formation and patterns.

7. Albedo/Surface:

   (a) Spectral-photometric observations of the planet in the VIS-NIR spectral range provide constraints on the planetary albedo and the surface type of a planet (provided there is a surface and the atmosphere is transparent enough to get a glimpse of it.).

   (b) Also in this case, polarization may be key to retrieve the type of surface.

   (c) The presence of liquid water at the surface might be detected.

8. Magnetic field, upper atmosphere:

   (a) Observations of ionized species mainly in the UV (notice though that H3+ is detectable in the NIR) offer the possibility of sounding the upper atmospheres of exoplanets, star-planet interaction, escape processes etc.

   (b) Exoplanetary radio emission might be detected with LOFAR, providing constraints on the presence and nature of the exoplanet magnetic field.

   (c) ENA hydrogen-cloud observations with Hubble/COS or after 2013 with the WSO-UV around exoplanets which form as a result of the interaction between the stellar wind plasma and the exosphere in the UV (Lyman-α) stellar wind plasma parameters and magnetospheric obstacles (allowing for an estimate of the planetary dipole moment) can be estimated.

Appendix B: Related projects and where they fit in

This section provides the underlying material from which the tables of Section 5 are built. Its structure matches the organization of the methods Working Groups of Blue Dots (see `http://www.blue-dots.net`).

B.1 Microlensing

Using the terminology defined in 5.1.1, microlensing corresponds to SPL1, namely *to carry ot a statistical study of planetary objects of various classes*.

Microlensing is unique amongst the various planet detection methods in that it does mot rely upon the detection of light from the planet or even the host star. The host star and planet(s) form a distorted gravitational lens. As the host star passes close to the line of sight with a background star its gravity causes the background star to appear brighter and then fainter as the line of sight closes and then widens. The presence of a planet is signaled by an deviation from a smooth change in brightness. Jupiter mass planets result in light curve anomalies lasting a few days while Earth mass planets cause deviations on a time-scale of hours. The sensitivity extends from the habitable zone outward to include free floating planets, The best sensitivity is just on the cold side of the habitable zone. Thus microlensing complements the other methods in surveying all types of cold planets.

- **Box 1 –** *Hot giant planets*

  The maximum sensivity of microlensing technique is at the snow line and decrease when getting closer to the star. It is not sensitive to hot giant planets.

- **Box 2/3 –** *Other giant and telluric planets*

  At present ground based microlensing is a 2 stage process with 2 wide field telescopes (MOA-2, OGLE-IV) searching for microlensing events by surveying millions of stars, and follow-up groups (PLANET, uFUN) that monitor a selection of these events to detect and characterise planetary events. A statistical estimate of the planet's mass and orbital separation can be obtained for any well covered event. However, the modelling of second order effects within the light curve and follow-up Adaptive Optics (AO) observations with large 8-10m class telescopes observation or HST observations can yield (10-20 %) accurate masses and separations.

  So far 18 planets have been found with microlensing ranging in mass from 1.6 M_{Earth} to several Jupiters. with 2 multiple planet systems. Analysis suggests that Neptunes and super Earths are $\simeq$7 times more common than in close-in systems probed by the Doppler/transiting methods.

  Over the next few years we expect the number of follow-up telescopes to increase, providing even better coverage of anomalous events. More significant will be the expansion of the network of survey telescopes, thus combining detection and follow-up thus allowing unbiased coverage of more and shorter time scale events. In particular sub-day events such as those from free floating planets will be searched for efficiently with wide field imager. If second order finite source effects are measured the mass can of a free floating planet can be estimated. These improvements the frequency of cold super-Earth to Jupiter mass + single planets, and multiple planet systems to be determined.

- **Box 4 –** *Telluric planets in HZ of M-type stars*

	Giant (close / young)	Giants (others)	Telluric (others)	Telluric HZ (M)	Telluric HZ (others)
Astrometry		1/2 (PRIMA,Gaia)	2 (SIM-Lite)	1 (SIM-Lite)	2 (SIM-Lite)
		2 (HST/FGS)	1(Gaia)	1(Gaia)	1(Gaia)
MAI	3(GENIE-like)		3(Darwin-like)	3	3(Darwin-like)
	3(Pegase)				
SAI	3(JWST,SPHERE)	3(EPICS)	3(TPFC-like)	3	3(TPFC-like)
Transit	3 (Spitzer,HST)	1/2(CoRoT,Kepler)	1/2(JWST)	3(JWST,SPICA)	1/2(JWST)
	2(Wide-field surveys,Corot)	1(LSST,PAN-STARRS-1)	1/2(Plato,TESS)	1/2(Plato,TESS)	1/2(Plato)
			1(Kepler)	2(Mearth), 1(WTS)	1(Kepler)
µlensing		1(Planet)	1(Planet)		1(Euclid/MPF)
RV	2(HARPS,HIRES,SOPHIE,Elodie)	2(HARPS,HIRES,SOPHIE,Elodie)	2(Expresso,Codex)	2(HARPS,HARPS-N,Expresso, Codex)	2(HARPS,Expresso, Codex)

Figure B1. Science potential of each family of detection techniques for different classes of exoplanets

Microlensing favours detecting planets in the KM dwarfs mass range stars because they are the most common stars. However, the HZ of M dwarfs is very close to the host star. The sensitivity of microlensing falls quickly interior to the Einstein radius and so is low for the HZ of M dwarfs. Because the habitable zone of more massive stars is further out (e.g. 1 AU for a G star compared to about 2 AU Einstein radius), with suitable small background stars, the HZ becomes accessible. Suitable, small radius, main sequence source stars cannot readily be detected from the ground because of atmospheric seeing, but are well within reach of 1m space telescope with a wide field imager.

- **Box 5 –** *Telluric planets in the habitable zone of solar-type stars*

  Even with a fully-fledged wide-field network, there will remain significant limits to the capabilities of planet detection from the ground. Only by monitoring smaller main sequence stars can we overcome the finite-source size effects that otherwise usually wash out perturbing signals from planets below few MEarth. Weather also remains a limiting factor to light-curve coverage. The only way to obtain uninterrupted surveillance of large numbers of well resolved main sequence stars in the bulge is to conduct a survey from space, where we escape atmospheric and weather limitations.

  Detailed simulations show that a dedicated space-based microlensing campaign (either a dedicated mission or part-time on say Euclid) can detect planets down to 0.1 M_{Earth} and moons. A space-based survey allows all analogues (except Mercury) of our own Solar System (measured relative to host mass), to be detected. It can also detect free-floating planets down to Earth mass as well as measure tens of thousands of planetary transit events. Space based measurements usually allow a complete model solution to be obtained without additional space based or Adaptive Optics follow-up. Access to such follow-up would become a bottleneck in the analysis of the planetary events of ground based observations. Whilst a dedicated space-based microlensing survey could extend the census down to 0.1 Mearth, a cost-effective survey down to Earth masses which push into the habitable zone could be achieved as a secondary science activity aboard a dark energy space mission, which has very strict telescope and camera requirements that are ideally suited to microlensing. The Euclid dark energy survey is a candidate for a medium-class mission within the ESA Cosmic Vision Programme and, if selected by ESA, would launch around 2018.

- **Required R&D Efforts:** on-going access to high angular resolution imaging (Adaptive Optics on large optical/IR ground based telescopes or HST/JSWT) is vital. With such imaging we can do very basic characterisation of the host star (spectral type) and planet mass and separation..

