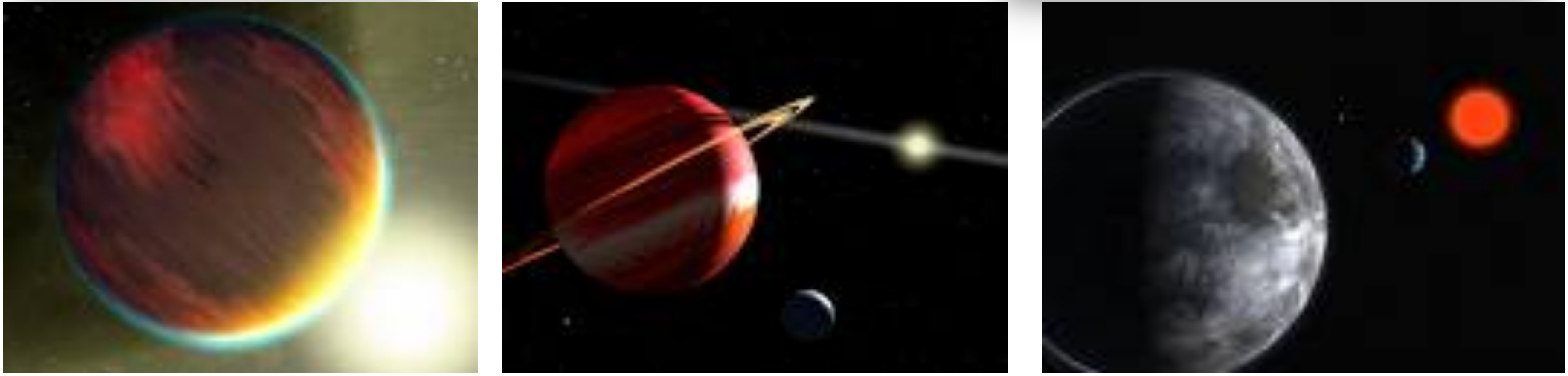
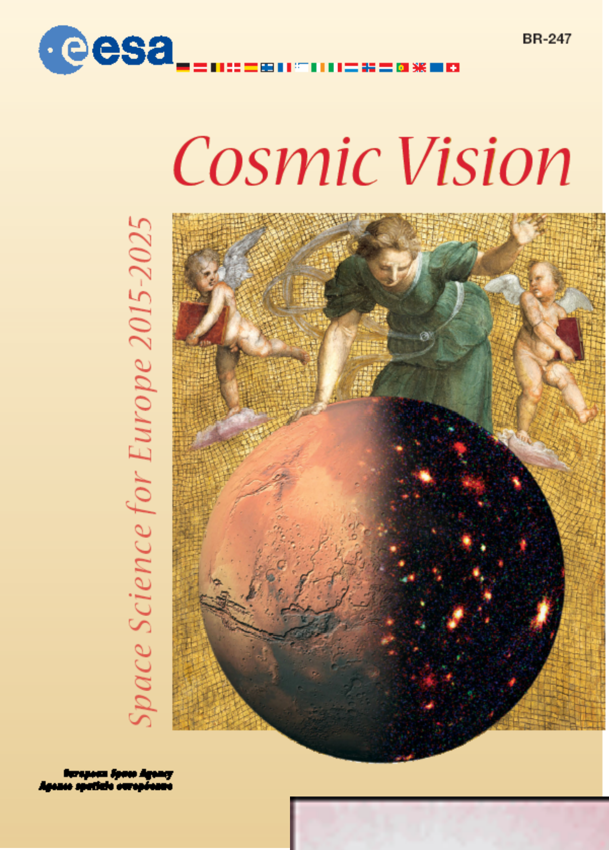
The astrophysics of the PLATO space mission-



“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?**

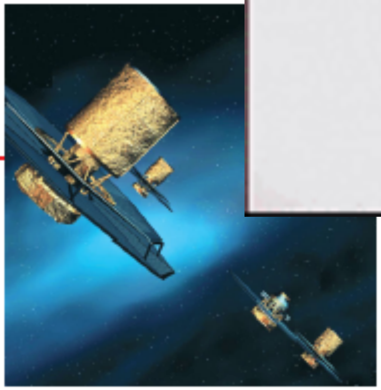

esa

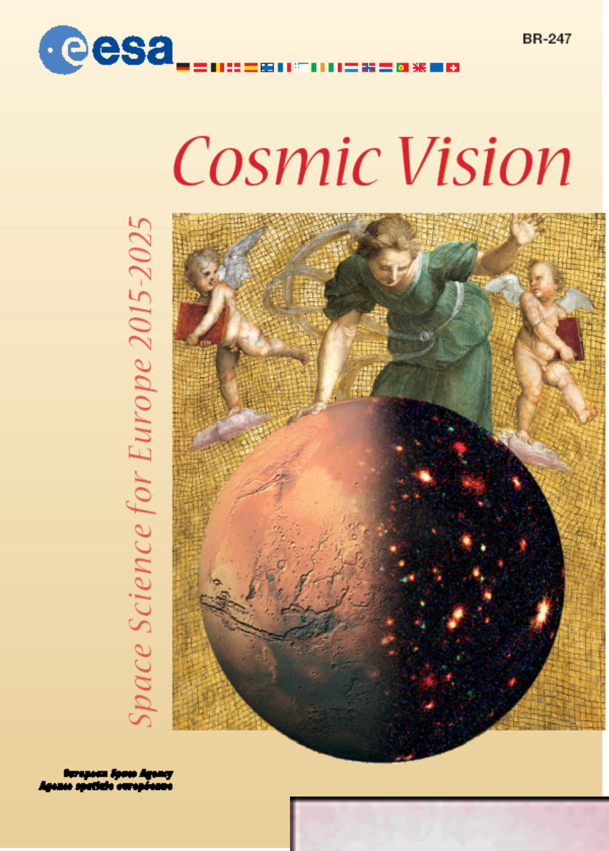
BR-247

Cosmic Vision

Space Science for Europe 2015-2025

European Space Agency
Agence spatiale européenne

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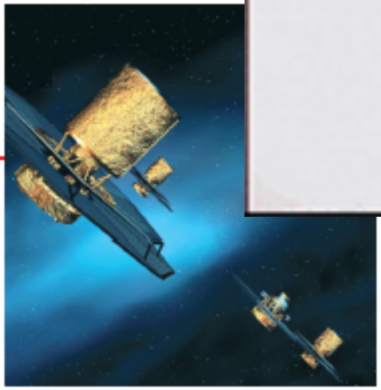


First: *In-depth analysis of terrestrial planets.*

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 shall, using the transit method & asteroseismology, discover and characterise, with high precision 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 → Derivation of mean density as well as constraining the scale height and composition of any atmosphere**
- **The Age → puts the planets and planetary system into an evolutionary sequence to be compared with that of the host star**
- **The catalogue will provide the necessary unique data allowing future spectroscopic studies and interpretation of exo-atmospheres, potential biospheres and ultimately searching for biomarkers**

Ultimate goal of exo-planetology is to understand ourselves!

Where we come from?

Where we are going?

Where and when does life arise?
How does planets evolve?
What makes a planet habitable?
How do planetary systems form and evolve?
Is our Solar system special?
Is the Earth unique, has life developed elsewhere?

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!

We need to find planets of all kinds but particularly small Earth-like ones

We need to determine physical parameters of these bodies (M_p, R_p, ages) ➔ average ρ_{planet},
Evolutionary stage of the planet

We need to understand the diversity of planetary systems as a function of type of system e.g.

Is it a compact system?
Or a solar system like one?
What kind of planetary composition?

And.... We need to do this for a large sample

We need to understand more fully the star – planet connection!!!

"Living with a star"

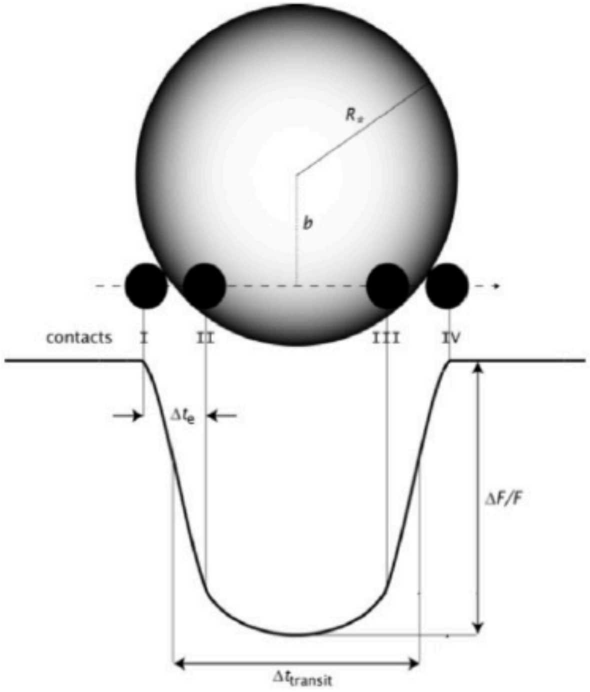
- How does the formation process impact both star and planet(s)?

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

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

Combining transit photometry and radial velocity

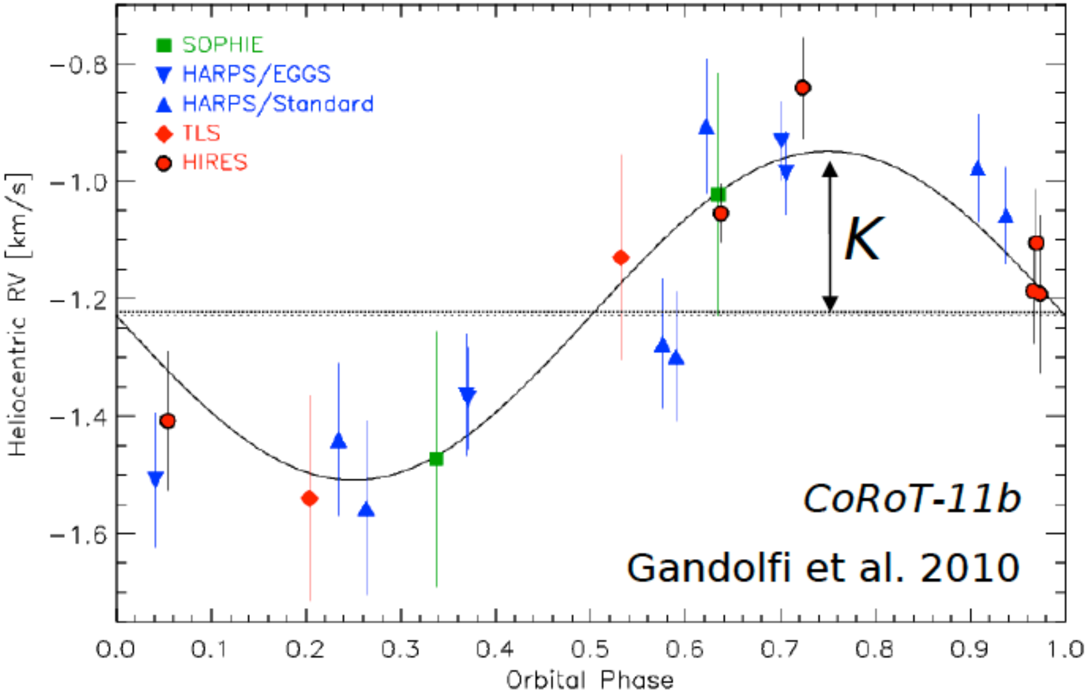
Transit



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

R_p can be derived !

Complementary Doppler observations



Gandolfi et al. 2010

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

M_p can be derived !

