Exoplanets: an overview
(the spectroscopic approach)

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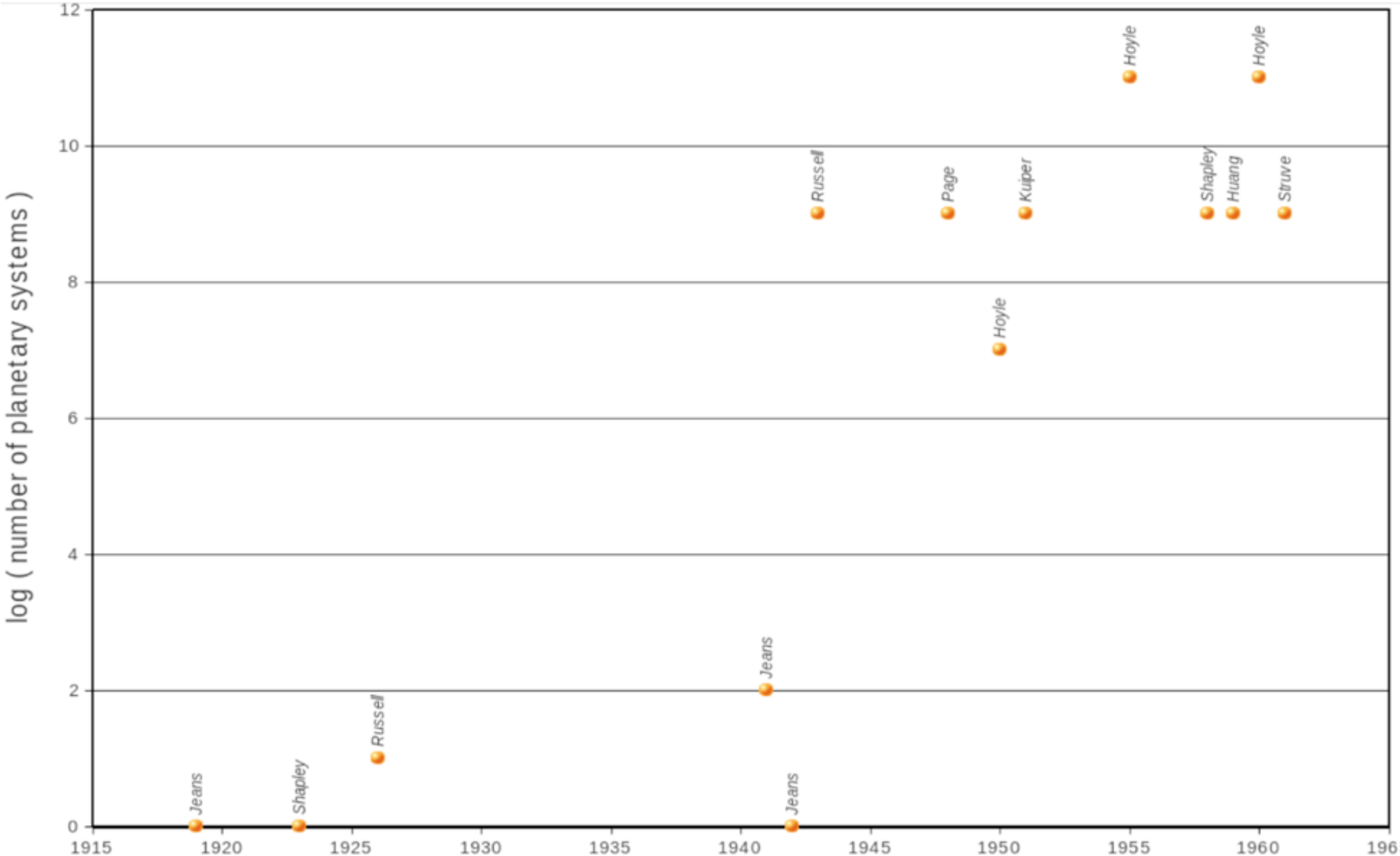
Outline

- Some history
- Main planet search methods
- The challenge of stellar activity
- The properties of the known planets (mostly based on RV surveys)
  - Statistics of gas-giant planets
  - Neptunes and Super-Earths
- The star-planet connection
- The future of Radial Velocities

What we know today about planet statistics

- Planets are very common: most (?) stars in the sky have planets
  - Results from RV surveys (Mayor et al. 2011, Bonfils et al. 2012)
  - Results from ground- and space-based Transit surveys (Kepler is best example)
- Theory and observations:
  - Planet formation can produce a huge variety of system properties
  - Rocky planets are the most common

How many planetary systems are there in the Milky Way?



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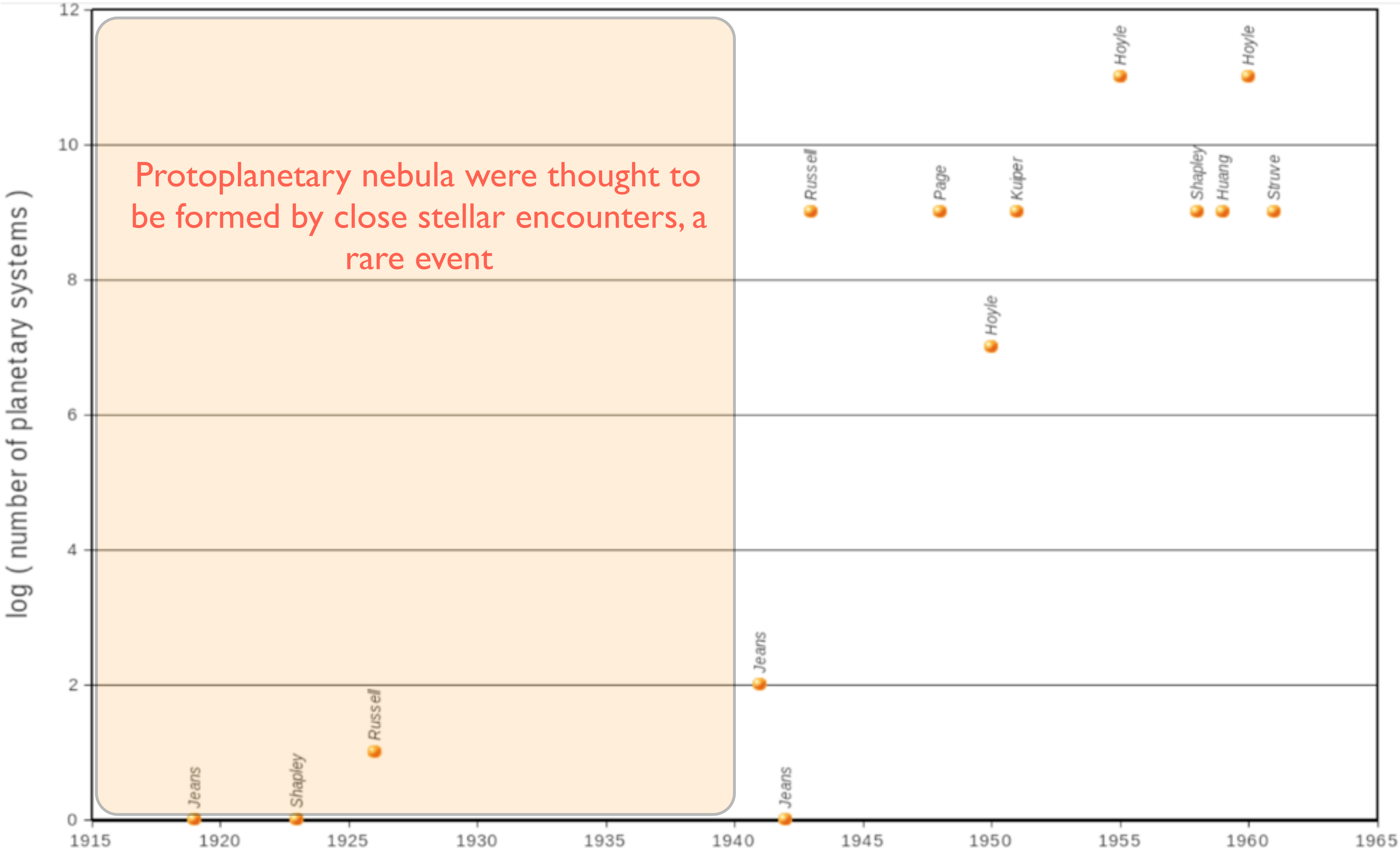

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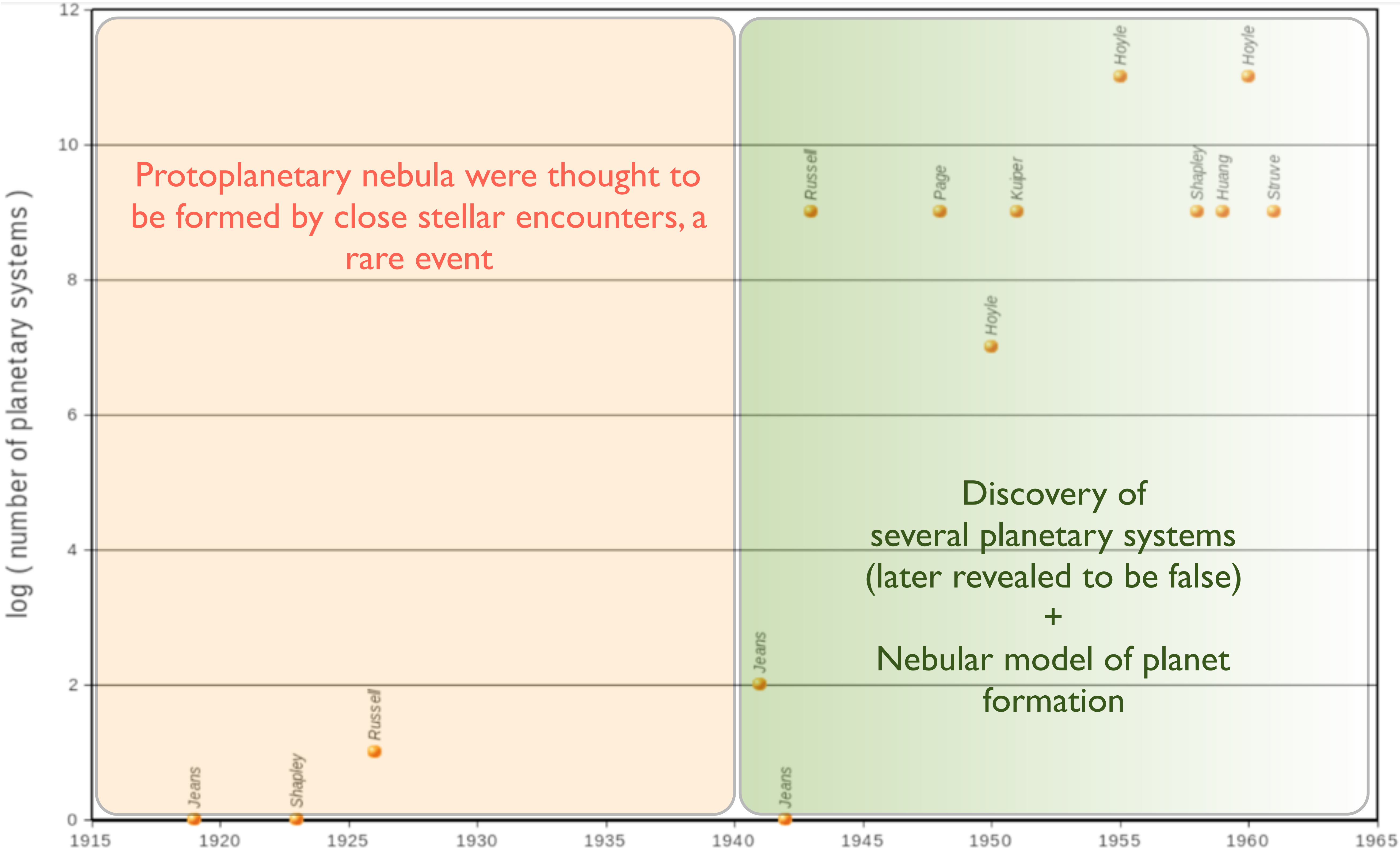

Finding planets: the main methods

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The methods: transit photometry

Measuring an exoplanet

Courtery ESO

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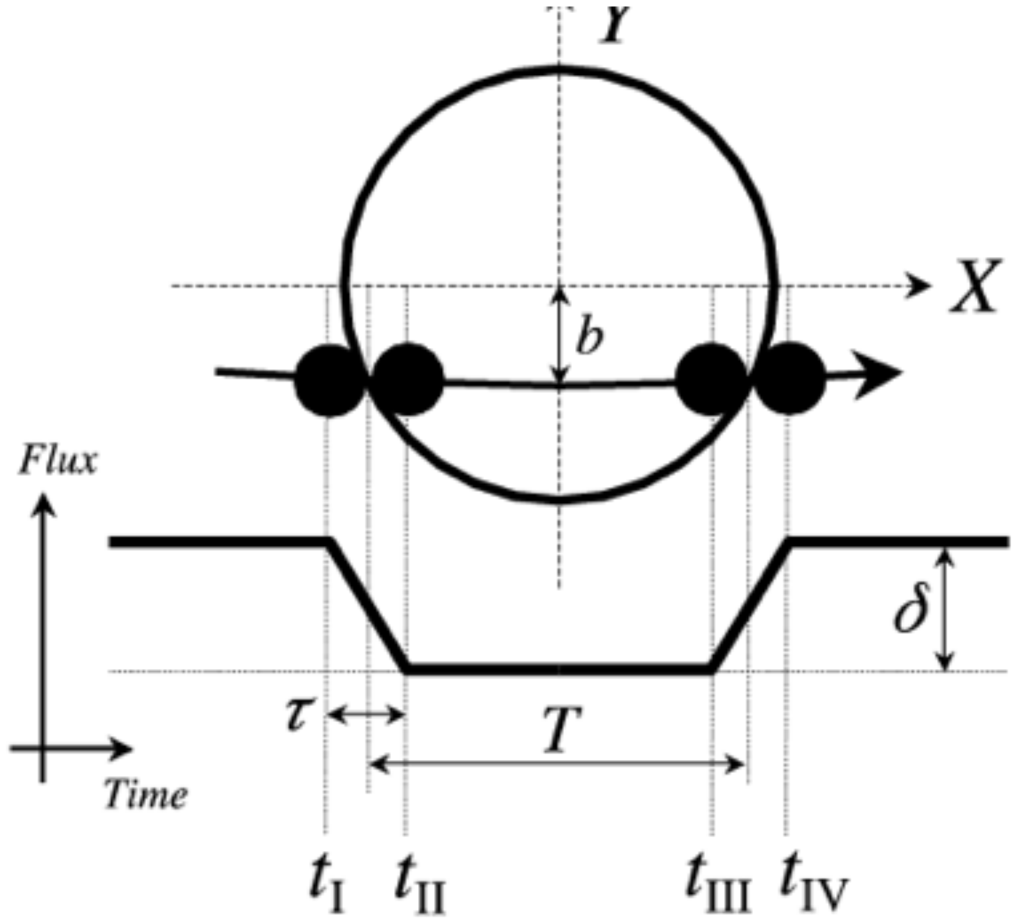
The methods: transit photometry

Measuring an exoplanet

$$P \sim \frac{(R_p + R_s)}{a} \sim \frac{R_s}{a}$$



More sensitive to short period “big” planets

$$\frac{\Delta F}{F} = \frac{R_p^2}{R_*^2}$$

Transit depth/signal: higher radius planets transit “deeper”

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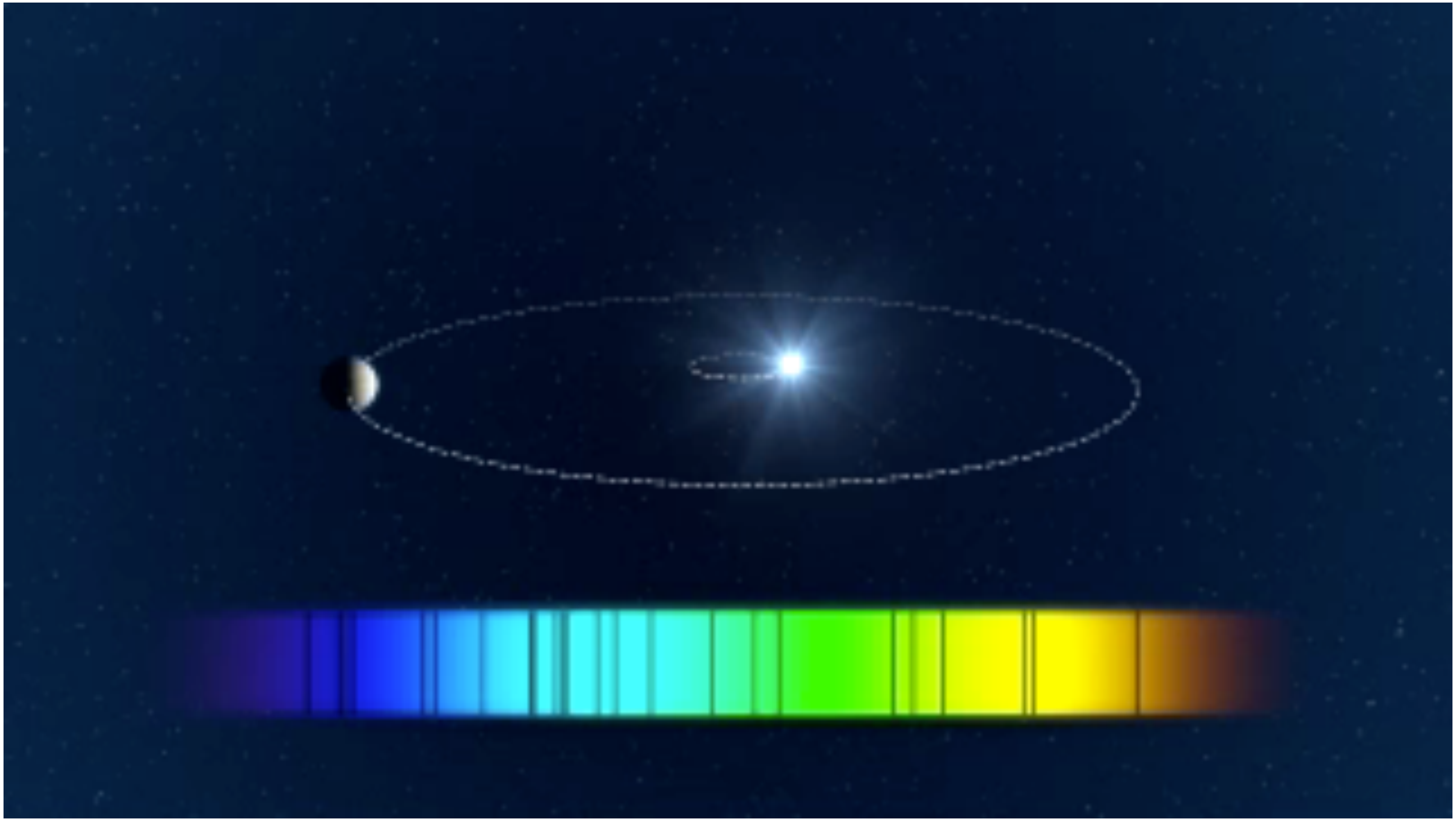
The methods: radial velocities

"weighting" an exoplanet: amplitude of the signal depends on **planet mass**



Courtery ESO

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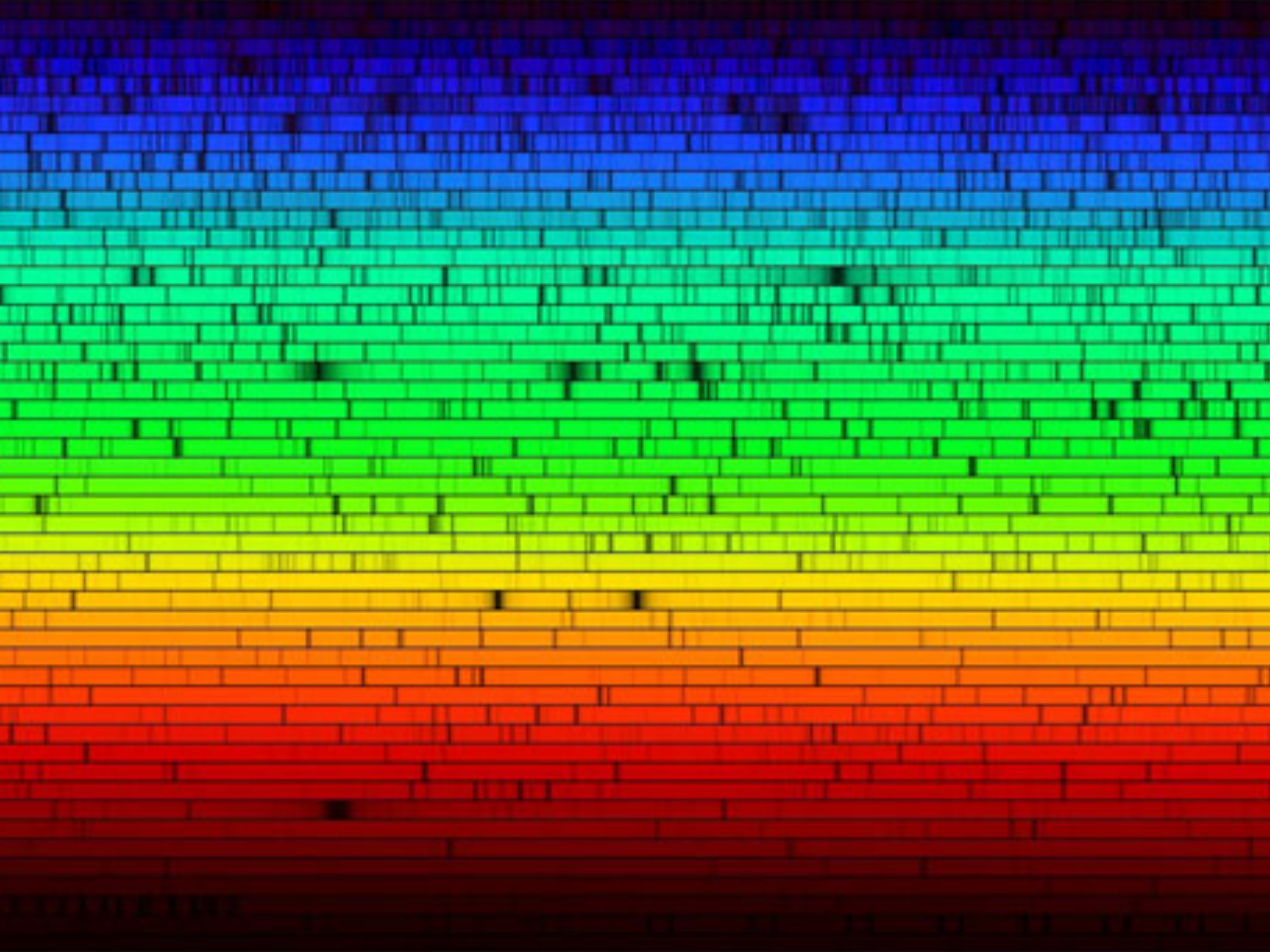
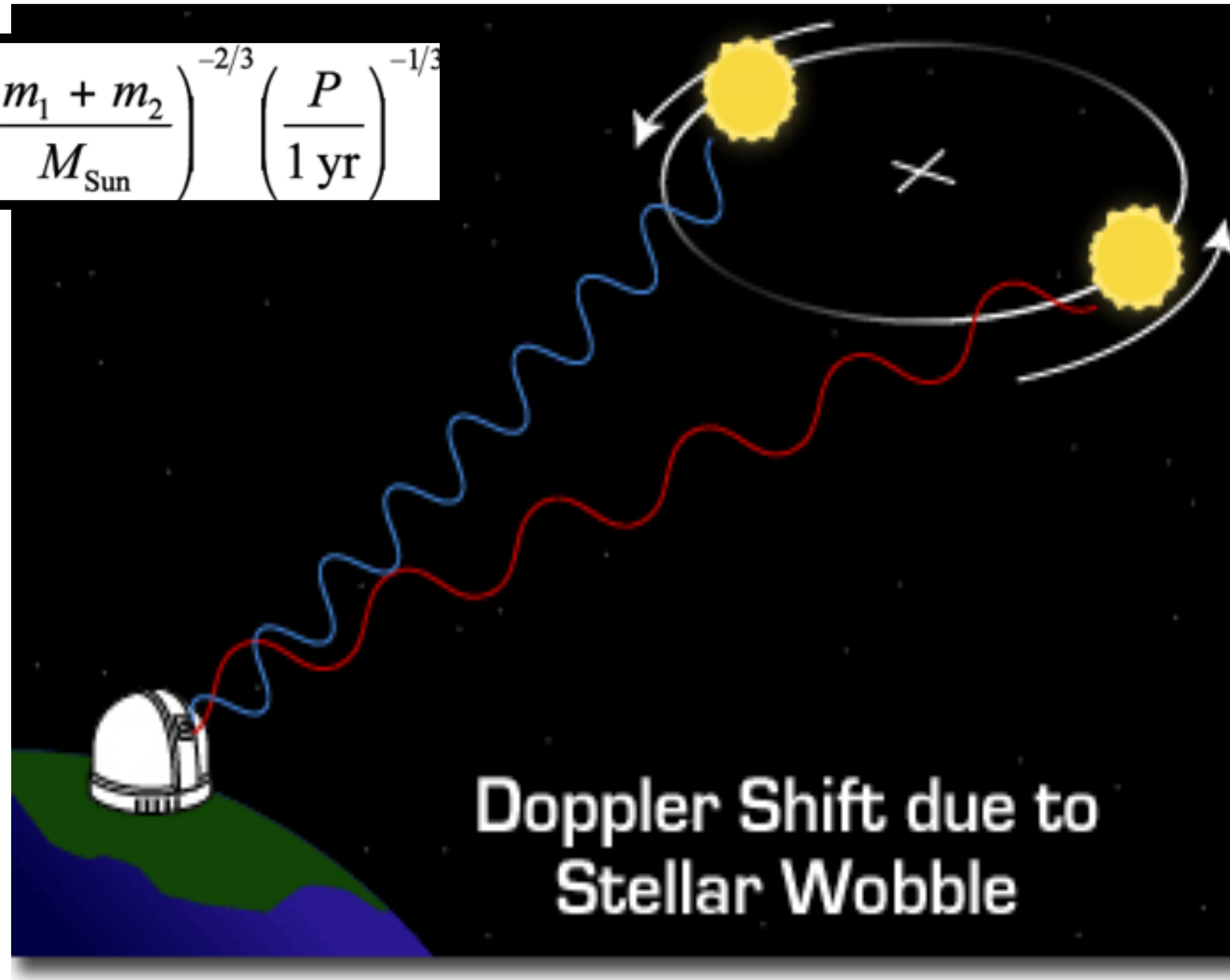


The methods: radial velocities

“weighting” an exoplanet

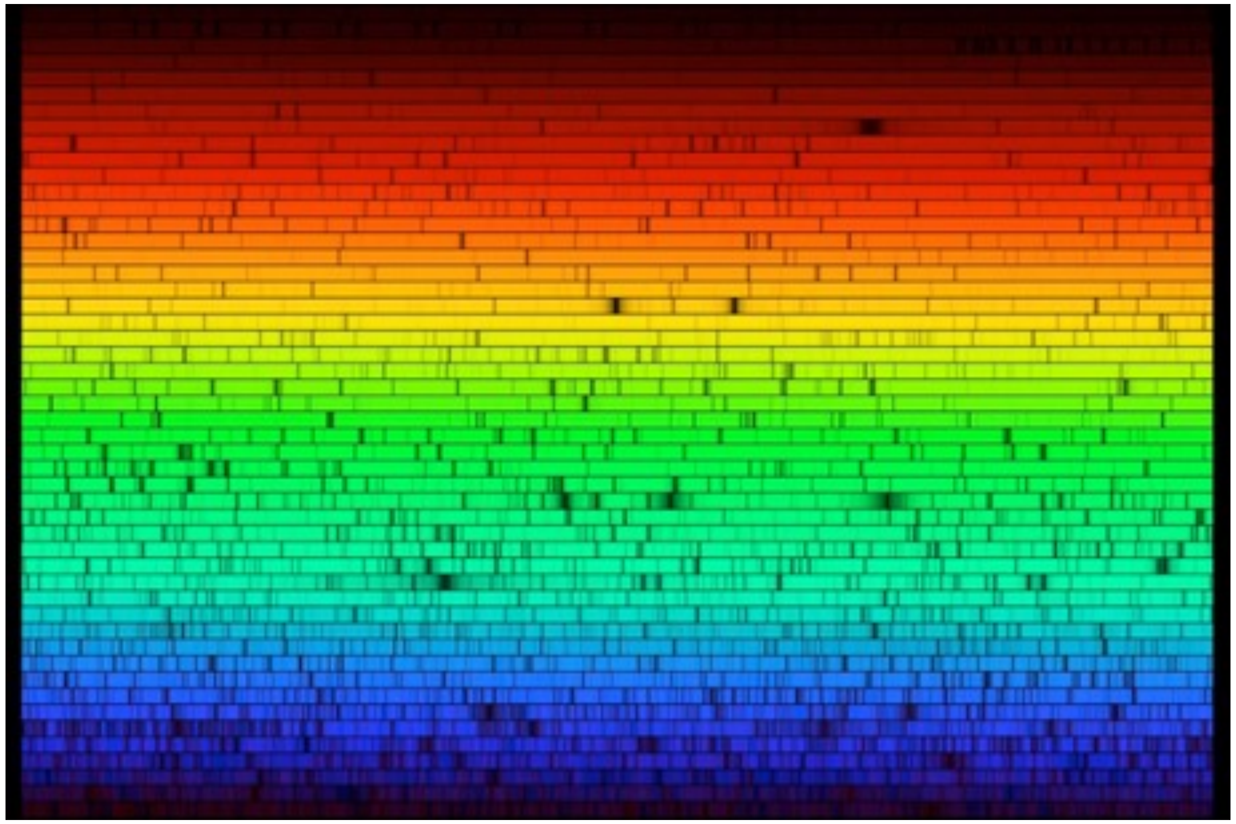
$$k_1 = \frac{28.4\,\mathrm{m\,s^{-1}}}{\sqrt{1-e^2}} \frac{m_2 \sin i}{M_{\mathrm{Jup}}} \left(\frac{m_1 + m_2}{M_{\mathrm{Sun}}}\right)^{-2/3} \left(\frac{P}{1\,\mathrm{yr}}\right)^{-1/3}$$

More sensitive to short period “massive” planets



Early Doppler surveys

- Detecting planets using doppler velocimetry was first proposed in the 1930’s (Belorizky 1932, Struve 1952)
- Early 1980's: first instruments capable of achieving ~15 m/s precision (Campbell & Walker 1985; Marcy & Butler 1988)
  - No planets detected in their small sample (Walker et al. 1995; Marcy et al. 1994)
- 1990’s: several surveys achieved precisions ~3-15 m/s (e.g. ELODIE@OHP-France, Lick survey)
  - The scenario was set for the discovery of giant planets orbiting solar-type stars



RVs at the m/s precision

- What RV precision amplitude is expected?

Planet	Separation (AU)	RV Amp. (m/s)
Jupiter	1	28.4
Neptune	0.1	4.8
Neptune	1	1.5
SuperEarth	0.1	1.4
SuperEarth	1	0.5
Earth	1	0.1

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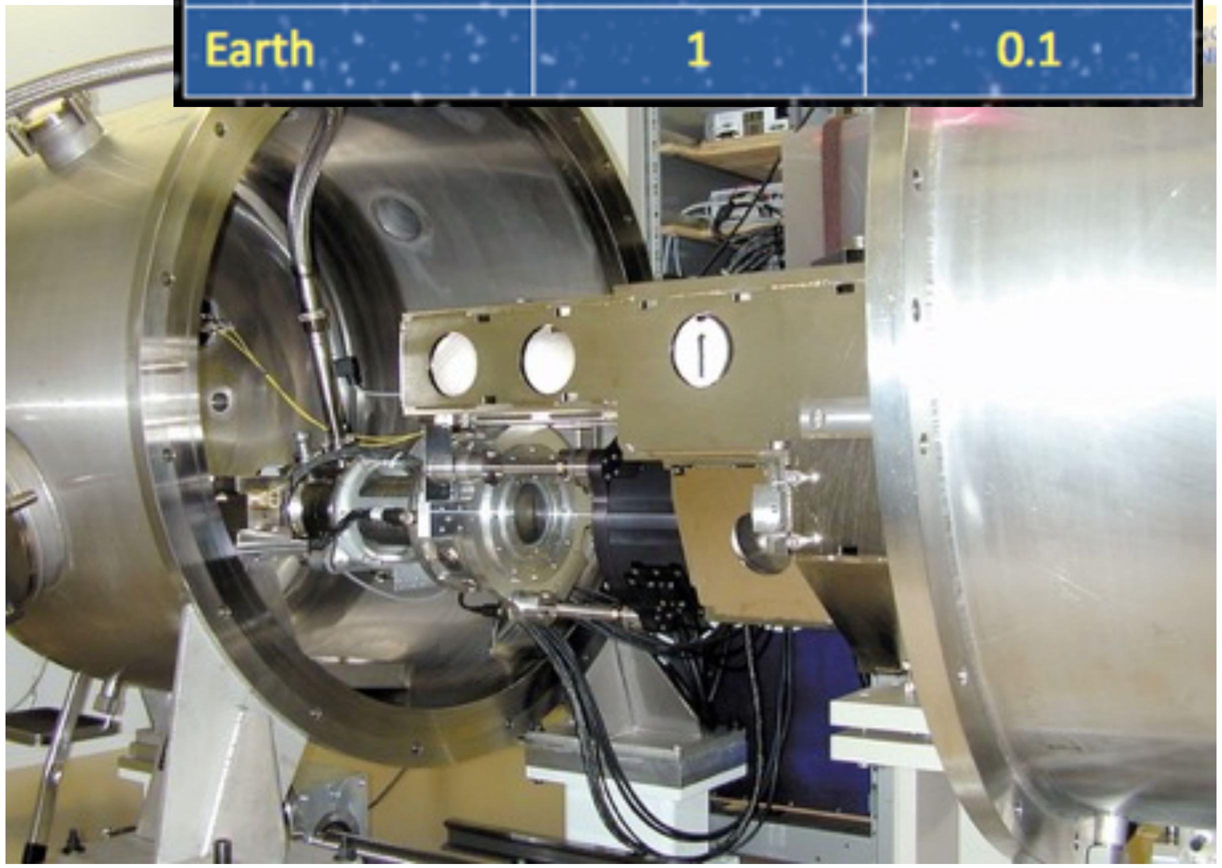
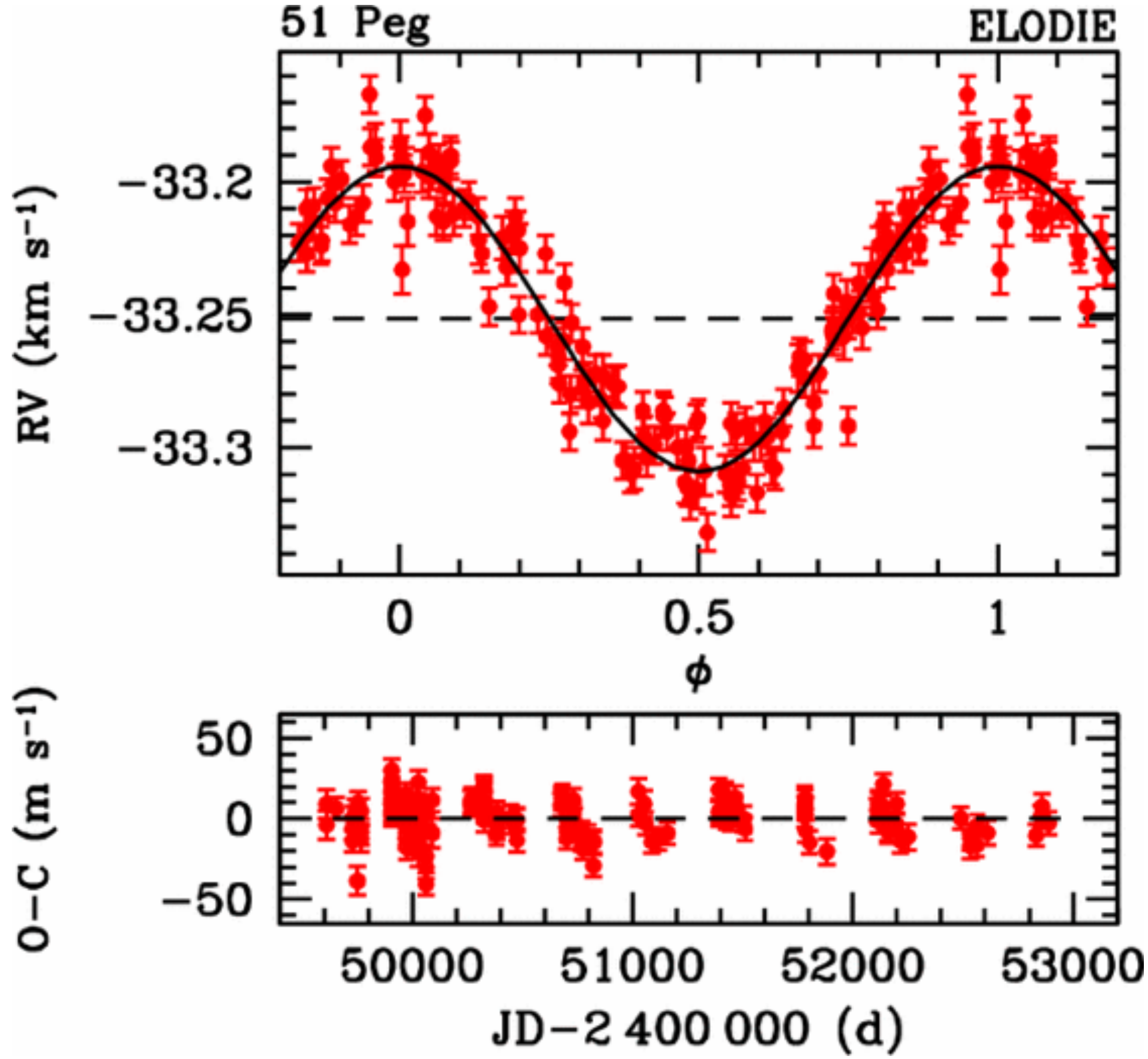
- We need high precision…
- Early 2000's: <1 m/s precision achieved by best instruments (e.g. HARPS/2003)



51 Peg b: 1995, the saga begins

- A bright G2V, metal-rich star
- A giant planet (~0.5 Mjup)
- A short period orbit (4.2 days)
- Everything astronomers were not expecting to find: is this a planet???



