CoRoT Symposium 3 - KASC meeting 7:

The Space-Photometry Revolution

7 July 2014

From super-Earths to Brown dwarfs:

The Planet-Diversity Revolution

Alexandre SANTERNE

Instituto de Astrofísica e ciências do espaço (IA)

Centro de Astrofísica da Universidade do Porto

alexandre.santerne@astro.up.pt

Credit: C. Pulliam & D. Aguilar (CfA)

instituto de astrofísica e ciências do espaço

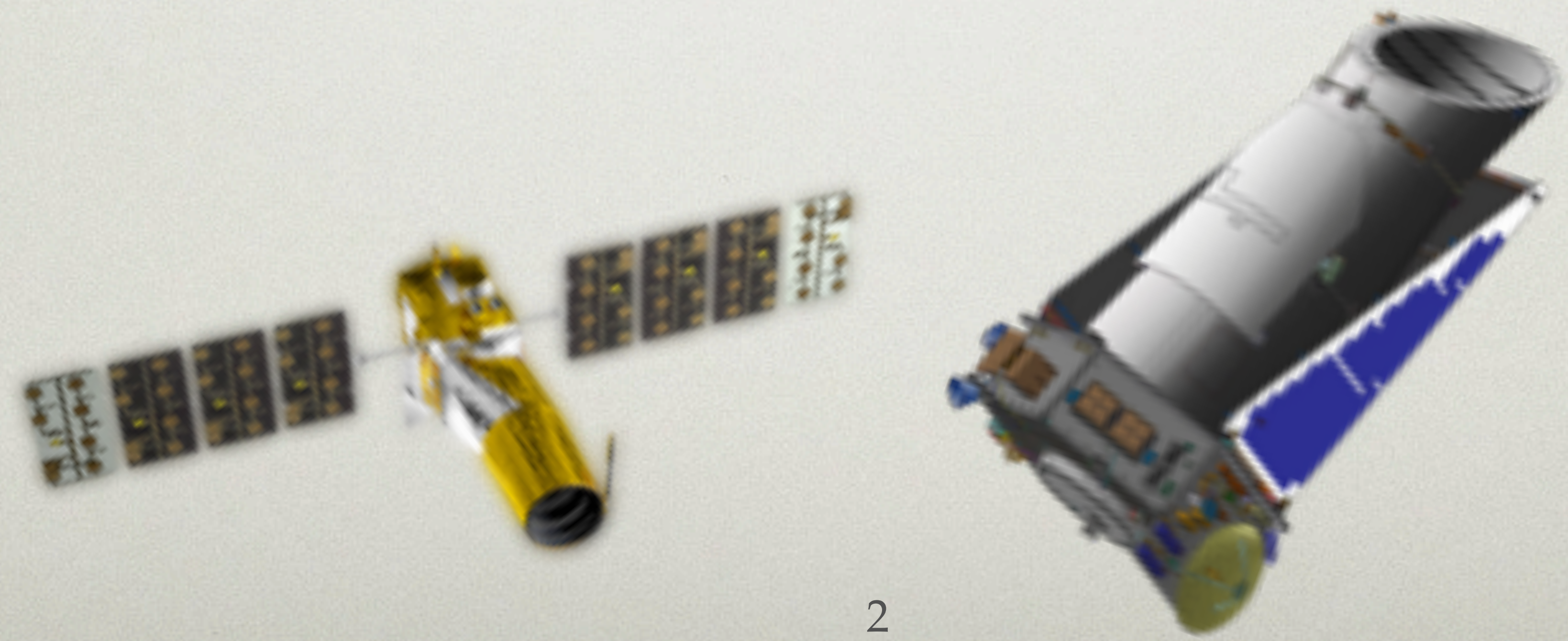
Seventh Framework Programme

erc

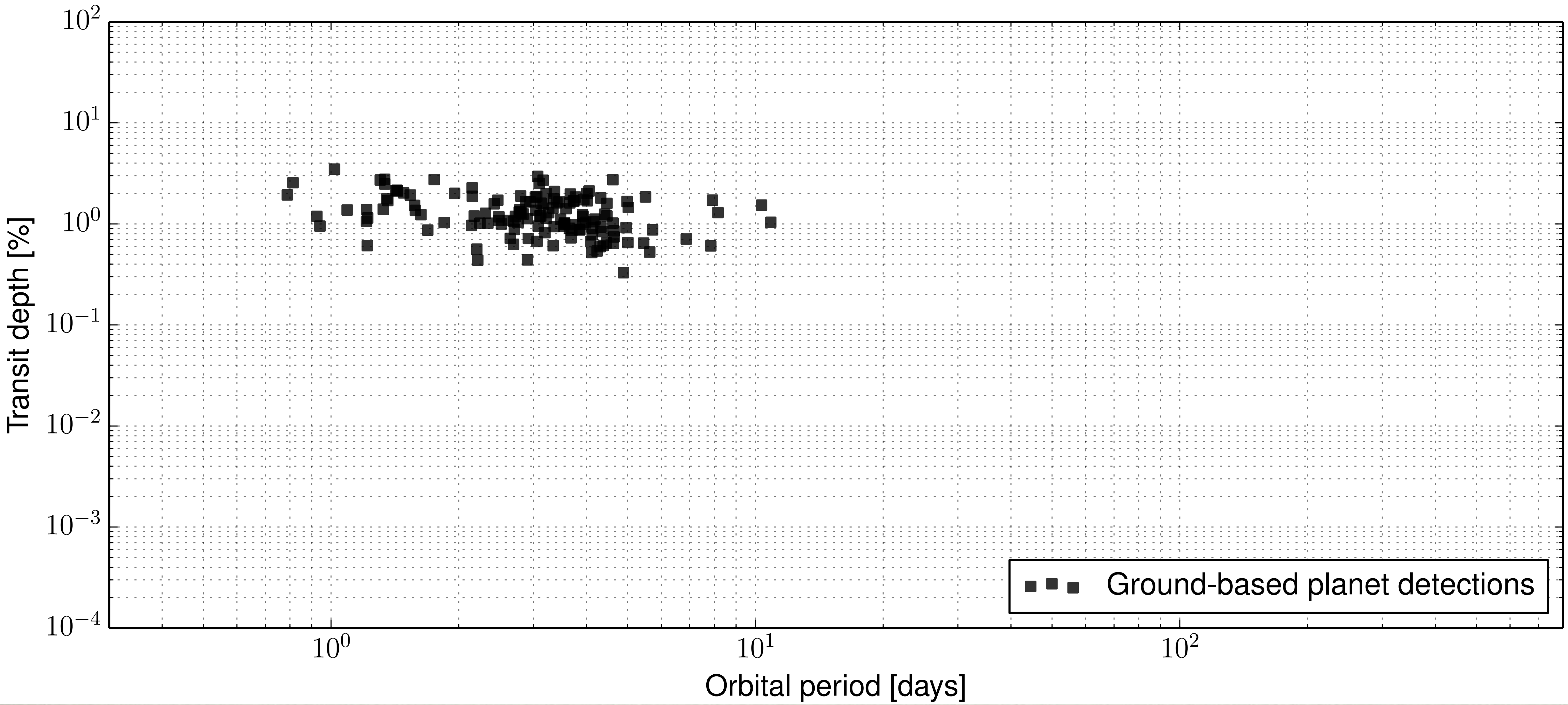
FCT Fundação para a Ciência e a Tecnologia

Outline

- The planet-diversity revolution: from super-earths to brown dwarfs
- Limitations to the exploration of planet’s density
- Planet statistics



THE REVOLUTION



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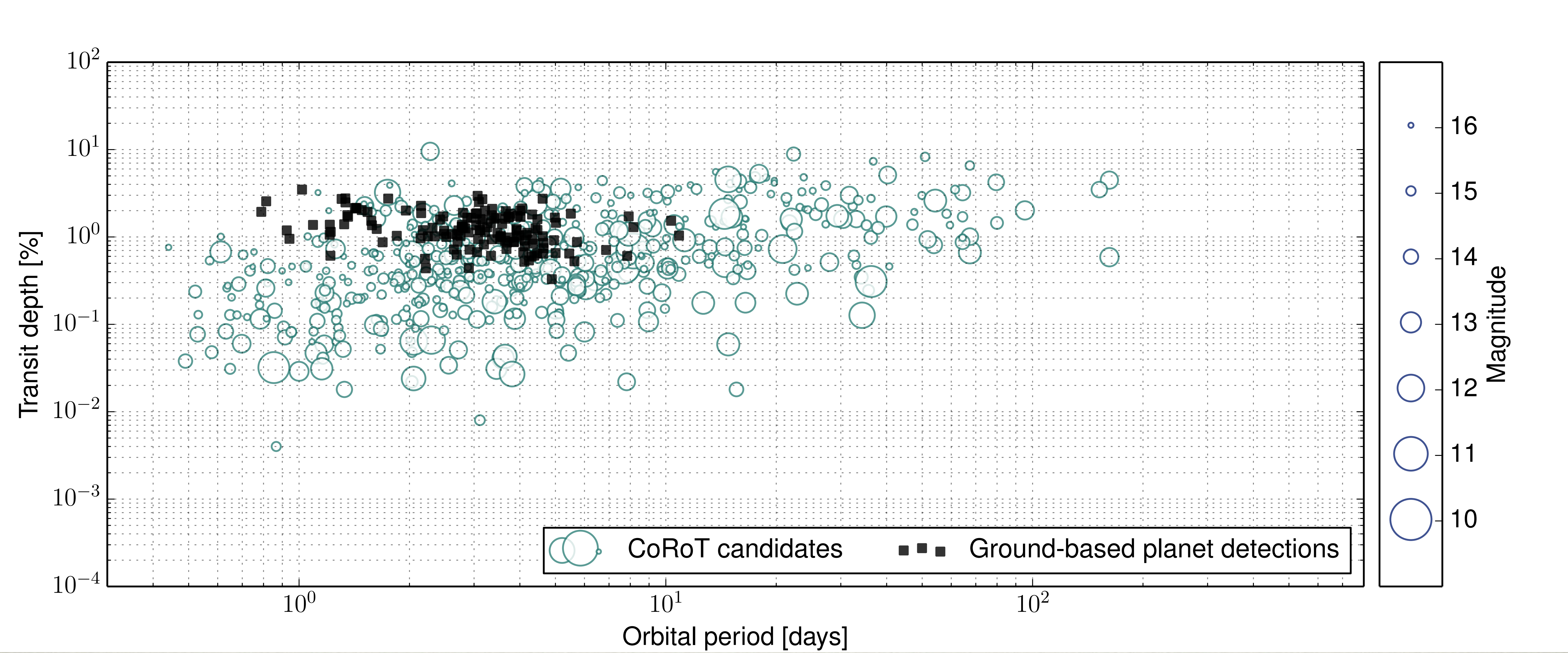

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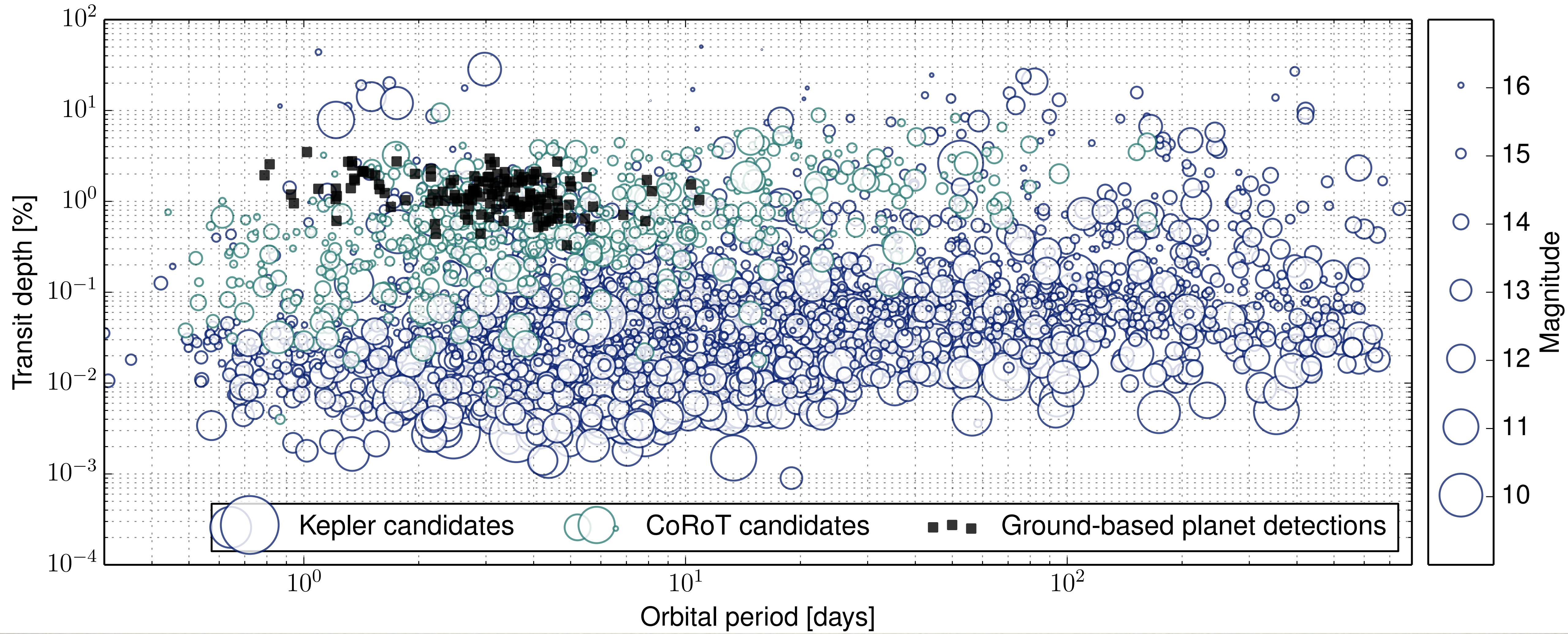
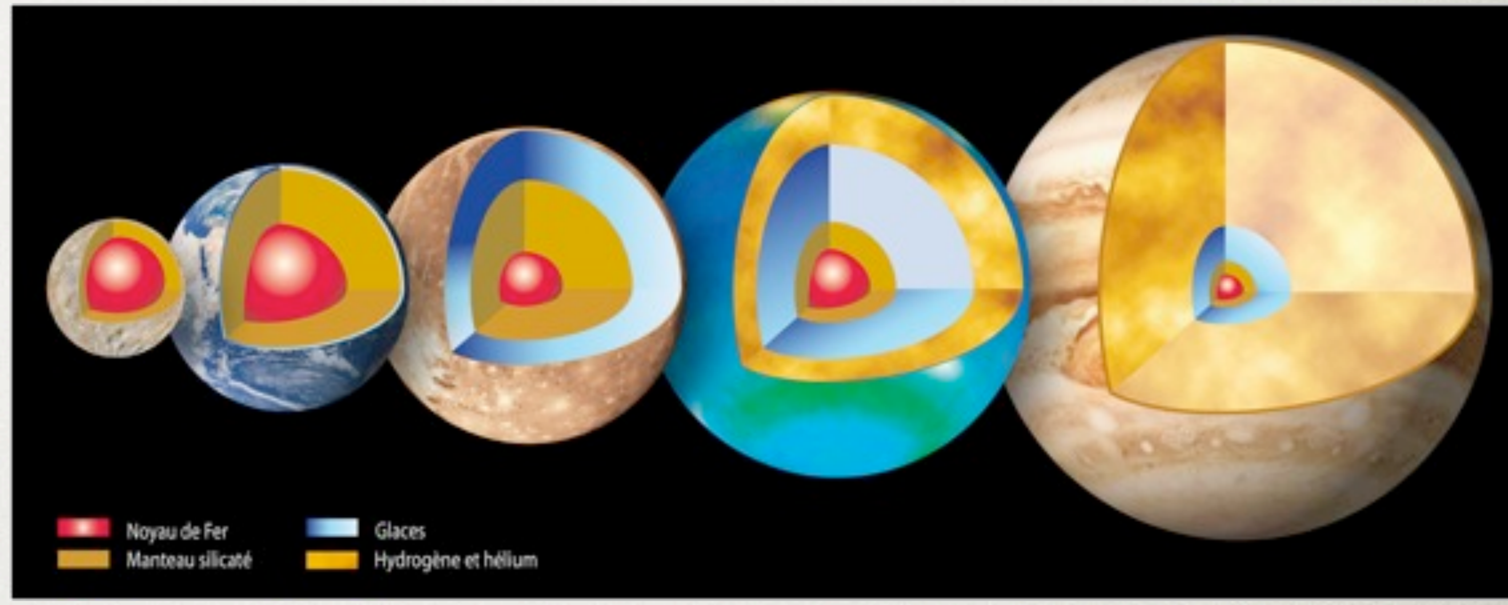


THE REVOLUTION

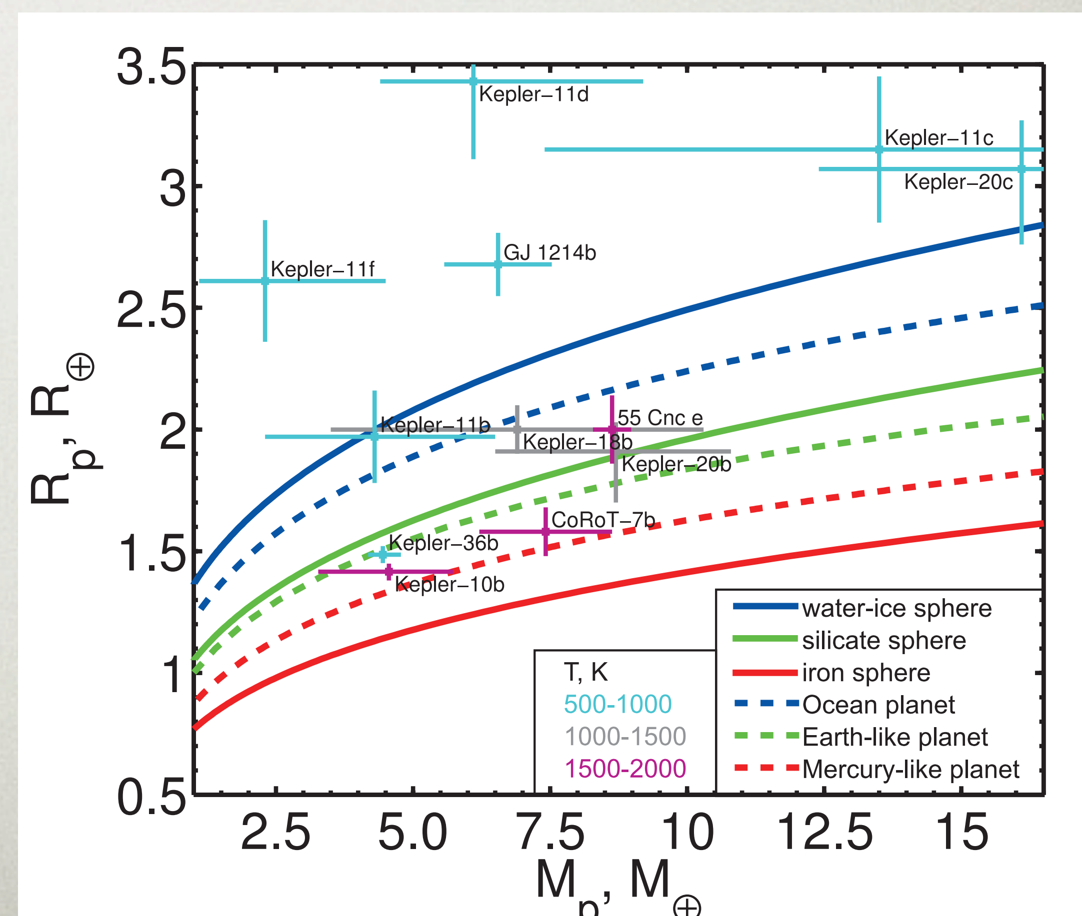
Transiting exoplanets = comparative planetology

Radius → Bulk density ← Mass



Know the mass & density: know the nature

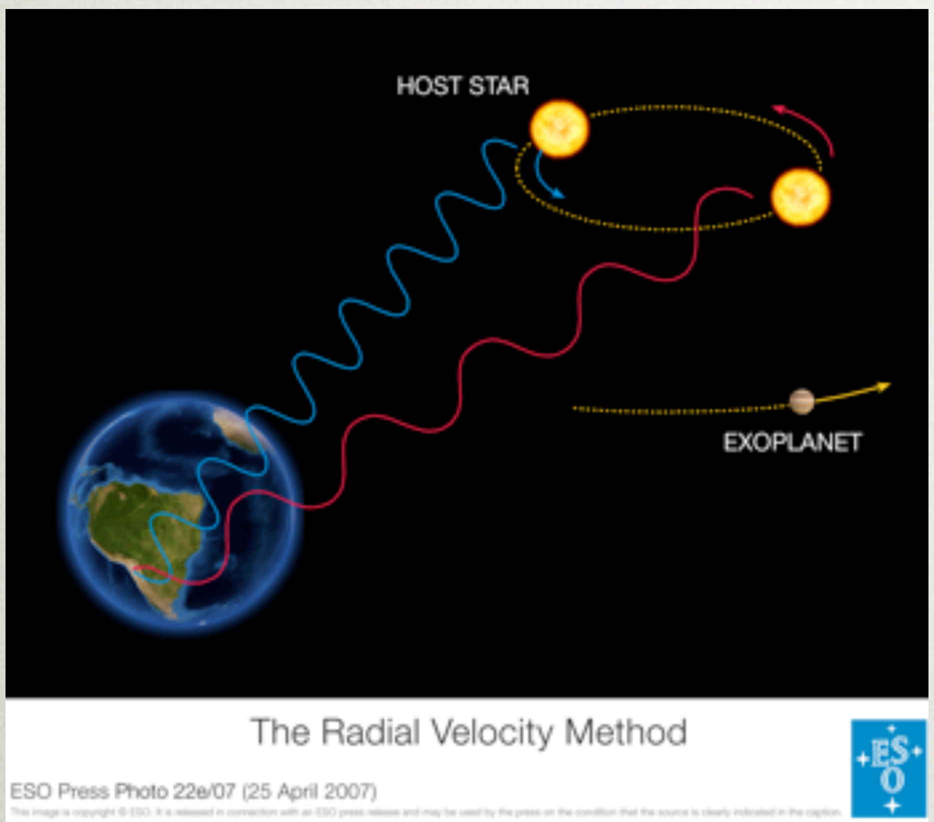
(rocky, Neptune-like, giant, brown dwarf, ...)



