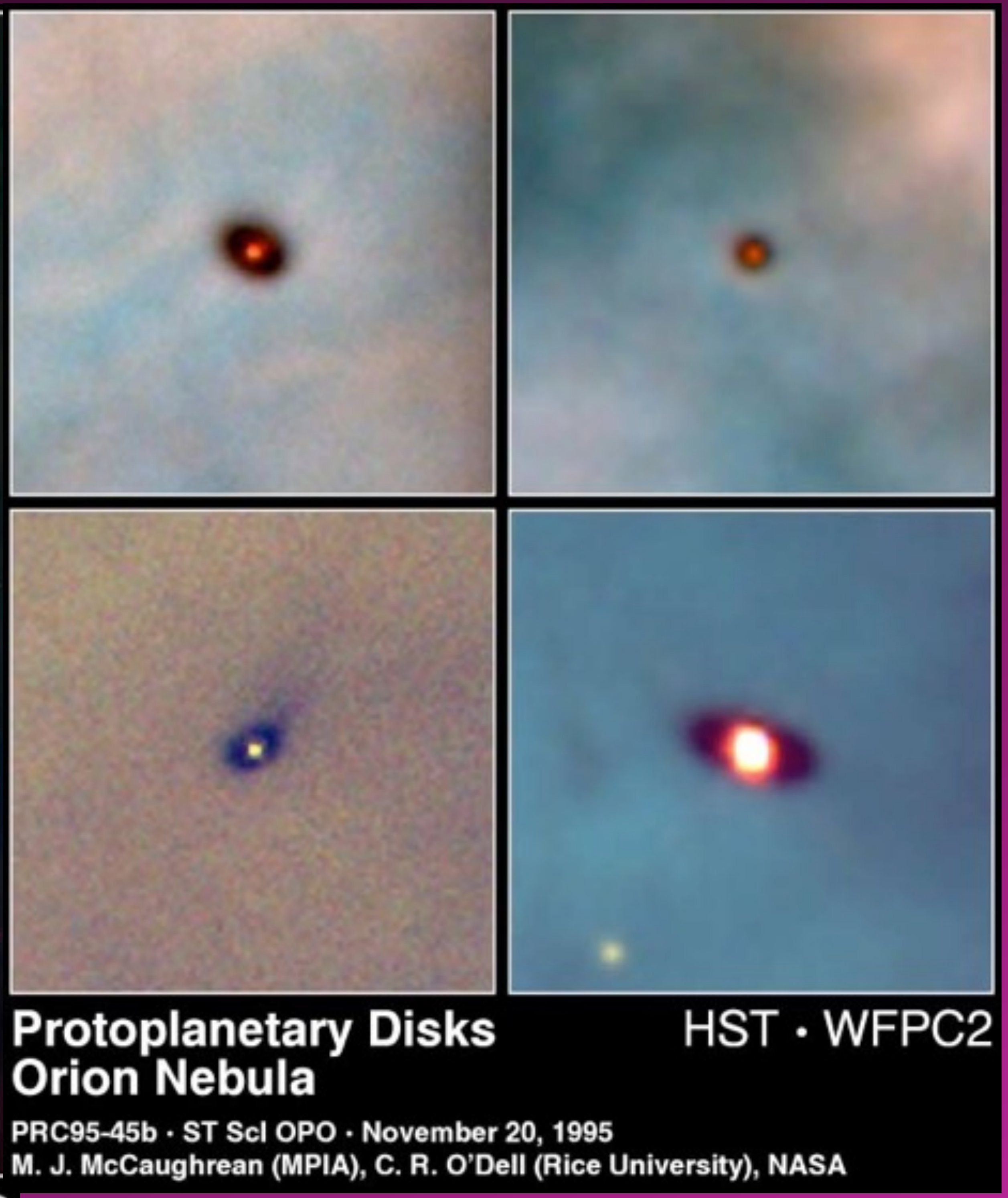
A path to the detection of Earth-type Planets

Michel Mayor
Geneva University

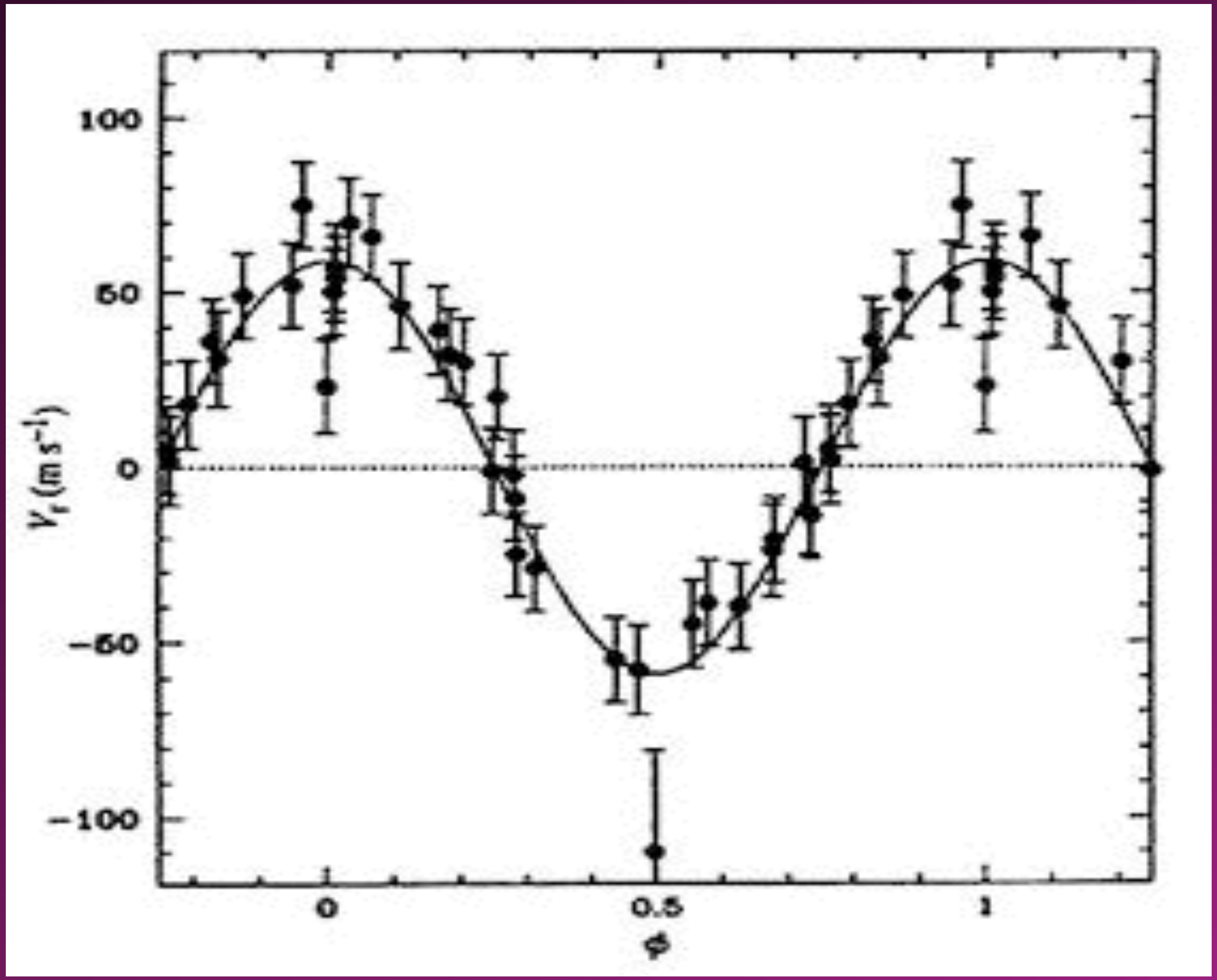
HST observations of accretion discs



A first exoplanet : 51 Pegasi
>>> orbital migration

Precision: 10 m/s

M_{pl} = 0.5 M_{Jup}
P = 4.2 days <<<<<!!!!!
a = 0.04 AU

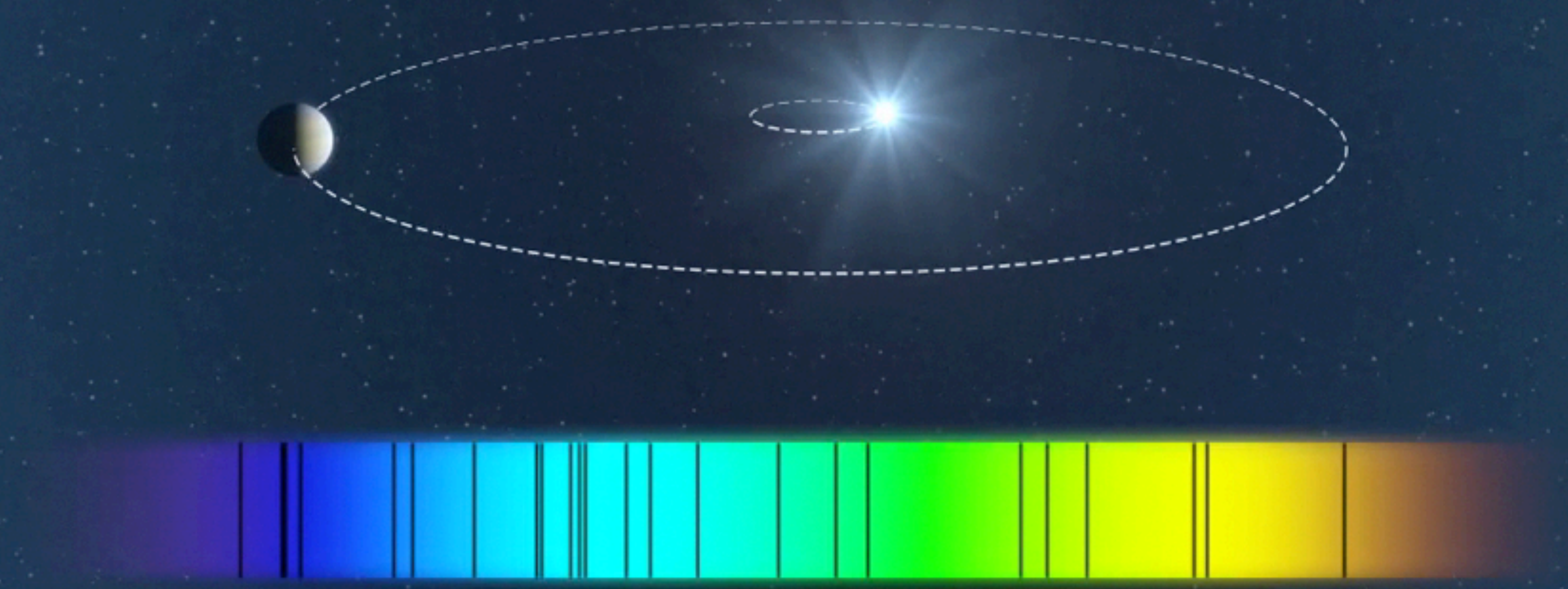


Observatoire de Haute-Provence 193 cm

Mayor & Queloz , Nature 1995

Detection of planets via Doppler spectroscopy

Present sensitivity $\delta\lambda/\lambda = 10^{-9}$

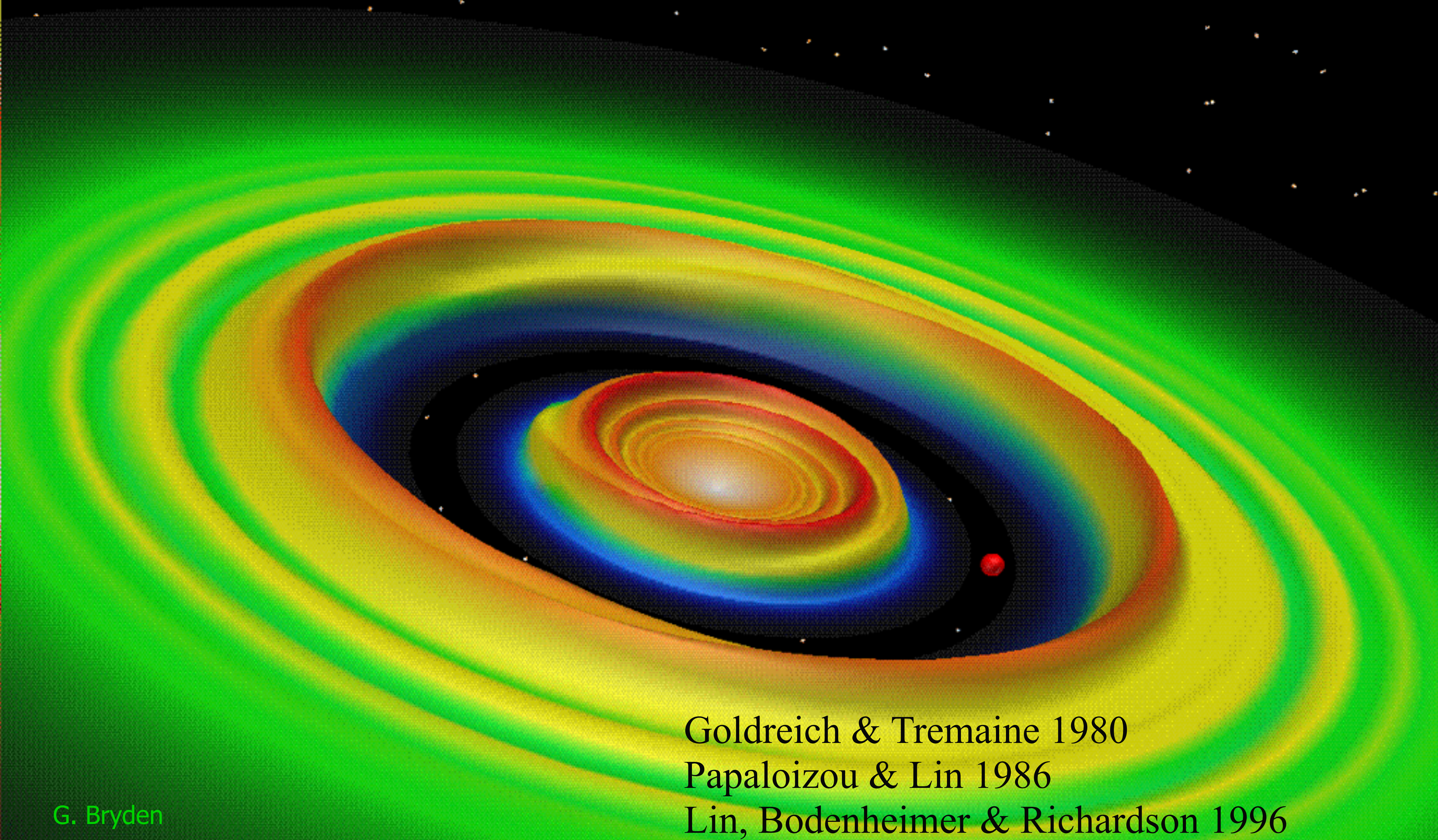


The spectrograph HARPS uses simultaneously 6000 spectral lines (cross-correlation technique)

Formation of planets with very short P : interaction disc - planet

Formation outside the "ice line" -> migration -> center

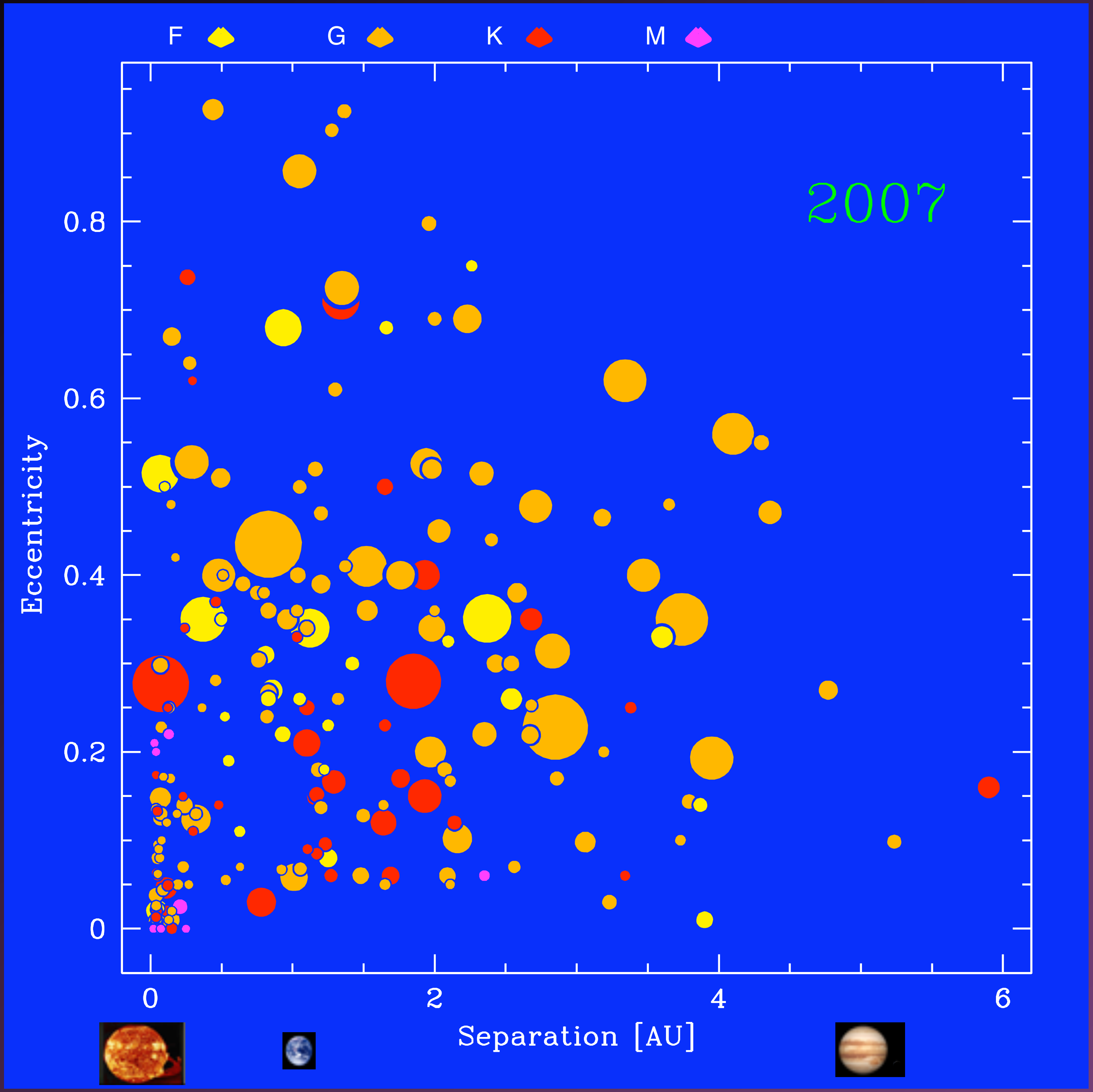
How to stop the migration ?



Goldreich & Tremaine 1980
Papaloizou & Lin 1986
Lin, Bodenheimer & Richardson 1996

>>>> The Diversity of planetary systems

1995-2016: >1000 RV-planets+ about 1000 (3000) detections from transits (ground-based and space)



Statistics :

- Occurence
  > 70% of stars have planetary systems
- Mass Distribution
  1 $M_{Earth} < M_{pl} < 20\ M_{Jup}$
- Periods
  0.3 d < P < several years
- Eccentricities
  0 < e < 0.93
- Multiplanetary systems
- Retrograd orbits
- Host star properties
  Metallicity , …

The HARPS search for low-mass planets

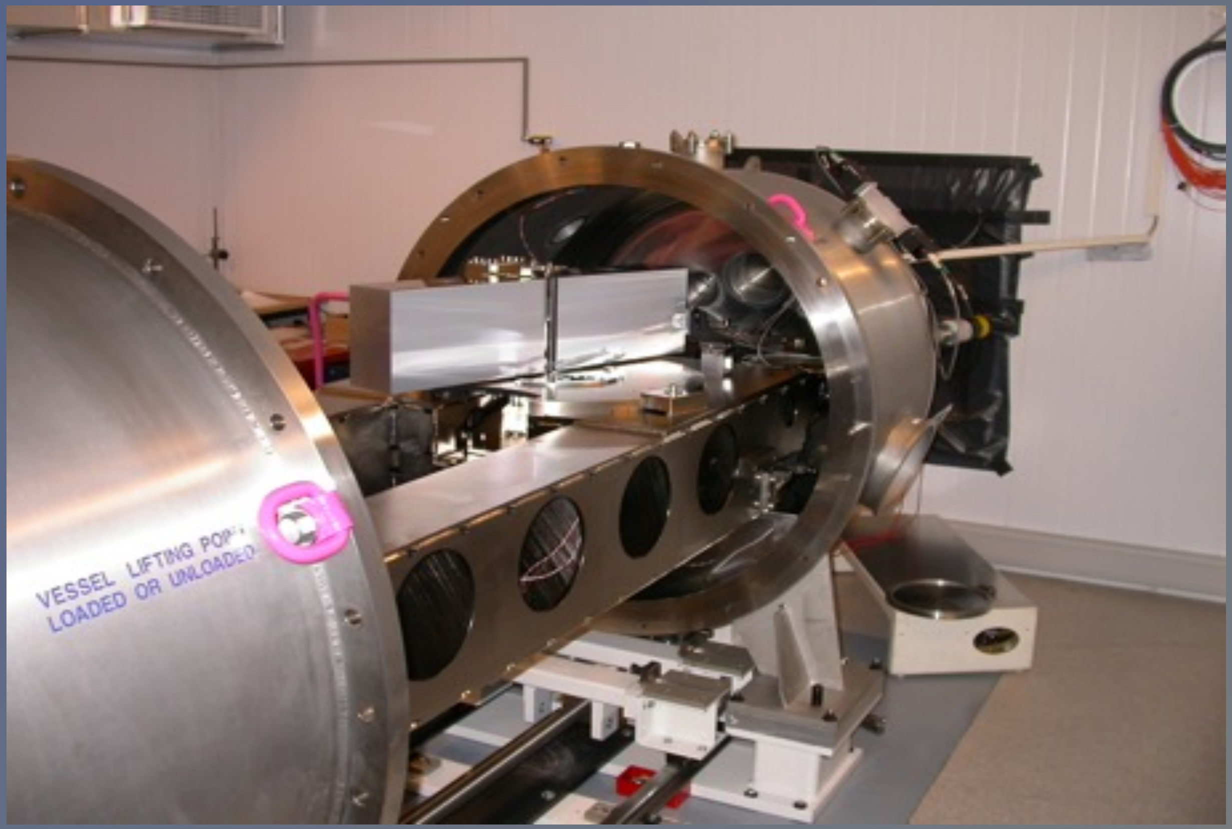
- Sample of ~350 slowly-rotating, nearby solar-type stars, <1m/s precision
- Non active and non evolved stars
- Observations ongoing since 2004
- Focus on low-amplitude RV variations

=> ~ 50% of HARPS GTO time (265 nights)

=> + 280 nights over 4 years (-->2013)

=> + 165 nights over 3 years (2013-->)

