# Next Generation Transit Light Curves

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# Outline

1. Present status
2. Future requirements
3. Present and planned instrument list
4. Transit light curves and stellar atmospheres
5. Summary

# Present status

## Present status:

# Number of known exoplanets

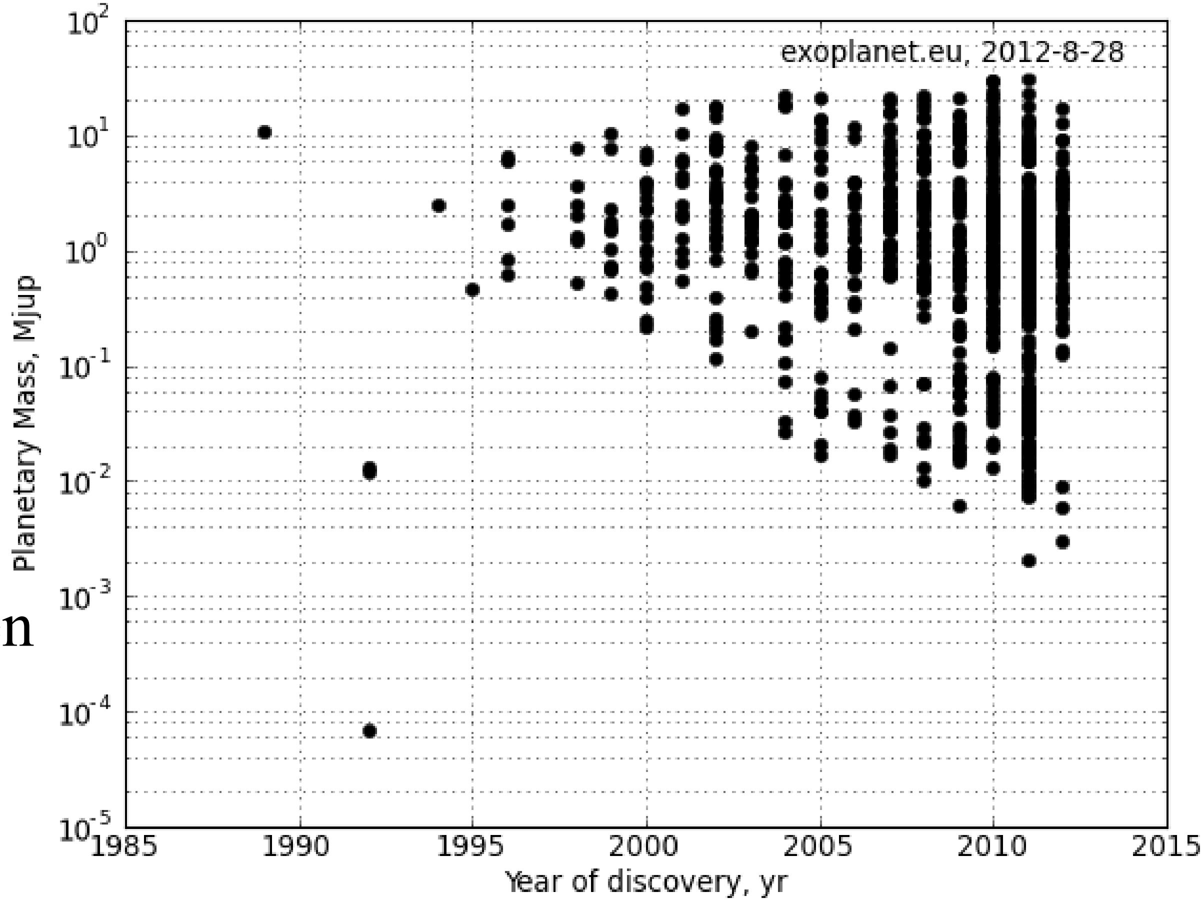
778 planets

> 3500 candidates

Planets around single and binary stars.

Planets down to size of Mars.

>100 systems, between 2-8 planets



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# CoRoT status report

22 runs

~156 000 stars observed

3870 planetary candidates detected

645 were followed-up

210 cases solved (binaries, hot stars etc)

120 candidates are in the loop

~30 planets + 1 brown dwarf

1 multiple transits (C-24bc)

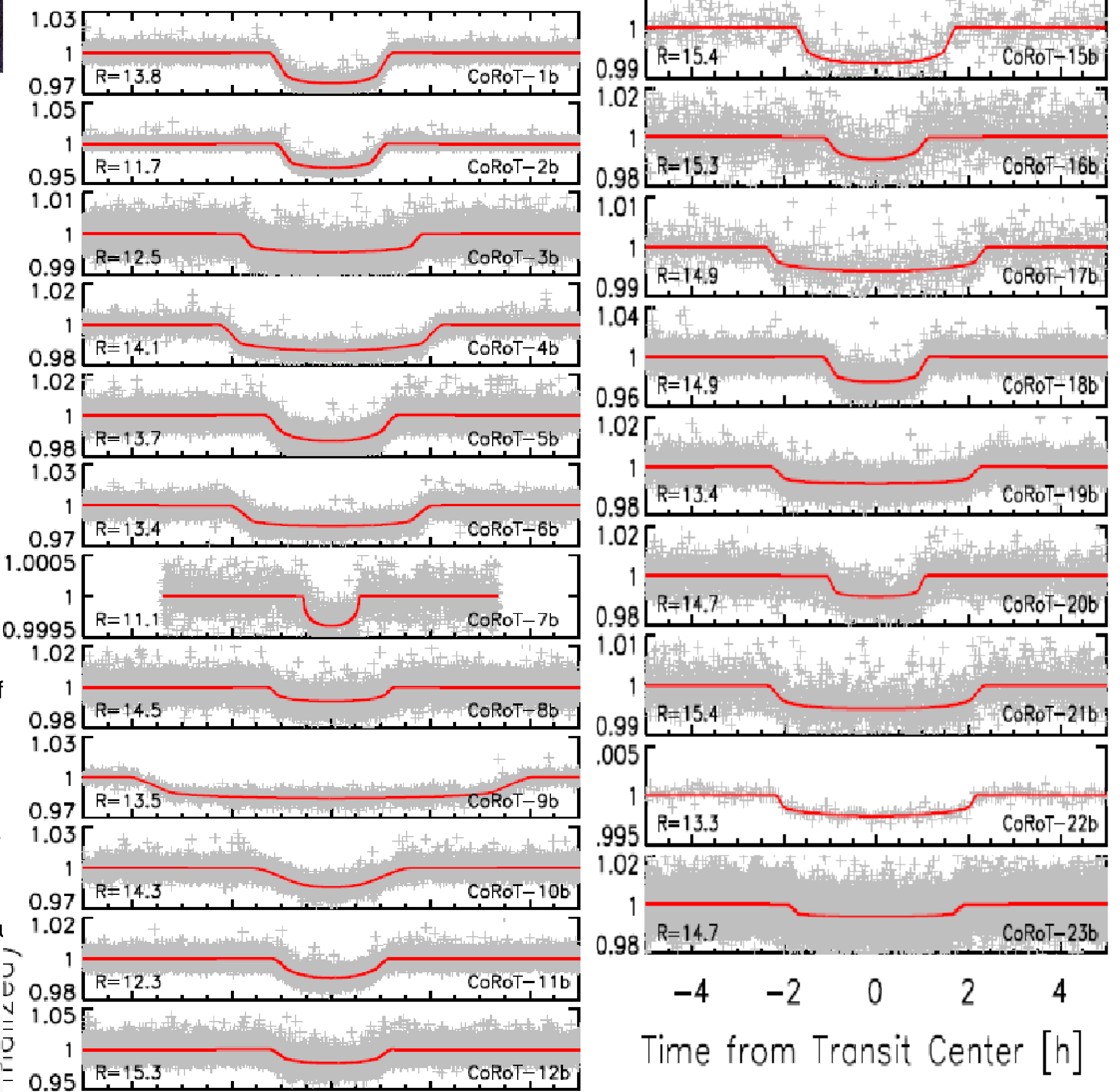
C-7bcd with multiple planets

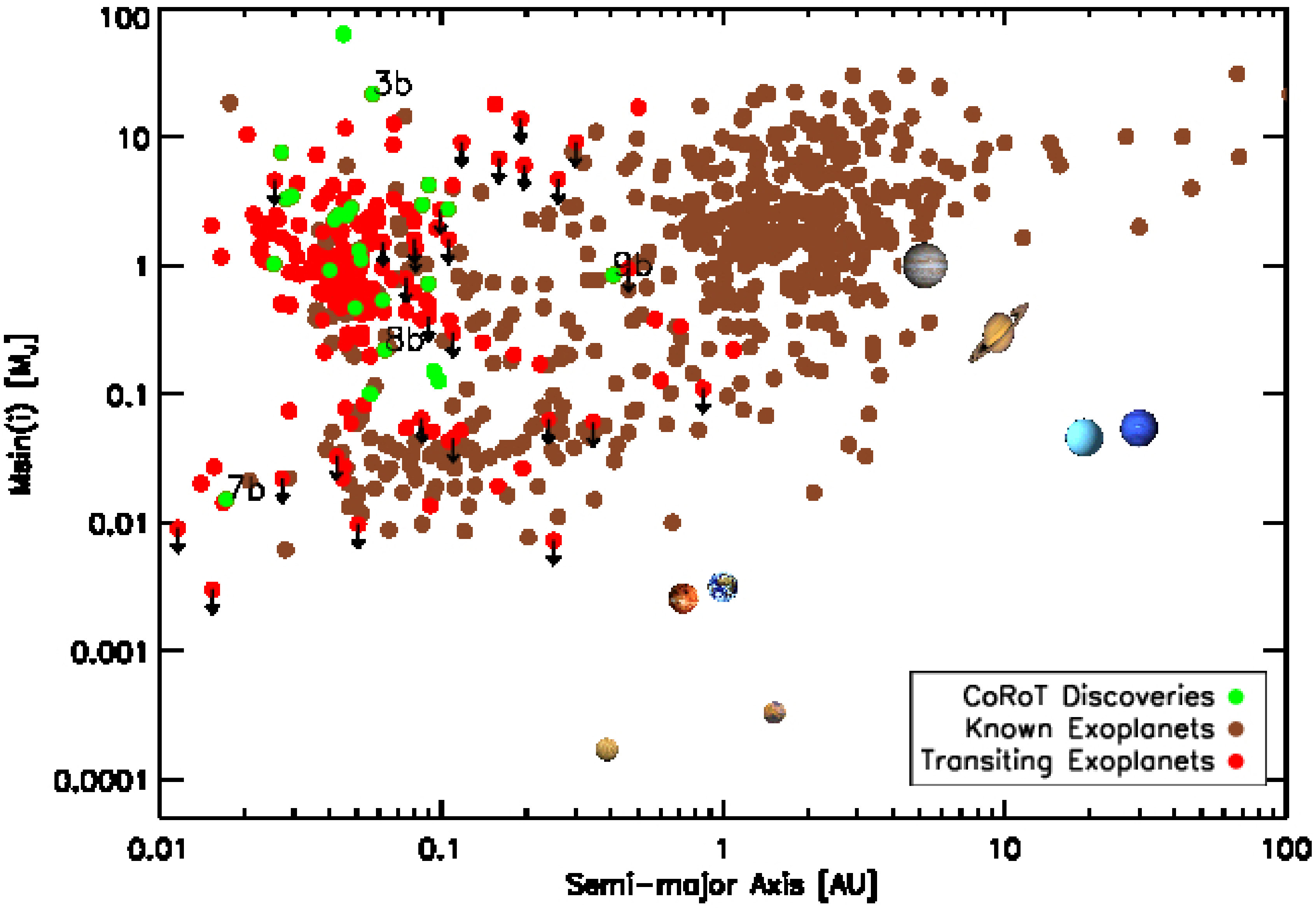
One very long period (C-9b)

First rocky planet with measu

radius (C-7b)