  The technology for the wide field high resolution optics needed for the survey telescope of a ground or space based telescope is well understood.

  Currently they are able to detect and alert microlensing events on a time-scale of hours to a day. With an aim to improving this timescale the community has begun experiments in the automated detection of anomalies, with subsequent triggering of autonomous follow-up observations.. Microlensing provides the toughest challenge for this sort of autonomous data gathering, because of the additional requirement to prioritise and schedule observations in a dynamic way based upon the behaviour of multiple events and telescope availability. This is an active area of research, with implementation envisioned in about 2015 for the world wide survey telescope network.

However the final process of modelling each event is a large non-linear computational problem within a large parameter space. Uniform, high cadence, high precision and uniform sampling expected from a uniform network of wide field telescopes or a space mission will alleviate some to computational burden. However any gain in efficiency will be swamped by the number of extra events.

Currently the output of microlensing is limited by the intricacies of modelling each event by a small number of experts. Speeding up the process by improving computational methods, adapting these to faster (parallel) computers and automating the overall modelling process is an area that requires an investment of human resources more than physical infrastructure. Such improvements are required in order to process the large number of events expected from a global network of ground based survey telescopes and/or a space based mission.

B.2 Transit : detection and characterisation

Using the terminology defined in 5.1.1, transit detection techniques can be used to achieve SPL1 and SPL2 (many-star surveys) or SPL3 (pointed spectrophotometry of transits).

The magnitude of the flux decrement (transit depth) due to a transiting planet scales with the square of the ratio of the planetary radius to the stellar radius. For reference, $\Delta F \approx (R_J/R_\odot)^2 \sim 0.01$ mag, while a transiting Earth-sized planet on a solar-radius primary produces a dip of $< 1 \times 10^{-4}$ mag, while a super Earth transiting a M dwarf would produce a dip of $<\sim 0.01$mag. Transit-discovery observations can contribute at the level of science potential level SPL1 and SPL2, while follow-up observations of known transiting systems with optical and/or infrared spectroscopy have the potential to achieve science potential level SPL3 (see Sect. 5.1.1).

- **Box 1 –** *Hot Giant Planets*

  Ground-based, wide-field transit surveys with typical photometric accuracy better than 0.01 mag, have allowed to detect several tens of hot Jupiters.

  The Spitzer and Hubble Space Telescopes have been utilized as follow-up tools for the broad spectral characterization of several hot Jupiters in the near, and mid IR wavelengths with detection of the molecules of water, methane, CO2, CO to date by both transmission spectroscopy (primary transit) and emisssion spectroscopy. Very recently, one group has shown that such observations could also be carried out successsfully from the ground.

- **Box 2 –** *Giant Planets at large orbital radii*

  CoRoT and Kepler (launched on March 5th, 2009) are capable to achieve an accuracy of $10^{-4} - 10^{-5}$ mag, respectively, in the visible (no spectral information). They will provide a census of transiting giant planets out to 1 AU based on $\sim 10^5$ targets. The proposed TESS all-sky survey concept would achieve a photometric precision similar to that of CoRoT, and will provide a census of transiting giants with periods up to several tens of days around bright stars. Statistical information on the rate of occurrence of longer-period giant planets will also be collected by ongoing and upcoming large-scale ground-based surveys, such as LSST and PANSTARRS. One very interesting prospect is the detection of exomoon around a giant in the habitable zone by transit timing variation and transit duration variation.

  Similar work to what has been achieved for characterisation of hot giants could be carried out on transiting giants on large orbits in the coming years and be compared with hot giants and those of our solar system.

- **Box 3/4/5 –** *Telluric Planets in and out of the Habitable Zone of M dwarfs and solar-type stars*

  CoRot and TESS have the potential to detect Super-Earth planets around all targets, and at a range of orbital radii, including the Habitable Zone of low-mass stars. Kepler has the potential to provide the first statistically sound estimate of $\eta_\oplus$. The ultra-high-precision photometry delivered by the proposed ESA PLATO mission (exceeding Kepler's) will also allow the detection of Earth-sized planets in the Habitable Zone of F-G-K-M targets.

  The recently started MEarth project, a photometric ground-based survey with an accuracy of $< 5.10^{-3}$ mag, is optimized for to search for transiting Super-Earths in the Habitable Zone of nearby M dwarfs. The WTS/UKIRT survey will target a large sample of low-mass stars, searching for transiting rocky planets with periods of a few days.

  Using existing facilities (HST, ground based IR spectroscopy) it is already possible to probe the atmosphere of transiting hot super earth such as GJ1214b. The James Webb Space Telescope and the proposed SPICA mission will be capable to perform spectral characterization (broad bands, spectra) in the near- and mid-IR possibly down to super Earth planets in HZ. The THESIS 1.4m space telescope concept is an exemple of a dedicated project to transiting extrasolar planets, from giants to super earth, from hot to habitable. It would cover a spectral range from 2-14 microns and will achieve photon limited stability over monthes time scale. The proposed SIMPLE instrument for the ELT would also be able to perform transmission spectroscopy of low-mass planets transiting M dwarfs.

B.3 Radial velocity

High-precision radial-velocity observations can contribute at the level of science potential level SPL1 and SPL2, according to the definitions adopted in Sect. 5.1.1.

The radial-velocity (RV) semi-amplitude expected for a star of mass $M_\star$ orbited by a companion of mass M_c with a period P and eccentricity e is given by:

$$K = 28.4 \left(\frac{P}{\mathrm{yr}}\right)^{-1/3} \left(\frac{M_\star}{M_\odot}\right)^{-2/3} \left(\frac{M_c}{M_J}\right) \frac{\sin i}{\sqrt{1-e^2}}\,\mathrm{m\,s^{-1}}, \tag{B1}$$

where i is the (unknown) inclination of the orbital plane. For the purpose of planet detection, the radial-velocity of the star must be measured from the Doppler shift using high-precision, high-resolution spectroscopic measurements. For reference (assuming $\sin i = 1$), a 1 M_J on a 11.8-yr orbit (and $e = 0$) induces $K \simeq 12.5$ m s^{-1} around a 1 $M_\odot$, a hot Jupiter with P=0.01 yr will have the parent star wobble with $K \simeq 130$ m s^{-1}, a Super-Earth (5 $M_\oplus$) in the Habitable Zone ($P \simeq 0.04$ yr) of a mid-M dwarf (0.4 $M_\odot$) induces $K \simeq 2.5$ m s^{-1}, while an Earth-like planet (1 $M_\oplus$, $P = 1$ yr) around a solar-mass star translates into $K \simeq 9$ cm s^{-1}.

- **Box 1/2 –** *Giant planets:*

  Current high-resolution spectrographs at visible wavelengths mounted on 4- to 10-m class telescopes, such as Coralie, Sophie, HARPS, HRS, and HIRES, are routinely achieving long-term precision of <3-5 m s^{-1}, contributing the vast majority of giant planet detections on short and long-period orbits (up to $\sim$ 15 yr) around solar-type stars recorded so far (including confirmation of transiting systems). This level of precision has also allowed for the detection of Neptune-mass objects on relatively short periods ($<$ 1 yr).