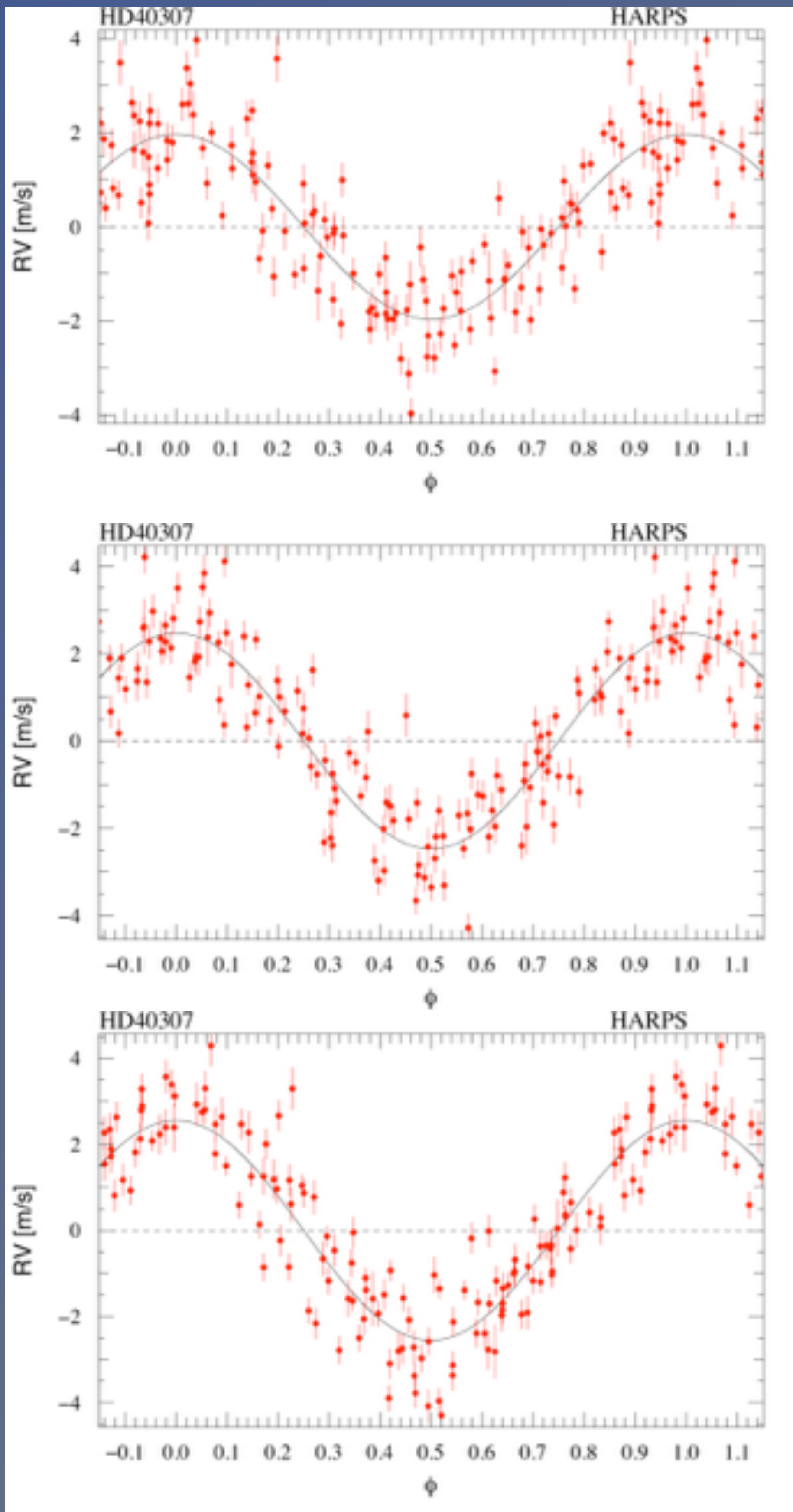
ESO-3.6m @ La Silla



HARPS

An emerging population of Hot Neptunes and Super-Earths

Mayor et al. A&A 2009



P_1 = 4.31 days
e_1 = 0.02
m_1 sini = 4.3 $M_\oplus$

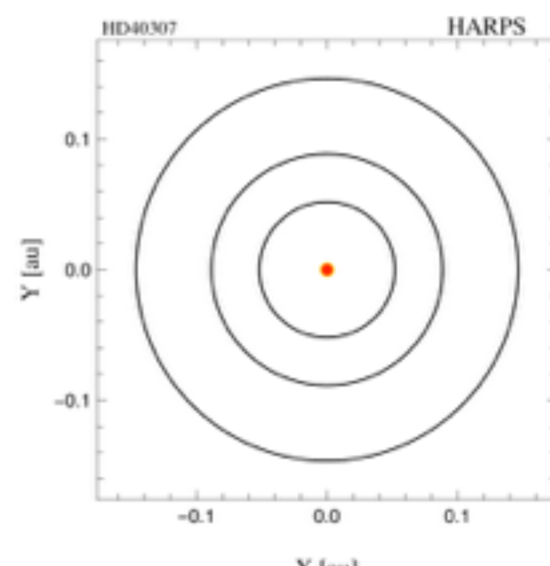
P_2 = 9.62 days
e_2 = 0.03
m_2 sini = 6.9 $M_\oplus$

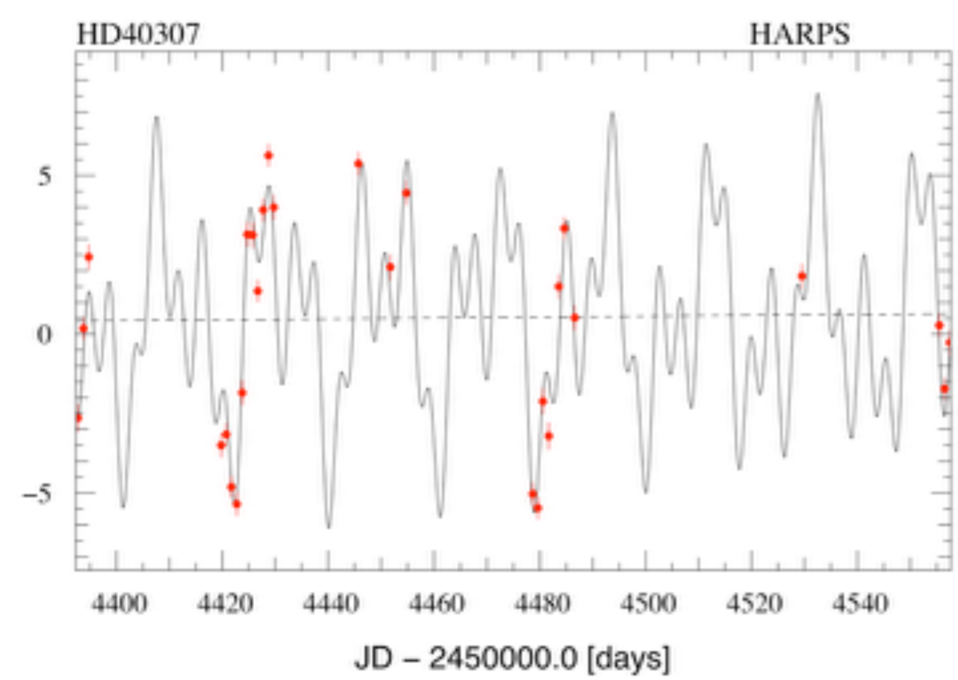
P_3 = 20.5 days
e_3 = 0.04
m_3 sini = 9.7 $M_\oplus$

HD 40307
K2 V
Dist 12.8 pc
[Fe/H] = -0.31

O-C = 0.85 m/s
135 observations

+ drift = 0.5 m/s/y





HD10180 : 7-planet system

P_1 = 1.18 day
e_1 = 0
m_1 sini = 1.5 $M_\oplus$

P_2 = 5.76 days
e_2 = 0.07
m_2 sini = 13.2 $M_\oplus$

P_3 = 16.4 days
e_3 = 0.16
m_3 sini = 11.8 $M_\oplus$

P_4 = 49.7 days
e_4 = 0.06
m_4 sini = 24.8 $M_\oplus$

P_5 = 122.7 days
e_5 = 0.13
m_5 sini = 23.4 $M_\oplus$

P_6 = 595 days
e_6 = 0.0
m_6 sini = 22 $M_\oplus$

P_7 = 2150 days
e_7 = 0.15
m_7 sini = 67 $M_\oplus$

Publi : N_{meas} = 124

Today : N_{meas} = 257

Lovis et al. 2010

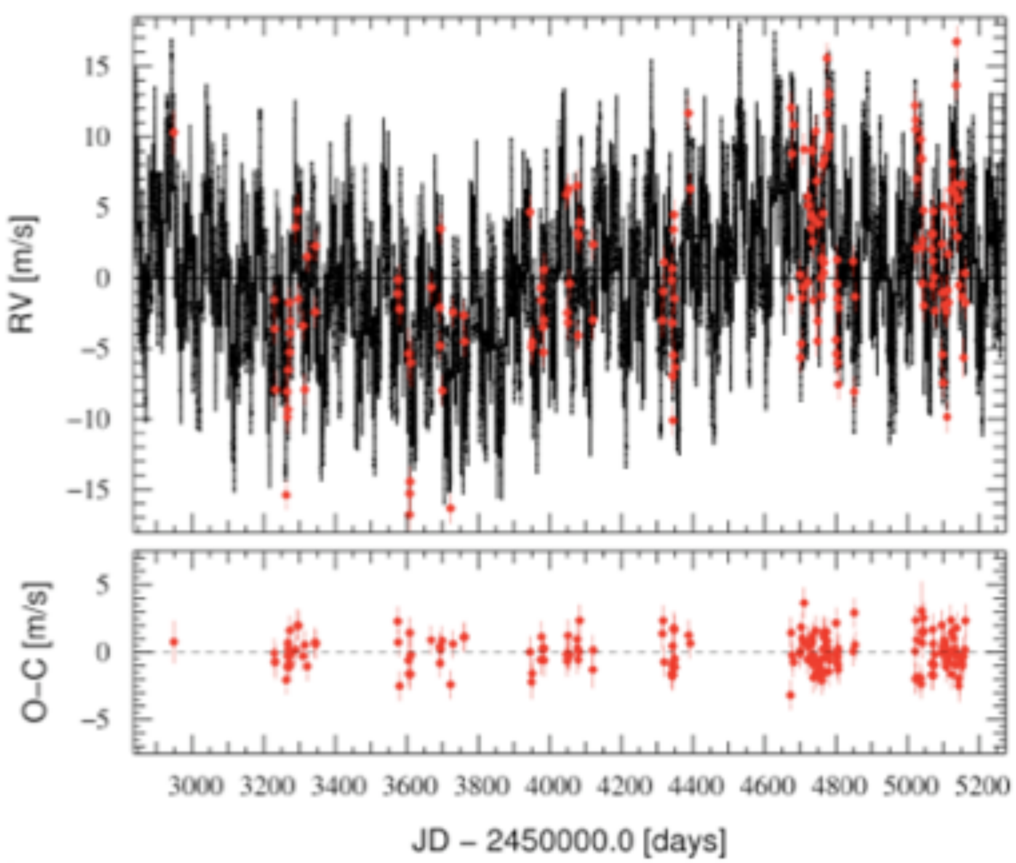
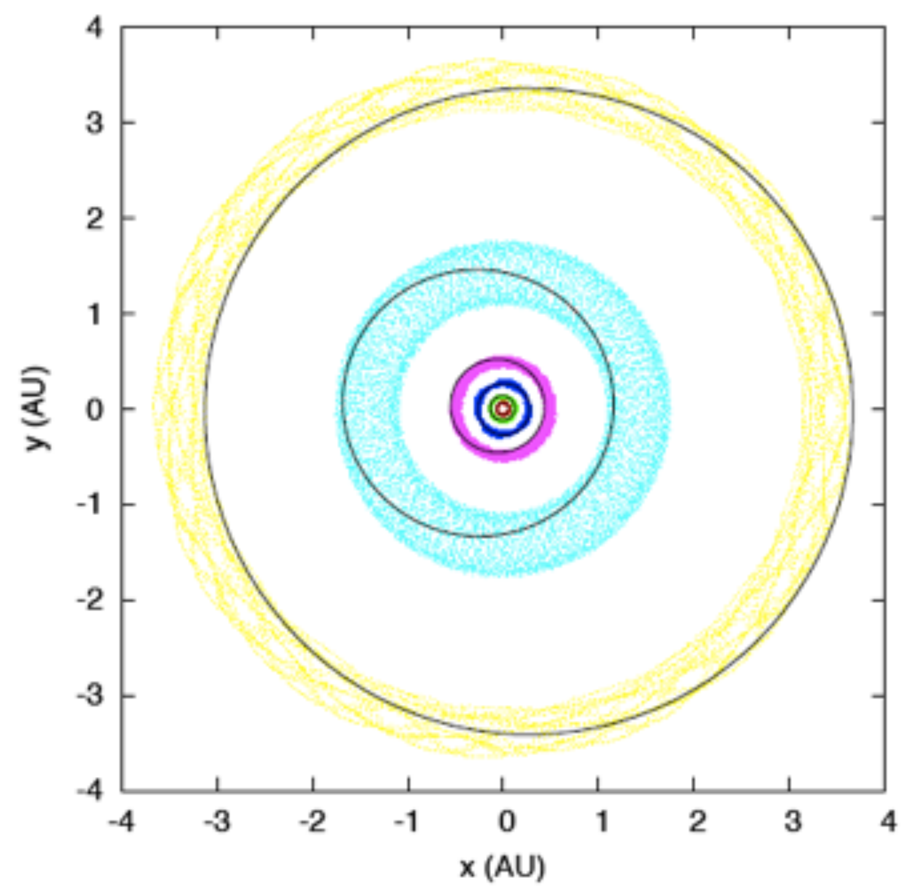
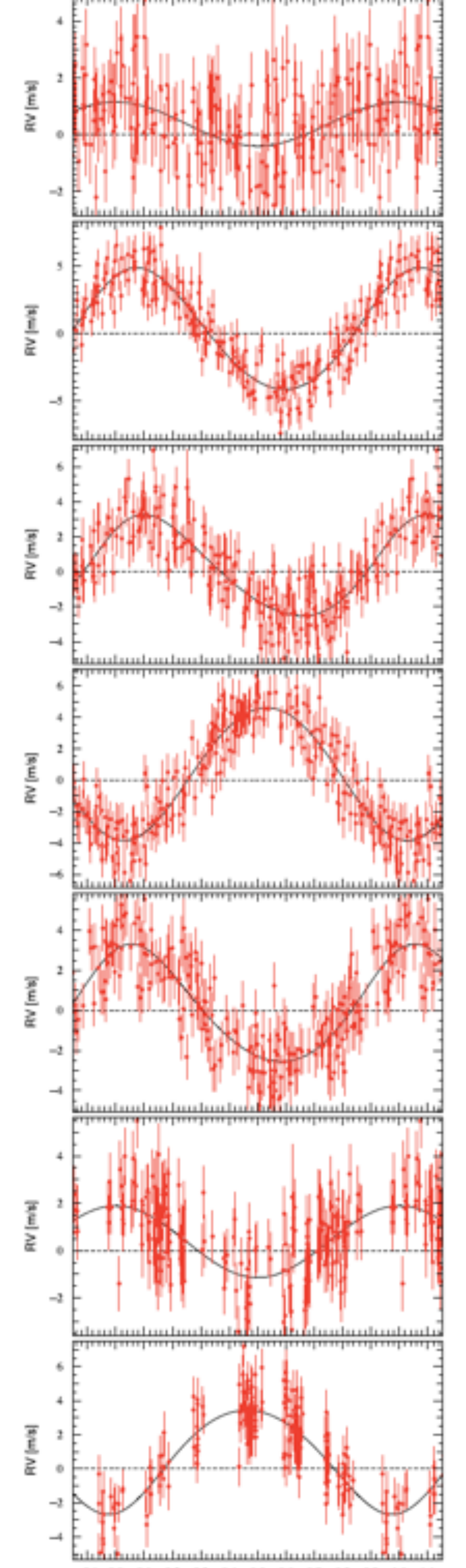


Fig. 5. Radial velocity time series with the 7-Keplerian model overplo





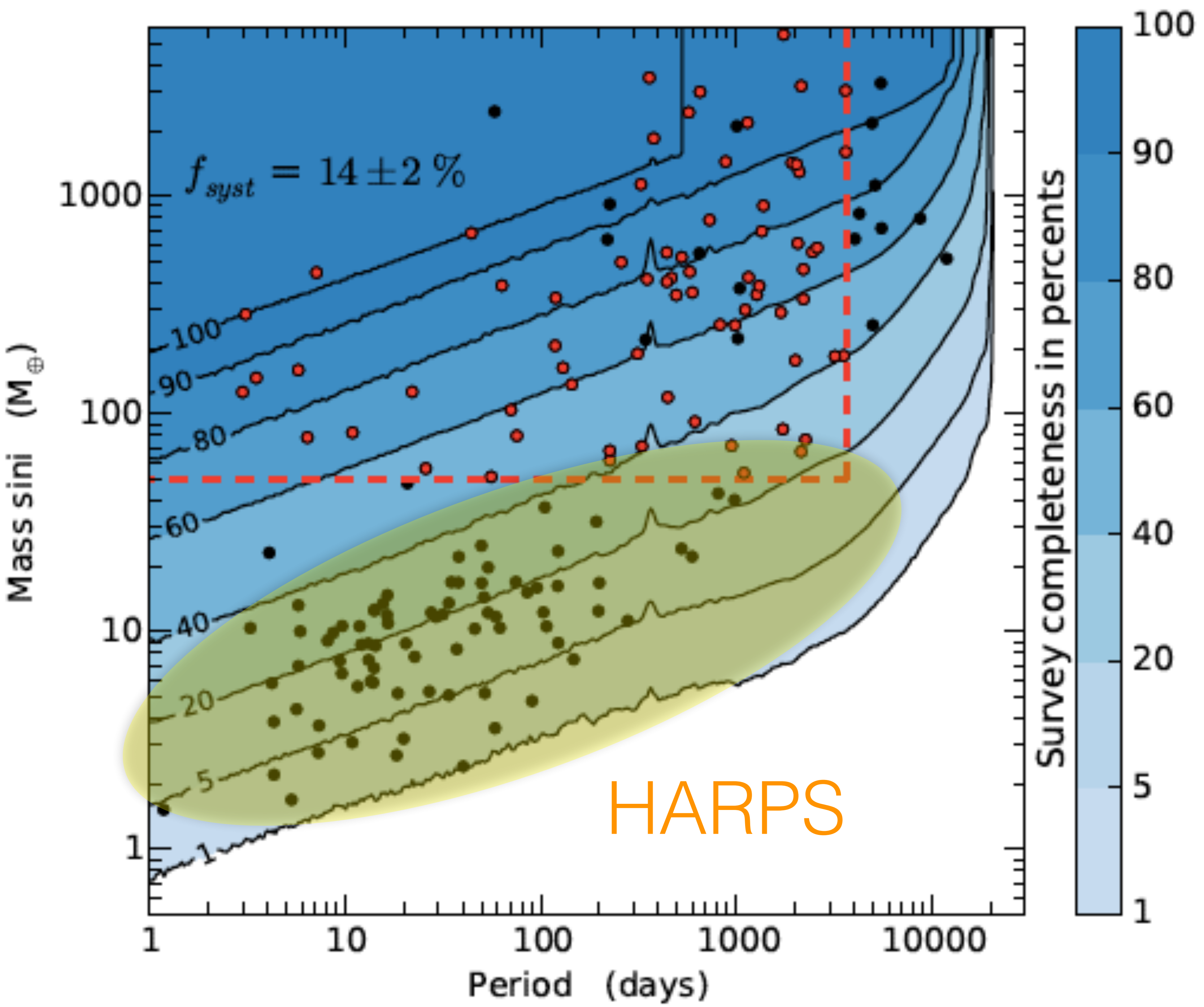


Fig. 5. Plot of the 169 planets of the considered HARPS+CORALIE sample in the $m_2 \sin i - \log P$ plane. The superimposed curves indicate the completeness of the survey. These detection probabilities are valid for the whole sample of 822 stars. After correcting for the detection bias, the fraction of stars with at least one planet more massive than 50 $M_{\oplus}$ and with a period smaller than 10 years is es-

Mayor et al. 2011

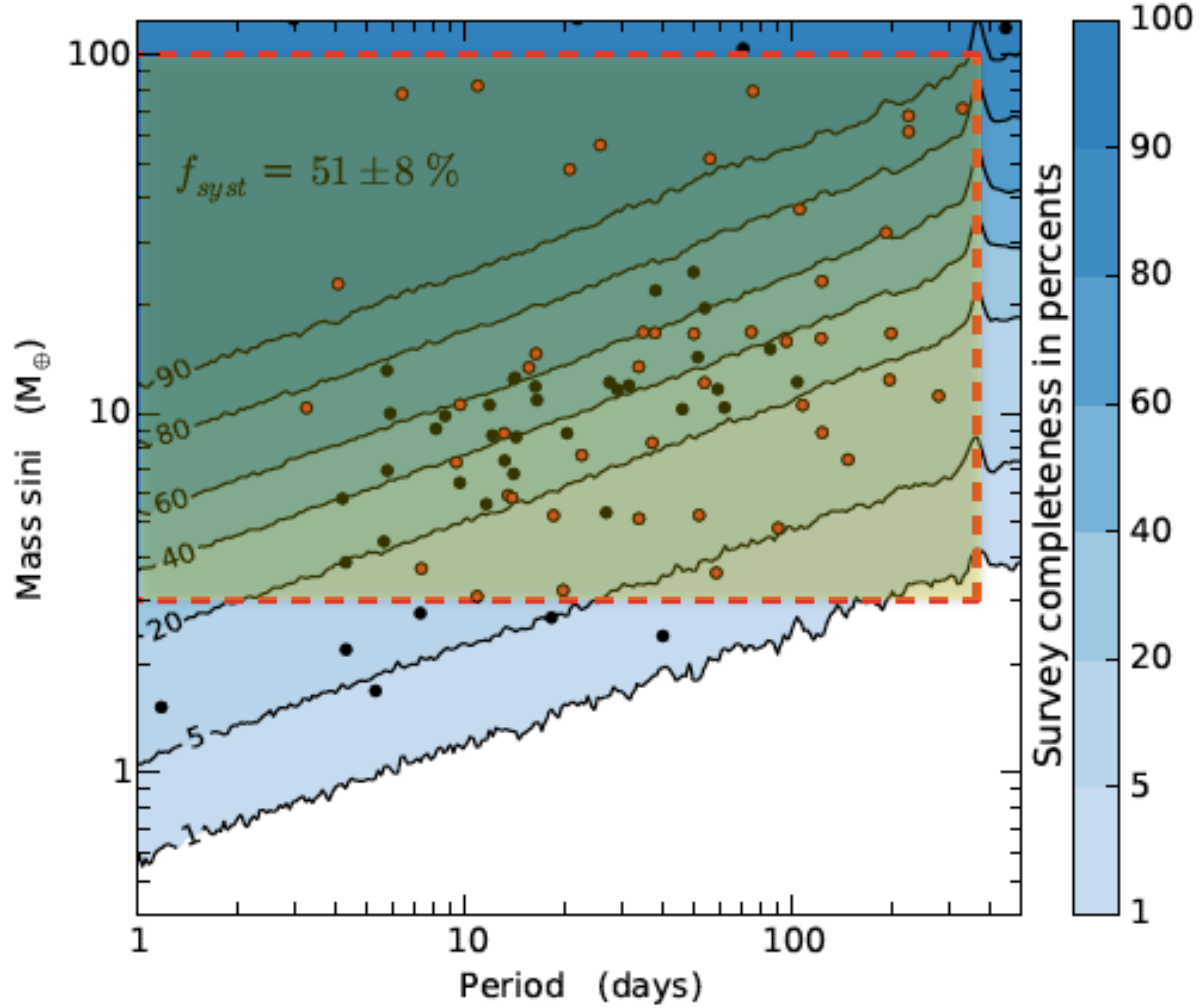


Fig. 6. Same as Fig. 5 but only for the HARPS subsample **of 376 stars.** The occurrence rate of planetary systems in the limited region between 3 and 100 M⊕, and with $P < 1$ year, is 51 ± 8 %. **Again, only one planet per system (represented by the red dots) have been considered for the computation of the occurrence rate.**