Sohl et al. (2012)

Characterize the mass: the two main techniques

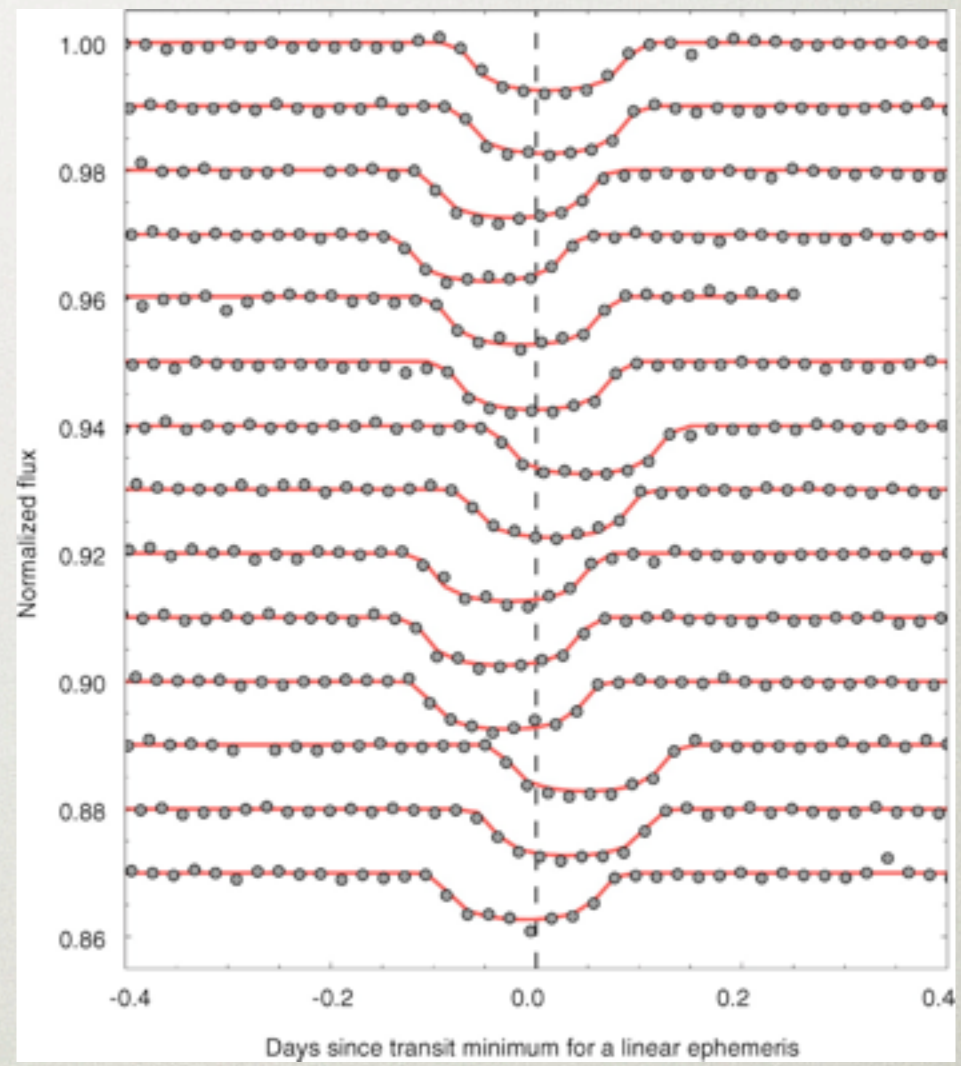
Radial velocity



Spectrographs:

SOPHIE, HARPS, HARPS-N, HiReS, HET, ...

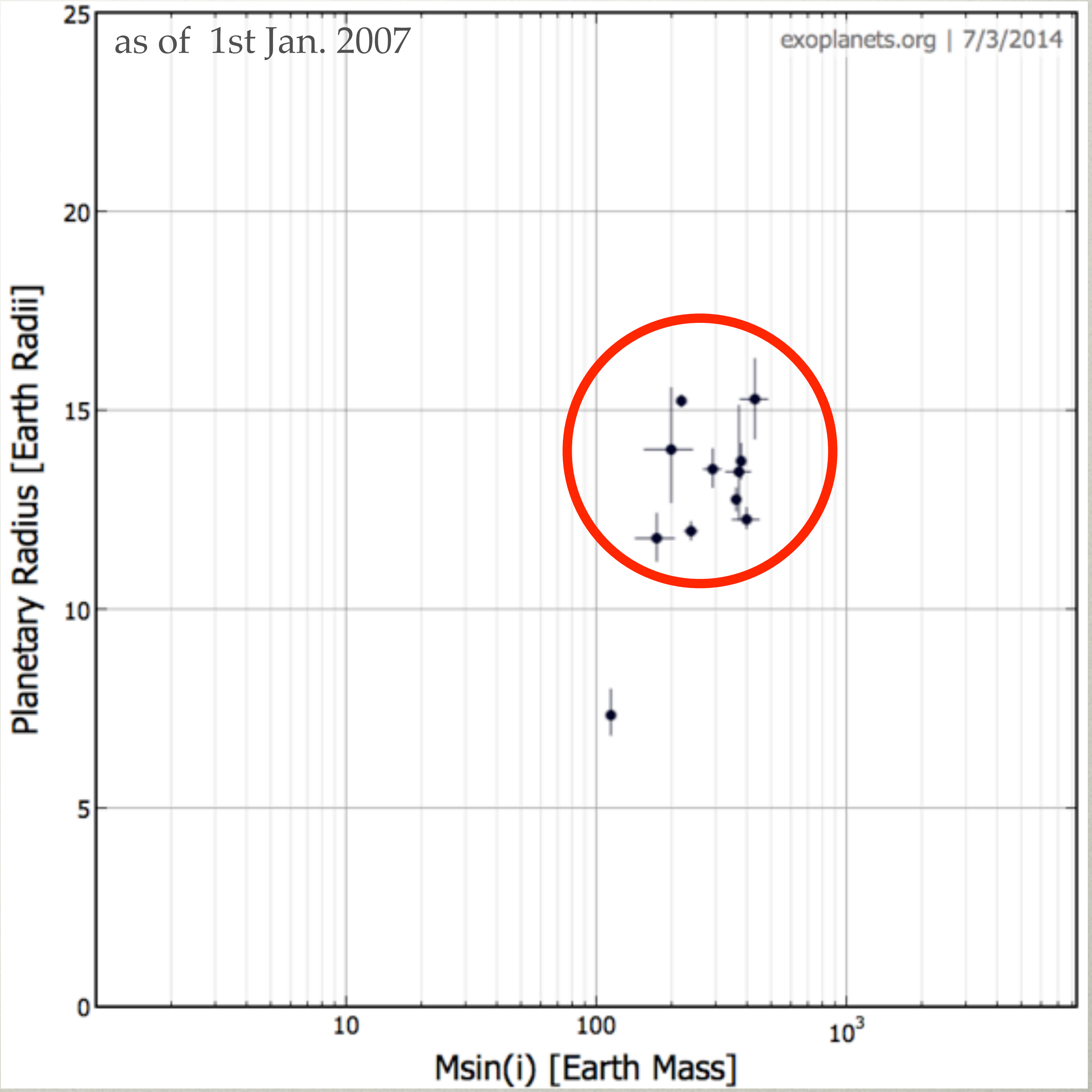
Transit Timing Variations



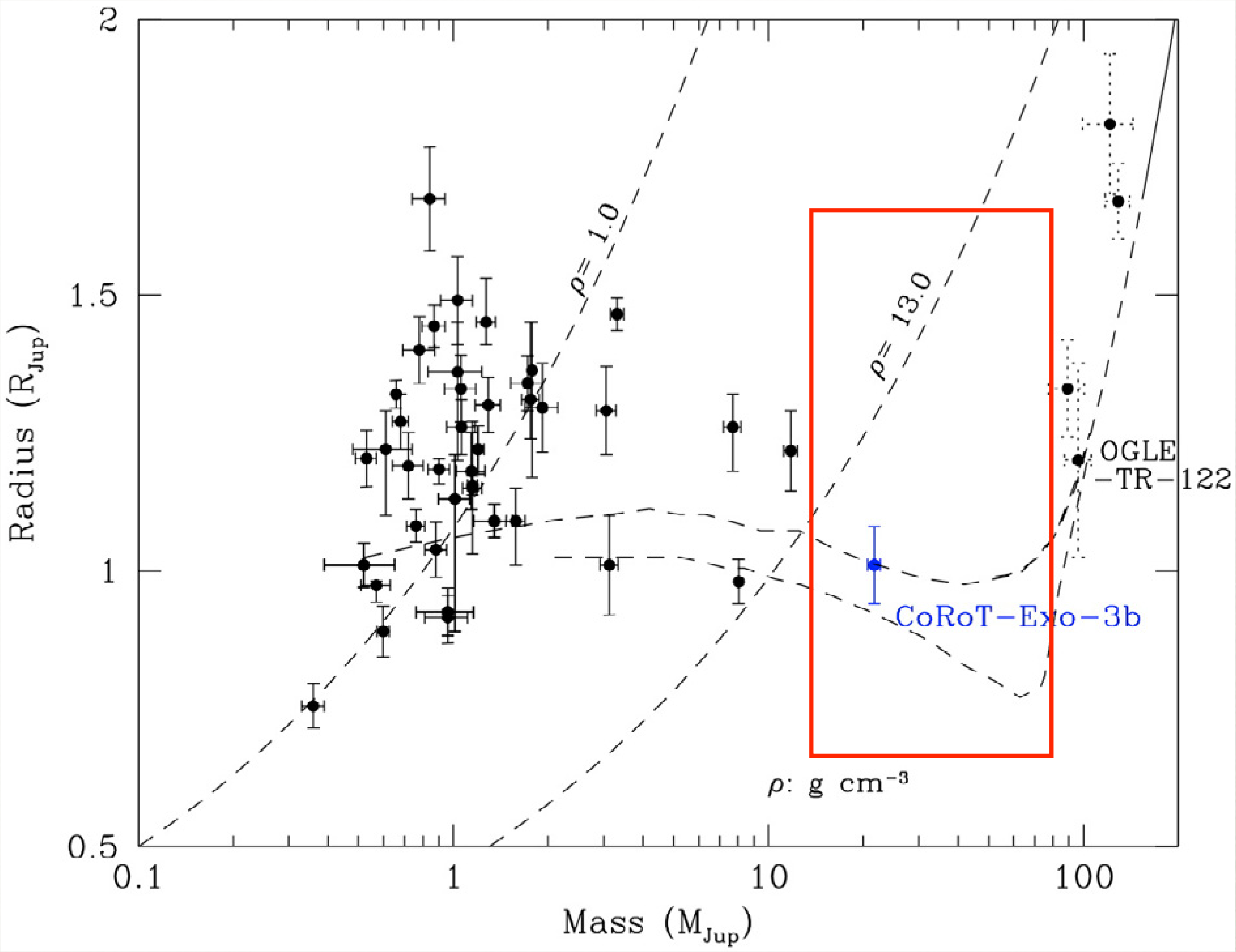
+ phase variations (ellipsoidal, beaming)

The planet-diversity revolution

BC:
before *CoRoT*

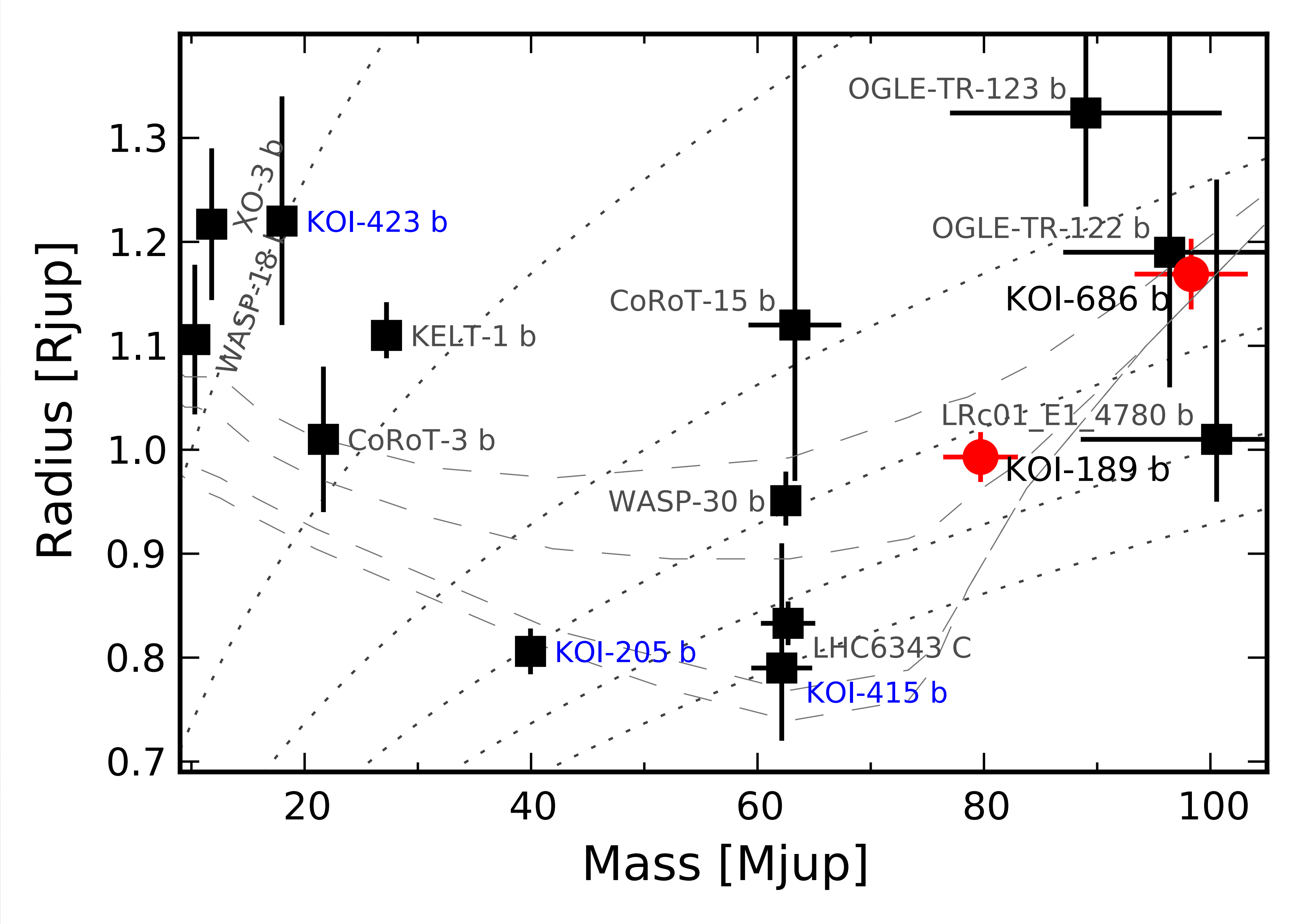


The planet-diversity revolution



Deleuil et al. (2008)

The planet-diversity revolution



Díaz et al. (submitted)

Deleuil et al. (2008), Bouchy et al. (2010), Johnson et al. (2011), Bouchy et al. (2011), Moutou et al. (2013), Díaz et al. (2013)
+ 2 ground-based detections

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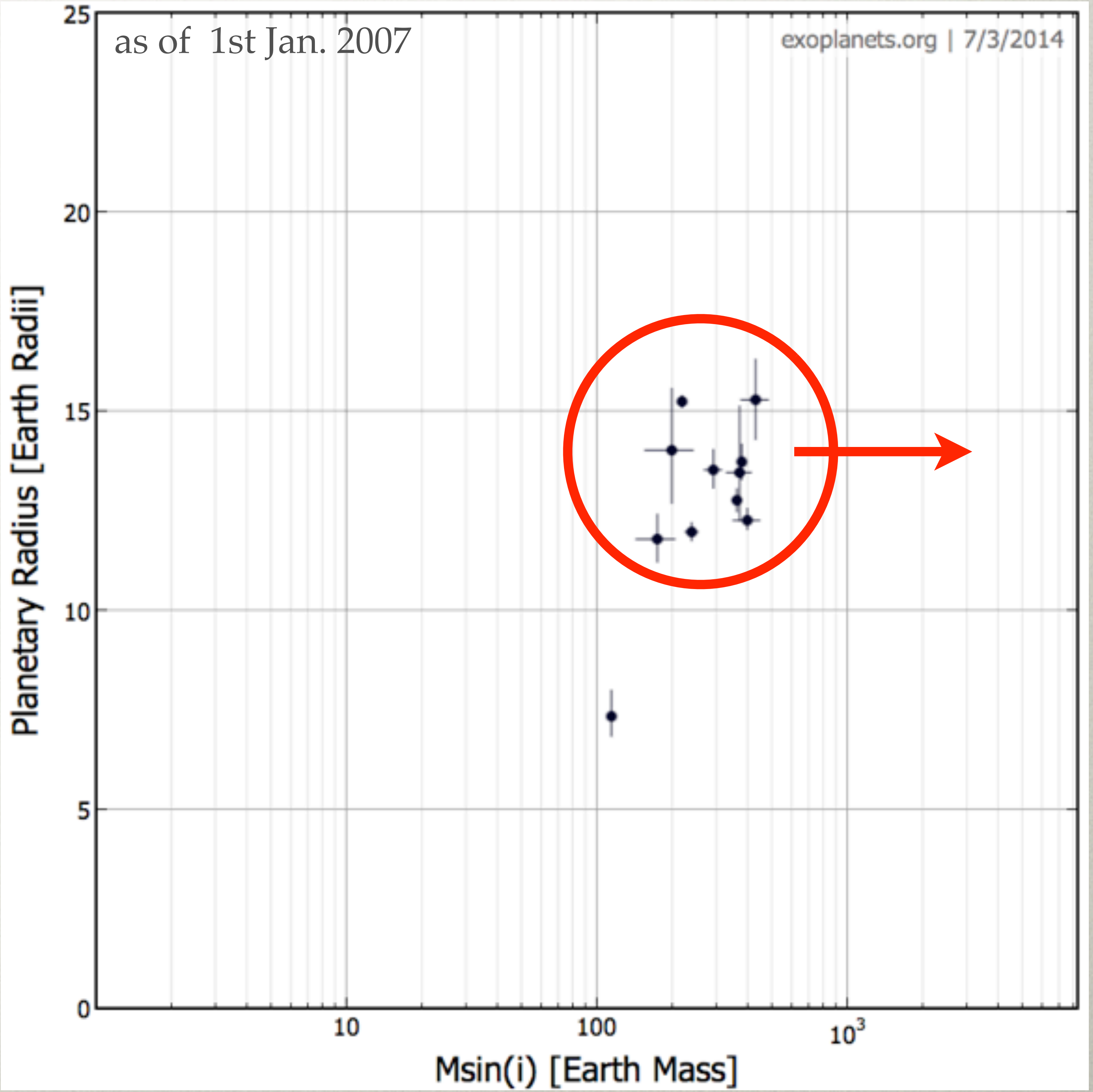

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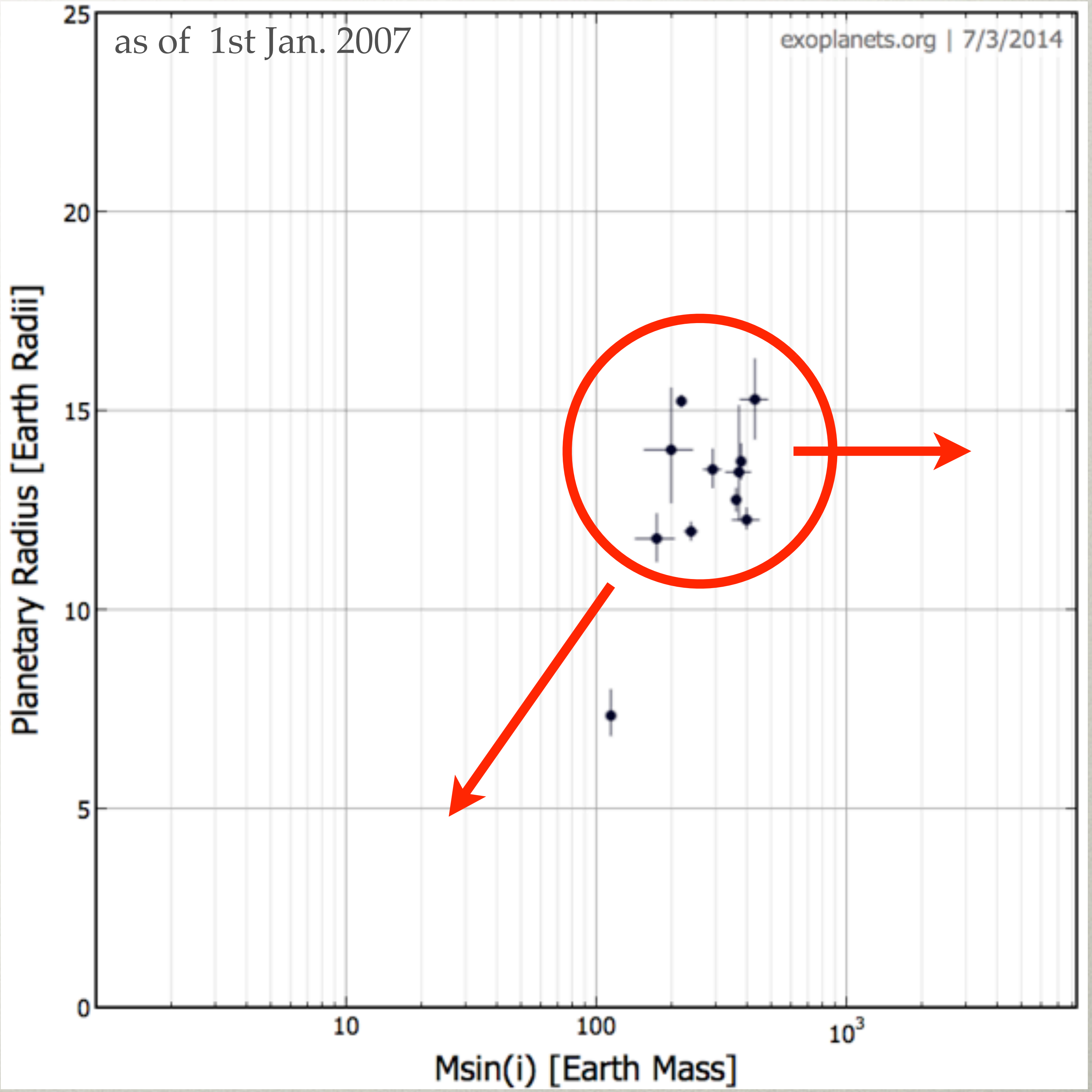