/figures: Csizmadia et al. 2012a, to be submitted/





H. Rauer, T. Pasternacki & S. Kirste, DLR, 2012-8-28 (based on exoplanet.eu)

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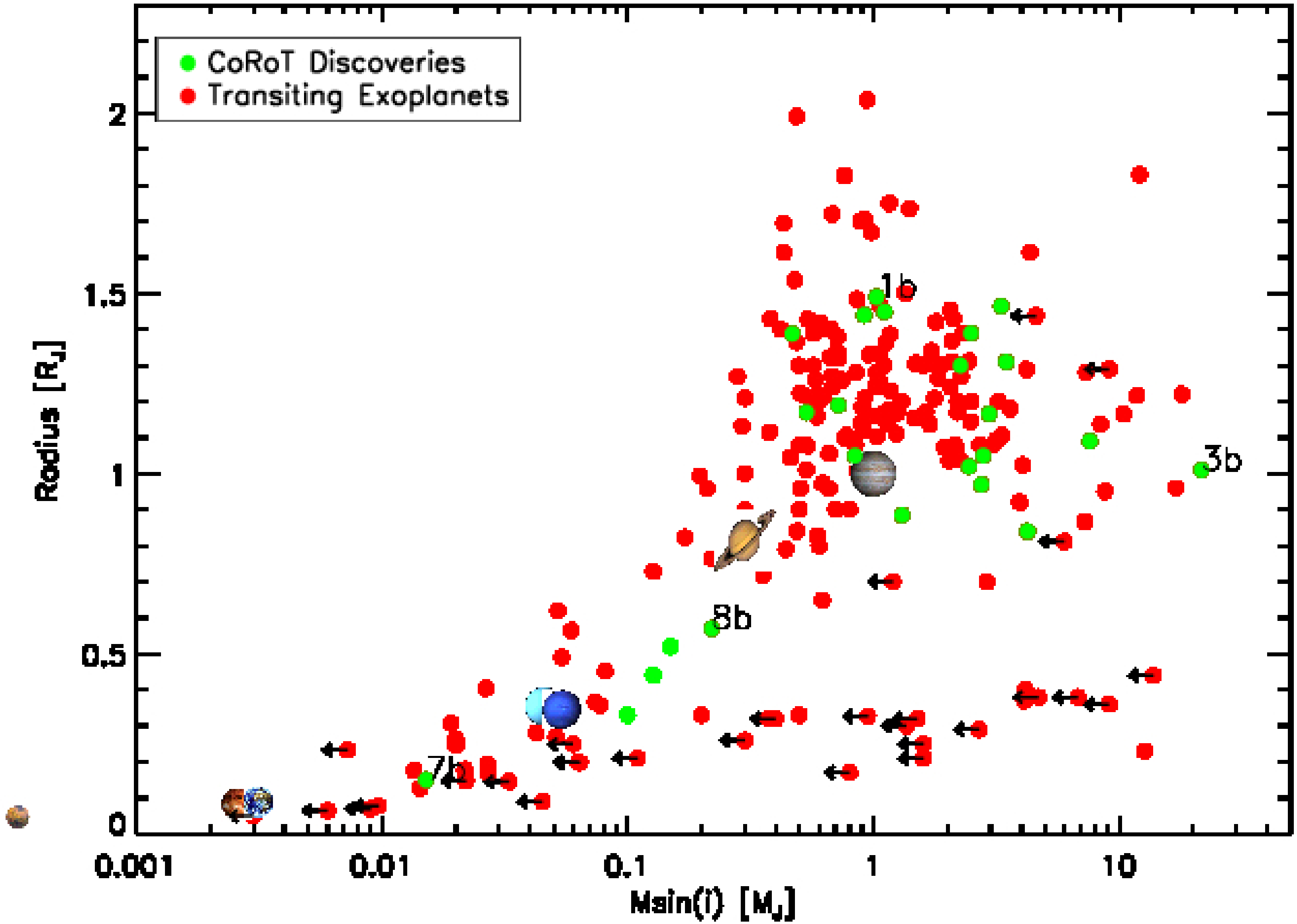
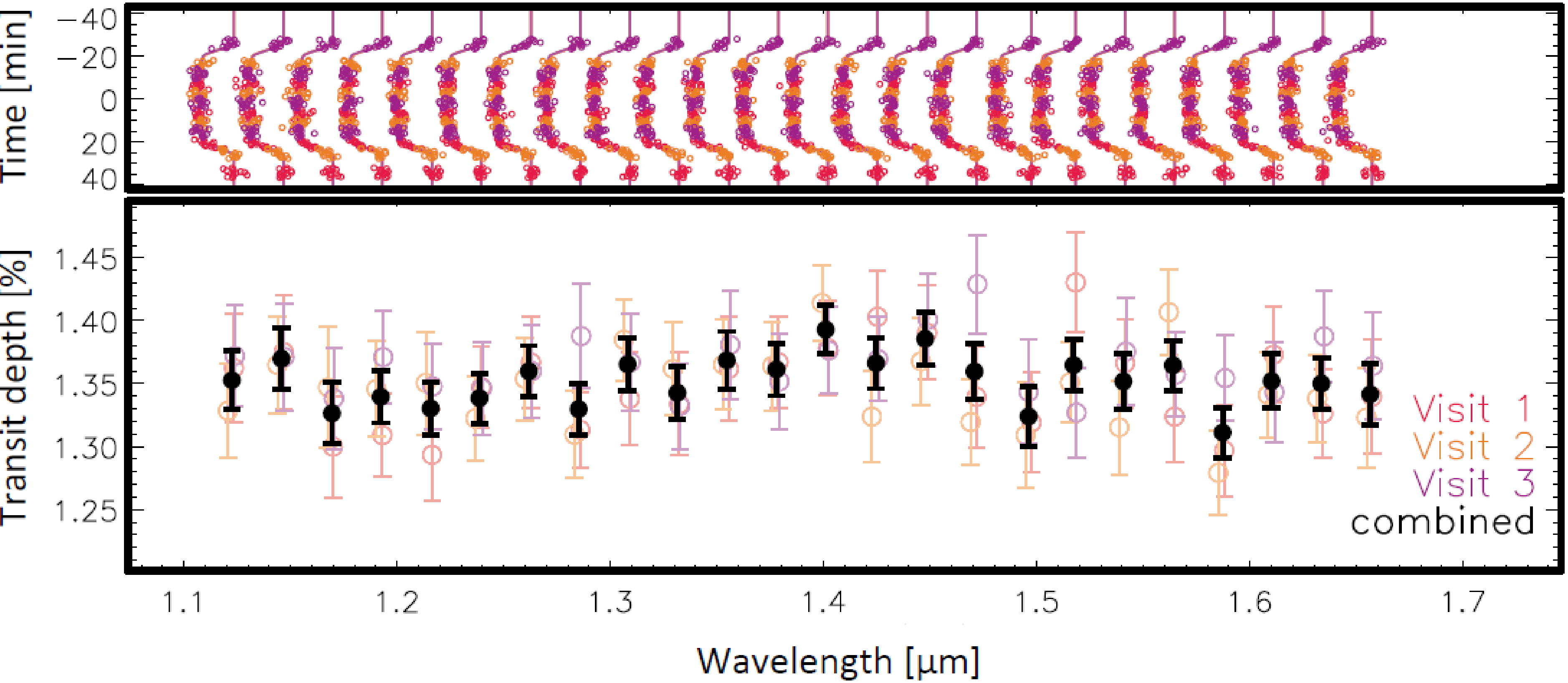


# Transmission spectroscopy



Needs ~0.1% precision in $R_{eff}$.

Berta et al. (2012)

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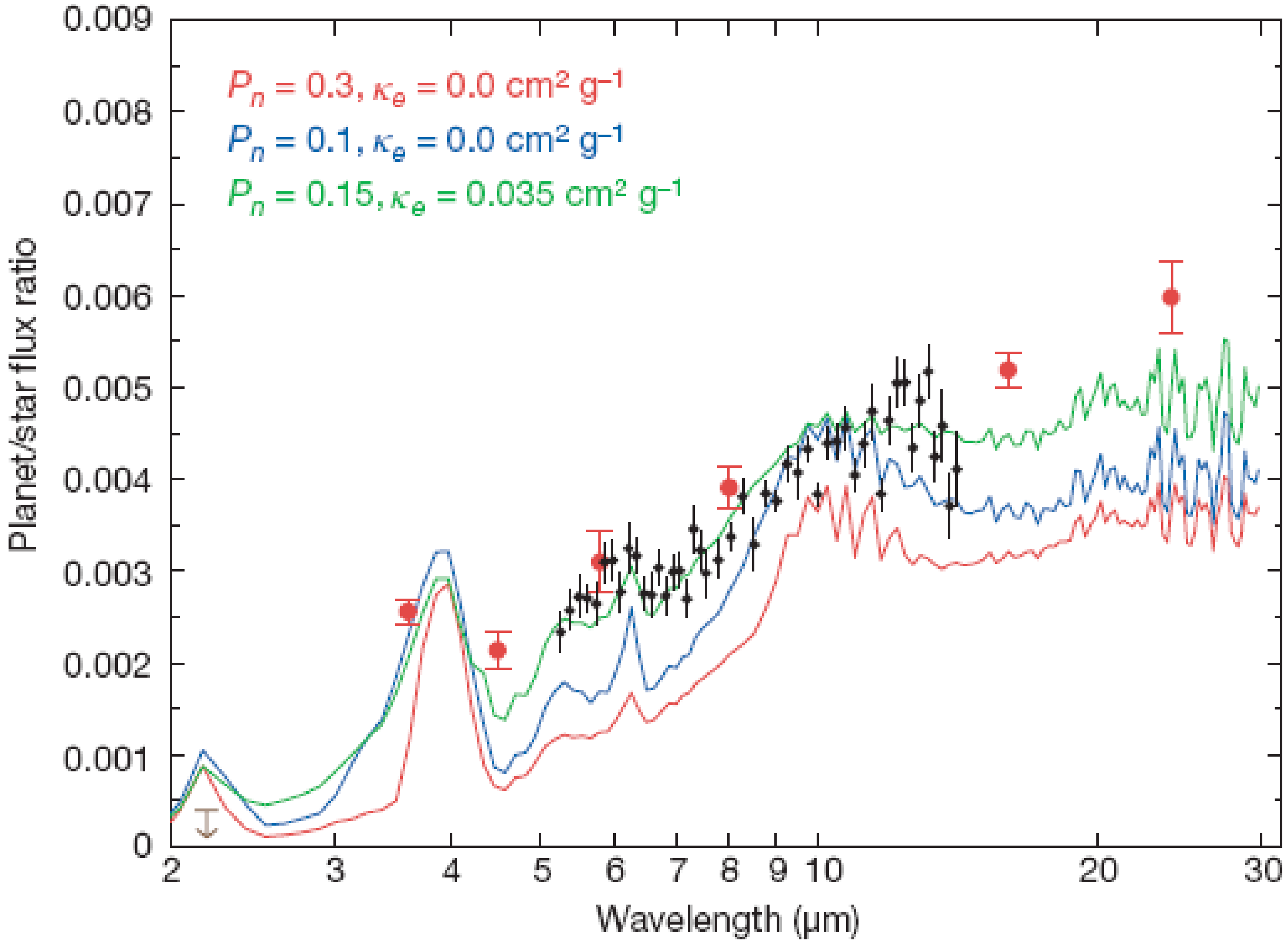
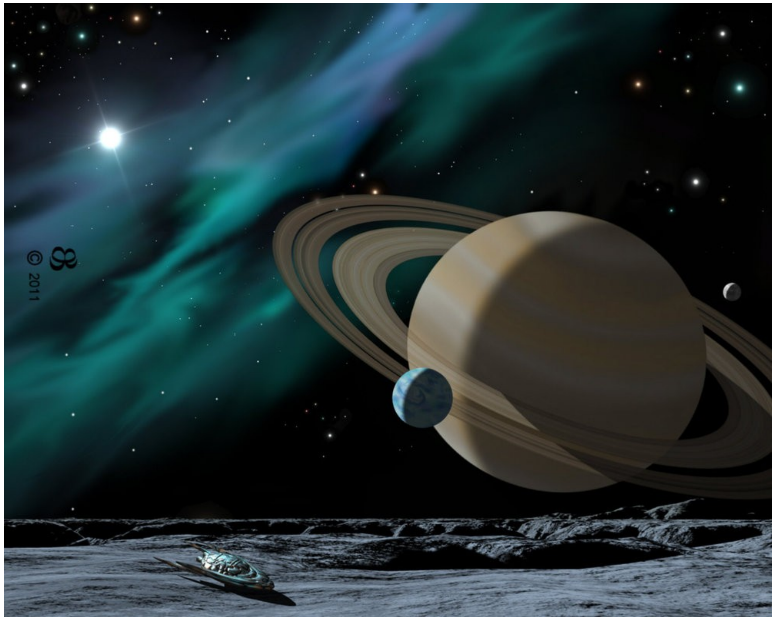
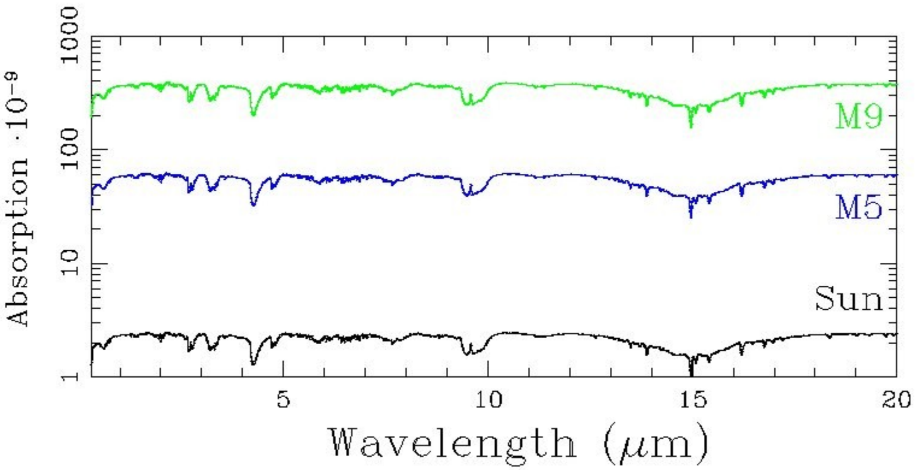
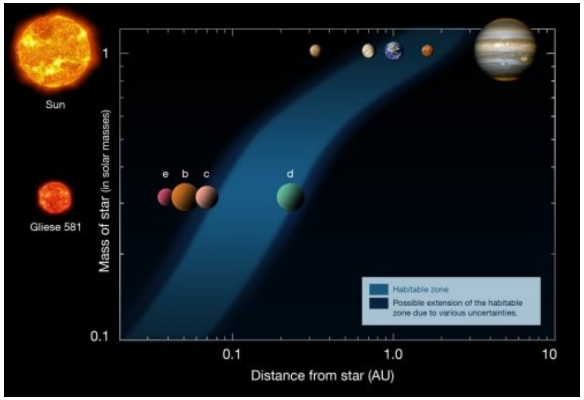