Smaller-mass planets

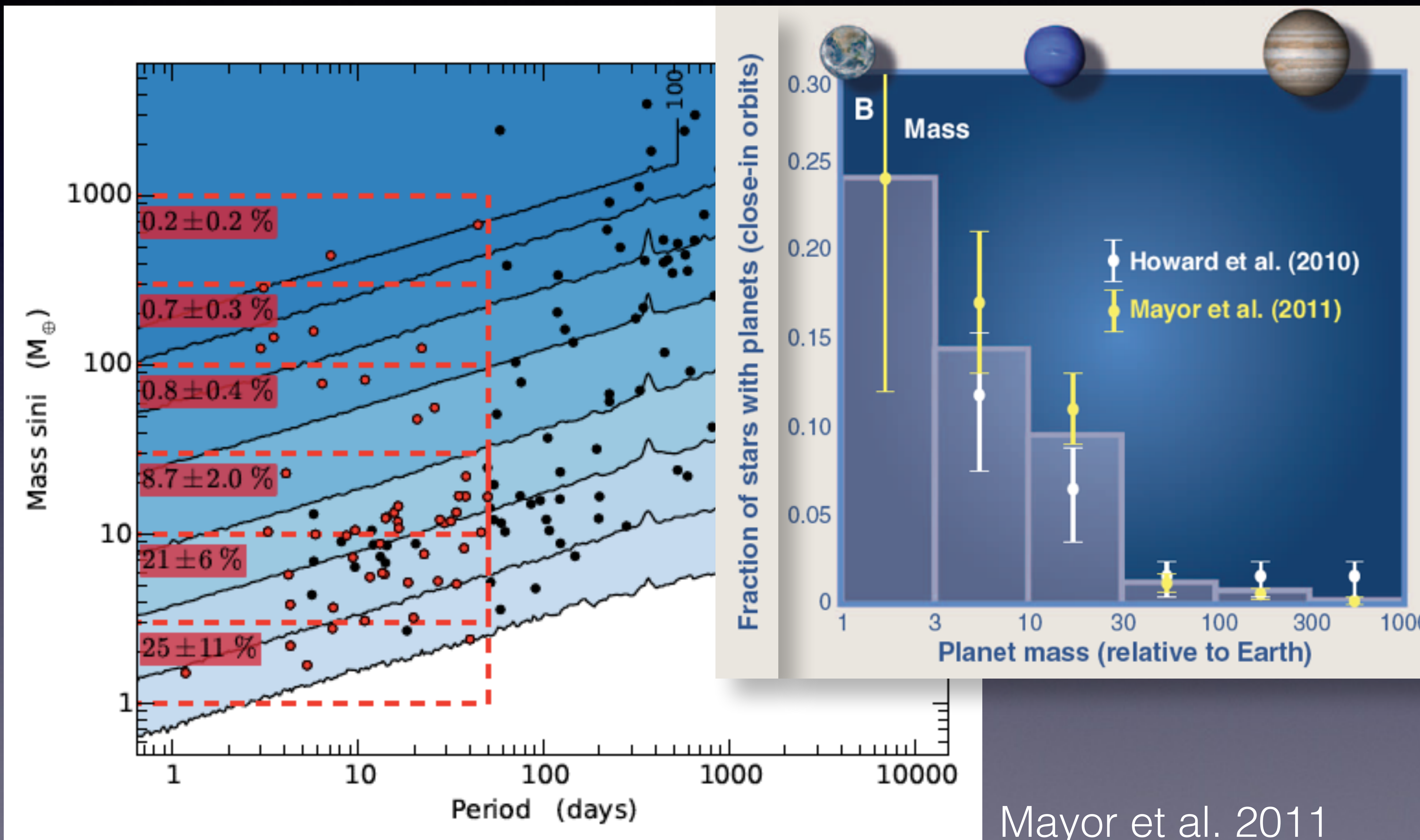
3 < M < 100 M⊕

P < 1yr

f_{syst} = 51 +/- 8 %

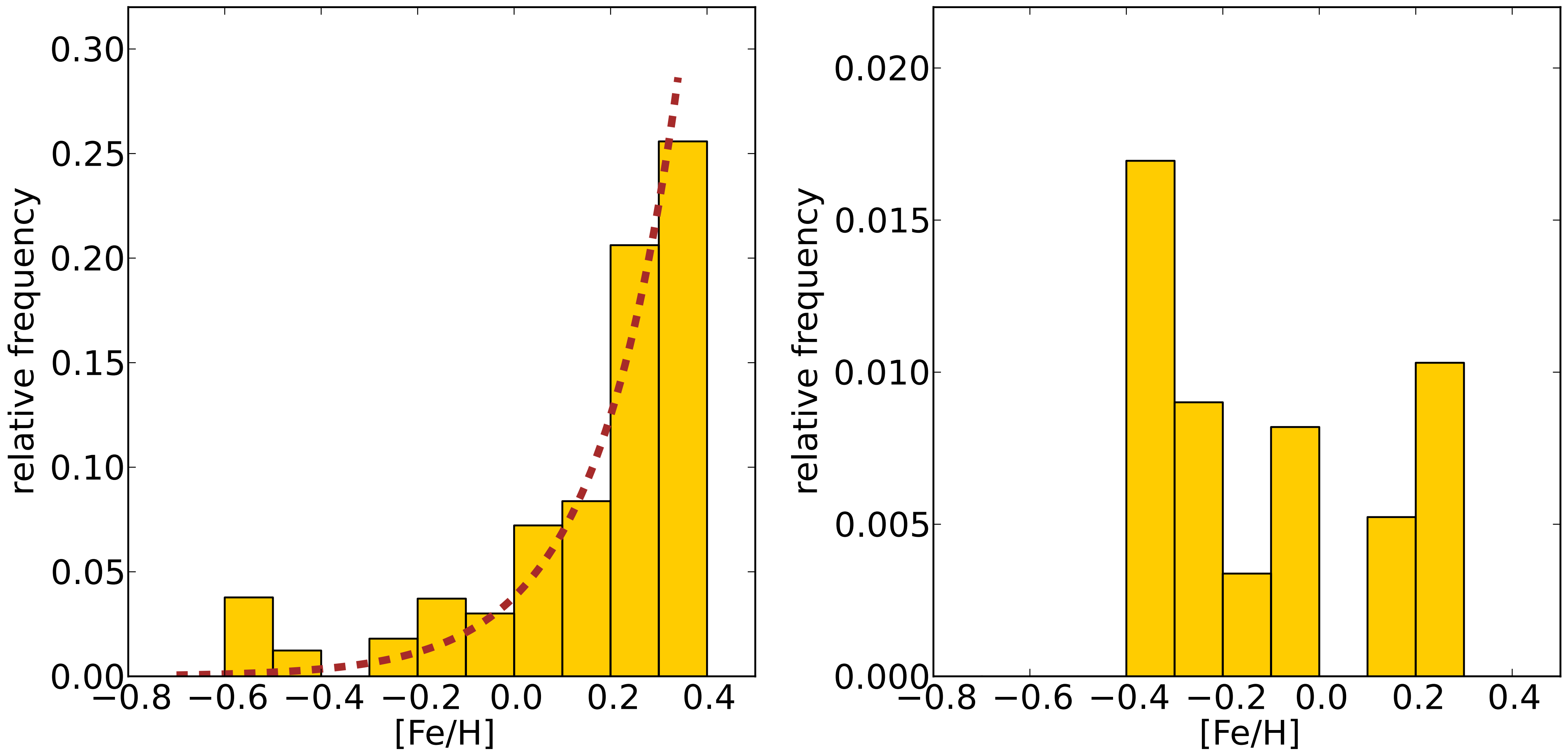
Mayor et al. 2011

Orbital periods < 50 days:
=> increase of f(m) towards low masses

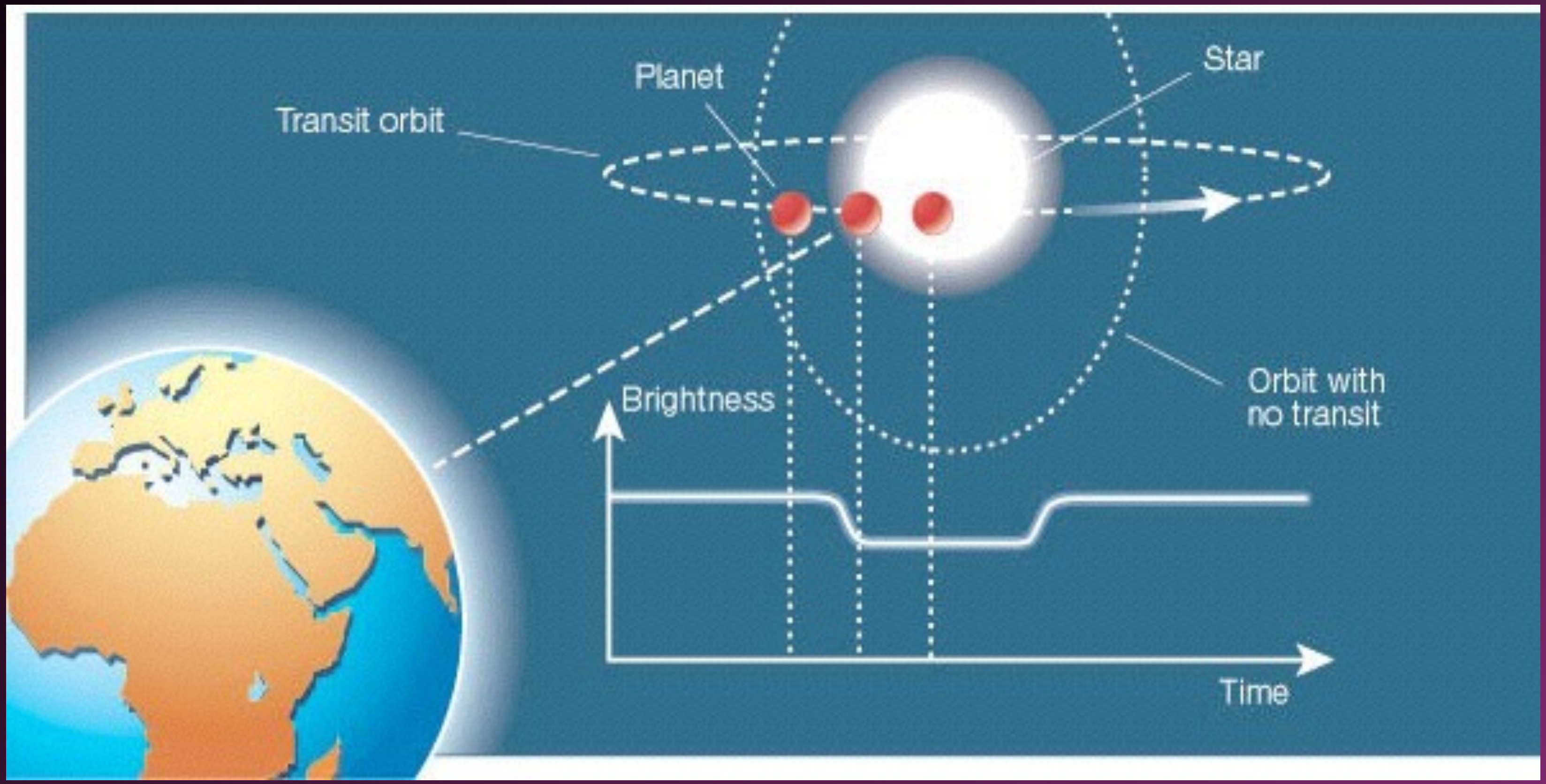


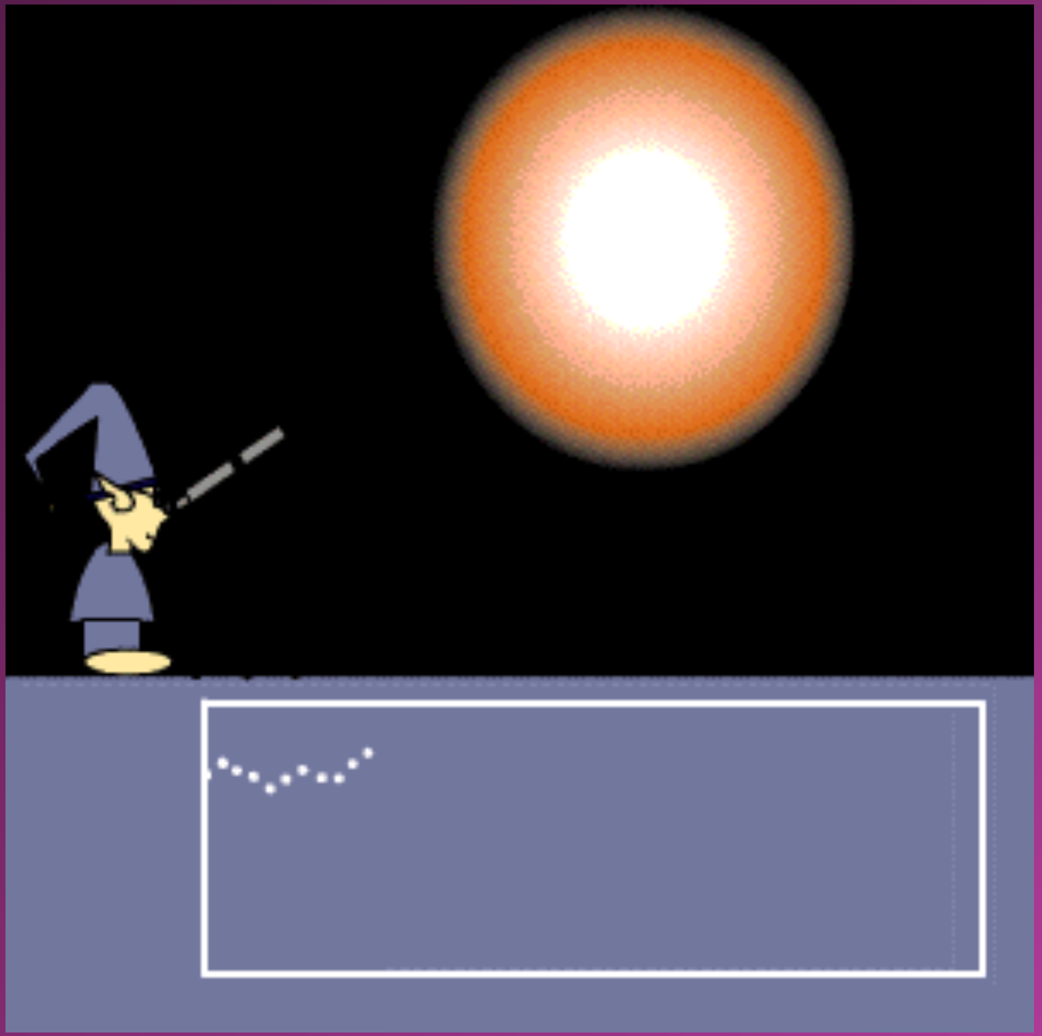
Mayor et al. 2011

A drastic difference of the occurence of planets as a function of stellar metallicity and planetary mass.



Photometric detection of planetary transits



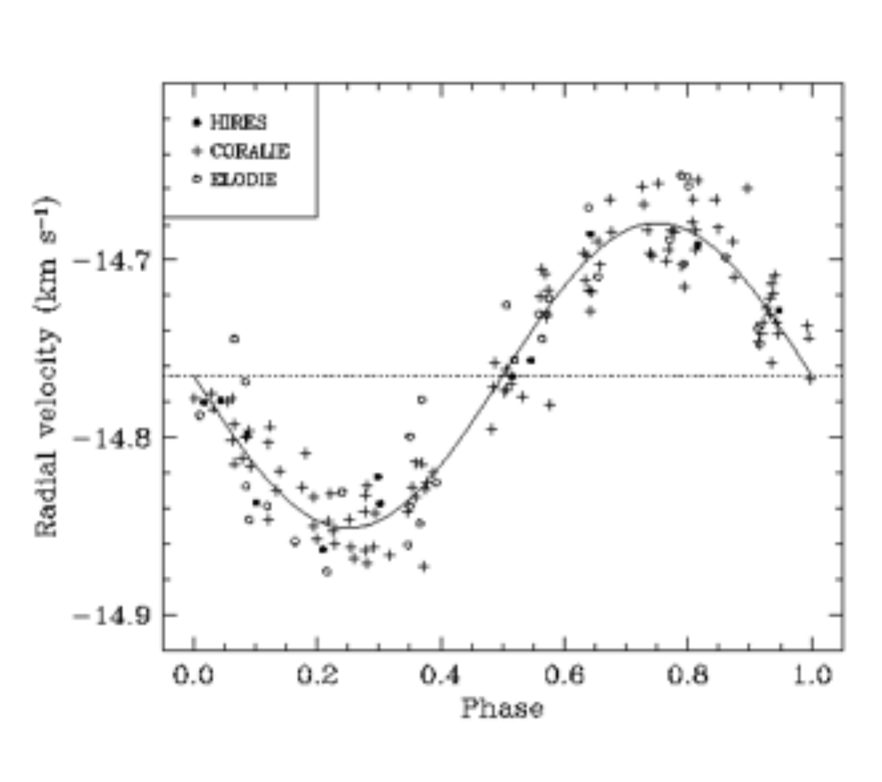


Radius

→ Mass

>> bulk density → Internal composition

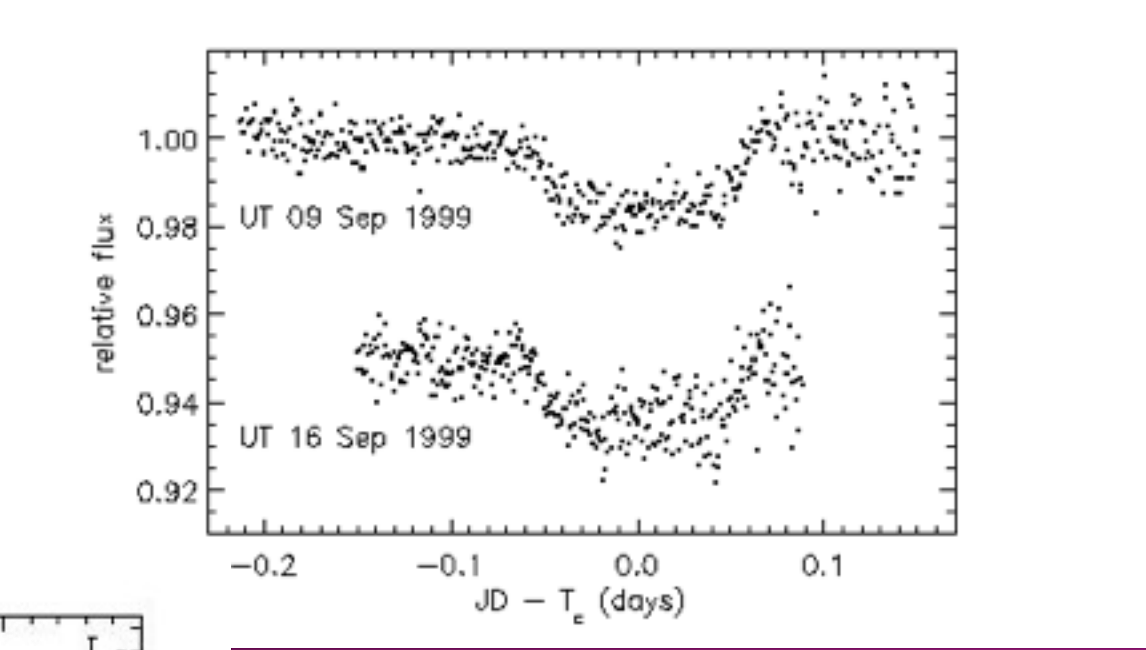
A first planetary transit : HD209458

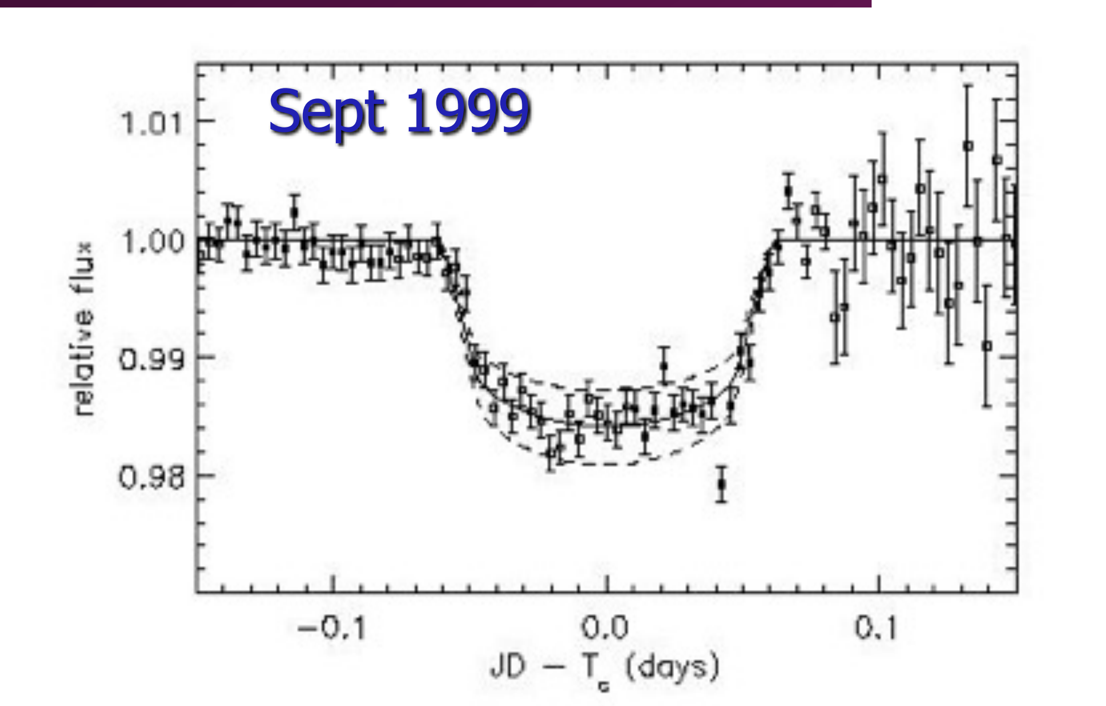


Mazeh et al 1999

P=3.5j

STARE





$R_{pl} = 1.4\ R_{Jup}$

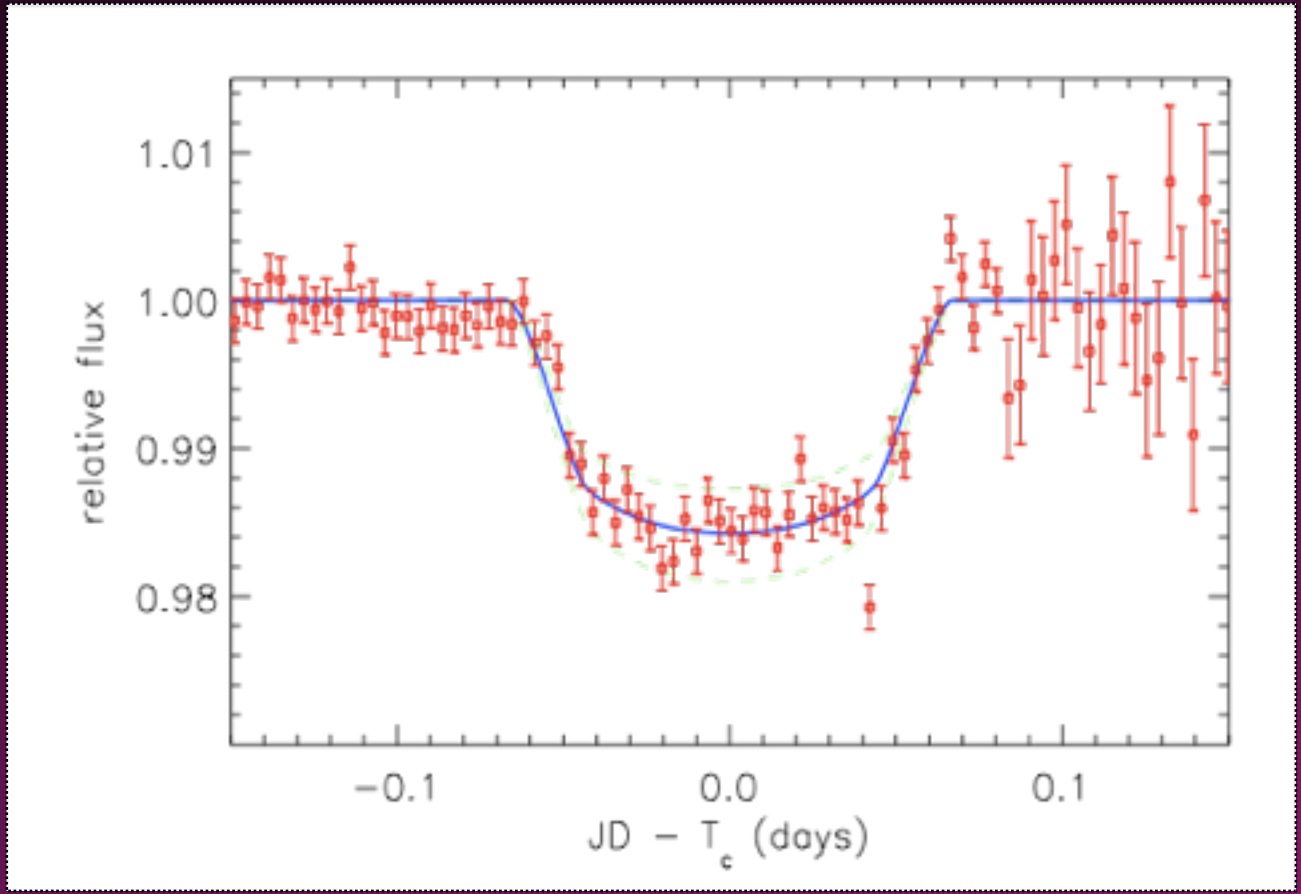
$M_{pl} = 0.69\ M_{Jup}$

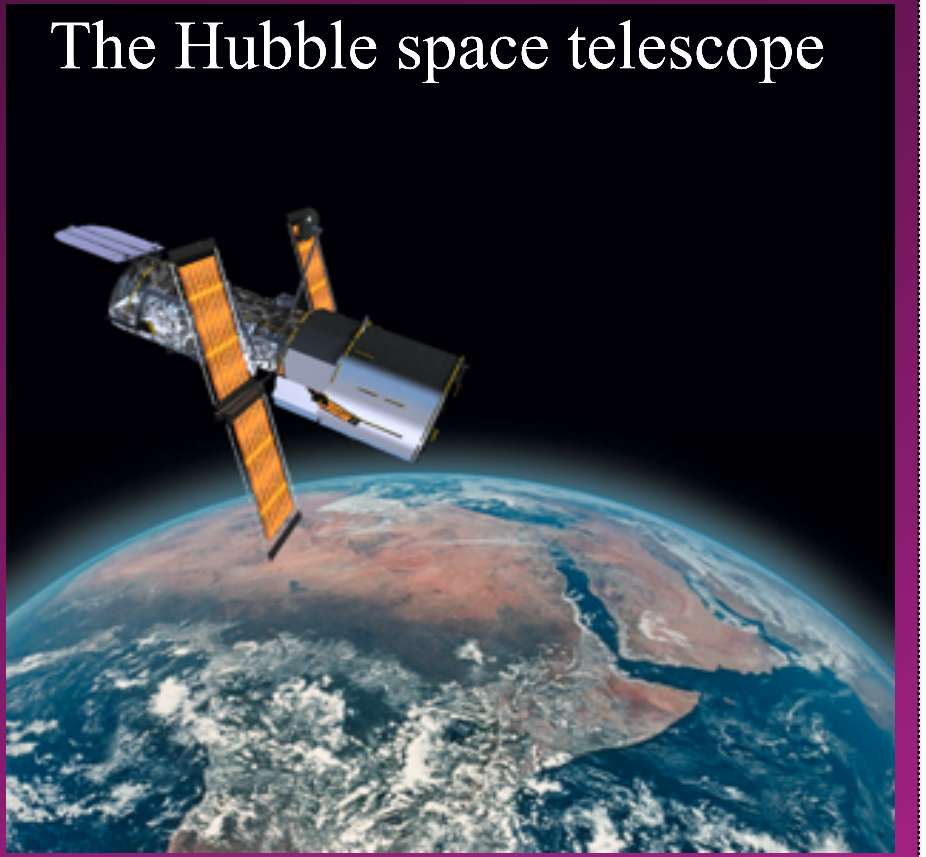
$\rho_{pl} = 0.31\ g/cm^3$

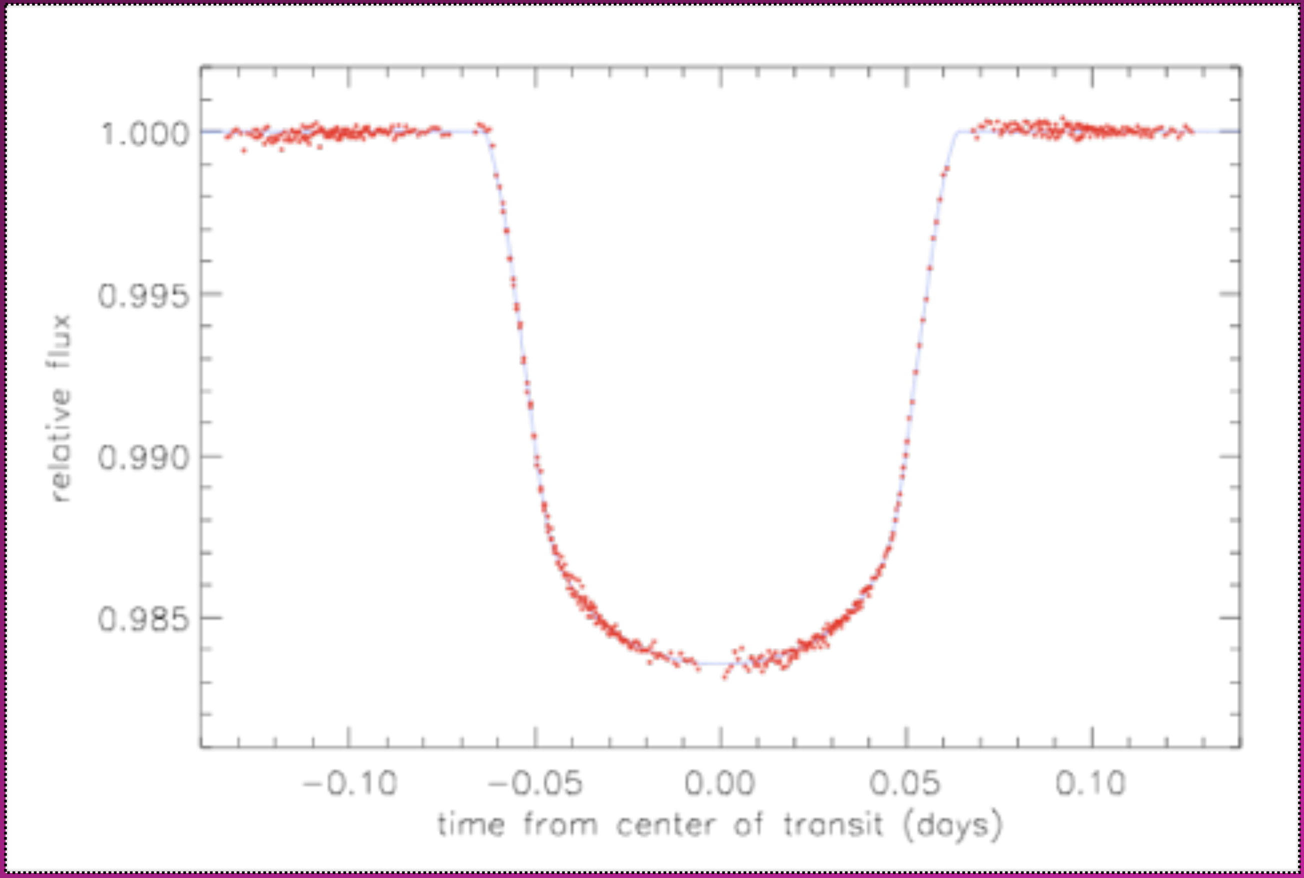
Charbonneau et al 2000

And from space ...