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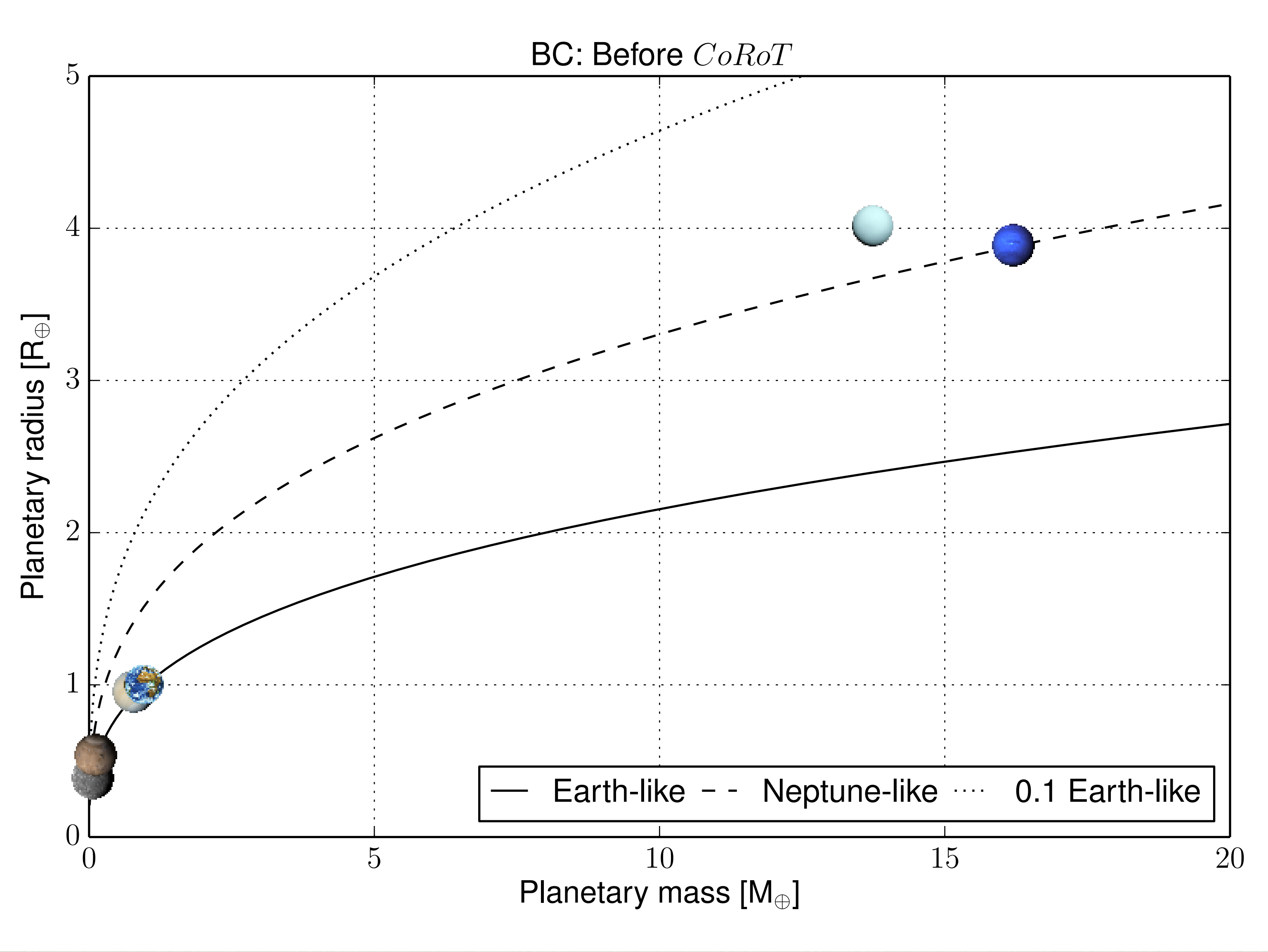

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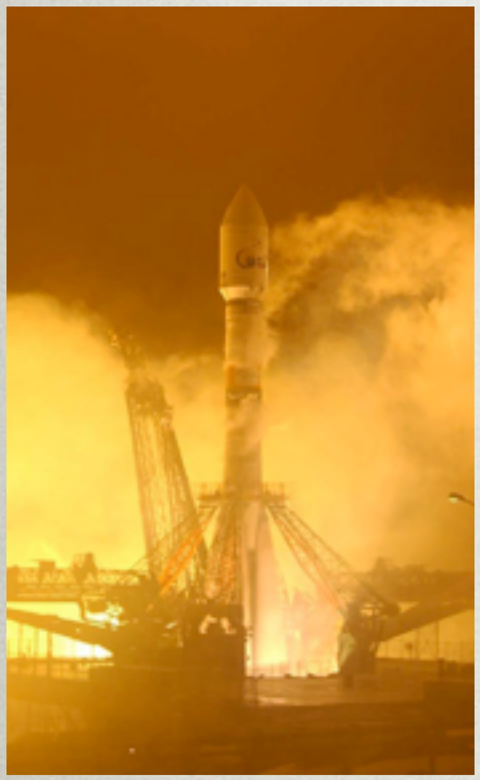
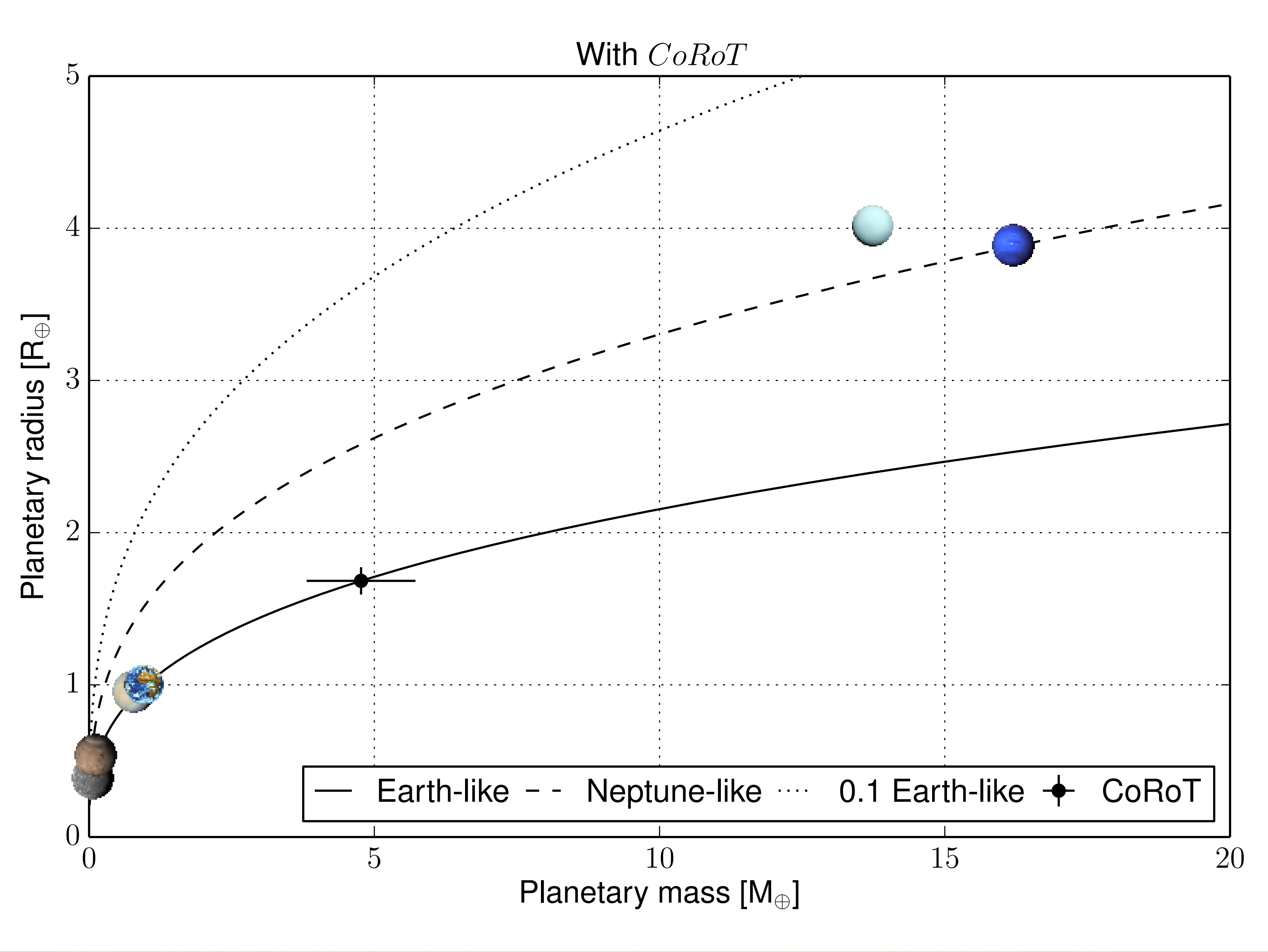
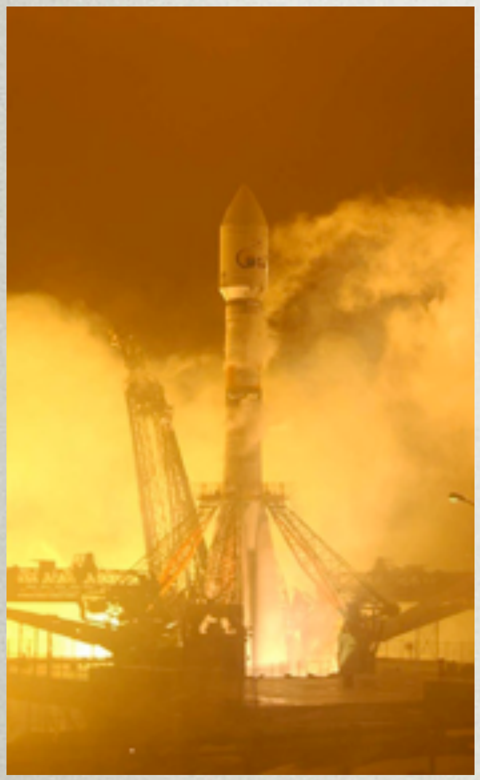
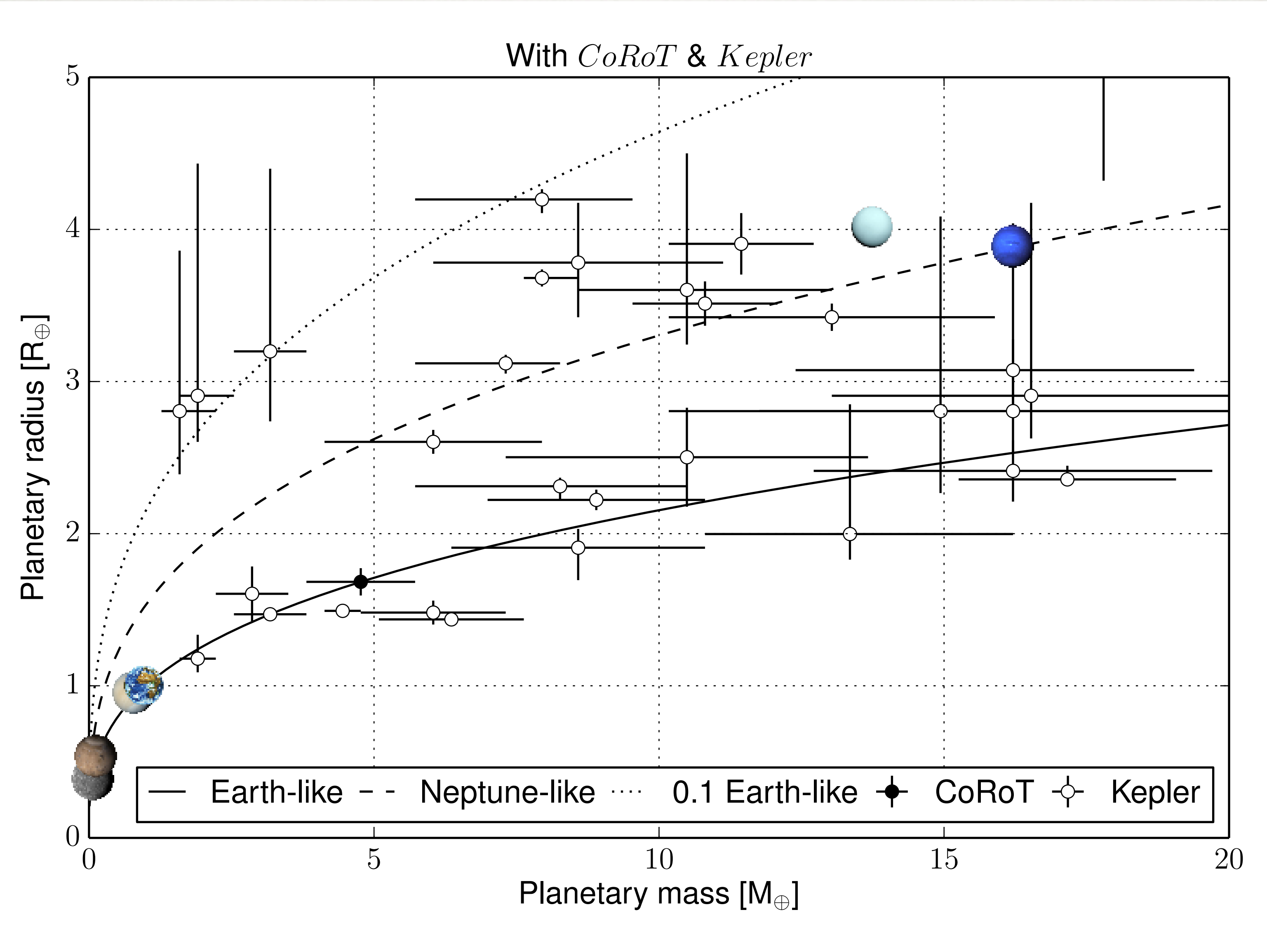




RVs: Queloz et al. (2009)

The planet-diversity revolution





RVs: Queloz et al. (2009), Batalha et al. (2010), Pepe et al. (2013), Howard et al. (2013), Marcy et al. (2014), Dumusque et al. (2014)

TTVs: Lissauer et al. (2011), Cochran et al. (2011), Gautier et al. (2012), Fabrycky et al. (2012), Carter et al. (2012), Gilliland et al. (2013), Nesvorný et al.(2013), Xie (2014)

TTVs vs RVs ?

TTVs is one of the main revolution of space photometry for the characterization of transiting exoplanets

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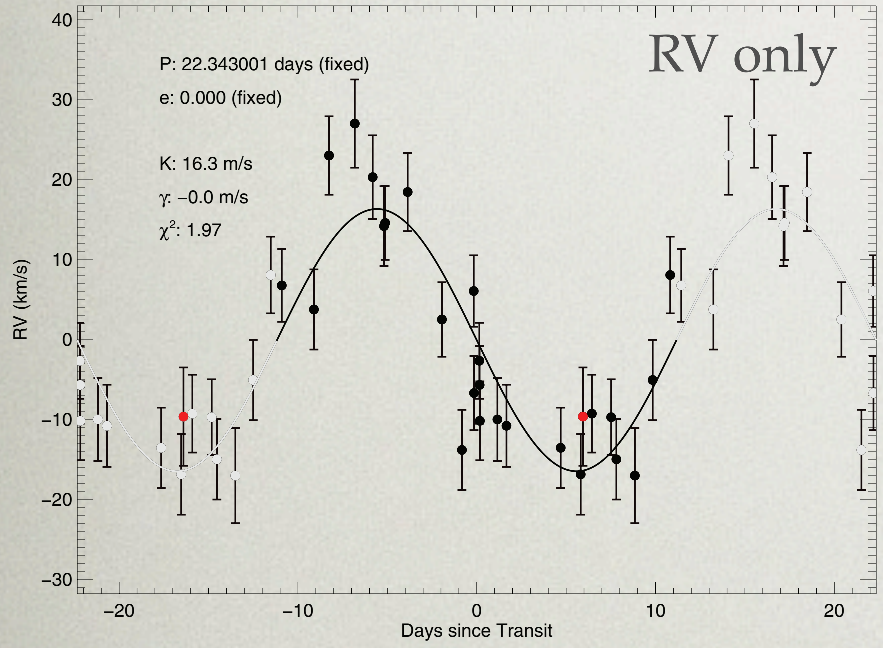
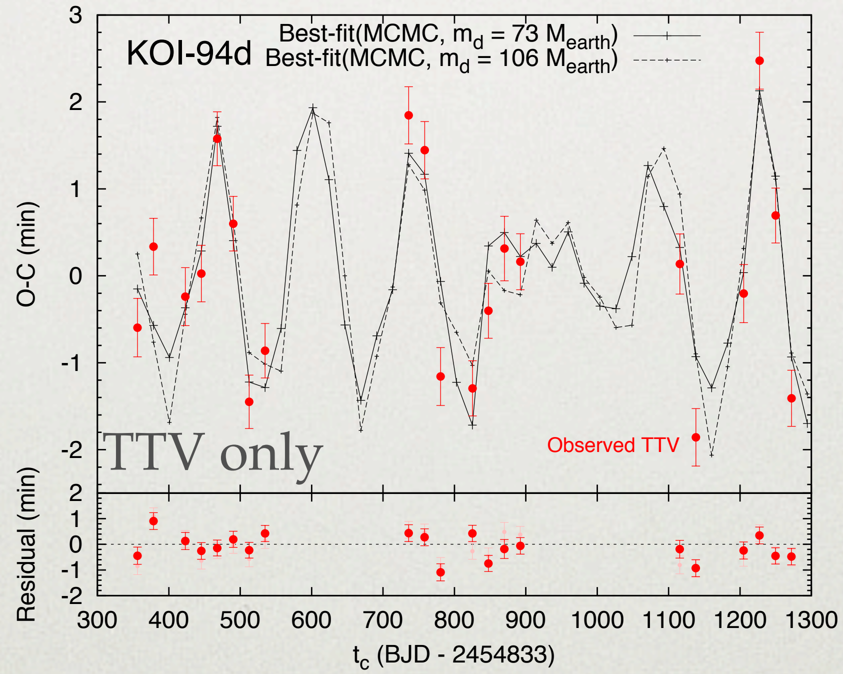
On the mass of KOI-94 d ...





$$m_d = 106 \pm 11 \mathrm{M}_\oplus$$

Weiss et al. (2013)

$$m_d = 52.1^{+6.9}_{-7.1} \mathrm{M}_\oplus$$

Masuda et al. (2013)

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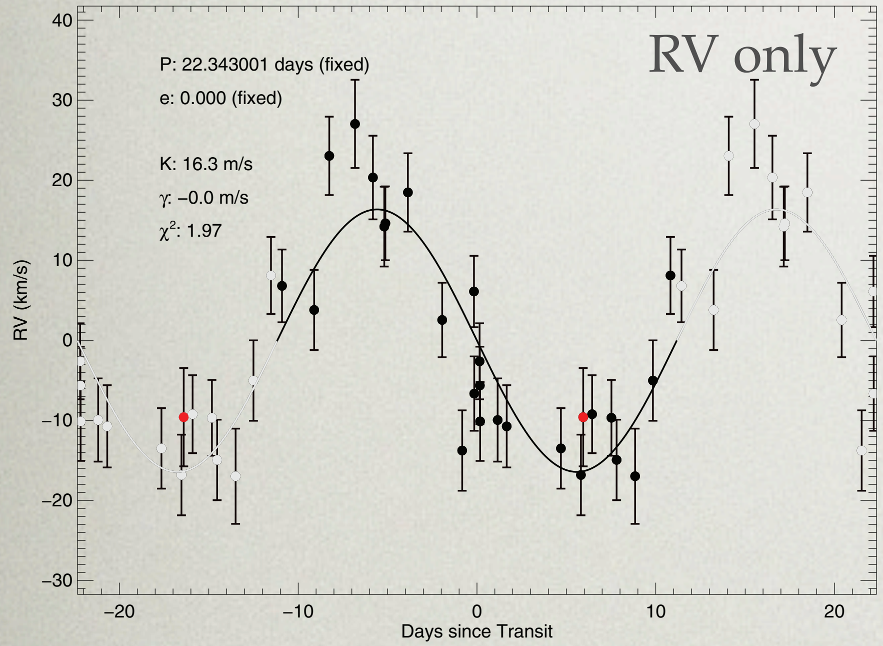

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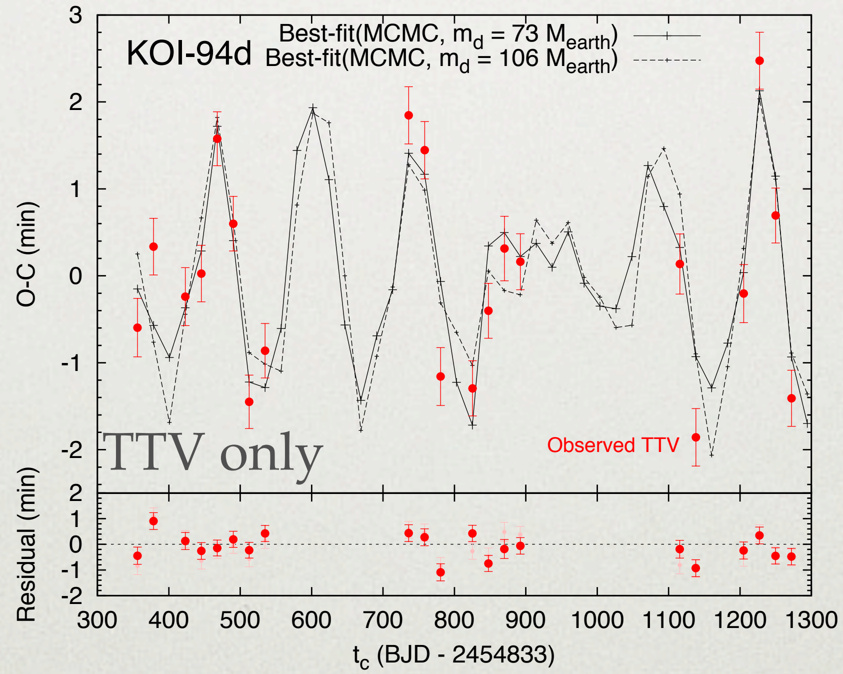

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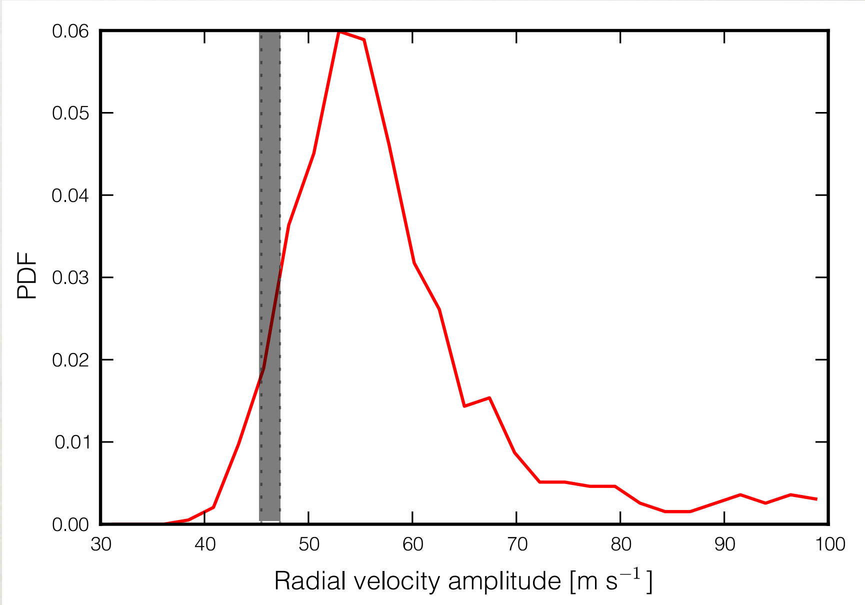
KOI-142:

"The King of Transit Timing"



Barros et al. (2014)

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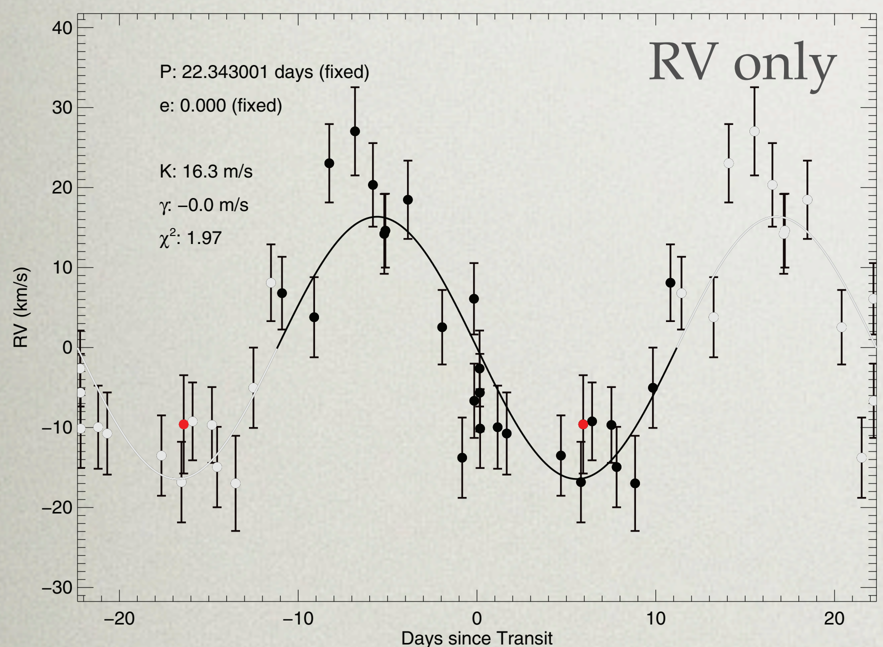

