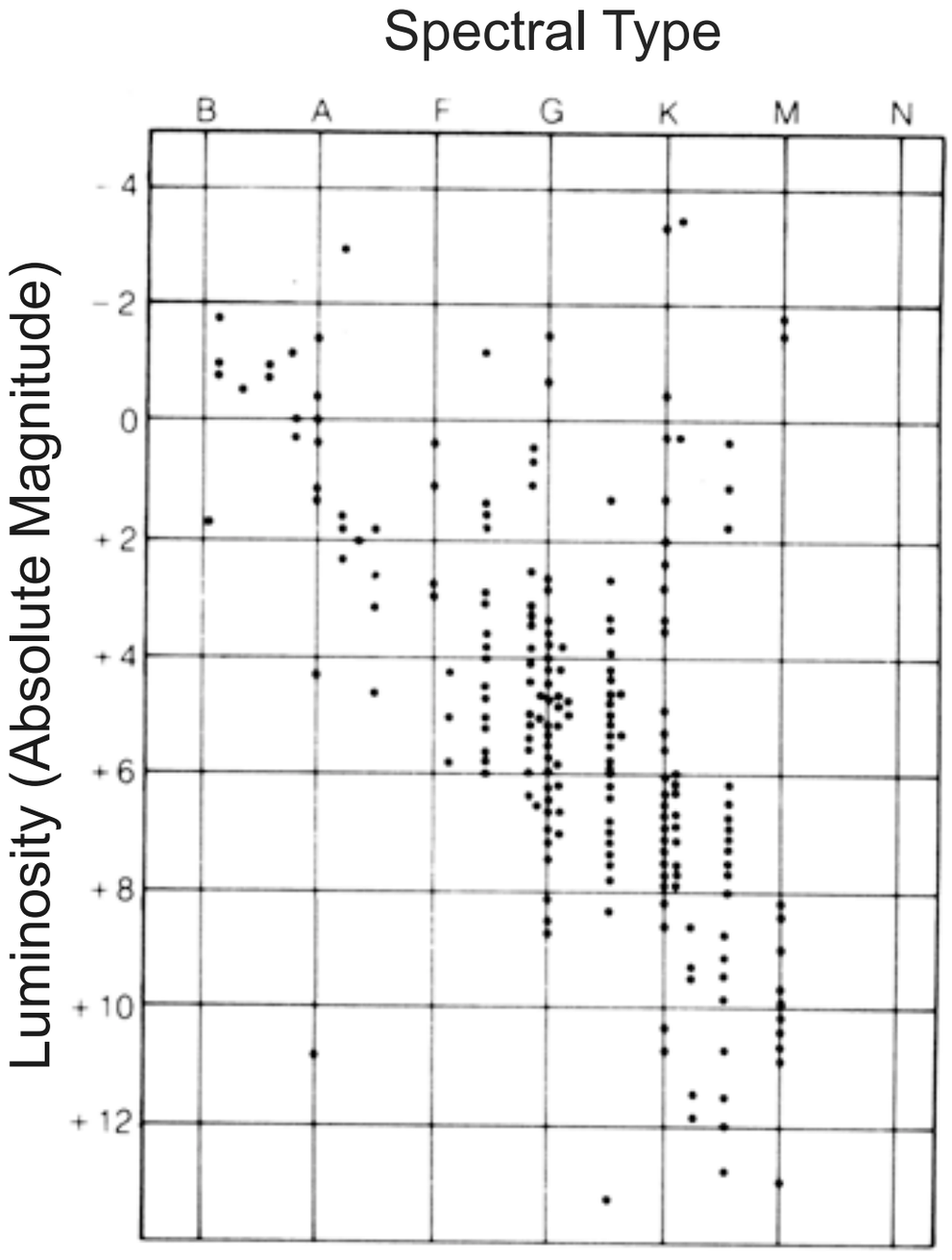
Origins and Properties of Super-Earths and Neptune-size Planets