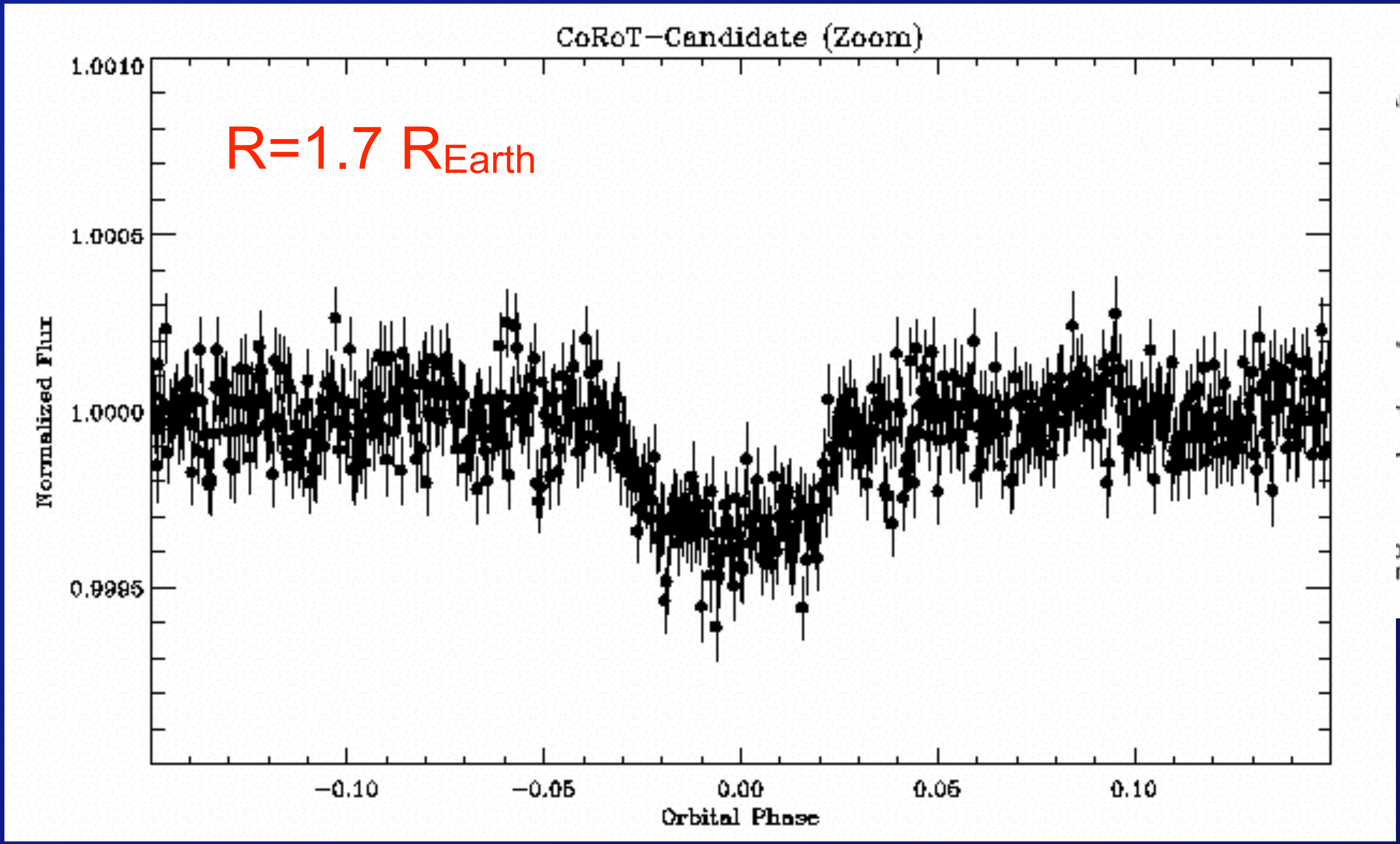
STARE



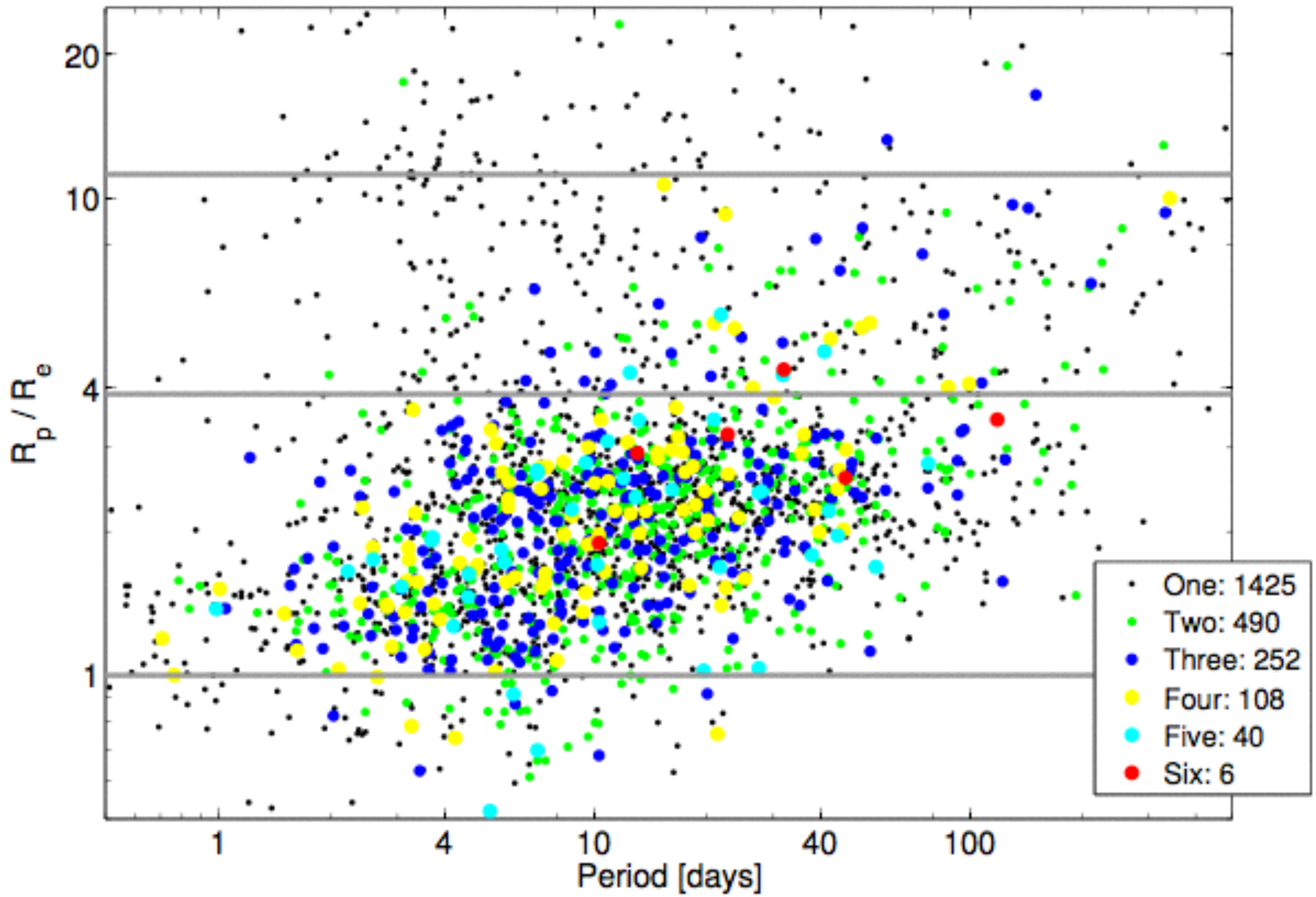


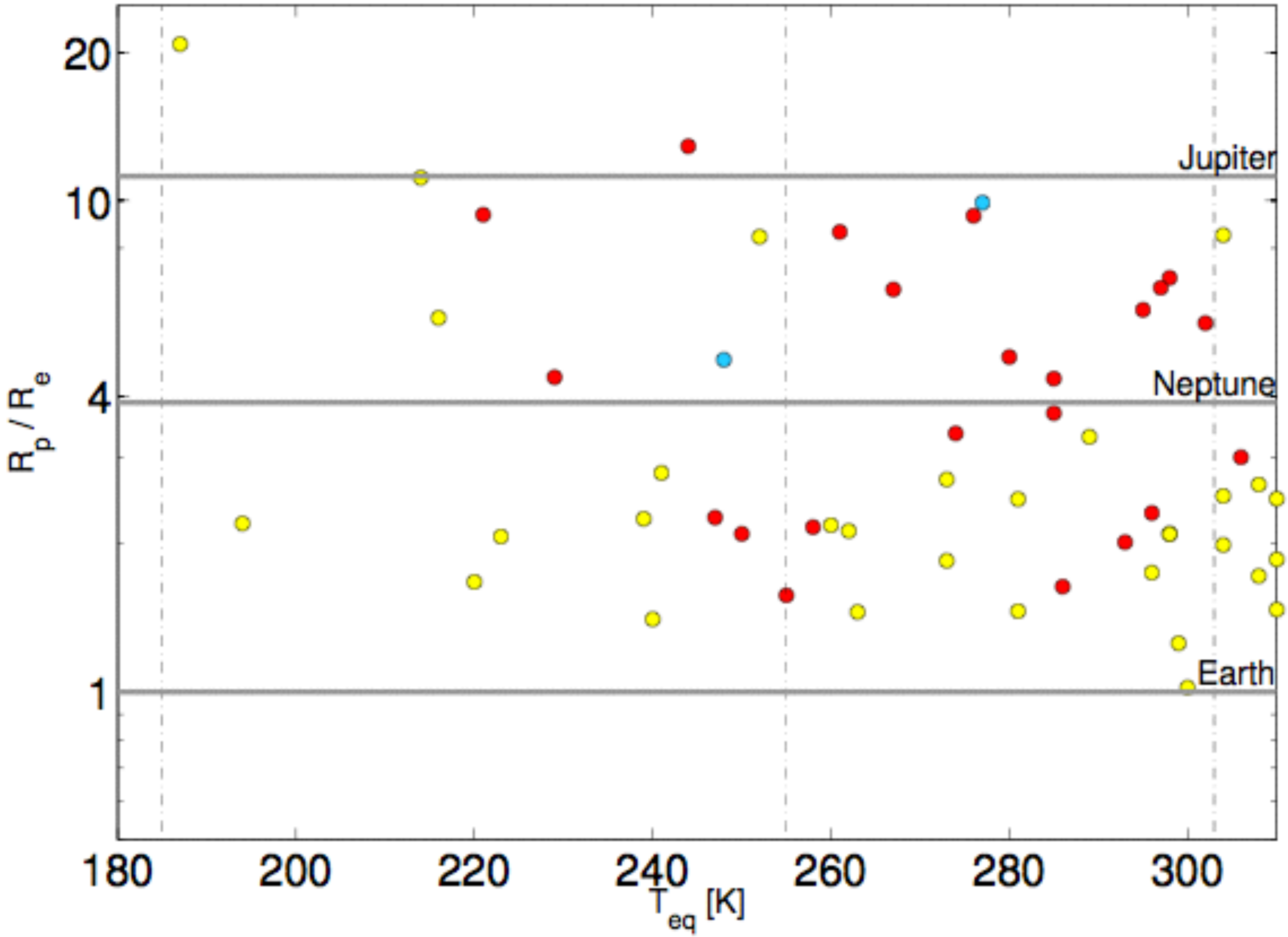


- Gaseous planets : 0.01 mag
- Rocky planets : 0.0001 mag



The Kepler mission





20
10
4
1
Jupiter
Neptune
Earth
R_p / R_e
180
200
220
240
260
280
300
T_{eq} [K]

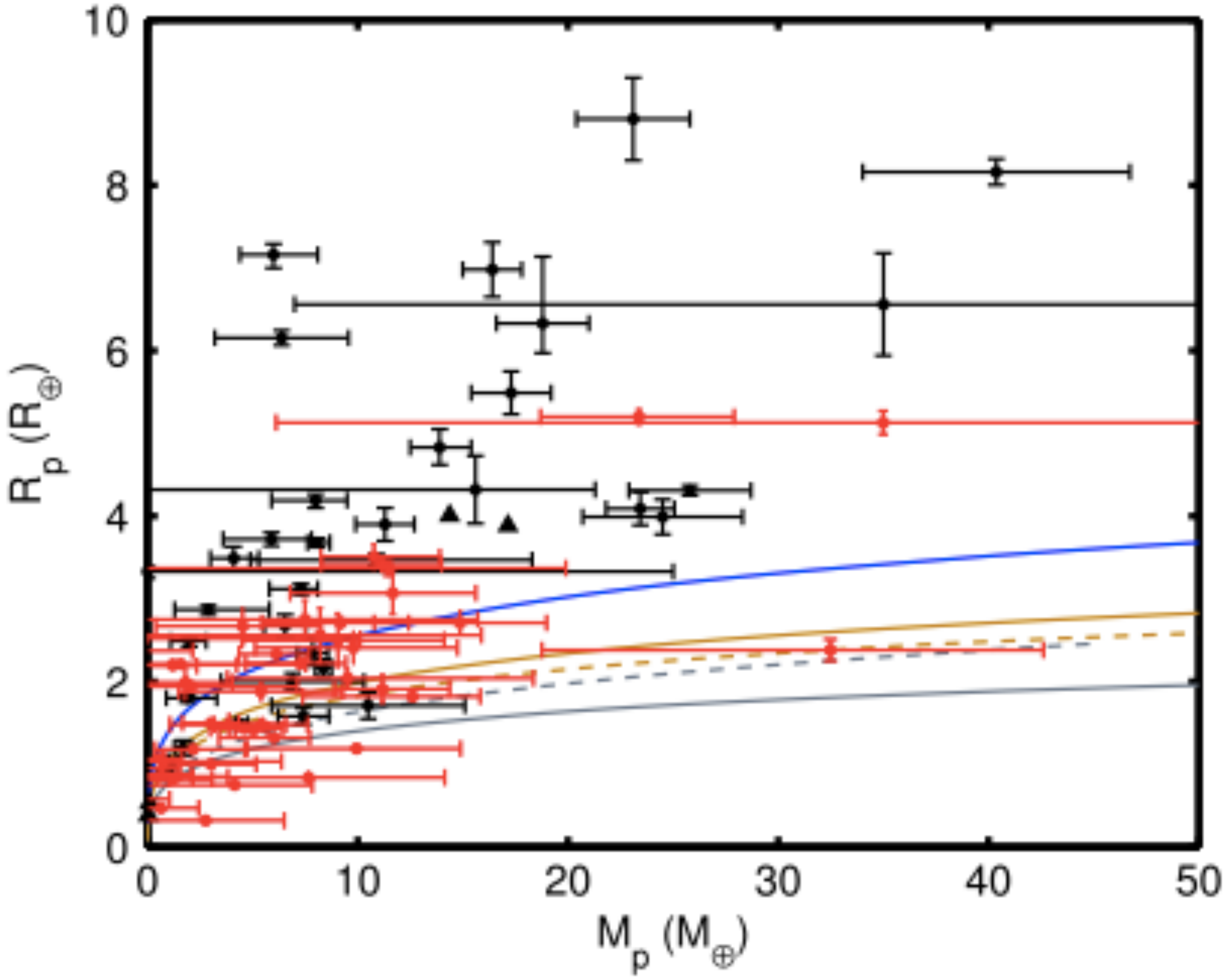
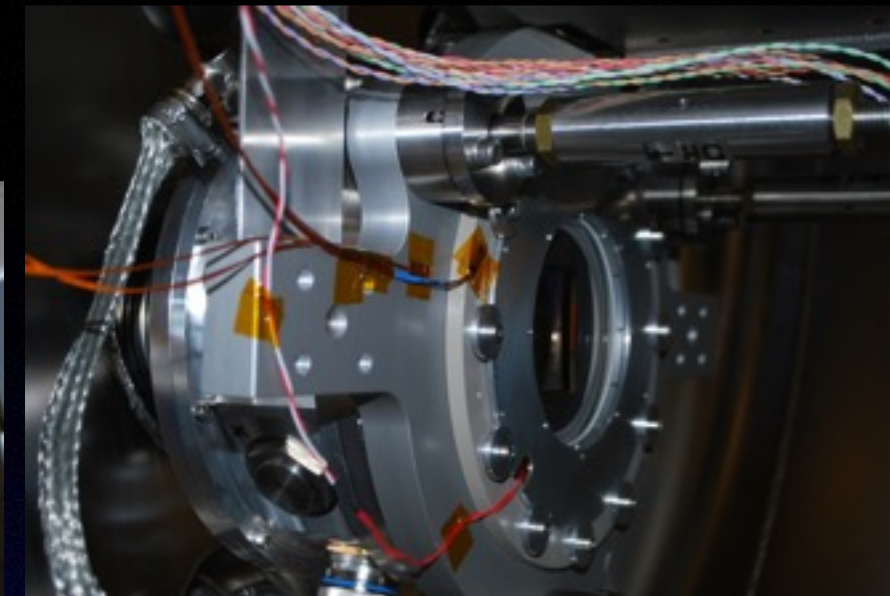
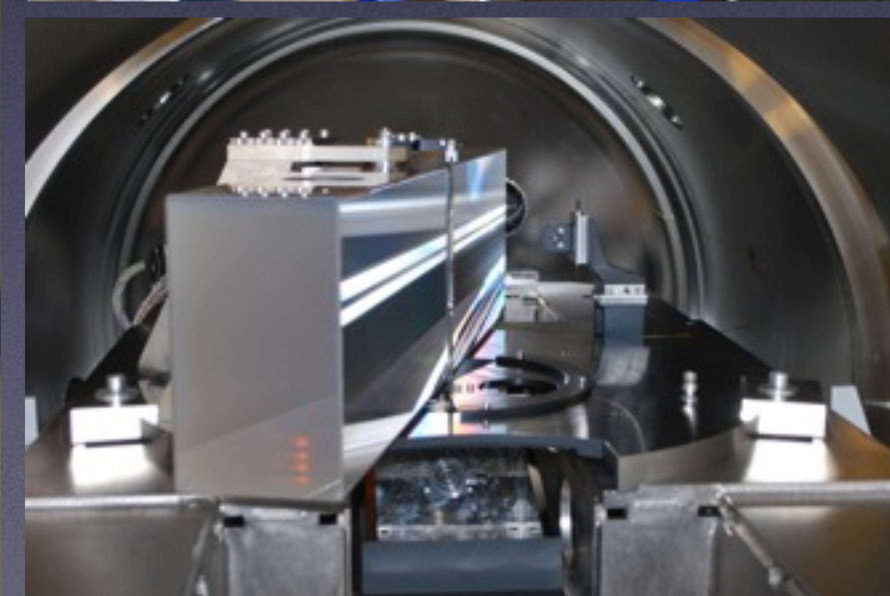


Figure 1. Planet mass–radius diagram. The sample of *Kepler* planets with RV follow-up used in this work are highlighted in red. Other confirmed transiting sub-Neptune-sized planets are indicated with black points, and the solar system planets are indicated with black triangles. The colored curves are theoretical mass–radius relations for constant planet compositions from Seager et al. (2007): pure water ice (solid blue), pure $MgSiO_3$ silicate (solid brown), Earth-like composition (32% Fe, 68% silicate, dashed brown), maximum-density limit for rocky planets from simulations of collisional stripping (Marcus et al. 2010, dashed gray) and pure Fe (solid gray).

HARPS-N La Palma





Two goals :

- Determine the masses of a few transiting planets with small radii … with an uncertainty less than 20%

>>> to have a significant R-M diagram for M< 20 Earth mass

- Search for very low mass planets hosted by very near solar -type stars (< 20 pcs)

HD 219134, Motalebi et al. (2015) A&A 584,72 2015 HARPS-N

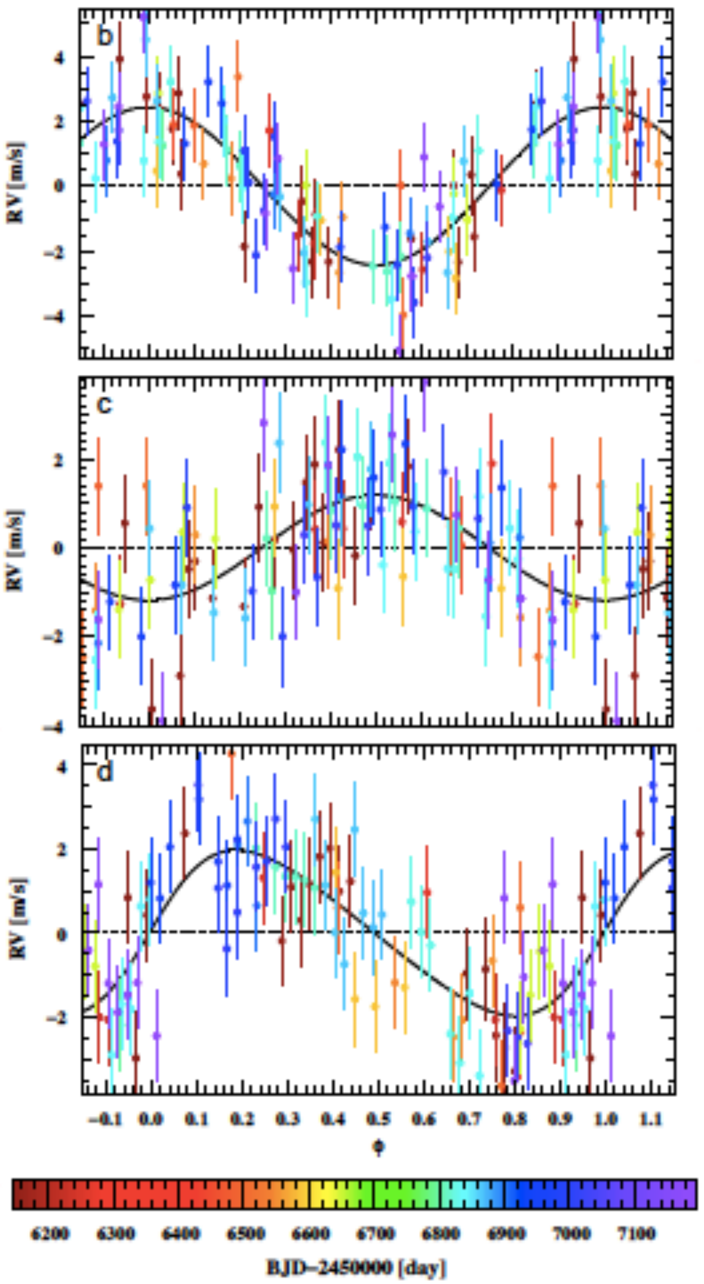


Fig. 4: Phase-folded radial-velocity measurements of HD 219134 with the corresponding Keplerian model (solid line) for each of the 3 inner super-Earths, after removing the contribution of all the other planets in the system. From top to bottom, we have the 3.09-, 6.76-, and 46.78-day periods.