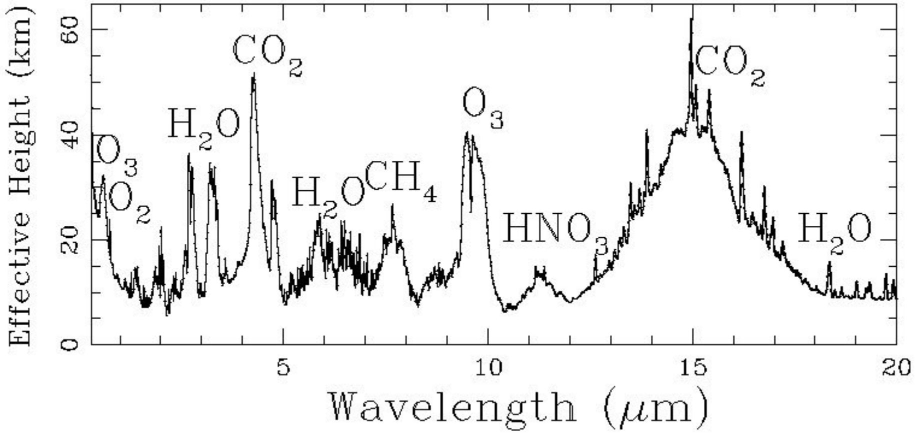
**Grillmair et al. 2008**

# Still waiting for





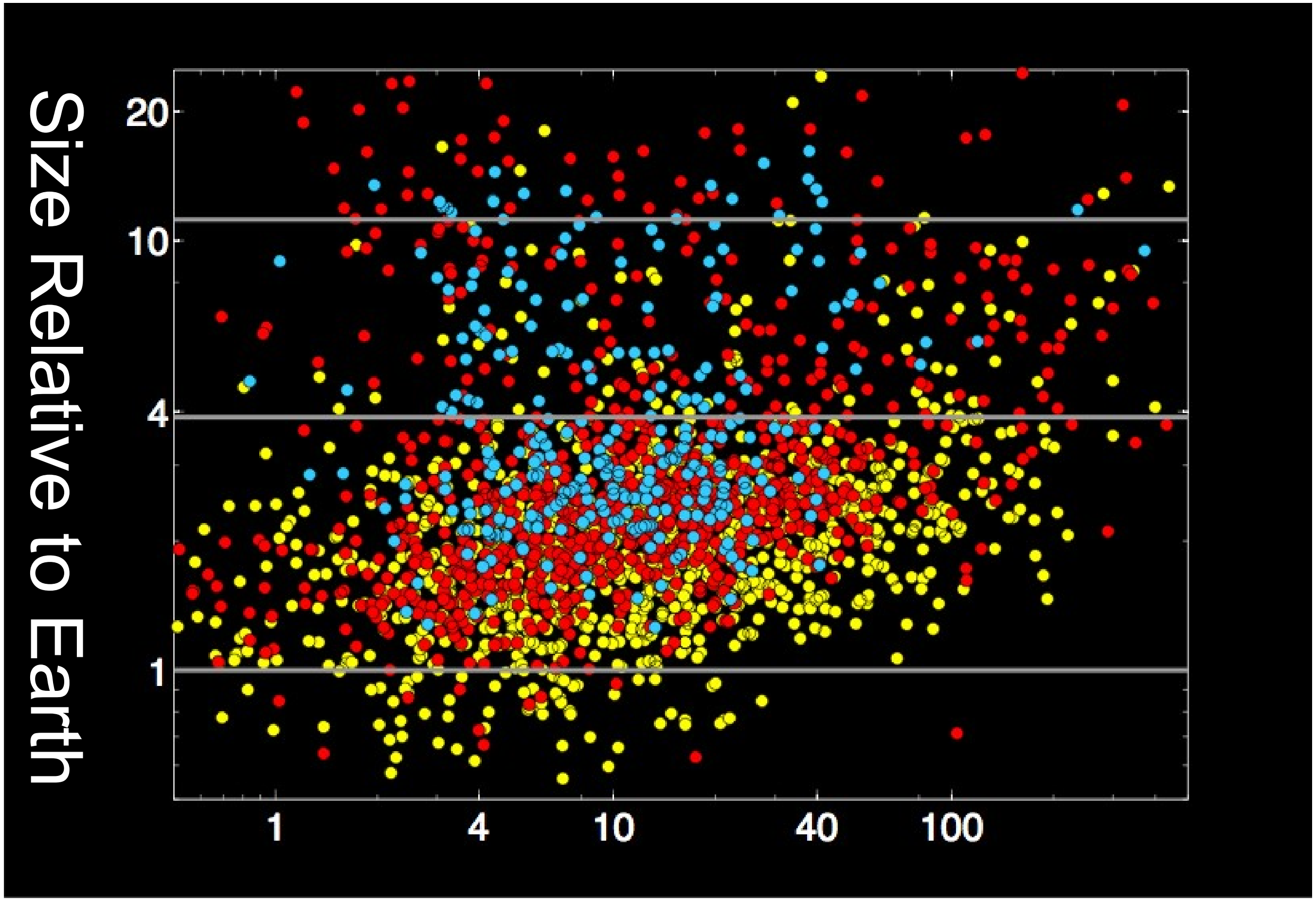




# When does future come?

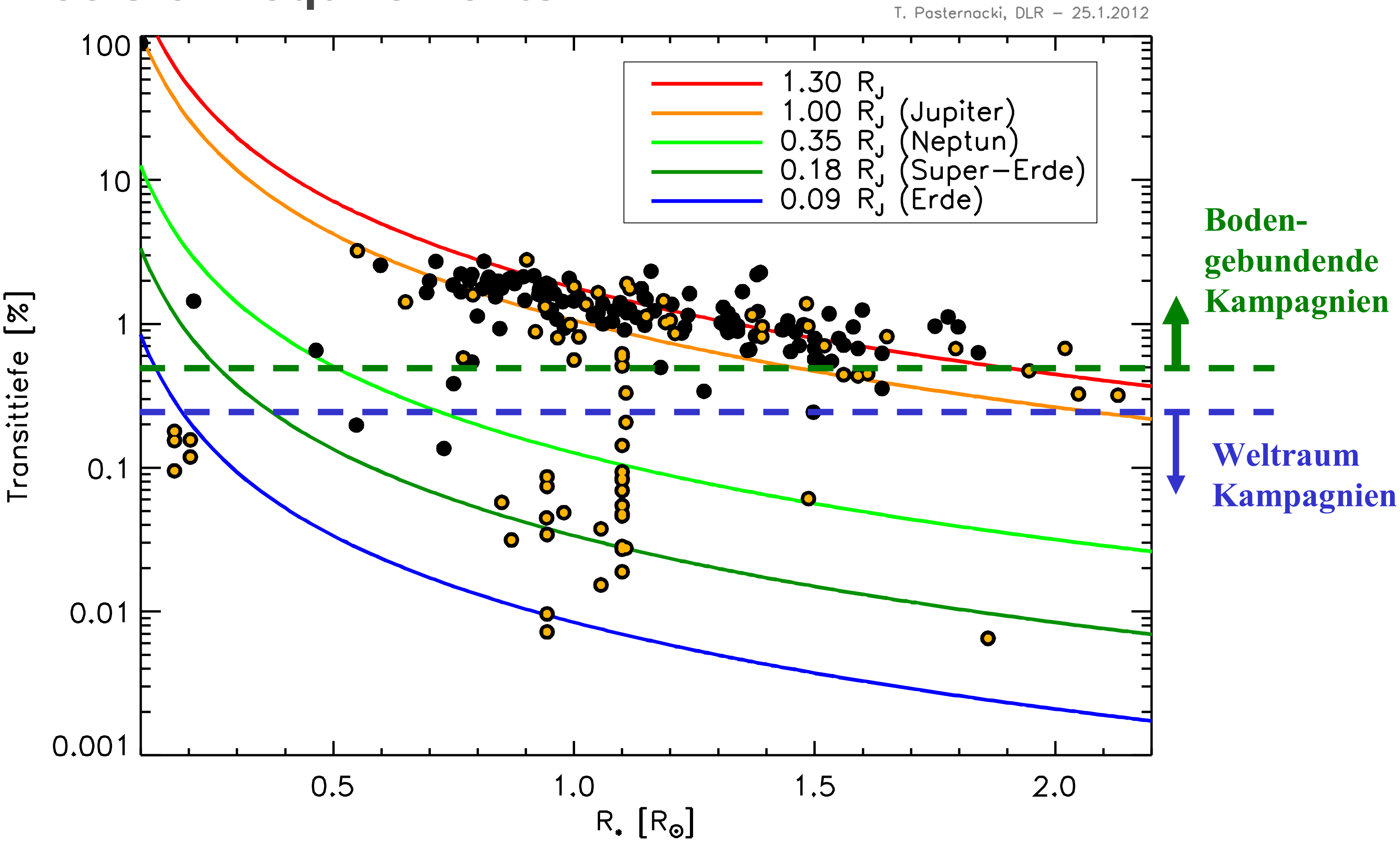
*Note:*

*Kepler (CoRoT) targets are faint for transmission /occultation spectroscopy. (Sometimes RV is problematic, too!)*
*We need brighter targets.*