Andrew W. Howard
UC Berkeley

Photo credit: Laurie Hatch

A Bit of History: The H-R Diagram



H. N. Russell, Nature, 93, 252 (1914)

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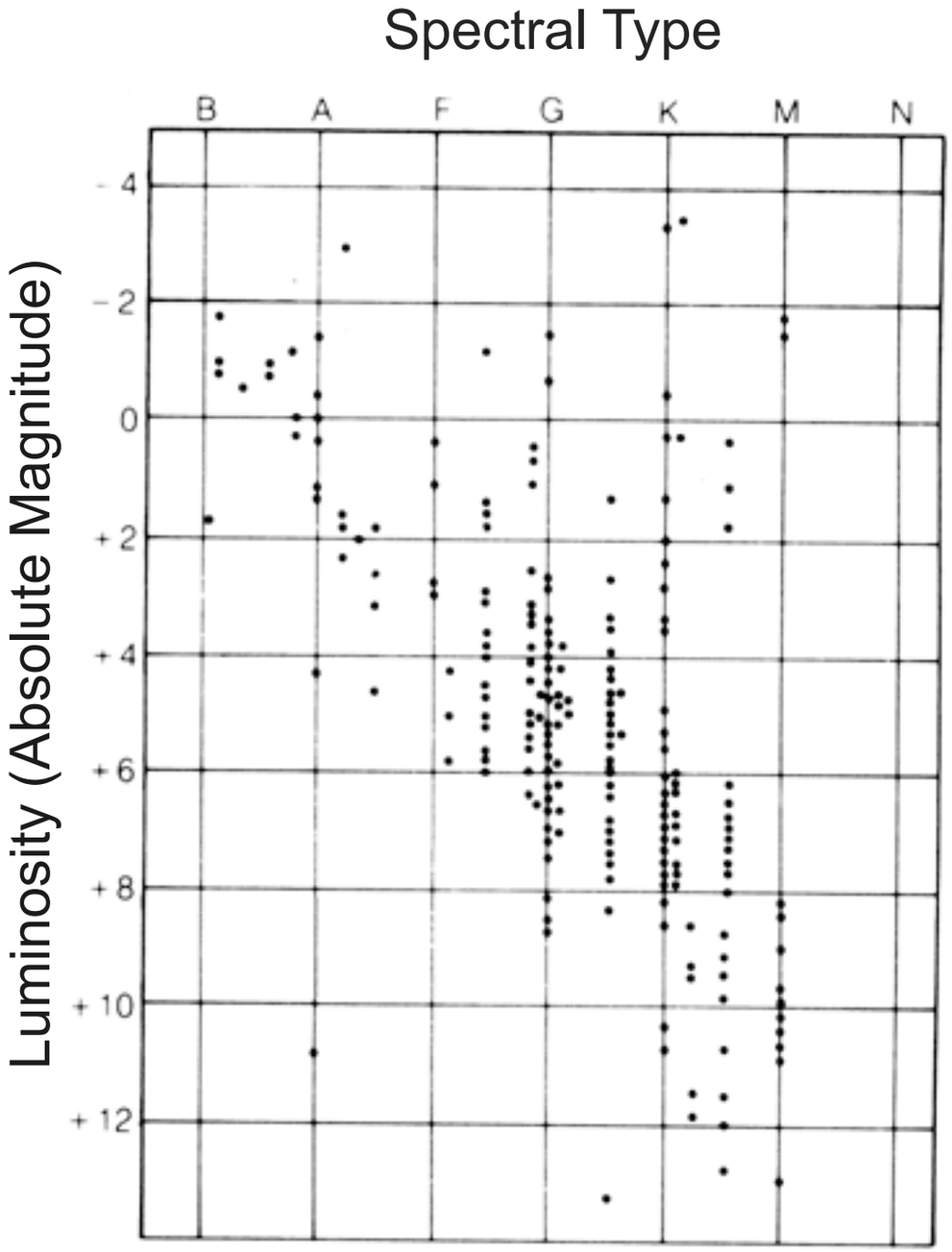