- **Box 3 –** *Telluric (Super Earths):*

  Super Earths (5-10 $M_\oplus$) on short periods have been detected by HARPS and HIRES. The HARPS-N spectrograph on the WHT telescope will soon be used for the spectroscopic follow-up of transiting Super Earths discovered by Kepler and CoRoT.

- **Box 4 –** *Telluric planets in HZ around M-dwarfs:*

  The next-generation, ultra-stable ESPRESSO spectrograph for the VLT (2014) will have the objective to reach $\sim$ 10 cm s^{-1} in the visible. This degree of precision will allow detection of Earth-mass planets within the Habitable Zone of lower-mass stars (later than K-type).

- **Box 5 –** *Telluric planets in HZ around solar-like stars:*

  The CODEX spectrograph concept for the ELT (2020) is set to achieve $\sim 1\,\mathrm{cm\,s^{-1}}$ precision, opening the door to the detection of Earth-mass planets in the Habitable Zone of solar-type stars.

- **Required R&D Efforts:** There are two main directions of research and development on which efforts are being and will be concentrated:

  Ultra-stable instrumentation in the visible: A first approach is set for the development of high-efficiency, high-resolution, fiber-fed spectrographs of high mechanical and thermal stability and using, if necessary, the simultaneous Thorium-Argon reference technique (or equivalent). These studies are ongoing for the CODEX/ELT spectrograph and its ESPRESSO/VLT precursor. A second option envisions the development of a novel calibration system based on laser frequency combs, which will be able to produce a super accurate, equally-spaced, stable source for wavelength calibration. This approach is planned for the HARPS-N spectrograph on the WHT telescope.

  High-precision instrumentation in the near-infrared: RV 'jitter' induced by intrinsic stellar variability (e.g., surface inhomogeneities) can be the ultimate limiting factor when attempting to reach the highest RV precision, needed to detect Earth-mass objects in the Habitable Zone of solar-type stars. In this respect, the development of spectrographs operating at near-infrared wavelengths can help mitigating this problem, as in the near-IR the contrast between stellar spots and the stellar disk is reduced. The first generation of near-IR spectrographs (e.g., CRIRES/VLT) is capable of delivering, at best, 5-10 m s^{-1} precision, not competitive with HARPS-level precision, but sufficient to highlight its importance when confirming/refuting claimed detections in the visible of giant planets orbiting very active and young stars. Future research and development is going to focus on achieving higher precision ($\sim 1-3$ m s-1) using calibration techniques based on either atmospheric absorption features or a gas cells, and optimizing the wavelength window for the observations. Such studies are ongoing in particular for the future NAHUAL and SPIROU near-IR spectrographs for the GTC and CFHT telescopes, respectively, which aim at improving the RV detection limits to $\sim$ 1 m s-1, particularly for cool, active M dwarf stars.

B.4 Astrometry

Using the terminology defined in 5.1.2, astrometry corresponds to SPL2, namely *be able to designate targets in the solar neighborhood for spectroscopic follow up study*.

The scales of astrometry projects span different types of missions:

- Ground-based astrometry on a large telescope like with FORS2 on the VLT can reach typically $100\,\mu$as over a few years necessary to detect giant planets at late M stars and Neptune-mass planets at brown dwarfs. These instruments already exist and should be classified in *green*. We can expect also future astrometric facilities based on use of adaptive optics and imaging cameras at large ground-based telescopes.

- Ground-based astrometry with an interferometer are already programmed and are being put into operation. One can quote VLTI/PRIMA and KI/ASTRA. They should be classified in *green* too, maybe a little bit darker and the expected performance $10 - 50\,\mu$as.
- Space-based global astrometry like GAIA/ESA mission will have a performance[2] of $25\,\mu$as but for star magnitude fainter than $V = 6$. The project is in construction with a launch foreseen in Aug. 2012. The project should be colored in *orange*.
- Space-based differential astrometry with SIM/NASA. A performance[3] of $0.2\,\mu$as is expected. The project is waiting for approval to go on phase C and could be launched as soon as 2015-2017. The cost of the mission is estimated to be the one of a ESA L-mission. The color code is therefore light *red*.

The astrometry signal is proportional to the planet mass M_P and the apparent semi-major axis a and inversely proportional to the stellar mass $M_\star$ and the distance d:

$$\alpha \quad \propto \quad a\, M_P\, M_\star^{-1}\, d^{-1} \tag{B2}$$

Ground-based projects can rely on 10 to 20 years of observations, when space-based missions are on a 5 year scale.

- **Box 1 –** *Hot giant planets* either because their are close to the orbits or because they are young.

  The brightness of the planet does not matter for astrometry but the distance planet-star does. For nearby stars, the typical astrometric signature due to close-in planets (giants around solar-type stars, terrestrial around M dwarfs) is:

  $$\alpha \approx 10 \left(\frac{a}{0.1\,\mathrm{AU}}\right) \left(\frac{M_P}{1\,\mathrm{M}_J}\right) \left(\frac{M_\star}{1\,\mathrm{M}_\odot}\right)^{-1} \left(\frac{d}{10\,\mathrm{pc}}\right)^{-1} \mu as \tag{B3}$$

  i.e. $\sim 10\,\mu$as or less.

  However astrometry is valuable for young giant Jupiters if this systems are not too far away. Closest distance to star forming region is 50pc to 140pc. A young Jupiter around a solar-mass stars and located at 140pc gives a signal of

  $$\alpha \approx 30 \left(\frac{a}{5\,\mathrm{AU}}\right) \left(\frac{M_P}{1\,\mathrm{M}_J}\right) \left(\frac{M_\star}{1\,\mathrm{M}_\odot}\right)^{-1} \left(\frac{d}{140\,\mathrm{pc}}\right)^{-1} .\mu as \tag{B4}$$

  This program is only reachable by SIM, and very marginally by GAIA.

  Box 1 should be in red.

- **Box 2 –** *Other giant planets* requiring a few $100\,\mu$as accuracy.

  $$\alpha = 500 \left(\frac{a}{5\,\mathrm{AU}}\right) \left(\frac{M_P}{1\,\mathrm{M}_J}\right) \left(\frac{M_\star}{1\,\mathrm{M}_\odot}\right)^{-1} \left(\frac{d}{10\,\mathrm{pc}}\right)^{-1} \mu as \tag{B5}$$

  A Jupiter around a nearby stars produce a signal of the order of $500\,\mu$as, therefore accessible to astrometry on a ground-based facility (large telescope or interferometer) or on HST/FGS. The box should be coded in green.

  GAIA will survey will survey many stars (450000) and will reach an accuracy of $25\,\mu$as very adequate for giant planets.

[2]The GAIA detection performance is based on a noise floor of $12\,\mu$as and a SNR of 2.
[3]The SIM detection performance is based on a noise floor of $0.035\,\mu$as and a SNR of 5.8.

However Jupiters or more massive giant planets producing a few $100\,\mu$as around nearby stars, are only the tip of the iceberg. There is the large family of lighter giants in the Uranus to Saturn mass regime, that produce only tens of μas. Here, 10-50 μas astrometry from the ground like VLTI/PRIMA or Keck/ASTRA (several yrs timeline required) will kick in for the 1-5 AU range. GAIA will also reach this accuracy, but its timeline may be too short, and with saturation at ~ 6 mag it cannot observe most of the nearby stars.

Box 2 should be green.