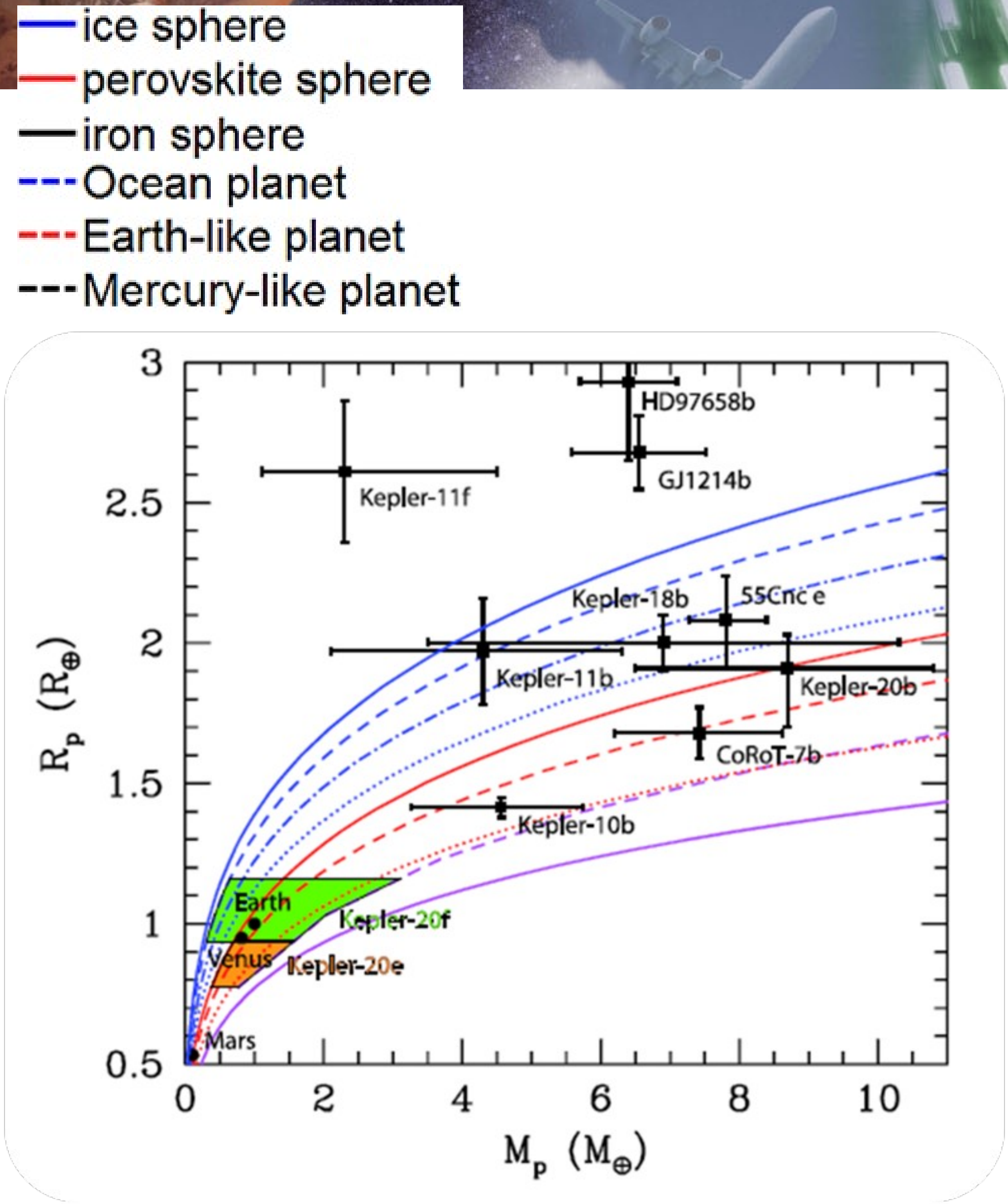
# Future requirements

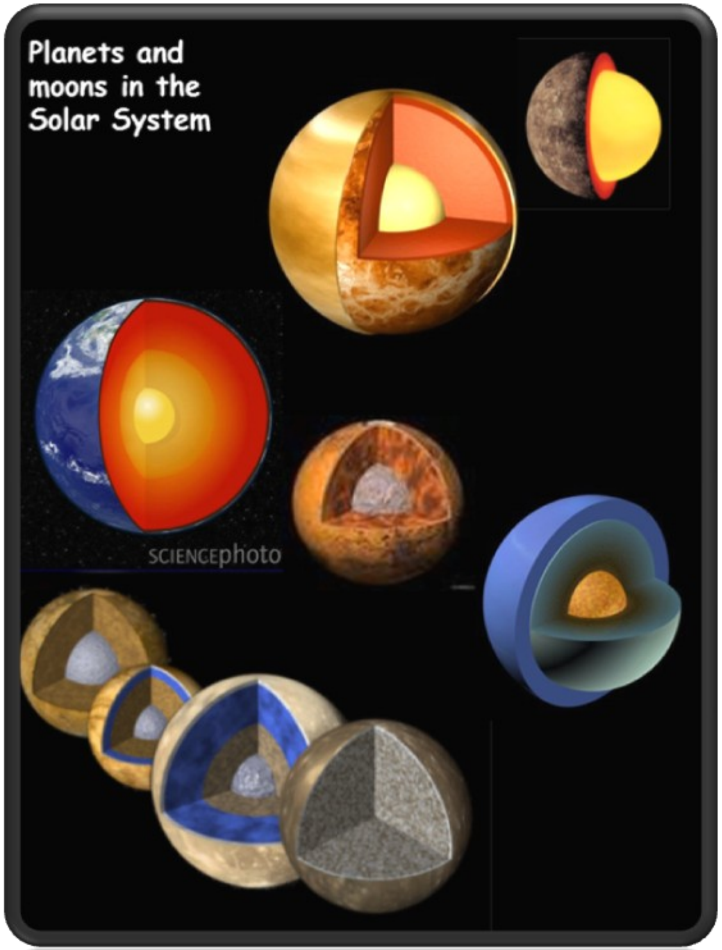
# Precision requirements

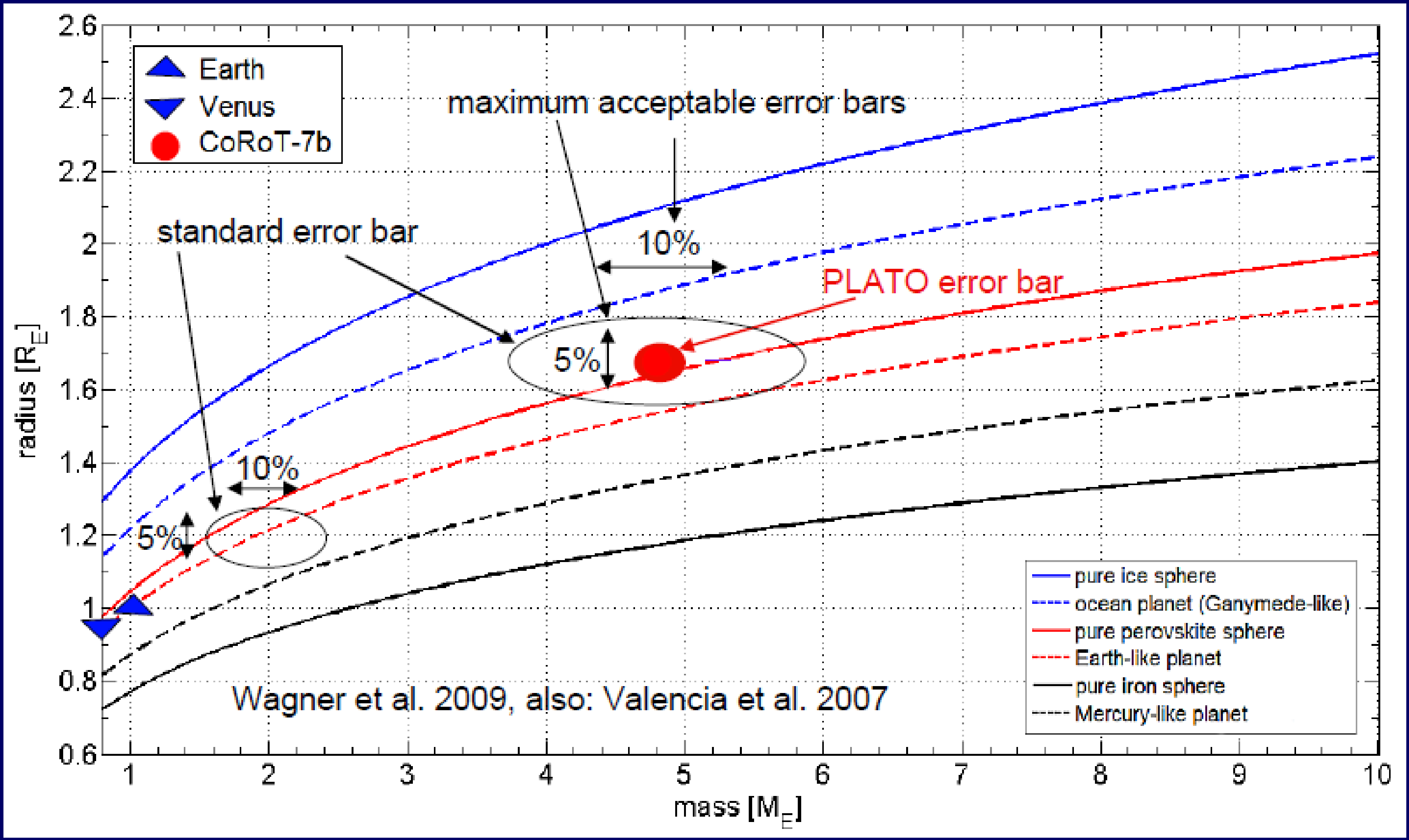


**Boden-gebundende Kampagnien**

**Weltraum Kampagnien**

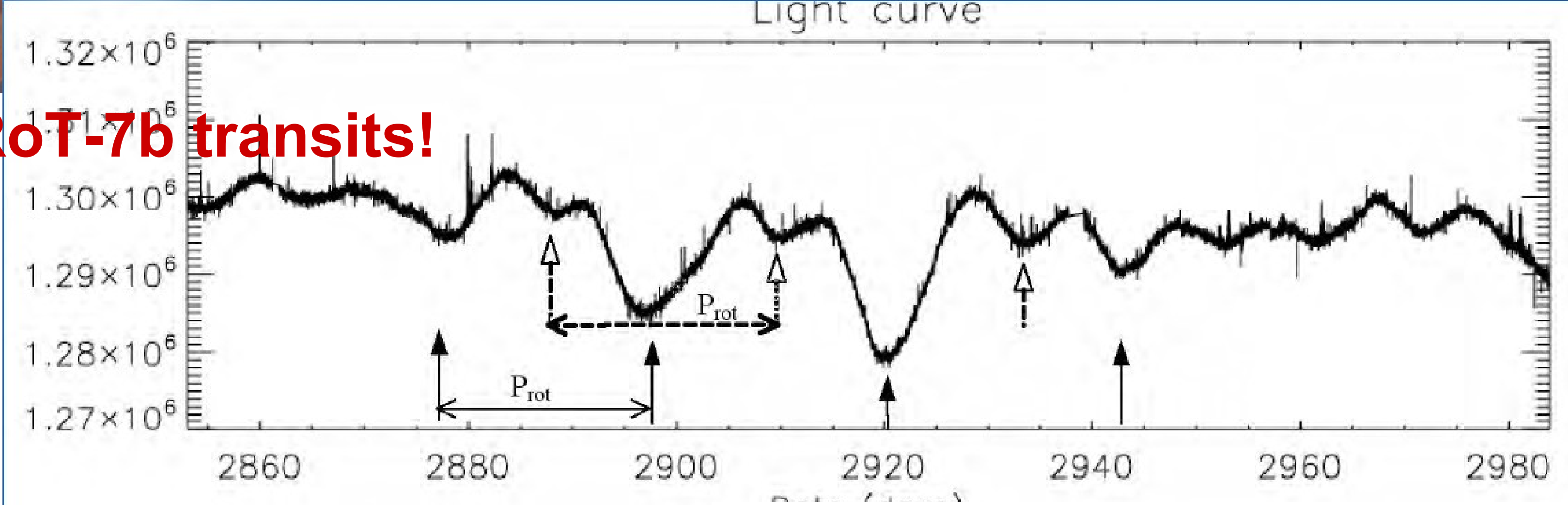

ice sphere
perovskite sphere
iron sphere
Ocean planet
Earth-like planet
Mercury-like planet
$R_p$ ($R_\oplus$)
$M_p$ ($M_\oplus$)
0.5
1
1.5
2
2.5
3
0
2
4
6
8
10
HD97658b
GJ1214b
Kepler-11f
Kepler-18b
55Cnc e
Kepler-11b
Kepler-20b
CoRoT-7b
Kepler-10b
Earth
Kepler-20f
Venus
Kepler-20e
Mars

