The *Gaia*-PLATO Synergy

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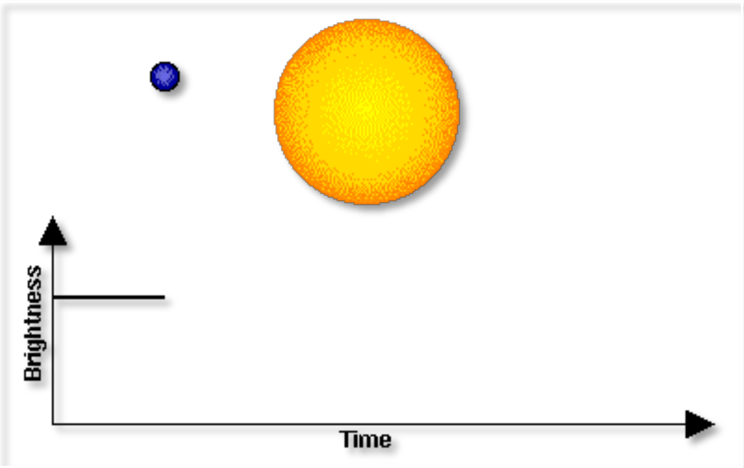
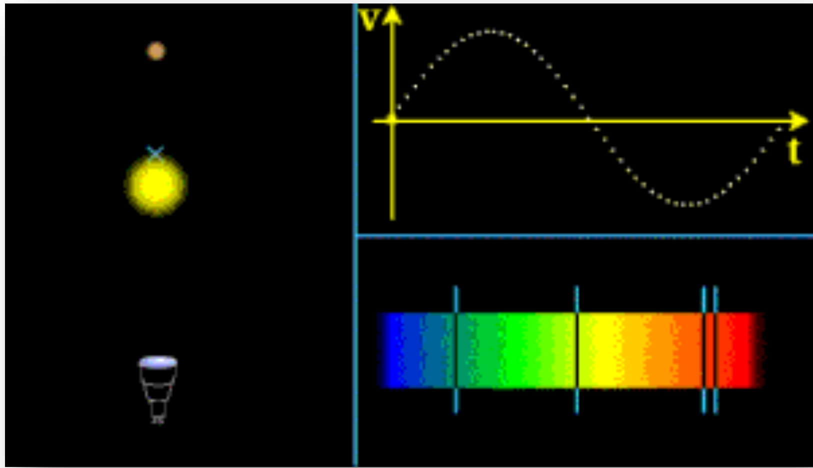
Radial Velocity & Transits: the power of complementarity

Transit Method



Radial velocity method



- Orbit parameters
- Orbital inclination, ***i***
- Planet radius, R_p

$$\frac{\Delta F}{F} = \left(\frac{R_p}{R_*}\right)^2$$

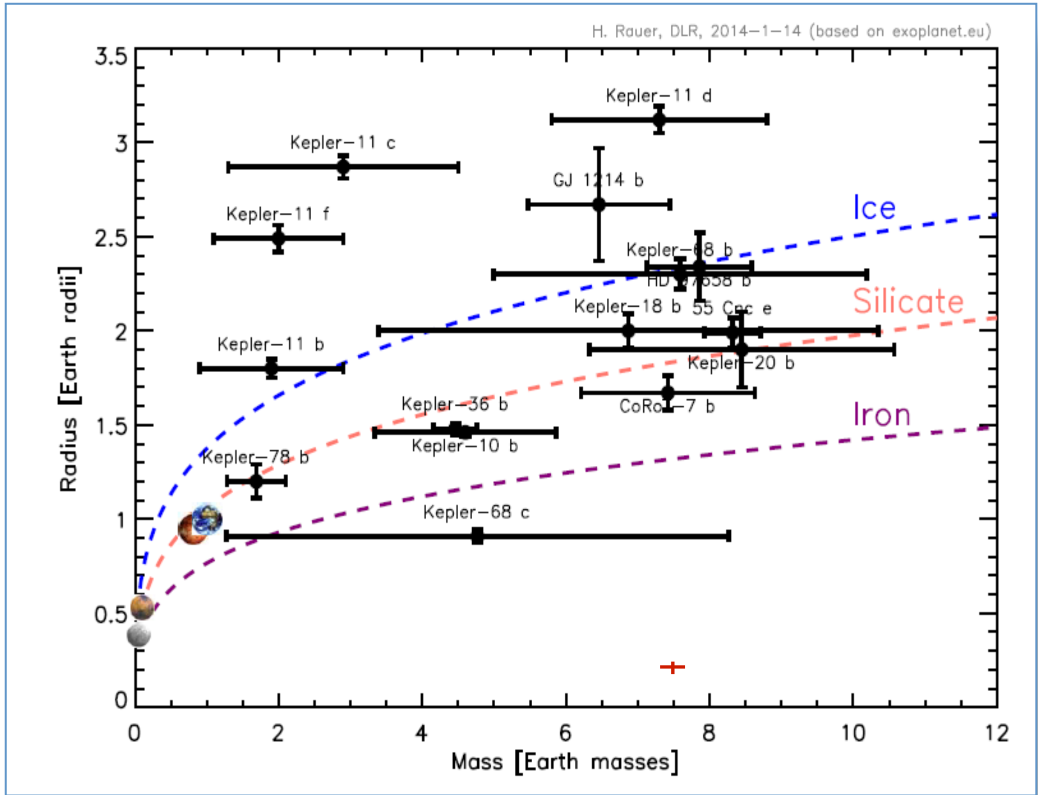
$$K = \left(\frac{2\pi G}{P}\right)^{1/3} \frac{M_P \sin i}{(M_* + M_P)^{2/3}} \frac{1}{\sqrt{1-e^2}}$$

- Orbital parameters
- Minimum planet mass, $M_p \sin i$

$$K \propto M_p / M_*^{2/3}$$

True planet mass and mean density

From CoRoT, Kepler and Most → Diversity of super-Earths

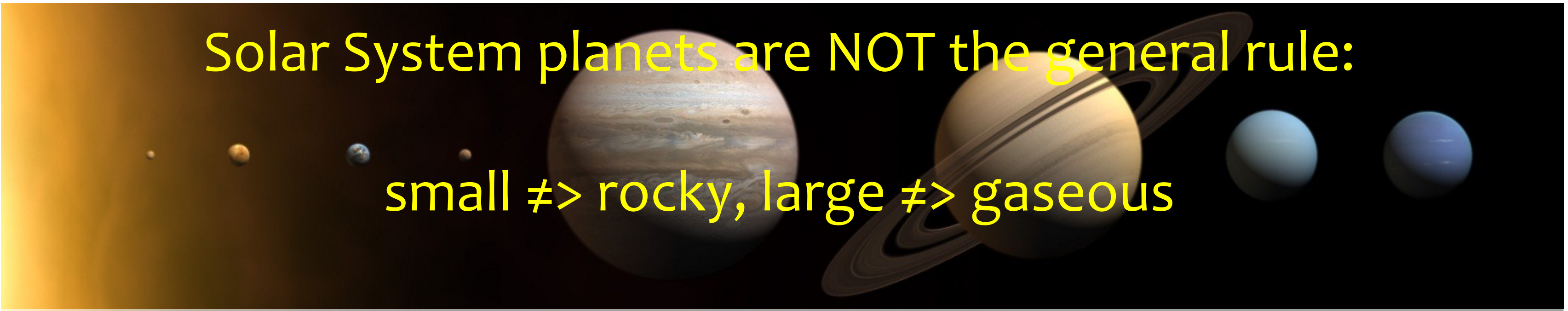


Super-Earths:
radius $1.2 < R < 2.0\ R_{Earth}$;
mass $< 10M_{Earth}$

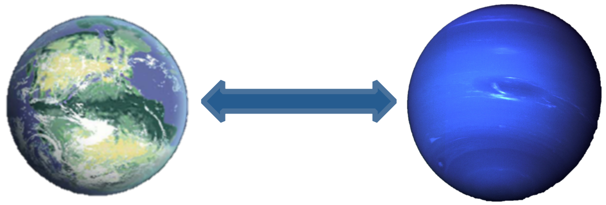
- ✓ Masses vary by a factor of ~4 (with large errors)
- ✓ Radii vary by a factor of ~3

Accurate masses & radii are required to separate terrestrial from mini-gas planets

Super-Earths: diversity and implications on habitability



- Small exoplanets are very diverse:
  from Earth-like to mini-gas planets



- Mini-gas planets are likely not habitable

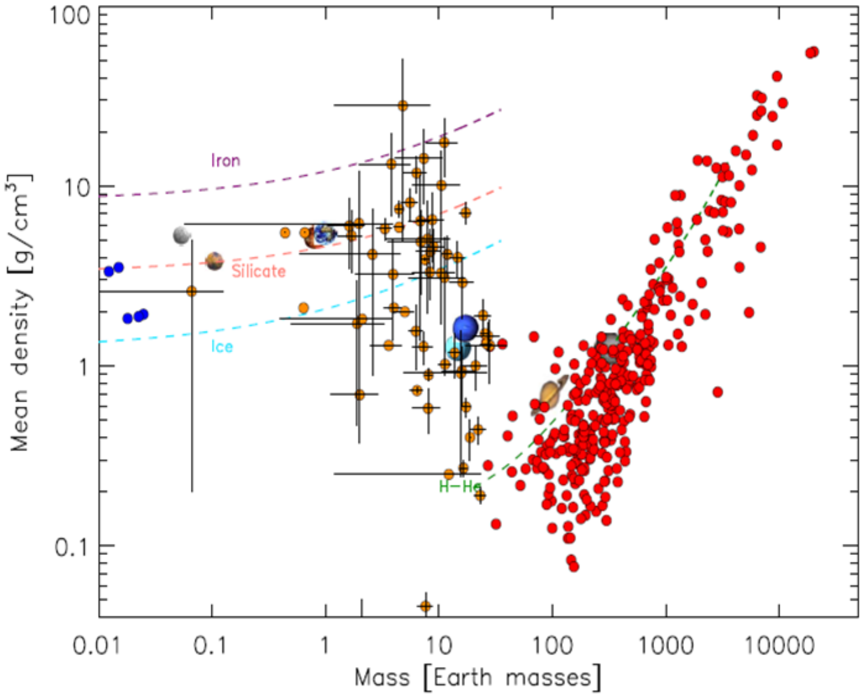
- Silicate-iron planets are prime targets for atmosphere spectroscopy

Searching for Habitability requires:
➢ accurate mean densities to identify terrestrial planets
➢ bulk characterize targets for atmosphere spectroscopy follow-up

A biased view on planet diversity

Our knowledge on planet nature is limited to close-in planets so far.

