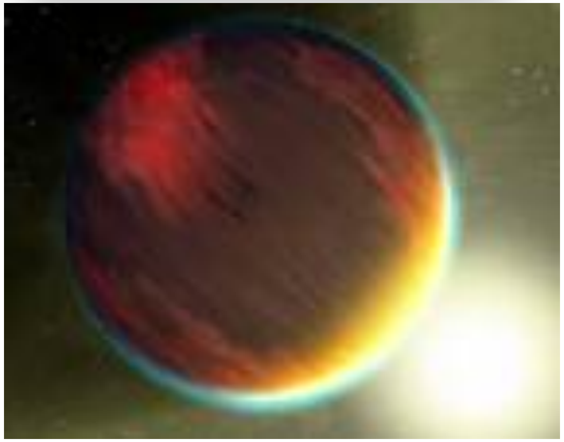
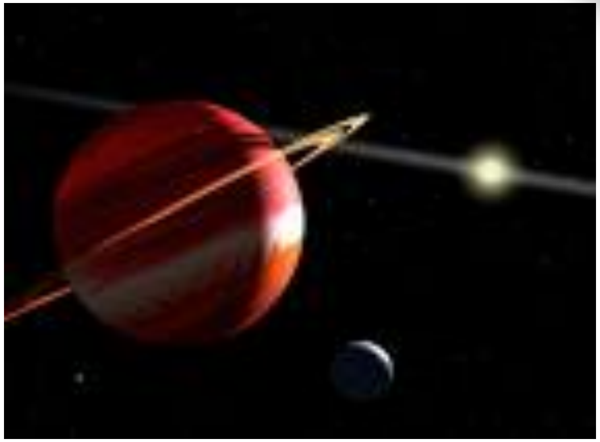
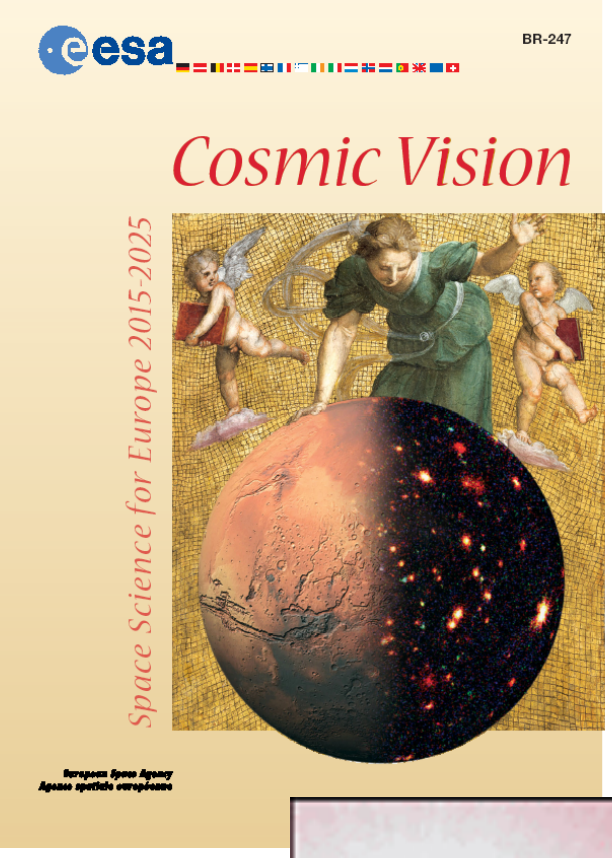
The astrophysics of the PLATO space mission-



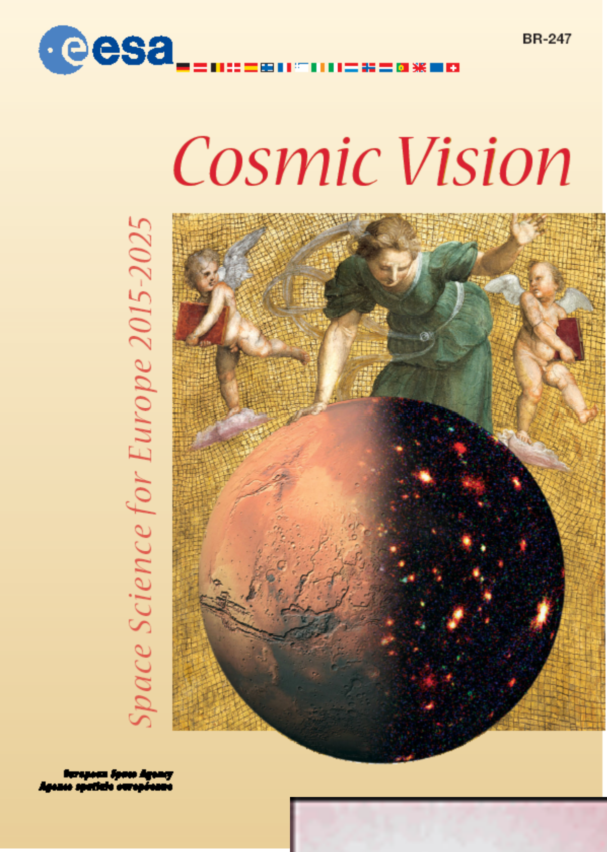


“Living with Stars”



Cosmic Vision is centered around four Grand Themes:

1. **What are the conditions for planet formation and the emergence of life?**
   - **From gas and dust to stars and planets**
   - **From exo-planets to biomarkers**
   - **Life and habitability in the Solar System**
2. **How does the Solar system work?**
3. **What are the Fundamental Physical Laws of the Universe?**
4. **How did the Universe originate and what is it made of?**



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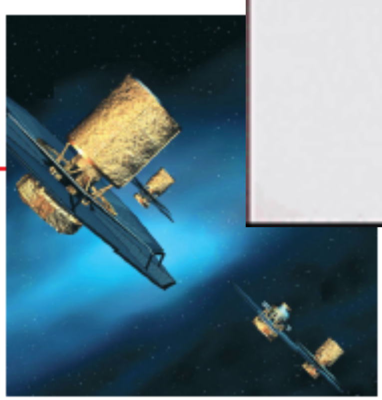


First: *In-depth analysis of terrestrial planets.*
Next: *Understanding the conditions for star & planet formation, and the origin of life.*
Later: *Census of Earth-sized planets, exploration of Jupiter's moon Europa.*
Finally: *Image terrestrial exoplanet.*

The PLATO mission statement

From planet frequency to planet characterization

PLATO 2.0 addresses the ESA Cosmic Vision science questions:
What are the conditions for planet formation and the emergence of life?
How does the Solar System work?

PLATO 2.0 follows the recommendations of ESA's Exoplanet Roadmap Advisory Team (EPRAT 2008 – 2010)

The PLATO mission statement

From planet frequency to planet characterization

PLATO shall, using the transit method & asteroseismology, discover and characterise large numbers of small, close by planets. ***(ESA's EPRAT roadmap 2010)***

- **Precision in exoplanet radius < 2% and mass < 10%**
- **Precision in age is < 10 – 20 %**

The result will be a catalogue with :

- **The planetary Masses, Radii → Mean density as well as constraining the scale height and composition of the atmosphere**
- **The Age → puts the planets into an evolutionary sequence**
- **The catalogue provides the necessary unique data allowing future spectroscopic studies and interpretation of exo-atmospheres, potential biospheres and ultimately searching for biomarkers**

Ultimate goal of exoplanetology is to understand ourselves!

Where we come from?

Where we are going?

Where and when does life arise? How does it evolve?

Is the Earth unique, has life developed elsewhere?

What makes a planet habitable?

Fundamental questions:

Did the Earth form in a special place in the Universe and/or under extraordinary circumstances?

How diverse are planets and planetary systems?

What are the characteristics of terrestrial planets in the habitable zones of stars?

How do planetary systems form and evolve?

Is our Solar system special?

Place the Solar System in context!

Carry out Comparative Planetology across interstellar distances *viz.*

- Analyse Solar System objects through observations and in-situ measurements!

- Define parameters measurable across interstellar distance to compare systems!

- Observe large enough sample to be statistically significant and to study evolution!

Understanding the star – planet connection!!!

"Living with a star"

- How do the formation process impact both star and planet(s)?

- How do the stellar evolution impact the planetary evolution – and vice versa?

- How does the star and stellar evolution impact the habitability – and life itself?

To answer these questions, we need to find planets of all kinds but particularly small Earth-like ones

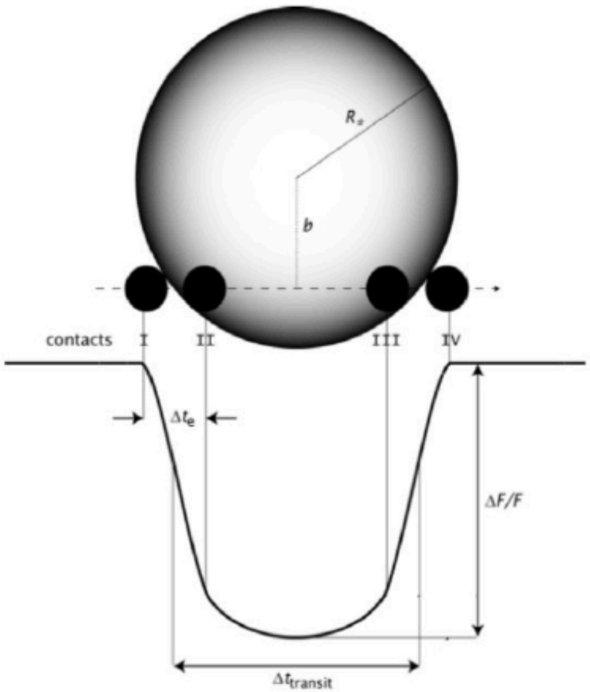
We need to determine physical parameters with high precision - first M_p, R_p, ages

We need to do this for a large sample

We are going to use two of the most common methods ones to give you (M_p, R_p, and with a new twist, The ages)

Combining transit photometry and radial velocity

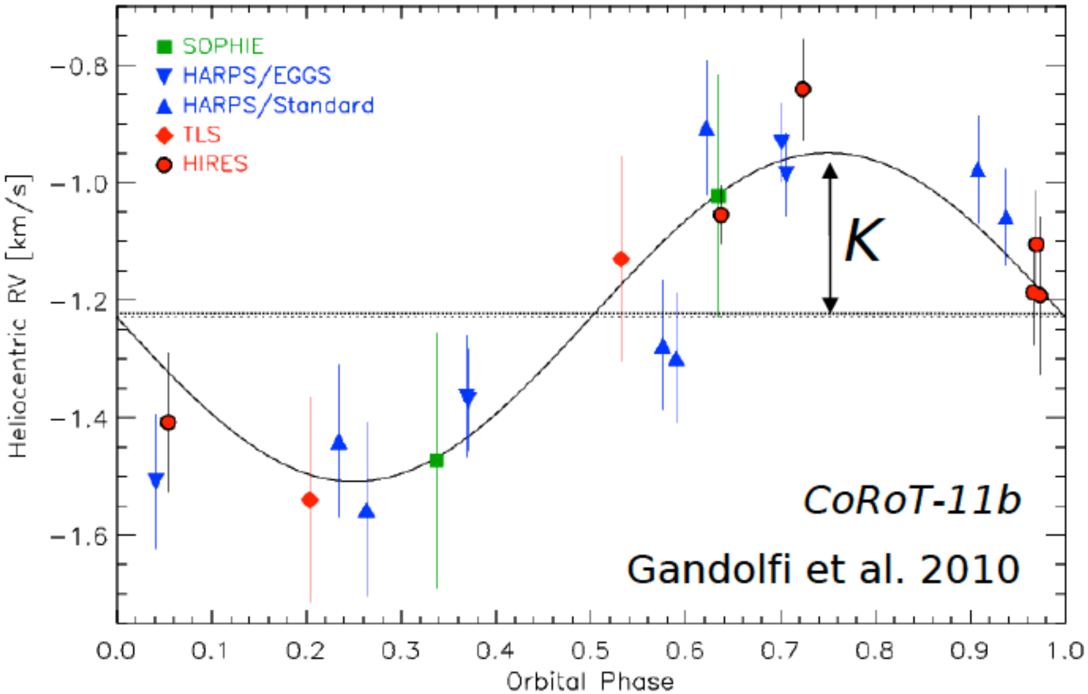
Transit



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

R_p can be derived !