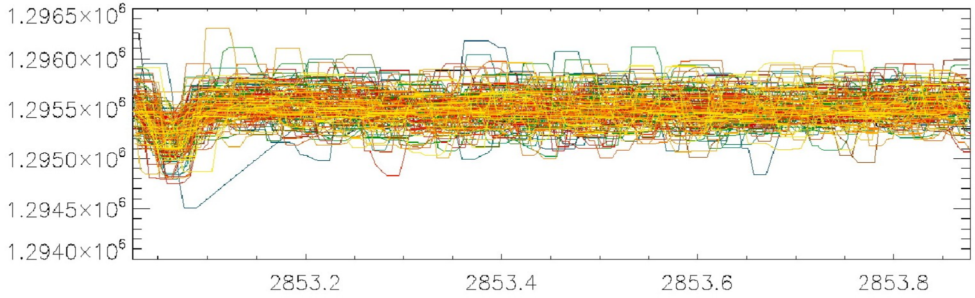

Planets and moons in the Solar System
SCIENCEphoto

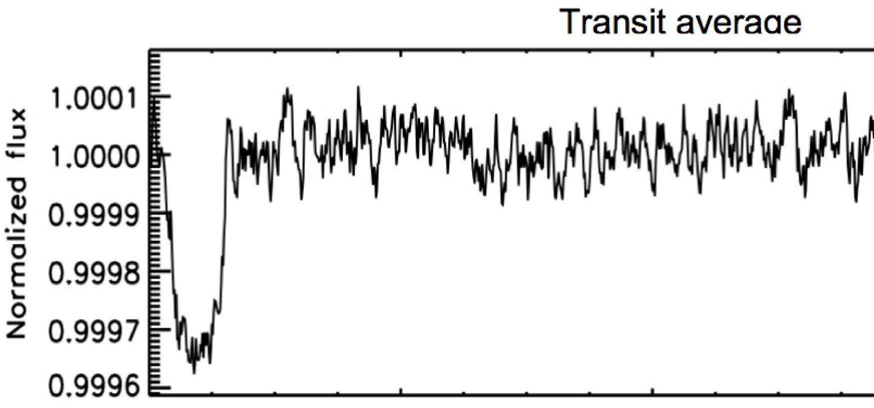


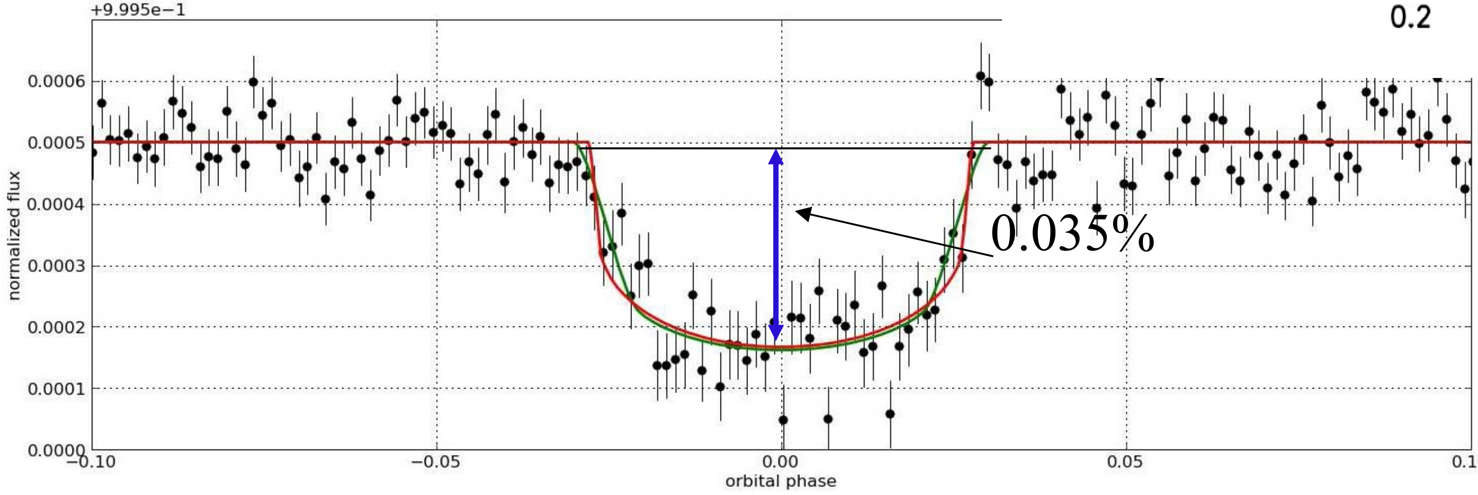
- **constraints on planet interiors**
- **radii and masses → atmospheres**
- **diversity**

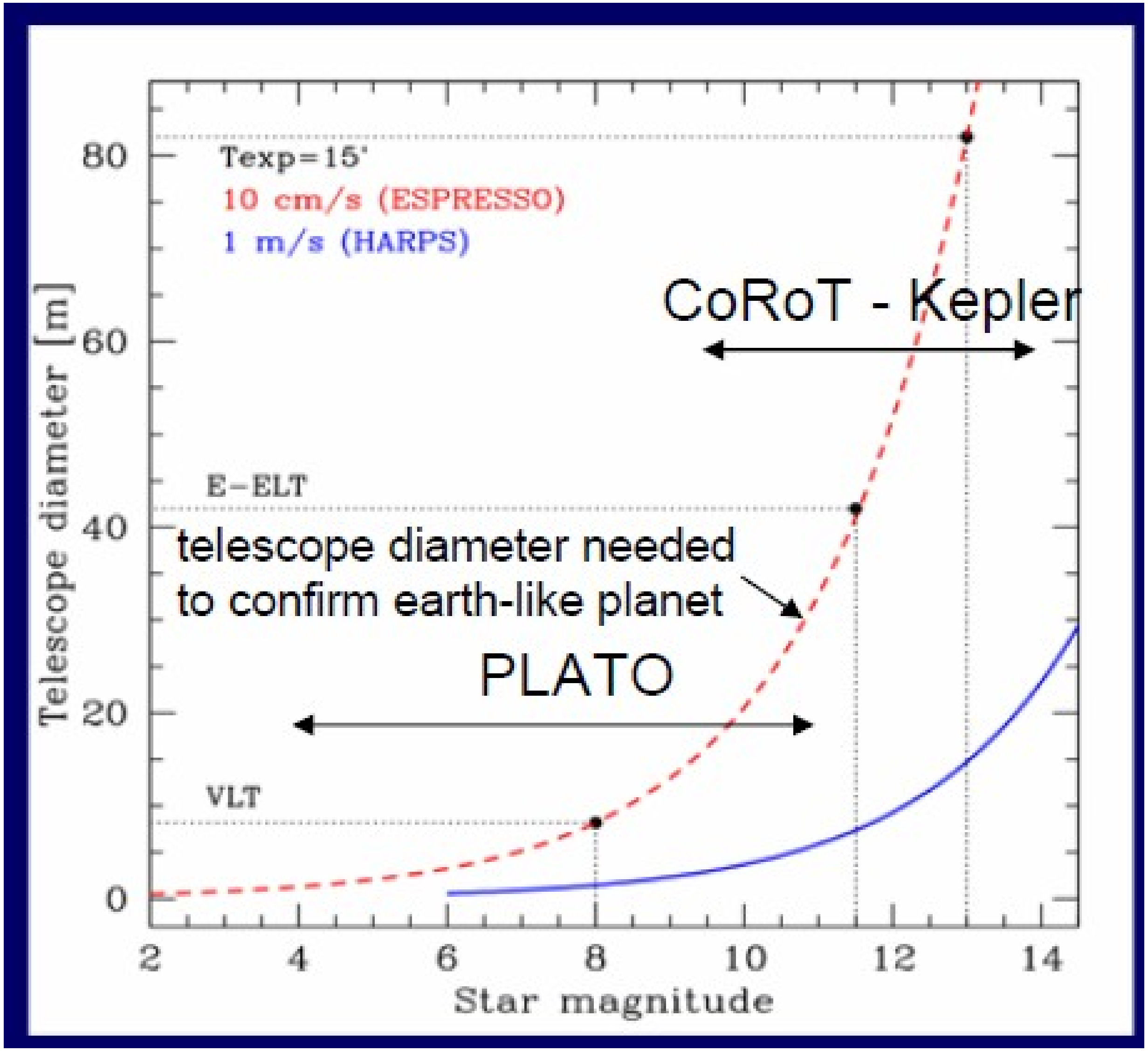
# Find CoRoT-7b transits!









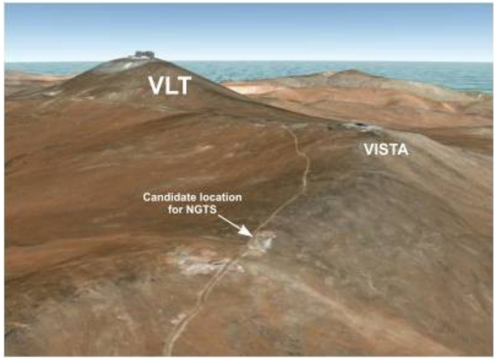

Texp=15'
10 cm/s (ESPRESSO)
1 m/s (HARPS)
CoRoT - Kepler
E-ELT
telescope diameter needed
to confirm earth-like planet
PLATO
VLT
Telescope diameter [m]
0
20
40
60
80
2
4
6
8
10
12
14
Star magnitude

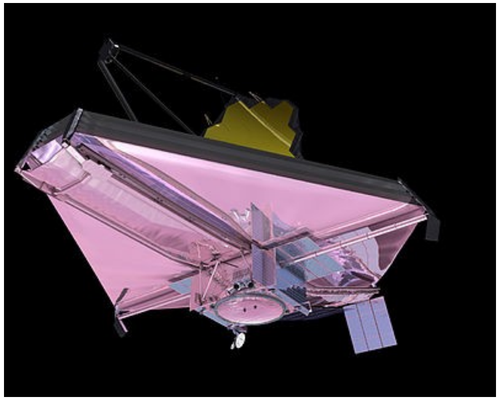
# Present and planned instruments

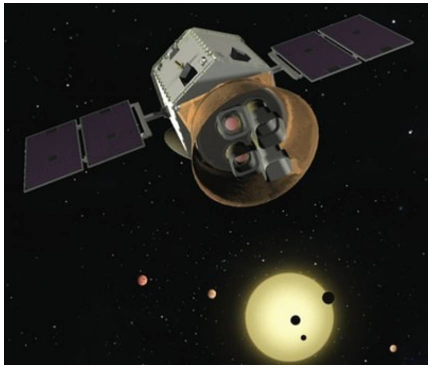
(far from a full list)

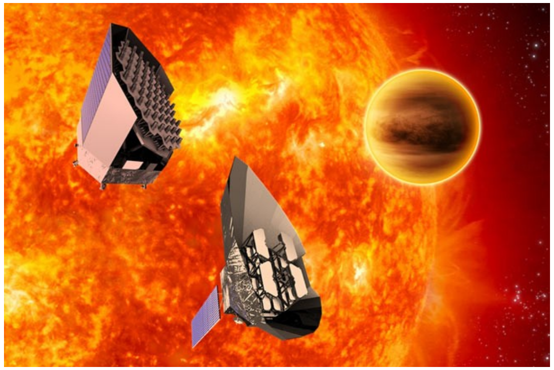
# (a) Photometric precision/bright stars,
# (b) RV-precision and spectra's SNR/R
# (c) analyzing tools

MASCARA
Multi-site All-Sky CAmeRA





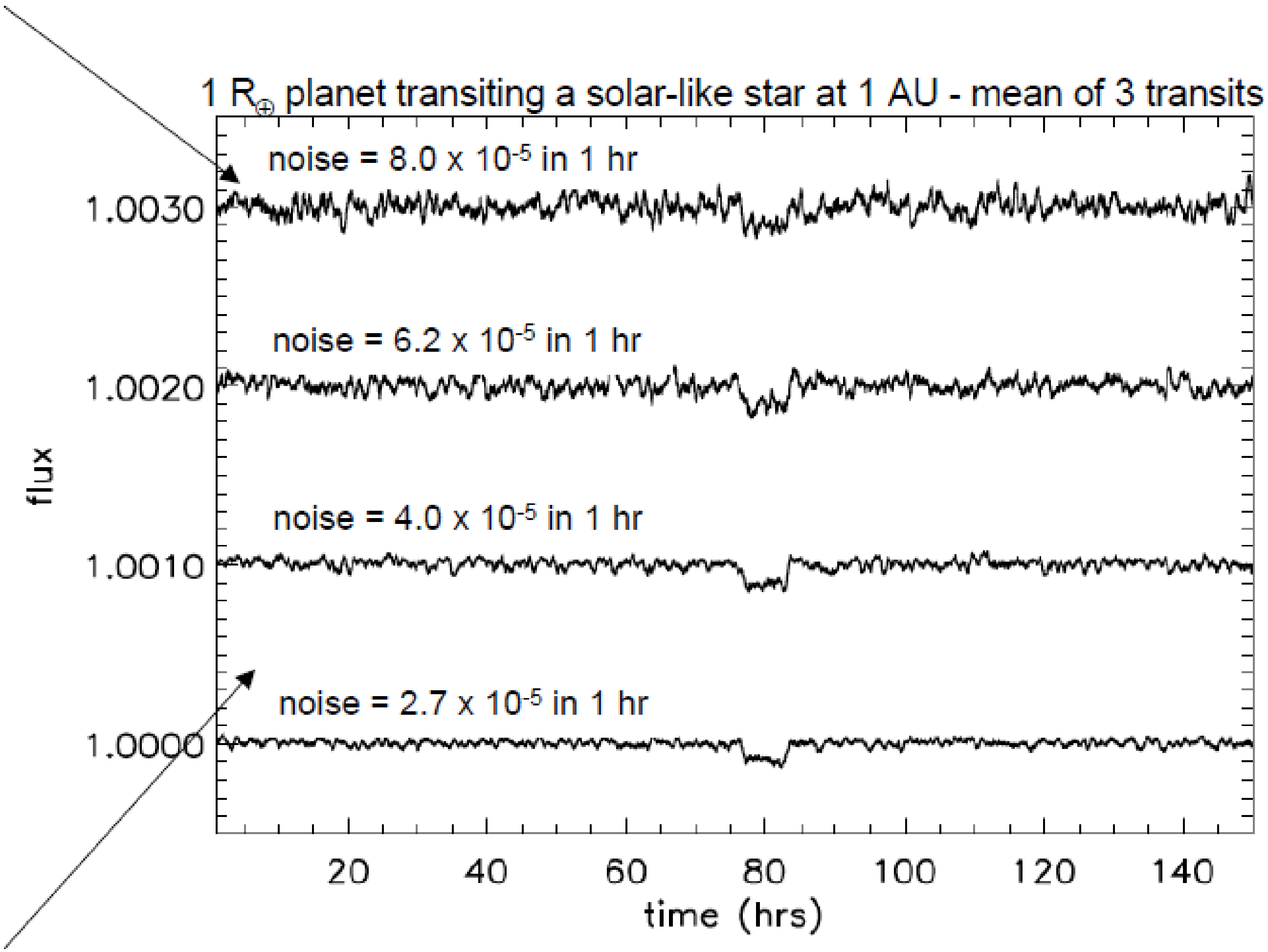




Goals: 50% of the sky down to V=11 with $10^{-5}$ mag (PLATO); 10 cm/sec on these stars (ESPRESSO); Atmosphere studies on E/SE/HJ from space (ECHO, JWST)