All planets



A biased view on planet diversity

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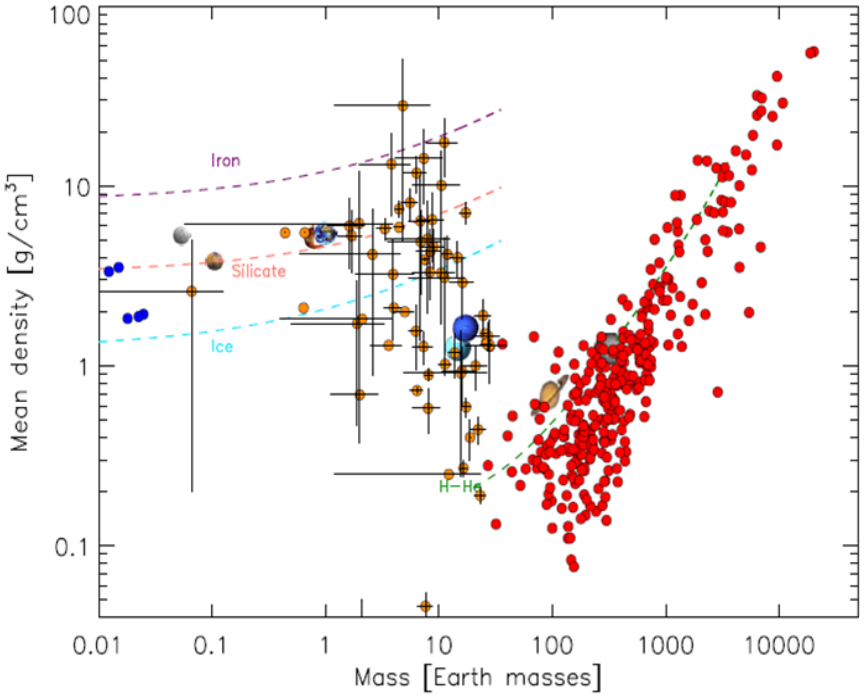
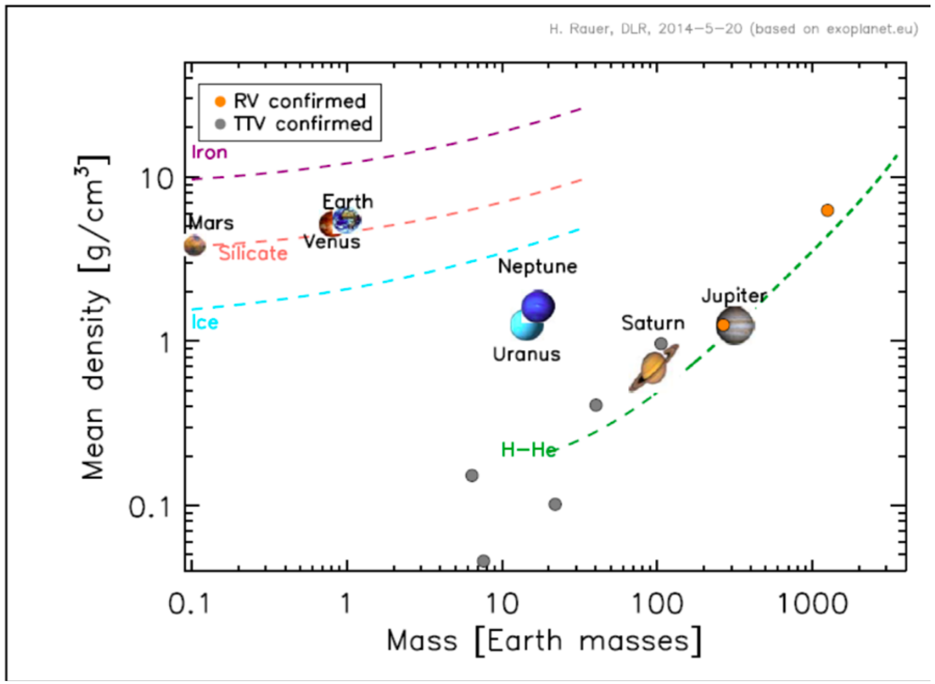
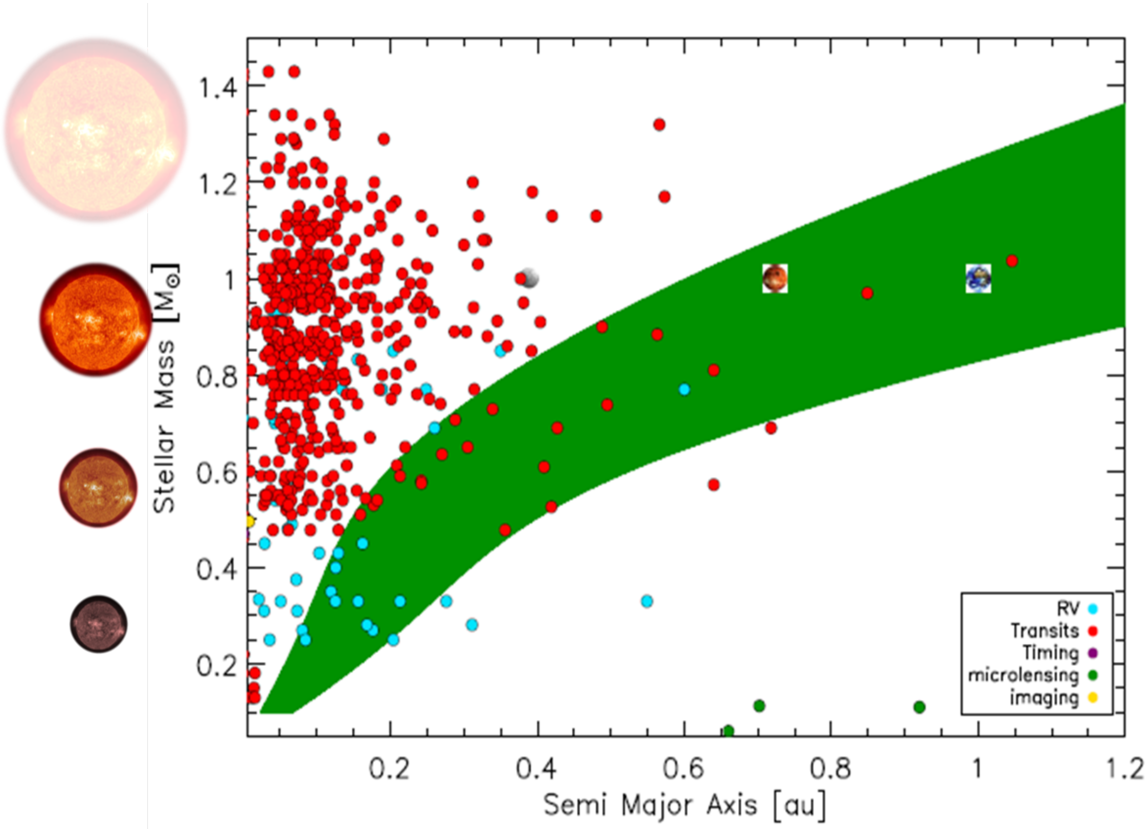


Planets with P>80 days



Super-Earths in the habitable zone

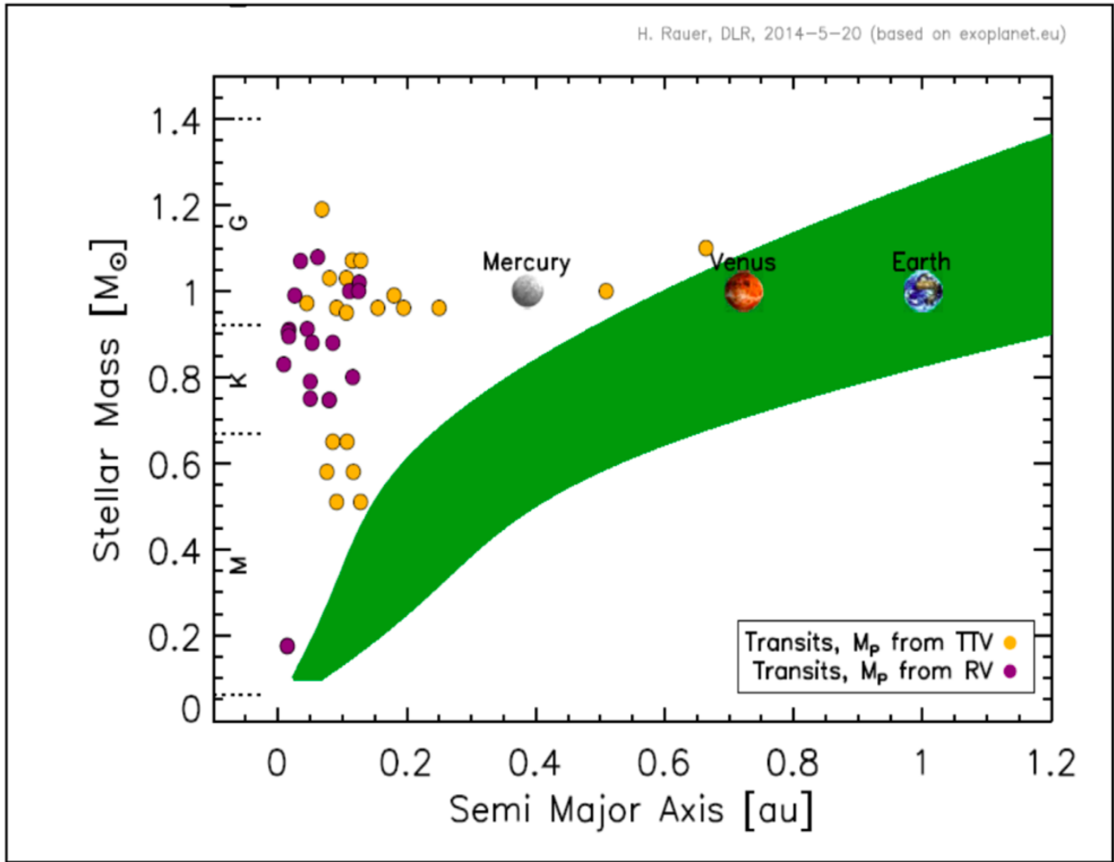
Detected super-Earths



- Goal: Detect and characterize super-Earths in habitable zones
- Status: very few small/ light planets in habitable zones detected