- **Box 3 –** *Telluric planets in general* may have a signal greater than the one from telluric planets in the habitable zone of solar-type stars. The signal would be:

$$\alpha = 0.3\left(\frac{a}{1\,\mathrm{AU}}\right)\left(\frac{M_P}{1\,\mathrm{M}_E}\right)\left(\frac{M_\star}{1\,\mathrm{M}_\odot}\right)^{-1}\left(\frac{d}{10\,\mathrm{pc}}\right)^{-1}\mu as \qquad \textbf{(B6)}$$

GAIA has the capacity to perform observations of $25\,\mathrm{M}_E$ planets at the best orbit (around 3 AU for a 5-yr mission) around a solar mass star at 10 pc.

SIM will be able to observe many of them. There is a large survey that will include them.

Box 3 is orange.

- **Box 4 –** *Telluric planets in HZ of M-type stars* are very close to their stellar host which compensates for the gain in stellar mass. The expected signal is below $0.2\,\mu$as.

For the moment no astrometric mission has been identified to be able to detect these objects.

Box 4 should remain white.

- **Box 5 –** *Telluric planets in the habitable zone of solar-type stars* will have have a signal of $0.3\,\mu$as (see Box 2). SIM has a deep survey around 60 stars to unravel them.

Box 5 is red.

- **Required R&D efforts:** Many astrometry projects have already conducted their own R&D. These efforts were concentrated on the calibration of the detector geometry, but also on metrology. Many R&D remain on data processing and the best way to reduce the astrometry data and calibrate them against systematic effects.

The SIM project has benefited of an exceptional R&D effort during almost 10 years which has allowed the promoters of this mission to solve almost all challenges related to stabilization of the spacecraft, nanometer vibration control and picometer metrology.

Another concept is being investigated by O. Guyon, called corono-astrometry[4]. A grid of dark (non-reflective) spots is physically etched/engraved on the primary mirror of the telescope. This mask creates a set of speckles at large angular separation from the optical axis. These speckles are radially elongated into diffraction spikes by the λ scaling factor in the focal plane. When the telescope is pointed at a bright star, these spikes will be superimposed on a background of numerous faint stars used as the astrometric reference. Precise measurement of the position of the bright central star against this background reference is possible by simultaneously imaging on a diffraction limited wide field camera both the spikes and the background of faint reference stars. Some tests are required to validate the method.

[4] `http://www.naoj.org/staff/guyon/04research.web/astrometry.web/astrometry.html`

B.5 Single aperture imaging

Using the terminology defined in 5.1.1, single aperture imaging has the potential to achieve SPL3, ie to carry out a spectroscopic characterization of various classes of exoplanets.

The following sub-section lists the various projects associated to single aperture imaging and briefly mention the science potential.

- **Box 1 –** *Warm Giant Planets:* Three classes of instruments are relevant here.

a/ Current AO (with or without coronagraphs) direct detection survey (VLT, Gemini, Keck, HST). Performance : a few M_J at few hundreds of AU for a few tens of Myr. As of today a few detection were obtained and photometric data points (mostly near IR and one in visible). Sometimes the mass regime is uncertain (planets/brown dwarfs limit). More recent results are those obtained for HR 8799 (Marois et al. 2008), Fomalhaut (Kalas et al. 2008) and β Pic (Lagrange et al. 2009).

b/ Future planet finder instruments on 8-m class telescopes (VLT / Gemini South / Subaru), namely SPHERE / GPI / HiCIAO will see first light in 2010-2011. These instruments will be capable of average contrast of $10^{-6} - 10^{-7}$ and possibly higher (10^{-8}) on some very bright and nearby stars. In the NIR (0.95 - 2.5 μm), this performance translates to a limiting mass of about $1M_J$ at few tens of AU and for a few tens of Myr. Main observations will consist in spectral characterization (R=20-50) of self luminous giants (young, massive). In the visible, SPHERE is capable to detect irradiated giants with $R > 1R_J$, at about 1AU for nearby stars.

c/ JWST includes 3 instruments relevant to exoplanet direct imaging (2014) : NIRCAM (2-5μm), TFI (2-5μm) and MIRI (5-28μm). They will achieve contrast of $10^{-4} - 10^{-6}$ and will complement planet finders especially on late type stars (K, M and L). Spectral characterization of mature giant planets is expectable. Performance: a few M_J at few tens of AU.

- **Box 2 –** *Cool Giant Planets:*

  Extremely Large Telescopes are scheduled for 2020s. EPICS and PFI (respectively at the E-ELT and TMT) are intended to reach $10^{-8} - 10^{-9}$ contrast in near IR (also in the Visible with EPICS). They will improve performances of 8m planet finders towards lower masses, older ages, farther objects with the ultimate goal to characterize mature giants and obtain first direct images (no spectral information) of Super Earths. METIS for the E-ELT will open a new area with unprecedented angular resolution in the mid IR therefore allowing the characterization of planets closer than those detected with JWST/MIRI.

- **Box 3 –** *Telluric (Super Earths):*

a/ Mission concepts were proposed to reach the realm of telluric planets with modest telescope sizes (1.5m, ideally 2m) provided large contrast and small Inner Working Angle can be met in order to characterize (R=50-100) large telluric planets and possibly telluric ones. This science program requires contrast as large as 10^{-10} which is expectable with fine wavefront control and achromatic coronagraphy. However, even if large telluric are potentially achievable small coronagraphs will mostly focus on spectral characterization of cool giants. Several concepts are being assessed in the US (ACCESS, PECO, EPIC) and one in Europe (SEE-COAST).

b/ Alternative solutions involving 2 spacecrafts are proposed: The concept of external occulters (50m in size) located at large distance (80000km) from the telescope takes advantage of Fresnel propagation. The Fresnel imaging array acts as a lens with no optics and is more modest in size. Both involves collecting telescope of 4m in diameter and will obviously overshoot the performance of small coronographic missions.

- **Box 4/5 –** *Telluric in HZ:*

  Angular resolution is definitely an issue to achieve the HZ especially around M stars. Therefore large telescopes are needed. Some missions concepts are proposed for the longer term: Large Fresnel imager (15m) and Large coronograph/occulter (8-16m). Objectives are 10^{-10} contrast in visible appropriate to characterize (R=50-100) telluric planets in the habitable zone.

- **Required R&D efforts:** For single aperture imaging, the main developments are dealing with 2 techniques "coronography" and "wavefront control", or more generally "stellar suppression" and "speckle nulling".

  – For coronography, there are several aspects, one is the achievable contrast. As of today, most coronographs provide in theory a complete attenuation of the starlight in some "perfect" conditions. The point is to reduce at the desired level the defects that are intrinsic to the manufacturing of coronographs. The second parameter is chromaticity. It is always desirable to improve the operating bandwidth of a coronograph first to attenuate the star at all wavelengths and second to allow for the use of spectrograph. Third, the distance at which the coronograph transmit 50% of the light from an off-axis source (named the Inner Working Angle) has to be matched with the science program (typically the distance where planets are expected to be found which is a few tenths to a few tens of AU) and with the angular resolution. The IWA can be relaxed for big telescopes like ELT while for small spatial telescopes it is very critical to retain a minimum value.

  – For wavefront control, the components (analyzers, deformable mirrors) have to be qualified at the system level and so high contrast testbeds are required (warm or cool depending on the concept). The development of algorithms to accurately correct and measure aberrations is also identified as a main research.

