Blue Dots initial report – v1.3

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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 we need to start making intermediate steps. The aim of this document is to provide a framework and some keys to help establish, before the end of 2009, a consensus around a roadmap. Projects issued from this roadmap would then be well positionned in the future competitions of our space (and possibly ground) agencies, and Blue Dots will work to take forward their promotion.

After the successful detection of several hundred extrasolar planets, their investigation, or exoplanetology, occupies in several respects a unique place in astronomy: because it is easily understandable by the general public and provides solid grounds to the question "is there life outside the solar system?". We believe that these aspects put exoplanetology, and its sister exo-biology which we incorporate here for simplicity in exoplanetology, in a different class than usual science and contribute more than any other astronomical discipline to the general culture.

Exoplanetology will require several generations of ground facilities and space missions. Even for the two first generations we already face quite a forest of projects and ideas. It it thus necessary to find a rational way to make the best choice(s) to orient ourselves in this forest.

We thus have to clarify the following points:

- What we want to know about the physical characeristics of exoplanets and life.
- What type of observations, including "biosignatures", can answer these questions.
- What methods and theoretical tools must be developed to make these observations and their interpretations possible

It is wise to not rely too much on prejudices about exoplanets and to be prepared to the unexpected. The present document develops a methodology to help further discuss and make the optimal choices. It is based on an integrated approach which deliberately puts specific projects on the side in a first phase (these are detailed in Appendix B), so as to be able to develop a synthetic picture of the situation from which a roadmap can be derived, keeping in mind the needs for diversity, open mindedness and flexibility as new elements appear.

3 Initial consensus

As a starting point of its work, BD identified points that make consensus within its community:

- A step by step approach is necessary and requires 3 steps : a statistical study of planetary objects in order to get information about their abundance, an identification of potential target and finally an analysis of these targets.
- Spectral analysis of Earth-like planets is mandatory, particularly to identify bio-signatures
- Direct characterisation of extrasolar planets should be done by spectroscopy, both in the visible and in the infrared spectral range.

The way leading to the direct detection and characterisation of planets is then paved with many questions, either concerning the pre-required science or the associated observational strategy. These questions are detailed in this document.

4 Science themes related to Blue Dots

This should be a summary and synthesis of Appendix A

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. For that we inevitably need some preconceptions on life. We do not want to be prisonniers of a too restrictive definition of life. We nevertheless accept to limit ourselves to life correlated to organic carbon chemistry developping in presence of liquid water at temperatures were complex molecules are stable. We also assume that the primary low entropy energy source to build complex molecules is stellar photons (we leave other alternatives open for future studies)..

These two apriori allow us to define "habitable niches". on planets were there is liquid water and a sufficient stellar flux.

We can therefore discuss further, beyond trivial questions, what is required to know about the planet to ensure that it satisfies these conditions. We include in this discussion all intermediate steps on planets without reference to life.

- *Stellar types and fraction of planets* How is the fraction of planets, particularly small planets, correleated to stellar tyape. Is the tendency of having small planets around small stars confirmed?
- *Architecture of planetary systems (including dust/bebris 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 gazeous part of the proto-planetary disc? [1].

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

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

- *Internal structure of planets* Are the ice-dominated, carbondominated, iron-dominated Earths and super-Earths?

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

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

5 Methods

5.0.1 Different families of techniques (definitions)

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:

- Single aperture imaging (SAI): this includes all types of coronographic techniques, including external occulters; as well as imaging techniques using Fresnel lenses;

- Multiple aperture imaging (MAI): interferometric nulling, hypertelescopes etc...

- Microlensing: photometry of microlensing events

- Radial velocities: this also includes timing techniques

- Astrometry: whether narrow-angle or global

- Transit photometry

It is clearly understood that these techniques are in many ways interrelated, inasmuch as observables obtained by one technique can often be interpreted only with the help of complementary information from another technique. The reader is referred to Appendix B for more details.