Complementary Doppler observations



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

M_p can be derived !

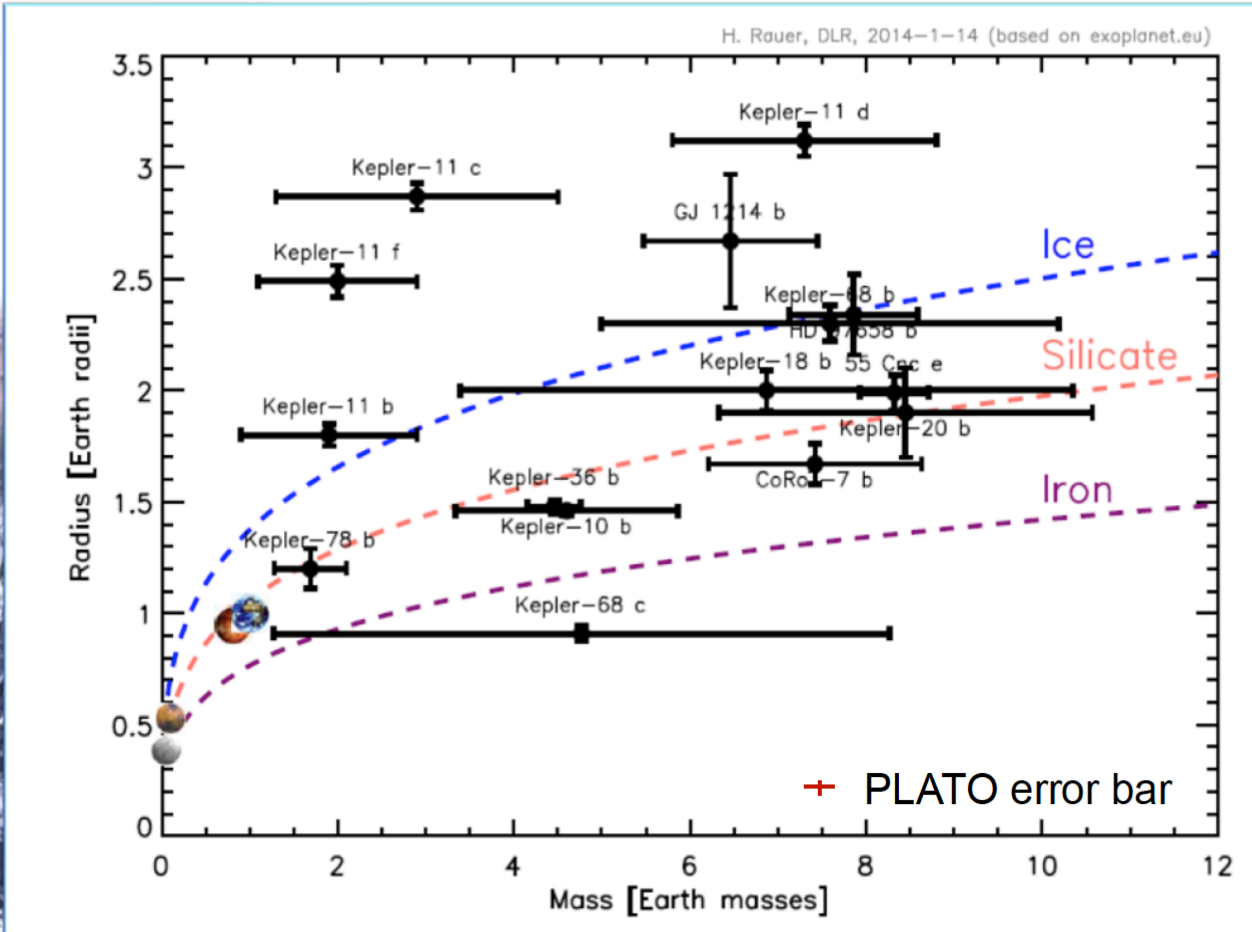
Where do the error bars come from?

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

$$\Delta F = \frac{F_{no-transit} - F_{transit}}{F_{no-transit}} = \left(\frac{R_P}{R_*}\right)^2$$

So if we need to know the planetary mass, radii, with a precision better than ~ few % we must know the parameters of the star to the same precision

Planet diversity from CoRoT, Kepler and MOST

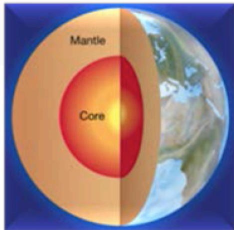


Wagner et al., 2012

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

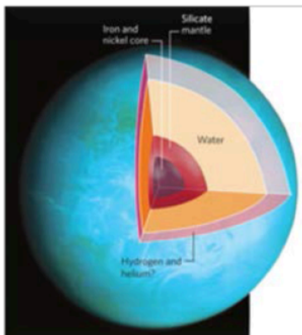
→ **We need both**: Accurate masses & radii to separate terrestrial from mini-gas planets.

Earth



5.5 g/cm^3

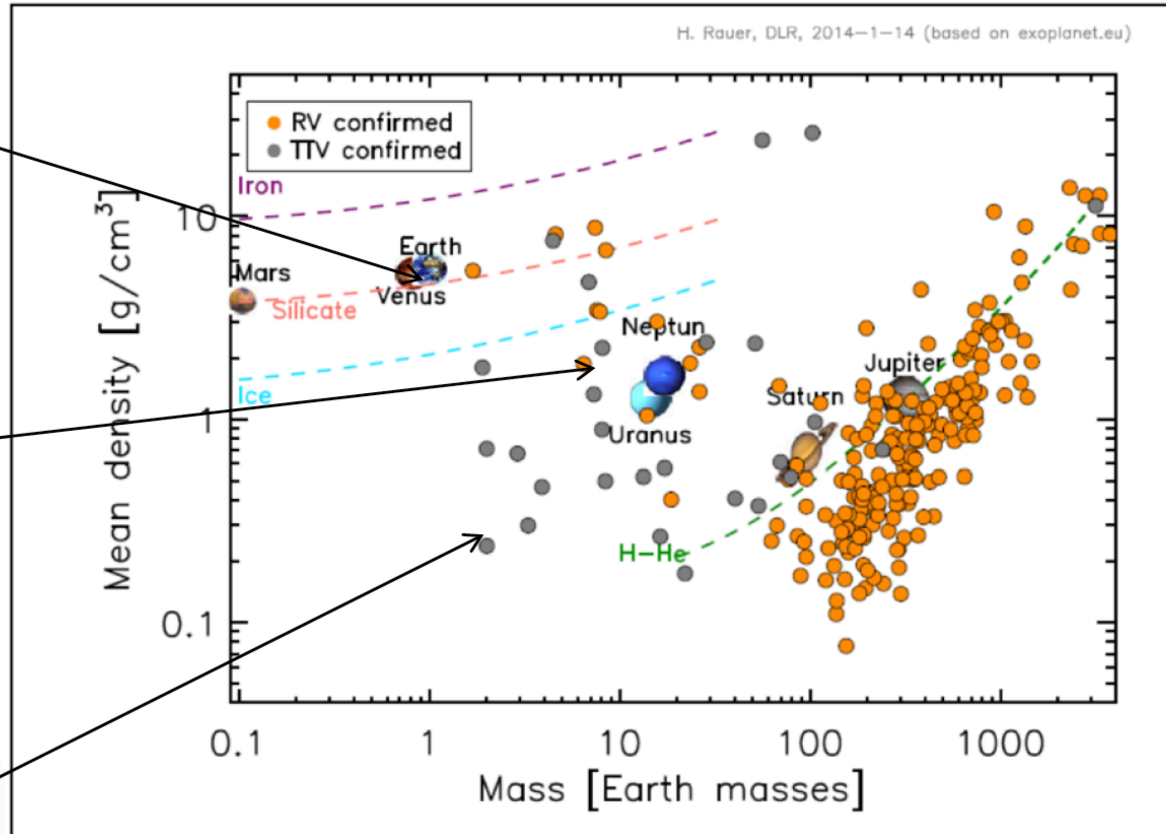
GJ1214b



1.6 g/cm^3

Mini gas planets

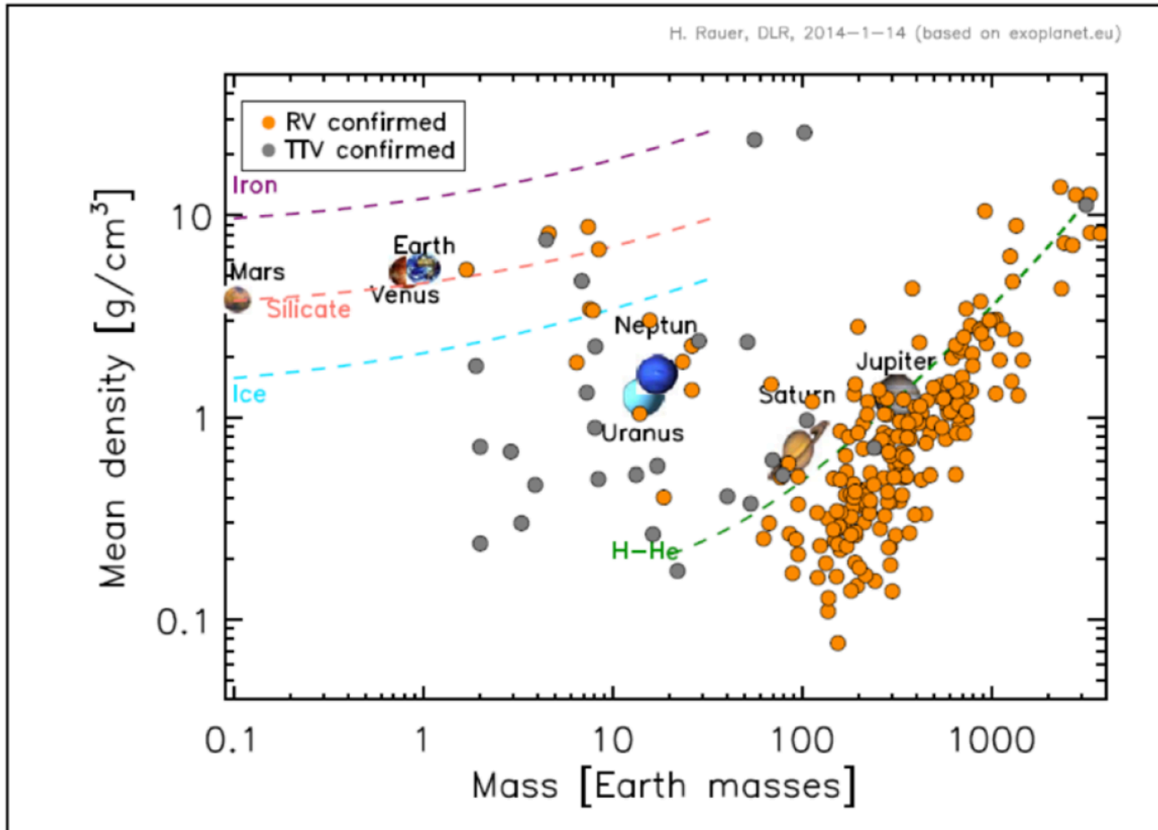
<~1 g/cm^3



Low-mass planets have a range of compositions and interior structures for similar masses.