  These concepts does not apply to the case of external occulters/lenses where the R&D should rather be focused on : the deployment and stability of large scale structures in space at the requested accuracy (mm to μm) and, as for interferometric missions, formation flying is also critical although the level of accuracy is here more relaxed.

B.6 Multiple aperture imaging

Using the terminology defined in 5.1.2, multi aperture imaging corresponds to SPL3, namely be able to carry out a spectroscopic characterization of the object. Several techniques can be considered to get spectral information about the source such as chromatic visibility measurement, differential phase interferometry, or, if the contrast between the star and the planet is too high (and practically this happens in the case of telluric planets) nulling interferometry. In that case, and as a coronograph would do it, the signal from the star is canceled or strongly reduced by destructive interference. This technique requires a perfect matching of the wavefronts in terms of amplitude, phase and polarization and as a consequence, leads to strong requirements on the array co-phasing. Most of the projects and instruments described in this section are based on this technique.

- **Box 1 –** GENIE/BLINC/ALADDIN - like : ground-based nulling interferometry projects studied in the context of second generation VLTI instrumentation (GENIE), LBTI instrumentation (BLINC) and Antactica project (ALADDIN). Capable of 10^{-3} contrast in the L' band and N Band (LBTI). Designed for study of stellar environments (exo-zodiacal clouds brightness knowledge required for future direct characterization visible and infrared instruments) and spectroscopic characterization of hot Jupiter (R=10) if long baselines are provided. The main difficulties of these projects are the compatibility with existing facilities not designed for nulling interferometry (case of GENIE-VLTI) or the cost of specific facilities in complex environments (ALADDIN Antactica). The L' band is a trade-off between the sky brightness (thermal emission of the Earth atmosphere) and the level of atmospheric turbulence. The expected performance is adapted the site atmospheric quality. Study of exozodis can be achieved at a level of a few to a few tens of solar zodis.

PEGASE and FKSI: Following the example of previous concepts, PEGASE and FKSI are spaceborn project of simple nulling interferometer (Bracewell configuration), capable of 10^{-4} contrast in the near IR (2.5-7μm) with a stability of about 10 $\%$. They focus mainly on study of stellar environments with the capability of exozodi study at a level of a few solar zodi level depending on the spectral type of the star. The spectral characterization of Pegasides (R=50) was also proposed as a science case, but the development of transit spectroscopy using existing visible and infrared space facilities reduces the pertinence of such science case.

- **Box 2 –** not relevant

- **Box 3/4/5 –** DARWIN / TPF: Space concept of nulling interferometer. Capable of a fraction of 10^{-5} contrast with high stability (10^{-9}). Focus on spectral characterization of telluric planets in the habitable zone of nearby stars in the 7-20μm range with R=50-100. Taking into account the space environment (Earth,Sun, target environment...) such a performance can only be achieved using complex arrays with several telescopes and several sub-arrays allowing internal modulations of the signal. Because of versatility of the instrument requirements, several breakthrough regarding technologies (such as formation flying and associated metrology to position the telescopes at their right position in the array) are mandatory (see next paragraph). The concept of the recombining instrument, even if it is very complex, is already under study in the laboratory, where mission requirements are yet quite obtained for a simple two telescope configuration. Because of the cost and the incredible complexity of such a project, an large international collaboration will be mandatory. In addition, several technological precursors will be necessary to validate from space the concept of such a mission. In an case, a large space interferometer dedicated to the spectral analysis of Earth-like planet atmosphere is a long term project.

- **Required R&D efforts:** It is certainly pre-mature to define what a large multi aperture observatory dedicated to the spectral analysis of Earth-like planet atmospheres could be, but several R&D efforts can already be identified to allow the definition and development of such observatories. Some concern the recombination instrument:

  – large spectral range optical sub-systems, from visible, near to thermal infrared (beam combiners, phase shifters or controllers, flux balance devices, fast and accurate delay lines, modal filtering, fringe trackers...

  – fast and accurate co-phasing algorithms : because of the important integration time required by weak planetary signal detection, performant and stable co-phasing is mandatory. This implies the control of instrumental and space system drifts,

  – space approved technology : one of the difficulties of interferometry, is the constant need to check the optical alignments to co-phase the array, the development of technology less sensitive to vibrations and thermo-mechanical variations appears necessary : e.g; integrated optics devices, molecular glued sub-systems, new reliable opto-mechanical devices...

  – high performance metrology : one of the key points of interferometry is the ability to measure and correct the optical path differences between the array arms. This requires the development of high accuracy metrology devices.

Other required developments concerns space engineering in general and particularly:

– formation flying : Free flying telescopes appear to be the best ways to get variable and configurable baselines for the interferometric array. This supposes that the space mission can manage the moves of the whole flotilla and the stabilization of a configuration. This last point requires also the development of precursors to test a technique that has never been used at present.The question of formation setup is also crucial and has to be studied carefully.
– space interferometry : the complexity of an interferometric array requires the development of new standards for spaceborn observatory design in term of sub-system redundancy, mission management, instrument calibration...Once again, a precursor will certainly be necessary to validate the concept of interferometry from space.

B.7 Modeling

The characterization of planetary atmospheres do not only require challenging observational techniques but also robust modeling tools and expertise still to be developed. Exoplanet atmospheric models are the key to the interpretation of the spectral/photometric data - and this is particularly true at the low resolution and SNR expected for planets smaller and cooler than Hot Jupiters. Modeling is necessary to constrain the design of the instrumentation, to identify the signatures to be searched for, and to eventually derive the physical and chemical properties of the observed atmosphere. To reach the required level of modeling improvements must be achieved on the following points:

- Completeness of molecular, kinetic and spectroscopic data without which model results are irrelevant,
- Versatility : models must be able to simulate a broad diversity of atmospheric compositions, pressure and temperature, subjected to various irradiation conditions
- Self-consistency between various processes: radiative transfer, vertical structure, photochemistry, 3D circulation, cloud formation.

In addition to these improvements on the modeling itself, it is also crucial to develop:

- Independent modeling approach, for inter-comparison and validation purposes,
- Virtual observation obtained by converting synthetic spectra into virtual observations using realistic instrumental noise and resolutions,
- Analysis techniques for the retrieval of atmospheric parameters from observation data (grids of model results cannot be used for terrestrial planets due to the large numbers of parameters)

Progress to be done in the modeling are not made on a timescale shorter than instrumental progress and they may require specific computing facilities and manpower that has to be taken into account within the definition of an observing campaign.

Appendix C: Discussion of the critical questions

Following is the current status of the discussion concerning the questions that have been identified as being central to any road mapping exercise on the Blue Dots theme:

C.1 Designating habitable planets for follow-up study: what are the relative parameter spaces of RV and astrometry?

The objective of this annex is to summarize the discussion that was held at the Blue Dot meeting #6 (Bern, 26 March 2009) about the complementarity for the two techniques *astrometry* and *radial velocities* to be able to detect telluric planets in the habitable zone of solar type stars (last column of Fig. 1). It has been recognized that this step is essential to launch a spectroscopic space mission (last science potential level SPL3) with the aim of detecting bio-signatures of Earth-like planets. Beyond the level of instrumental noise of the instruments, the main issue is how to cope with stellar photometry variations due to stellar spots?

