Single and Multi-Planet Systems from *Kepler*

- Occurrence of Planets
- Statistics of Multi-Planet Systems
- Low False Positive Rate

Geoff Marcy
UC Berkeley

Acknowledgements

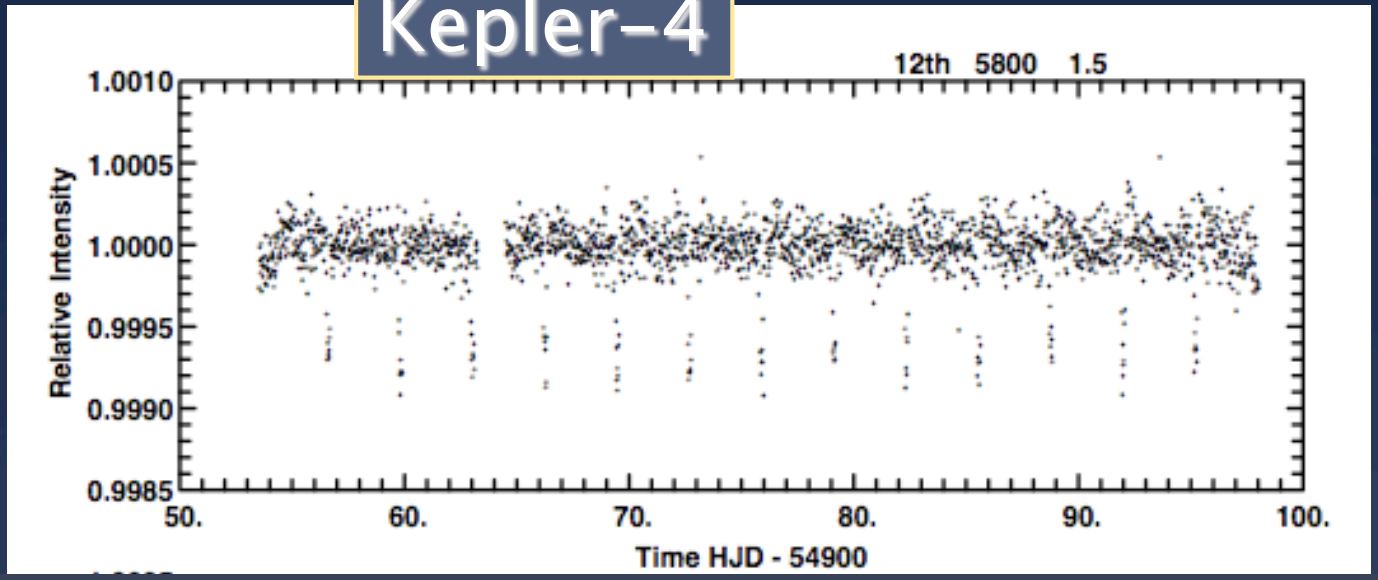
Kepler Team:

Jack J. Lissauer, Daniel C. Fabrycky, Darin Ragozzine, Jason H. Steffen, Eric B. Ford, Jon M. Jenkins, Avi Shporer, Matthew J. Holman, Jason F. Rowe, Elisa V. Quintana, Natalie M. Batalha, William J. Borucki, Stephen T. Bryson, Douglas A. Caldwell, Joshua A. Carter, David Ciardi, Edward W. Dunham, Jonathan J. Fortney, Thomas N. Gautier III, Steve B. Howell, David G. Koch, David W. Latham, G Robert C. Morehead, Dimitar Sasselov

Special Thanks to:

Jack Lissauer, Andrew Howard

Kepler-4

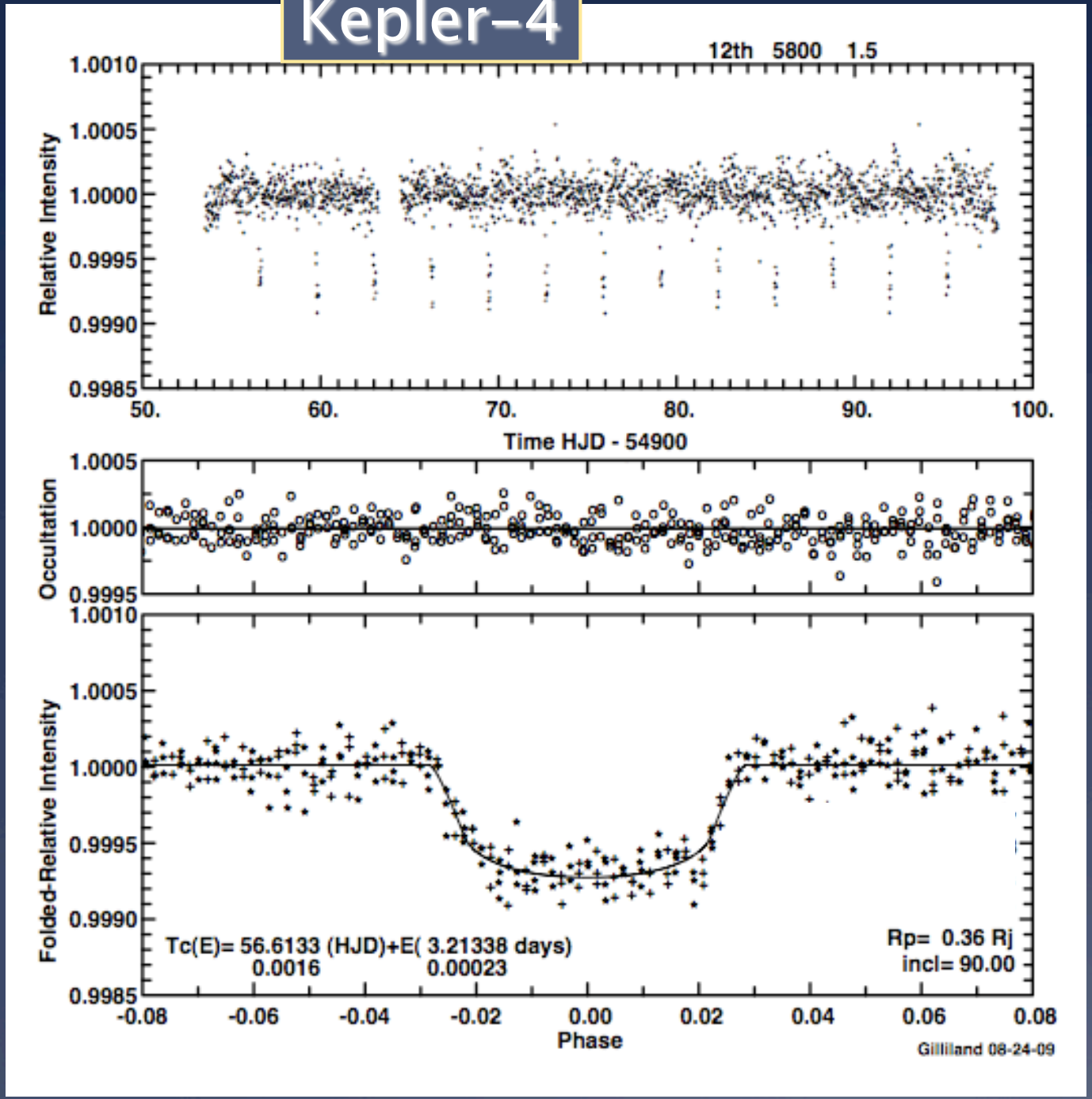


Planet Properties:

Period = 3.213day

Radius = 4.1 R_{Earth}

Kepler-4



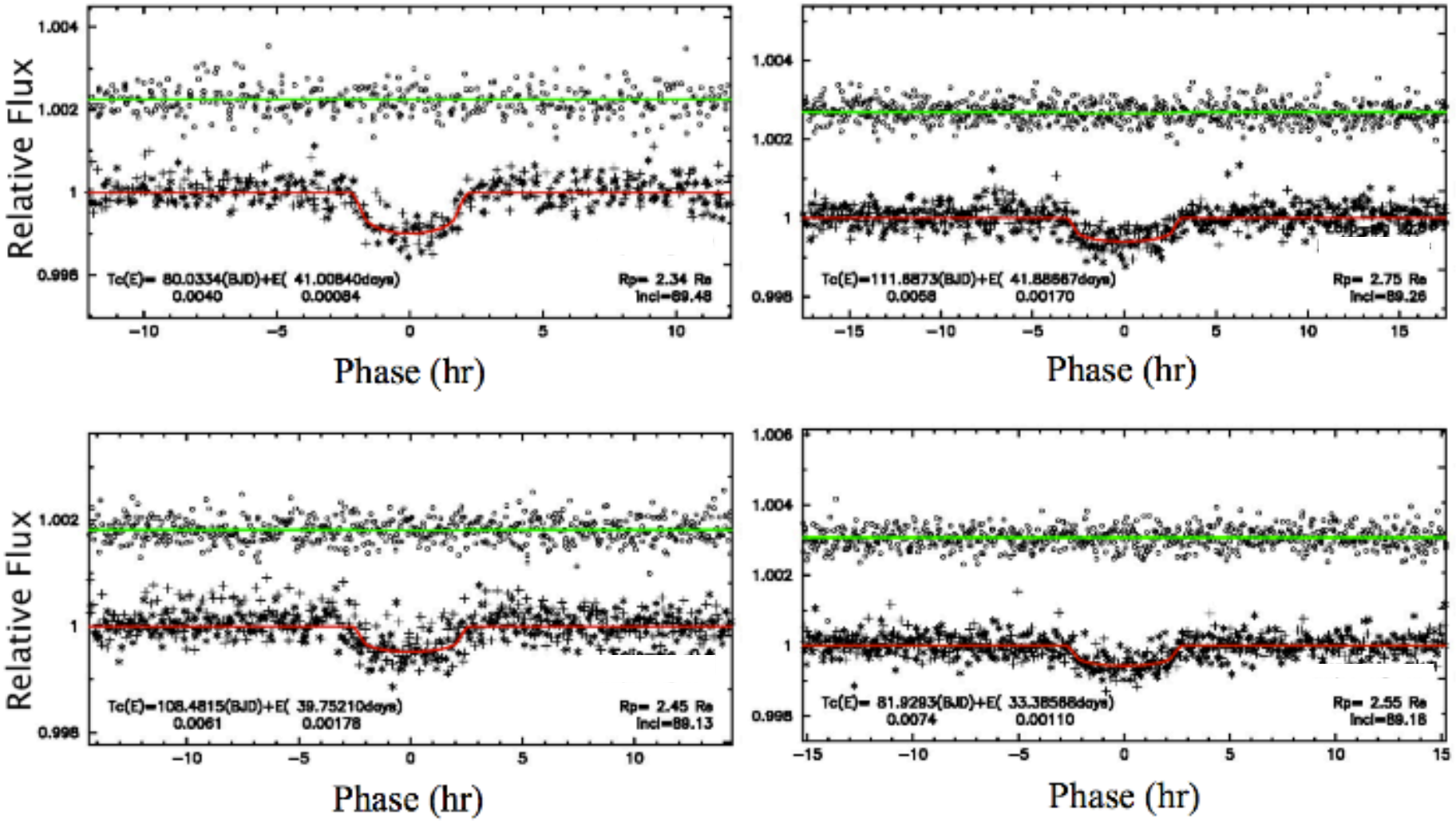
Planet Properties:

Period = 3.213day

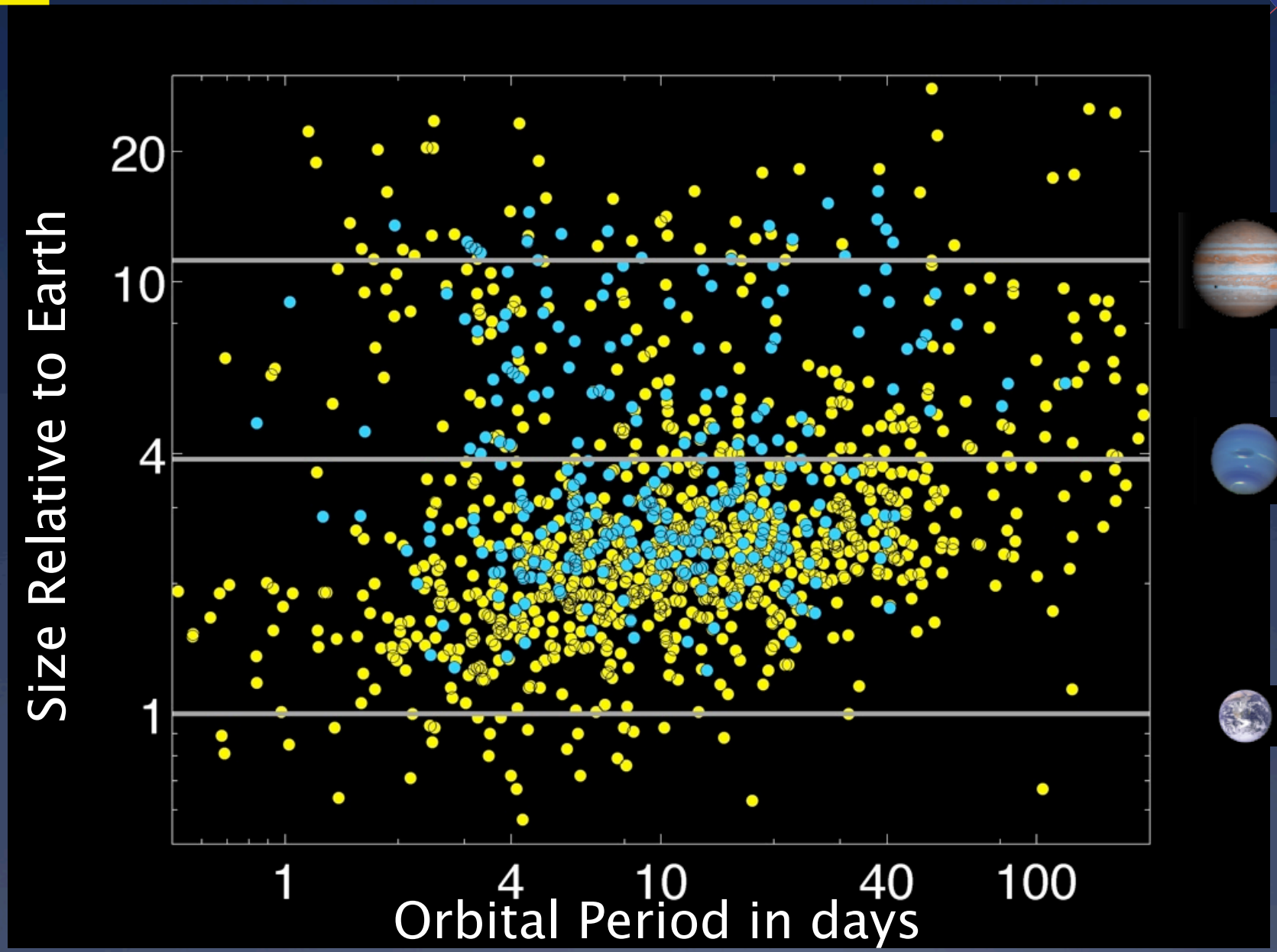
Radius = 4.1 R_{Earth}

Representative

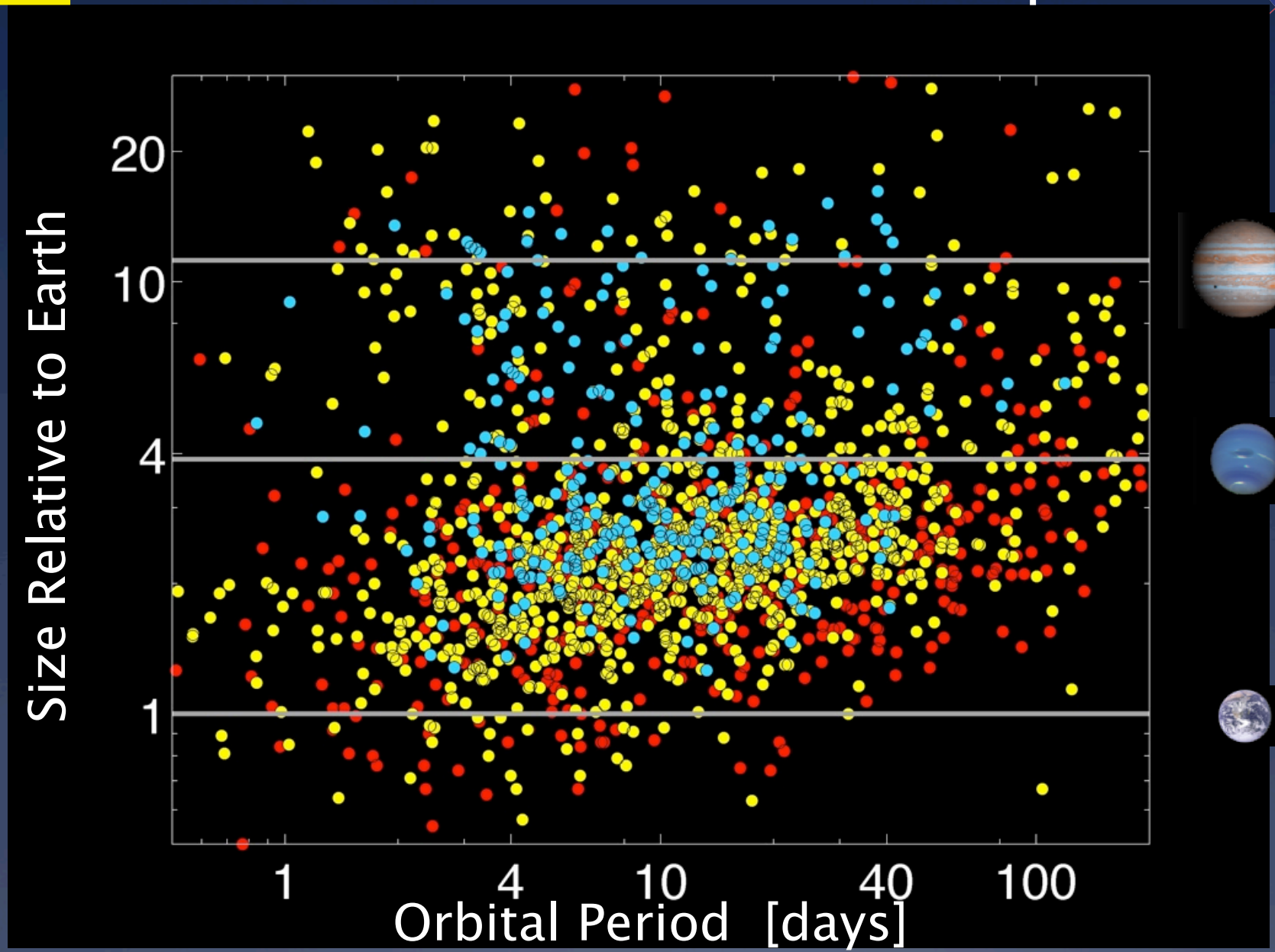
Kepler Transits: R = 2 - 3 R_{Earth}



1235 Planets Candidates as of Feb 2011

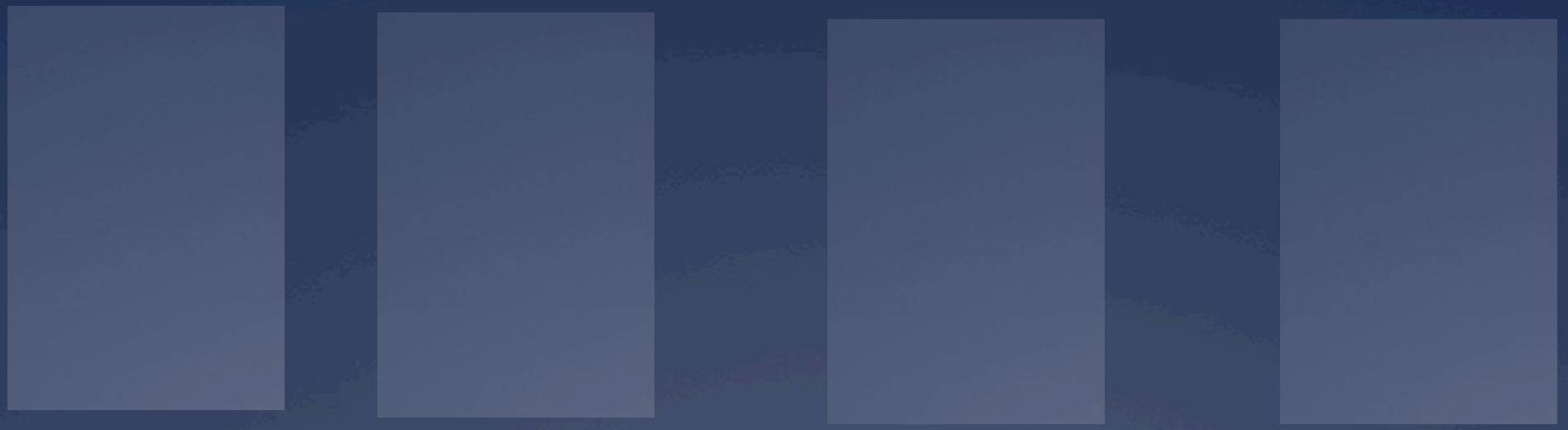


1781 Planets Candidates as of **Sep** 2011



1781 Planet Candidates as of Sep 12, 2011

45 % increase since February 2011



1781 Planet Candidates as of Sep 12, 2011

45 % increase since February 2011

⬆95%

<1.25 R_e

123

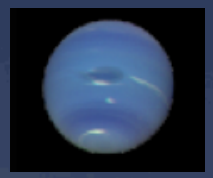
1781 Planet Candidates as of Sep 12, 2011

45 % increase since February 2011

⬆95%	⬆58%		
			
<1.25 R_e	1.25 – 2 R_e		
123	412		

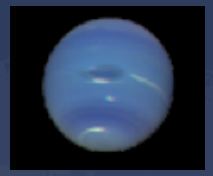
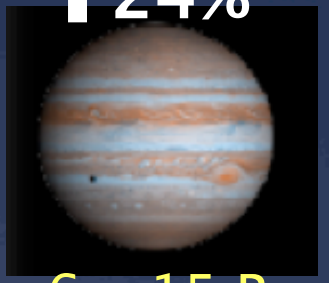
1781 Planet Candidates as of Sep 12, 2011

45 % increase since February 2011

⬆95%	⬆58%	⬆41%
		
<1.25 R_e	1.25 – 2 R_e	2 – 6 R_e
123	412	988

1781 Planet Candidates as of Sep 12, 2011

45 % increase since February 2011

⬆95%	⬆58%	⬆41%	⬆24%
			
<1.25 R_e	1.25 – 2 R_e	2 – 6 R_e	6 – 15 R_e
123	412	988	204

Occurrence of Planets: Correct for Biases in *Kepler*

* 1) Consider only Main Sequence FGK stars (and their planets)
* 2) Operate in differential cells in the plane: R_{PL} – Period
* 3) Correct for:
    - 3a) Non-transiting geometries
    - 3b) Varying detectability (Photometric Noise in each star)

Define Planet Occurrence

For each R_{PL} and Period:

$$\text{Occurrence} = \frac{\text{\# planets}}{\text{\# stars}}$$

Choose planets carefully:
- Signal/noise > 10
- Correct for inclined orbits

Choose stars carefully:
- Surface temp & gravity
- Brighter than 15th mag
- Signal/noise > 10

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Define the Stellar Domain:
Stellar Parameters and SNR of Transit

Stellar Domain: FGK Main Sequence

Teff = 4100 – 6100 K

log g = 4.0 – 4.9

Kepmag < 15 mag

Define the Survey Domain:
Stellar Parameters and SNR of Transit

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Note:
Only 59,000 Kepler Target stars meet these stellar criteria

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SNR Threshold of Transit: 10

Demand SNR > 10 in Quarter 3 alone

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Note:
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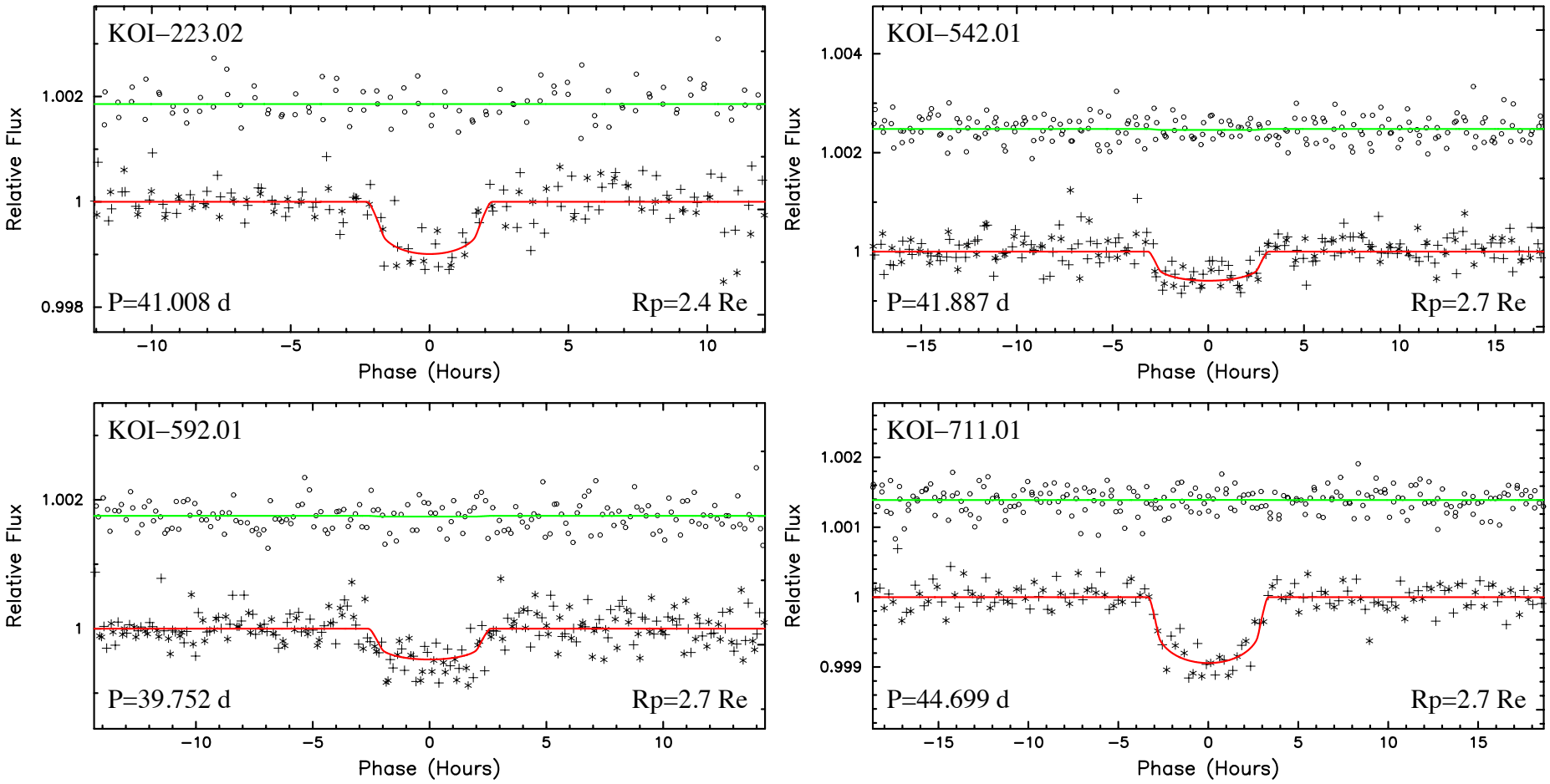
SNR Threshold of Transit: 10

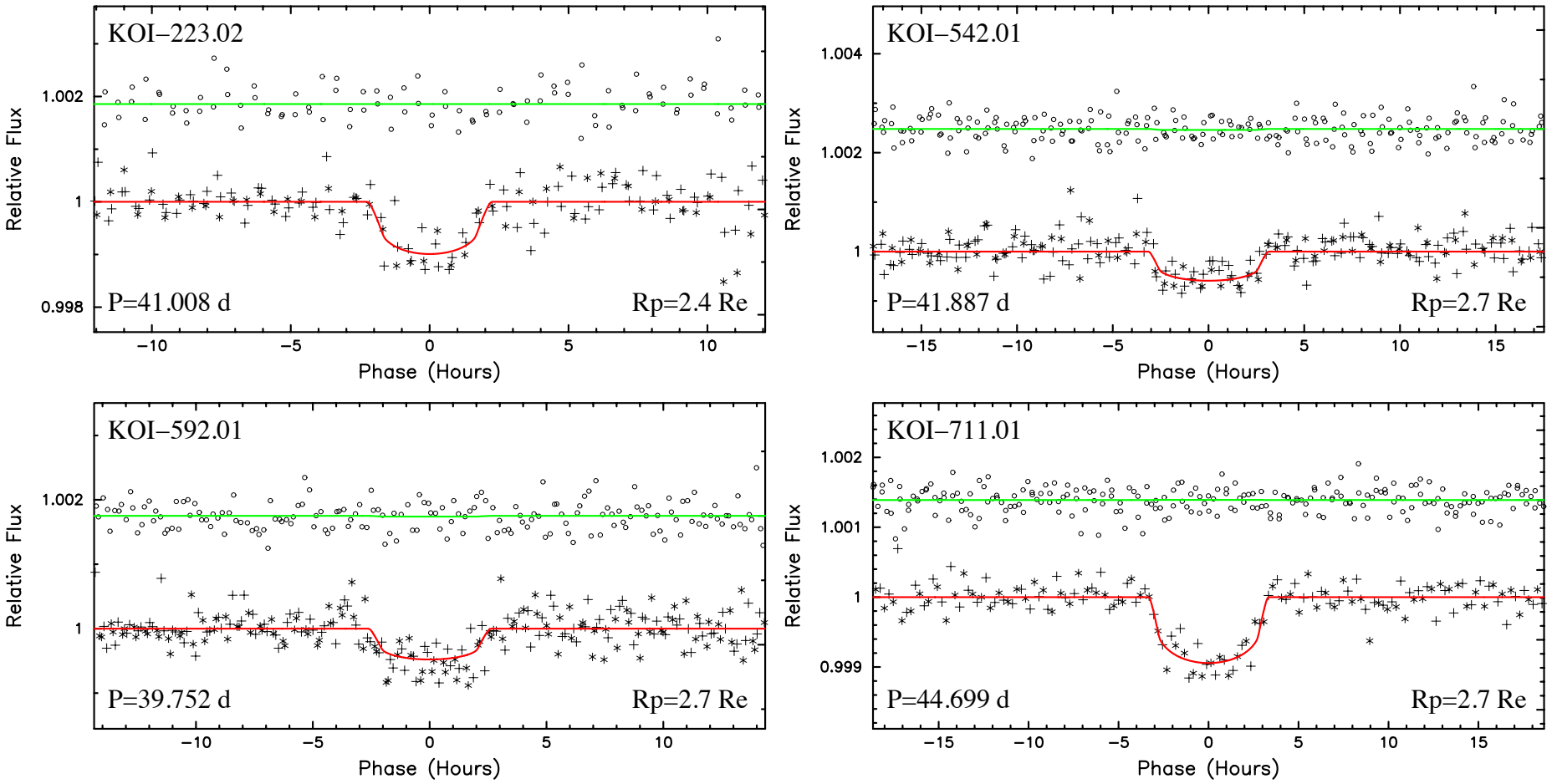
Demand SNR > 10 in Quarter 3

SNR Depends on
- planet radius
- # of transits
- Photometric noise

Kepler Transits with SNR ≈ 10



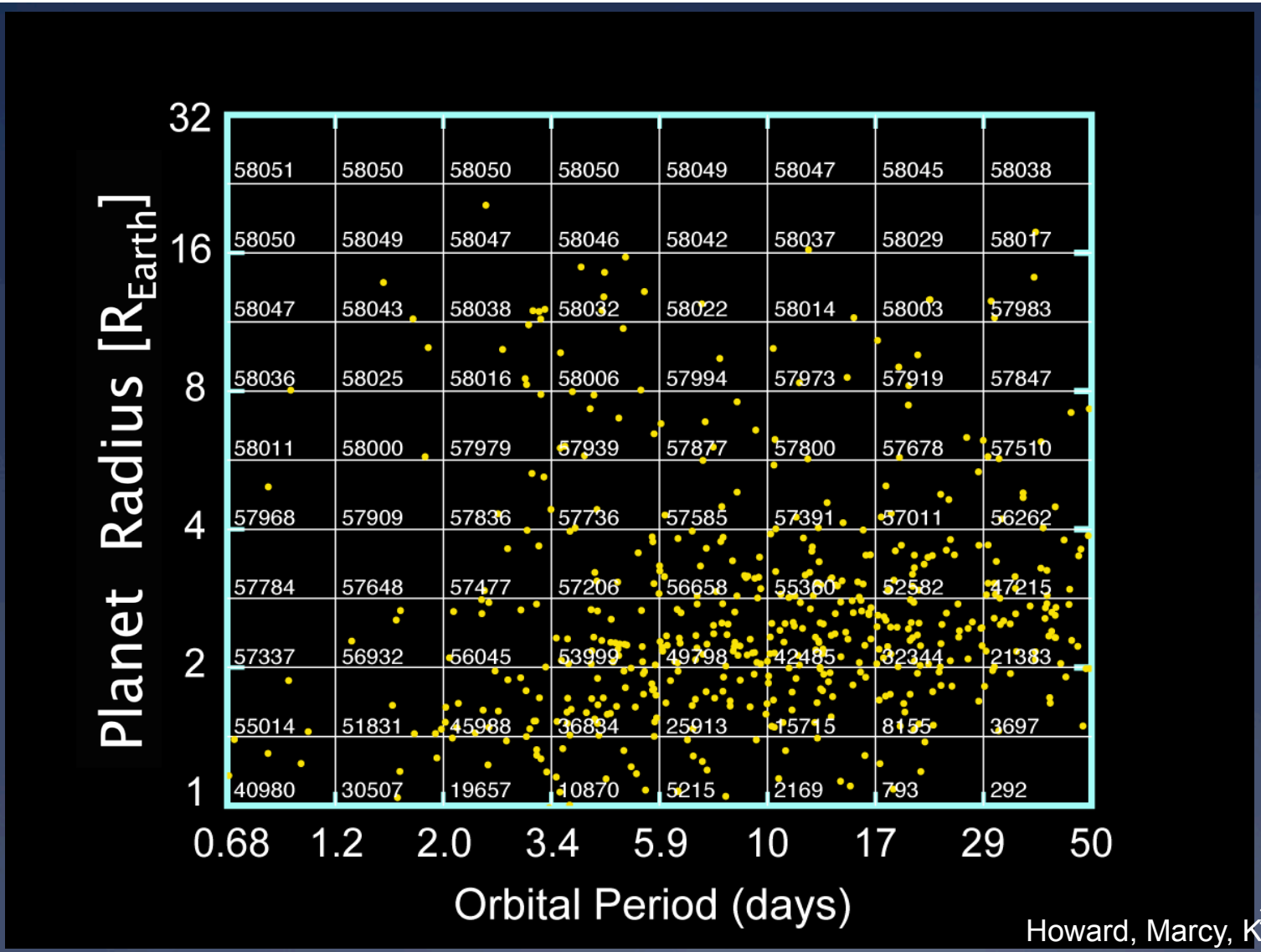
Kepler Transits with SNR ≈ 10



SNR=10: Sound Detections; Few missed.
Low False Alarms; High Completeness

Number of Target Stars Capable of Achieving SNR > 10 in Quarter 3

Target Star Parameters: Teff=4100–6100 K, log g=4.0–4.9, Kepmag<15



Howard, Marcy, Kepler Team. (2011)