# *Noise level requirements for PLATO*

$8.0 \times 10^{-5}$ in 1 hr for marginal transit detection (faint targets)

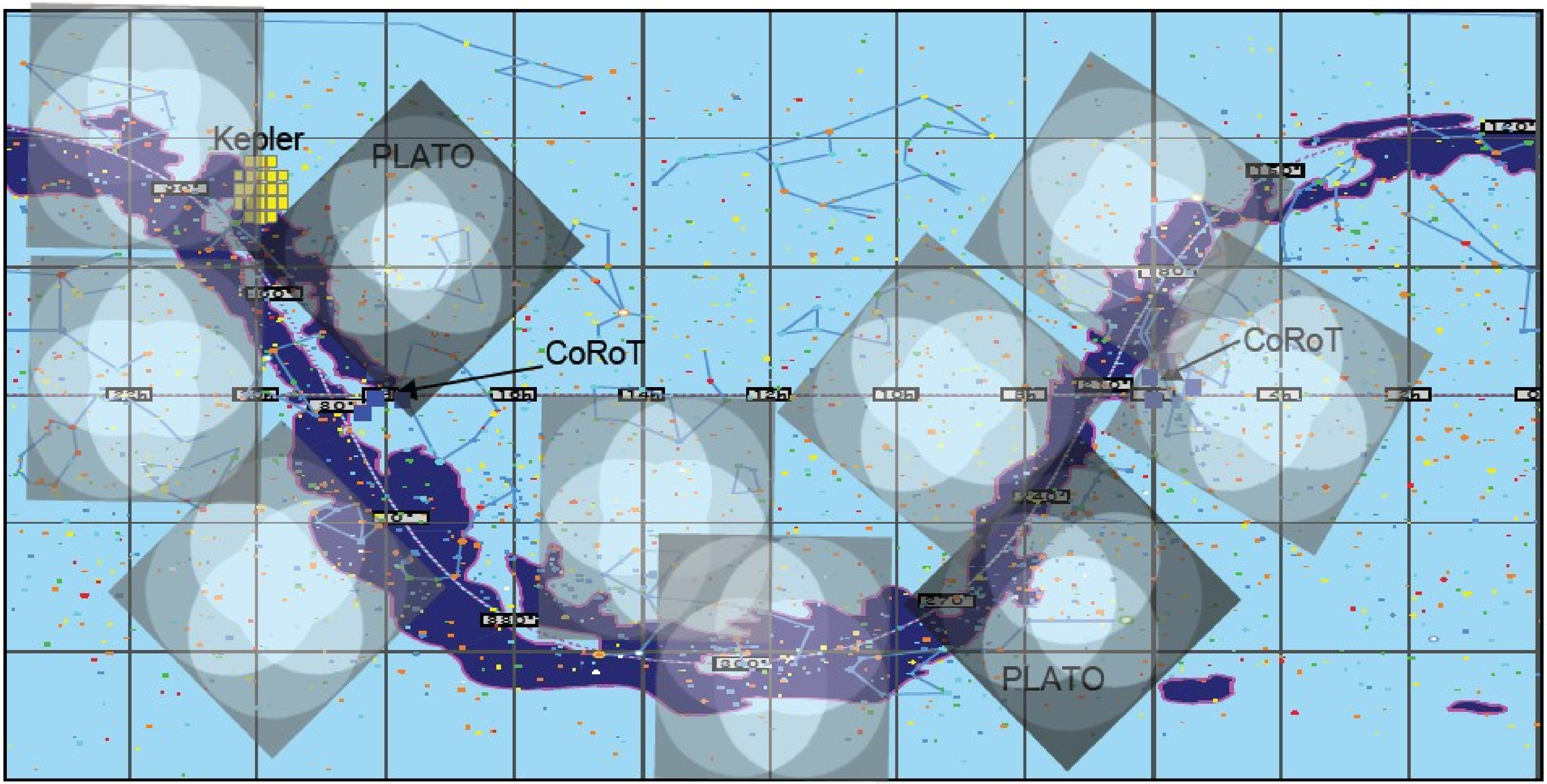


1 $R_\oplus$ planet transiting a solar-like star at 1 AU - mean of 3 transits

$3.4 \times 10^{-5}$ in 1 hr for high S/N transit measurement: also required for seismic analysis

# *Observation strategy and sky coverage*

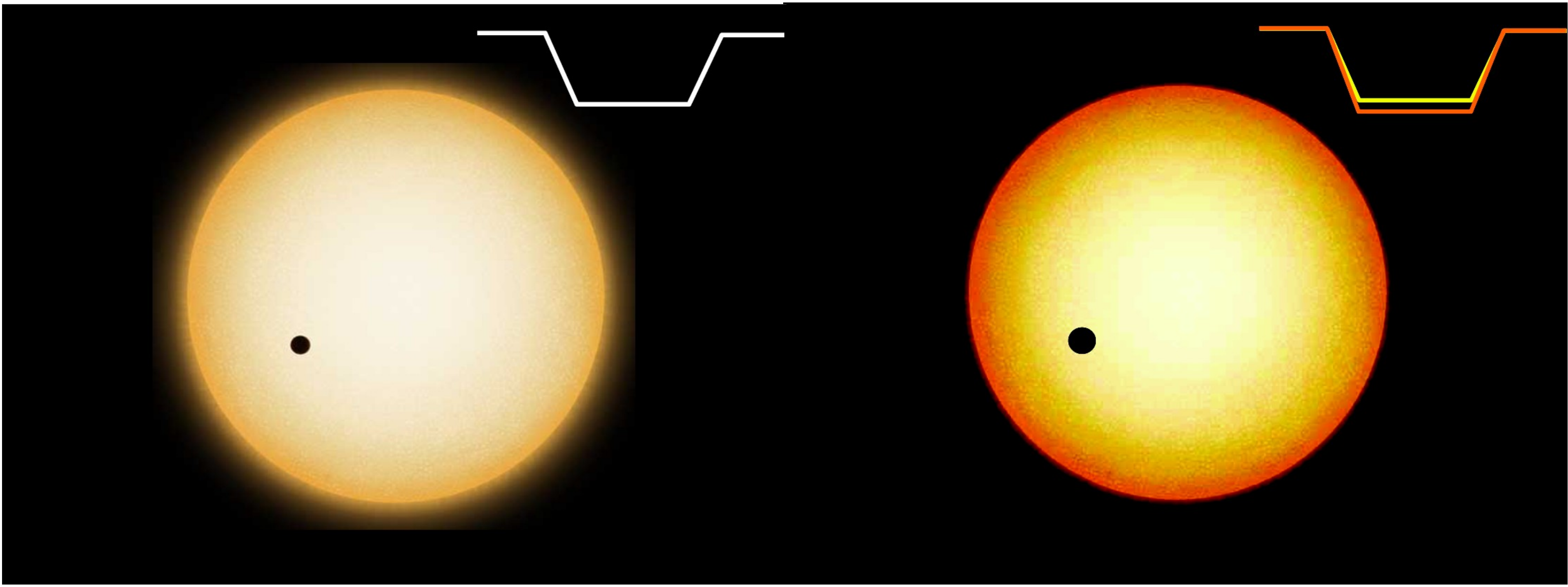
1. two long pointings : 3 years or 2 years
2. « step&stare » phase (1 or 2 years) : *N* fields 2-5 months each



***~ 50% of the sky !***

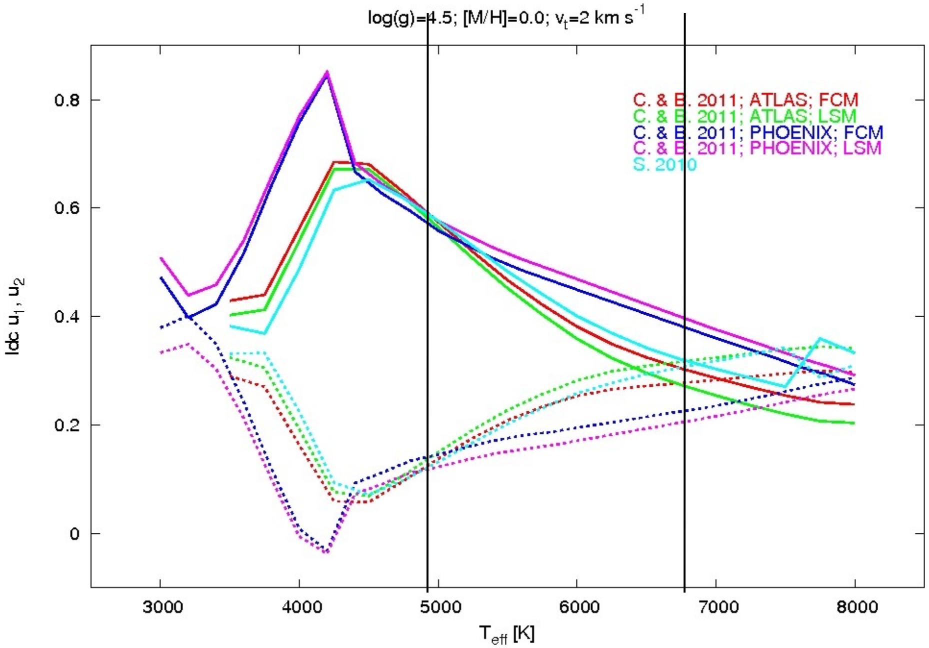
# Transit light curves and stellar atmospheres

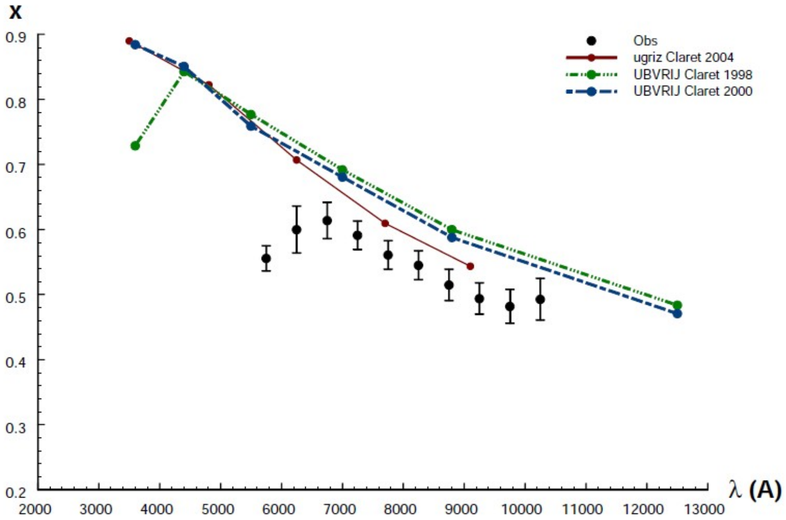
# Transits with and without Limb-Darkening



Limb darkening is a function of:

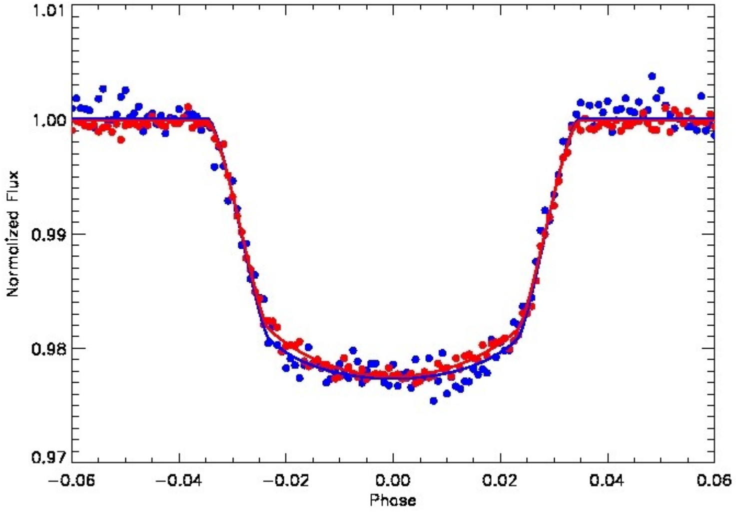
- effective surface temperature
- wavelength
- metalicity, surface gravity,
- microturbulence