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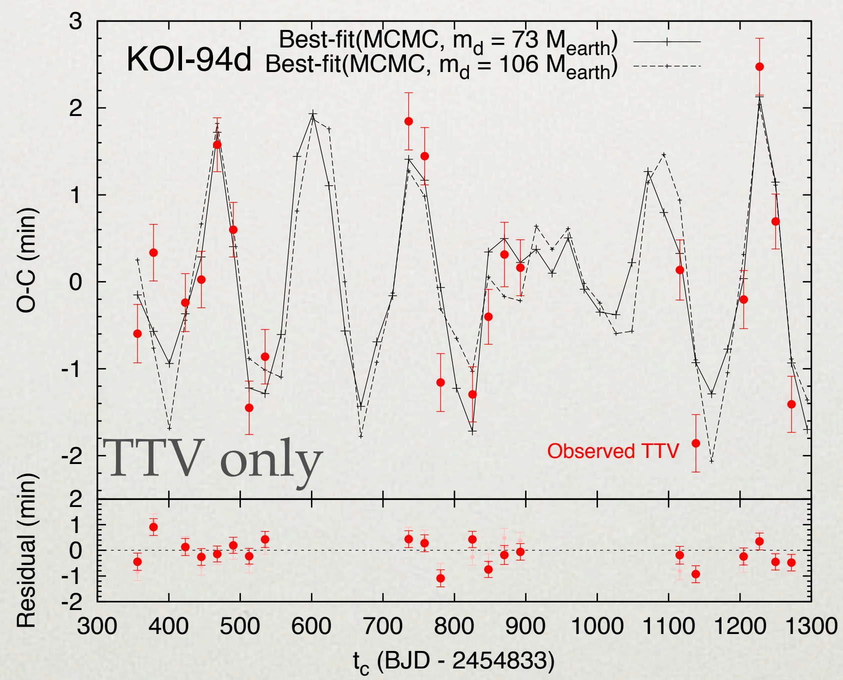

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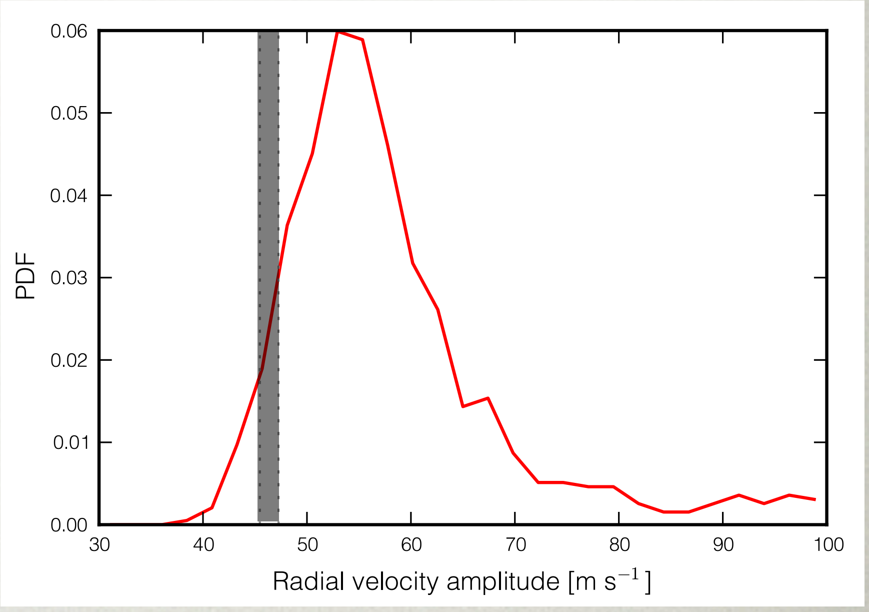
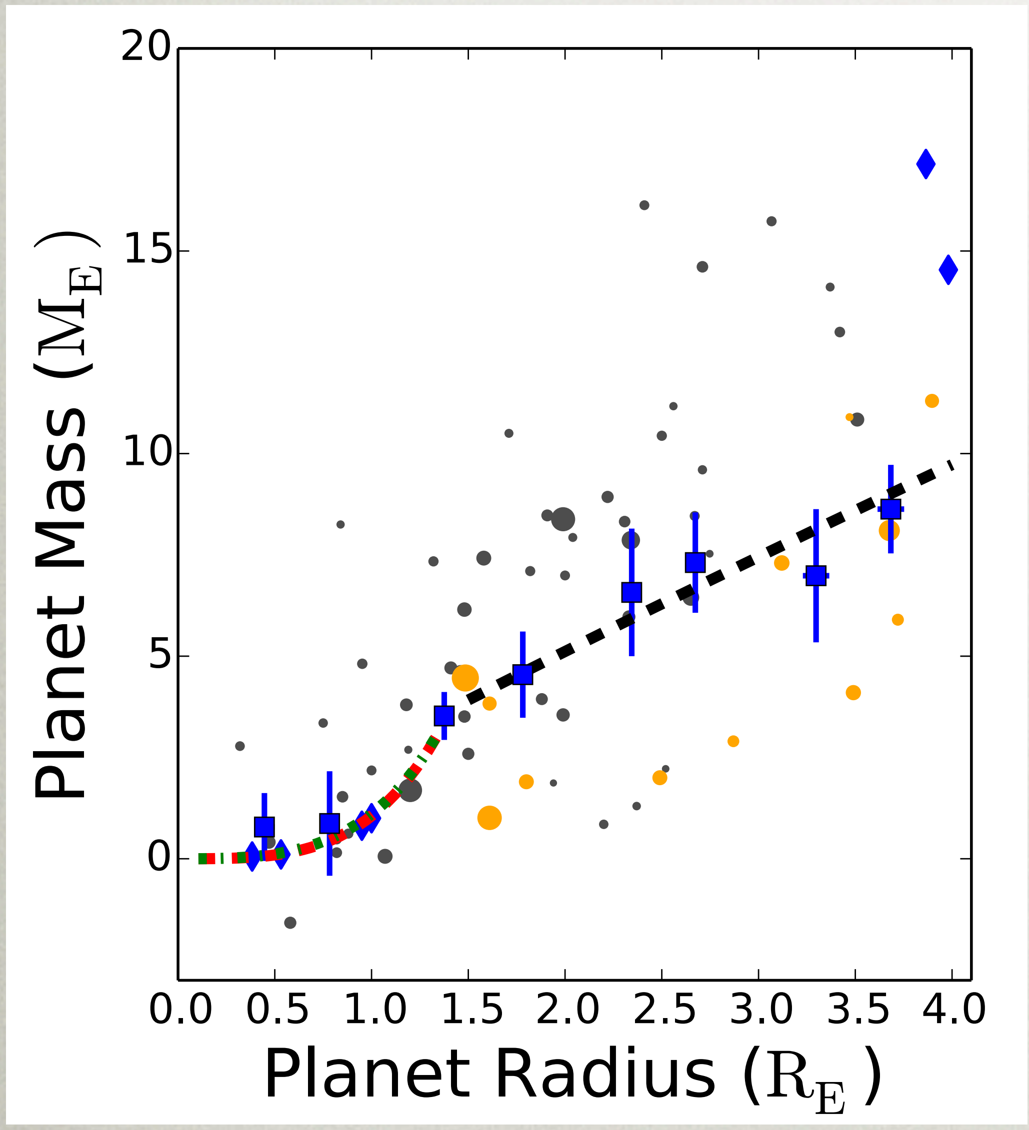


Barros et al. (2014)

TTVs vs RVs : Who's right ?

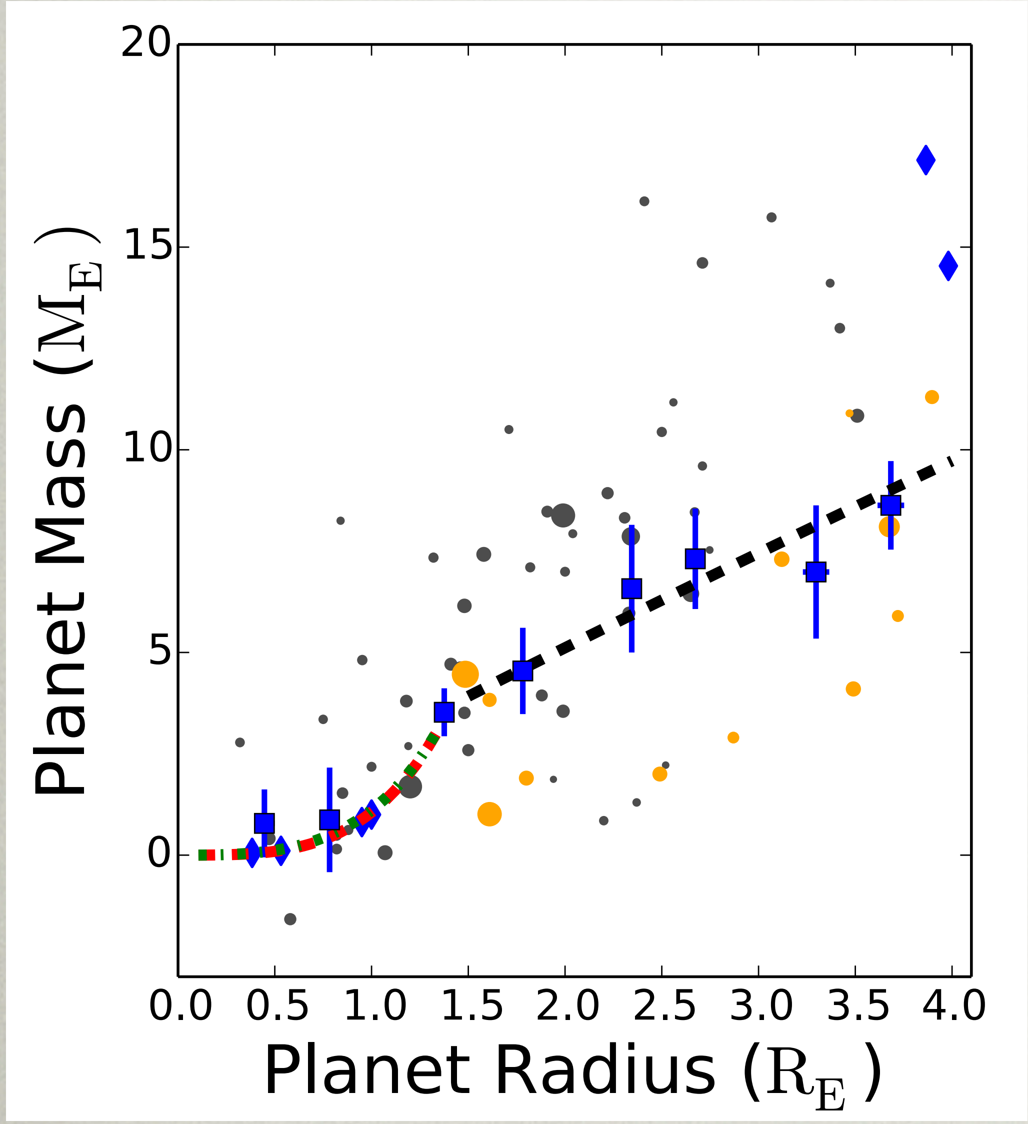
TTVs vs RVs ?



Weiss & Marcy (2014)

A systematic bias ?
... or a physical property of
packed planetary system ?

TTVs vs RVs ?



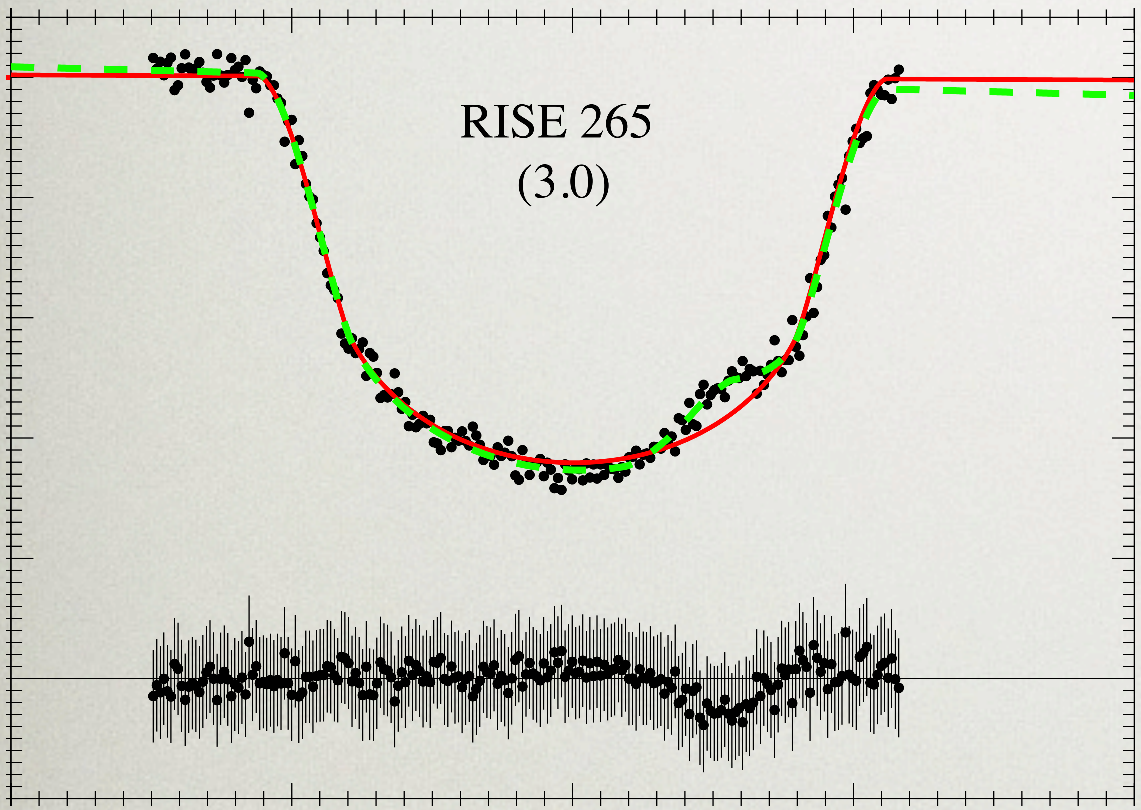
Weiss & Marcy (2014)

A systematic bias ?
... or a physical property of packed planetary system ?

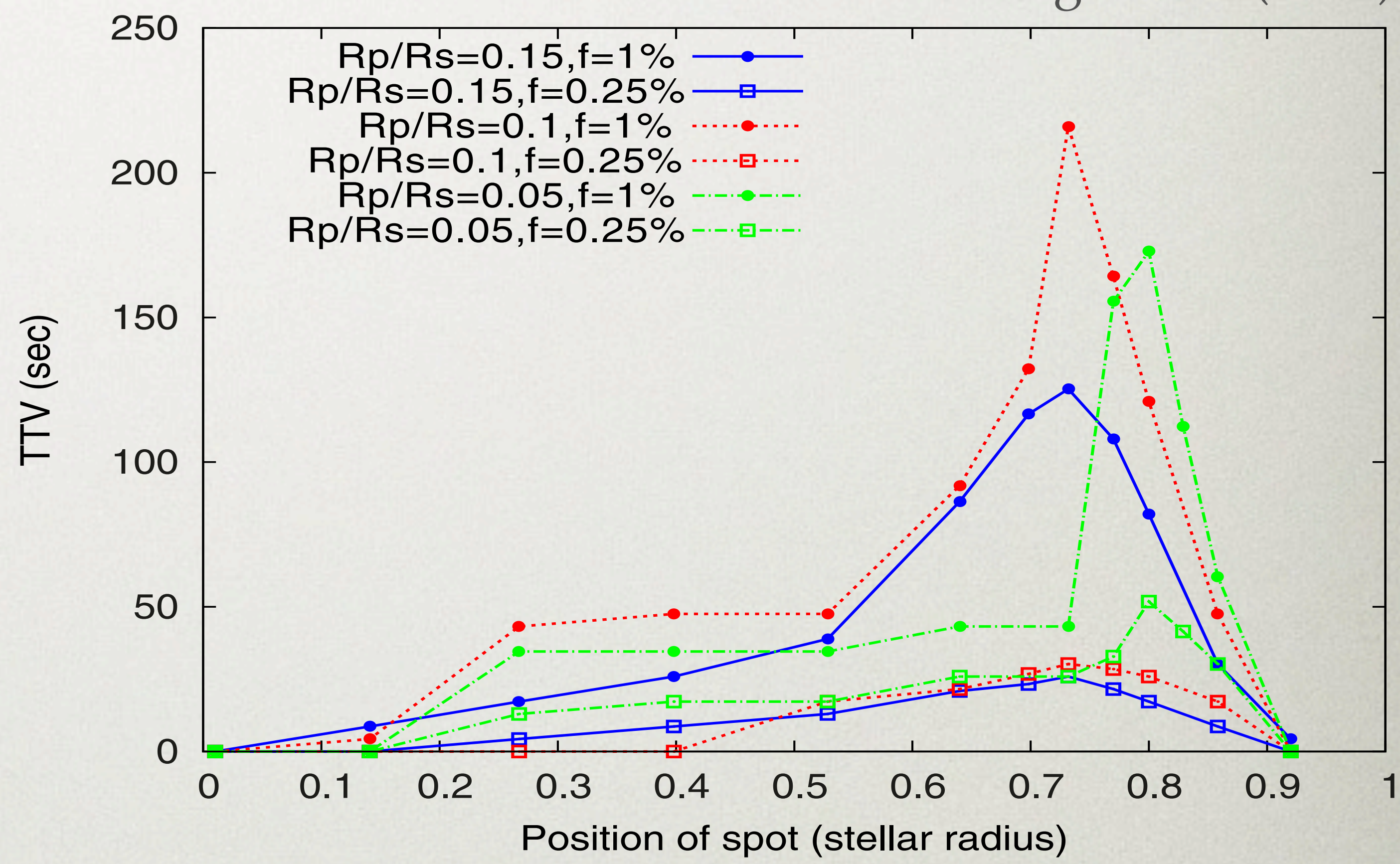
Need more RV / TTV comparison

STELLAR ACTIVITY

Barros et al. (2012)



Oshagh et al. (2013)



Planet-spot occultation might create fake TTVs / TDVs

CHARACTERIZED PLANETS

~ 600 candidates detected

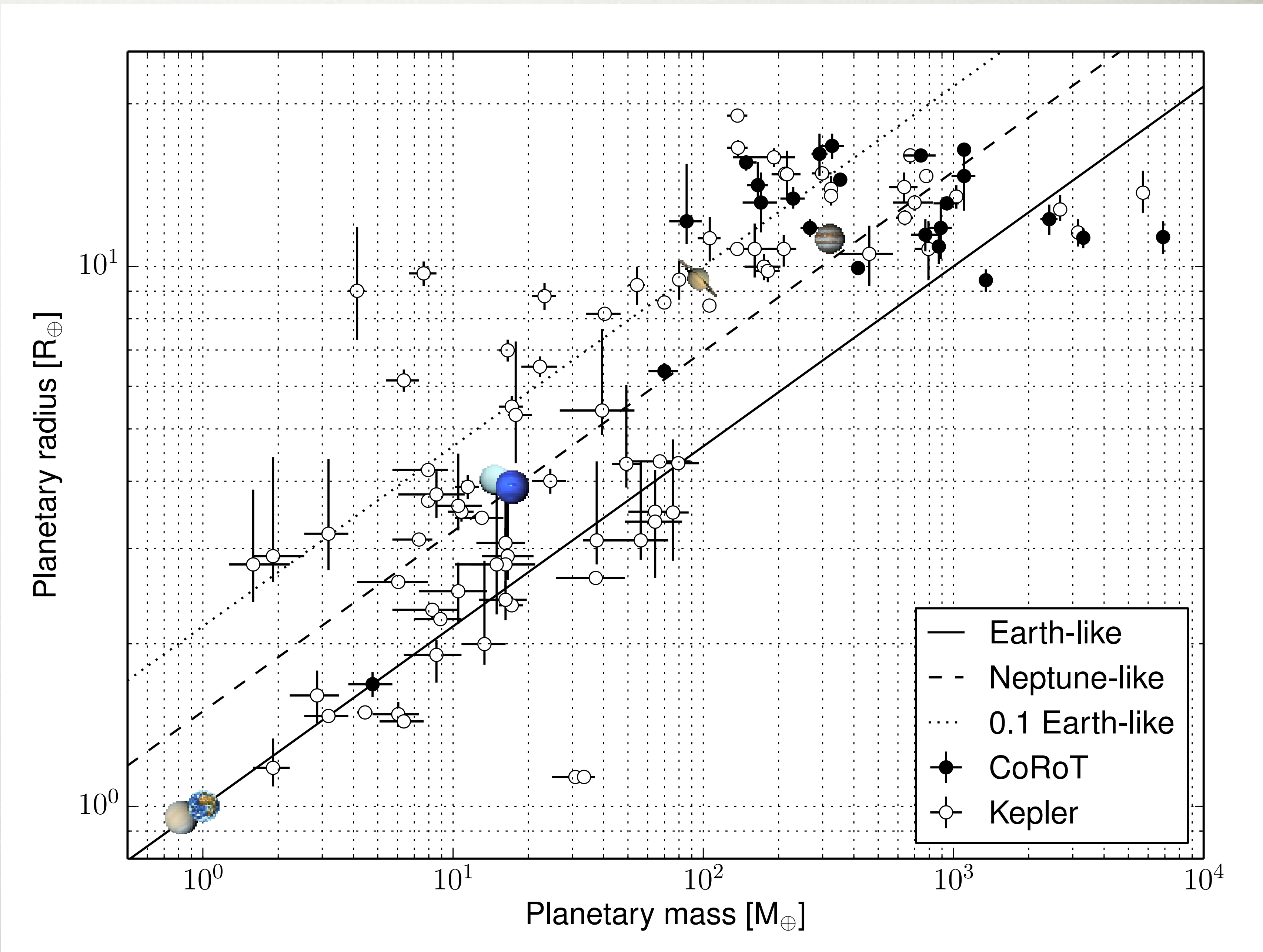
27 planets characterized

(with mass constraint > 3 σ)

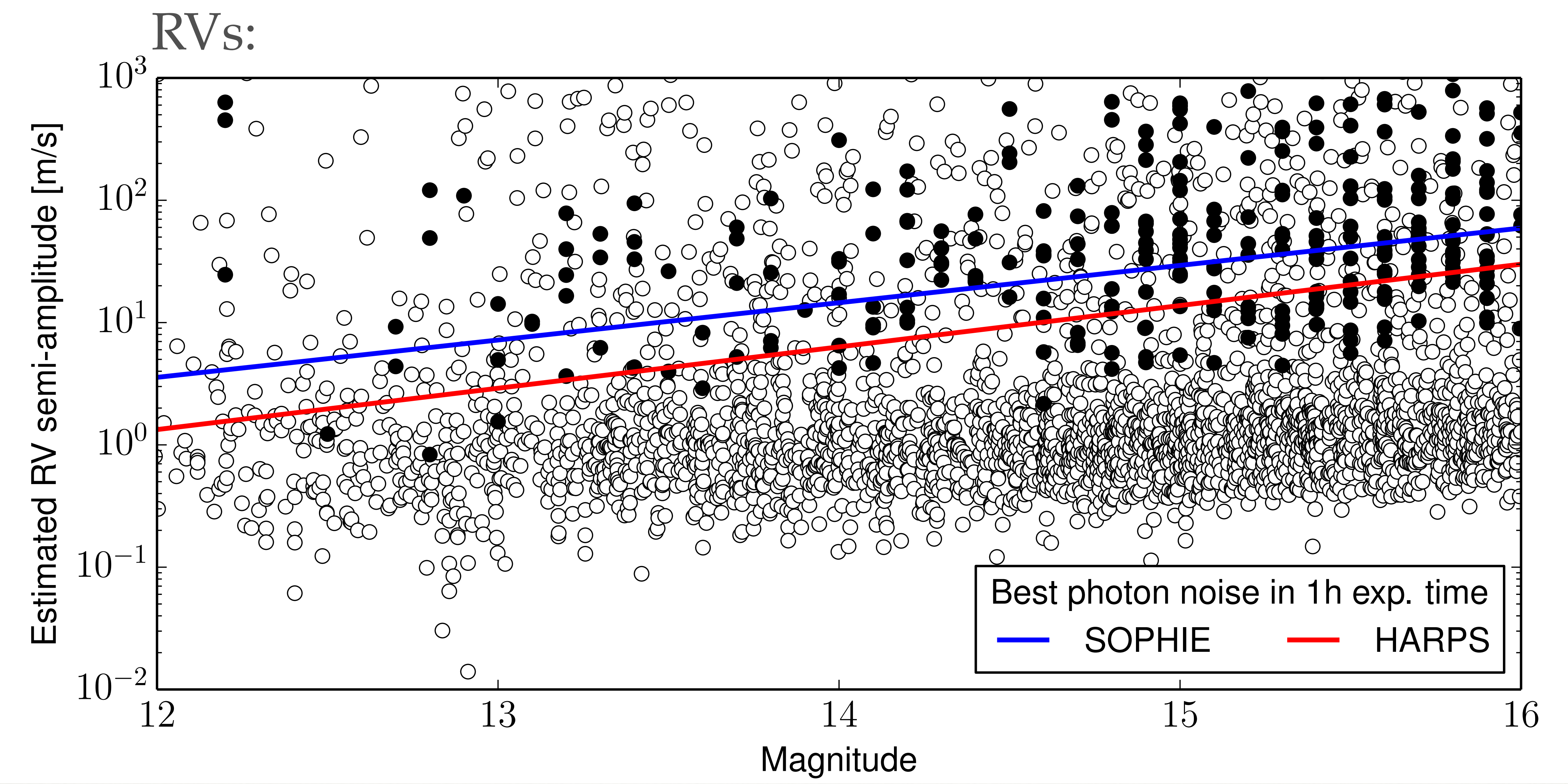
~ 4000 candidates detected

80 planets characterized

(with mass constraint > 3 σ)



WHAT ABOUT THE OTHER CANDIDATES ?