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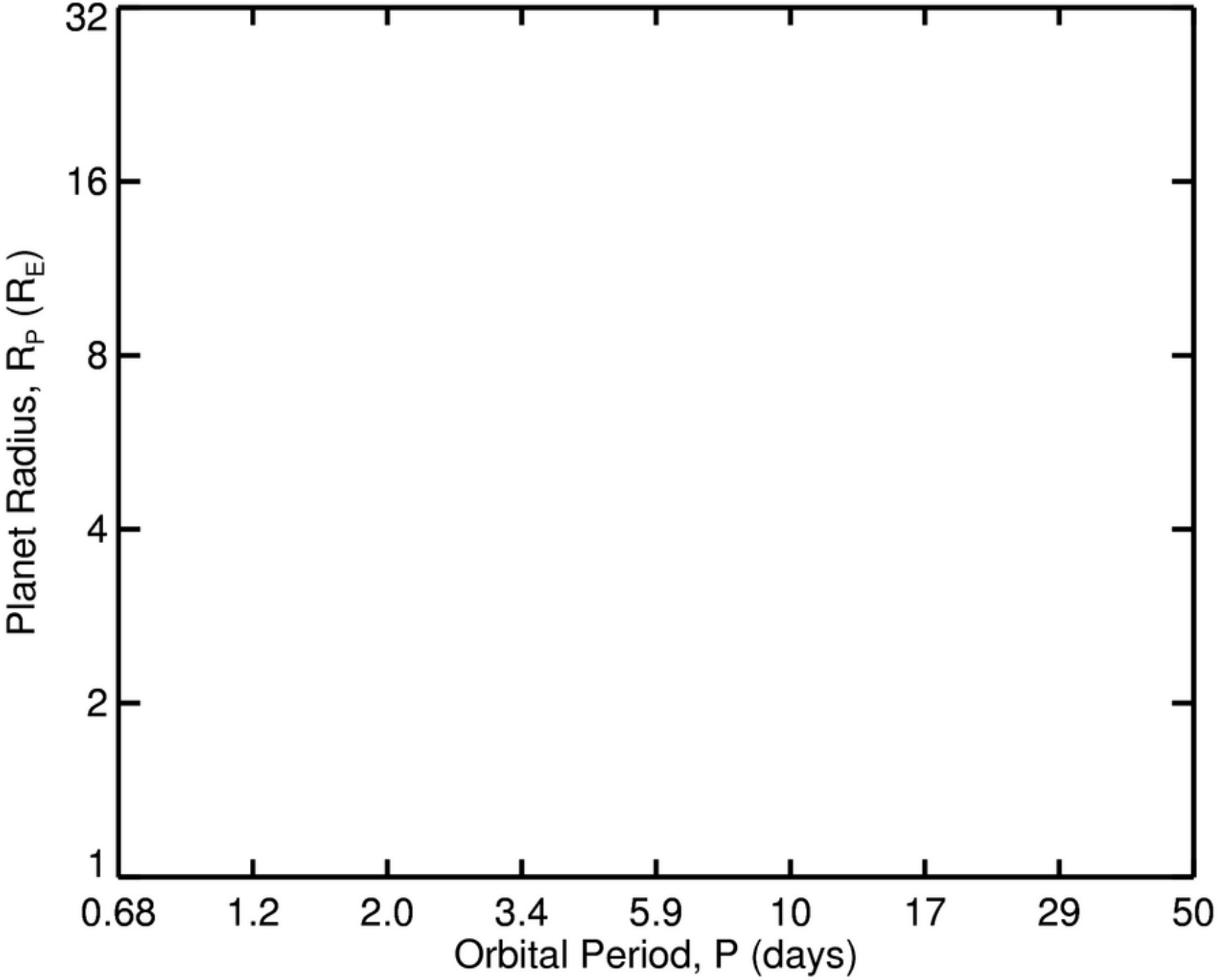
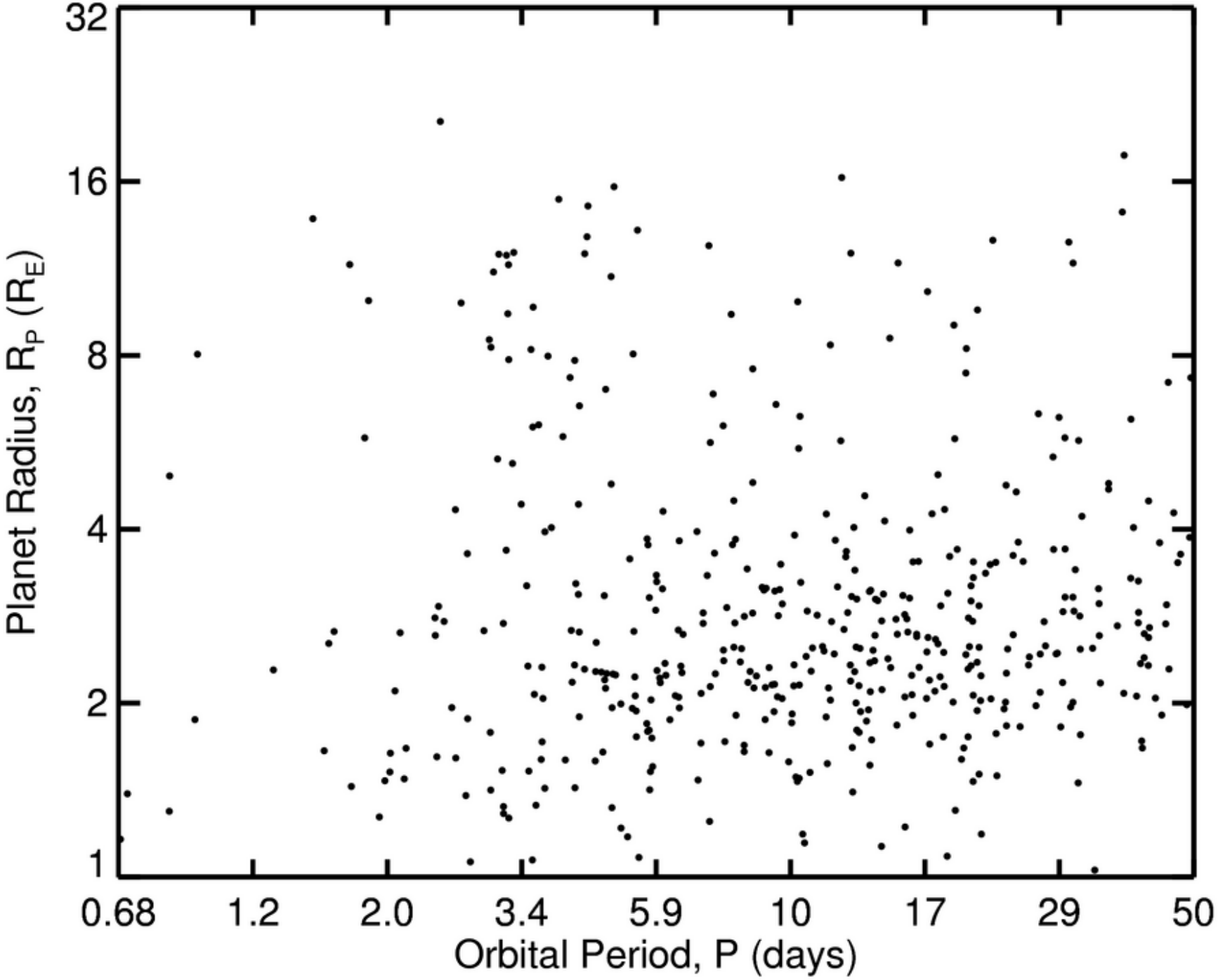
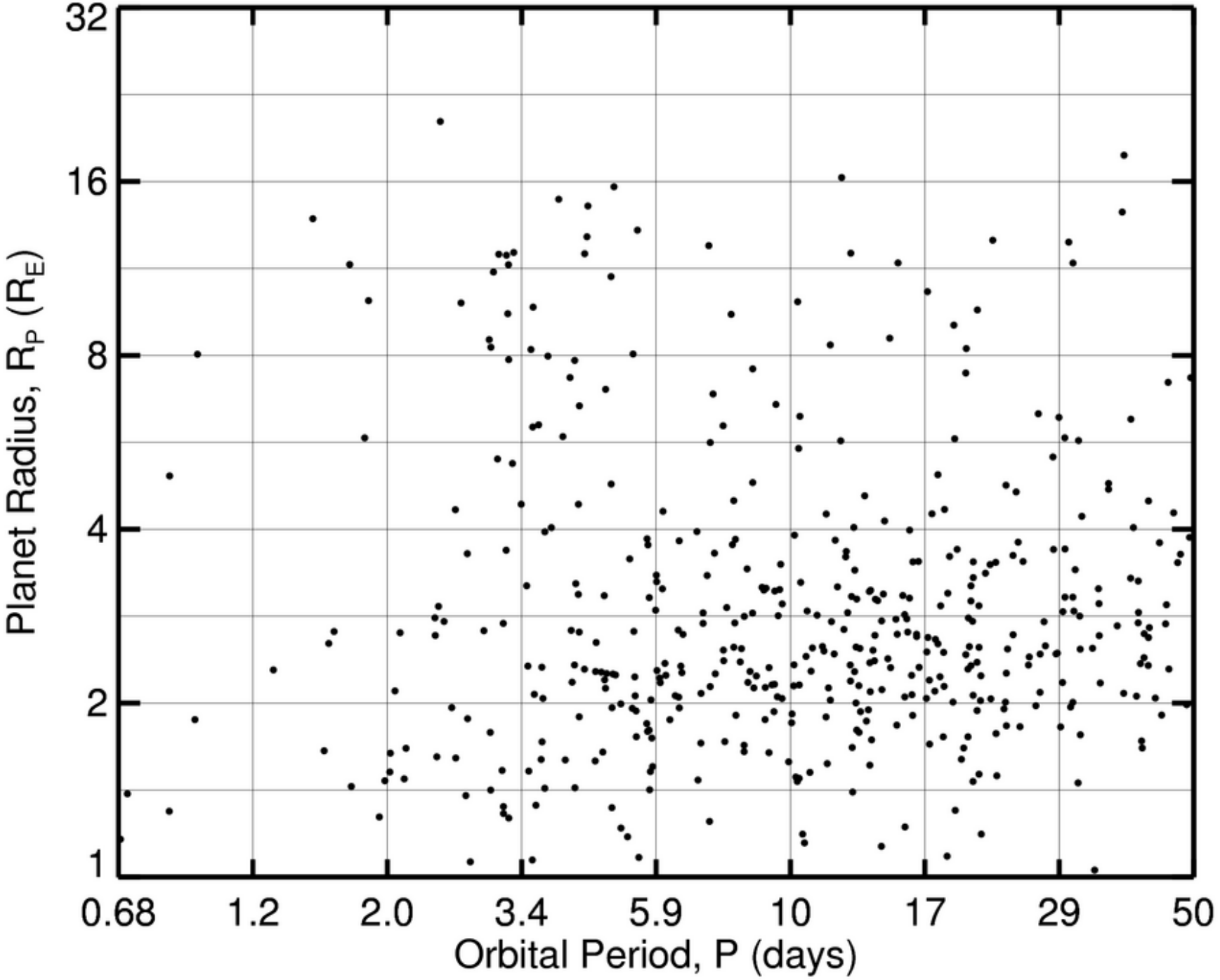


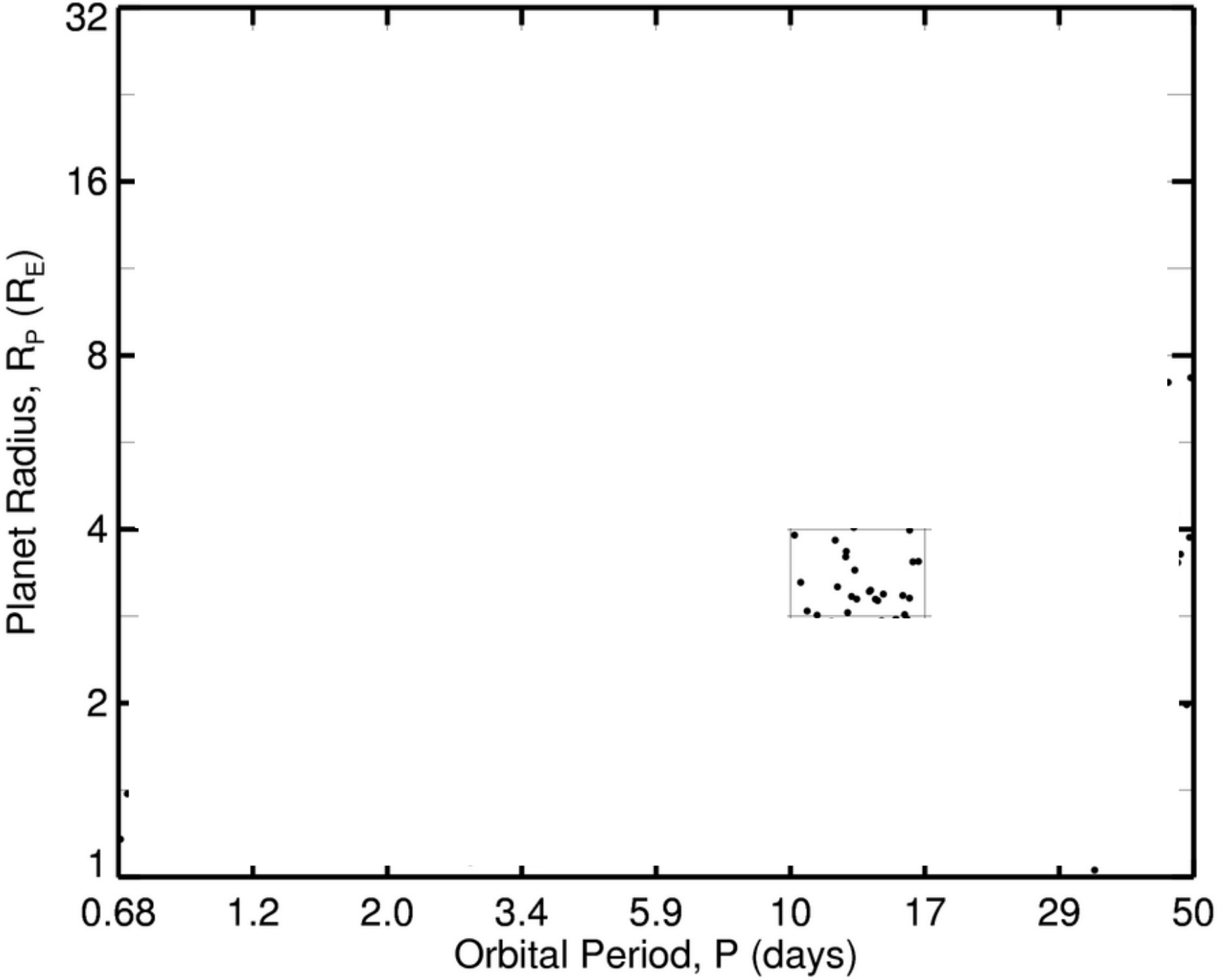
Howard, Marcy, Kepler Team (2011)