(Mayor & Queloz 1995)

The surprise of hot Jupiters

- Models (based on Solar System) expected giant planets to be formed and orbit beyond the ice-line (e.g. Pollack et al. 1996)
- Lin et al. (1996): planet migration is possible!
- Transit detections: confirm that these are indeed planets (first in Charbonneau et al. 1999)

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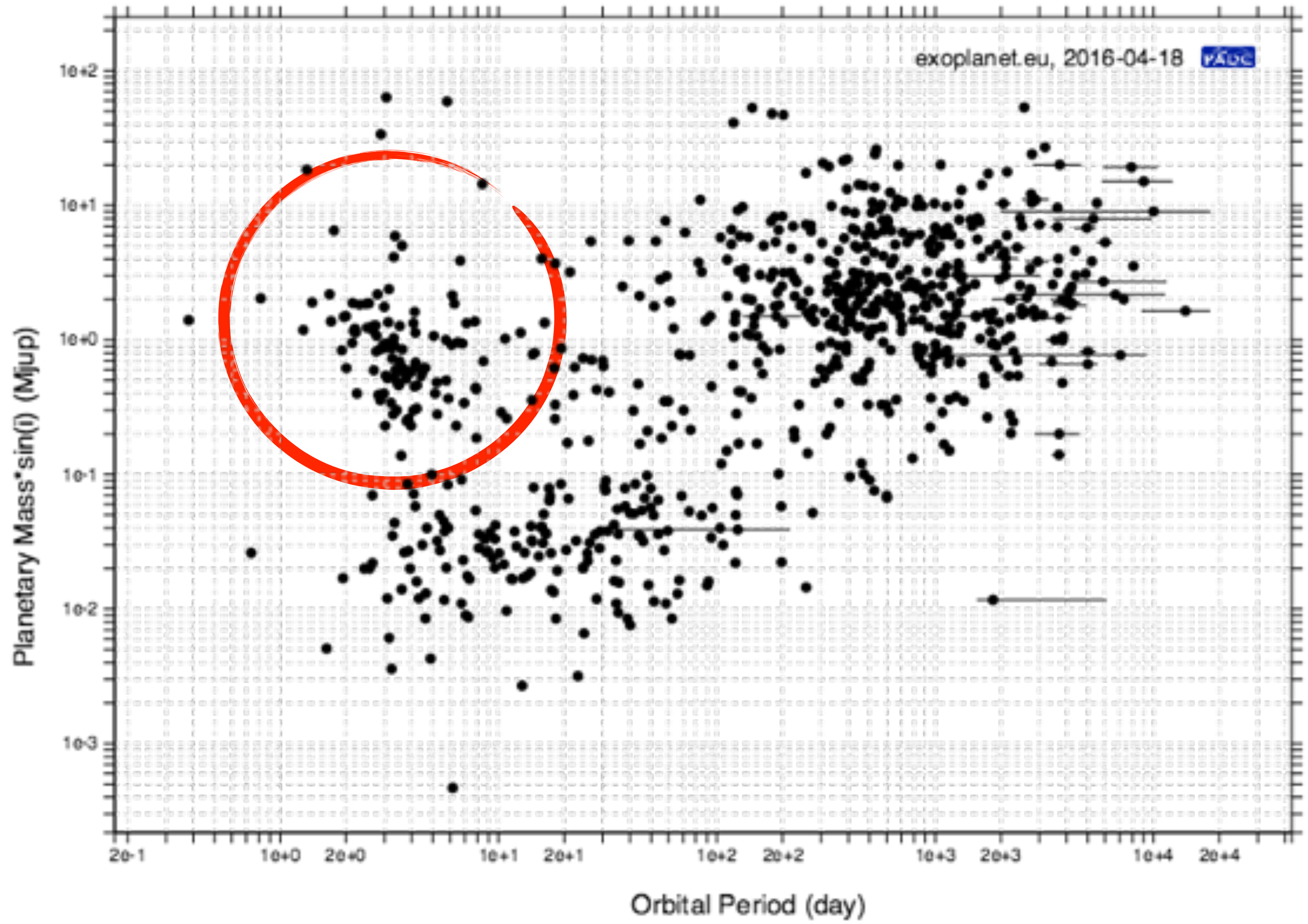
- We know today that short period giant planets are "common"



Hot Jupiters are "common"!

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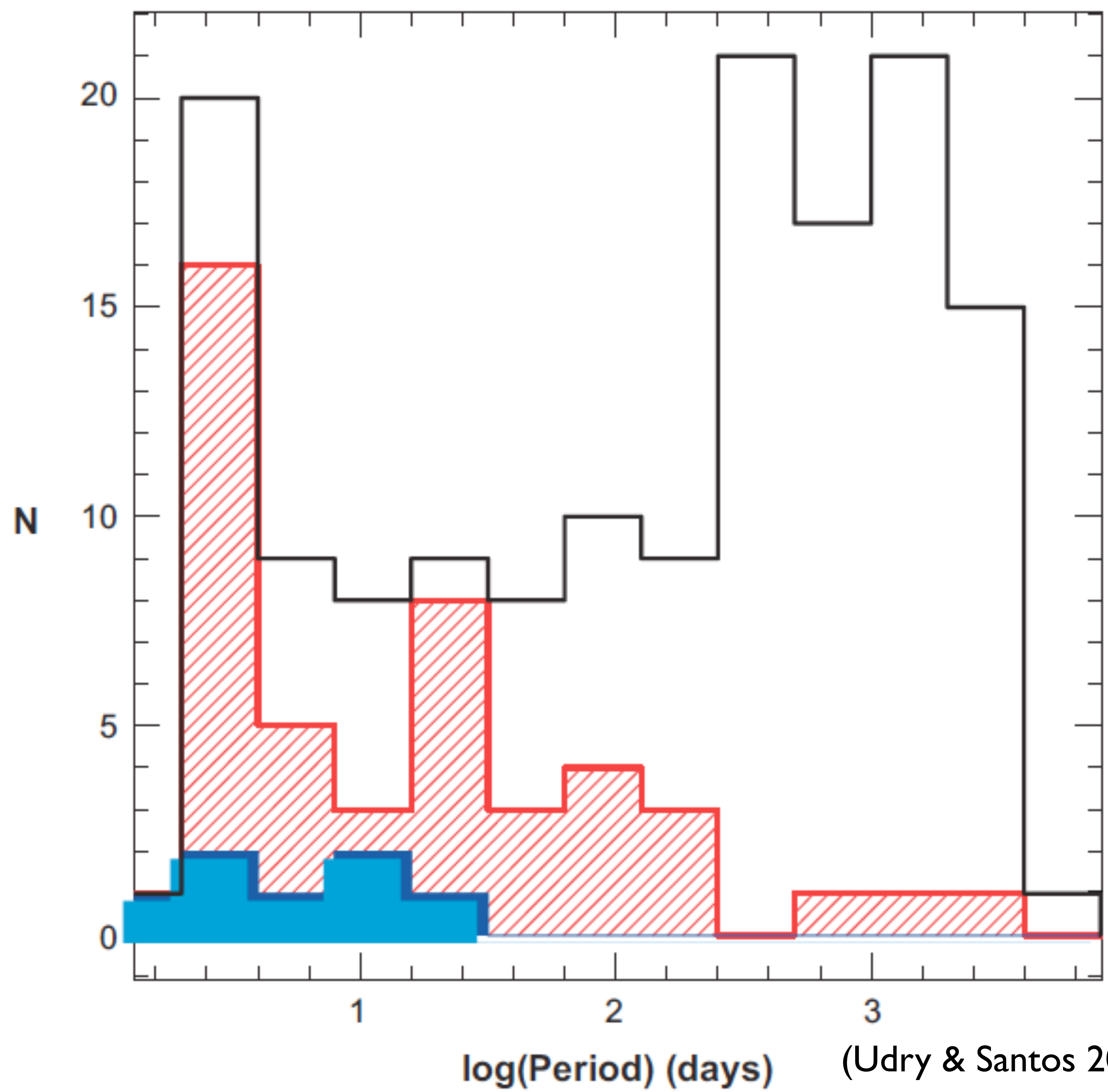
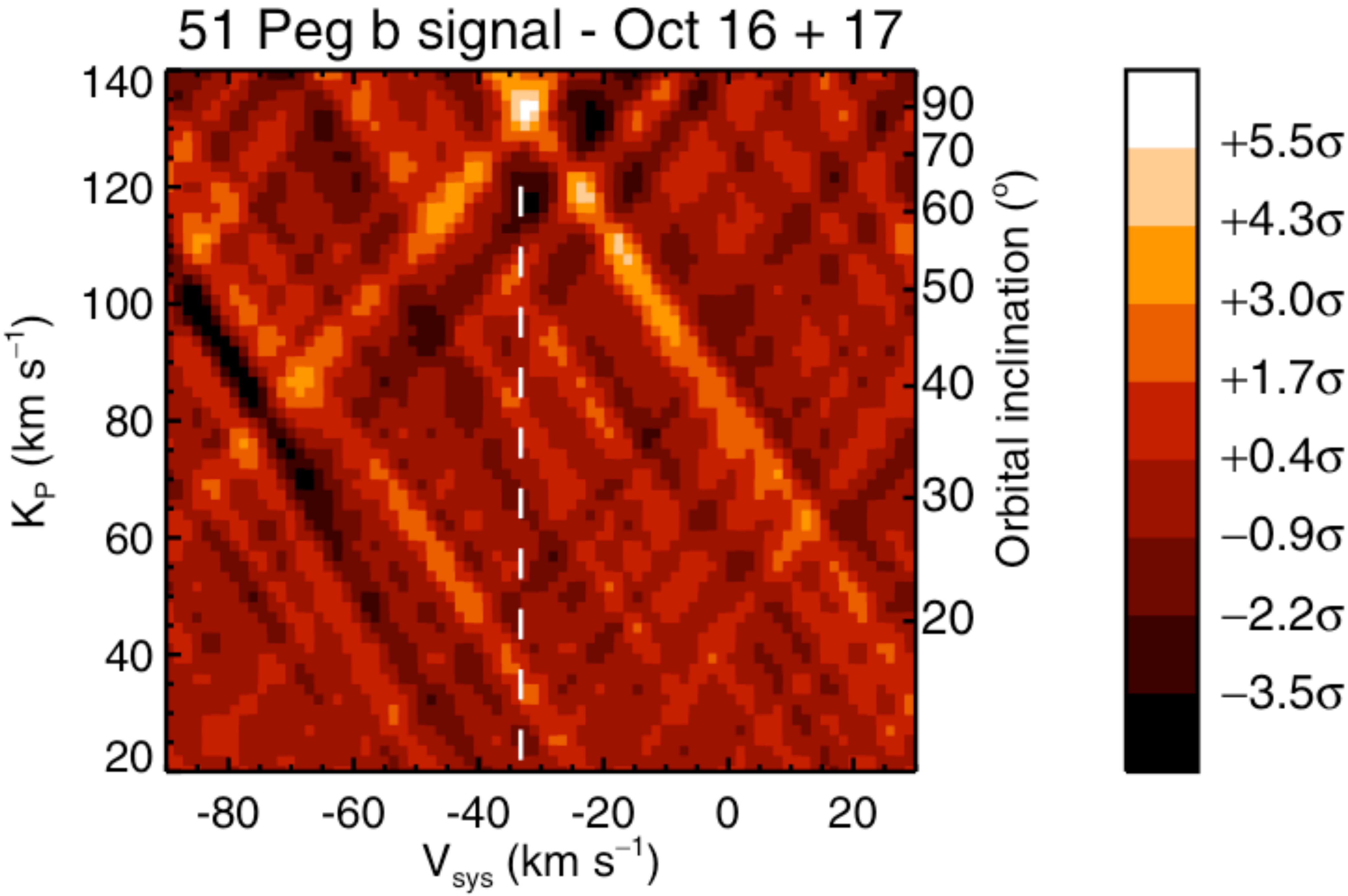


(Udry & Santos 2007)

- We know today that short period giant planets are "common"

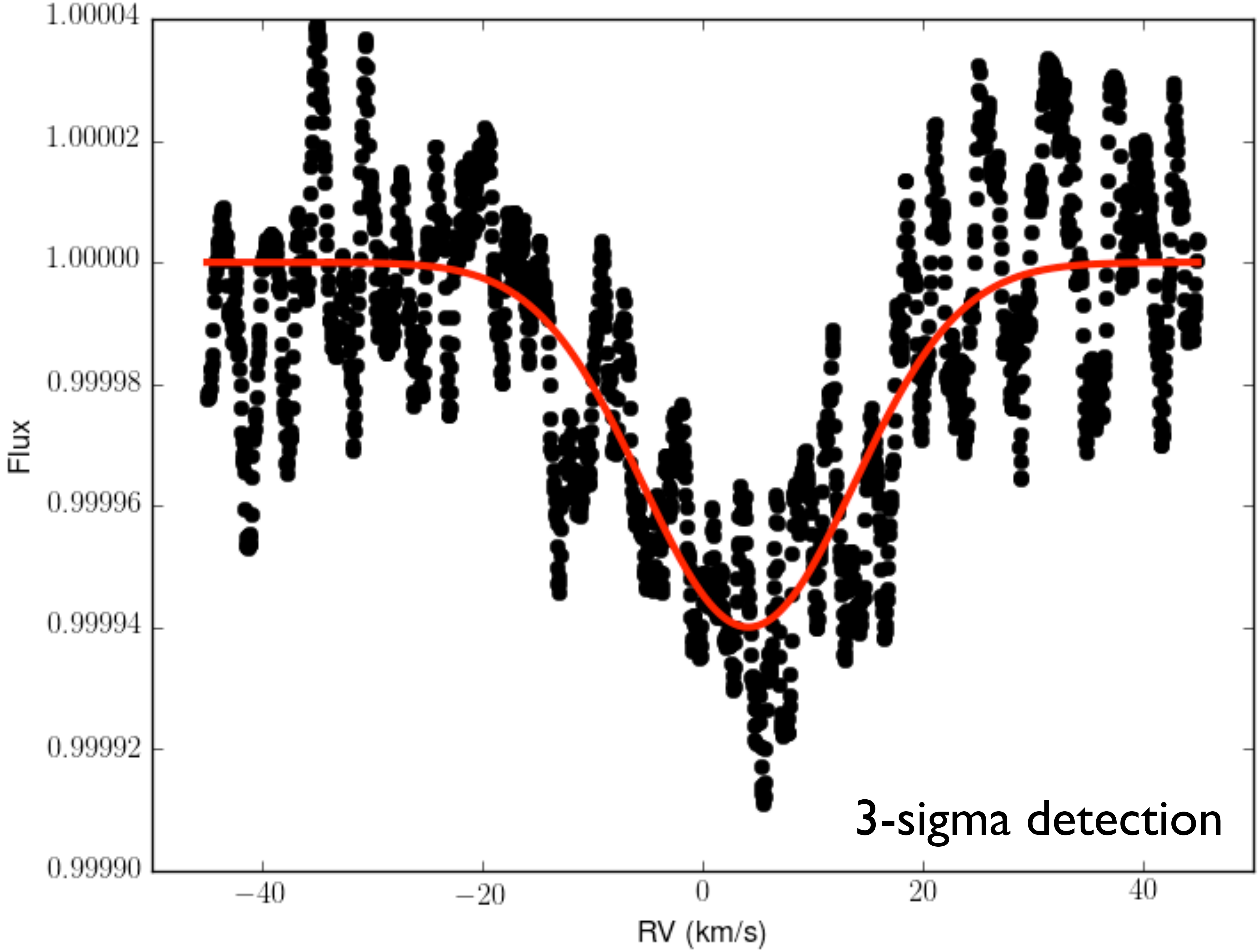
Molecular absorption from the atmosphere of 51 Peg b



(from Infra-Red spectroscopy - Brogi et al. 2013)

The detection of the reflected spectrum: 51 Peg b

Martins et al. 2015



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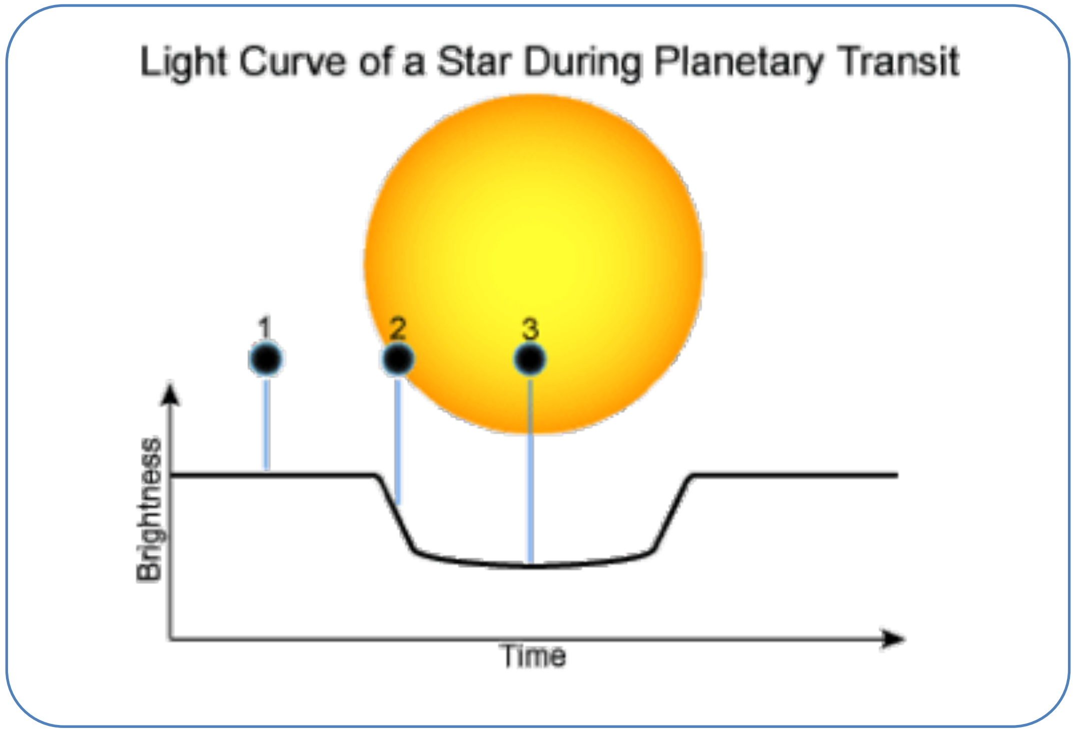
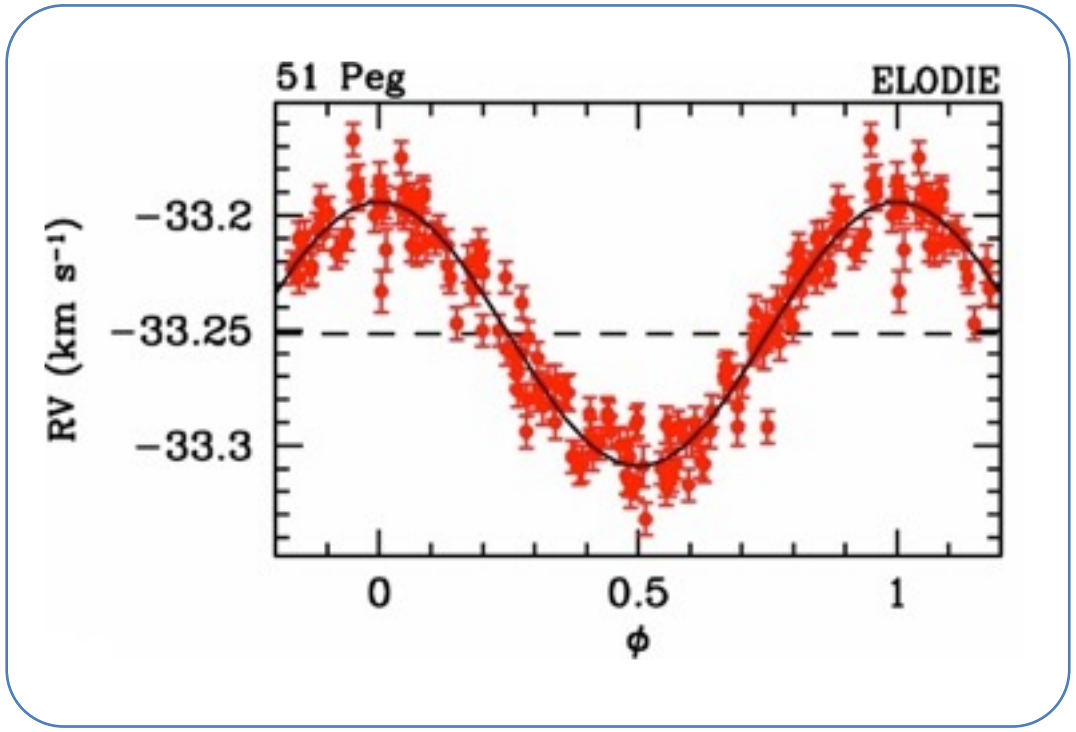
Combining methods...





➡Orbit parameters
➡Planet radius

➡Orbit parameters
➡Planet mass

Planet mass and mean density!
Composition through models!

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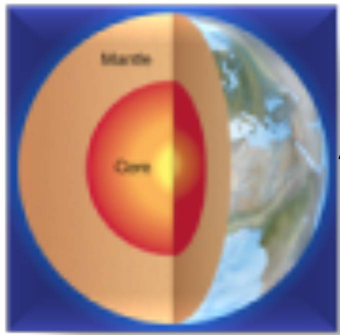
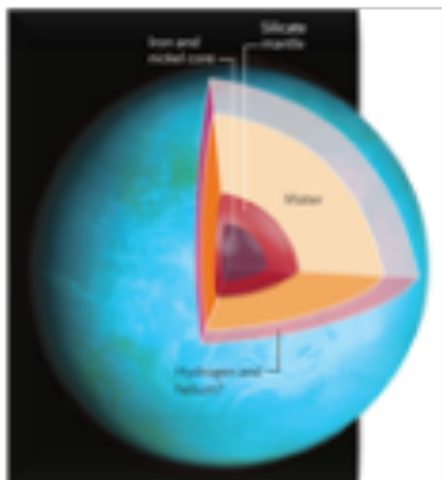
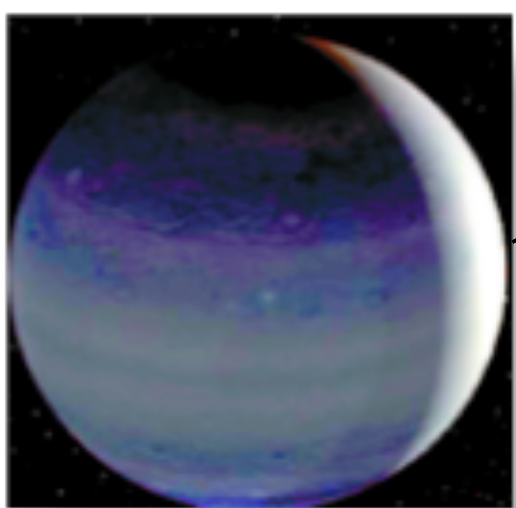


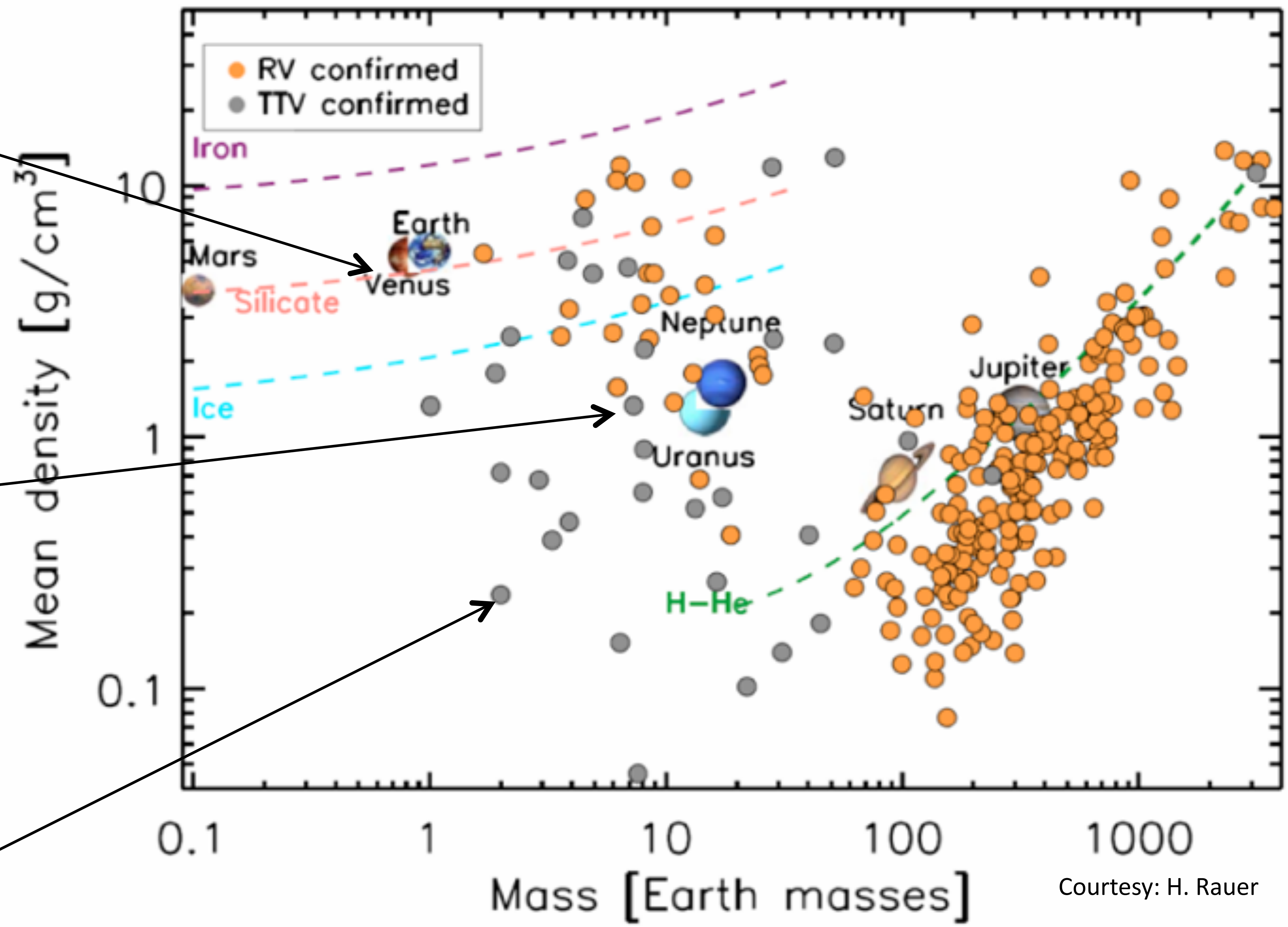
Earths (5 g/cm^3)



"ice giants" (1.6 g/cm^3)



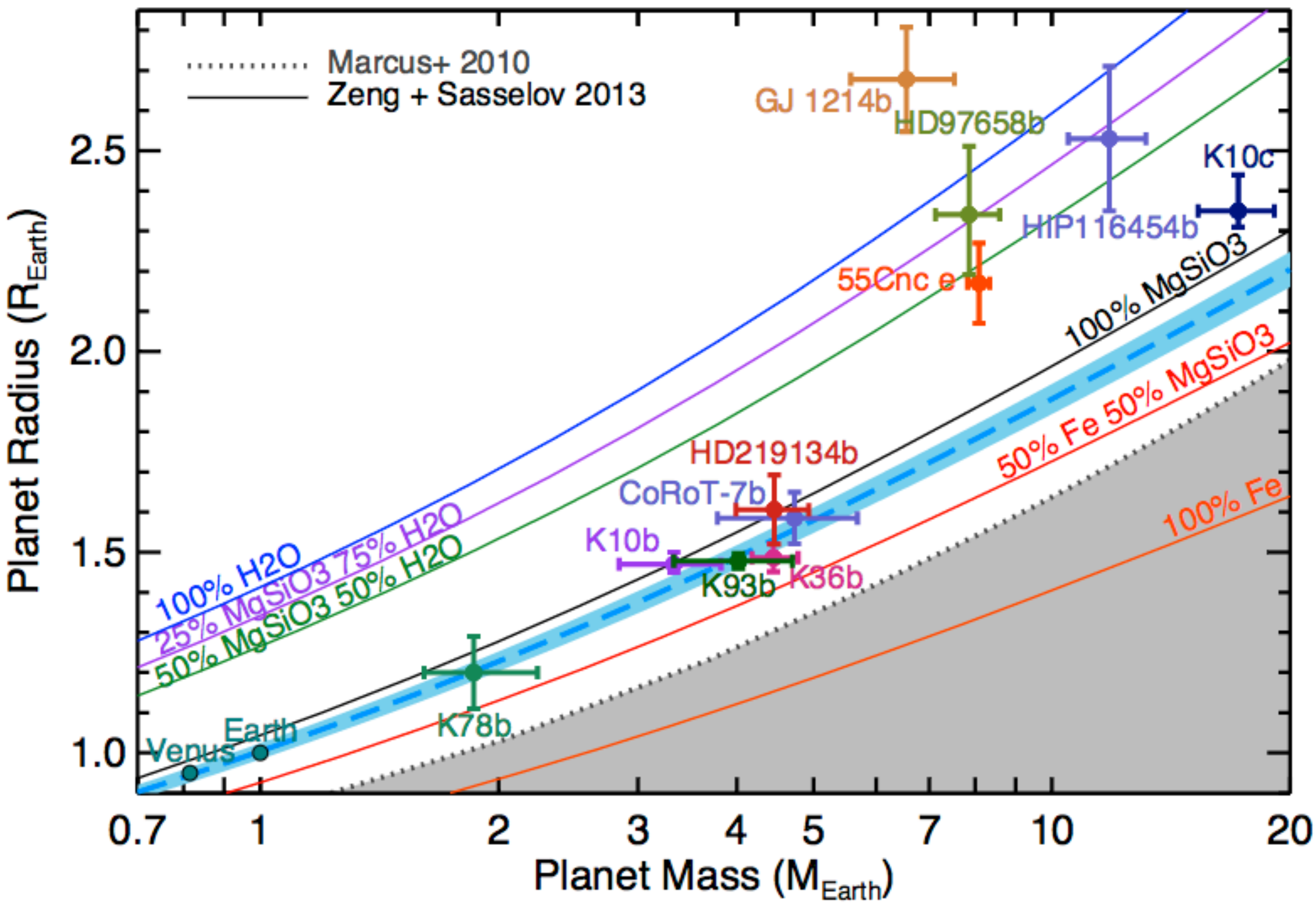
"mini-gas giants" (<1 g/cm^3)



Courtesy: H. Rauer

Combining the two...

The low end of the mass-radius diagram



Dressing+2015, Motalebi+2015

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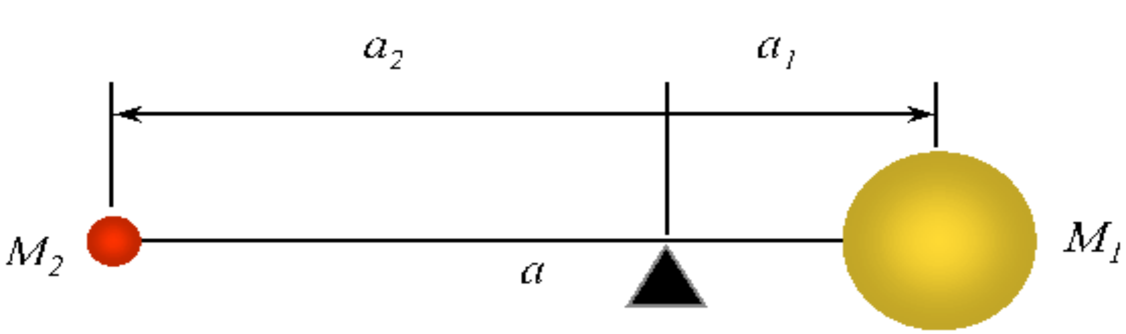
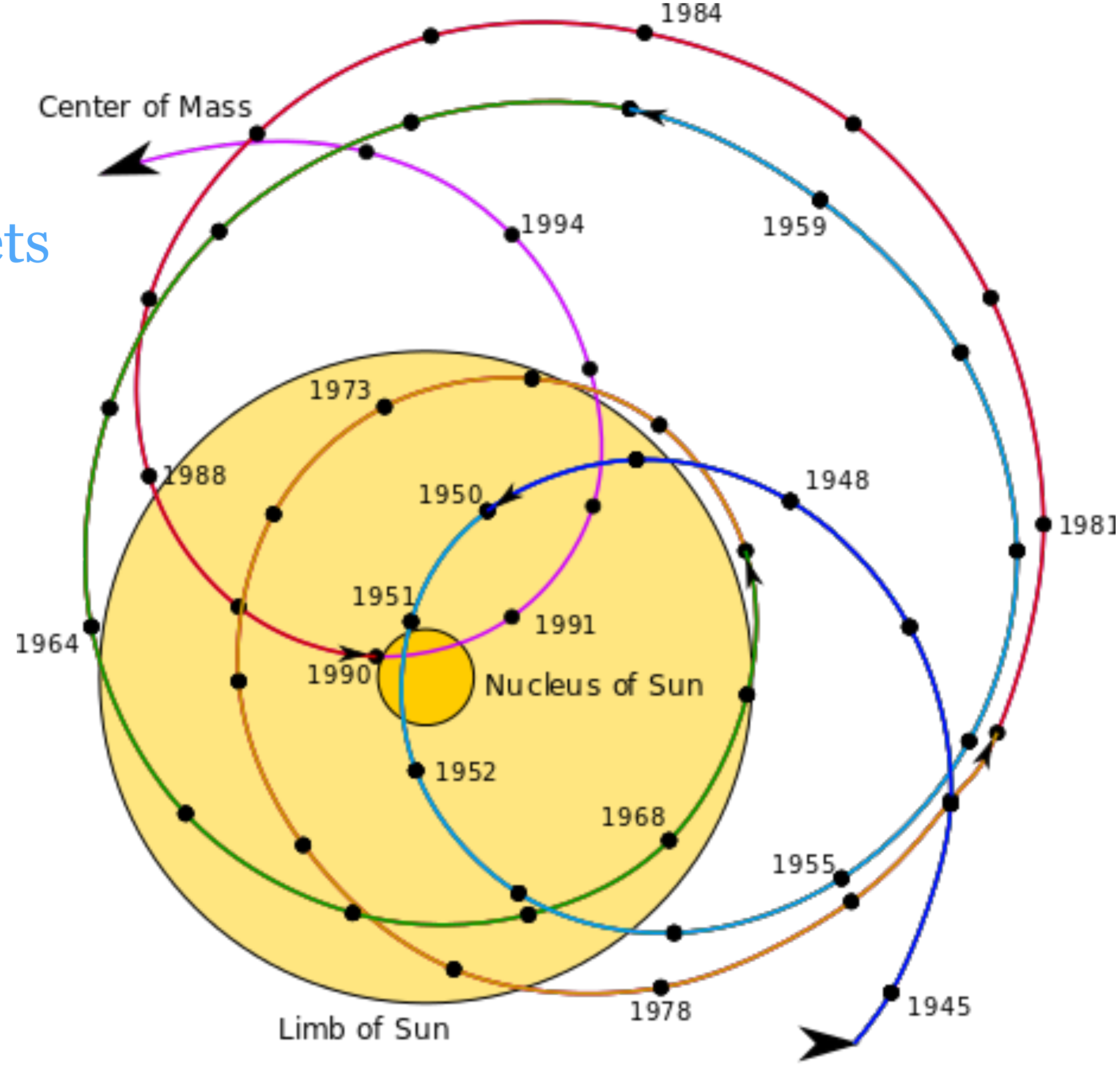
Finding planets: other methods

The methods: astrometry

Amplitude of signal depends on distance to star, planet mass, stellar mass, orbital period

More sensitive to long period planets





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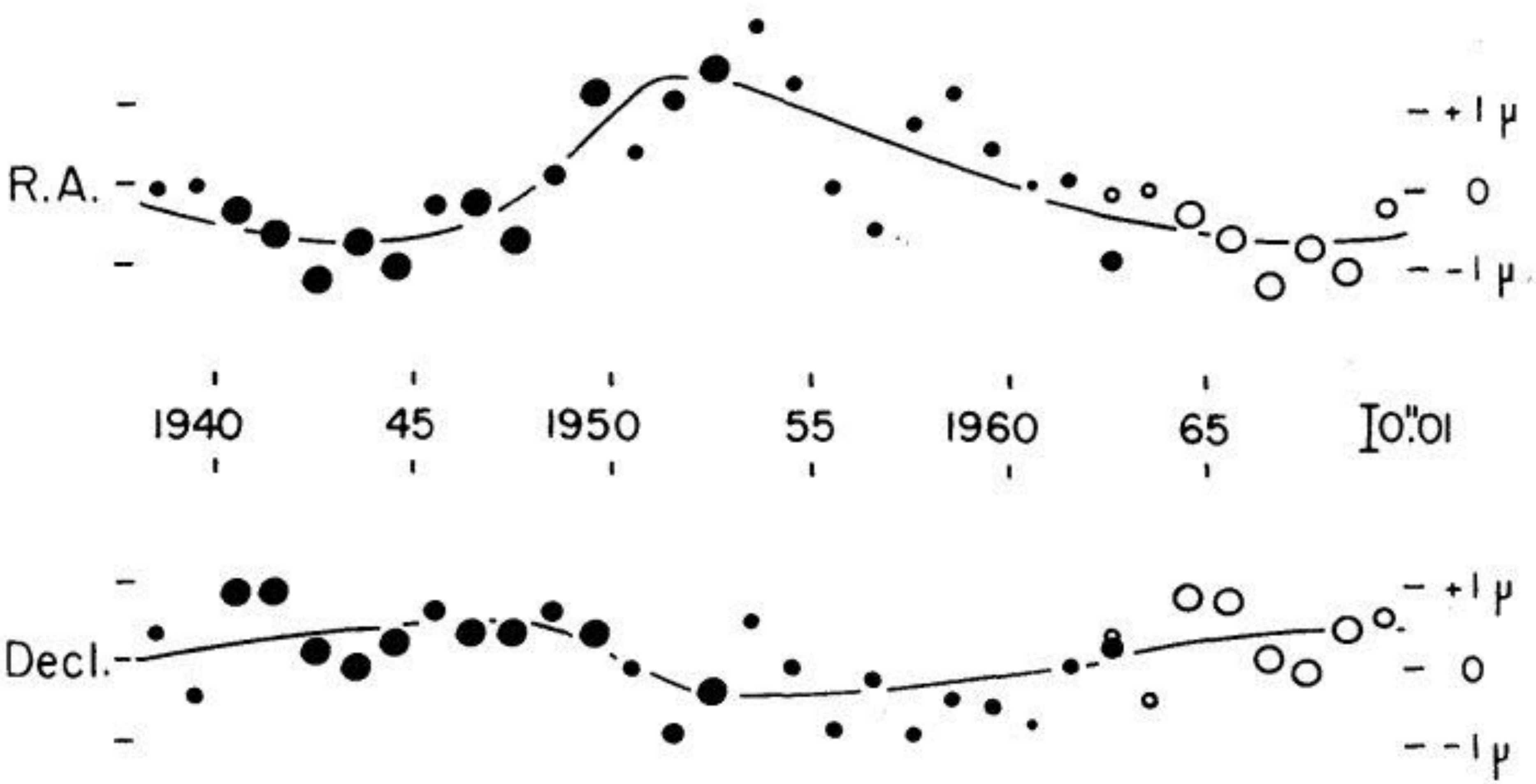
Peter van de Kamp

Astrometry of Barnard's star: up to 3 planets!



