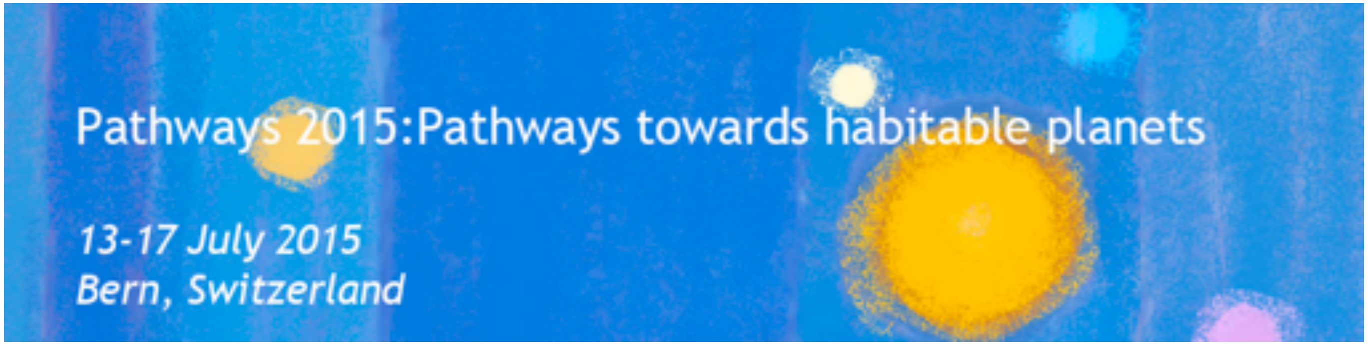
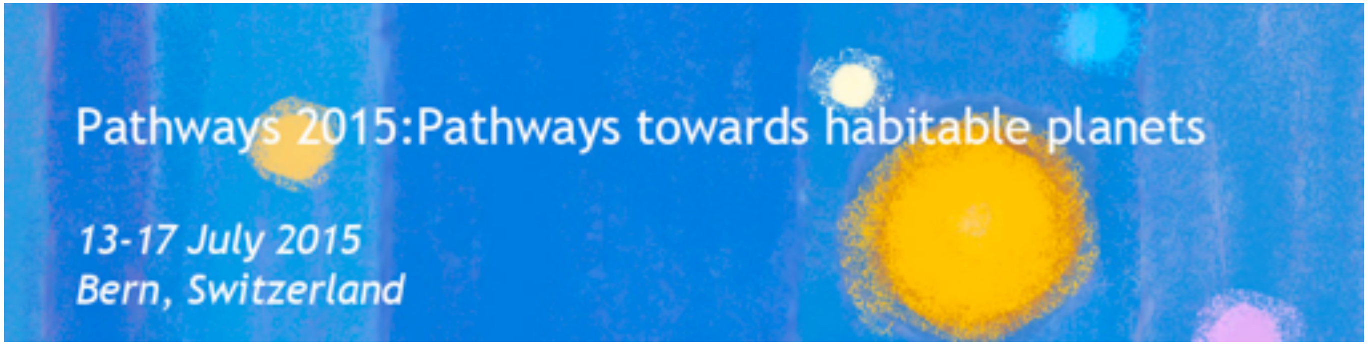


Tentative conclusions and discussion

Michel Blanc

ISSI, Bern



- Two introductory talks
- 7 « key questions »
- A host of satellite meetings

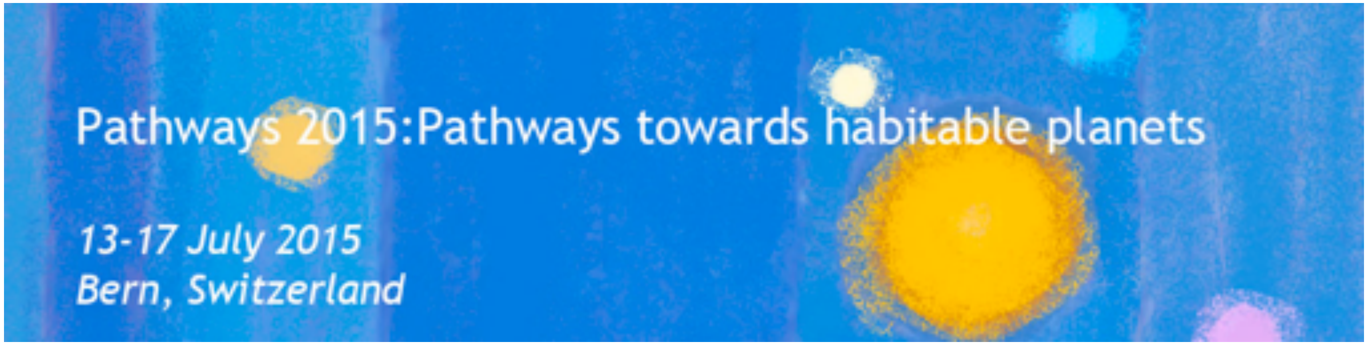
All trying to address the same « big question »

Where to go next, and along which pathway(s)?