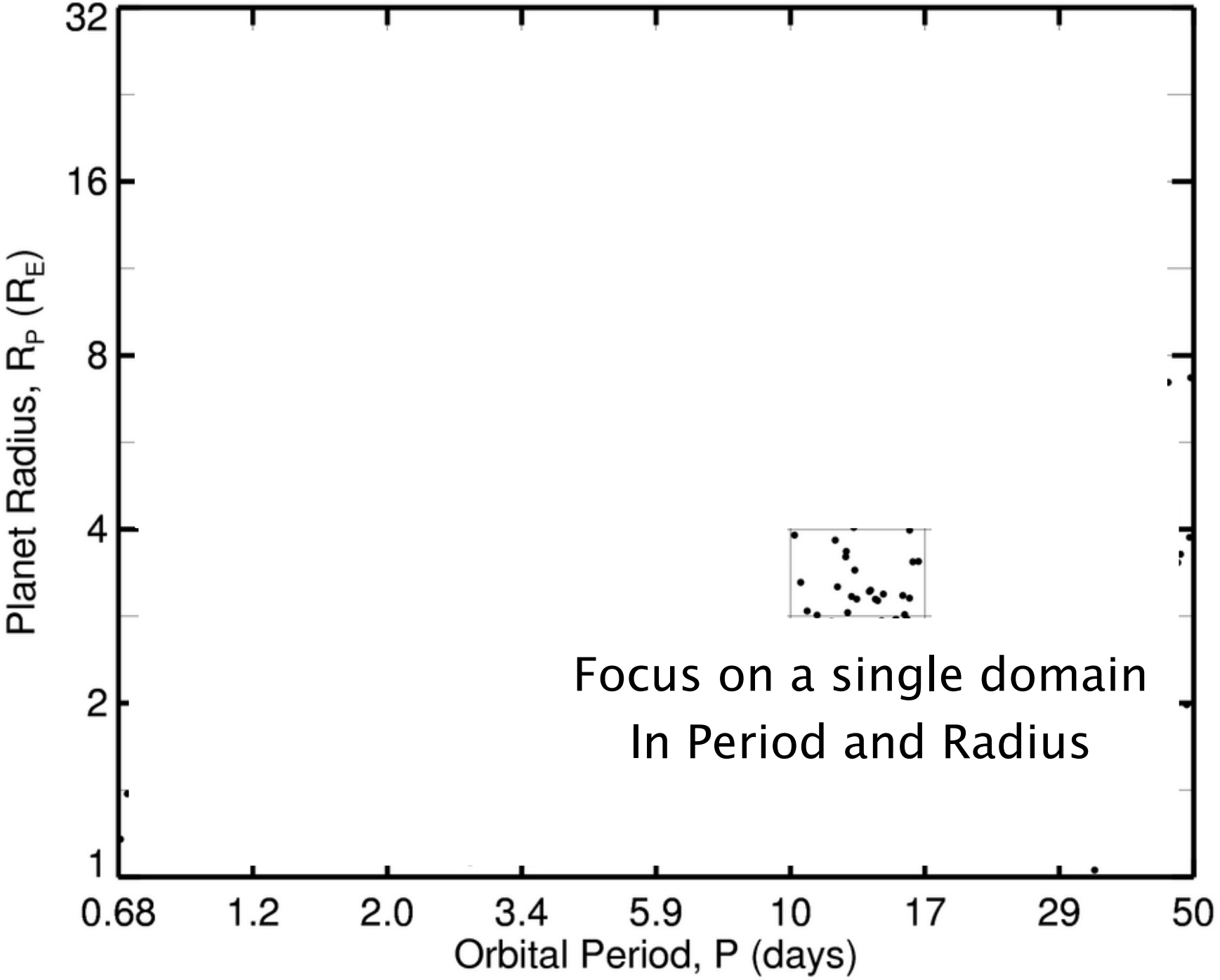
Howard, Marcy, Kepler Team (2011)



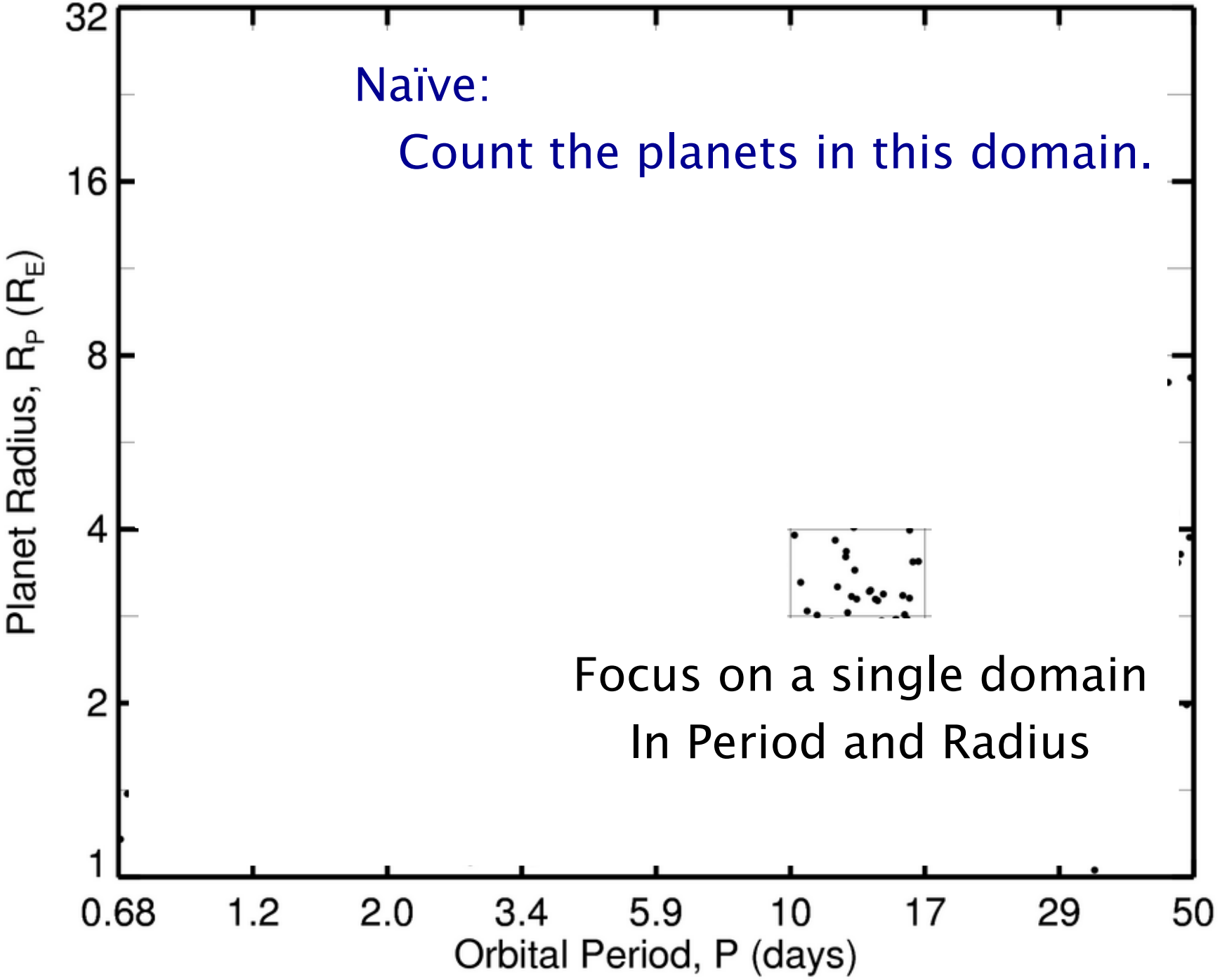
Howard, Marcy, Kepler Team (2011)



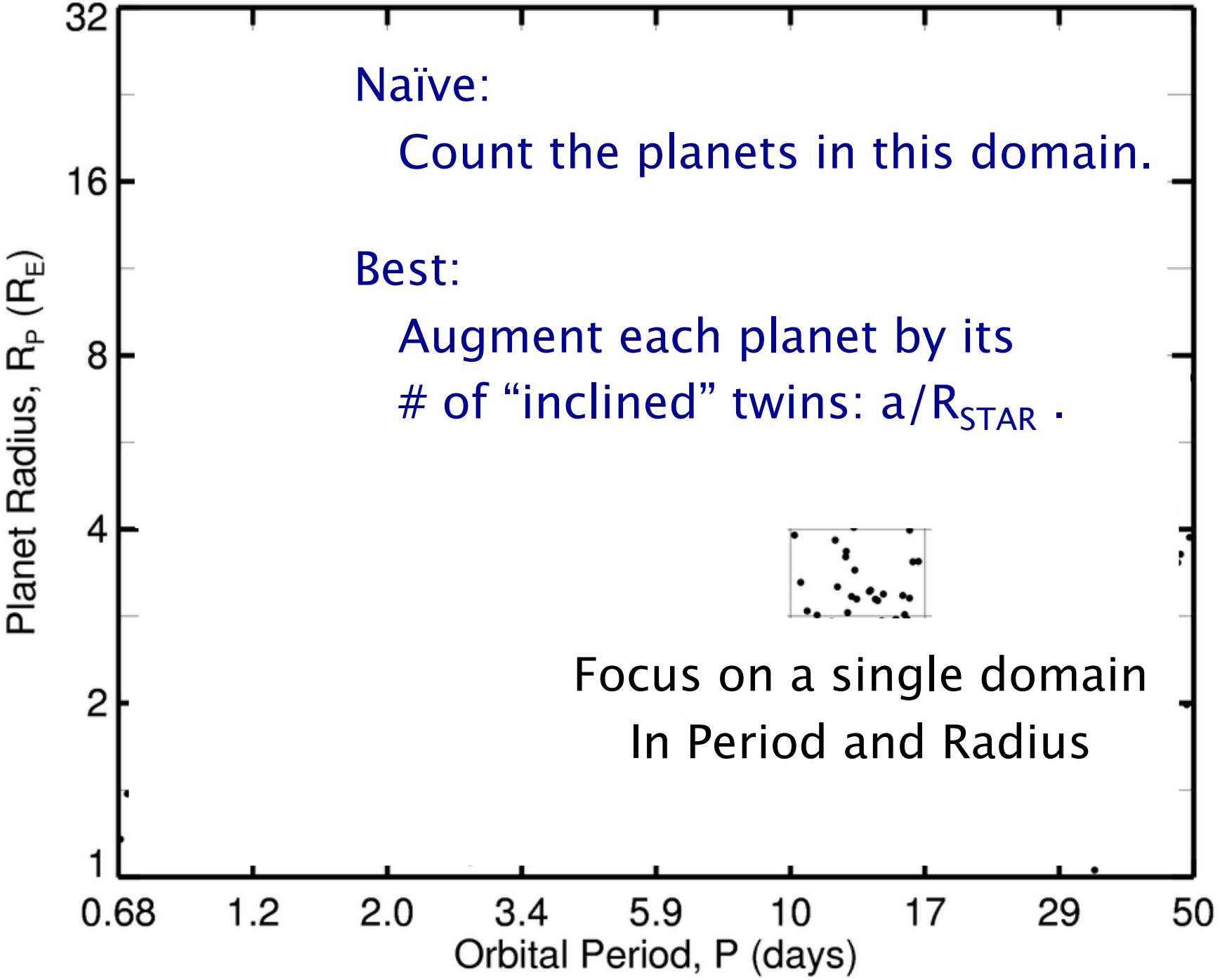
Howard, Marcy, Kepler Team (2011)



Howard, Marcy, Kepler Team (2011)

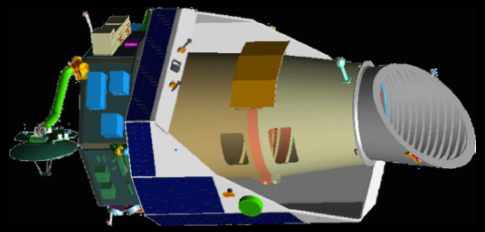


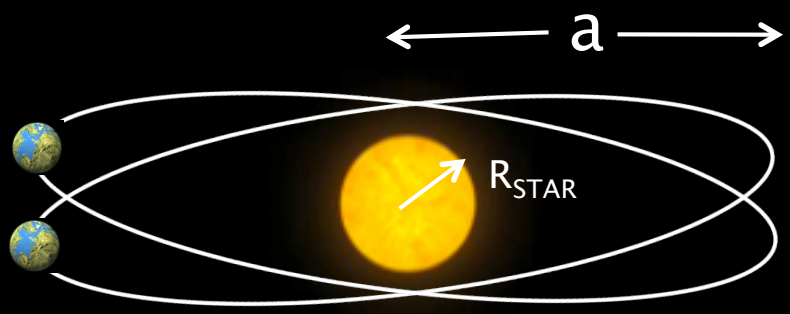
Howard, Marcy, Kepler Team (2011)



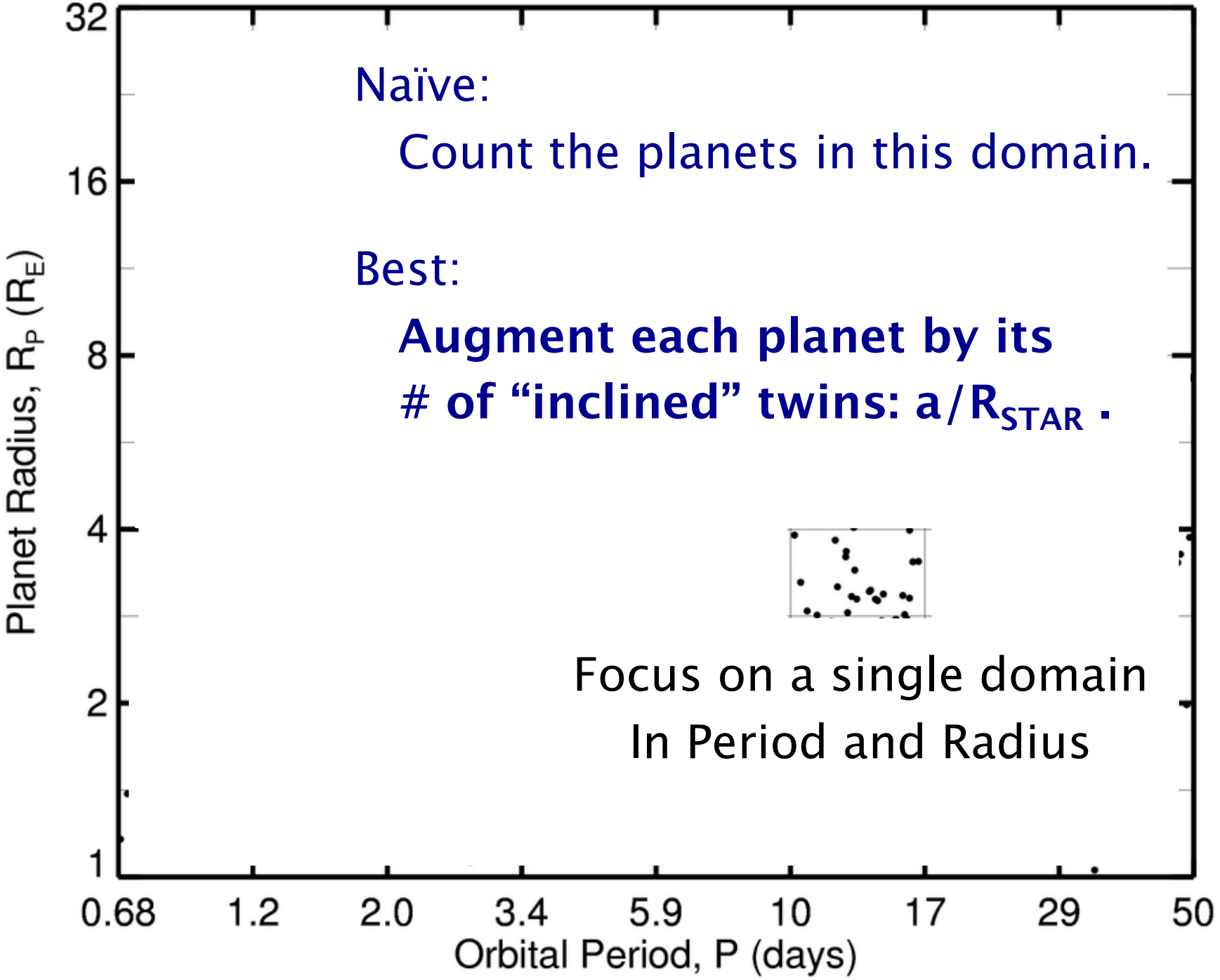
Howard, Marcy, Kepler Team (2011)

Augment Each Transiting Planet by the # of (undetected) Inclined Twins

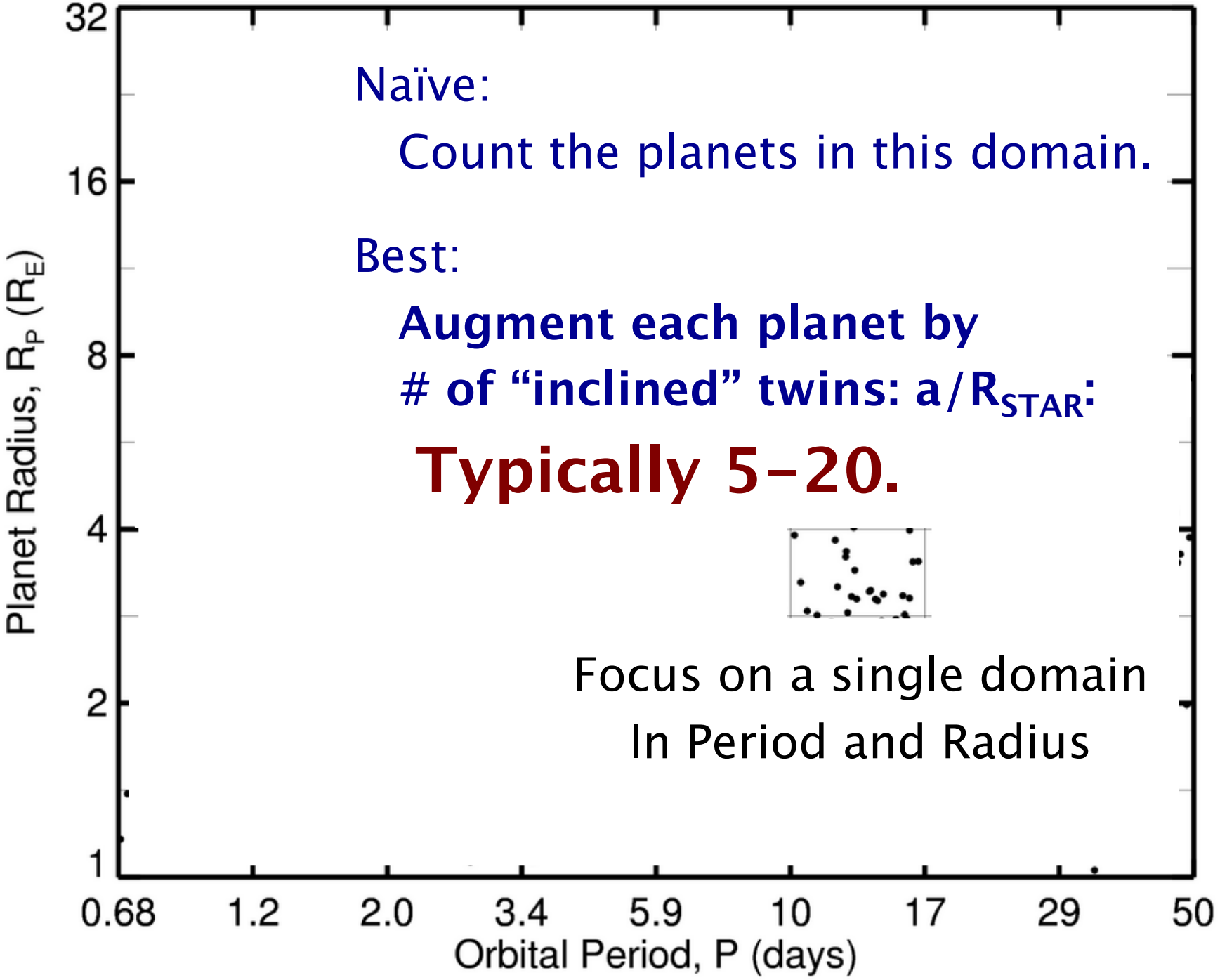




Planets at <u>All Inclinations</u> = a / R_{STAR}



Howard, Marcy, Kepler Team (2011)