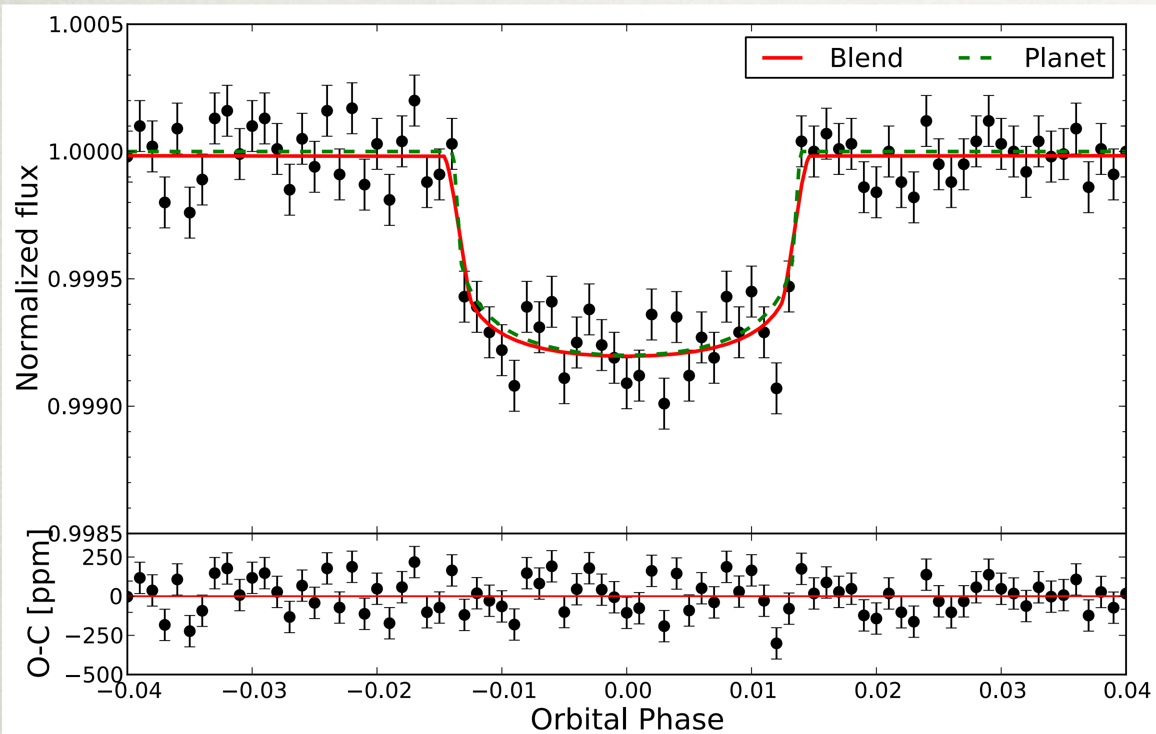


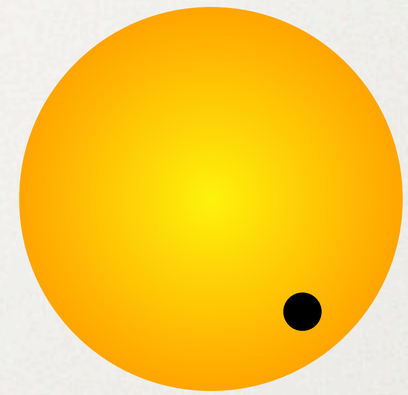
Santerne et al. (2012)

TTVs: need systems close to orbital resonance

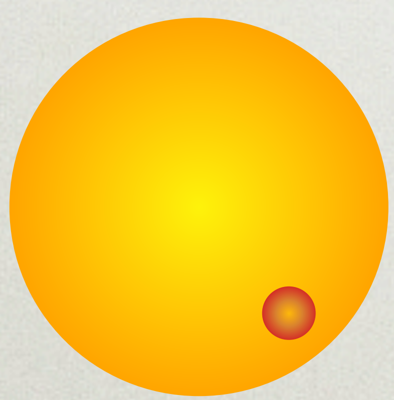
Astrophysical false positives

see, e.g., Cameron (2012, Nature)

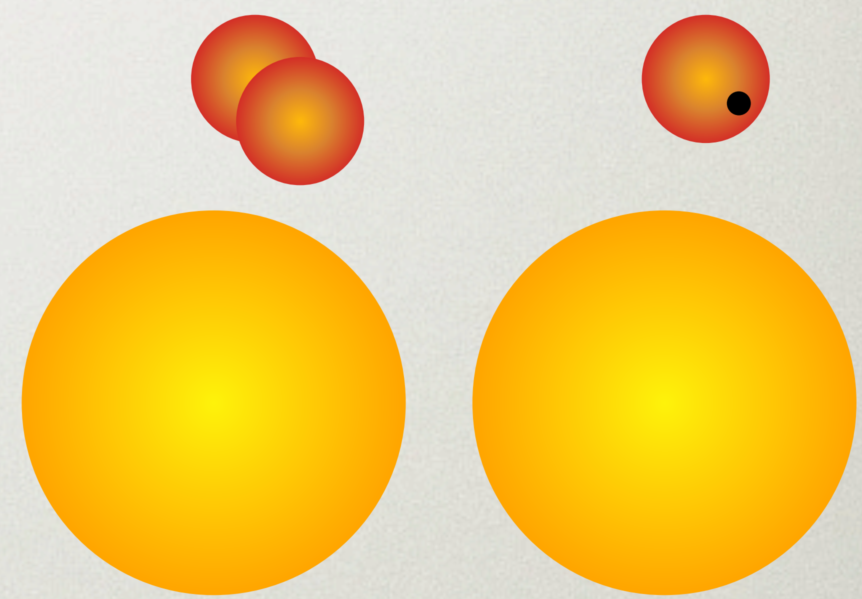




Planet



Undiluted eclipsing binary



Diluted eclipsing binary / giant planet

The Planet-Validation technique (to the rescue)

Main objective:

validate statistically the planetary nature when other techniques cannot

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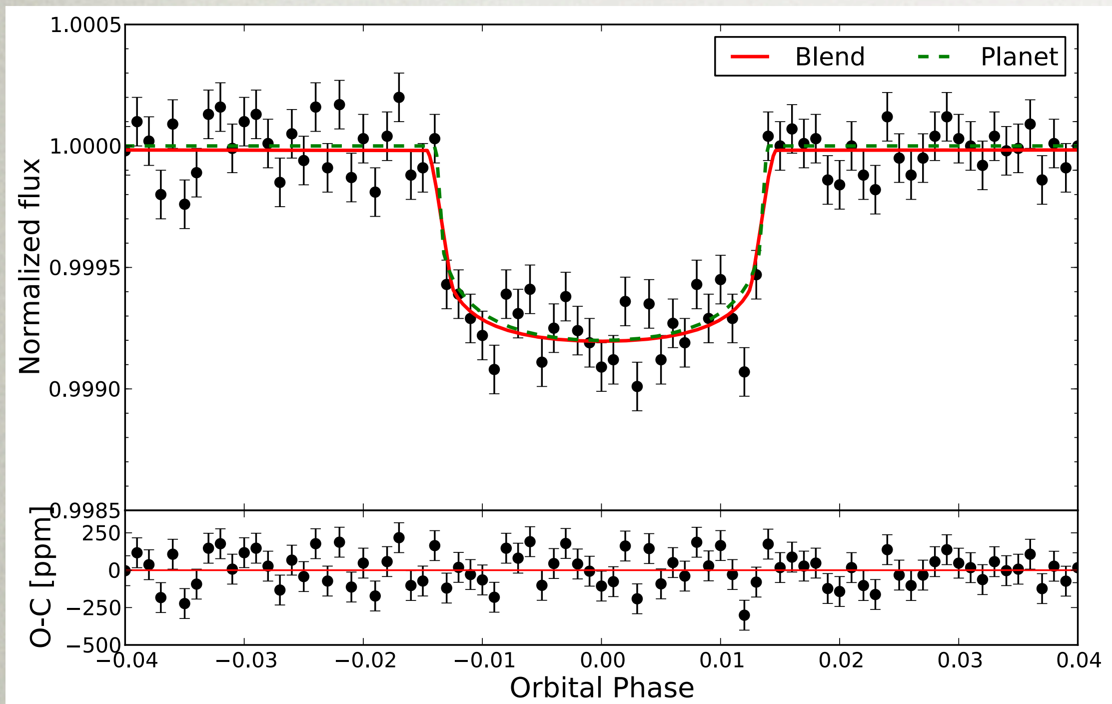

Almenara et al. (2011)

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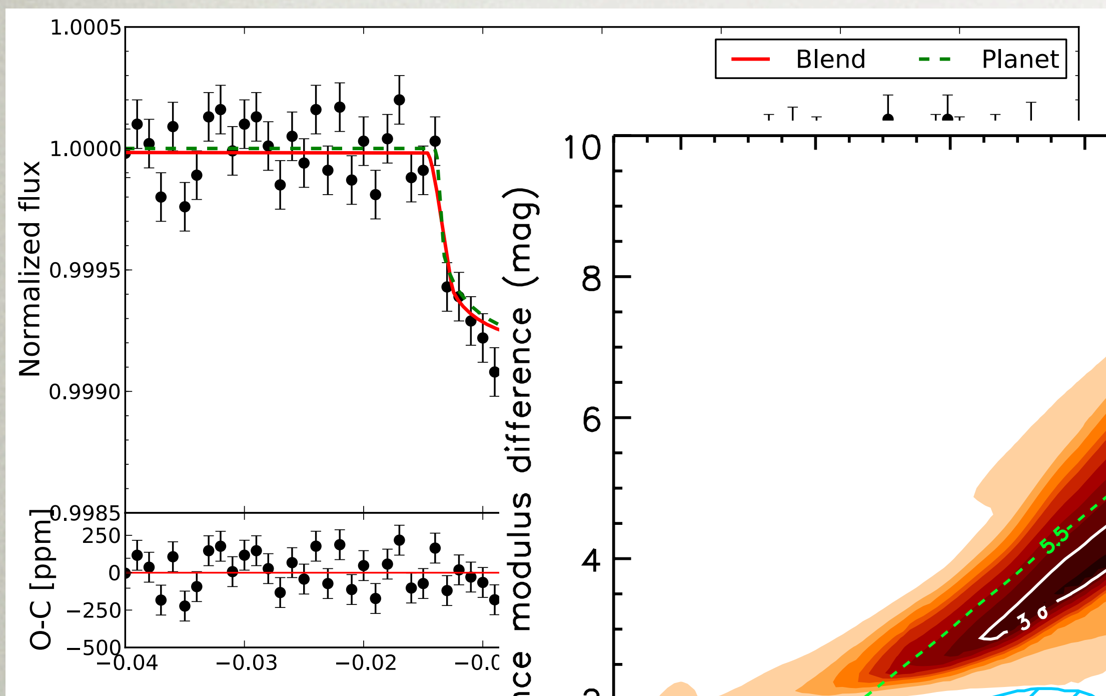

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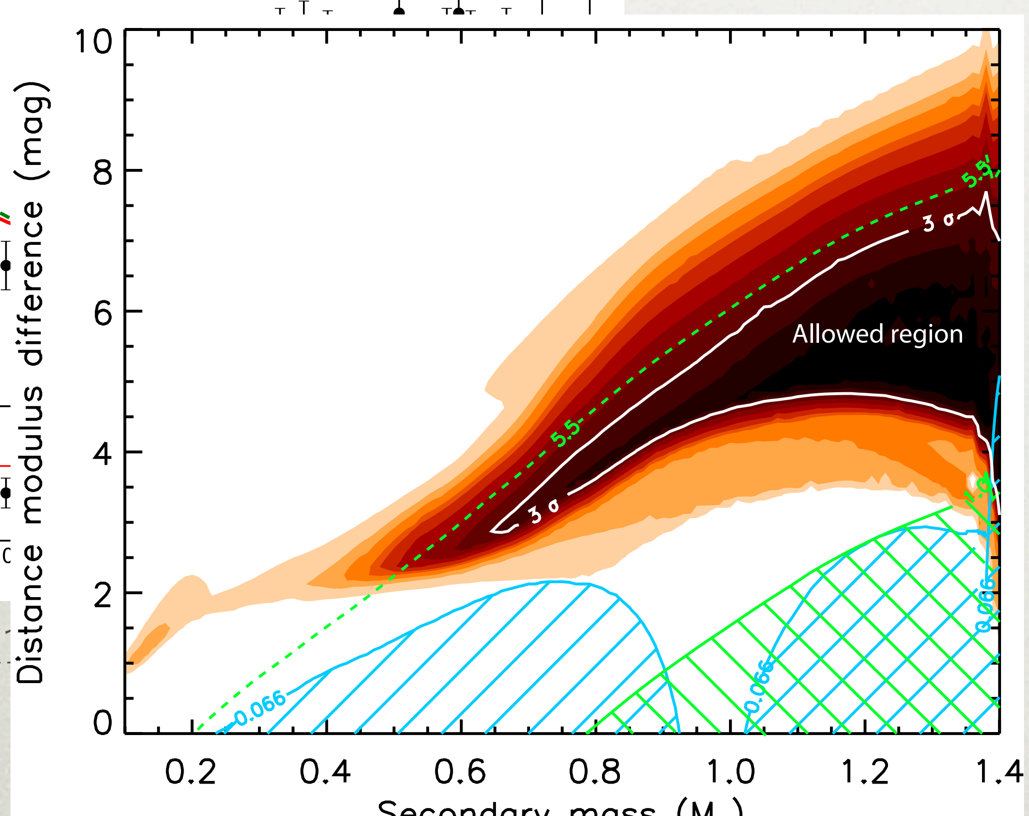

Torres et al. (2011)

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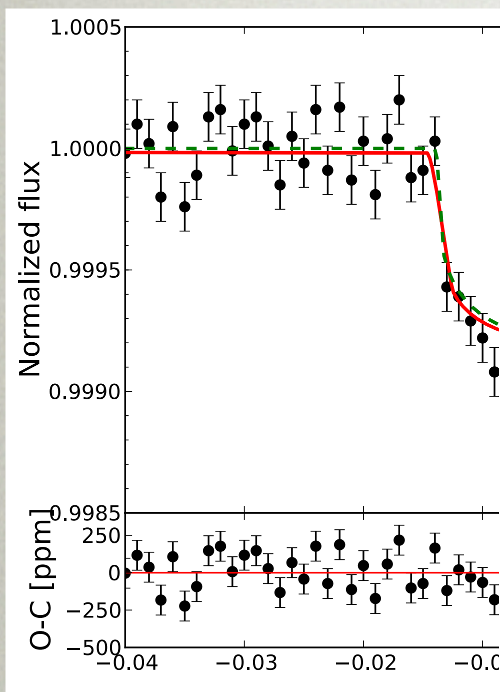
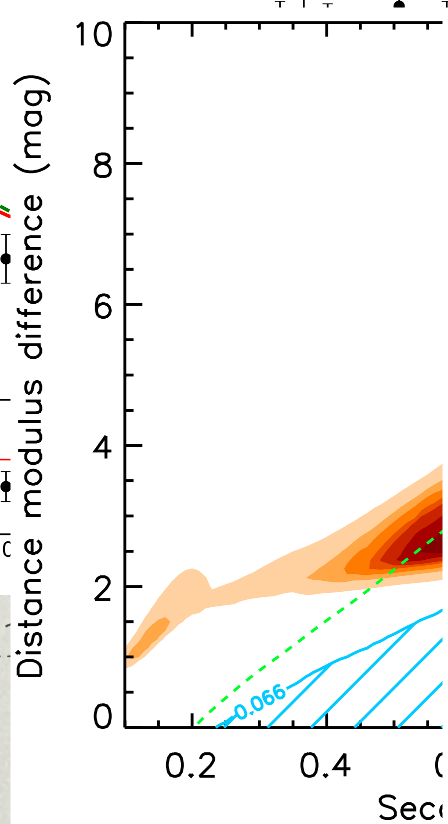
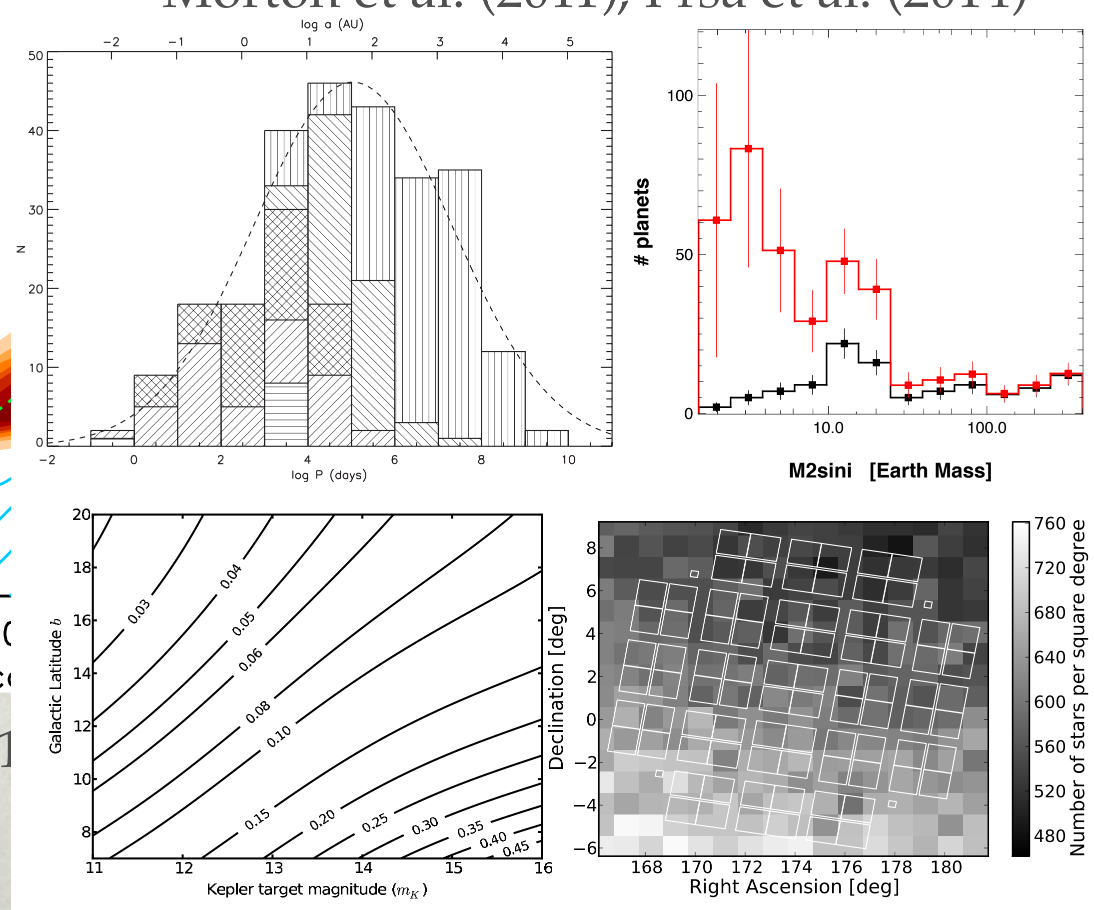


Almenara et al. (201



Torres et al. (201

Raghavan et al. (2010), Mayor et al. (2011), Morton et al. (2011), Prsa et al. (2014)



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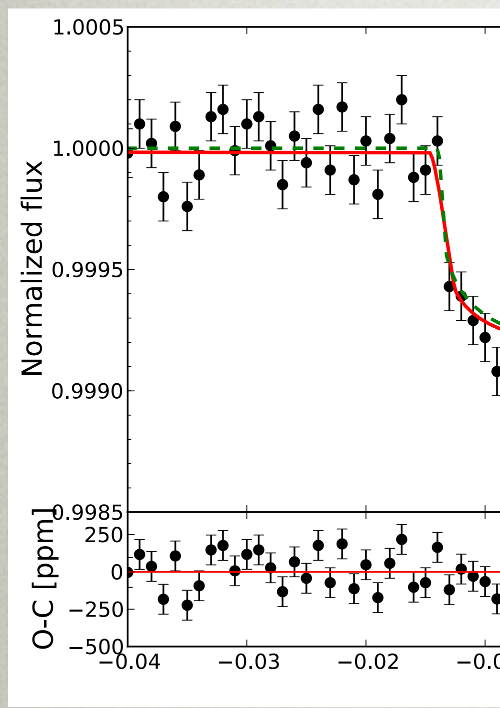