Super-Earths in the habitable zone

Super-Earths with measured radius and mass

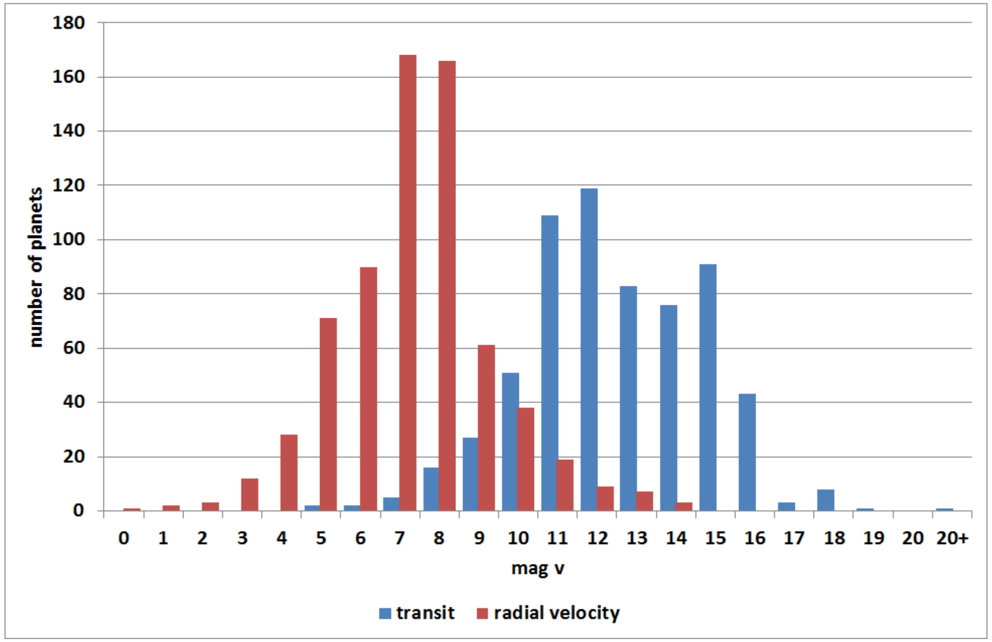


- Goal: Detect and characterize super-Earths in habitable zones
- Status: very few small/ light planets in habitable zones detected

No „super-Earths“ with known mean density in the habitable zone !

The need for bright stars

Known planets from radial velocity and transit surveys



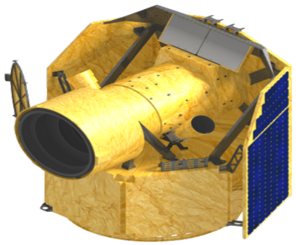
Why have so few targets been characterized?

- Transit surveys targeted faint and distant stars to maximize detection performance.

- Radial velocity surveys need bright stars (≤11 mag) to keep telescope resources limited.

Lessons learned:
Future transit missions must target bright stars!

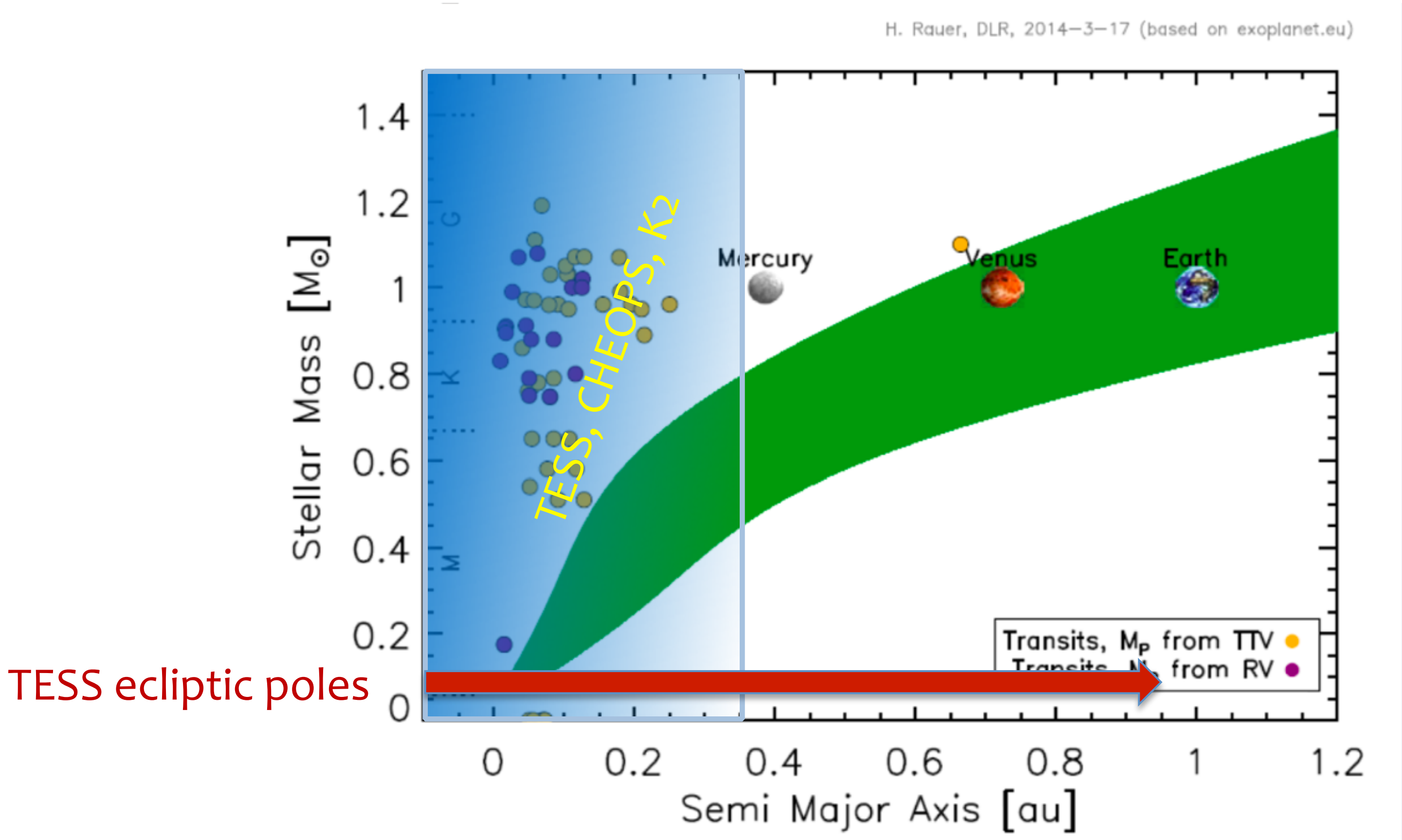
Transit missions: What's next?



K-2 (Kepler 2) (NASA)	Observes fields in the ecliptic plane for ~80 days/field. Ongoing. 452 candidates, 132 confirmed
TESS (NASA, launch 2018):	All sky survey, 27 days/field; ~2% of sky at poles for 1 year
CHEOPS (ESA, launch 2018):	Follow-up, radii of detected (RV) planets, planet characterization, follow-up of TESS planets.

Prospects for characterized super-Earths in the habitable zone

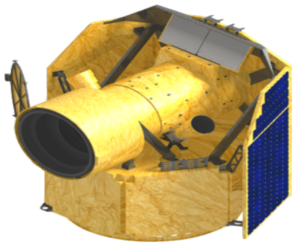
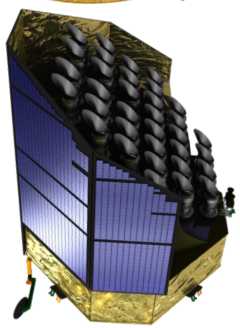
„Super-Earths“ with measured radius and mass



TESS, CHEOPS, K2 will mainly cover orbital periods up to ~80 days

Transit missions: What's next?



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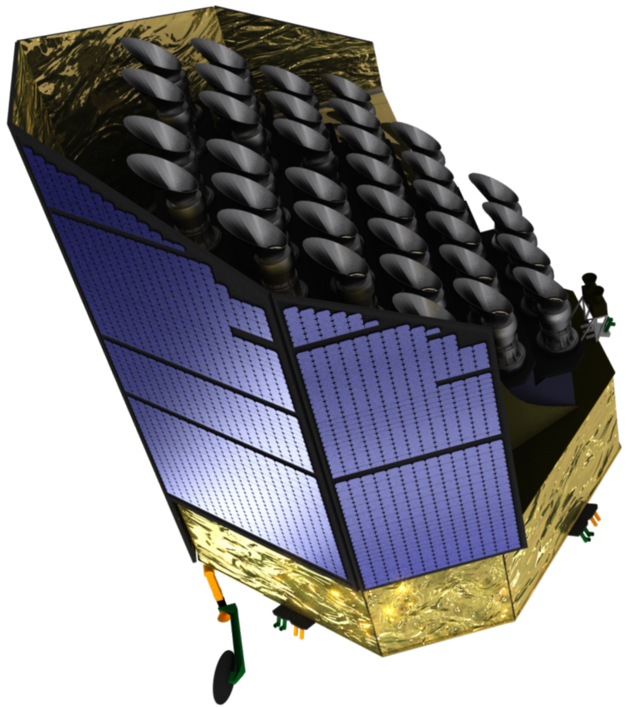
CHEOPS (ESA, launch 2018):	Follow-up, radii of detected (RV) planets, planet characterization, follow-up of TESS planets.
PLATO (ESA, launch 2026)	Large field of view for detection and characterizization (density, age) of terrestrial planets around solar-like stars up to the habitable zone