Here is a non-specialist's understanding of what you have answered…

Our 7 « key questions »

- KQ 1 – Is the Sun-Earth pair a good paradigm for an inhabited system?
- KQ 2 – How do we define meaningful biomarkers?
- KQ 3 – Is the habitable zone a well defined concept?
- KQ 4 – What can we learn from solar system synergies?
- KQ 5- How do we build synergies between ground and space?
- KQ 6 – What can we expect from approved projects?
- KQ 7 – What future capacity is needed?



Or in other words:

- Where to look? (KQ1, KQ3)
- What to look for? (KQ2, KQ4)
- How to optimize the use of existing or planned facilities ? (KQ5, KQ6)
- What new facilities to design and use? (KQ7)

Setting the stage
(F. Forget, M.-C. Maurel)

1- It takes life (as we know it) four conditions to emerge:

- Liquid water
- Energy
- Chemical species
- … and time!

Habitability should deal with these four dimensions, not just liquid water!

2 – even if we look at the « water » dimension only, there are at least four classes of habitability, out of which only class I deals with durable surface water! (Lammer et al., 2009)

3 – For class I habitability, one can define a HZ as covering the range of orbits around a star where it is not impossible to find a habitable planet with surface liquid water. However being in the HZ does not mean that a planet will be habitable: this depends on each relevant planet's climate system, and may vary with time: note that the Earth has developed a « strategy » (with the carbonate-silicate cycle) to remain habitable.

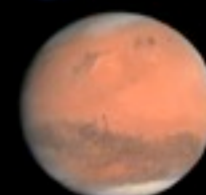
Pathways 2015:Pathways towards habitable planets

13-17 July 2015
Bern, Switzerland

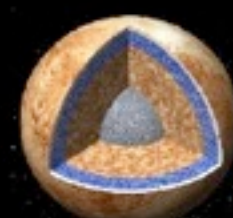
4 kinds of « habitability »

(Lammer et al. Astron Astrophys Rev 2009; Forget 2013)

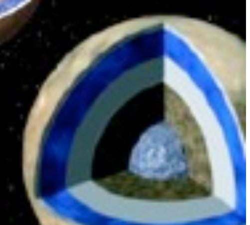
- **Class I:** Planets with permanent surface liquid water: *like Earth*



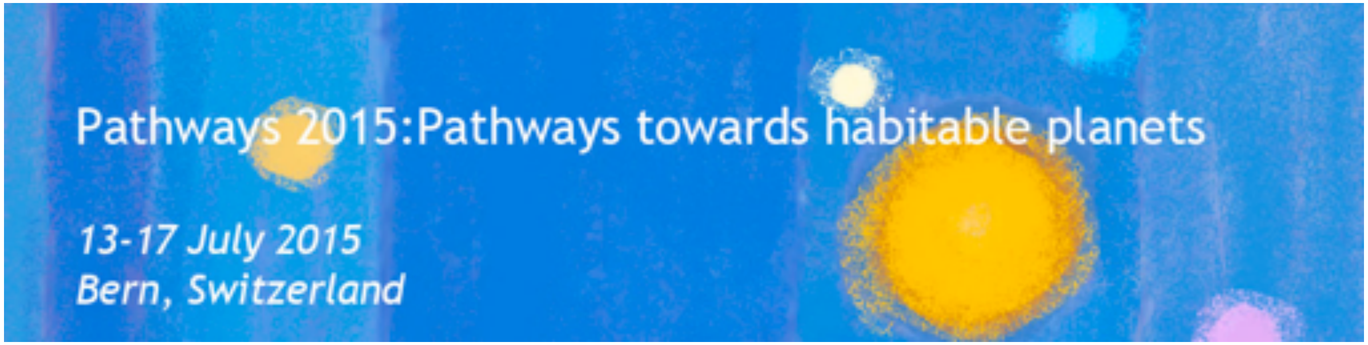
- **Class II :** Planet temporally able to sustain surface liquid water but which lose this ability (loss of atmosphere, loss of water, wrong greenhouse effect) : *Early Mars, early Venus ?*