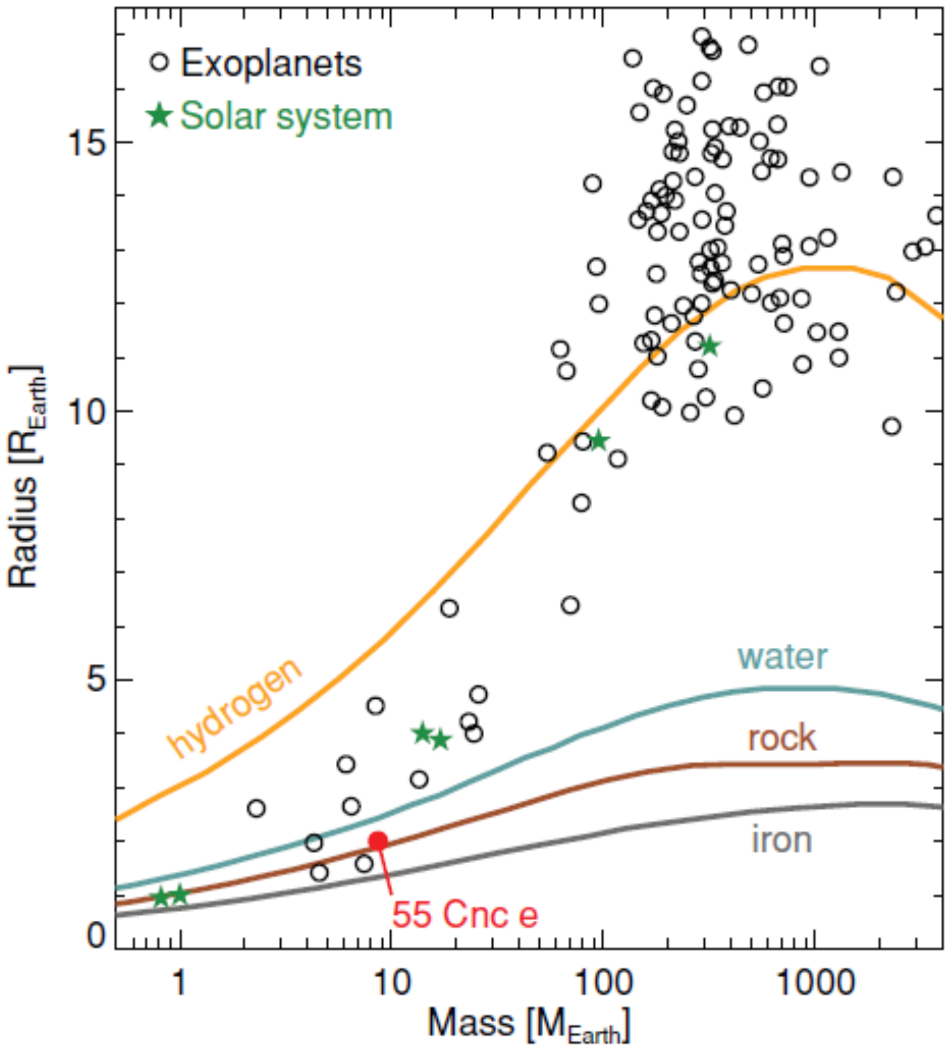
Where do the error bars come from? ....Apart From actual measurement errors?

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

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

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

Why do we need masses AND radii?



Planet diversity from CoRoT, Kepler and MOST, Dressing et al. 2015

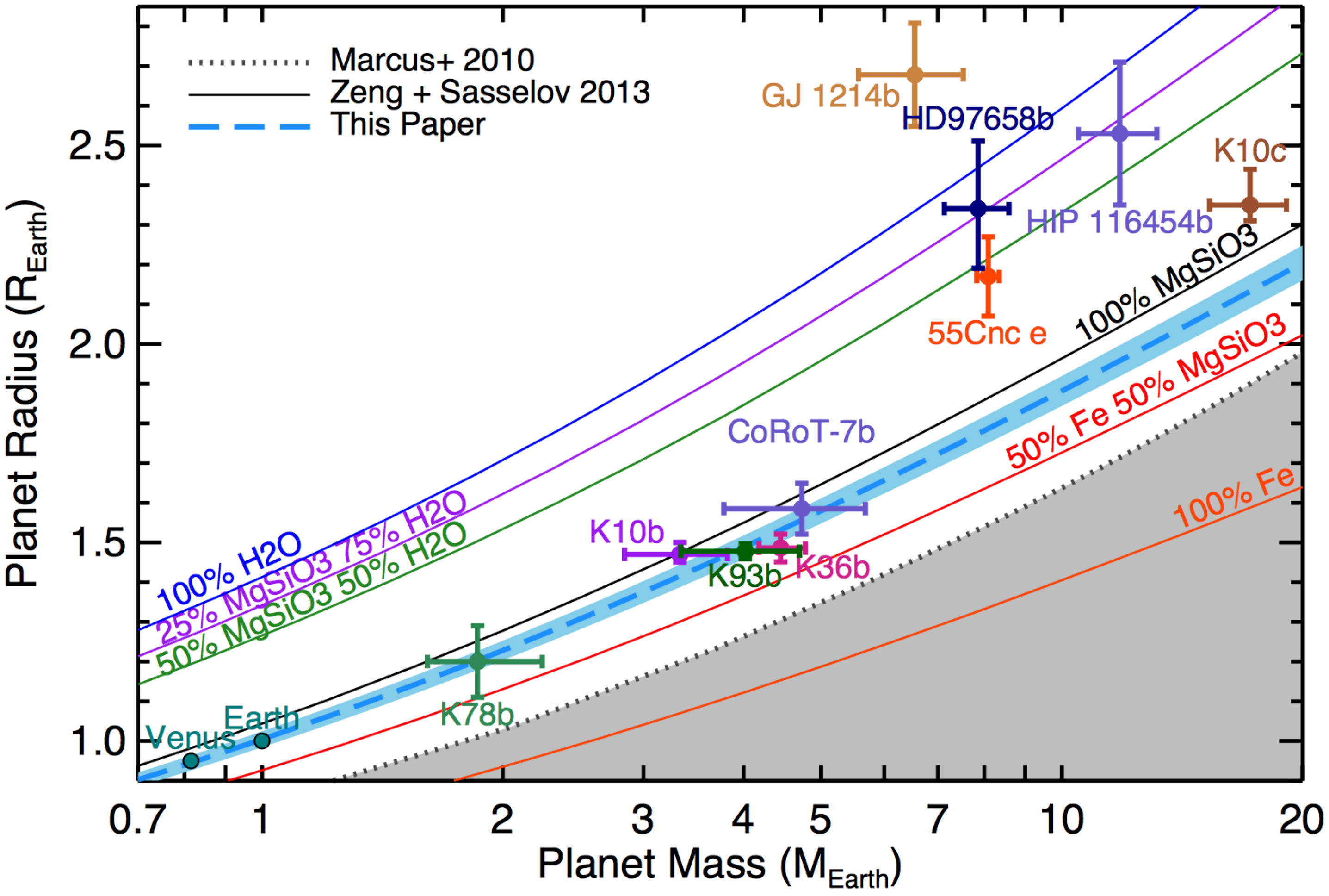


FIG. 4.— Mass-radius diagram for planets smaller than $2.7\,R_\oplus$ with masses measured to better than 20% precision. The shaded gray region in the lower right indicates planets with iron content exceeding the maximum value predicted from models of collisional stripping (Marcus et al. 2010). The solid lines are theoretical mass-radius curves (Zeng & Sasselov 2013) for planets with compositions of 100% H_2O (blue), 25% $MgSiO_3$ – 75% H_2O (purple), 50% $MgSiO_3$ – 50% H_2O (green), 100% $MgSiO_3$ (black), 50% Fe – 50% $MgSiO_3$ (red), and 100% Fe (orange). Our best-fit relation based on the Zeng & Sasselov (2013) models is the dashed light blue line representing an Earth-like composition (modeled as 17% iron and 83% magnesium silicate using a fully-differentiated, two-component model). The shaded region surrounding the line indicates the 2% dispersion in radius expected from variation in Mg/Si and Fe/Si ratios (Grasset et al. 2009).

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)

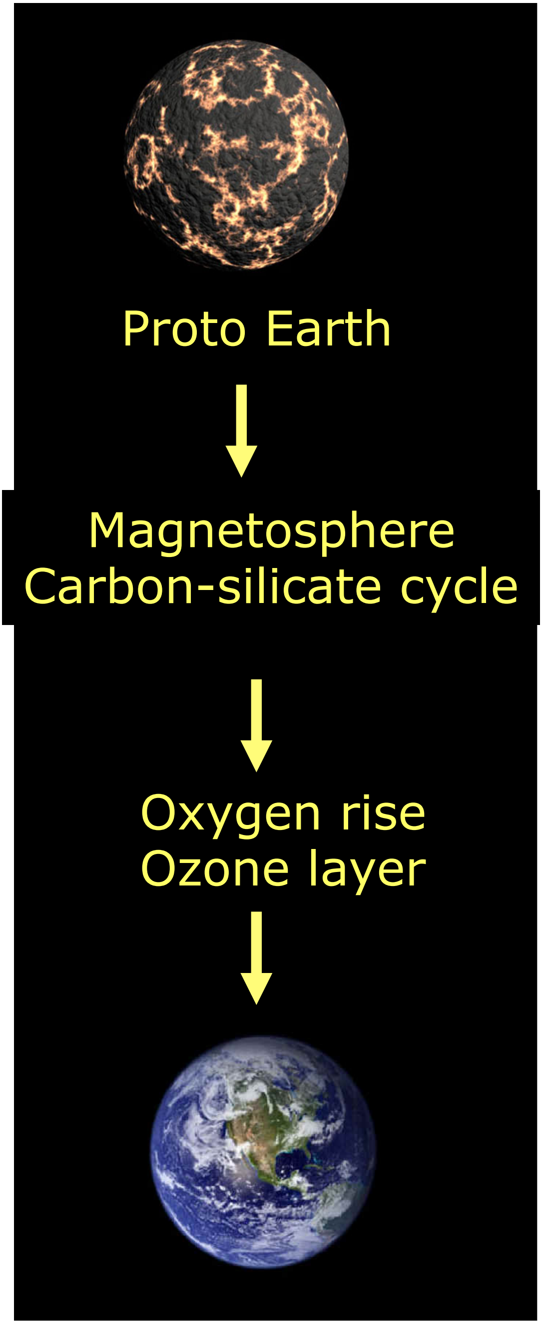
- **Stellar mass, radius**

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

  (planet insolation)
- **Stellar age**

  (defines planet age)

Impact of age measurement



Proto Earth

Magnetosphere
Carbon-silicate cycle

Oxygen rise
Ozone layer

- Study planet evolution

- age must be known better than the evolution timescales

- Targets of future characterization dated by PLATO (Earth-like, but also Neptunes, hot Jupiters…)

What we can do now:

- Place exoplanetary systems into an evolutionary context

- Date targets for future spectroscopic follow-up observations

Study of exo-atmospheres

- Study planet evolution
    - Impacts on atmospheric evolution
    - Impacts on geological evolution (tectonics)
    - Atmosphere/interior connection (outgassing and impacts)
    - Impacts on life

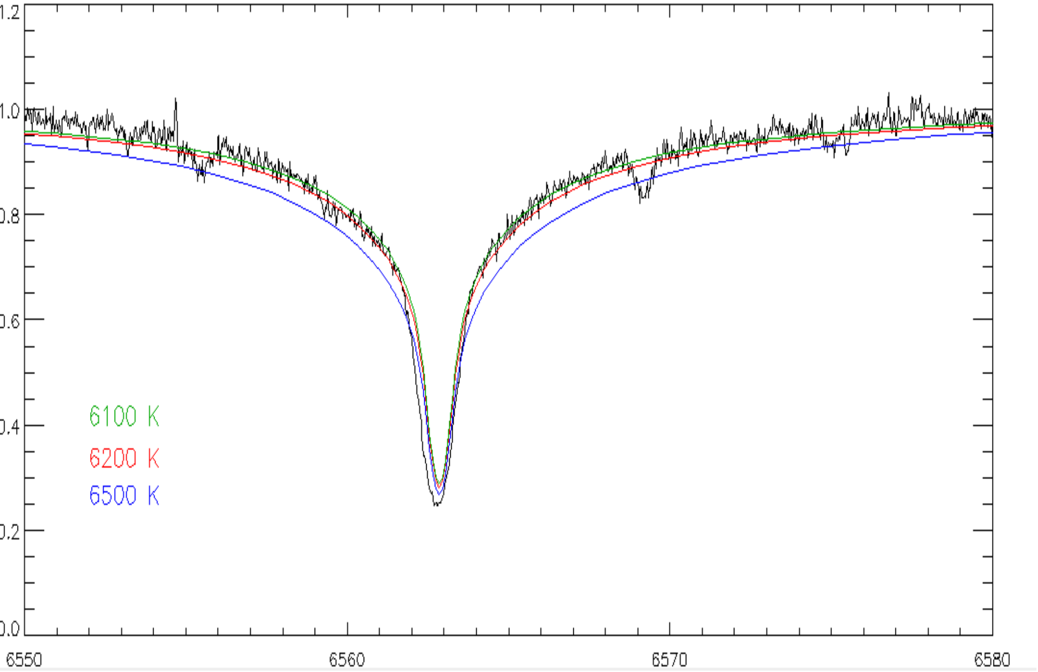
What can do now:

- Find targets that can be observed in low-resolution mode (e.g. ground, space)