The methods: astrometry

$$\xi = \alpha_0 + \mu_\alpha(t - t_0) + P_\alpha \pi + y$$

$$\eta = \delta_0 + \mu_\delta(t - t_0) + P_\delta \pi + x$$

Propper motion and parallax

Planet signal

$$x = AX + FY$$

$$y = BX + GY$$

$$X = \cos E - e$$

$$Y = \sqrt{1 - e^2} \sin E$$

Thiele-Innes parameters:

$$A = a(\cos\Omega\cos\omega_* - \sin\Omega\sin\omega_*\cos i)$$

$$B = a(\sin\Omega\cos\omega_* + \cos\Omega\sin\omega_*\cos i)$$

$$F = a(-\cos\Omega\sin\omega_* - \sin\Omega\cos\omega_*\cos i)$$

$$G = a(-\sin\Omega\sin\omega_* + \cos\Omega\cos\omega_*\cos i)$$

The methods: astrometry

$$\xi = \alpha_0 + \mu_\alpha (t - t_0) + P_\alpha \pi + y$$

$$\eta = \delta_0 + \mu_\delta (t - t_0) + P_\delta \pi + x$$

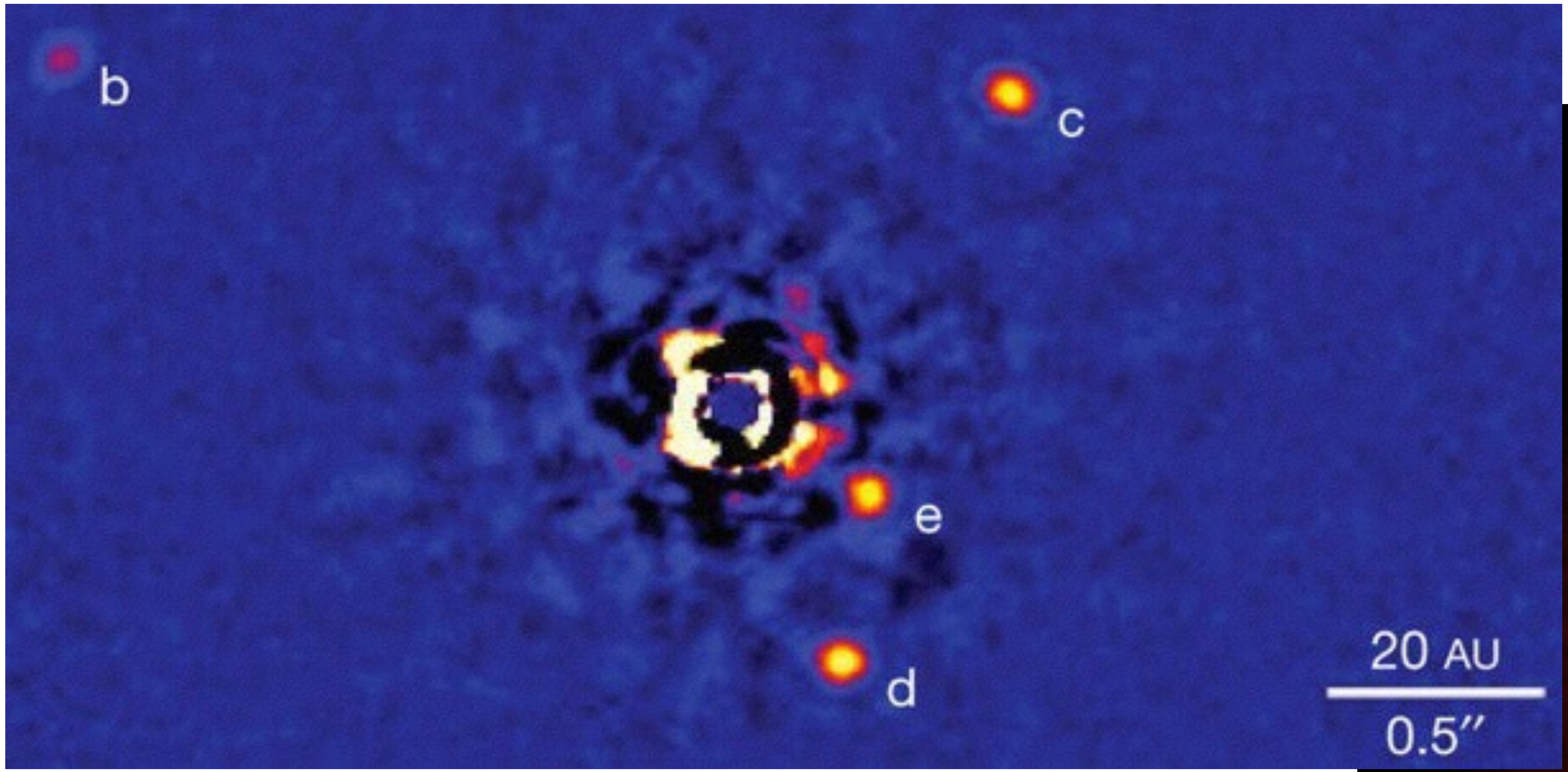
30 mas 60 mas 0.05 mas

(orders of magnitude for a star closer than 30pc)

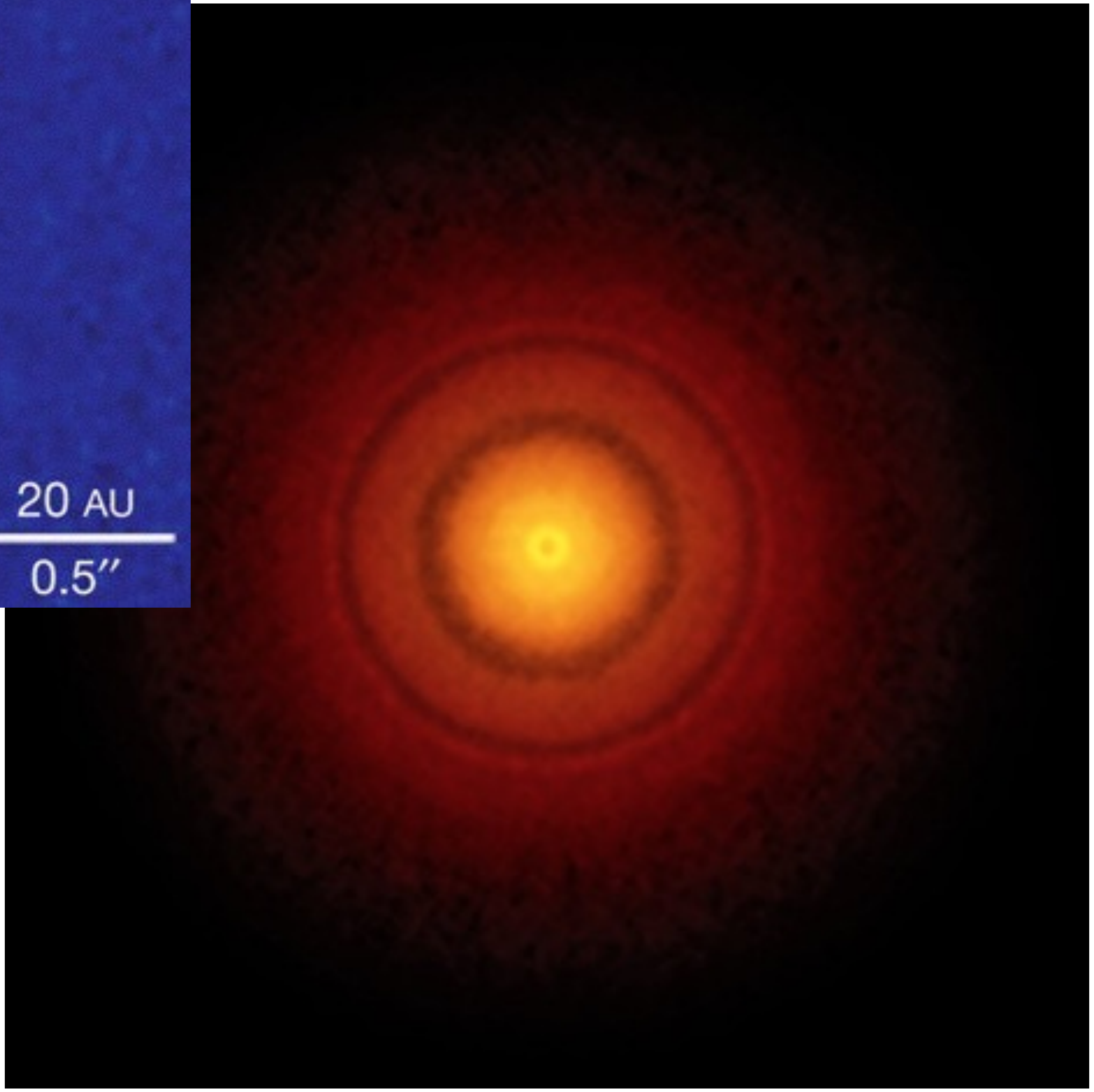
Bright future ahead with GAIA (giant planets in long period orbits)

The methods: direct imaging

“seeing” (young) exoplanets



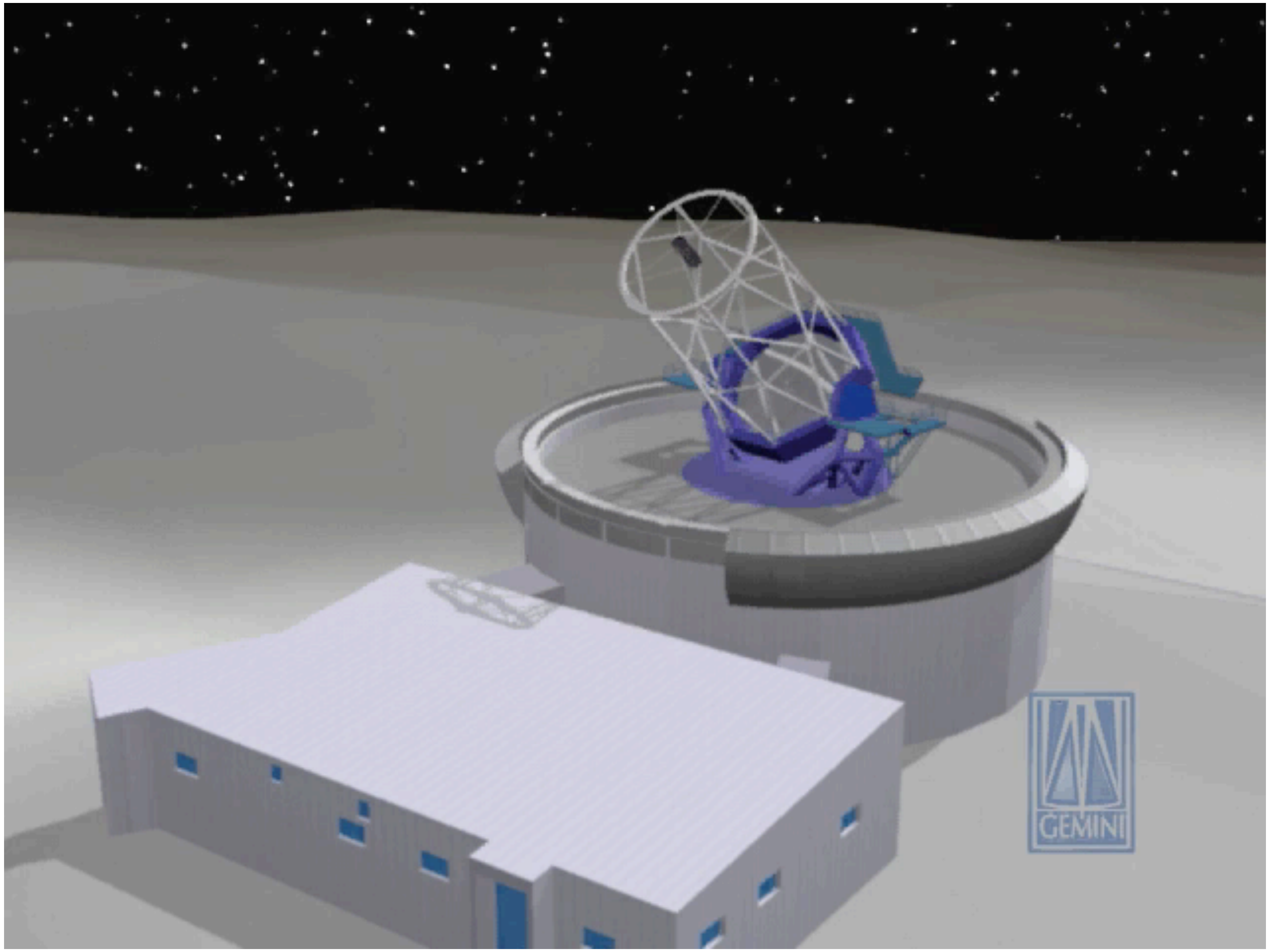
Marois et al. 2013 (3 planets with AO)



ALMA observations of structures in disks

The methods: AO

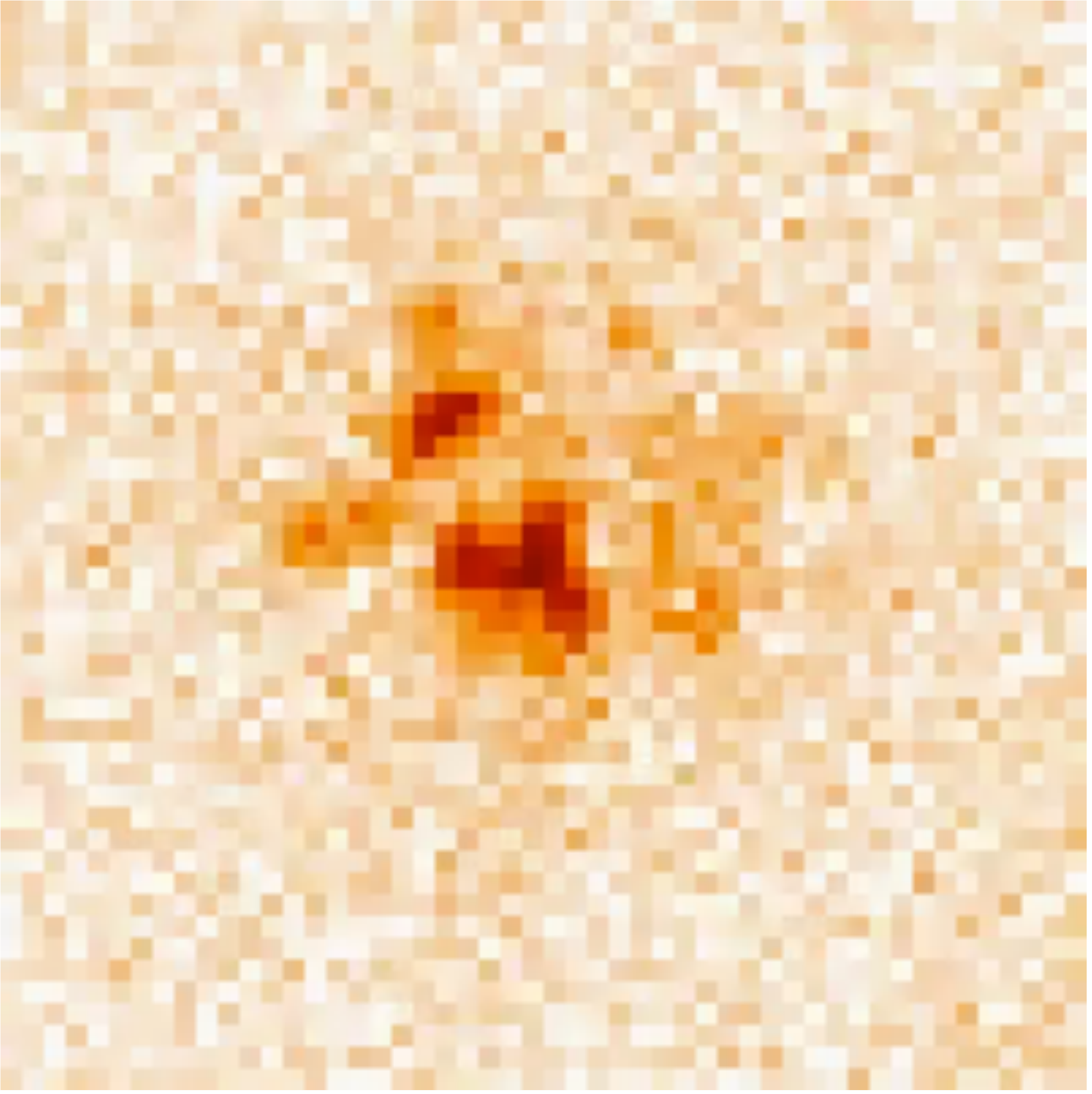
Goal: transform your telescope in a diffraction limited instrument

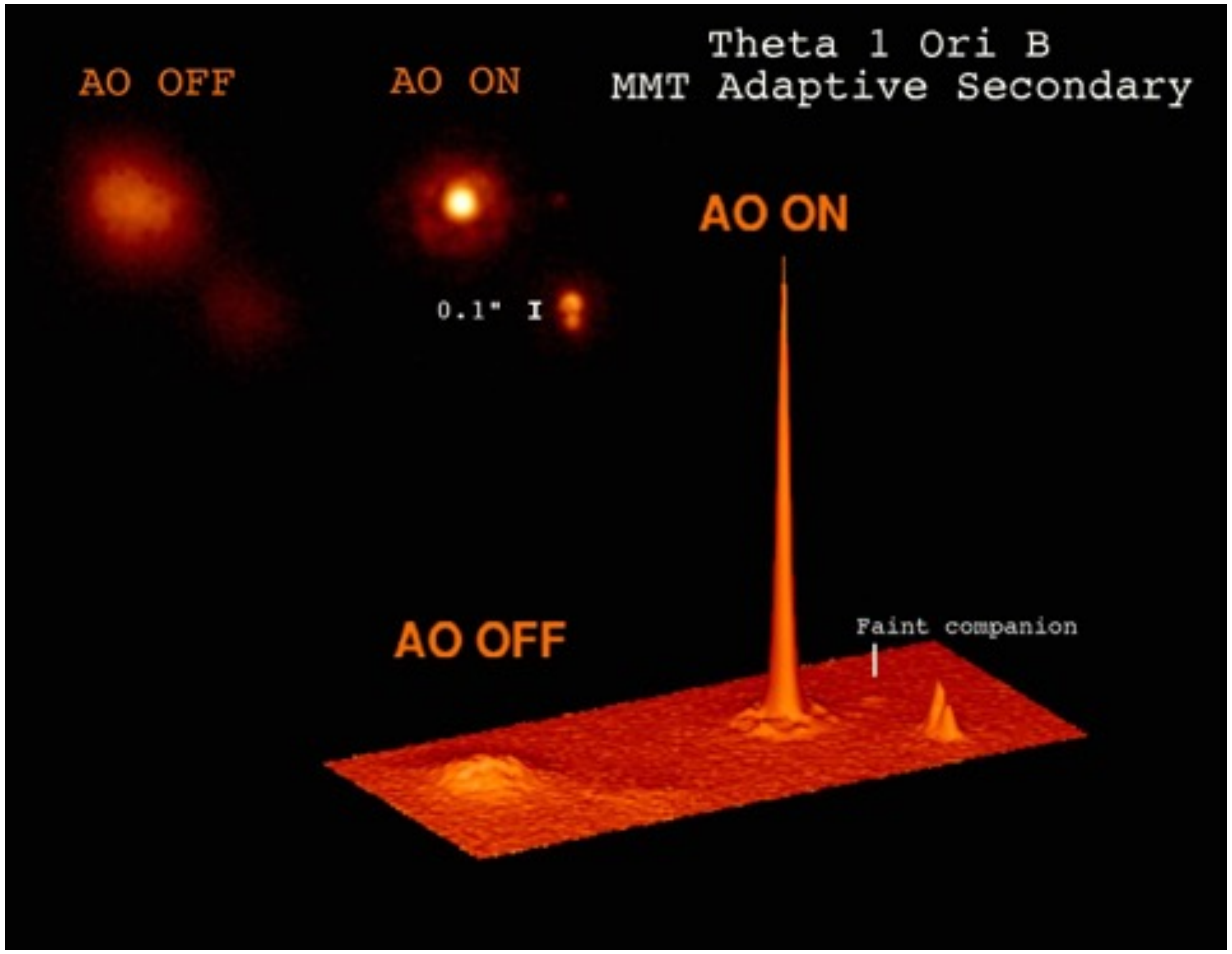


Rayleight criterium:

$$\theta = 1.22\ \lambda/D$$

The methods: AO





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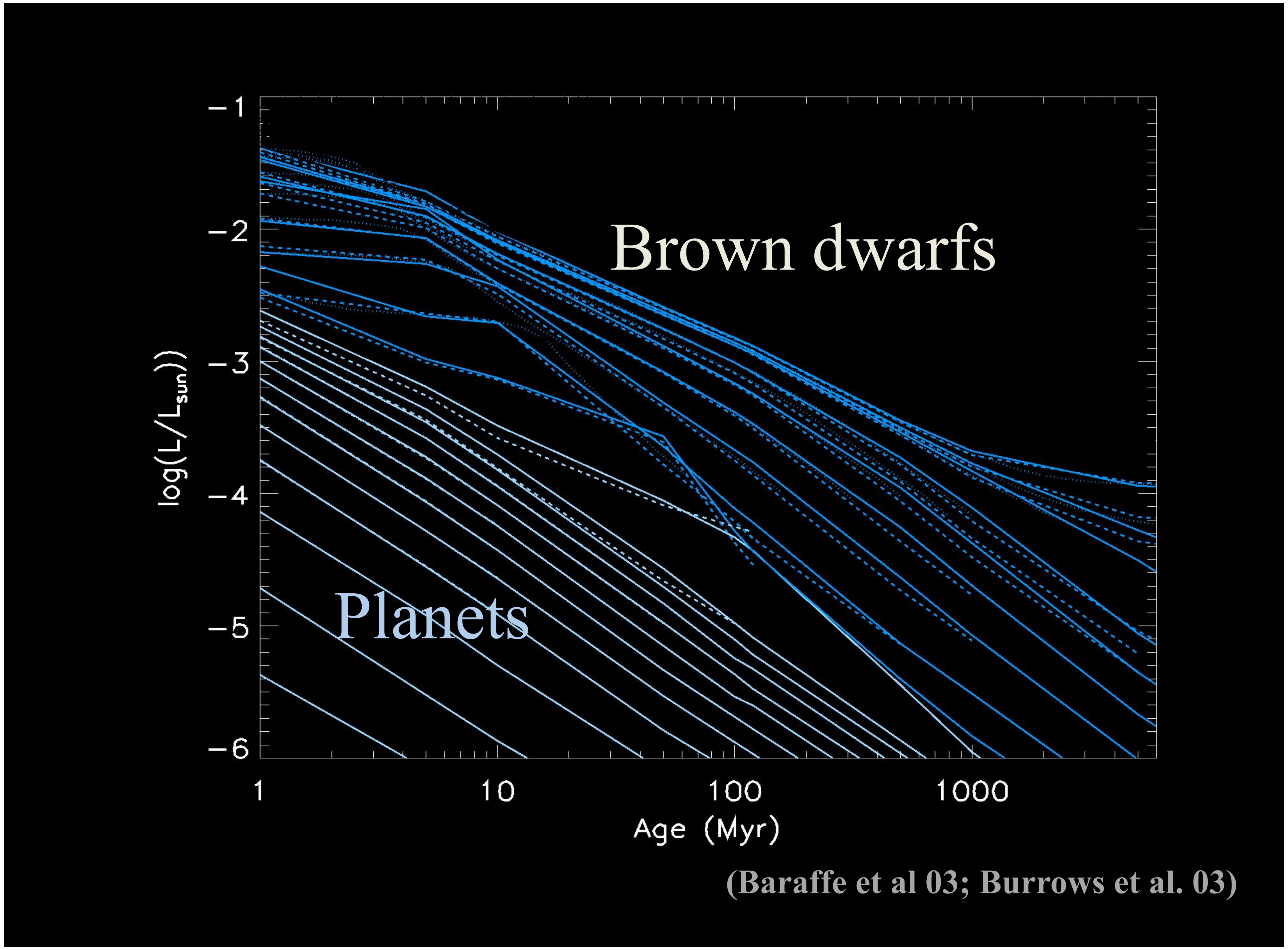

More sensitive to hot young planets

Finding planets: the stellar issue

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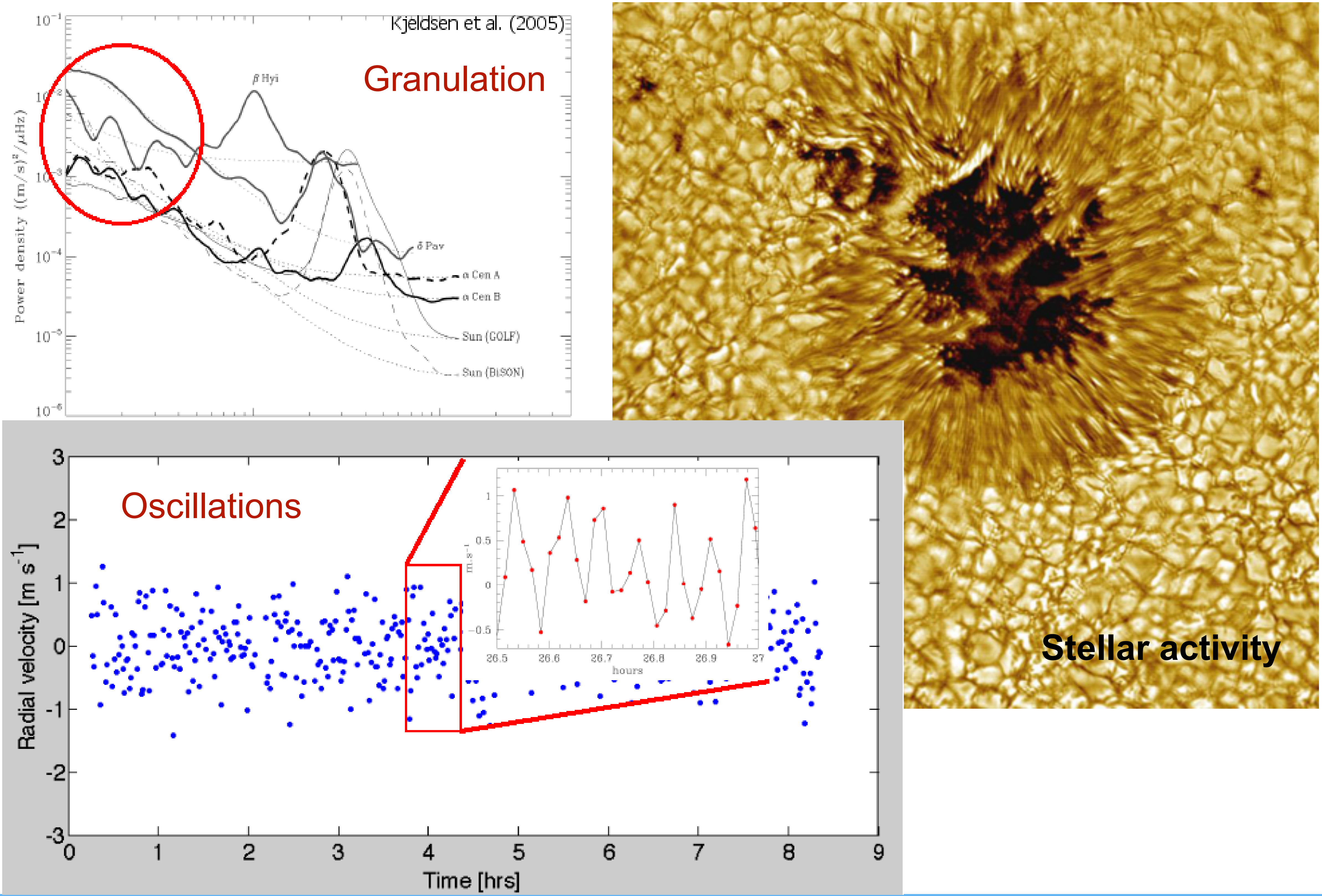
At this level things are not easy



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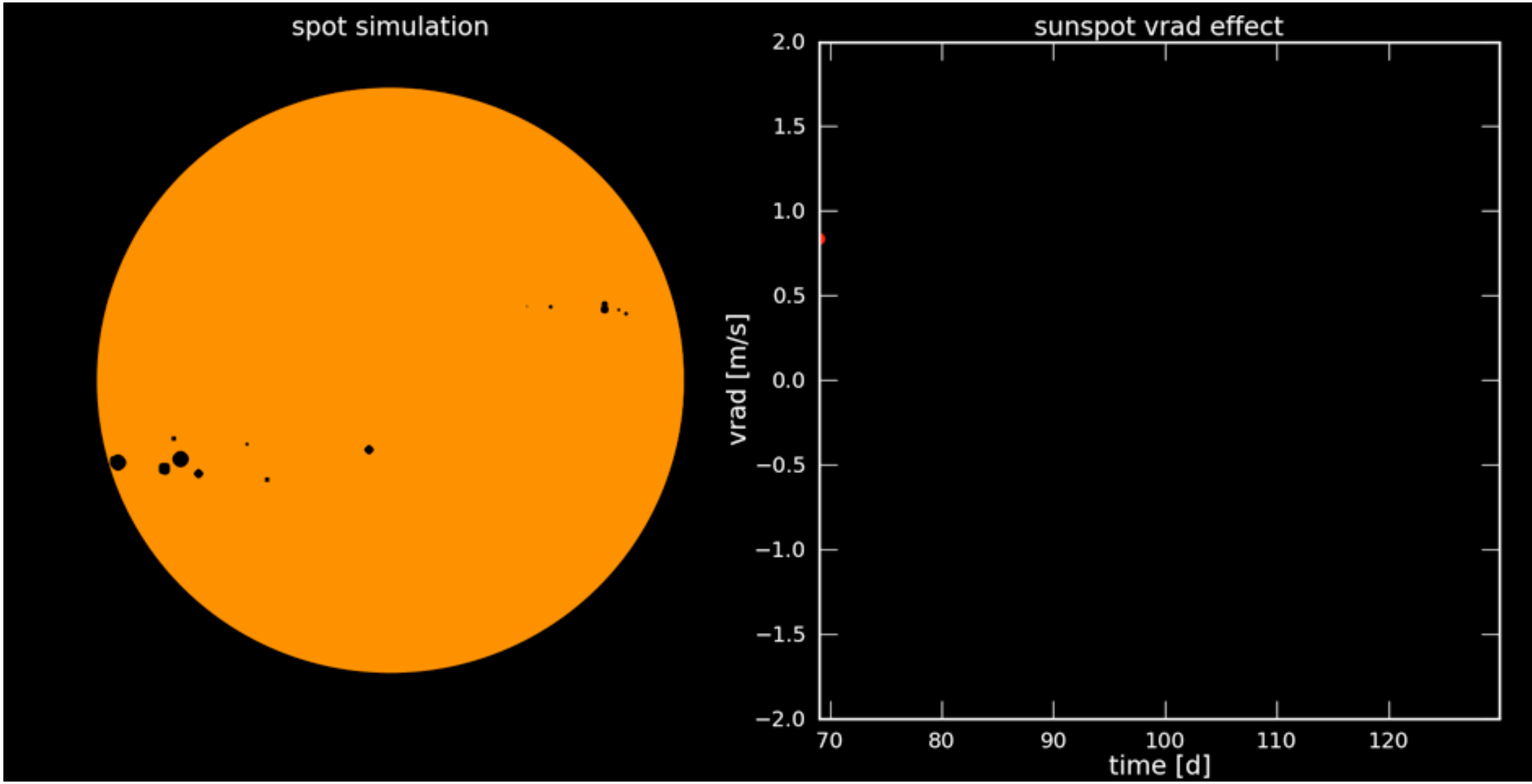
The effect of spots in RV

Simulated solar activity (at maximum) and its effect on RVs



(Courtesy X. Dumusque)

