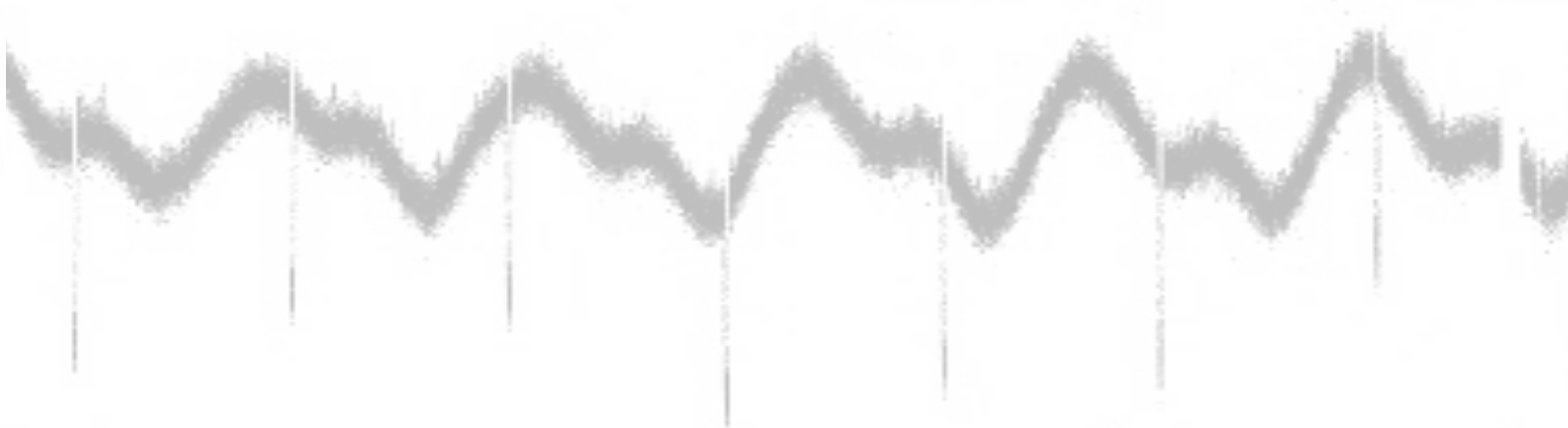
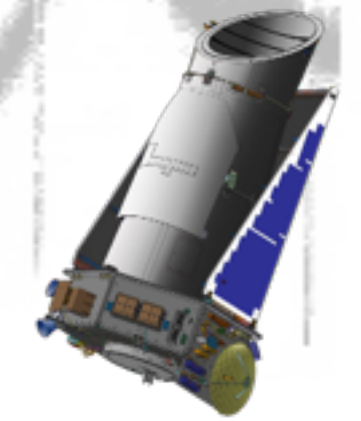
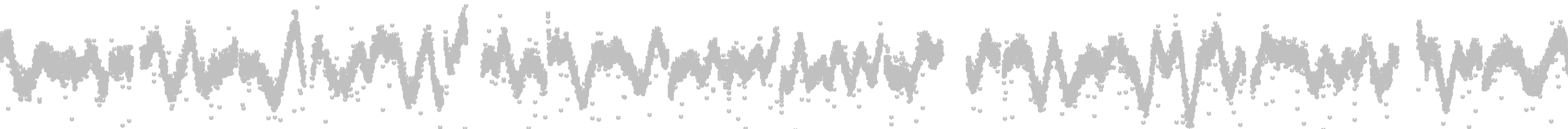
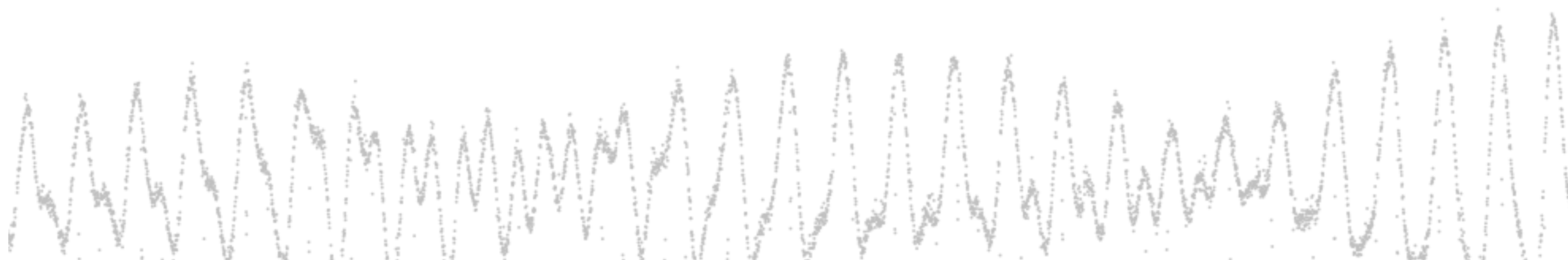






TRANSITING EXOPLANETS: THE REVOLUTION FROM SPACE-BASED OBSERVATIONS



M. Deleuil, Laboratoire d’Astrophysique de Marseille - France
Institut Universitaire de France
Coordinator of the CoRoT/Exoplanet program

COnvection ROtation & planetary Transits

CoRoT:
A French/European/Brazilian mission led by CNES
Scientific Program :
- stellar structure - asteroseismology
- planet search - transit method
- stellar physics

Operations: 01/2007 - 10/2012
Polar orbit
FOV ~ 4o□ (half after 2009)
$11.5 \leq$ r-mag $\leq 16.$
Photometric precision 700 ppm/hr
169 967 light curves
time sampling : 512 sec or 32 sec

47 284 FGKM dwarfs (based on color separation)

Kepler

NASA mission

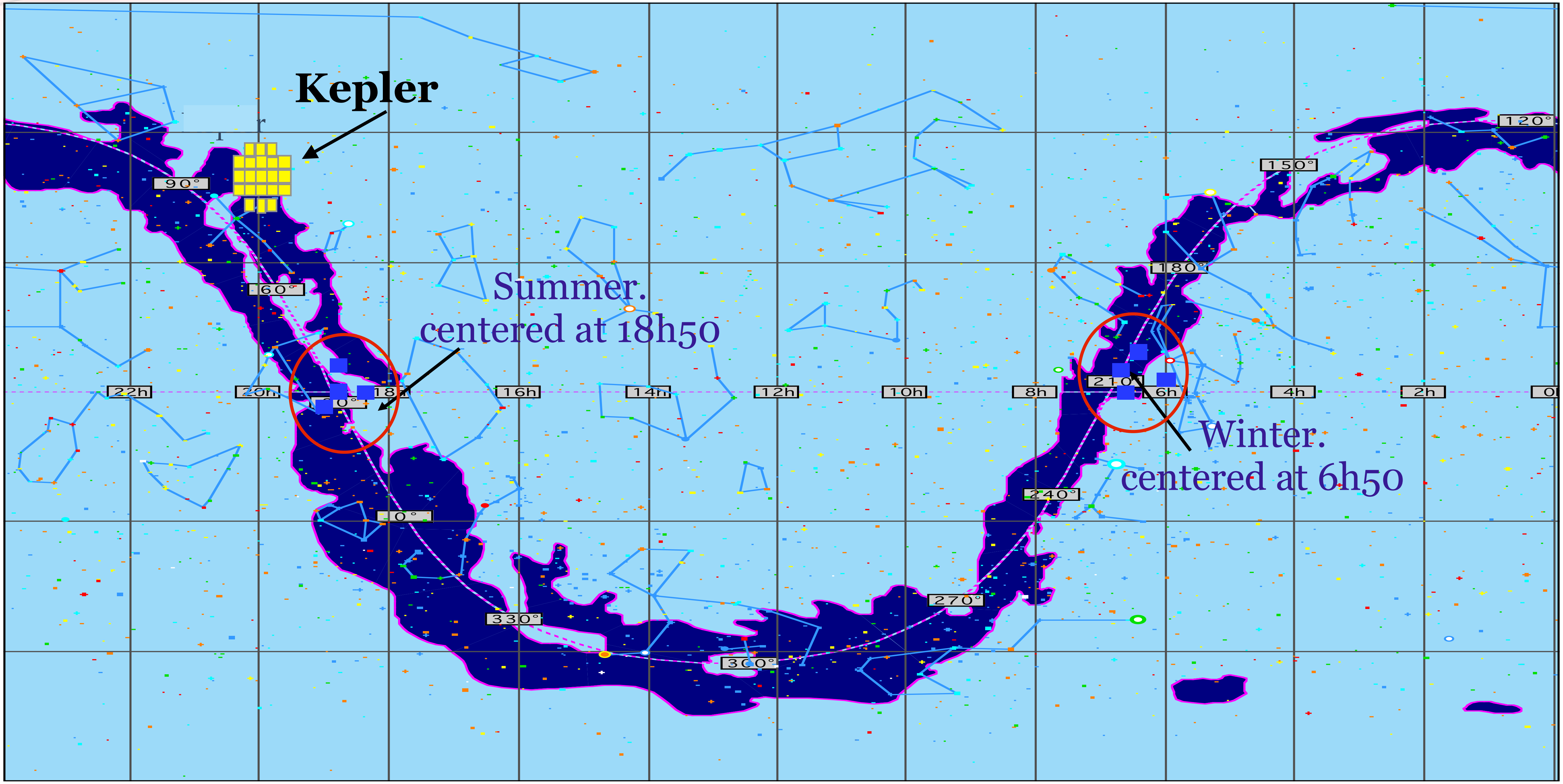
Scientific objective : detection of Earth analogs (transit method)

Operations: 03/2009 - 05/2013
Earth-trailing heliocentric orbit

FOV ~ 105°□
$9 \leq$ Kp-mag ≤ 15
Photometric precision 80 ppm/hr

160 000 light curves
time sampling: 30 min or 1 min
44 000 FG dwarfs

Observing strategy



- CoRoT : 26 stellar fields observed with duration ranging from ~22 days up to 150 days
- Kepler: 1 stellar field observed for 4 years

Planet detection - methods

Transits

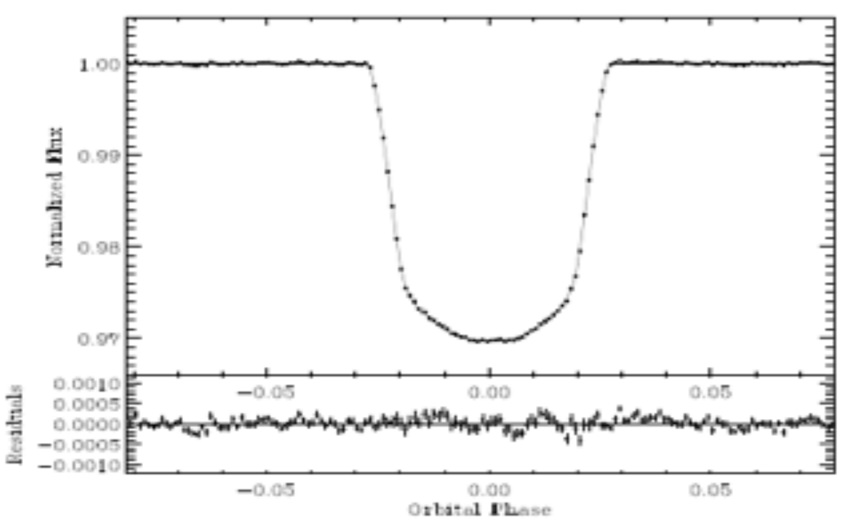
$$\frac{\Delta F}{F} = \left(\frac{R_p}{R_*}\right)^2$$

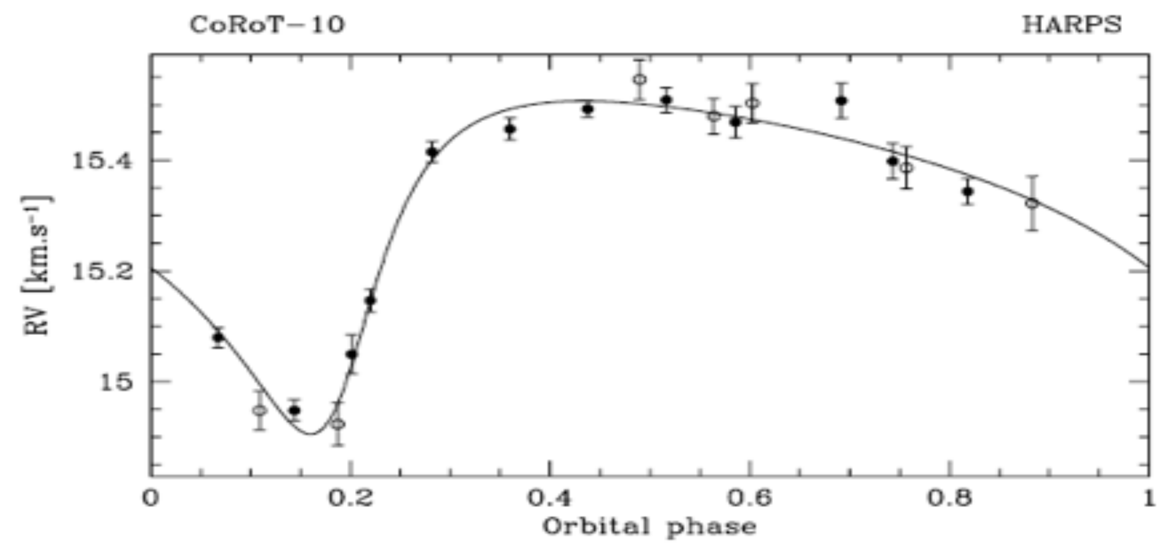
Transits & radial velocity:

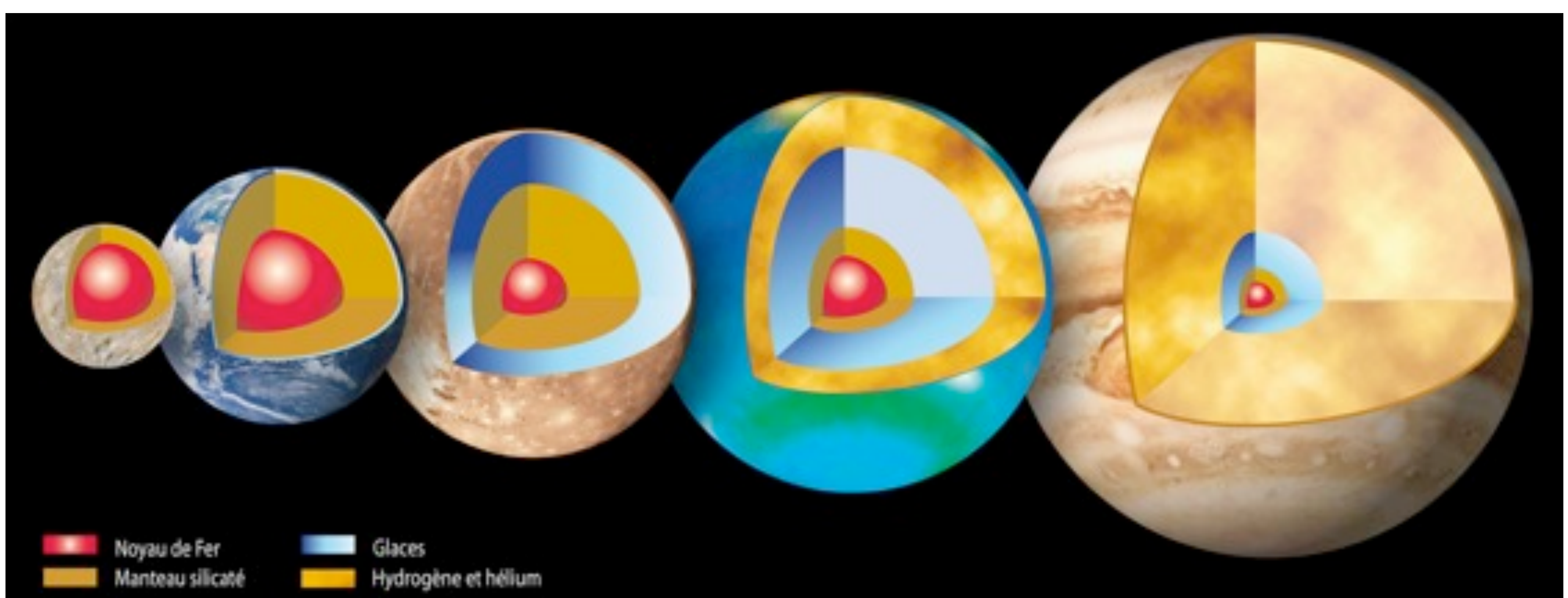
$R_p + M_p \rightarrow \rho_p$

radial velocity

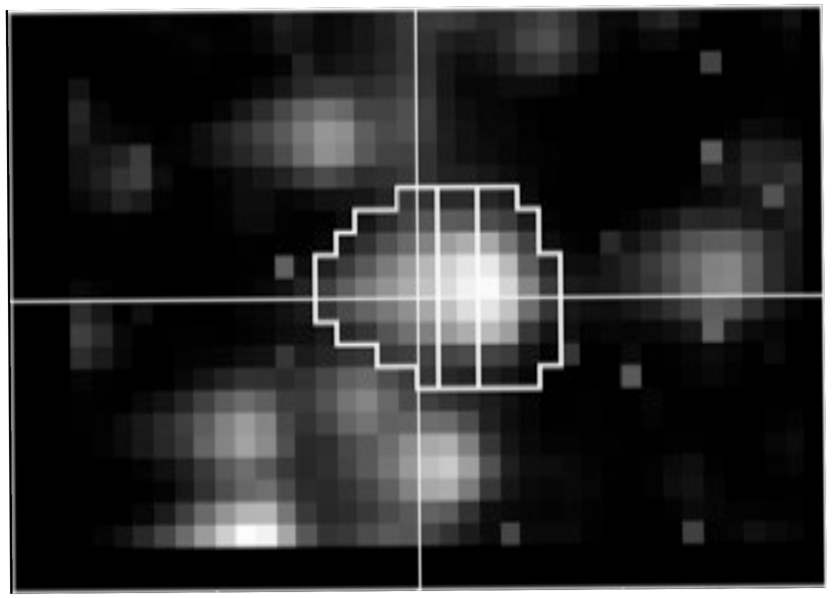
$$k = \frac{28.4\ ms^{-1}}{\sqrt{1-e^2}} \frac{m_p \sin i}{M_{Jup}} \left(\frac{P}{1\ yr}\right)^{-1/3} \left(\frac{m_*}{1M_\Theta}\right)^{-2/3}$$