In order to obtain a better understanding of the question, the Blue Dot team has invited the two major contributors in this domain during the BDT meeting #6, Dr. Mike Shao from the Jet Propulsion Laboratory and PI of SIM and Dr. Stéphane Udry from the Geneva Observatory, key member of HARPS and ESPRESSO[5], and PI of an ESO Large Program on the *Search for super-Earths around solar-type stars*[6] with HARPS.

- **Performances needed**

  The astrometric signal of such an Earth-mass planet located at 10 pc around a solar-type star is $0.3\,\mu$as and decreases linearly with the distance of the star and. The radial velocity of the same planet is 9 cm/s (~ 8 cm/s for average inclination) and is independent of the distance.

- **Instrumental limitations**

  The SIM R&D has demonstrated in lab that they can reach a floor noise level of $0.035\,\mu$as which will allow SIM to be able to detect astrometric planet signatures down to $0.22\,\mu$as therefore either a Earth-mass planet at 15 pc or a $0.7\,M_\oplus$ planet at 10 pc. This correspond to a SNR of 6.

  HARPS has demonstrated on sky the capacity to reach RV residuals down to 0.8 m/s over a 4-5 years. These residuals contains instrumental noise, (telescope guiding,...), noise from stellar origin (pulsations, activity,...) and also smaller planets non yet detected. Many possibilities are undertaken to lower the instrumental noise level. The key elements are the stability and repeatability, the importance of good centering and guiding, and, calibration and wavelength solution. The claim is to be able to reach 0.5 m/s with a single Thorium Ar line stable to 1m/s over 1 month. In the last published data, Mayor et al. (2009, arxiv:0906.2780) announced the discovery of a $1.9\,\mathrm{M}_\oplus$ planet corresponding to a signal of 1.85 m/s with a residual of 1.53 m/s, i.e. a SNR of 1.2 smaller than the one used in astrometry.

  The next generation RV instrument is for the VLT and is called ESPRESSO with a goal of 0.1 m/s errors. First light should be 2014. Exposures of 900s require an 8-m telescope to reach 10 cm/s for stars brighter than $V = 8$. RV instrument on a ELT has a goal of 1 cm/s precision

[5] PI is F. Pepe from Geneva Observatory.
[6] 280 nights distributed over 4 years.

over a decade. Will there be enough access to do exoplanet surveys? In the discussion, the ELT solution was not considered.

- **Stellar intrinsic noise**

  The main limitation for both techniques at the level of Earth twins is the noise from stellar sources, i.e. biases coming from stellar pulsation, atmosphere granulation and worse of all stellar activity due to stellar spots.

  Using a spot area of 0.1% over a Sun-like star located at 10 pc, M. Shao computed that the spot can introduce a bias of the $0.25\,\mu$as for astrometry and 1 m/s for the radial velocity technique. Using a sun-like spot models, the SIM team has demonstrated that in fact the astrometry jitter due to solar-type activity is indeed about $0.08\,\mu$as per measurement and the RV jitter is 0.45 m/s. In case of the Sun, this bias becomes random only for epochs separated by more than 1 week.

- **Stellar noise correlation time**

  The stellar activity effect can only be averaged out on time scales longer than the stellar rotation (in case of the Sun the rotation period is one month). The noise is highly correlated if the lifetime of spots are longer. According to M. Shao, with a typical 1 week of correlation time, then to detect an RV signal of 10 cm/s at SNR=5-6 will take 3600 weeks, i.e. 50-65 years unless the stellar activity can be modeled out. S. Udry do not think it is the case, because this would require a stellar noise at all frequencies, which is not certain nor even known.

  Simulations of realistic stellar spots based on what is known from the Sun have been made since the Bern meeting by the Geneva group [7]. The group obtains RMS of 5-20 cm/s by bin of 10 days for the less active stars (log R'_{HK} between -5.0 and -4.9).

  The plan of the HARPS/ESPRESSO team is to observe each star for 15 min in order to average out the P-mode noise. The noise that is left after 15 min is about 0.5 m/s if it averaged out as $\sqrt{T/15\,\mathrm{min}}$. Then to perform 3-4 measures per night over 3-4 hours to average out the granulation effect. The goal is to observe the star over several consecutive nights to average the activity effects.

- **How quiet is the Sun? How quiet are most stars?**

  A preliminary analysis by M. Shao of about 100 stars observed by COROT was presented and it shows that $\sim 40\%$ of the stars are about 10 times or more variable than the Sun. Most likely only 10-15% of stars are quieter than the Sun. S. Udry replied that HARPS has been following about 1500 stars for several years and the 10-15% number seems to be consistent with that data.

  S. Udry since the Bern meeting has checked that the distribution of $\log\,R'_{HK}$ in a limited volume of stars around the Sun observed with HARPS shows that there are 25% of stars more quiet than $\log\,R'_{HK} = -5.0$, and 47% of stars more quiet than $\log\,R'_{HK} = -4.9$. For comparison, the Sun is -5.0 in quiet phase and -4.8 in active phase. This corresponds to the literature (e.g. Fig. 6 of Lockwood et al. 2007, ApJS 171, 260L). According to S. Udry, between 25% (log $R'_{HK} < -5.0$, ideal case) and 50% (log $R'_{HK} < -4.9$) of the dwarfs stars ([F]GK) can be considered as favorable cases for the RV technique if one is satisfied of the 20 cm/s by 10-day bin obtained for stars with $\log\,R'_{HK} = -4.9$.

  There seems to be some disagreement here between M. Shao and S. Udry. The point of convergence could come from Fig. 7 of the same paper, where we can see that despite the fact the Sun has not the lower $\log\,R'_{HK}$, it still has the lowest photometric variation as pointed out by Lockwood et al. (2007). So based on the $\log\,R'_{HK}$ criterion, S. Udry's analysis is certainly

[7] Information not yet published sent by S. Udry when finalizing this contribution.

right, whereas based on measured photometric variations, M. Shao's analysis is also consistent with observations.

To be able to detect Earth-like planets around a majority of stars, we will likely have to deal with star spot noisier[8] than the Sun. COROT data and KEPLER data should be able to confirm this first crude estimation in the short term although COROT data might be limited by hot pixel behavior.

- **Activity indicators**

  The idea is to derive simultaneous diagnostics to characterize the activity level of the star to correct the effect if possible or to select a posteriori the *good* observations (i.e. minimum of stellar activity).

  For example, during 2 yrs of the 11 year solar cycle, the Sun is very quiet. If there is an independent diagnostic to say, *this is really good data* then one has much more confidence in saying the signal is a planet rather than some stellar activity.

- **Detection of new Earths with radial velocities**

  S. Udry proposes to conduct a large survey with the ESPRESSO instrument on the VLT. 100 measurements per stars are needed, corresponding to a total of 5 nights per stars. The list is therefore limited to about 50-70 stars, which will be chosen to be the quietest ones.

  Another strategy is to search for Earth-like planets around M-stars in the IR using laser combs. It will be certainly interesting, but will it be considered at good candidates for spectroscopic follow-up? Also these stars are usually more active than solar-type stars (see discussion above).

- **Earth-like planets in the habitable zone of a star in the solar neighborhood**

  The ultimate goal that is pursued is to detect at least one Earth-Mass planet located in the Habitable Zone. The star which hosts this planet must be located at a distance close enough from the Sun so that enough photons can reach the telescopes to perform spectroscopic observations in a reasonable time in the next step of characterization. DARWIN and TPF studies have concluded that these stars should not lie further than **15-20 parsecs** from the Sun[9].