PLATO

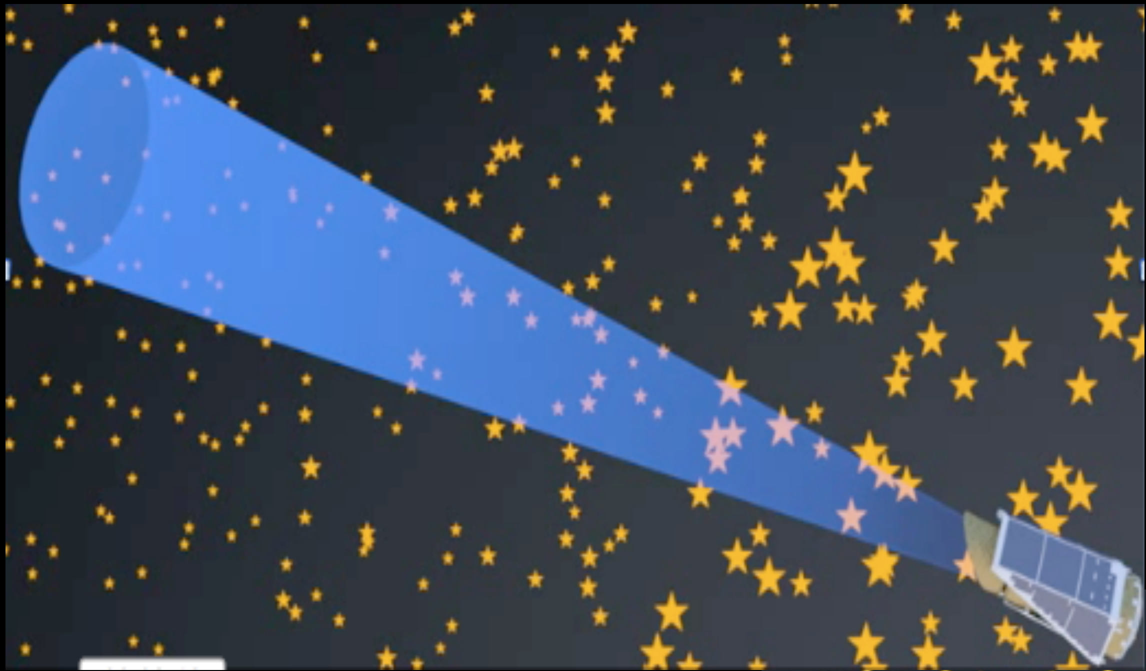
PLAnetary Transits & Oscillations of Stars

– M class mission (M3)
– Budget envelope ~ 650 M€ (≤ 500 M€ from ESA)
– Launch (after 2016 ministerial): 2026
– Launcher Soyuz Fregat (?) from Kourou
– Operation: 4 (+2?) yrs
– (consumables for 8 years)



esa

PLATO strategy

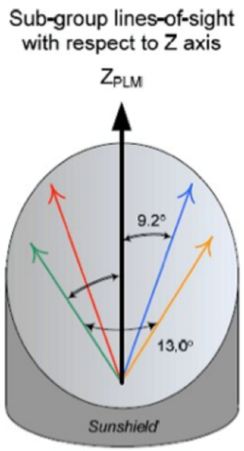


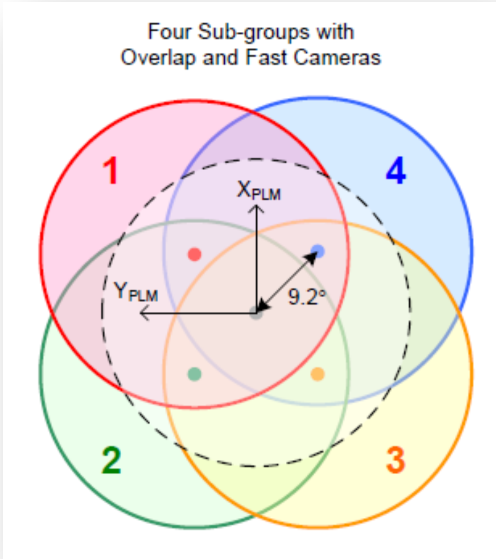
Kepler strategy

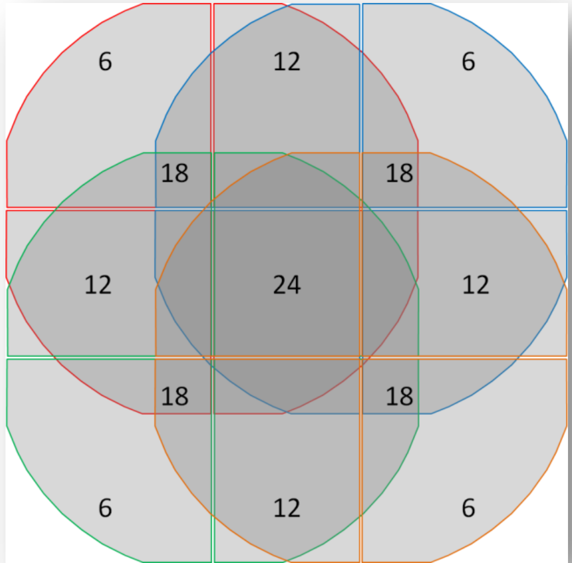
PLATO concept

Concentrate on bright stars

Telescopes on the satellite





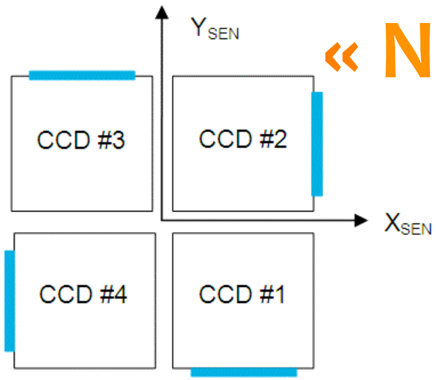


- 24 (4x6) “Normal” telescopes, 25 s cadence
- 2 “Fast” telescopes, 2.5 s cadence
- Instantaneous FoV~ 2232 deg^2 (22 times Kepler area)

Equivalent pupil size:

- 587.9 mm for 24 cam
- 509.1 mm for 18 cam
- 415.7 mm for 12 cam
- 293.9 mm for 6 cam

Fast and Normal Telescopes



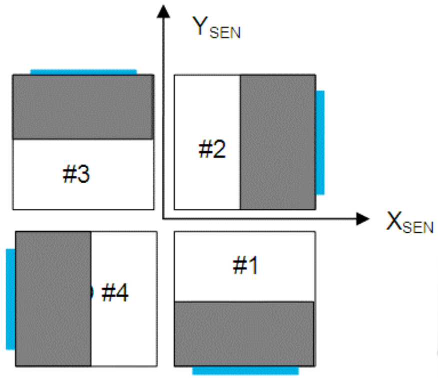
« Normal »

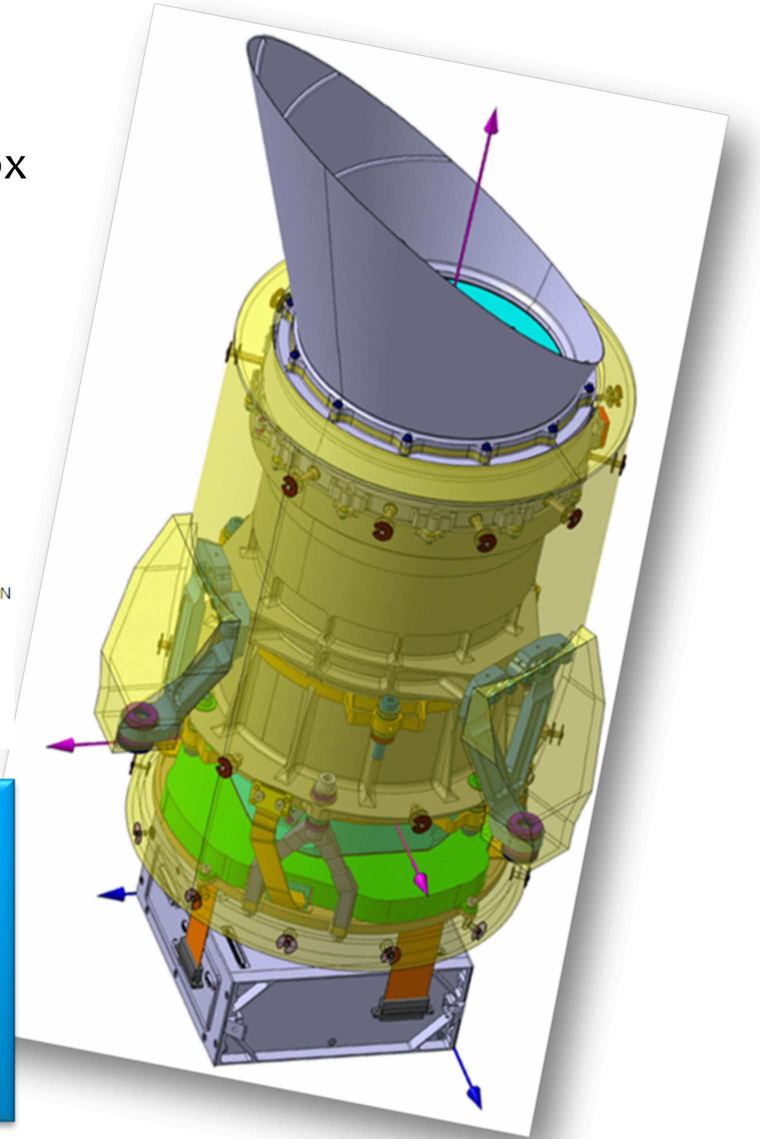
Full frame CCD
4510 × 4510 18 µm sq px
$m_V > 8$
t=25 s

« Fast »

Frame transfer CCD
4510 × 2255 18 µm sq px
$m_V \sim 4–8$
t=2.5 s

AOCS





- ✓ 104 CCDs **~ 0.70 sq meter (largest CCD area ever sent to space)**
- ✓ 1 FEE / camera;
- ✓ 1 DPU / 2 cameras;
- ✓ 2 ICUs in cold redundancy

PLATO will provide full characterization of both exoplanets and hosting stars (in synergy with *Gaia*)