- Mean density varies by two orders of magnitude for a given mass

- Planets of Earth mass and below remain to be detected and characterized



Characterization of exoplanets … needs characterization of stars

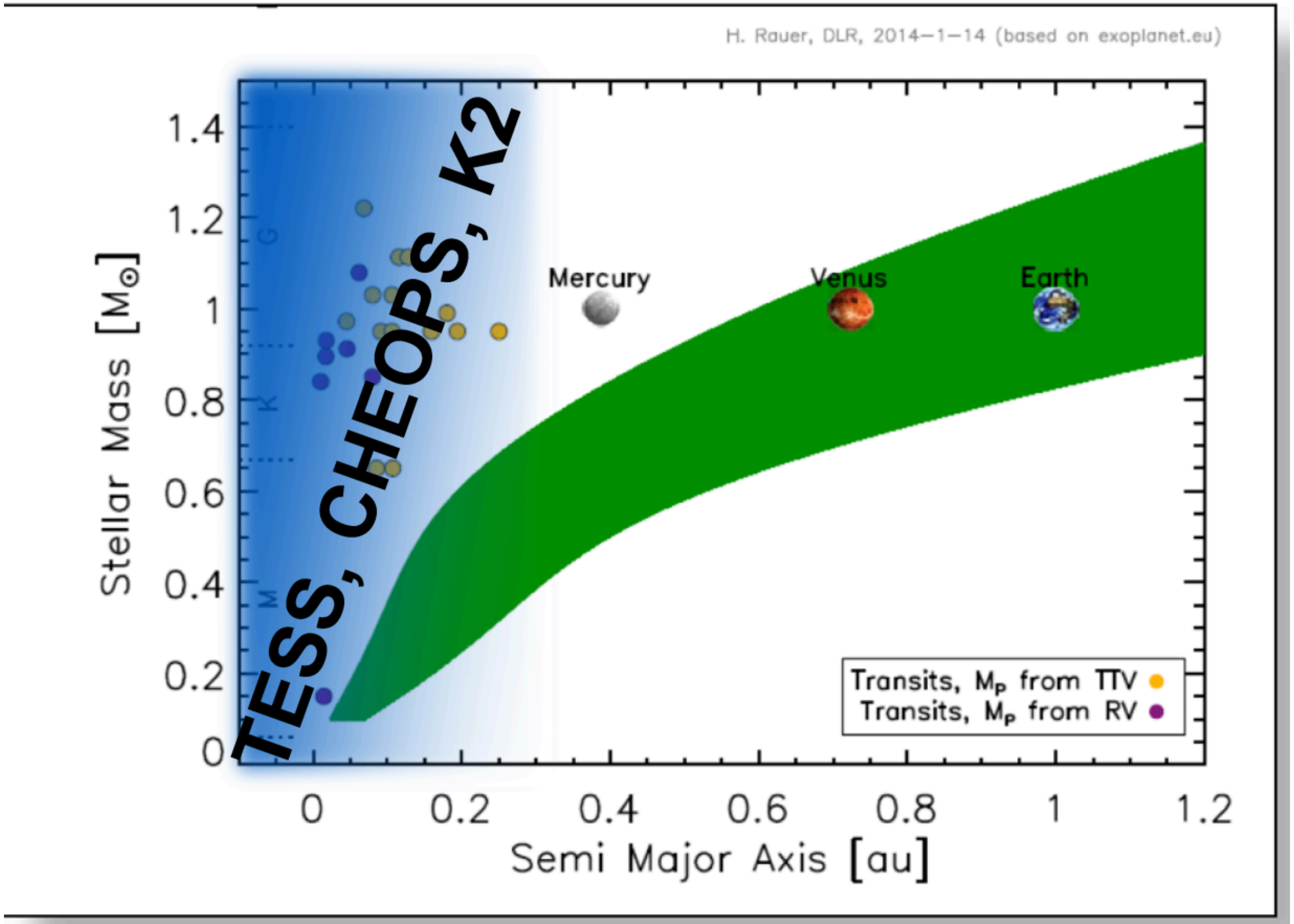
- **Mass + radius → mean density**
  (gaseous vs. rocky, composition, structure)
- **Orbital distance, atmosphere**
  (habitability)
- **Age**
  (planet and planetary system evolution)

- **Stellar mass, radius**
  (derive planet mass, radius)
- **Stellar type, luminosity, activity**
  (planet insolation)
- **Stellar age**
  (defines planet age)

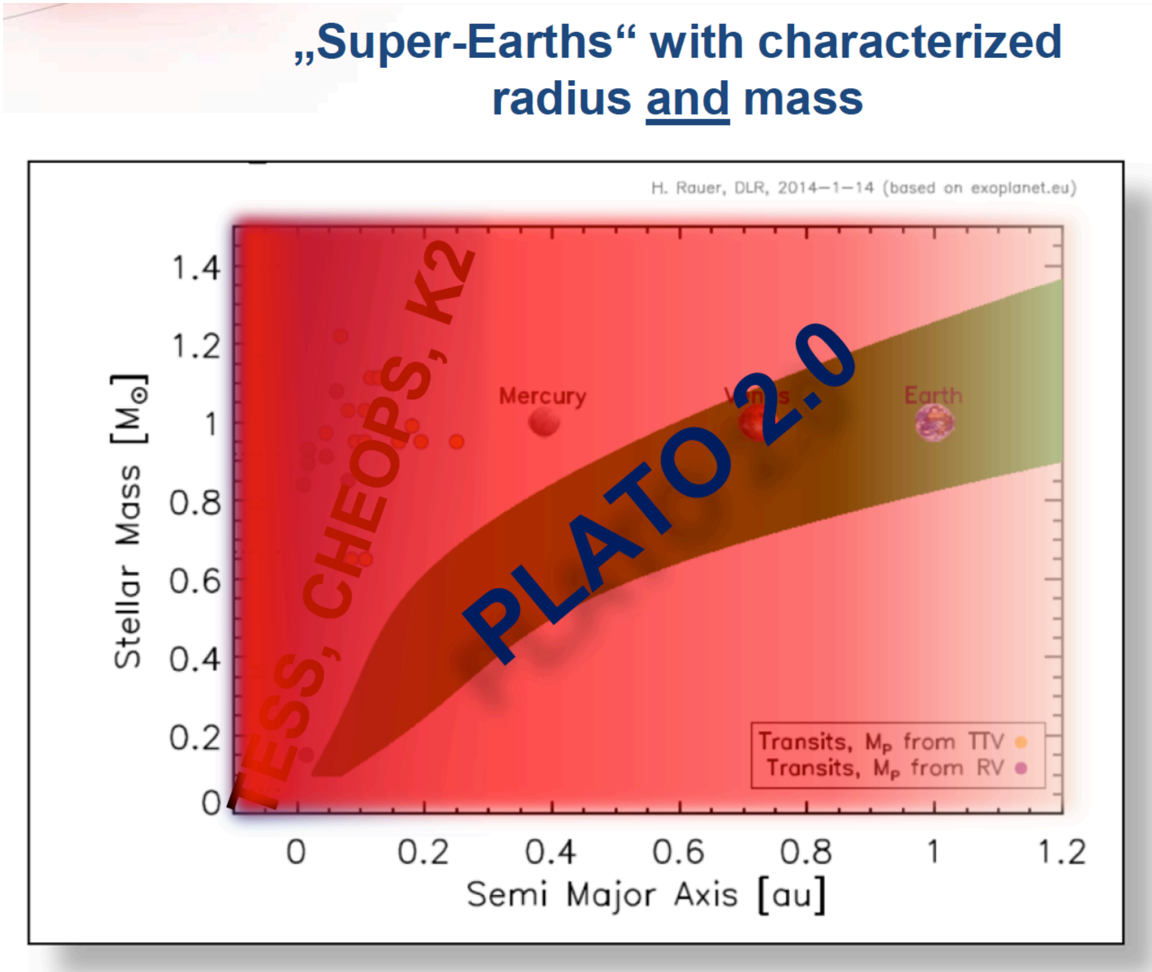
The need for bright stars

- Lessons learned from CoRoT and Kepler: Future transit missions must target bright stars
- TESS (NASA): Scans the ~ whole sky, 1 month per field. 2% of sky will be covered during several hundred days, 4 x10cm telescopes offset
- CHEOPS (ESA/CH+partners) Follow-up of RV
- K-2 Kepler extension 80 d/field along ecliptic