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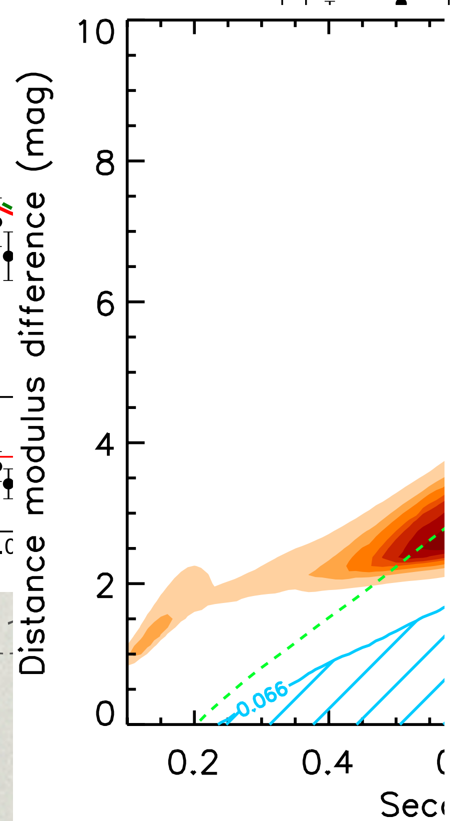

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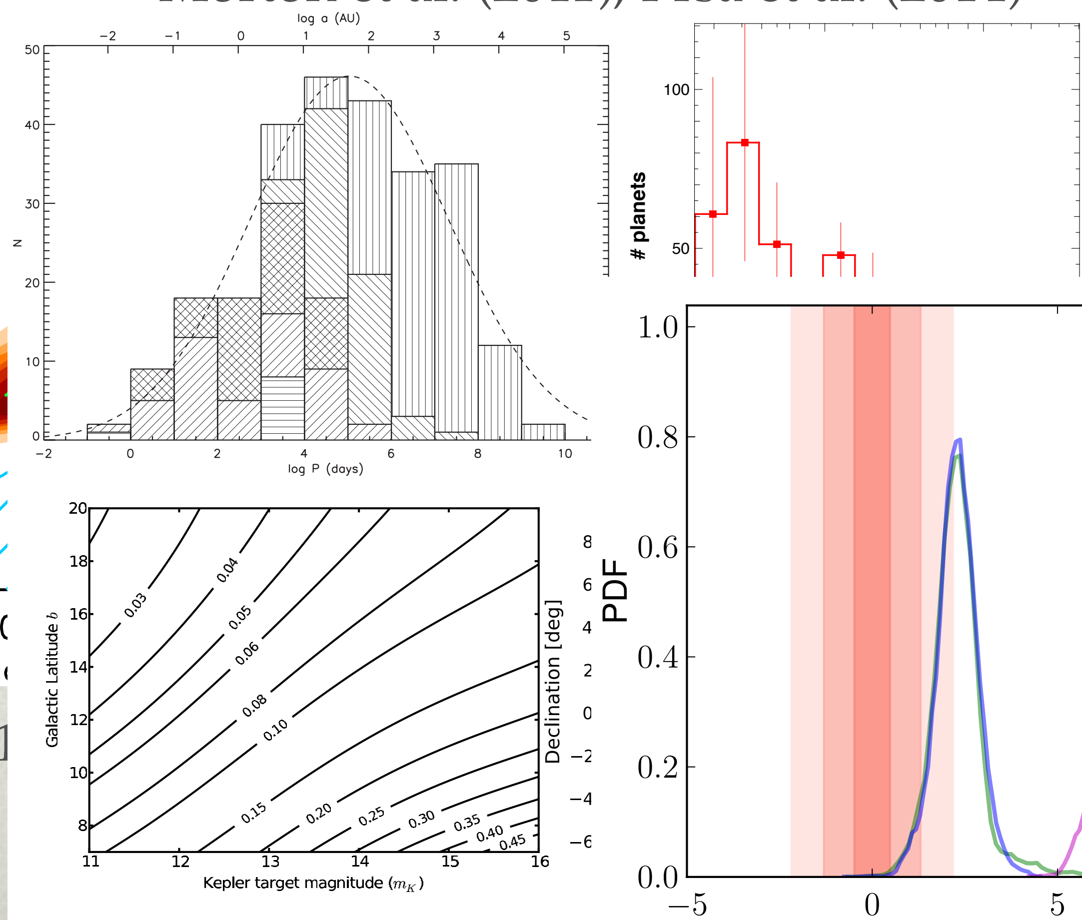
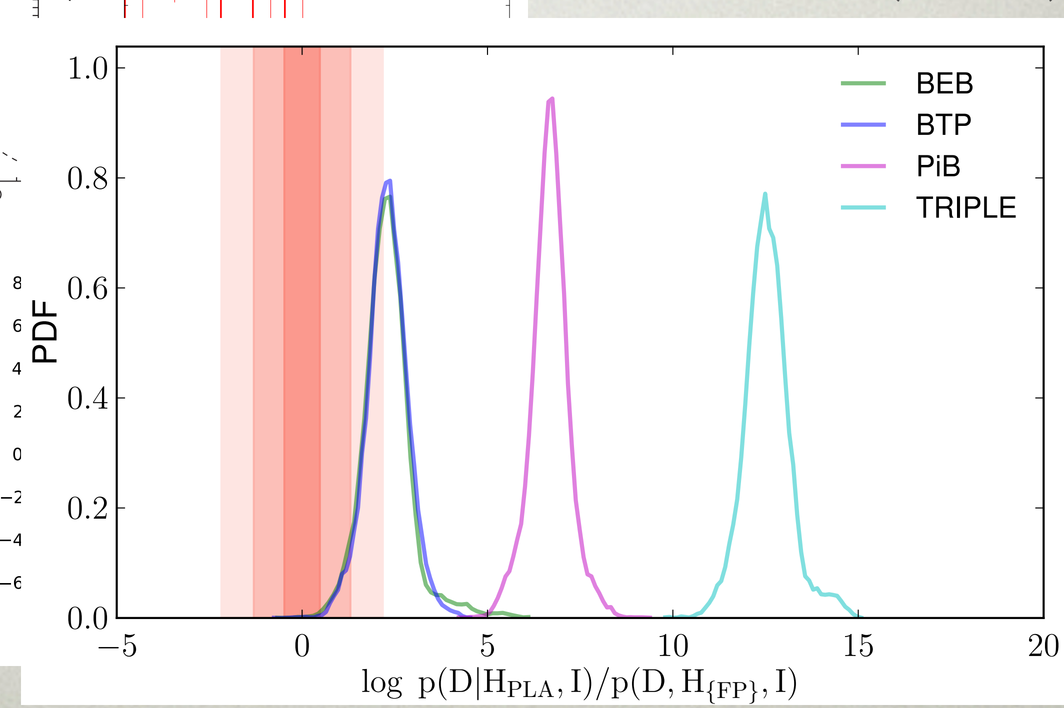


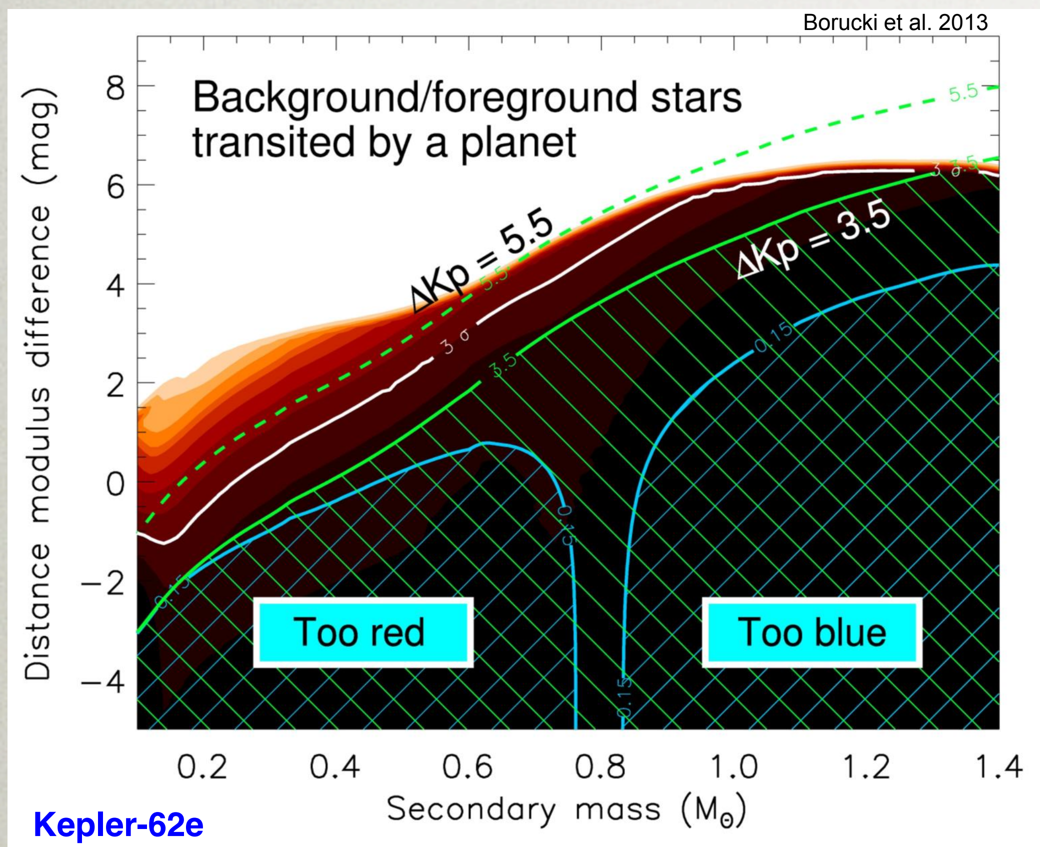
Moutou et al. (subm.)



Two main tools

BLENDER

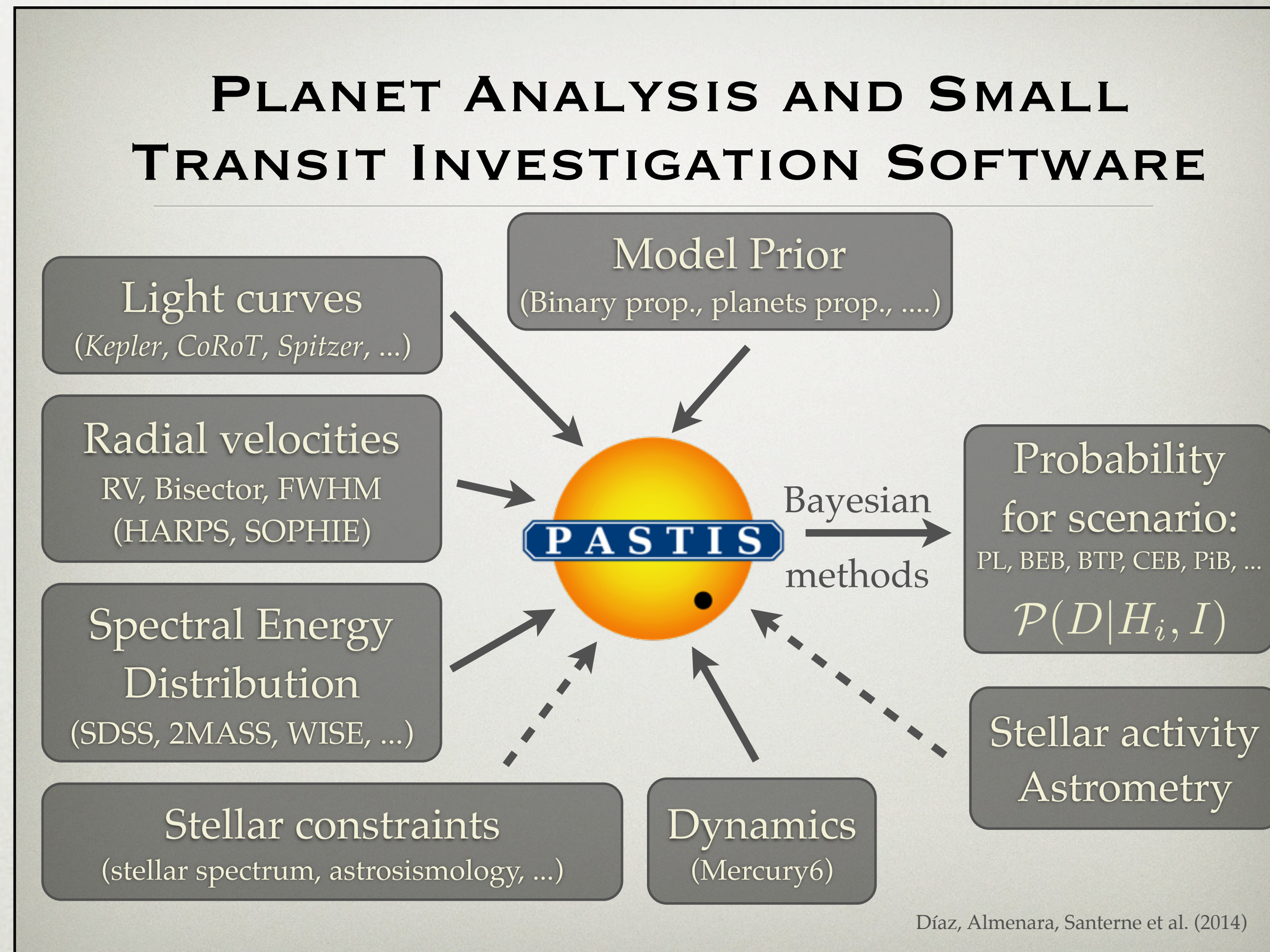
Torres et al. (2011), Fressin et al. (2011,12a,b)



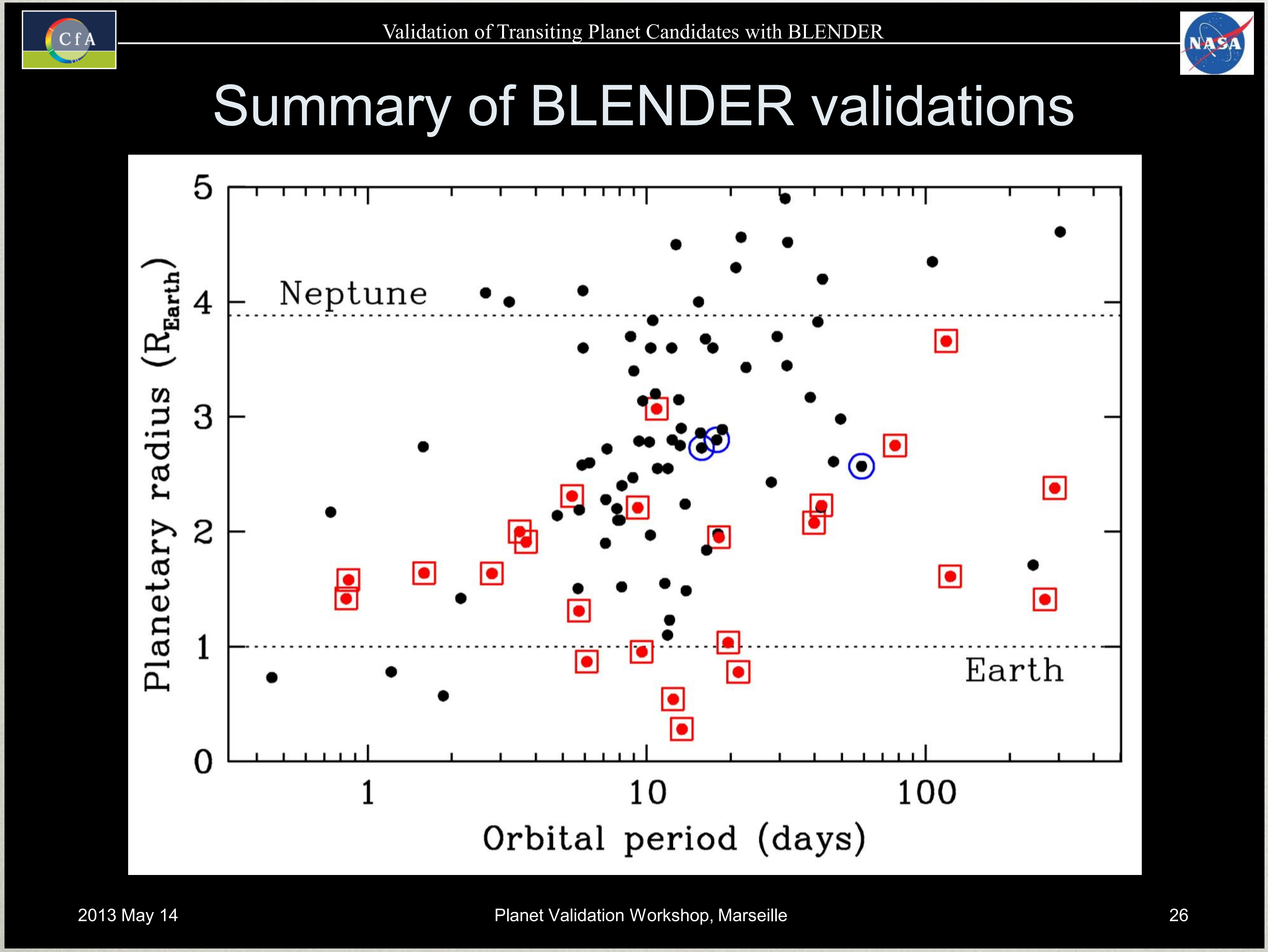
computing time:
a few 10 000 hours

PASTIS

Díaz et al. (2014), Santerne et al. (in prep.), Almenara et al. (in prep.)



VALIDATED PLANETS



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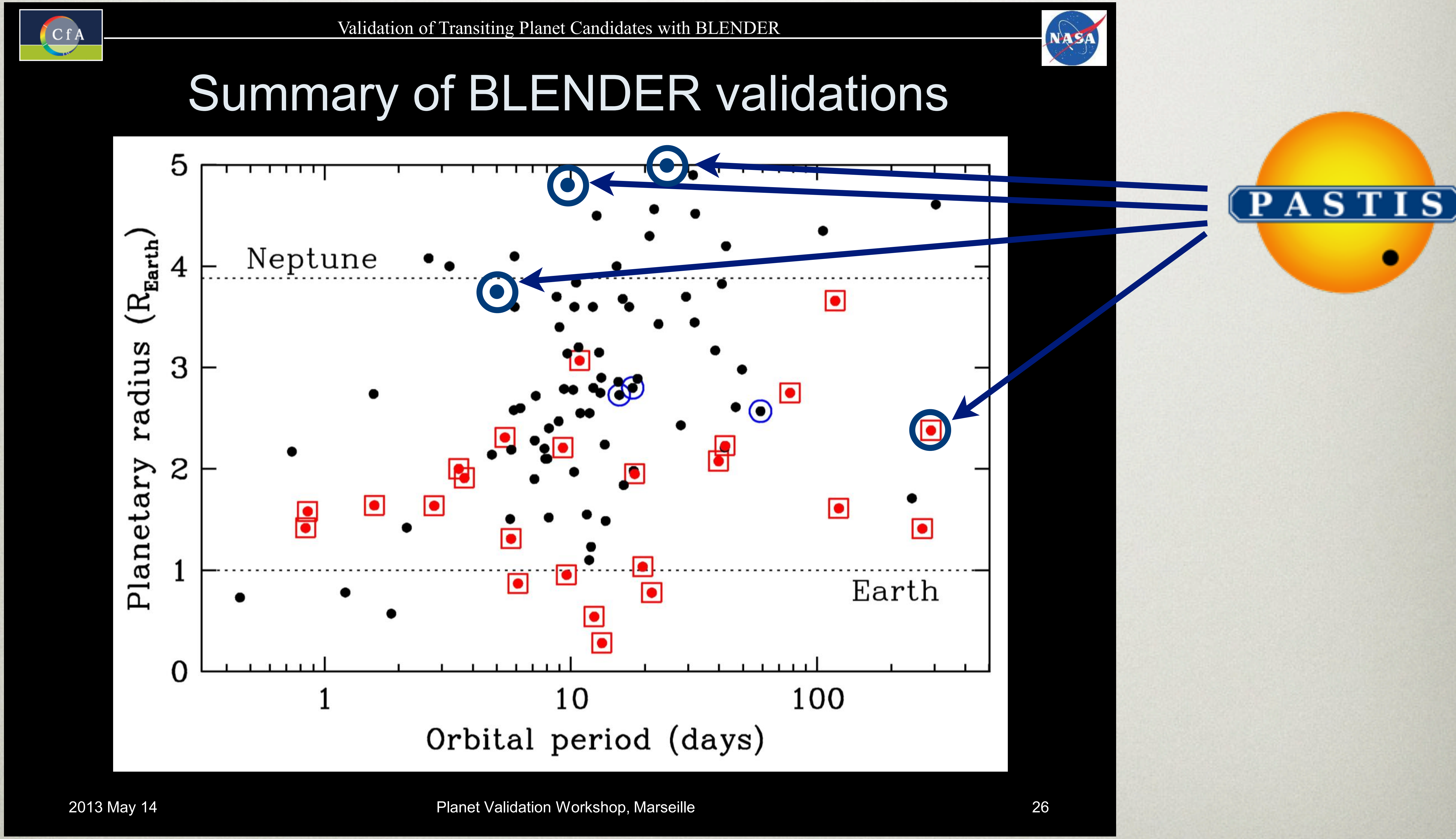

Exoplanet statistics with Kepler candidates

The key for statistical study of *Kepler* candidates:

The False-Positive Probability !