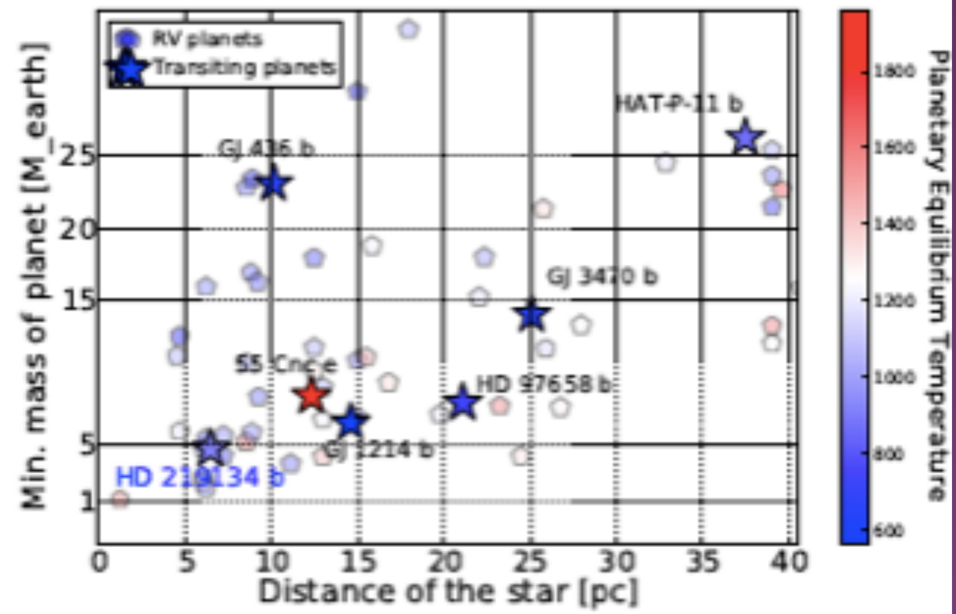


Fig. 12: Planet mass vs distance to the host stars for planets in close neighborhood. Transiting planets with good mass and radius (density) determinations are shown as ★ in this diagram. The planets detected by radial velocity are also shown using the minimum-mass as a proxy for the mass (data taken from www.exoplanets.org).

Model		$K4 + \mathcal{N}\left(0, \sqrt{\sigma_i^2 + s^2}\right)$			
		HD 219134 b	HD 219134 c	HD 219134 d	HD 219134 e
P	[days]	3.0937 ± 0.0004	6.765 ± 0.005	46.78 ± 0.16	1190^{+379}_{-34}
K	[m/s]	2.33 ± 0.24	1.09 ± 0.26	1.94 ± 0.29	4.46 ± 0.52
λ_0	[deg]	82 ± 8	295 ± 20	98 ± 16	206^{+3}_{-45}
T_t	[BJD-2400000]	57126.7001 ± 0.001	57129.46 ± 0.45		
$\sqrt{e}.\cos(\omega)$		0.05 ± 0.19	0.17 ± 0.26	-0.43 ± 0.18	0.21 ± 0.23
$\sqrt{e}.\sin(\omega)$		-0.11 ± 0.21	-0.03 ± 0.31	0.03 ± 0.21	-0.35 ± 0.24
e		$0.00^{+0.13}_{-0.00}$	$0.00^{+0.26}_{-0.00}$	0.32 ± 0.14	0.27 ± 0.11
ω		undefined	undefined	143 ± 33	288 ± 45
$m_{pl} \sin i$	[$M_\oplus$]	4.46 ± 0.47	2.67 ± 0.59	8.67 ± 1.14	62 ± 6
a	[AU]	0.0382 ± 0.0003	0.064 ± 0.001	0.234 ± 0.002	$2.14^{+0.43}_{-0.02}$
γ		-18.4203 kms^{-1} ± 0.6 ms^{-1}			
N_{meas}		98			
s	[m/s]	1.18 ± 0.06			

Table 5: Orbital solution for the 4 Keplerian model (K4) and planet inferred parameters for the system around HD 219134. T_t is the expected date of transit. λ_0 is the mean longitude at the time 2457126.7001 day, corresponding to the transit timing (see Sect. 5)

After the discovery with HARPS-N of the planetary system hosted by HD 219134, a search for a possible transit has been done with the Spitzer satellite.

The transit detected from space:
contrast : 356 ppm !

The closest transiting rocky planet
at a distance of 6.5 pcs

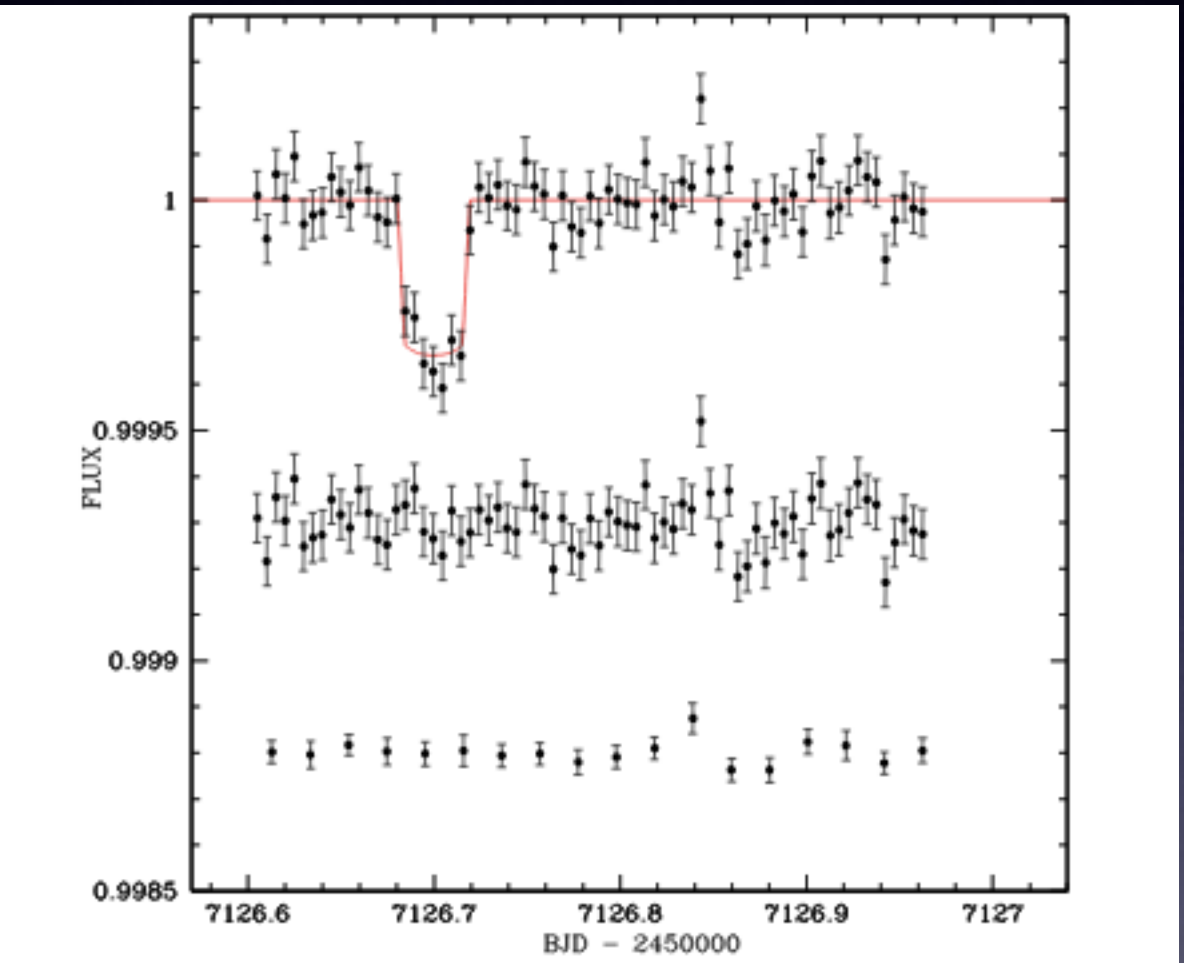


Fig. 11: *Spitzer* photometry divided by the best-fit baseline model and binned per 0.005d = 7.2min, with the best-fit transit model over-imposed in red. Below are shown the *y*-shifted residuals of the fit binned per 7.2 min and 30 min intervals. Their standard deviations are, respectively, 57 ppm and 25 ppm. Over the

 (Rogers,L).

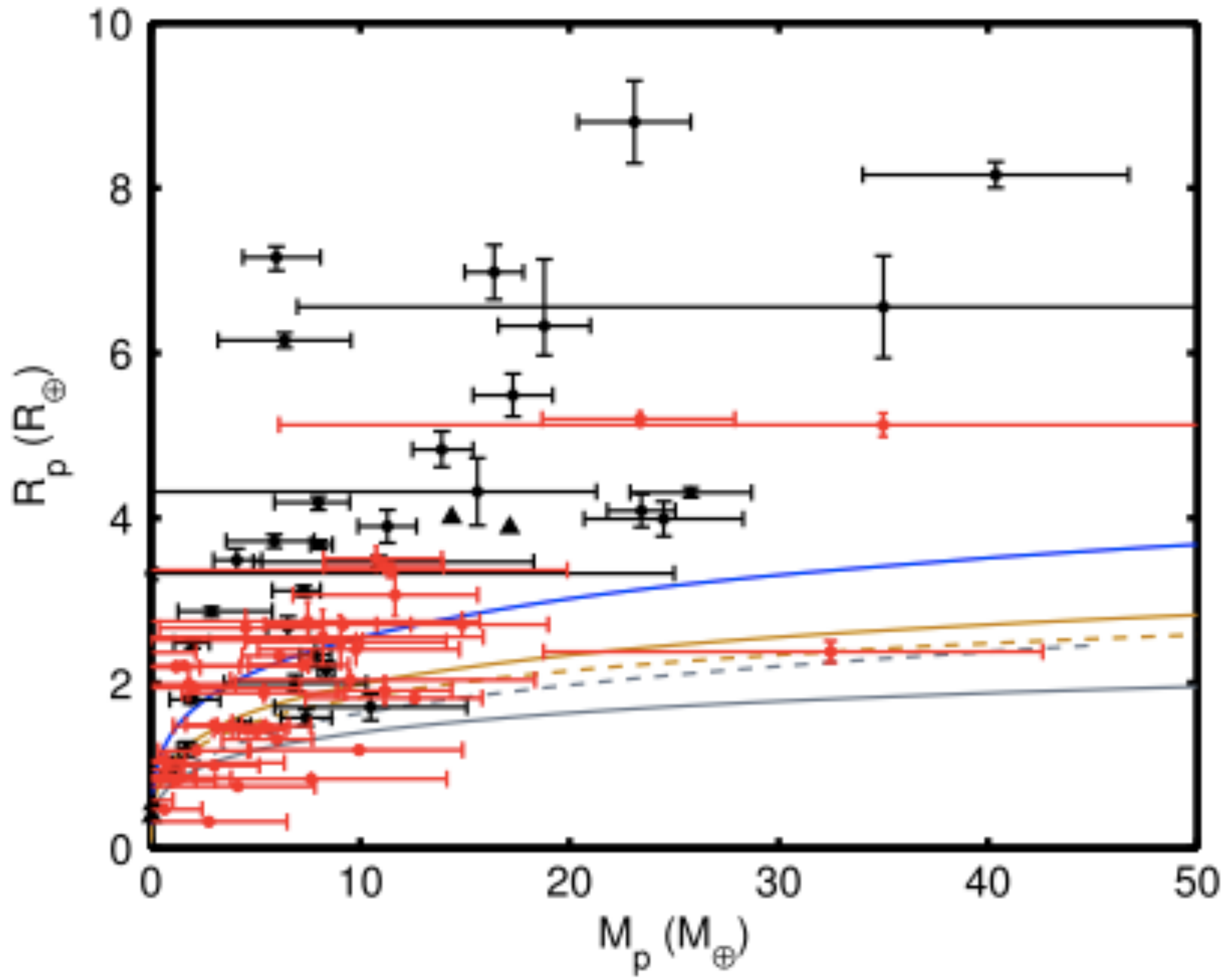
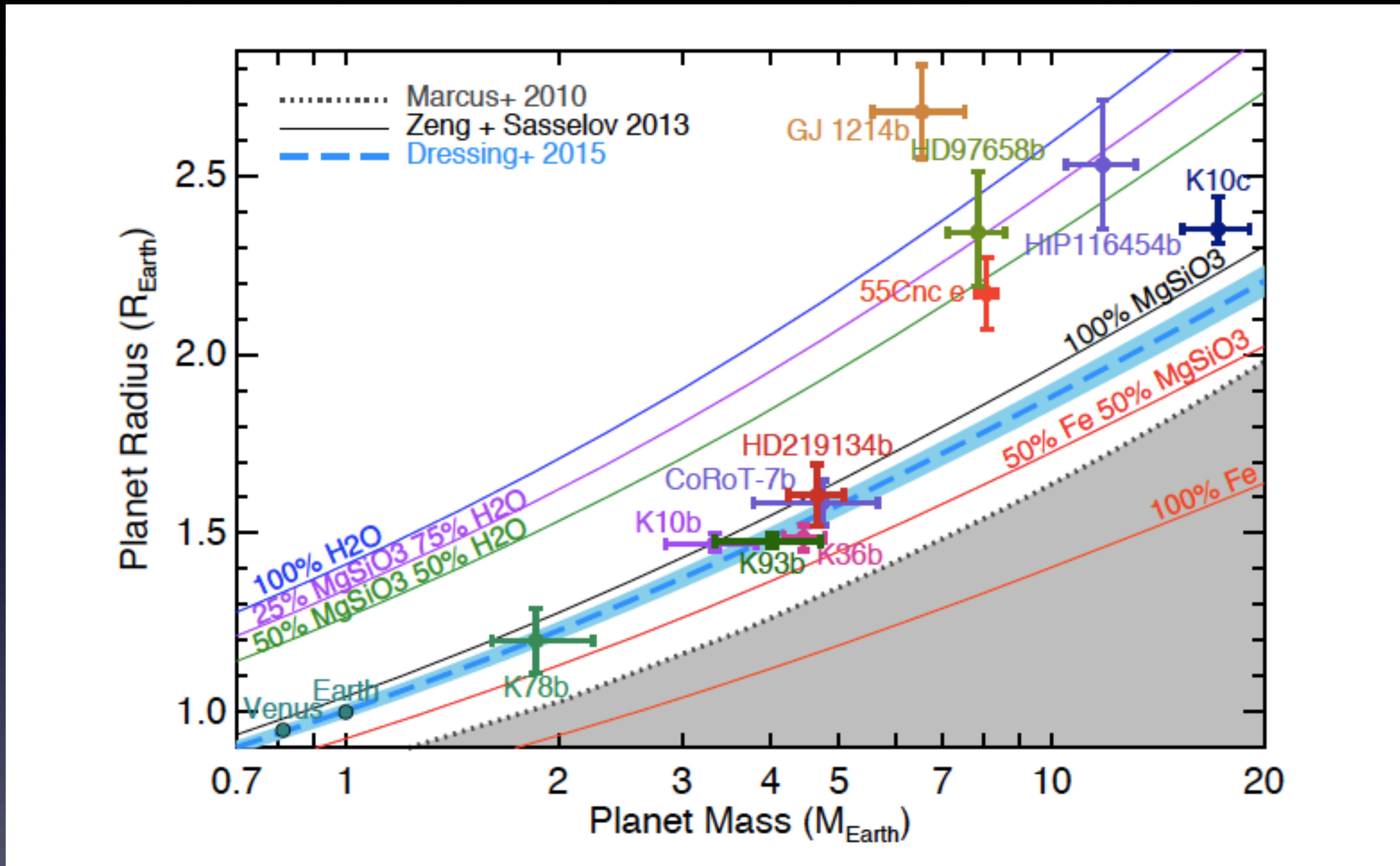
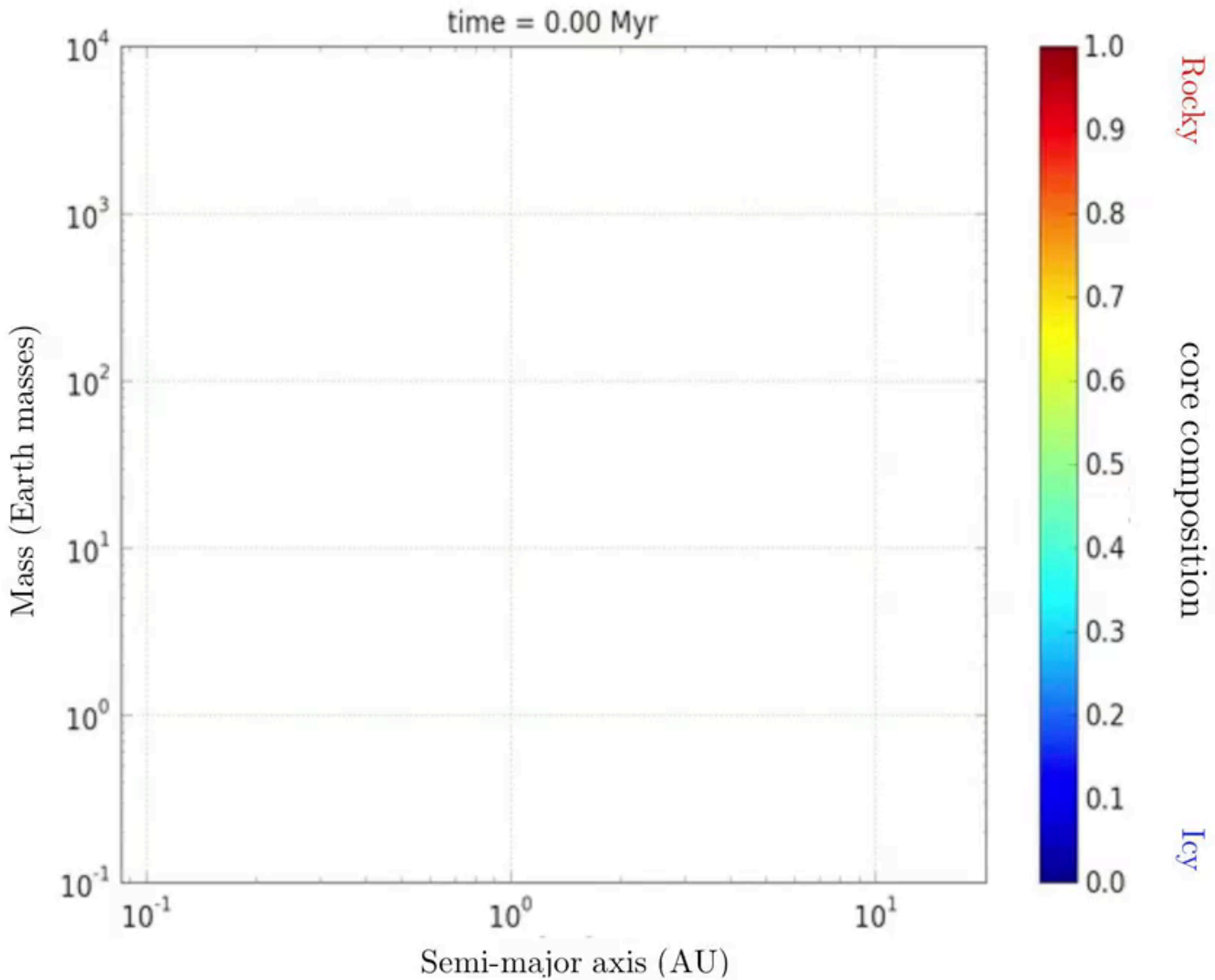


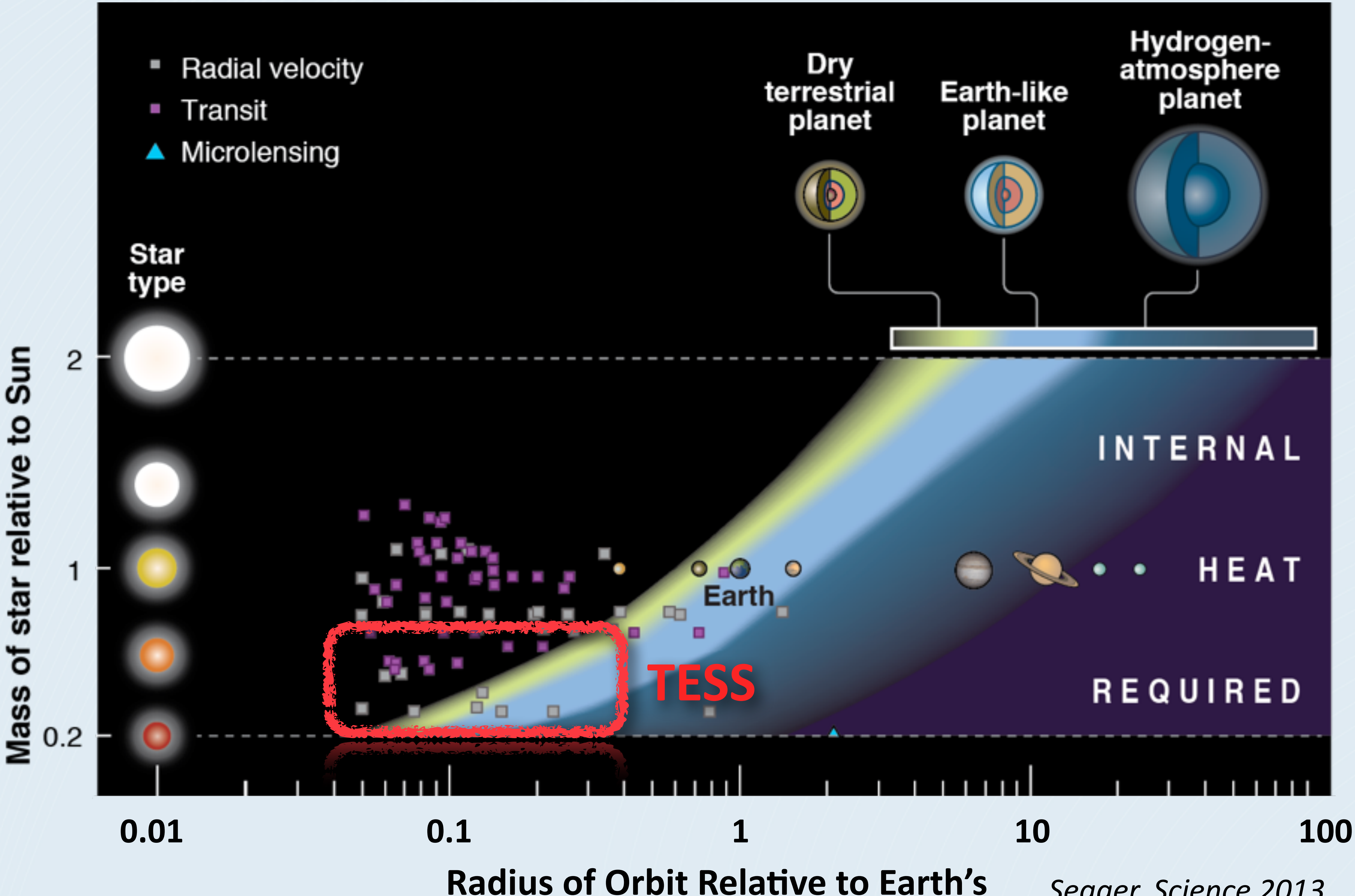
Figure 1. Planet mass–radius diagram. The sample of *Kepler* planets with RV follow-up used in this work are highlighted in red. Other confirmed transiting sub-Neptune-sized planets are indicated with black points, and the solar system planets are indicated with black triangles. The colored curves are theoretical mass–radius relations for constant planet compositions from Seager et al. (2007): pure water ice (solid blue), pure $MgSiO_3$ silicate (solid brown), Earth-like composition (32% Fe, 68% silicate, dashed brown), maximum-density limit for rocky planets from simulations of collisional stripping (Marcus et al. 2010, dashed gray) and pure Fe (solid gray).