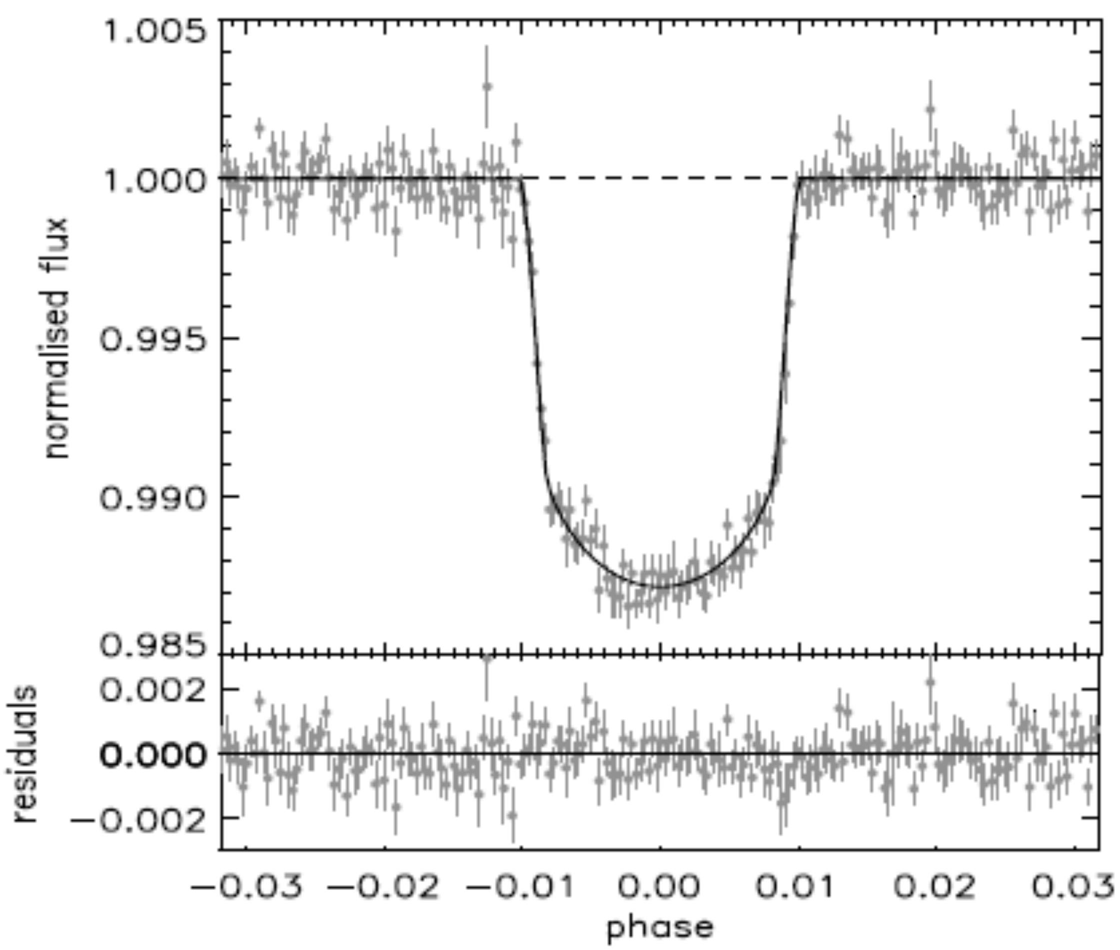


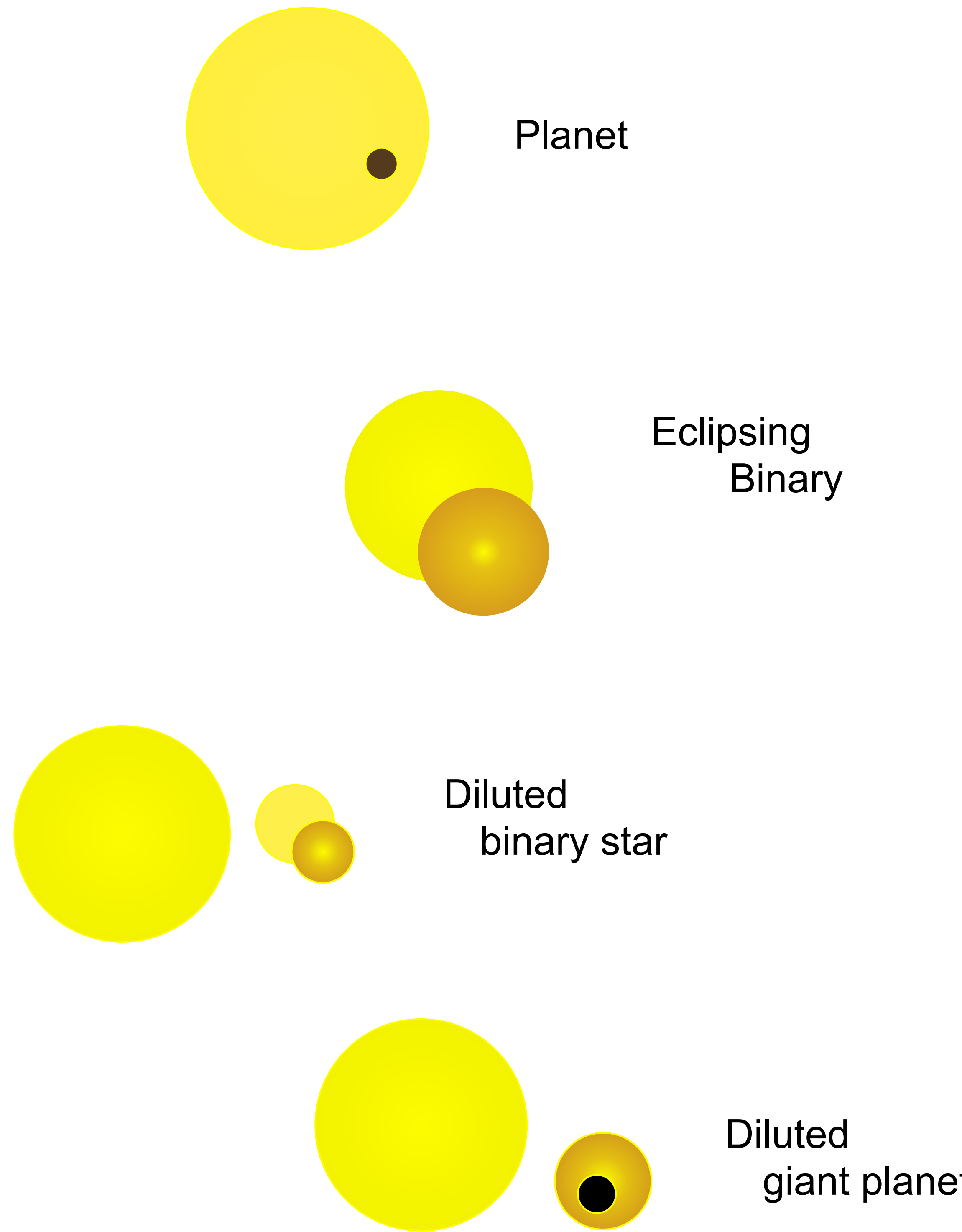




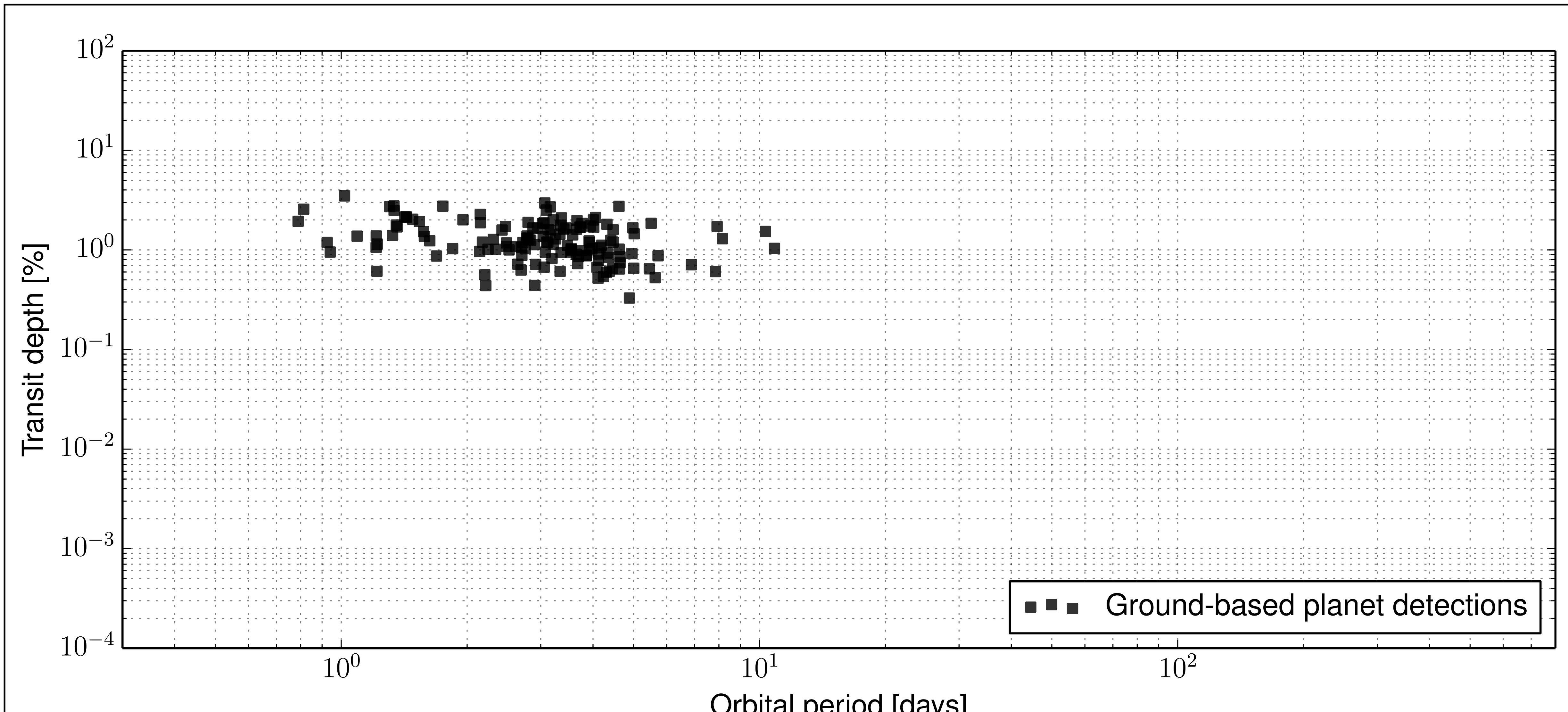
Transits - blends issues



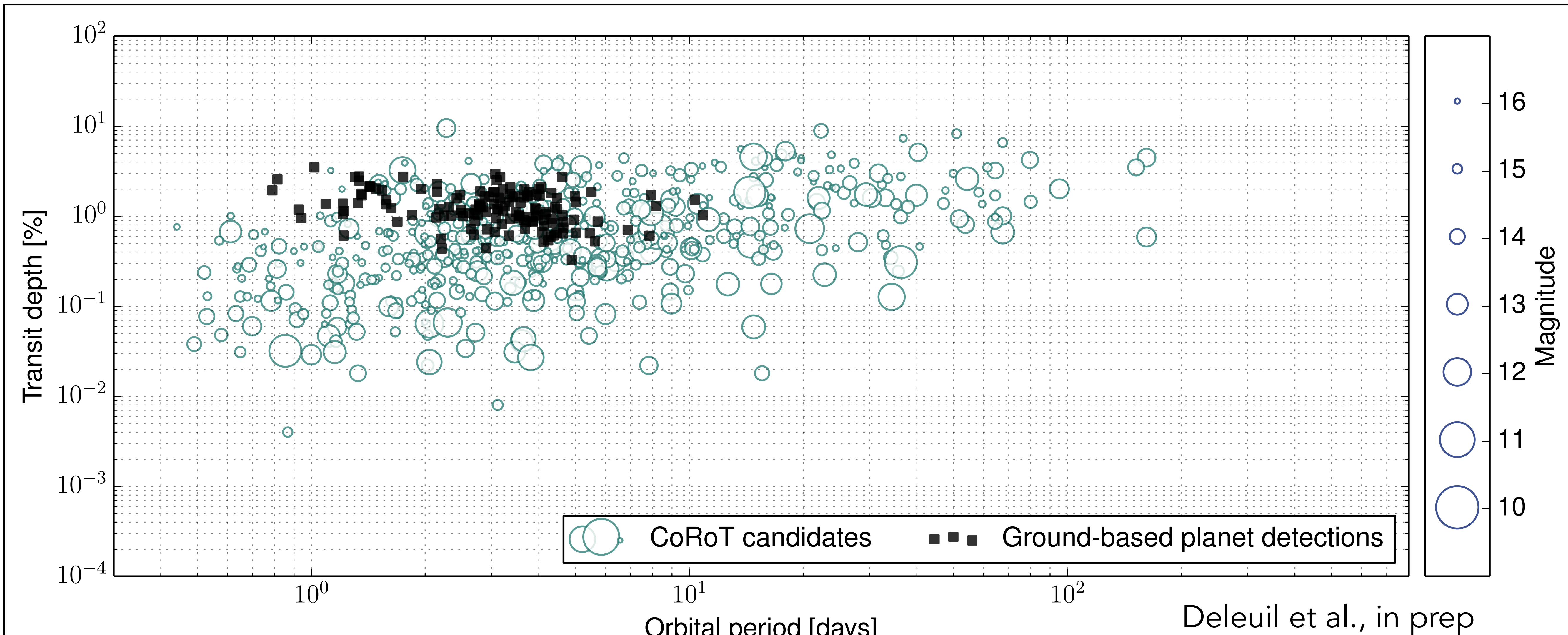




Ground-based surveys



CoRoT vs ground-based



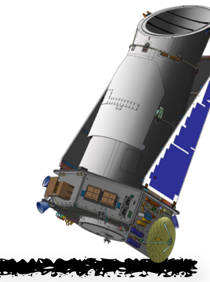
CoRoT

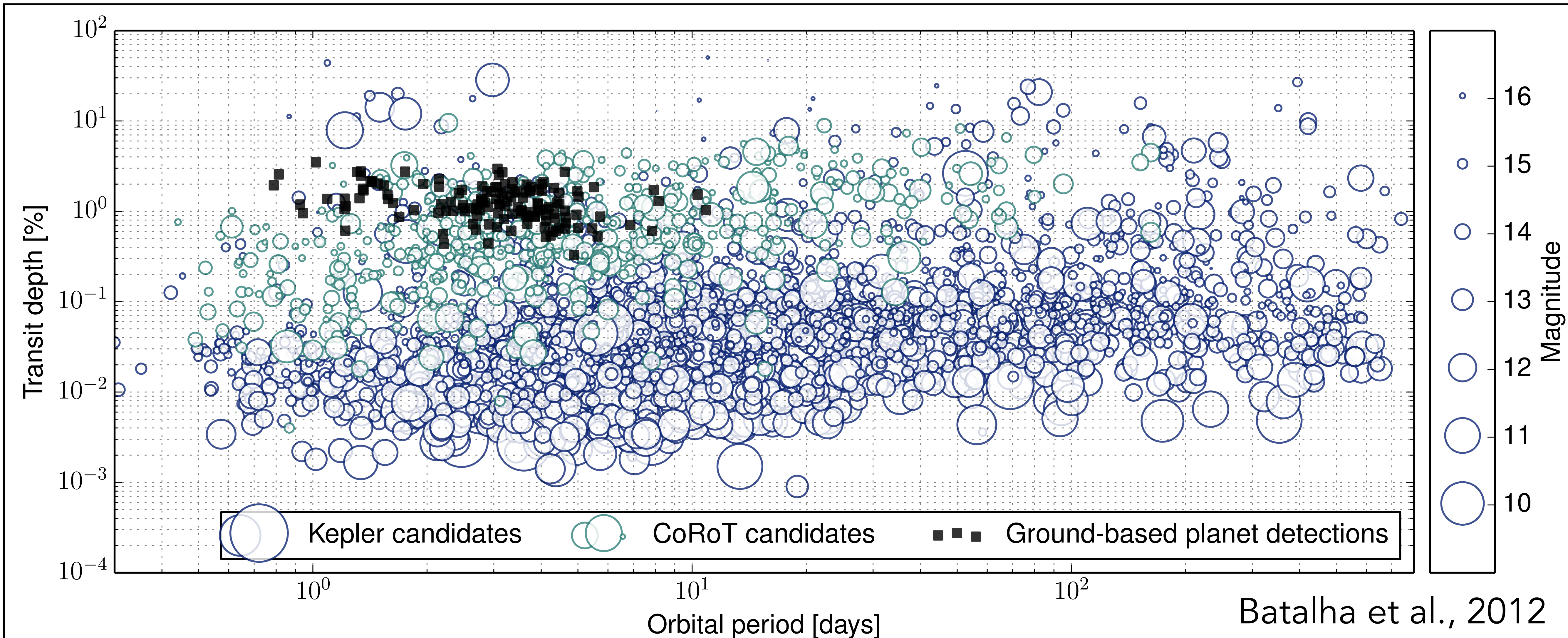
~ 600 candidates detected

32 planets/BD characterized

(with mass constraint > 3 σ)

Kepler vs ground-based





Batalha et al., 2012

CoRoT

~ 600 candidates detected

32 planets/BD characterized

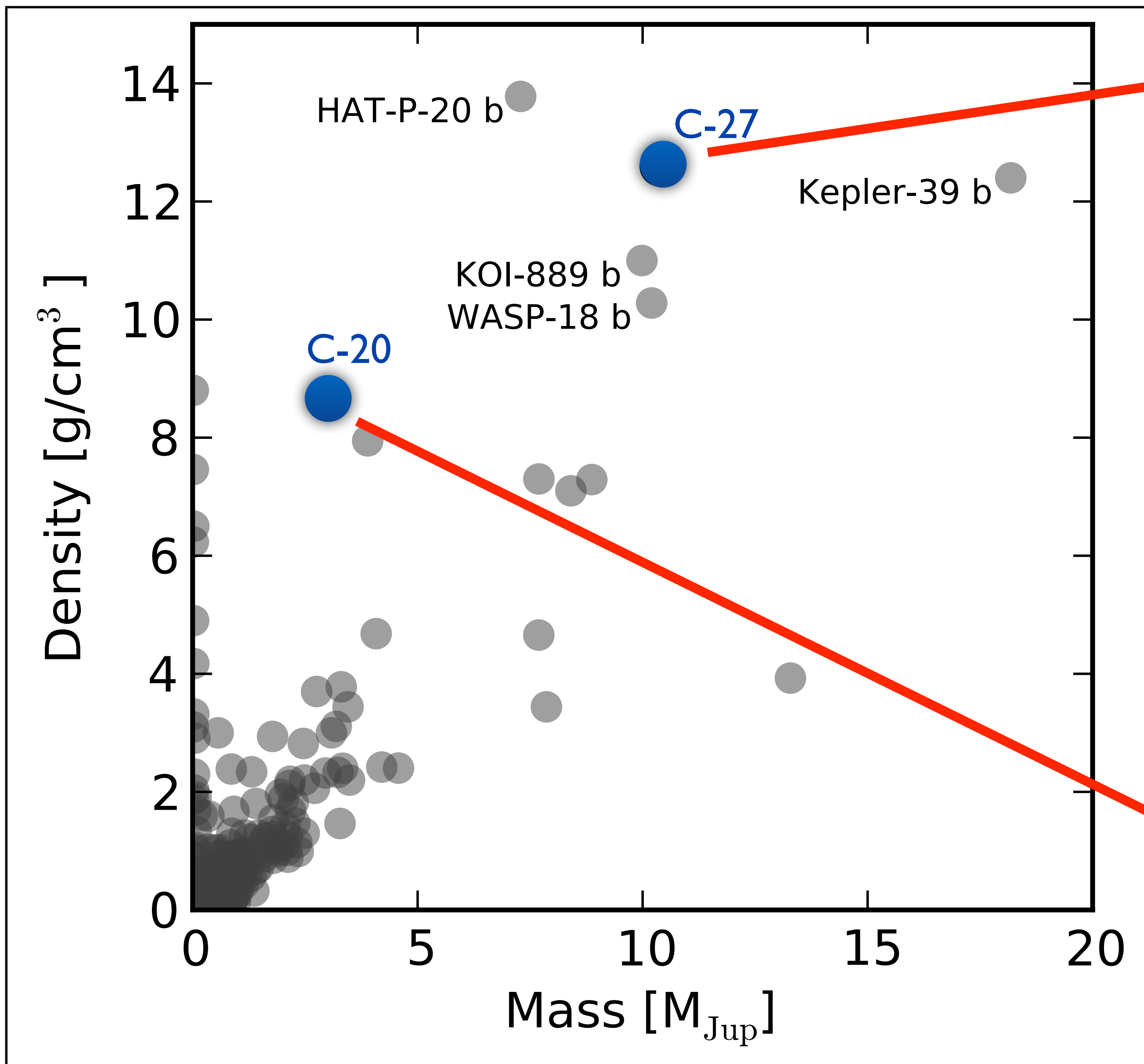
(with mass constraint > 3 σ)

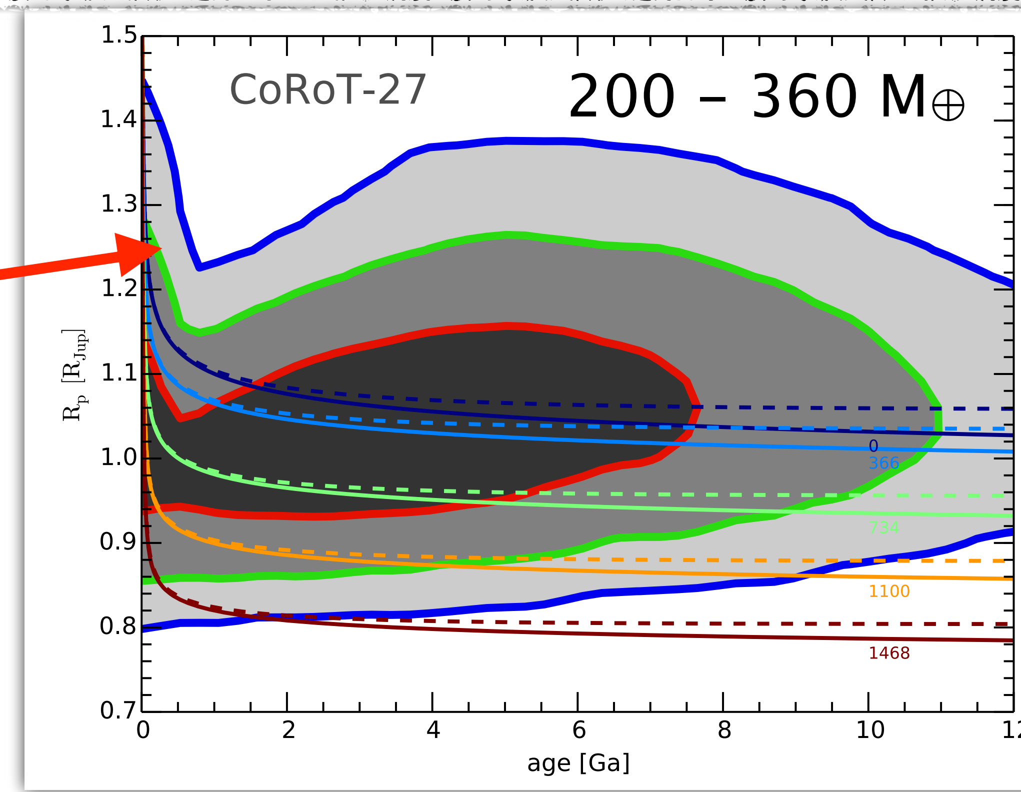
Kepler

~ 4000 candidates detected

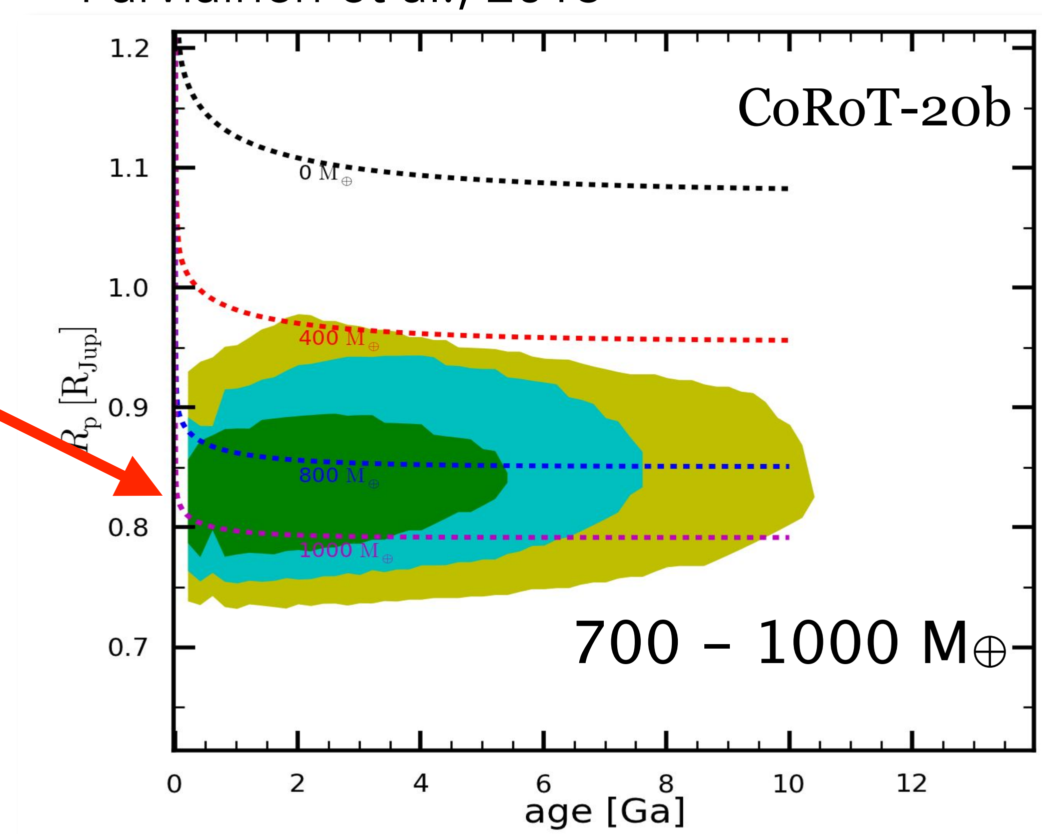
80 planets characterized

Massive planets- internal structure





Parviainen et al., 2013

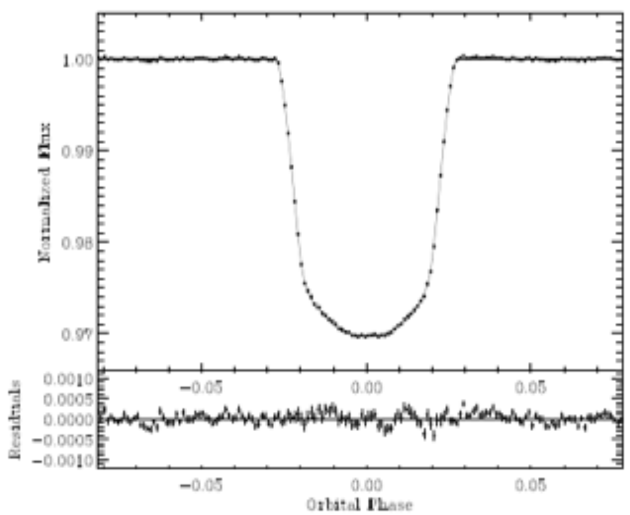


Deleuil et al., 2012

Formation & evolution

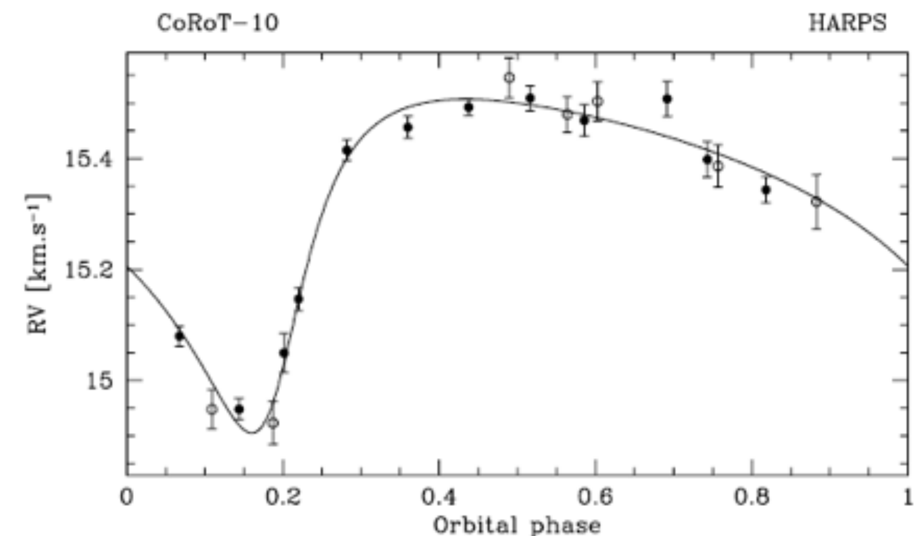
$$\frac{\Delta F}{F} = \left(\frac{R_p}{R_*}\right)^2$$

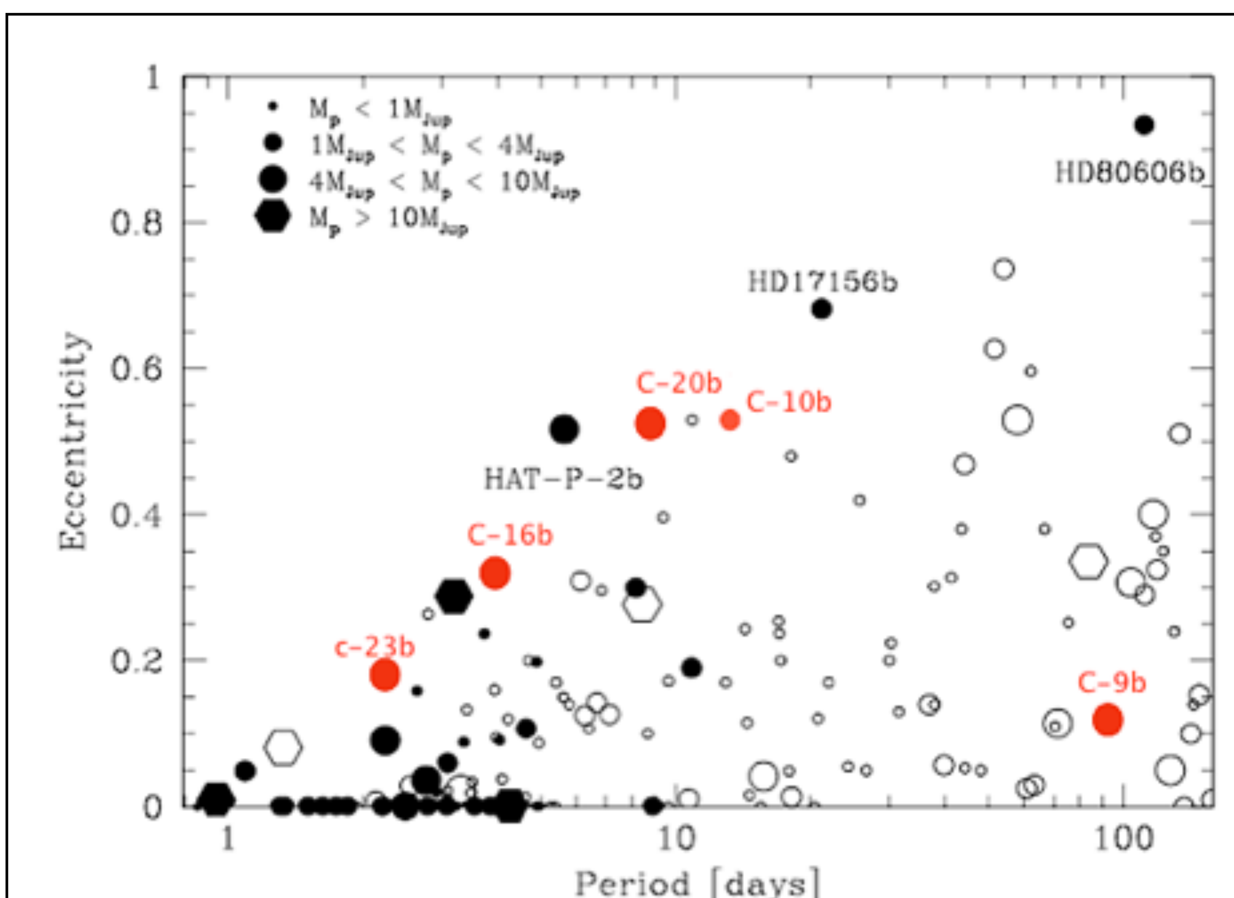
$$k = \frac{28.4\ ms^{-1}}{\sqrt{1-e^2}} \frac{m_p \sin i}{M_{Jup}} \left(\frac{P}{1\,yr}\right)^{-1/3} \left(\frac{m_*}{1M_\odot}\right)^{-2/3}$$



Transits & radial velocity:
$R_p + M_p \rightarrow \rho_p$

orbital parameters : period, eccentricity, inclination ..