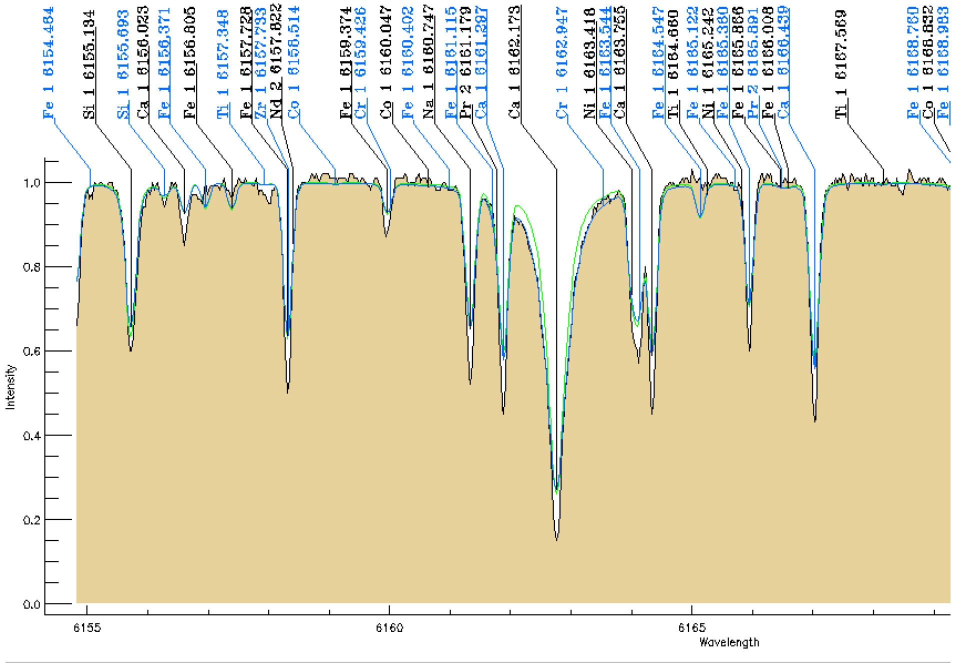
- Find targets that can be observed in more detail later (e.g. Darwin/TPF)

Trying to understand the host star

Spectroscopy is one tool



The models themselves have internal errors of the same order or larger than the measurements

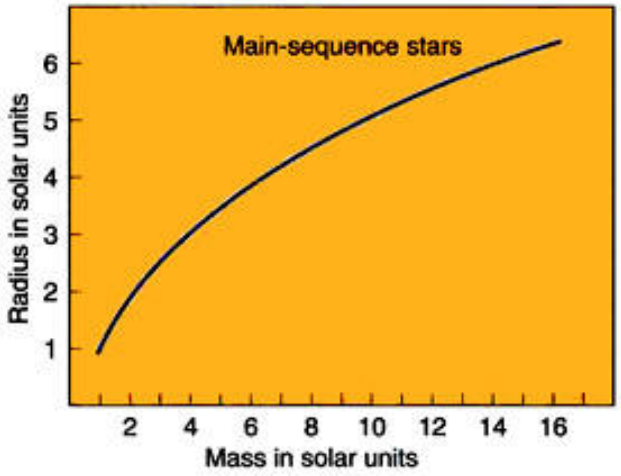


Stellar Masses and radii

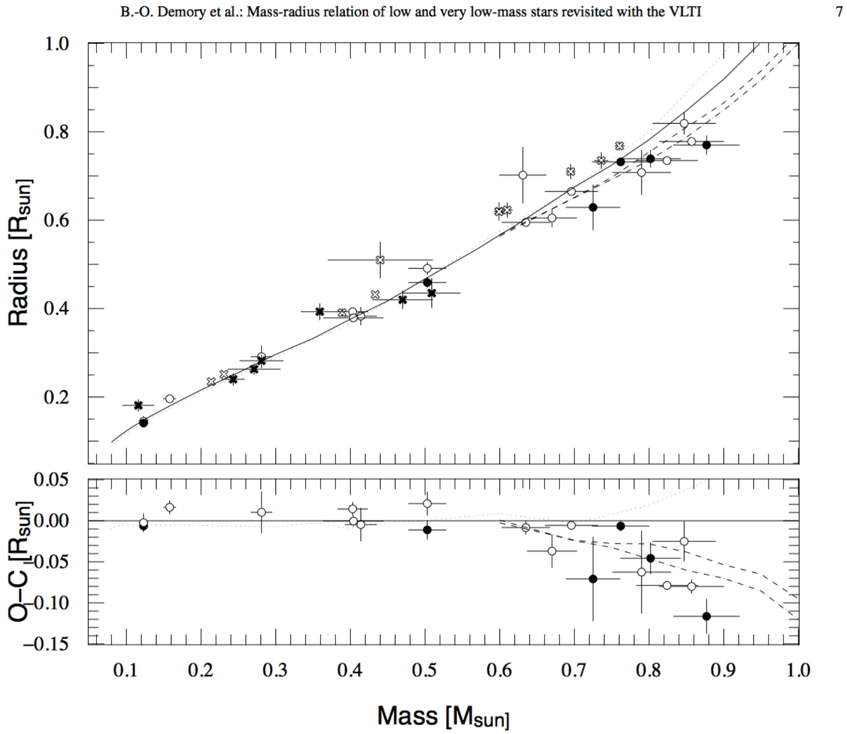
We have a stellar mass radius relation

$R = M^{0.8}$ assumed for main sequence stars.

This has been derived using binary stars and modeling ➔



But in reality ➔



➔ Errors > 20% and in the mass range where our interest will be

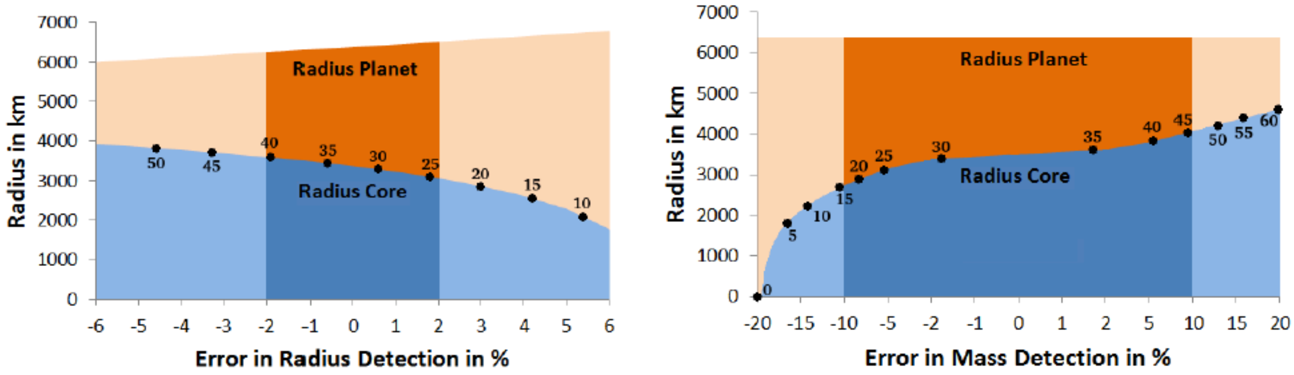
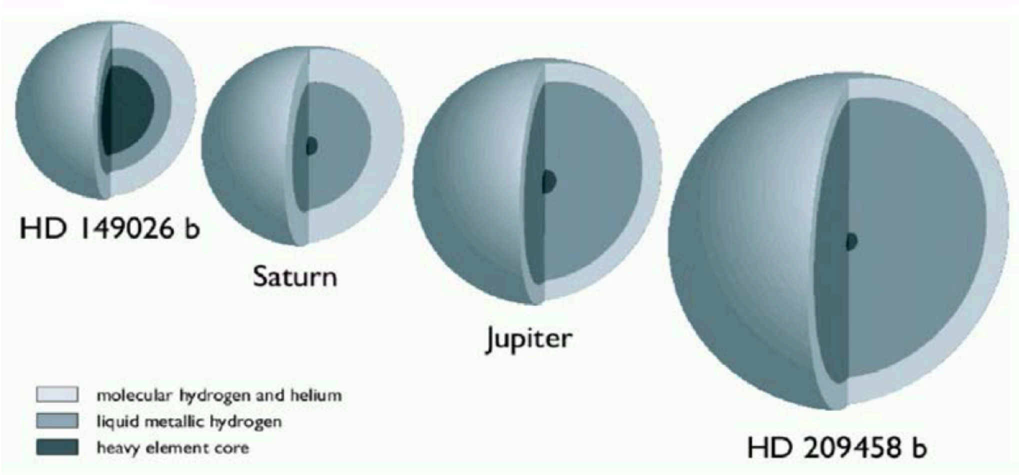


Figure 2.6 *Left:* Radius of planet and its core depending on the uncertainty in radius R_{planet} or *Right:* planetary mass M_{planet}. Left, we assume a planet of 1 Earth-mass and vary the radius (0 corresponds to 1 R_{Earth}) within current uncertainties (±6% in radius). Right: same, but keeping the radius fixed at 1 R_{Earth} and vary the planet mass within current uncertainties (±20%). Numbers at black dots provide the core mass fraction as percentage of total mass. The dark shaded regions illustrate the expected PLATO 2.0 accuracy (±2% and ±10% in radius and mass, respectively). See text for details.



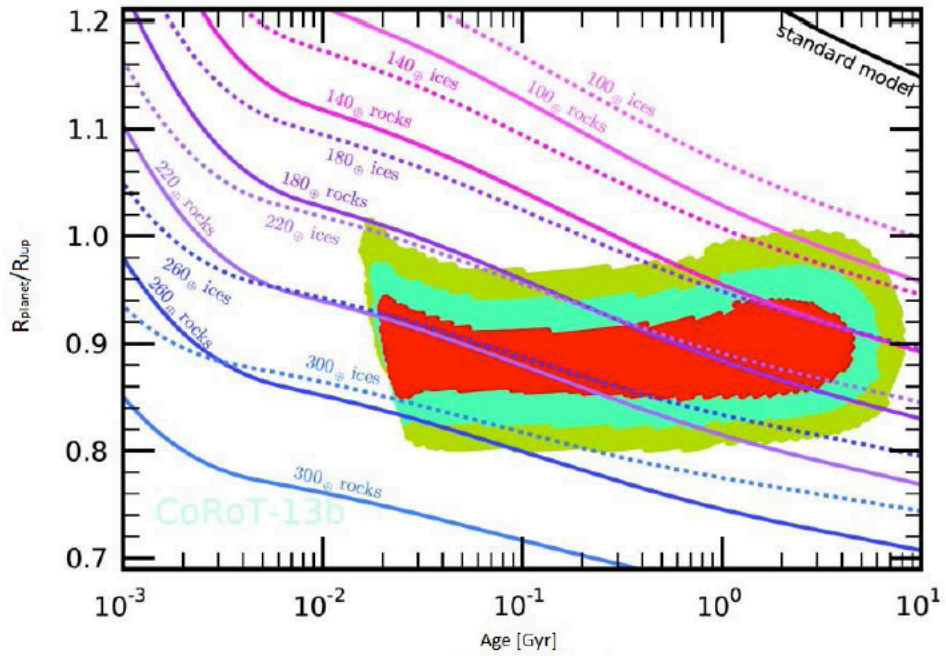
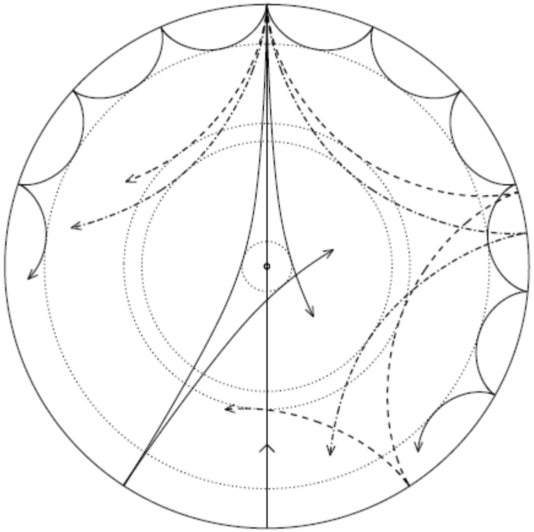


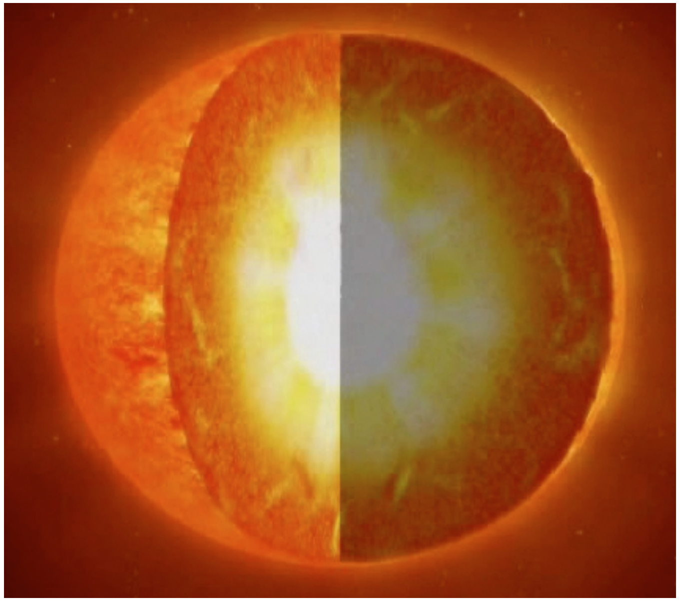
Figure 2.8: CoRoT-13b radius development over age (Cabrera et al. 2010b and references therein). The coloured areas provide the uncertainty in planet radius and in stellar age derived from stellar evolution models matching the stellar density and effective temperature (within 1 (red) to 3 (green) sigma uncertainty). The curves show evolution tracks for CoRoT-13b (assuming M = 1.308 M_{Jup}, T_{eq} = 1700 K) for different amounts of heavy elements concentrated in a central core, surrounded by a solar-composition envelope.