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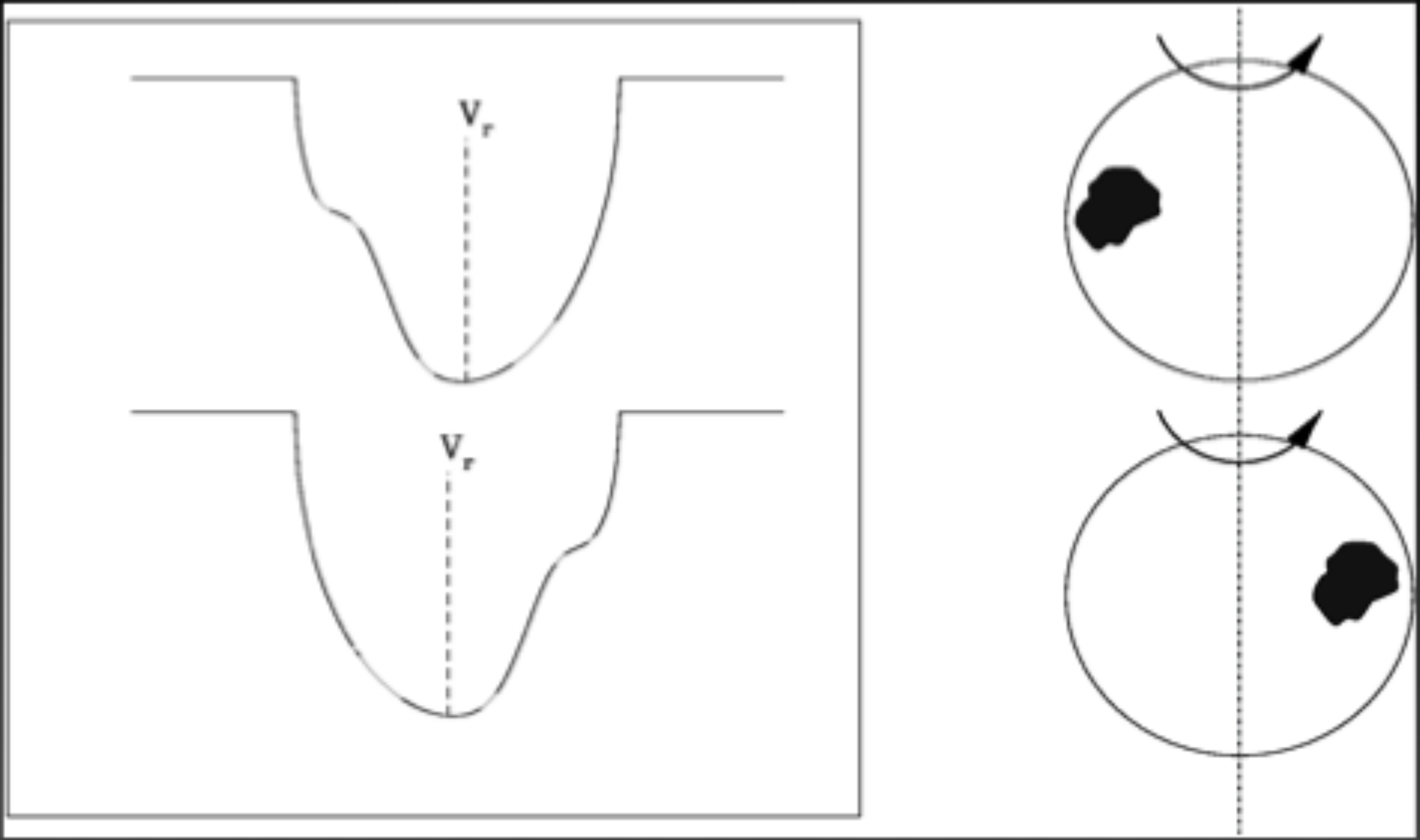
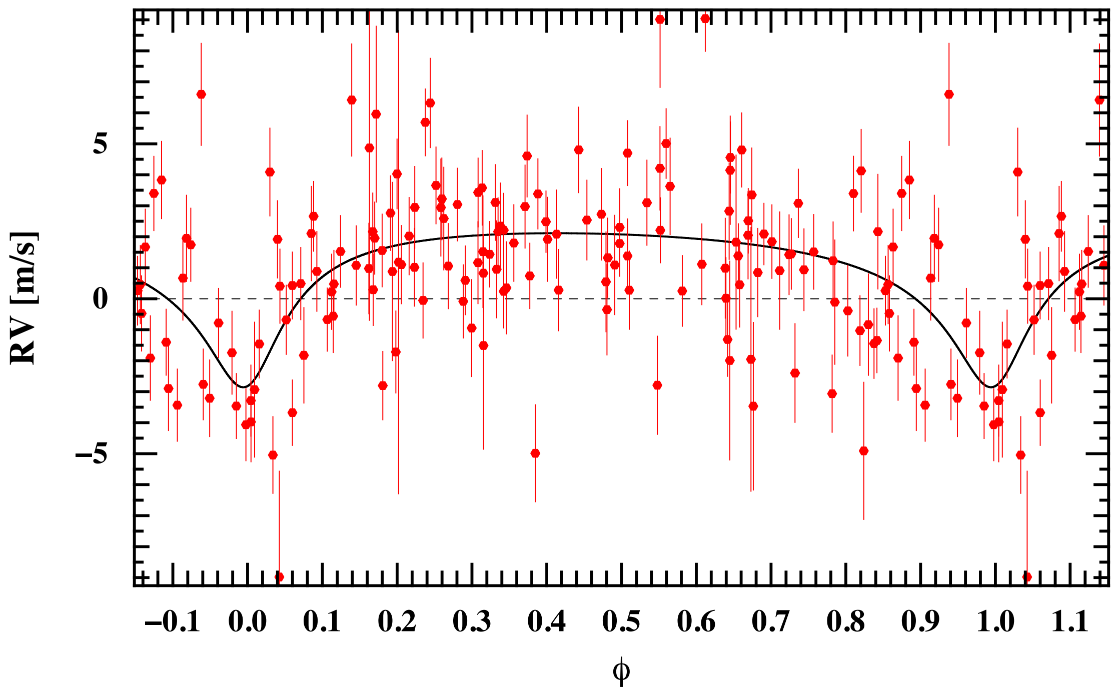
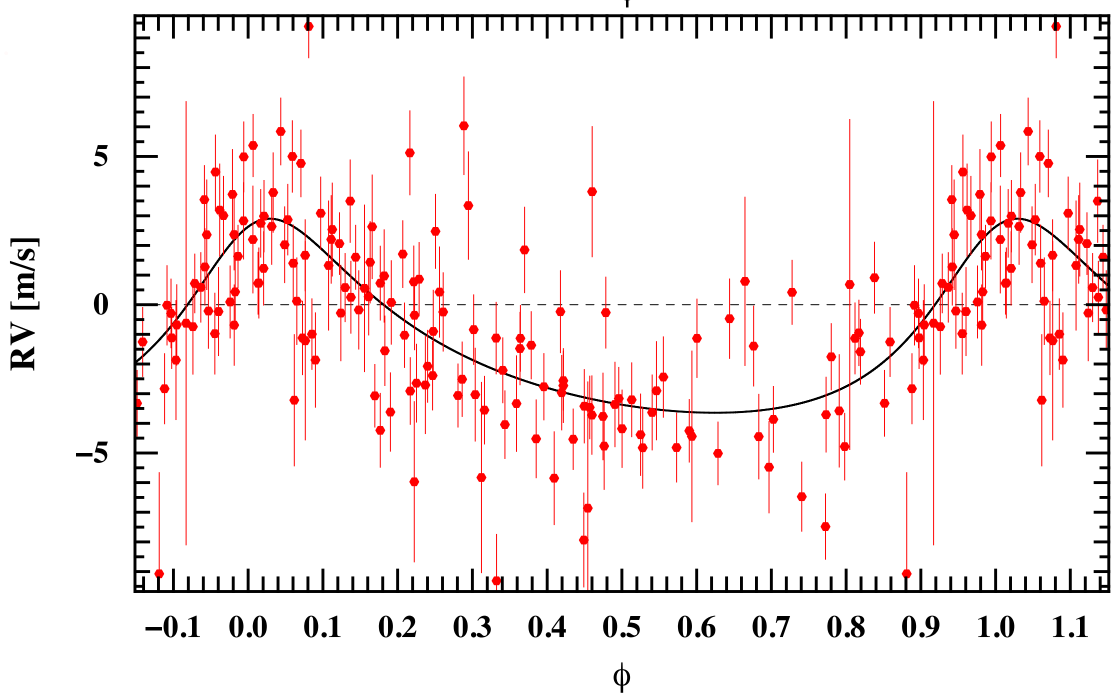
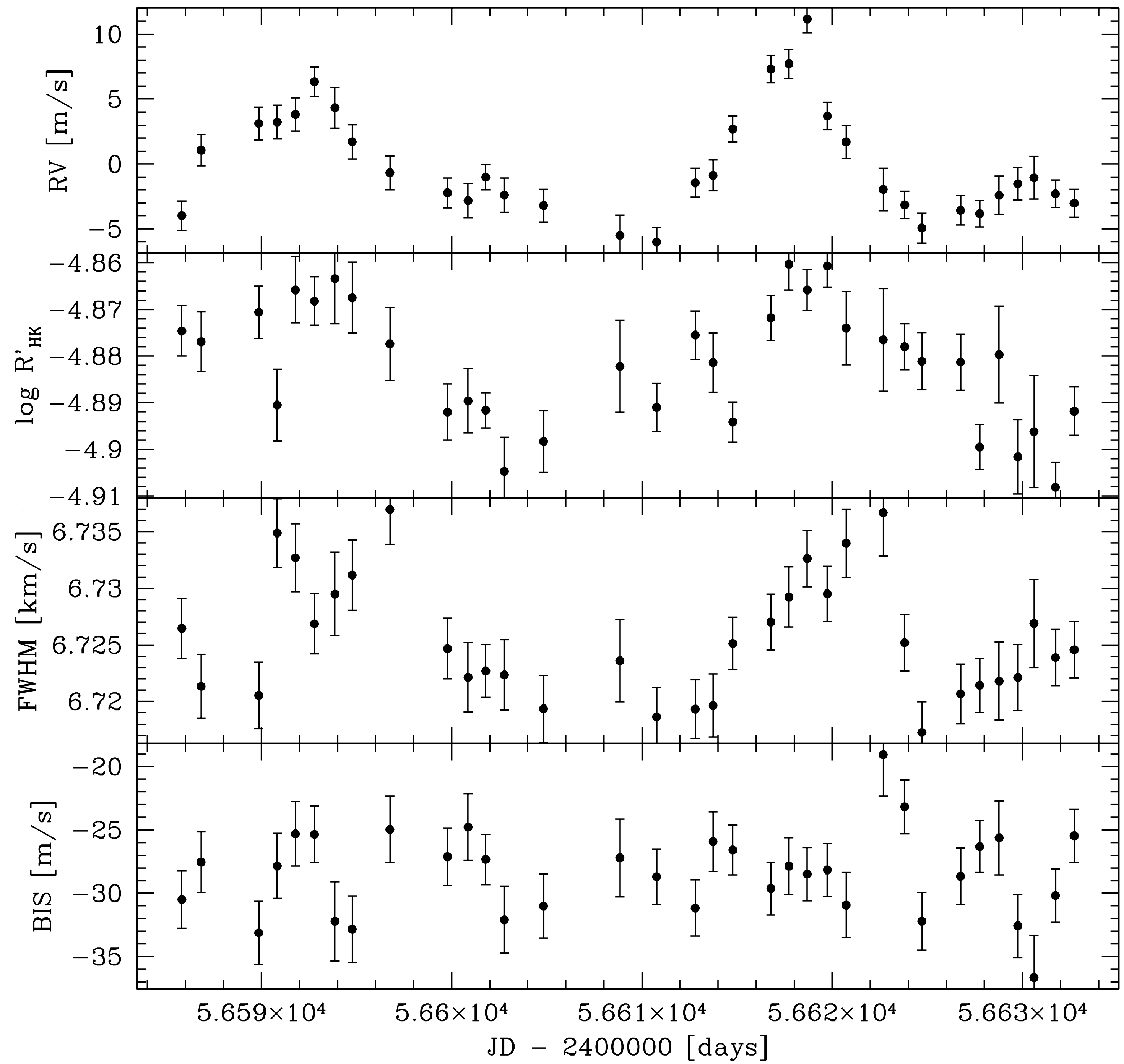
Spots will produce line-profile variations



Activity and RVs: the "fake" planets around HD41248

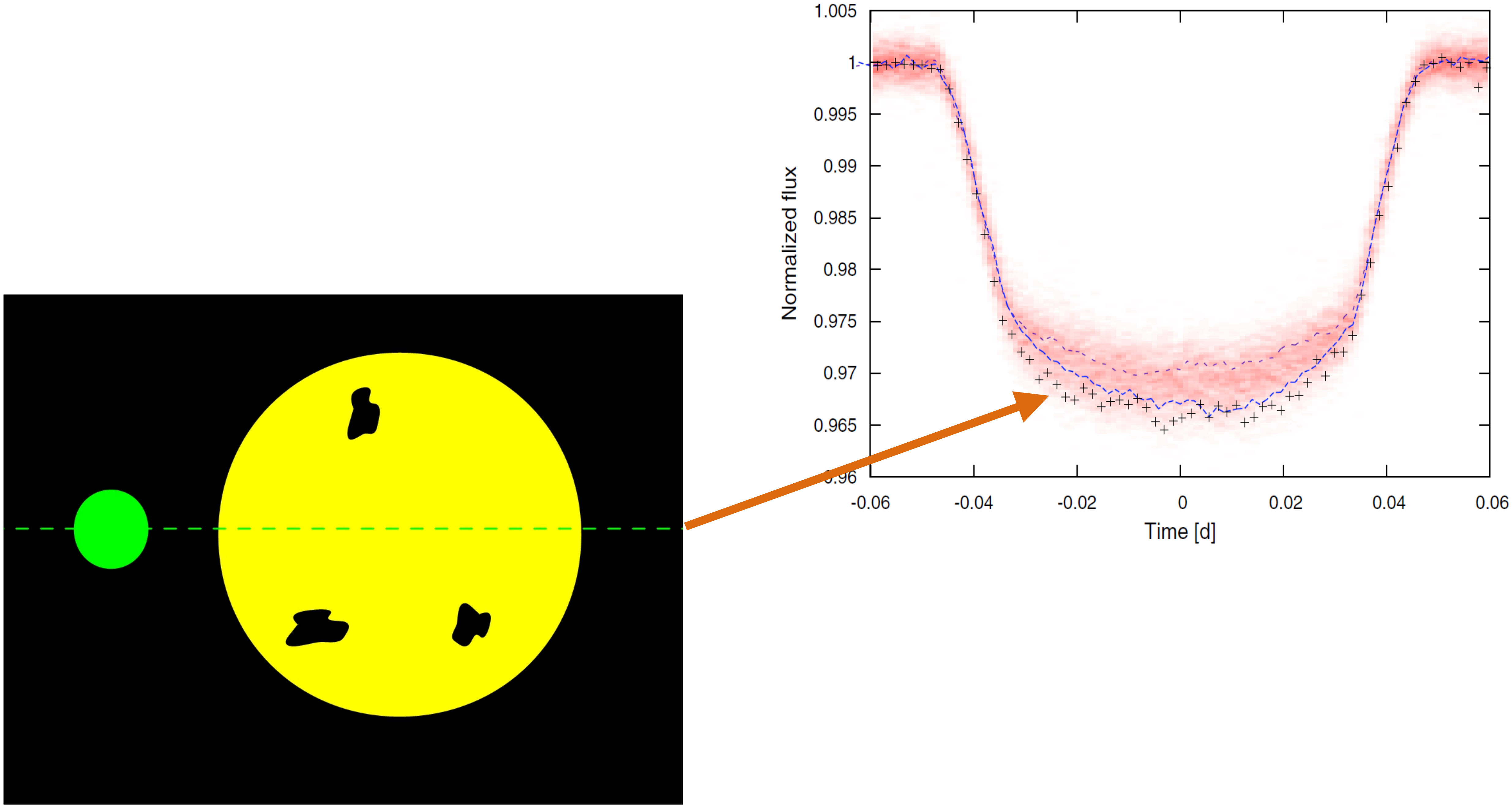






(Santos et al. 2014)

How **non-occulted** spots affect transit parameters



Overestimation of the planet radius, reaching up to 4% (Czesla+2009)

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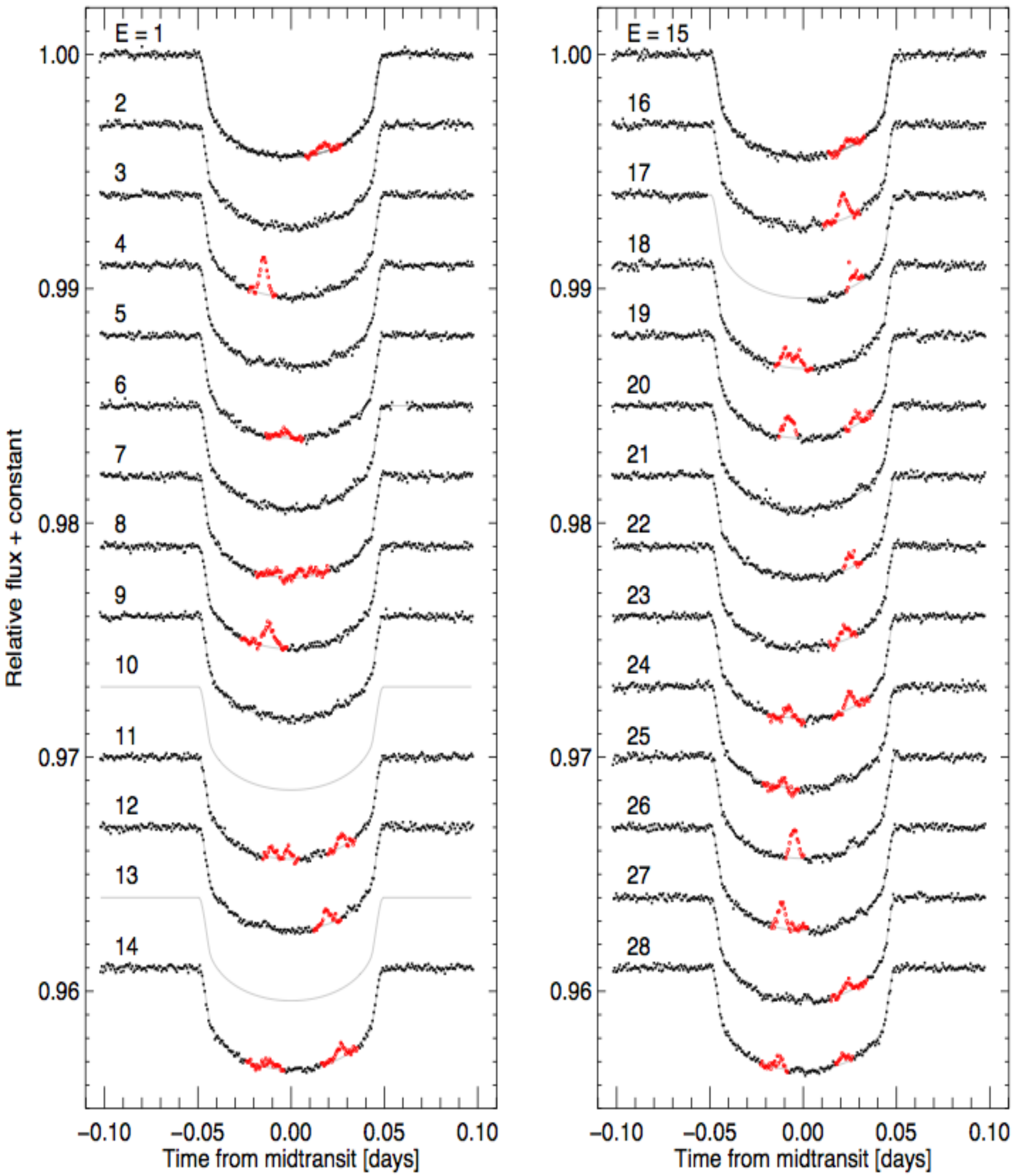
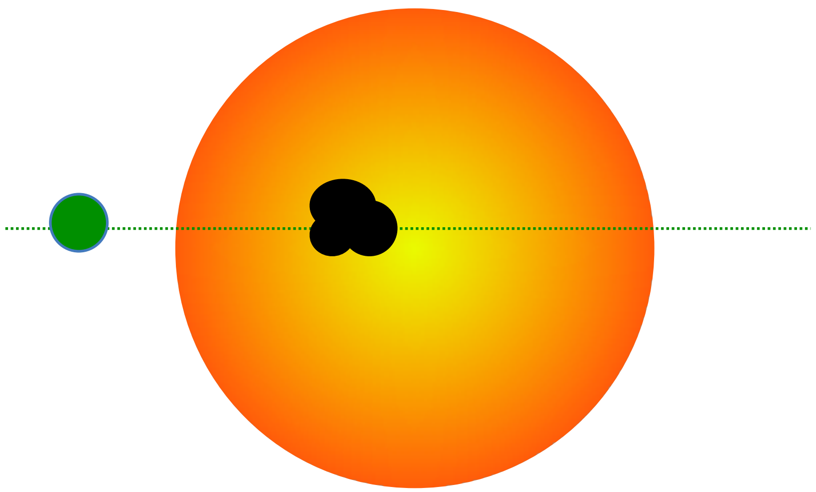
How **occulted** spots affect transit parameters

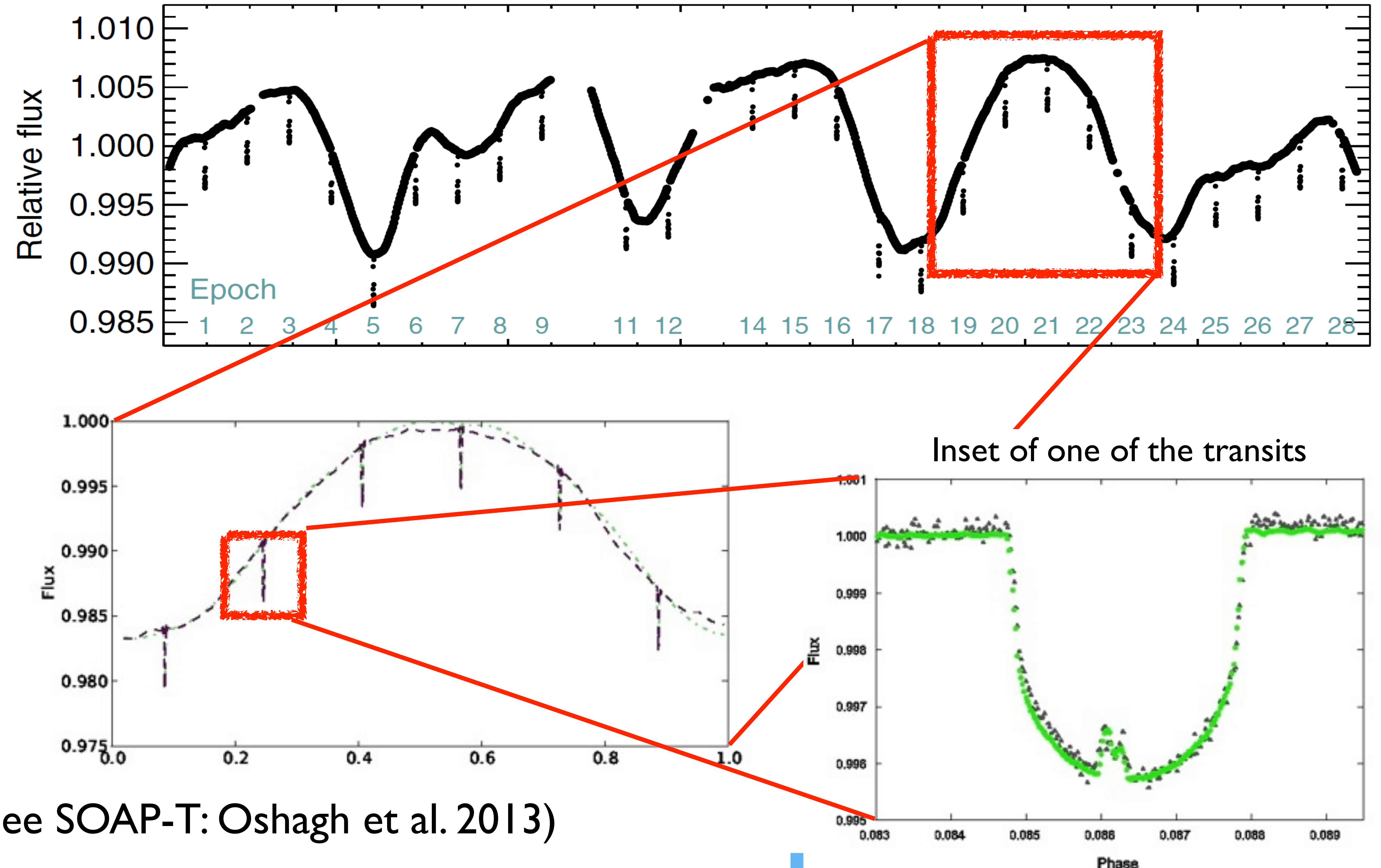


- Spots in rotating star induce "bumps" in the photometry during transit!



(Sanchis-Ojeda+2011)

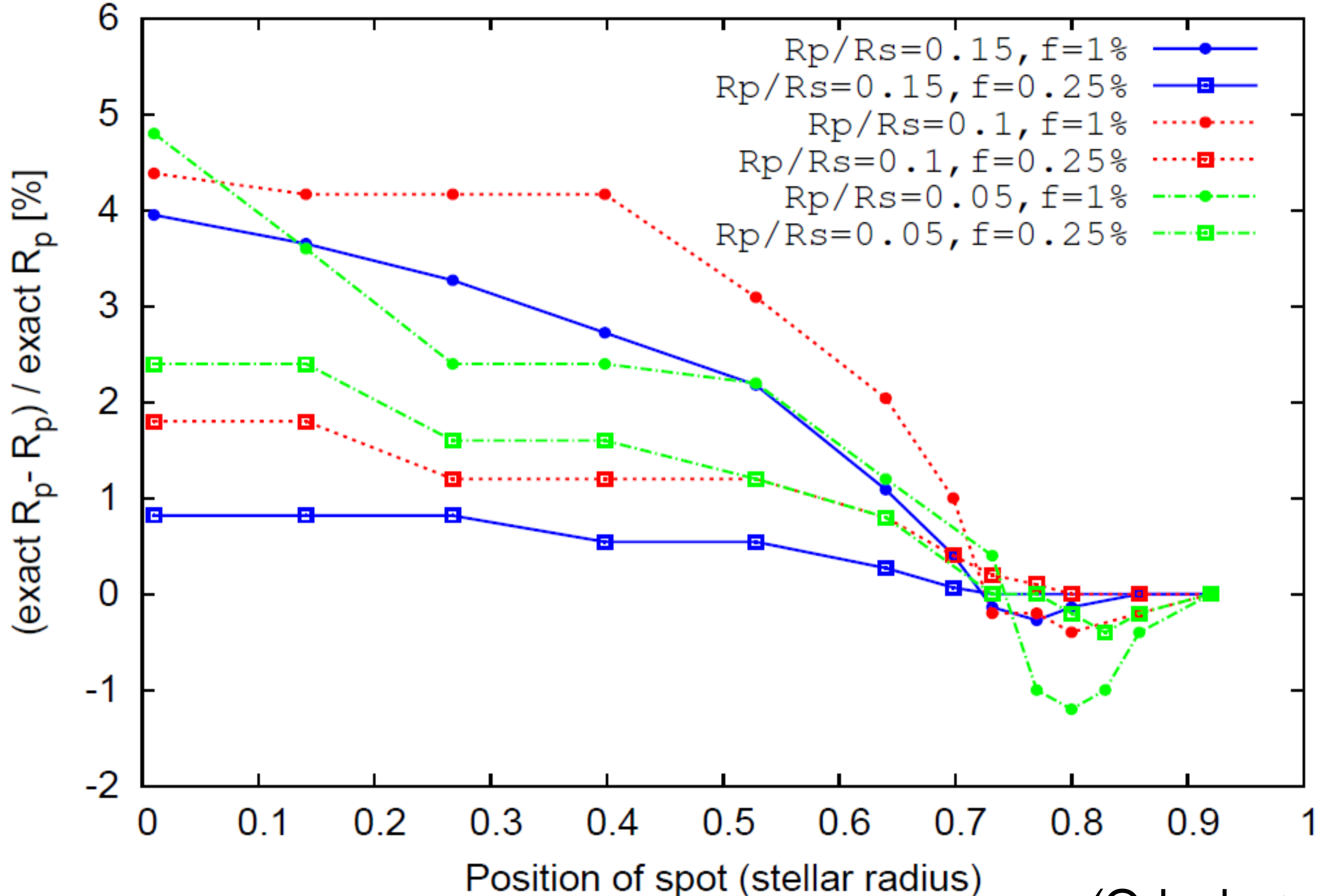
Activity and photometry: HAT-P-11 (Kepler data)



(see SOAP-T: Oshagh et al. 2013)

Transit depth: the effect of spots

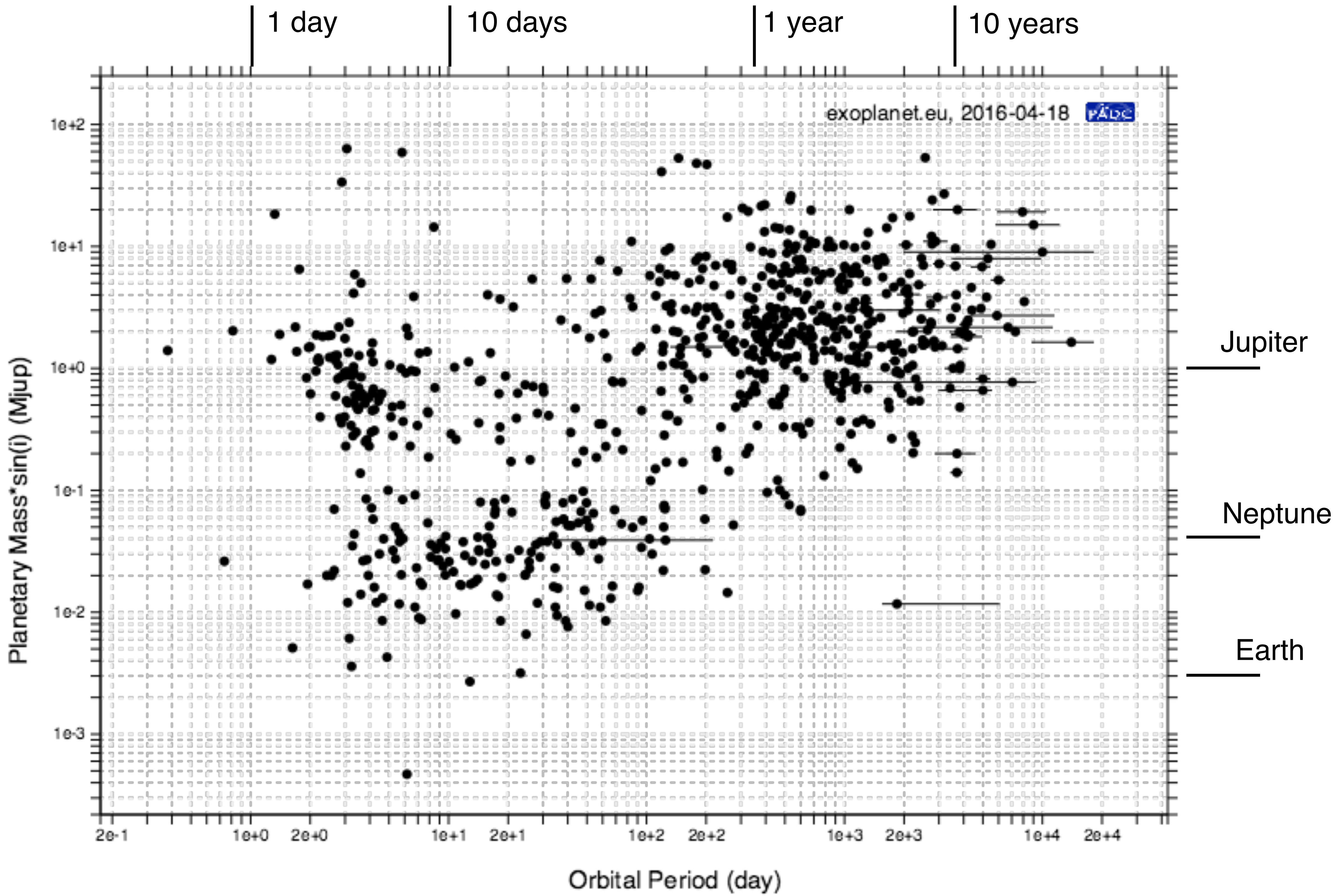
- Spots can induce wrong **transit depths**: wrong planet radii



(Oshagh et al. 2013)

Planet statistics: the RV view

Exoplanet discovery status



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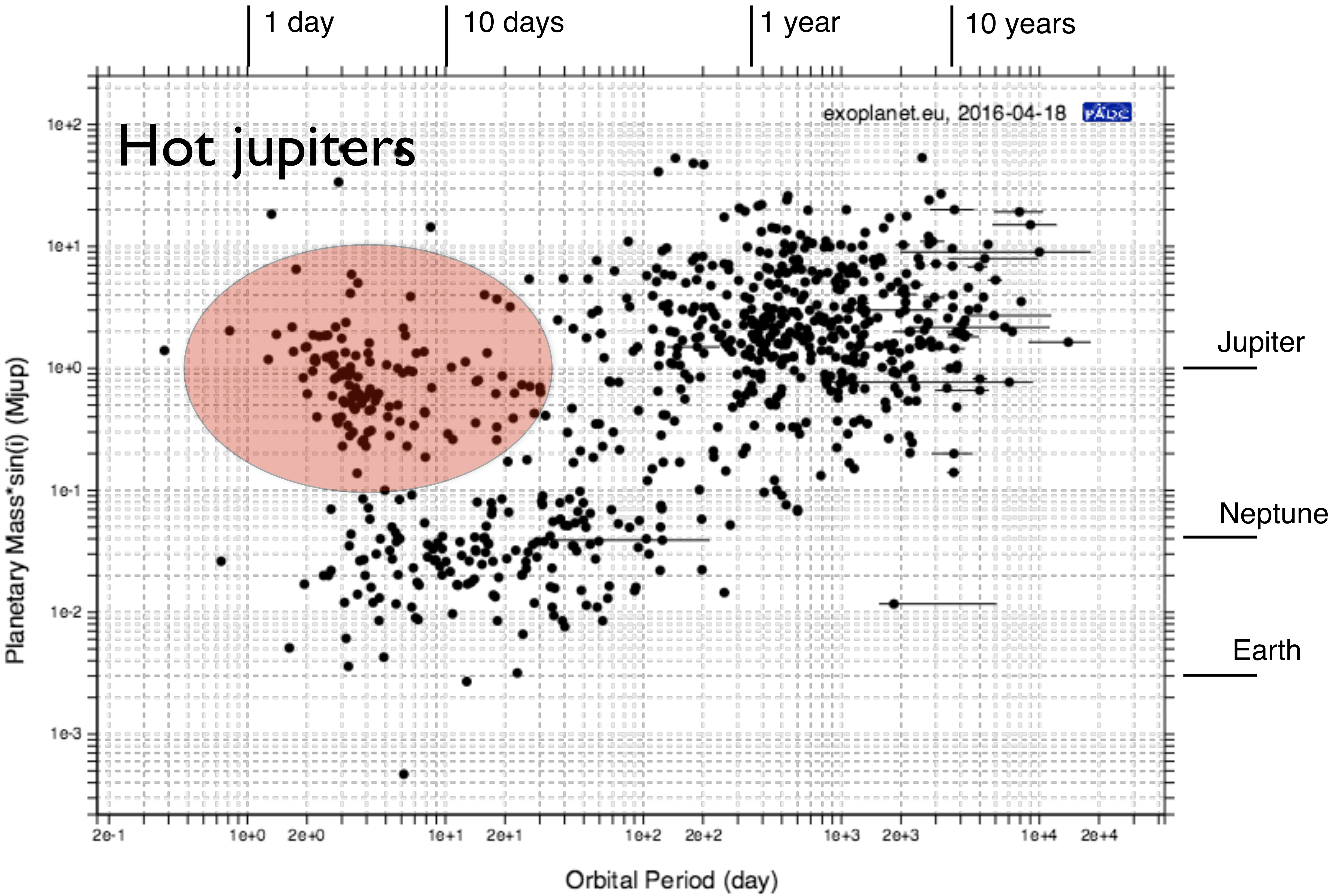

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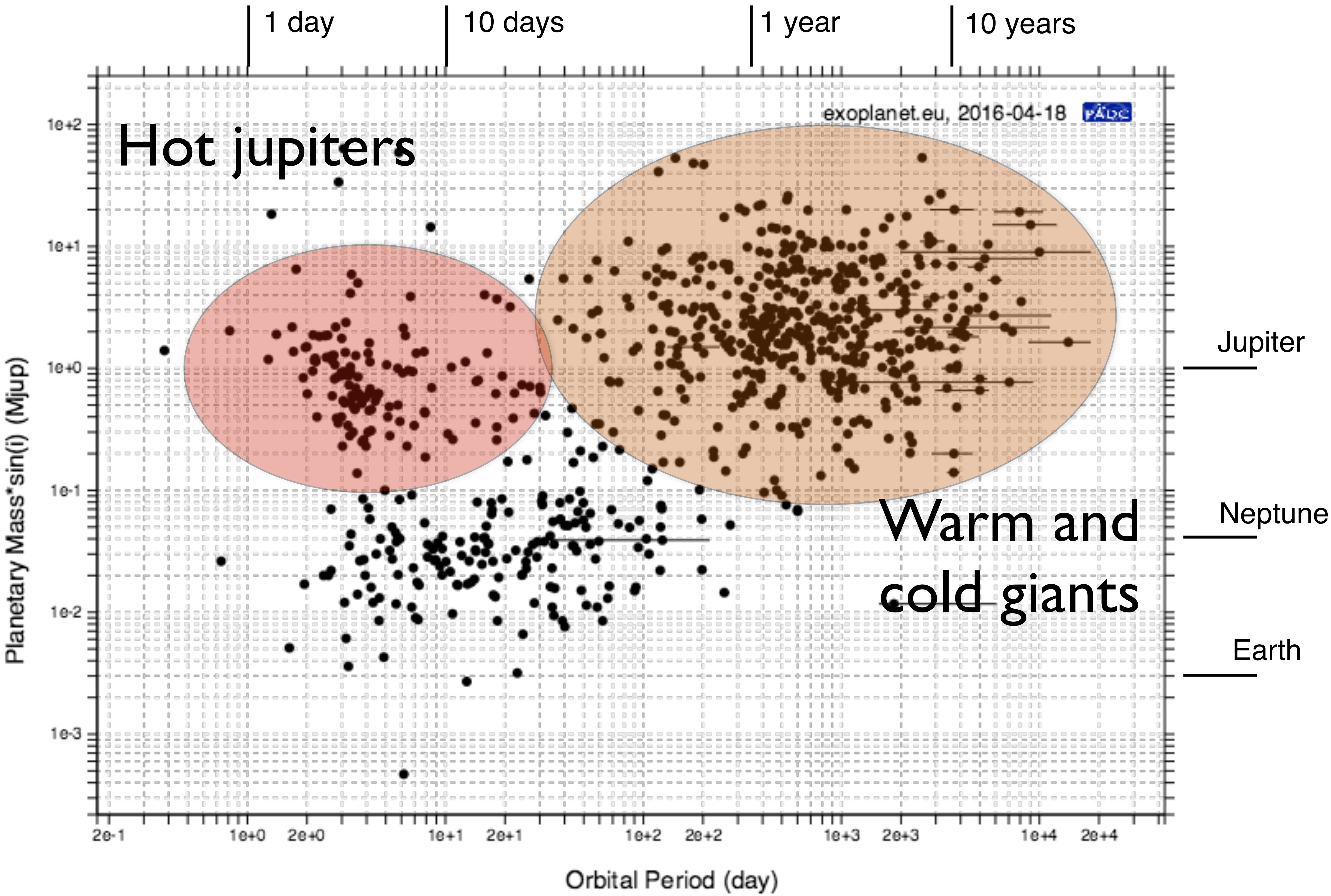

Main statistics of the *giant* planet population

- Overall occurrence rate: ~15% (Msini > 50 MEarth, P<10 years)
- An overall occurrence rate of ~1% for "hot Jupiters" (P < 10 days)
- Multi-planet systems are common

(see Mayor et al. 2014 for references)