Orbital evolution

CoRoT-20b

Mp = 4.24 ± 0.23 *M*Jup

Rp = 0.84 ± 0.04 *R*Jup

P = 9.24 days

e = 0.56

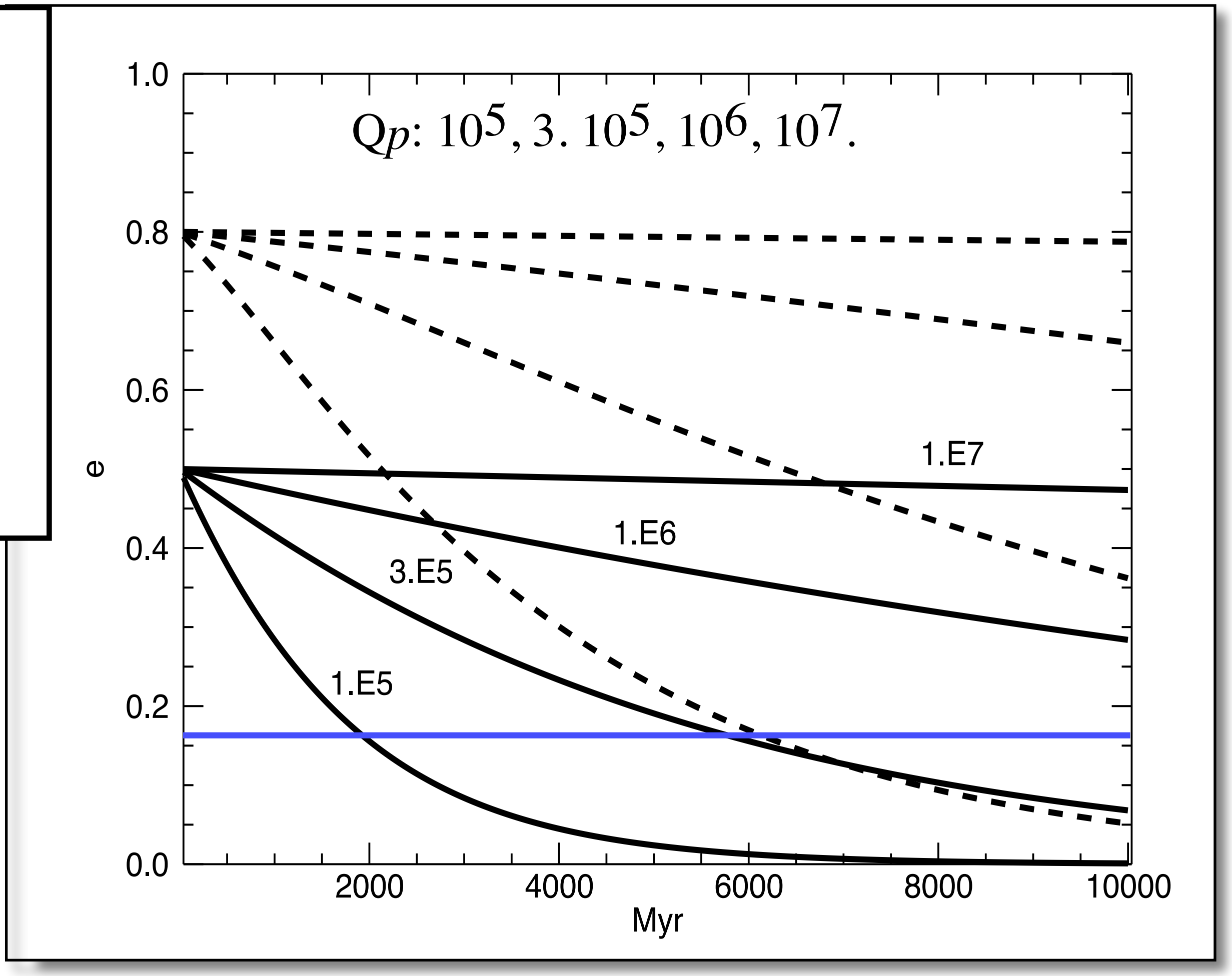
CoRoT-23b

Mp = 2.8 ± 0.3 MJup

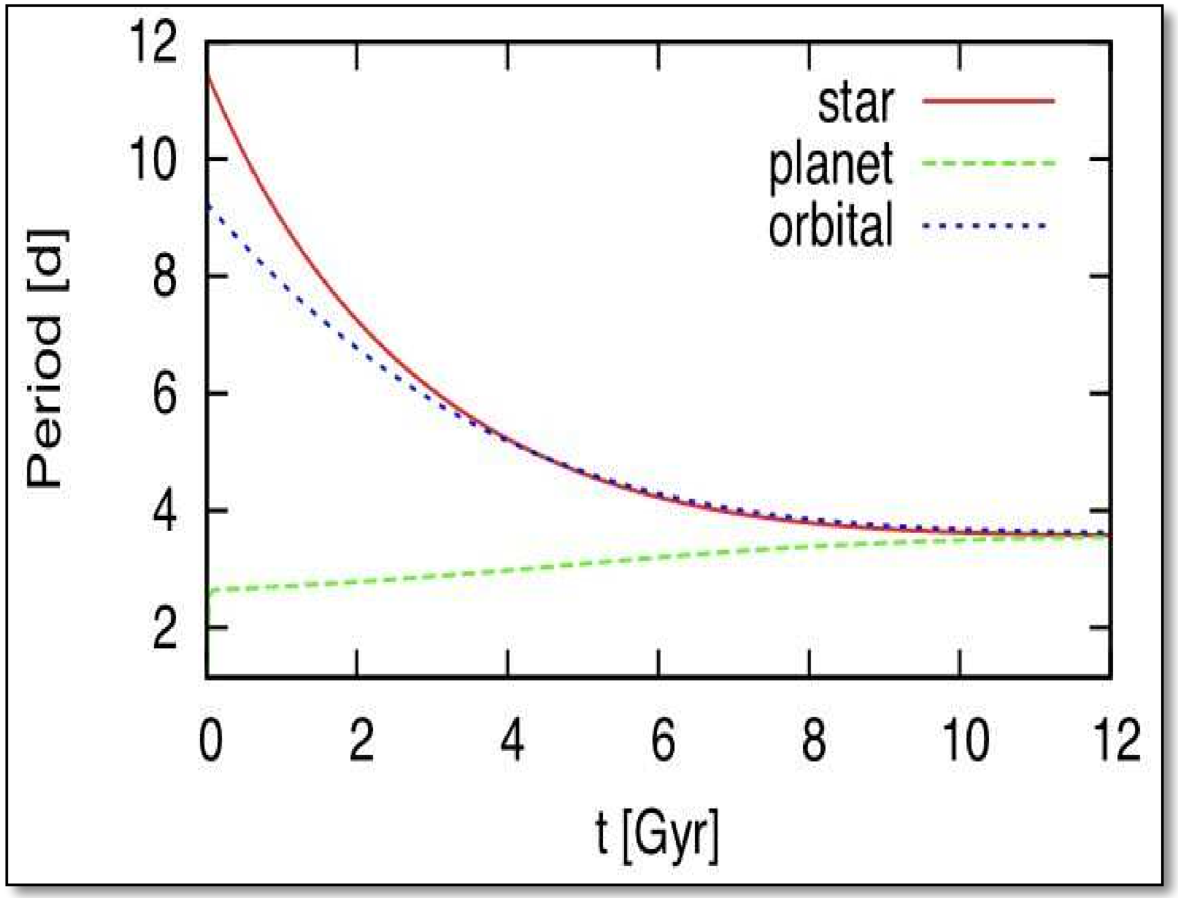
Rp= 1.05 ± 0.13 RJup

P = 3.6314 days

e = 0.16

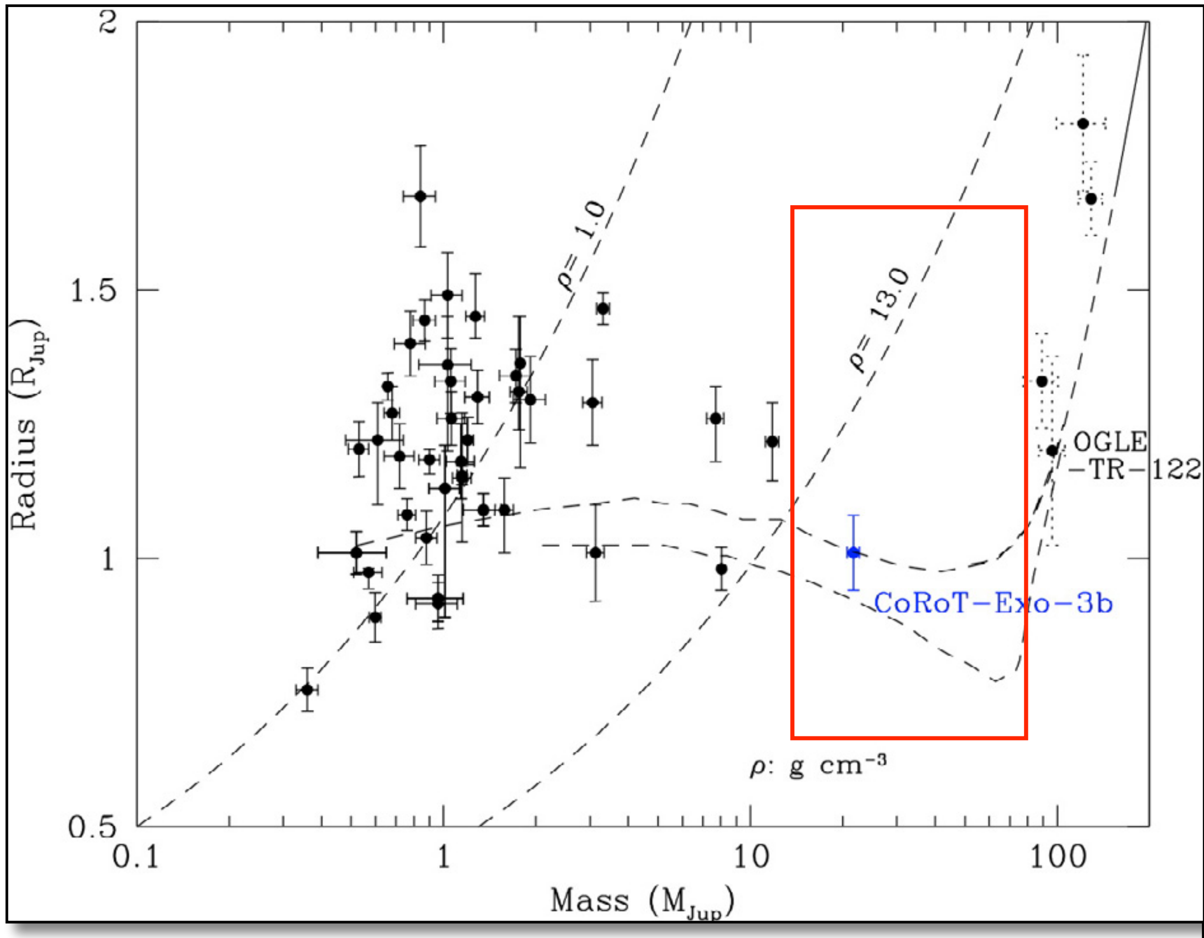


Rouan et al., 2011



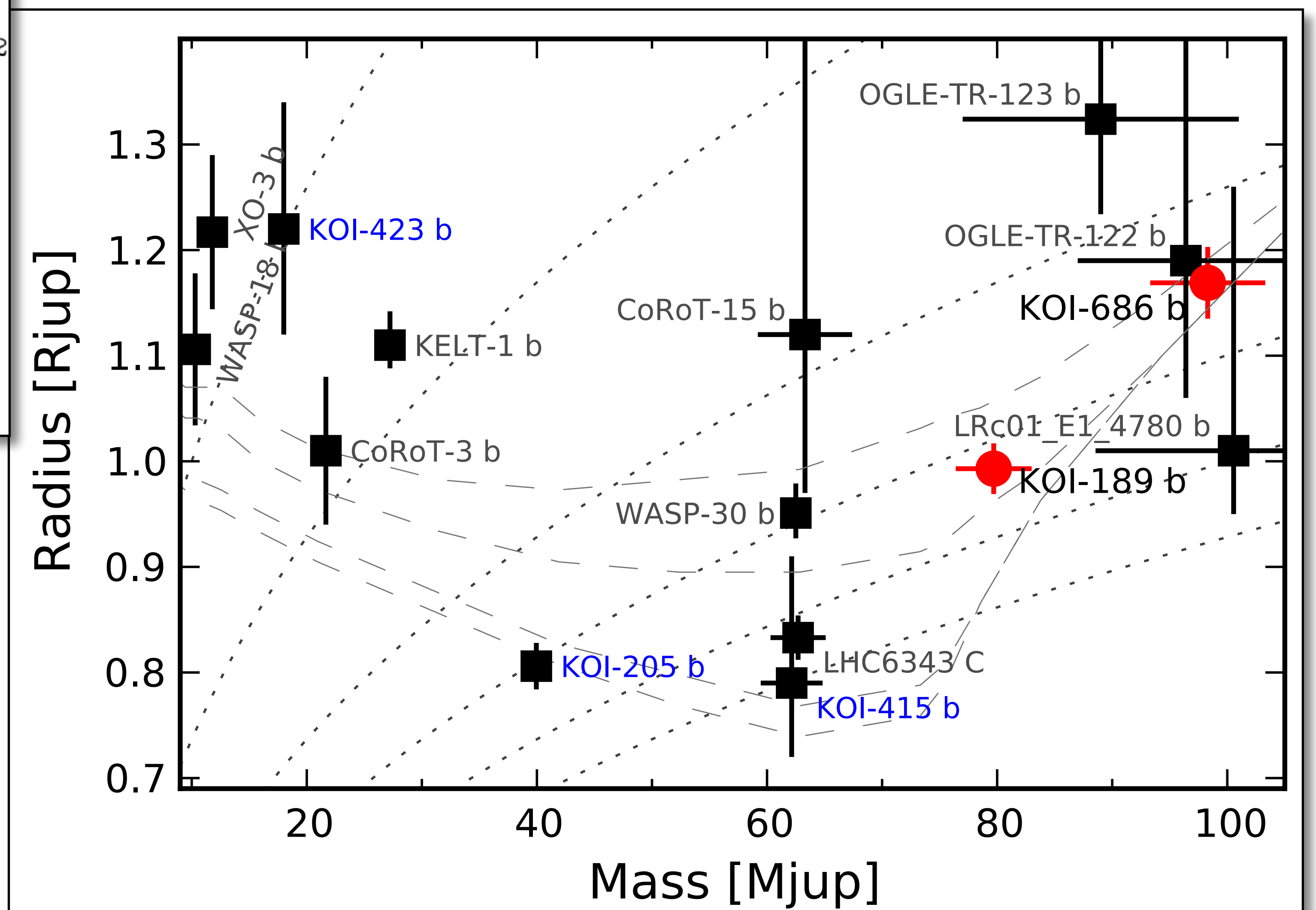
Deleuil, Bonomo. Ferraz-Mello et al., 2012

Close-in brown dwarfs



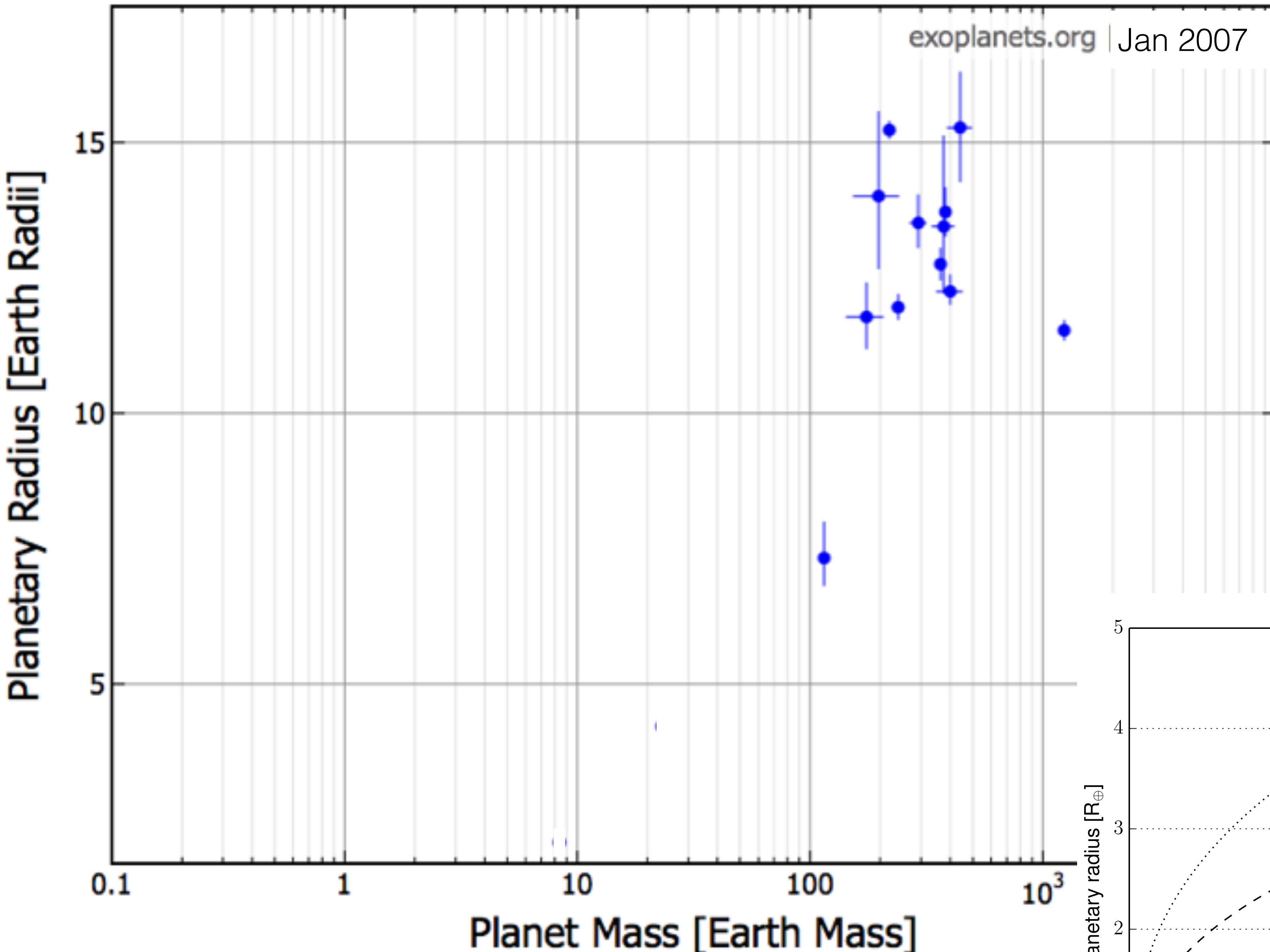
Deleuil et al., 2008

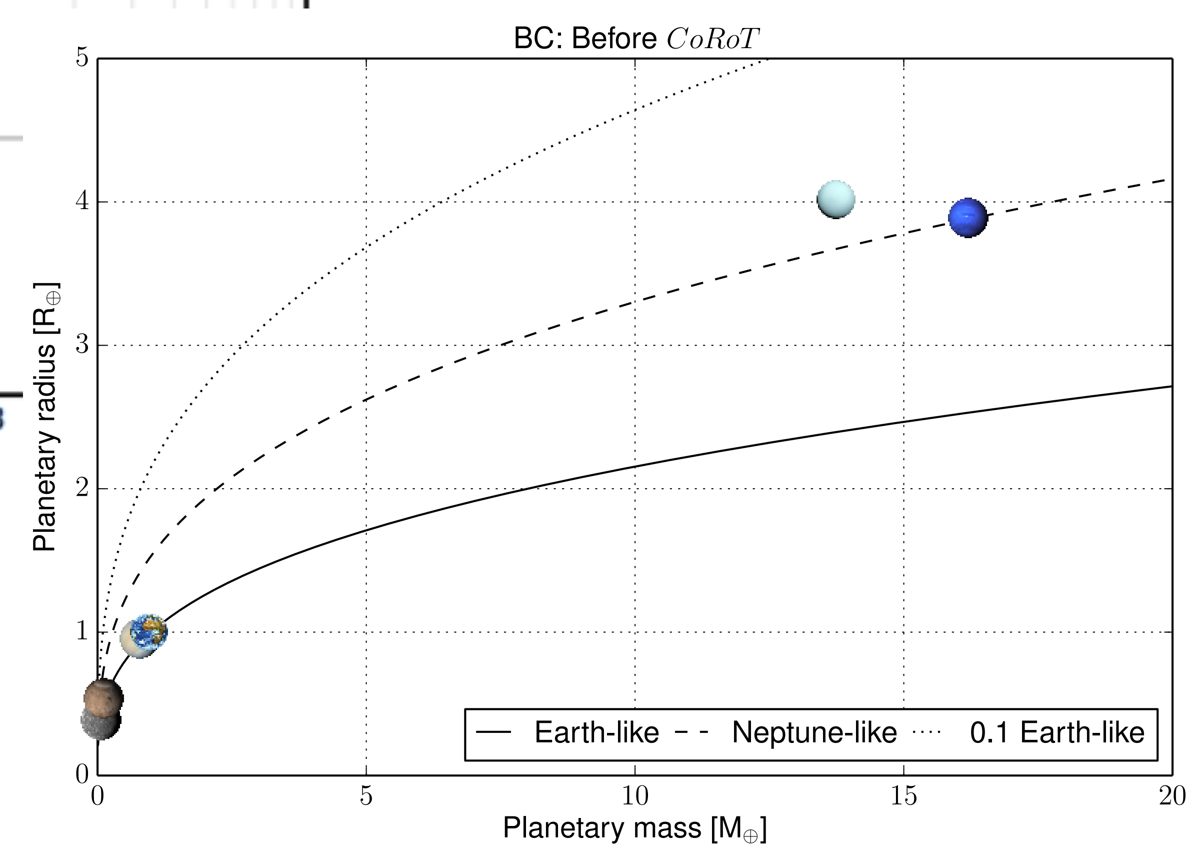
P= 4.26 days



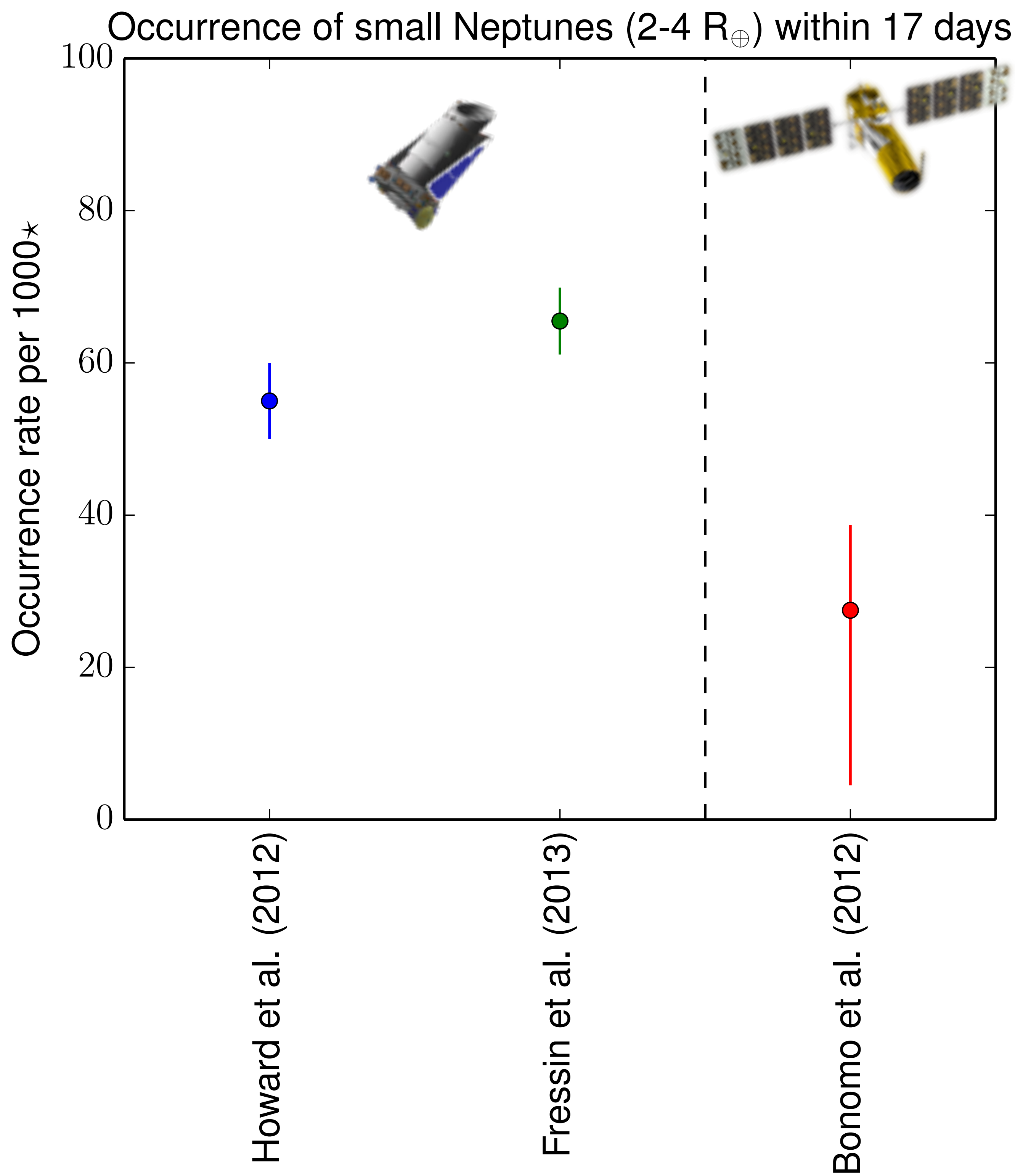
Bouchy et al., 2010, Johnson et al., 2011, Bouchy et al., 2011, Moutou et al., 2012, Diaz et al., 2013