The discussion has allowed the Blue Dots Team to understand that in the ***very restricting case of Earth like planets located in the habitable zone***:

– Everybody in the audience agreed that radial velocity has the capacity with an 8-m telescope to detect several[10] $4-5\,\mathrm{M}_\oplus$ planets in the habitable zone if the instrumental noise is decreased to a level of 0.1-0.2 m/s within $d \leq 50\,$pc.

– Some participants think that after the first such detection, we should try to go direct detection to get the spectra of the exo-Earths and that astrometry will probably have more exhaustive results but an astrometric mission is not necessary.

[8] At the meeting, the statement was 2-3 times worse than the Sun, but S. Udry think it was a quick statement.

[9] M. Shao gave the following numbers extracted from coronographic imaging project. For a spectroscopic mission, the integration time goes as d^4, for background limited detection/spectroscopy. For example to detect an Earth clone with a SNR=10 and a 5% throughput efficiency instrument, it requires the following amount of time to detect (broad band) and to get a spectrum (50 spectral channels):

	2.5m telescope			4m telescope		
Distance	10 pc	20 pc	25 pc	10 pc	20 pc	25 pc
First visit detection	10 hours	3d	16 days	1.5 hours	1 day	2.5 days
Spectrum acquisition	21 days	11 months	2.2 years	3 days	51days	4 months

,

[10] And obviously even much more if the objective is not limited to the habitable zone.

– However in the previous estimation for the detection of $4 - 5\,\mathrm{M}_{\oplus}$ planets with RV, other participants point out that the sample which has been chosen extends to 50 pc. Because of flux limitation with a space coronograph, only the exoplanets found within 15 pc should be considered. This a reduction by a factor $(50/15)^3 = 40$. So it might be that at the end, only 1 or 2 $4 - 5\,\mathrm{M}_{\oplus}$ planets can be found with chances to be observed spectroscopically with a coronograph.

– Space-based astrometry on the other hand is a more expensive but systematic approach and has the capacity to detect Earth-like planets in the habitable zone around the 60 stars closest to the Sun.

– There is consensus that the RV approach should be followed even if there is a limited chance of finding appropriate habitable Earths at an accessible distance, because nobody wants to miss such a system. However for the identification of Earth-like systems for a spectroscopic follow-up for bio-signatures detection, astrometry is probably required to ensure a result but also more expensive.

– There was a discussion about the capability of coronographs to directly conduct the detection of Earth-like planets. However, the need to have more than 1 visit to confirm the mass of the detected candidates and the fact that Earth-like planets will not be visible about 66% of the orbit because they are under the coronographic mask does not make the technique very efficient with a number of stars limited about 10.

– There was a discussion about the relevance of searching for Earth-mass planets in the habitable zone of M stars despite the fact they are usually more active. One concern is that these planets located at 0.1 AU from a $0.01\,\mathrm{L}\odot$ star will be tidally locked. Of course these type of planets would be interesting but not necessary relevant for the search of life in habitable Earth-like planets. The second concern is the angular resolution needed to carry out the spectroscopic follow-up. 0.1 AU at 10 pc corresponds to 30 mas detectable by a DARWIN/TPF mission but not a coronograph whose inner working angles are usually larger than 40 mas. Even a late K star of $0.1\,\mathrm{L}\odot$ whose habitable zone is at 0.3 AU corresponds to 30,mas will not be a good candidate for a spectroscopic coronographic mission.

The conclusion of this debate was that radial velocity (ESPRESSO @ VLT) may have the capability (with the assumptions reported above) to detect a maximum of 1 or 2 habitable super-Earth within a reasonable distance from the Sun to allow spectroscopic follow-up. In the current state of the art, astrometry (SIM-Lite) is capable to survey the 60 closest stars from the Sun to search for planet as low as $0.8\,\mathrm{M}_{\oplus}$.

C.2 Can we characterize habitable planets with transits ?

The following is a summary of the corresponding panel discussion at the Pathways meeting

The panel has adressed the question of the feasibility of using transits to characterize habitable planets. D. Sasselov who chaired the panel introduce the question in the frame work of the Pathways conference. He says that the transit technique has reached a level of maturity that allowed to detect transits on 60 planetary systems to date. On a few of them, transit spectroscopy has been performed with HST and Spitzer opening a new way to characterize the atmosphere of planets using transmission spectra (primary transit) and thermal emission spectra (secondary transit). the topic of this panel is to discuss if one can expect to use this technique to characterize the atmosphere of habitable planets. Four experts have been invited: D. Sasselov (CfA, USA), G. Tinetti (UCL, London), M. Swain (JPL, USA), W. Traub (JPL, USA).

W. Traub recall the content of the article Kaltenegger and Traub (2009ApJ...698..519K), "Transits of Earth-like Planets" where using the Earth itself as a proxy they showed the potential and limits of the transiting technique to detect biomarkers on an Earth-analog exoplanet in transit. They calculated the optimum SNR for spectral features in the primary eclipse spectrum of an Earth-like exoplanet around a Sun-like star and also M stars for JWST. They found that the SNR for all important spectral features are on the order of unity or less per transit except for the closest stars. Their conclusion is that it is difficult to detect such features in one single transit. About the question of the case of a super-Earth (10 Earth-mass), their quite definitive answer is that it is even worse because the gravitationnal force decrease the atmosphere scale height.

M. Swain & G. Tinetti immediately remark that these conclusions are valid only for primary transit. In contrast, secondary transits, not mentionned by Traub, are very encouraging.

Tinetti describes the results obtained on hot Jupiters with detection of water, methane, CO2, CO in both primary and secondary transits. She stress the difficulty of the exercice to distantangle the degeneracies between temperature profiles and abundances to perform the atmosphere retrieval, and the importance to cover a wide range of wavelength. Data line lists are also a crucial ingredient in the process, with need to developpements especially at high temperature. M. Swain describe the concept of a 1.4m space telescop (THESIS) that could perform the transit spectroscopy of planets over the wavelength range 2-14 microns. It would be a very efficient tool for probing for hot/warm/cool Jupiter and Neptunes in a systematic way. The sensitivity will also extend from hot super Earth to habitable super earth. At the question if secondary transit spectroscopy of super earth not be done by the JWST, M. Swain answer that there is a need to have a large range of wavelengths from the visible to the mid-IR in order to break the degeneracy of the signature some chemical species. G. Tinetti says that some habitable planets around M-dwarfs could be characterized with this method. They clearly stress the major difference between probing Earth orbiting solar analogue in primary transit and super-Earth orbiting M dwarfs observed in secondary transit. There is a need for a change of paradigm instead of focussing on Earth twins, to take the opportunity to study warm and habitable transiting super earth.

The discussion continues with the question of which target can be observed? The number of photons collected by a space instrument limits the number of targets. In a way, aiming at M-dwarfs rather than solar-type stars in the solar neighborhood (d<20 pc) is more favorable because M-dwarfs are much more numerous than FGK stars. But somebody also raise the question of the magnitude of the M-dwarfs. G. Tinetti says that one already knows a M-dwarf of magnitude 9 located at 13 pc with a transiting planet where such technique may have success (GJ1214b, Charbonneau et al. 2009). Somebody in the audience points out that the probability to find such a favorable scenario is very small.