Red is 1 sigma and green is 3 sigma uncertainties in current stellar parameters

How can we (significantly!) improve the determination of radii and masses of stars?

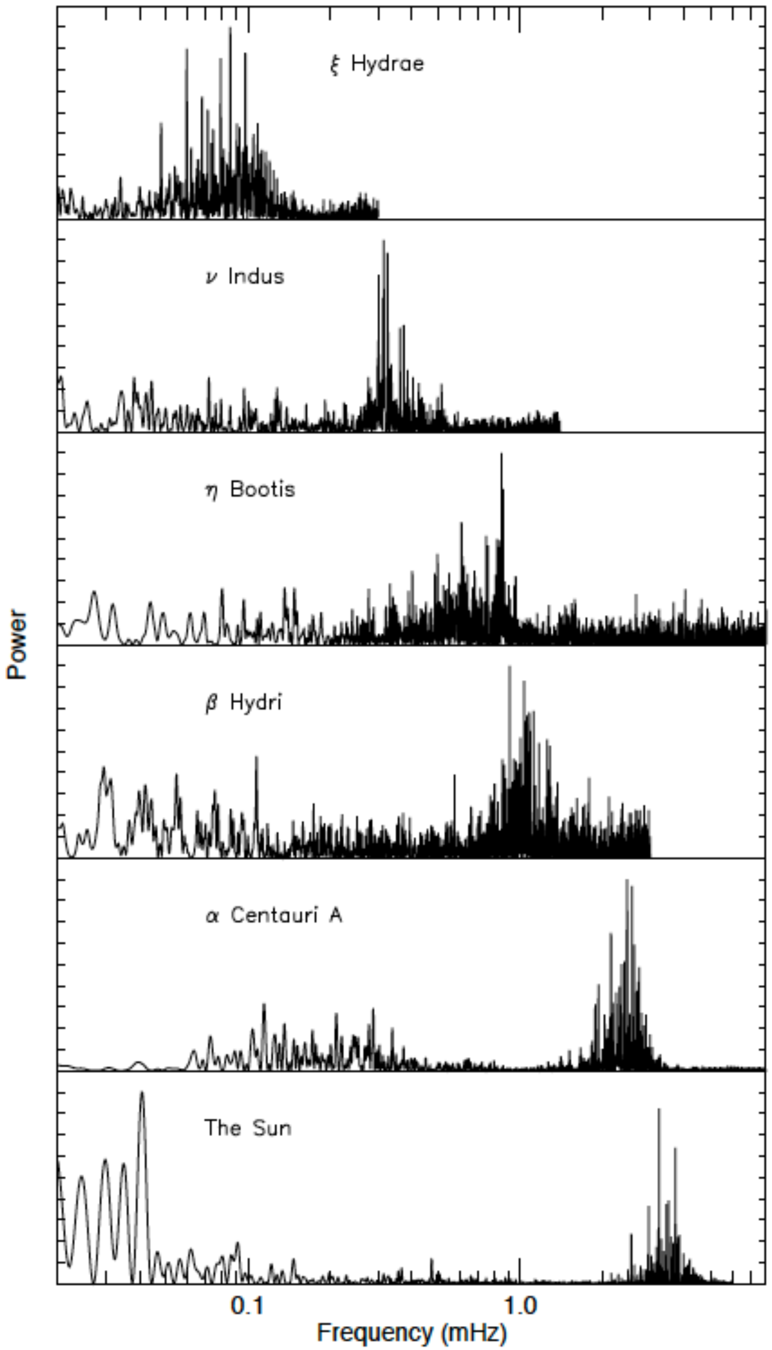
In order to determine the mass, the radius and the age of the star with high accuracy





The Sun oscillates because acoustical waves are excited stochastically by convection.
There are two kinds g-modes and p-modes

p-modes are acoustical waves where the correcting force is the pressure



3:rd magnitude GIII at 130 ly 60L_O

The P-modes causes the total light output to flicker with amplitudes of ppm. If we take the power spectra high quality light curves of solar type stars we find:

G0 IV 37 Ly metal rich

G2IV ~ 6.7 Gyr Li rich 3.53 L_O

G2V, 4.85 Gyr Solar analogue similar to β Hydri

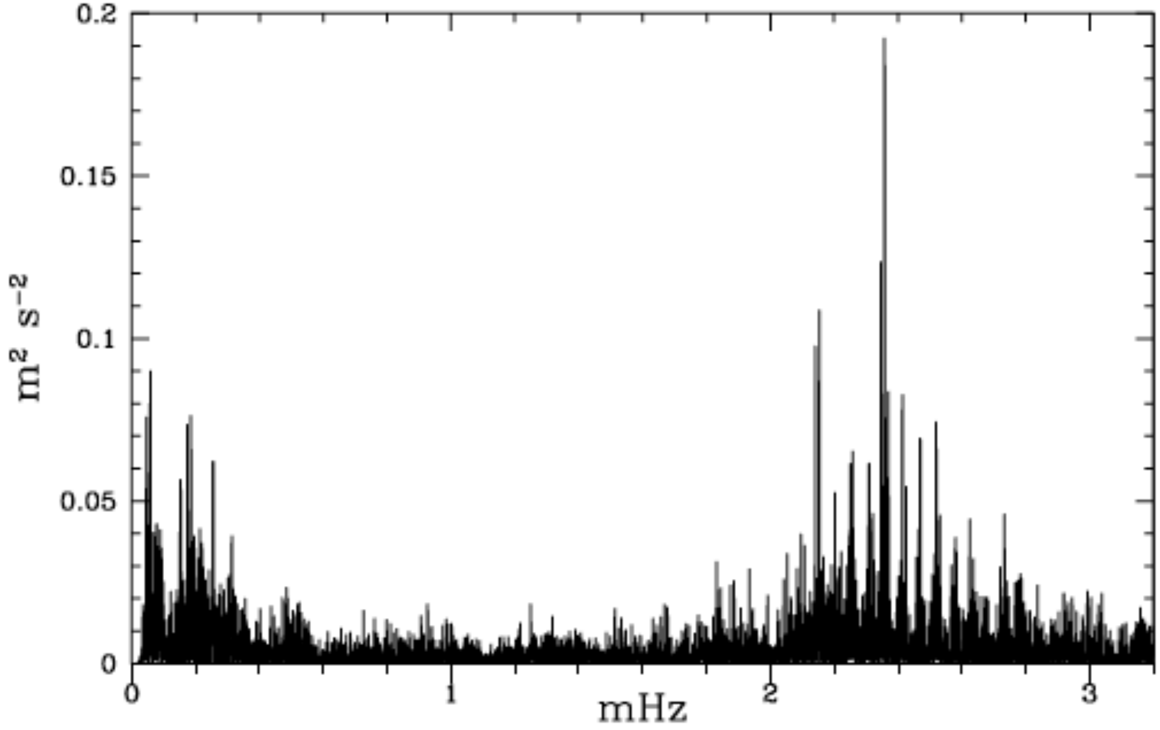


Figure 2.21: Power spectrum of oscillations of α Cen A, from radial-velocity observations with the CORALIE spectrograph. (From Bouchy & Carrier 2001.)

High regular frequency structure! This is a consequence of:

$$\nu_{nlm} \cong \Delta\nu_0\left(n + l/2 + \varepsilon\right) - l\left(l+1\right)D_0 + m\Delta\nu_{rot}$$

$$\Delta\nu_0 \propto \left\langle \rho_* \right\rangle^{1/2} \quad \Delta\nu_{rot} = 1/\Pi_{rot}$$

Ignore rotation at this resolution
n and ***l*** are overtone and degree respectively

$$\Delta\nu_0 = \nu_{n+1,l} - \nu_{n,l}$$

Large separation

$$\delta\nu_l = \nu_{n,l} - \nu_{n-1,l+2} \cong \left(4l + 6\right)D_0$$

Small separation

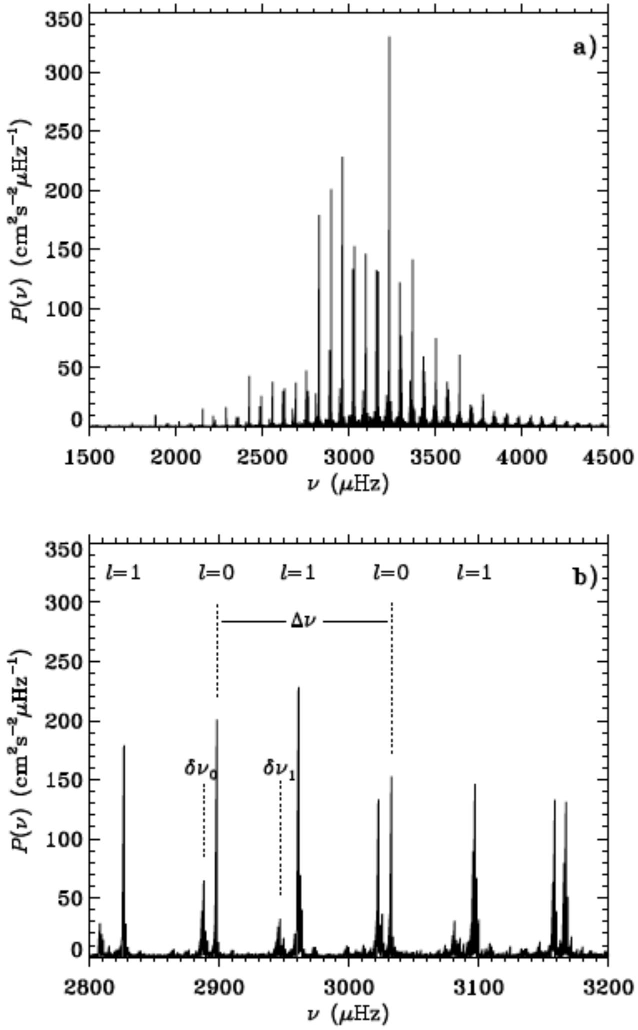
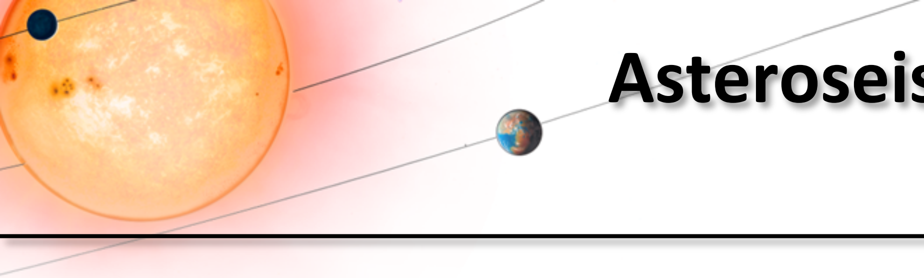


Figure 2.14: Power spectrum of solar oscillations, obtained from Doppler observations in light integrated over the disk of the Sun. The ordinate is normalized to show velocity power per frequency bin. The data were obtained from six observing stations and span approximately four months. Panel (b) provides an expanded view of the central part of the frequency range. Here some modes have been labelled by their degree l, and the large and small frequency separations $\Delta\nu$ and $\delta\nu_l$ [*cf.* equations (2.40) and (2.41)] have been indicated. (See Elsworth *et al.* 1995.)



Asteroseismology 101

- **P-modes in stars with T_{eff} < 7000K**
- **Excited stochastically by near-surface convection**
- **High radial order**

$$\Delta\nu_0 = \left(2\int_0^R \frac{dr}{c(r)}\right)^{-1}$$

$$\nu_{nlm} \cong \Delta\nu_0(n + l/2 + \varepsilon) - l(l+1)D_0 + m\Delta\nu_{rot}$$

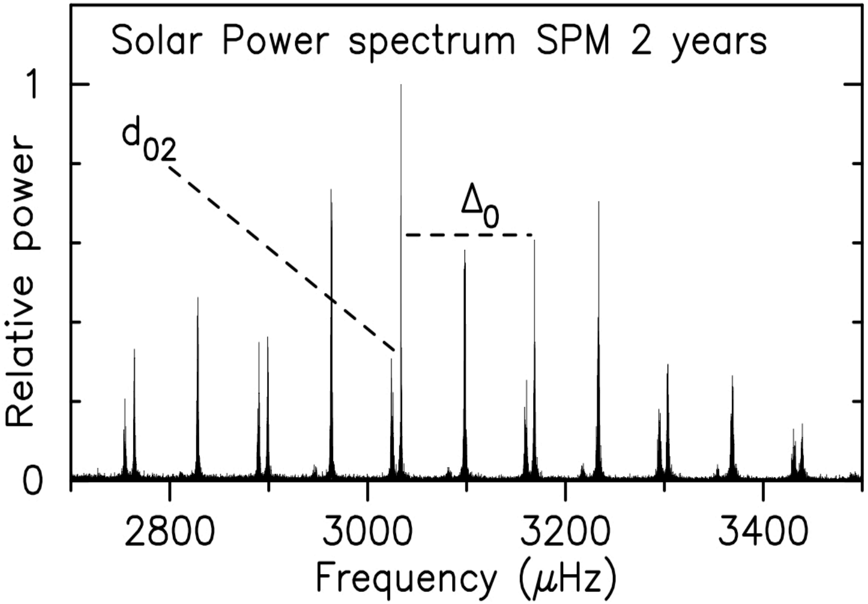
Large separation, c(r) is soundspeed

$$\Delta\nu_0 \propto \langle\rho_*\rangle^{1/2} \quad \Delta\nu_{rot} = 1/\Pi_{rot}$$

Π_{rot} Is an average over the star of the rotation period

ν_{nl} is cyclic frequency, *l* is the degree (*l*=0 is radial pulsation; $\Delta\nu_0$ is closely related to the inverse sound speed and thus stellar density; D_0 depend on conditions near centre ➔ stellar age; ε depend on conditions just below the surface

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.