Characterization of exoplanets …

- **Mass + radius → mean density**

  gaseous vs. rocky, composition, structure

- **Orbital distance, atmosphere**

  habitability

- **Age**

  planet and planetary system evolution

needs characterization of stars

- **Stellar mass, radius**

  derive planet mass, radius

- **Stellar type, luminosity, activity**

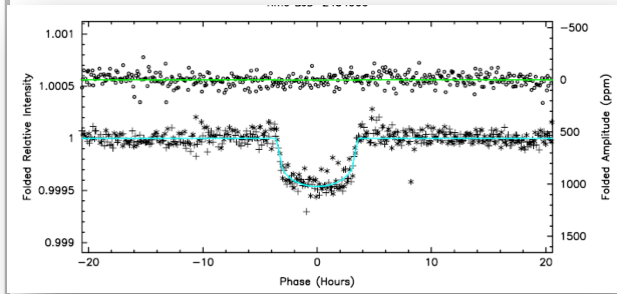
  planet insolation

- **Stellar age**

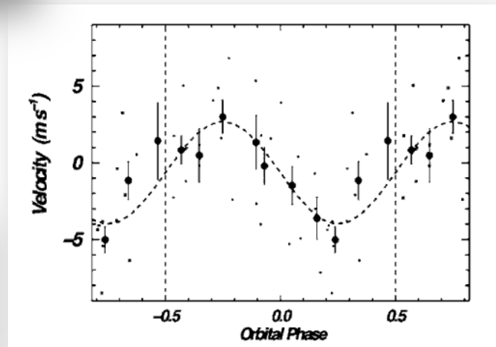
  defines planet age

The Method

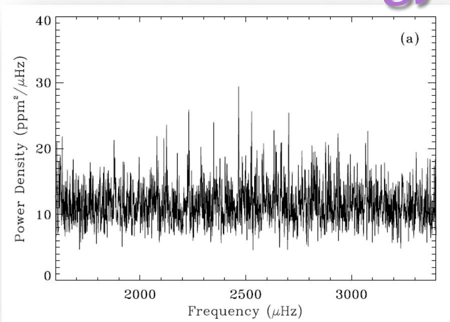
Photometric transit



RV – follow-up



Asteroseismology



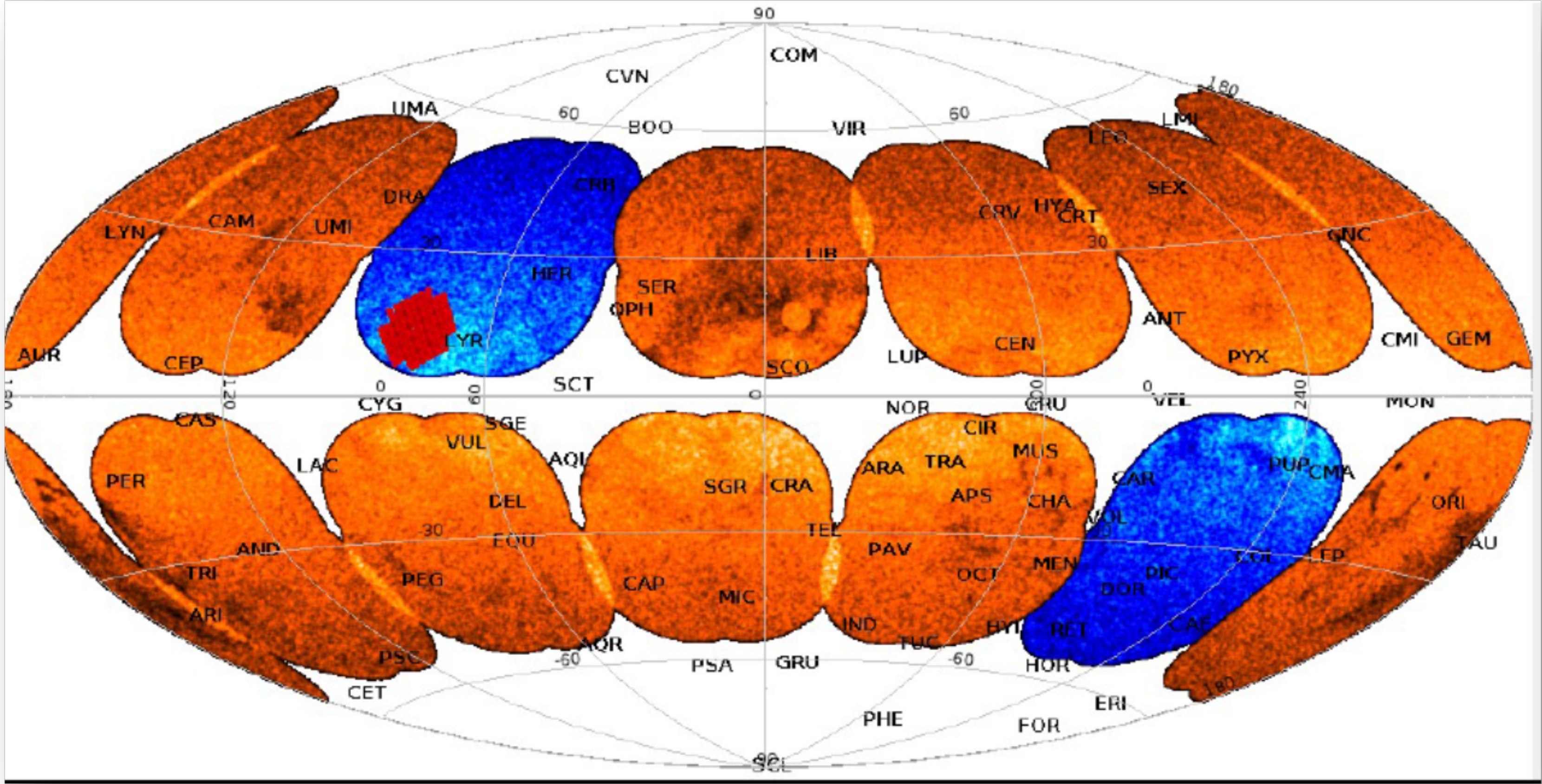
Example: Kepler-10 b (V=11.5 mag)

- radius ~2%
- Mass ~10%
- Age ~10%

Observing Strategy (tbd)

Long duration pointing (2yrs+) + Step and Stare (>2months)
The observing duty cycle will be at least 95%.

The PLATO sky



→ ~50% sky coverage

(with mission extension to six years)

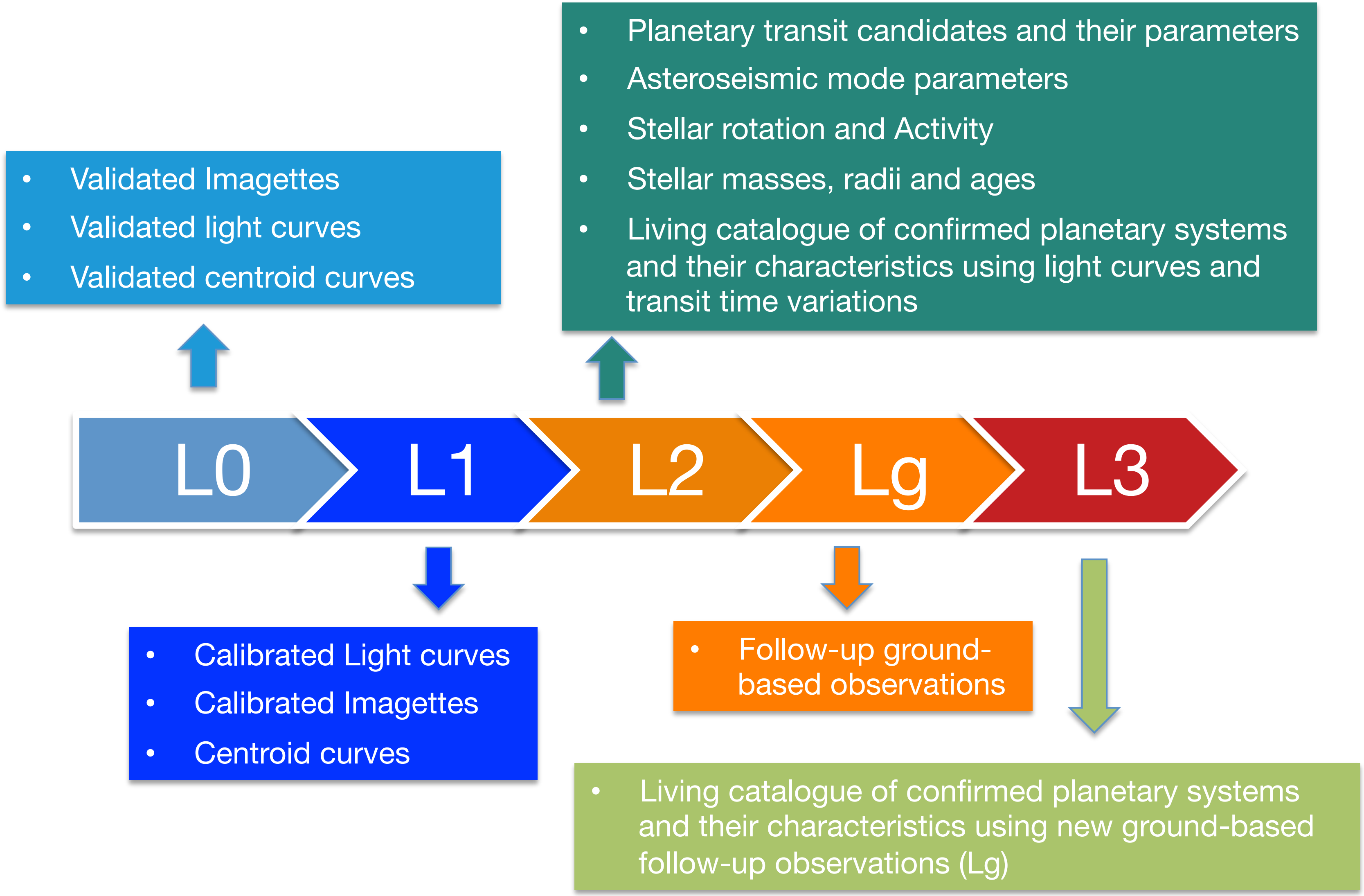
PLATO Stellar Sample

	Sample 1 (P1)	Sample 2 (P2)	Sample 4 (P4)	Sample 5 (P5)
Stars	≥ 15 000 (goal 20 000)	≥ 1000	≥ 5000	≥ 245 000
Spectral type	Dwarf and subgiants F5-K7	Dwarf and subgiants F5-K7	M dwarfs	Dwarf and subgiants F5-K7
Limit *V*	11	8.2	16	13
Random noise (ppm in 1 hour)	34	34	800	
Observation phase	LOP	LOP	LOP	LOP
Sampling time (s) Initial measurement	-	-	-	≤ 600
Centroid measurements	-	-	-	≤ 50 for 5% of targets
Transit oversampling			-	≤ 50 for 10% of targets
Imagettes	25	2.5	25	25 for > 9000 targets
Wavelength	500–1000 nm	500–1000 nm 300 stars with colour information	500–1000 nm	500–1000 nm

PLATO needs an input catalog (PIC)

