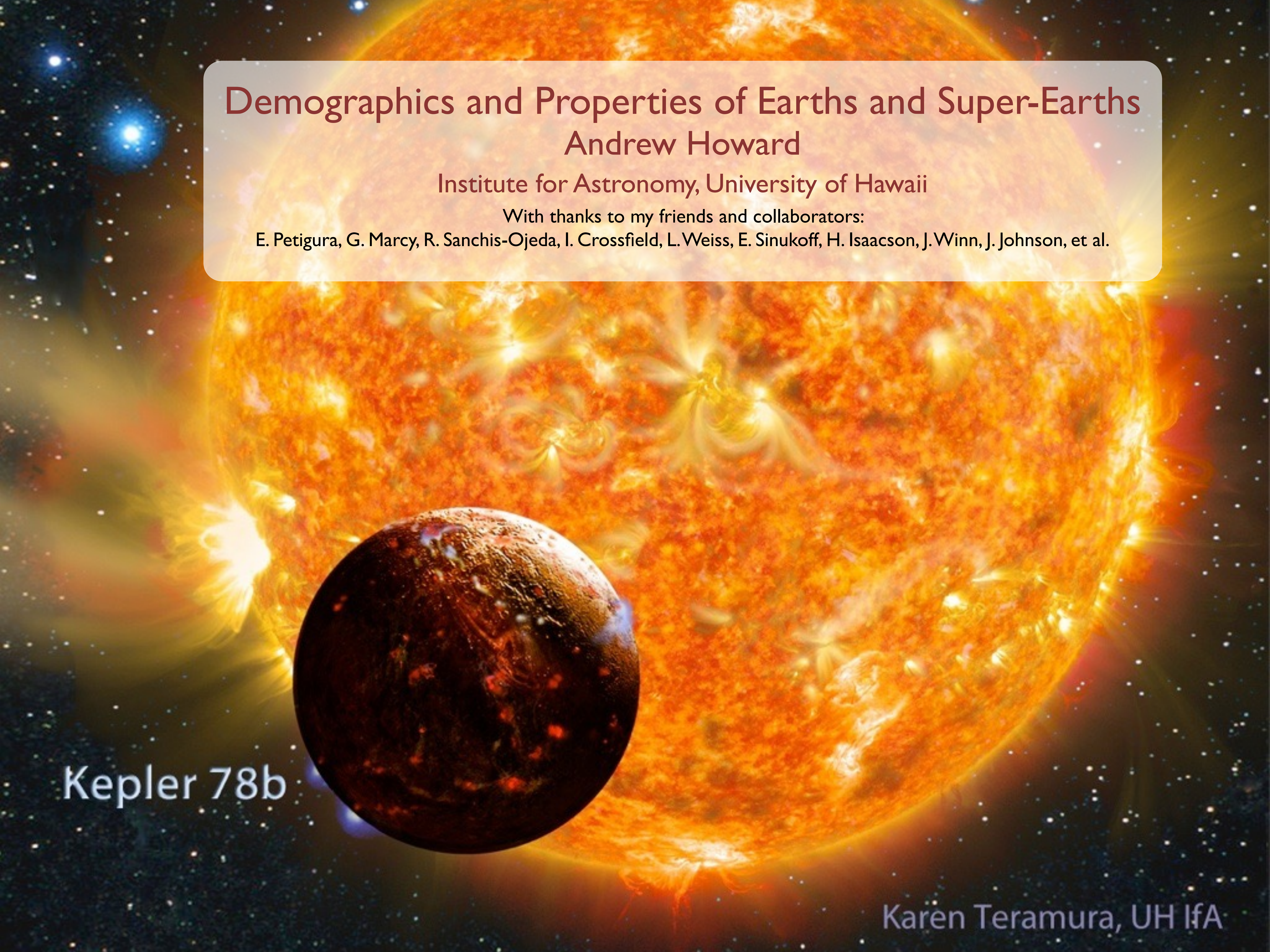
Demographics and Properties of Earths and Super-Earths

Andrew Howard

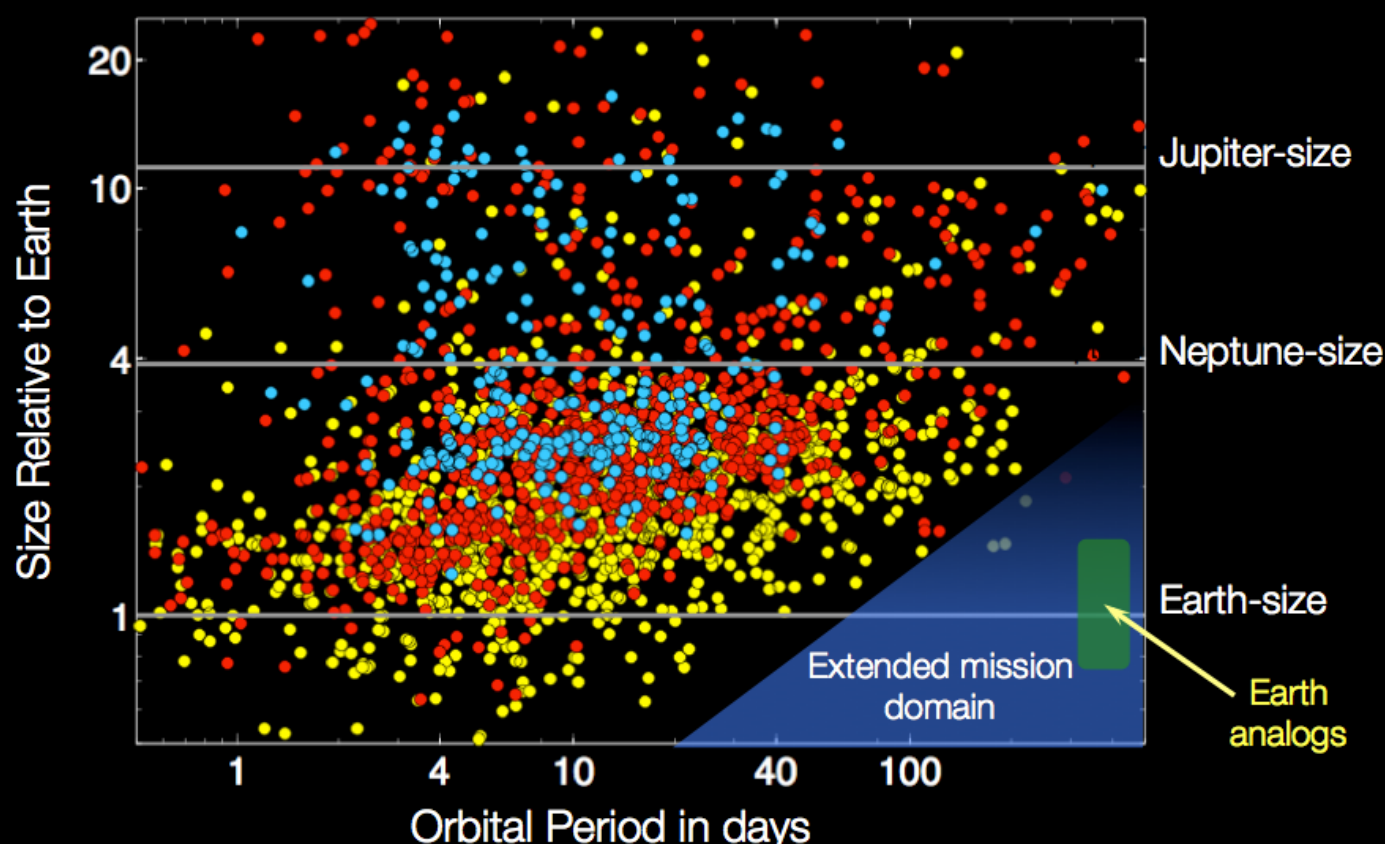
Institute for Astronomy, University of Hawaii

With thanks to my friends and collaborators:
E. Petigura, G. Marcy, R. Sanchis-Ojeda, I. Crossfield, L. Weiss, E. Sinukoff, H. Isaacson, J. Winn, J. Johnson, et al.

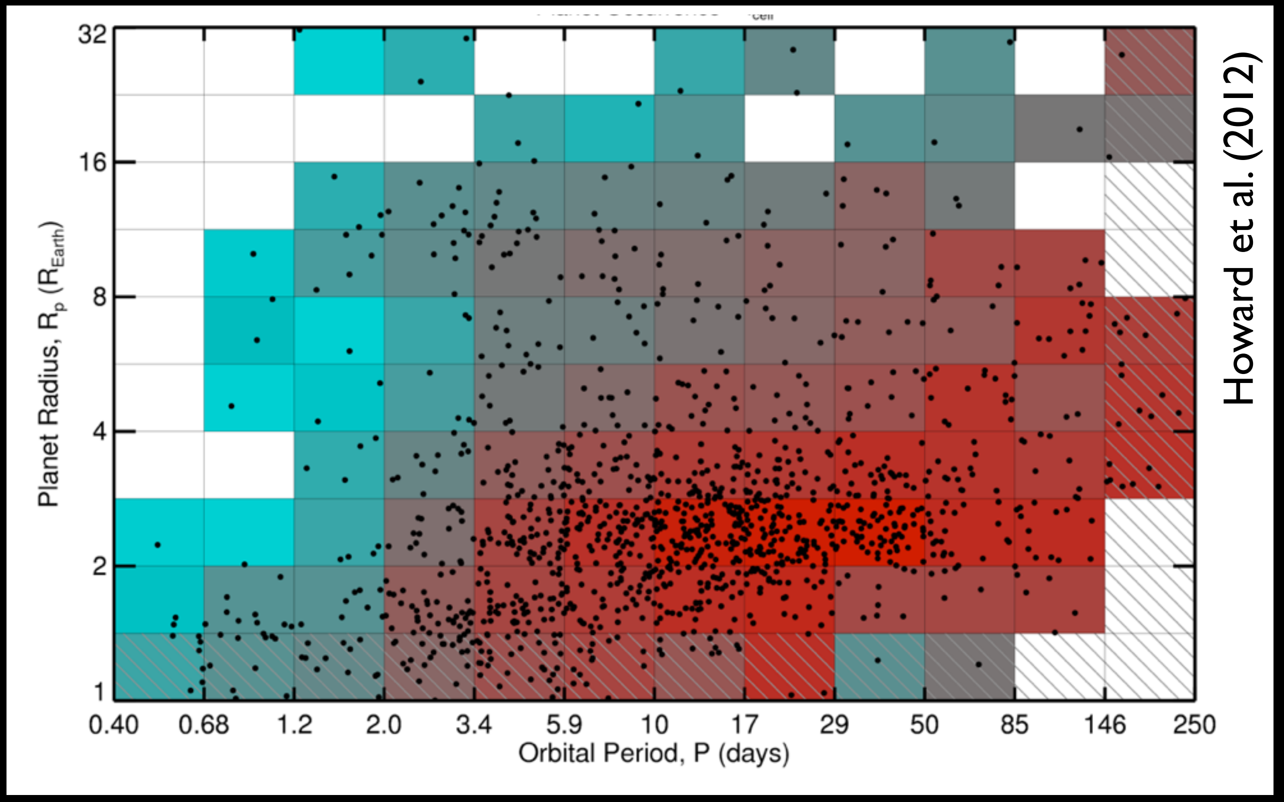


Planet Occurrence from Kepler

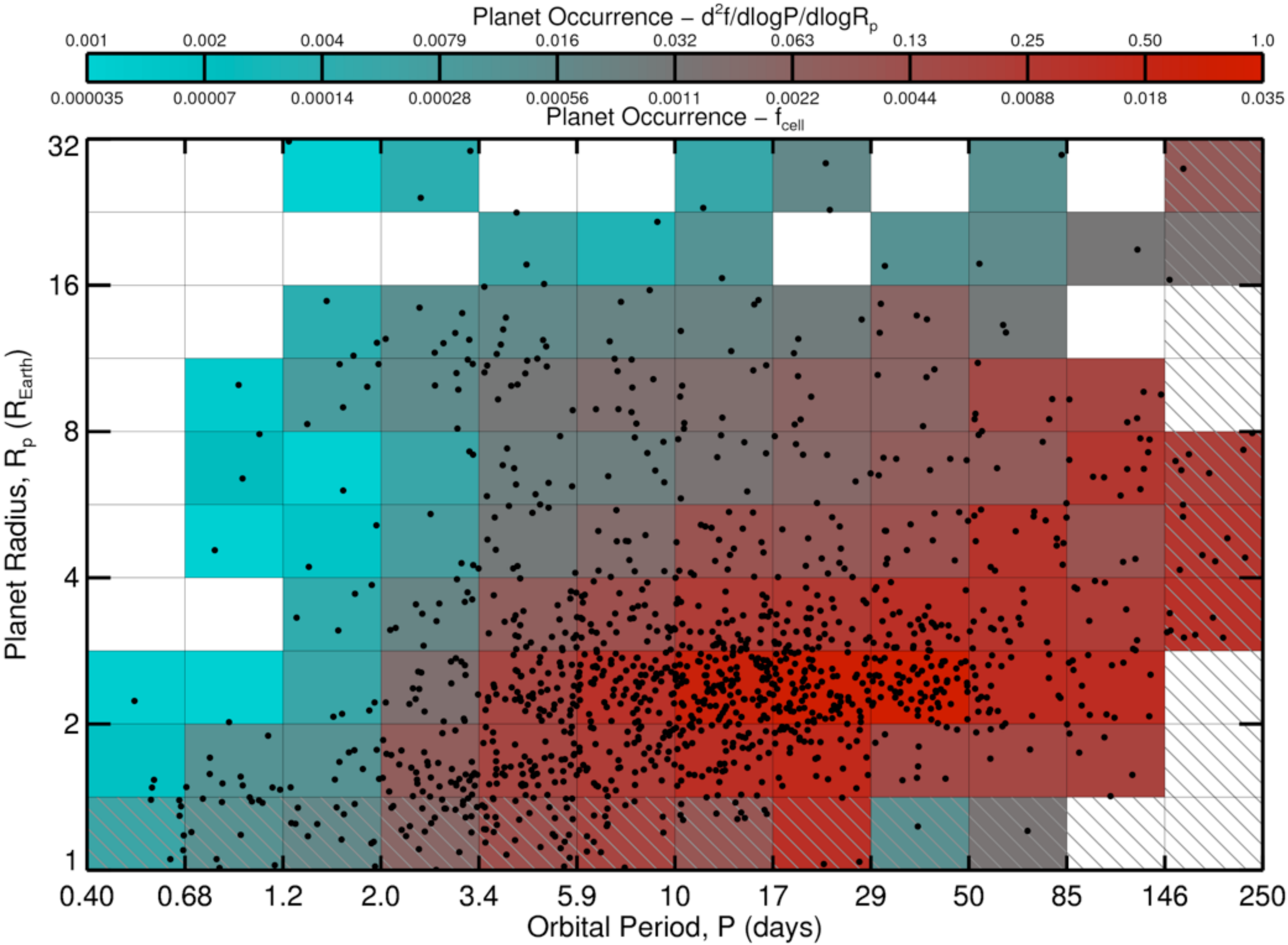
Observed Planets



Intrinsic Planet Distribution



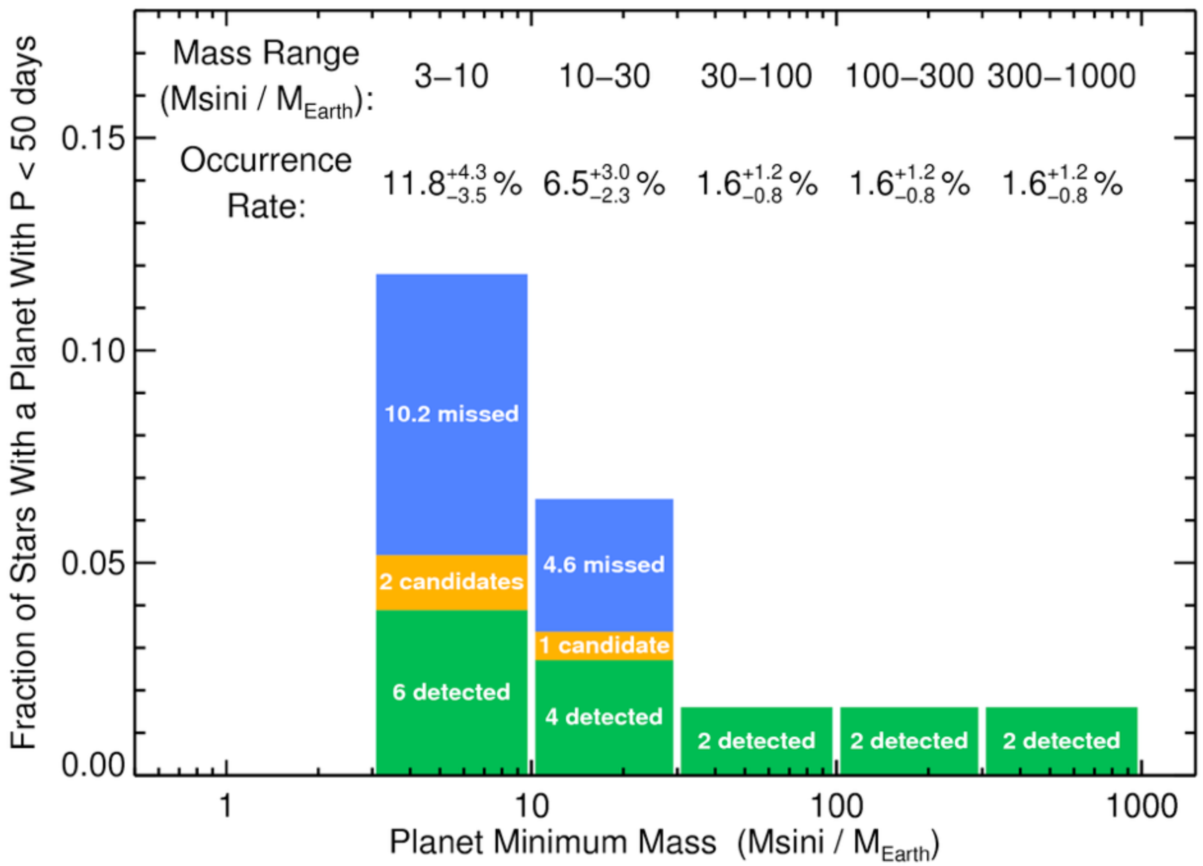
Correct for: • Inclined orbital planes
• Photometric noise
Assume: • 100% complete planet search to SNR threshold



Howard et al. (2012; updated)

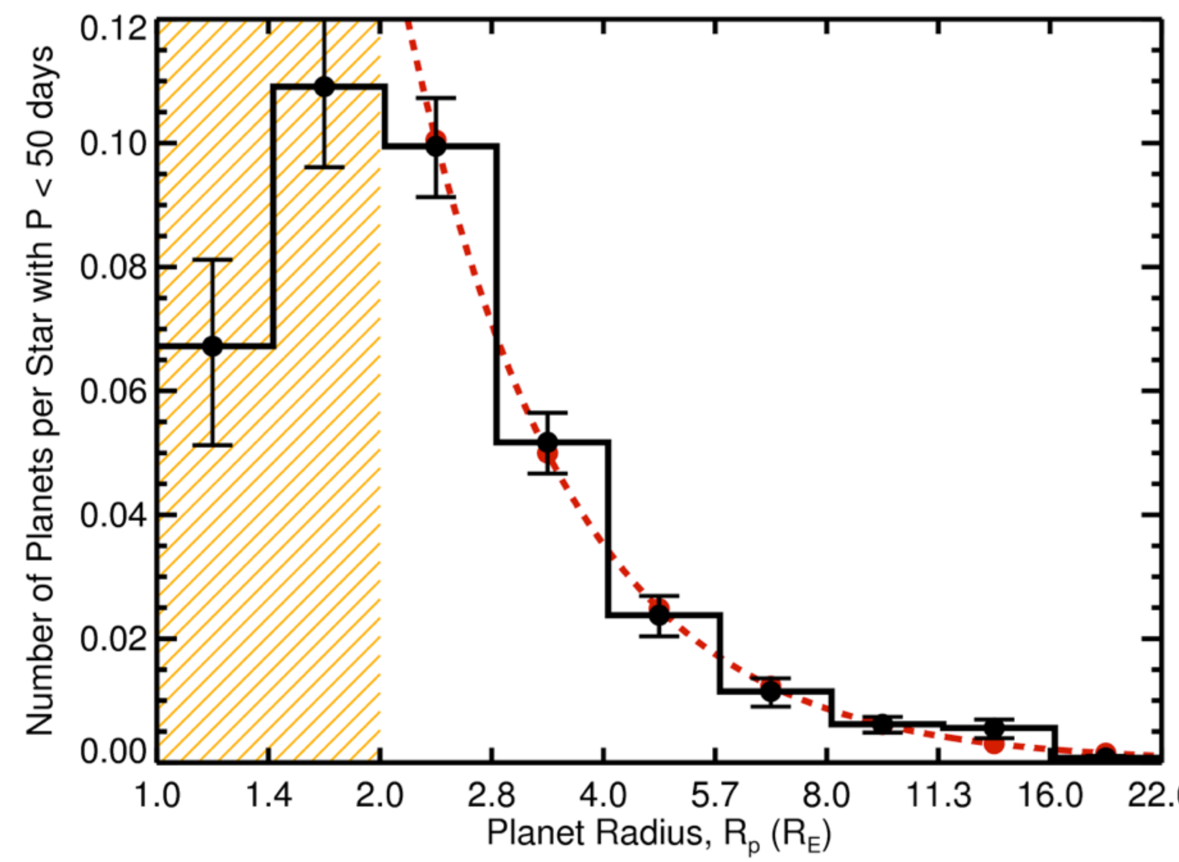
Planet Mass Distribution
Eta-Earth Survey (*Doppler*)