Small-size domain





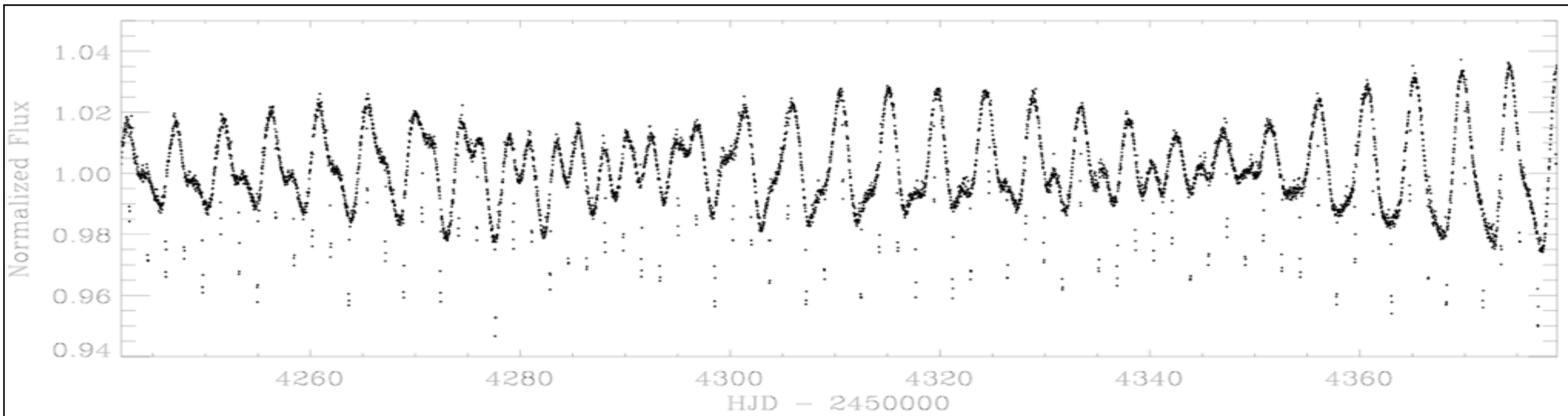
Occurrence of small Neptunes



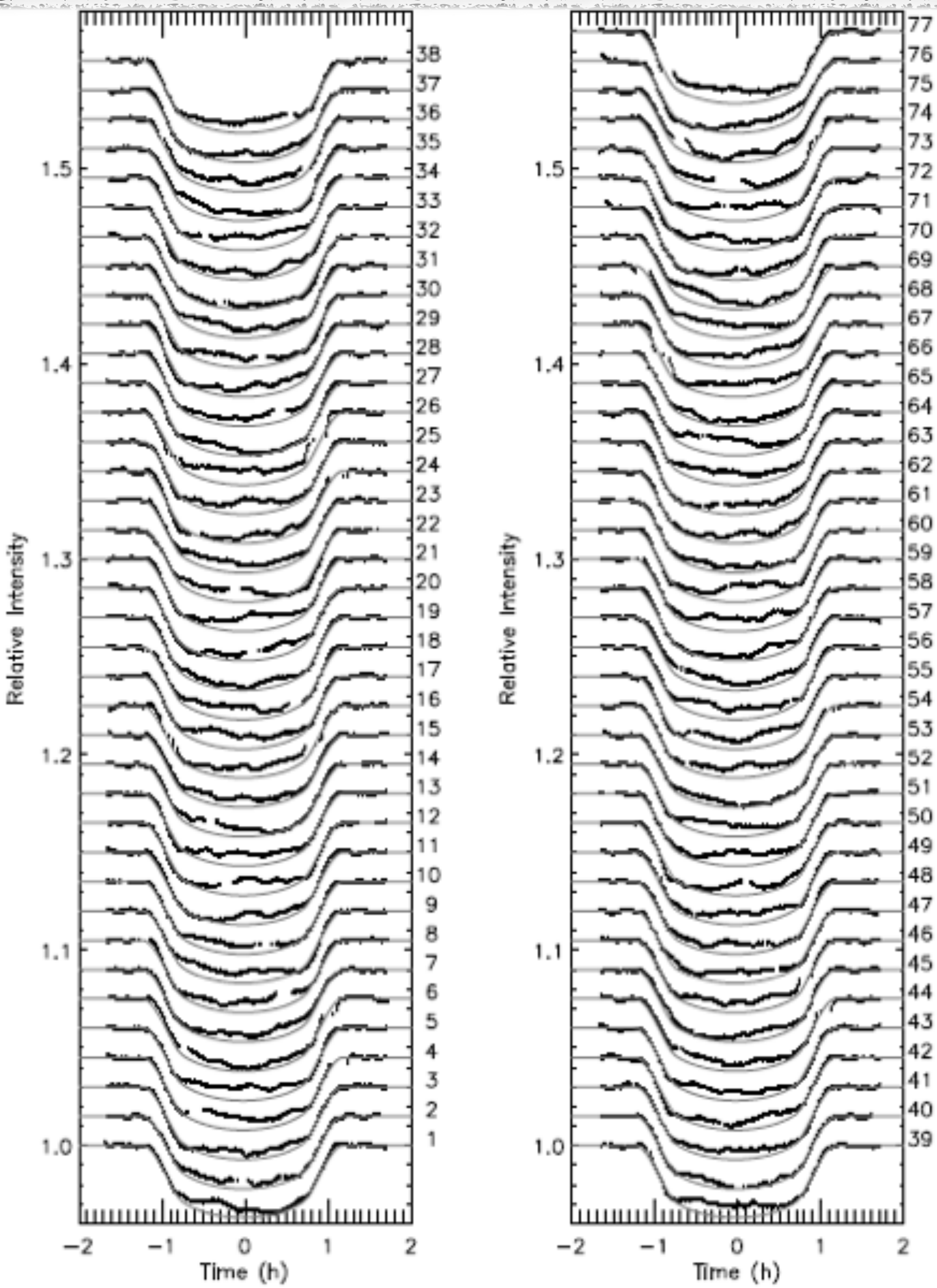
Kepler detected nearly twice more Neptunes than *CoRoT*

Active stars and planets

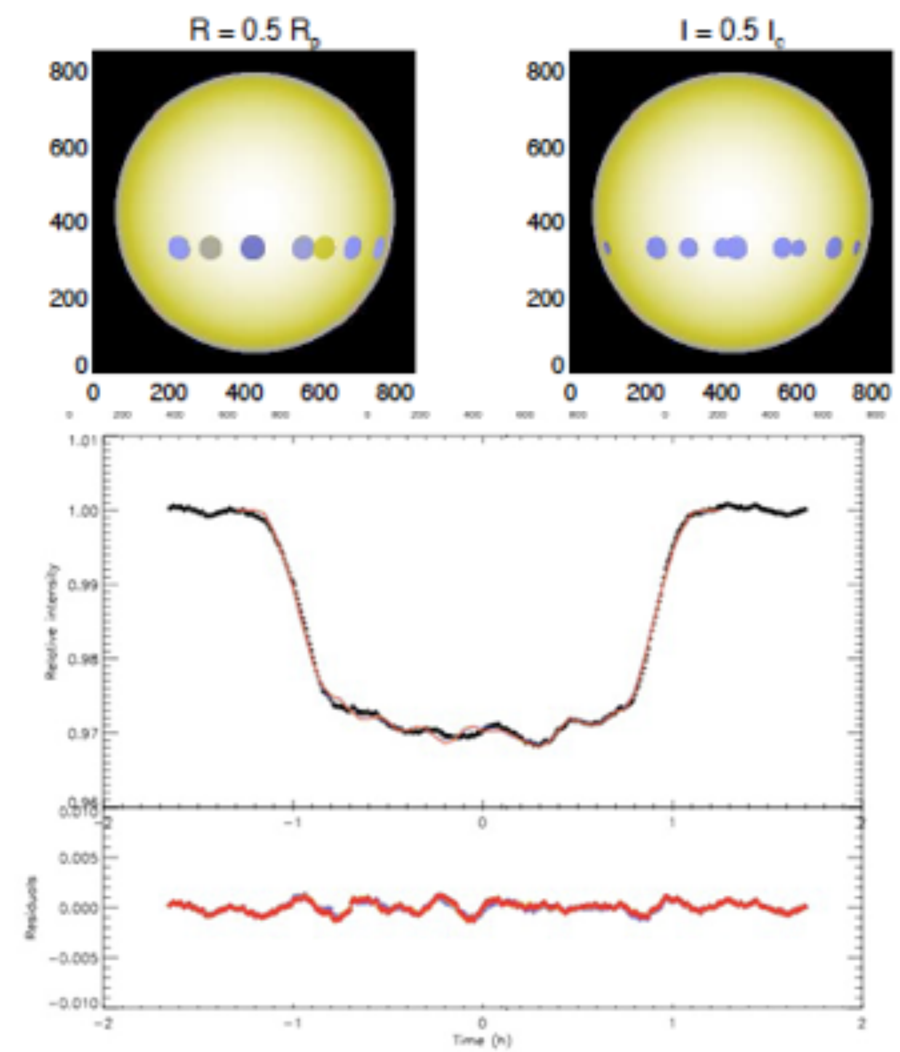
Alonso et al., 2008



Probing the stellar surface

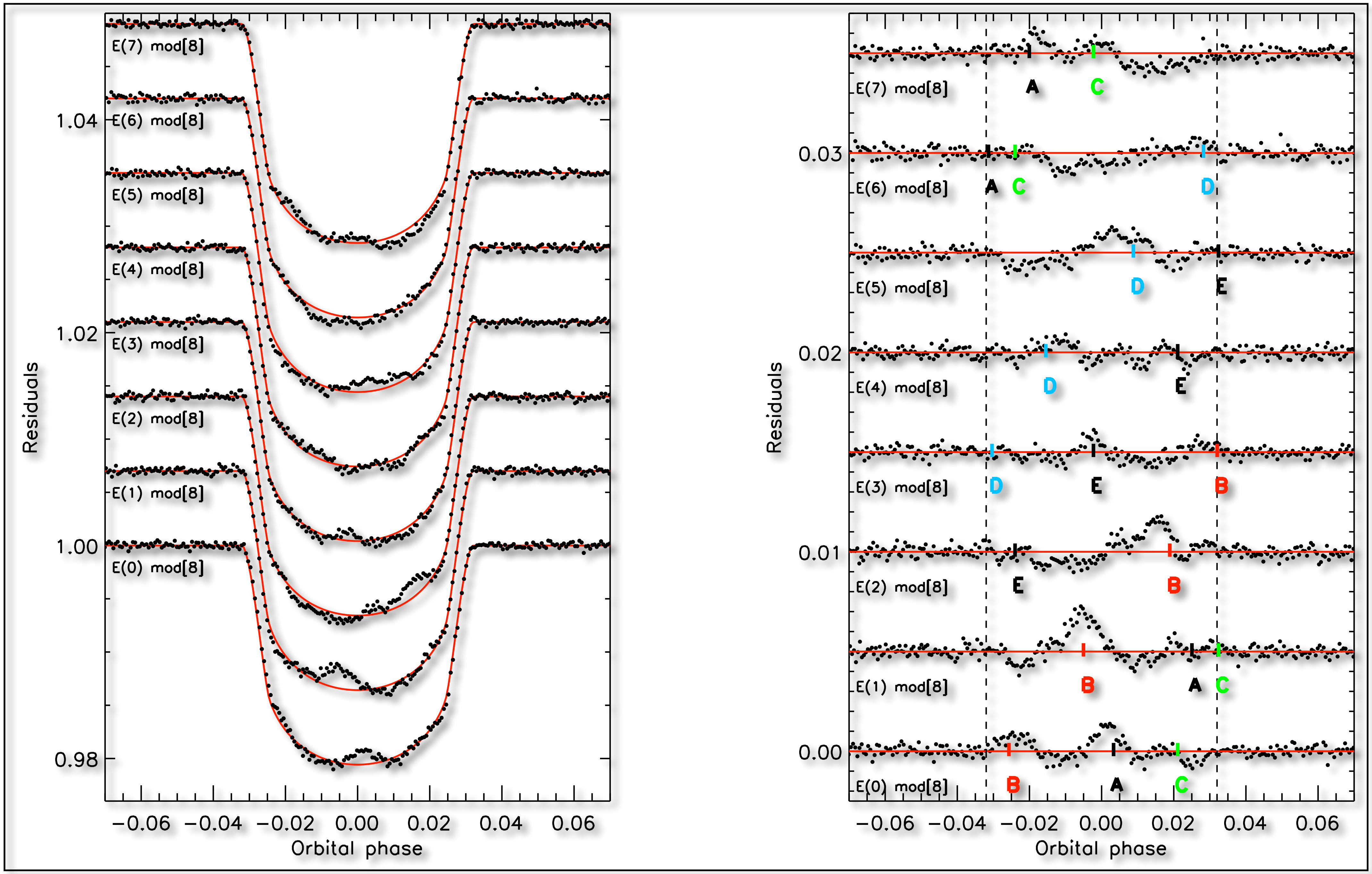


- $R_p/R_\star$ = 0.172 (3% larger)
- At least 18 spots in total
- Average of 7 spots covered per transit
- spot size : 0.3 - 0.6 Rp
- Temperature : 4600 to 5400 K ($R_\star$ =5625K)
- rise & decay ~ 30 days