Right: inverse limb darkening in HD 189733 (Abubekerov et al. 2012, arXiv

Left: comparison of Sing (A&A 510, A21, 2010) and Claret & Bloemen (A&A 529, A75, 2011)



**CoRoT host stars (Csizmadia et al. 2012a):**

24 systems, 25 transiting planets

14 coloured+white Lcs:

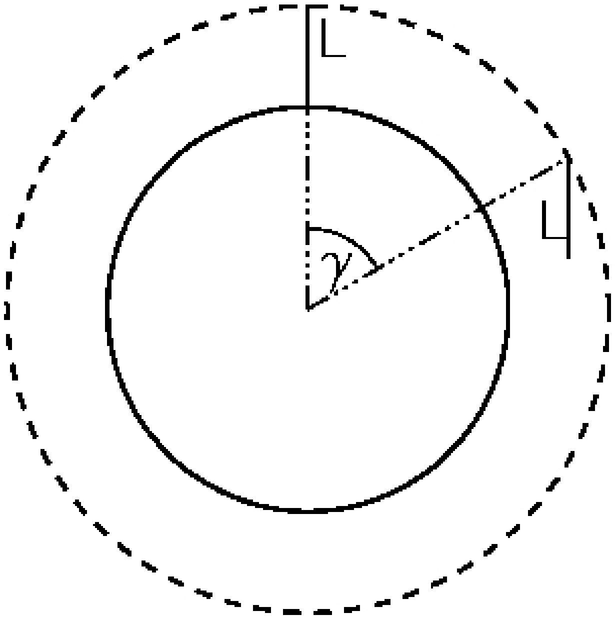
8 has normal behaviour (57%)

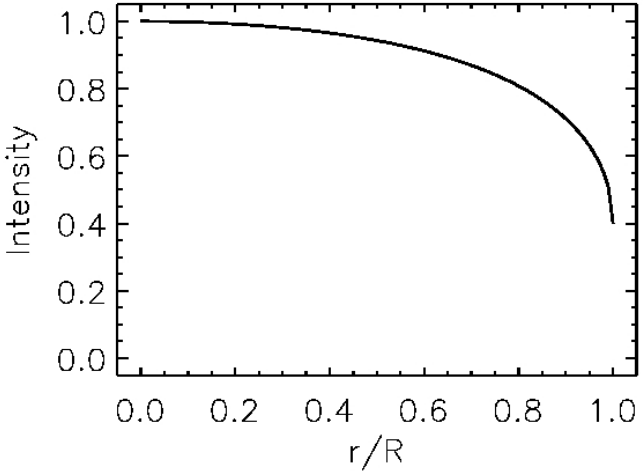
6 has inverse behaviour (43%)

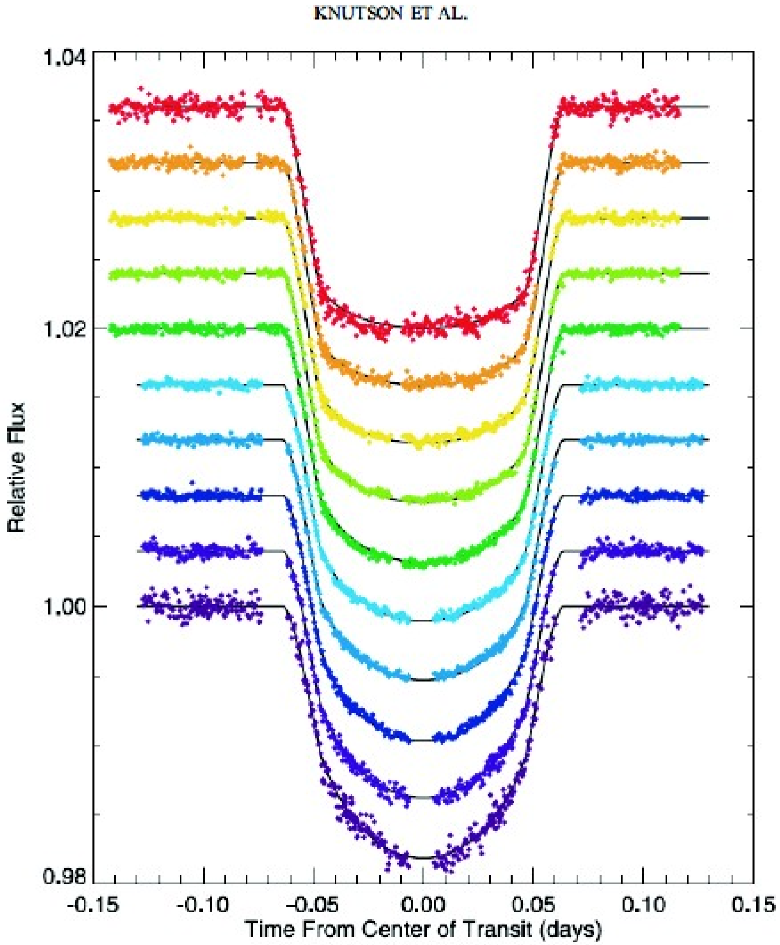
# How does it work?

$$\delta = 1 - \cos\gamma$$

$$I(r) = I(0)\left(1 - u_1\delta - u_2\delta^2 - \dots\right)$$







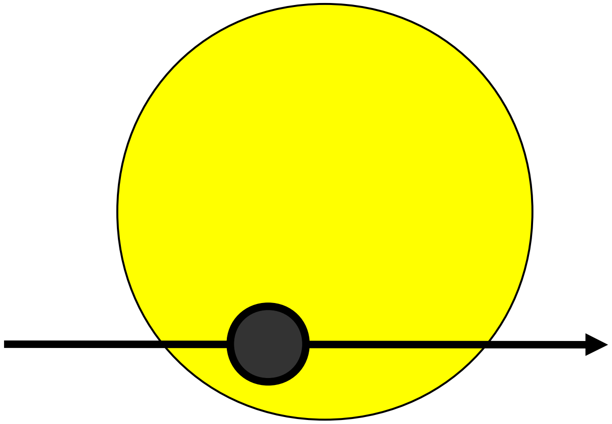
# How to measure planet-to-stellar radius ratio?

$$F_{star} = \oint I(r)\cos\gamma\, dA_{star}$$

$$F_{star} = \pi R_{star}^2 \left(1 - \frac{u_1}{3} - \frac{u_2}{6} - \dots\right) \times f_{distance} \times f_{absorption} \times f_{extinction}$$

$$\Delta F_{blocked} \approx \pi R_{planet}^2 \left(1 - u_1\delta - u_2\delta^2 - \dots\right) \times f_{distance} \times f_{absorption} \times f_{extinction}$$

$$\frac{\Delta F_{blocked}}{F_{star}} = \left(\frac{R_{planet}}{R_{star}}\right)^2 \frac{1 - u_1\delta - u_2\delta^2 - \dots}{1 - \frac{u_1}{3} - \frac{u_2}{6} - \dots}$$



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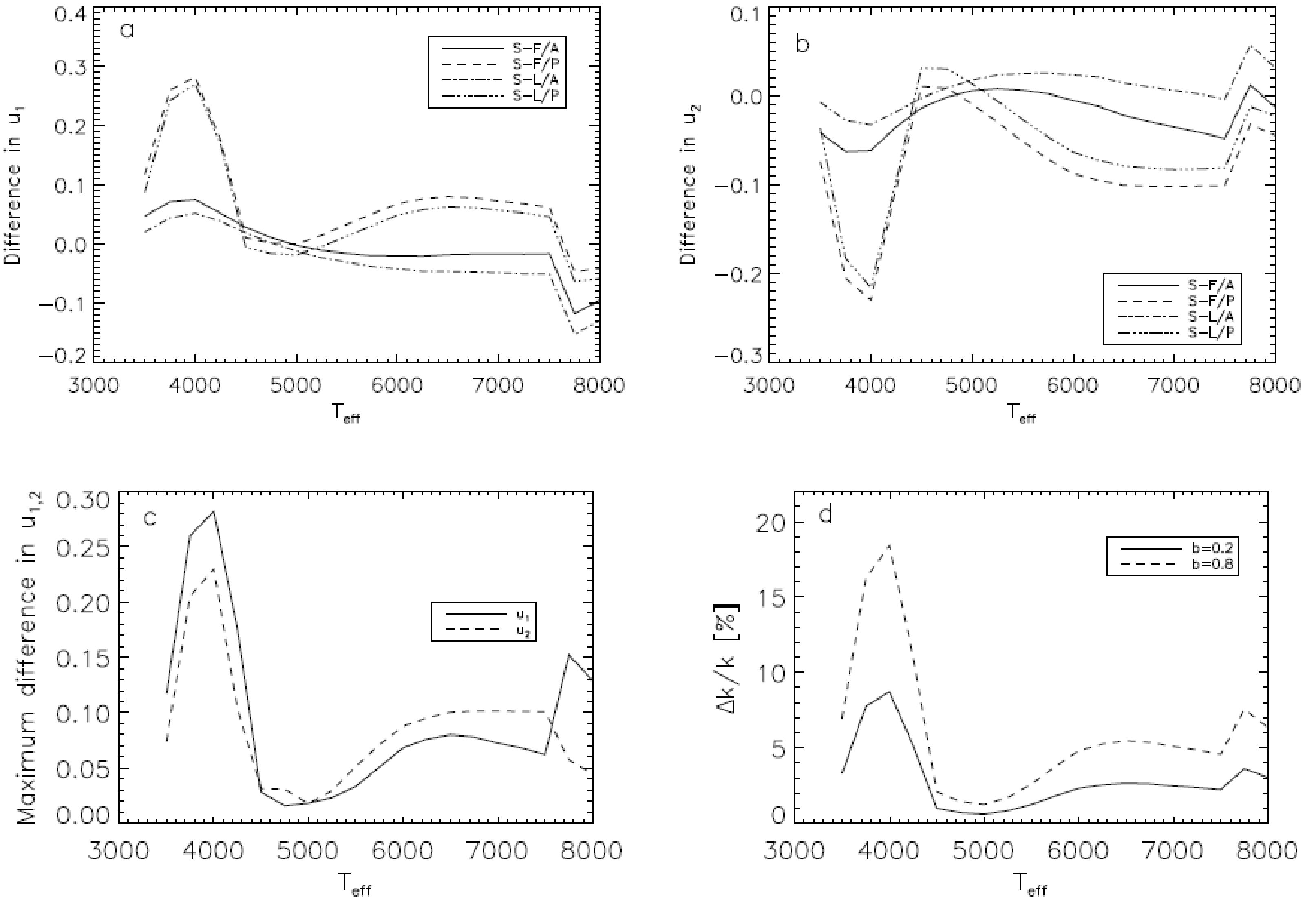
Csizmadia et al. 2012b, A&A, submitted



# Reasons for misunderstanding limb darkening coefficients (Csizmadia et al. 2012b, A&A submitted)

**Theory of limb darkening predictions:**

(1) different numerical methods for the calculation.

(2) Plane paralell vs spherical symmetry.

(3) 1D vs 3D model differences.

(4) Convection in stellar atmospheres.

**Factors not under consideration in theory:**

(5) Uncertainities in the input stellar parameters (Teff, logg, FeH).

(6) Systematic underestimation of the errors of the input stellar parameters.

(7) Systematic errors in the stellar structure models due to neglect of spots

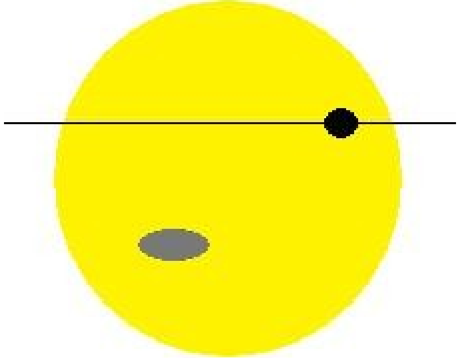
(8) Systematic errors in the Teff determination due to spots

(9) Inhomogeneties of the stellar surface: we observe a mixture but models calculate for homogeneous stellar surfaces

(10) Interactions with ellipsoidal shape, reflection effects etc.