Howard et al. 2010, Science, 33, 653



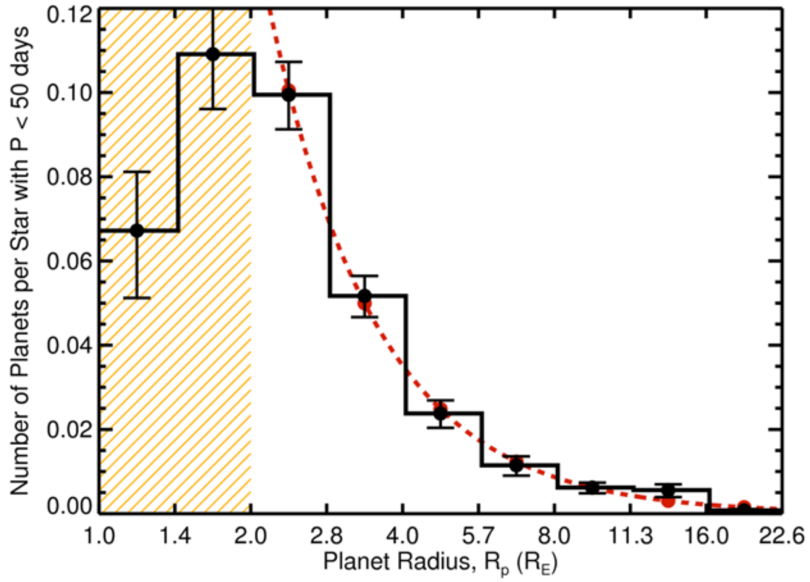
Planet Radius Distribution
Kepler

Howard et al. 2012, ApJ, 330, 653

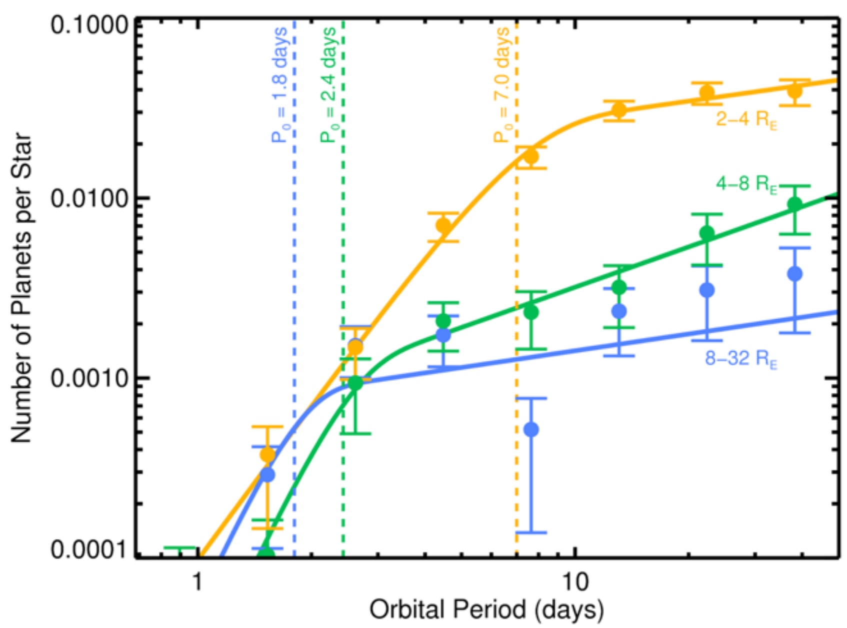


Key Planet Occurrence Trends for GK dwarfs stars from Kepler

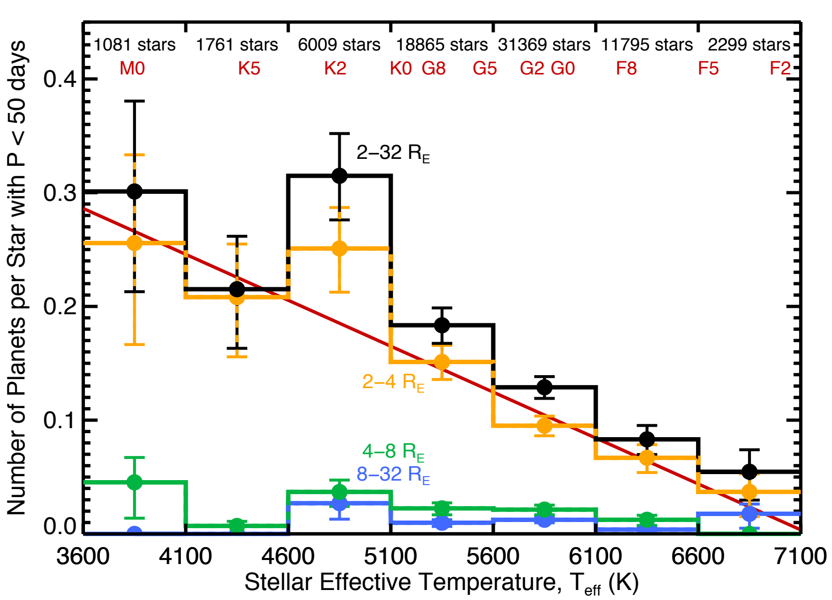
Howard et al. 2012, ApJ, 330, 653



Small planets are common



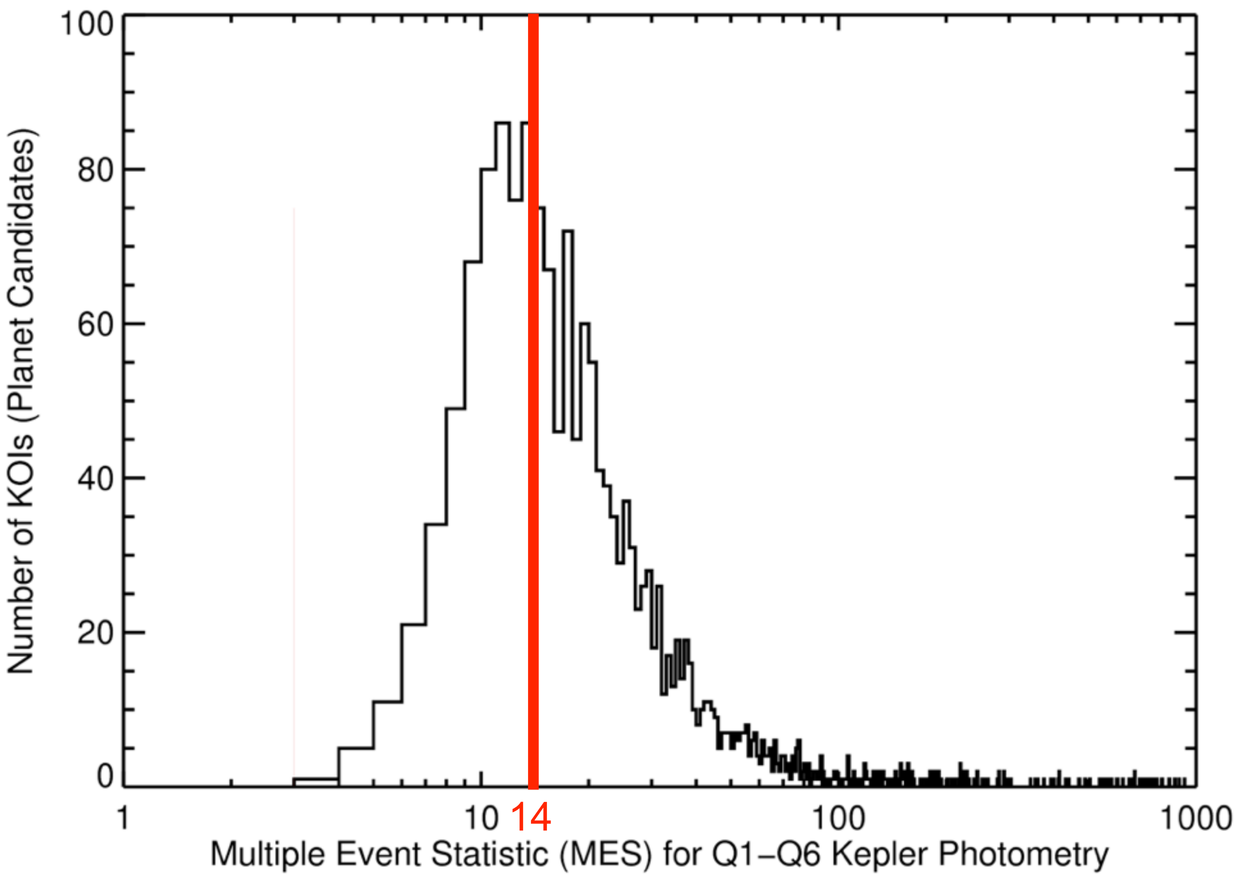
Occurrence vs. period: cut-off power law

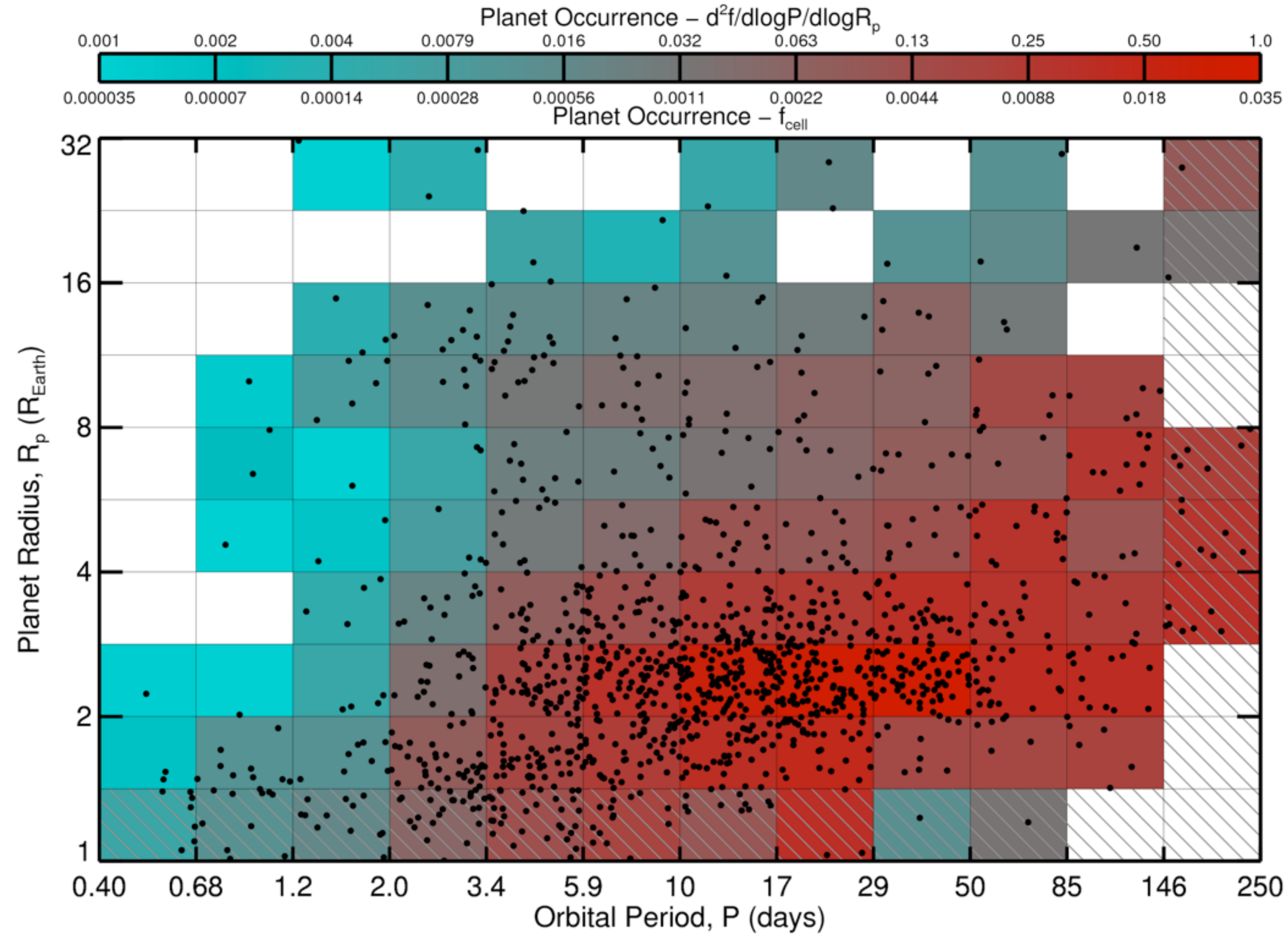


Small planets prefer small stars

Kepler Planet Occurrence

Detection Completeness Studies

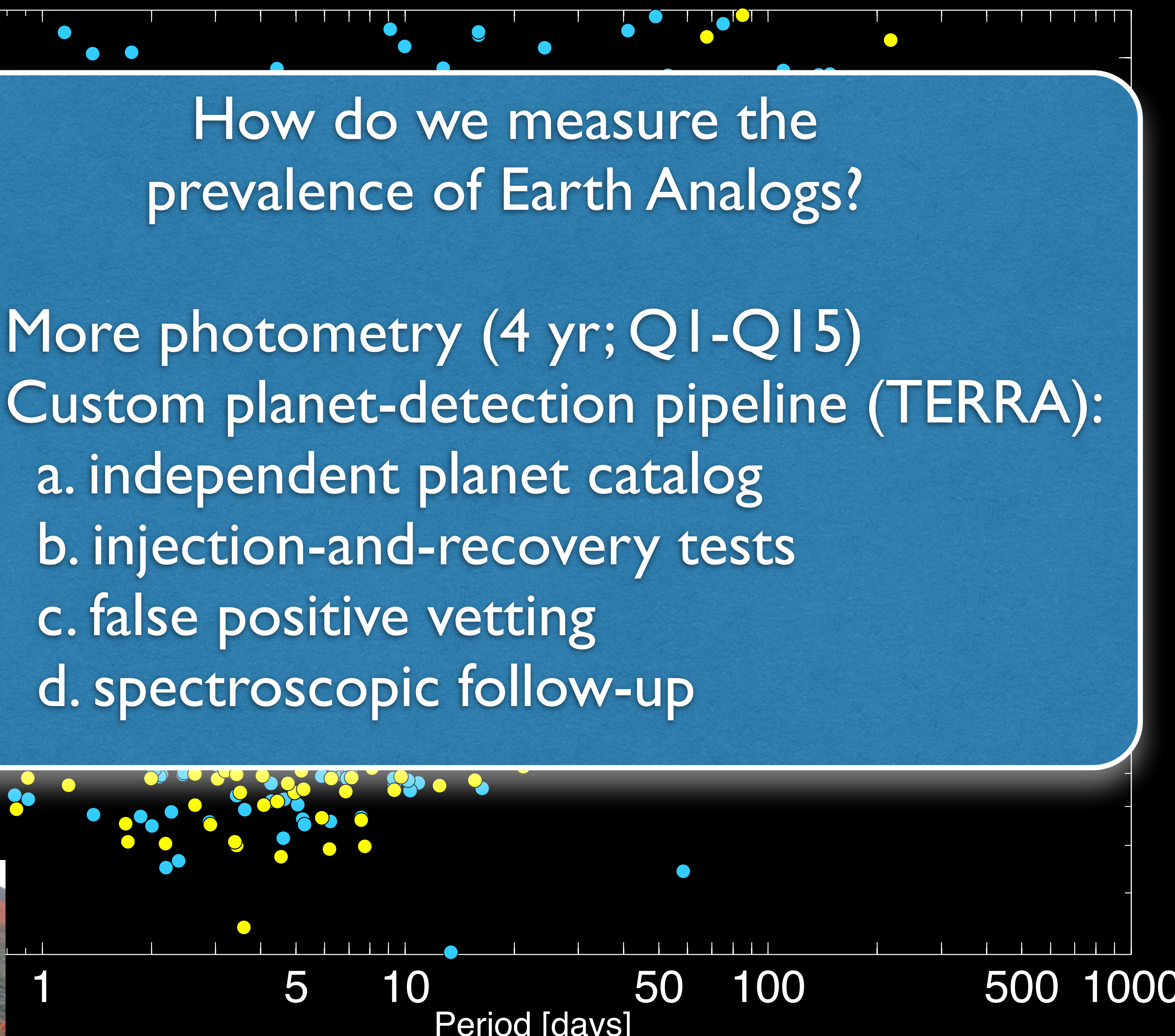




Source of detection incompleteness:

- shot noise - SNR (easy to correct)
- transit geometry (easy to correct)
- pipeline incompleteness (hard to assess)

Kepler Planets



How do we measure the prevalence of Earth Analogs?

1. More photometry (4 yr; Q1-Q15)
2. Custom planet-detection pipeline (TERRA):
    a. independent planet catalog
    b. injection-and-recovery tests
    c. false positive vetting
    d. spectroscopic follow-up

Erik Petigura

Rowe et al. (2013)

TERRA – optimized for small planets

Time domain preprocessing

- Start with raw photometry
- Gaussian process detrending
- Calibration
- Petigura & Marcy 2012

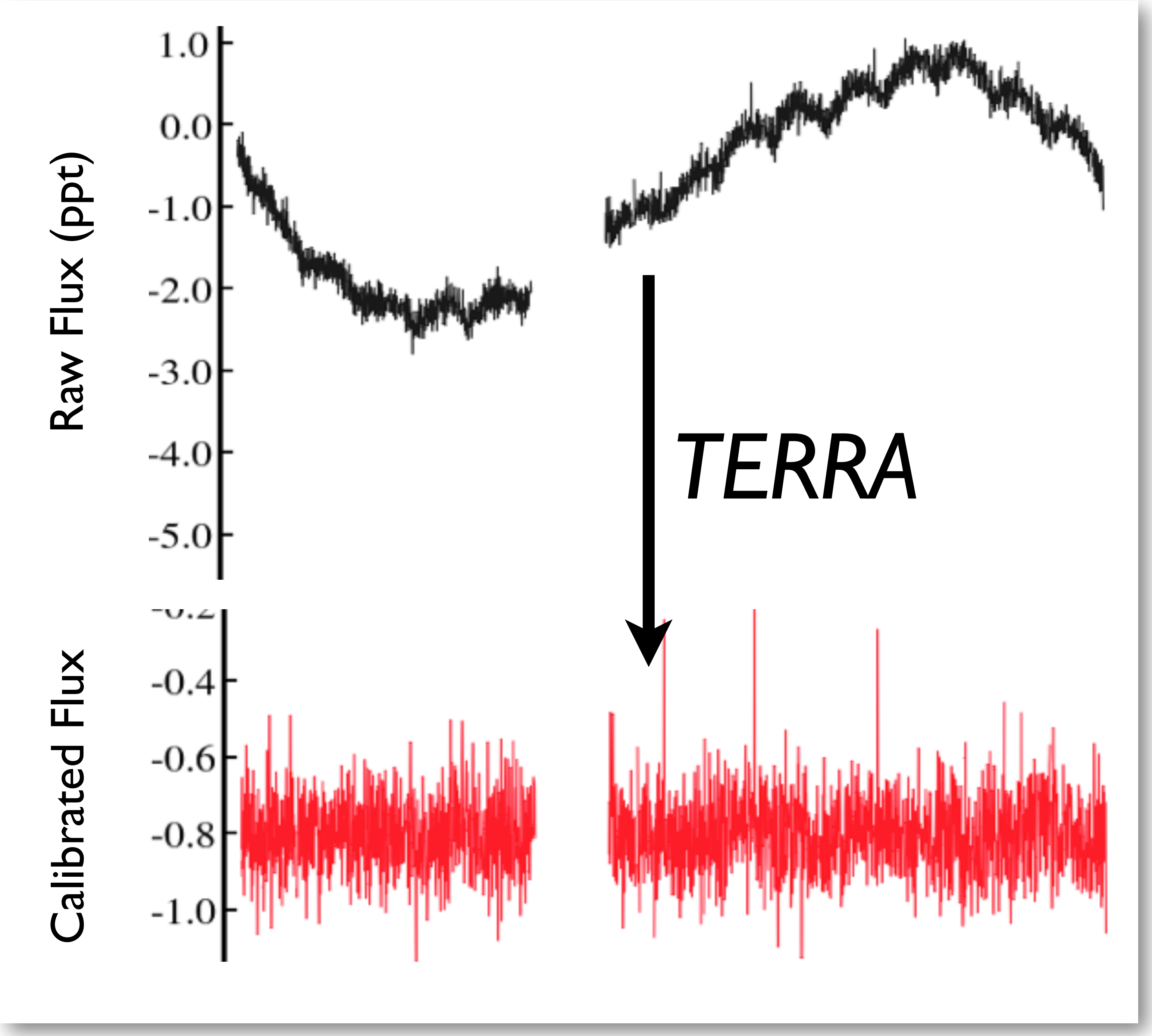
Transit search

- Matched filter
- Similar to BLS algorithm (Kovcas+ 02)
- Leverages Fast-Folding Algorithm (Staelin+ 68; Petigura+ 13, in prep)

Data validation

- Significant peaks in periodogram, but inconsistent with exoplanet transit

Detrended/calibrated photometry

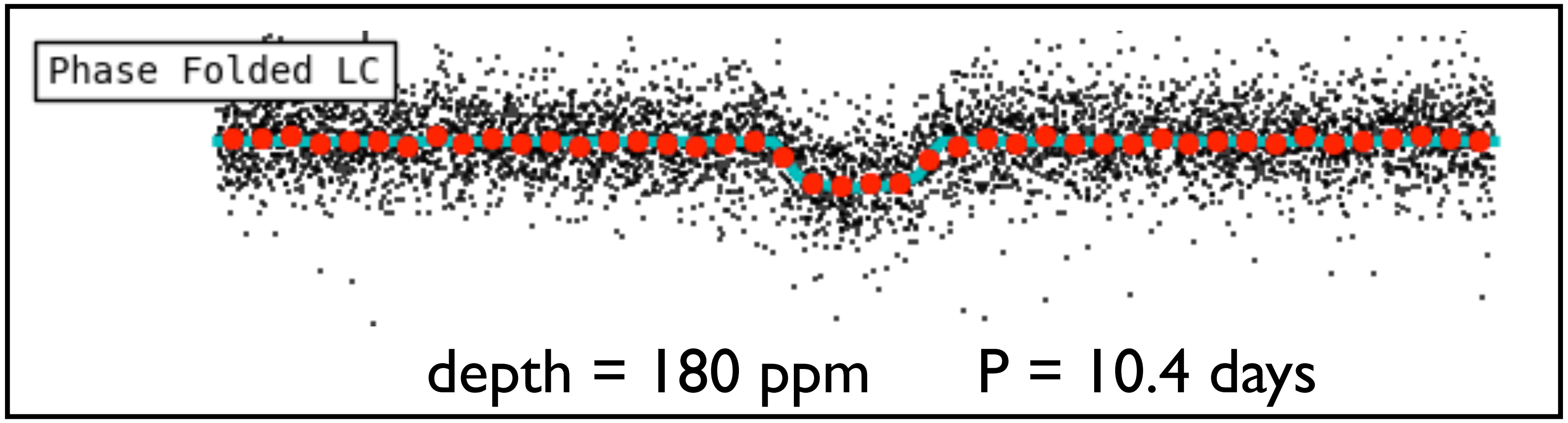


TERRA – optimized for small planets

Time domain preprocessing

- Start with raw photometry
- Gaussian process de-trending
- Calibration
- Petigura & Marcy 2012