Chaplin et al, 2011, 2011Sci...332..213C

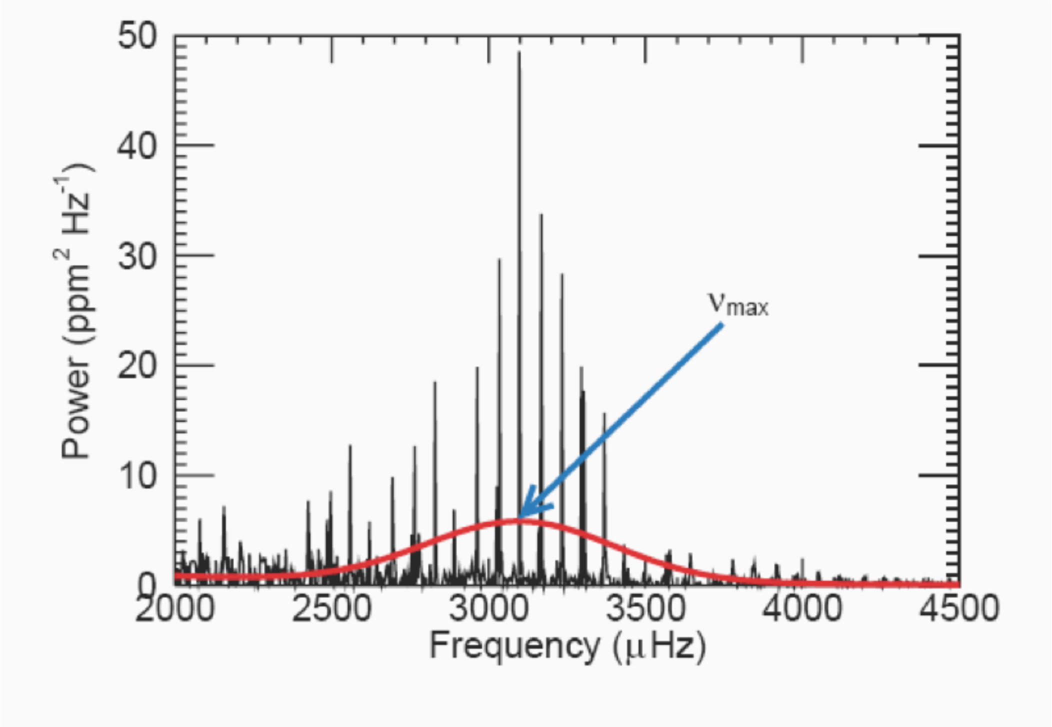


Figure S2: Frequency spectrum of low-degree oscillations shown by the Sun (in Sun-as-a-star photometry data from the VIRGO/SPM instrument on board the ESA/NASA SoHo spacecraft). The red line follows the Gaussian-like power envelope of the observed oscillations, with the frequency of maximum power marked by ν_{max}.

Chaplin et al, 2011, 2011Sci...332..213C

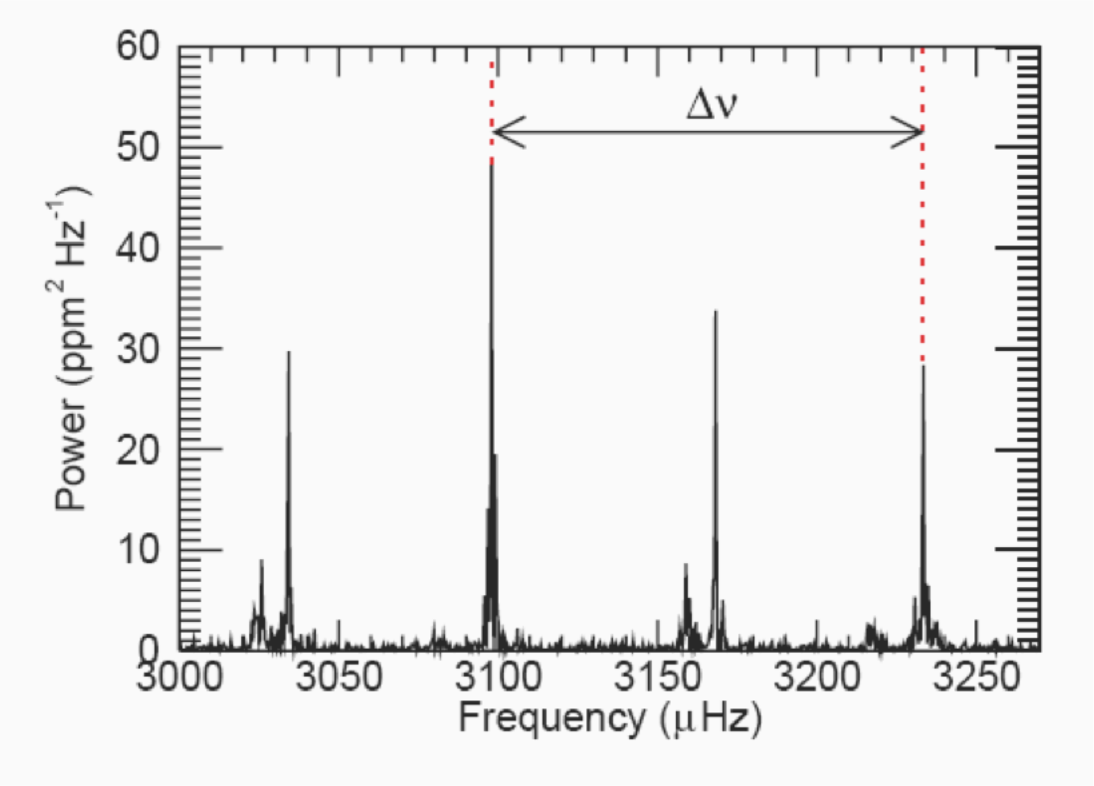


Figure S3: Zoom on the central frequency region of the oscillations spectrum plotted in Fig. S2, to show the large frequency separation, Δν.

ν_{max} is the frequency of maximum power of the oscillations. For the Sun it is 3090+/-30 μHz

$\Delta\nu$ is the large frequency separation between consecutive overtones. For the Sun it is =135.1+/-0.1 μHz

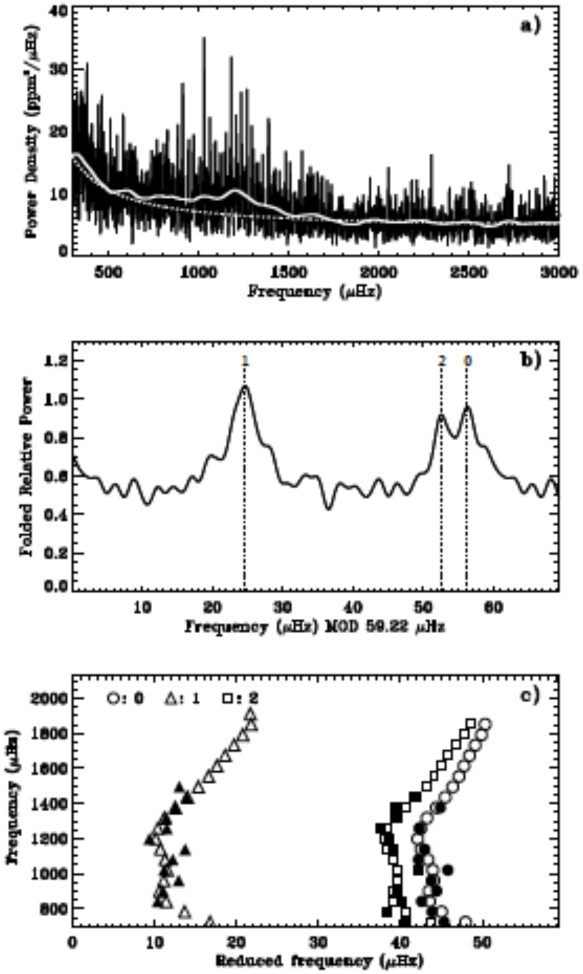
There exist scaling relations accordingly:

$$\frac{M_\star}{M_\odot} \simeq (\frac{\nu_{max}}{\nu_{max,\odot}})^3 (\frac{\Delta\nu}{\Delta\nu_\odot})^{-4} (\frac{T_{eff}}{T_{eff,\odot}})^{3/2}$$

$$\frac{R_\star}{R_\odot} \simeq (\frac{\nu_{max}}{\nu_{max,\odot}})(\frac{\Delta\nu}{\Delta\nu_\odot})^{-2} (\frac{T_{eff}}{T_{eff,\odot}})^{1/2}$$

With $T_{eff,Sun}$ = 5777K

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:

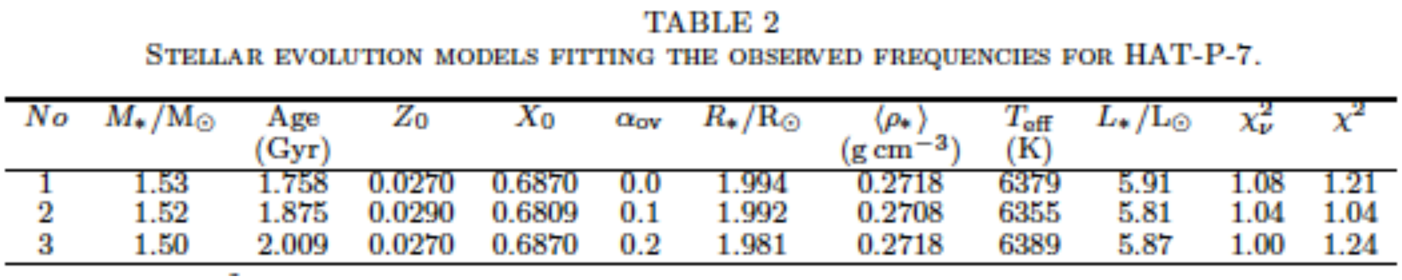
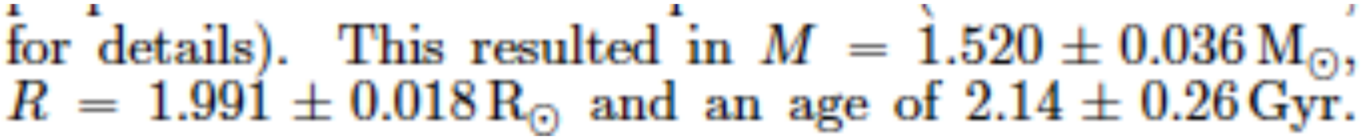


TABLE 2
STELLAR EVOLUTION MODELS FITTING THE OBSERVED FREQUENCIES FOR HAT-P-7.

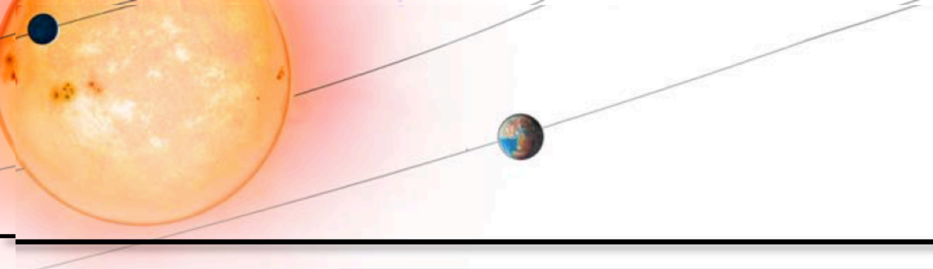
No	$M_*/\mathrm{M}_\odot$	Age (Gyr)	Z_0	X_0	$\alpha_{\rm ov}$	$R_*/\mathrm{R}_\odot$	$\langle\rho_*\rangle$ ($\mathrm{g\,cm^{-3}}$)	$T_{\rm eff}$ (K)	$L_*/\mathrm{L}_\odot$	χ^2_ν	χ^2
1	1.53	1.758	0.0270	0.6870	0.0	1.994	0.2718	6379	5.91	1.08	1.21
2	1.52	1.875	0.0290	0.6809	0.1	1.992	0.2708	6355	5.81	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 $M = 1.520 \pm 0.036\,\mathrm{M}_\odot$, $R = 1.991 \pm 0.018\,\mathrm{R}_\odot$ and an age of 2.14 ± 0.26 Gyr.