The need for bright stars



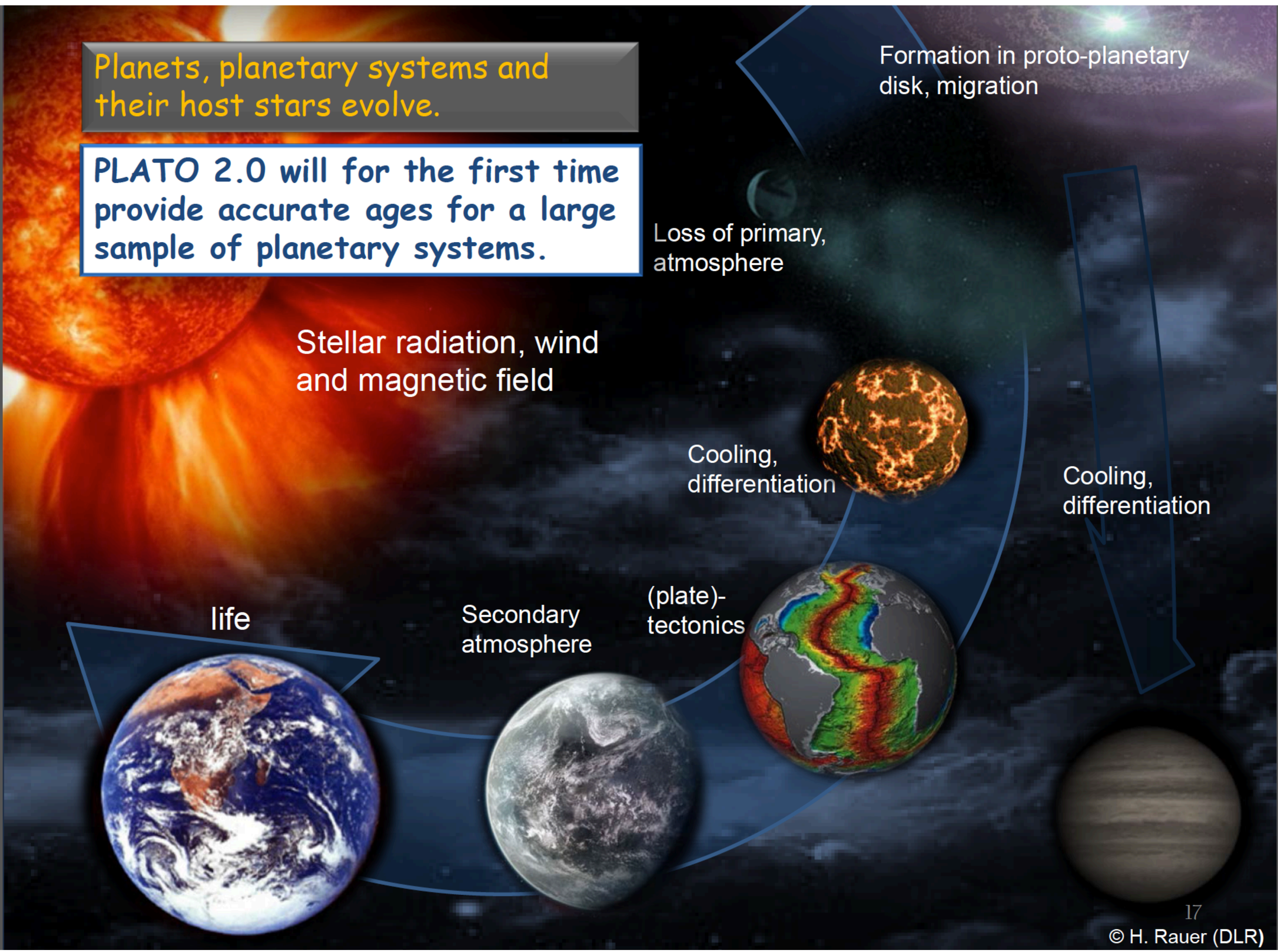
The need for bright stars



PLATO 2.0 will detect and bulk characterise small planets in the HZ of solar-like stars

Planets, planetary systems and their host stars evolve.

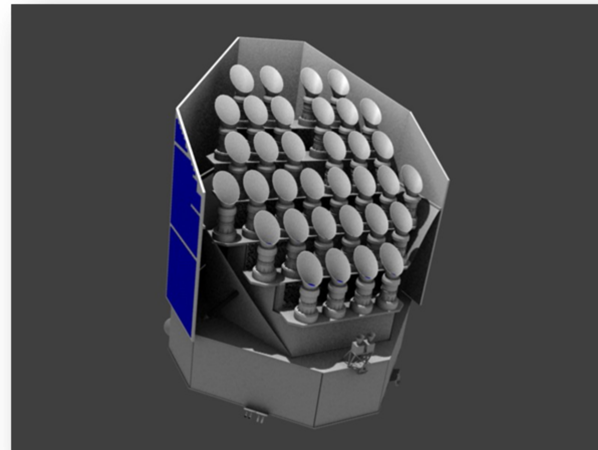
PLATO 2.0 will for the first time provide accurate ages for a large sample of planetary systems.



The PLATO 2.0 Mission

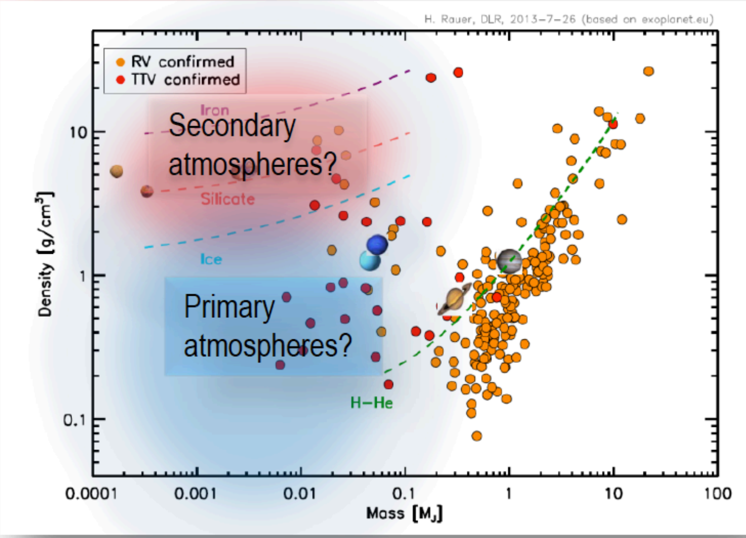
Selected as ESA's M3

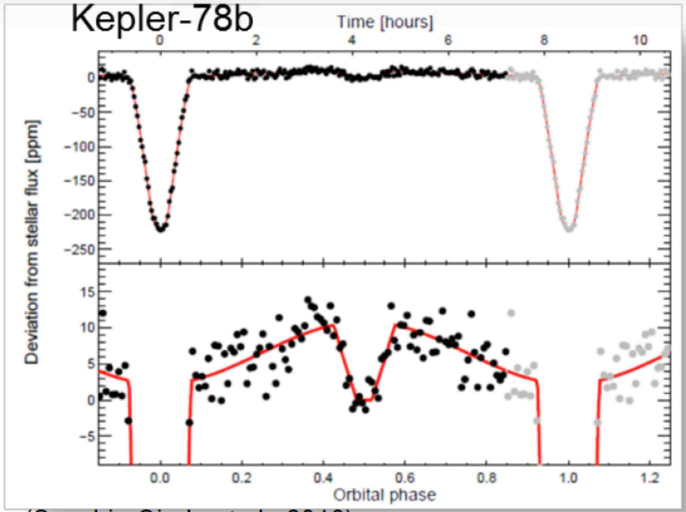
- PLATO will provide a large catalogue of highly accurate bulk planet parameters:
  - radii (transit)
  - masses (RV follow-up)
  - mean densities
  - ages (astroseismology)
  - well-known host stars



- Focus on warm/cool Earth to super-Earths, up to the habitable zone of solar-like stars
- Focus on solar-like host stars to put the Solar System into context
- Observe bright stars for feasible RV follow-up and targets for atmosphere spectroscopy by e.g. JWST, E-ELT, future space missions
- Provide a huge legacy for planetary, stellar and galactic sciences

Planet diversity & comparative planetology





(Sanchis-Ojeda et al., 2013)

PLATO 2.0 will provide planets with:

- mean density
  → composition and structure (rocky, mini-gas)
  → constrain atmosphere scale heights
- albedo and its diversity
  → indicative for clouds, hazes
- accurate ages
  → evolutionary pathways
- characterized host stars
  → incident flux, stellar activity

PLATO 2.0 will
→ explore the wealth of planets, systems, host stars
→ provide well-characterized targets for atmosphere spectroscopy

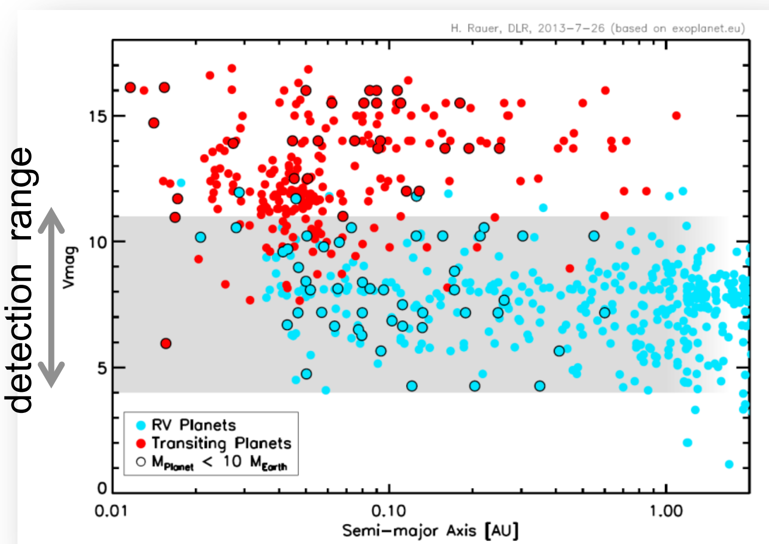
The Method (in summary)

Characterize bulk planet parameters

Accuracy for Earth-like planets around solar-like (F – K) MS stars:

- Radius < 2%
- mass < 10%
- age known to ~ 10%

bright host stars:

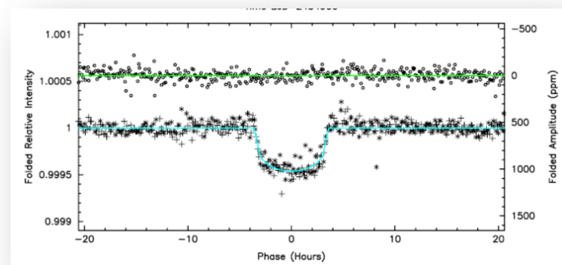


PLATO prime detection range

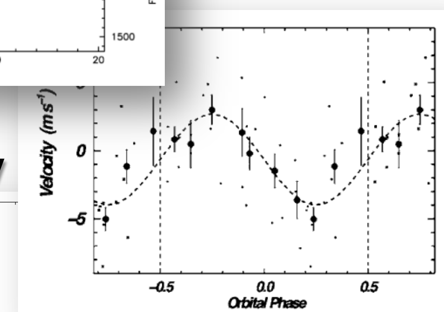
Techniques

Example: Kepler-10 b

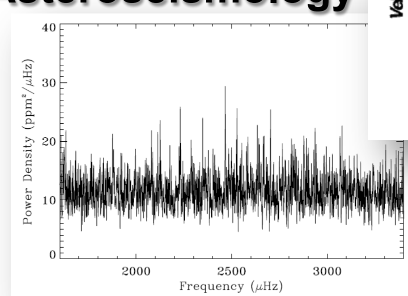
Photometric transit



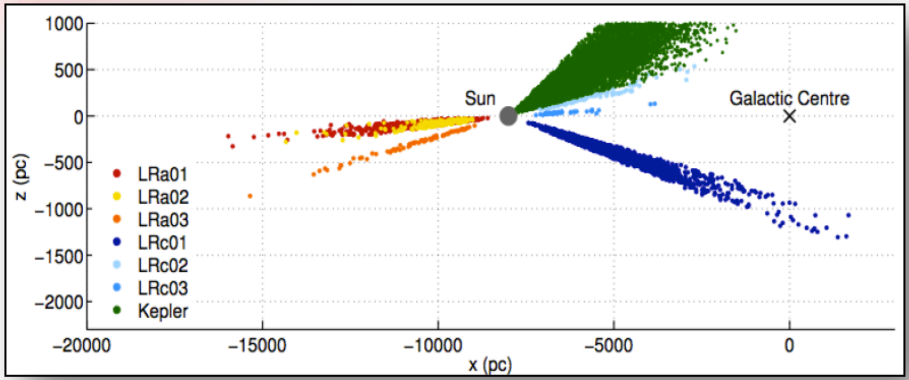
RV – follow-up



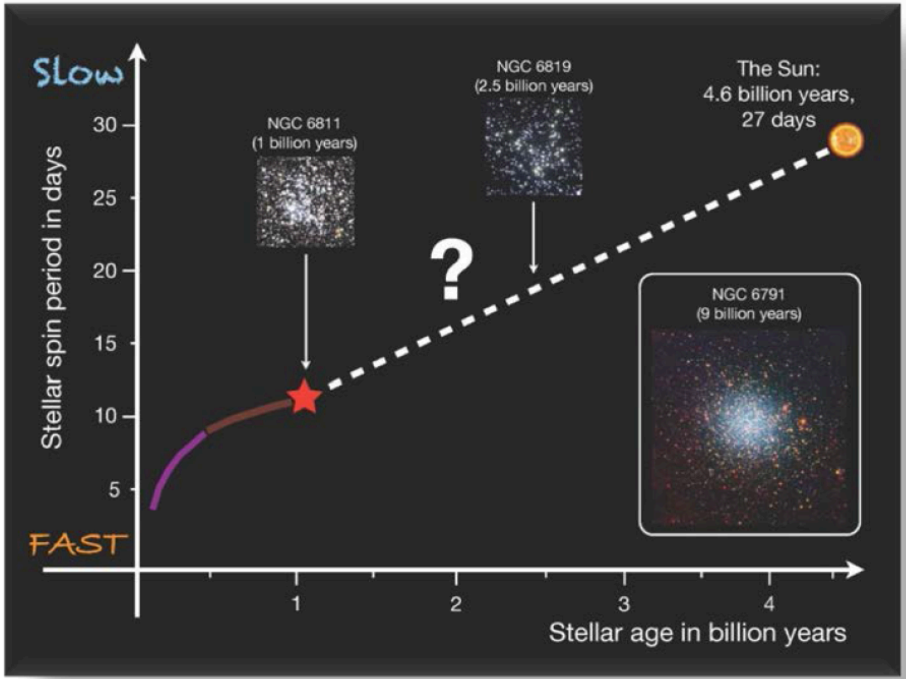
Asteroseismology



Structure and evolution of the galaxy with PLATO 2.0



Miglio et al. (2013)



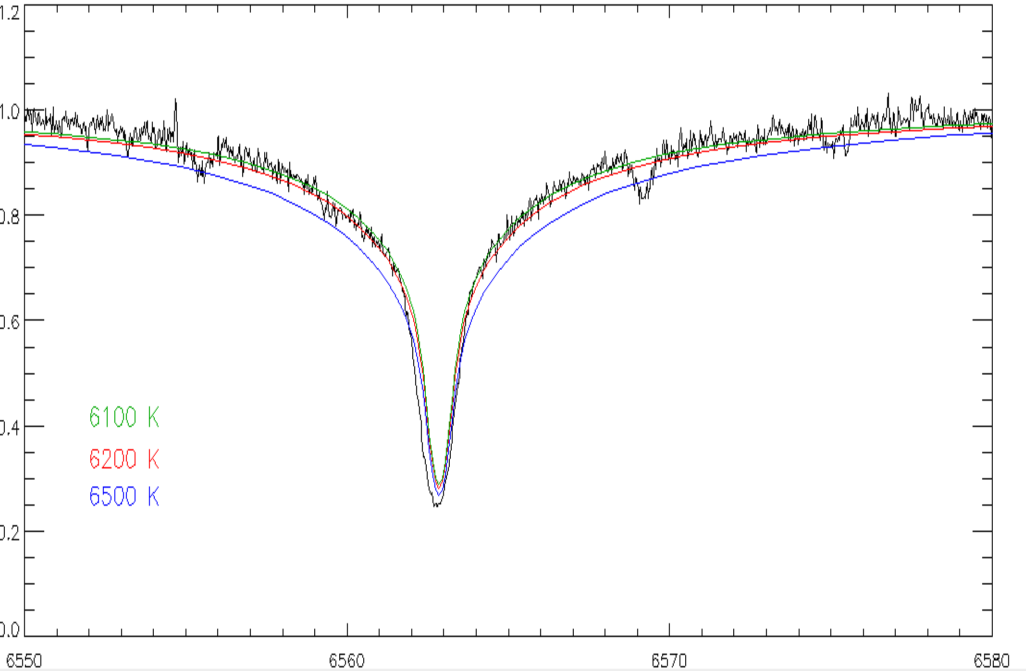
Meibom et al. (2011)

- Gyrochronology of stars via age-rotation relationship:
  → seismic age versus rotation period
  from spots

- PLATO 2.0 & Gaia:
  - seismic + astrometric distances
  - seismic age-metallicity relations for giants

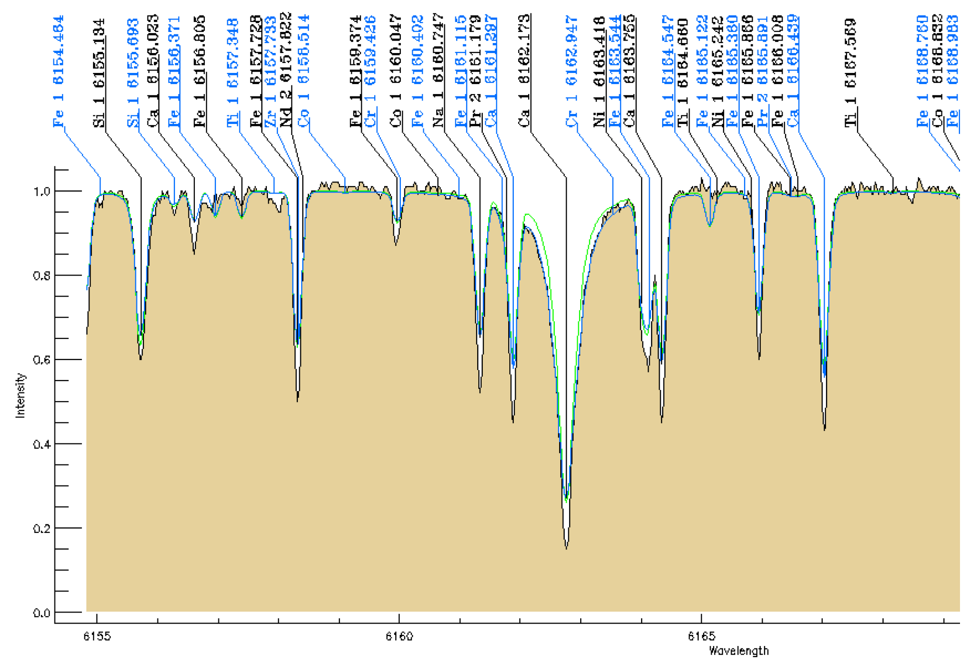
→ Provide accurate ages
→ Calibrate stellar evolution theories
→ Calibrate Galactic age-metallicity relationship

→ Probe the structure and the evolution of our Galaxy



Understand the stars themselves around which the planets orbit

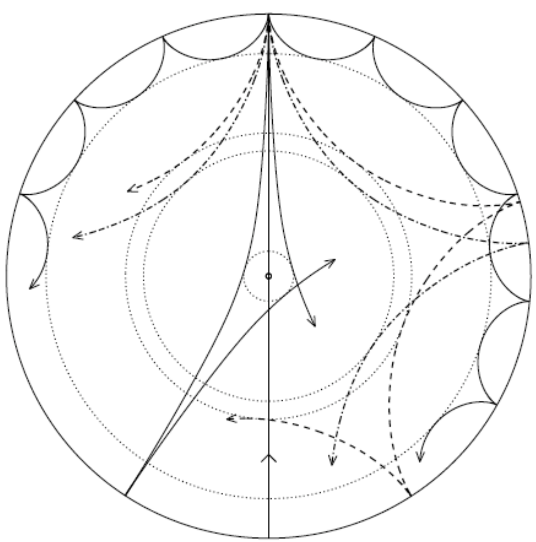
Spectroscopy has so far been the most important tool

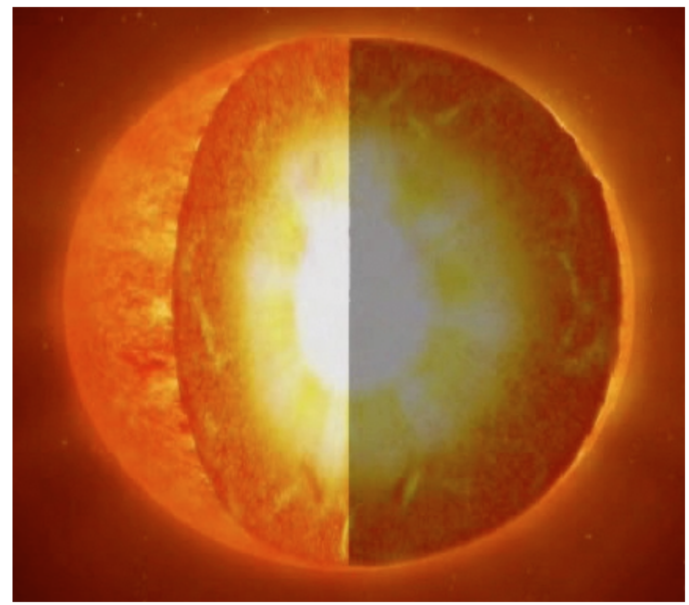


PLATO 2.0 will have to provide stellar physics in bulk!!