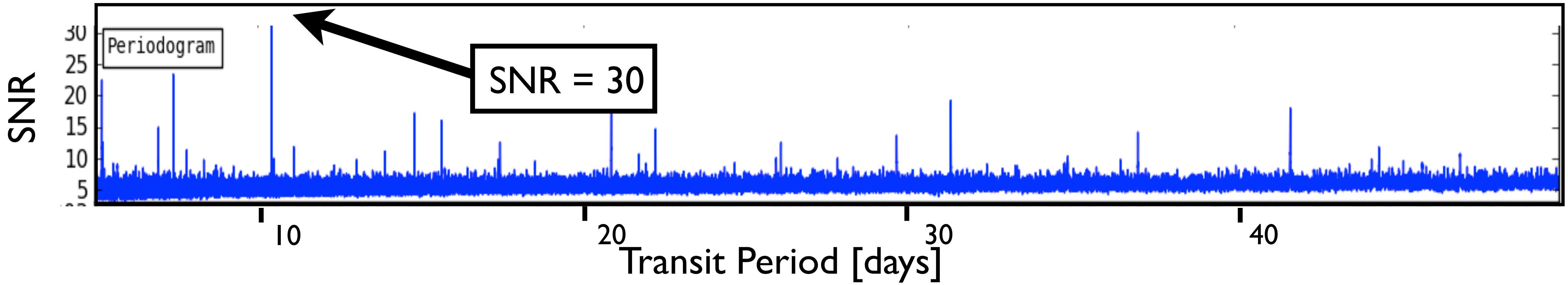
Earth-size planet found



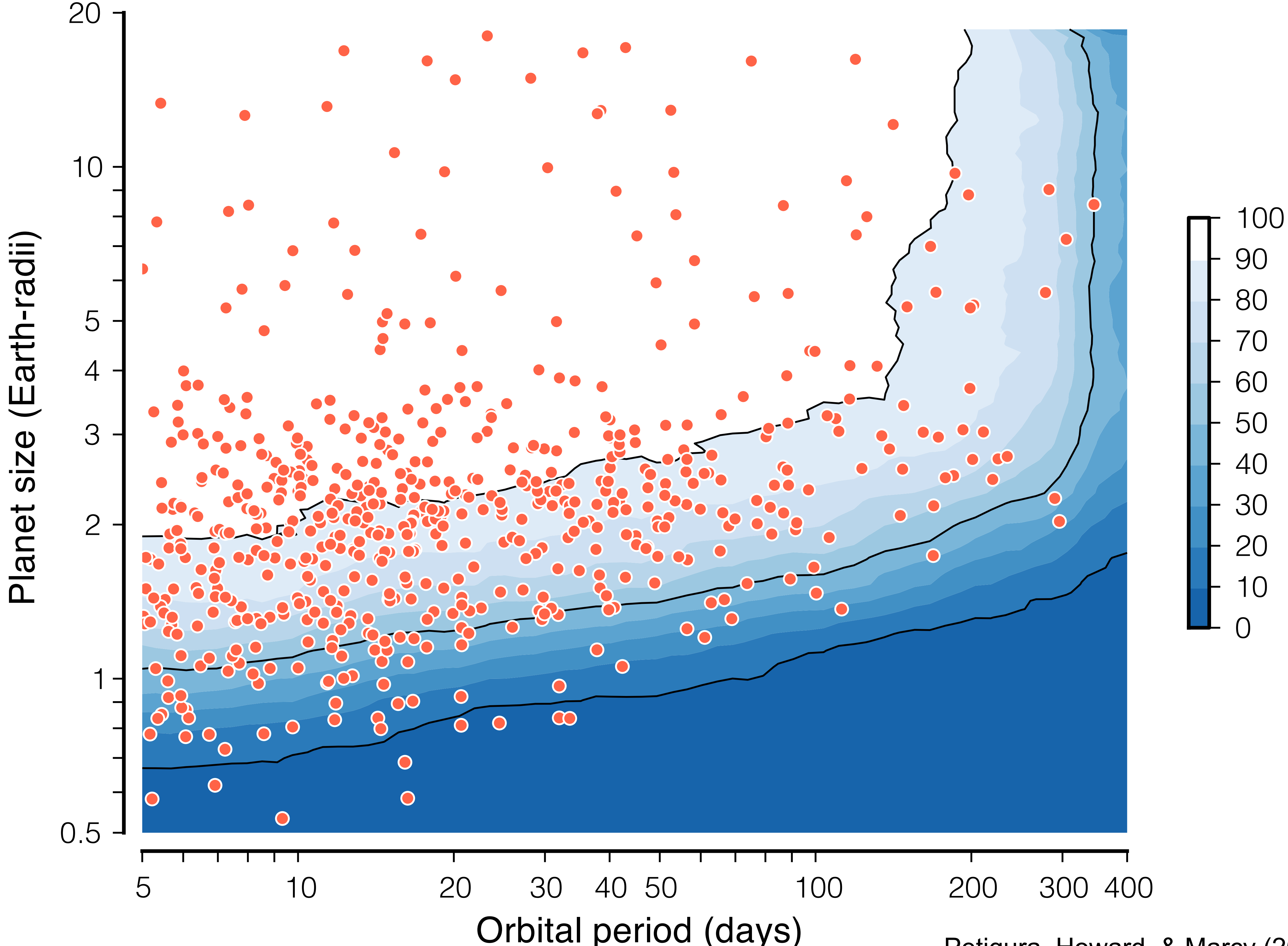
Transit search

- Matched filter
- Similar to BLS algorithm (Kovacs+ 02)
- Leverages Fast-Folding Algorithm (Staelin+ 68; Petigura+ 13, in prep)

Transit Periodogram

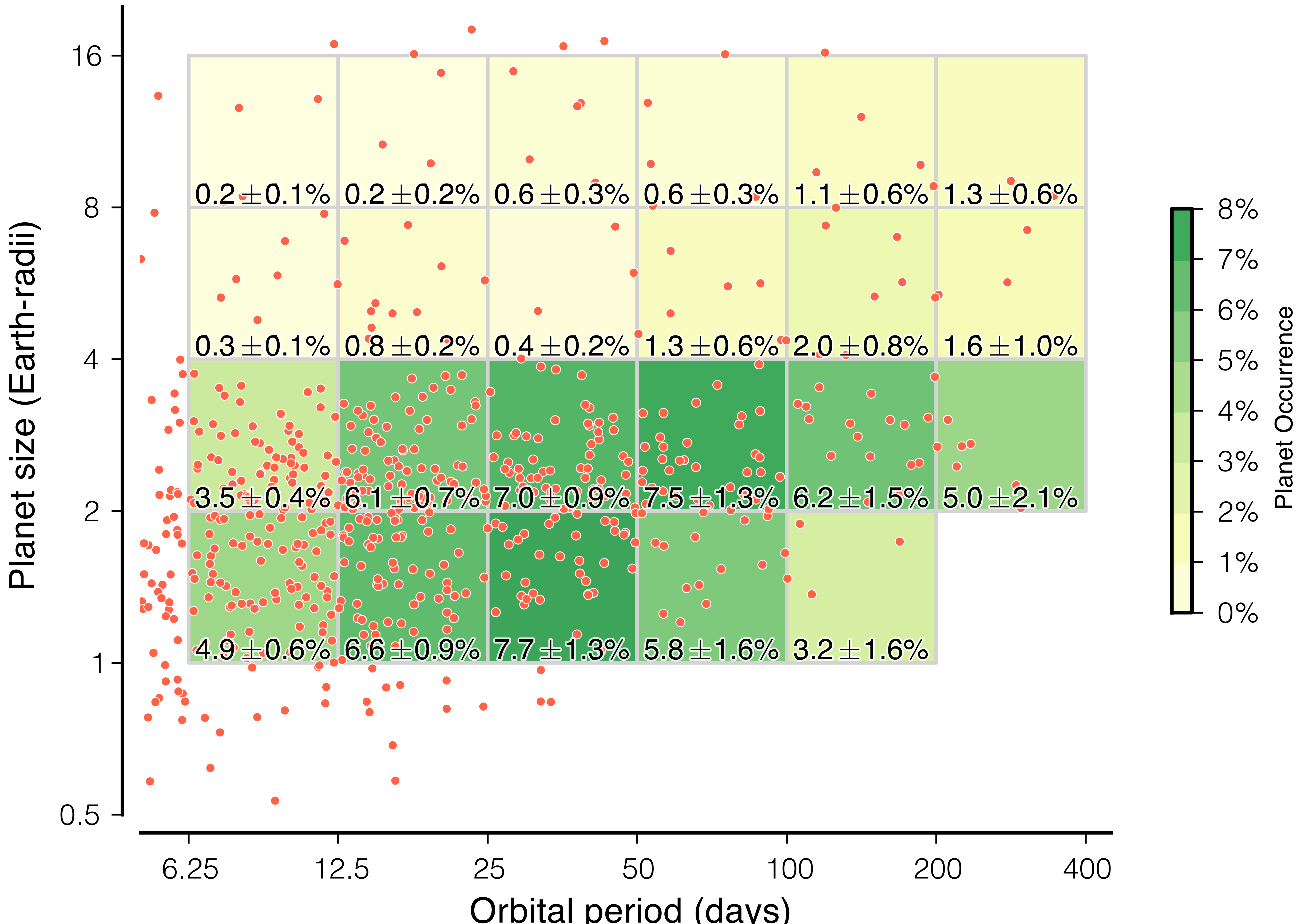


TERRA Planet Detection Efficiency

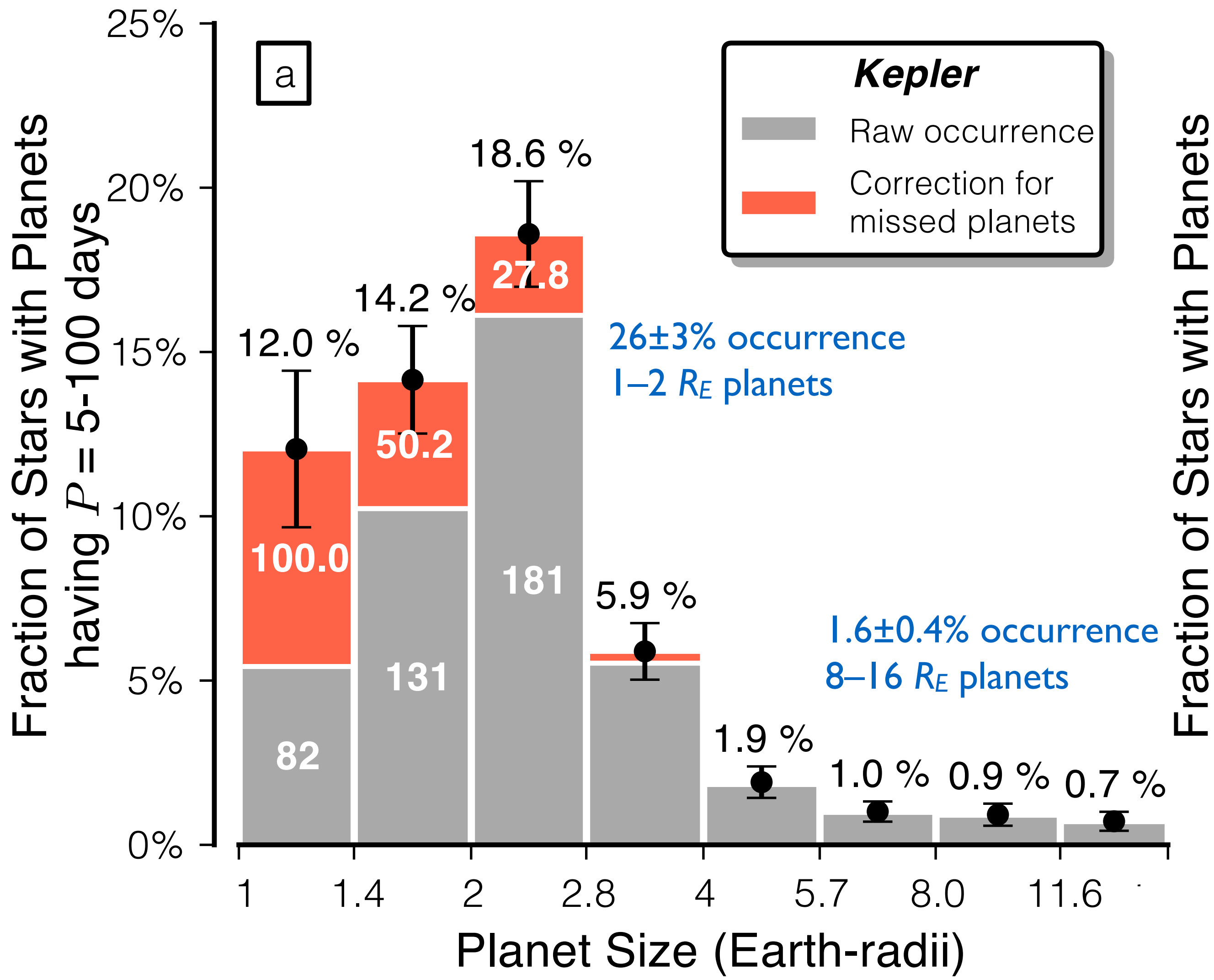


Petigura, Howard, & Marcy (2013)

Kepler Planet Occurrence

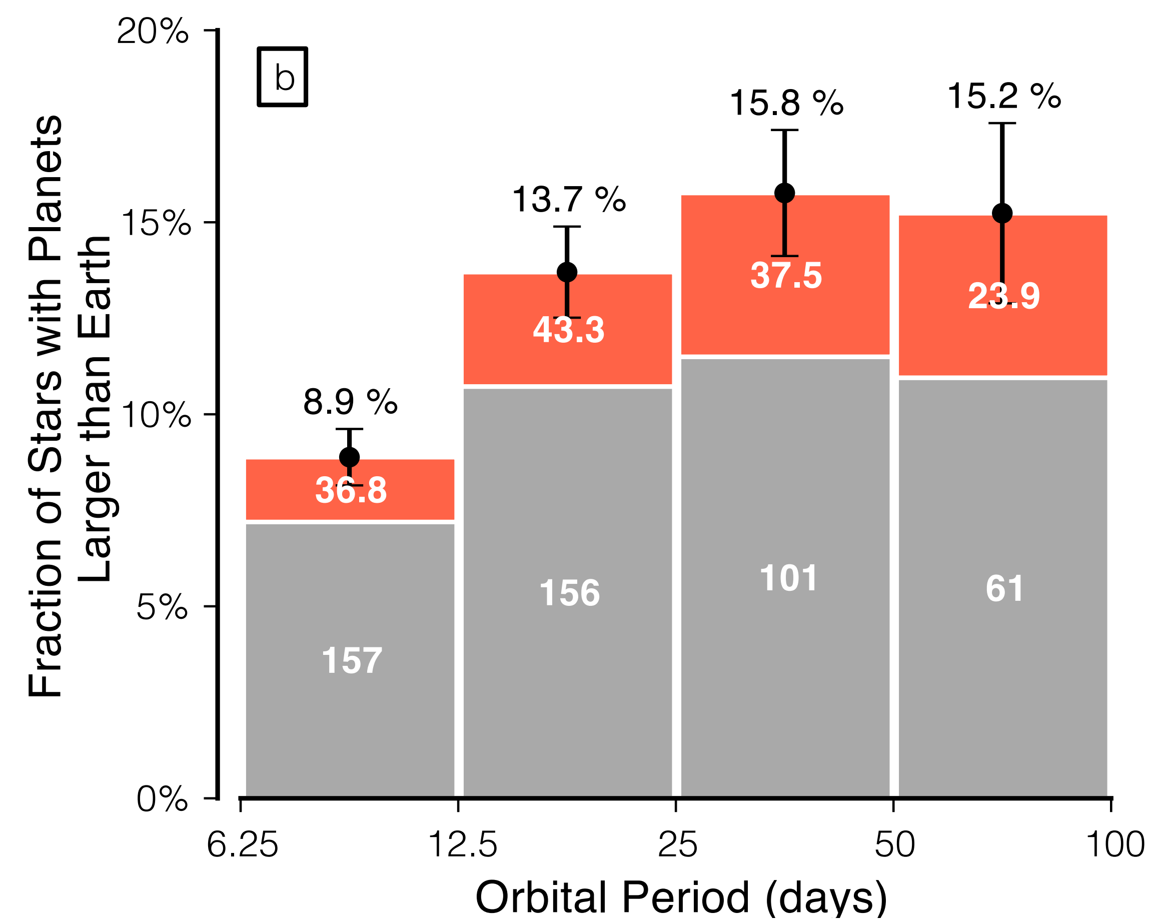


Petigura, Howard, & Marcy (2013)



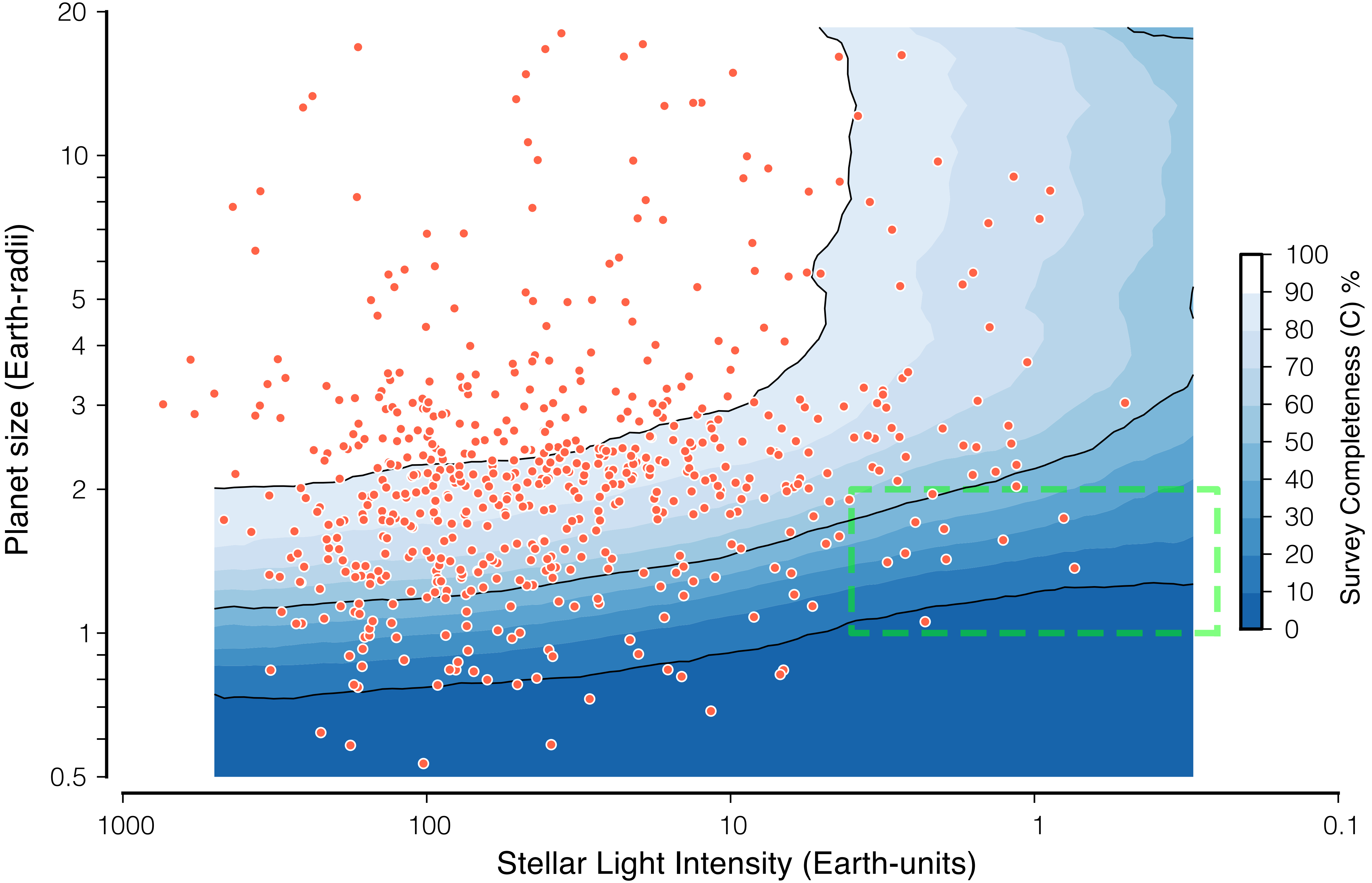
Planet Size Distribution

Planet Period Distribution



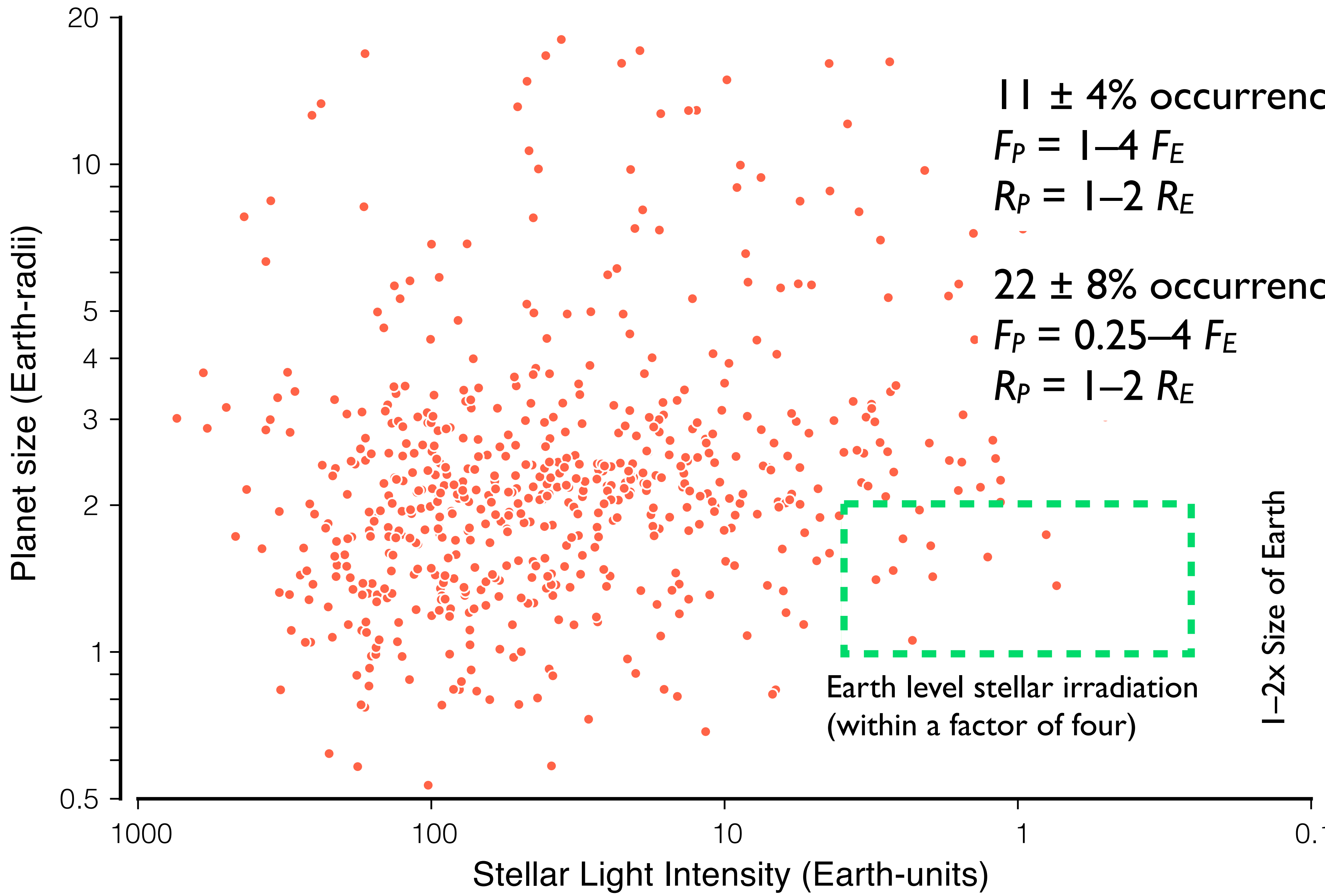
Petigura, Howard, & Marcy (2013)

Planet Size and Incident Flux



Petigura, Howard, & Marcy (2013)

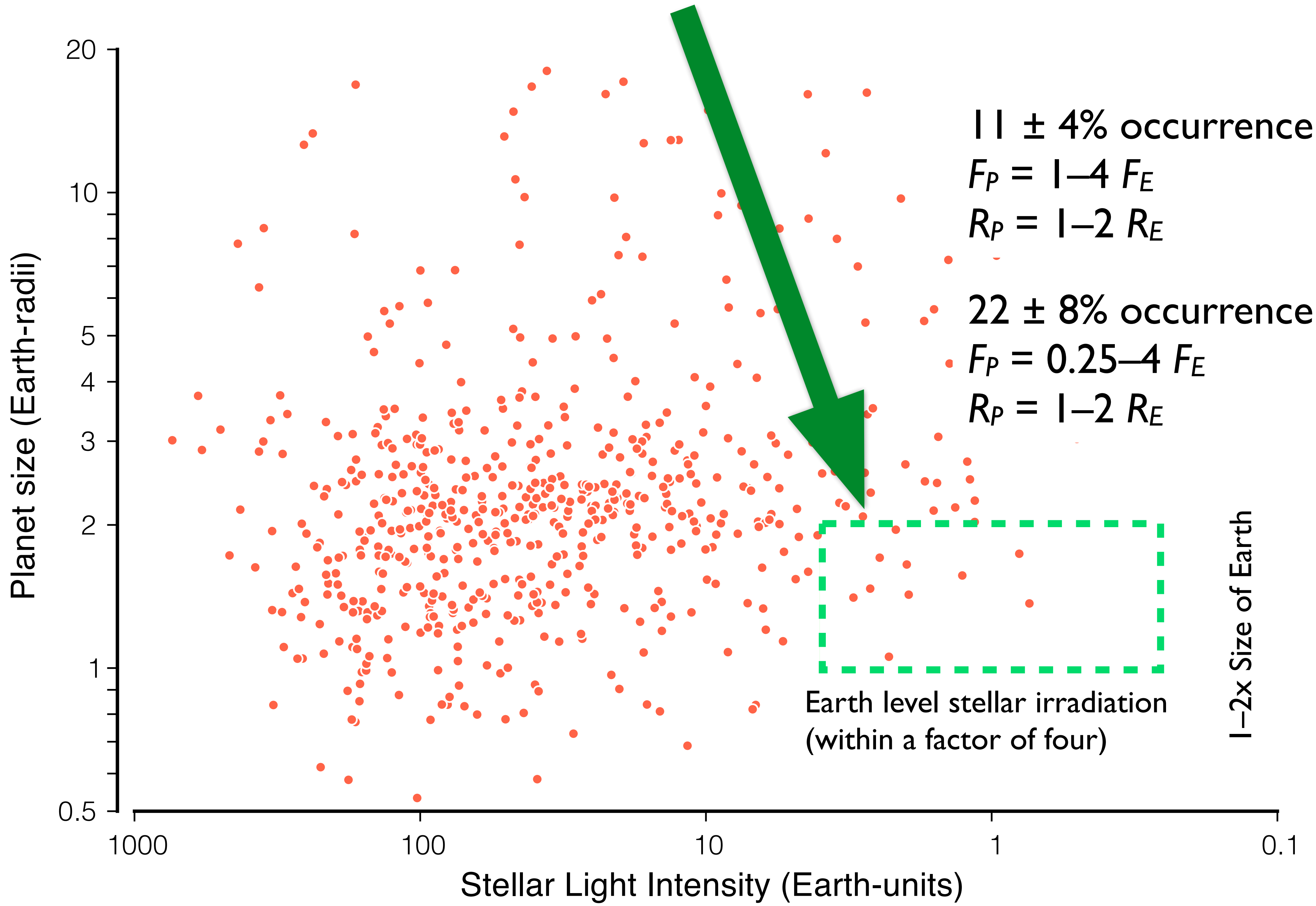
The Occurrence of Warm, Earth-size Planets



Petigura, Howard, & Marcy (2013)

Uncertainties

How big is the $\eta_\oplus$ Box?