5.0.2 Modelling as a method

The characterization of planetary atmospheres do not only require challenging observational techniques but also robust modelling tools and expertise still to be developped. 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. Modelling is necessary to constrain the design of the instrumentation, to identifify 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 modelling 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:

- Independant modelling approach, for inter-comparison and validation purposes,
- Virtual observation obtained by convertinc 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 modelling are not made on a timescale shorter than instrumental progrees and they may require specific computing facilities and manpower that has to be taken into account within the definition of an observing campaign.

5.0.3 Different scales of projects

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

- Existing, or already programmed efforts, are coded in green;

	1	2	3	4	5
	Giant (close / young)	Giants (others)	Telluric (others)	Telluric HZ (M)	Telluric HZ (others)
Astrometry	2	2	2		2
MAI	3		3	3	3
SAI	3	3		3	3
Transit	3	2 ?	3 ?	3	1
µlensing		1	1	1	1
RV	2	2	2	2	2

Figure 1: Science potential of each family of detection techniques for different classes of exoplanets. See Appendix for details and examples of projects in each case.

- Projects which are not yet funded but whose effort is equivalent to that of a ground based instrument on an extremely large telescope ($\simeq$30 M\$, 5-10 years) are coded in yellow;
- Projects whose effort is comparable to an ESA M-class mission ($\simeq$450 M\$) are coded in orange;
- Flagship projects corresponding to an ESA L-class mission, or even larger projects 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.

5.1 The grids

5.1.1 Techniques vs. planet types (SPL)

Fig. 1 aims at providing a synthetic view of the potential of each family of detection techniques for different classes of exoplanets. 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 can be hot either because they are irradiated, or because they are young;
2. Other giant planets: these include the warm and cold gaseous giants, down to Neptune size;
3. Telluric planets (generic);
4. Telluric planets in the habitable zone of M-type stars;
5. Telluric planets in the habitable zone of solar-type stars.

	SPL	Existing	G	M	L - XL
Radio	3	Hot giants			All others
Astrometry	2	Giant planets	Giants (far)	Telluric planets	Young + telluric
MAI	3		Hot giants		All others
SAI	3	Young giants	Giants (far)		Telluric
Transit	2 - 3 ?	Close giants		All others	
µlensing	1	Giants		Habitable telluric	
RV	2	Giants, telluric	Habitable telluric		

Figure 2: Timelines for various families of detection techniques

5.1.2 Science potential

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

1. carry out a statistical study of objects in a given class;
2. be able to designate targets in the solar neighborhood for spectroscopic follow up study;
3. carry out a spectroscopic characterization of the object

5.1.3 Timelines for the different detection families

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

5.2 Critical questions

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

- Is transit spectroscopy of telluric planets around M stars possible ?
- What are the spectral range and spectral resolution needed ?
- What is the complementarity between astrometry and radial velocities to discover habitable planets ?
- Do we need to solve the exozodi question ? If yes, how to best solve it ?
- Do we need precursors to large flagship missions ?
- Are institutional structures compatible with an ambitious exoplanetary program ?

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, bottom left of the table) to where we want to go (a SPL3 in the last column, or in the last two columns if habitability is possible around M stars). The answer to that very question "Is habitability possible around M stars?" is therefore one cornerstone of the roadmap.

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 one class of exoplanets (hot 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 table (not every method is relevant for every class of object). This means (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's 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 SPL2 on habitable exoplanets should be carried out preferably from the ground (yellow) by radial velocity. This is contingent to the acceptation of the fact that RV techniques are indeed capable to identify telluric habitable exoplanets (second cornerstone question). Likewise, spectroscopic characterization (SPL3) of habitable planets around M stars should be attempted by transit photometry if it is indeed possible (third cornerstone question). If it is, this means that the goal of Blue Dots, at least in a select sample of targets, can be achieved with a medium term (orange) project. If not, and in any case for the solar type stars, spectroscopic characterization will require a flagship mission (red) which will involve either an infrared interferometer , or an imager in the visible (and obviously preferrentially both). It is not possible at this stage to choose between the two options, but we can work on collecting the elements that will help make the decision:

- Pursue the study of the exozodi issue 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 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.