To determine the mass, the radius and the age of the star with high accuracy

Here P-modes are the key





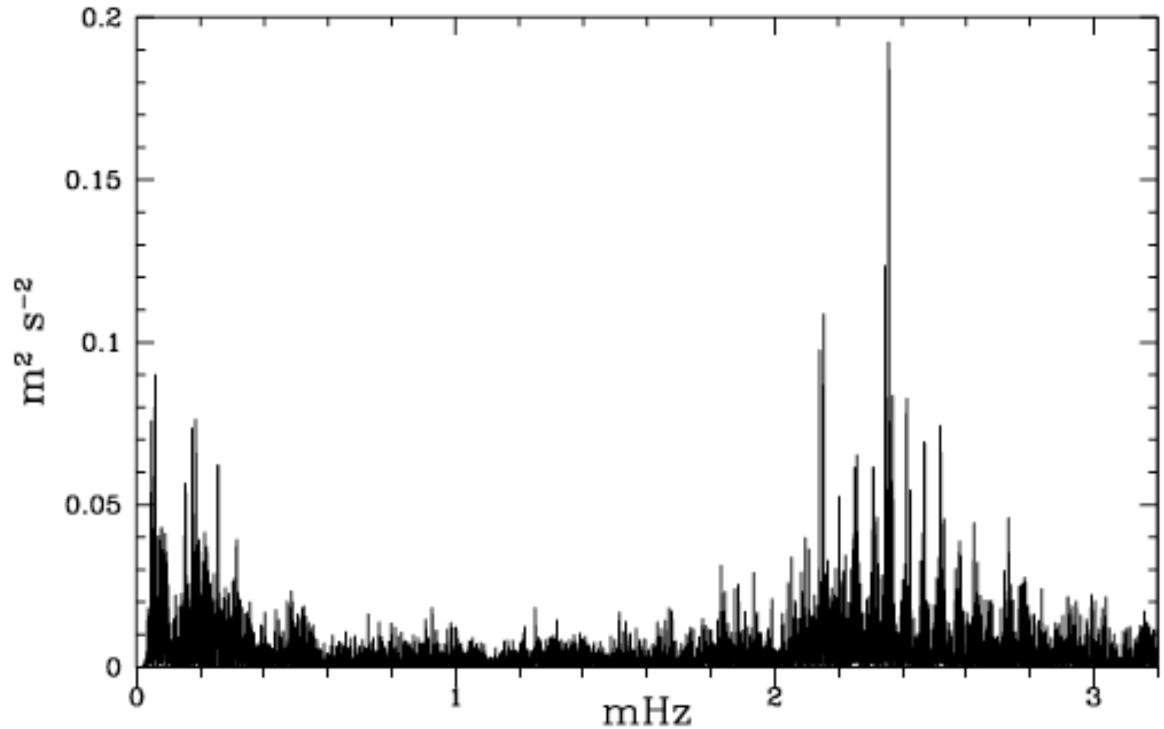
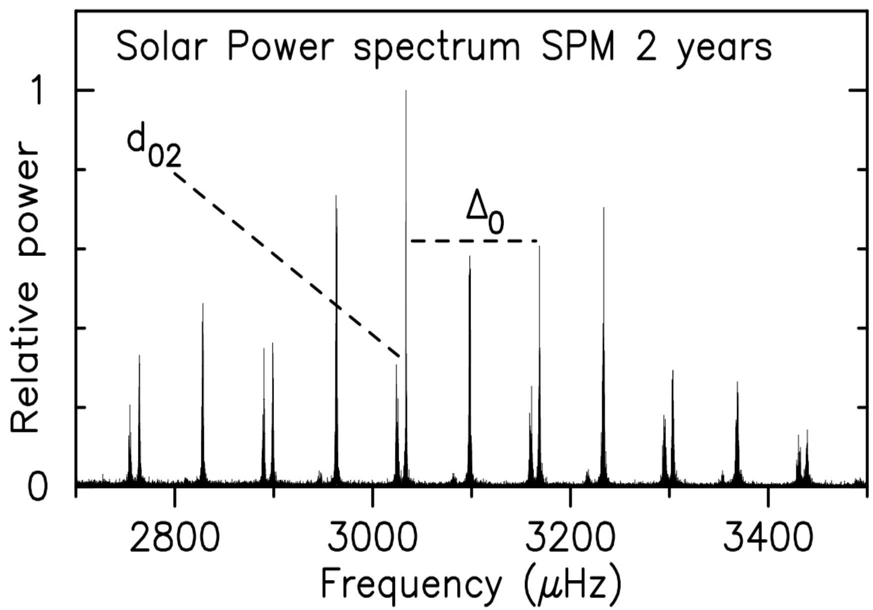


Figure 2.21: Power spectrum of oscillations of α Cen A, from radial-velocity observations with the CORALIE spectrograph. (From Bouchy & Carrier 2001.)

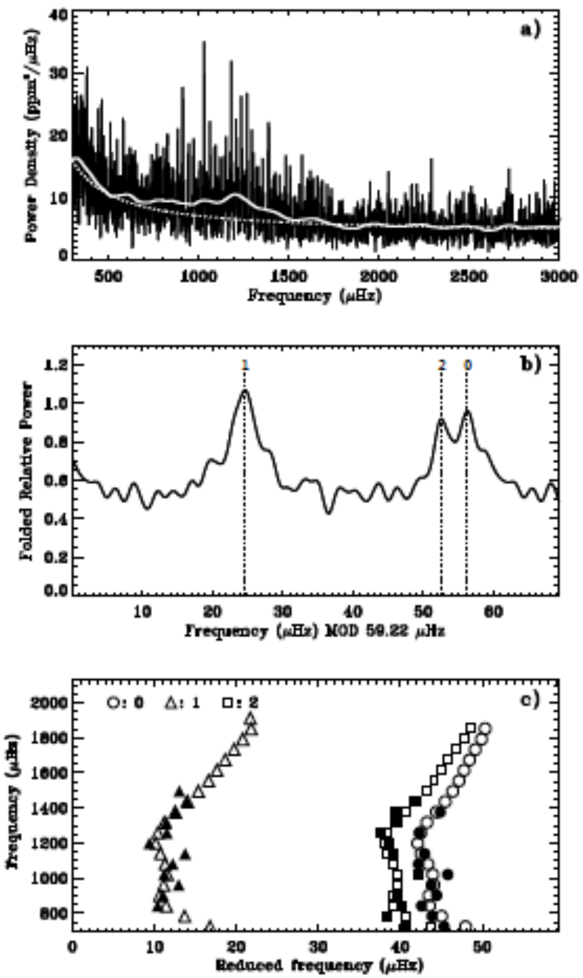
Asteroseismology – providing mass and age of host stars



1. Large separations $\Delta_0 \propto \sqrt{M/R^3}$
   → mean density
2. Small separations d_{02}
   → probe the core → age
3. Inversions + mode fitting
   → consistent ρ, M, age

Asteroseismology has been successfully applied to bright Kepler stars, showing how powerful this technique is.

Kepler asteroseismology



P-modes in Hat-P-7

Blow-up showing *l*=0,1,2

$\Delta\nu_0$ for *l* = 0,1,2; filled symbols is data, open is model 3

Kepler asteroseismology

Kepler result is following:

TABLE 2
STELLAR EVOLUTION MODELS FITTING THE OBSERVED FREQUENCIES FOR HAT-P-7.

No	$M_*/M_\odot$	Age (Gyr)	Z_0	X_0	α_{ov}	$R_*/R_\odot$	$\langle\rho_*\rangle$ ($g\,cm^{-3}$)	T_{eff} (K)	$L_*/L_\odot$	χ^2_ν	χ^2
1	1.53	1.758	0.0270	0.6870	0.0	1.994	0.2718	6379	5.91	1.08	1.21
2	1.52	1.875	0.0290	0.6809	0.1	1.992	0.2708	6355	5.81	1.04	1.04
3	1.50	2.009	0.0270	0.6870	0.2	1.981	0.2718	6389	5.87	1.00	1.24

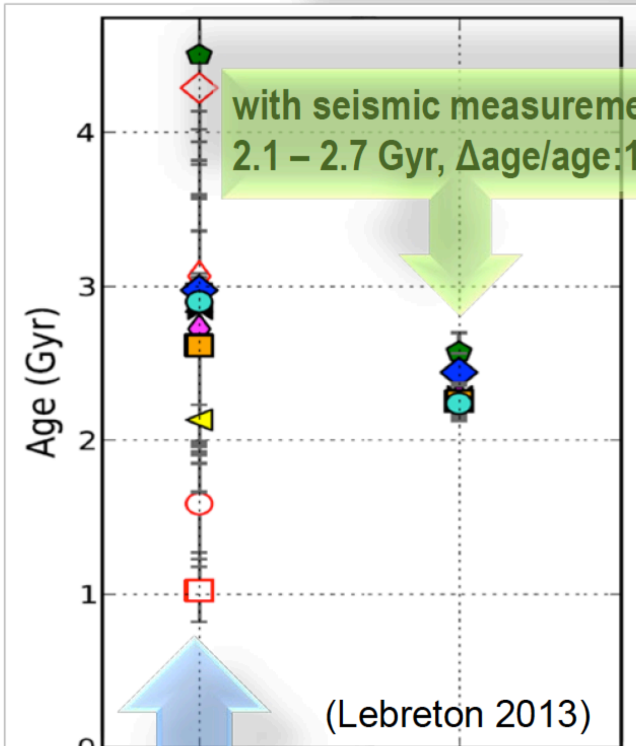
for details). This resulted in $M = 1.520 \pm 0.036\,M_\odot$, $R = 1.991 \pm 0.018\,R_\odot$ and an age of 2.14 ± 0.26 Gyr.

Planet parameters are now known to < 5% instead of >50%!!!

2010ApJ...713L.164C Christensen-Dalsgaard et al

Asteroseismology

CoRoT and Kepler have demonstrated that the required accuracies can be met

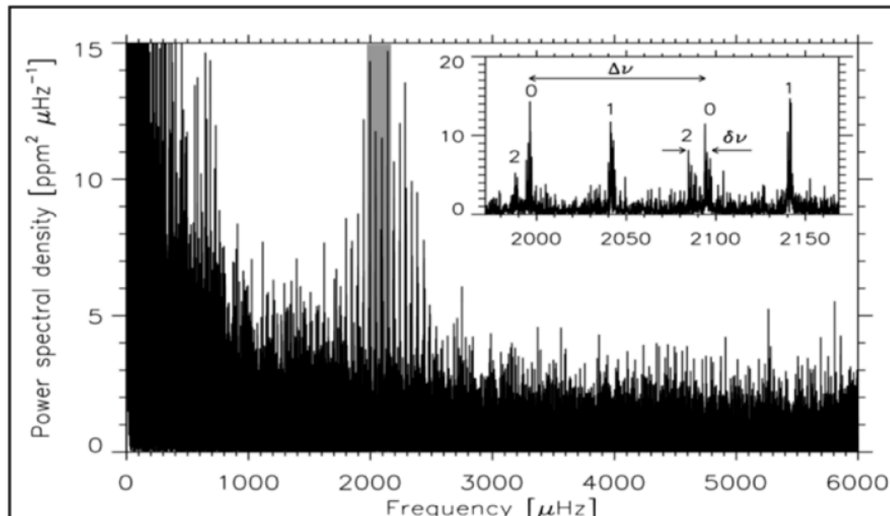


(Lebreton 2013)

with seismic measurement, 2.1 – 2.7 Gyr, Δage/age:13%

no seismic measurement, 0.8 – 5.9 Gyr, Δage/age: 75%

Example: HD 52265 (CoRoT), a G0V type, planet-hosting star, 4 months data



(Gizon et al. 2013)