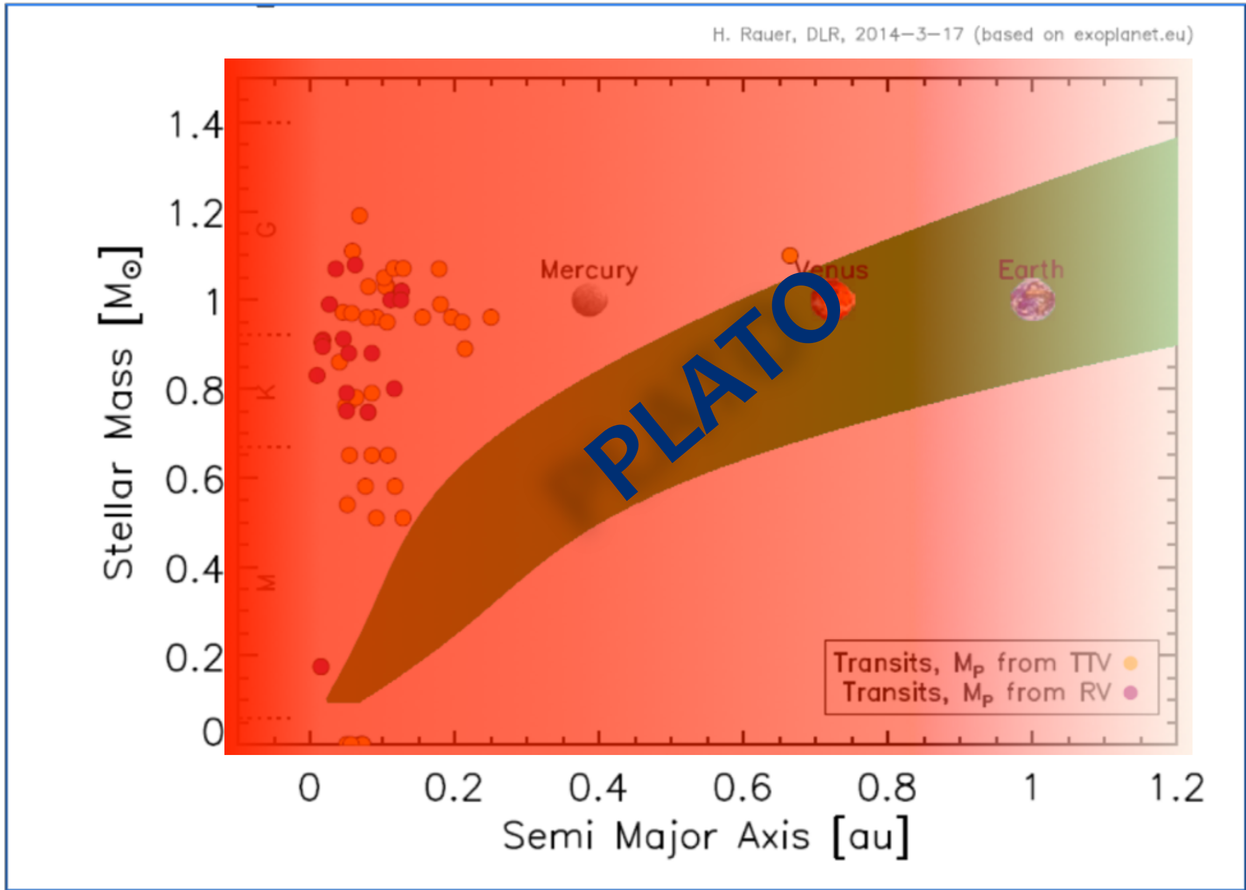
- Note: 8% of the telemetry dedicated to general (public) programs. Open call for proposals issued by ESA (time tbd)

Data products: all data public



PLATO will measure the density of Super-Earths with P> 80 g

„Super-Earths“ with measured radius, mass and ages



Gaia-PLATO Synergy

I. Preparation of the PLATO input catalog (PIC)
   a) identification of targets
   b) map of target contaminants

II. Characterization of the stellar hosts
   a) for asteroseismology
   b) for exoplanet parameters improvement

III. Characterization of the exoplanetary systems
   a) extension of exoplanetary system parameters
   b) follow-up of *Gaia* exoplanets

I. Populating the PIC: a) target selection

- PLATO will observe dwarfs and subgiants with 4<*V*<16, SpT >F5 ➔ **all possible PLATO targets will also had been observed by *Gaia*.**
- Simulations from DPAC's CU2 team showed that **simple cut in *Gaia* G-mag and d** is able to provide a "clean" sample of main-sequence dwarfs later than F5, with only ~1% "pollution" from cool giants
- Pollution lowered to ~ 0.1%, using Teff/log(g)/[Fe/H] from ***Gaia* spectro-photometry and *Gaia* and ground-based spectroscopy**
- **Real work will start after DR2 release,** though we started to play with DR1

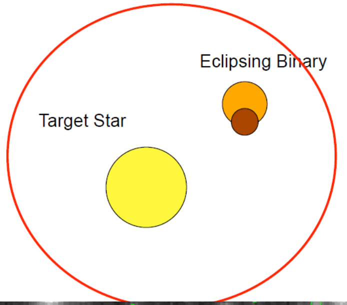
I. Populating the PIC: b) contaminants identification

- Previous ground- and space- based experience has shown that from 50% up to 90% of transit signals are false positive

- A map of stars surrounding PLATO targets is crucial for:

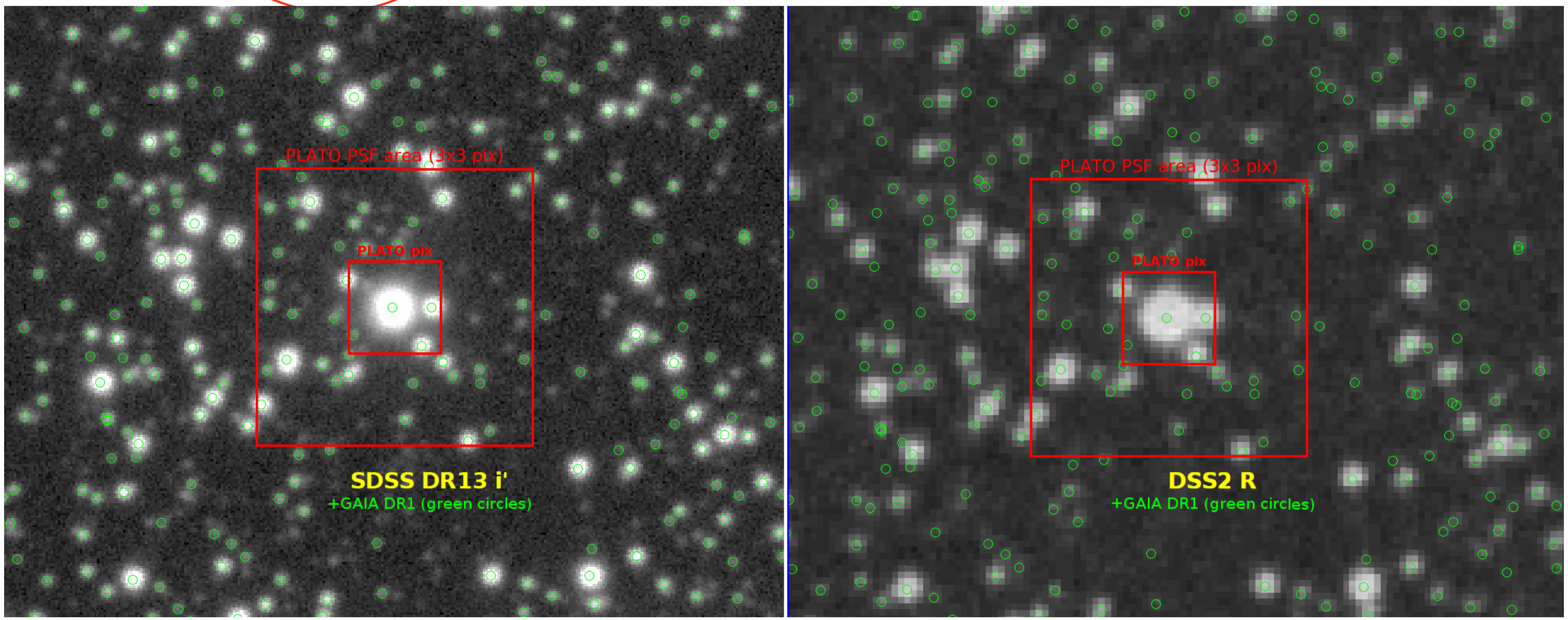
a) prioritization of targets;
b) preparation of observations (optimal aperture photometry mask definition);
c) deriving the true exoplanet radius, after removal of the dilution effect due to contaminants;
d) vetting of exoplanet candidates, optimizing the use of follow-up resources.

I. Populating the PIC:
b) contaminants identification



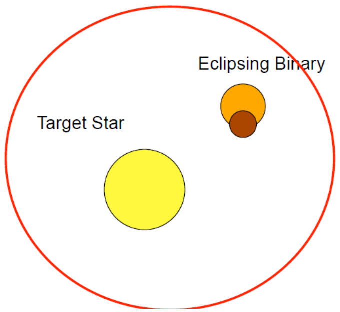
Typical false positive source: an eclisping binary, fainter than the target, within the PSF radius of the target.

The problem becomes serious in «crowded fields», e.g. towards the Galactic plane for PLATO



PLATO pix size 15 arcsec; 90% of PSF light in 2.5x2.5 pix (center)→3.0x3.0 (border)

I. Populating the PIC:
b) contaminants identification

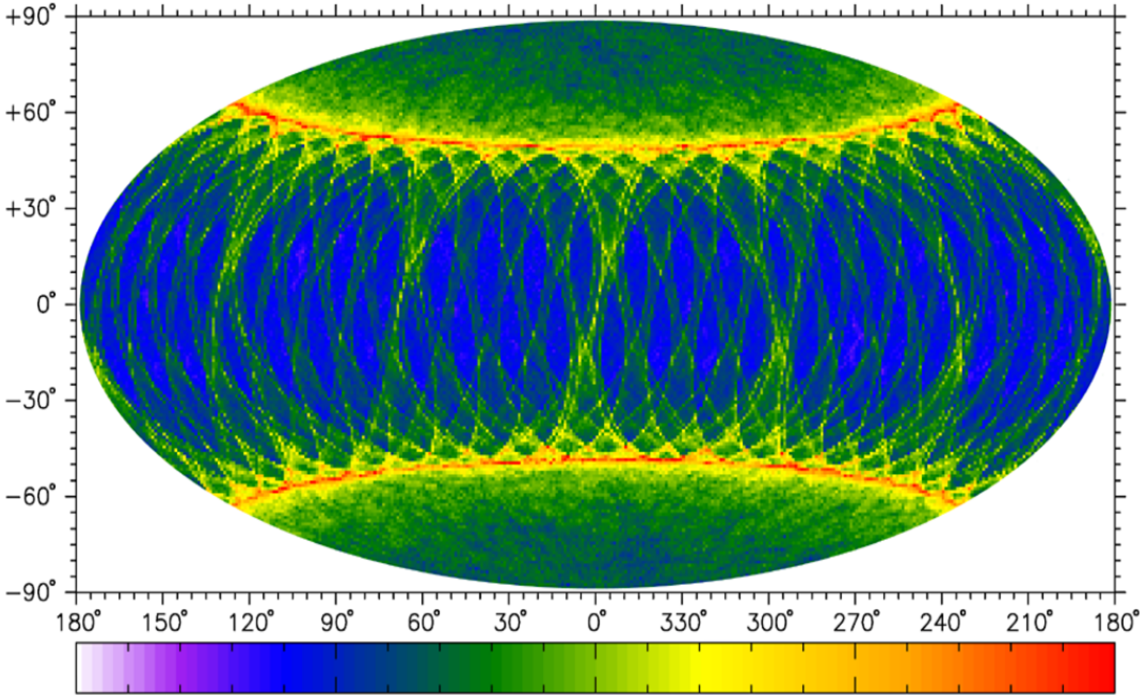


The key quantity is Δm, the magnitude difference between the target and the eclipsing binary in the background. If δ is the measured transit depth, it could be due either to a transit in front of the target, or to an eclipse of depth δ_c of a star Δm fainter, following