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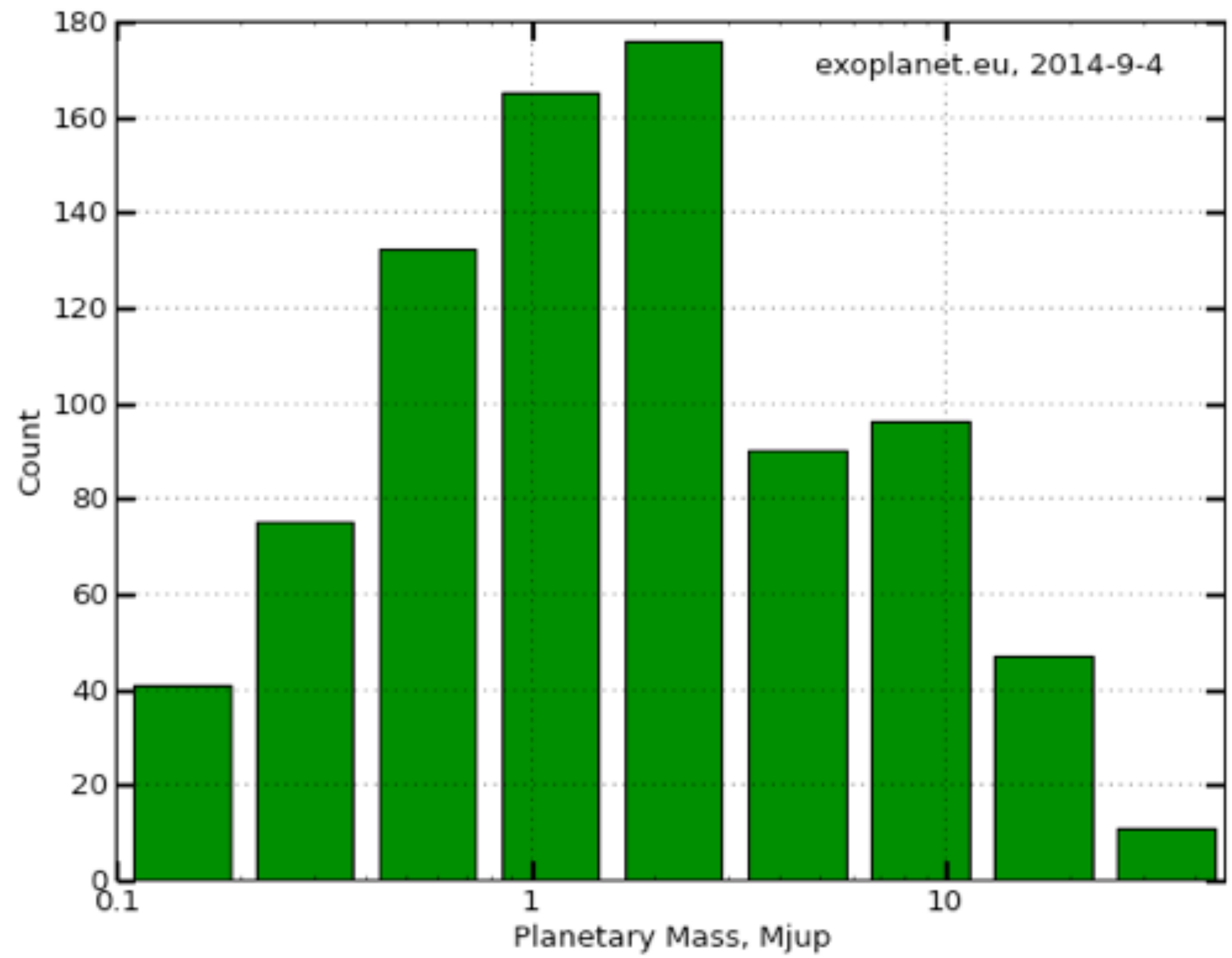
- Mass distribution peaking at 1–2 MJup with a "brown dwarf desert" above 10–20 MJup



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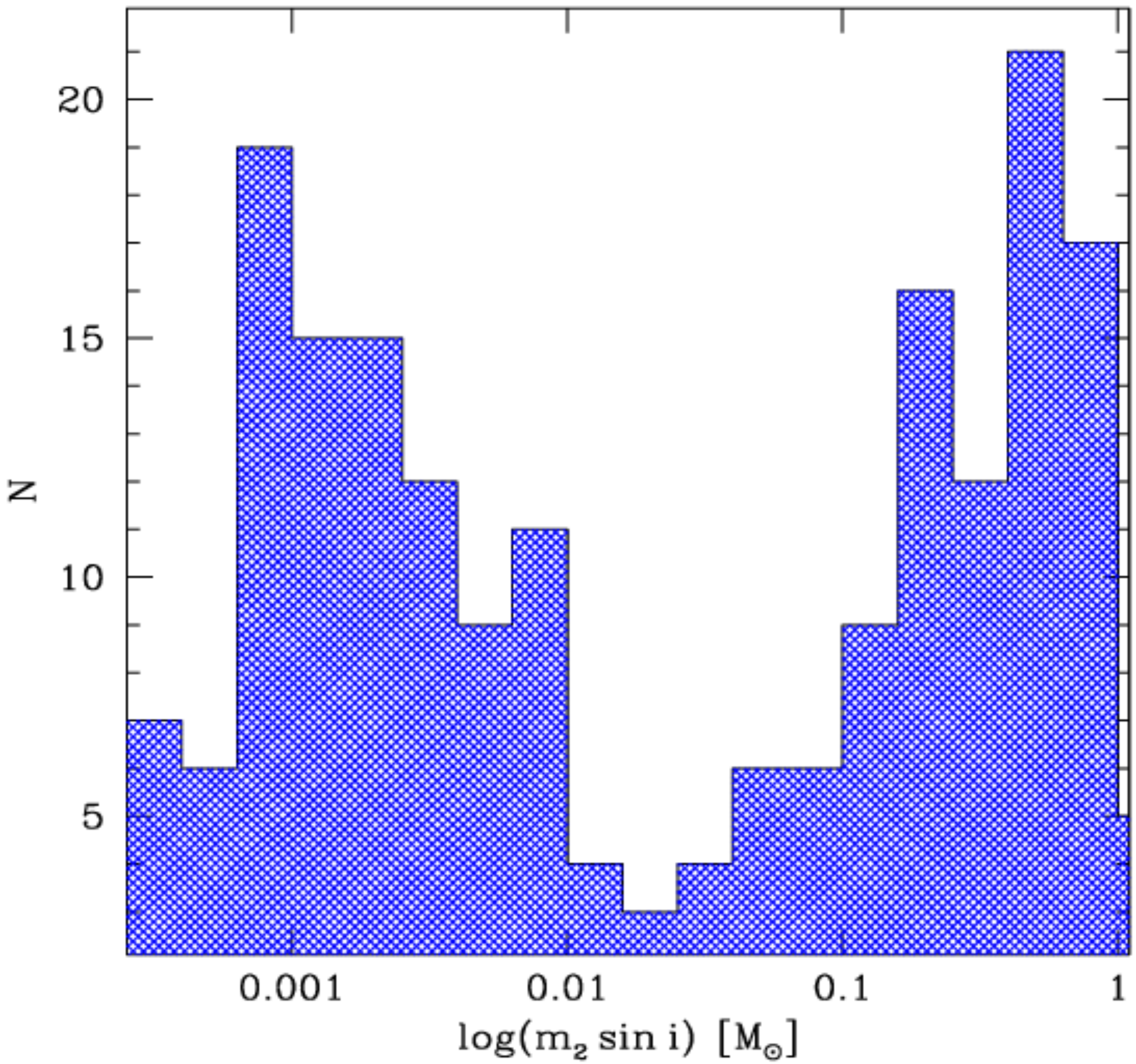

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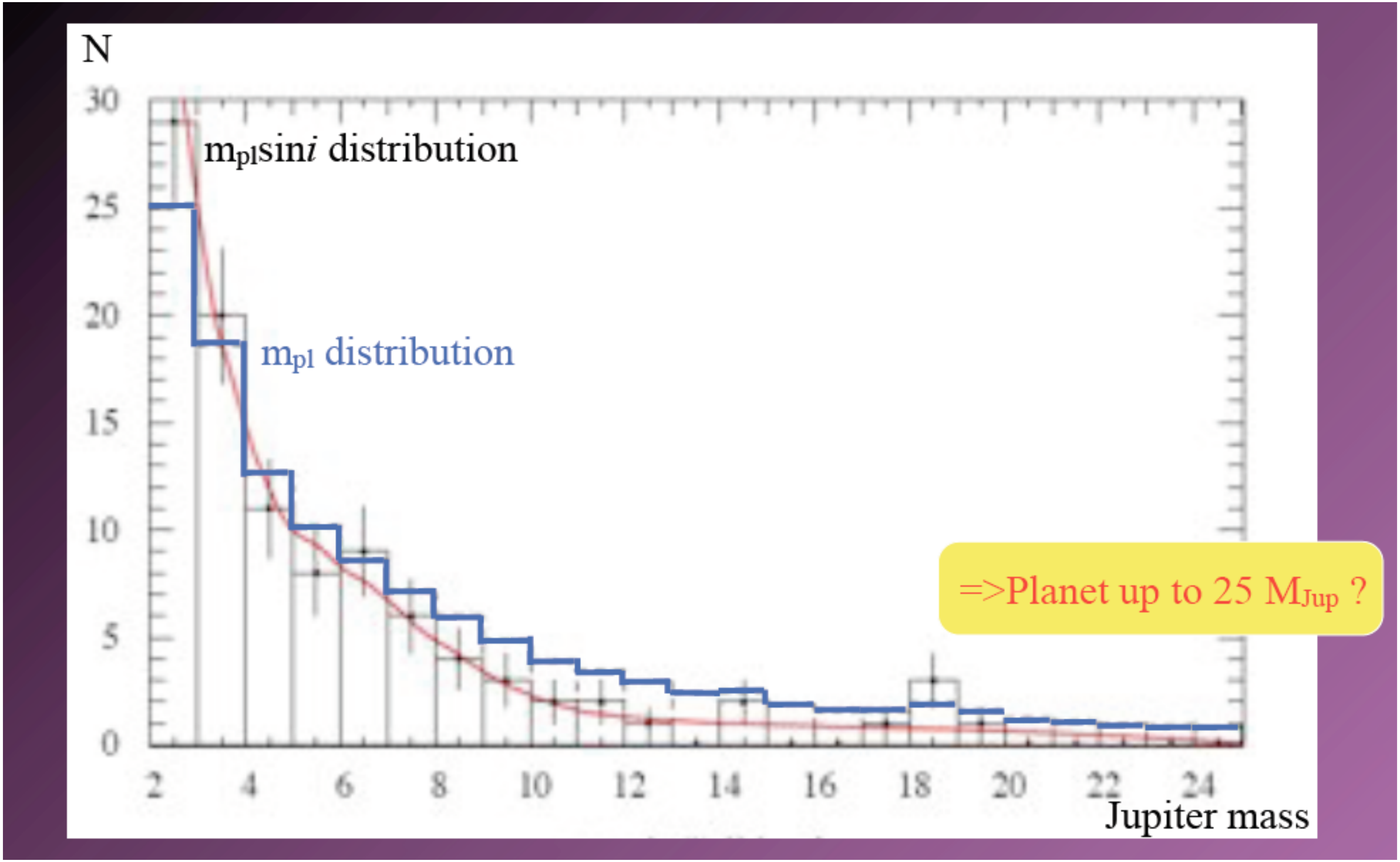

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- Wide distribution of orbital eccentricities

(see Mayor et al. 2014 for references)

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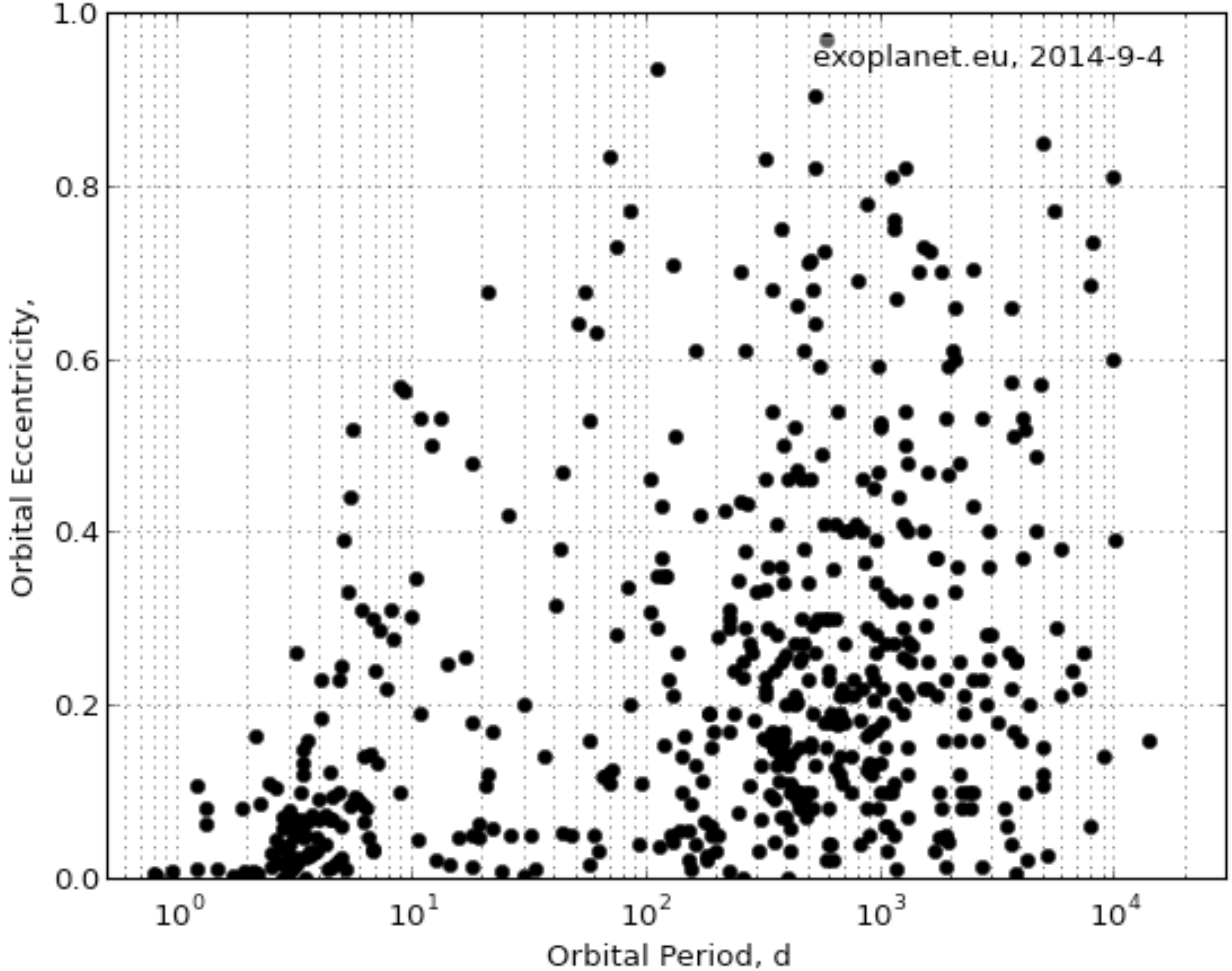
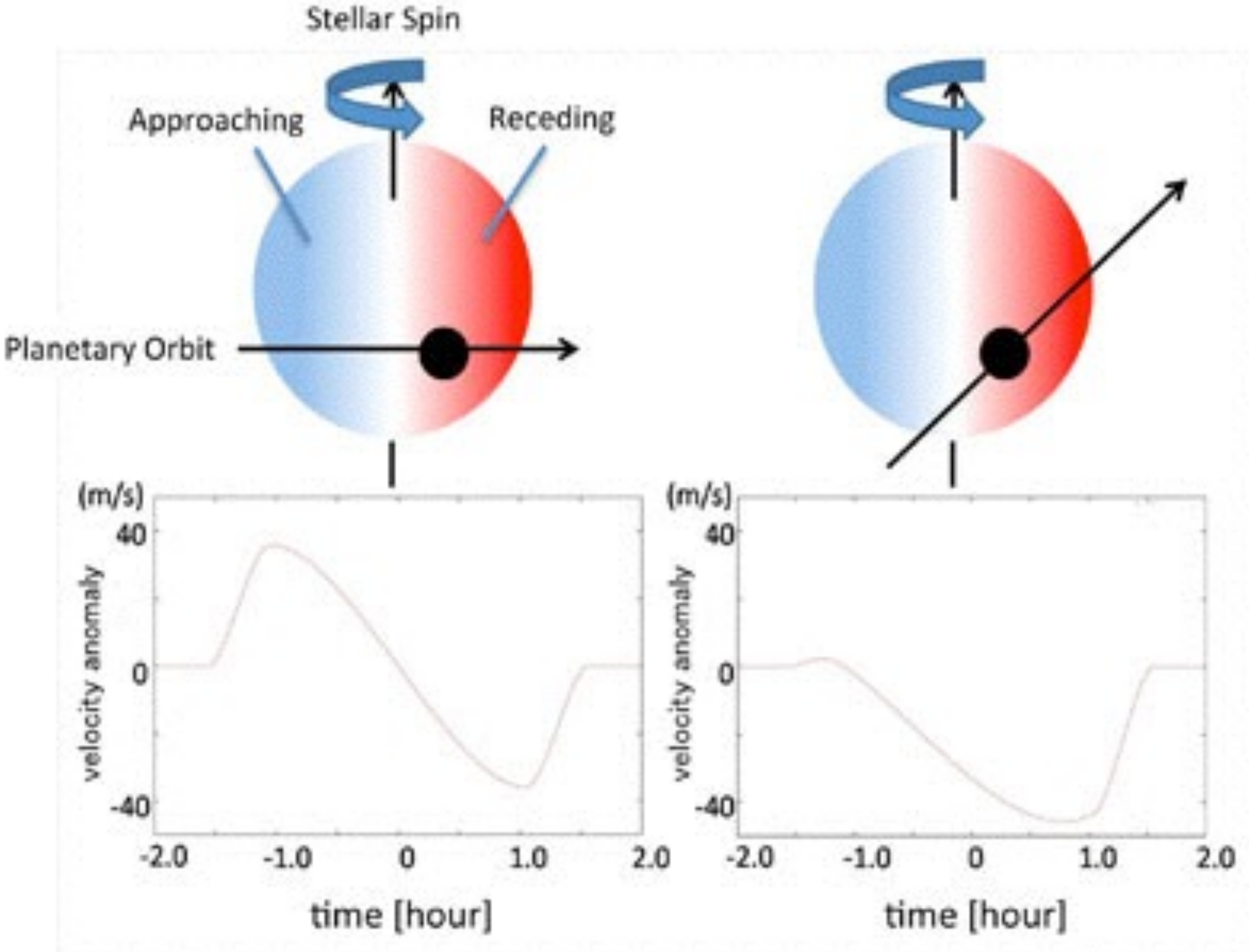
- Multi-planet s
- Mass distribu above 10–20 M
- Wide distribu

A signature of planet-planet scattering or interactions with bound or passing stellar companions

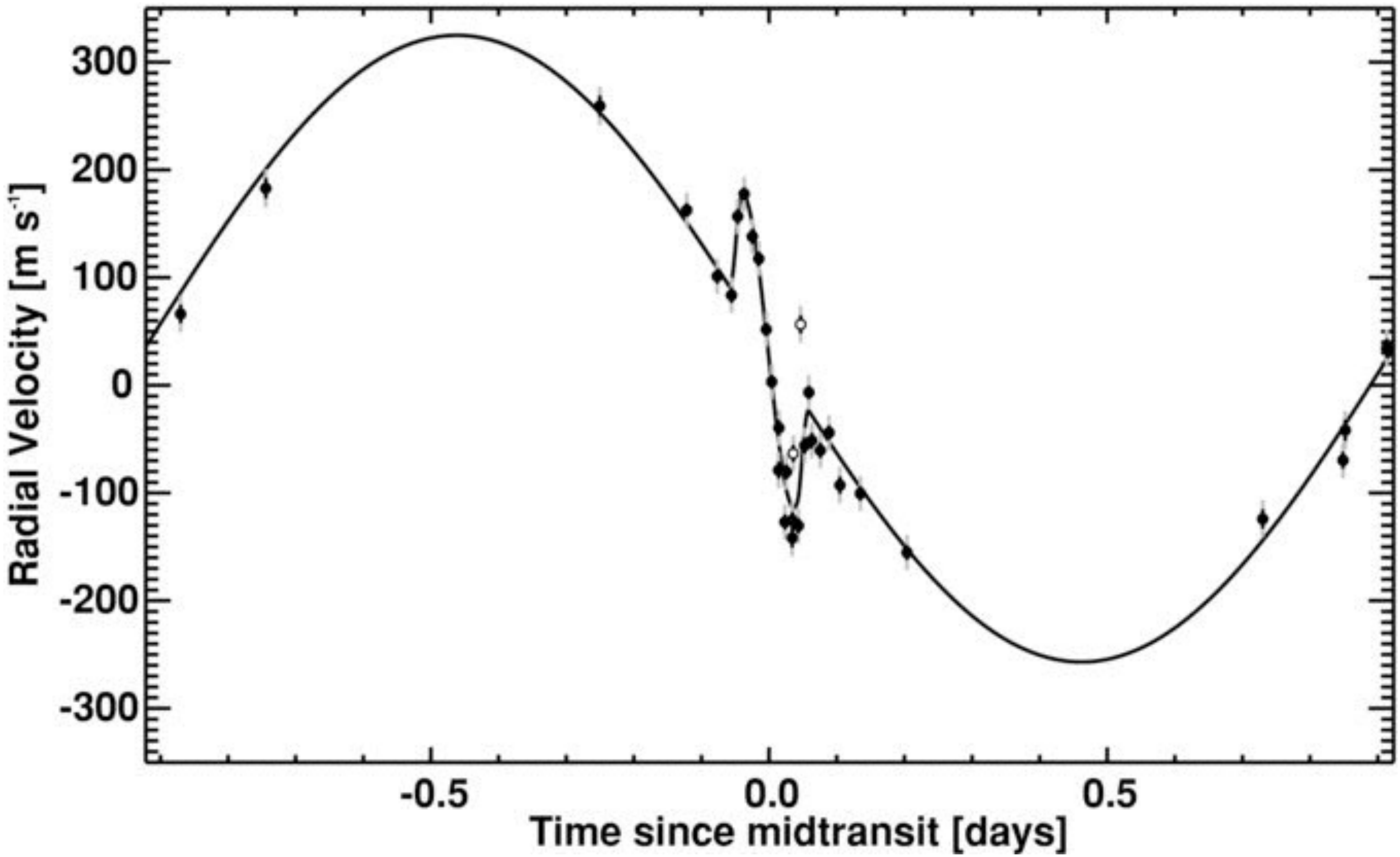


Transits in radial velocity: Rossiter McLaughlin effect



Transits in radial velocity: Rossiter McLaughlin effect

- Shape and amplitude of signal depend on stellar rotational velocity, geometry of the system, limb darkening, size of planet, …



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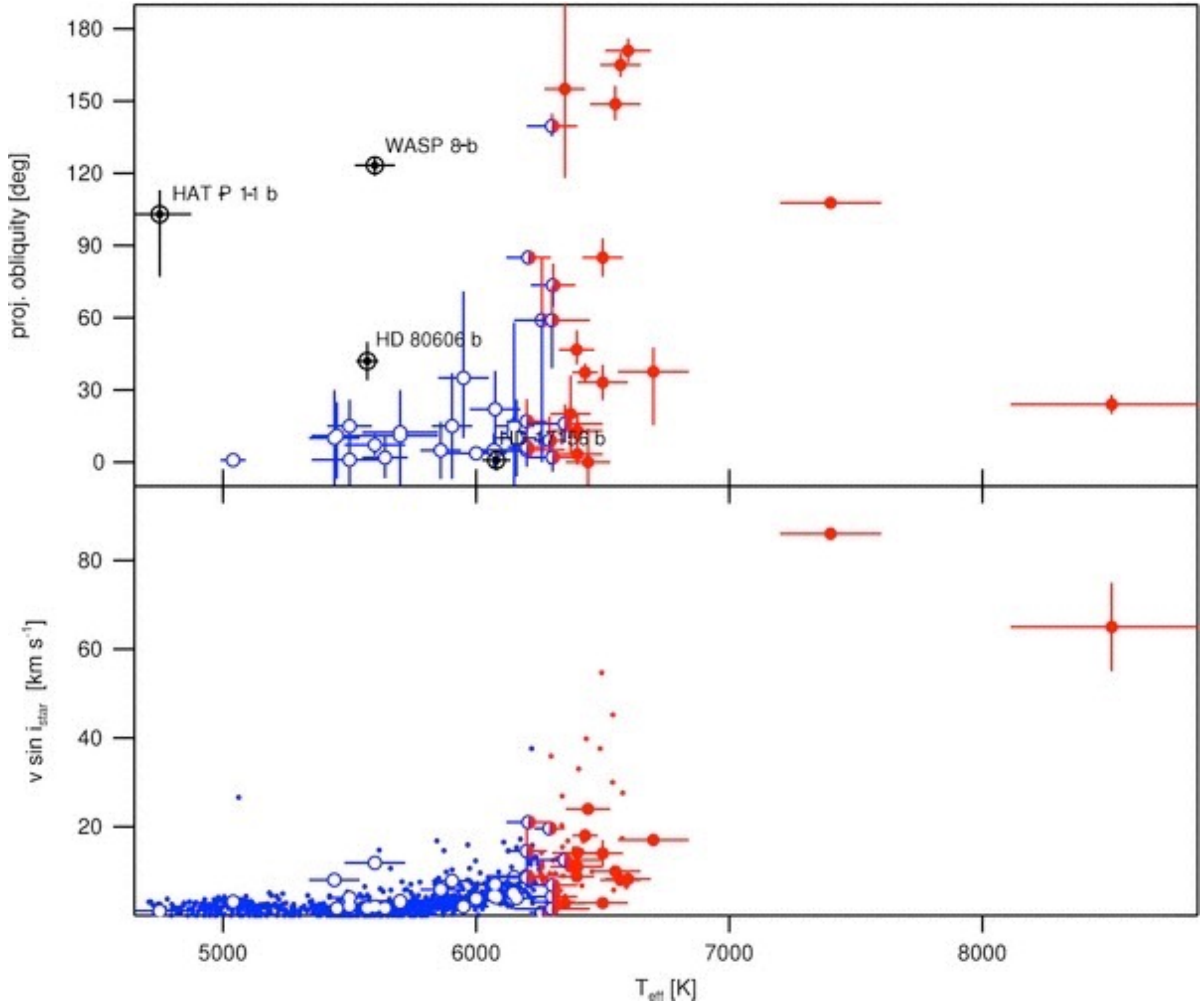
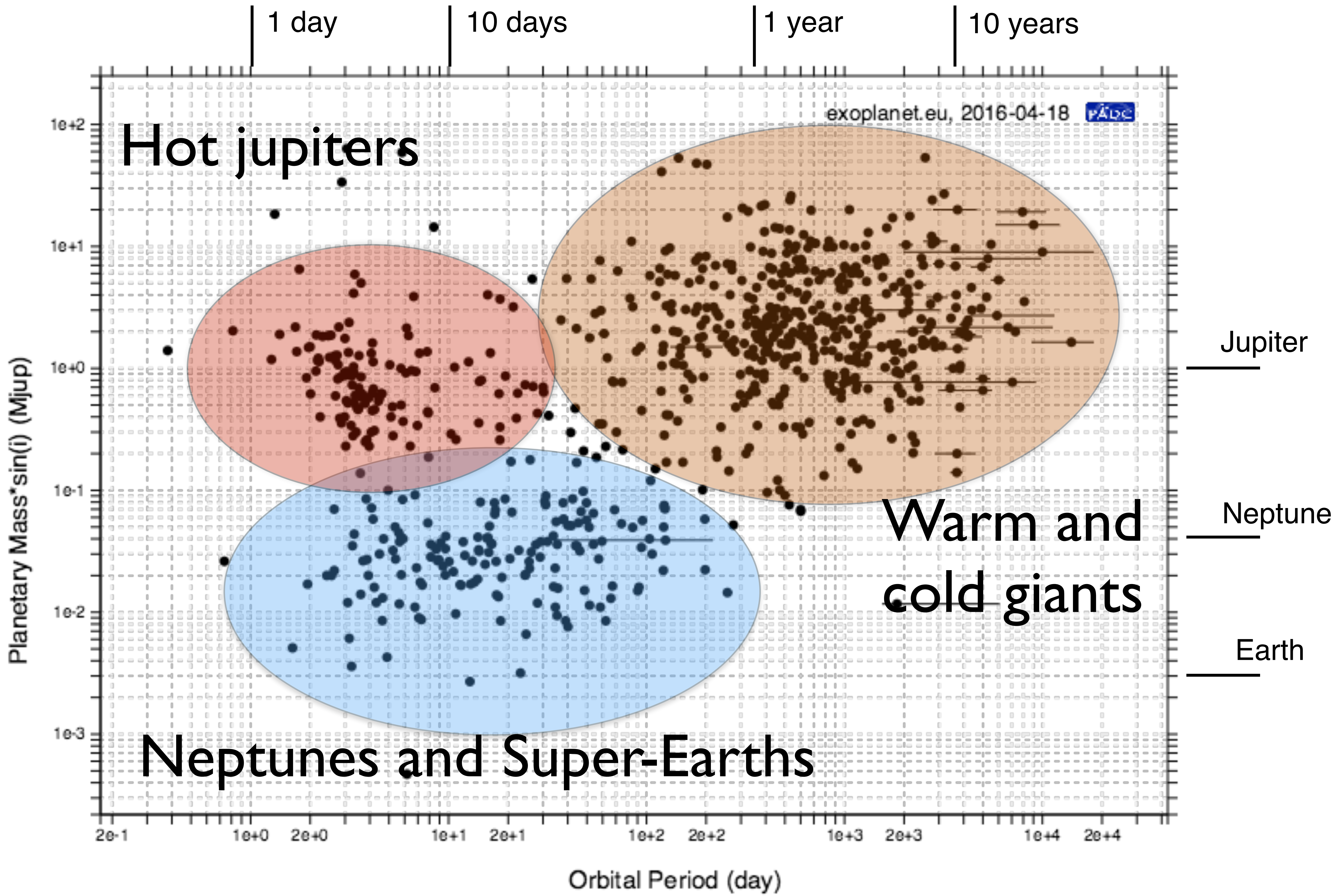
Some insight from transit searches

- Detection of a population of hot jupiters that are misaligned
- Calls for:
  - Planet-planet interactions
  - Interactions with massive companion (Kozai cycles) + orbital decay,
  - Original disk tilt (due to stellar encounters)?



(see e.g. Winn et al. 2010, Triaud 2011, Albrecht et al. 2012, Crida et al. 2014)

Exoplanet discovery status



Main statistics of the *low mass* planet population

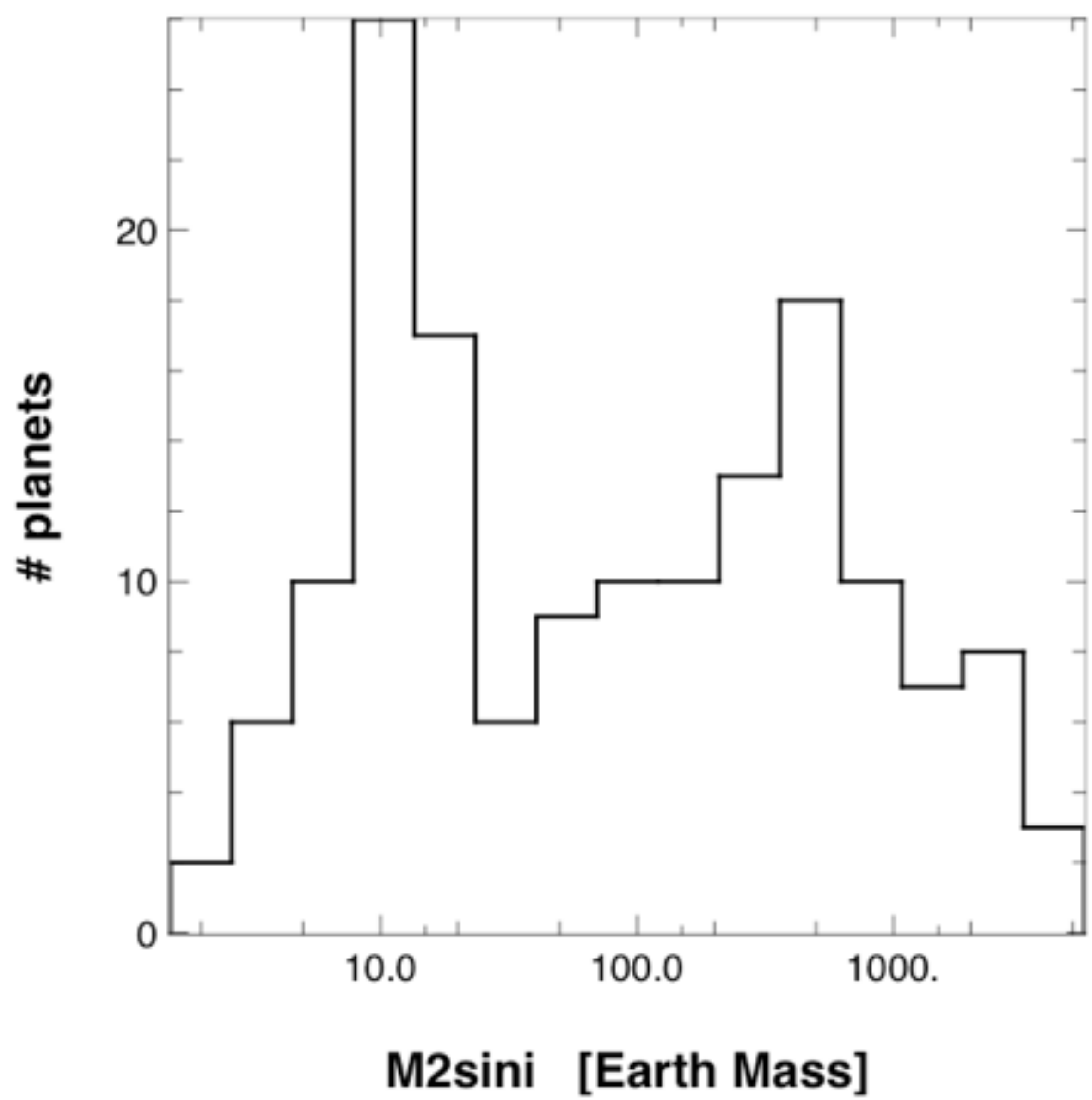
- FGK stars, a global occurrence rate of ~0.33 planets-per-star for masses between 3–30 MEarth and P < 50 days
- M dwarfs: a global occurrence rate of ~0.40 planets-per-star for Msini between 3–30 MEarth and P < 50 days
- Multiplicity rate of ~70% among systems with at least one Neptune or super-Earth
  - Most low-mass planets are found in multi-planet systems

(see Mayor et al. 2014 for references)

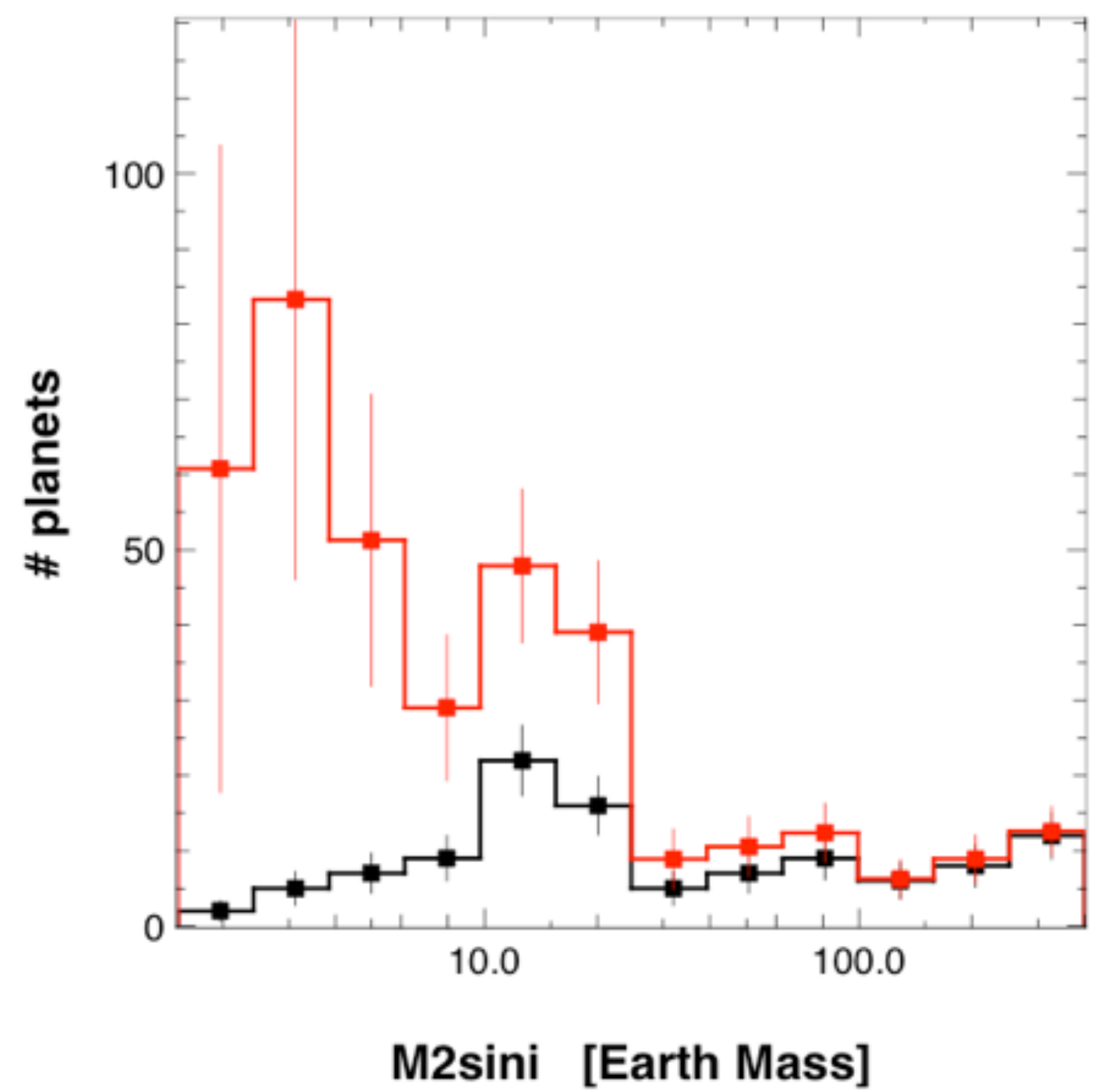
The mass distribution (RV planets)

- Low mass planets are the most common! (in particular in short periods)

Observations



Observations + corrected



(from Mayor et al. 2011)