- **Class III :** Bodies with subsurface ocean which interact with silicate mantle *(Europa)*



- **Class IV :** Bodies with subsurface ocean between two ice layers *(Ganymede)*



The « time » dimension, and the evolutionary path of life. Lessons learnt from biology:

- It takes billions of years for life, if/where it exists, to emerge/evolve
- Each evolutionary path towards « life » is necessarily unique: little chance that the terrestrial evolutionary path (which may have started several times) has been repeated elsewhere
- In addition, on Earth we can no longer trace a clear boundary between living and abiotic !
- In these conditions, we can still define what would be biomarkers from the Earth case, but extrapolation to other worlds is partly arbitrary
- Search for « anomalies » instead, based on the exploration/ characterization of a large class of objects: one must not be too focused

THUS WE HAVE A PROBLEM TO START WITH

- We can define the HZ (where to look a priori), but this does not guarantee habitability, which is strongly dependent on each planet's climate system

- Defining the biomarkers (what to look for) is to some extent dependent in an unknown way on the characteristics of each planet

First conclusion: the need to explore the planetary systems we study, and then to characterize as well as possible the planets they harbor, is a prerequisite to the study of « habitable » objects

Where to look? (KQ1)

Should we look only at planets in HZ around G stars?

- It is interesting to look there (to better understand the Sun-Earth system), but we need to look around other stars. For instance, looking around M stars would be statistically more significant in terms of the expected number of habitable planets.
- What we must take from the Sun-Earth pair is the underlying processes which have made it able, with time, to support life:
  - Overall history of collisions and migration among planetesimals and planets in the parent planetary system
  - Delivery of volatiles (and water) via icy planetesimals and comets?
  - Delivery of organics,
  - Stellar irradiation conditions, primarily UV fluxes, and their evolution
  - Coronal Mass Ejections (CME's), super CME's, energetic particle fluxes and their effect on atmospheric composition
  - Presence of a magnetosphere and its evolution, geological evolution, gain/loss of atmosphere
- In that sense it is meaningful to investigate whether we can find other star-planet systems similar to the Sun-Earth system, or other ones which work differently: the study of star-planet systems is a subject in itself.

Where to look? (KQ3)

Should we look only in the HZ?

- The HZ concept is a convenient way to assign targets to our search, and is used extensively: see work on the determination of the occurrence frequency of terrestrial planets in the HZ using Kepler data (SatMeet 5).
- But the search must remain broader, because:
  - Being in the HZ does not automatically imply habitability, which involves stellar, planetary and planetary system parameters (see SatMeet 8 « connecting stellar abundances and planet habitability »)
  - It does not accomodate well all planetary situations (excentric orbit planets, planets on synchronous orbits…)
  - One can understand the mechanisms characterizing the HZ only in the broader context of what happens to planets beyond its inner and outer limits (examples: the « Venus zone », the dry planets…)
- Regard the HZ merely as a way of defining our main « Hunting Zone », but keep as our priority the goal of characterizing planetary systems as a whole

What to look for?
(KQ4)

- What we learn from studying the Solar System is key to understanding exoplanetary systems
- Reciprocally, processes discovered at exoplanets (e.g., migration) have provided key elements for our understanding of solar system history
- In the Solar System, the diversity of planet classes corresponds to an equal diversity of atmospheric compositions, and it connects directly to their formation conditions in the Nebula.
- Thus we must explore this diversity in exoplanetary atmospheres and see what it tells us on planets formation and evolution – transit spectroscopy makes it uniquely possible!
- Cosmochemistry studies have successfully connected the composition of extrasolar asteroids to that of solid Earth!

We must continue to build on solar system/exoplanets synergies.

We must continue to explore, step by step, the diversity of exoplanets structures and compositions. The time of detailed characterization of a few objects will come, the time of exploration of the whole family is far from over!

What to look for?
(KQ2)

Look for biosignatures?