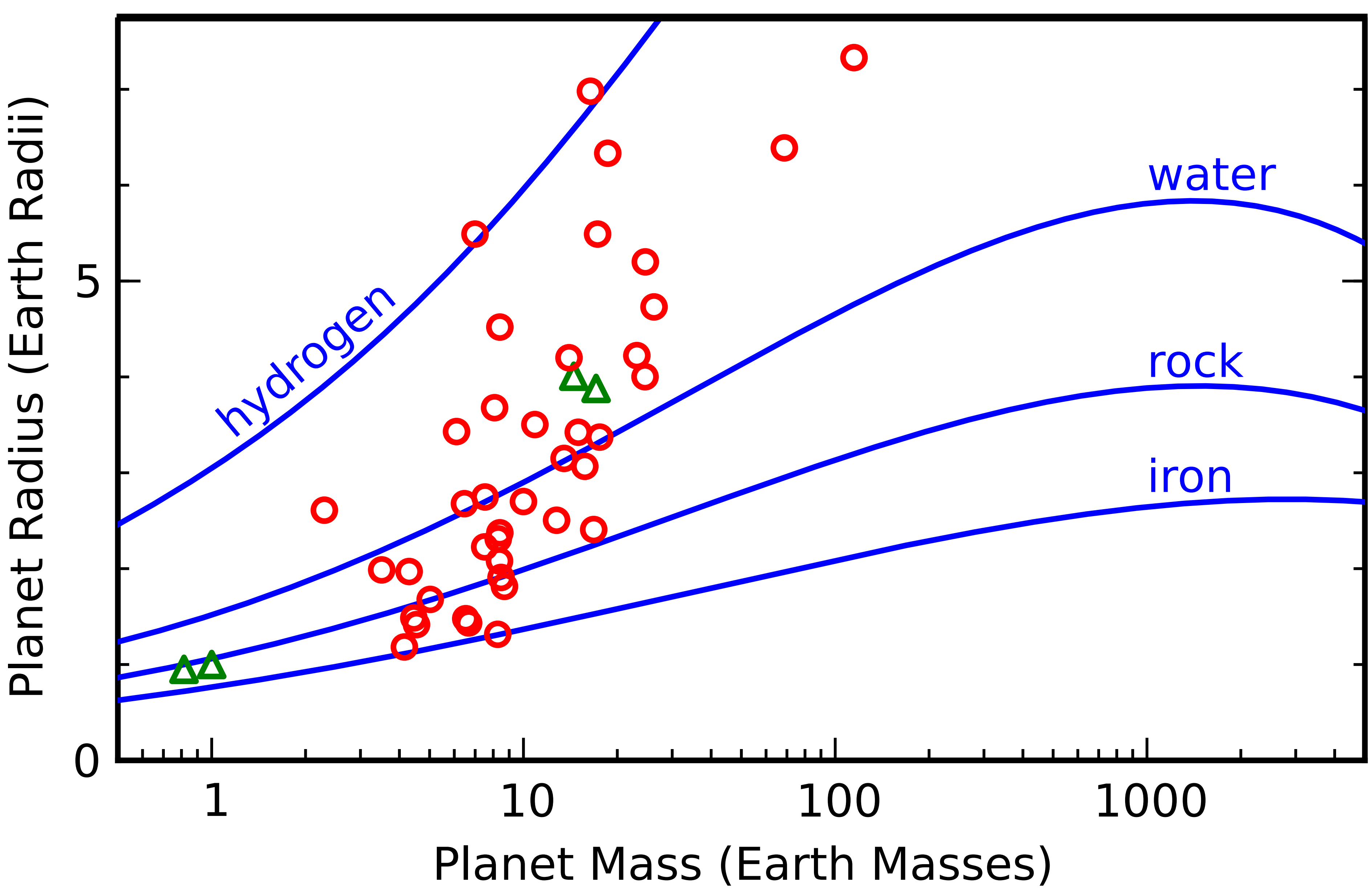
Petigura, Howard, & Marcy (2013)

Uncertainties

Mass-Radius Relationship

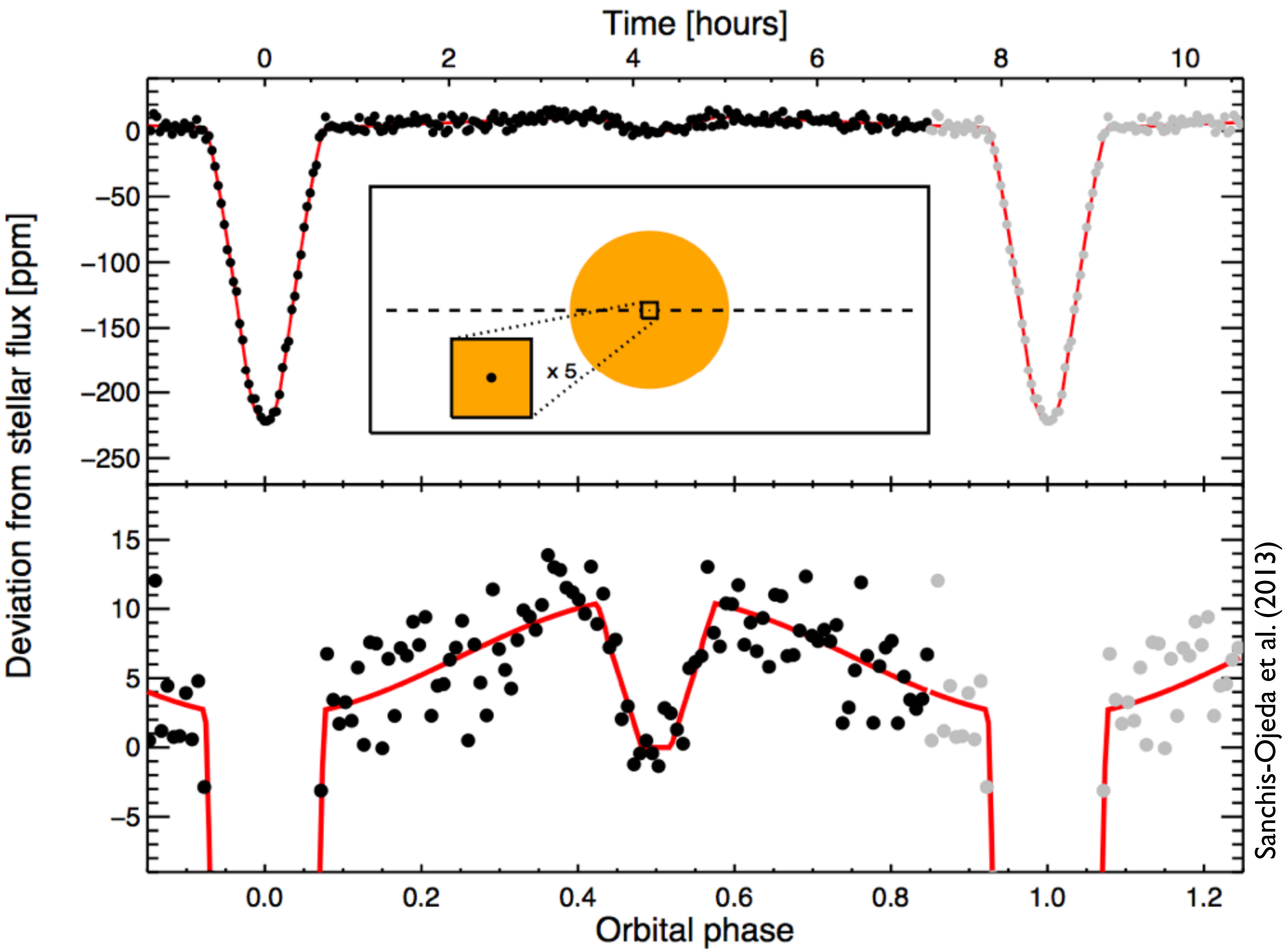
What is an Earth?

Where is the rocky/gas-rich transition?



Kepler-78b Transit Discovery

Sanchis-Ojeda et al. (2013)



Planet Radius:

$1.16^{+0.19}_{-0.14}\ R_{\oplus}$

Orbital Period:

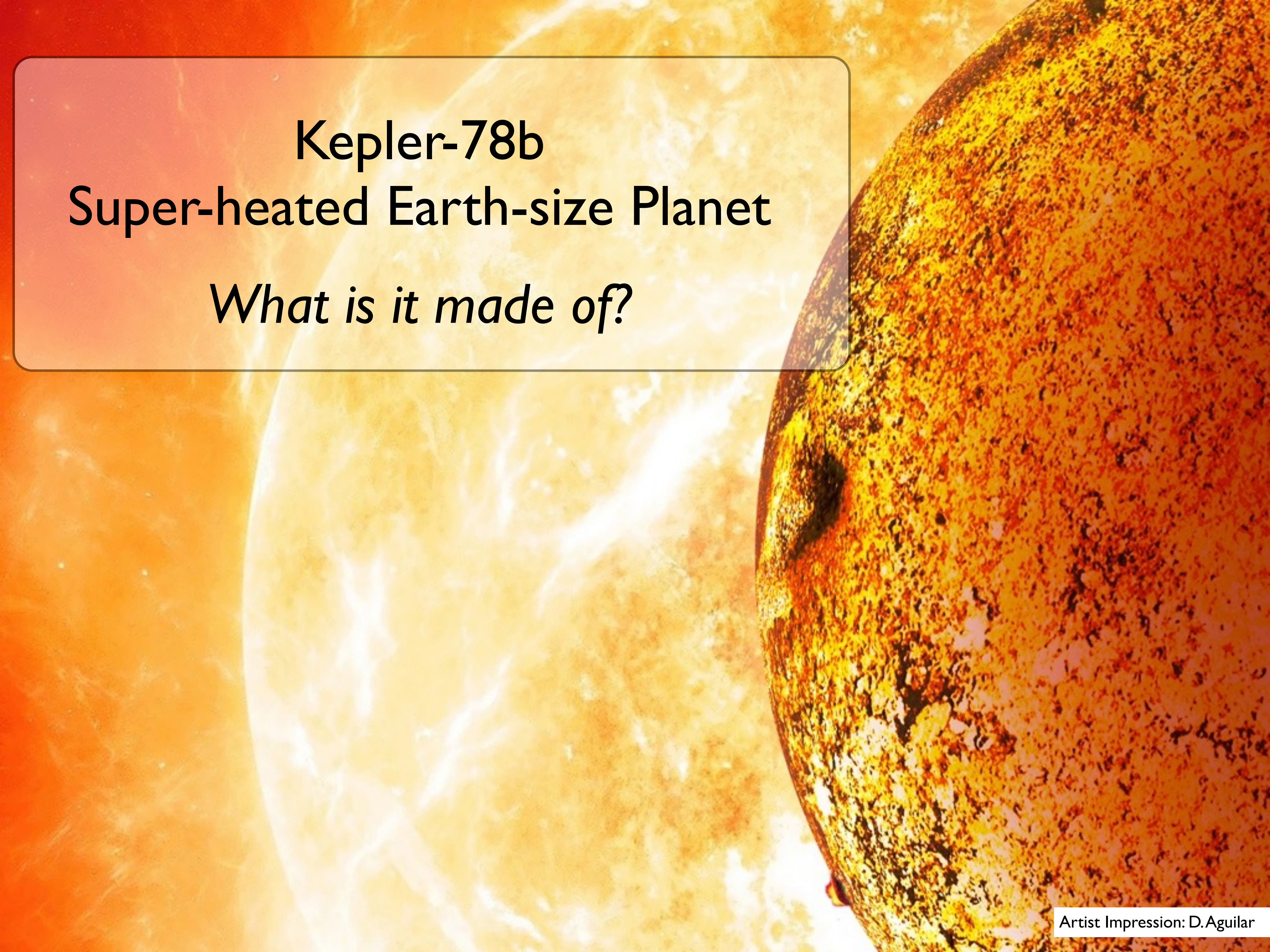
8.5 hours!

Roberto Sanchis-Ojeda

Kepler Photometry

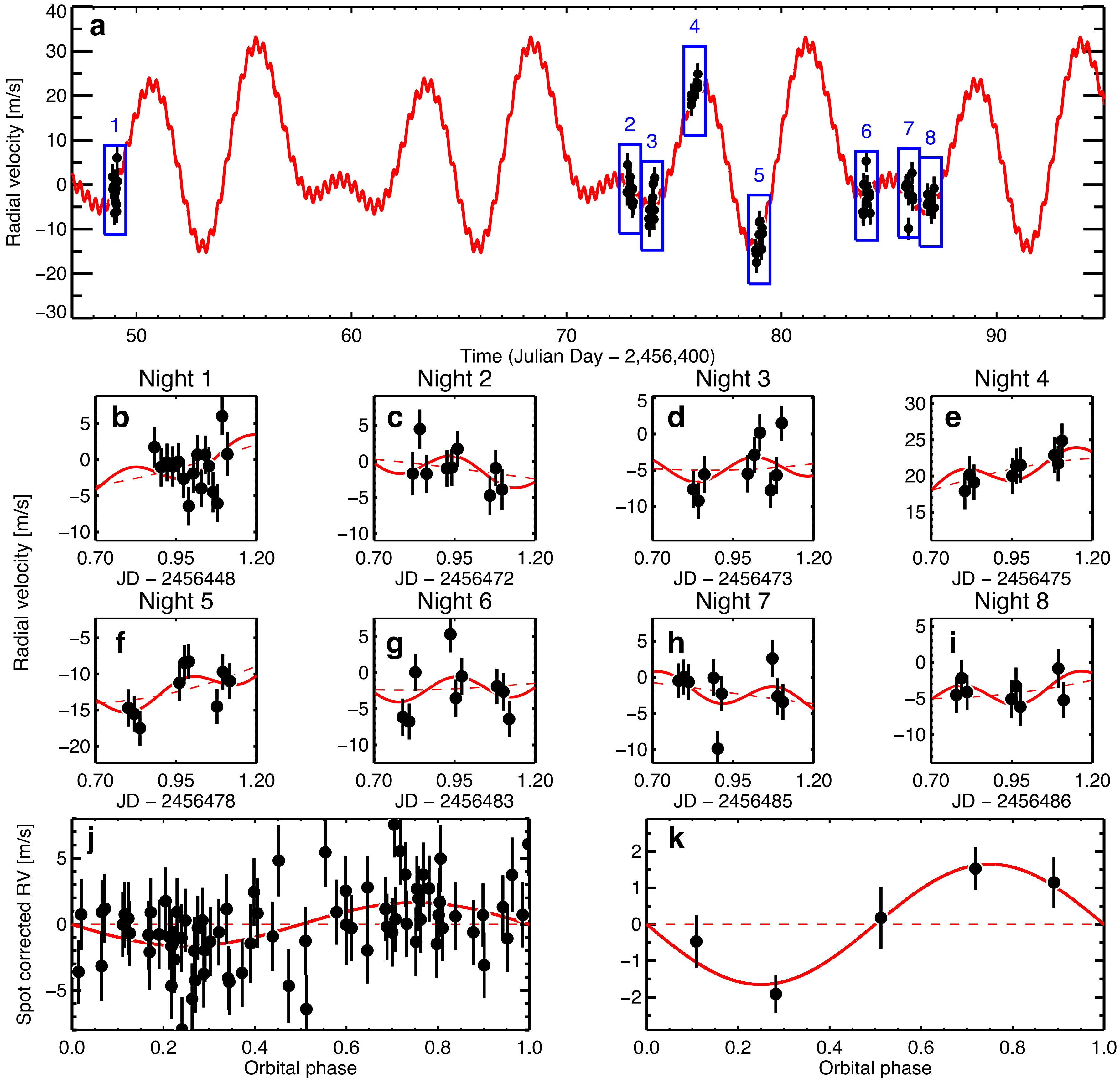
Kepler-78b
Super-heated Earth-size Planet

What is it made of?



Artist Impression: D. Aguilar

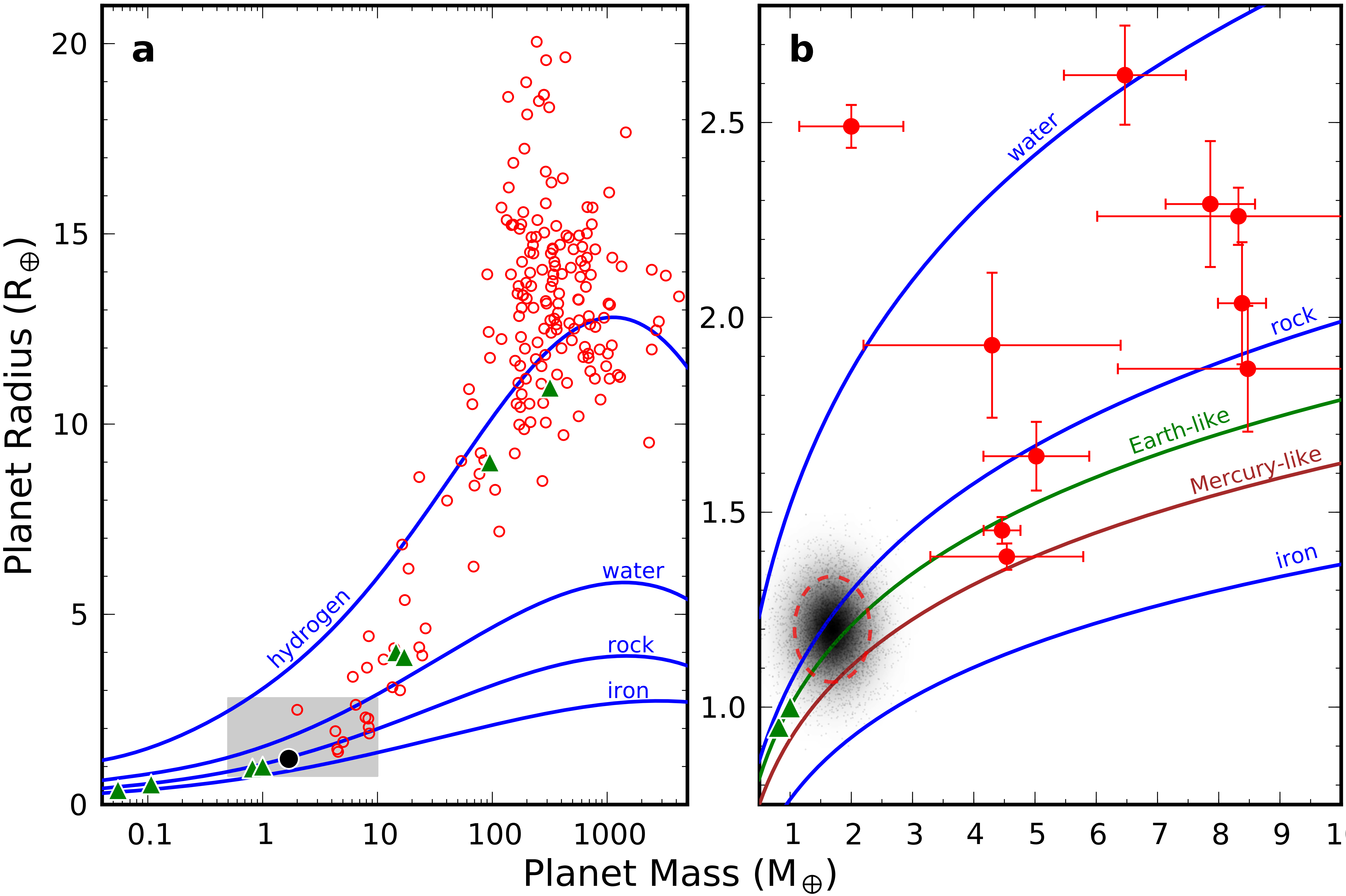
Kepler-78b - Keck-HIRES Doppler Measurements



1.66 ± 0.40 m/s
1.69 ± 0.41 M⊕

Howard et al. (2013)

Known Planets - Masses and Radii



Howard et al. (2013)