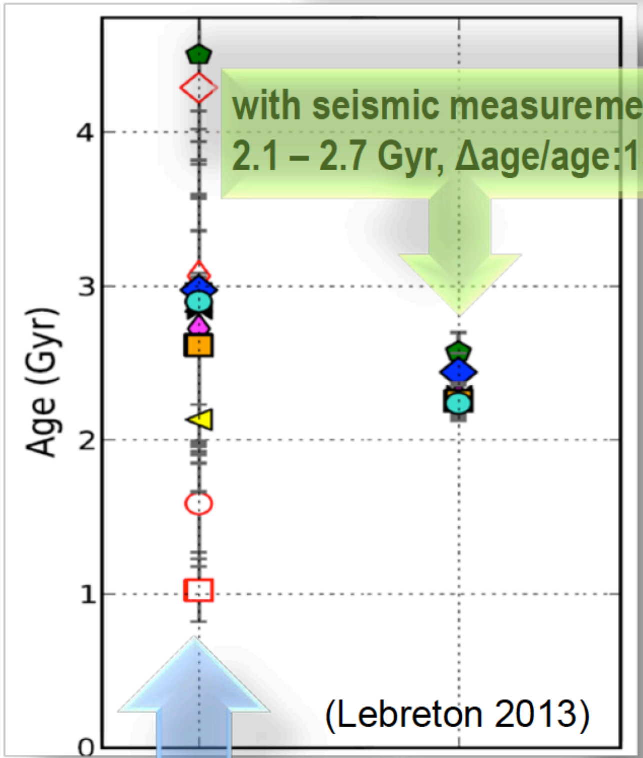
Planet parameters are now known to < 5% instead of >50%!!!

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



Asteroseismology

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

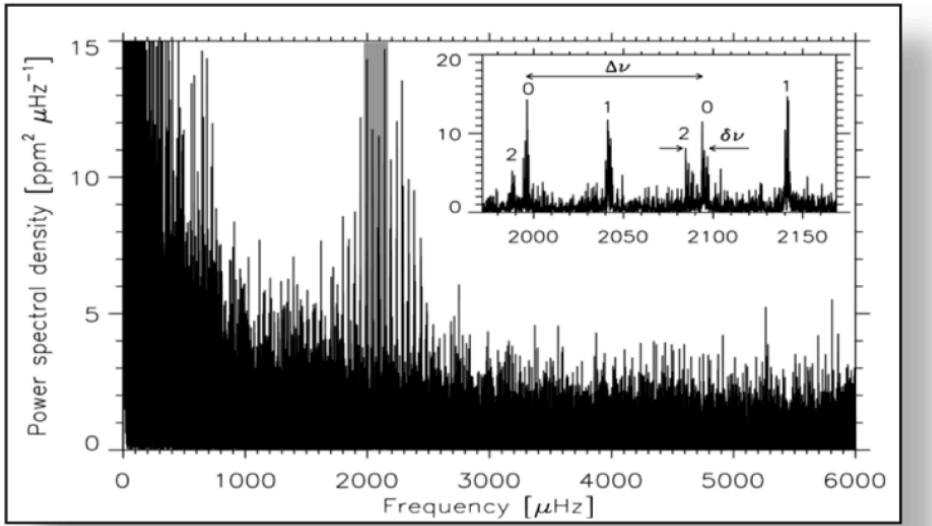


with seismic measurement,
2.1 – 2.7 Gyr, Δage/age:13%

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

(Lebreton 2013)

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

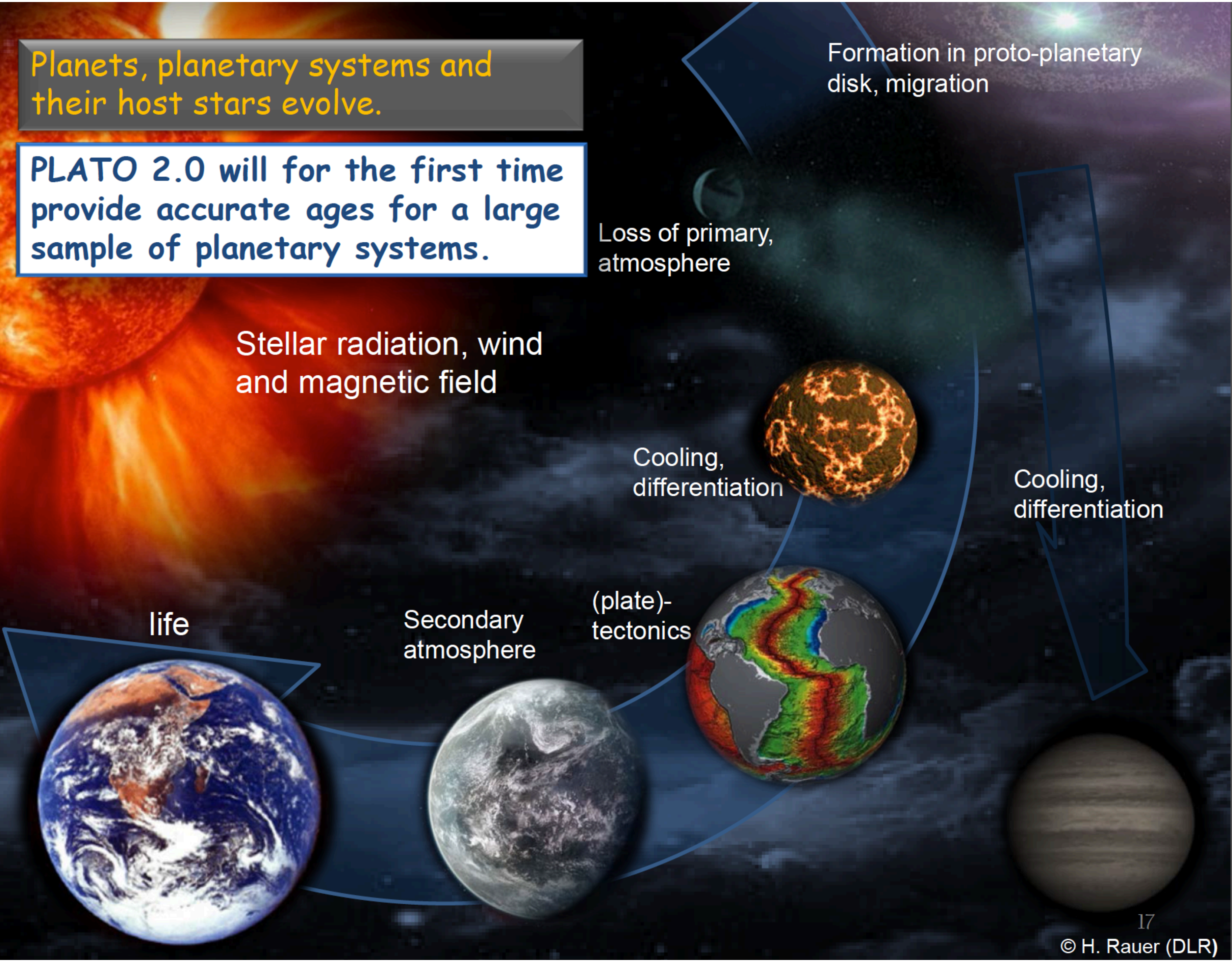


(Gizon et al. 2013)

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

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.



Formation in proto-planetary disk, migration

Loss of primary, atmosphere

Stellar radiation, wind and magnetic field

Cooling, differentiation

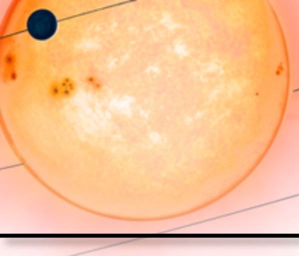
Cooling, differentiation

(plate)-tectonics

Secondary atmosphere

life

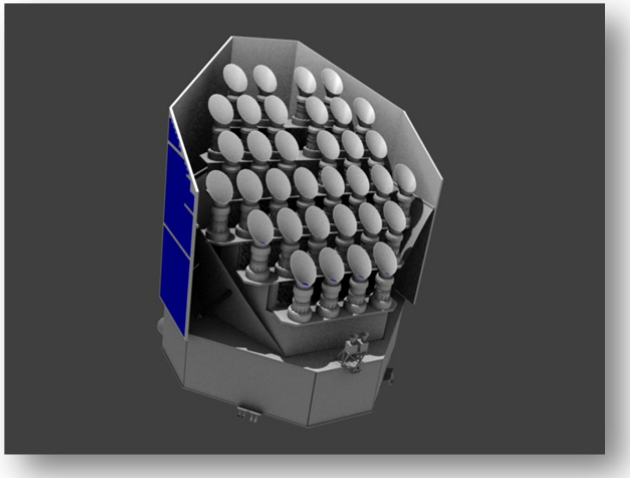
© H. Rauer (DLR)



The PLATO 2.0 Mission

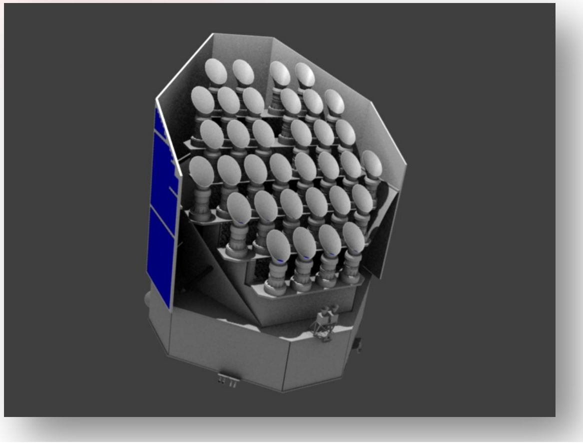
Selected as ESA's M3

- 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

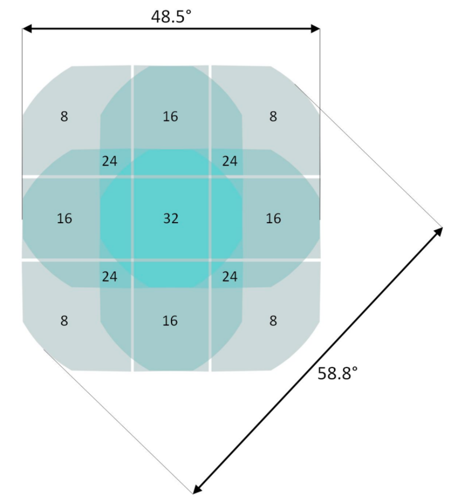


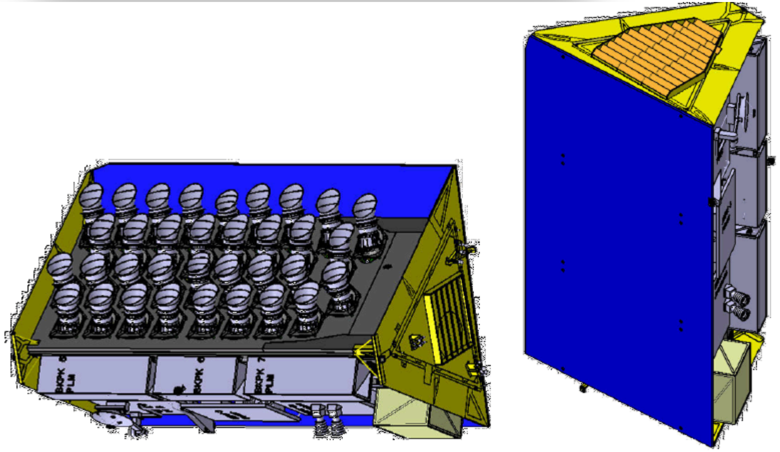
- Focus on warm/cool Earth to super-Earths, up to the habitable zone of solar-like stars
- Focus on solar-like host stars to put the Solar System into context
- Observe bright stars for feasible RV follow-up and targets for atmosphere spectroscopy by e.g. JWST, E-ELT, future space missions
- Provide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