Recommandation: to better integrate ground support with space programs.

A 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.

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 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 (microvariability, 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 (parameterized 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. Circumstellar disk evolution and Planet formation

    (a) How are the temporal evolution of circumstellar disks and the formation of planets connected? What is the role of planet-disk interactions on the planetary system formation process?

    (b) Which roles do host mass and metallicity play?

    (c) What is the role of the star/planet formation environment (low-mass vs. high-mass star forming regions, clusters)?

    (d) Which are the conditions that decide about predominance the planet formation scenario: Core accretion vs. Gravitational instability?

    (e) Are there fundamental differences in the planet formation in single vs. binary/multiple systems?

    (f) What range of terrestrial planet compositions is produced through the processes of planet formation?

2. Evolution of planetary systems

    (a) Are there common criteria for the long-term stability of planetary systems?

    (b) What is the "typical" planetary architecture, and what range is realized in nature?

    (c) How does planet migration affect the resulting planetary architectures?

    (d) What is the correlation of the presence of telluric planets with existence of superearths and gas giants?

    (e) Is there a correlation between the existence and location of planetesimal belts and the existence of planets?

    (f) Do exo-Oort's clouds exist and what is their role in the planet formation/evolution process?

    (g) What are the properties of potentially existing free-floating Earth-mass objects?

    (h) Which are the major unique characteristica of the Solar System?

3. Habitable Zone

    (a) Which parameters determine the region of the habitable zone in planetary systems? (Rem.: Is the term "habitable zone" a good working term at all?: a) There are many parameters that play a role to provide liquid water. b) There are many further parameters – beyond the existence of liquid water – that obviously played a major role to make Earth habitable.)

(b) Are giant outer planets a prerequisite for inner telluric planets with habitable zones?

(c) How does the stellar habitable zone evolve in time?

(d) Which are additional criteria which determine the habitability of planetary satellites?

(e) Is it possible to identify / separate a galactic habitable zone (bulge, disk, halo, clusters)?

(f) How might the formation history and subsequent dynamical evolution affect the potential for habitability? (e.g. outgasing, loss of atmosphere, internal energy and hence plate tectonics, impacts, orbital change, stability).

1. Circumstellar disk evolution and Planet formation

   (a) How do the structure and content of circumstellar disks (gas/dust) and major physical quantities/processes (e.g., magnetic fields, dust growth, planet migration) evolve in time?

   (b) How general are the answers to the above question, i.e., what is the influence of the chemical (metallicity), dynamical (e.g., multiple systems, clusters, planet-disk, planet-planet-interaction), and general physical environment (e.g., criteria for various planet formation scenarios, low/high-mass star-forming regions)?

   (c) Exemplary approaches: Observations of disk at various stages of their evolution; Planet population synthesis studies; Modelling planetary system dynamics, with and without gas disk; Simulating planetesimal evolution with different initial conditions; Thermal evolution of dusty disks; form rocky, icy, and water worlds

2. Evolution of planetary systems

   (a) Which are the criteria and which is the relative importance of these that determine the evolution of proto-planets in primordial disks and planets in debris disks (e.g., observation of planet-disk interaction)?

   (b) What is the influence of the environment on planetary systems (small scale: planetesimal belts; intermediate scale: exo-Oort's clouds; large scale: stellar neighbourhood)?

   (c) Exemplary approaches: Observation of planet-disk interactions; Determination of orbital parameters and masses of exoplanets

3. Habitable Zone

   (a) Space mission to Jupiter's Europe to find liquid water, etc.