Motalebi et al. 2015


time = 0.00 Myr
Mass (Earth masses)
10^4
10^3
10^2
10^1
10^0
10^{-1}
10^{-1}
10^0
10^1
Semi-major axis (AU)
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
Rocky
core composition
Icy

The Habitable Zone



Seager, Science 2013

Habitability of Terrestrial-Mass Planets in the HZ of M Dwarfs. I. H/He-Dominated Atmospheres

James E. Owen, Subhanjoy Mohanty

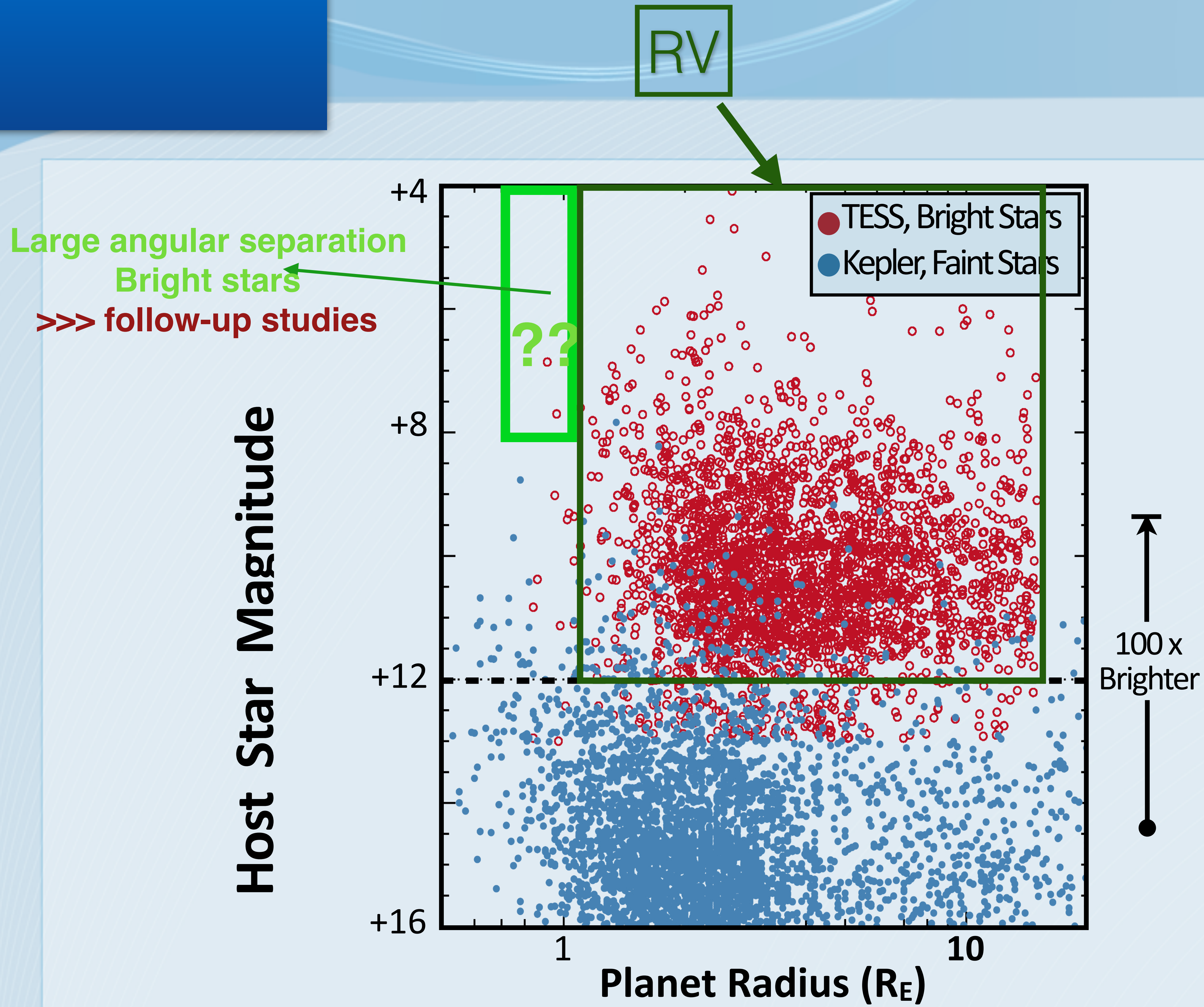
arXiv :1601.051431.0

(Submitted on 20 Jan 2016)

The ubiquity of M dwarfs, combined with the relative ease of detecting terrestrial-mass planets around them, has made them prime targets for finding and characterising planets in the "Habitable Zone" (HZ). However, Kepler has revealed that terrestrial-mass exoplanets are often born with voluminous H/He envelopes, comprising mass-fractions (M_{env}/M_{core}) $\gtrsim 1$\%. If these planets retain such envelopes over Gyr timescales, they will not be "habitable" even within the HZ. Given the strong X-ray/UV fluxes of M dwarfs, we study whether these planets can lose sufficient envelope-mass through photoevaporation to become habitable. We improve upon previous work by using hydrodynamic models that account for radiative cooling as well as the transition from hydrodynamic to ballistic escape. Adopting the XUV spectrum of the active M dwarf AD Leo as a template, including stellar evolution, and considering both evaporation and thermal evolution, we show that: (1) the envelope-mass lost is significantly lower than previous estimates that use an "energy-limited" formalism and ignore the transition to Jeans escape, (2) at the inner edge of the HZ, planets with a core mass $\lesssim 0.9$ $M_{\oplus}$, can lose enough H/He to be habitable at late times if their initial H/He envelope mass-fraction is ~1\%, (3) at the outer edge of the HZ, evaporation is ineffective at removing a ~1\% H/He envelope even from cores down to 0.8 $M_{\oplus}$. Thus, if planets form with bulky H/He envelopes, only those with low core masses may eventually become habitable. Cores $\gtrsim 1$ $M_{\oplus}$ with $\gtrsim$1\% natal H/He envelopes, will not be habitable in the HZ of M dwarfs.

But also :

*** Tidal locking (Lecomte + 2015)
*** Runaway greenhouse effects (Kopparapu 2013)
*** Water loss (luger + 2015)
*** Solid core + 1% enveloppe H/He. (Wolfgang and Lopez 2015)



Is it possible to find earth-twins ?

(In the HZ, < 30 pc)

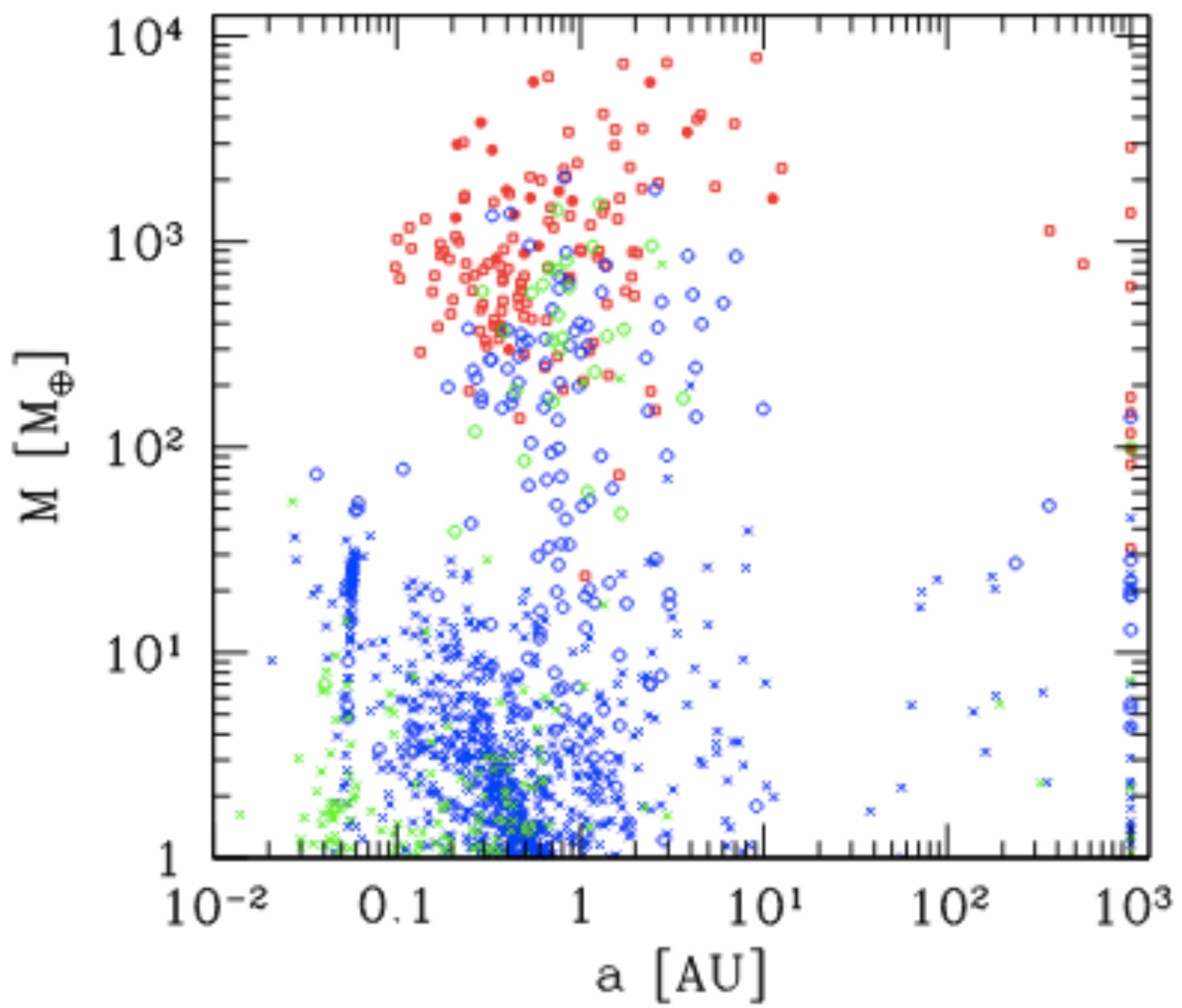
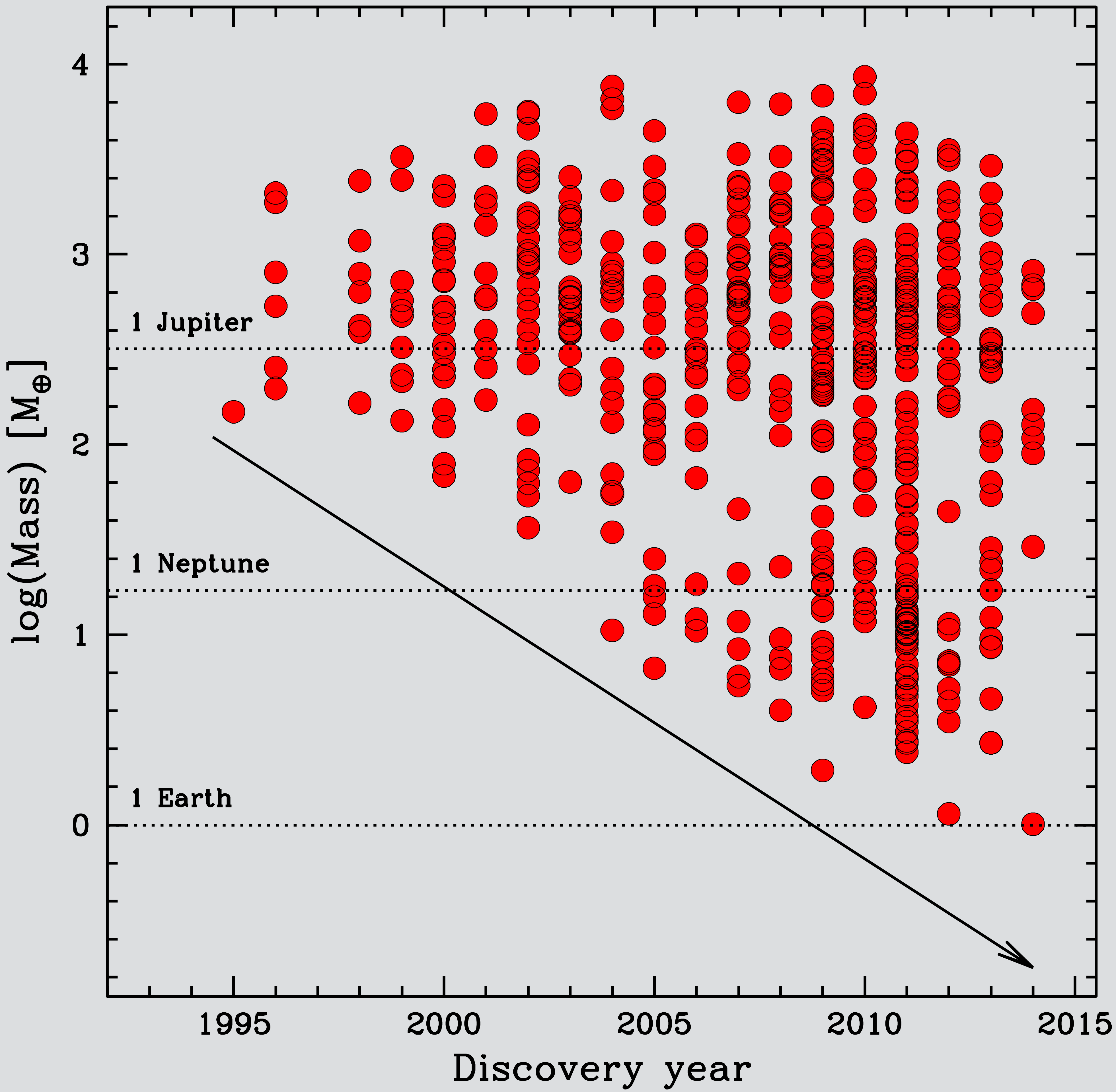


Fig. 3.— Synthetic mass-distance diagram at the time the proto-planetary nebula vanishes. The green (blue) crosses are rocky (icy) planets with a gaseous envelope less massive than the core. The open green (blue) circles are rocky (icy) planets with an envelope 1-10 times more massive than the core. The red filled circles (empty squares) are giant planets with a rocky (icy) core. The envelope is at least 10 times more massive than the core. The model assumes ten proto-planets concurrently forming per disc.

Alibert, Mordasini, Benz (Bern)
Ida (Tokyo), Lin (Santa Cruz)



1 Jupiter
1 Neptune
1 Earth
log(Mass) [$M_\oplus$]
Discovery year
4
3
2
1
0
1995
2000
2005
2010
2015

Solar telescope at HARPS-N

See:
Dumusque, X. et al., ApJ Letters, Dec. 2015
Glenday A., Phillips D. F. et al., in prep.

Photos by David Phillips

HARPS-N OBSERVES THE SUN AS A STAR

Xavier Dumusque[1,6], Alex Glenday[1], David F. Phillips[1], Nicolas Buchschacher[2], Andrew Collier Cameron[3], Massimo Cecconi[4], David Charbonneau[1], Rosario Cosentino[4], Adriano Ghedina[4], David W. Latham[1]

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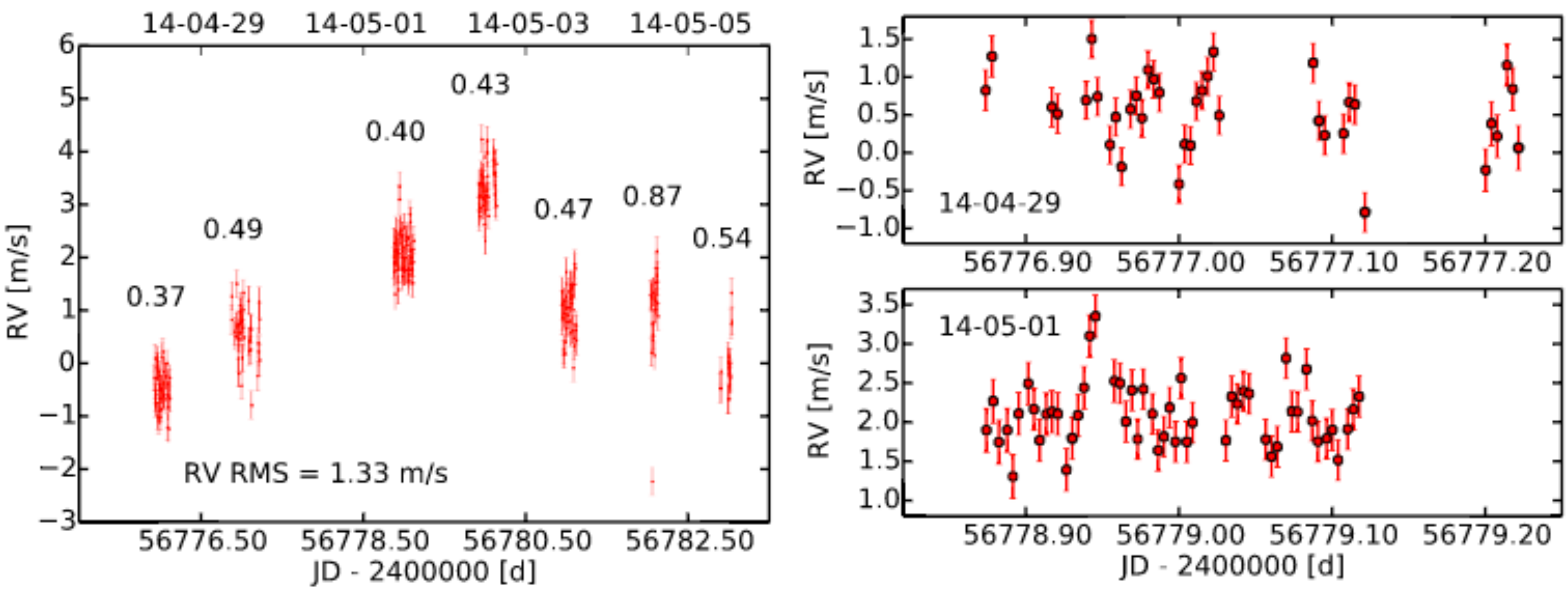


Fig. 2.— *Left:* Solar radial velocities (RVs) after barycentric correction obtained by the HARPS-N solar telescope during one week using simultaneous astro-comb wavelength calibration. The RV rms over the week time span of the observation is 133 cm s^{-1} , and the daily RV rms is shown above each daily observations on the plot. *Right:* Subset of RVs highlighting the daily variations seen on 2014 April 29 and 2014 May 01.

Stellar effects

1) high-frequency stellar intrinsic variations

- acoustics modes: a few minute timescale
- (super-)granulation: timescale up to several hours

2) "short-period" activity-related variations

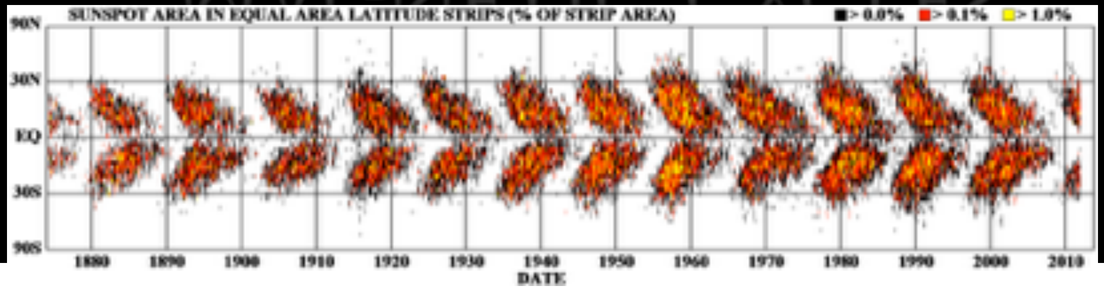
- spots: effet over the rotation period of the star

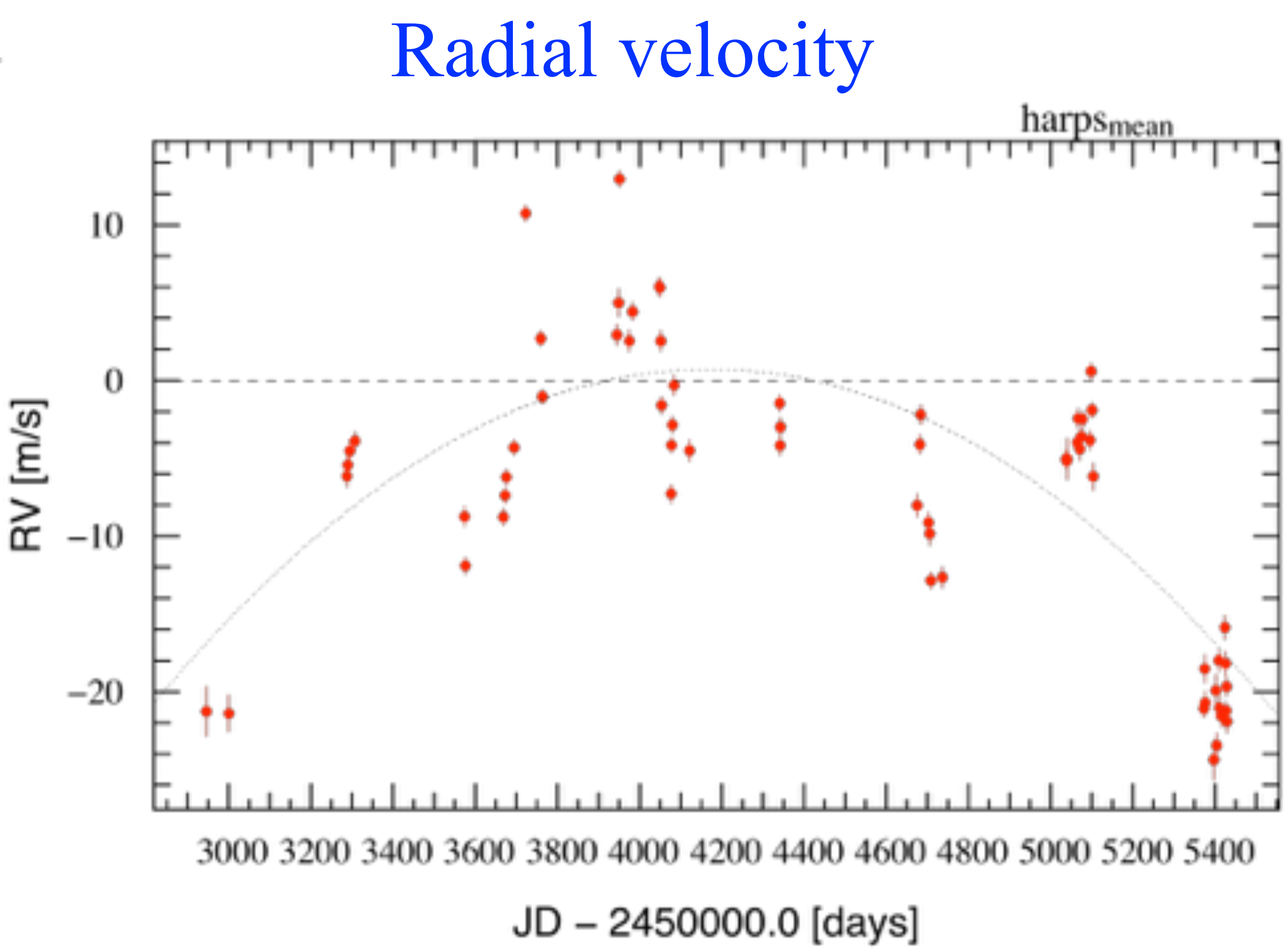
3) long-term activity-related variations

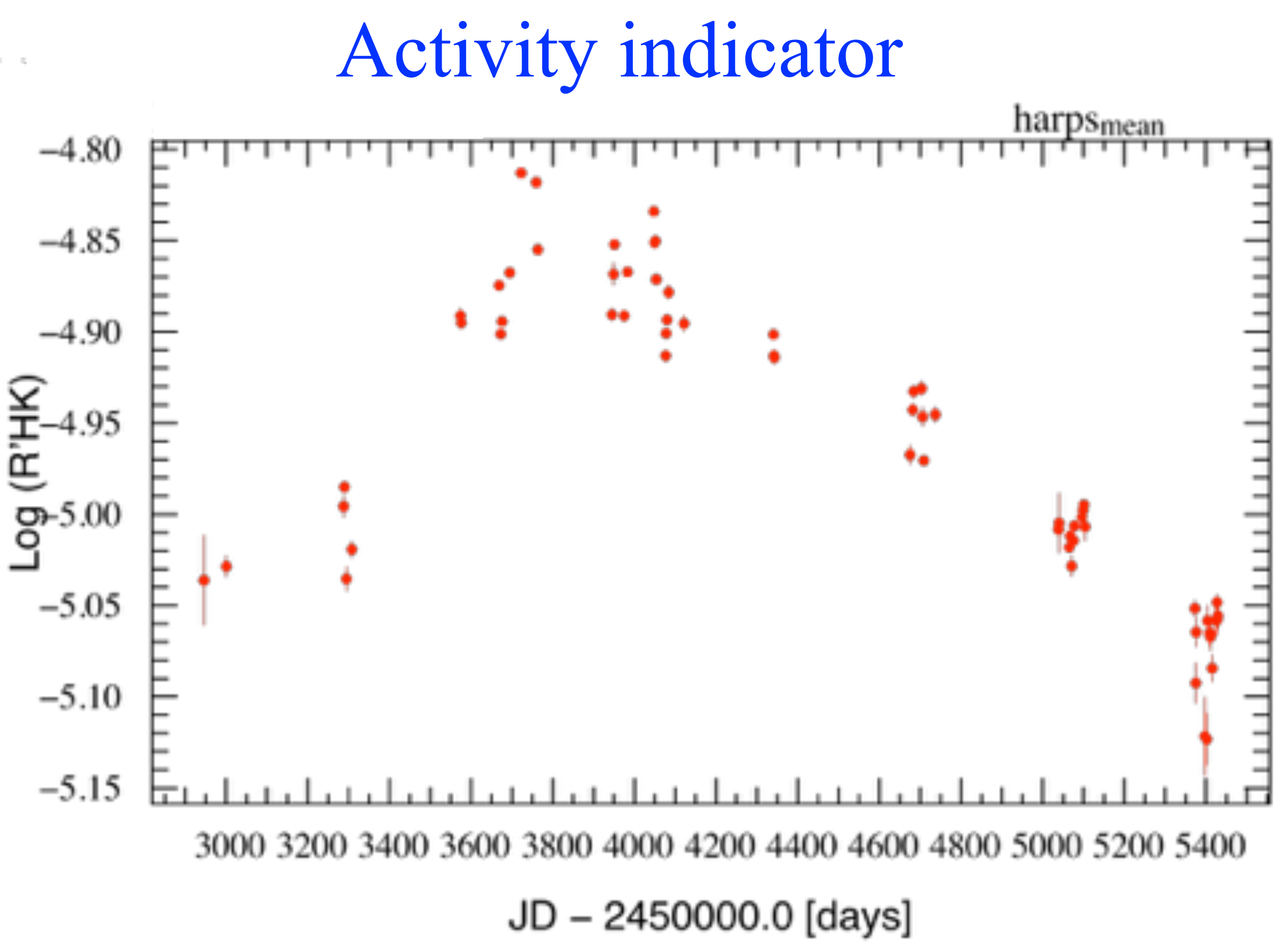
- magnetic cycles: several years timescale

Question: low-level stellar intrinsic variation
with a 6 month - 1.5 year timescale ?