- The least one can say is that biosignatures are not a well defined concept (e.g., talk by M.-C. Maurel): rather look for chemical « anomalies » and complexity
- Even O2 can produce « false positives » for certain stellar spectral types
- What we need is to provide for « habitability candidates » a comprehensive description of the molecular content of their atmospheres, based on a broad survey of atmospheric spectra, and placed in the broader context of a characterization of the planet, its family of objects and the planetary system as a whole. The ExoMol tool (UCL) will be very useful for that purpose
- Distinction between biotic and abiotic features will possibly emerge from this approach, again based on comprehensive spectral data sets and the support of models/theory.

optimizing the use of existing or planned facilities (1)

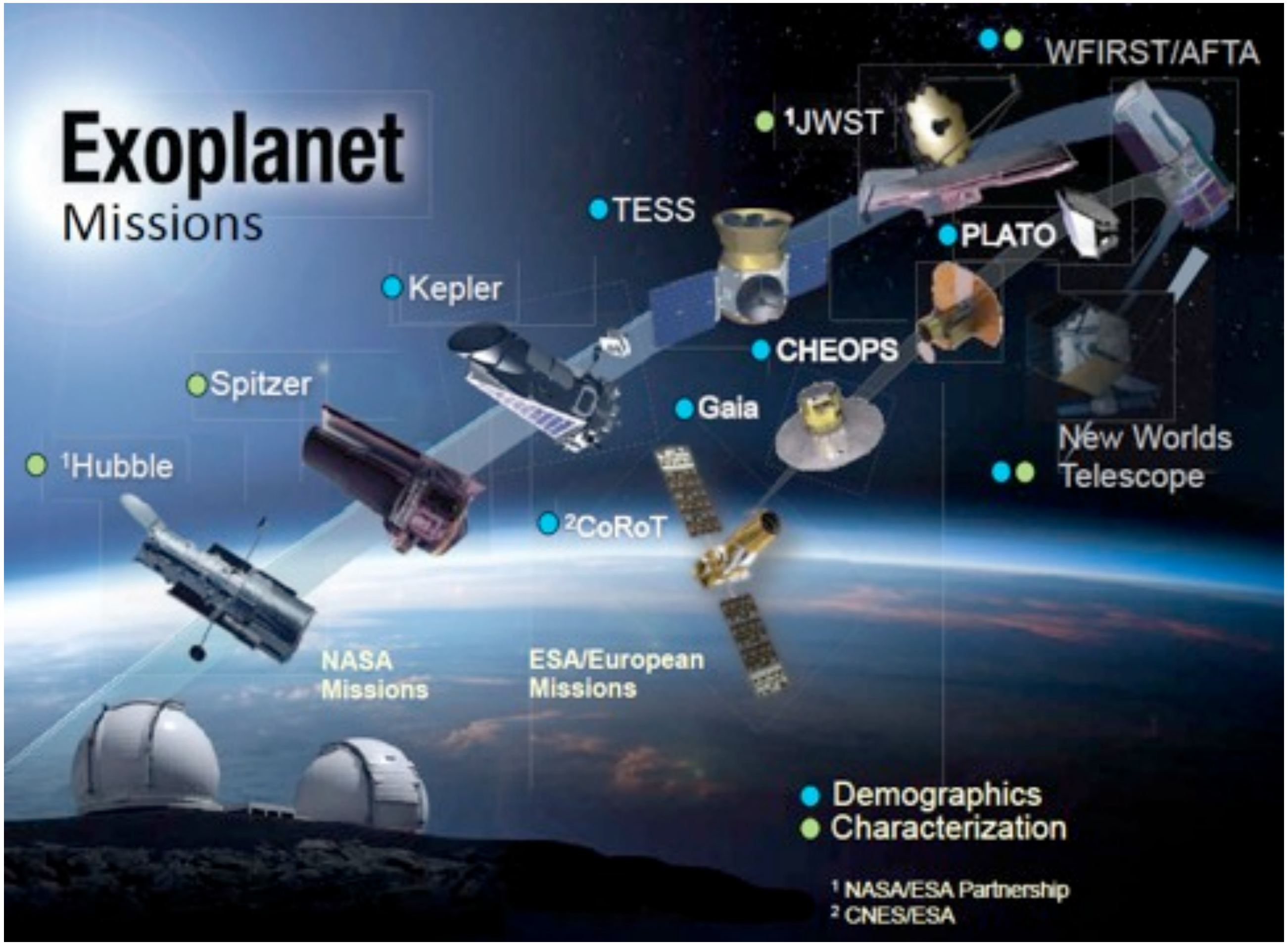
- This meeting has very nicely illustrated how the search for habitable worlds to-day can rely on:
  - Four complementary observation techniques (RV, transits, direct imaging, microlensing), all fully operational
  - Their implementation on space or ground-based platforms
- In this contex the status of space/ground-based synergies is good, but still has to be improved by:
  - A careful determination of the research areas where space is absolutely needed
  - An optimization of the complementarities and commonalities between ground and space, from enabling technologies and instrument design to mission/observation planning.
  - An optimization of the complementaries in terms of observations (e.g., follow-up programmes). See example of Plato where they are part of the design
  - A proper evaluation of the ground-based surveys needed in support of space missions very early on.