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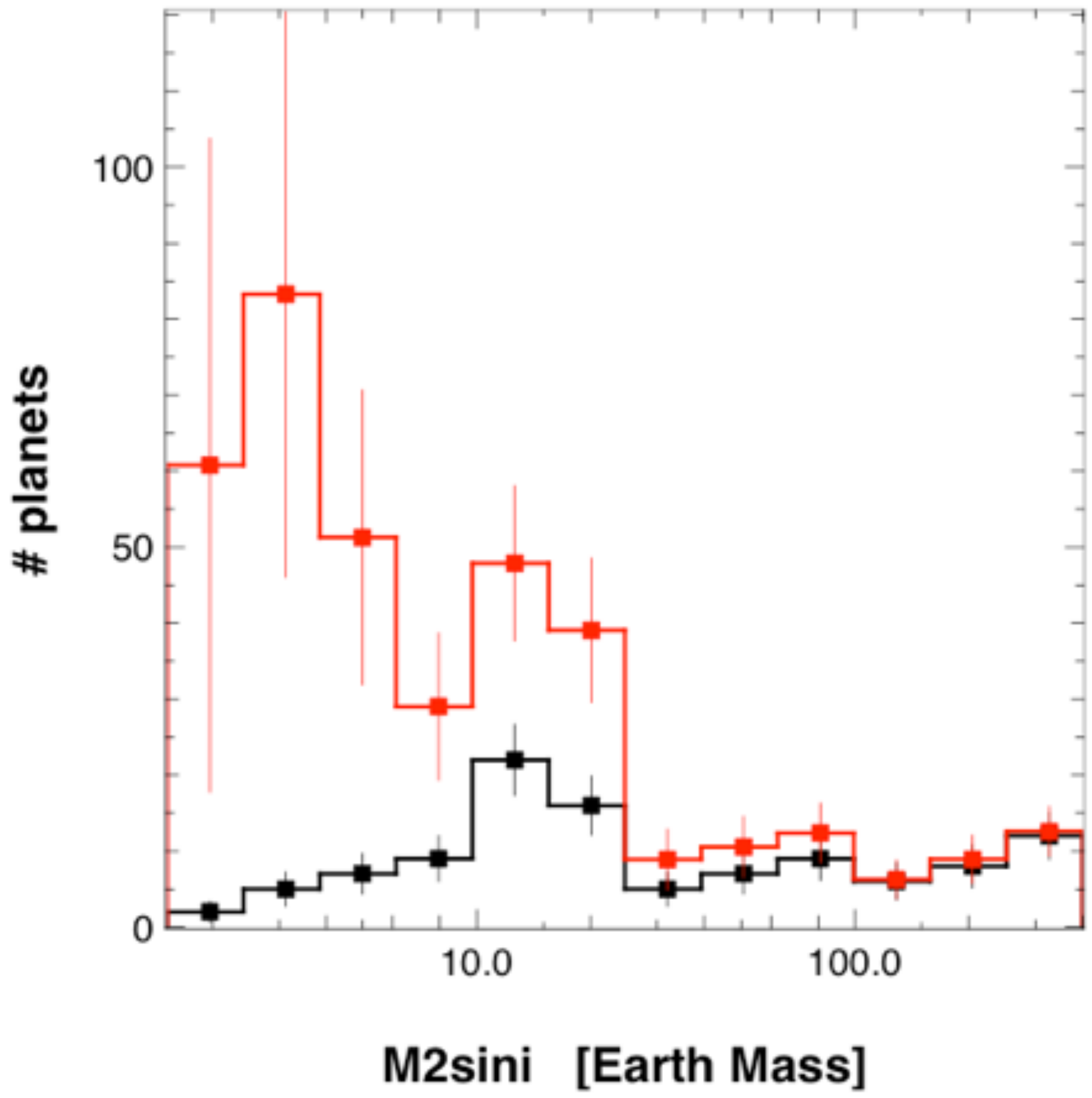
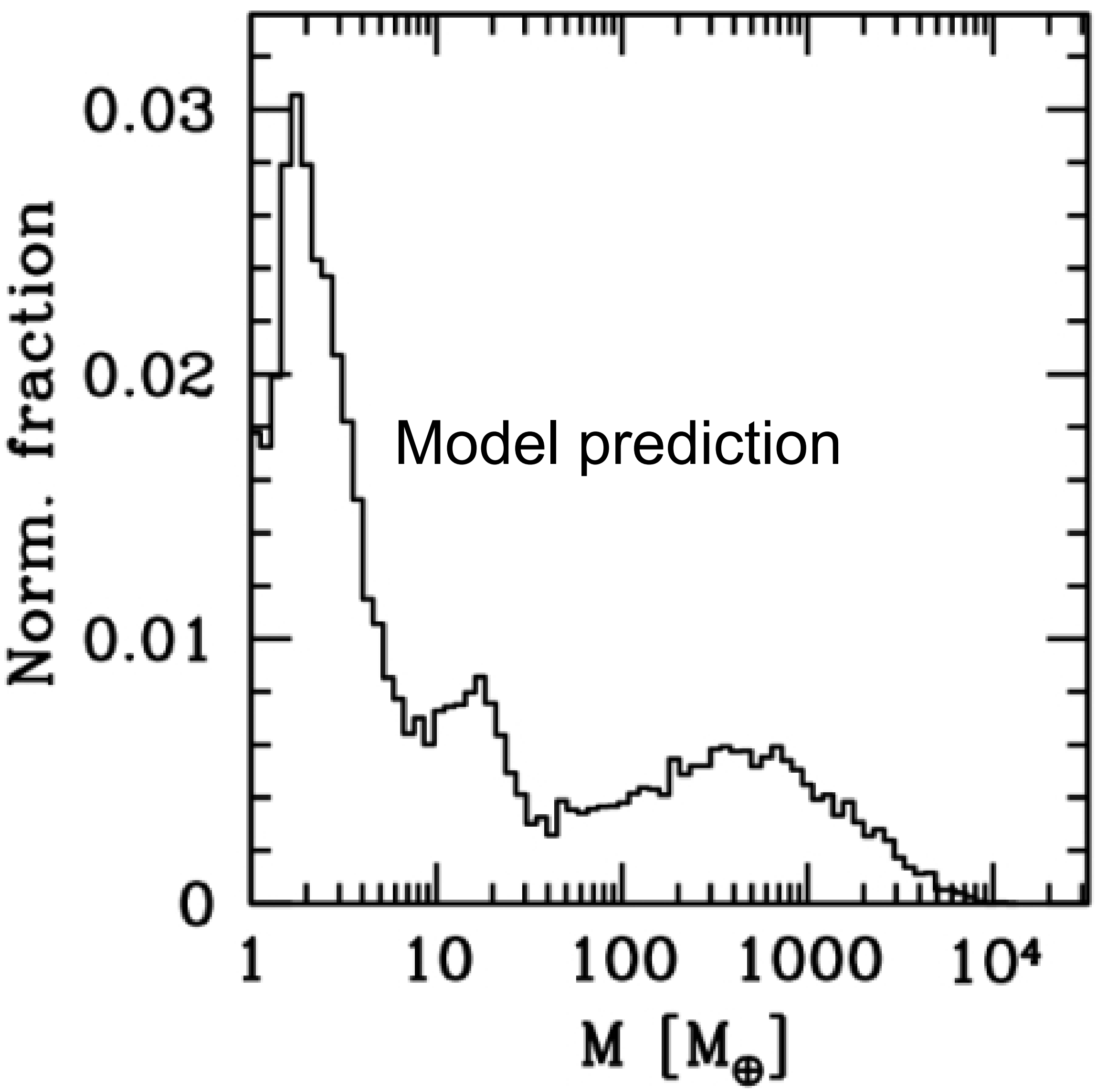
Comparison with model predictions (Mordasini et al.)

Observations





Model prediction

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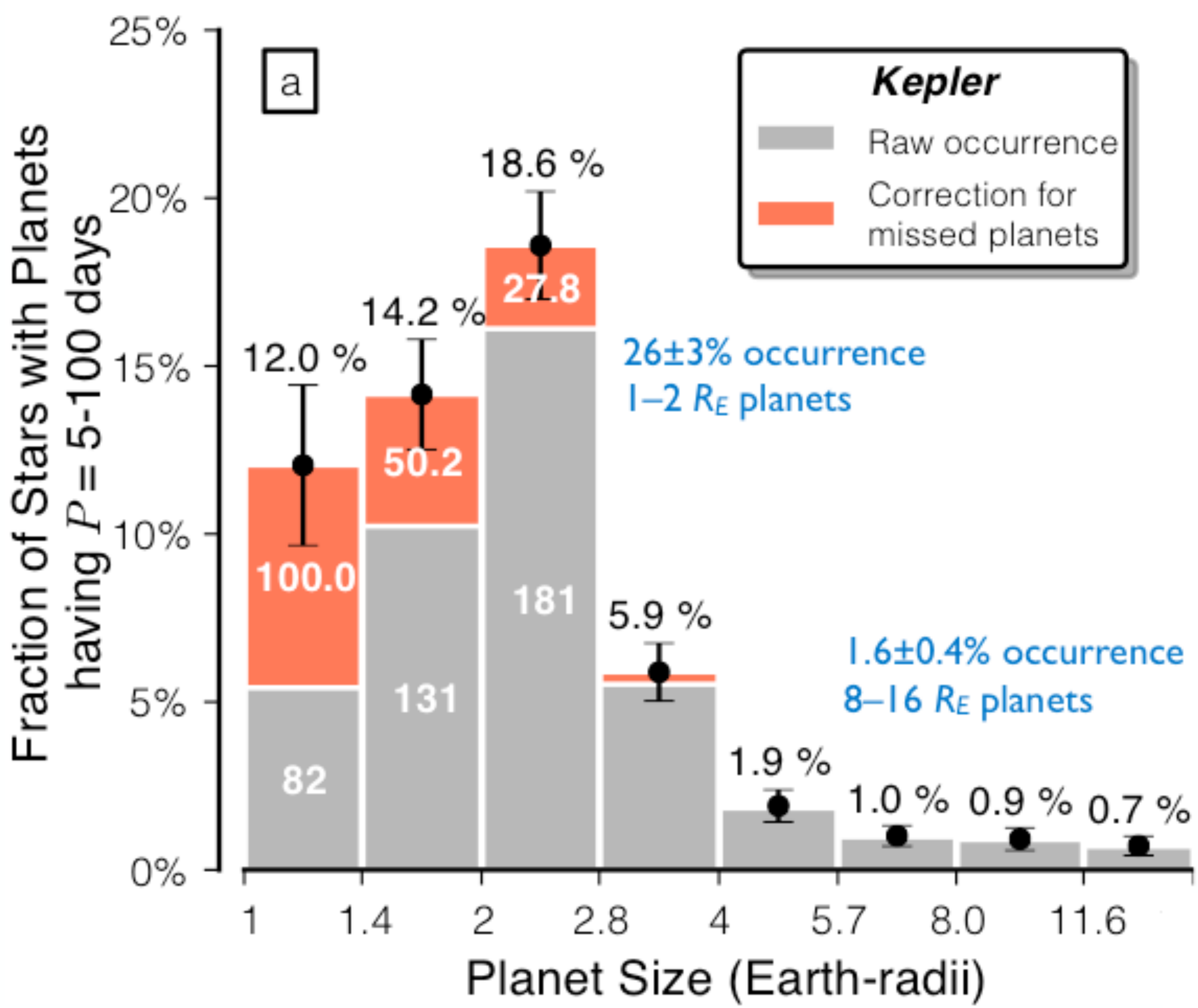
Kepler results show the same trend (in radius)



Know the stars, know the planets

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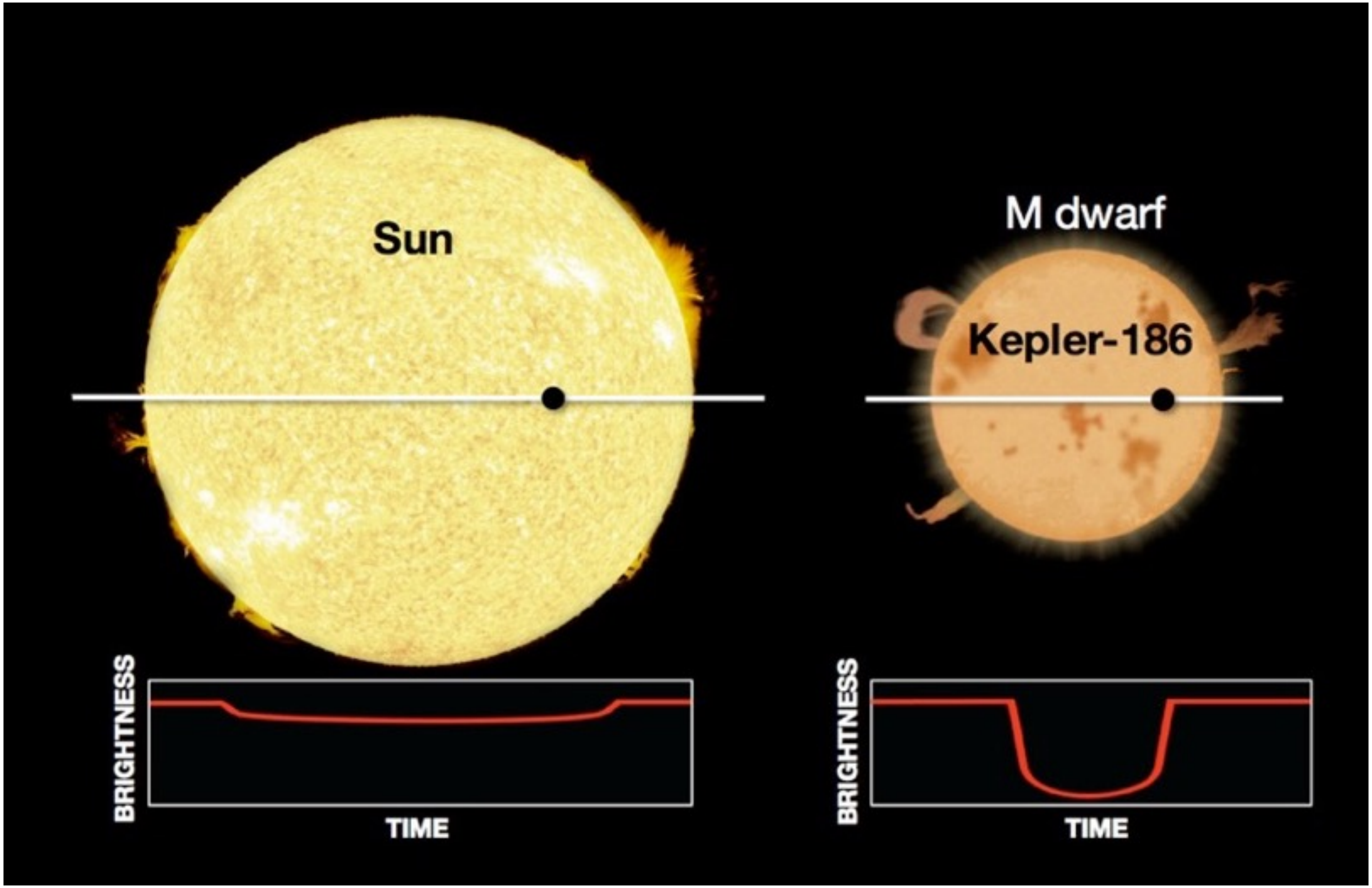
Stellar parameters are important in exoplanets

- Stellar parameters are crucial for the determination of planet properties
  - Planet mass, radius, mean density => stellar mass and radius
  - System's age => stellar age
  - Habitability => stellar irradiation (temperature, luminosity, activity, composition...)

Know the planets => know the stars



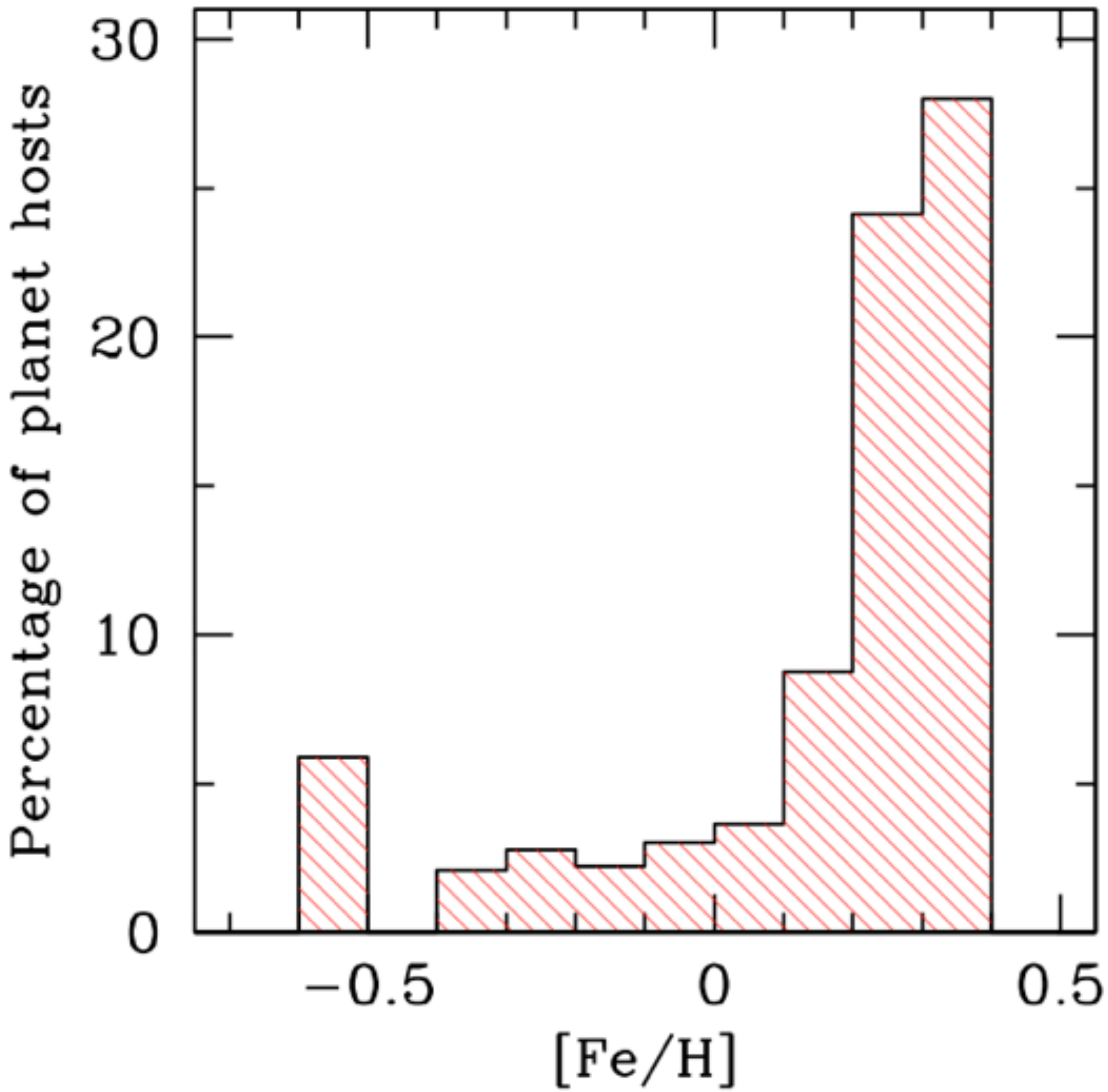
Stellar parameters are important in exoplanets

- Stellar parameters are crucial for the determination of planet properties
  - Planet mass, radius, mean density => stellar mass and radius
  - System's age => stellar age
  - Habitability => stellar irradiation (temperature, luminosity, activity, composition...)
- Observed correlations between planet and stellar properties are observed (clues to formation/evolution):
  - Stellar properties: abundances, luminosity, mass, irradiation, activity, ...
  - Planet properties: internal structure (metallicity), composition, radius, orbital parameters...

Clues from stellar chemistry

Based on RV programs: for **FGK** dwarfs, metallicity is key factor controlling the frequency of *Giant* planets

(e.g. Gonzalez et al. 1998; Santos et al. 2001, 2004; Fischer & Valenti 2005; ...)



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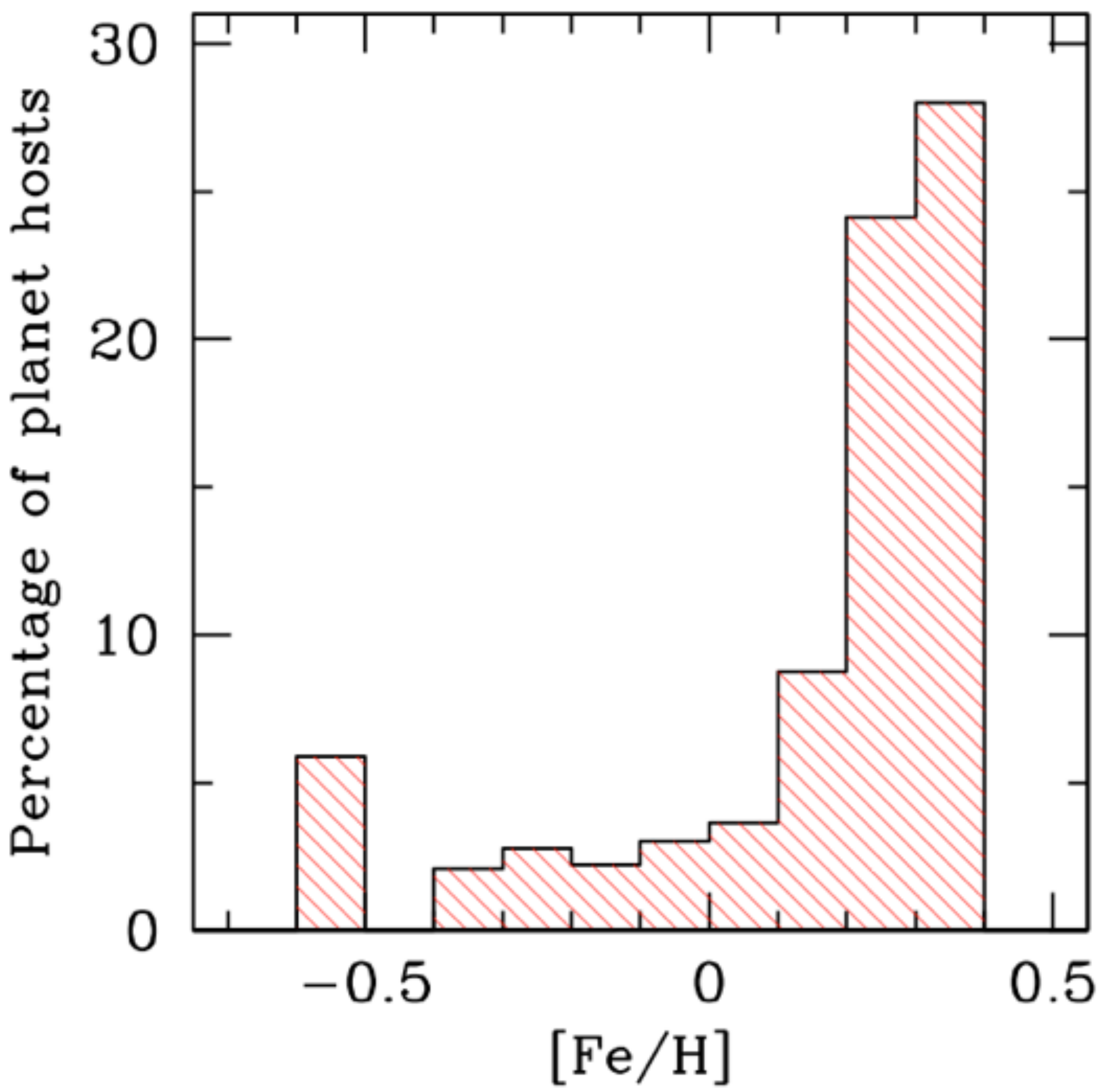
Clues from stellar chemistry

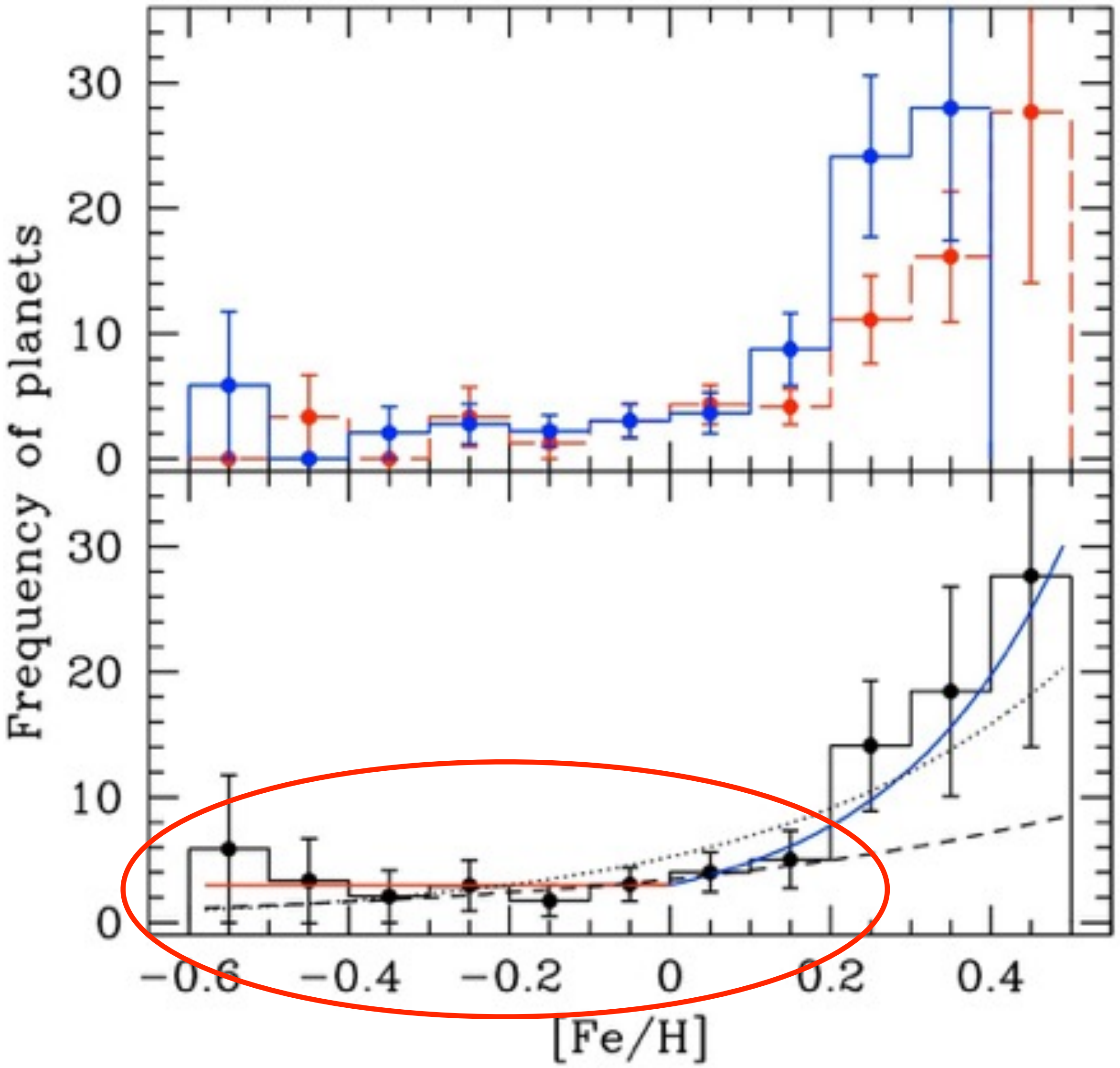
- Clues for planet formation models
  - Core accretion model: metallicity dependence predicted (e.g. Mordasini et al. 2012)
  - Disk instability models: less clear if metallicity should play a role (e.g. Boss et al. 2002)



The Functional Form for giant planets: the "discussion"

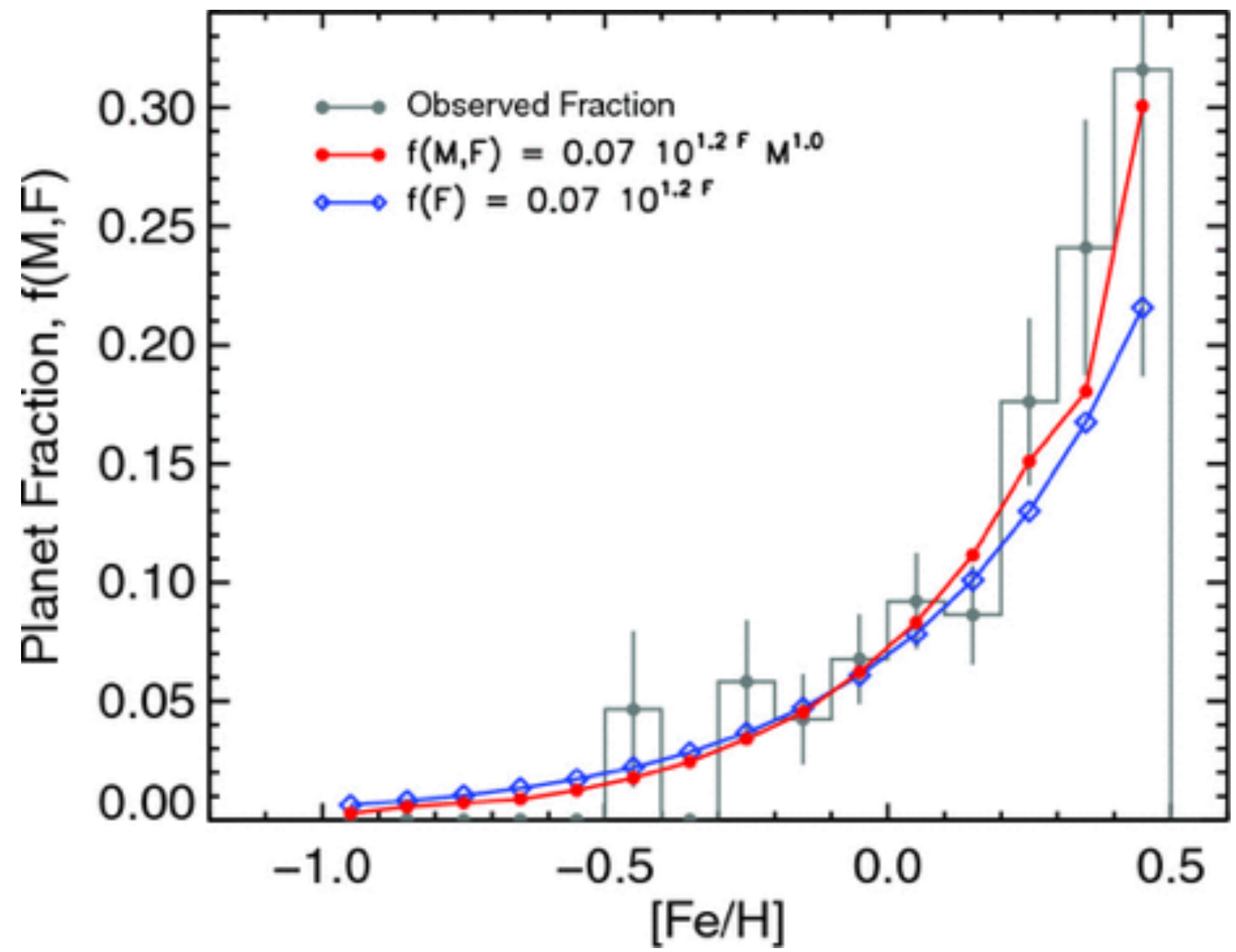
- Contradictory results exist: different formation processes at different metallicity?

A flat tail for low metallicities?



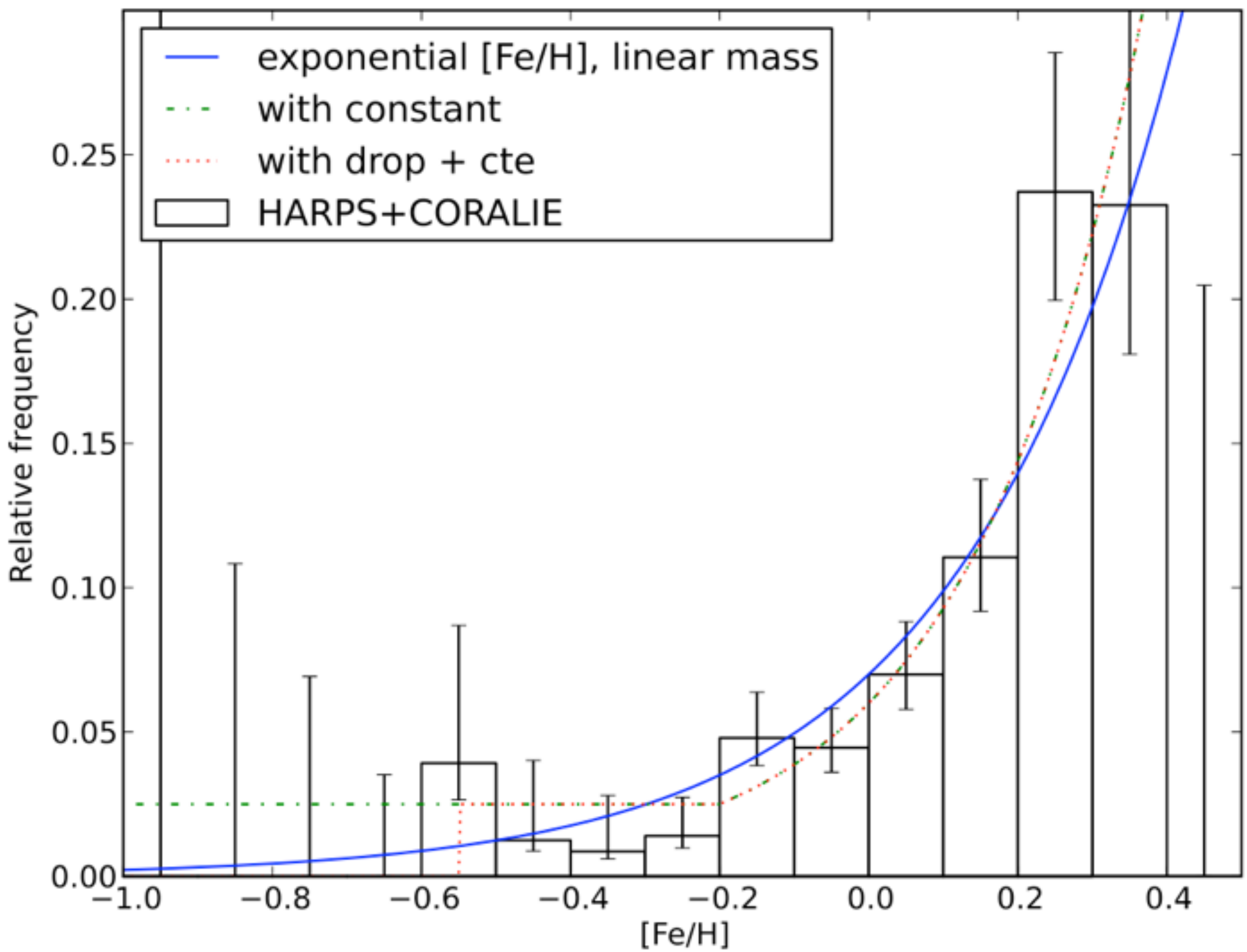
Santos et al. (2004); Udry & Santos (2007)

A simple power-law?