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- Morton & Johnson (2011): median FPP ~ 5% (modelisation)
- Santerne et al. (2012): 35% for giant close-in candidates (observations: SOPHIE data)
- Fressin et al. (2013): global FPP ~ 9.4% (modelisation)
- Santerne et al. (2013): re-evaluation of Fressin's value to 11.3% (modelisation)
- Santerne et al. (in prep.): ~50% for all giant candidates (observations: SOPHIE data)

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For multiples (Lissauer et al., 2012, 14):

$$FPP = \frac{n_{FP}}{n_{KOIs}} \Rightarrow \begin{array}{l} p(FP) = \frac{n_{FP}}{n_\star} \\ p(pl) = \frac{n_{KOIs} - n_{FP}}{n_\star} \end{array}$$

$$p(2FPs) = p(FP) \times p(FP)$$

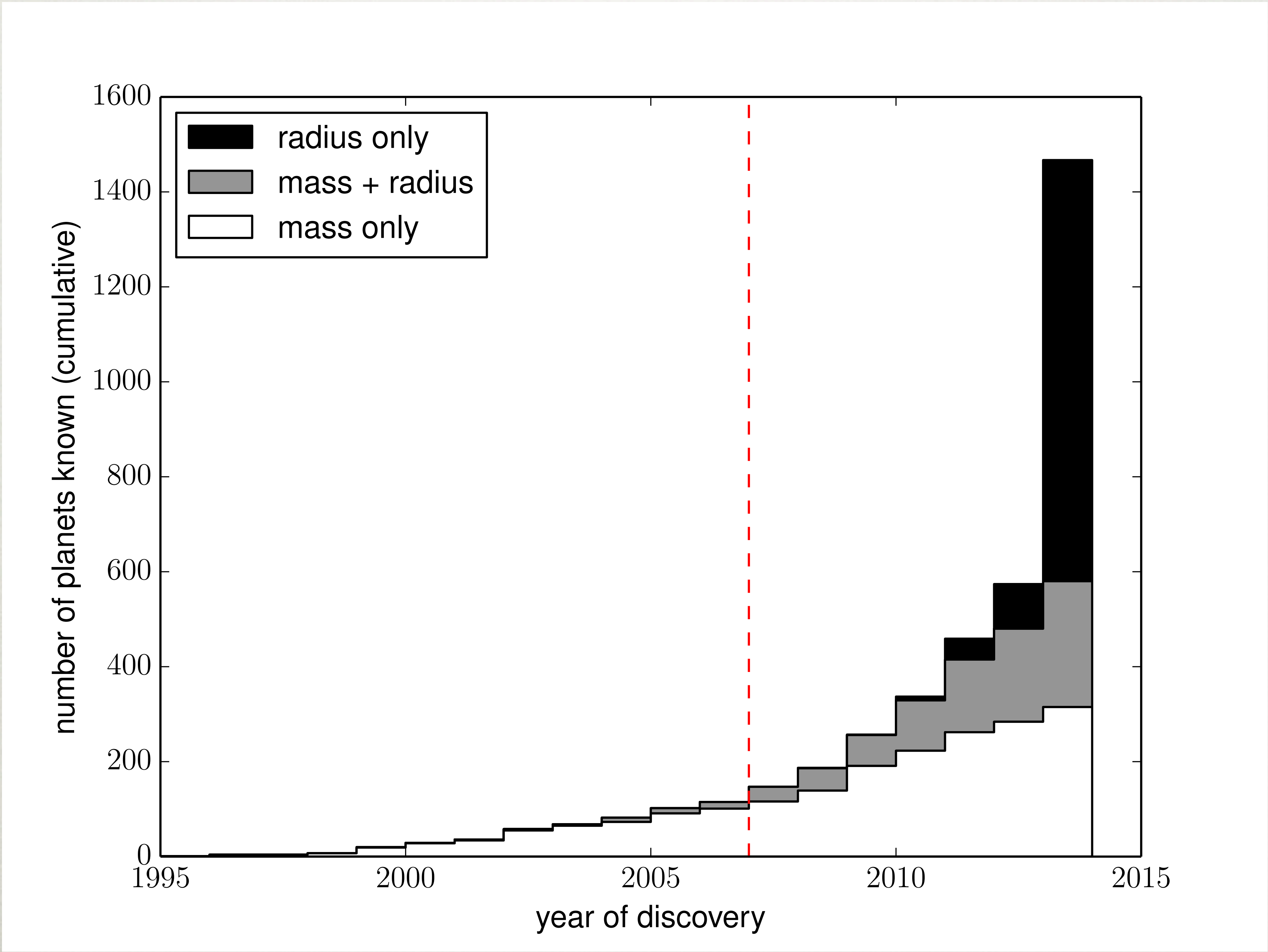
$$p(1pl + 1FP) = p(1pl) \times p(FP)$$

Table 3

Statistical Estimates of Unidentified False Positives in Multis

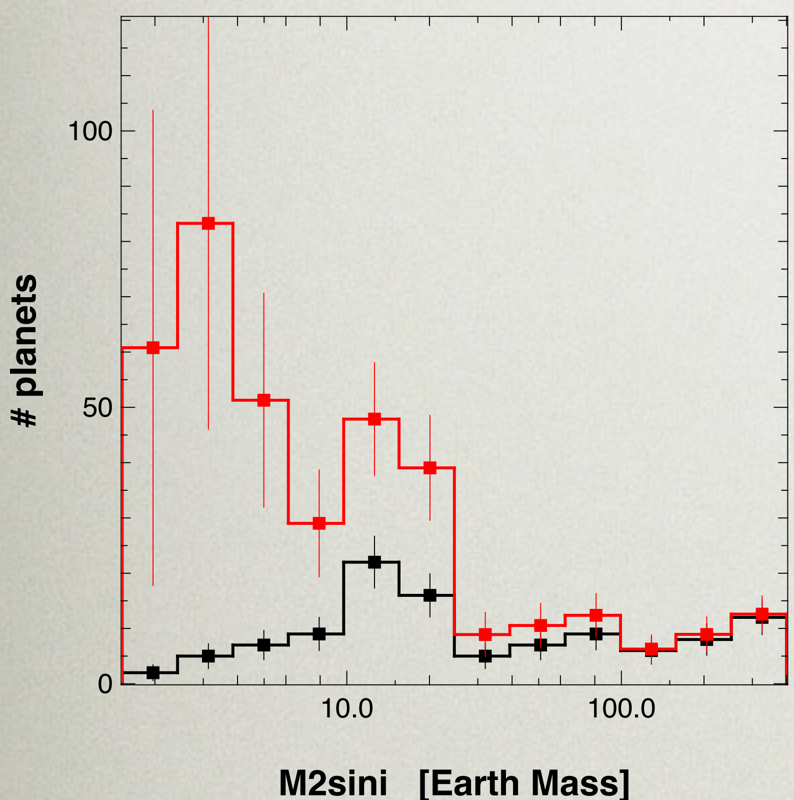
Class (Formula)	Expected Number (for $\mathcal{P}_1 = 0.9$)
2 FPs (Equation (2))	0.063
3 FPs (Equation (3))	2.0×10^{-5}
1 planet + 1 FP (Equation (4))	1.447
1 planet + 2 FPs (Equation (5))	5.3×10^{-4}
⩾2 planets + 1 FP (Equation (6))	0.517
⩾2 planets + 2 FPs (Equation (7))	1.9×10^{-4}
Total FPs (Number of false candidates)	2.09

A new "class" of constraints



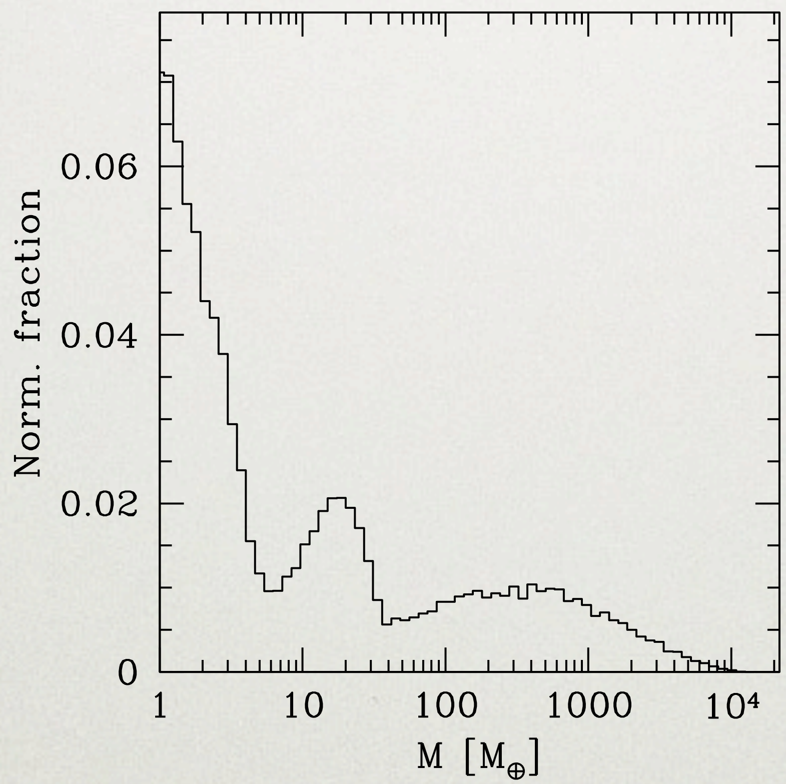
Occurrence of planets

HARPS:
Mayor et al. (2011)



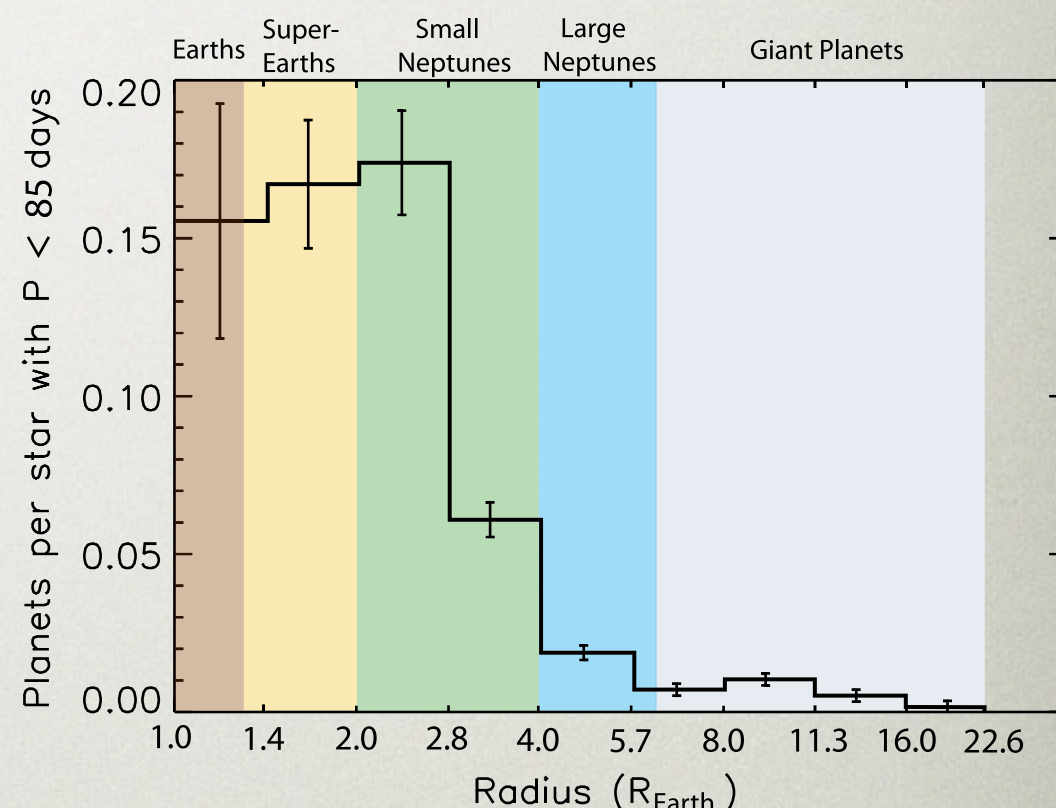
$M_p\sin(i)$

Simulation:
Mordasini et al. (2009)



M_p

Kepler:
Fressin et al. (2013)



R_p

The occurrence of habitable Earth-like planets around M dwarfs

HARPS

102 M dwarfs

Msin(i) < 10Me

2 Super-Earth in HZ

➙ $\eta_{\oplus} = 41^{+54}_{-13}$ %

Bonfils et al. (2013)

Kepler

3897 M dwarfs

0.5 Re < R_p < 1.4 Re

2 Earth-size planet-candidates in HZ

➙ $\eta_{\oplus} = 15^{+13}_{-6}$ %

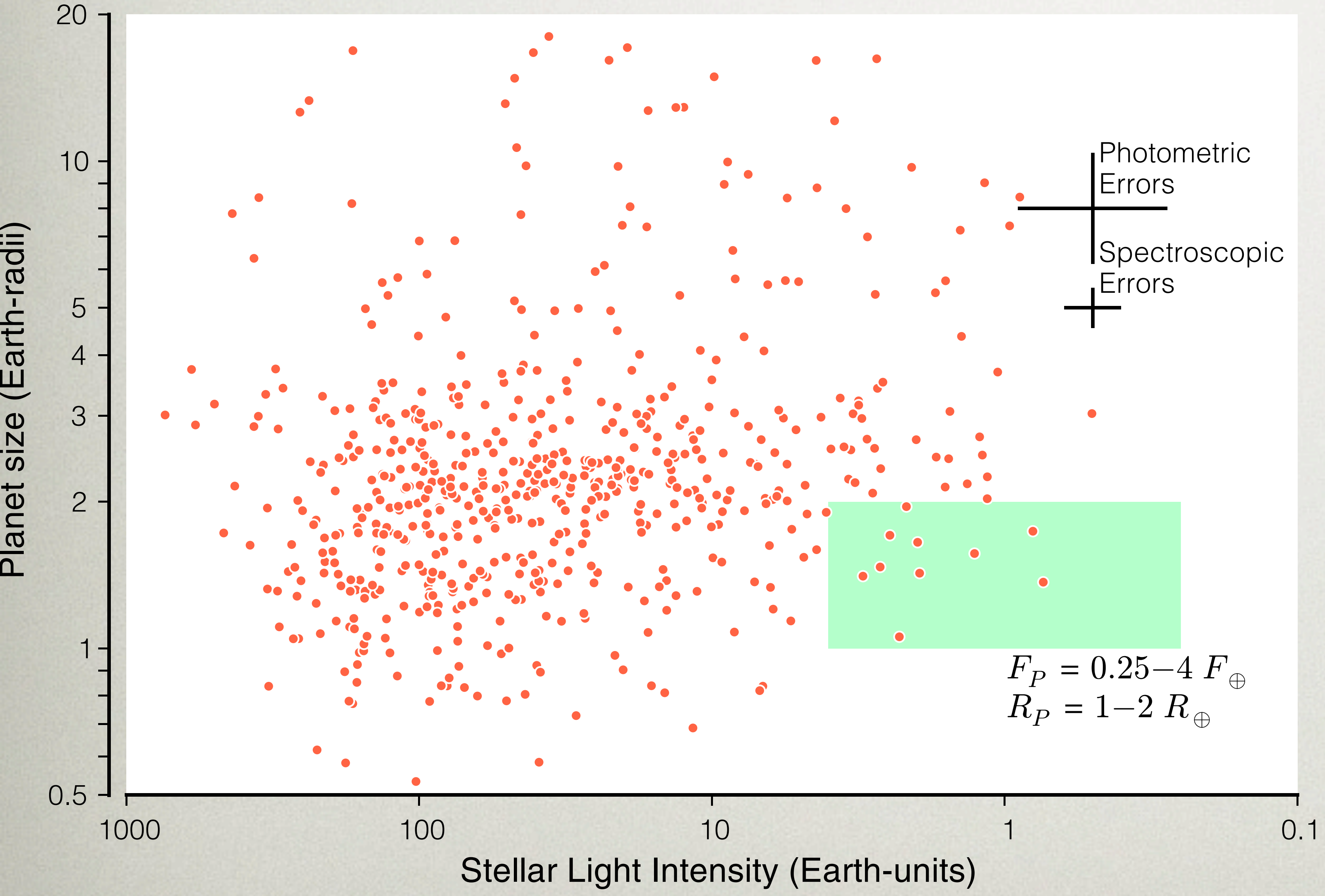
Dressing & Charbonneau (2013)

But FPP ~ 0% assumed !

➙ **Planetary nature needed !**

OCCURRENCE OF EARTH ANALOGS

Petigura, Howard & Marcy (2013)



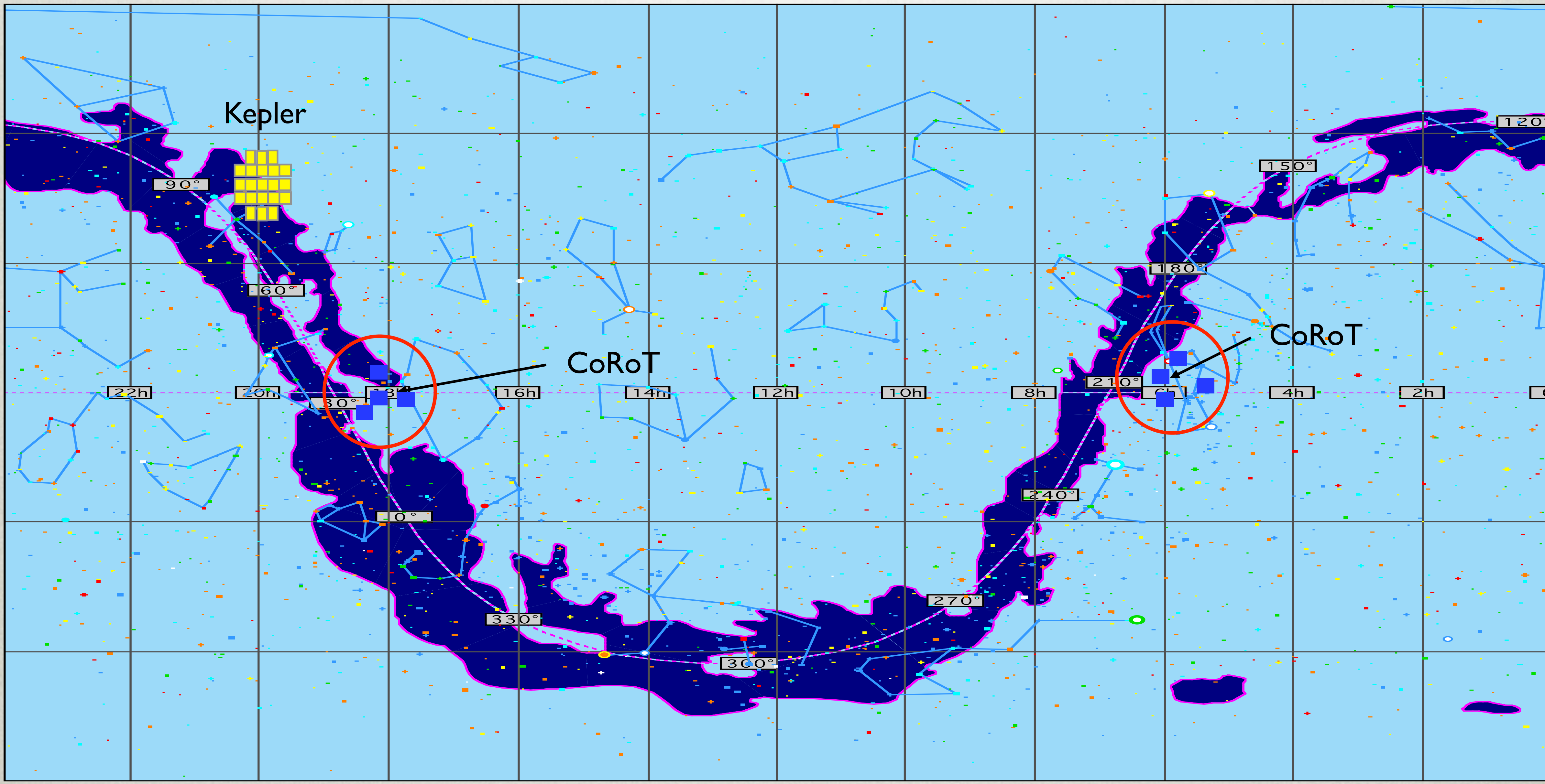
22 ± 8 % of Sun-like stars harbor an Earth-size planet in the HZ

Planet statistics limitations

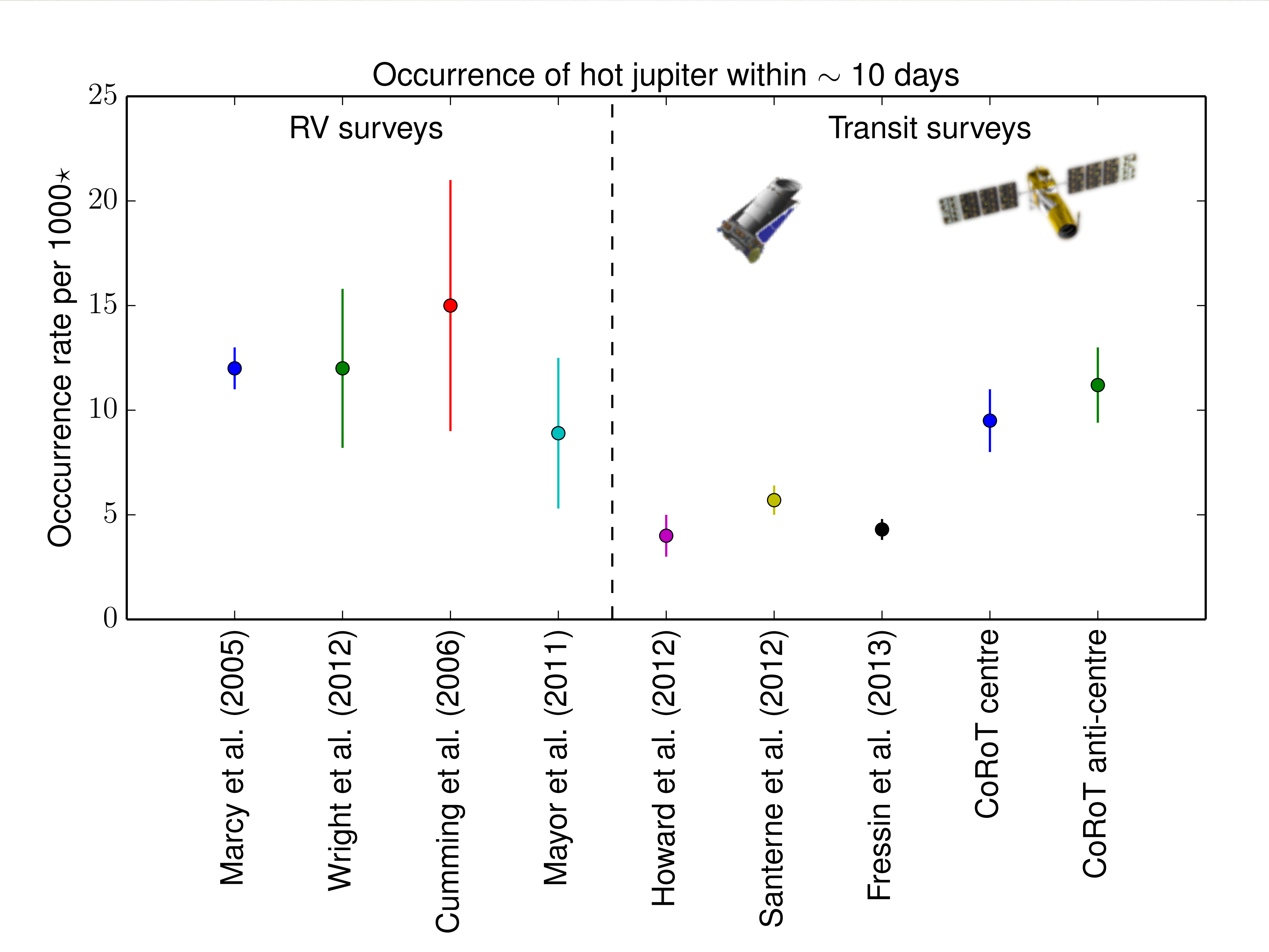
Planet statistics need:

- Accurate false-positive rate
- Accurate pipeline completeness
- Accurate planetary radius **(based on accurate stellar radius)**
- Accurate definition of the HZ
- High number statistics
- No extrapolation