   (b) Study the effect of high-energy photons and particles (T Tauri phase of young stars) and their interaction with protoplanetary atmosphere

A.3 Habitability Criteria

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 O2 and the simultaneous presence of CH4 traces are strongly suggestive of biology. To characterize a planet's atmosphere and its potential habitability, we 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 O2, O3, CH4, and N2O. CO2 and H2O are in addition important as greenhouse gases in a planet's atmosphere and potential sources for high O2 concentration from photosynthesis. The presence or absence of these spectral features (detected individually or collectively) will indicate similarities or differences with the atmospheres of terrestrial planets, and its astrobiological

A.3.1 The KEY questions:

- Biosignatures
  - what could constitute a (remotely detectable) biosignature under what conditions?
- Conditions under which other biosignatures can form
  - e.g. methane biosignature and the limits of methanogens.?
- Minimum physical & chemical requirements to create a habitable environment
  - Early environments impact on evolution of life
  - Extreme physical & chemical limits for life in general
  - Physical and chemical limits of photosynthesis
  - Impact of total atmospheric pressure on microbes
  - Man-made biosignatures & identification of advanced life
  - SuperEarth environments and life
  - Influence of stellar activity on an atmosphere
  - Is there a min or maximum mass for habitability?
  - Is there a minimum mass for plate tectonics on a planet?
  - What geochemical cycles could globally dominate a planet?

A.4 Planetary Atmospheres and Surfaces

1. **What are the physical characteristics of the atmospheres (T, P, haze, clouds, winds) ?**
   Spectra, polarization, spectral models
2. **What is the nature and composition of the surface: rocky, liquid, icy ?**
   Spectra, polarization, spectral models
3. **What is the time (and seasonal) variability of those features ?**
   Spectra, polarization, spectral models
4. **What is the internal structure of those planets?**
   Magnetosphere, planetary models
5. **What are the signatures for life ?**
   Input from the biology community

The following is the information needed to address those questions:

1. Bulk planetary composition, internal structure:
   (a) Radius + mass -> density
   (b) Atmospheric composition -> (distinguish Neptune-like planet from terrestrial one, any trace of volcanic gases? Etc.)
2. Molecular composition of the atmosphere:
   (a) Most abundant/with strongest signature molecules could be found at low/medium spectral resolution, both VIS and IR.
   (b) Less abundant/weaker signature/chemical gradients/temporal variations NEED higher spectral resolution (> 100), very good S/N, short integration time (few hours/days).
3. Vertical Thermal structure:
   (a) IR, NEED higher spectral resolution (> 100), very good S/N, short integration time (few hours).
4. Dynamics
   (a) IR, NEED Very short integration times + repeated observations to detect temporal variability.
5. Clouds/aerosols
   (a) All wavelengths
   (b) Easier to identify in VIS with the contribution of polarization

(c) Very short integration times + repeated observations to detect temporal variability

6. Albedo/Surface

   (a) VIS

   (b) Polarization can make a crucial contribution

7. Magnetic field, upper atmosphere

   (a) UV, ionized species, very high Res.

   (b) R, H3+ very high Res.

8. Biosignatures

   (a) As 2b, need to detect chemical gradients, temporal variations.

B Appendix B: Related projects and where they fit in

	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 3: Science potential of each family of detection techniques for different classes of exoplanets

B.1 Radial velocity

Box 1/2/3 – Current instrumentation : Coralie, Sophie, HARPS, HIRES, Lick, AAPS ... Already capable of long term precision of <1m/s allowing detection of Neptune and Super Earths objects on short period (<1year) and Jupiter on long period (10 years).

- NAHUAL @ GTC and SPIROU @ CFHT (2014). To improve the detection limit to 1m/s around M stars.

Box 4 – ESPRESSO @ VLT (2014). Objective is 10cm/s to allow detection of Earth mass planets within the HZ of K-M stars.

Box 5 – CODEX @ ELT (2020). Objective is 1cm/s to allow detection of Earth mass planets within the HZ of F-M stars.