optimizing the use of existing or planned facilities (2)

Some of the targets covered by planned facilities:

- HARPS, HARPS-N: hot Jupiters around Open Clusters stars
- VLT/SPHERE: direct imaging of young giant planets
- CHEOPS: transit/RV characterization of Earths/super-Earths, and Neptunes
- Plato 2.0: detection of small planets at intermediate distances, up to the HZ, around K F G stars. Planet density determination and asteroseismology
- LBTI: imaging of exodust and giant planets
- JWST: transit broadband spectroscopy of brown dwarfs, gas giants, Neptunes, sub-Neptunes…
- ELT's : detection/characterization of super-Earths by 2030

What new facilities?



What new facilities? (1)

- Intense exchanges and discussions on this theme, in particular at satellite meetings:
  - Mission concepts for a FIR space mission
  - Review of mapping techniques for brown dwarfs and planets
  - Technical pathways for observing exomoons
  - …

- Importance of exozodiacal light and its effect on the detectability of planets: an issue of special concern with several open questions

- Exoplanet detection and characterization is at the forefront of the programmes of all major space agencies: see next slides.

What new facilities? (2)

NASA is developing the TESS mission to survey the sky for nearby transiting exoplanets, and WFIRST which will conduct a microlensing survey and perform coronagraphic imaging and spectroscopy of exoplanets around nearby stars.

NASA will soon begin detailed study of two major missions for the direct imaging and spectroscopy of exoplanets, as candidates in the 2020 Decadal Survey for a flagship mission to be developed in the 2020s that will look for habitable planets:

- HabEx – optimized for high-contrast imaging of exoplanets
- LUVOIR – an observatory mission for a wide range of astrophysics objectives in the UV, optical, and near-IR, with high-contrast imaging of exoplanets as a major goal

NASA is also pursuing a suite of technologies that will be needed by the next generation of exoplanet imaging missions. Starshade technology is a major part of this effort, with possible application to a mission that could include WFIRST or the 2020s Decadal Survey mission.

NASA is also considering a mid-IR interferometer, the 'ExoEarth Mapper', that could be developed in the 'Visionary Era' (2030s) of the NASA 30-Year Roadmap.

What new facilities? (3)

ESA has its own « road map » for exoplanets

CHEOPS and PLATO 2.0 already selected

ARIEL (M4 candidate) nicely complements this programme: will achieve a broad exploration of the diversity of atmospheric compositions. Looking for its selection…

JAXA studies SPICA, to be M mission candidate in the ESA programme: transit spectroscopy of sub-Neptunes and super-Earths

And some contributions outside the « main stream »…

- « Small is beautiful »: a plan to directly image a habitable planet around Alpha Centauri using a 30-45 cm space telescope
- Coronagraphs vs. Interferometry: do we make the right choice? much to think from Alain Léger’s talk

EPILOGUE

- Echoing the exploration of the diversity of solar system objects, the time has come to use all available platforms and techniques to explore the physical and chemical diversity of exoplanets and their systems
- This systematic exploration is made possible by the spectacular progress made in detection and characterization techniques, and by the optimization of space/ground synergies
- It is in the context of this broad exploration effort that the more focused search for habitable planets will find not only its place, but also its science base, and will develop progressively with time.
- The set of on-going or accepted projects, and the set of future projects, ideally serve this purpose. Altogether, they will cover the largest part of detectable objects, while initiating the development of observing tools that will make it possible, in the decades to come, to characterize habitable planets.
- We foresee that this momentum will continue to be reinforced in the coming years: exploration of the diversity of exoplanets and their systems will intensify, while in parallel efforts to prepare the detection and characterization of habitable planets will continue.
- I am confident that, by the time of the next « Pathways » conference, new and major achievements will be ready for scientific reporting on these two complementary avenues of our fascinating research field!