The general conclusion is then that transit spectroscopy is of high interest for characterizing planets but might be at the edge of what is possible for habitable Earth mass planets. The most favorable case is secondary transit of habitable super Earth around a M-dwarf. The Mearth project has already demonstrated its hability in finding a first hot super Earth in its first year of operation. The prospect of having few habitable super earth in a few years are very good.

C.3 Do we need to solve the exozodi question ? If yes, how to best solve it ?

The following are the conclusions and recommendations of the corresponding panel discussion at the Pathways meeting – a full summary of the discussion can be found in the Pathways Proceedings

When observing an extrasolar planetary system, the most luminous component after the star itself is generally the light scattered and/or thermally emitted by a population of micron-sized dust grains. These grains are expected to be continuously replenished by the collisions and evaporation of larger bodies just as in our solar zodiacal cloud. Exozodiacal clouds (“exozodis”) must therefore be seriously taken into account when attempting to directly image faint Earth-like planets (exo-Earths, for short).

The final SNR for direct exo-Earth detection depends on the quantity of exo-zodiacal dust around main sequence stars. On one hand, it drives the required integration time to detect the planetary signal as soon as its density reaches a few tens of zodis, and on the other hand, its potential asymmetries induce biases and false positives, which in turn demand the planetary systems to be observed longer in order to extract the actual planetary signal. If space missions had an unlimited lifetime, this wouldn't be a major issue, as one would just skip the inappropriate targets, or integrate longer to eventually reveal their planets. However, space missions are limited in time, and the exozodi issue could thus become a major hurdle in case bright exozodis are common. The sensitivity of current exozodi finders ($\sim$ 300 zodis at best) is not appropriate to assess whether exozodis in the 10–100 zodi range are common or not. A dedicated effort to solve this question is therefore mandatory.

Three possible avenues have been identified to make sure that exo-Earth imaging missions will be capable of reaching their goals:

- Perform an exozodi survey with a sensitivity of $\sim$ 30 zodis on a statistically meaningful sample of main sequence stars to constrain the distribution of exozodi brightness down to an appropriate level. Space missions can then be designed (in terms of aperture size and mission lifetime) to cope with the inferred mean exozodi level.
- Measure the exozodi level with an accuracy of $\sim$ 10 zodis on all the candidate mission targets, once the targets have been identified (e.g., Sun-like stars hosting exo-Earth(s), detected through high-precision astrometric or radial velocity surveys).
- Use the fact that the statistical distribution of cold debris disks will soon be known at a level similar to the density of the solar Kuiper belt thanks to Herschel. Extrapolating the statistics of cold debris disks towards that of warm exozodis is however not straightforward based on theoretical models, and needs to be backed up by observational data anyway.

The Panel therefore recommends that significant efforts and support be put in next generation exozodi finders, starting with LBTI and continuing with mid-term ground-based, balloon-borne or space projects such as ALADDIN or FKSI. The Panel also underscores the importance of continued modeling efforts to better understand the origin and dynamics of second generation dust grains around main sequence stars.

C.4 How to consolidate efforts within the community and the related agencies?

The following section is a summary of the discussions that took place in the Blue Dots meeting and that was finally discussed in a panel at the Pathways meeting.

Exoplanet science, and more generally the search for life on other worlds, is a recent field, yet one that corresponds to one of the most ancient quests of humanity, and one which has a very strong visibility within the general public with a positive image. In an era when general disaffection if not suspicion is felt for science, it is instrumental to bring the public's interest an excitement back into public research.

Yet because the field is relatively new, and multidisciplinary in nature, it does not have the institutional visibility that would match the general interest about the theme, and it is not yet seen as a discipline in its own right. More often than not, at all structuring levels of the scientific community, exoplanet science and exobiology appear implicitly as a subset of other disciplines - planetary sciences, instrumentation, biology etc. As a consequence, support for related projects is often fragmented, and each piece has to compete in its own field with already well-established programs.

The situation is particularly critical for space missions. The current trend among space agencies (ESA and NASA alike) is to select missions which are both low-risk and with an immediate return for science. This tends to favor "more-of-the-same" projects which are a more elaborate version of a previous mission: the community behind those projects is already well organized, the risks can be easily assessed, little new technology is involved, and the science case is easier to put forward.

It is clear that the goal of spectroscopic characterization of the atmosphere of habitable planets, in search of biomarkers, will ultimately require one or more very ambitious and innovative missions using new techniques like free-flying spaceships, coronography or interferometry. Those cannot meet the feasibility criteria as currently established by the space agencies. And the science return of a more affordable demonstrator (one that would retire the risk on the bigger mission) cannot meet the agency standards. This paradox implies that the current frame of mission selection by NASA, ESA and the likes is not compatible with a roadmap towards the detection of life on other worlds.

Another issue is the community support. In the long run, the community may want a DARWIN/TPF type mission, but which probe or M-class mission would lead to it? Is there a consensus first in the exoplanet community before looking for support of the astronomical and scientific communities?

In the panel discussions, three questions were tackled:

1. How to unite the community (behind a habitable planet search and study project)?
2. How to set up collaborations, and ultimately,
3. Do we need to re-organize our efforts, i.e., do we need to found a transnational exoplanet institute?

The first item was quickly addressed by the panel emphasizing that the community has to speak with one voice. In Europe, we must prepare the astronomical community for ESA Cosmic Vision Cycle No. 2 while the decadal review sets the stage in the U.S. Everybody recognizes that an event like the meeting *Pathways towards Habitable Planets* is a good way to have discussion within the community and converge to a message shared by mots of the community and should be pursued. Also the need for teaching people about interferometry or other advanced techniques is also fundamental in order to decrease the fear for new innovative methods that might help us to make a leap forward.

In the discussion of the second point, there was a general agreement to define a lead responsibility by one agency and therefore to favor a 80/20 NASA/ESA mission (or vice et versa) instead of an equally shared 50/50 mission. It was pointed out that ALMA does not qualify as a role model for a space mission. It was also emphasized that the community not only needs collaboration but even more needs coordination of all efforts!

The third question address the need for a new organisational vision, like a European or even a world-wide institute that would be dedicated to this exoplanet objective. This would not be the first time that a transnational institution is created to address a single scientific or technological challenge. An example that comes to the mind is ITER (China-EU-India-Japan-Korea-USA) which aims at demonstrating the scientific and technical feasibility of fusion power. At a European level, one can cite the CERN and the Large Hadron Collider to search for the Higgs Boson.

This Exolife Institute (or whatever its name) would be both a scientific center and a policy-making organization, carrying enough weight to become the natural partner of the different ground and space agencies, in order to build collaborations between them and coordinate their efforts of scientific and technological nature. It could receive enough support from its member states to be a structuring force in the field – some of that funding could actually go back to the respective agencies in exchange for their participation, which would ensure the authority of the Institute over those matters.

Of course, one of the immediate subquestions turned out to be whether a real institute would be necessary with a new building or just a virtual institute. Based on US experience with the NASA Exoplanet Science Institute (NExScI) in California and with the NASA Astrobiology Institute (NAI), the answer is not clear cut. In Europe, ESO and ESA terms of reference are different which would not lead to a conflict of interest. However it seemed finally more efficient to spread support over many nodes rather than having a centralized system to get a broad support. The possibility of creating exoplanet fellowships like the Carl Sagan fellowship appears to be maybe more efficient. In conclusion, the feeling was that a single new exoplanet institute was not such a good idea in the end.