$$\delta_c = -2.5 \log_{10}(10^{-04\Delta m} - \delta) - \Delta m$$

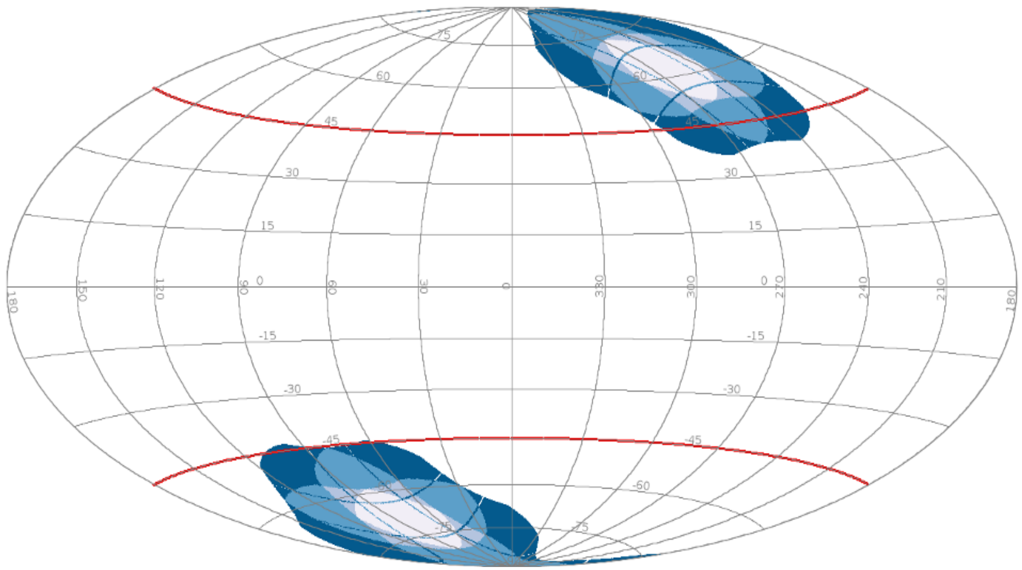
Example for an (extreme) case of an eclipsing binary with depth δ_c=1 mag simulating a transit of δ depth in a target Δm magnitude brighter

case	δ	Δm	m_{lim} (V=8)	m_{lim} (V=11)	m_{lim} (V=13)
gas giant	0.01	4.45	12.45	15.45	17.45
Neptunian	0.001	6.95	14.95	17.95	19.95
Earth	80 ppm	9.69	17.69	20.69	22.69



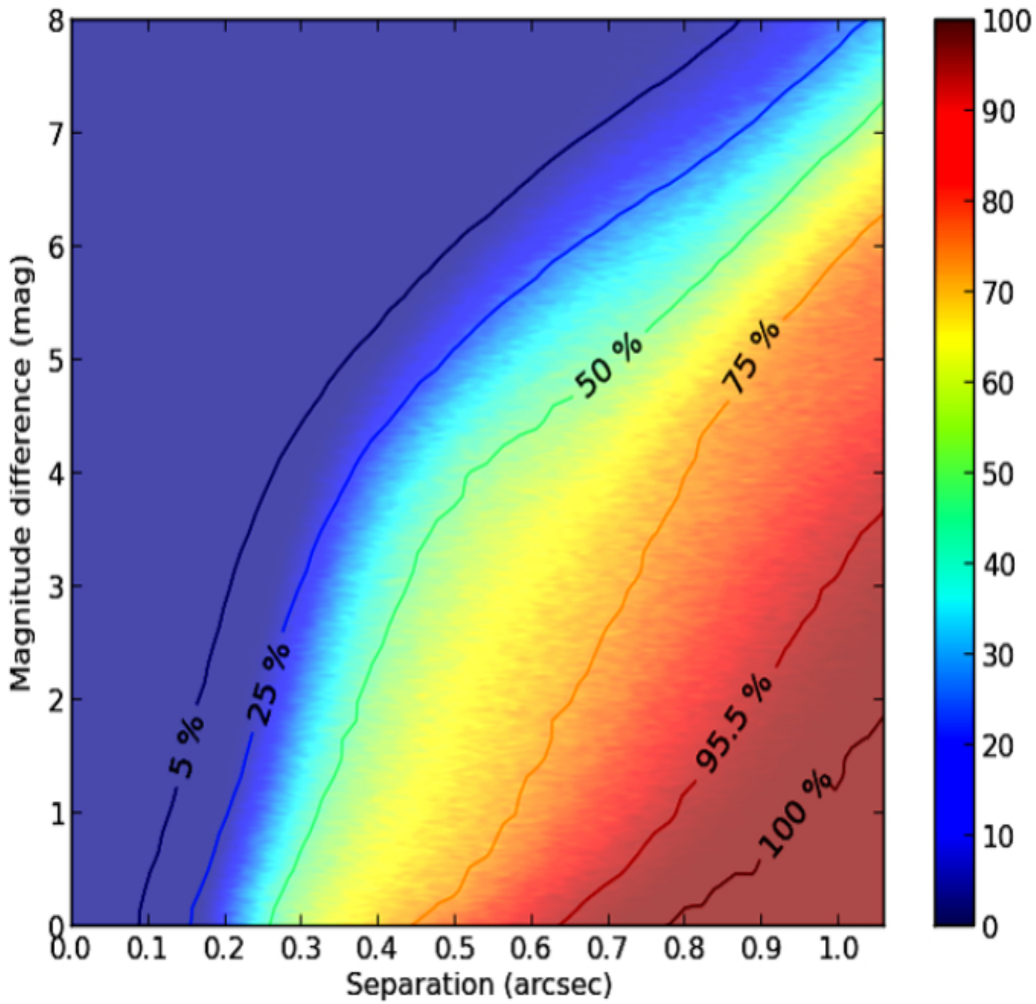
PLATO long duration pointing fields compared with the Gaia scanning law at end of mission.

Red circles represent the region of highest coverage by Gaia



Most of the sky area covered by the LD PLATO fields is going to be monitored by 70-80 GAIA observations on average

Gaia detection completeness



Blends at $\Delta m \leq 4$ can be resolved at 50% completeness (or better beyond 0.5") from the central source, while the minimum separation increases up to 1" at $\Delta m = 8$.

Gaia will be able to solve harder blends also closer 0.5" but only for smaller Δm. Data may be available only from DR4, but still on time for the PIC

Gaia can provide variability indication, helping to identify contaminating eclipsing

II. Characterizing the stellar hosts

Bright (V<13) F-G-K stars (D<200-300 pc) and not very faint (V<16) M dwarfs (D<50-60 pc) will have **distances measured by *Gaia* to (sometimes much) better than 1%.** The consequent very accurate absolute luminosities, combined with T_{eff} from ground-based spectroscopy, will give **stellar radii with uncertainties of 1-2%.**

There are many important implications for PLATO science:

a) For PLATO asteroseismology:

- determination of **masses with <10% errors;**
- determination of **ages with <10% errors;**

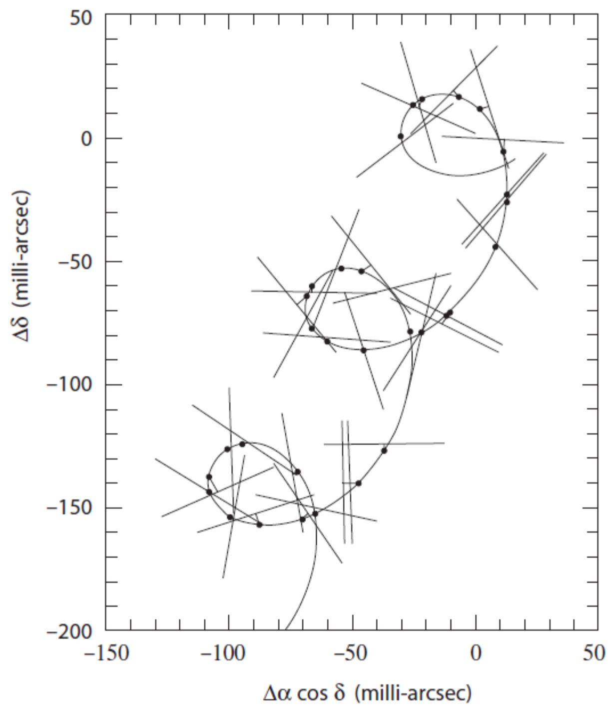
And therefore:

b) For PLATO exoplanets:

- radius with 1-2% errors, and masses with <10% errors, imply **high precision density for planet structure studies;**
- ages with <10% errors, will give us the possibility to **study exoplanets (and their atmosphere) and exoplanetary systems evolution.**

III. Characterizing exoplanetary systems
a) extension of exoplanetary systems parameters

- *Gaia* astrometric detection method is biased towards massive, cool planets hosted by low-mass, nearby stars, and with large periods (a poorly explored region, so far)
- *Gaia* is expected to discover ~25,000 such planets, of which 25-40 transiting (Perryman+ 2014); ~1,000 will be brighter than G~8.
  - 2-3 M_J planets at 2<a<4 AU are detectable out to~200 pc around solar analogs
  - Saturn-mass planets with 1<a<4 AU are measurable around nearby (<25 pc) M dwarfs
- Most of these exoplanets, can not be detected by PLATO, but *Gaia* will observe ALL stars observed by PLATO (including stars hosting PLATO exoplanets). **_Gaia_ results will complement PLATO findings.**
- A four-fold goal will be achieved: extended phase coverage, a wider range of the parameter space (M, P, orientation) covered, improved characterization of global architecture of multiple systems, all as function of the hosting star properties (and location).