LETTER

doi:10.1038/nature12767

A rocky composition for an Earth-sized exoplanet

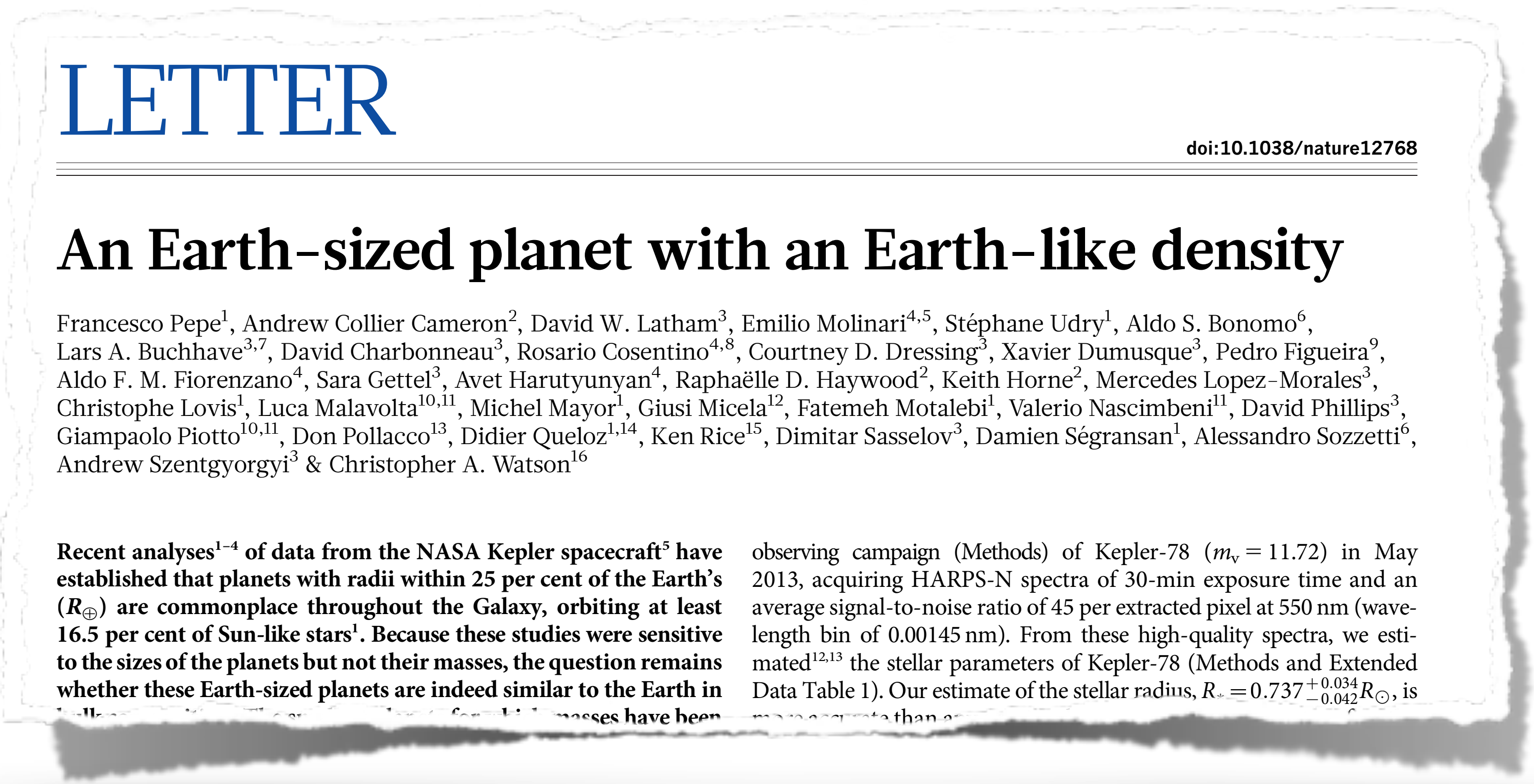
Andrew W. Howard[1], Roberto Sanchis-Ojeda[2], Geoffrey W. Marcy[3], John Asher Johnson[4], Joshua N. Winn[2], Howard Isaacson[3], Debra A. Fischer[5], Benjamin J. Fulton[1], Evan Sinukoff[1] & Jonathan J. Fortney[6]

Planets with sizes between that of Earth (with radius $R_\oplus$) and Neptune (about $4R_\oplus$) are now known to be common around Sun-like stars[1–3]. Most such planets have been discovered through the transit technique, by which the planet's size can be determined from the fraction of starlight blocked by the planet as it passes in front of its star. Measuring the planet's mass—and hence its density, which is a clue to its composition—is more difficult. Planets of size 2–$4R_\oplus$ have proved to have a wide range of densities, implying a diversity of compositions[4,5], but these measurements did not extend to planets as small as Earth. Here we report Doppler spectroscopic measurements of the mass of the Earth-sized planet Kepler-78b, which orbits its host star every 8.5 hours (ref. 6). Given a radius of $1.20 \pm 0.09R_\oplus$ and a mass of $1.69 \pm 0.41M_\oplus$, the planet's mean density of $5.3 \pm 1.8\,\mathrm{g\,cm^{-3}}$ is similar to Earth's, suggesting a composition of rock and iron.

$8M_\oplus$ could be ruled out because the planet's gravity would have deformed the star and produced brightness variations that were not detected.

We measured the mass of Kepler-78b by tracking the line-of-sight component of the host star's motion (the radial velocity) that is due to the gravitational force of the planet. The radial-velocity analysis is challenging not only because the signal is expected to be small (about 1–$3\,\mathrm{m\,s^{-1}}$) but also because the apparent Doppler shifts due to rotating star spots are much larger (about $50\,\mathrm{m\,s^{-1}}$ peak-to-peak). Nevertheless the detection proved to be possible, thanks to the precisely known orbital period and phase of Kepler-78b that cleanly separated the timescale of spot variations ($P_{\mathrm{rot}} \approx 12.5$ days) from the much shorter timescale of the planetary orbit ($P \approx 8.5$ hours). We adopted a strategy of intensive Doppler measurements spanning 6–8 hours per night, long enough to cover nearly the entire

Keck/HIRES (10-m)



LETTER

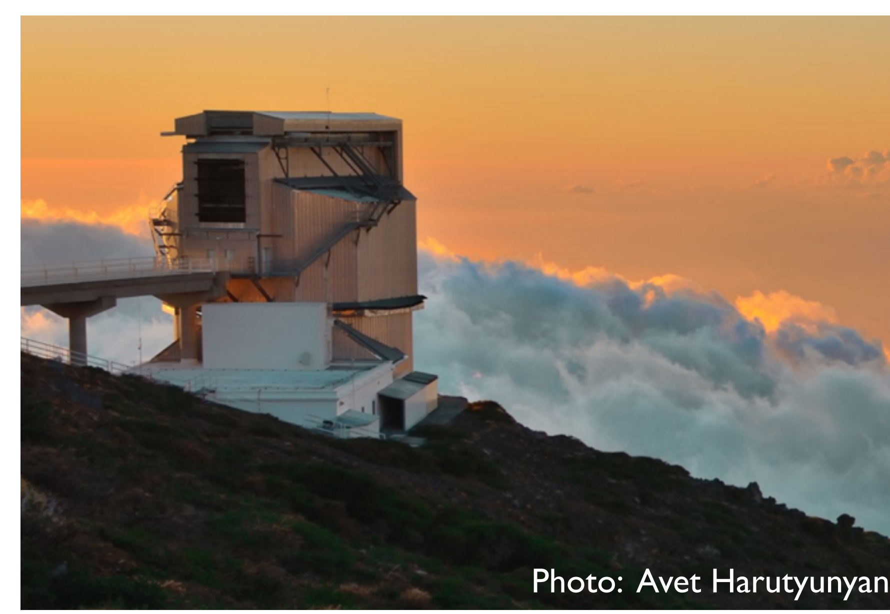
doi:10.1038/nature12768

An Earth-sized planet with an Earth-like density

Francesco Pepe[1], Andrew Collier Cameron[2], David W. Latham[3], Emilio Molinari[4,5], Stéphane Udry[1], Aldo S. Bonomo[6], Lars A. Buchhave[3,7], David Charbonneau[3], Rosario Cosentino[4,8], Courtney D. Dressing[3], Xavier Dumusque[3], Pedro Figueira[9], Aldo F. M. Fiorenzano[4], Sara Gettel[3], Avet Harutyunyan[4], Raphaëlle D. Haywood[2], Keith Horne[2], Mercedes Lopez-Morales[3], Christophe Lovis[1], Luca Malavolta[10,11], Michel Mayor[1], Giusi Micela[12], Fatemeh Motalebi[1], Valerio Nascimbeni[11], David Phillips[3], Giampaolo Piotto[10,11], Don Pollacco[13], Didier Queloz[1,14], Ken Rice[15], Dimitar Sasselov[3], Damien Ségransan[1], Alessandro Sozzetti[6], Andrew Szentgyorgyi[3] & Christopher A. Watson[16]

Recent analyses[1–4] of data from the NASA Kepler spacecraft[5] have established that planets with radii within 25 per cent of the Earth's ($R_\oplus$) are commonplace throughout the Galaxy, orbiting at least 16.5 per cent of Sun-like stars[1]. Because these studies were sensitive to the sizes of the planets but not their masses, the question remains whether these Earth-sized planets are indeed similar to the Earth in

observing campaign (Methods) of Kepler-78 ($m_v = 11.72$) in May 2013, acquiring HARPS-N spectra of 30-min exposure time and an average signal-to-noise ratio of 45 per extracted pixel at 550 nm (wavelength bin of 0.00145 nm). From these high-quality spectra, we estimated[12,13] the stellar parameters of Kepler-78 (Methods and Extended Data Table 1). Our estimate of the stellar radius, $R_* = 0.737^{+0.034}_{-0.042}R_\odot$, is



TNG/HARPS-N (3.6-m)

Known Planets - Masses and Radii

HIRES (Howard et al. 2013)

Radius: 1.20 ± 0.09 $R_\oplus$

Mass: 1.69 ± 0.41 $M_\oplus$

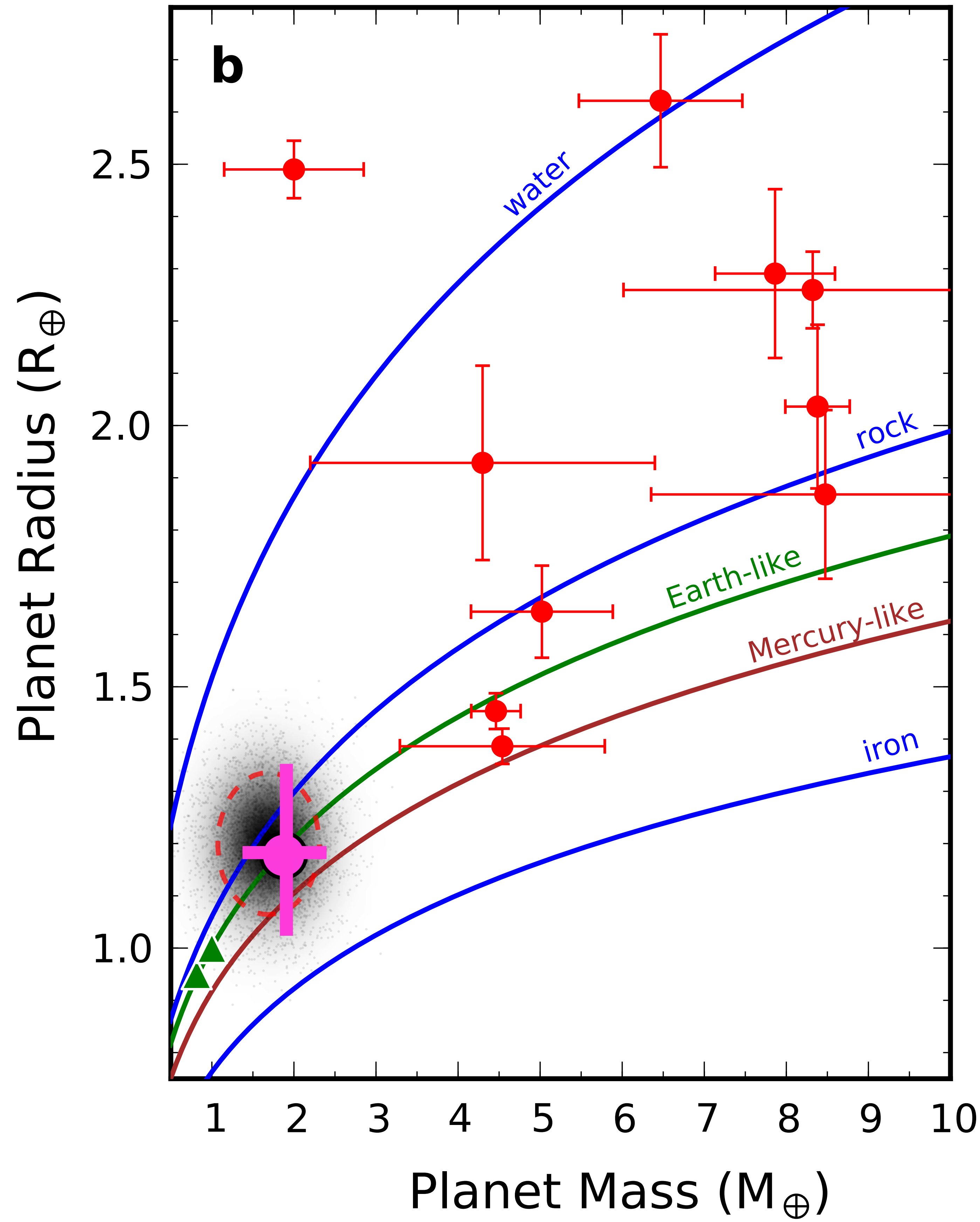
Density: $5.3^{+2.0}_{-1.6}\ \mathrm{g\,cm^{-3}}$

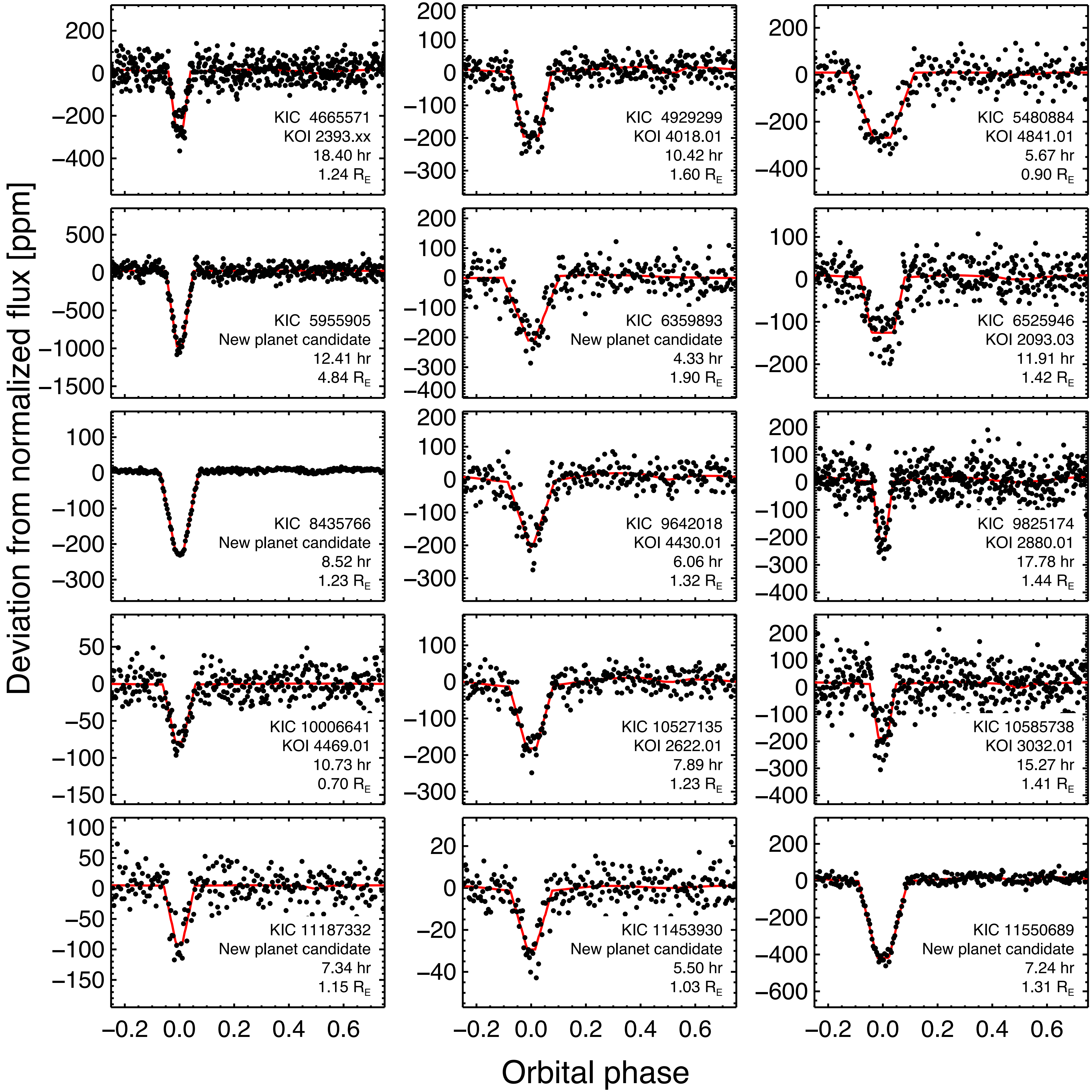
Iron fraction: 0.20 ± 0.33

HARPS-N (Pepe et al. 2013)

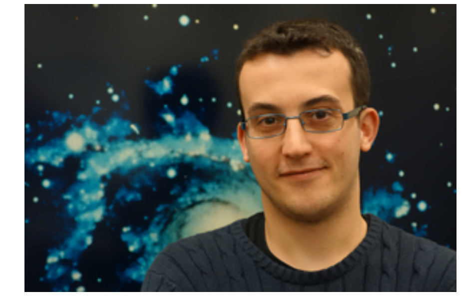
Mass: $1.86^{+0.38}_{-0.25}\ M_\oplus$

Density: $5.6^{+3.0}_{-1.3}\ \mathrm{g\,cm^{-3}}$



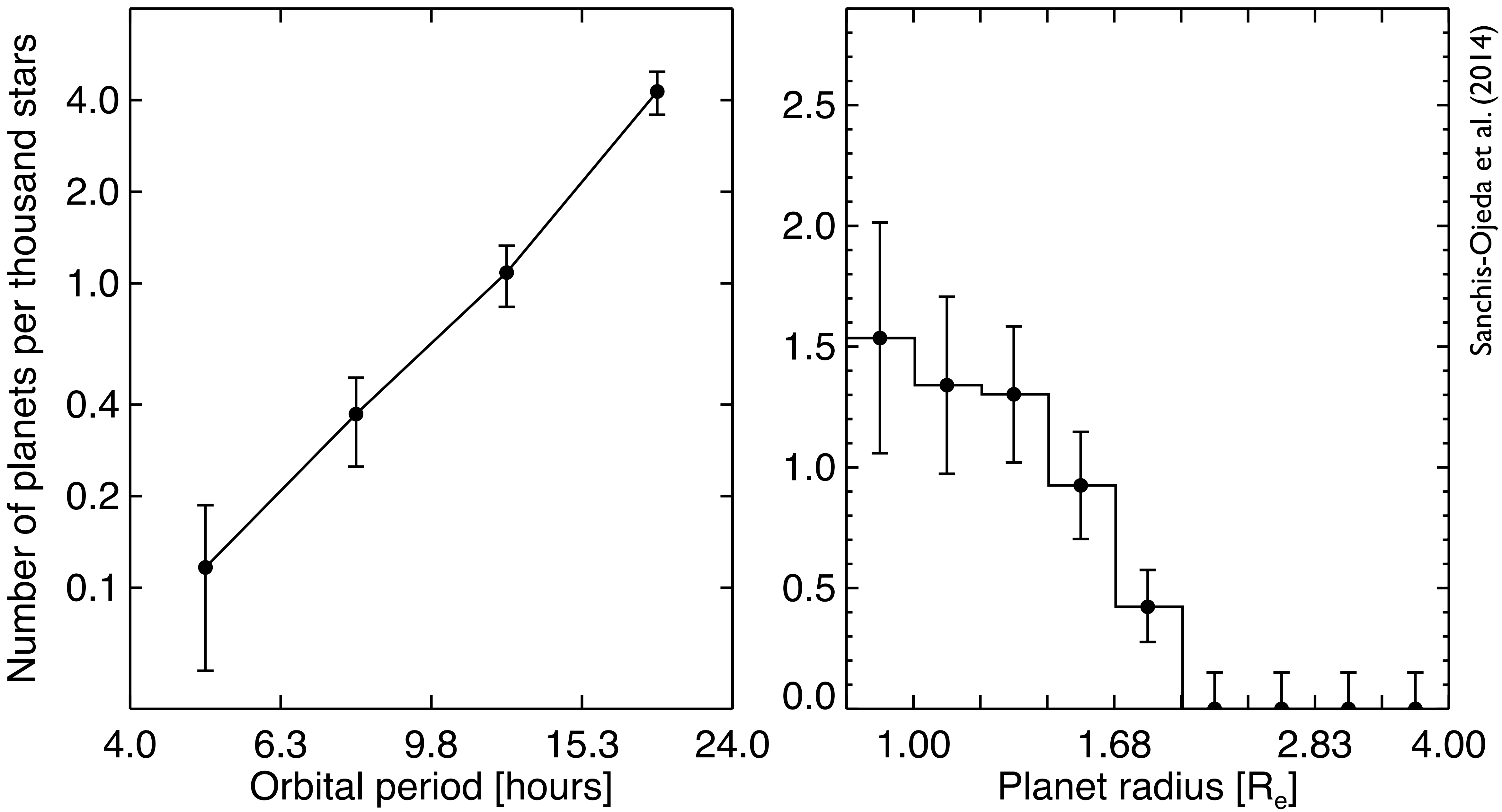


Sanchis-Ojeda et al. (2014)