Statement about IR and visible

B.2 Micro lensing

Box 1/4 – not relevant

Box 2/3 – Planet: TBD

Box 5 – Euclid: TBD

B.3 Transit

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, $\Delta F \approx (R_J/R_\odot)^2 = 0.01$ mag, while a transiting Earth-sized planet on a solar-radius primary produces a dip of $< 1 \times 10^{-4}$ mag. Transit-discovery observations can contribute at the level of science potential level 1 and 2, while follow-up observations of known transiting systems have the potential to achieve science potential level 3 (see Section 5).

Box 1 – **Hot Giant Planets**: Ground-based, wide-field transit surveys (for a comprehensive list of ongoing and upcoming projects see Table 4), with typical photometric accuracy of 0.01 mag, have allowed to detect several tens of hot Jupiters. The ongoing CoRoT mission is also providing many detections of close-in Giants.

The Spitzer and Hubble Space Telescopes have been utilized as follow-up tools for the (broad-band) spectral characterization of several hot Jupiters at visible, near, and mid IR wavelengths (several molecules identified).

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 (2012) will 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.

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. (CoRoT has recently announced its first detection). 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 Eart-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.

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 telluric planets in HZ. The proposed SIMPLE instrument for the ELT would also be able to perform transmission spectroscopy of low-mass planets transiting M dwarfs (still debated).

Survey	Location	Apert.(mm)	CCD	FOV (deg^2)	Range(mag)	Scale(")	Since	Nr. stars	Filters
OGLE[a]	Las Campanas	1300	8K×8K	0.34		0.26	1992	$> 10^6$	UBVRI
APT[b]	Australia	500	2K×2K	6	9.4	10-15	1995		B,V,R,I
Vulcan[c]	Lick Obs.	120	4K×4K	49	< 13		1999	6000	V, R
STARE[d] (TrES)	Tenerife	99	2K×2K	32		10.8	1999	>24000	B,V,R
ASAS-3[e]	Las Campanas	2×71, 250, 50	$2\times2K \times 2K$	64, 4.8, 936			2002		V,I
SuperWasp[f]	S. Africa, La Palma	2×8×111	2K×2K	16×61	<13	13.7	2002	$> 100K$	
BEST[g]	OHP	195	$2K \times 2K$	9.6	10-14	5.5	2002	100K	clear
XO[h]	Haleakla	2 × 110	1K×1K	51.84	12	25.4	2003	$> 100K/year$	400-700 nm
WHAT[i]	Wise Obs.	110	2K×2K	67.24	10-14	14	2004	15000	I
HATNet[j]	Hawaii, FLWO	6×110	2K×2K	67	I<14	14	2003	96K	I
VulcanSouth[k]	Antarctic	200	4K×4K				2004-2005		600-700nm
SLEUTH[l](TrES)	Palomar	100	2K×2K	36	< 14		2003	10000	r',g,i,z
PSST[m](TrES)	Arizona	100	2K×2K	36	10-13	10	2004	4000-12000	B,V,R, VR
BEST II[n]	Armazones	250	$4K \times 4K$	2.8^o	10-16	1.5	2007	100K	clear
TEST[p]	Tautenburg	300	$4K \times 4K$	4.8	10-15	2	2007	50000	(UBVI)R
ASTEP-South[q]	Antarctic	100	$4K \times 4K$				2008		
MEarth[r]	FLWO	2×400	$2K \times 2K$	0.18	< 9	0.75	2008	4131	
PANSTARRS[s]	Haleakla	4×1800	1.4bil pix.	49	<24	0.3	ongoing	6000/night	g,r,i,y
VISTA-ROPACS[t]	Paranal	4000	$8K \times 8K$			0.339	ongoing		Z,Y,J,H,K_s
ASTEP	Antarctic	400					2010		
PASS[u]	Antarctic	all sky		5.5-10.5				250K	
ICE-T[v]	Antarctic	2×600		65			2012	1.3M	yes
OmegaTrans[w]	Paranal	2600	16K×16K	1	13.5-17.5	0.26		200K	R

Figure 4: Ground-based transit surveys summary table.