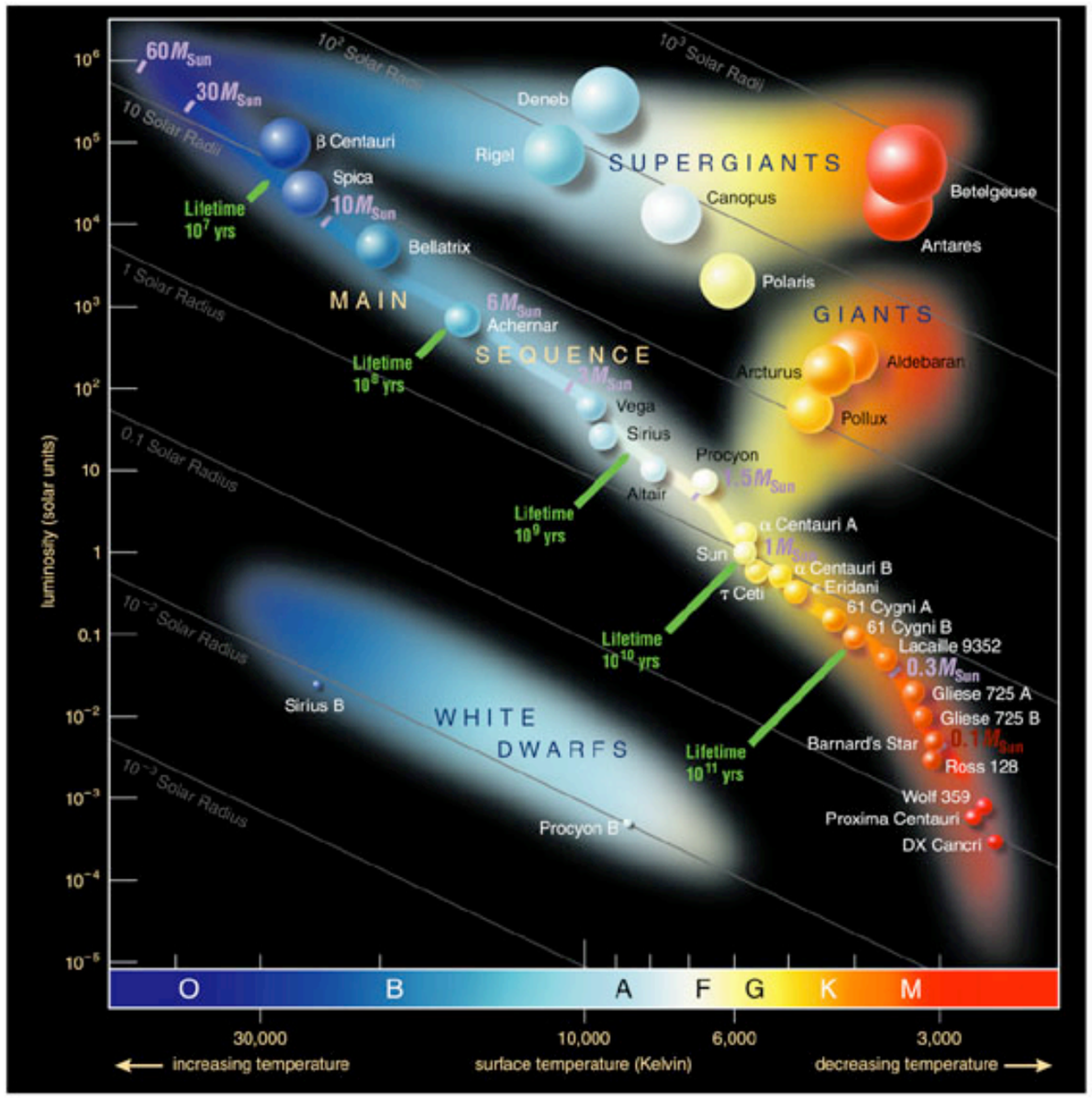
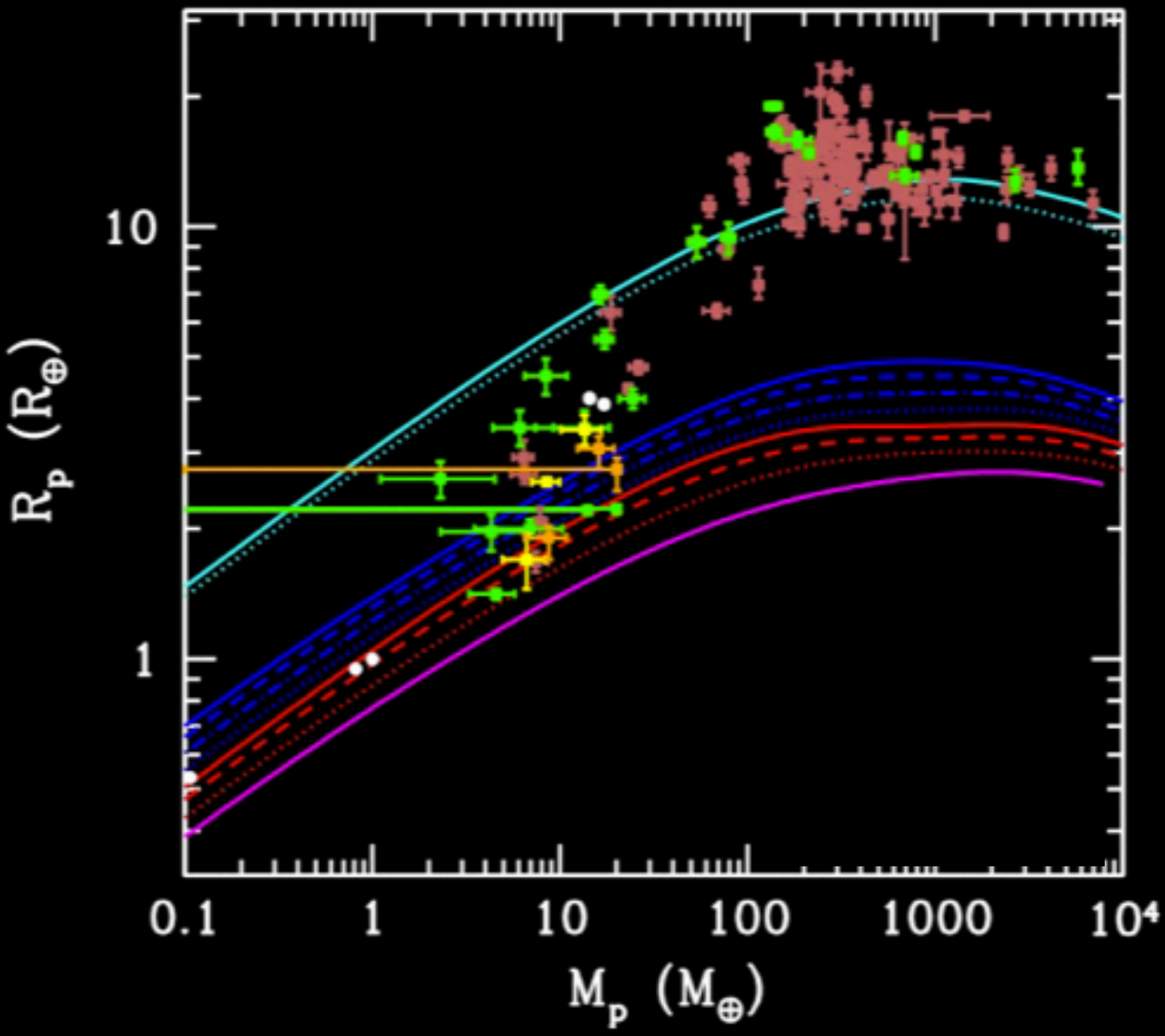