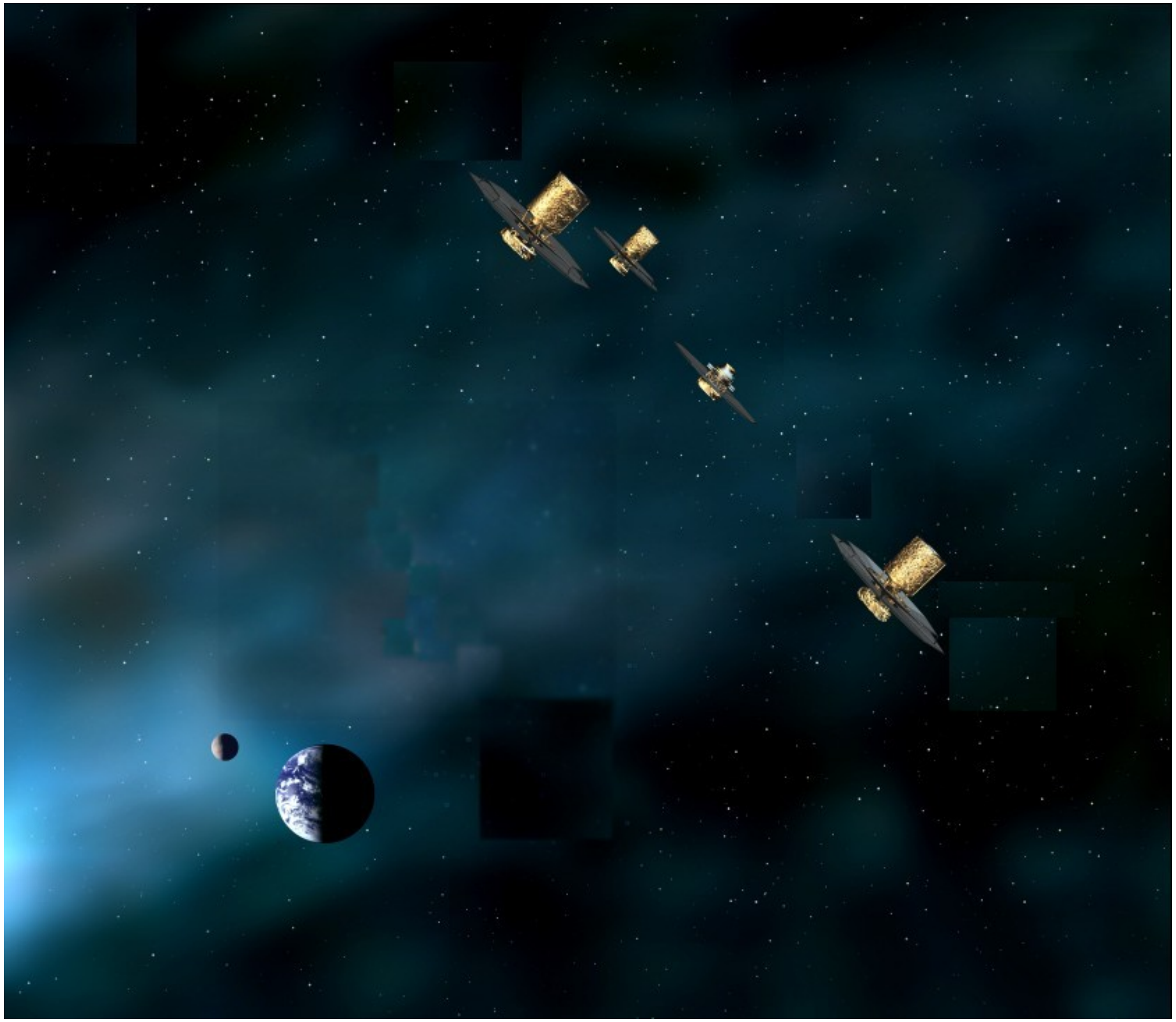
Seismic parameters: Radius: 1.34 ± 0.02 R_{sun},
Mass: 1.27 ± 0.03 M_{sun},
Age: 2.37 ± 0.29 Gyr

So is there any way around having to do asteroseismology for every host star?

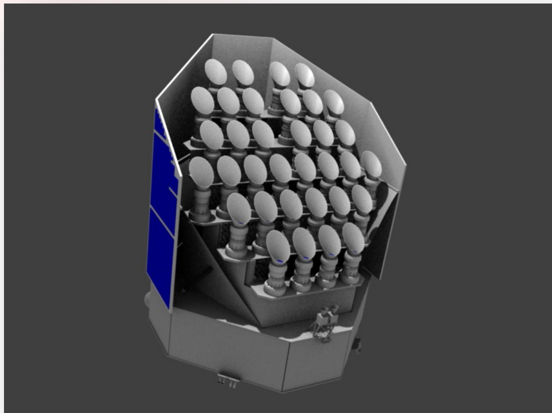
NO!!

If we want to be able to determine other physical aspects like atmospheric composition, stratification, evolutionary stage, etc ➔ Asteroseismology

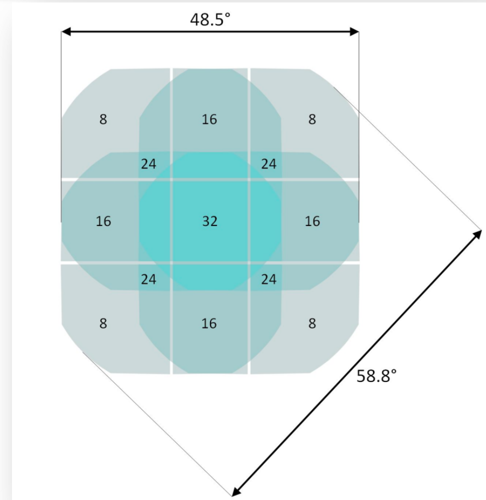
Not even Darwin or TPF can avoid needing this information

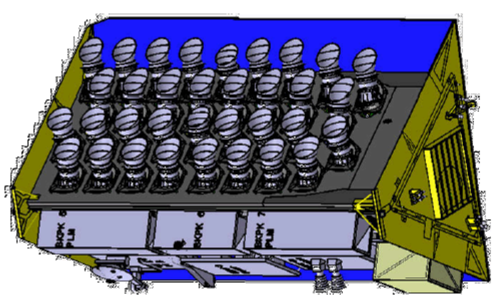


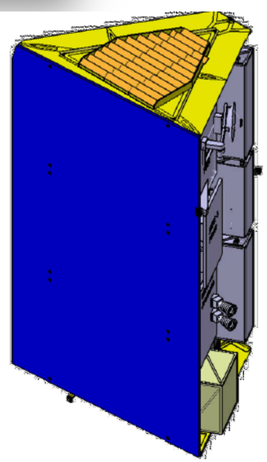
PLATO instrument



Two designs that can do the job







- Cameras are in groups
- Offset to increase FoV
- Nominal mission covers ½ the sky

Multi-telescope approach give

- *Large FOV (Large number of bright stars)*
- Large total collecting area *(provides high sensitivity allowing asteroseismology)*

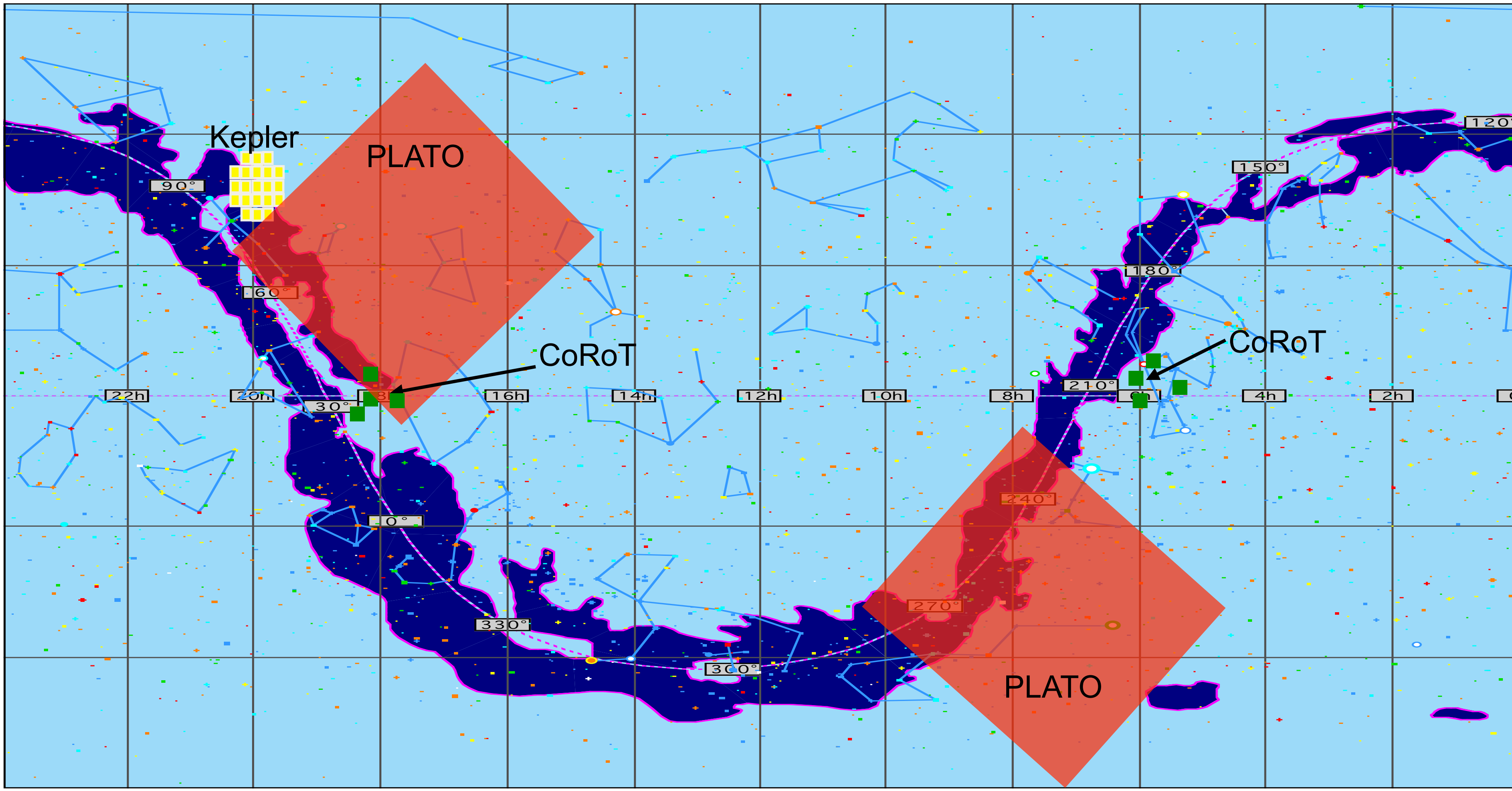
- 32 « normal » 12cm cameras, cadence 25 sec
- 2 « fast » 12cm cameras : cadence 2.5 sec, 2 colours
- dynamical range: $4 \leq m_V \leq 16$
- Nominal mission 6 years, FOV 48.5 x 48.5 deg = 2250 sq deg

Basic observation strategy

very wide field + 2 successive long monitoring phases:

3 years + 2 years

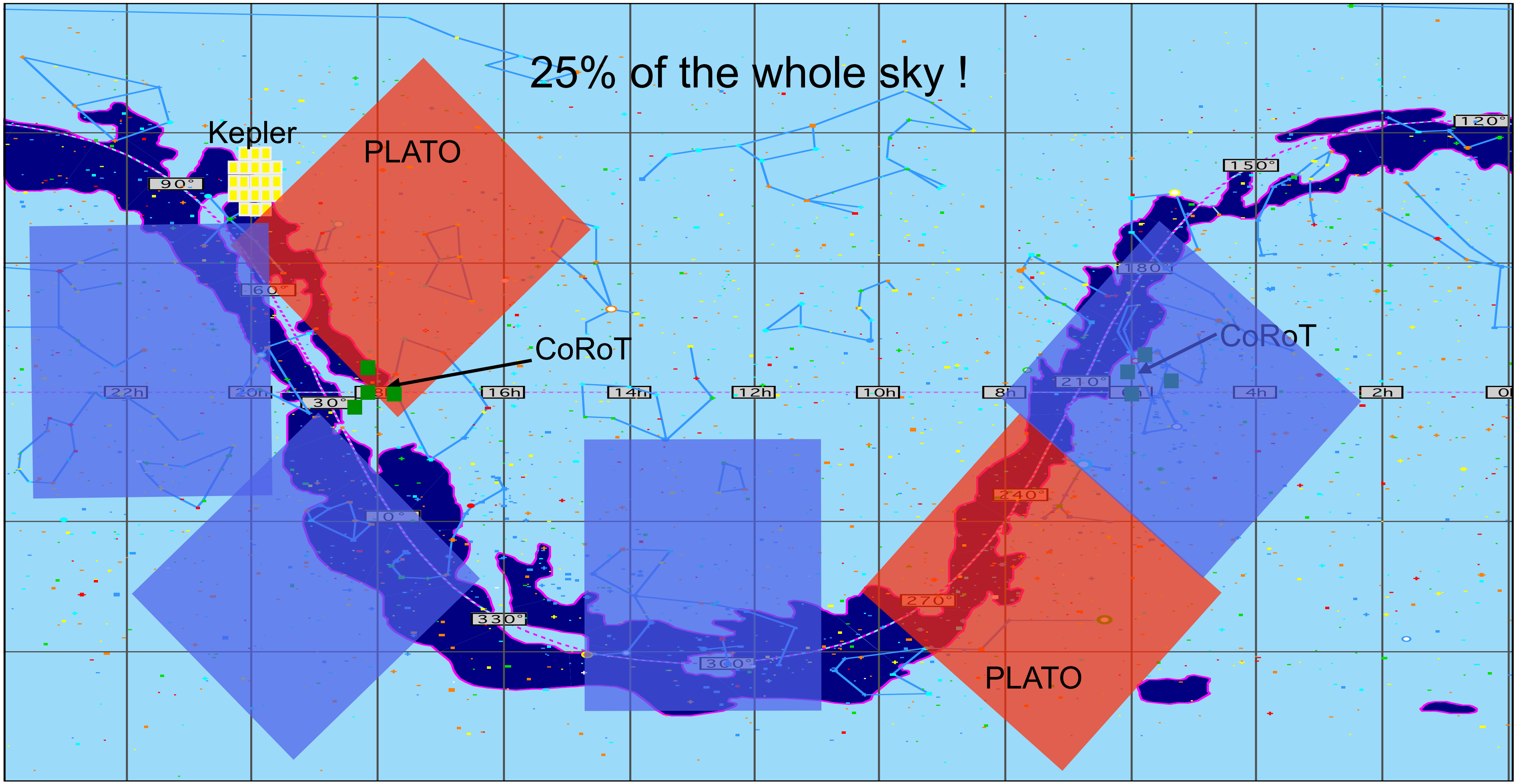
comply with duration requirement



Basic observation strategy

step and stare phase (1 year) : N fields for 3-5 months each

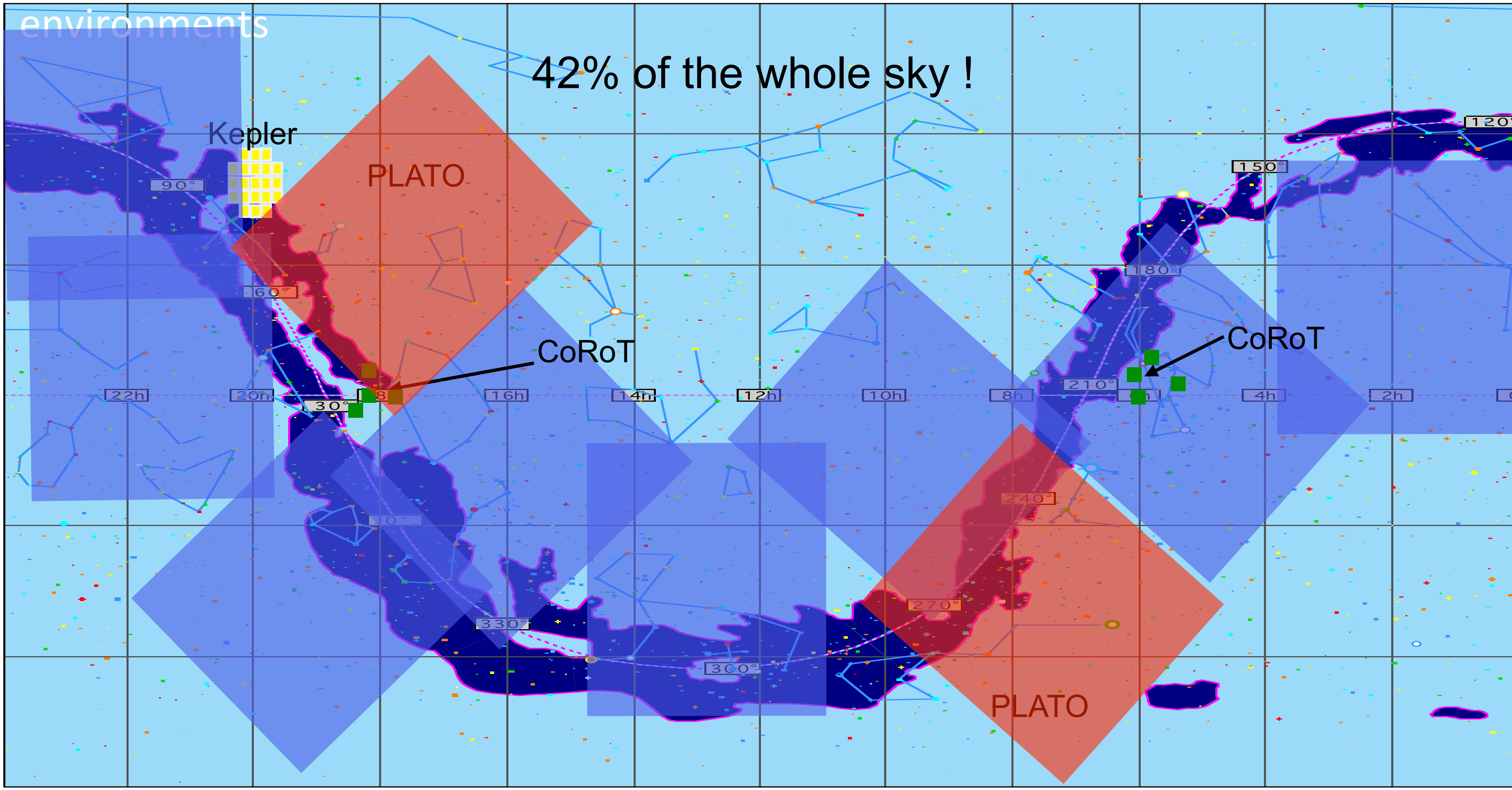
- increase sky coverage
- potential to re-visit interesting targets



Basic observation strategy

step and stare phase (2 years) : N fields for 3-5 months each

- increase sky coverage
- potential to re-visit interesting targets
- explore various stellar environments



Number of light curves

For the baseline observing strategy:

Noise level	Magnitude limit	4300 deg^2 (long stare fields)	20,000 deg^2 (plus step and stare fields)
(ppm/√hr)	m_V	Number of cool stars	Number of cool stars
34	11	**22,000**	**85,000**
80	13	**267,000**	**1,000,000**

Detection of Earth-sized planets
+ asteroseismology
+ radial velocity

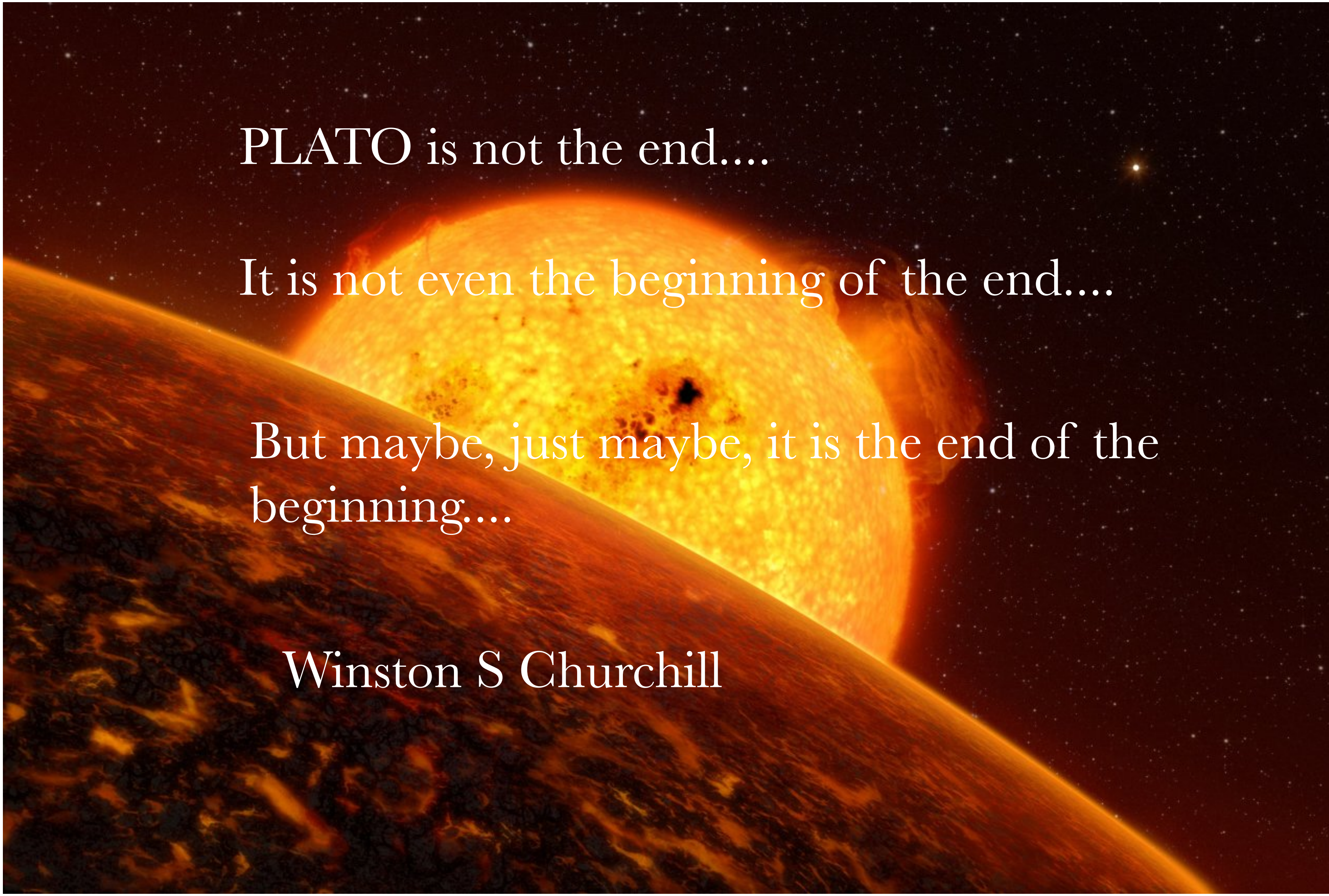
+ Detection of Earth-sized planets
+ ...

Follow-up

Full follow-up of the expected planet yield from core sample

Radial velocity precision	Telescope	Type of objects	Example time distribution
10m/s	1-2m	Giant planets on short/ medium orbits	50 nights/yr for 6 yrs on 3 tel.
1m/s	4m	Giant planets, long orbits. Super-Earths on short medium orbits	40 nights/yr for 6 yrs on 3 tel.
<20cm/s	8m	Earths/Super-Earths on long orbits	40 nights/yr for 6 yrs on 1 tel.

Few hardest cases (eg faintest hosts with Earths in the habitable zone) will need E-ELT


PLATO is not the end....
It is not even the beginning of the end....
But maybe, just maybe, it is the end of the beginning....
Winston S Churchill