Type I

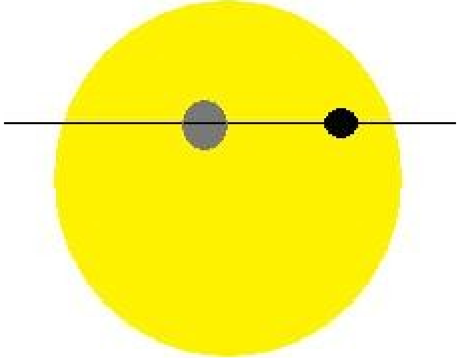
Temporary,
not occulted



Can be removed by
baseline-fitting

Type II

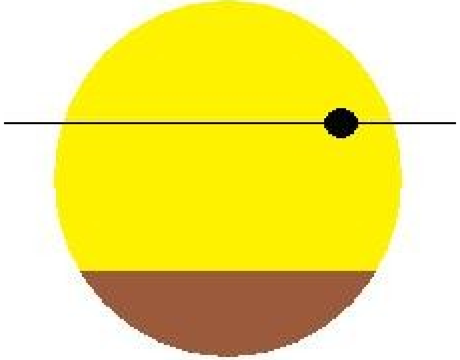
Temporary,
occulted



Can be removed
by modeling

Type III

Long life-time,
inclination/slow rotation



No LC modulation or
sudden change

# Effect of spots on limb darkening coefficients

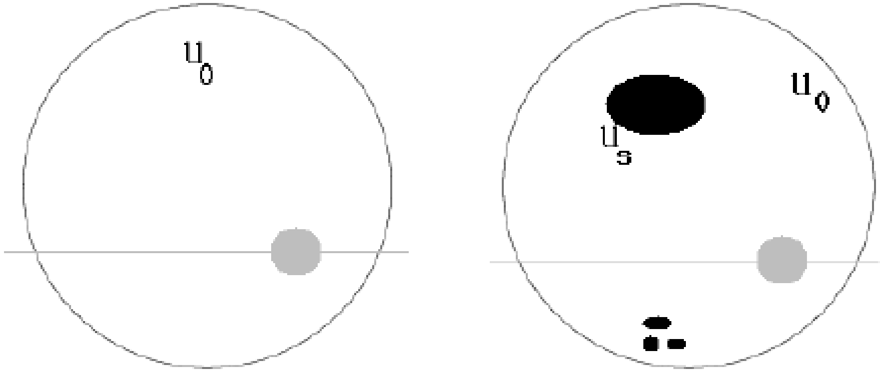
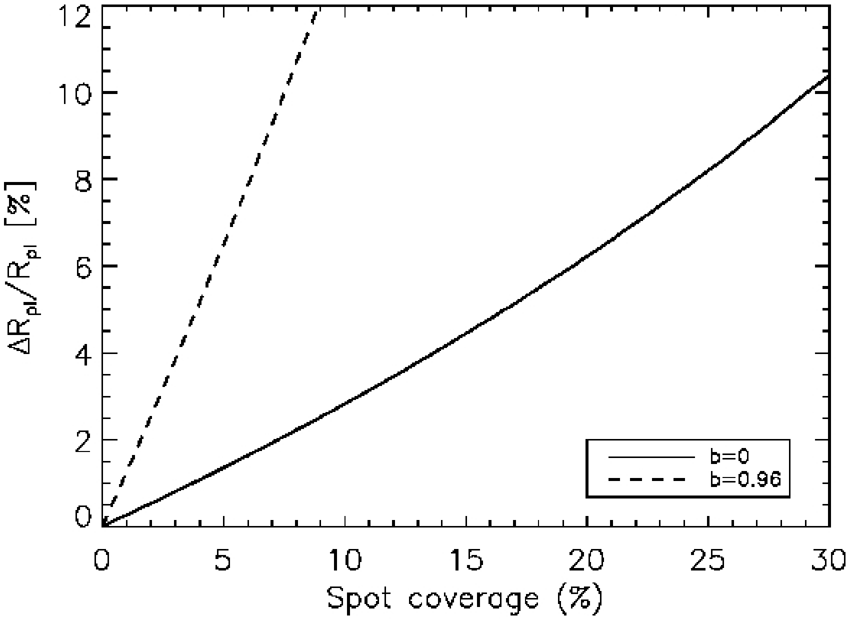
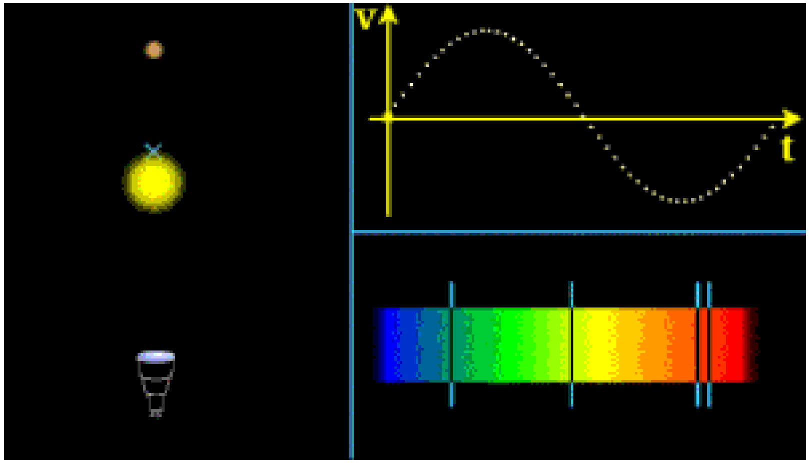


**Fig. 4.** Illustration of the effect of Type I spots. Left: the planet crosses an unmaculated star which is characterised with some limb darkening coefficient $u_0$. Right: the planet crosses the apperant stellar disc of a spotted star, where the spots and the planet have different impact parameters as well as the stellar photosphere and the spots have different limb darkening coefficients ($u_0$, $u_s$). Gray area is the planet, black ellipses are representing the spots.



# How precisely do we know the planet parameters at all?



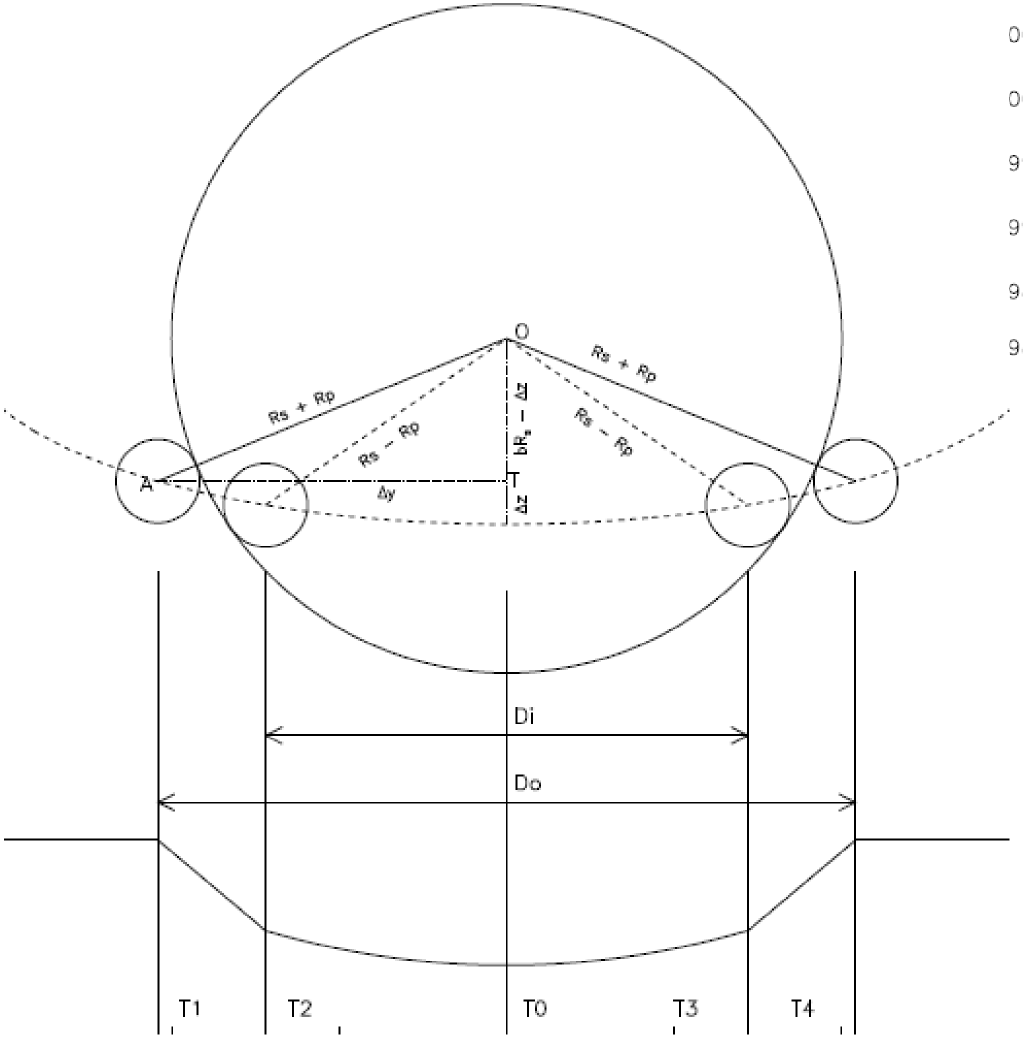
$$R_p = k\, R_s$$

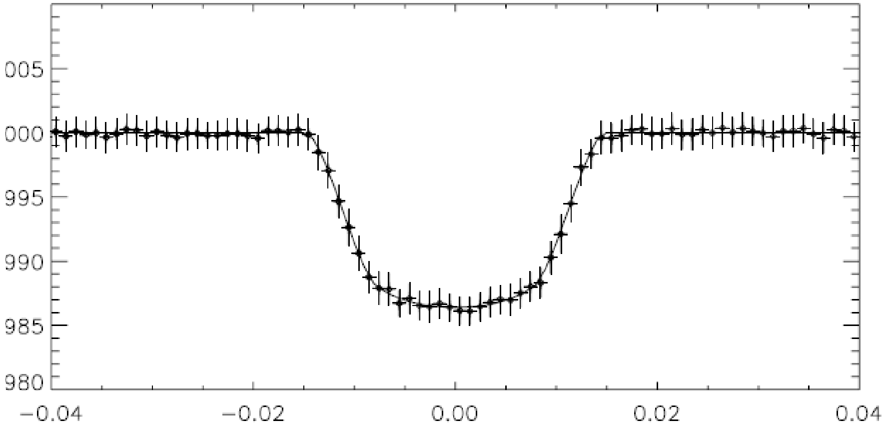
$$M_p \sin i \approx M_s^{2/3}\, K \sqrt{1-e^2} \left( \frac{P}{2\pi G} \right)^{1/3}$$

Precision in radius/mass:

- quoted errors are sometimes below 5%
- LD not good: k up to 40%
- stellar masses from isochrone-fit (future: asteroseismology)
- Clausen et al (2009): evolutionary calculated radii of <1 Msun stars are not supported by observations
- Torres et al.: $R_s$, $M_s$ can be different by 20% due to spots. (logg : up to 100%)
- very low mass stars (dM): role of magnetic field
- very likely many error bars are underestimated and many planet parameters are necessary to revise

# Limb darkening free way for radius ratio





CoRot-5b, Rauer et al.

$$V_y \times T_{10} = (R_s + R_p) \times f_{inclination}$$

$$V_y \times T_{20} = (R_s - R_p) \times f_{inclination}$$

For details see Csizmadia 2012c, A&A

# New and planned projects to solve old problems and to open way of new science

(a) **Ultraprecise photometry:** better radius, mass; exorings, exomoons; smaller planets.
(b) **Longer observational windows:** long-period planets ($P_{Earth}$ = 1 yr); mass-determination improvements; TTVs (Love-numbers, $J_2$, internal structure properties via tidal interaction between star/planet and planet/moon). Hot Jupiters are lonely?
(c) Formation of moons?
(e) Stellar masses, radius, **age of the system via asterosoeimology** (SNR, run length). How systems evolve (dynamically) and how planets vary in time? (E.g. Earth changed a lot during Gyrs.)
(f) Bright stars (SNR): detection of bioindicators, temperature distribution in atmospheres (life, stability, content).
(g) Volcanism on planets; detection of artificial objects.

# Summary

(1) Highlights of exoplanetary researches.

(2) The necessity of very precise planet parameters (1% in R, 2% in M).

(3) The necessity of additional constrains (like J2 etc.)

(4) Discussing some related effects which have impact on parameter determination. Deeper understanding and improvements are also presented.

(5) Arguing for new, long-term, ultraprecise photometry from space.