H. N. Russell, Nature, 93, 252 (1914)



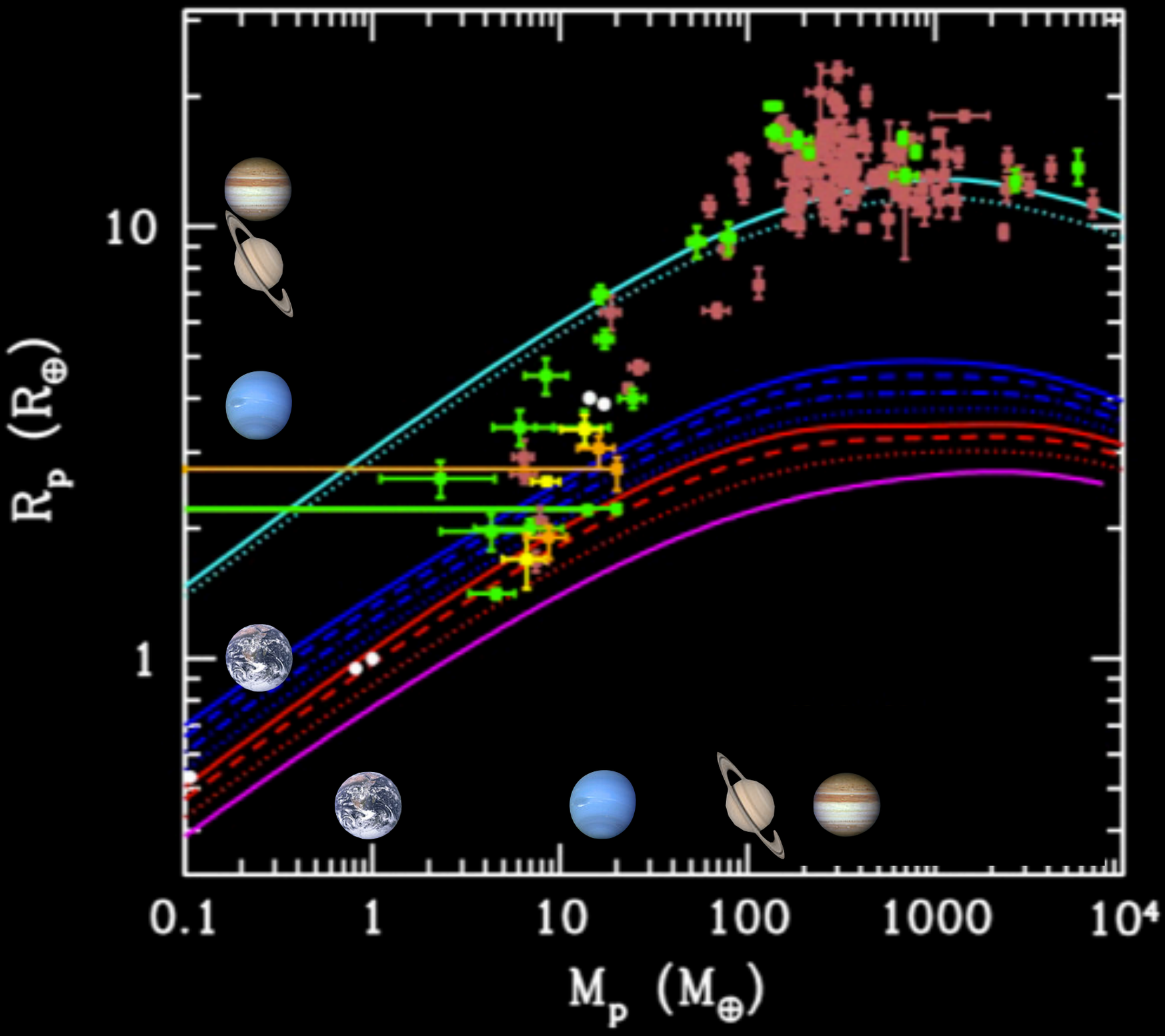
Addison Wesley (2004)

Planet Mass-Radius Diagram



Adapted from S.Seager (2011)