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)*

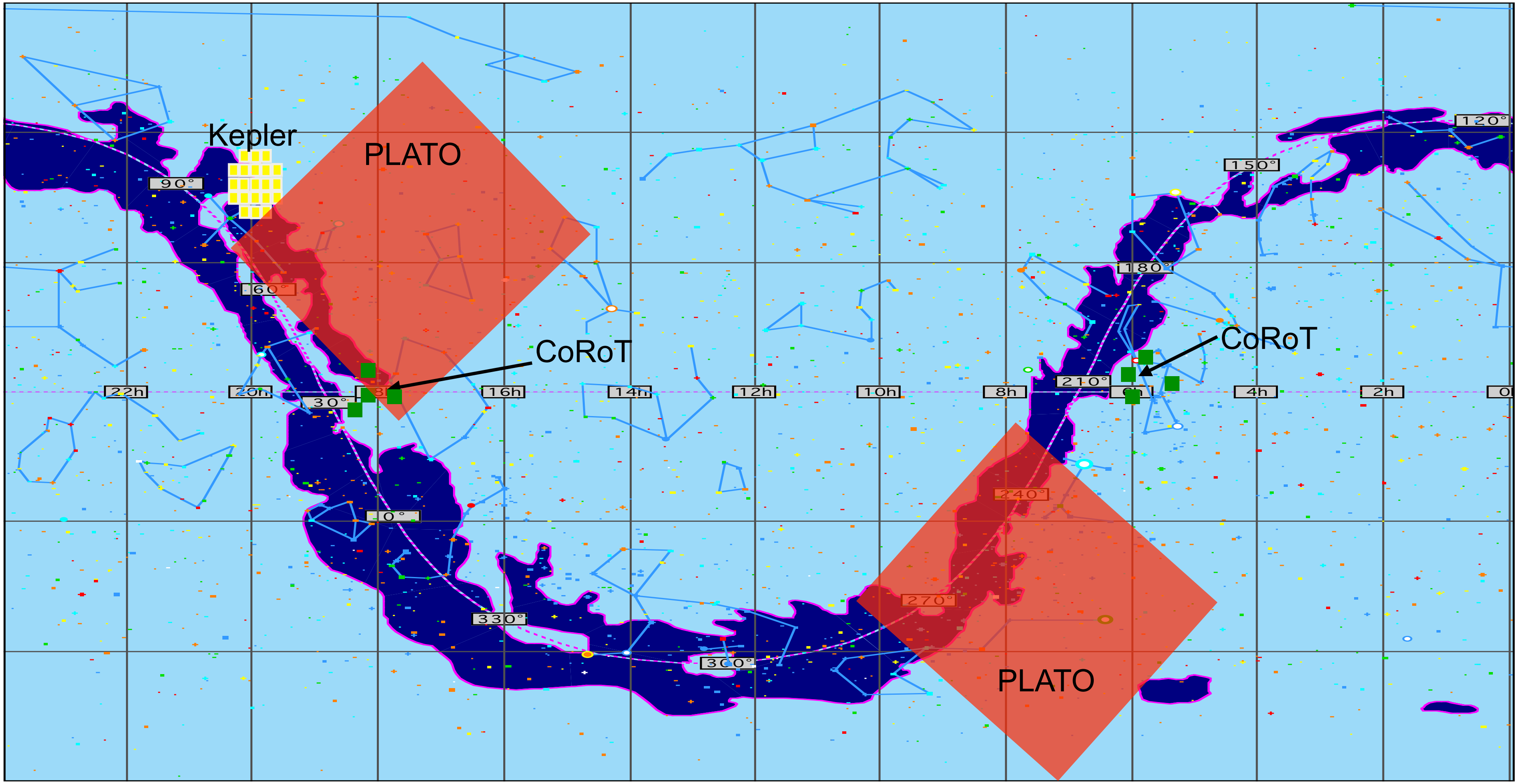
- 32 « normal » 12cm cameras, cadence 25 sec
- 2 « fast » 12cm cameras : cadence 2.5 sec, 2 colours
- dynamical range: $4 \leq m_V \leq 16$
- Nominal mission 6 years, FOV 48.5 x 48.5 deg = 2250 sq deg

Basic observation strategy

very wide field + 2 successive long monitoring phases:

3 years + 2 years

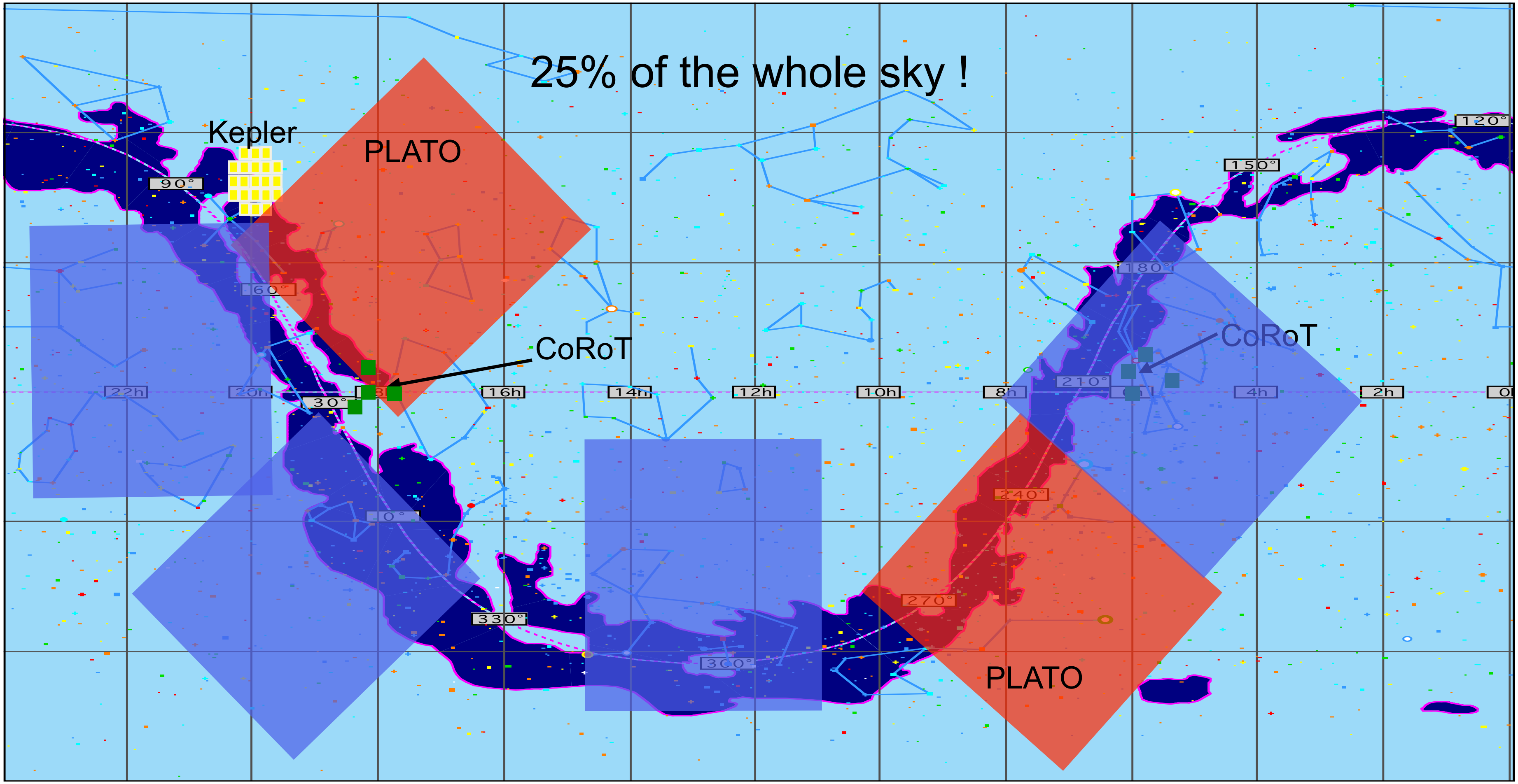
comply with duration requirement



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

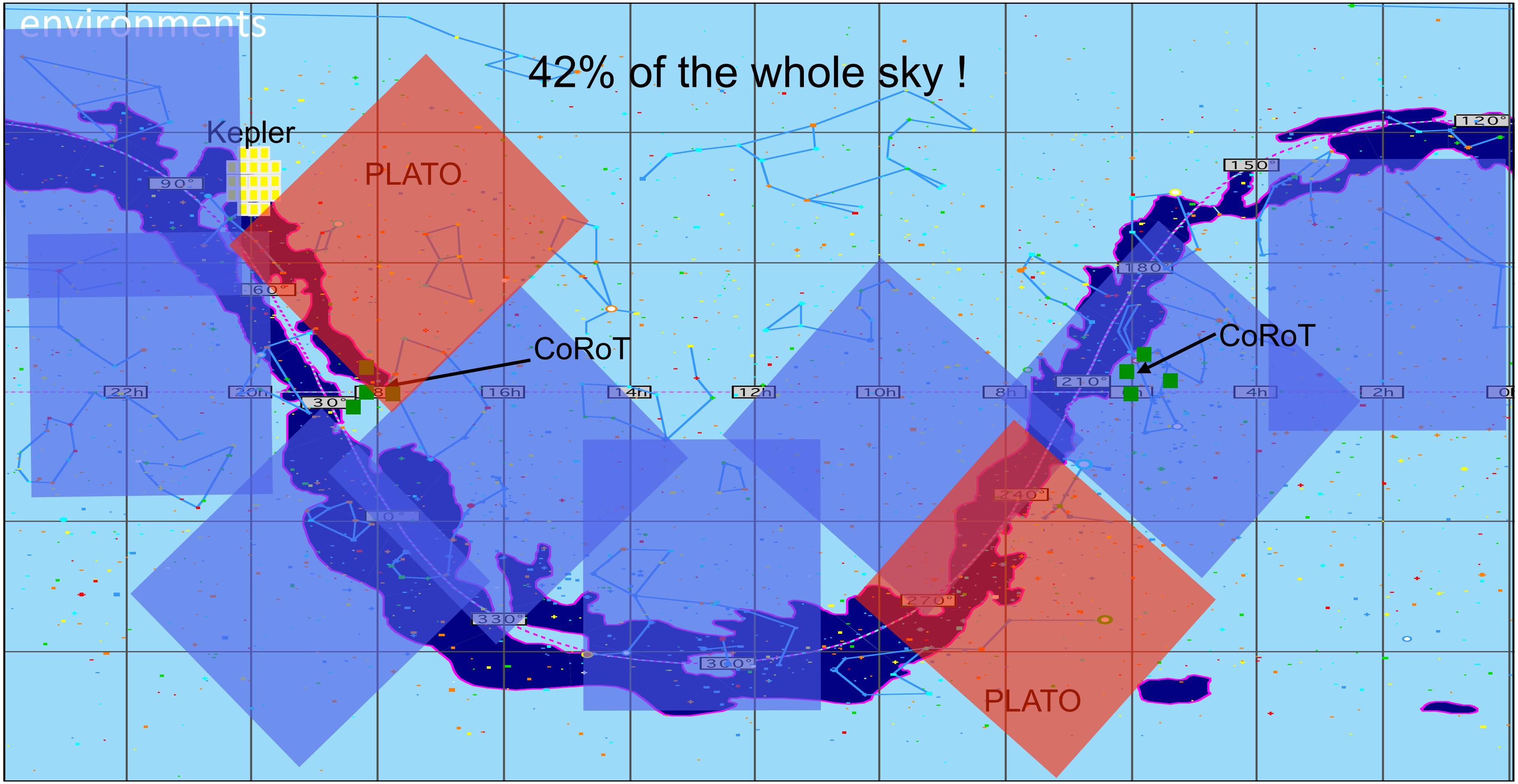


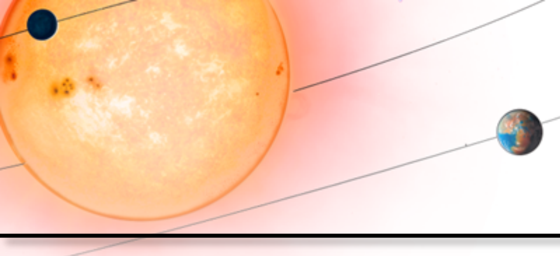
25% of the whole sky !