Howard, Marcy, Kepler Team (2011)

Define Planet Occurrence

within each cell:

$$\text{Occurrence} = \frac{\#\ \text{planets}}{\#\ \text{stars}}$$

Choose planets carefully:
- Signal/noise > 10
- Correct for inclined orbits

Choose stars carefully:
- Surface temp & gravity
- Brighter than 15th mag
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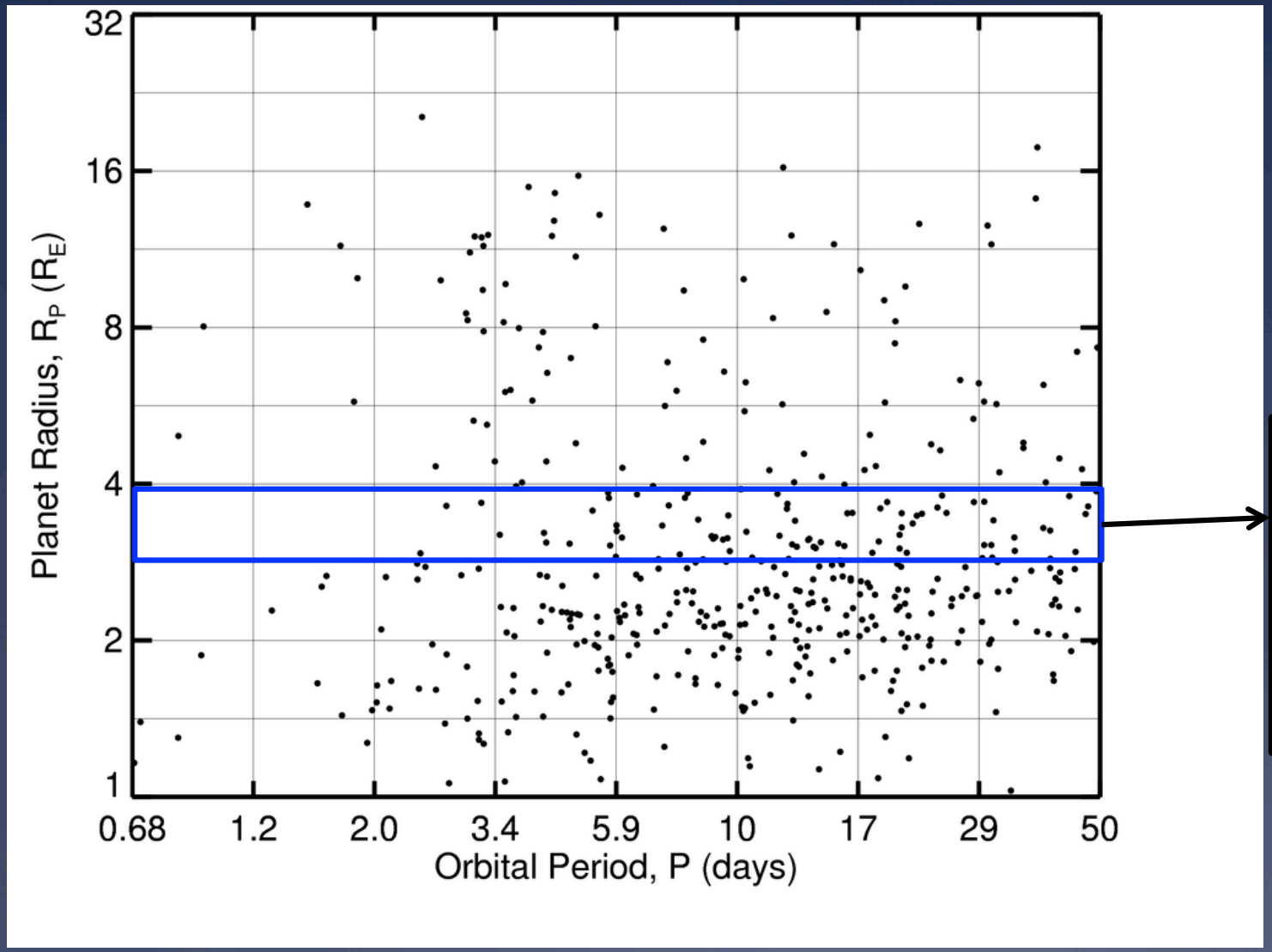
Compute Occurrence vs. Planet Radius

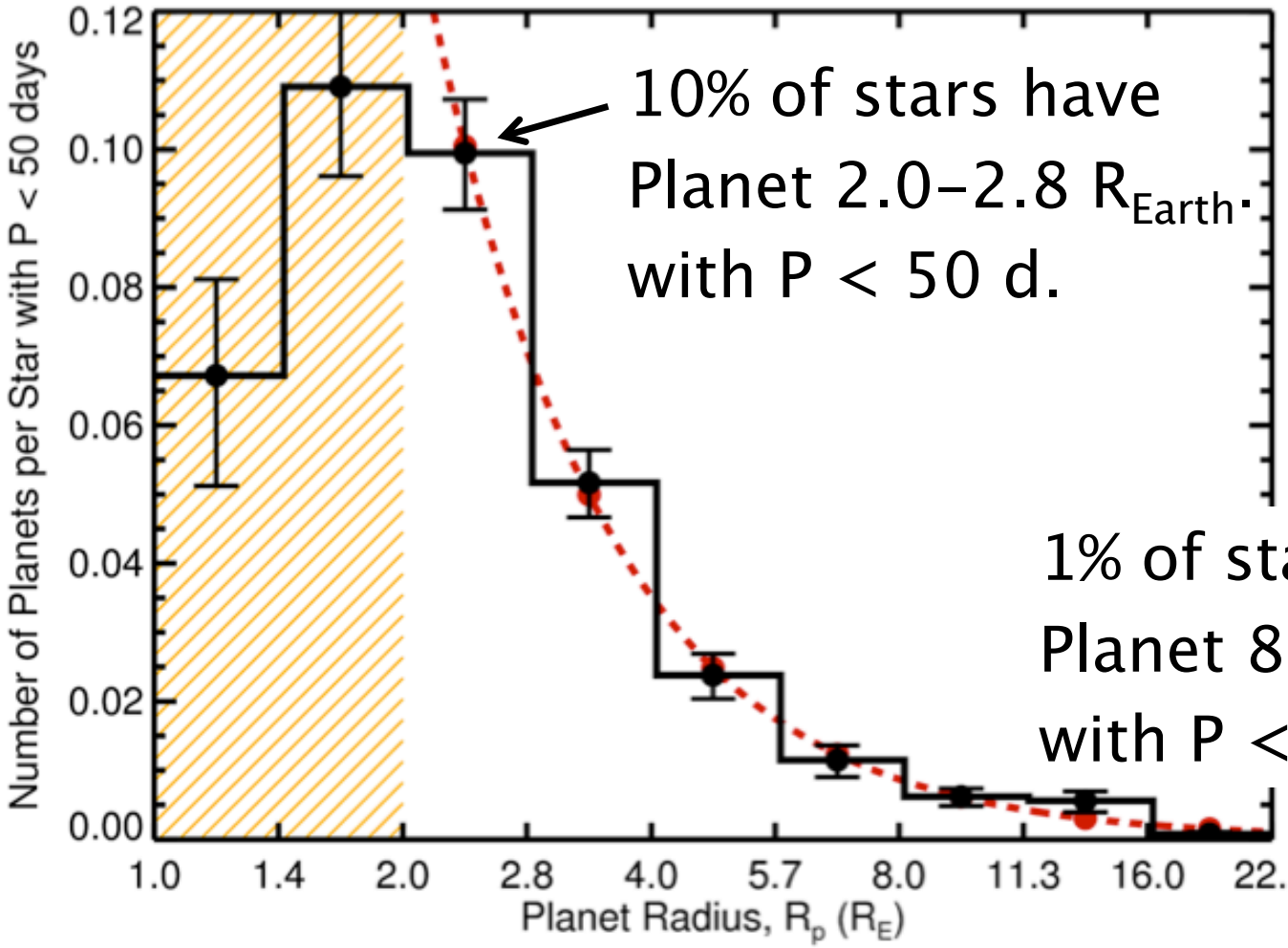


Sum Occurrence over all Periods

Howard et al. (2011)

Distribution of Planet Radii

For Orbital Periods < 50 Days

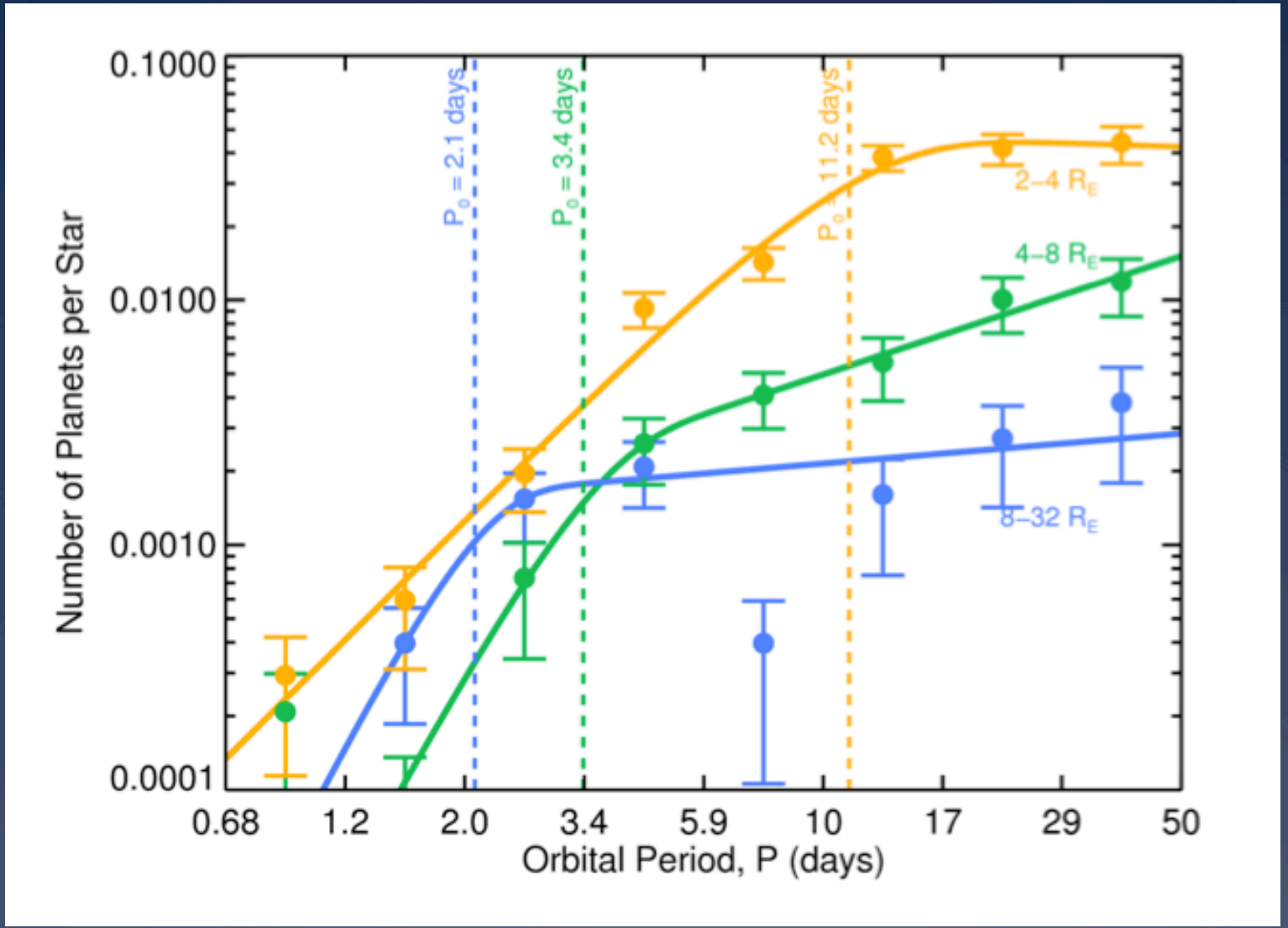


10% of stars have Planet 2.0–2.8 R_{Earth}. with P < 50 d.

1% of stars have Planet 8–12 R_{Earth}. with P < 50 d.

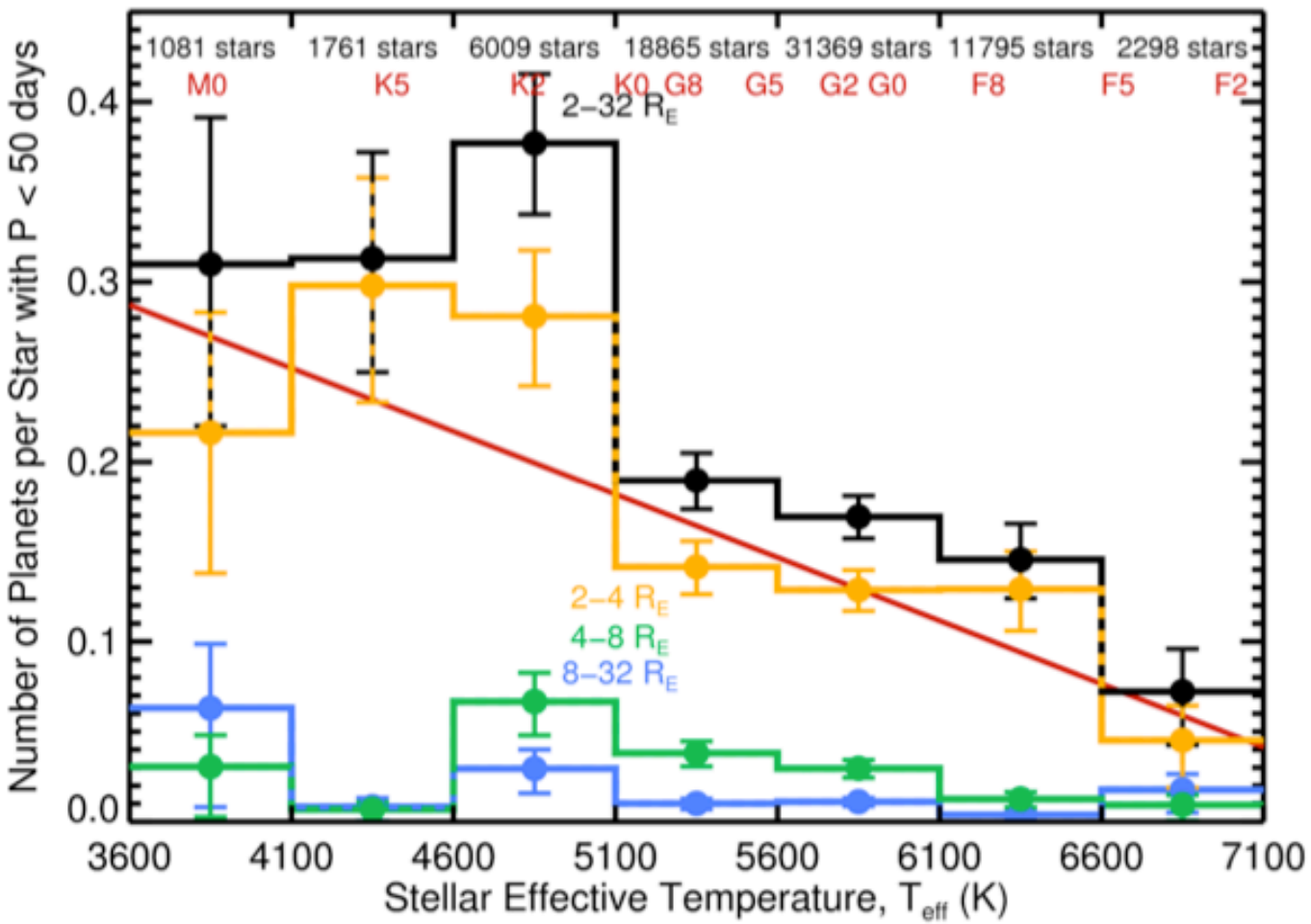
Howard, Marcy, Kepler Team, as of Sept. 2011