III. Characterizing exoplanetary systems

b) Gaia exoplanet transits follow-up

A few exoplanets discovered by *Gaia* astrometry will transit (25-40, Perryman+ 2014): PLATO may be able to follow them (though, periods may be longer than PLATO long pointing duration).

III. Charactering exoplanetary systems

b) Gaia exoplanet transits follow-up

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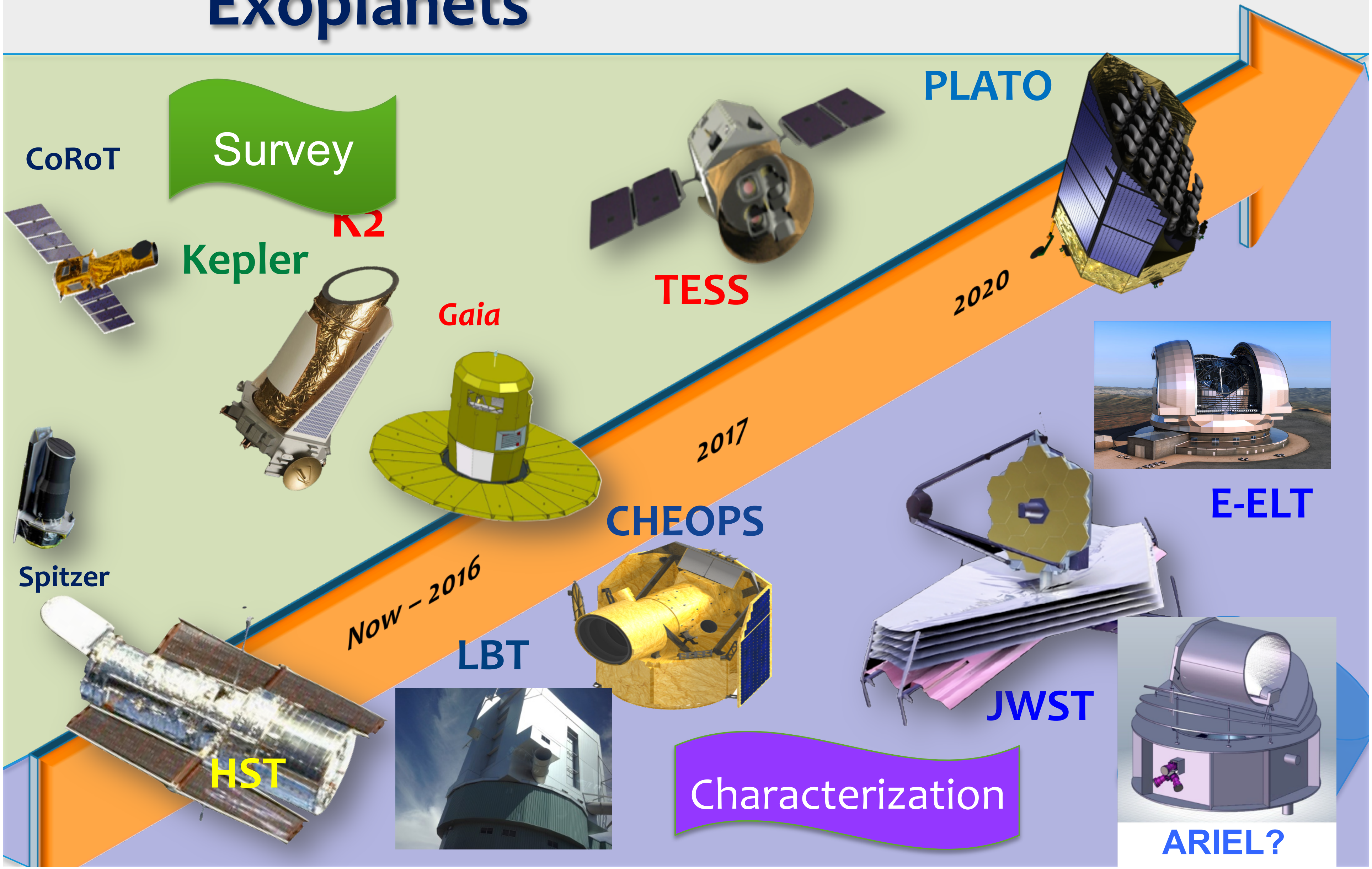
	Minimum Number of Points in Transit	$G = 14$	$G = 16$
	3	230	999
$w = 1$ hr	5	42	178
	7	7	30
	3	596	2605
$w = 2$ hr	5	209	902
	7	73	310
	3	720	3191
$w = 3$ hr	5	364	1577
	7	156	669

Expected yield of hot Jupiters and very hot Jupiters from Gaia photometry, for different transit duration (Dzigan and Zucker 2012)

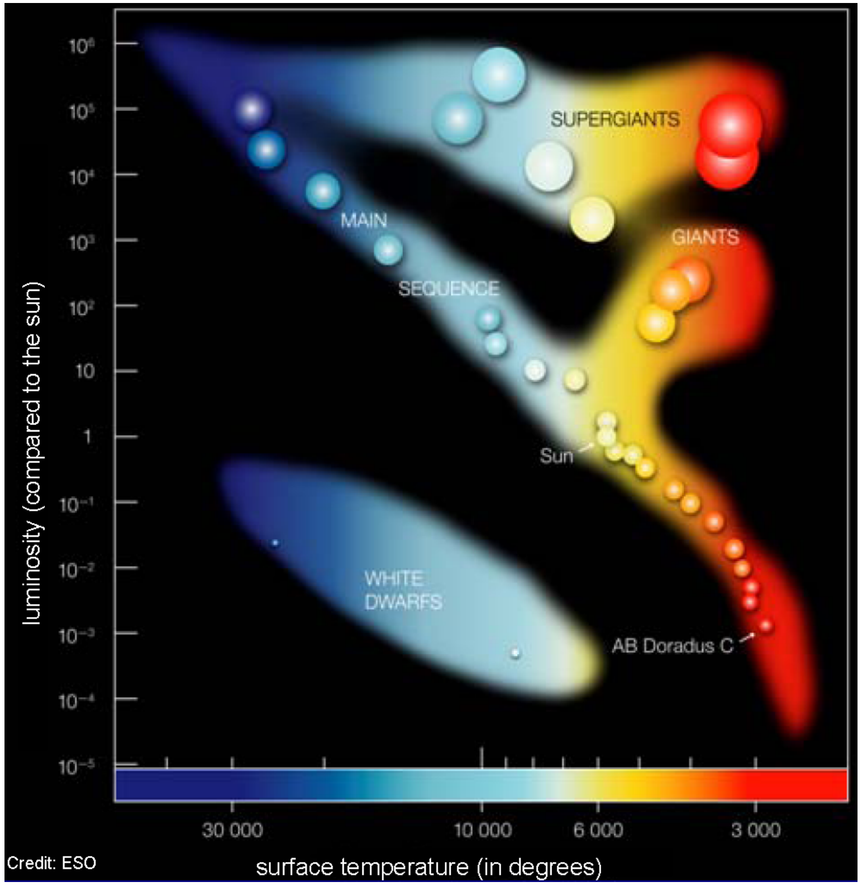
Of more interest the possibility offered by PLATO to follow-up massive, transit exoplanets discovered by *Gaia*, extending the phase coverage

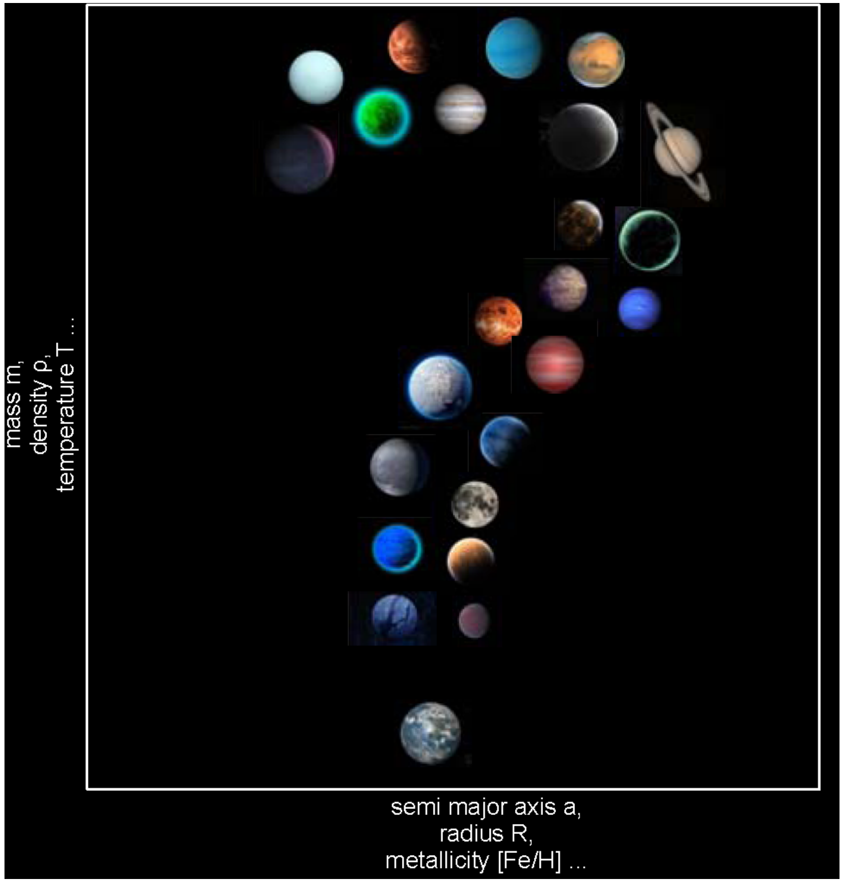
There may be from a few hundreds to a few thousands of them.

Missions and Observatories for Exoplanets



A possible HR-like diagram for planets?





….and have the best possible targets for the study of exoplanet atmospheres

Summary

PLATO will represent a breakthrough for the knowledge of exoplanets and exoplanetary systems.
PLATO will discover a few thousands of candidate exoplanets, including hundreds of Earths and Super-Earths.

PLATO will fully characterize (including mass) a few hundreds of Earths, and Super-Earths also in habitable zone, including a few (5-10) Earth analogous.

There is a fundamental synergy between *Gaia* and PLATO as:

- *Gaia* will allow the preparation of the PLATO input catalog, including contaminant idetinfication and characterization
- *Gaia* will allow proper characterization of exoplanet host stars
- *Gaia* will discover planets typically not in PLATO reach, enhancing the complementarity of the two projects in exoplanets characterization.