Comparison CoRoT / Kepler

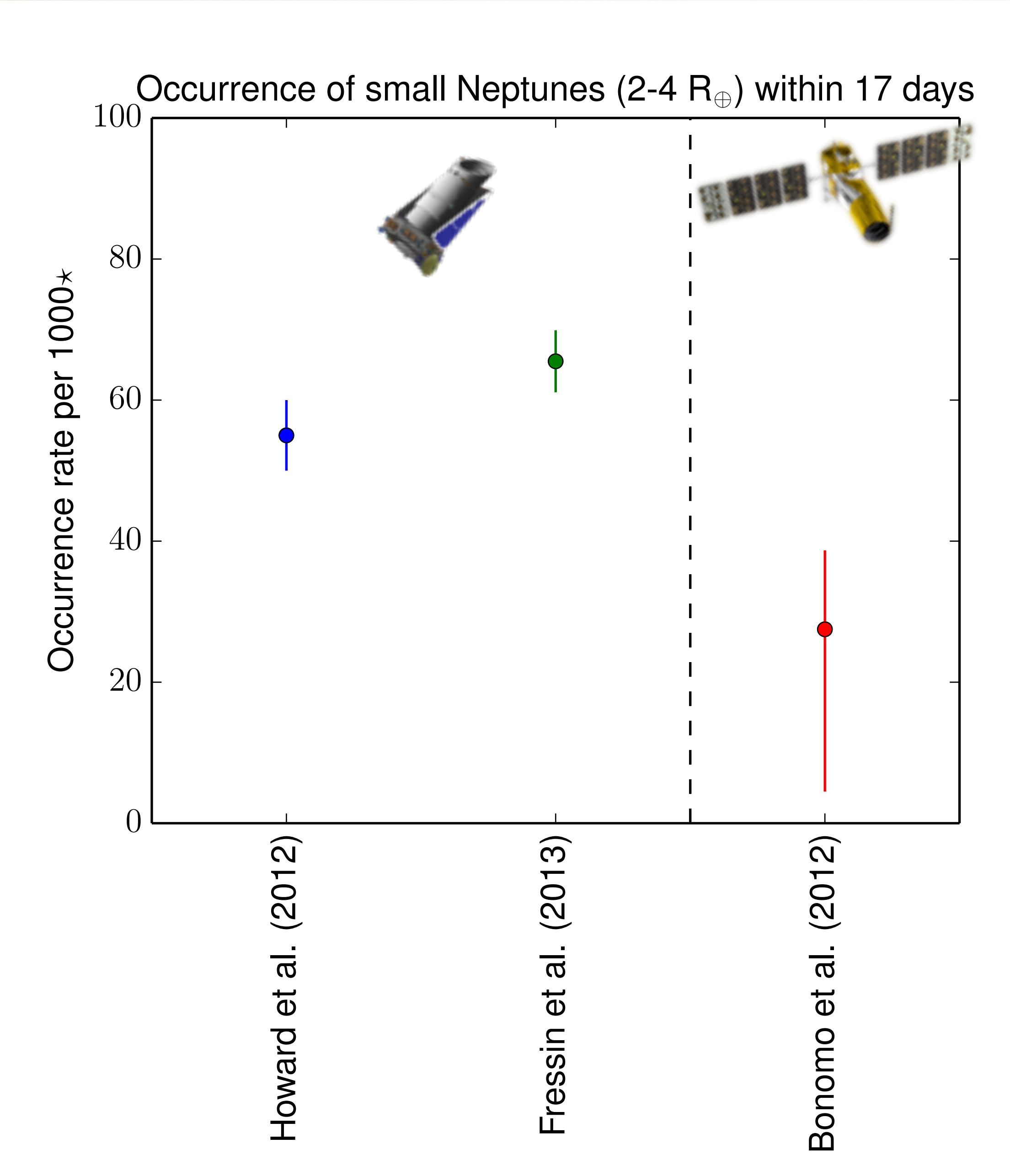


Occurrence of hot-jupiters



Santerne (PhD Thesis), Deleuil et al. (in prep.)

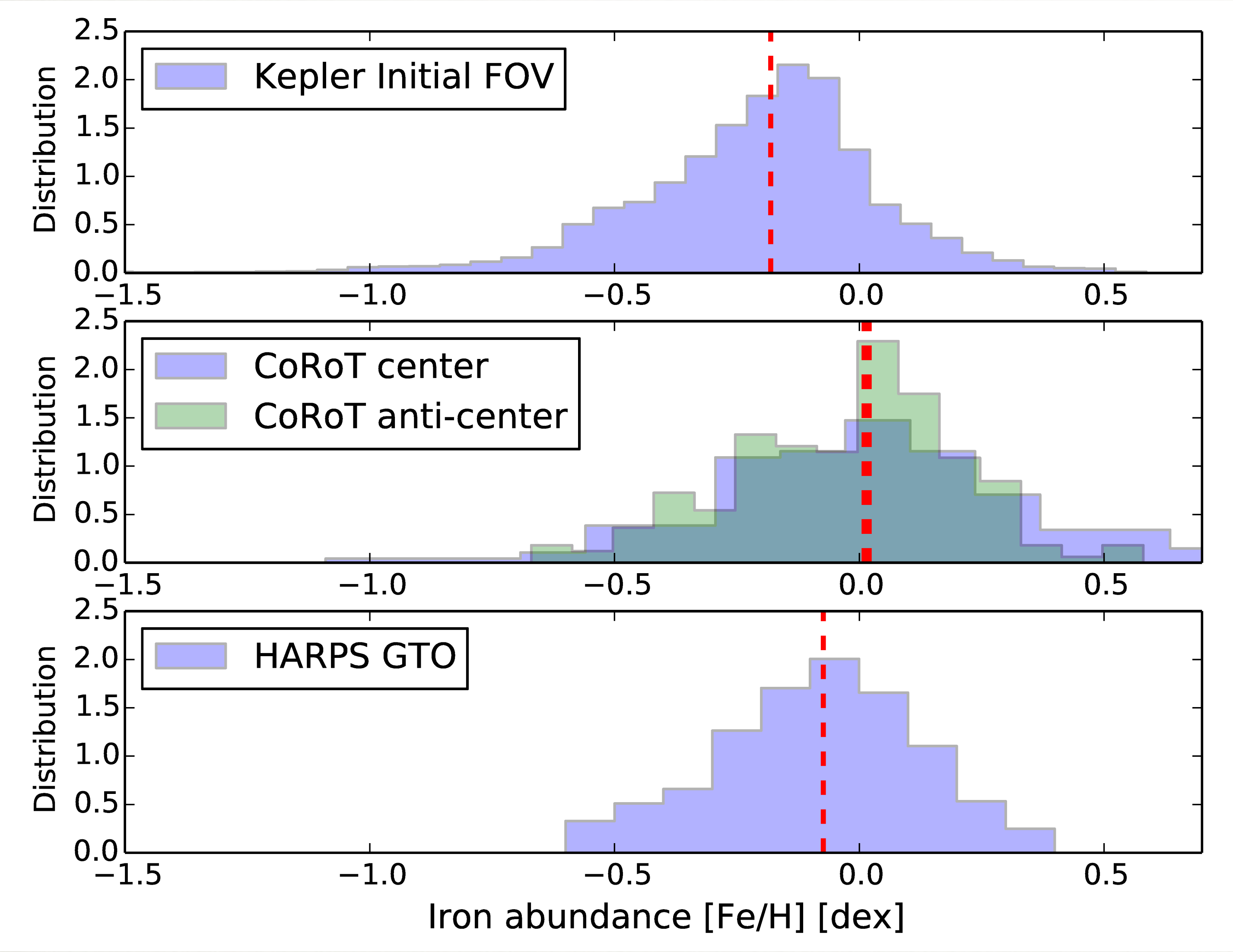
Occurrence of Small Neptunes



Kepler detected nearly twice more Neptunes than *CoRoT*

Bonomo et al. (2012)

DIFFERENT STELLAR POPULATION

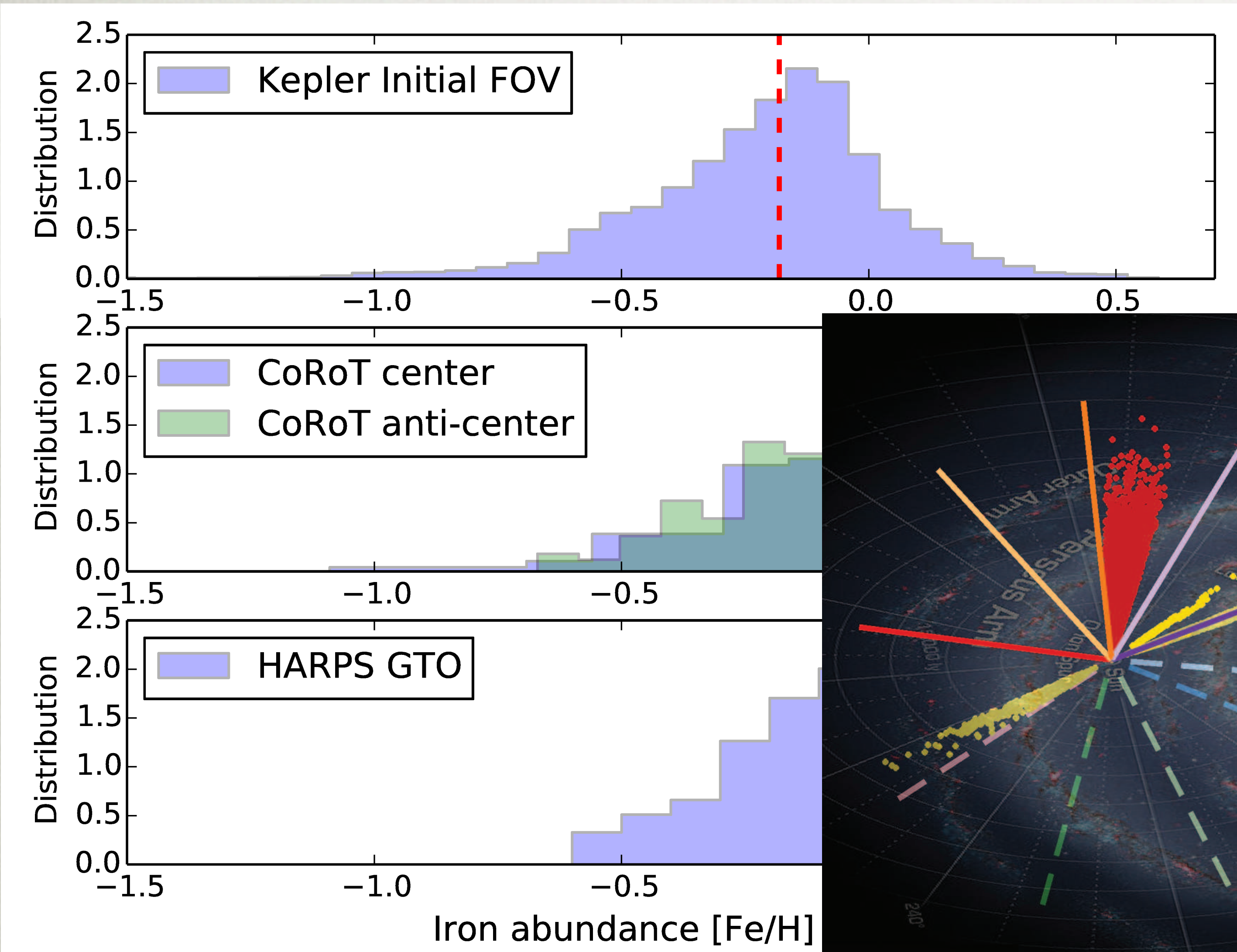


KIC: Brown et al. (2011)

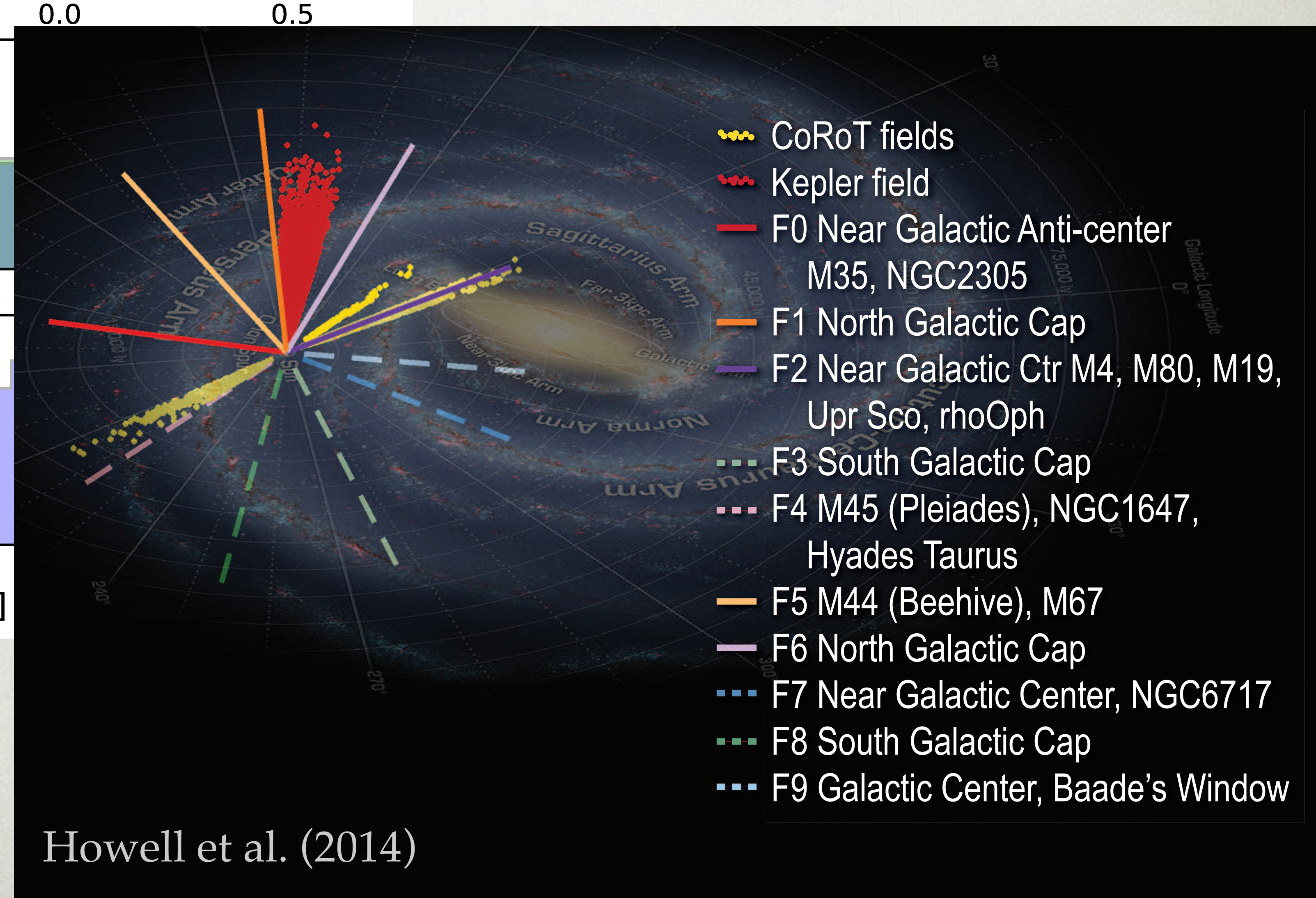
Gazzano et al. (2010)

Sousa et al. (2008)

DIFFERENT STELLAR POPULATION



KIC: Brown et al. (2011)



Howell et al. (2014)

CONCLUSIONS

- Space-photometry revolution = planet-diversity revolution (super-Earths & Brown dwarfs).
- TTVs: efficient technique to characterize exoplanets based on photometric data.
- Some discrepancy exists between RVs' and TTVs' mass (need to be further explored).
- Planet-validation tools (e.g. BLENDER, PASTIS) can establish the planetary nature of small & cool planets.
- *CoRoT* & *Kepler* provided constraints on planet statistics (occurrence rates, distribution, etc..) mostly based on their *radius*.
- Need more characterized planets to derive statistics of rocky, Neptune-like, ... planets.
- Occurrence rates from *CoRoT* and *Kepler* give different results ➙ different stellar population ?

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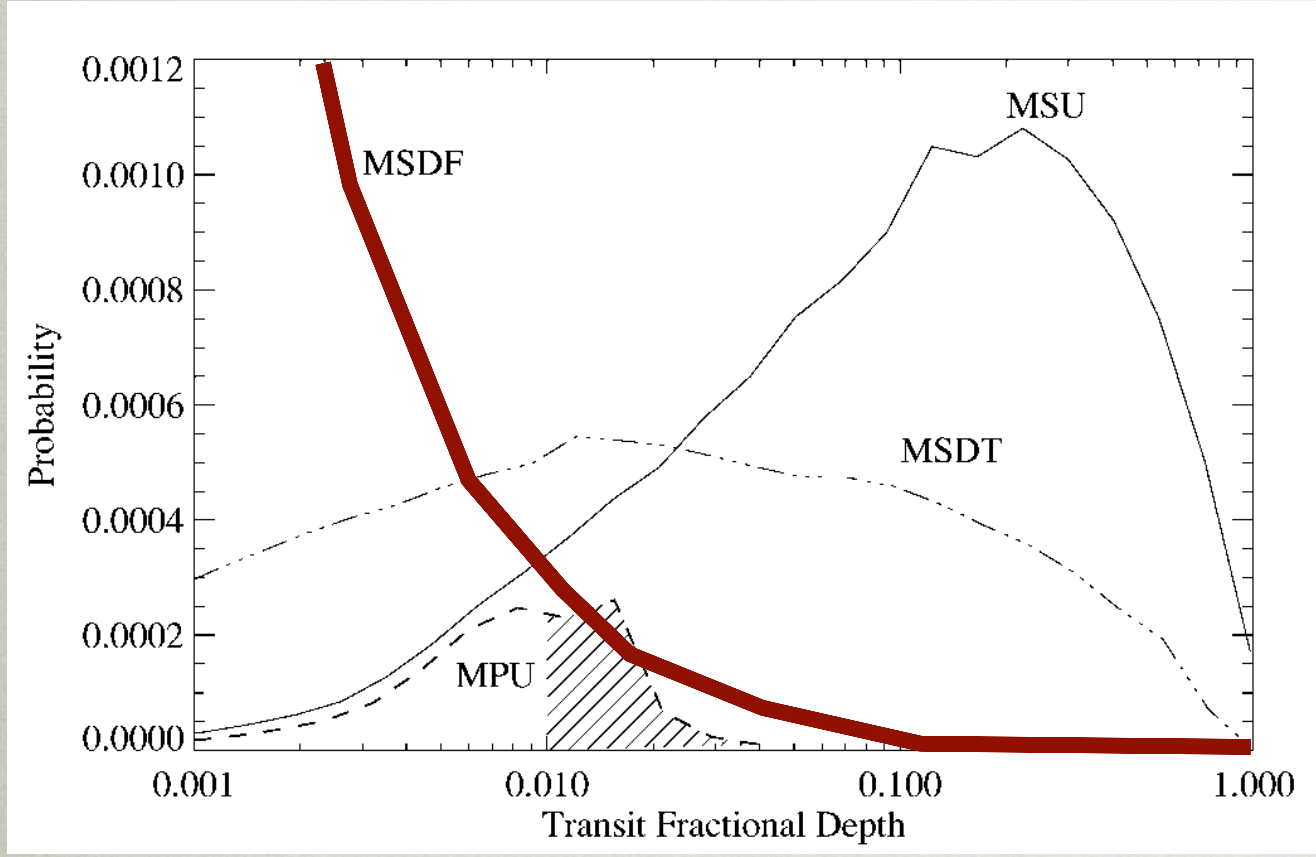
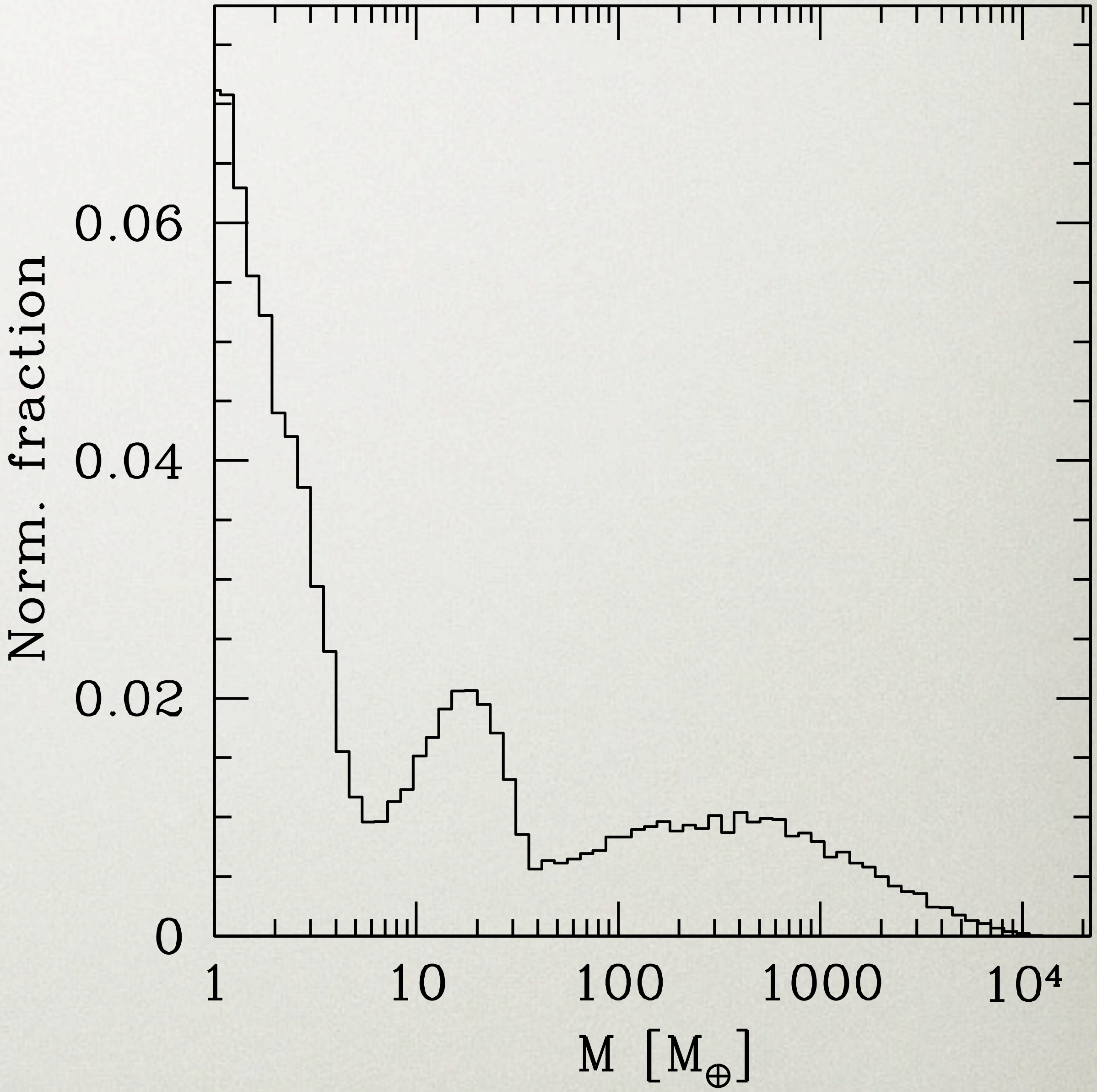
- Thanks for your attention -

Extrapolating the FPP toward smaller candidates



Brown (2003)



Mordasini et al. (2009)