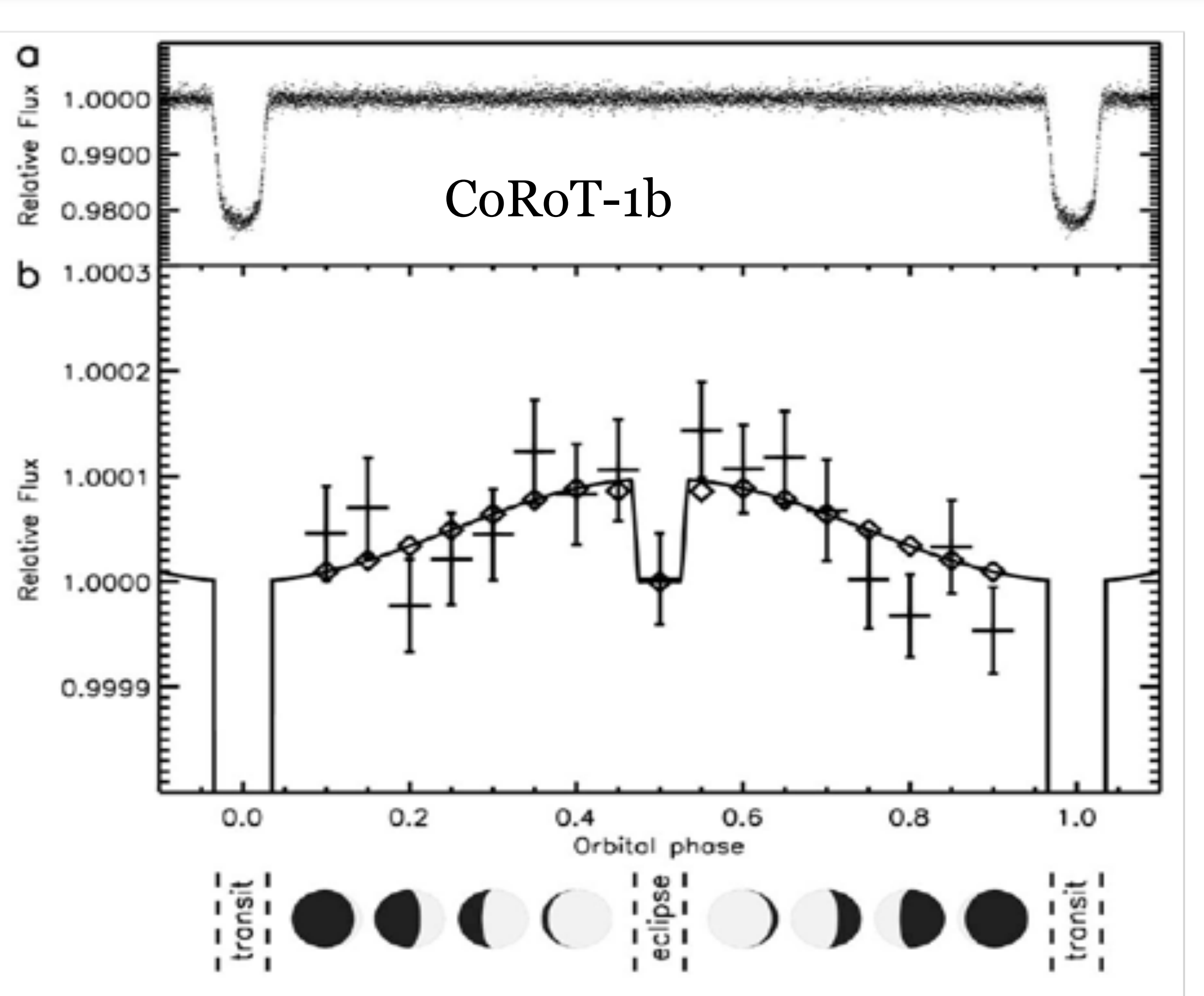
Silva-Valio et al., 2009

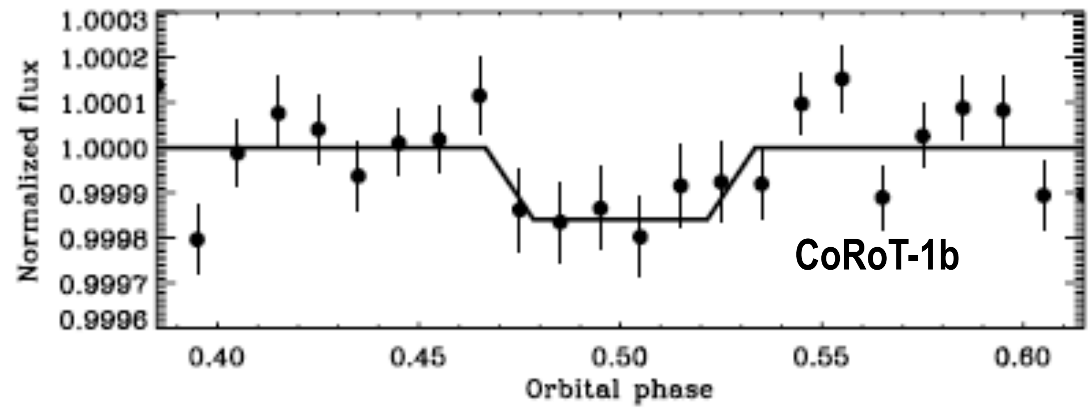
Active regions on Kepler-17

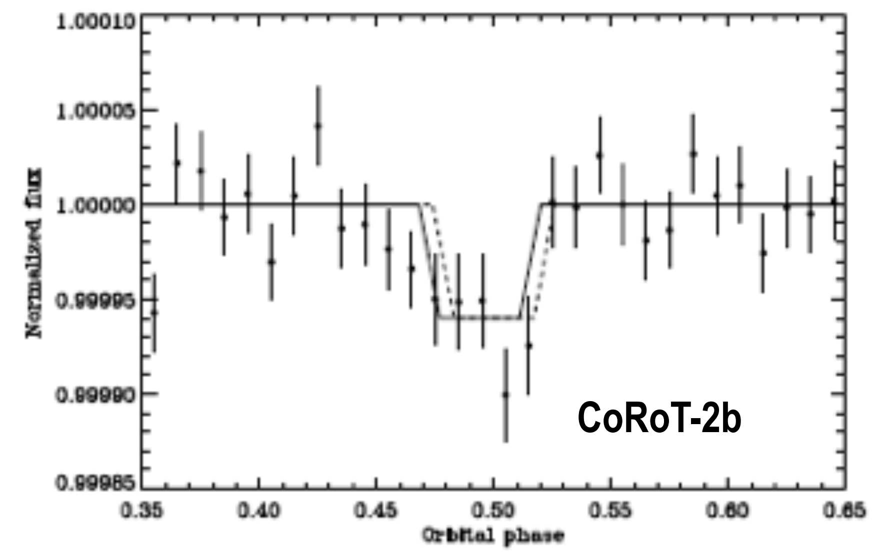


Desert et al., 2011

Planet phase light curve







CoRoT-1b *A*g < 0.20

Snellen et al., 2009, Nature

Alonso et al., 2009a A&A

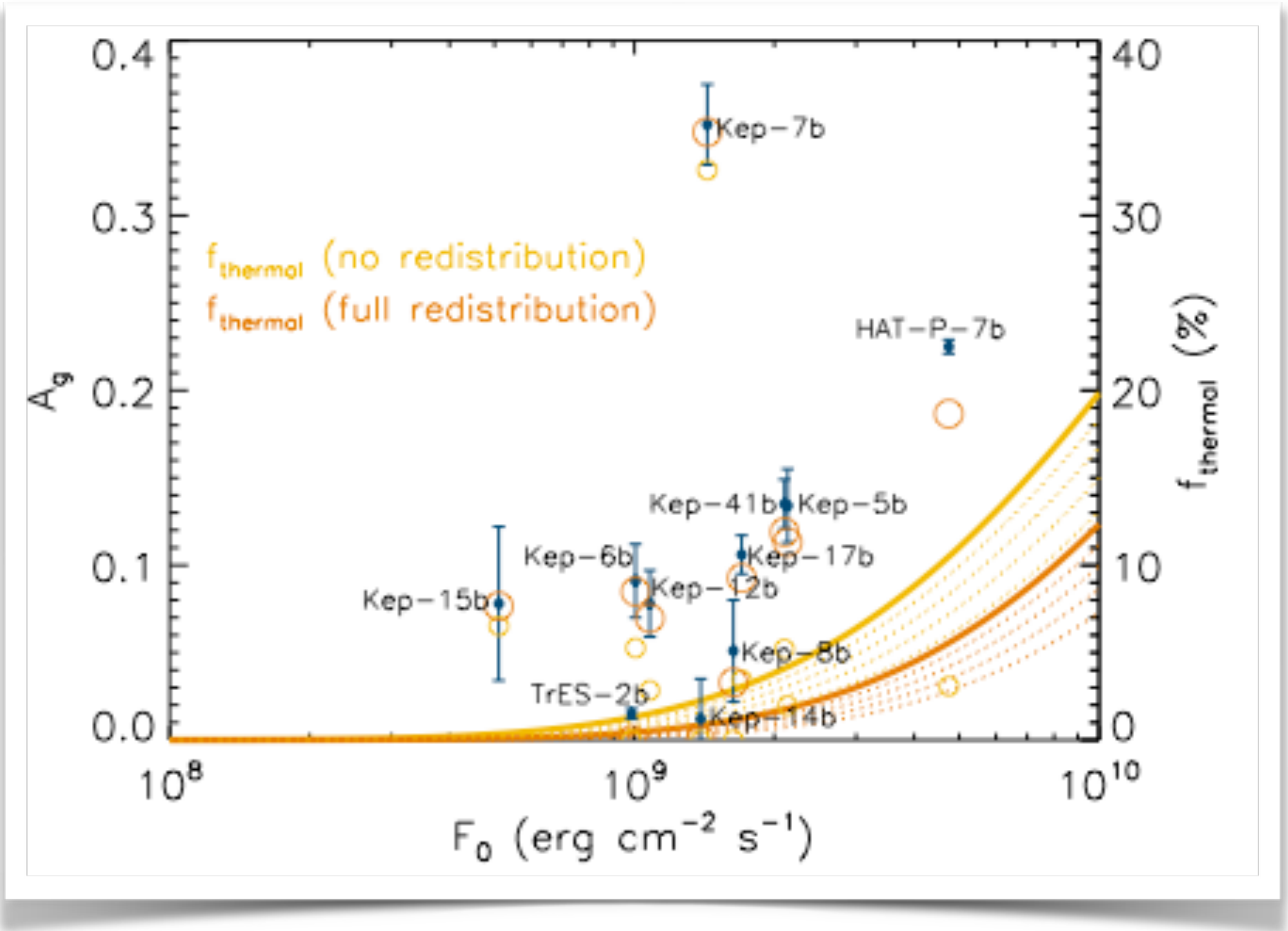
CoRoT-2b

Occultation depth = 0.006 ± 0.002%

*A*g = 0.06 ± 0.06,

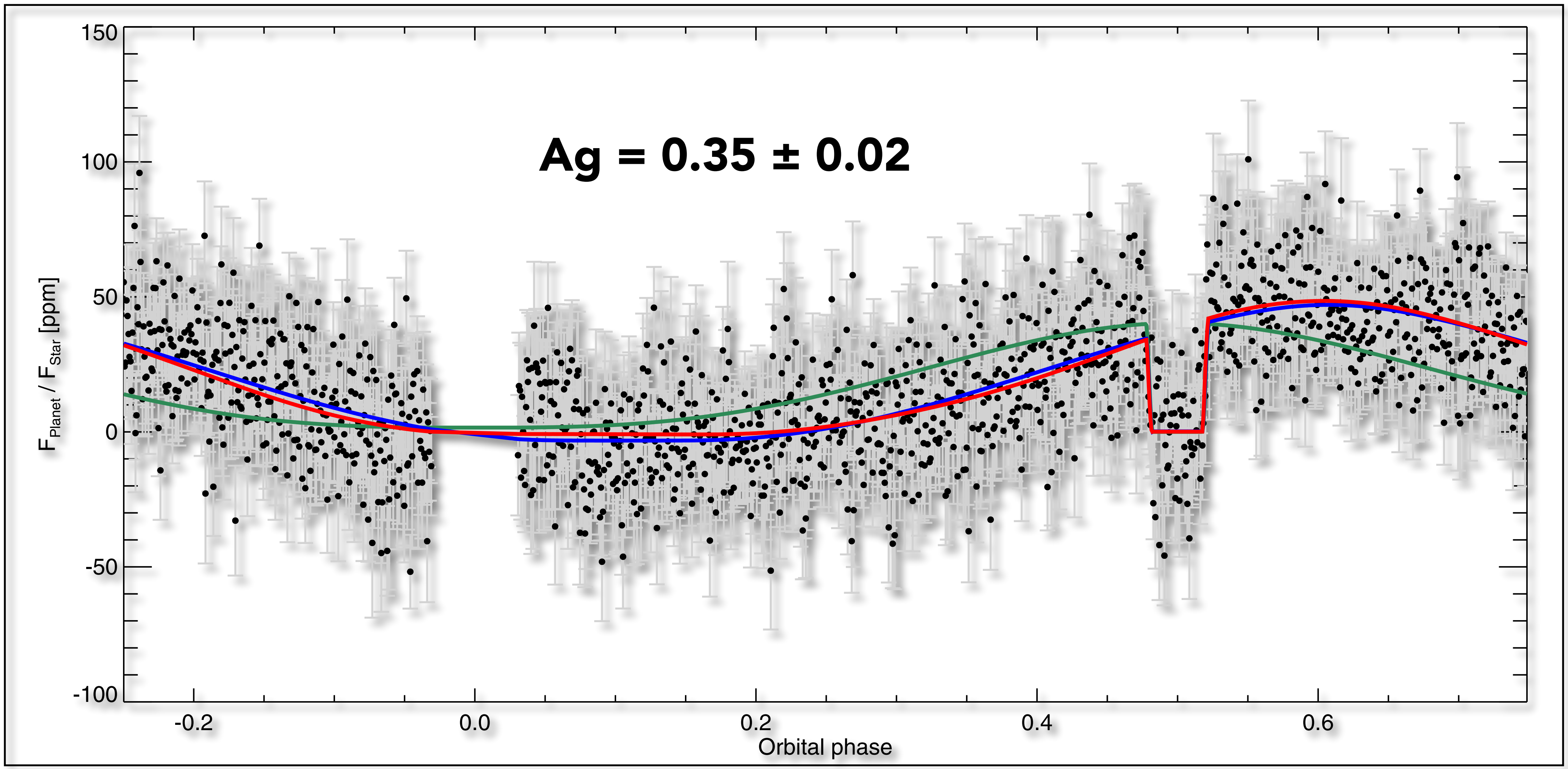
Alonso et al., 2009b A&A

Hot-Jupiters are dark



Heng & Demory, 2013 A&A

Atmosphere properties

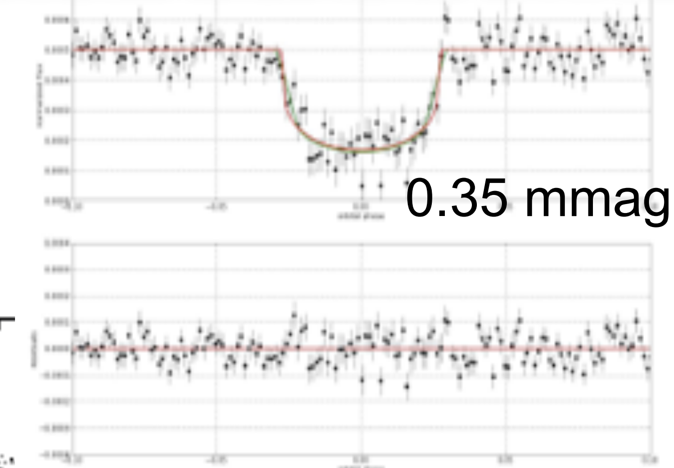


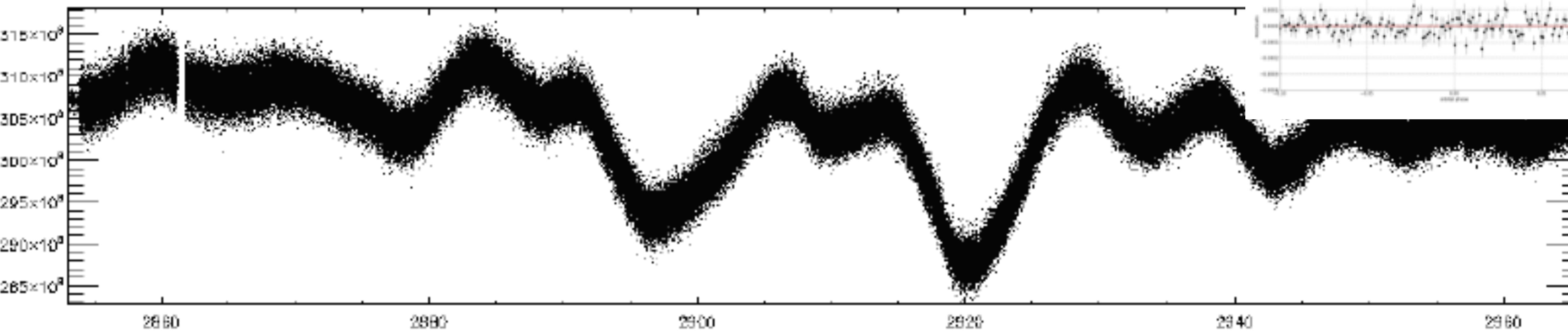
Latham et al. 2010

Demory et al., 2011 & 2013

Super-Earths: a new population

CoRoT-7 :
K0V
[Fe/H] =0.12 +/- 0.06





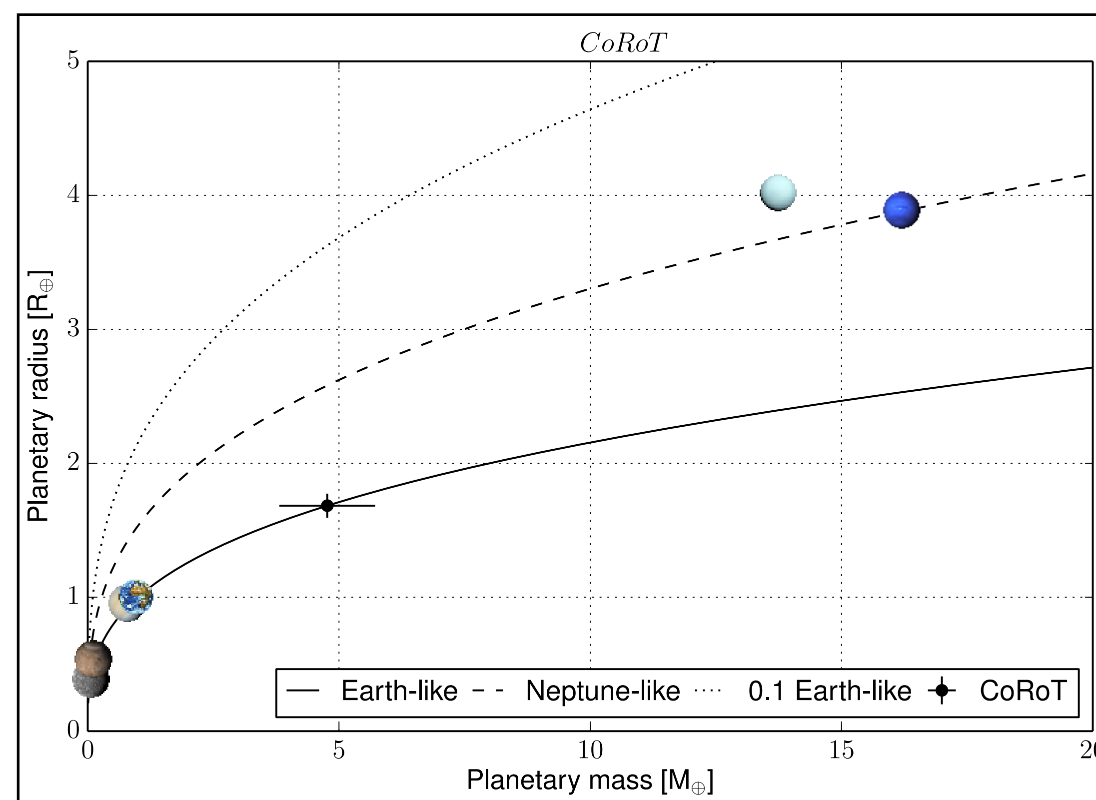
Léger et al., 2008
Queloz et al., 2009

Haywood et al., 2014
Barros et al., 2014

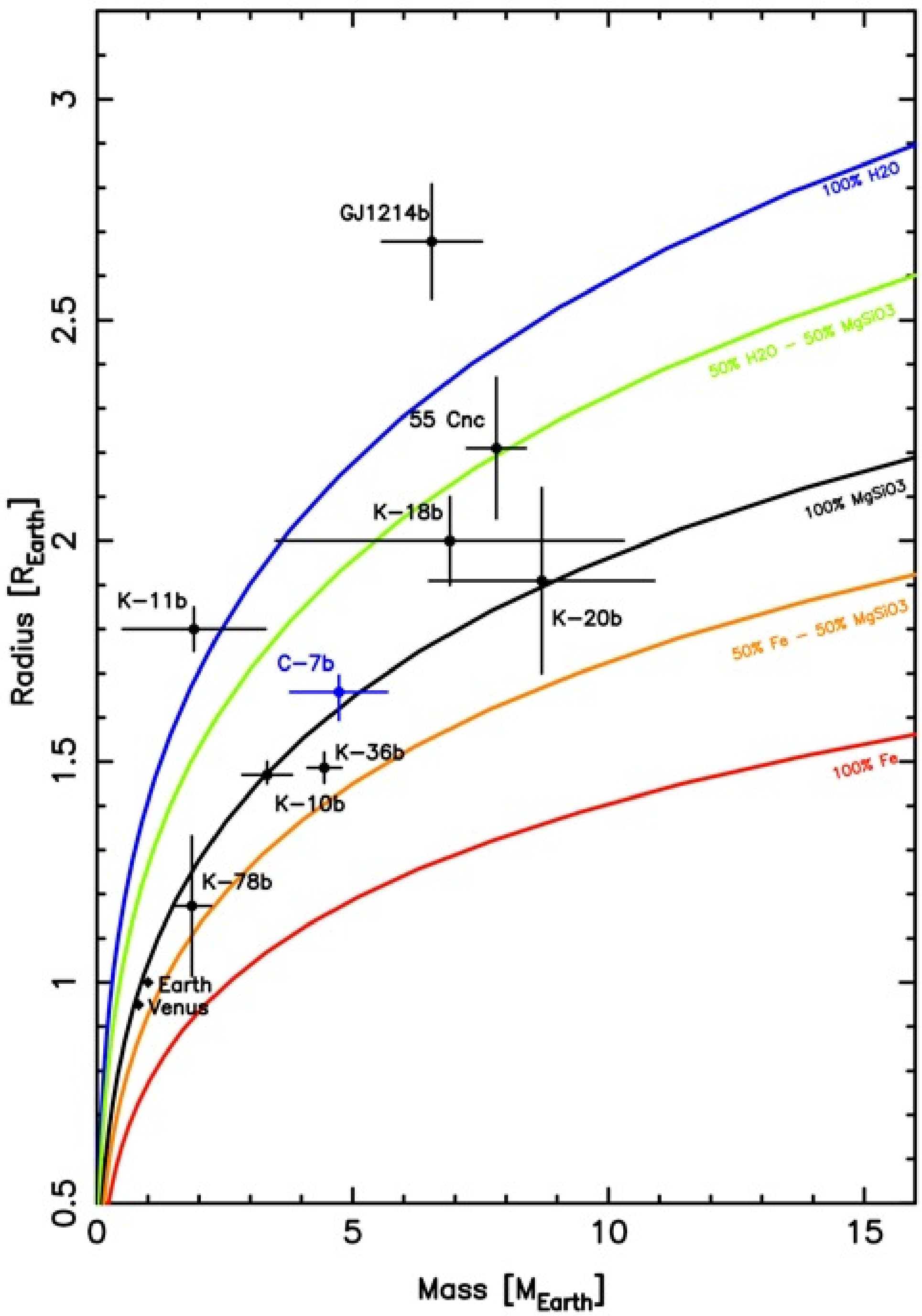
Rp = 1.585 ± 0.064 *R*⊕,

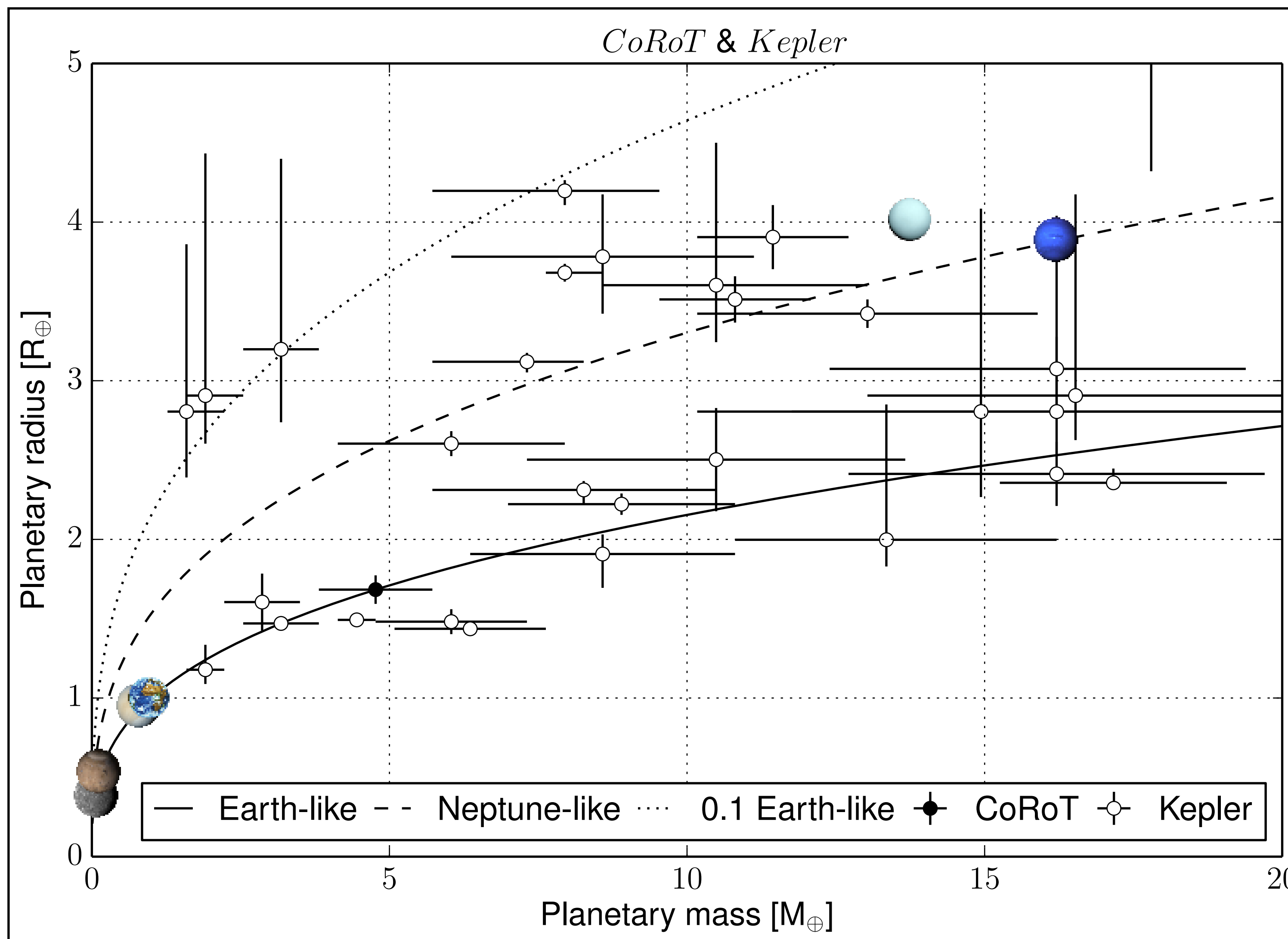
Mp = 4.73 ± 0.95 *M*⊕

Period = 0.85365 days



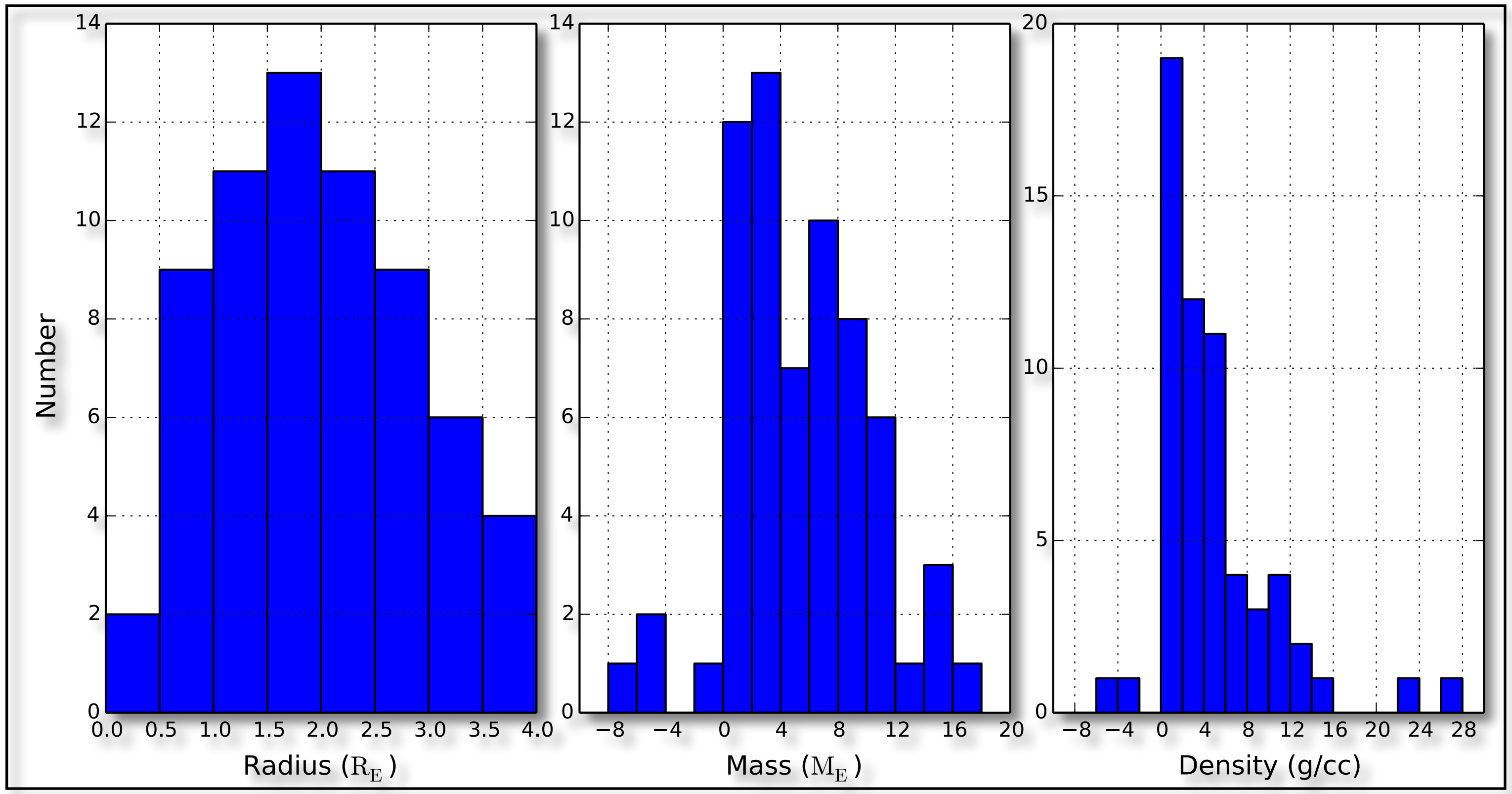
Super-Earths: properties diversity





Batalha et al., 2010
Pepe et al., 2013
Howard et al, 2013
Marcy et al. 2014
Dumusque et al., 2014