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





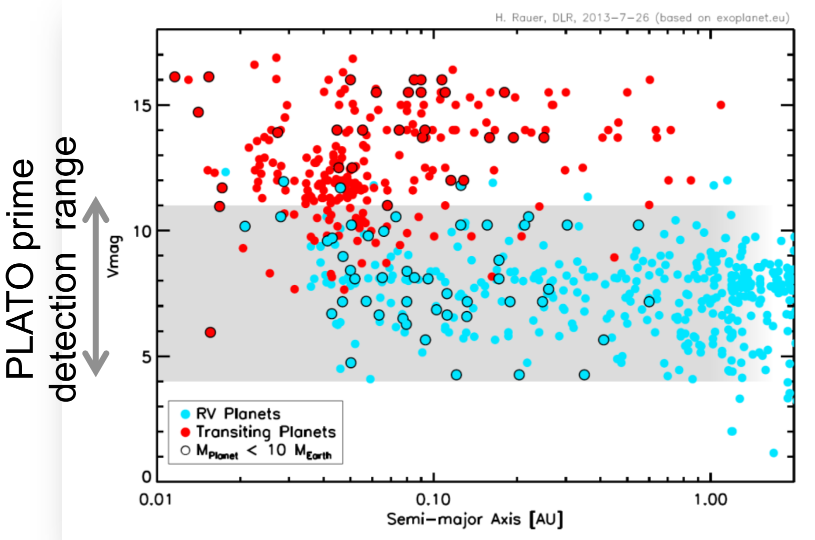
The Method(in brief)

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:



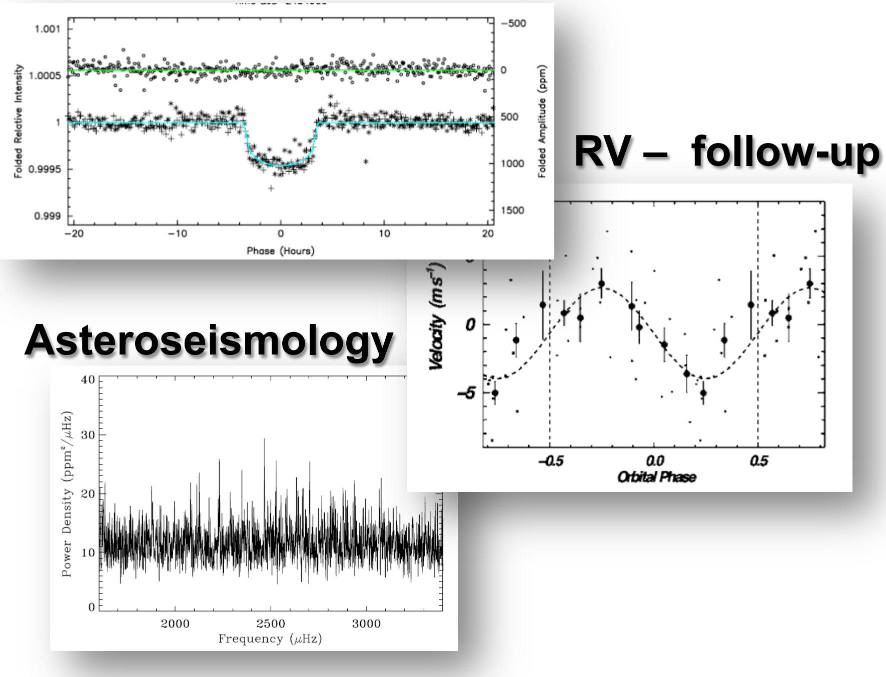
Techniques

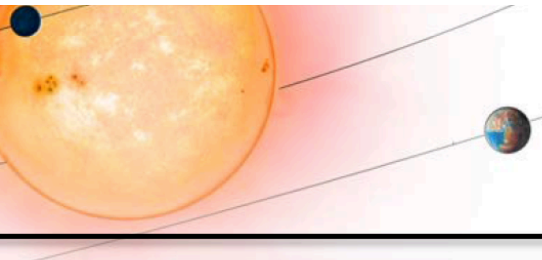
Example: Kepler-10 b

Photometric transit

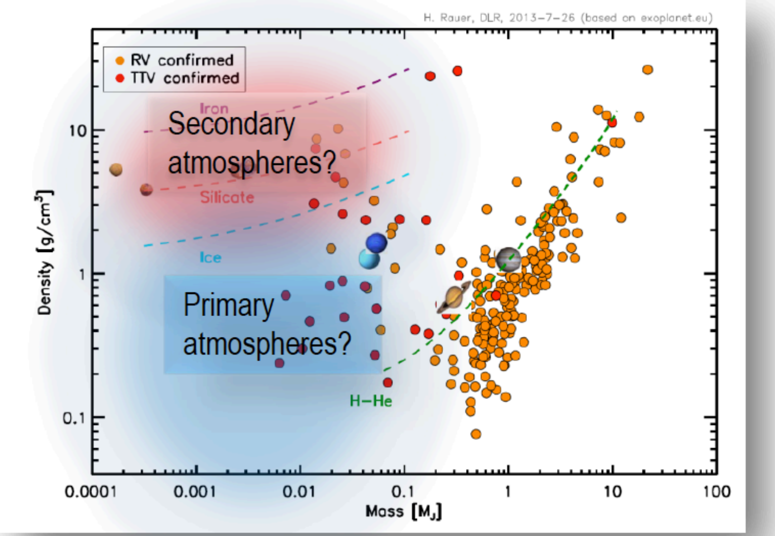
RV – follow-up

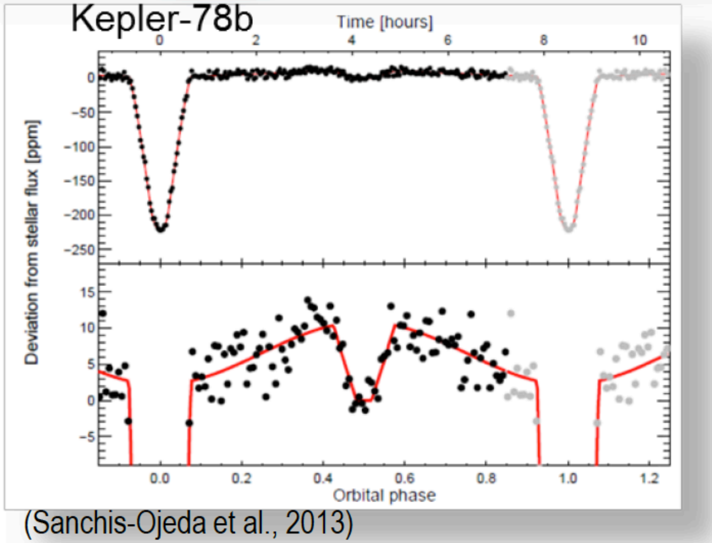
Asteroseismology





Planet diversity & comparative planetology





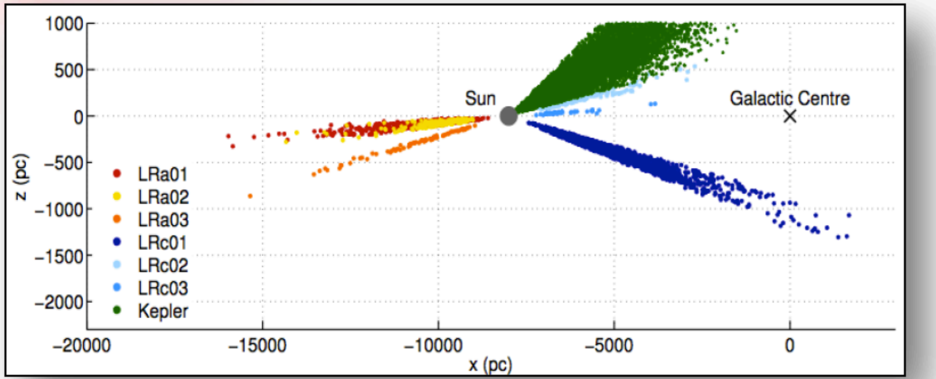
(Sanchis-Ojeda et al., 2013)

PLATO 2.0 will provide planets with:

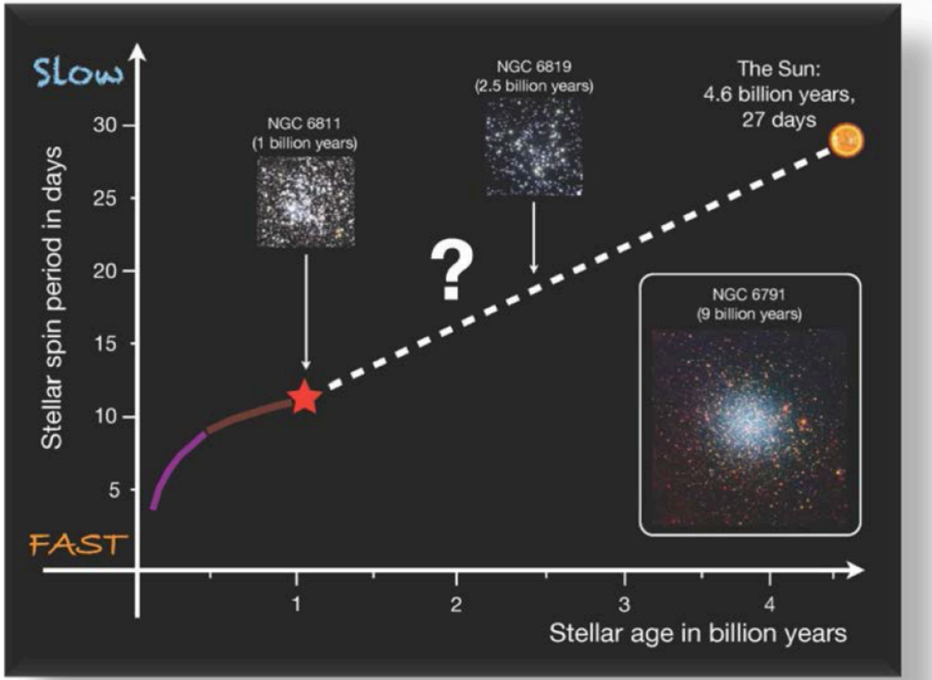
- mean density
  → composition and structure (rocky, mini-gas)
  → constrain atmosphere scale heights
- albedo and its diversity
  → indicative for clouds, hazes
- accurate ages
  → evolutionary pathways
- characterized host stars
  → incident flux, stellar activity

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

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

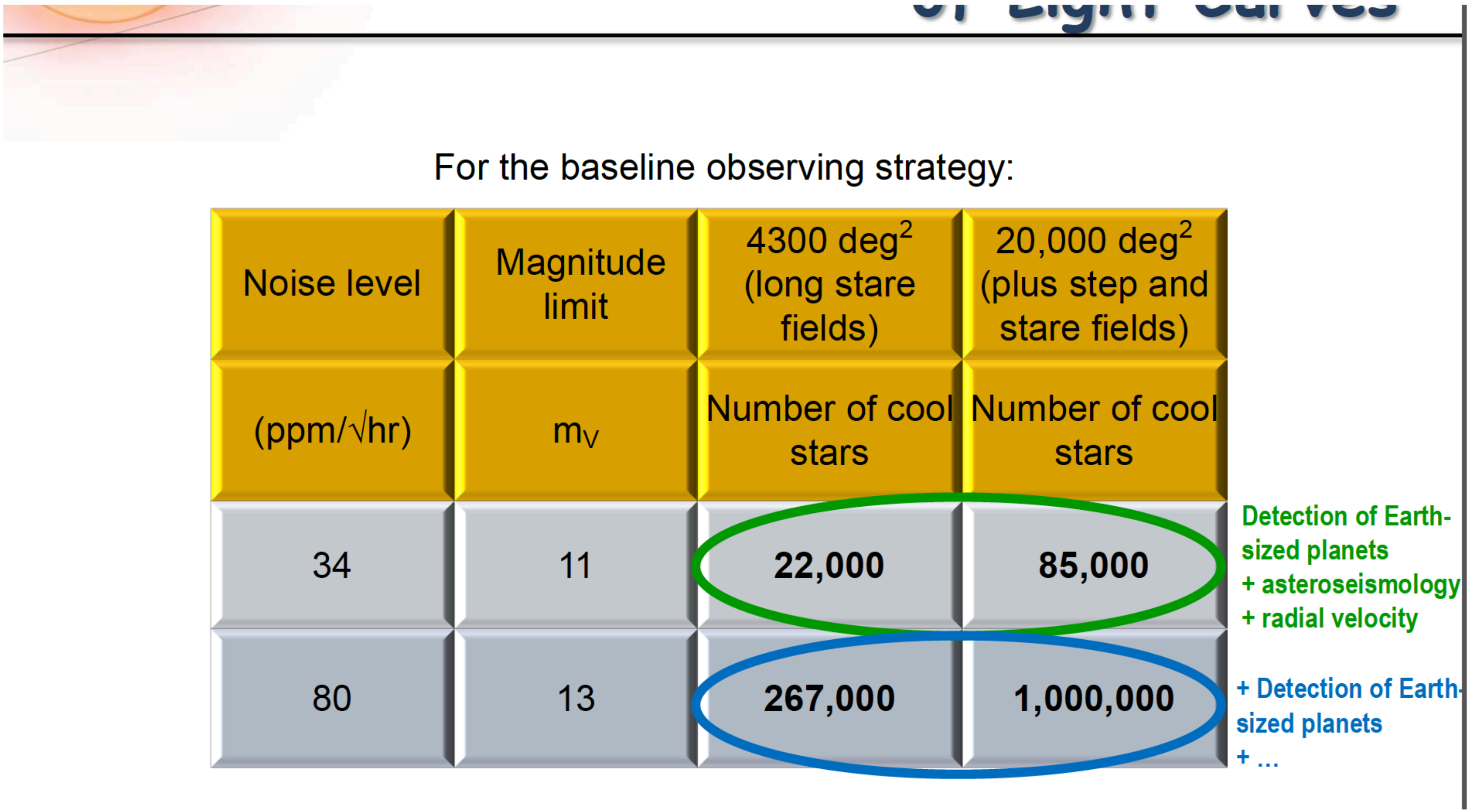
→ Provide accurate ages

→ Calibrate stellar evolution theories

→ Calibrate Galactic age-metallicity relationship

→ Probe the structure and the evolution of our Galaxy

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