Planet Occurrence vs. Orbital Period



Howard, Marcy, Kepler Team Sept 2011

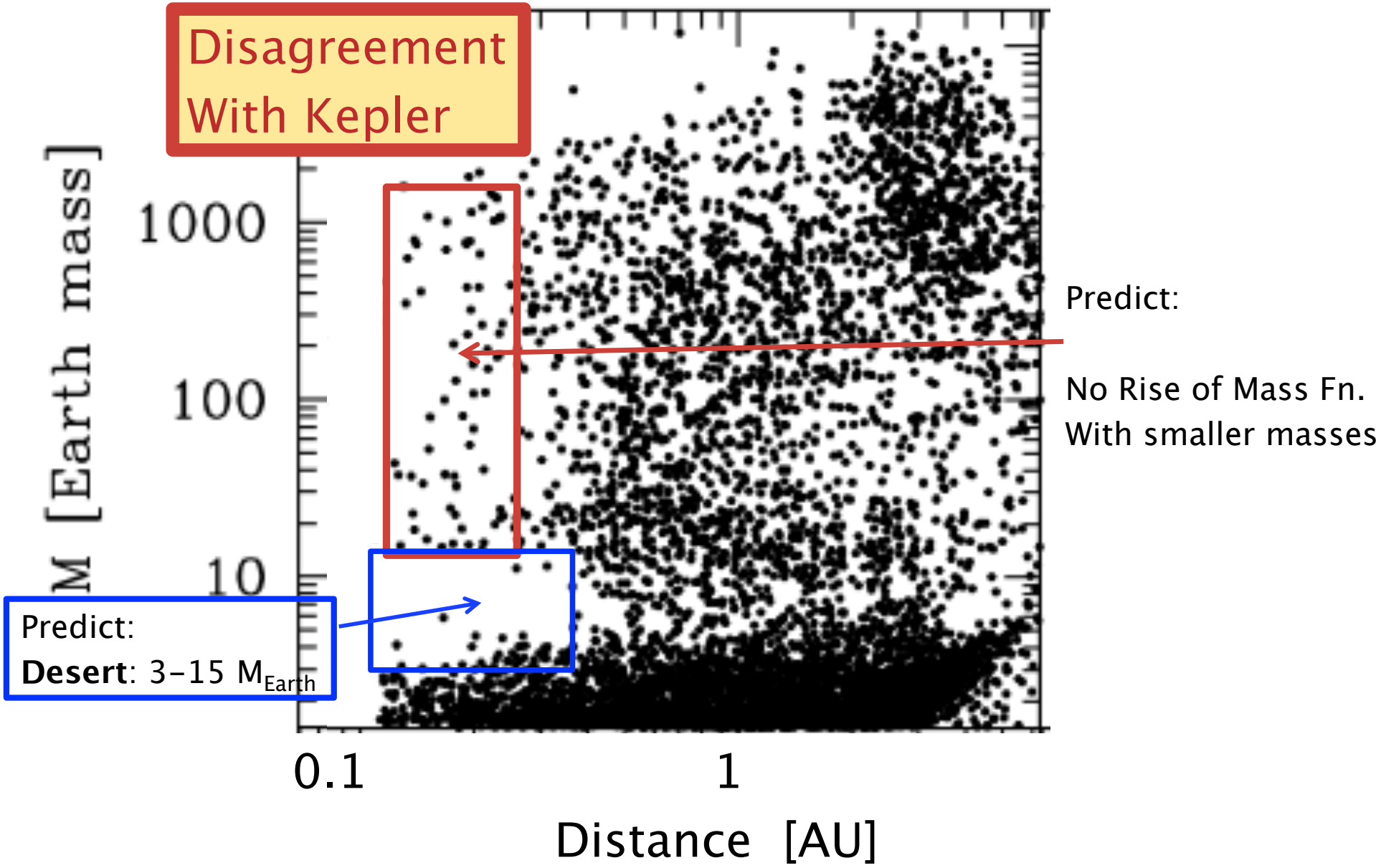
Planet Occurrence vs. Stellar T_{eff}



Howard, Marcy, Kepler Team. (Sept. 2011)

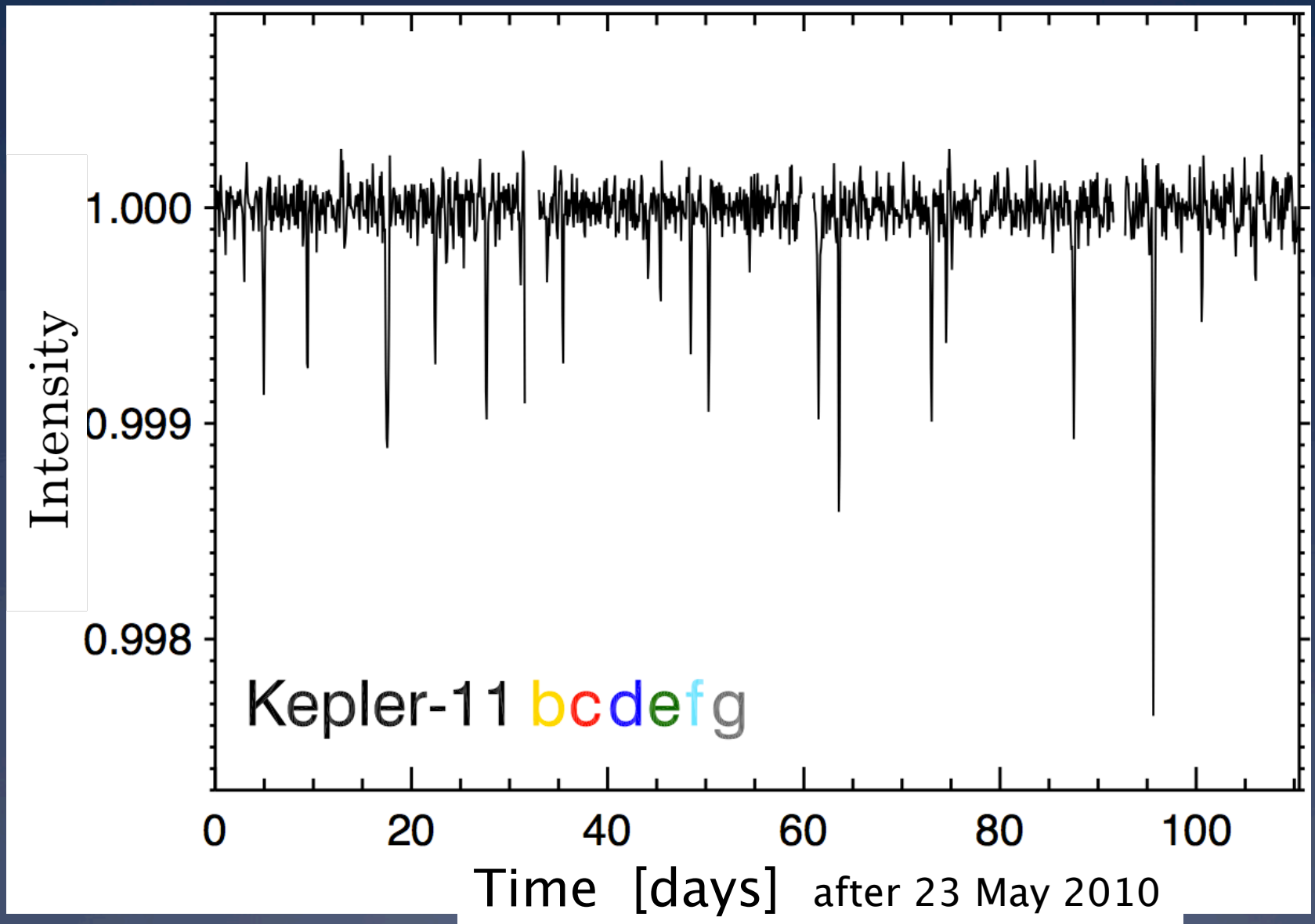
Extrasolar planet population synthesis

Lin & Ida (2010); Alibert, Mordasini, Benz (2011)



Systems with Multiple Transiting Planets

Kepler-11: Six Transiting Planets



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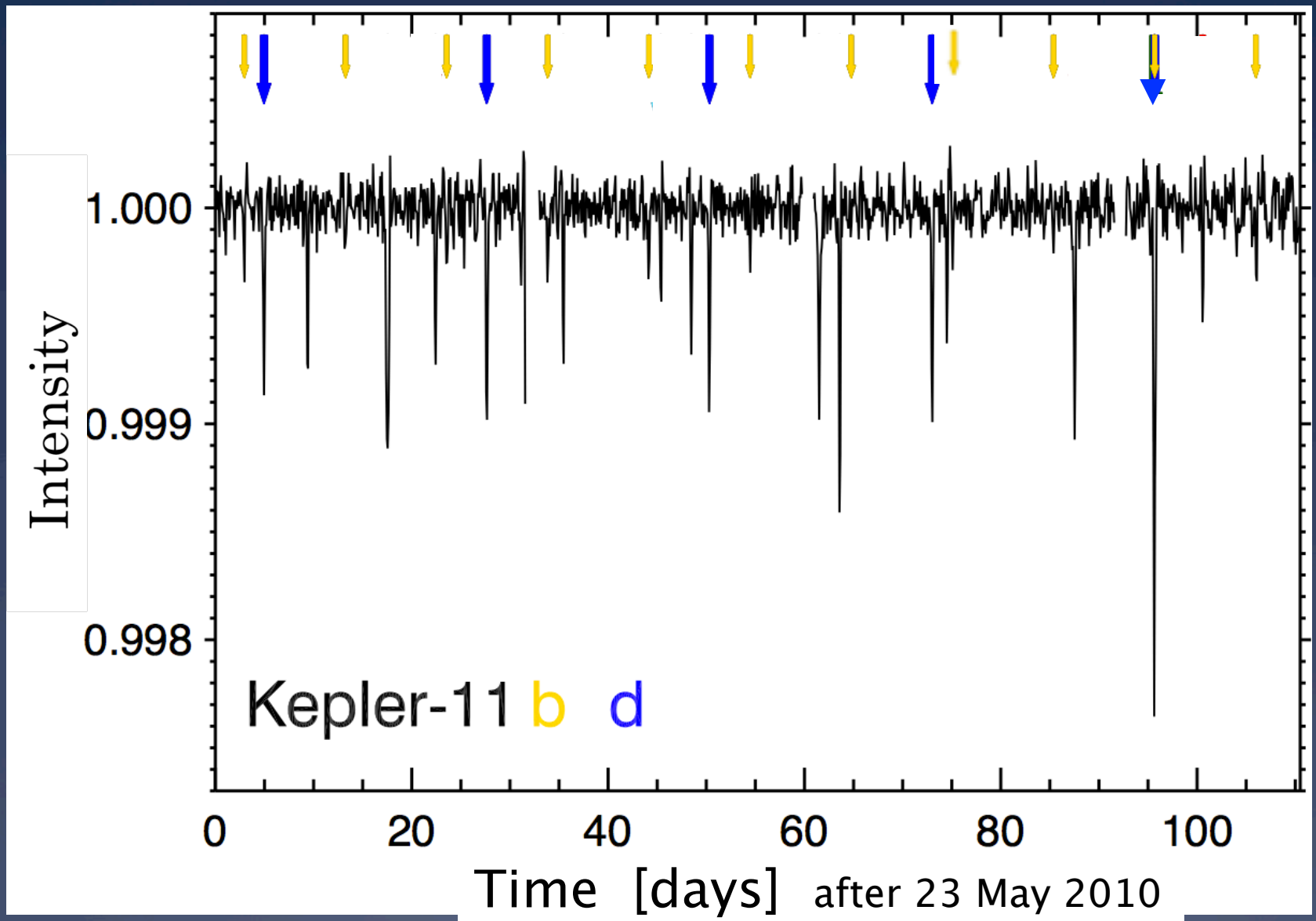
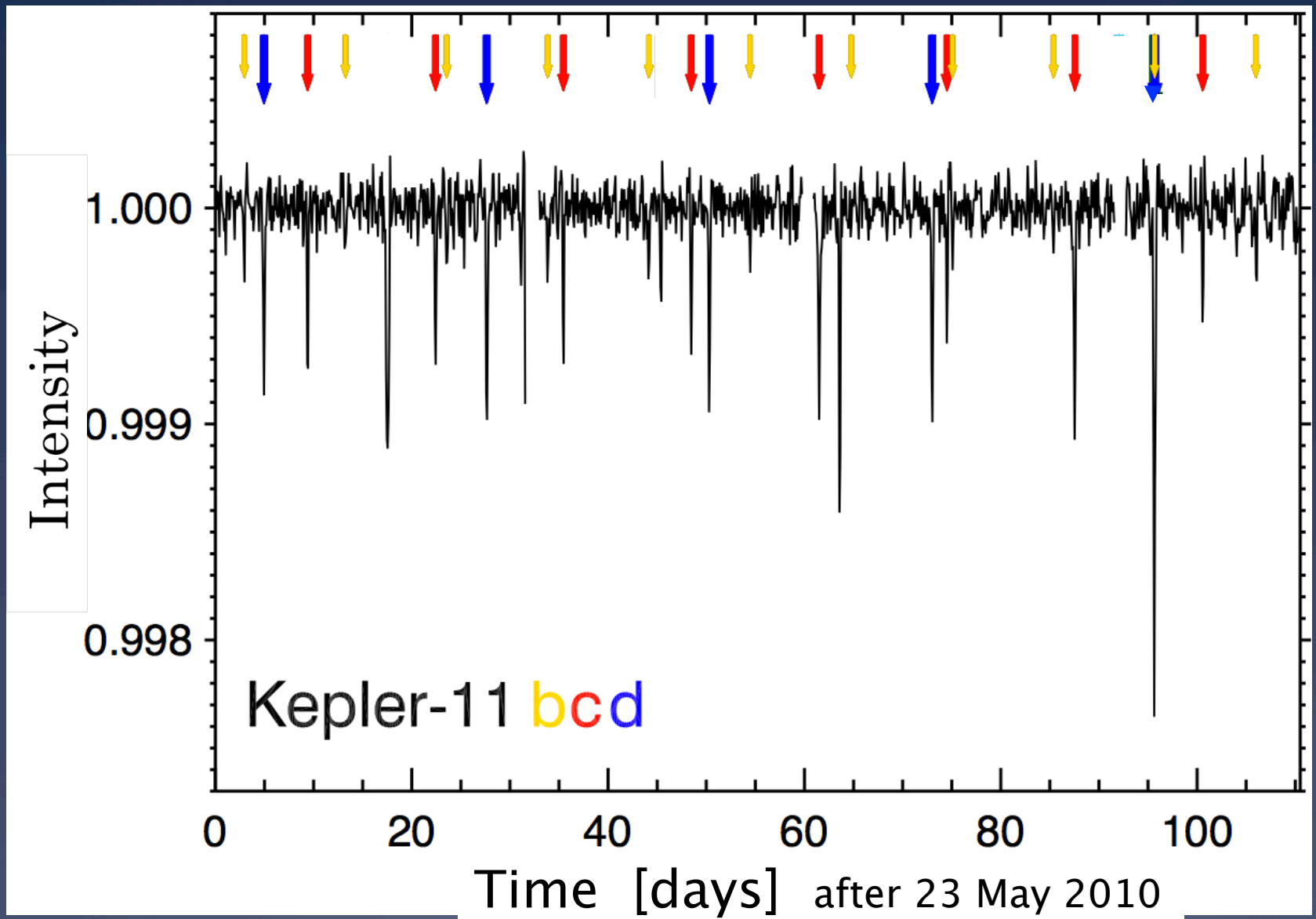