Johnson et al. (2010)

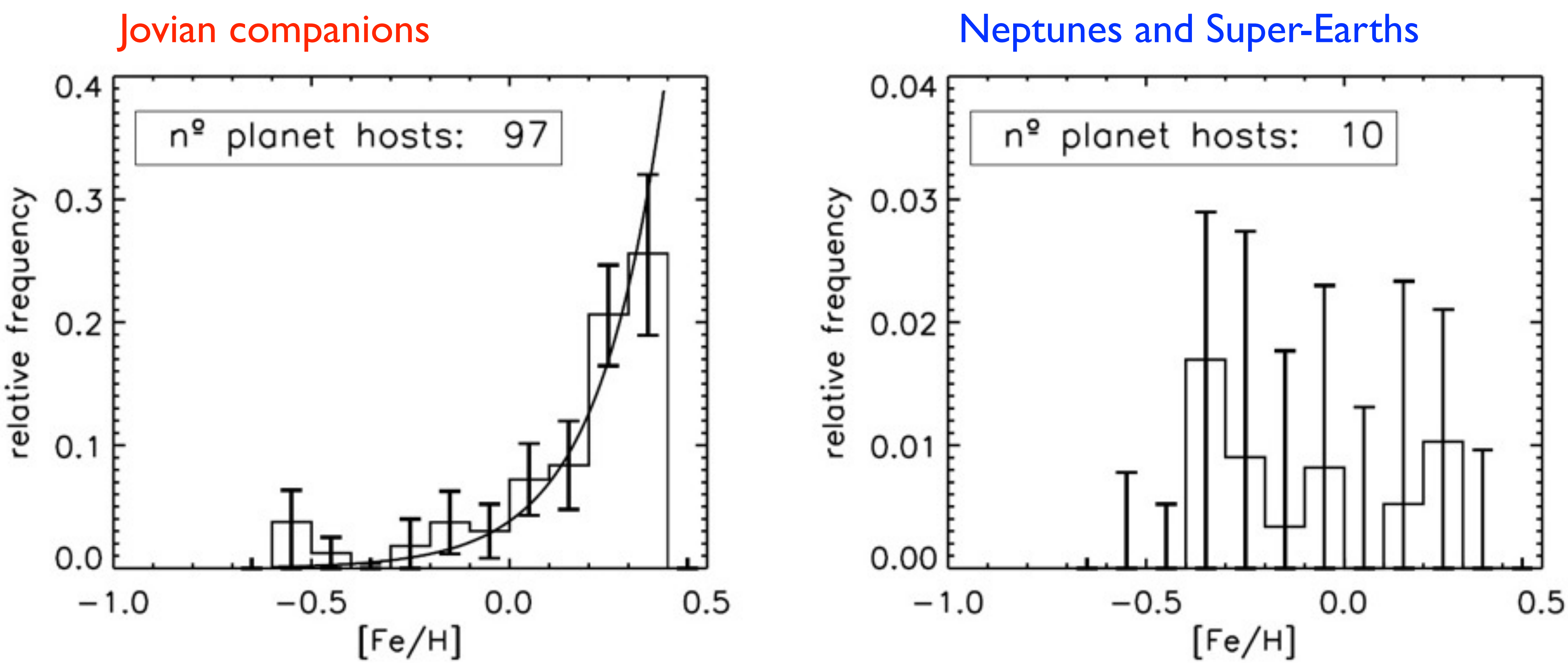
Results from the analysis of the HARPS sample



Mortier et al. (2012)

New *planet mass* domains explored

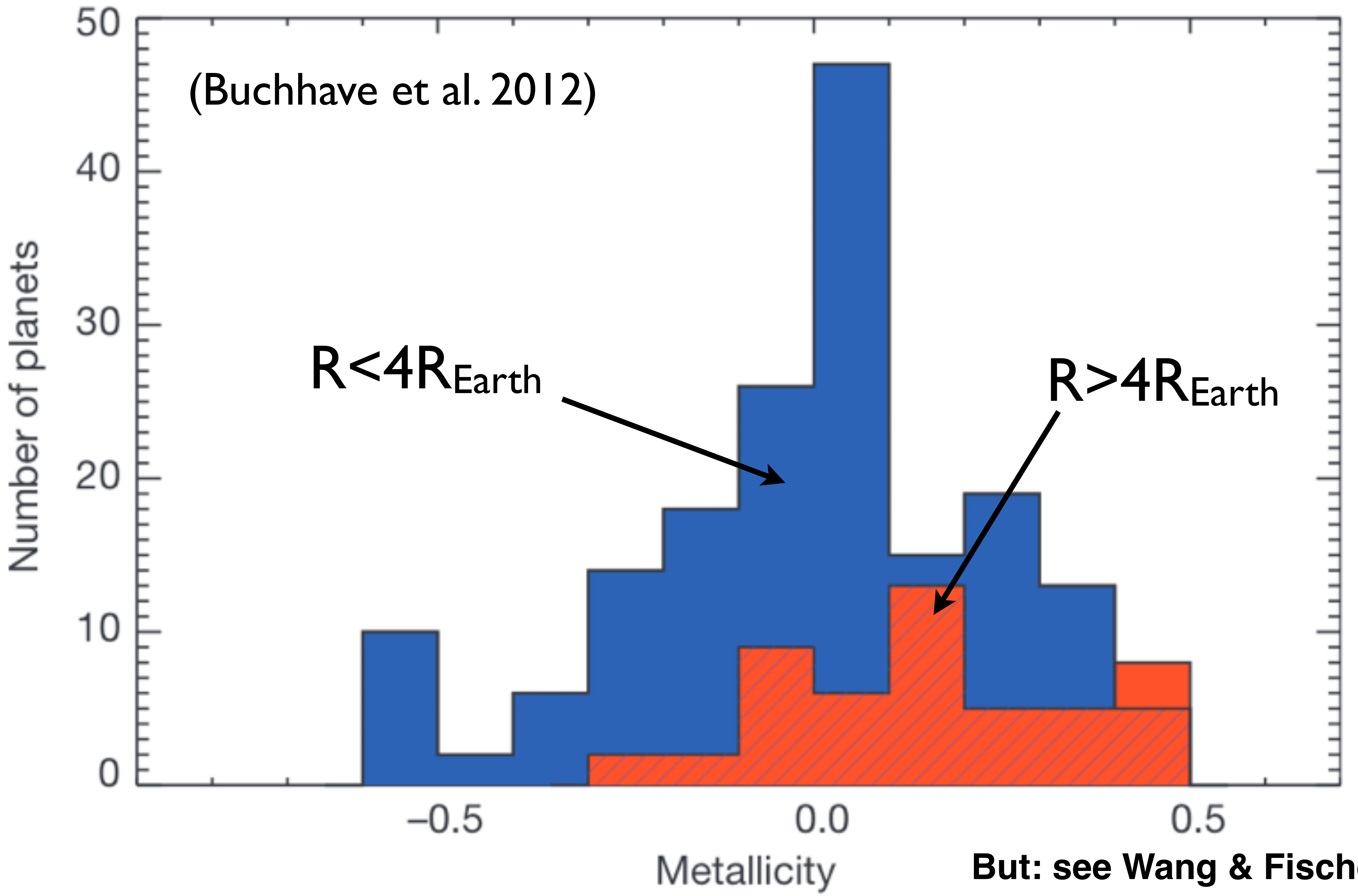
- HARPS: no correlation found for Neptune-**mass** planets (e.g. Udry et al. 2007; Sousa et al. 2011; Mayor et al. 2011)



From Sousa et al. (2011) - see also Mayor et al. (2011)

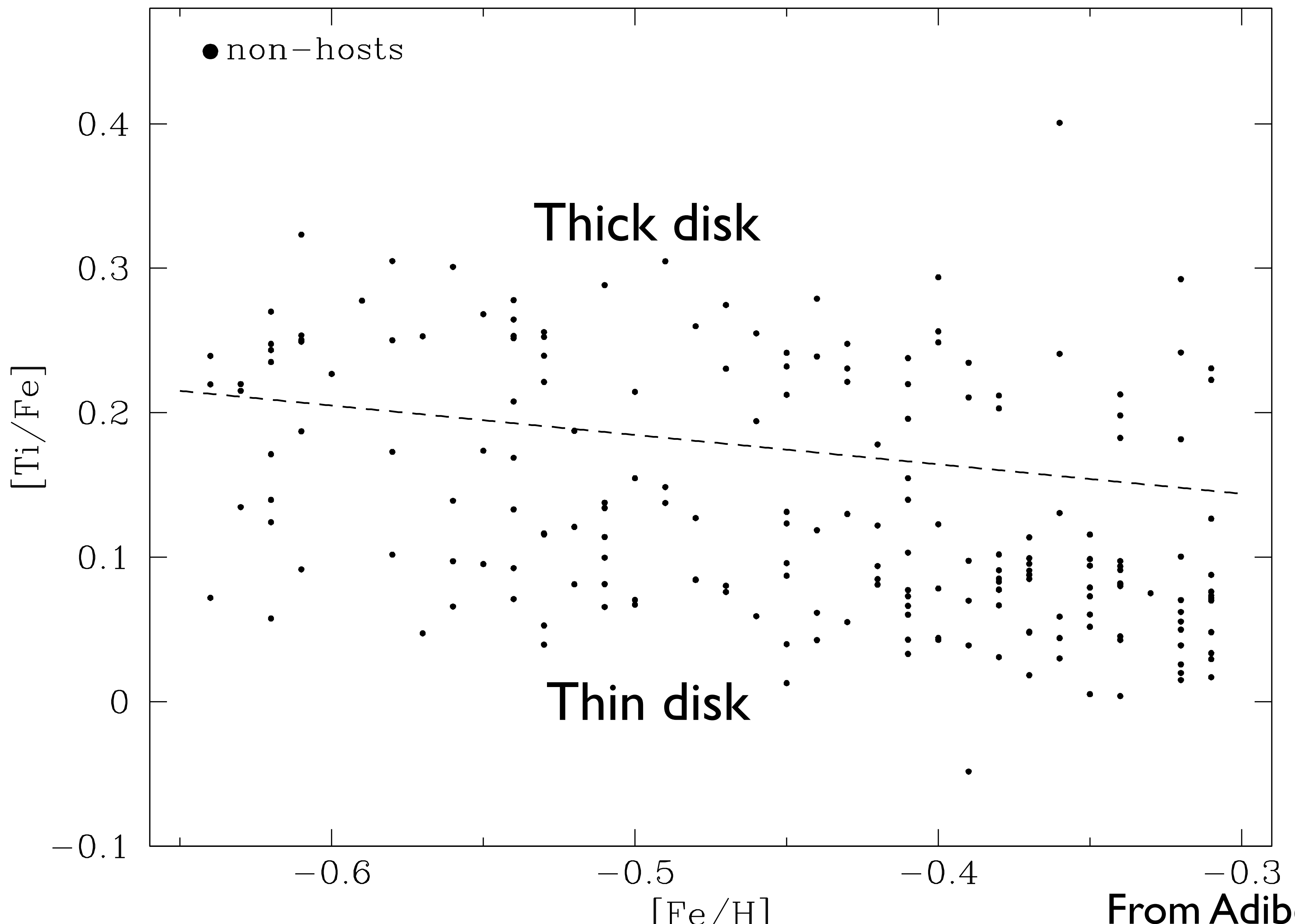
New *planet radius* domains explored

- Kepler: no correlation found for Neptune-**sized** planets



But: see Wang & Fischer (2015)

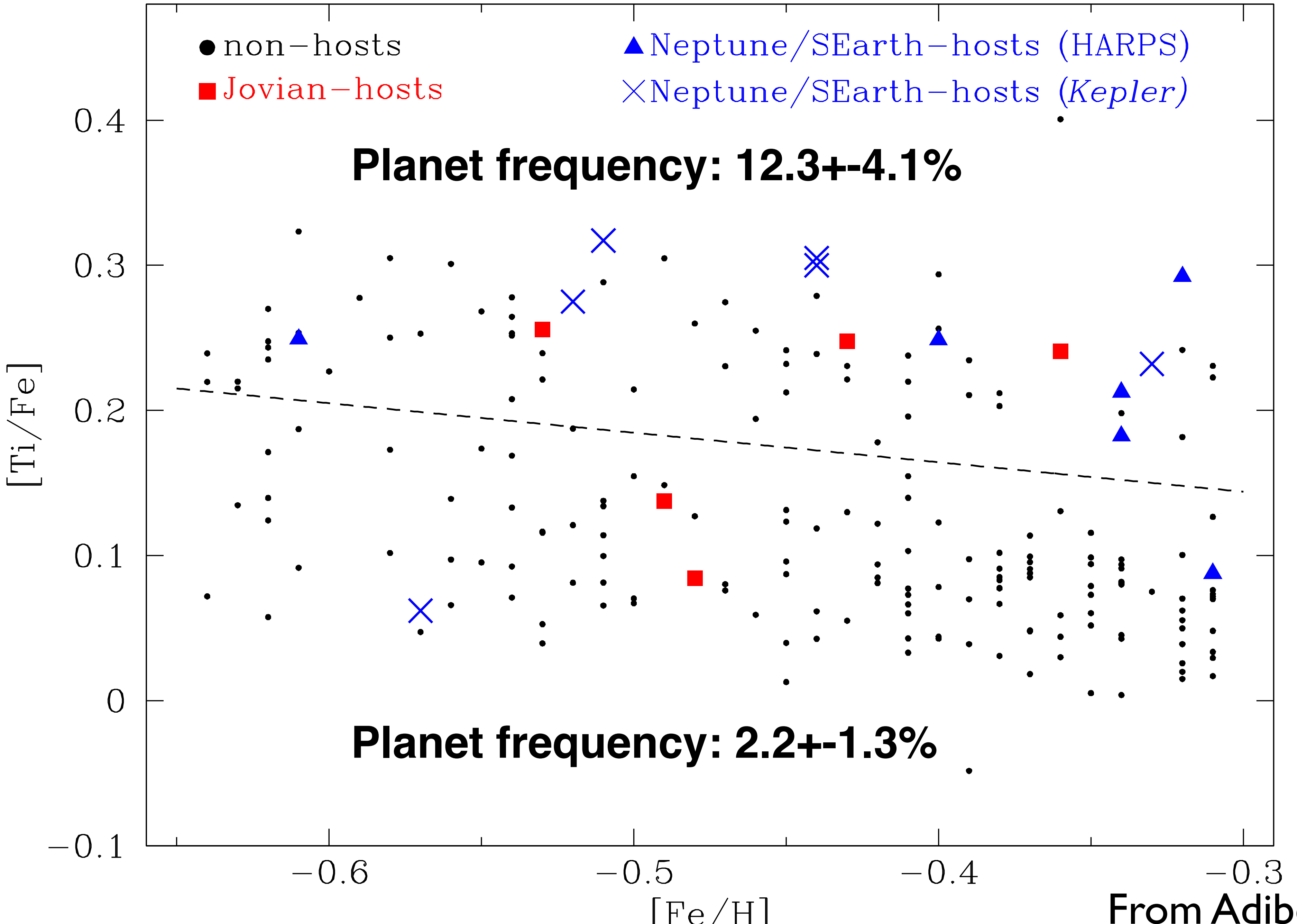
The role of alpha elements



From Adibekyan et al. (2012)

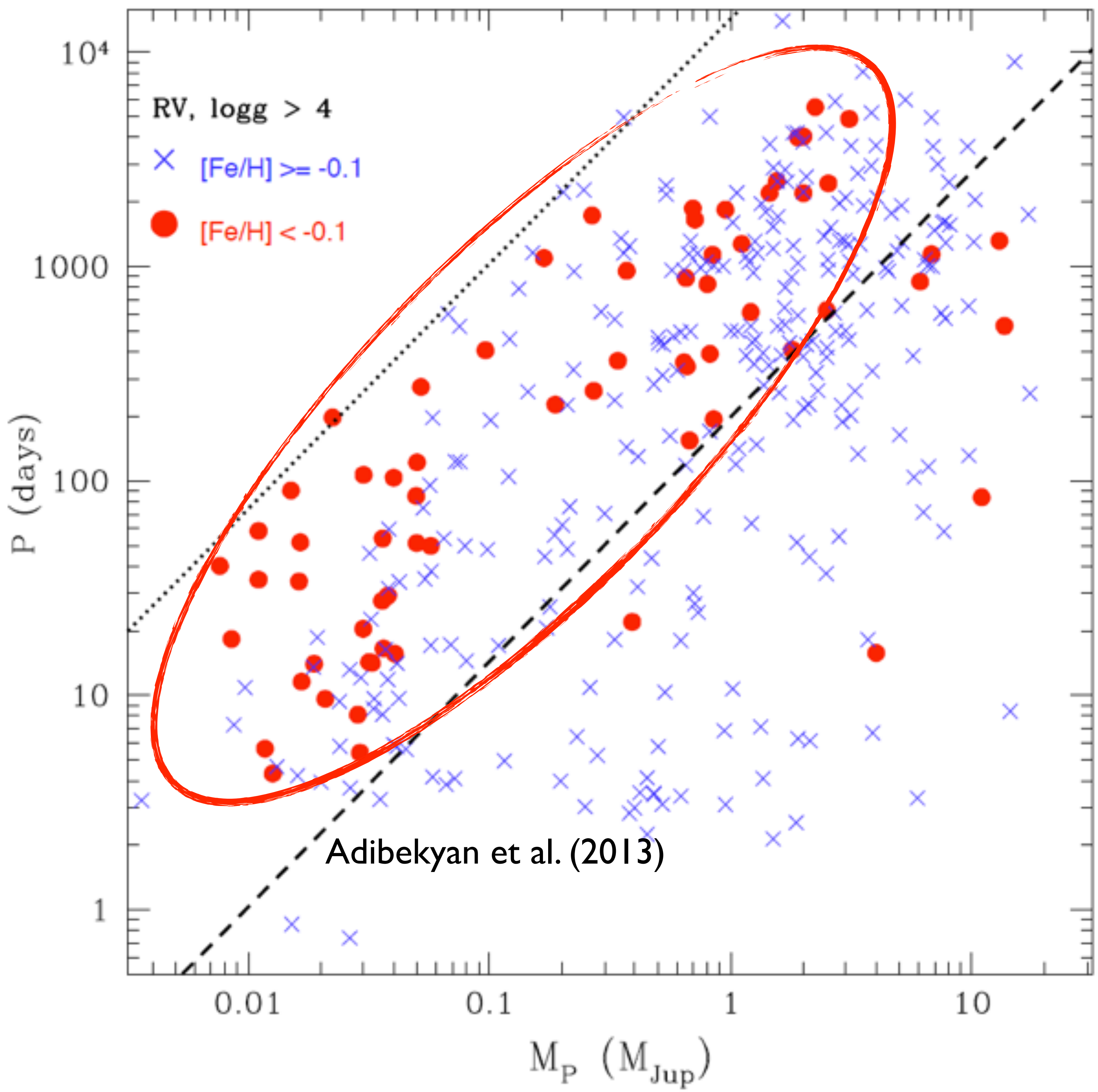
The role of alpha elements

- Conclusion 1: higher frequency of planets if star is rich in alpha element Ti
- Conclusion 2: metals critical in metal-poor stars even for low mass planet formation



From Adibekyan et al. (2012)

Metallicity in the mass-period diagram

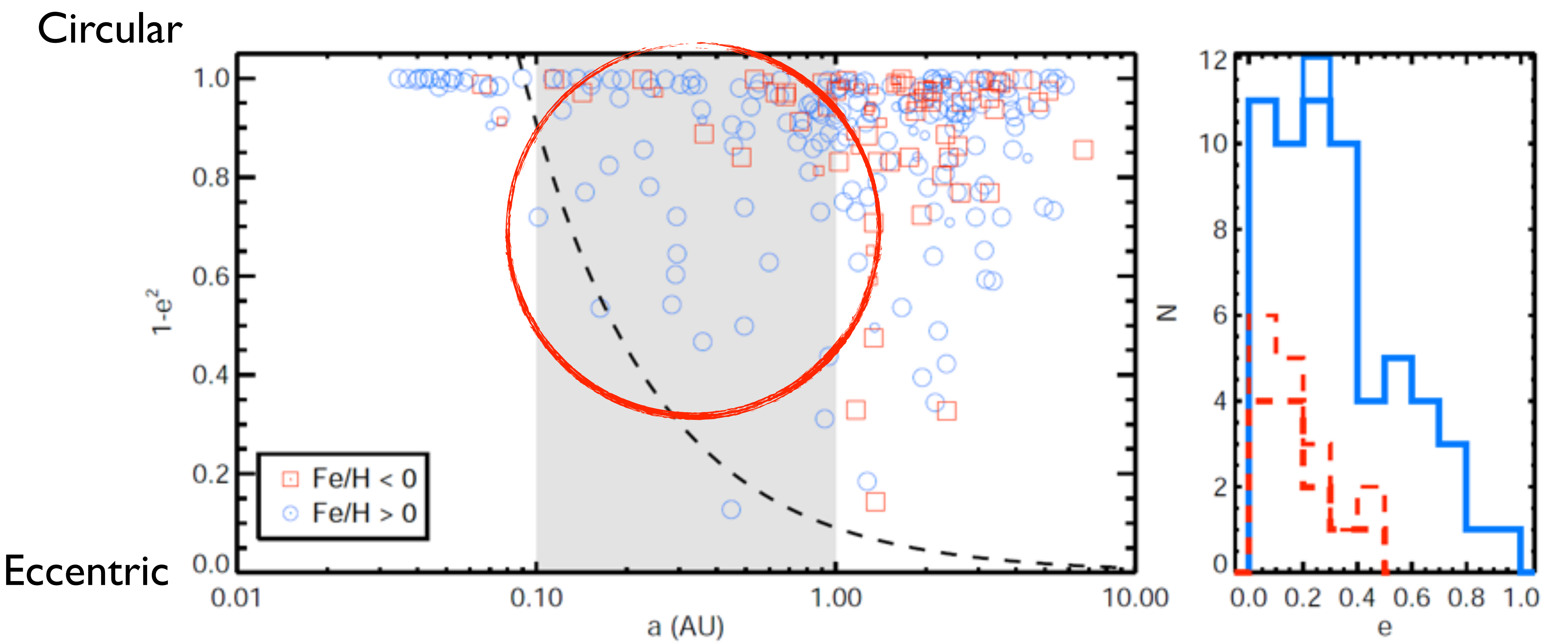


Hints about migration?

Planets form further out in metal-poor systems?

From Adibekyan et al. (2013); see also Beaugé & Nesvorny (2013)

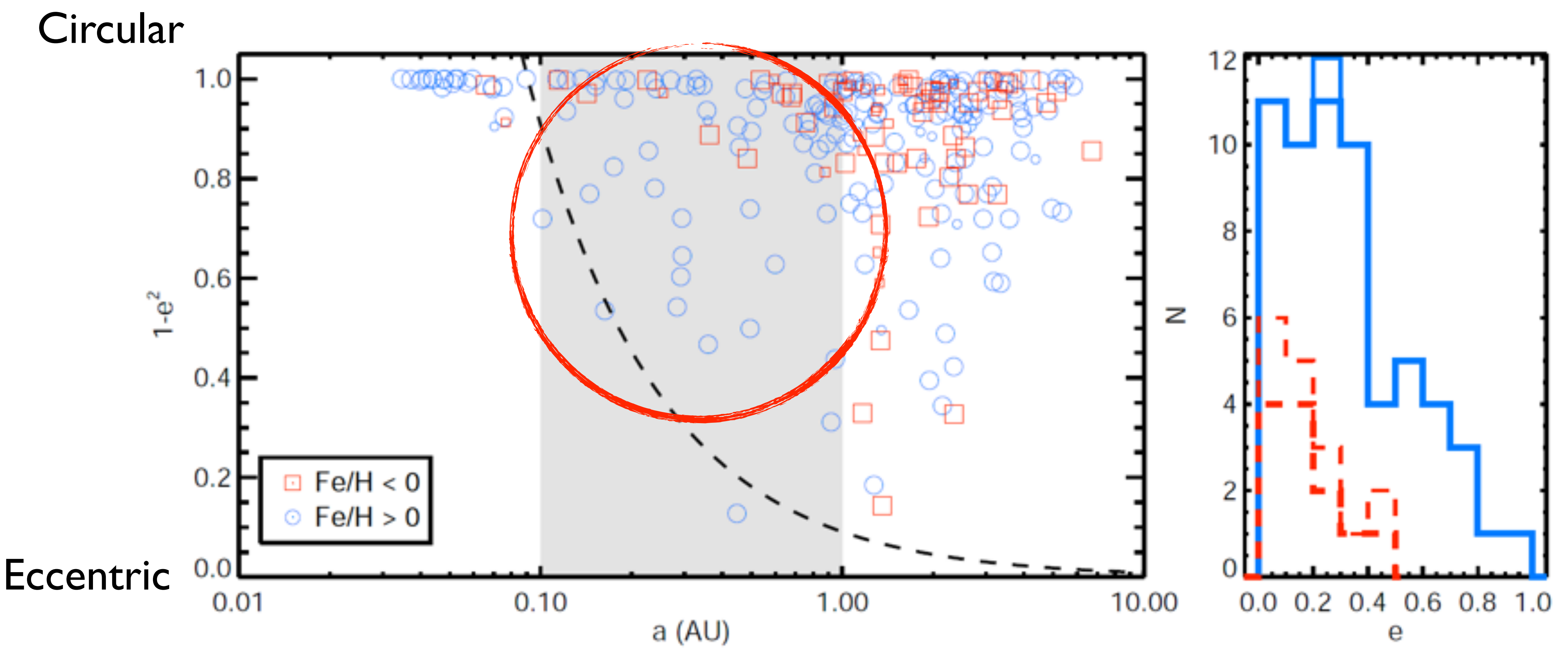
Planets, metallicity, and eccentricity



Dawson & Murray-Clay (2013)

Hints for higher eccentricity for planets orbiting higher [Fe/H] stars

Planets, metallicity, and eccentricity

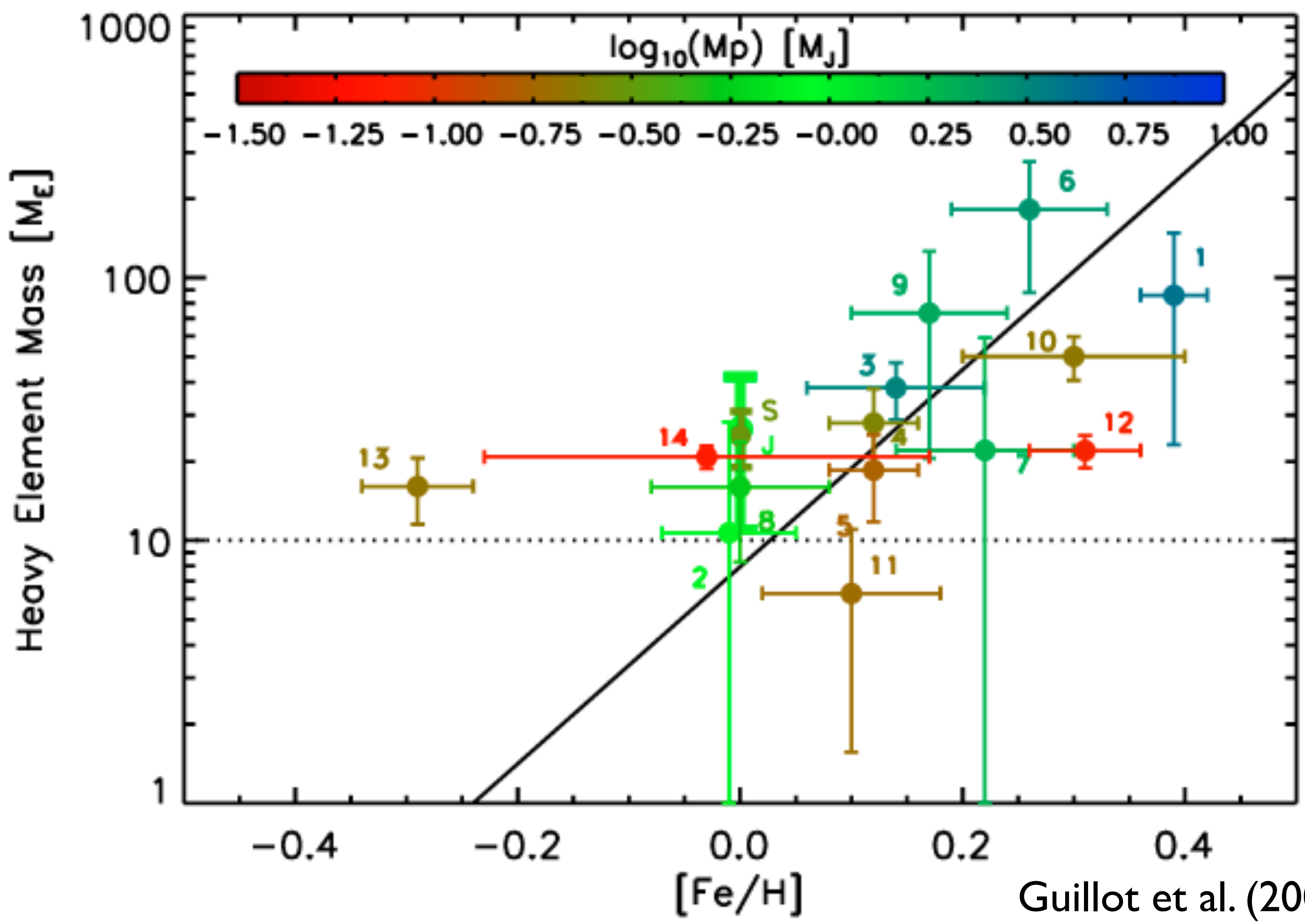


Dawson & Murray-Clay (2013)

Effect of planet-planet scattering?

Disk interaction depends on [Fe/H]? (Tsang et al. 2014)

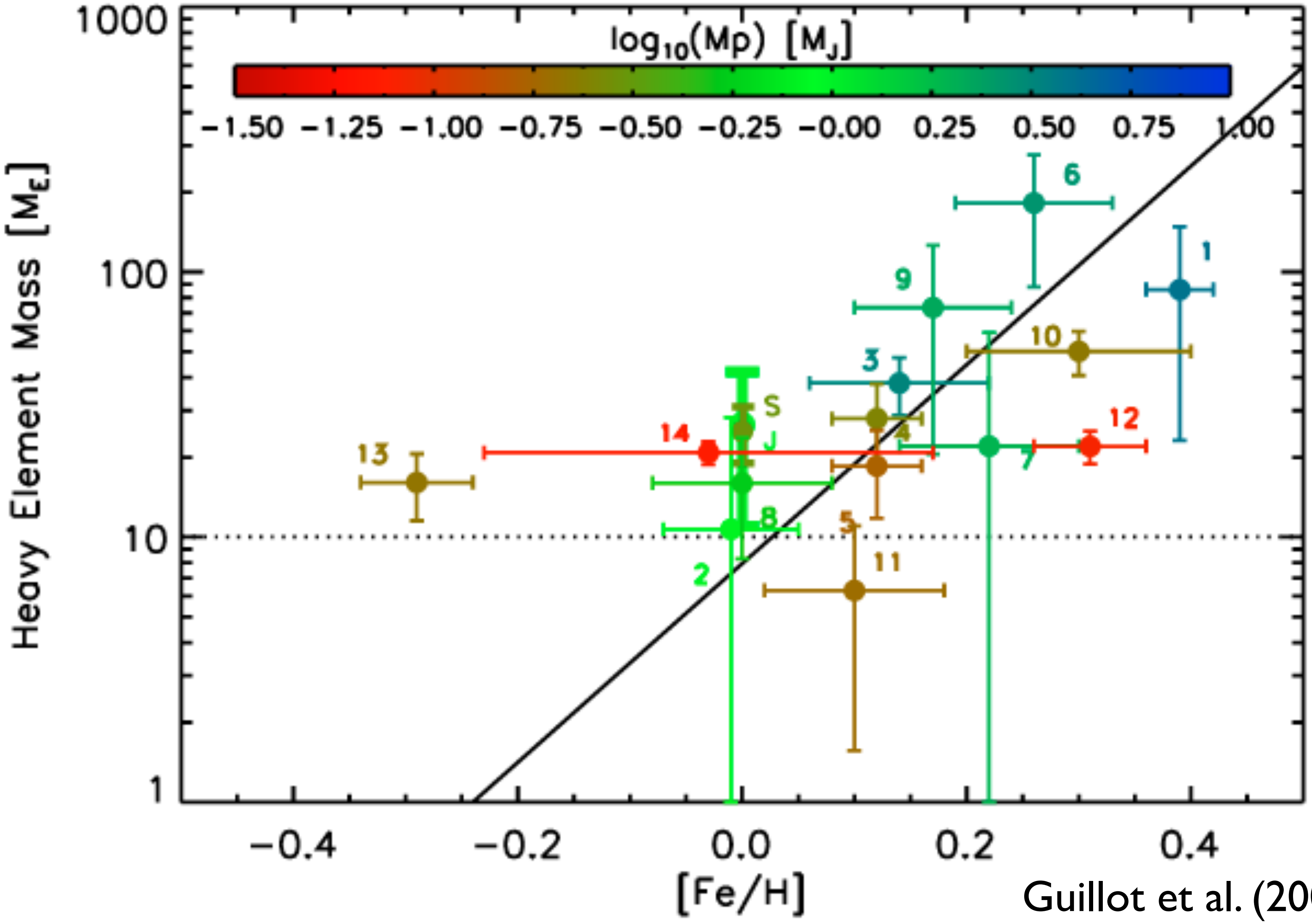
Giant planet core-mass and stellar [Fe/H]



Guillot et al. (2006), Fortney et al. (2007), Miller & Fortney (2011)

Giant planet core-mass and stellar [Fe/H]

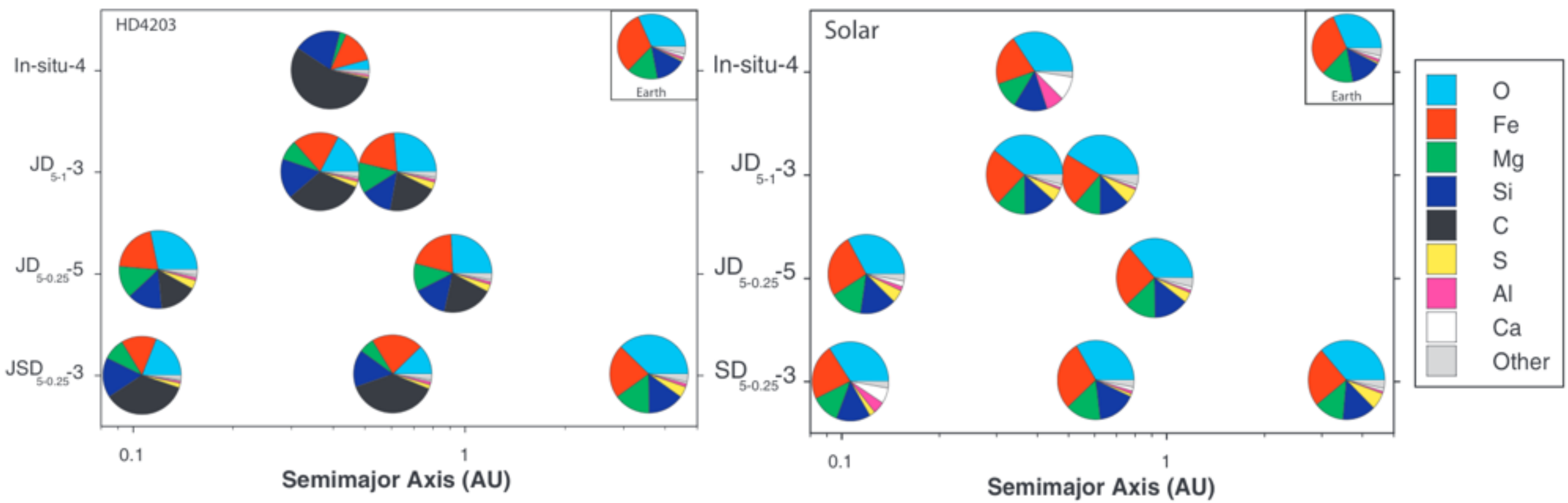
- Can we use this "principle" to derive the content of rocky planets from stellar chemistry?



Guillot et al. (2006), Fortney et al. (2007), Miller & Fortney (2011)

Different disk abundances => different planets

- Simulated planets considering different C/O ratios (using abundances in HD4203 and the Sun as reference)



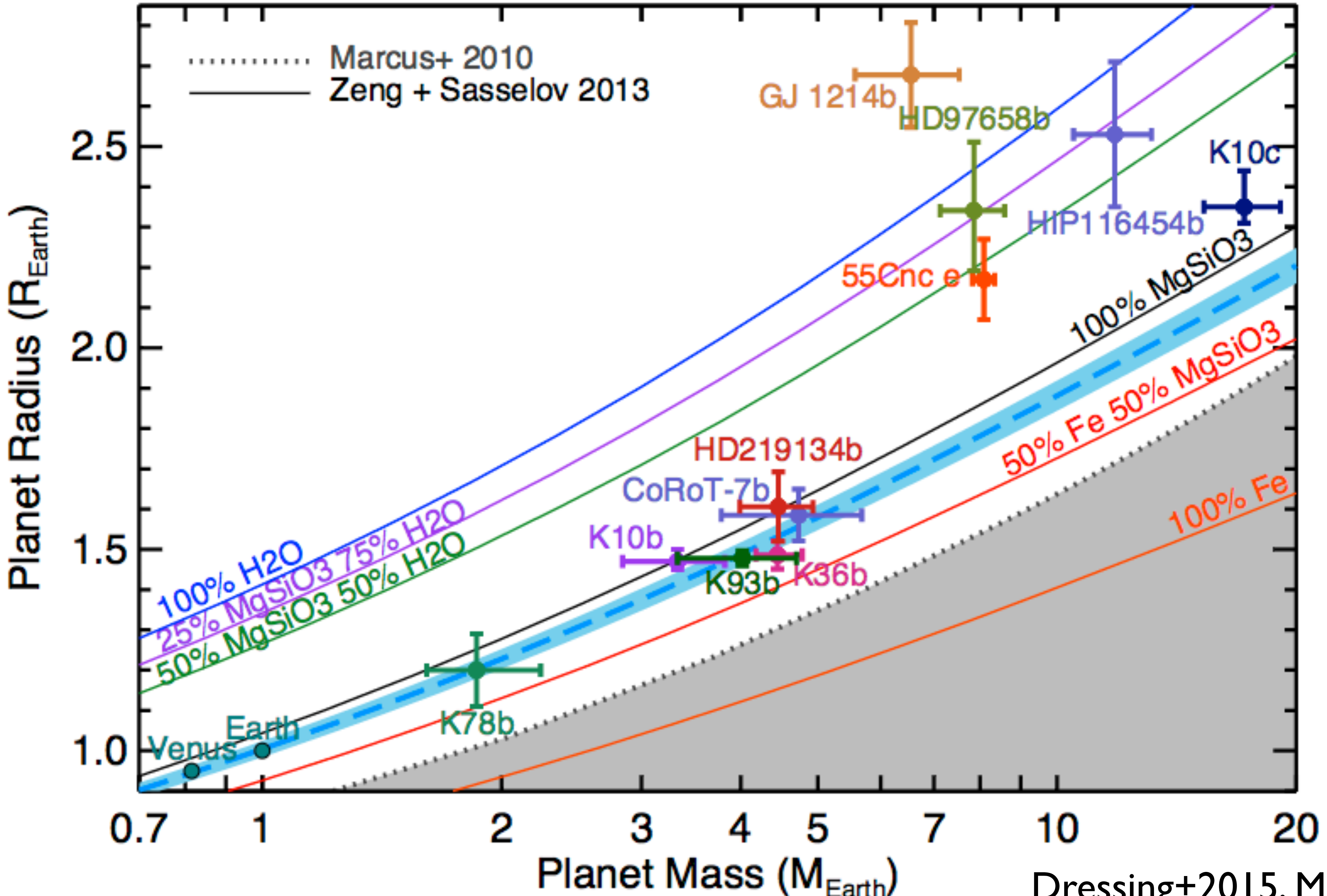
Carter-Bond et al. (2013), Dorn et al. (2015), Alibert et al. (2015)

What do we know from our Solar System?