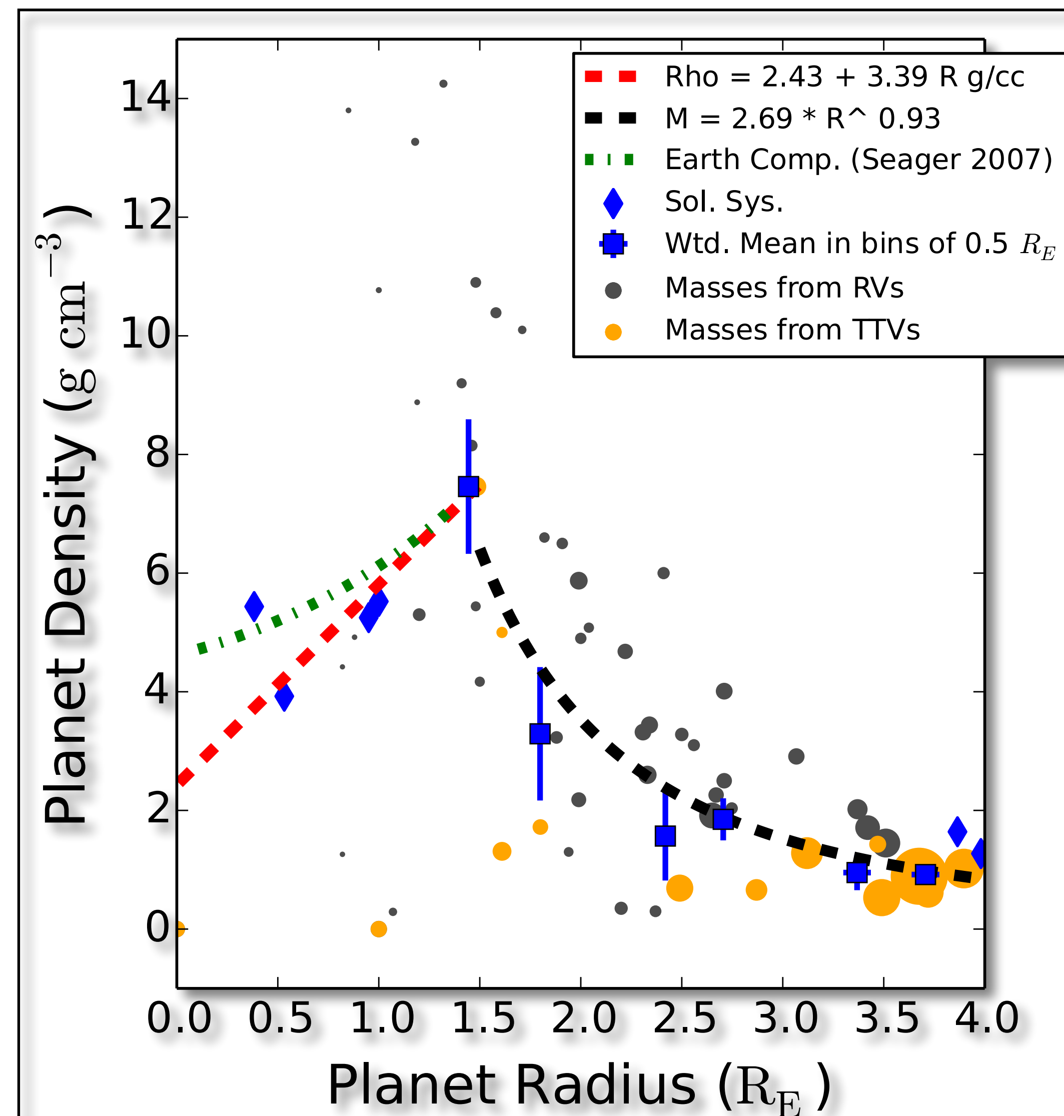
Super-Earths: diversity



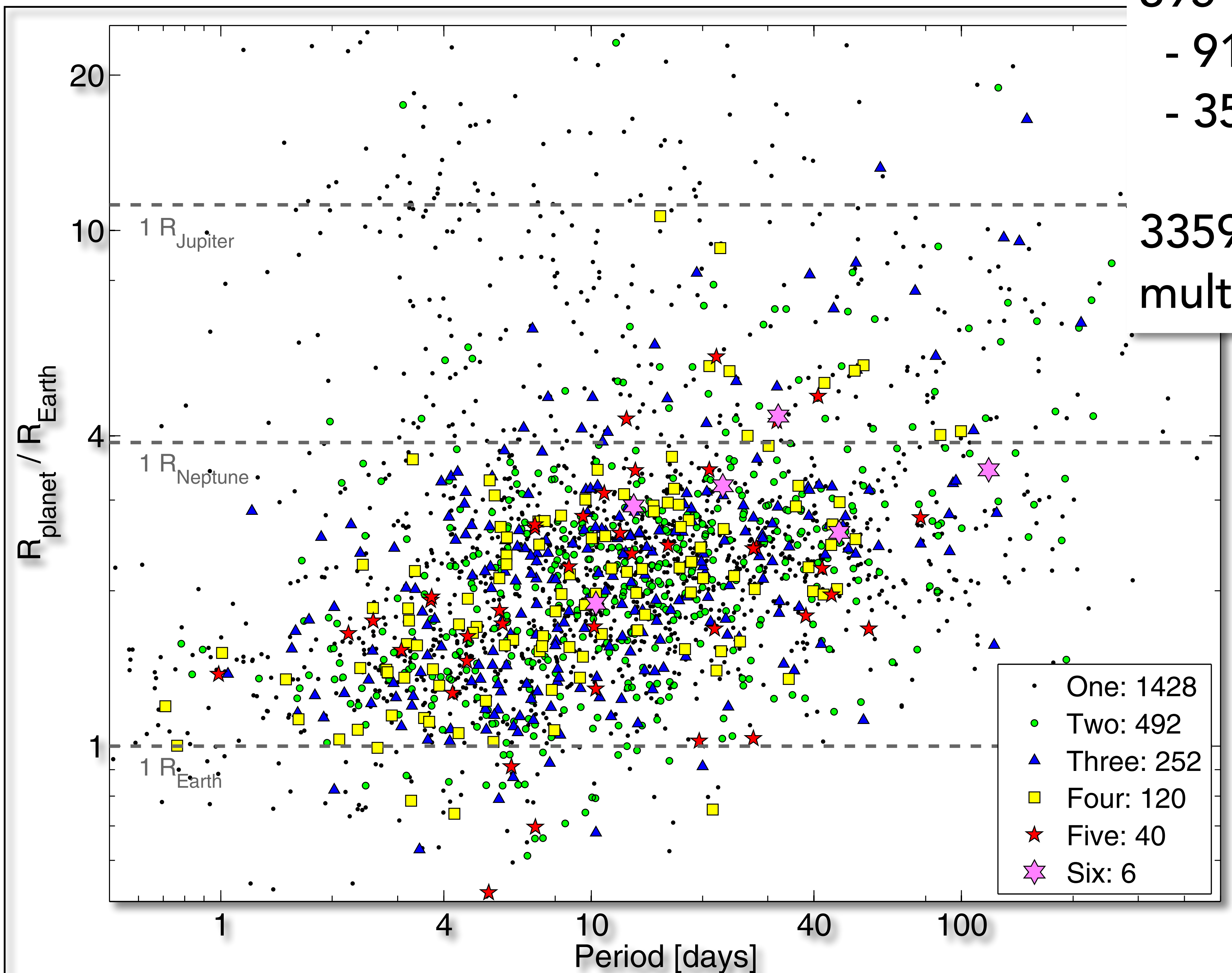
Weiss & Marcy, 2014

Sample: 65 Kepler exoplanets

R < 4 R⊕ and P < 100 days



Multi-planet systems

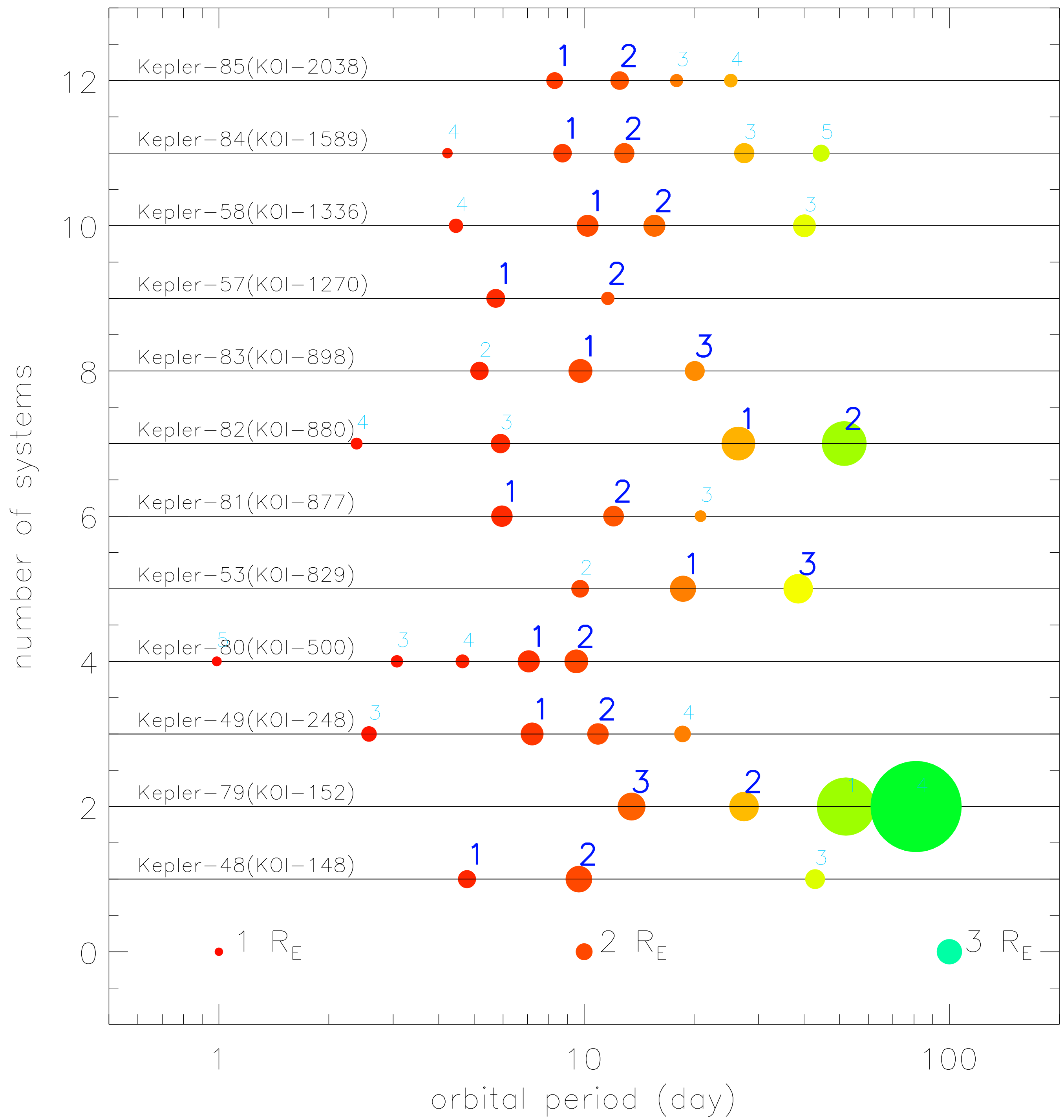


August 2014:
395 planetary systems
- 917 planets
- 351 multiple planet systems

3359 candidates (KOI)
multis ~ 40% of the candidates

Borucki et al., 2010
Batalha et al., 2012
Burke et al 2014

Test for dynamical evolution

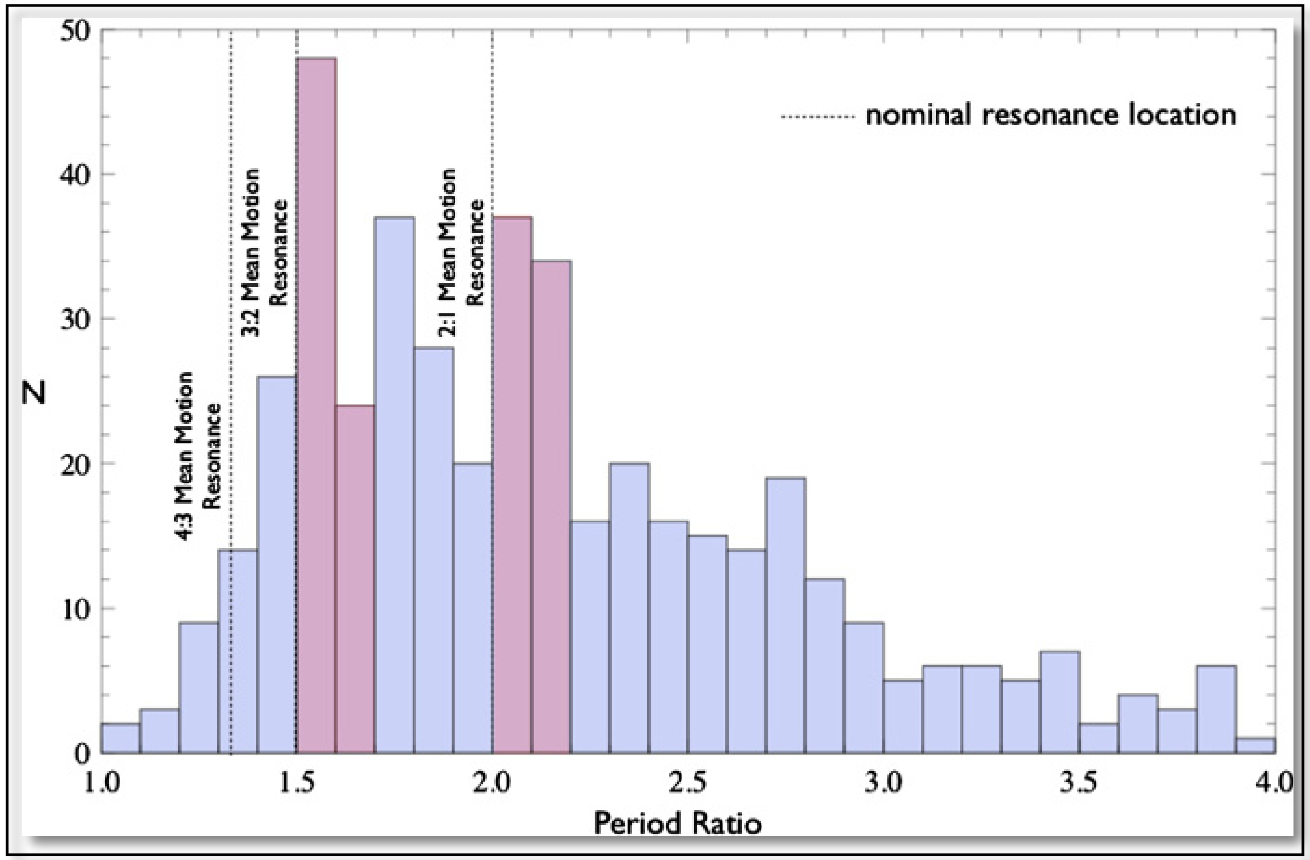


Xie, 2013

Flat systems

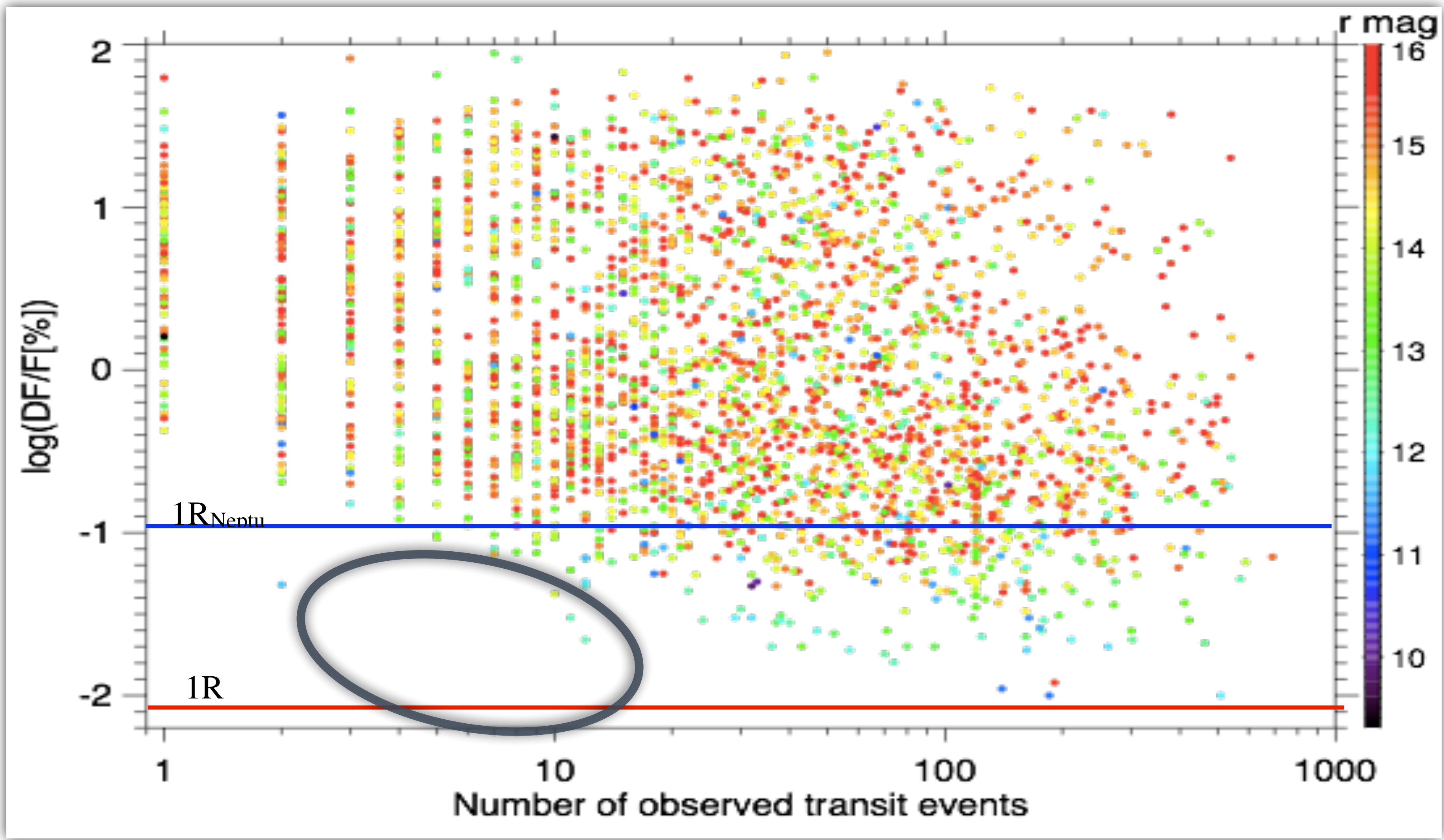
mutual inclinations of planetary orbital planes within ~ 2°

Lissauer et al. 2011
Fabrycky et al. 2014



Batygin & Morbidelli, 2013
Lithwick & Wu, 2012

Multi-planet systems with CoRoT



CoRoT-24 b & c

- P=5.1 d

R_1=3.7 ± 0.4 $R_\oplus$

M_1 < 5.7 $M_\oplus$

- P=11.8 d

R_2=5.0 ± 0.5 $R_\oplus$

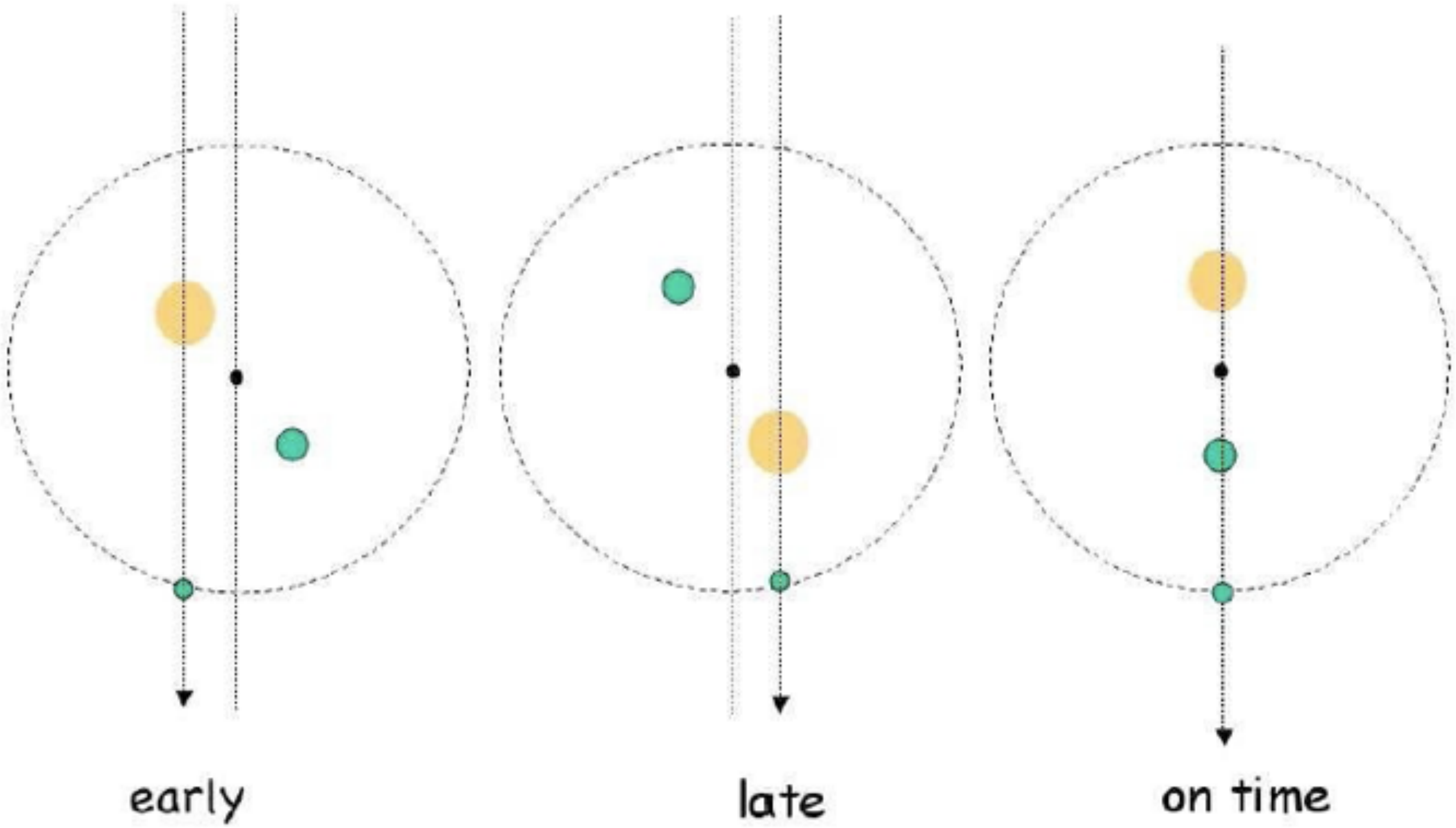
M_2 = 28 ± 11 $M_\oplus$

(Alonso et al., 2014)

- CoRoT-7 b & non-transiting c & d (Queloz et al 2009)
- Corot-20b & non-transiting c (Bouchy et al., tbs)

Numerous in the low mass, long period range

TTVs: the unexpected revolution



$$\Delta t \approx -\frac{x_*}{v_{pl} - v_*} \approx -\frac{T_{pl} a_{in} \mu_{in} \sin[2\pi(mT_{pl} - t_0)/T_{in}]}{2\pi a_{pl}}$$

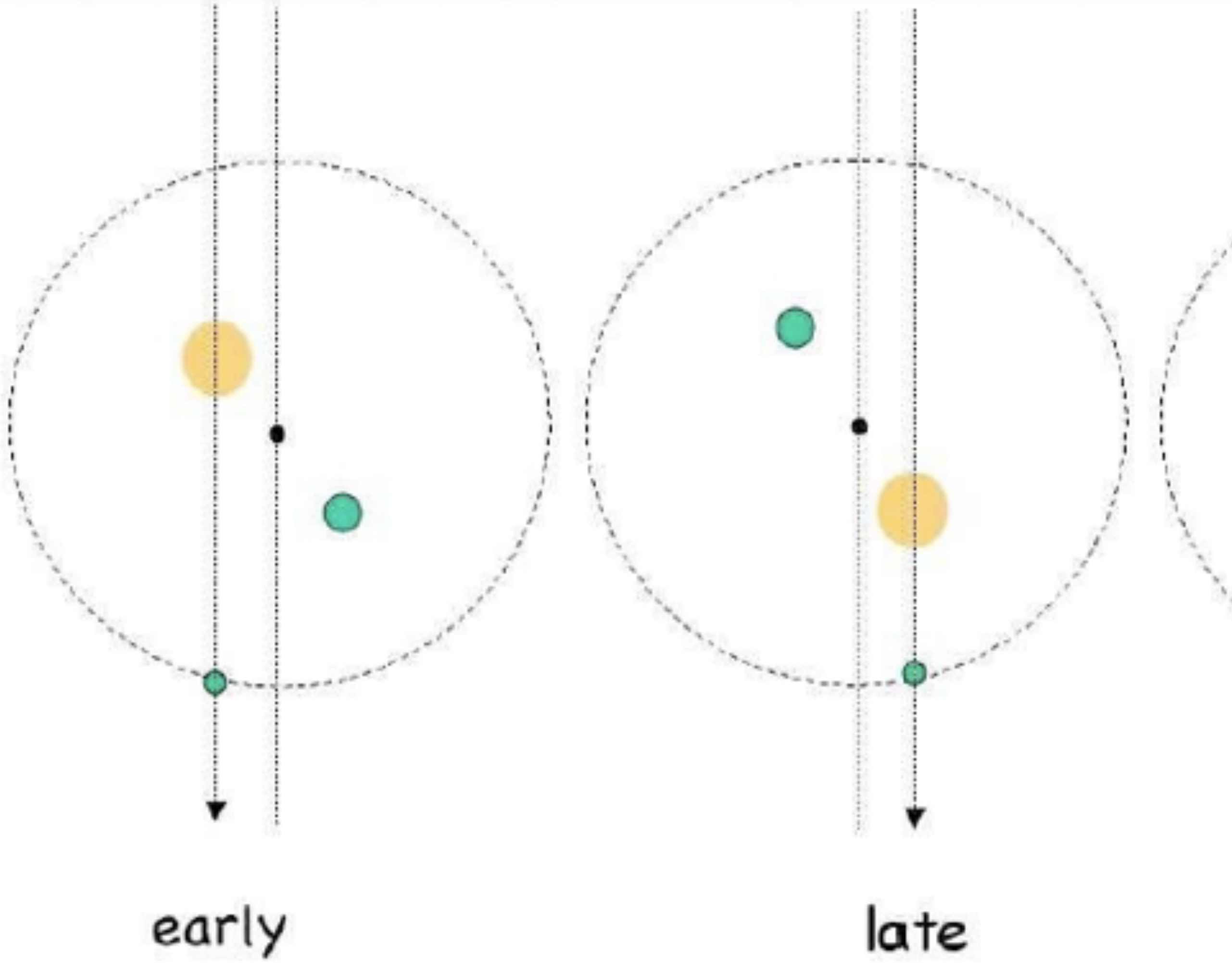
Agol, E. et al., 2005, MNRAS, 359, 567

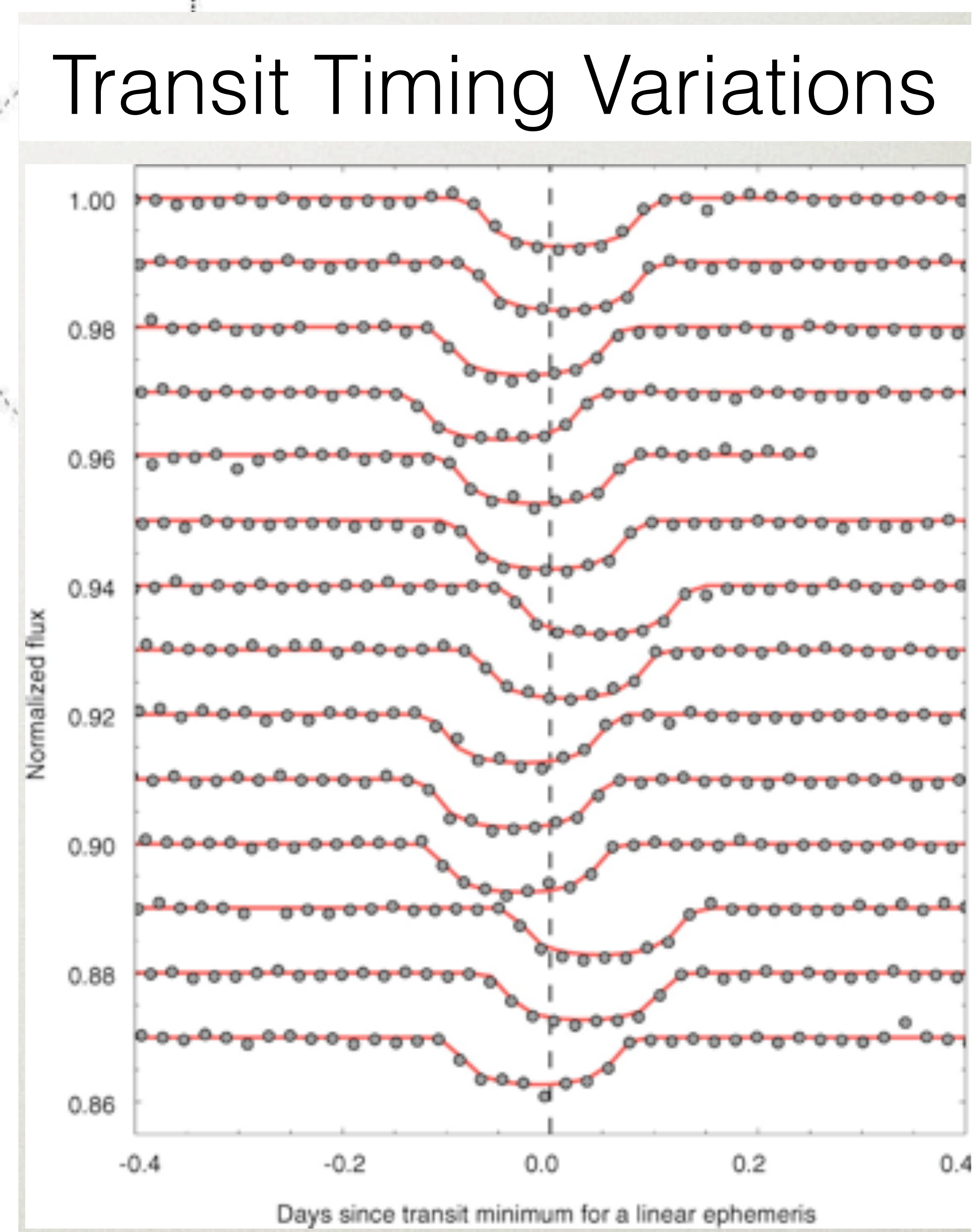
Transiting planet: Jupiter

Perturbing planet: Earth

$\Delta t \approx 34$s

TTVs: the unexpected revolution



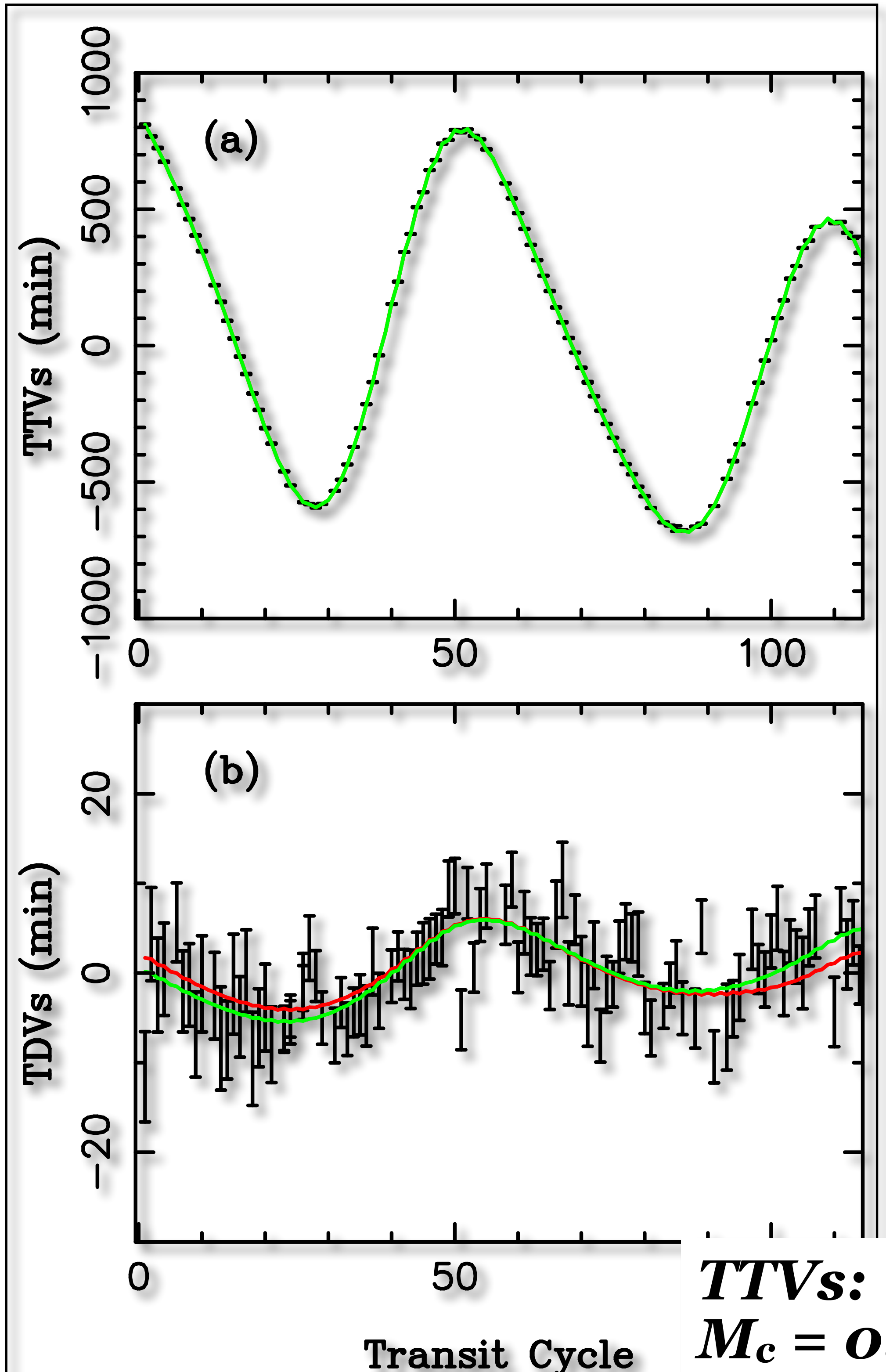


$$\Delta t \approx -\frac{x_*}{v_{pl}-v_*} \approx -\frac{T_{pl} a_{in} \mu_{in} \sin[2\pi(mT_{pl}-t_0)/T_{in}]}{2\pi a_{pl}}$$

Agol, E. et al., 2005, MNRAS, 359, 567

➙planet mass estimate from the photometry only!