B.4 Single aperture imaging

Box 1 – Current AO/coronagraphic direct detection survey (VLT, Gemini, Keck, HST). Performance : a few M_J at few hundreds of AU for a few tens of Myr. A few detection and photometric data points (mostly near IR and visible).

SPHERE / GPI / HiCIAO (2010-2011): planet finder instruments on 8-m class telescopes (VLT / Gemini S. / Subaru). Capable of $10^{-6} - 10^{-7}$ contrast in the near IR (0.95 - 2.5 μm). Focus on spectral characterization (R=20-50) of self luminous giants (young, massive) and nearby irradiated giants. Performance in near IR : $>M_J$ at few tens of AU and for a few tens of Myr. Performance in Vis : $>1R_J$, about 1AU.

JWST (2014) : NIRCAM (2-5μm) and MIRI (5-28μm). Capable of $10^{-4} - 10^{-6}$ contrast. Focus on spectral characterization of Mature Giant planets. Performance: a few M_J at few tens of AU.

Box 2 – Extremely Large Telescope Instruments (2018-2020): EPICS / METIS @ European ELT and PFI @ TMT. Objectives are $10^{-8} - 10^{-9}$ contrast in near IR and Vis (lower performance in mid IR). Performance expected: improves 8m planet finders towards lower masses, older ages, farther objects.

Box 3 – TPFC-like concepts (ACCESS, PECO, EPIC, SEE-COAST) of 1.5 - 2m class telescopes, external Occulters (4m) small Fresnel imaging lens (4m). Objectives are $10^{-8} - 10^{-10}$ contrast in visible appropriate to characterize (R=50-100) large telluric planets and possibly telluric ones.

Box 4/5 – Large Fresnel imager (15m) and Large coronagraph (8m). Objectives are $10^{-8} - 10^{-10}$ 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 "coronagraphy" and "wavefront control", or more generally "stellar suppression" and "speckle nulling".

- For coronagraphy, there are several aspects, one is the achievable contrast. As of today, most coronagraphs provide in theory a complete attenuation of the starlight in some conditions. The point is to reduce at the desired level the defects that are intrinsic to the manufacturing. The second parameter is chromaticity. It is always desirable to improve the operating bandwidth of a coronagraph first to attenuate the star at all wavelengths and second to allow for the use of spectrograph. Third, the distance at which the coronagraph 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 much relaxed for big telescope like ELT while for small spatial telescope it is very critical to retain a minimum value.

– For wavefront control, it is important to test the components (analyzers, deformable mirrors) at the system level and so high contrast testbeds are required. 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 and, as for interferometric missions, formation flying is also critical although the level of accuracy is here much relaxed.

B.5 Multiple aperture imaging

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 exemple of previous concepts, PEGASE and FKSI are speceborm project of simple nulling interferometre (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 interferometre. 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 interferometre dedicated to the spectral analysis of earthlike 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 earthlike 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 controlers, 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 keypoints 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 stabilisation 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 interfermetry : the complexity of an interferometric array requires the development of new standards for spaceborn observatory design in term of sub-system redondancy, mission management, instrument calibration...Once again, a precursor will certainly be necessary to validate the concept of interferometry from space.

B.6 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 μas 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 μas but for star magnitude fainter than $V = 6$. The project is in construction with a launch foreseen in Dec 2011. The project should be coloured in *orange*.