- Solar system planets:
  - Earth, Venus, Mars, and meteorites all have "solar" Fe, Mg, and Si composition - e.g. Sanloup et al. 1999
  - Can we use stellar Fe, Mg, and Si to predict the composition of rocky exoplanets? (Dorn et al. 2015)

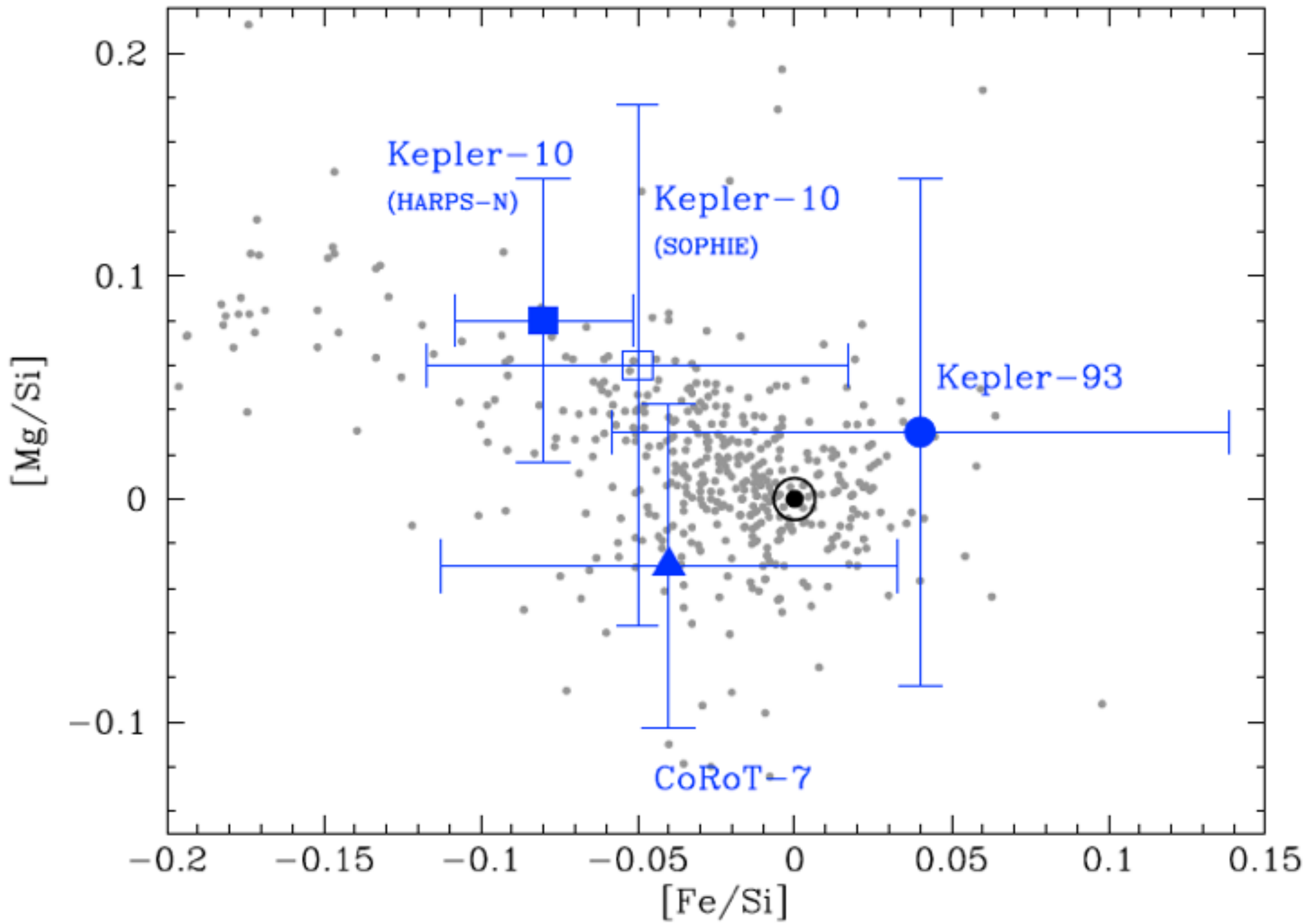
Rocky exoplanets: same composition?

- Rocky planets: follow the Earth composition line!



Dressing+2015, Motalebi+2015

Rocky exoplanets: same composition?



Santos+2015

Rocky exoplanets: same composition

$$
\begin{aligned}
N_{\mathrm{O}} &= N_{\mathrm{H_2O}} + 3N_{\mathrm{MgSiO_3}} + 4N_{\mathrm{Mg_2SiO_4}} \\
N_{\mathrm{Mg}} &= N_{\mathrm{MgSiO_3}} + 2N_{\mathrm{Mg_2SiO_4}} \\
N_{\mathrm{Si}} &= N_{\mathrm{MgSiO_3}} + N_{\mathrm{Mg_2SiO_4}}
\end{aligned}
$$

Table 1. Mass fractions of heavy element, total fraction of heavy elements, and iron mass fraction among refractory species (values in %).

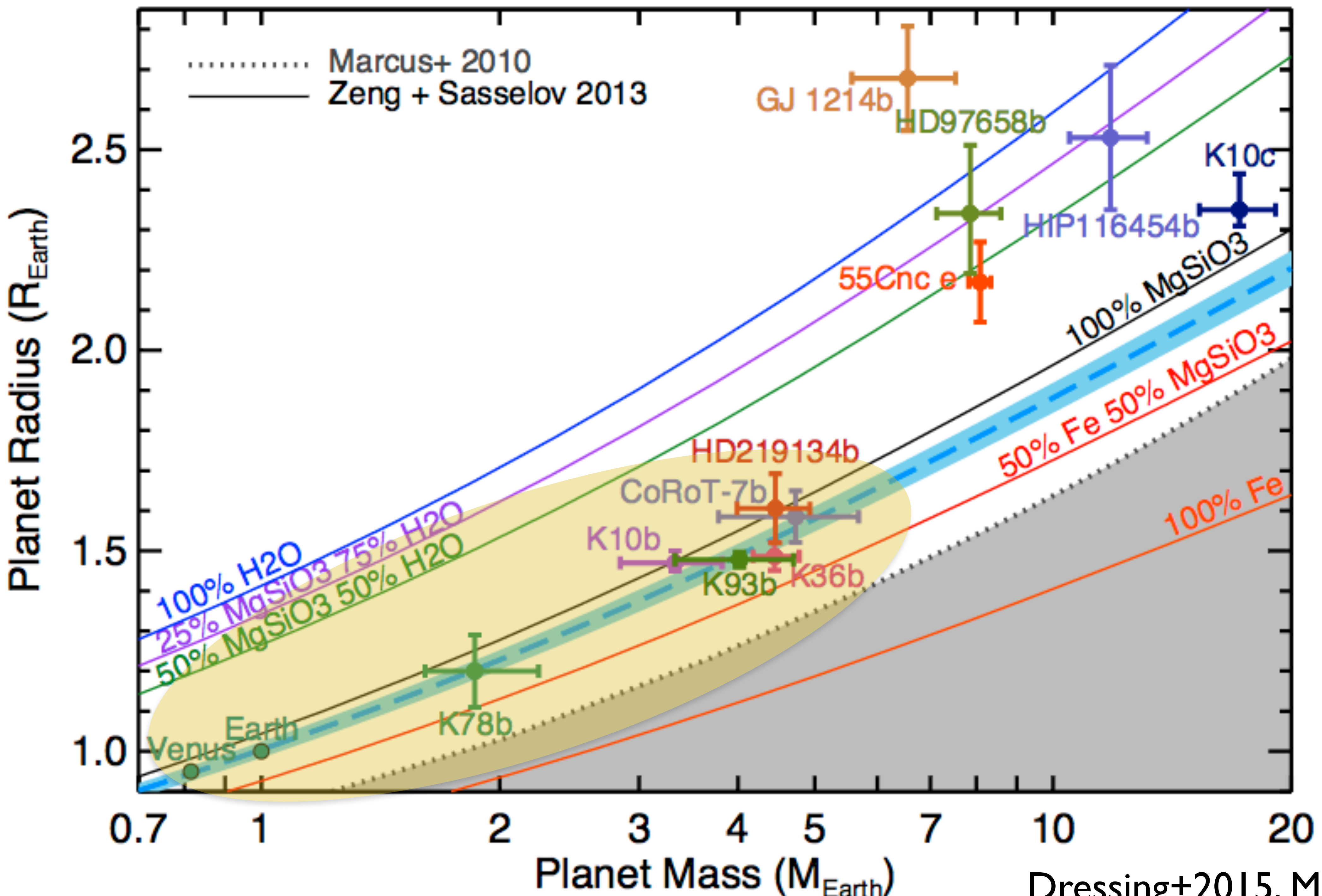
Quantity	C-7	K-93	K-10	Sun	Sun[f]
H_2O[a]	0.75±0.31	0.54±0.22	0.98±0.20	0.50	0.51
CH_4[a]	0.32±0.05	0.35±0.13	0.36±0.04	0.37	0.29
Fe[a]	0.14±0.01	0.09±0.01	0.10±0.00	0.13	0.17[d]
$MgSiO_3$[a]	0.25±0.08	0.10±0.06	0.11±0.05	0.19	0.27[e]
Mg_2SiO_4[a]	0.05±0.06	0.08±0.06	0.14±0.06	0.08	
Z[b]	1.50±0.31	1.17±0.25	1.69±0.21	1.26	1.32
f_{iron}[c]	31.6±2.6	34.7±3.7	27.5±1.7	33.2	38.0

[a] The m_{H2} and m_{He} are between 74.7-75.1% and 23.6-23.7%, respectively. [b] Summed mass percent of all heavy elements. [c] $m_{\mathrm{Fe}}/(m_{\mathrm{Fe}} + m_{\mathrm{MgSiO3}} + m_{\mathrm{Mg2SiO4}})$. [d] Includes all metal species and FeS. [e] Includes all silicates and oxides. [f] Lodders (2003).

Santos+2015

Rocky exoplanets: same composition?

- Rocky planets: follow the Earth composition line!



Dressing+2015, Motalebi+2015

What next?

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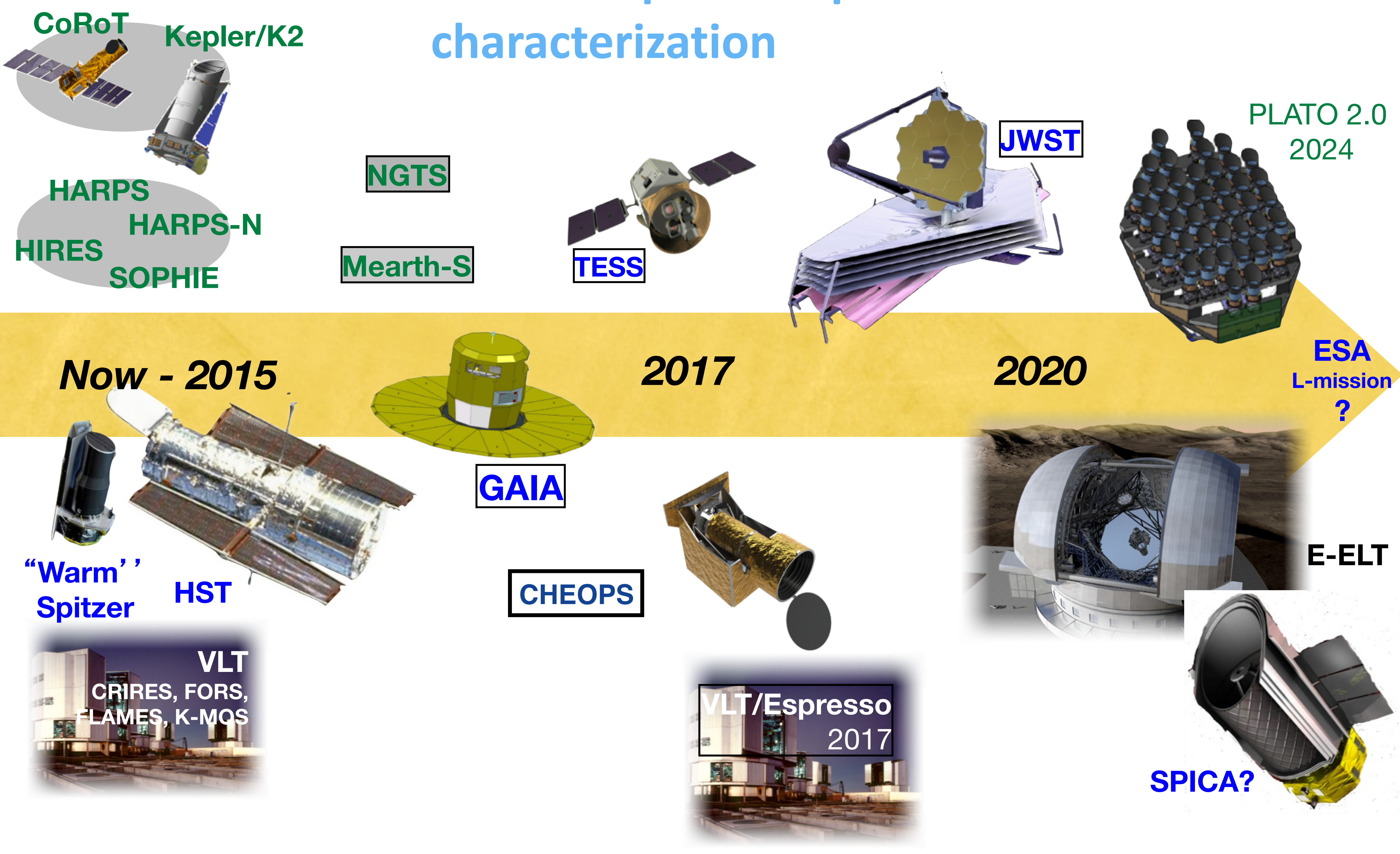
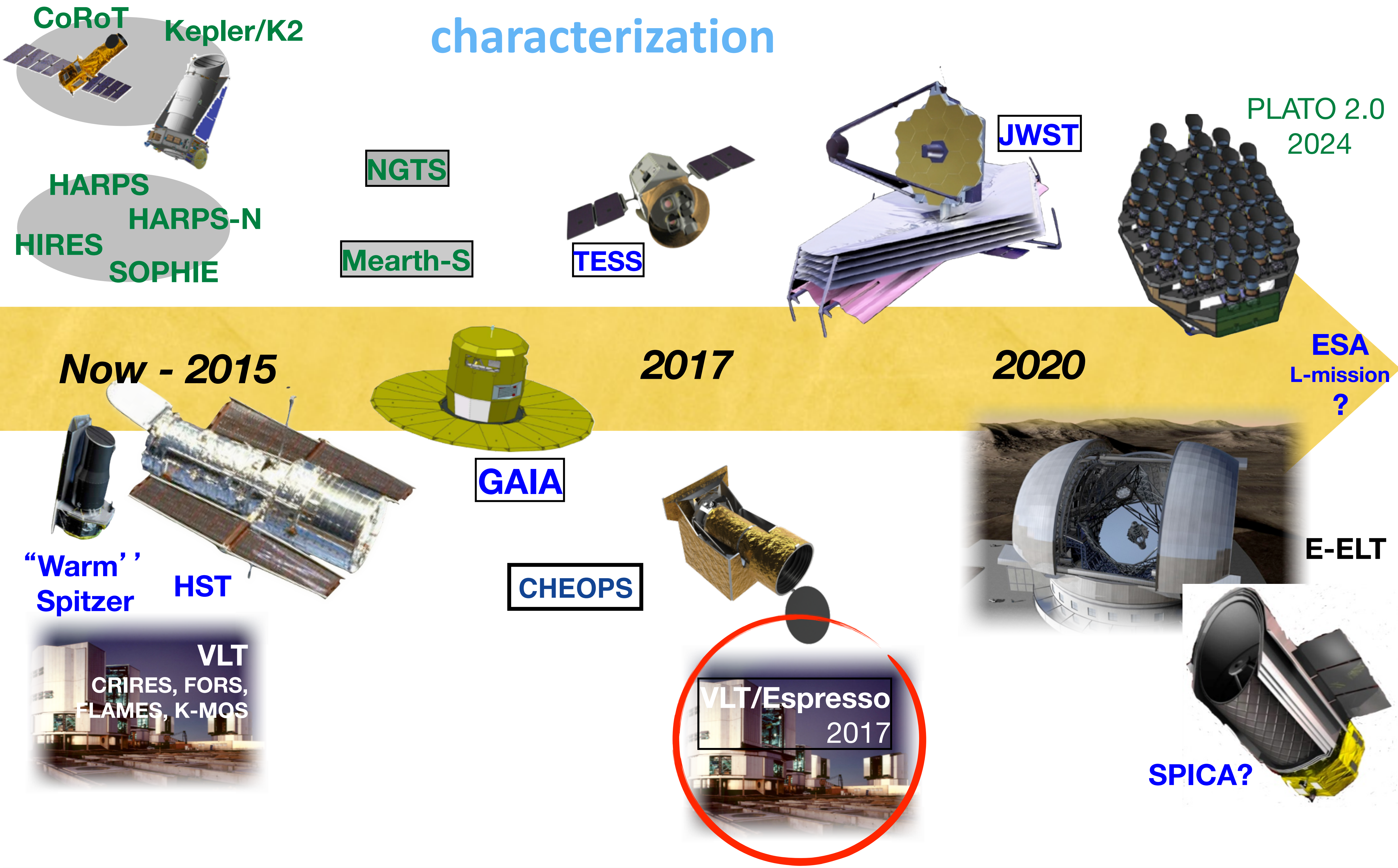
A roadmap for exoplanet detection and characterization

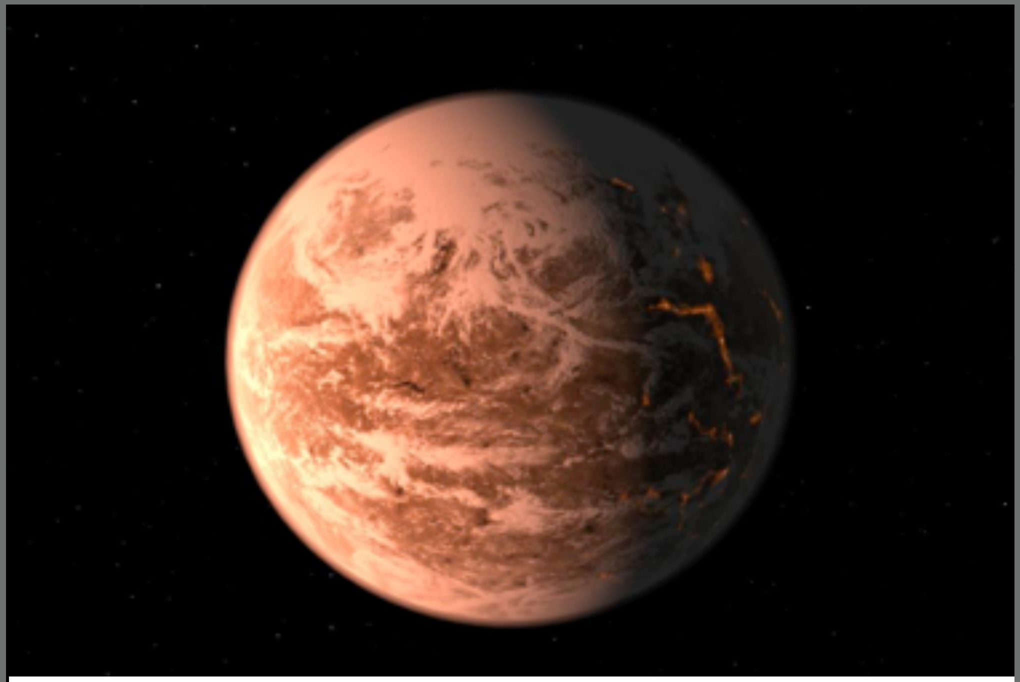


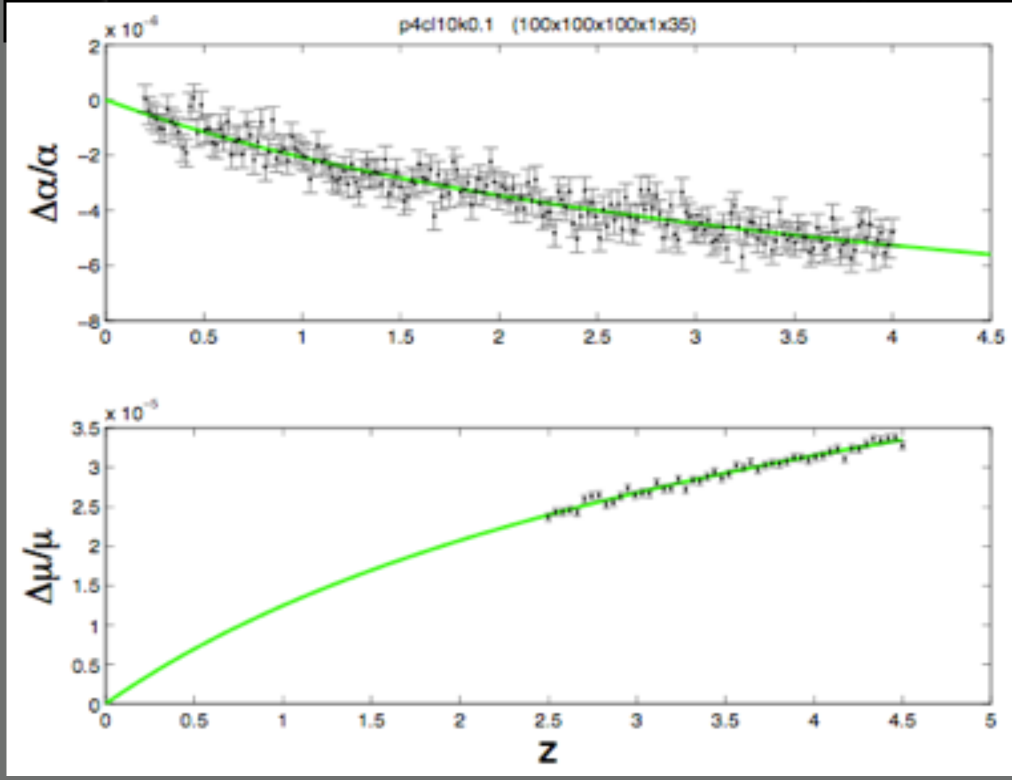
A roadmap for exoplanet detection and characterization



Ground-based follow-up: “Weighting” planets with ESPRESSO@VLT

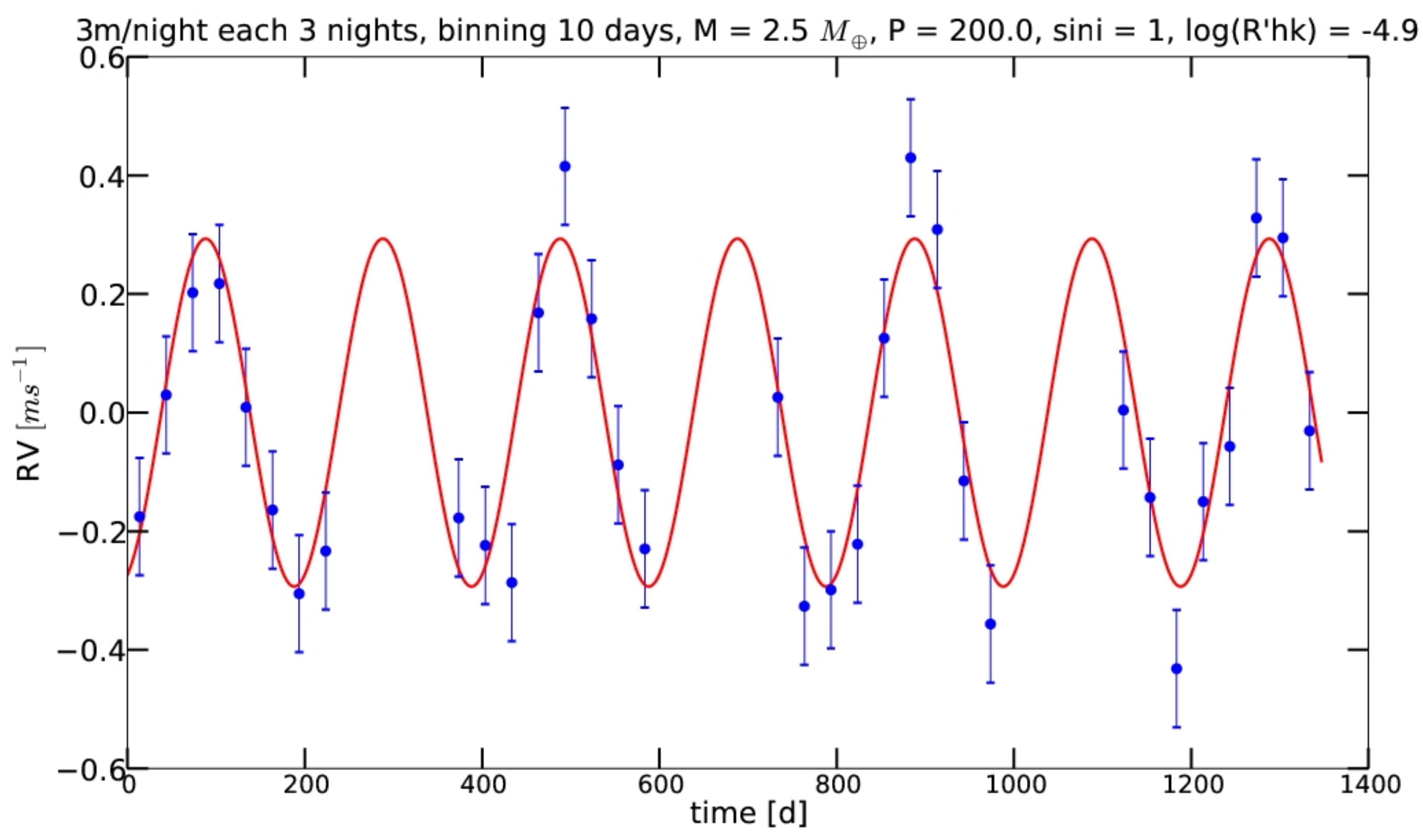
- New high resolution, stable spectrograph for the ESO-VLT
- Search for Earth-like planets orbiting solar-type stars (using RV method)
- Variability of physical constants
- Other state-of-the-art





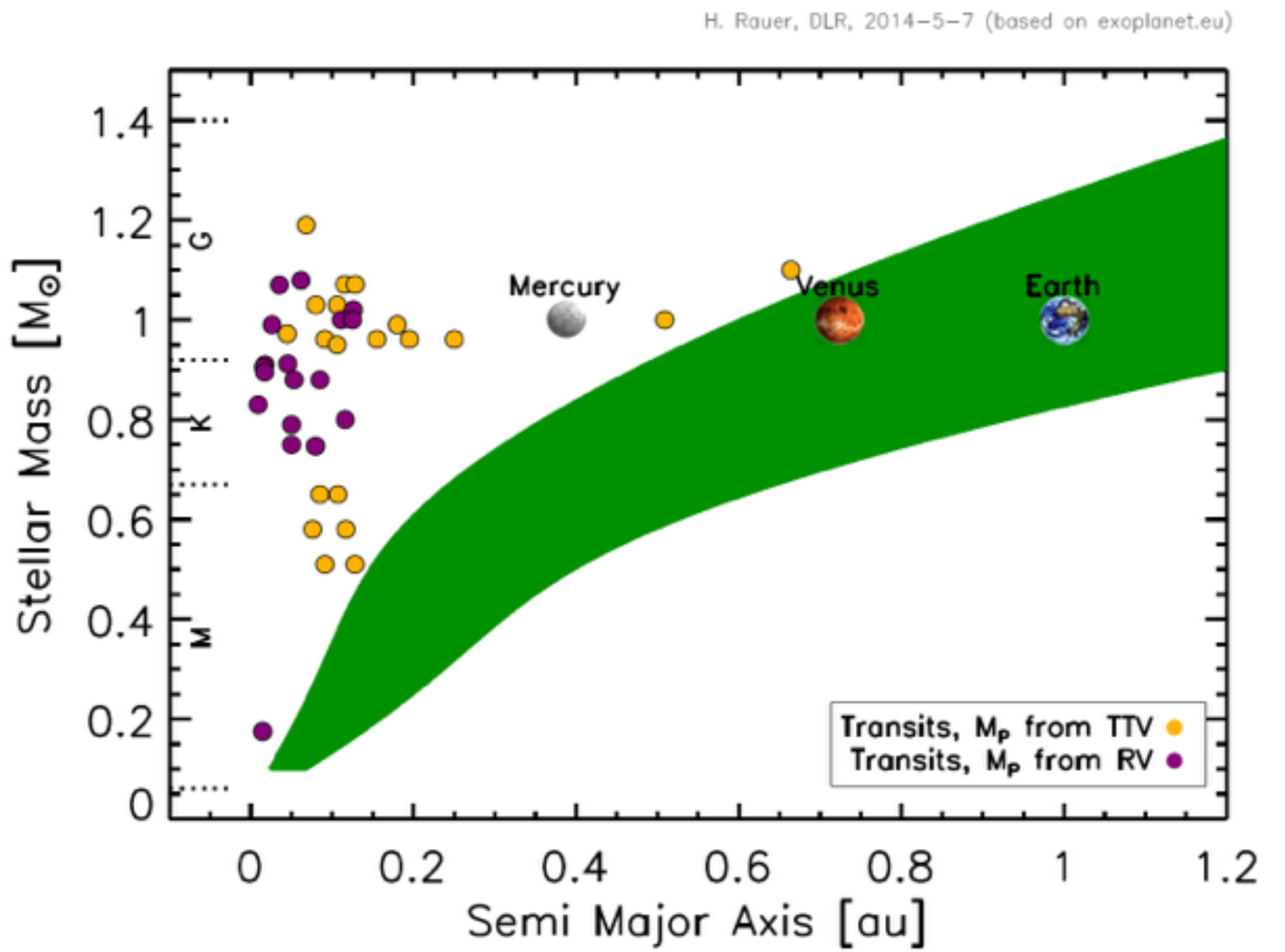
Simulated 2.5 M_{Earth} planet detection

- P=200 days
- K-dwarf
- ESPRESSO can detect planets in Habitable Zone!



Status: Characterized „super-Earths" in their habitable zone

„Super-Earths" with characterized radius and mass

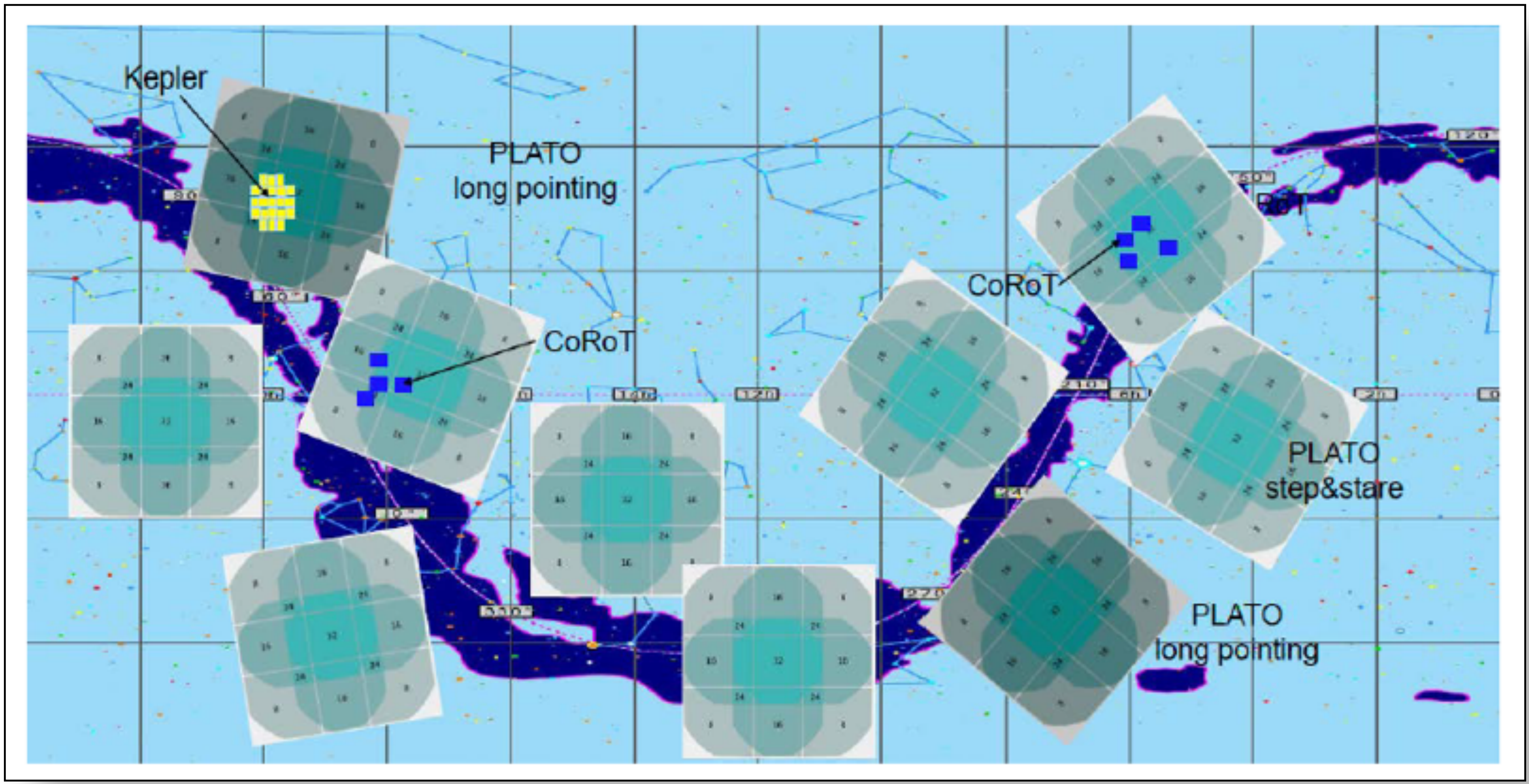


- Goal: Detect and characterize super-Earths in habitable zones
- Status: very few small/ light planets in habitable zones detected

→ No characterized „super-Earths" in the habitable zone

PLATO2.0 (ESA, 2024)

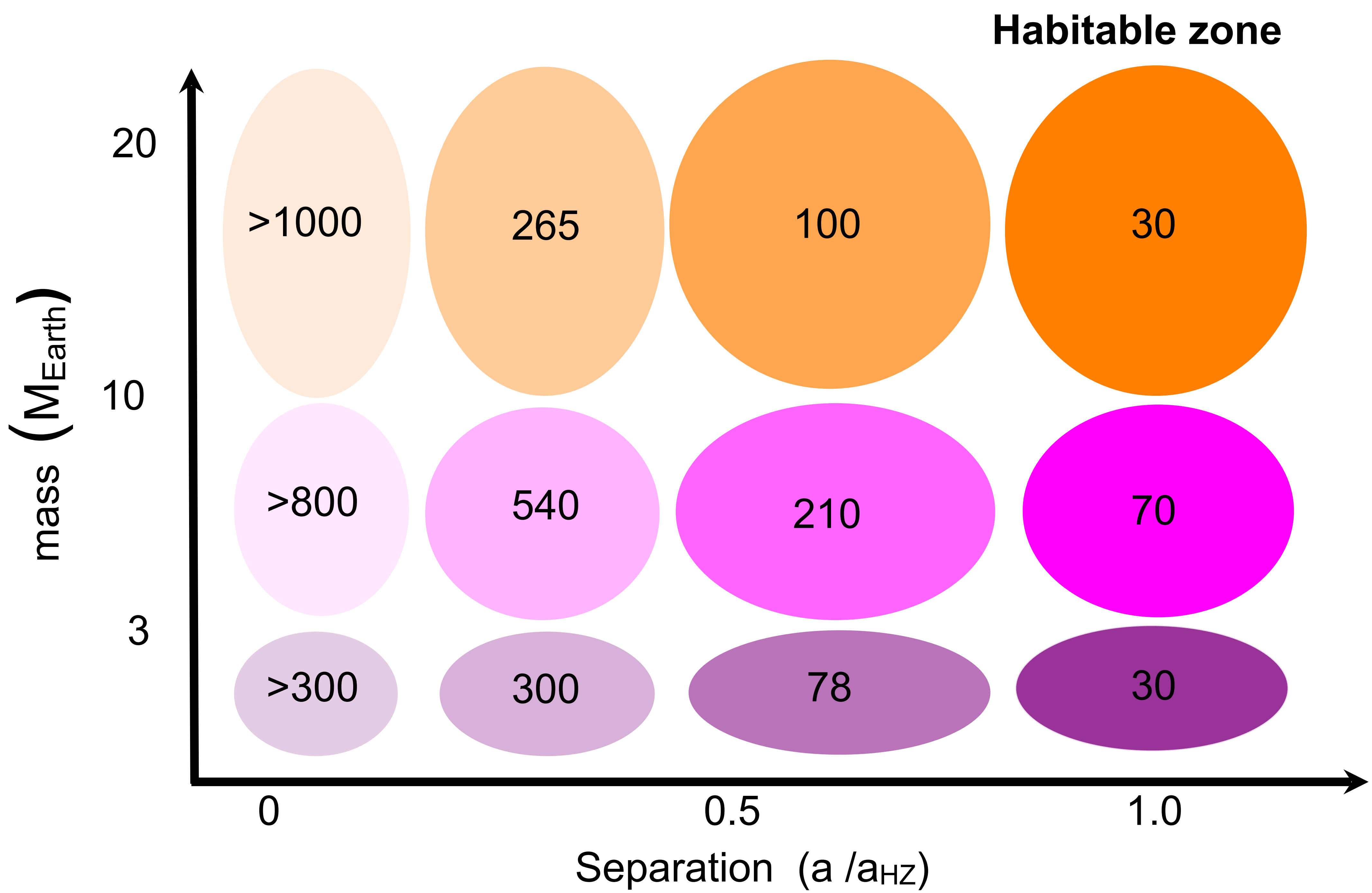
6 years nominal science operation:
- 2 long pointings of 2-3 years
- step-and-stare phase (2-5 months per pointing)



→ **covers ~50% of the sky**

Total numbers of characterized planets in core sample

Number of characterized planets (**Earth to Neptune mass**) after detailed model of radial velocity efforts and the impact of stellar activity:



Conclusions

- Planets are common (from RV and transit surveys), and come in all sorts of flavors
- Low mass planets are the most common!
- Statistical properties of planets: huge amount of information for planet formation models
- Planet-host star properties are relevant in this process
- Bright future of RVs: both for survey mode and follow-up of space transit data

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Thank you!

Questions?

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