KOI-142b: the king of TTV

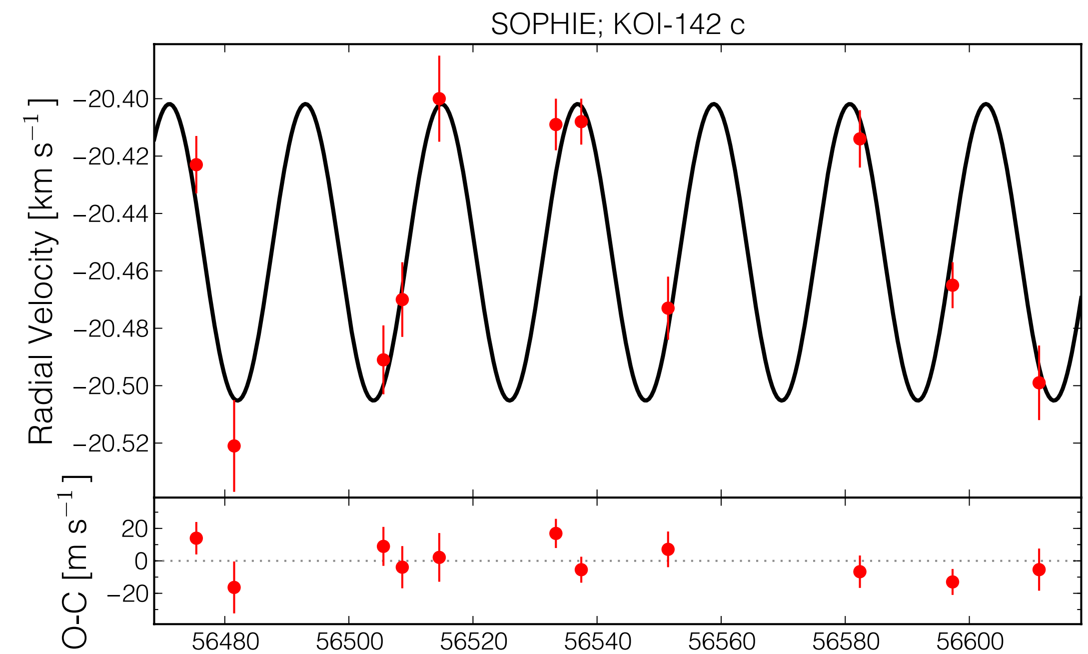


$M_b < 17.6\ M_\oplus$

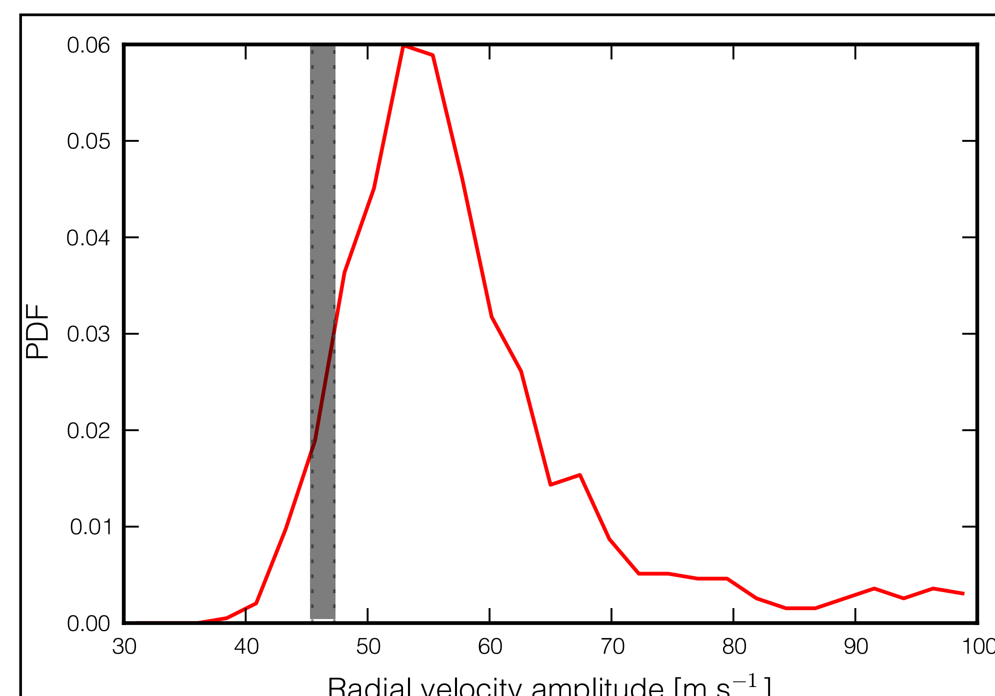
$P_b \simeq 10.95$ days.

$P_c = 22.10 \pm 0.25$

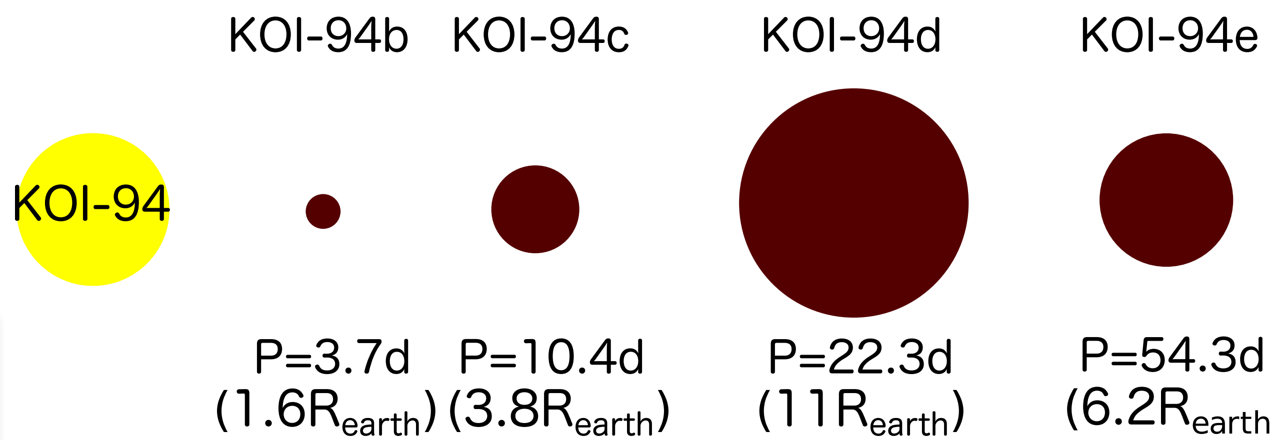
TTVs:
$M_c = 0.626 \pm 0.03\ M_{Jup}$
Nesvorný et al., 2013

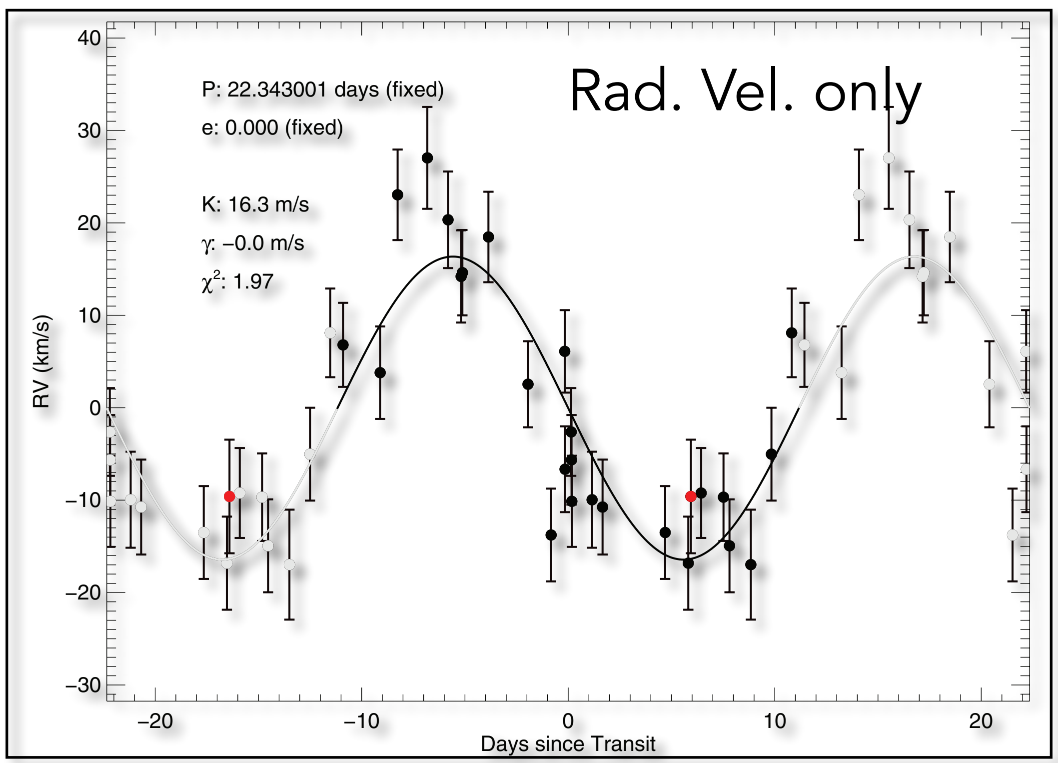


Radial velocity:
$M_c = 0.76 \pm 0.36\ M_{Jup}$
Barros al., 2014



TTV versus Vrad

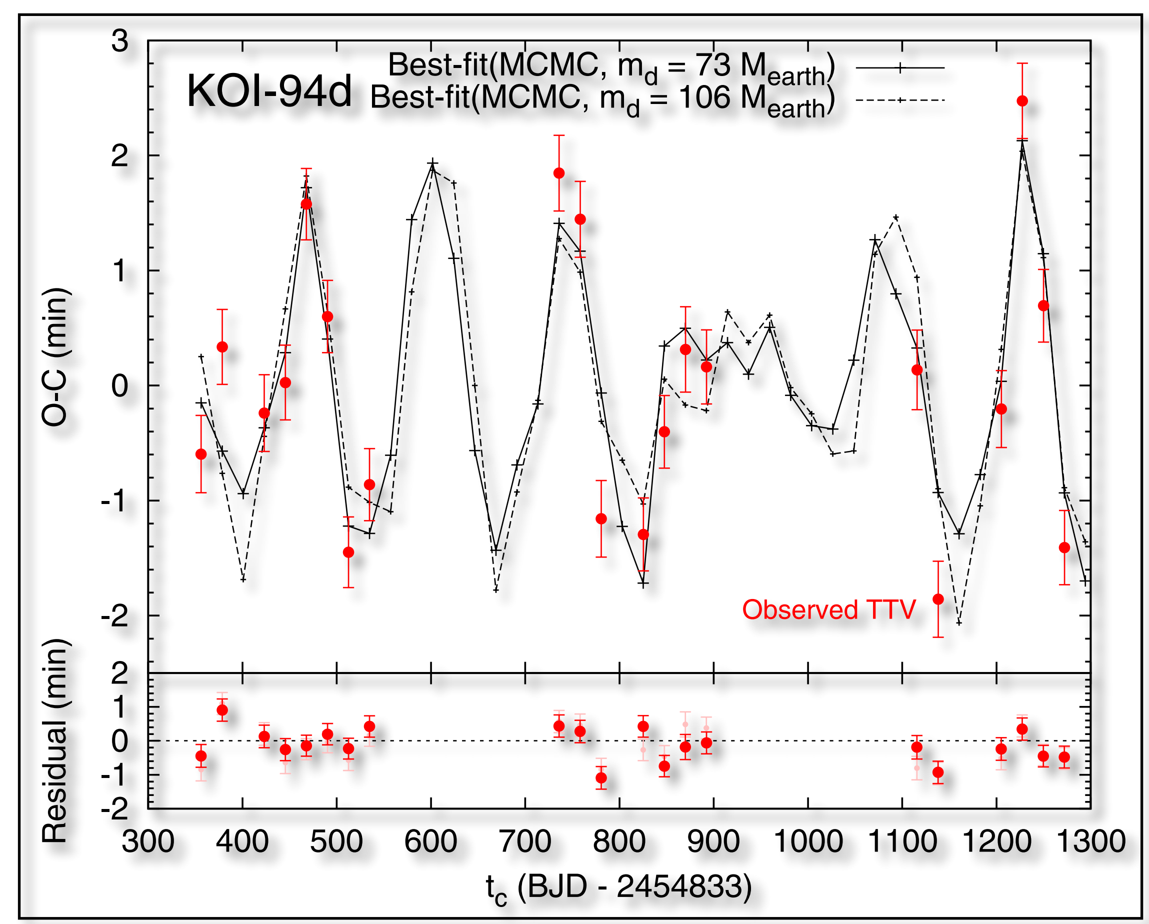




$M_d = 106 \pm\ 11\ M_\oplus$

Weiss et al., 2013

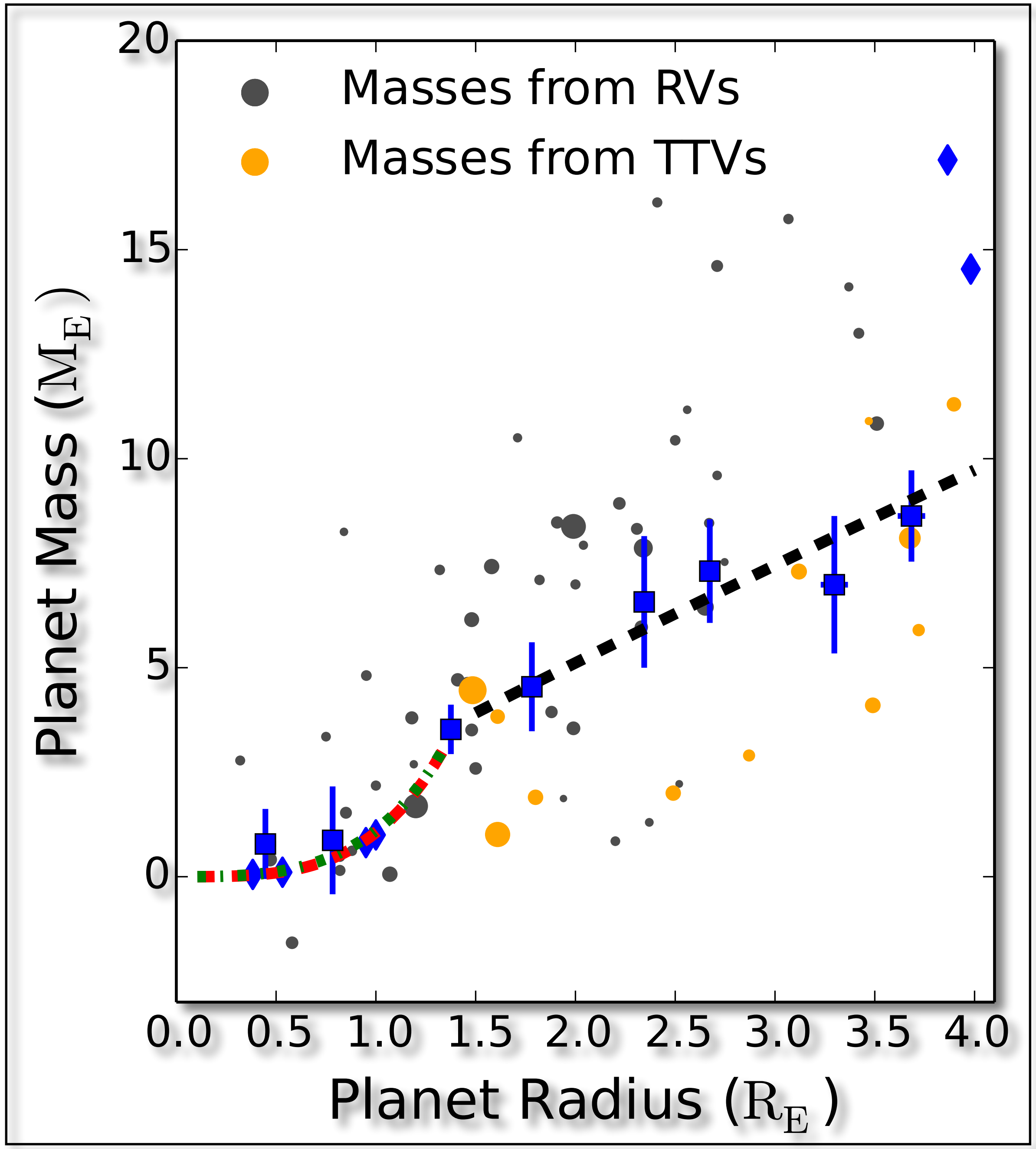
The mass of KOI-94 d
TTVs vs RVs: who is right?



$M_d = 52.1\ {+6.9}\ {-7.1}\ M_\oplus$

Masuda et al., 2013

TTV versus Vrad



Weiss & Marcy, 2014

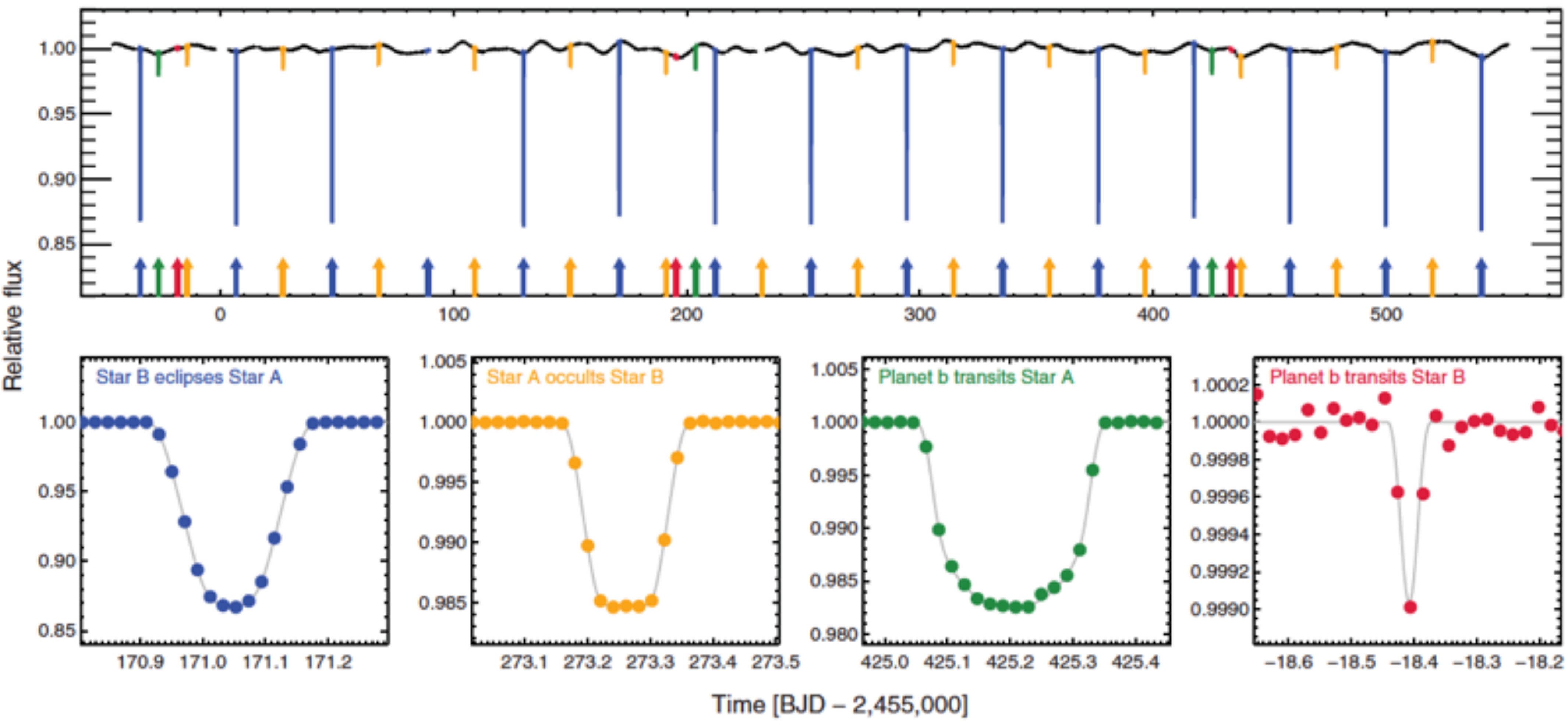
Sample: 65 Kepler exoplanets

R < 4 R⊕ and P < 100 days

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

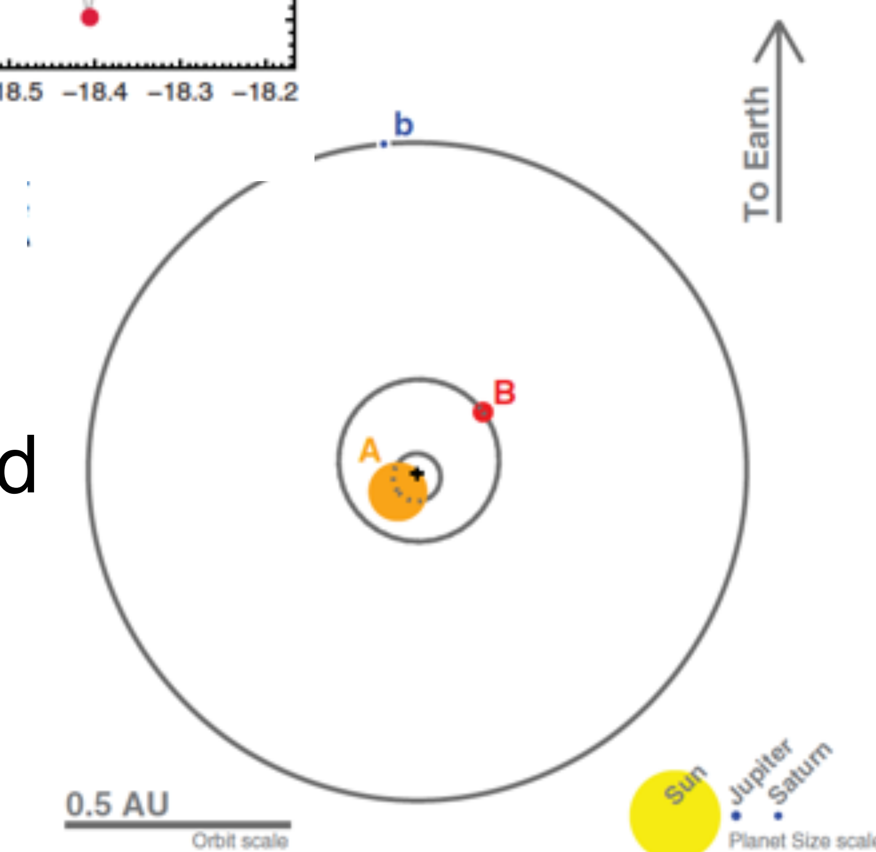
Circumbinary planets

Doyle et al., 2011
Bender et al., 2012

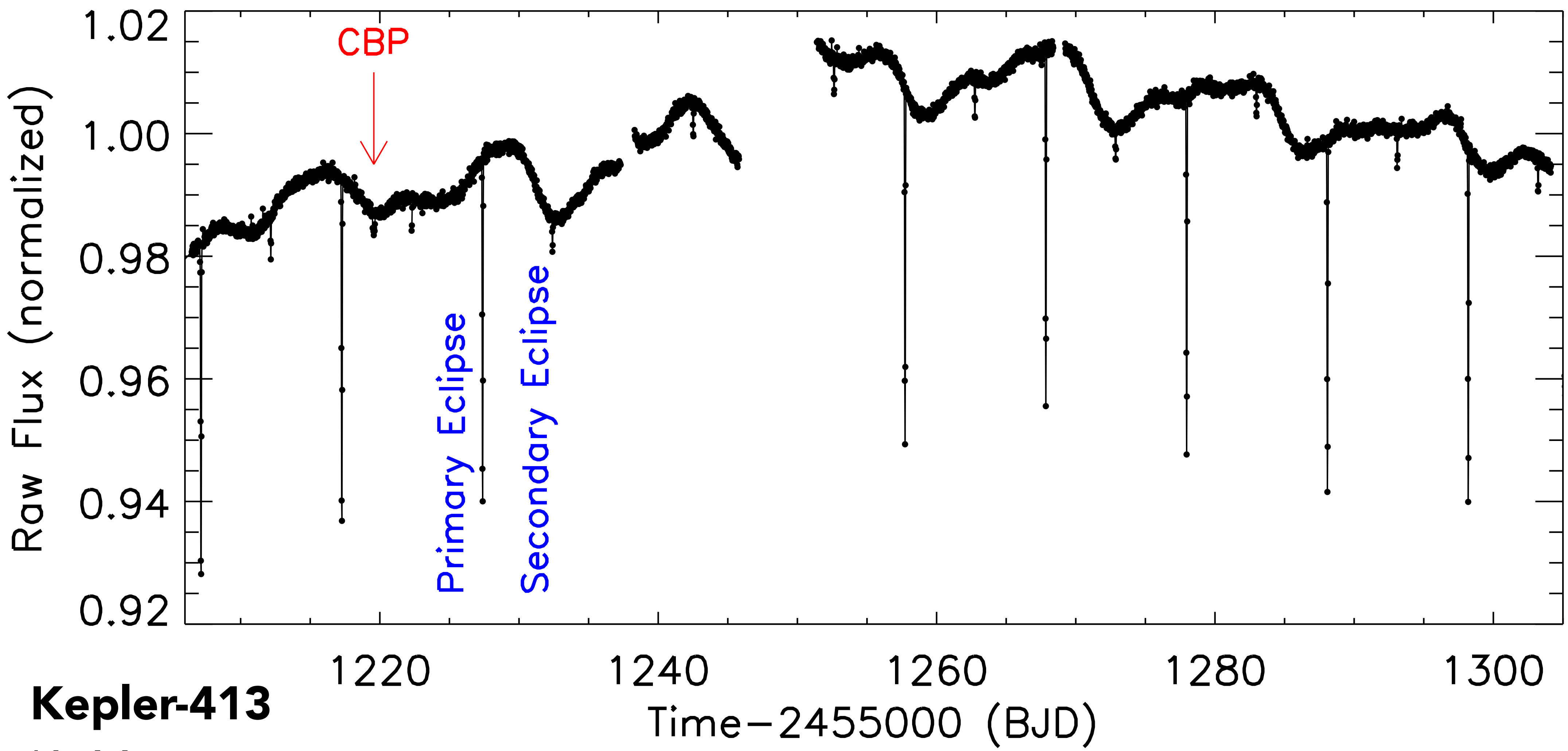


Kepler 16 system

K+M stars in an eccentric (e=0.159) 41-days period
precision on the masses: 0.5% and 0.2%
precision on the radii: 0.2% and 0.26%
Planet: 228.7 days