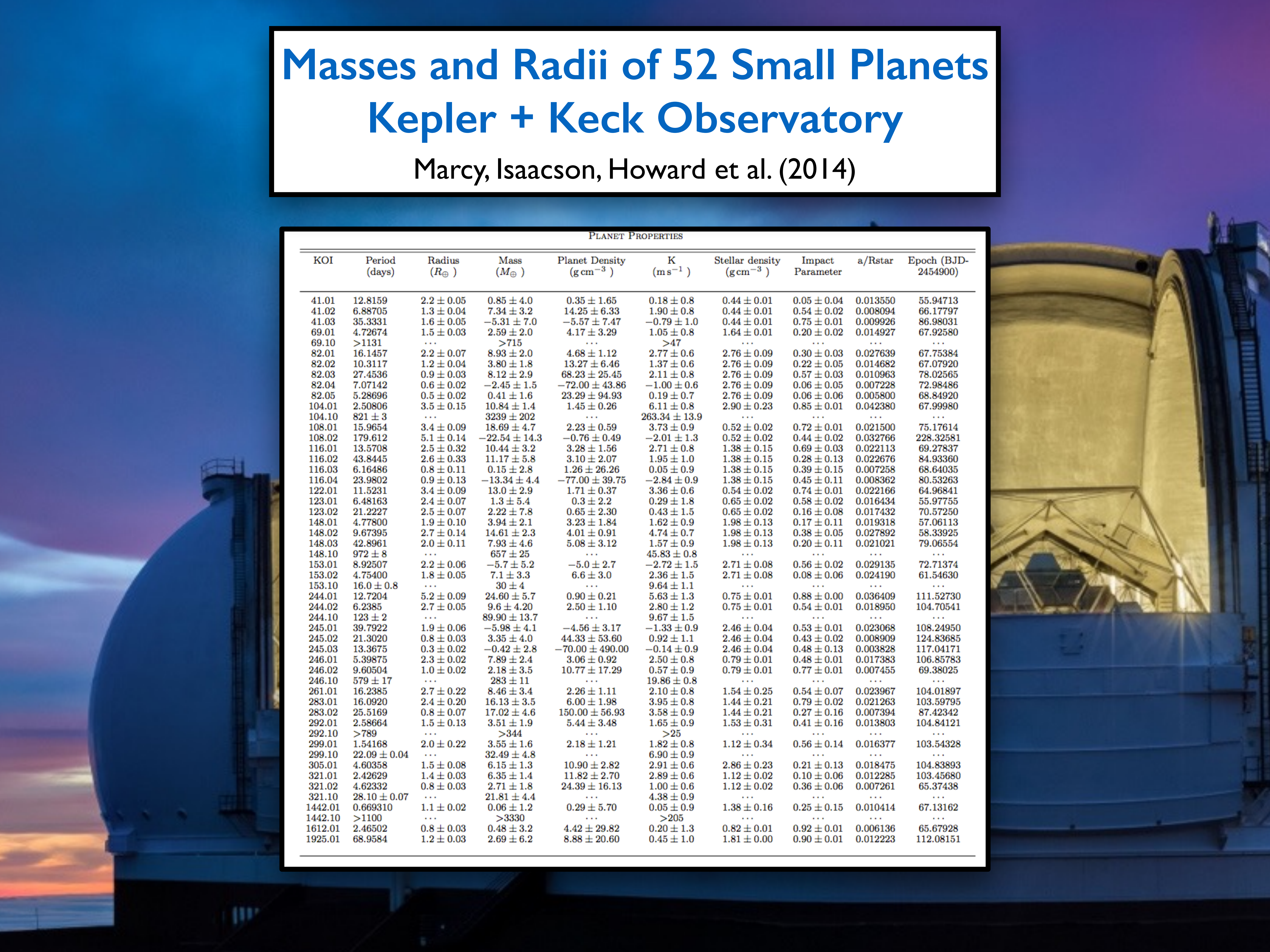


Roberto Sanchis-Ojeda

Occurrence Distribution - P < 1 day



Roberto Sanchis-Ojeda

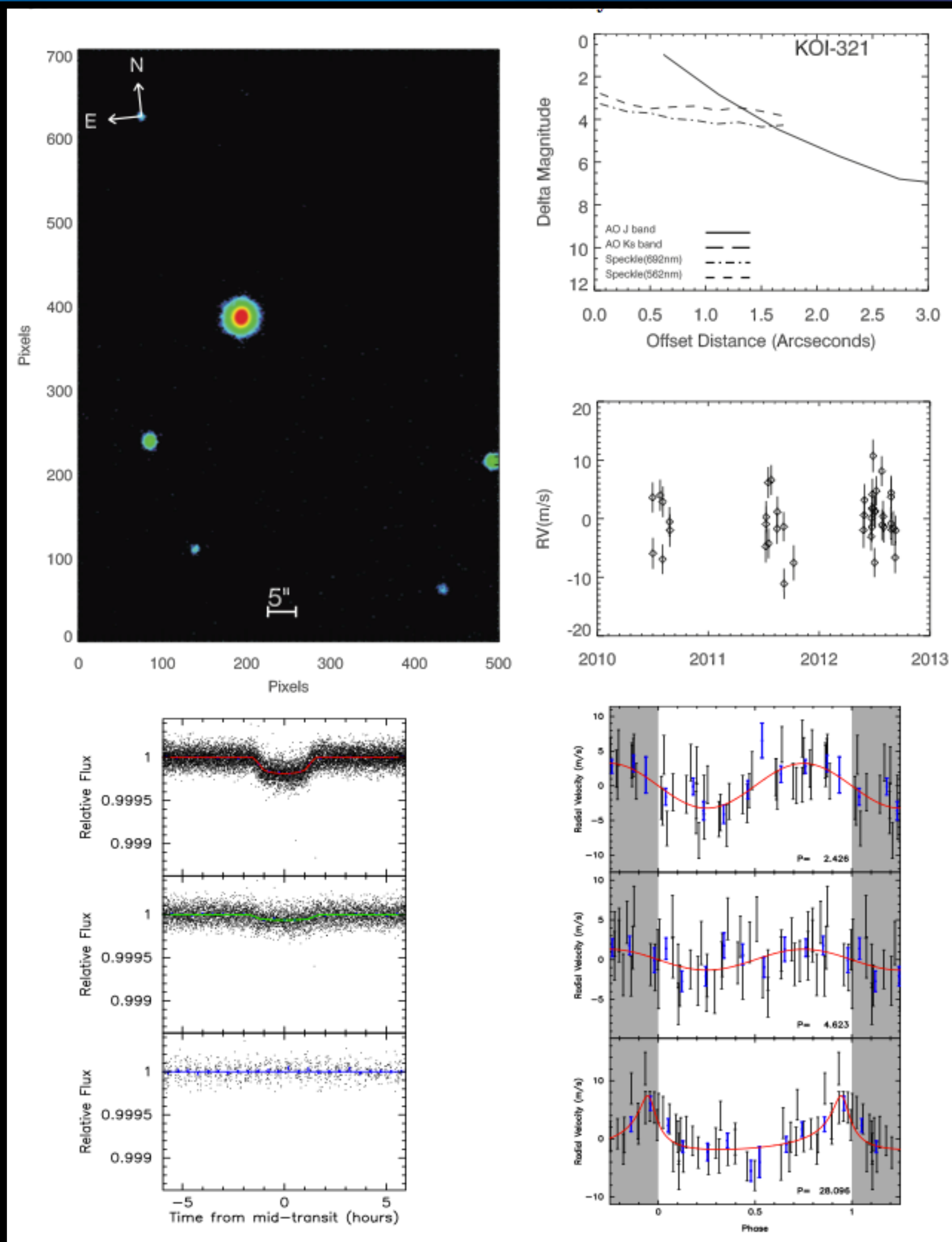


Masses and Radii of 52 Small Planets
Kepler + Keck Observatory

Marcy, Isaacson, Howard et al. (2014)

Planet Properties

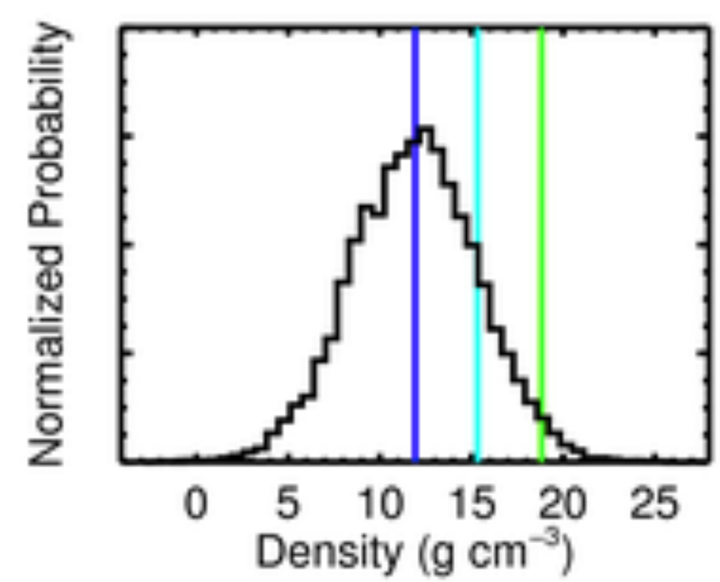
KOI	Period (days)	Radius ($R_\oplus$)	Mass ($M_\oplus$)	Planet Density ($\mathrm{g\,cm^{-3}}$)	K ($\mathrm{m\,s^{-1}}$)	Stellar density ($\mathrm{g\,cm^{-3}}$)	Impact Parameter	a/Rstar	Epoch (BJD-2454900)
41.01	12.8159	2.2 ± 0.05	0.85 ± 4.0	0.35 ± 1.65	0.18 ± 0.8	0.44 ± 0.01	0.05 ± 0.04	0.013550	55.94713
41.02	6.88705	1.3 ± 0.04	7.34 ± 3.2	14.25 ± 6.33	1.90 ± 0.8	0.44 ± 0.01	0.54 ± 0.02	0.008094	66.17797
41.03	35.3331	1.6 ± 0.05	−5.31 ± 7.0	−5.57 ± 7.47	−0.79 ± 1.0	0.44 ± 0.01	0.75 ± 0.01	0.009926	86.98031
69.01	4.72674	1.5 ± 0.03	2.59 ± 2.0	4.17 ± 3.29	1.05 ± 0.8	1.64 ± 0.01	0.20 ± 0.02	0.014927	67.92580
69.10	>1131	···	>715	···	>47	···	···	···	···
82.01	16.1457	2.2 ± 0.07	8.93 ± 2.0	4.68 ± 1.12	2.77 ± 0.6	2.76 ± 0.09	0.30 ± 0.03	0.027639	67.75384
82.02	10.3117	1.2 ± 0.04	3.80 ± 1.8	13.27 ± 6.46	1.37 ± 0.6	2.76 ± 0.09	0.22 ± 0.05	0.014682	67.07920
82.03	27.4536	0.9 ± 0.03	8.12 ± 2.9	68.23 ± 25.45	2.11 ± 0.8	2.76 ± 0.09	0.57 ± 0.03	0.010963	78.02565
82.04	7.07142	0.6 ± 0.02	−2.45 ± 1.5	−72.00 ± 43.86	−1.00 ± 0.6	2.76 ± 0.09	0.06 ± 0.05	0.007228	72.98486
82.05	5.28696	0.5 ± 0.02	0.41 ± 1.6	23.29 ± 94.93	0.19 ± 0.7	2.76 ± 0.09	0.06 ± 0.06	0.005800	68.84920
104.01	2.50806	3.5 ± 0.15	10.84 ± 1.4	1.45 ± 0.26	6.11 ± 0.8	2.90 ± 0.23	0.85 ± 0.01	0.042380	67.99980
104.10	821 ± 3	···	3239 ± 202	···	263.34 ± 13.9	···	···	···	···
108.01	15.9654	3.4 ± 0.09	18.69 ± 4.7	2.23 ± 0.59	3.73 ± 0.9	0.52 ± 0.02	0.72 ± 0.01	0.021500	75.17614
108.02	179.612	5.1 ± 0.14	−22.54 ± 14.3	−0.76 ± 0.49	−2.01 ± 1.3	0.52 ± 0.02	0.44 ± 0.02	0.032766	228.32581
116.01	13.5708	2.5 ± 0.32	10.44 ± 3.2	3.28 ± 1.56	2.71 ± 0.8	1.38 ± 0.15	0.69 ± 0.03	0.022113	69.27837
116.02	43.8445	2.6 ± 0.33	11.17 ± 5.8	3.10 ± 2.07	1.95 ± 1.0	1.38 ± 0.15	0.28 ± 0.13	0.022676	84.93360
116.03	6.16486	0.8 ± 0.11	0.15 ± 2.8	1.26 ± 26.26	0.05 ± 0.9	1.38 ± 0.15	0.39 ± 0.15	0.007258	68.64035
116.04	23.9802	0.9 ± 0.13	−13.34 ± 4.4	−77.00 ± 39.75	−2.84 ± 0.9	1.38 ± 0.15	0.45 ± 0.11	0.008362	80.53263
122.01	11.5231	3.4 ± 0.09	13.0 ± 2.9	1.71 ± 0.37	3.36 ± 0.6	0.54 ± 0.02	0.74 ± 0.01	0.022166	64.96841
123.01	6.48163	2.4 ± 0.07	1.3 ± 5.4	0.3 ± 2.2	0.29 ± 1.8	0.65 ± 0.02	0.58 ± 0.02	0.016434	55.97755
123.02	21.2227	2.5 ± 0.07	2.22 ± 7.8	0.65 ± 2.30	0.43 ± 1.5	0.65 ± 0.02	0.16 ± 0.08	0.017432	70.57250
148.01	4.77800	1.9 ± 0.10	3.94 ± 2.1	3.23 ± 1.84	1.62 ± 0.9	1.98 ± 0.13	0.17 ± 0.11	0.019318	57.06113
148.02	9.67395	2.7 ± 0.14	14.61 ± 2.3	4.01 ± 0.91	4.74 ± 0.7	1.98 ± 0.13	0.38 ± 0.05	0.027892	58.33925
148.03	42.8961	2.0 ± 0.11	7.93 ± 4.6	5.08 ± 3.12	1.57 ± 0.9	1.98 ± 0.13	0.20 ± 0.11	0.021021	79.06554
148.10	972 ± 8	···	657 ± 25	···	45.83 ± 0.8	···	···	···	···
153.01	8.92507	2.2 ± 0.06	−5.7 ± 5.2	−5.0 ± 2.7	−2.72 ± 1.5	2.71 ± 0.08	0.56 ± 0.02	0.029135	72.71374
153.02	4.75400	1.8 ± 0.05	7.1 ± 3.3	6.6 ± 3.0	2.36 ± 1.5	2.71 ± 0.08	0.08 ± 0.06	0.024190	61.54630
153.10	16.0 ± 0.8	···	30 ± 4	···	9.64 ± 1.1	···	···	···	···
244.01	12.7204	5.2 ± 0.09	24.60 ± 5.7	0.90 ± 0.21	5.63 ± 1.3	0.75 ± 0.01	0.88 ± 0.00	0.036409	111.52730
244.02	6.2385	2.7 ± 0.05	9.6 ± 4.20	2.50 ± 1.10	2.80 ± 1.2	0.75 ± 0.01	0.54 ± 0.01	0.018950	104.70541
244.10	123 ± 2	···	89.90 ± 13.7	···	9.67 ± 1.5	···	···	···	···
245.01	39.7922	1.9 ± 0.06	−5.98 ± 4.1	−4.56 ± 3.17	−1.33 ± 0.9	2.46 ± 0.04	0.53 ± 0.01	0.023068	108.24950
245.02	21.3020	0.8 ± 0.03	3.35 ± 4.0	44.33 ± 53.60	0.92 ± 1.1	2.46 ± 0.04	0.43 ± 0.02	0.008909	124.83685
245.03	13.3675	0.3 ± 0.02	−0.42 ± 2.8	−70.00 ± 490.00	−0.14 ± 0.9	2.46 ± 0.04	0.48 ± 0.13	0.003828	117.04171
246.01	5.39875	2.3 ± 0.02	7.89 ± 2.4	3.06 ± 0.92	2.50 ± 0.8	0.79 ± 0.01	0.48 ± 0.01	0.017383	106.85783
246.02	9.60504	1.0 ± 0.02	2.18 ± 3.5	10.77 ± 17.29	0.57 ± 0.9	0.79 ± 0.01	0.77 ± 0.01	0.007455	69.38025
246.10	579 ± 17	···	283 ± 11	···	19.86 ± 0.8	···	···	···	···
261.01	16.2385	2.7 ± 0.22	8.46 ± 3.4	2.26 ± 1.11	2.10 ± 0.8	1.54 ± 0.25	0.54 ± 0.07	0.023967	104.01897
283.01	16.0920	2.4 ± 0.20	16.13 ± 3.5	6.00 ± 1.98	3.95 ± 0.8	1.44 ± 0.21	0.79 ± 0.02	0.021263	103.59795
283.02	25.5169	0.8 ± 0.07	17.02 ± 4.6	150.00 ± 56.93	3.58 ± 0.9	1.44 ± 0.21	0.27 ± 0.16	0.007394	87.42342
292.01	2.58664	1.5 ± 0.13	3.51 ± 1.9	5.44 ± 3.48	1.65 ± 0.9	1.53 ± 0.31	0.41 ± 0.16	0.013803	104.84121
292.10	>789	···	>344	···	>25	···	···	···	···
299.01	1.54168	2.0 ± 0.22	3.55 ± 1.6	2.18 ± 1.21	1.82 ± 0.8	1.12 ± 0.34	0.56 ± 0.14	0.016377	103.54328
299.10	22.09 ± 0.04	···	32.49 ± 4.8	···	6.90 ± 0.9	···	···	···	···
305.01	4.60358	1.5 ± 0.08	6.15 ± 1.3	10.90 ± 2.82	2.91 ± 0.6	2.86 ± 0.23	0.21 ± 0.13	0.018475	104.83893
321.01	2.42629	1.4 ± 0.03	6.35 ± 1.4	11.82 ± 2.70	2.89 ± 0.6	1.12 ± 0.02	0.10 ± 0.06	0.012285	103.45680
321.02	4.62332	0.8 ± 0.03	2.71 ± 1.8	24.39 ± 16.13	1.00 ± 0.6	1.12 ± 0.02	0.36 ± 0.06	0.007261	65.37438
321.10	28.10 ± 0.07	···	21.81 ± 4.4	···	4.38 ± 0.9	···	···	···	···
1442.01	0.669310	1.1 ± 0.02	0.06 ± 1.2	0.29 ± 5.70	0.05 ± 0.9	1.38 ± 0.16	0.25 ± 0.15	0.010414	67.13162
1442.10	>1100	···	>3330	···	>205	···	···	···	···
1612.01	2.46502	0.8 ± 0.03	0.48 ± 3.2	4.42 ± 29.82	0.20 ± 1.3	0.82 ± 0.01	0.92 ± 0.01	0.006136	65.67928
1925.01	68.9584	1.2 ± 0.03	2.69 ± 6.2	8.88 ± 20.60	0.45 ± 1.0	1.81 ± 0.00	0.90 ± 0.01	0.012223	112.08151



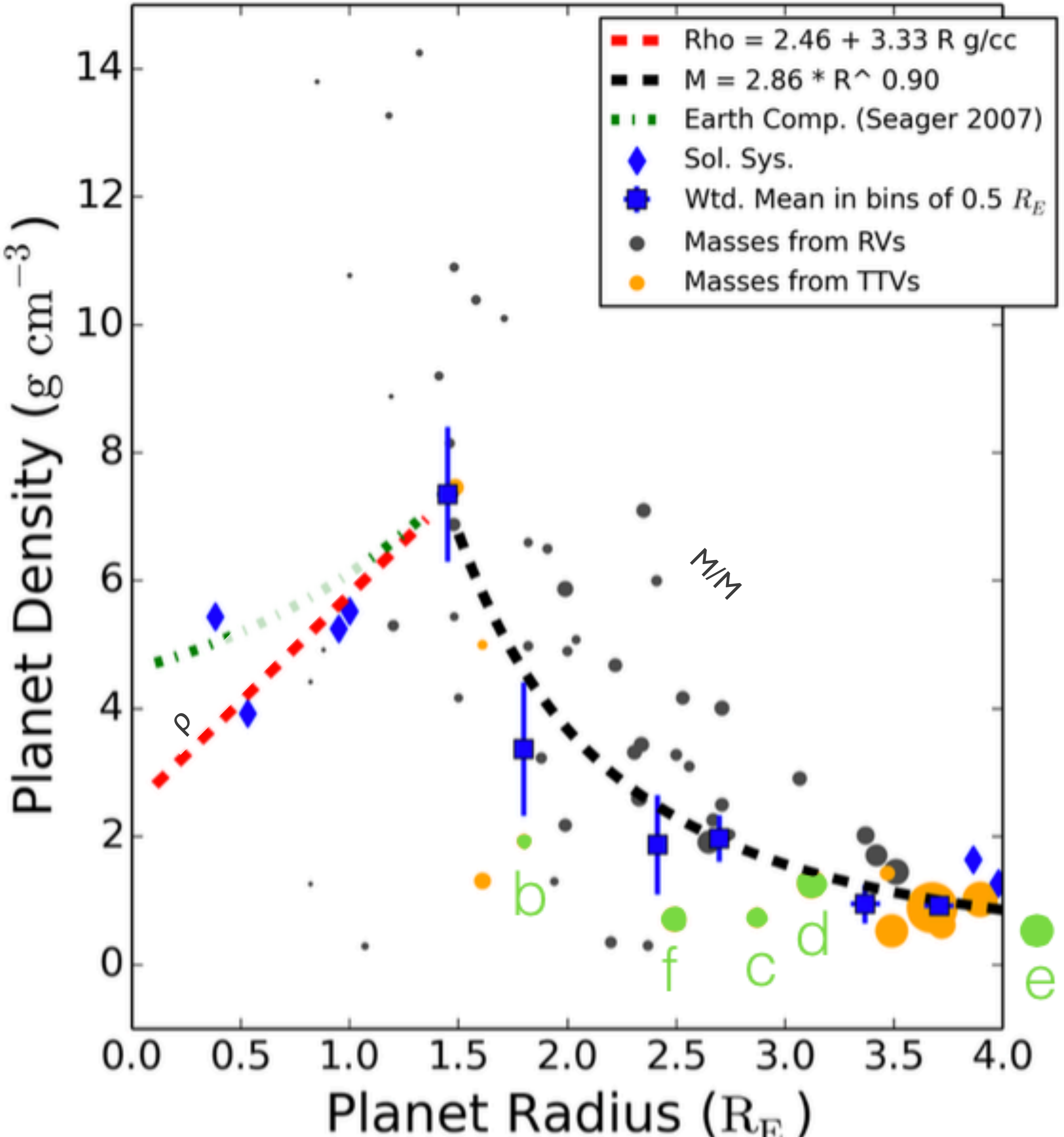
KOI-321: New Rocky Planet

321.01		321.02	
Per(days):	2.43	Per2(days):	4.62
R_p(R_e):	1.41	R_p(R_e) =	0.85
M_p(M_e):	6.69	M_p(M_e):	1.43
Rho_p(g/cc):	13.05	Rho_p(g/cc):	12.93
K(m/s)=	3.04	K(m/s)=	0.53

Density: 321.01



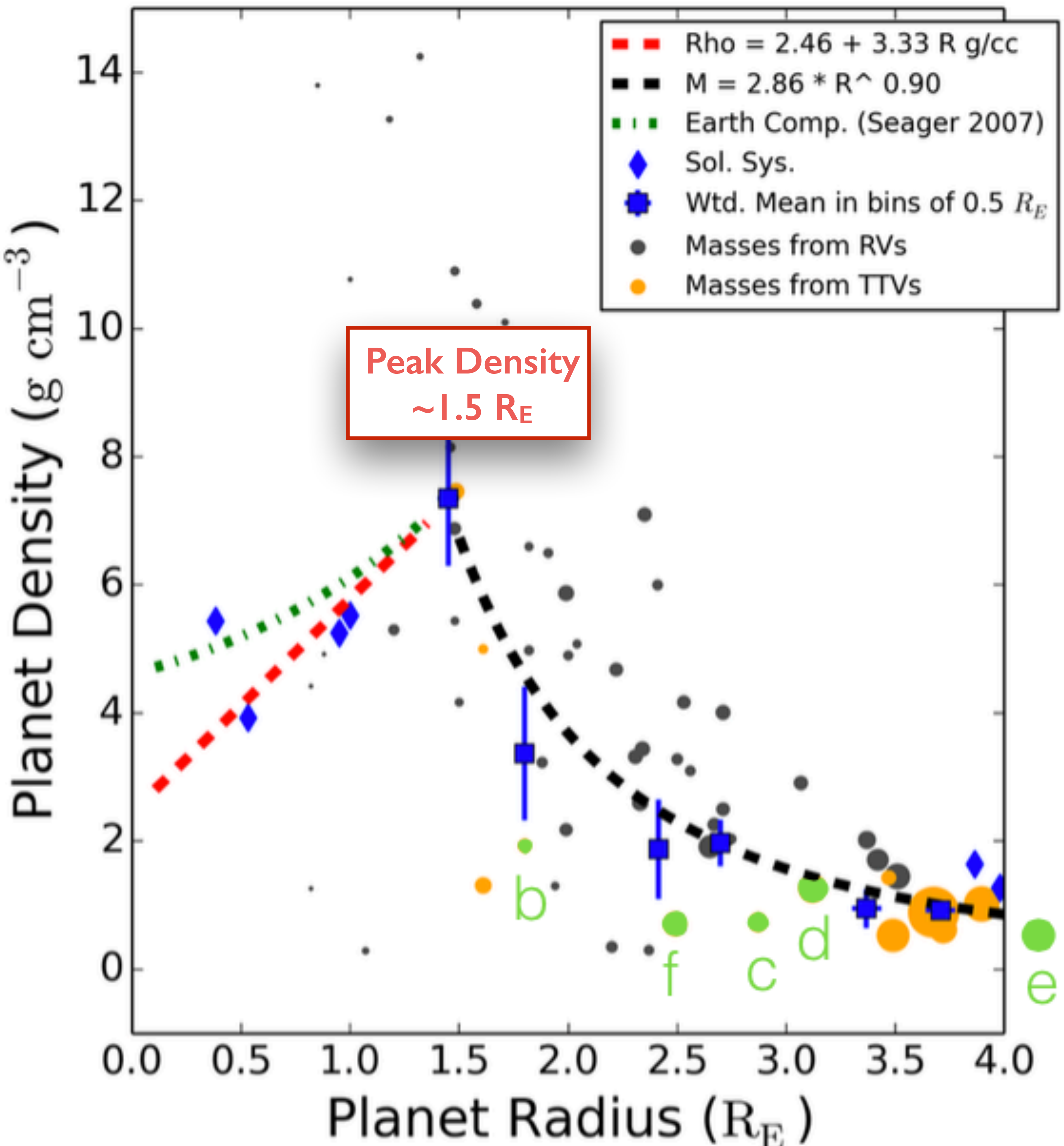
Rock → Gas Transition



Weiss & Marcy (2014)