- Space-based differential astrometry with SIM/NASA. A performance[3] of 0.2 μas 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 colour 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:

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

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

[2]The GAIA detection performance is based on a noise floor of 12 μas and a SNR of 2.
[3]The SIM detection performance is based on a noise floor of 0.035 μas and a SNR of 5.8.

due to close-in planets (giants around solar-type stars, terrestrial around M dwarfs) is:

$$\alpha \approx 10 \left(\frac{a}{0.1\,\mathrm{AU}}\right) \left(\frac{M_P}{1\,\mathrm{M}_J}\right) \left(\frac{M_\star}{1\,\mathrm{M}_\odot}\right)^{-1} \left(\frac{d}{10\,\mathrm{pc}}\right)^{-1} \mu as \tag{2}$$

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

$$\alpha \approx 30 \left(\frac{a}{5\,\mathrm{AU}}\right) \left(\frac{M_P}{1\,\mathrm{M}_J}\right) \left(\frac{M_\star}{1\,\mathrm{M}_\odot}\right)^{-1} \left(\frac{d}{140\,\mathrm{pc}}\right)^{-1} .\mu as \tag{3}$$

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.

$$\alpha = 500 \left(\frac{a}{5\,\mathrm{AU}}\right) \left(\frac{M_P}{1\,\mathrm{M}_J}\right) \left(\frac{M_\star}{1\,\mathrm{M}_\odot}\right)^{-1} \left(\frac{d}{10\,\mathrm{pc}}\right)^{-1} \mu as \tag{4}$$

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.

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:

$$\alpha = 0.3 \left(\frac{a}{1\,\mathrm{AU}}\right) \left(\frac{M_P}{1\,\mathrm{M}_E}\right) \left(\frac{M_\star}{1\,\mathrm{M}_\odot}\right)^{-1} \left(\frac{d}{10\,\mathrm{pc}}\right)^{-1} \mu as \tag{5}$$

GAIA has the capicity to perform observations of $25\,M_E$ 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.

C 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 roadmapping exercise on the Blue Dots theme:

C.1 Is transit spectroscopy of telluric planets around M stars possible ?

To be filled here with a summary of the corresponding panel discussion at the Pathways meeting

C.2 What is the complementarity between astrometry and radial velocities to discover habitable planets ?

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 #3) 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[4], and PI of an ESO Large Program on the *Search for super-Earths around solar-type stars*[5] 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 μas and decreases linearly with the distance of the star and. The radial velocity of the same planet is 9 cm/s ($\sim$ 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 μas which will allow SIM to be able to detect astrometric planet signatures down to 0.22 μas 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.

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

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 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 μas 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 μas 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 [6]. 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's 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

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

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 litterature (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 anlaysis is certainly 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[7] 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 behaviour.

- **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

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

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[8].

The discussion has allowed the Blue Dot 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[9] $4-5\,\mathrm{M}_{\oplus}$ 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.

– 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.

[8] 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

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

– 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 biosignatures 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 mnore active. One concern is that these planets located at 0.1 AU from a 0.01 $L\odot$ 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 $L\odot$ 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 $0.8\,M_{\oplus}$.

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

To be filled here with a summary of the corresponding panel discussion at the Pathways meeting

C.4 Do we need precursors to large flagship missions ?

C.5 Are institutional structures compatible with an ambitious exoplanetary program ?

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 (a positive image) within the general public. In an era when general disaffection (if not suspicion) is felt for science, it is instrumental to bring the public's interest (even 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 (bias) 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. 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.

Besides, this goal should not be Europe's, or America's, or anybody else's affair, but belongs to humanity as a whole. It appears therefore desirable that its pursuit be delegated to a single, transnational institution that would be dedicated to this 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.

The 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 should 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.

The first step towards the creation of the Exolife Institute is the clear expression of such a need, in a solemn declaration by a group of world-class scientists. There are many opportunities for this in 2009: the International Year of Astronomy, the IAU General Assembly in August, the Pathways conference in September. Implementing such an organization and securing transnational support is obviously a challenging task of political engineering. Support from private money (eg. the Kavli foundation etc.) could be sought for a quick start, although this alone will not be enough to create something of sufficient magnitude. One may also consider direct sponsoring by research institutions (bypassing their respective government).