Kepler-11: Six Transiting Planets



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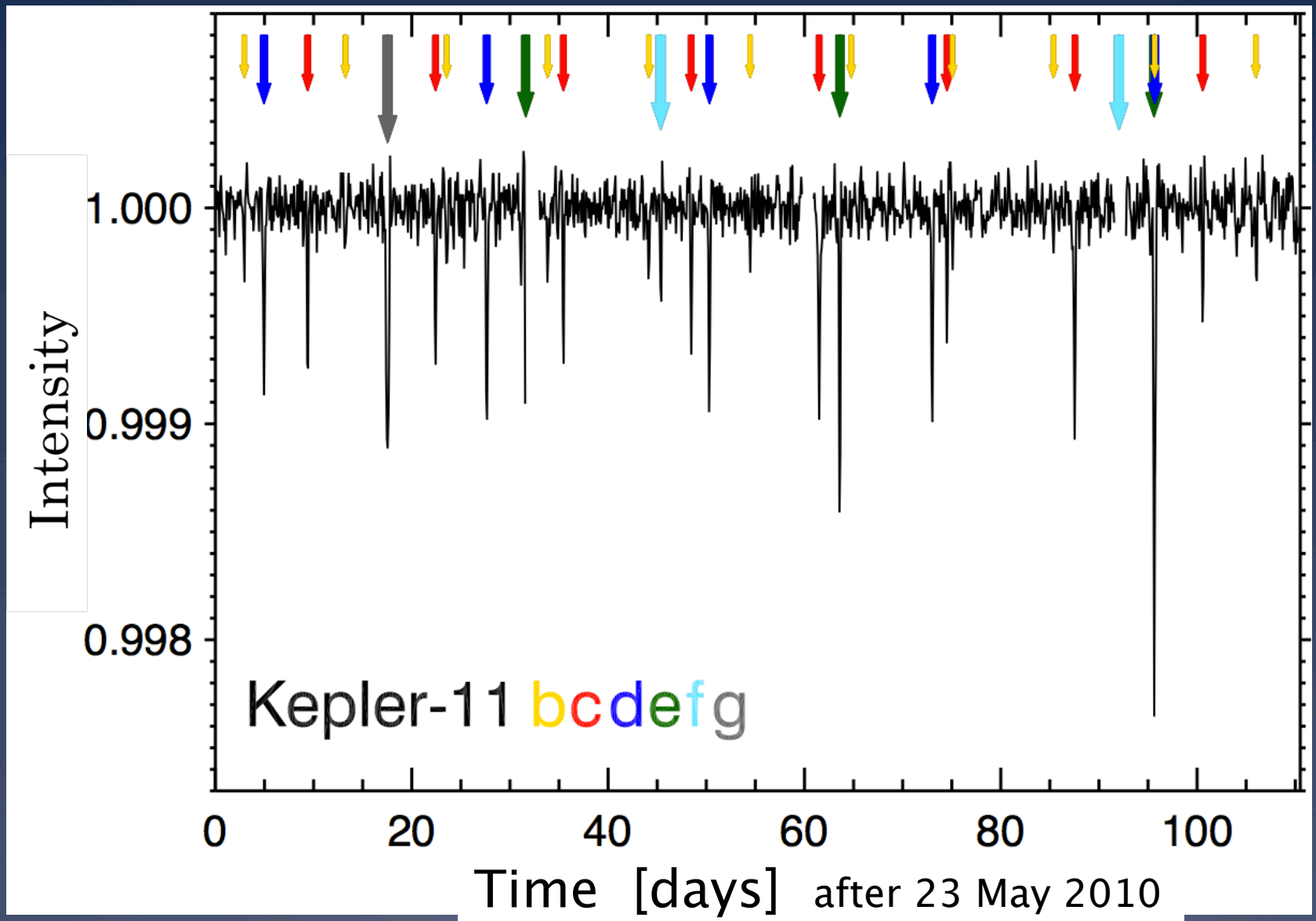
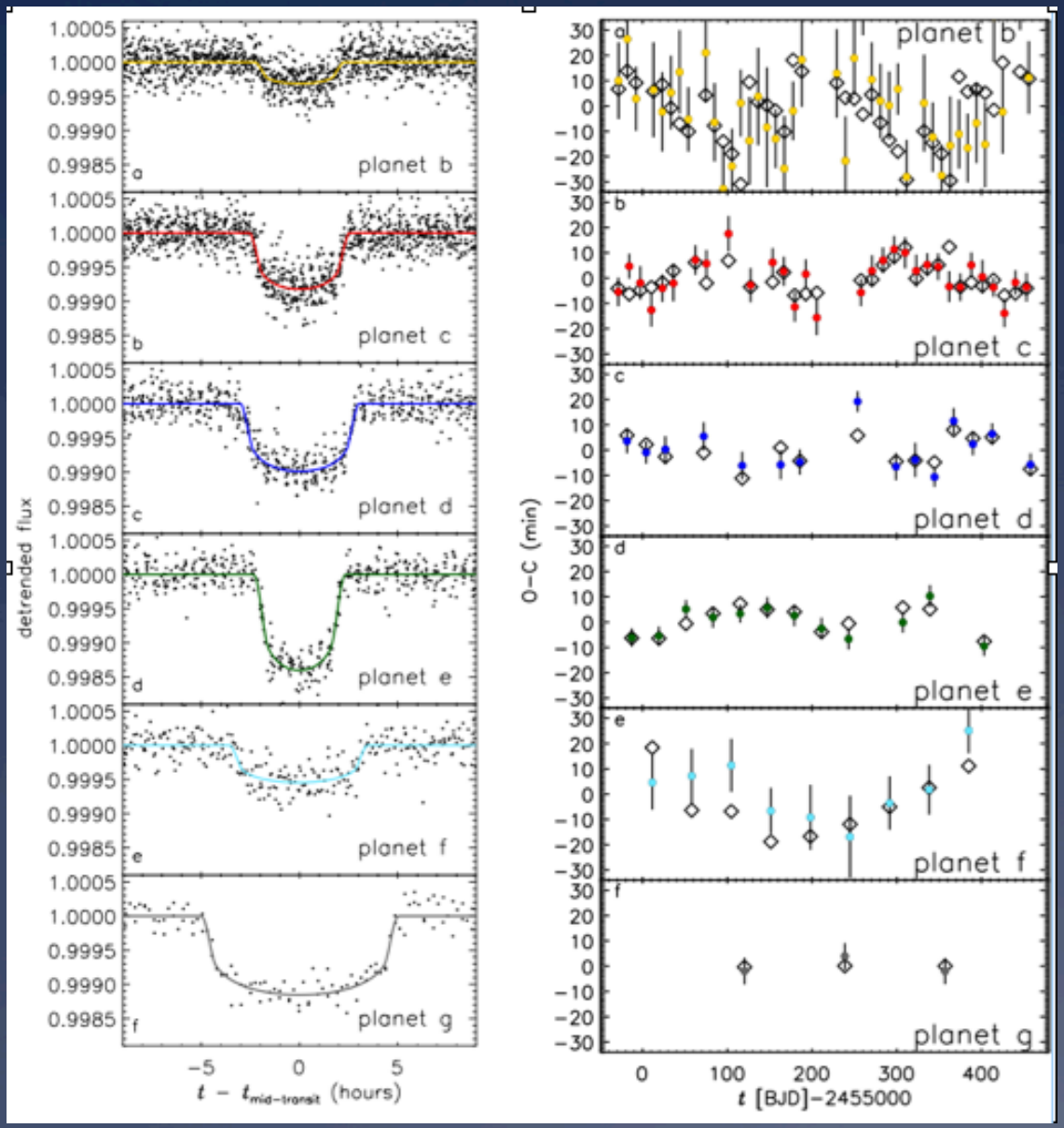


Transit-Timing Variations:



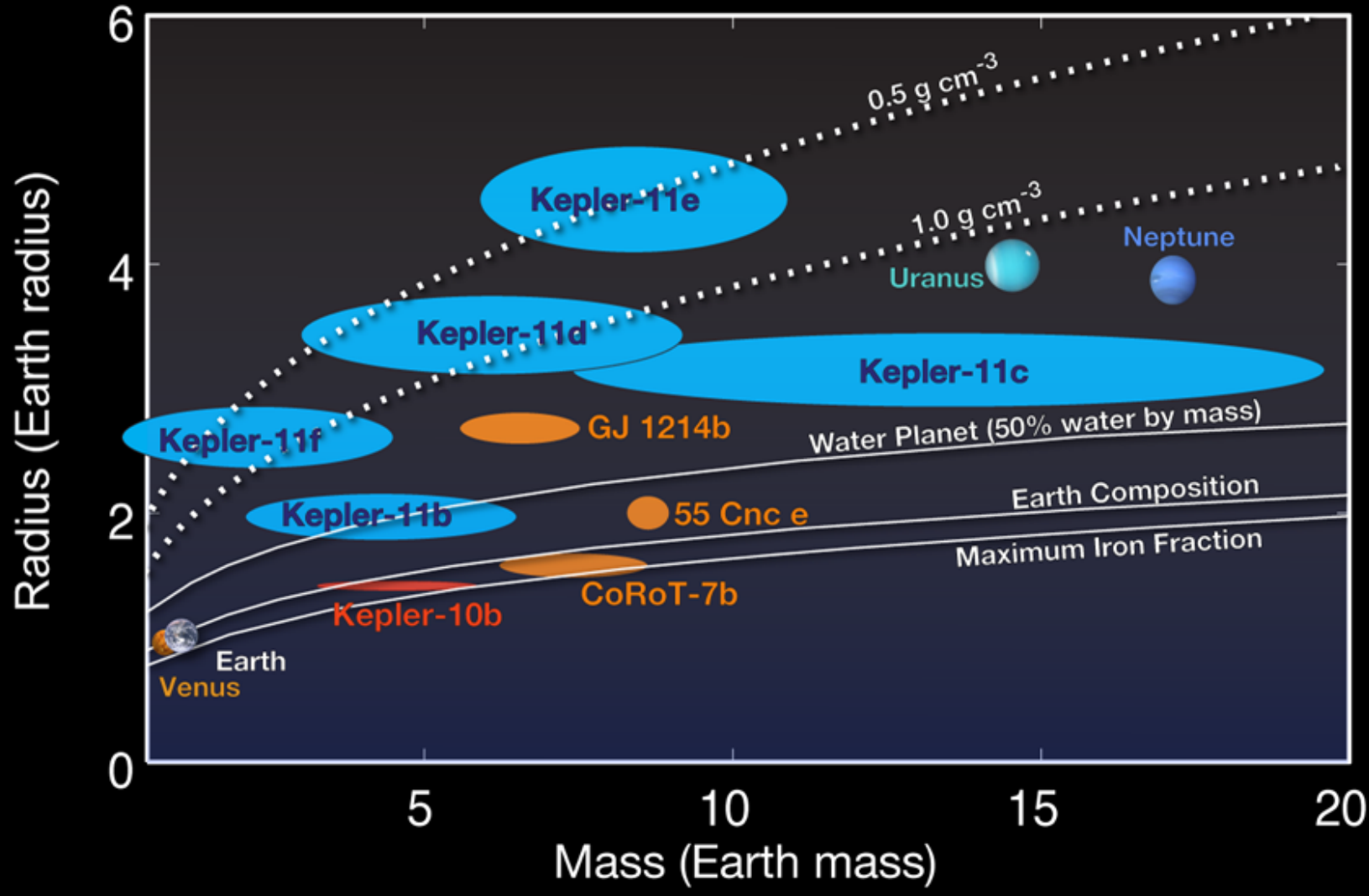
Transit-Time Variations due to planet-planet Interactions:

Planet Masses

Kepler-11 parameters

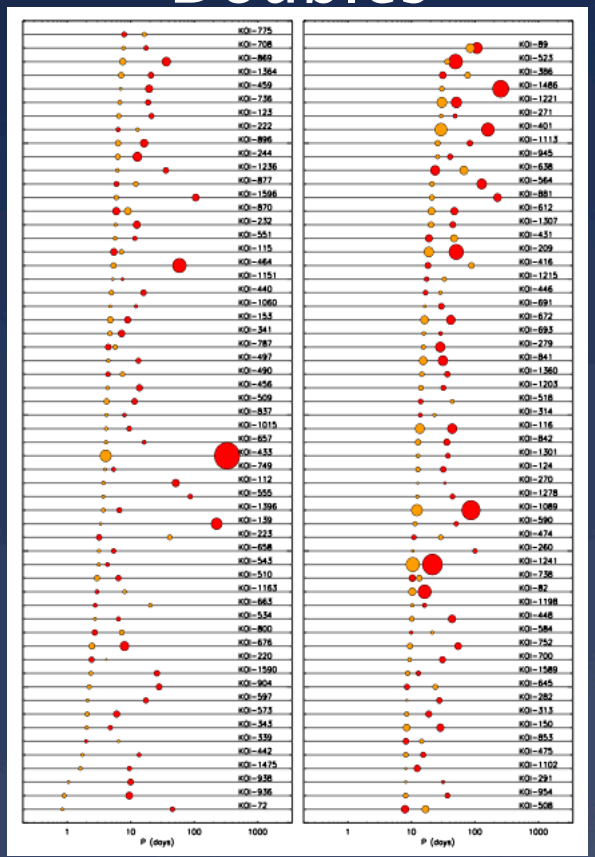
Planet	Period (days)	Radius ($R_\oplus$)	Mass ($M_\oplus$)	Density (g/cm³)
	10.30375	**1.97**	**4.3**	**3.1**
b	± 0.00016	± 0.19	+2.2,-2.0	+2.1,-1.5
	13.02502	**3.15**	**13.5**	**2.3**
c	± 0.00008	± 0.30	+4.8,-6.1	+1.3,-1.1
	22.68719	**3.43**	**6.1**	**0.9**
d	± 0.00021	± 0.32	+3.1,-1.7	+0.5,-0.3
	31.99590	**4.52**	**8.4**	**0.5**
e	± 0.00028	± 0.43	+2.5,-1.9	+0.2,-0.2
	46.68876	**2.61**	**2.3**	**0.7**
f	± 0.00074	± 0.25	+2.2,-1.2	+0.7,-0.4
	118.37774	**3.66**		-
g	± 0.00112	± 0.35	< 300	

Mass-Radius Diagram



Multi-Planet Candidate Systems (Sept. 2011)

Doubles



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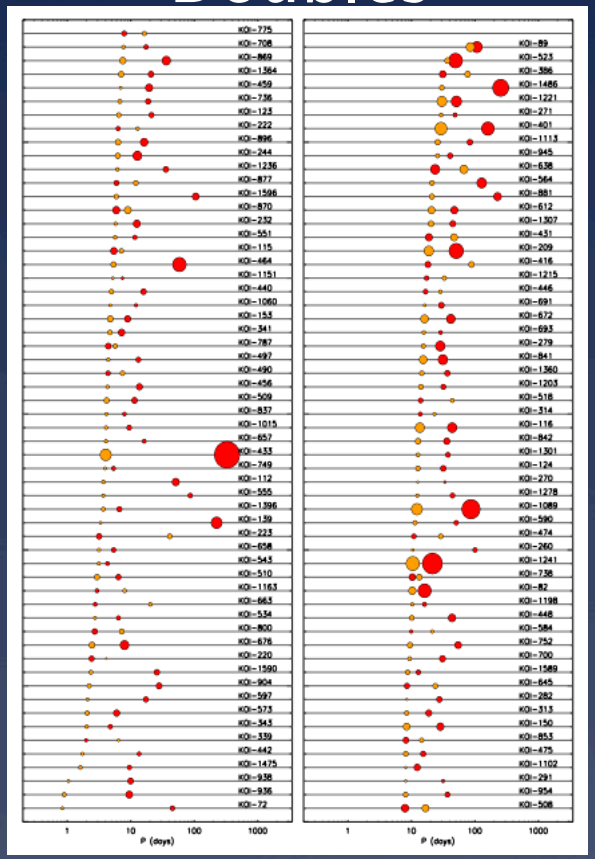
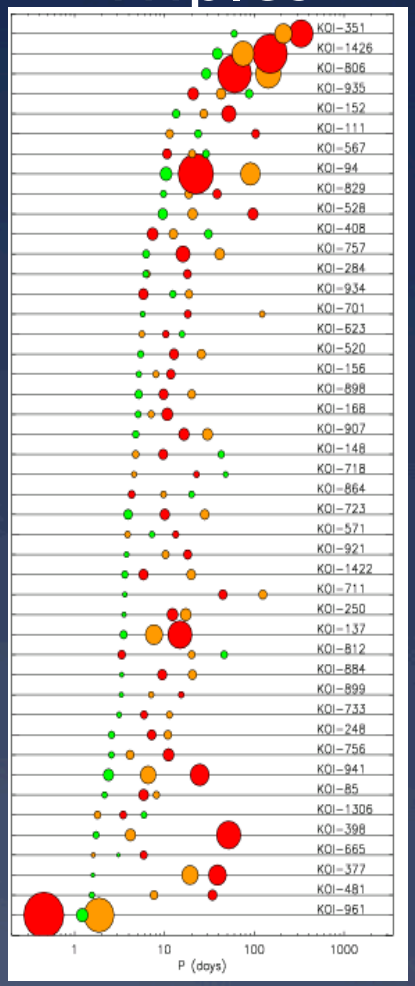
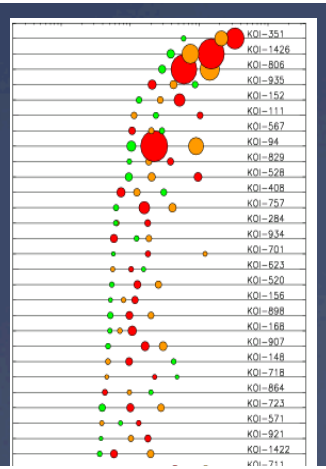
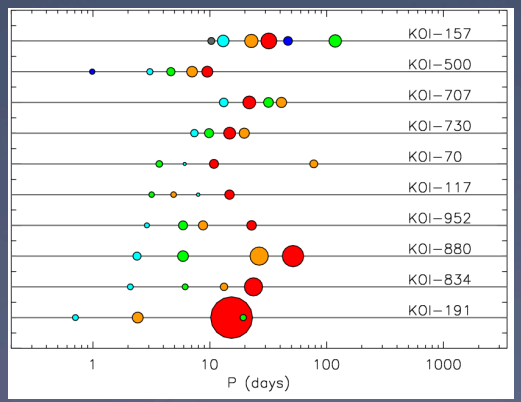