Lauren Weiss (Berkeley)

Rock → Gas Transition

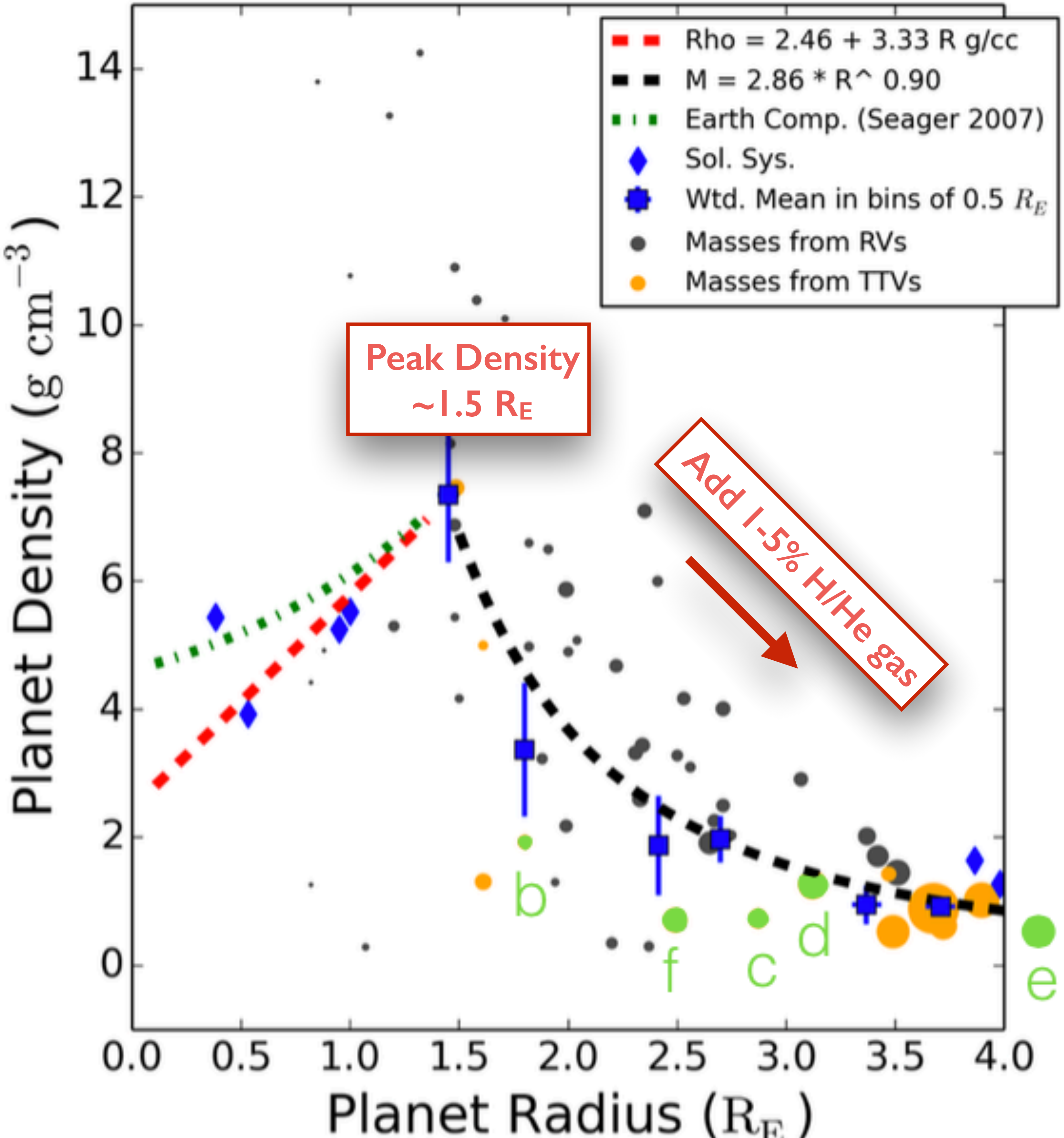


Weiss & Marcy (2014)

1. Peak Density ~1.5 R_E

Lauren Weiss (Berkeley)

Rock → Gas Transition

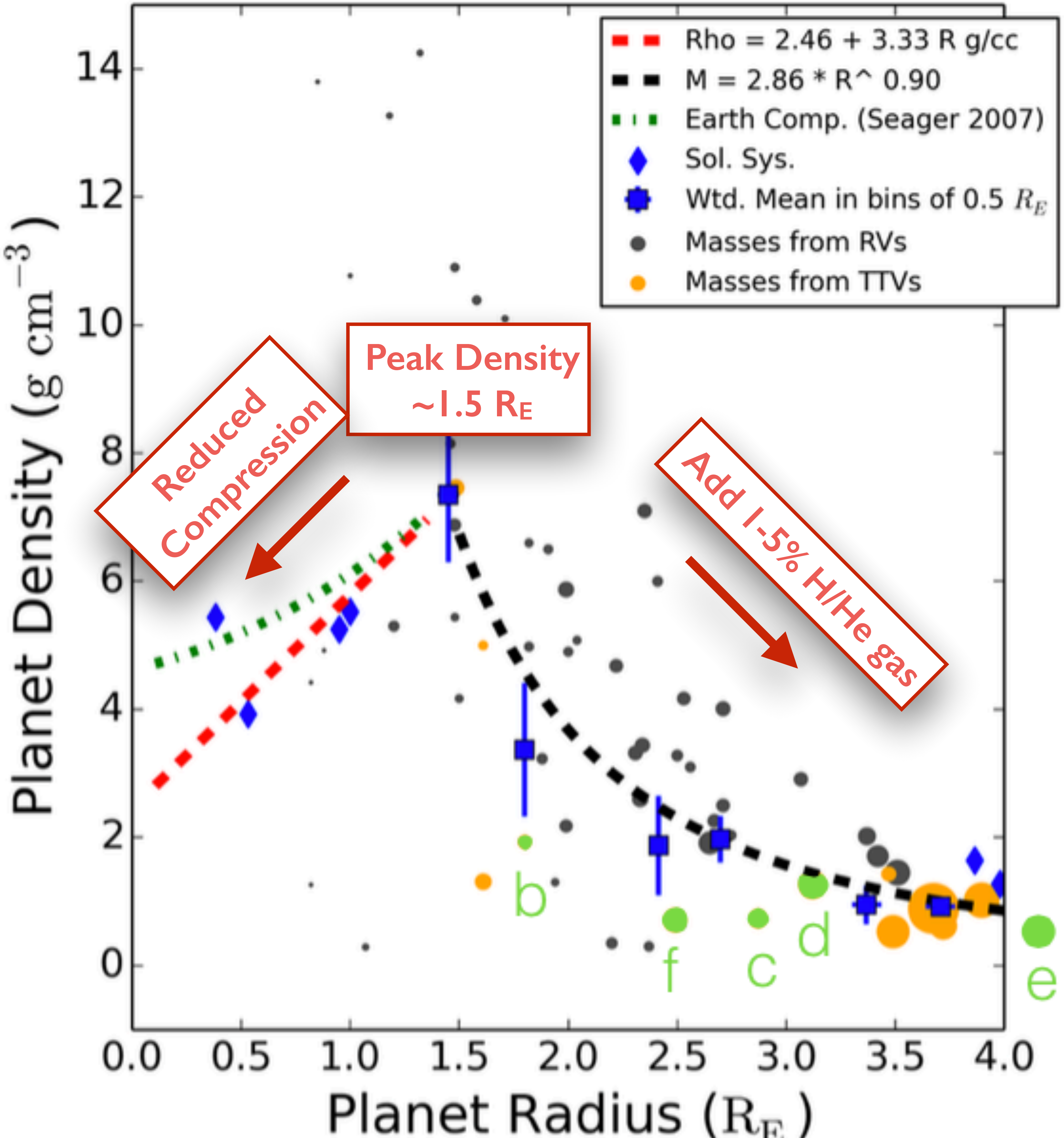


Weiss & Marcy (2014)

1. Peak density ~1.5 R_E
2. ≳1.5 R_E → smaller density
   add 1-5% H/He gas
   density → 1 g cm^{-3}

Lauren Weiss (Berkeley)

Rock → Gas Transition

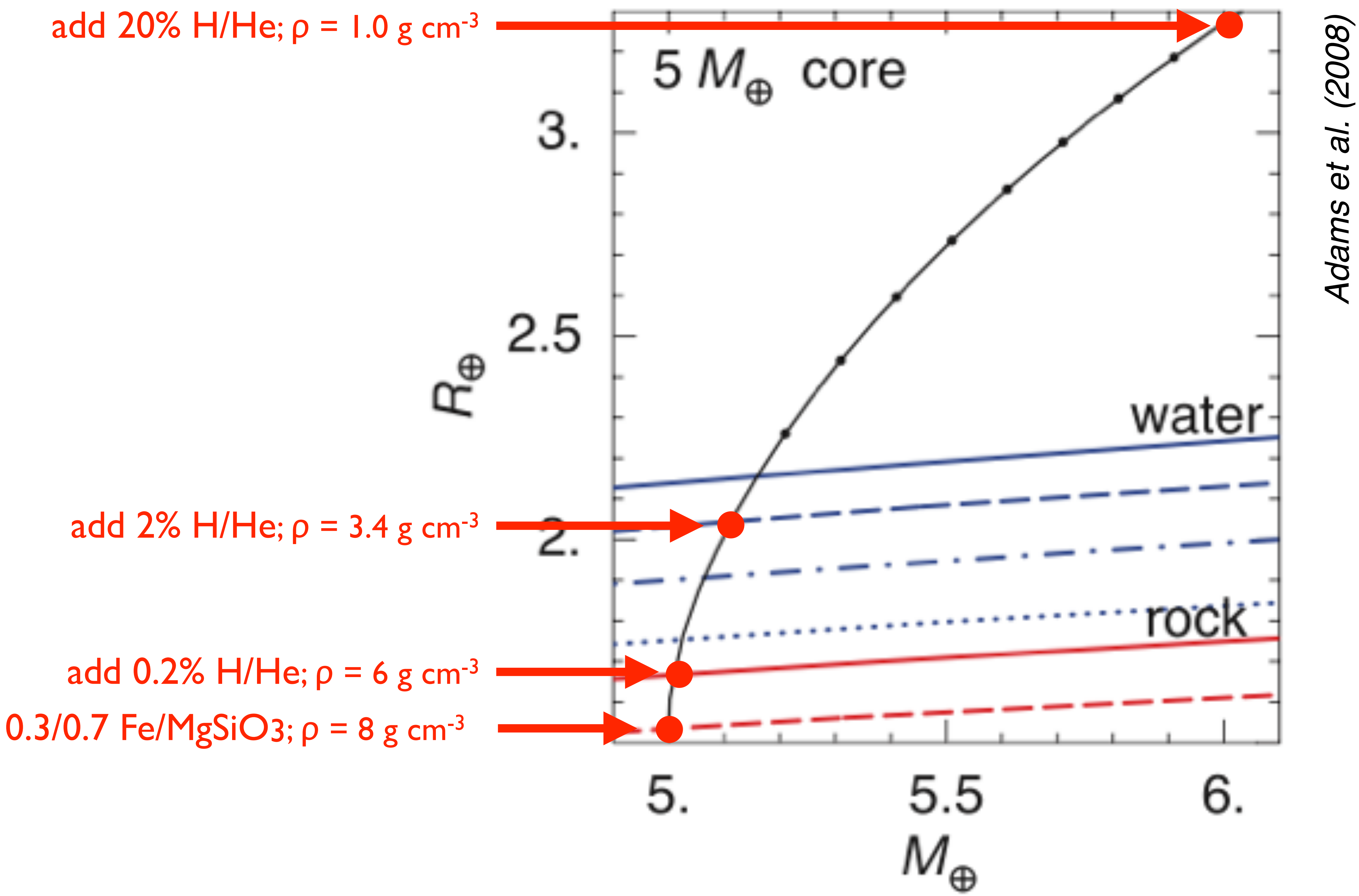


Weiss & Marcy (2014)

1. Peak density ~1.5 R_E
2. ≳1.5 R_E → smaller density
   add 1-5% H/He gas
   density → 1 g cm^{-3}
3. ≲1.5 R_E → smaller density
   same rocky composition
   with reduced compression?

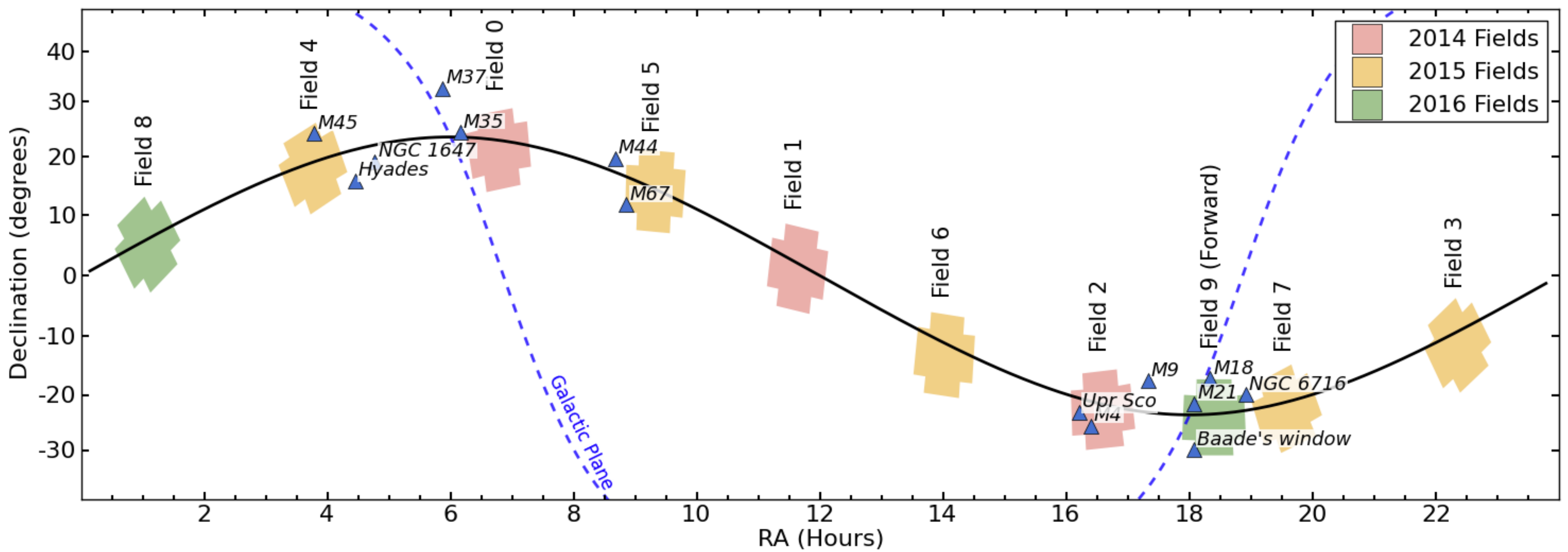
Lauren Weiss (Berkeley)

Adding an Atmosphere

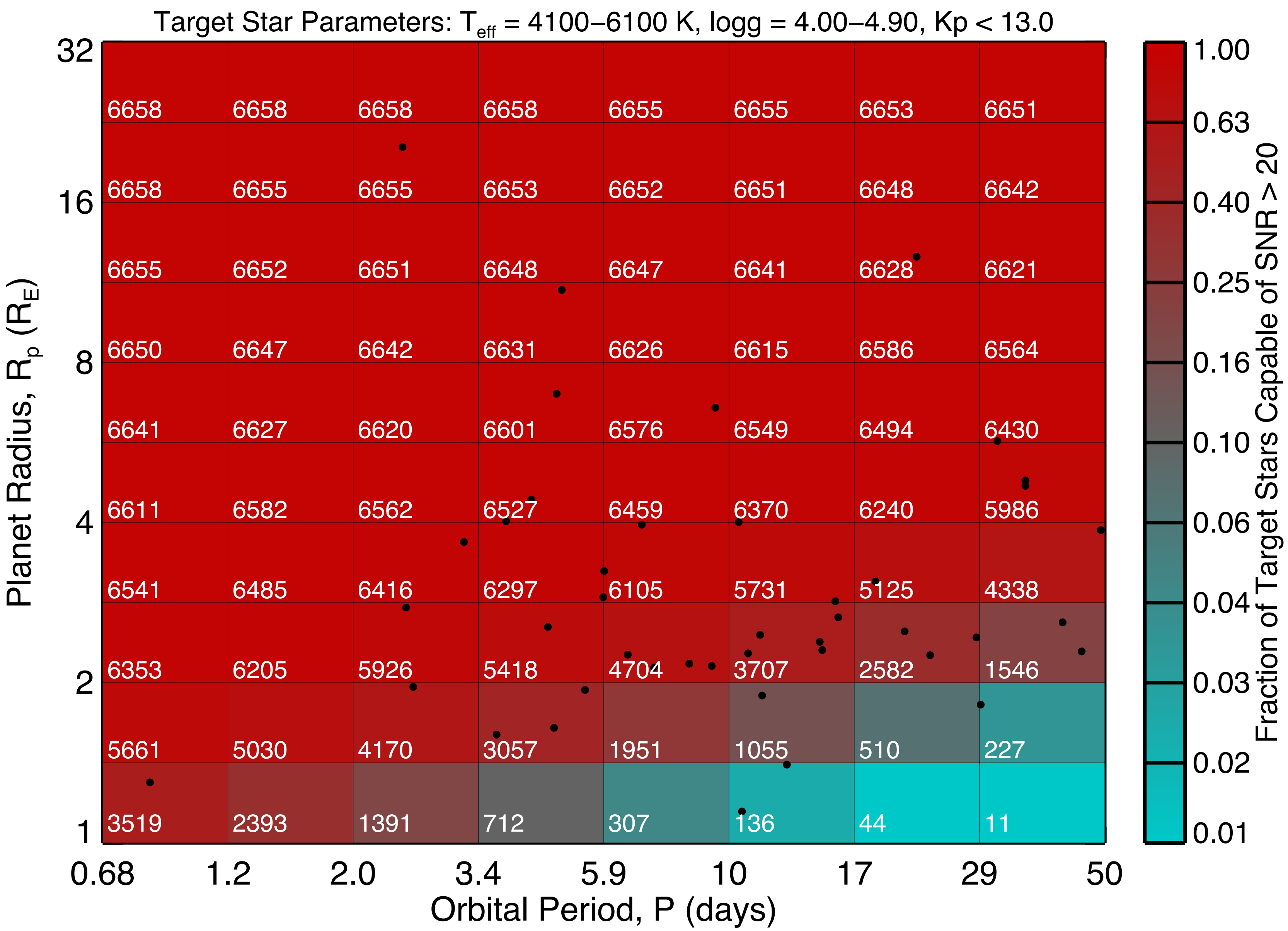


Planet inflation depends on: M_{core}, T_{eff}, internal heat sources

K2 Mission — 13 Fields on the Ecliptic



K2 Search Completeness / Expected Yield



<u>Simulated K2 Performance</u>

Kp < 13 (bright)