MAGNETIC CYCLES







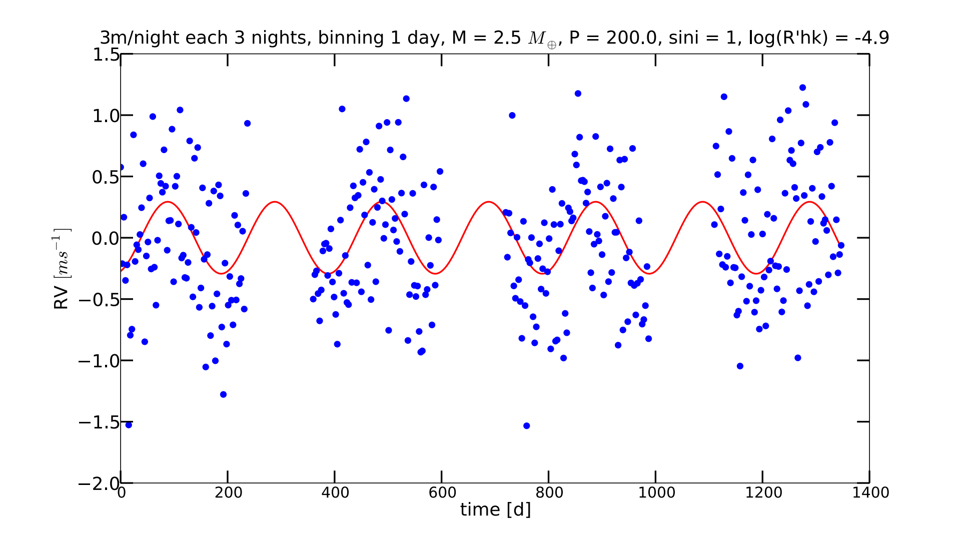
HARPS: >30% of low-activity stars show magnetic cycles →

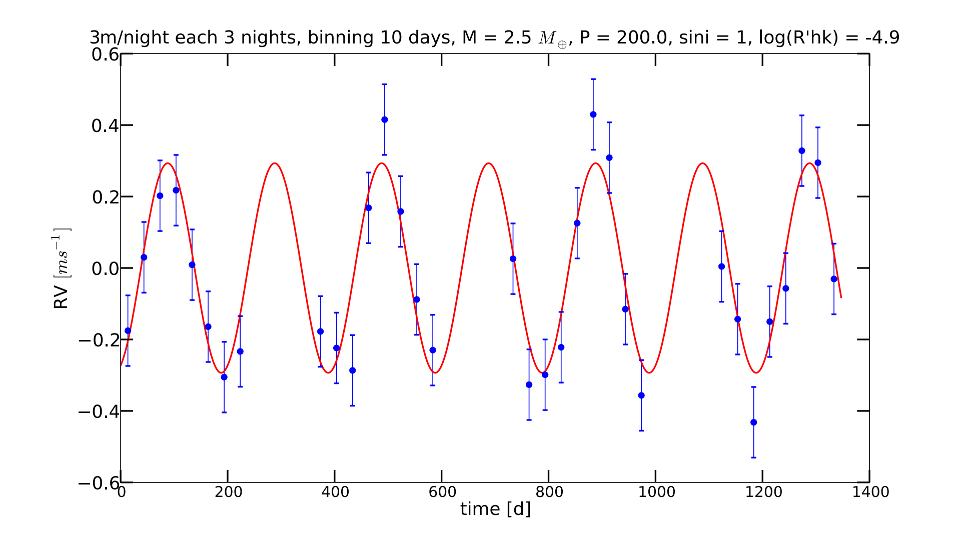
- Impact on parameter estimate
- derived architecture
- Importance of diagnostics

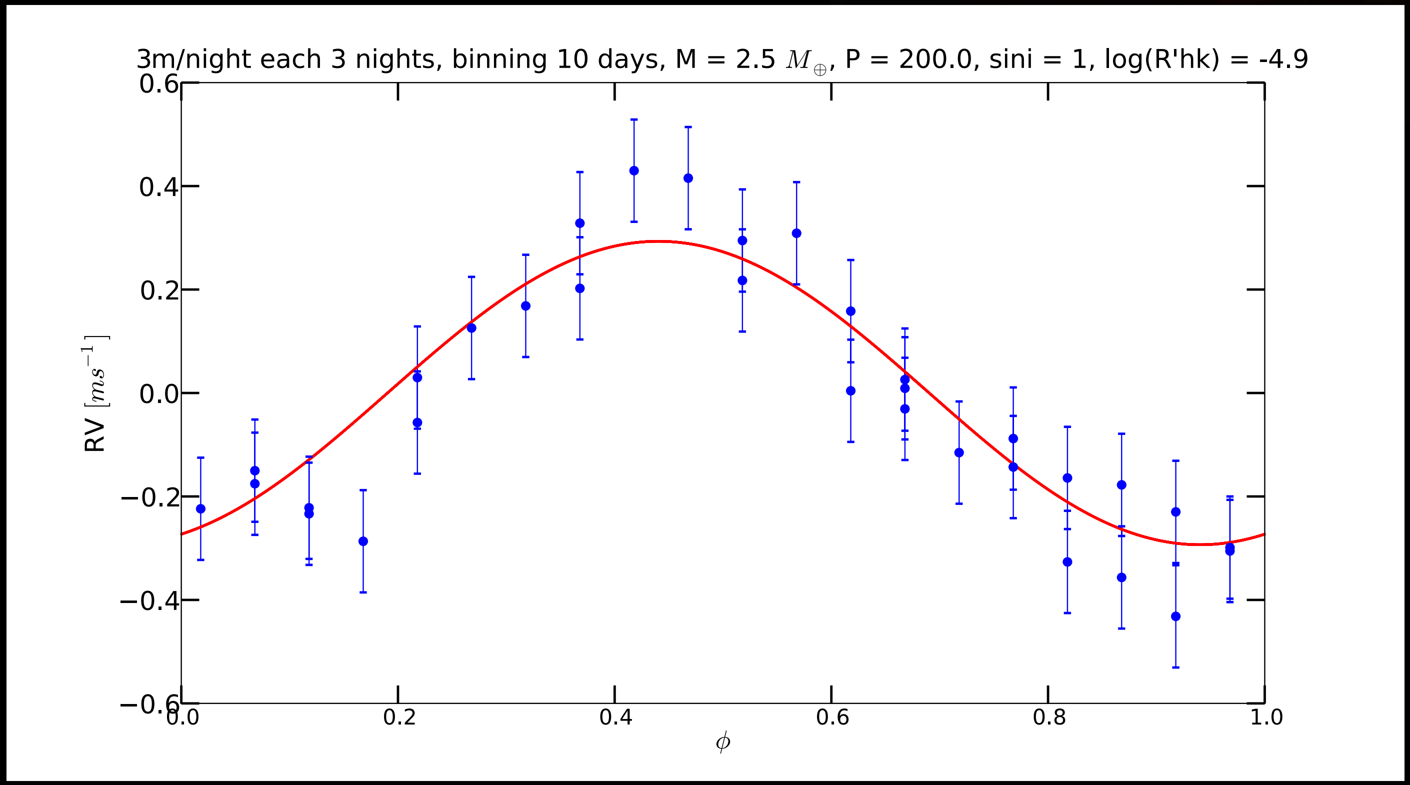
High precision radial velocities

…Decrease intrinsic stellar noises (non active stars, strategy)
…Large collecting area (VLT)
…Ultra stable spectrograph (ESPRESSO/VLT, 2016)

Example : A 2.5 Earth-mass planet orbiting a non active-K star in the HZ (P=200 days)







(Dumusque et al., 2010b)

HD 85512 b (Pepe et al. 2011)

P = 58.4 days, m2sini= 3.6 M Earth

185 measurements

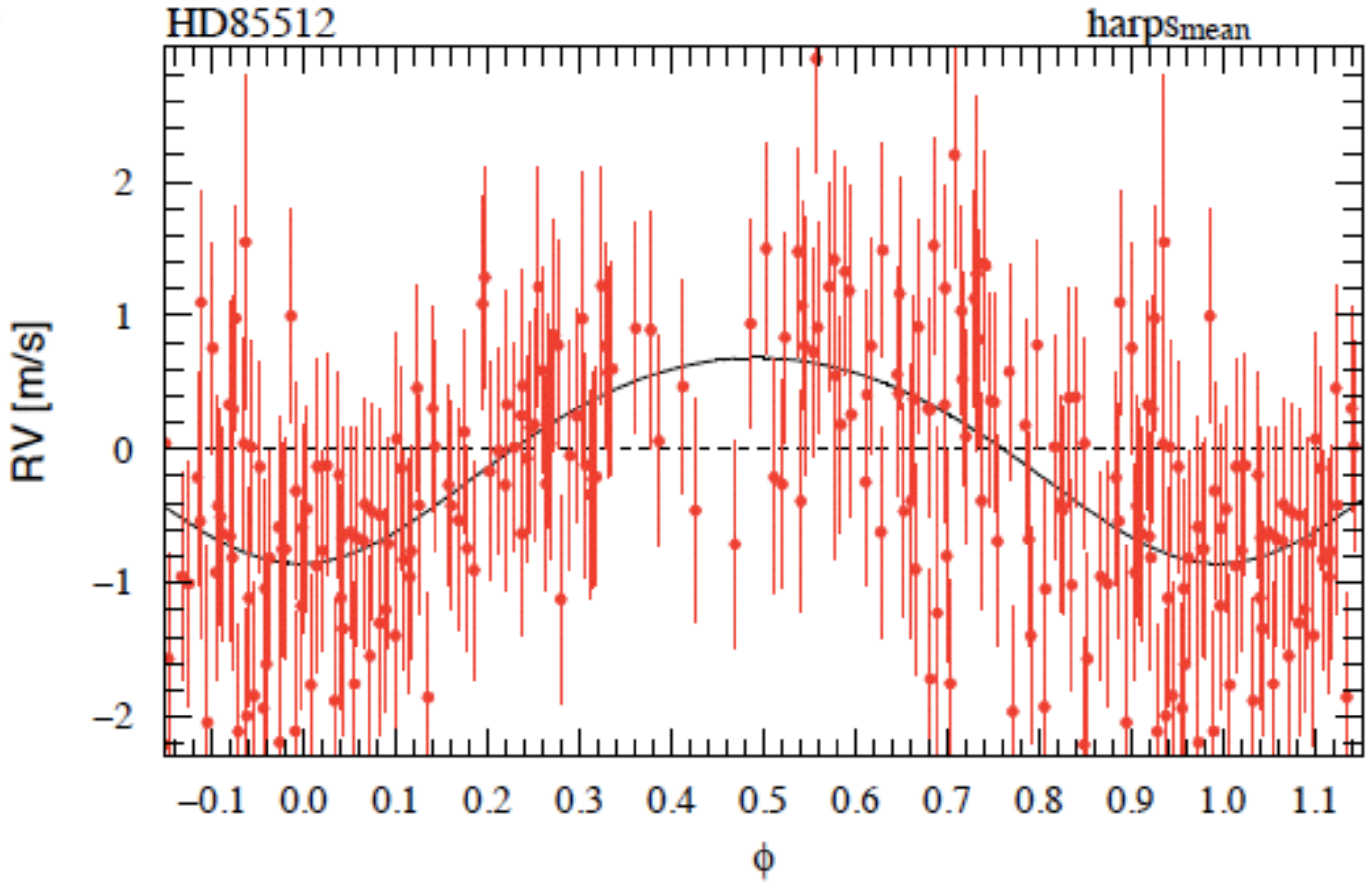
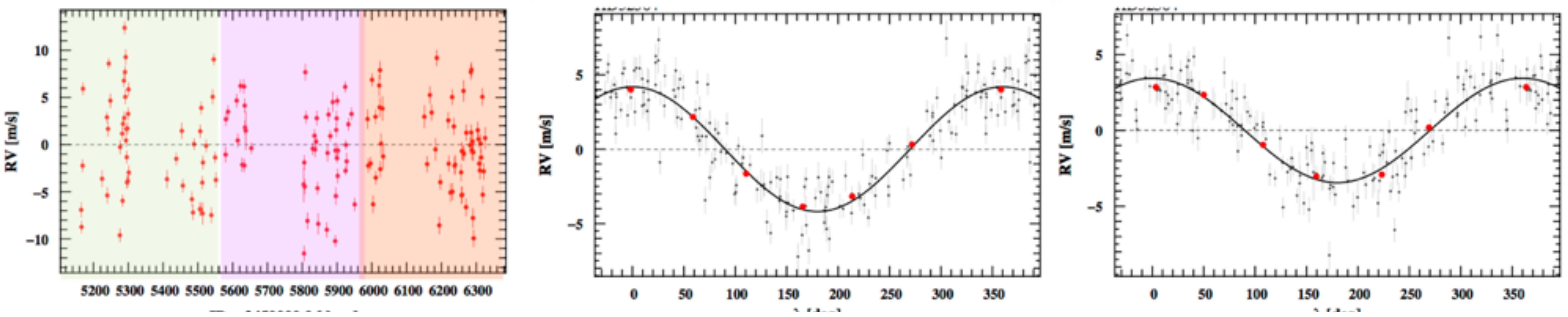


Fig. 13. Phase-folded RV data of HD 85512 and fitted Keplerian solution. The dispersion of the residuals is 0.75 m s^{-1} *rms*.

Importance of the number of measurements

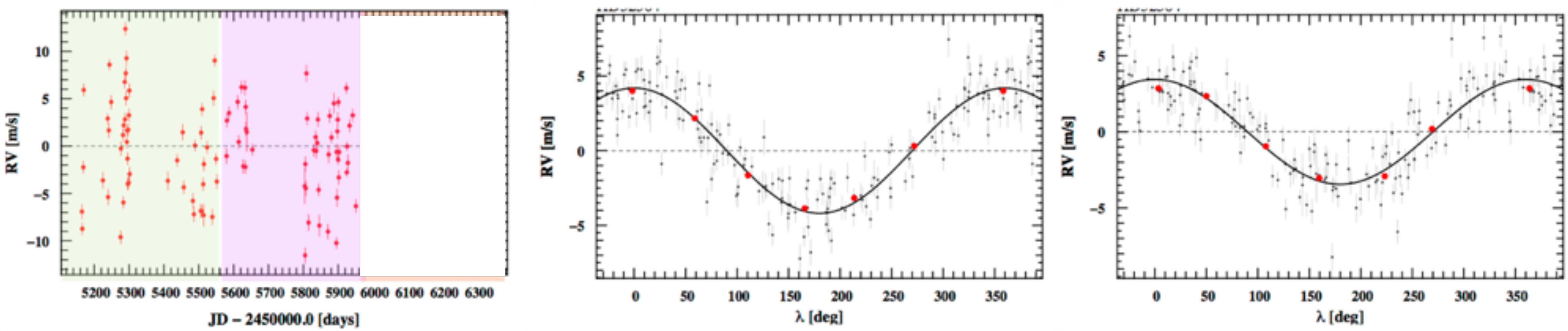
A new low mass multiple planetary system orbiting a nearby very quiet K dwarf

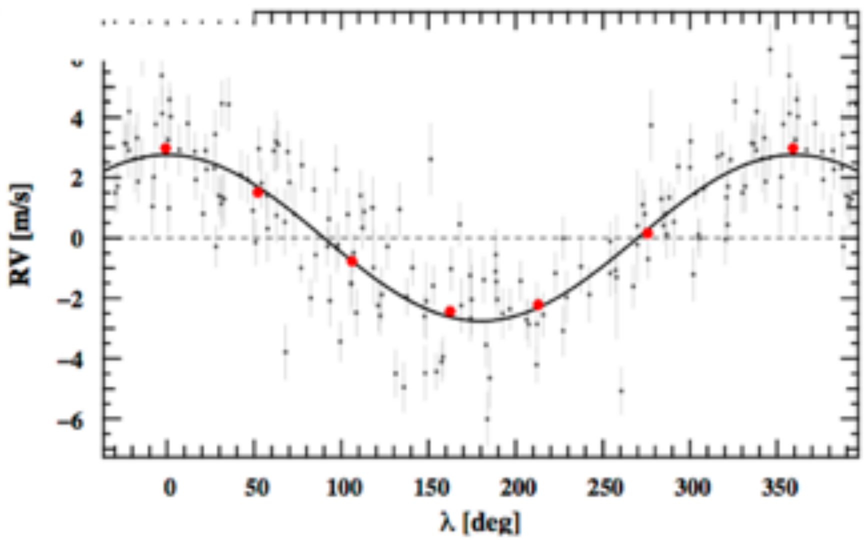


- 50 observations: a system with 2 planets
- (+ uncertainties due to aliasing)

Importance of the number of measurements

A new low mass multiple planetary system orbiting a nearby very quiet K dwarf

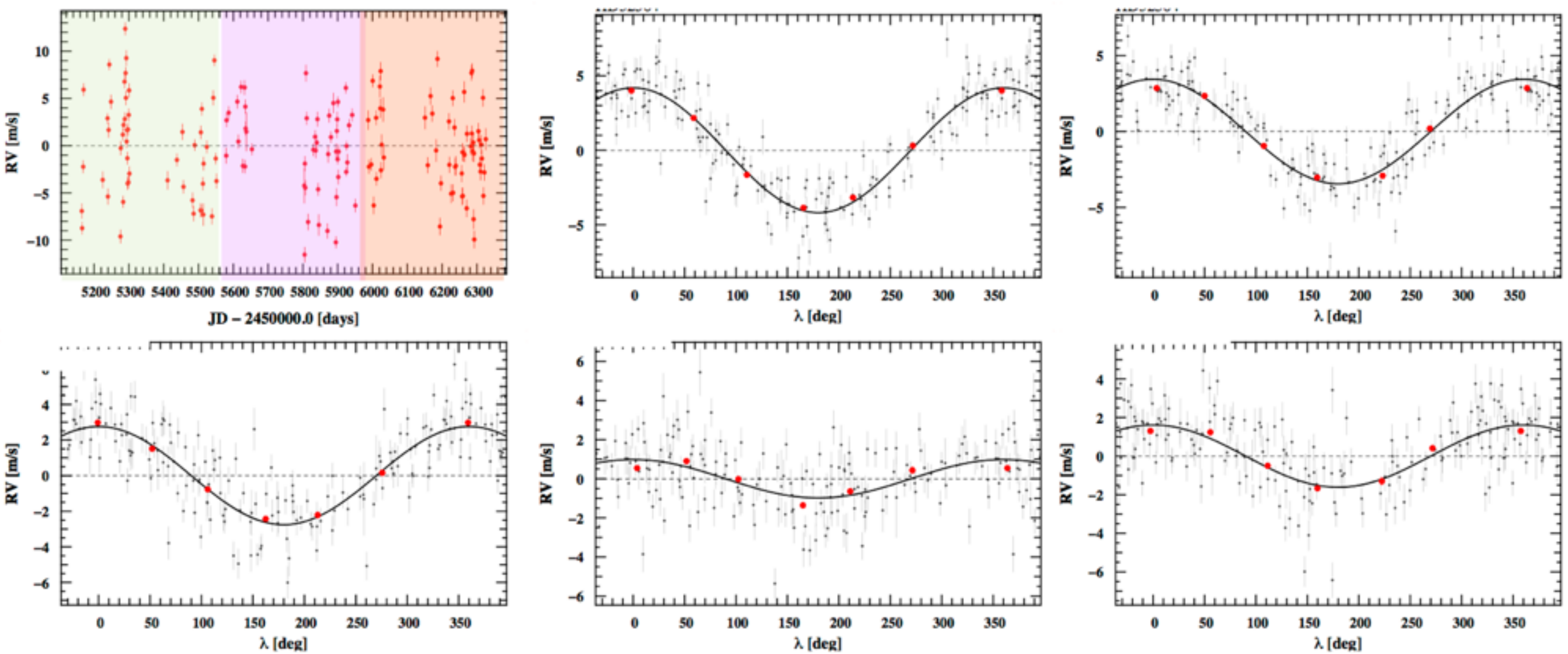




- 50 observations: a system with 2 planets
- (+ aliasing uncertainties)
- 100 observations: a system with 3 planets well defined.

Importance of the number of measurements

A new low mass multiple planetary system orbiting a nearby very quiet K dwarf

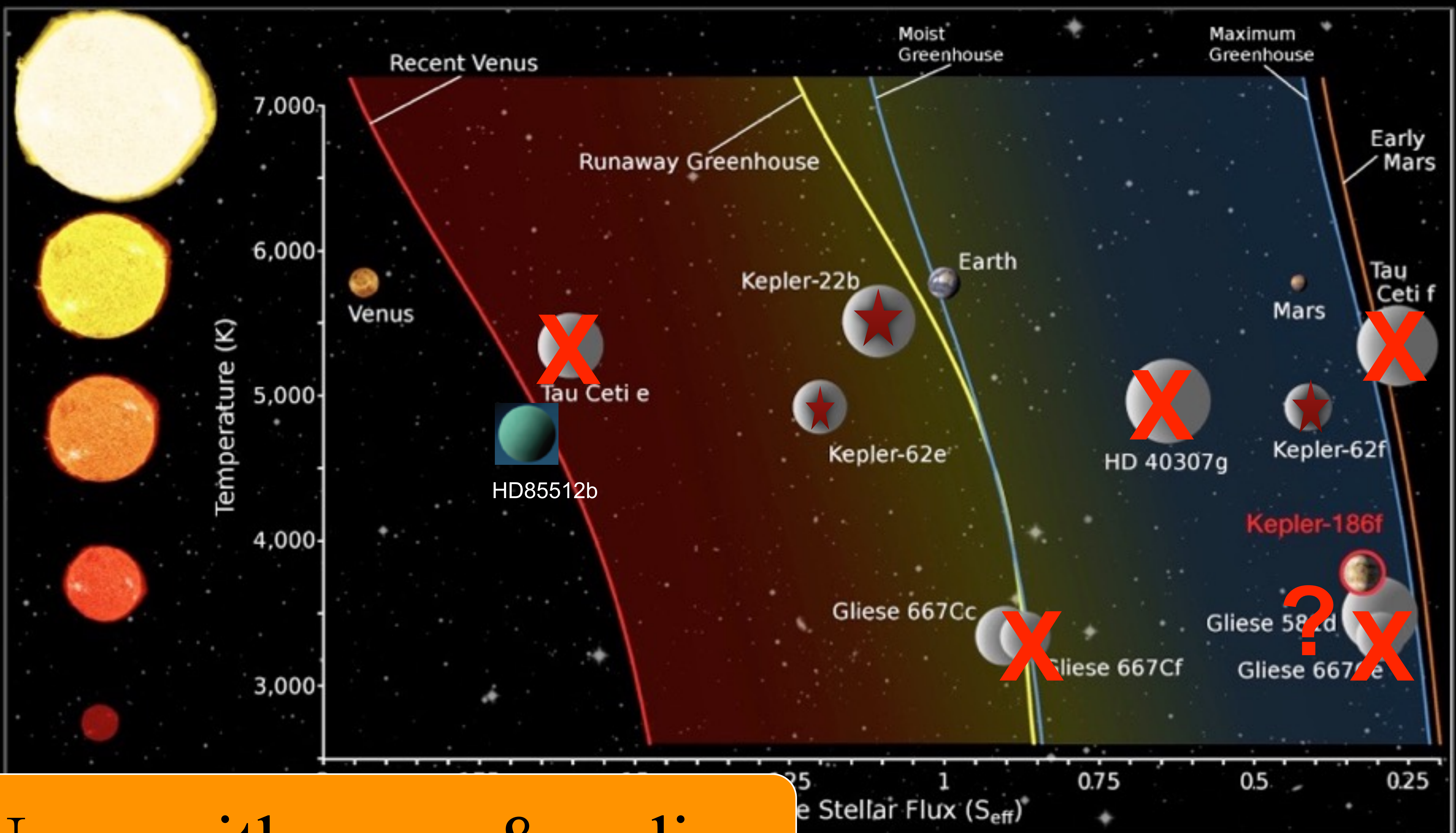


- 150 observations: a system with 5 planets.

=> requires a large number of measurements for a “complete” census! (>150 meas !)