Circumbinary planets



Kostov et al., 2014

Kepler-413

K+M

Period=10.11 days

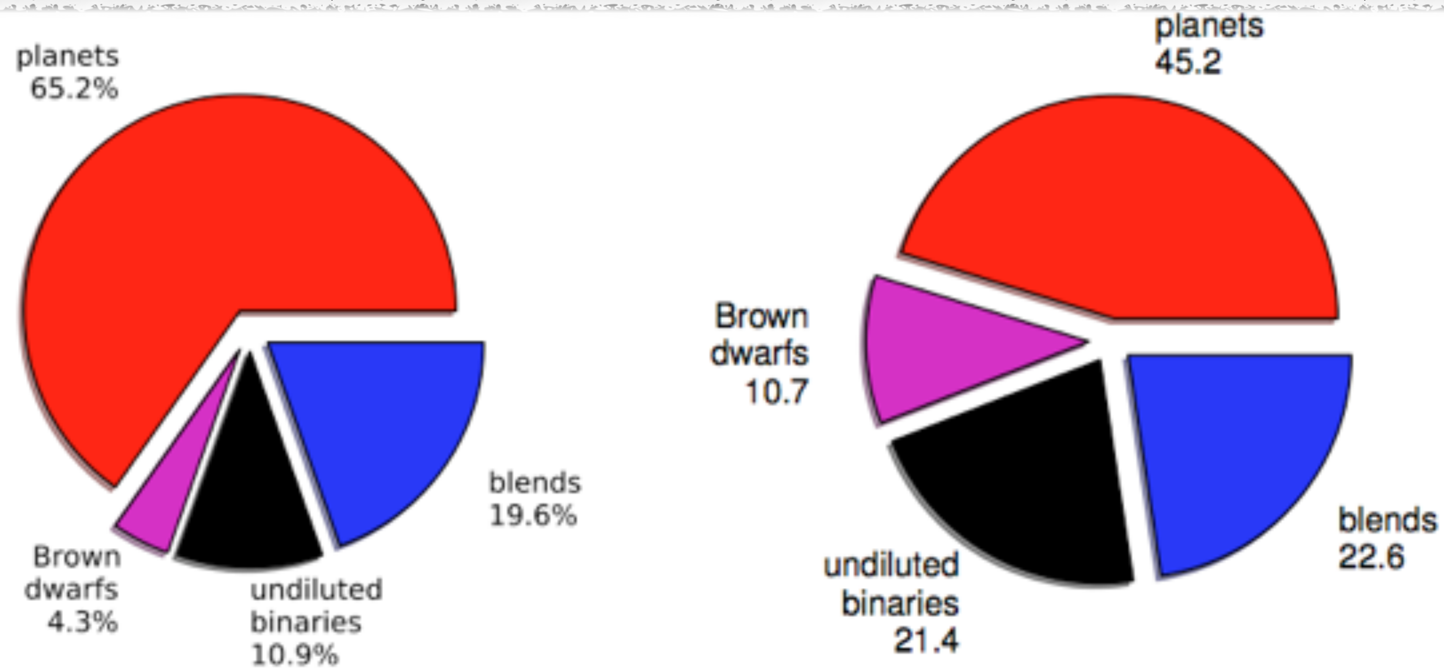
e = 0.0372

$R_p = 4.347 \pm 0.099\ R_\oplus$

Period ~ 66 days

e = 0.118

KOI: false positive rate



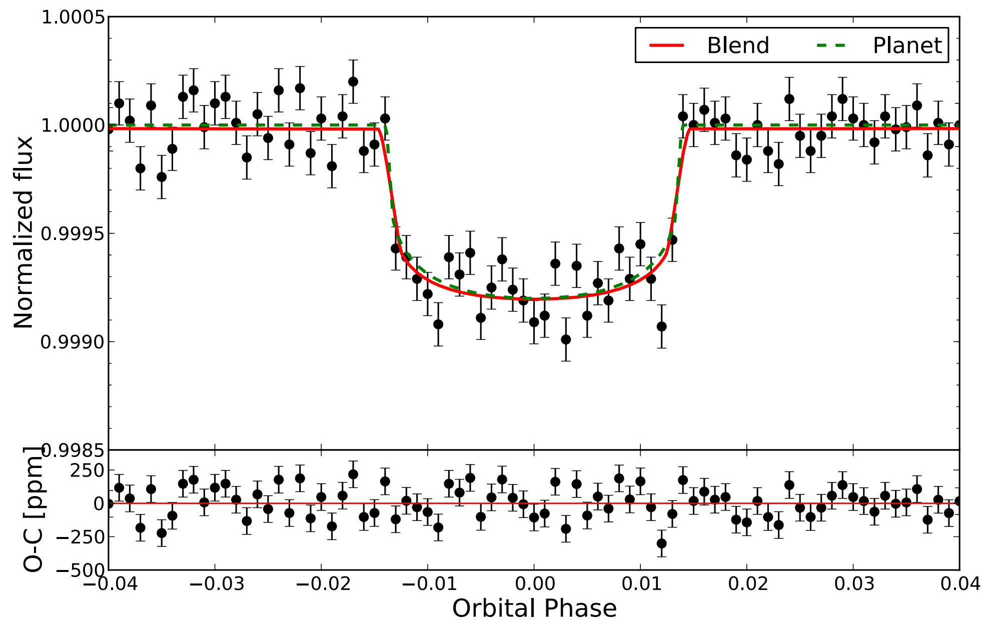
Short periods
FPR ~ 35%

Long periods
FPR ~ 55%

- Morton & Johnson (2011): median FPR ~ 5% (modeling)
- Santerne et al., (2012): 35% for giant close-in candidates (radial velocity observations with SOPHIE)
- Fressin et al., (2013) global FPR ~9.4% (modeling): giants 17.7%, Small Neptunes 6.7% and Earth-size 12.3%
- Santerne et al. (2013): re-evaluation of Fressin's value to 11.3% (modeling)
- Santerne et al. (in prep): 50% for all giant candidates (SOPHIE observations)

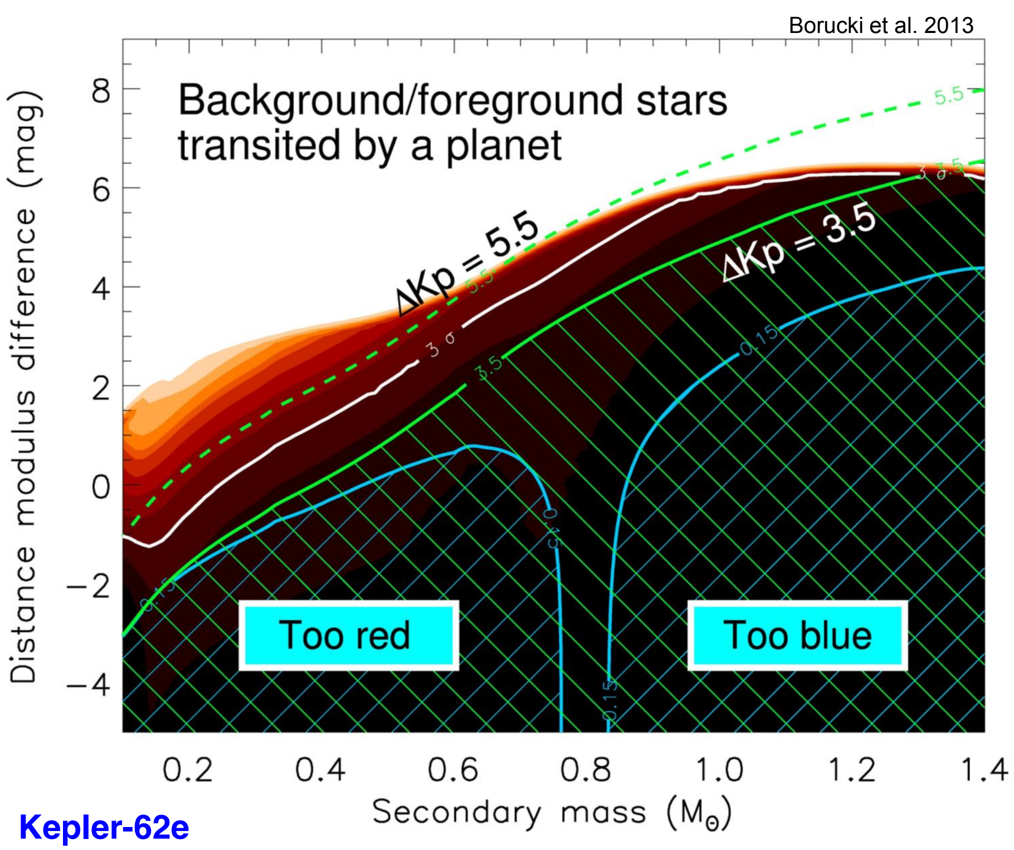
Planet validation

Goal : validate the planetary nature when other technics cannot by comparing the probabilities of all conceivable scenarii

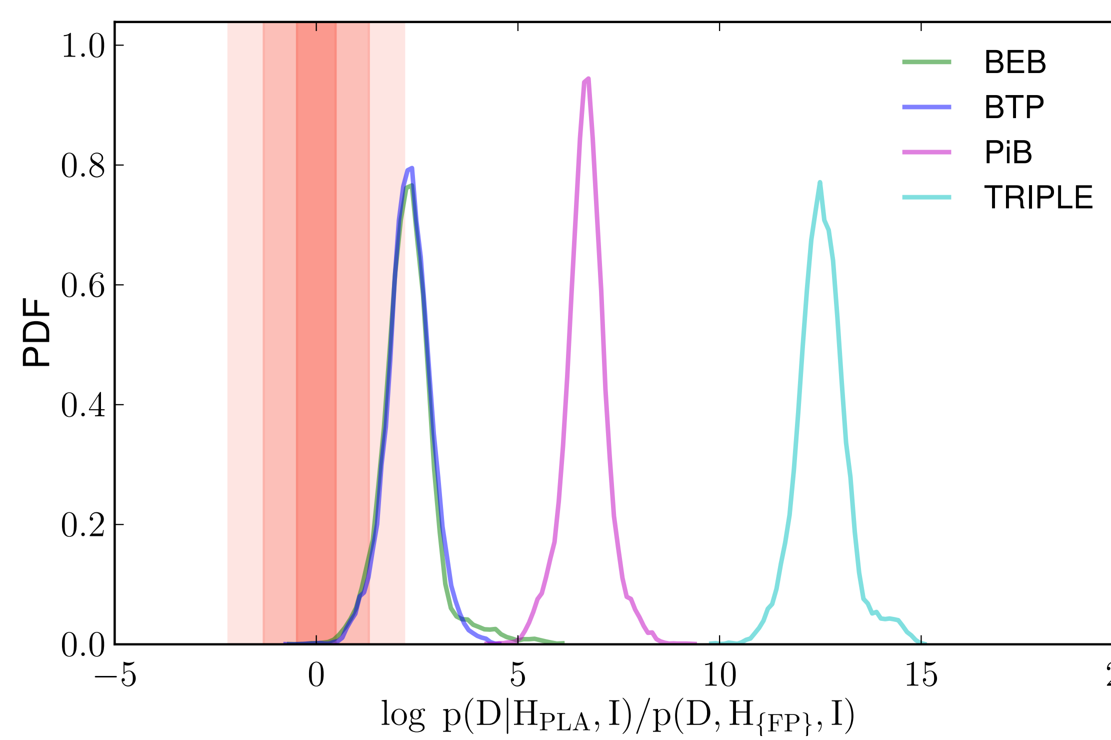


Almenara et al., 2011

BLENDER Torres et al., 2011



PASTIS Diaz et al., 2014



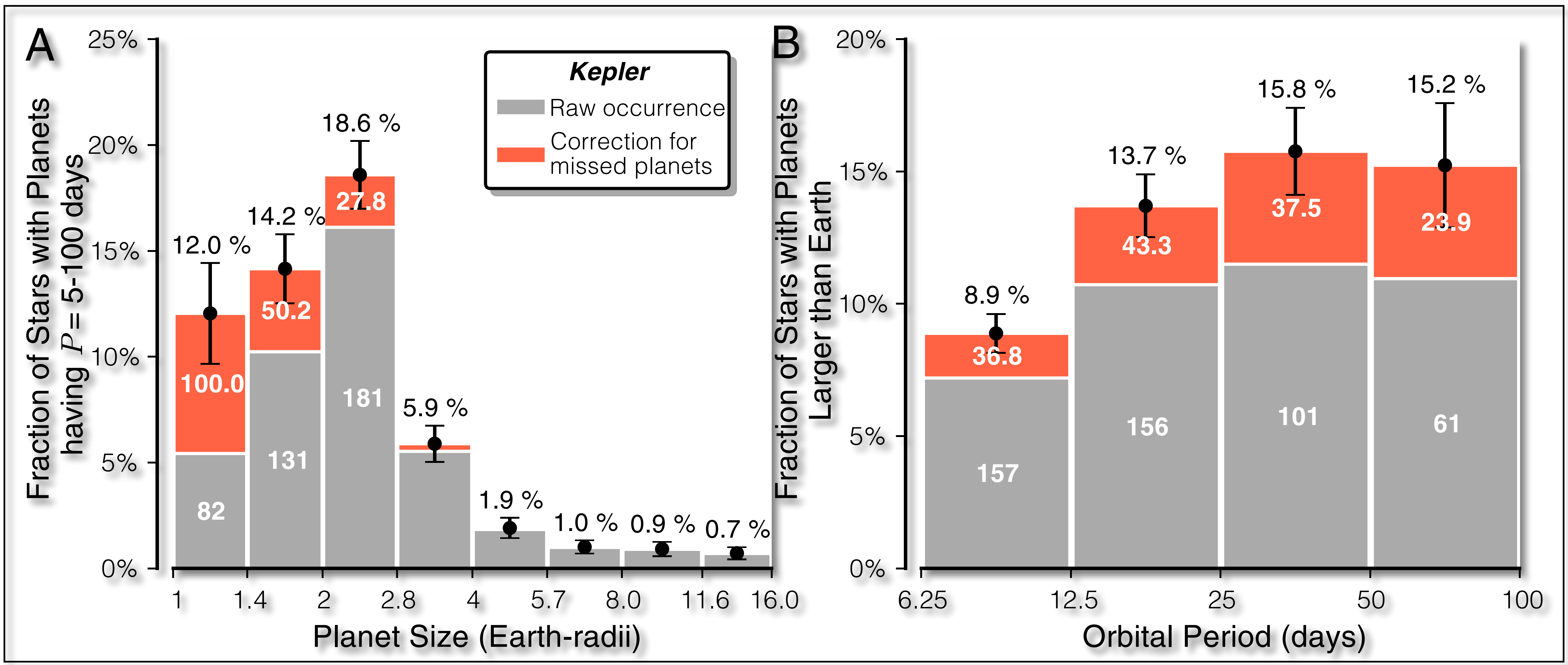
Moutou et al., 2014

Occurrence of planets

Sun-like stars (42 557 GK dwarfs), KOI with P = 5–100 d:

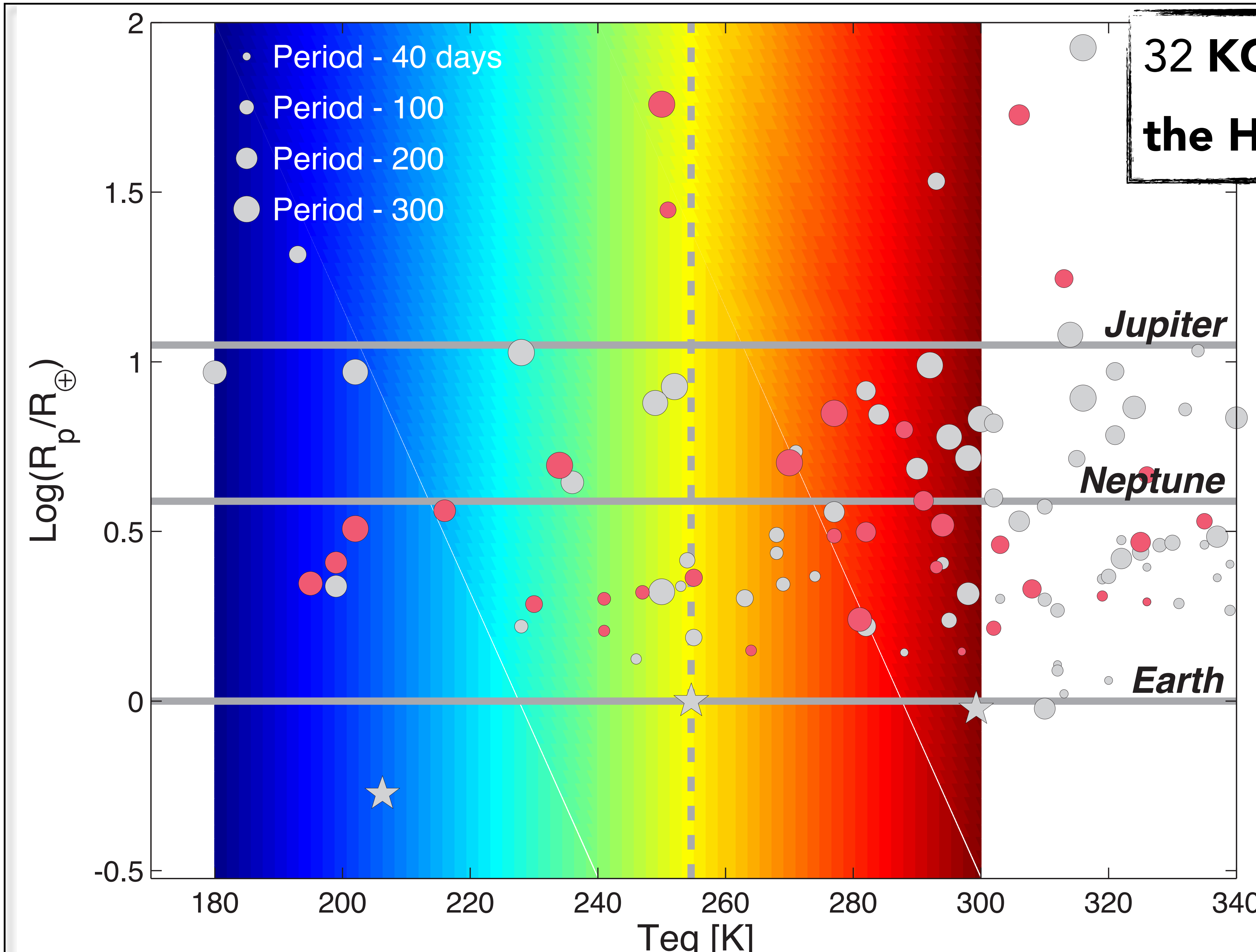
Jupiter-size (8 – 16 R⊕): 1.6 ± 0.4%

Earth-size: 23 ± 3%



Petigura et al., 2013
Petigura et al., 2014, PNAS

Candidates in the Habitable Zone



32 KOIs in the HZ

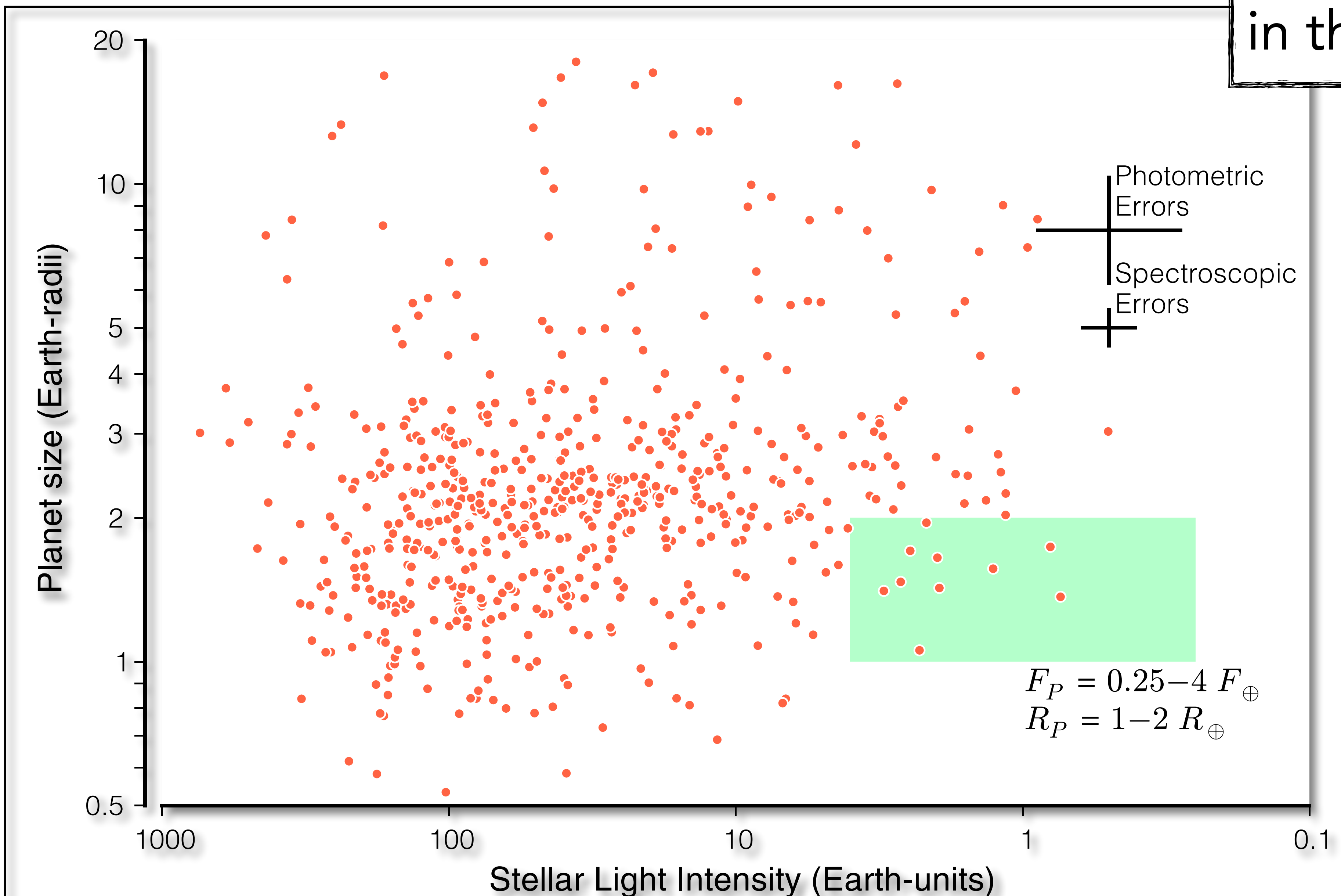
Burke et al., 2014

Occurrence of Earth analogs

Sun-like stars (42 557 GK dwarfs)

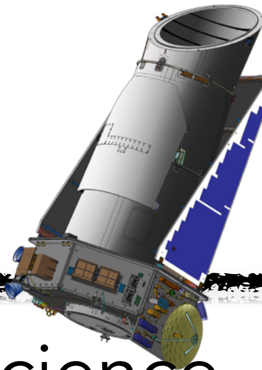
11 ± 4% of Sun-like stars harbor a planet
with R_p = 1 – 2 R⊕ and F_P = 1 – 4 F⊕

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



Petigura et al., 2014

Conclusions



- High precision photometry light curves are a gold mine for planet science and stellar physics.
- Various planet population domains are now open to exploration: small size planets, multi-planet systems, circumbinary planets …. **Diversity is the rule!**
- CoRoT and mostly Kepler provide constraints on planet statistics: occurrence rate, distribution, properties… based on their radius. More characterized planets are needed in the small-size domain
- Packed multi-planet systems occurrence is high. TTVs = efficient technique to get the planet masses based on photometric data only. Some discrepancy exists between RVs and TTVs mass - should be further explored. Benchmark to test formation and dynamical evolution
- Planet validation tools are needed to establish the planetary nature of small and cool planets

PLATO - ESA M3

PLATO will overcome all the limitations we're facing in the quest of Earth analogs