Teff=4100-6100K, logg=4.0-4.9

→ 6658 stars selected

2X worse noise

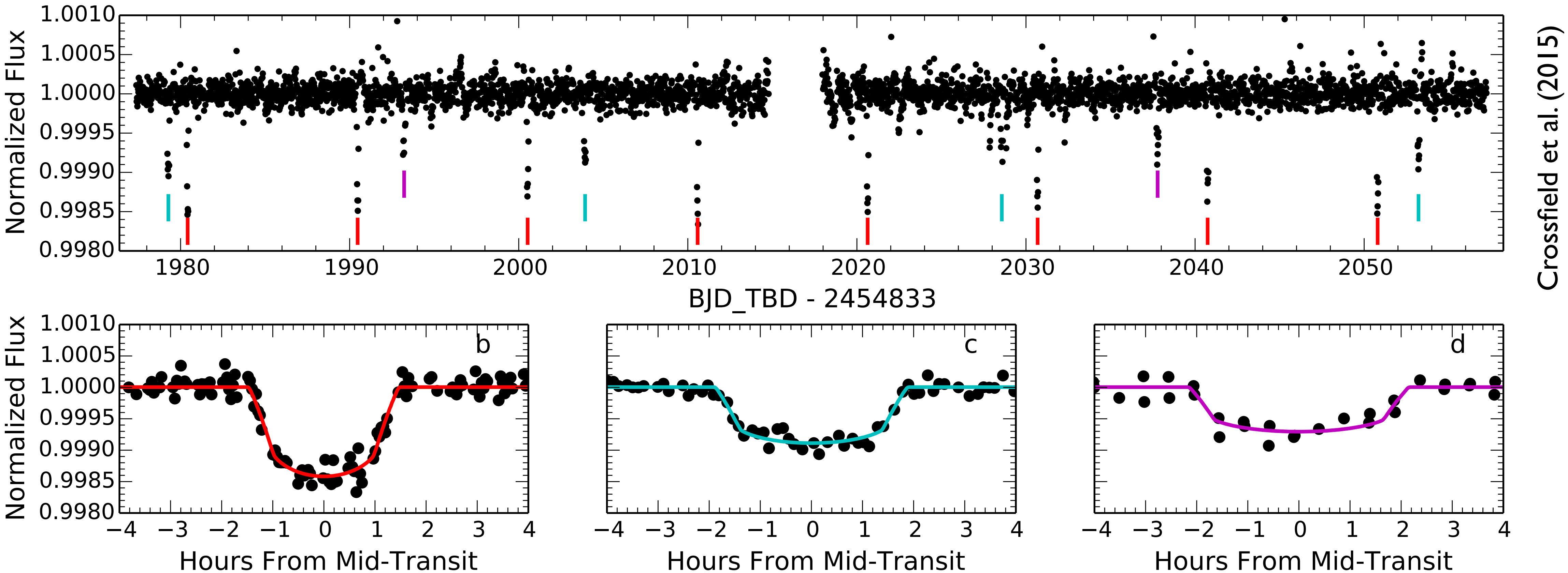
require SNR>20 in 75 days

→ N_{pl} = 46 planets detected

N_{pl} = 26 with R_p = 2-4 R_{Earth}

N_{pl} = 9 with R_p = 1-2 R_{Earth}

Planets from K2 - EPIC 201367065

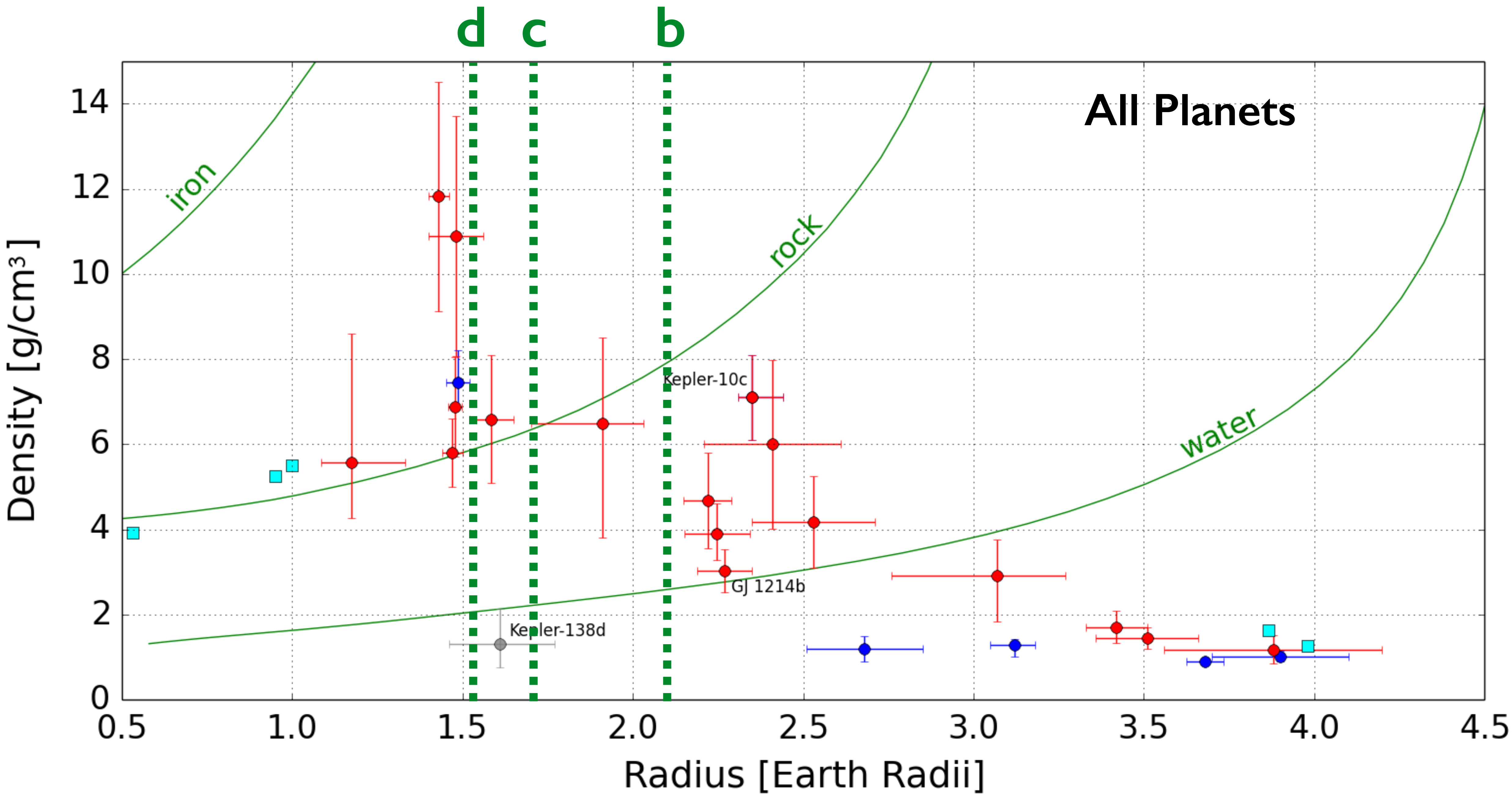


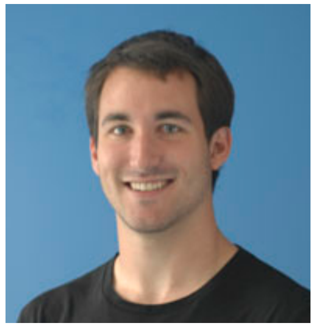
P = 10 days	P = 25 days	P = 45 days
R_p = 2.1 R_{Earth}	R_p = 1.7 R_{Earth}	R_p = 1.5 R_{Earth}
T_{eq} = 470 K	T_{eq} = 350 K	T_{eq} = 280 K

Host star is *nearby & bright* (V=12.2, K=8.5)
⇒ mass & atmosphere followup possible

Ian Crossfield (Arizona)

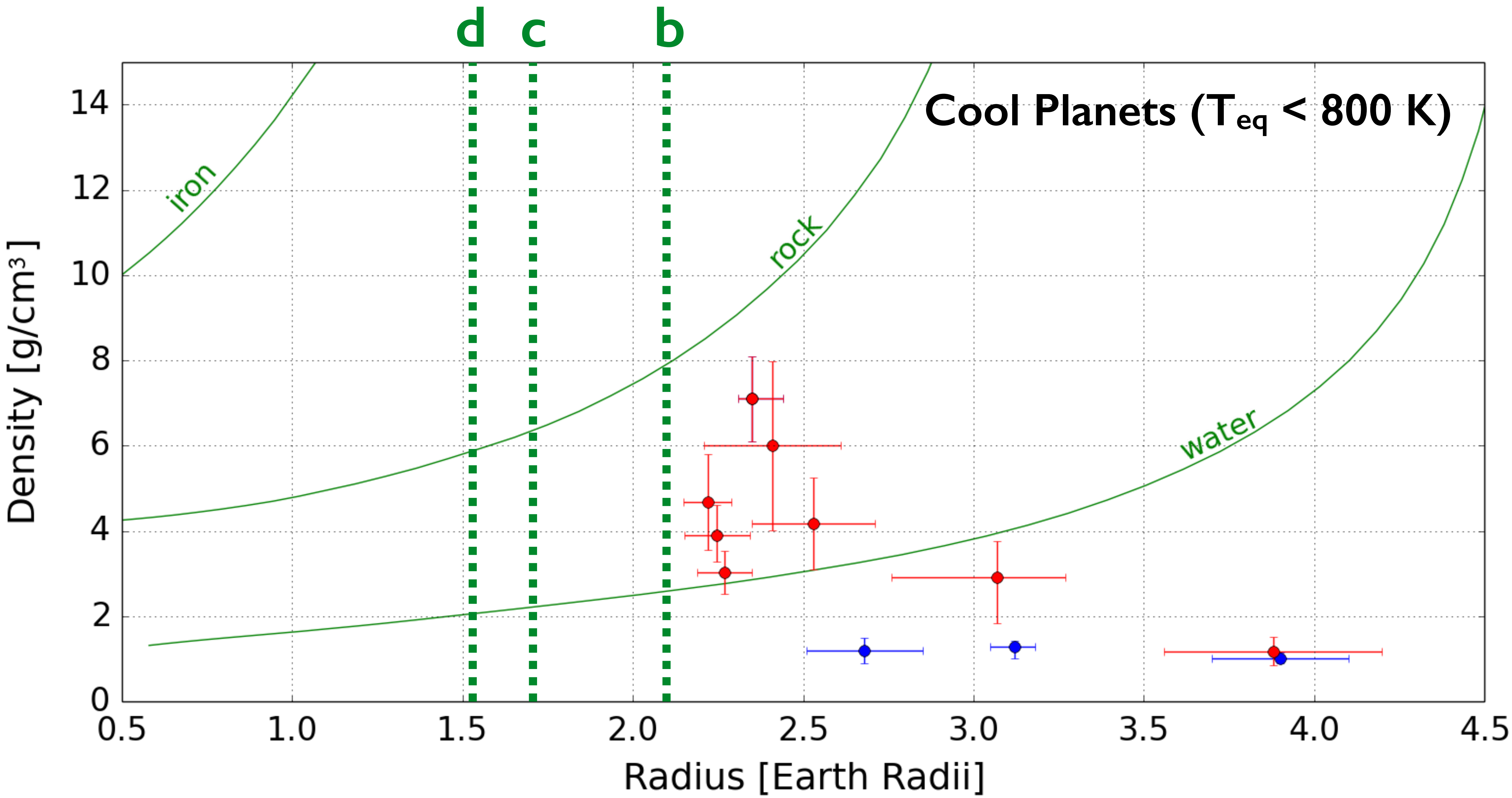
Planets from K2 - EPIC 201367065

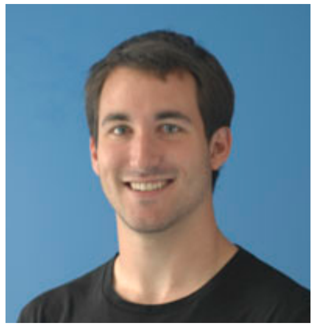




Evan Sinukoff (IfA)

Planets from K2 - EPIC 201367065

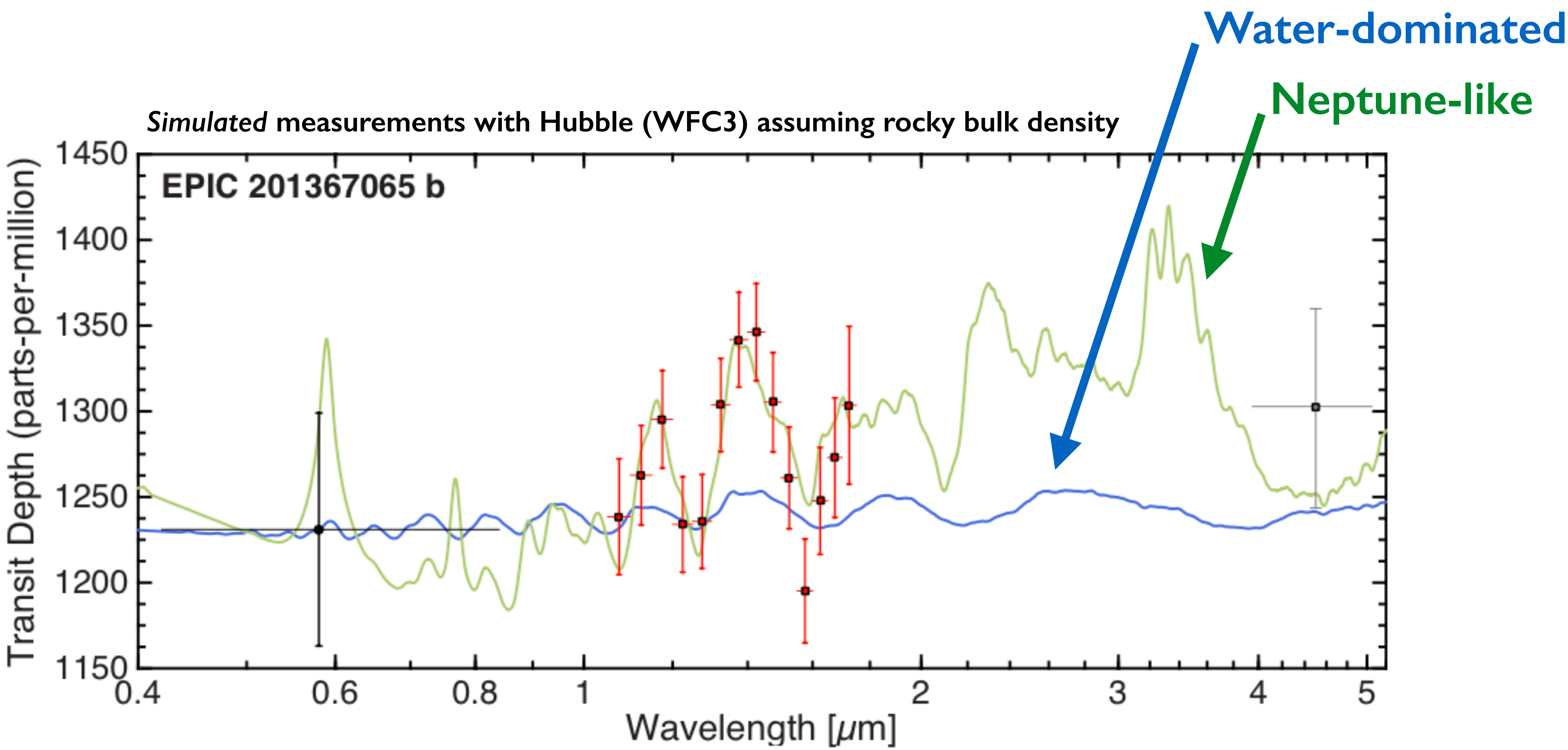




Evan Sinukoff (IfA)

Atmospheric Characterization - Planet ‘b’

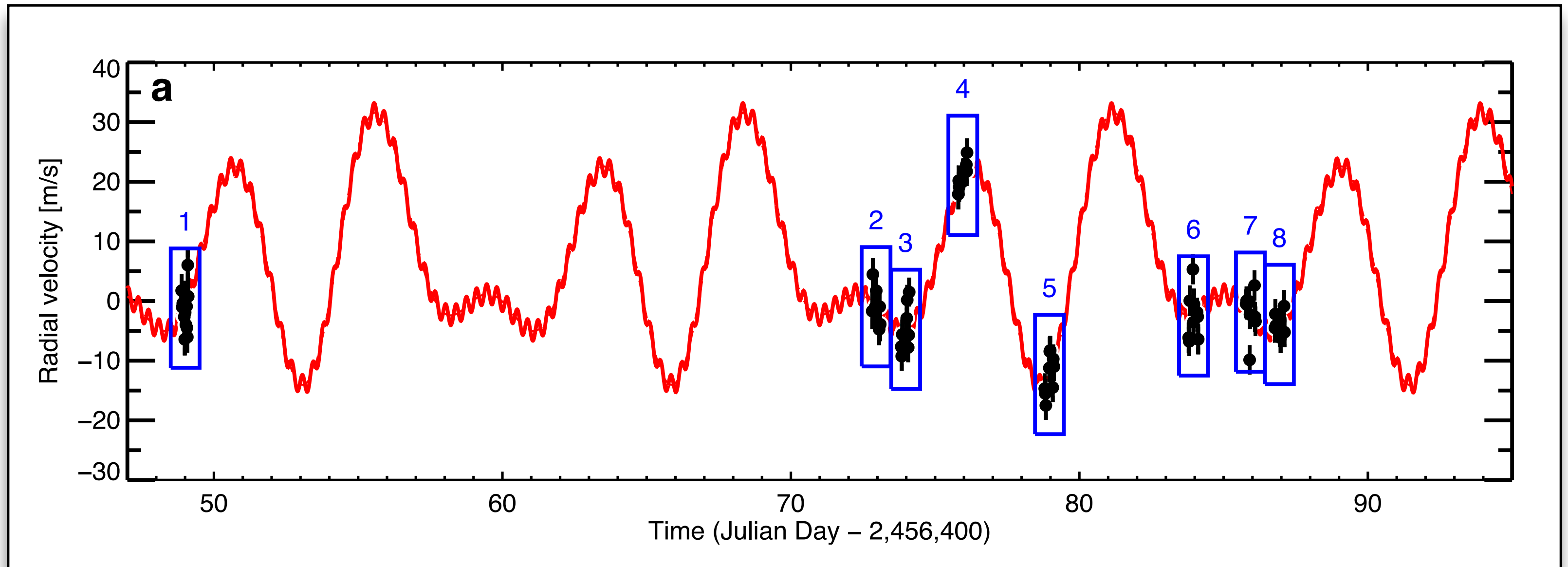
Simulated measurements with Hubble (WFC3) assuming rocky bulk density



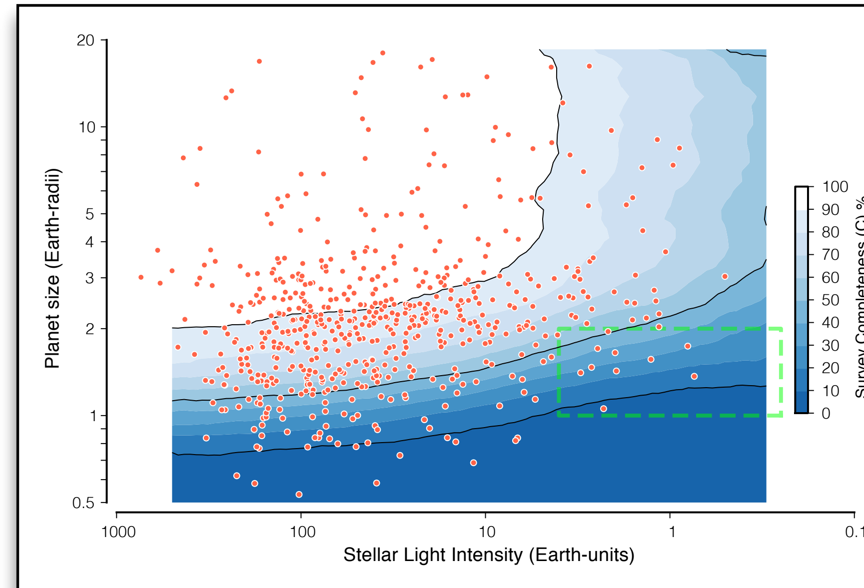
Simulations by Bjoern Benneke

But note that scale height (H) depends on planets mass - $H = kT / \mu g$

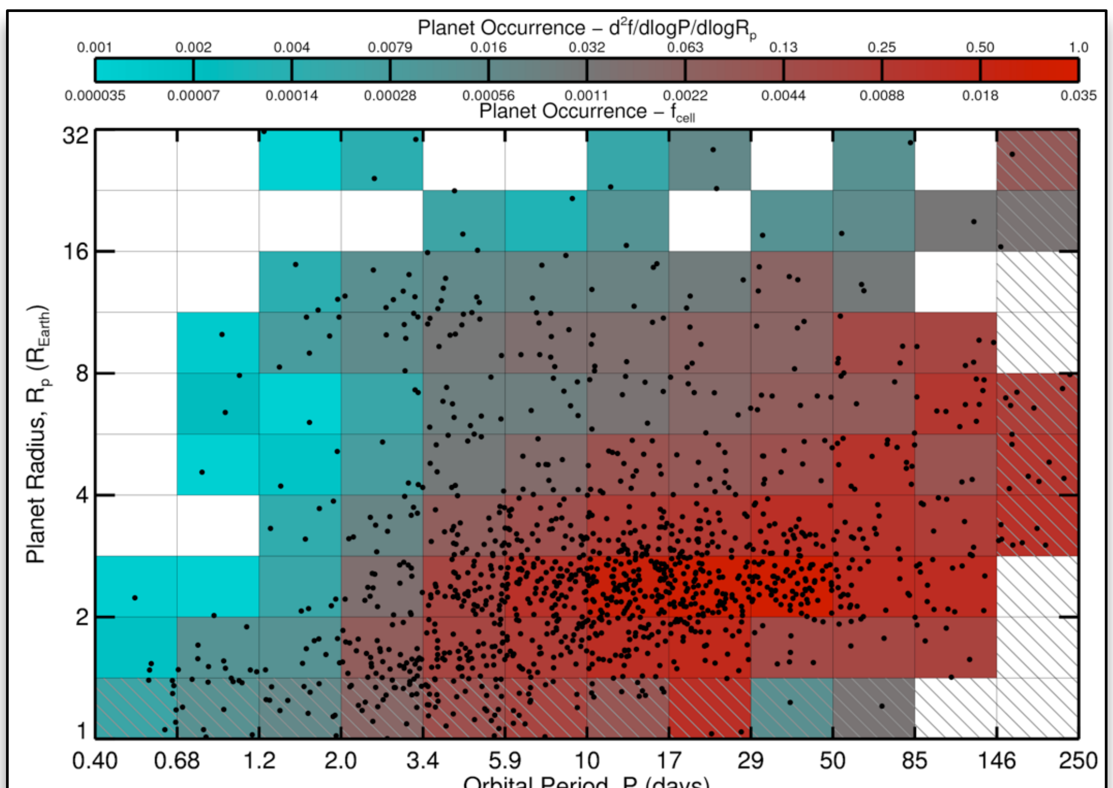
Questions?



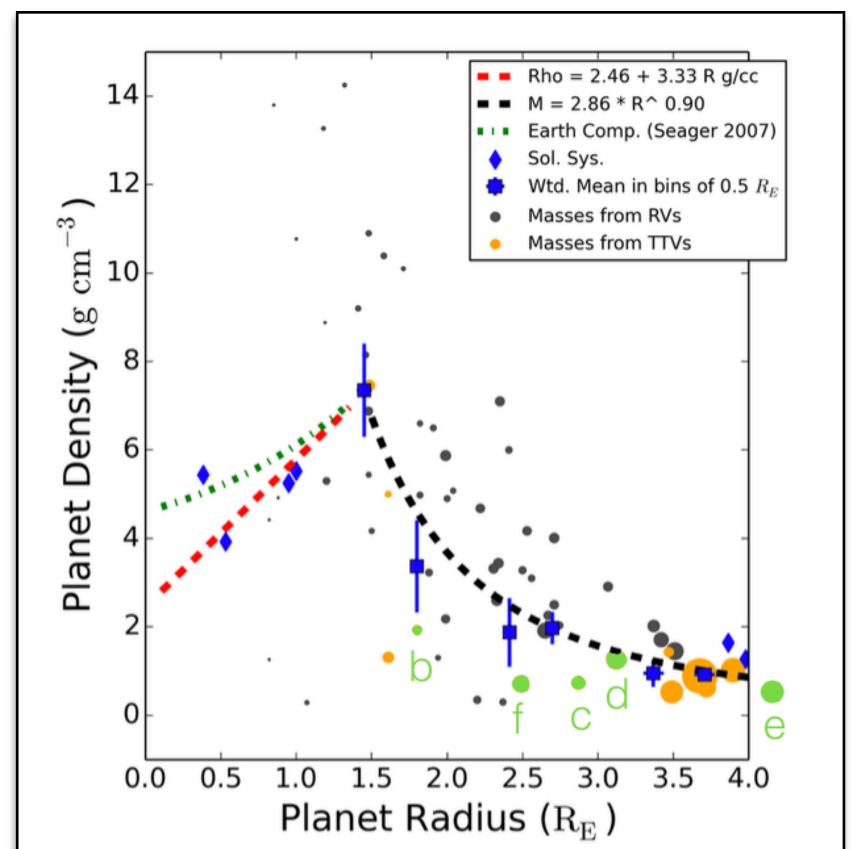
a
Radial velocity [m/s]
Time (Julian Day – 2,456,400)
1
2
3
4
5
6
7
8



Planet size (Earth-radii)
Stellar Light Intensity (Earth-units)
Survey Completeness (C) %



Planet Occurrence – $d^2f/d\log P/d\log R_p$
Planet Occurrence – f_{cell}
Planet Radius, R_p (R_{Earth})
Orbital Period, P (days)



Rho = 2.46 + 3.33 R g/cc
M = 2.86 * R^ 0.90
Earth Comp. (Seager 2007)
Sol. Sys.
Wtd. Mean in bins of 0.5 R_E
Masses from RVs
Masses from TTVs
Planet Density (g cm^{-3})
Planet Radius (R_E)
b
c
d
e
f