Triples



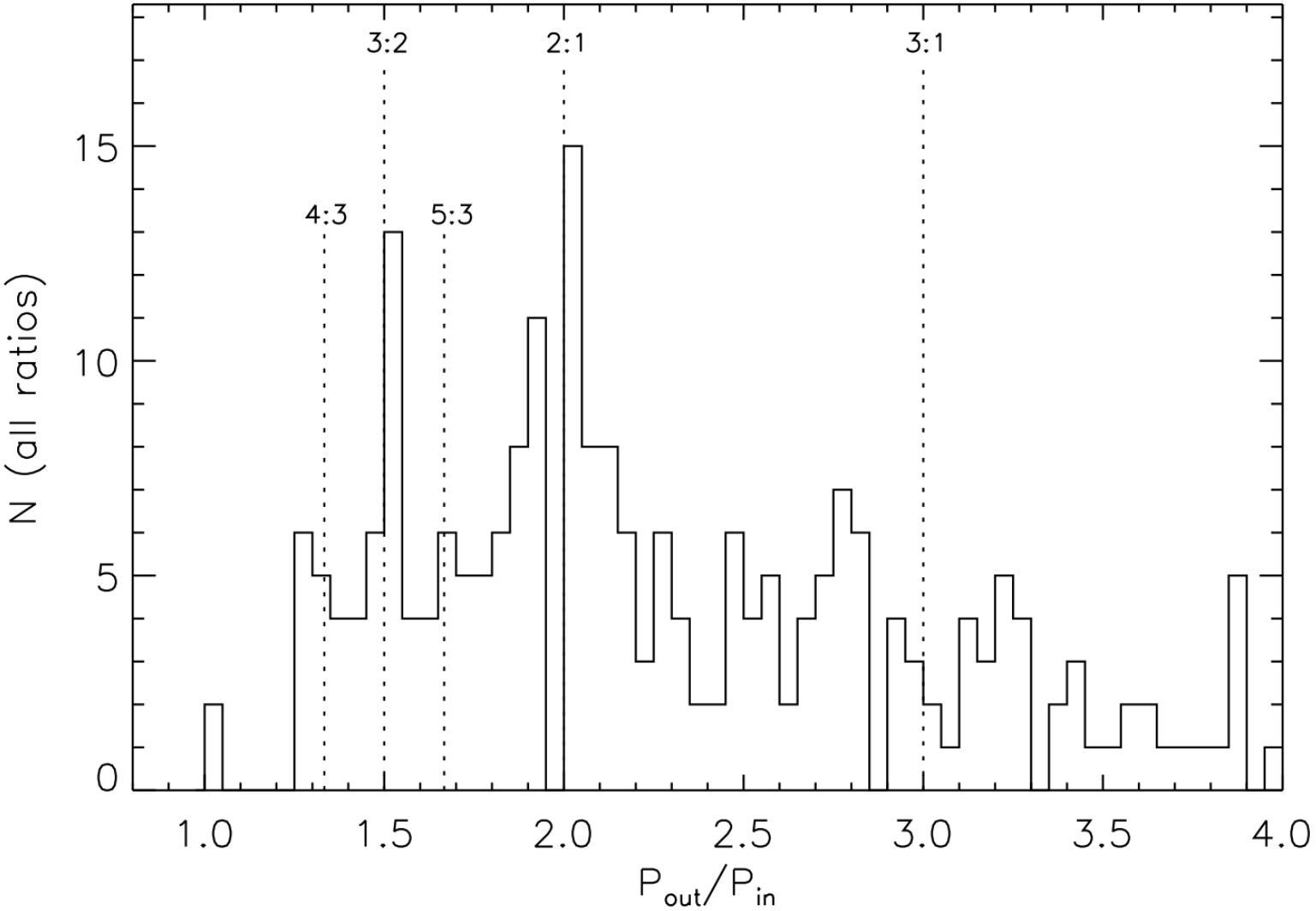
Quadruple





Quintuple & Sextuple

Resonance Preference



Dynamical analysis shows most near-MMR planets are NOT in MMR.

Suggestion: Planets form and migrate into MMRs, but later are drawn out of MMR. Tides from spinning star? (Veras & Ford, submitted).

Multiple Transiting Planets

# Planets	Feb 2011	Sept 2011
1	791	965
2	115	218
3	45	73
4	8	25
5	1	8
6	1	2

Prob of Transit is low: $R_{star}/a \sim 0.05$

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Doubles/Singles =
218/965 = 0.23

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218/965 = 0.23

Triples/Doubles =
73/218 = 0.33

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Doubles/Singles =
218/965 = 0.23

Triples/Doubles =
73/218 = 0.33

Prob of Transit is low: $R_{star}/a \sim 0.05$

Large ratios of doubles/singles and triples/doubles implies systematically co-planar orbits.

Kepler's Multiple-Transiting Planets

* Multiplanets are on firm statistical footing

Kepler's Multiple-Transiting Planets

* Multiplanets are on firm statistical footing
* Mostly sub-Neptune size ($R < 4\ R_{Earth}$)

Kepler's Multiple-Transiting Planets

* Multiplanets are on firm statistical footing
* Mostly sub-Neptune size ($R < 4\ R_{Earth}$)
* Architectures:
  - Flat Plane

Kepler's Multiple-Transiting Planets

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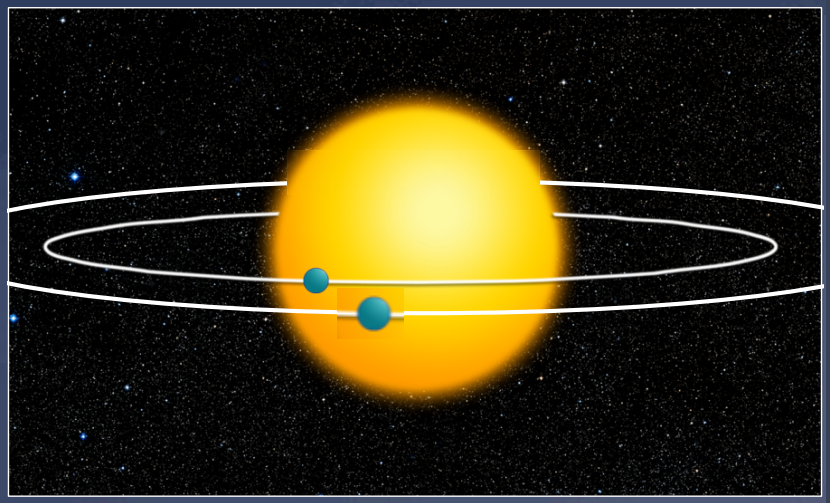
* Transit timing variations (TTV): Planet Masses

Double Planets:

Two Planets or

Double Transit signal could be due to:

Two Transiting Planets



Double Planets:
Two Planets or Planet + EB?

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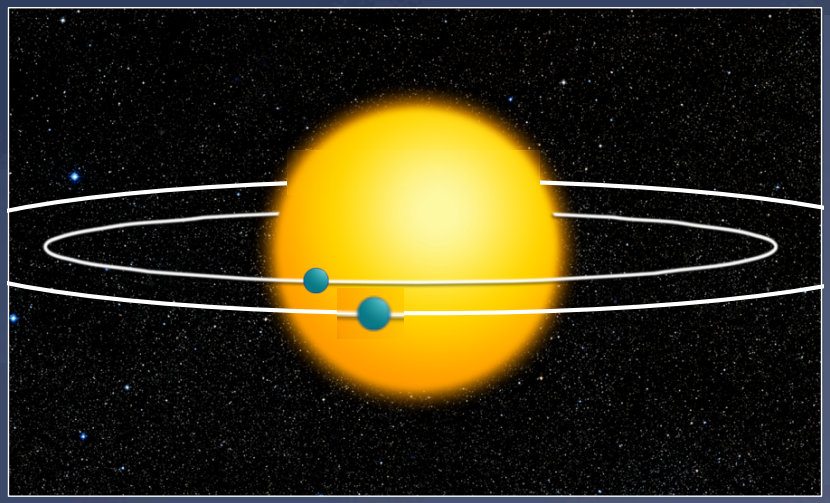
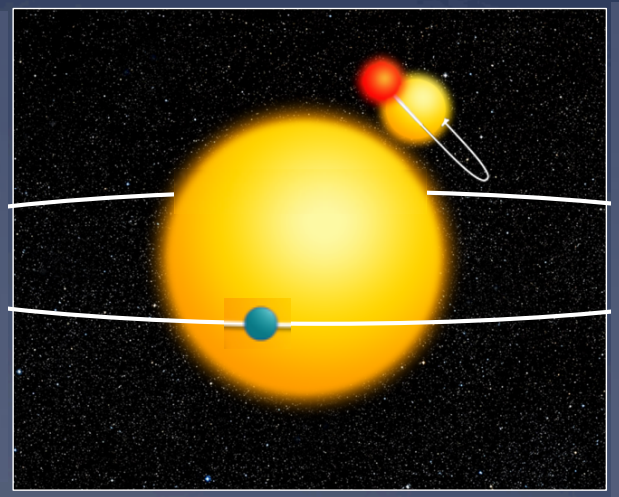


1 Planet + Eclipsing Binary



False Positives in Multi-Planet Transiting Systems

- Consider a target star with:

  Transiting planet and a nearby Eclipsing binary.

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But there are 170 multi-planet systems!

Nearly all Multi-Planet Systems are pure planets.

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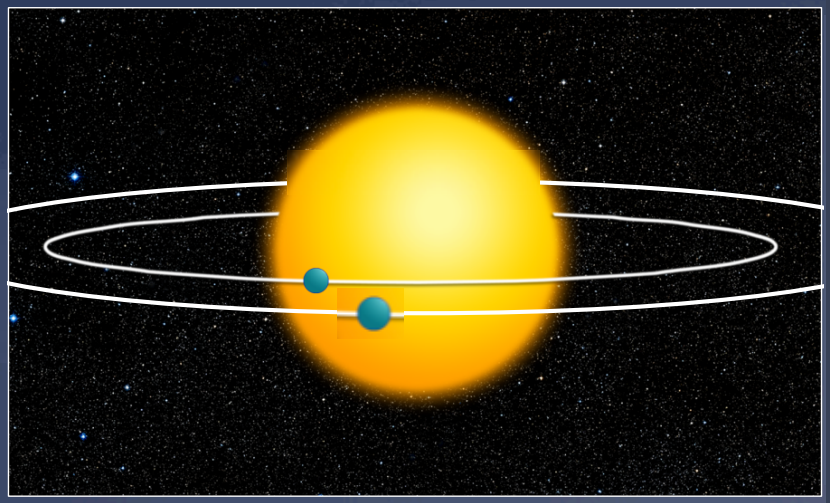

Double Planets:
Two Planets or Two stars

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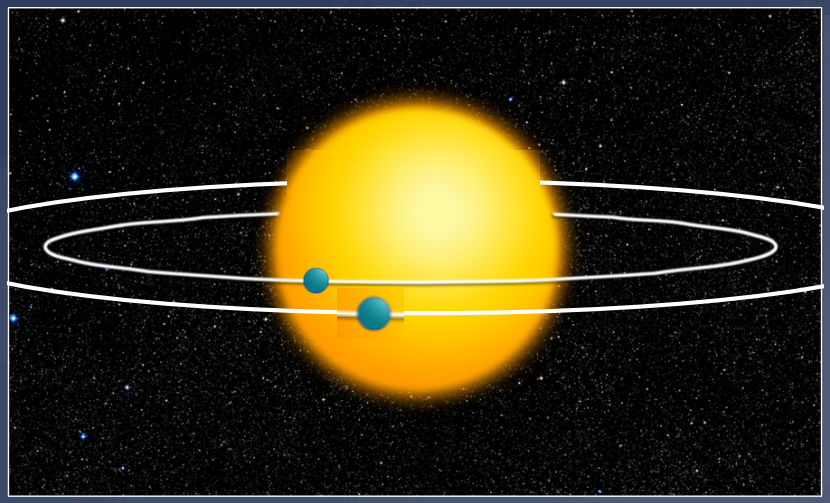

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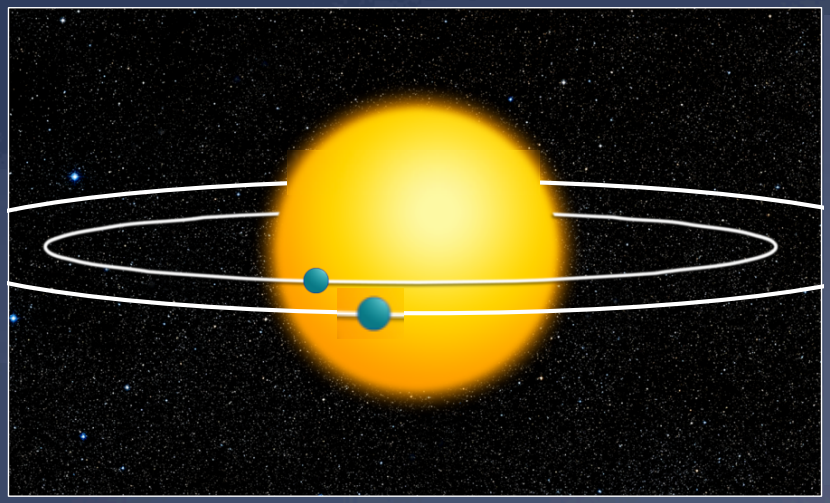

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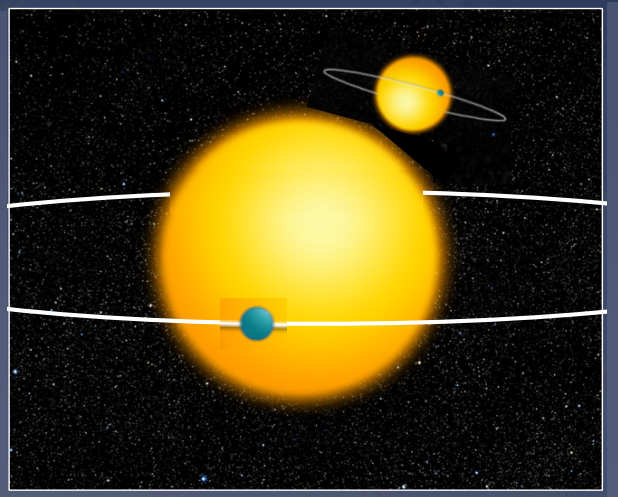

"False Positives" in Multi-Planet Transiting Systems

- Consider a target star that is a BINARY STAR

  One Transiting planet around each star.

- *It **masquerades as a double planet.***

- *How common are these?*

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But there are 170 multi-planet systems!

Most apparent Multi-Planets are Planetary Systems

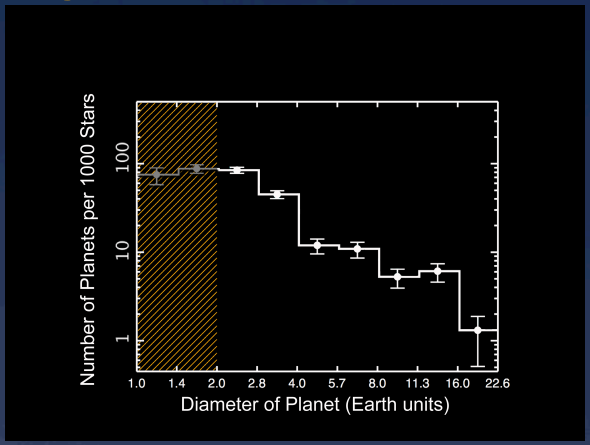
Summary

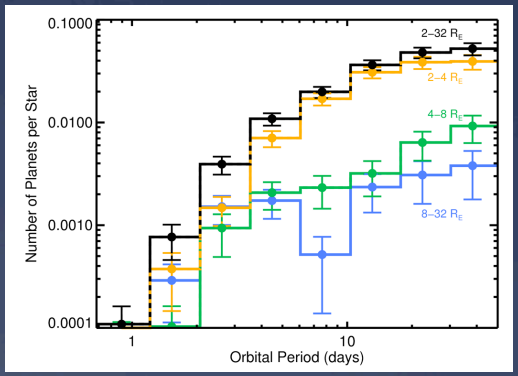
- Planet Occurrence increases toward smaller radii, to 1.5 R_{Earth}
- Planet Occurrence increases toward larger orbits
- Planet Occurrence increases toward smaller stars

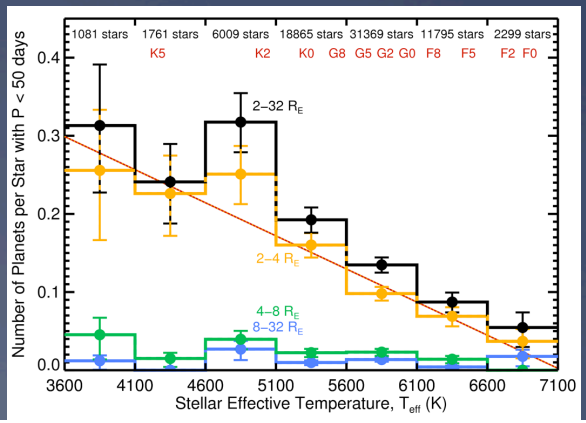
- 170 Apparent multi-planet systems consist of real planets in systems around one star.

Conclusions

* Planet Occurrence:
  * Increases with smaller size
  * Increases with larger orbits
* Small planets are more frequent around smaller stars







Basic Equation:

Expected # of Multis w/ FP

$$1 \text{ planet or FP } + 1 \text{ FP}: \frac{n_c}{n_t} \times \frac{n_c(1-P)}{n_t} \times n_t = (1-P)\frac{n_c^2}{n_t} = 9.5(1-P)$$

n_c is # candidates

n_t is # targets

P is fraction of candidates that are true planets

- 160,000 targets
- 1700 KOIs (1% of the targets)
- 170 false positives (10% estimate for FPs)
- FPs are distributed randomly

Equation (1) predicts only 1 multi-transiting system with a FP

But we observe 170 multis (with 408 planet candidates)!

Nearly all 170 multi-transiting planet systems Contain real planets.

KOI-500

planet	P (days)	Mp(Mearth)
500.05	0.9867790	1.5
500.03	3.0721660	2.2
500.04	4.6453530	4.4
500.01	7.0534780	8.0
500.02	9.5216960	8.5