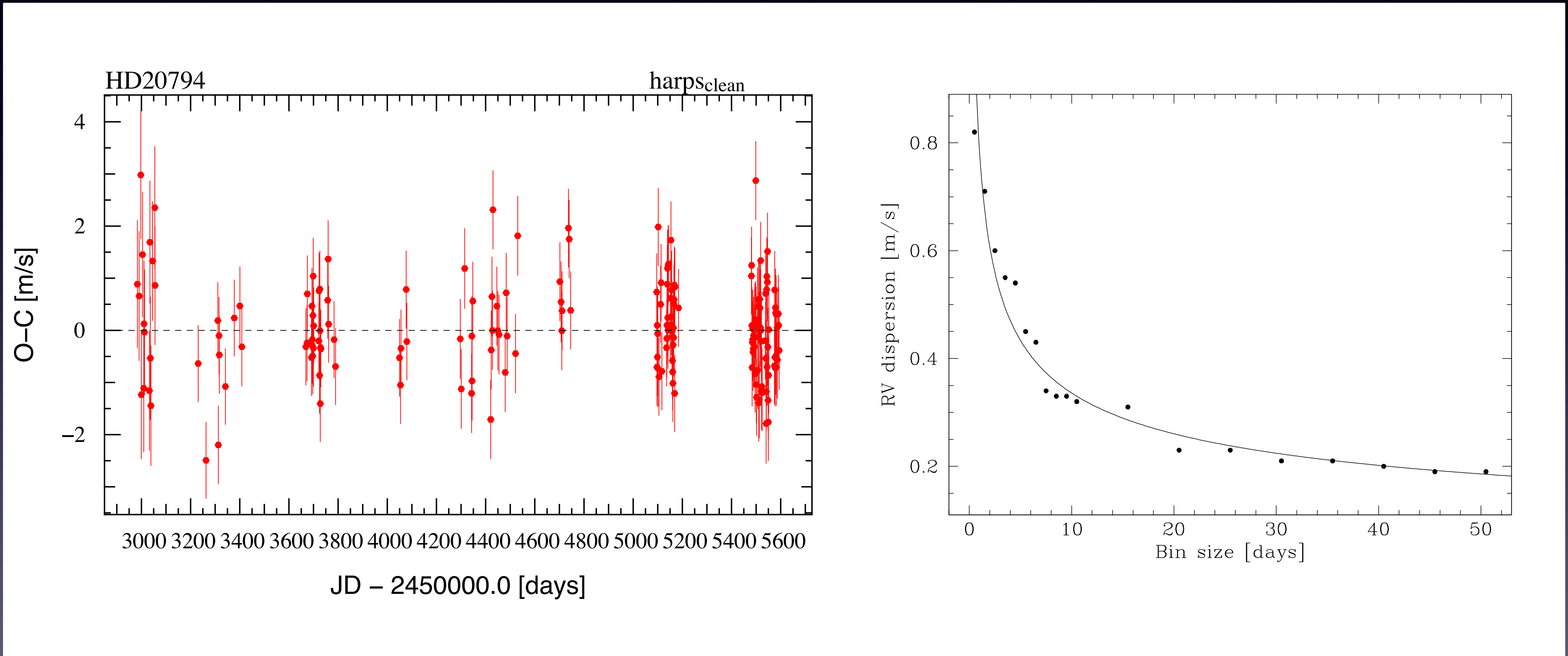
SETI INSTITUTE

The Habitable Zone



None with mass & radius

HD20794: Three Earth-mass planets



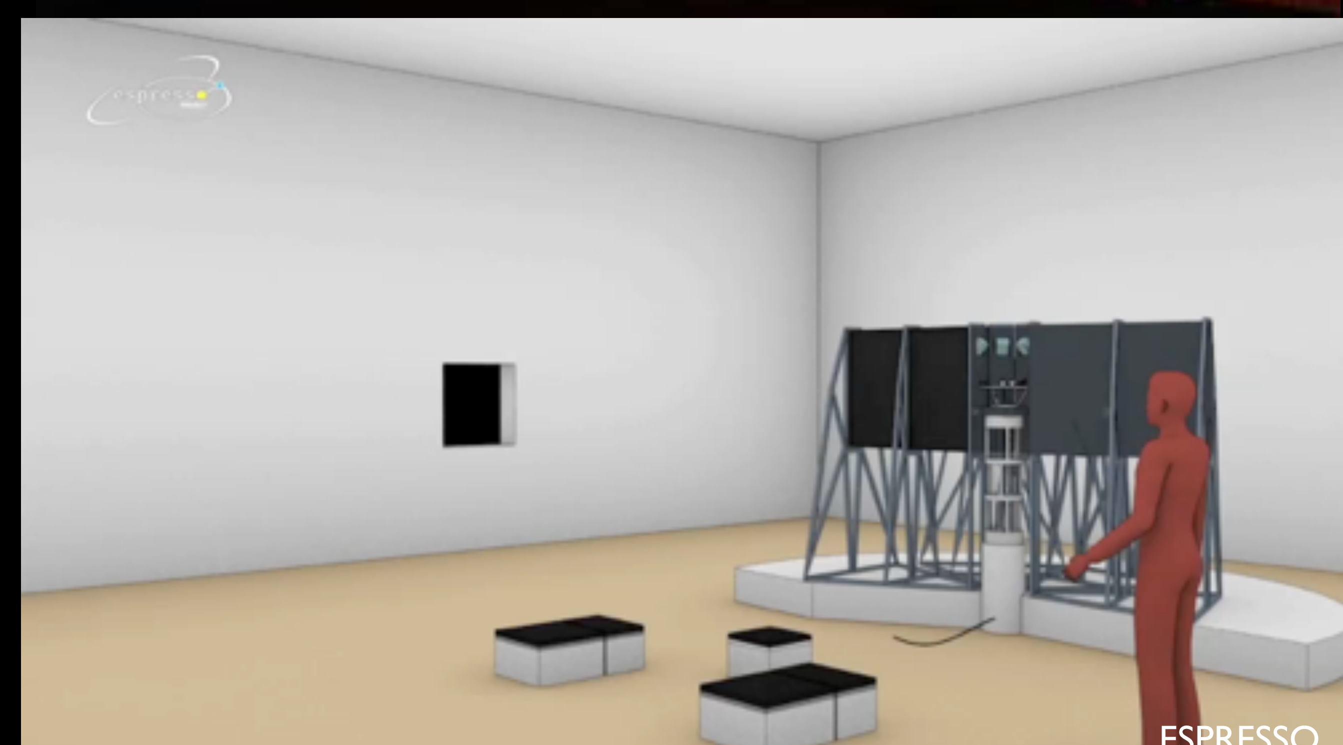
Already today, to search for long period planets, binning on 30 days allows a rms of 20 cm/s

ESPRESSO a spectrograph for the VLT (diameter 8.2m)

«**E**chelle **SP**ectrograph for **R**ocky **E**xoplanets and **S**table **S**pectroscopic **O**bservations»

Pi: Francesco Pepe

- Ultrastable spectrographe for the VLT
- Consortium : Switzerland, Italy, Portugal, Spain
- First light : 2017
- Expected precision RV : < 10 cm/s
- Goal : detection and characterization of small planets.

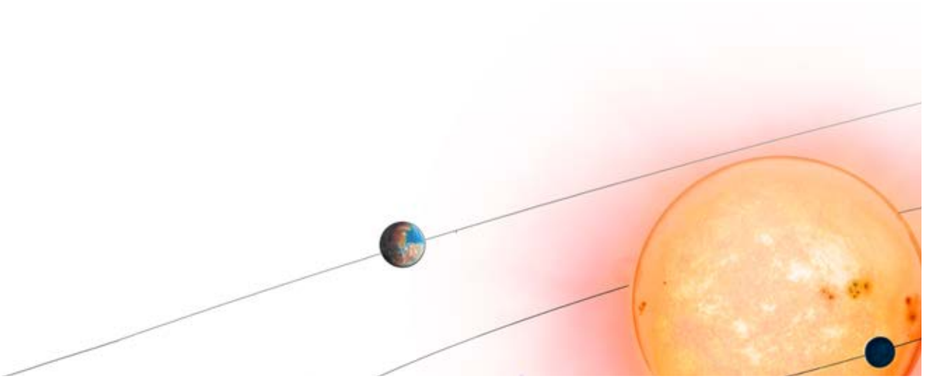


ESPRESSO: integration=>end 2016, vacuum tank in Geneva

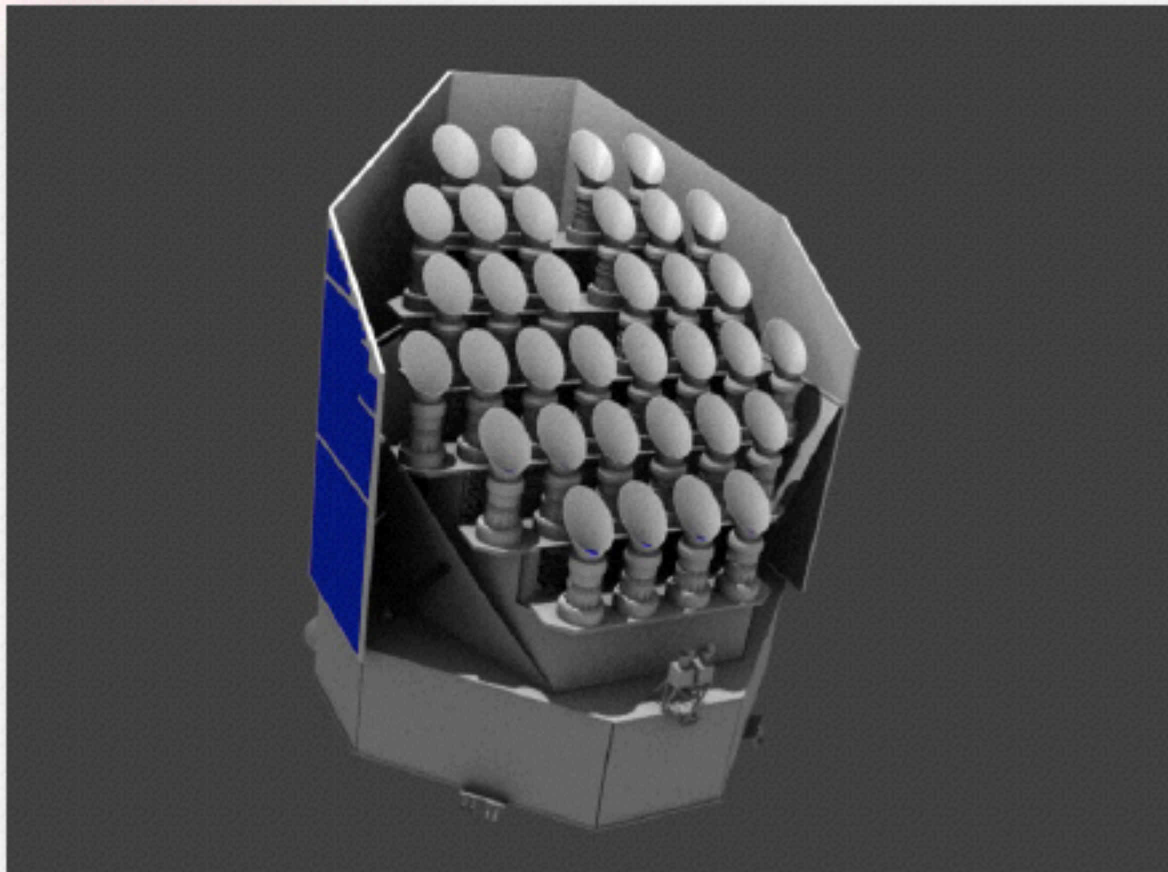
PLATO 2.0

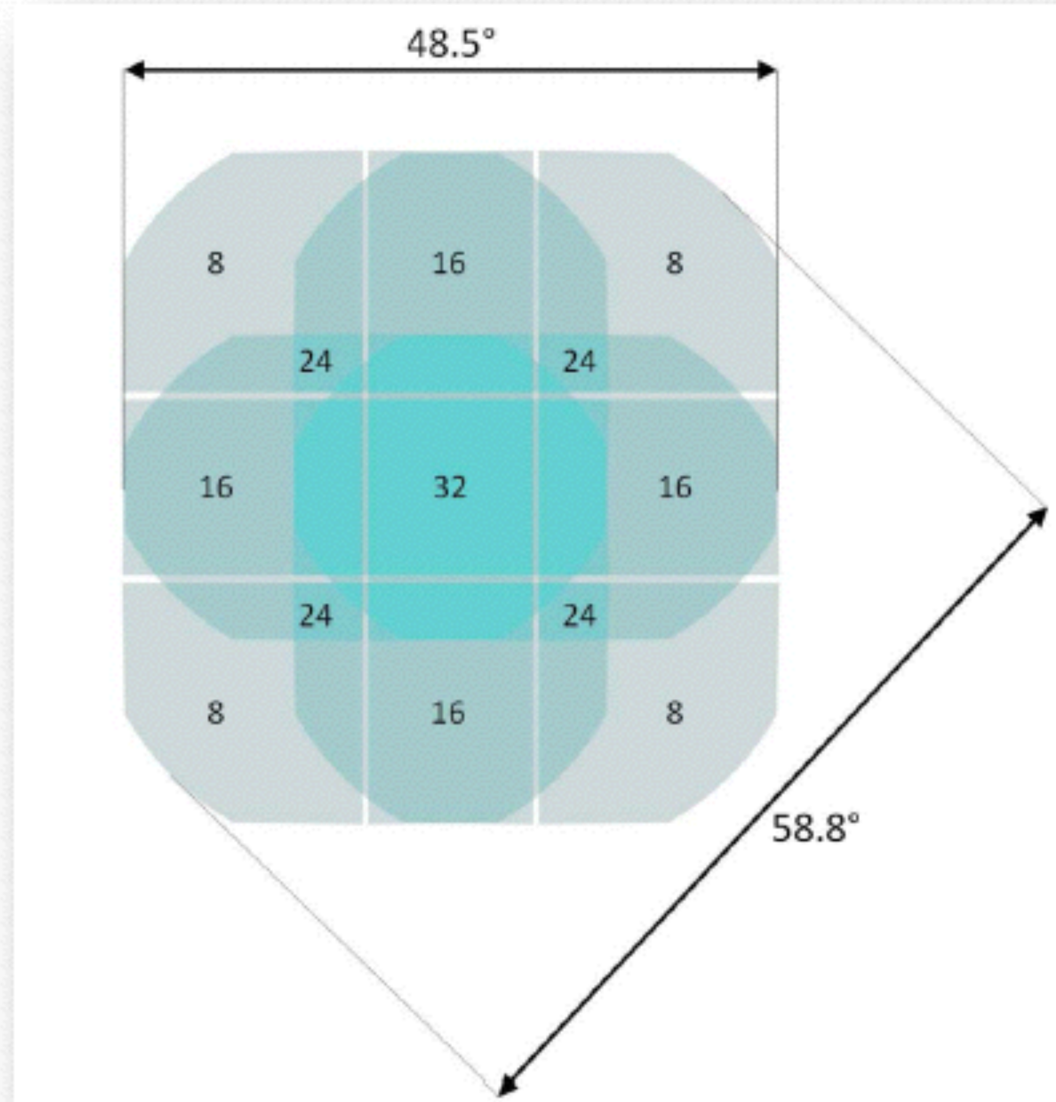
Science objectives and consortium overview

Heike Rauer and the PLATO Team



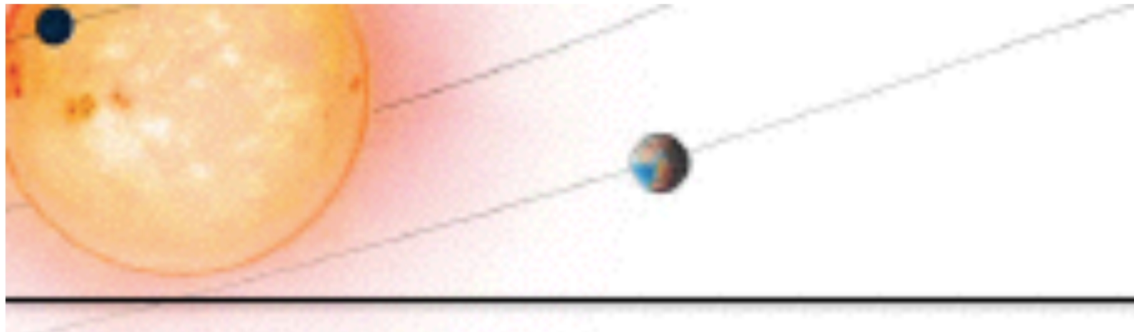
PLATO instrument





- 32 « normal » cameras, cadence 25 sec
- 2 « fast » cameras : cadence 2.5 sec, 2 colours
- dynamical range: $4 \leq m_V \leq 16$

- Cameras are in groups
- Offset to increase FoV



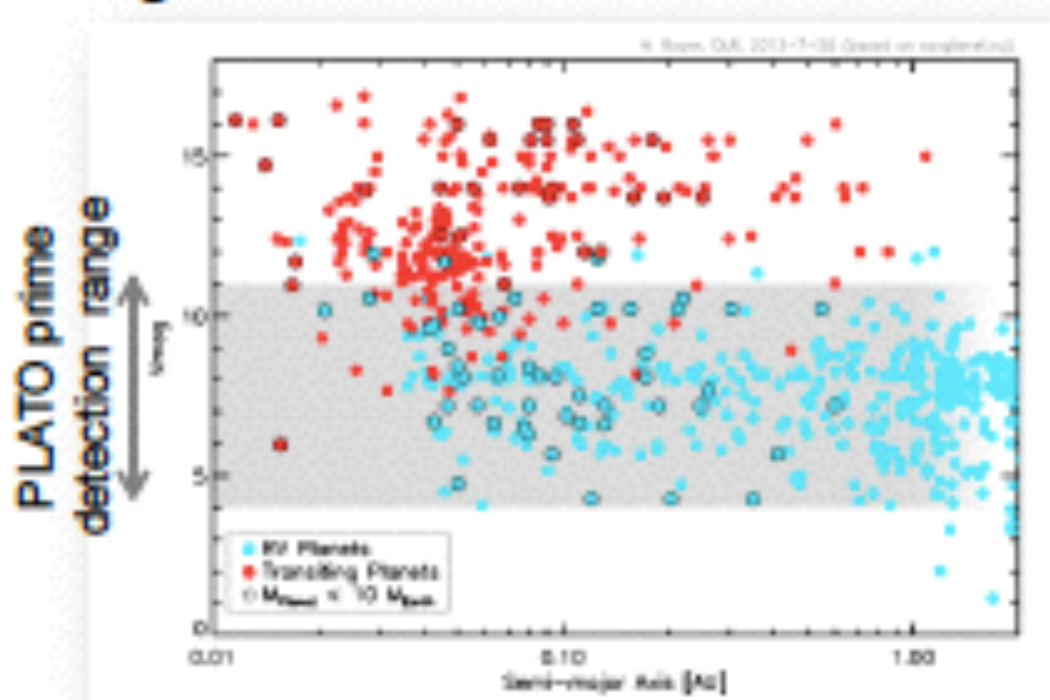
The Method

Characterize bulk planet parameters

Accuracy for Earth-like planets around solar-like stars:

- radius ~2%
- mass ~10%
- age known to 10%

bright host stars:



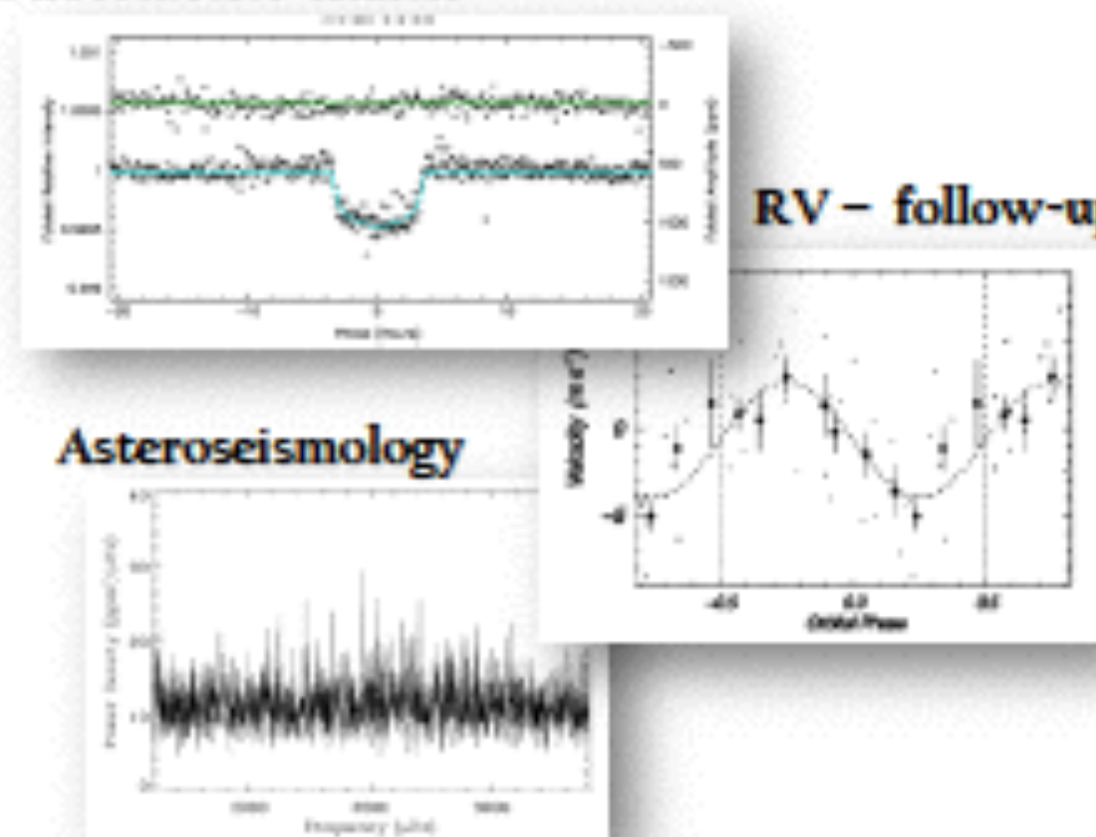
Techniques

Example: Kepler-10 b

Photometric transit

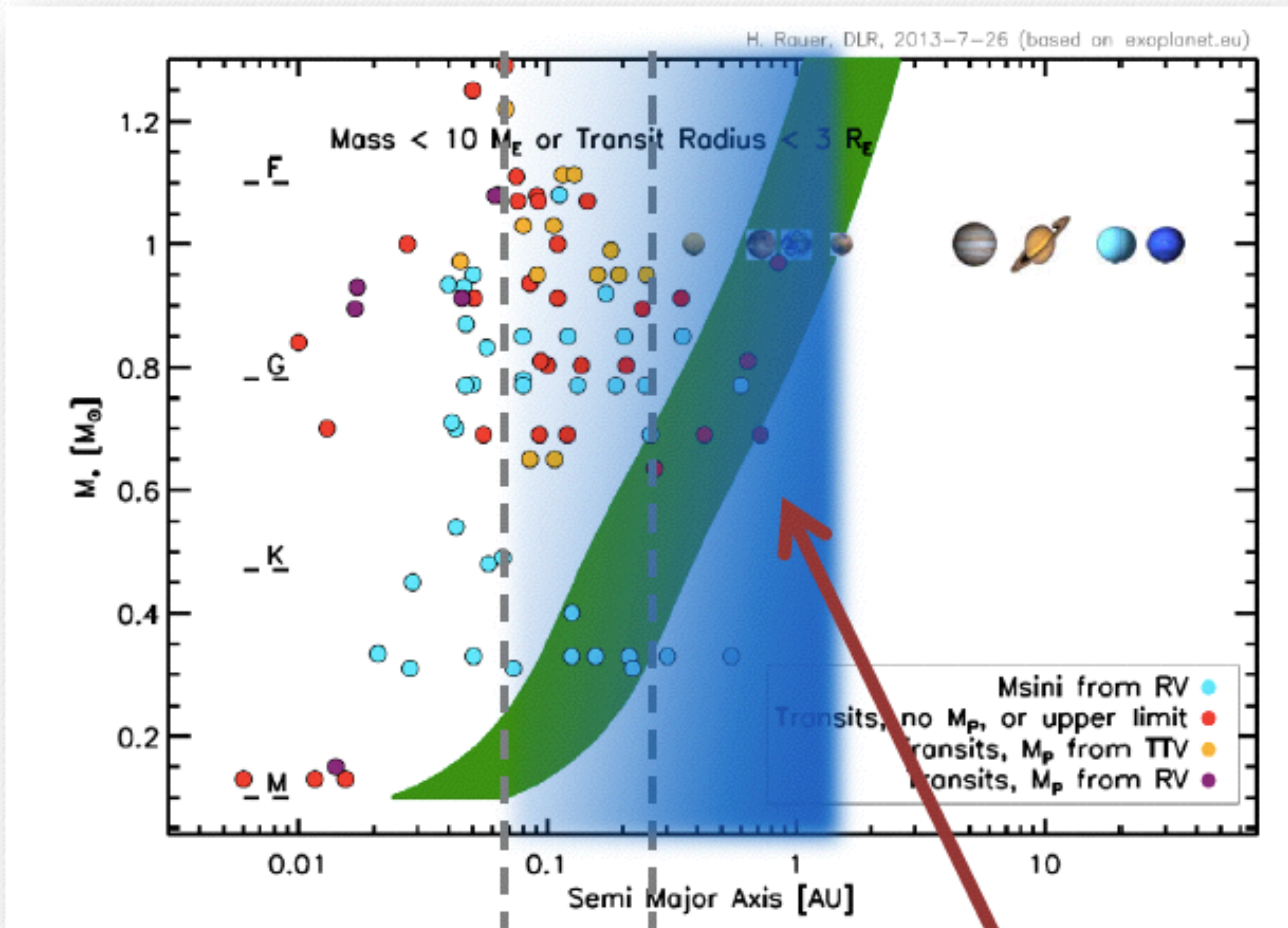
RV – follow-up

Asteroseismology



Bulk properties of Earth-like planets up to the HZ

Status super-Earths detection and characterization



Transits and mass from RV

Mass from TTVs

Main target range for PLATO 2.0 characterization (transit + RV)