Planet Mass-Radius Diagram



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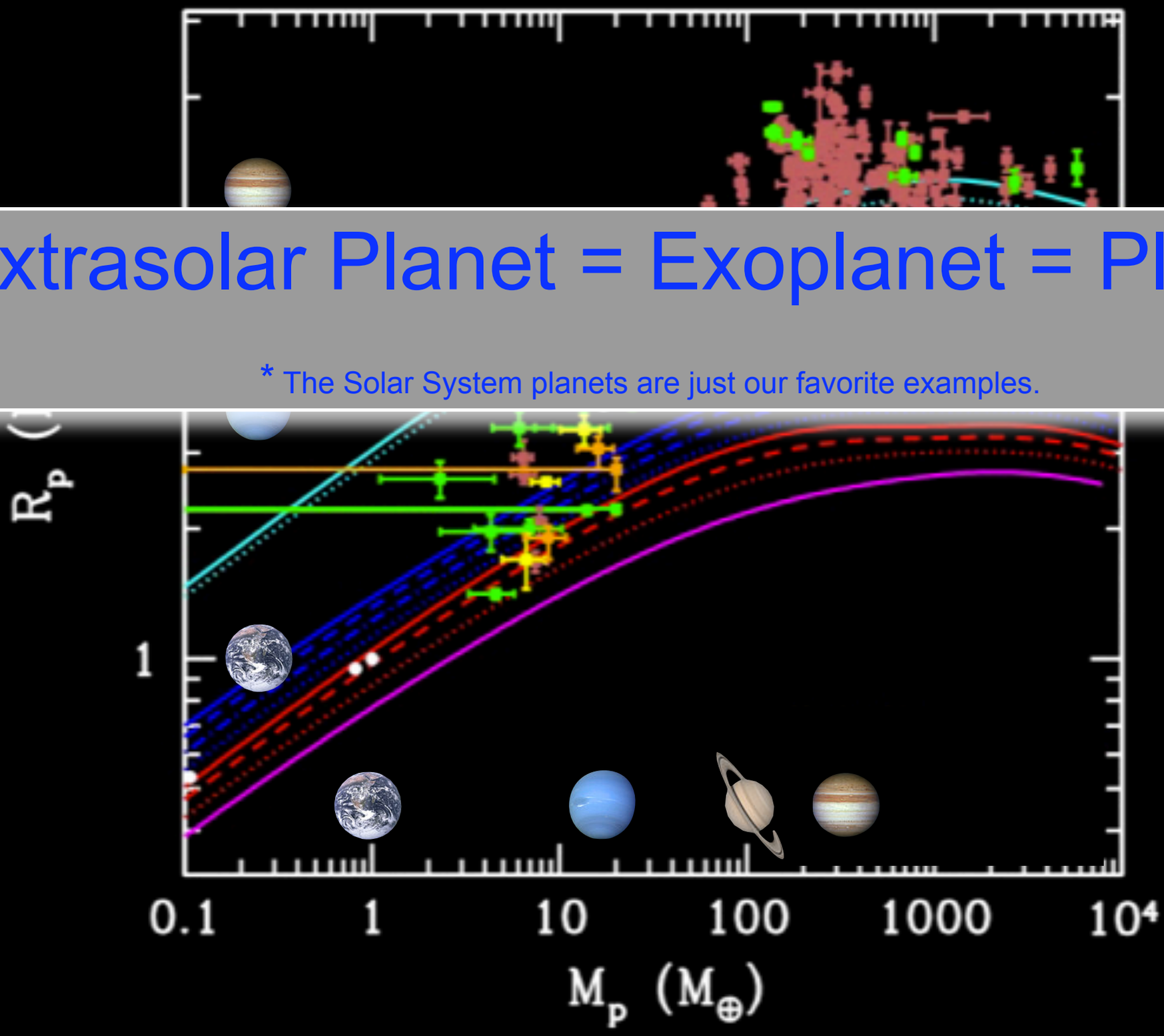
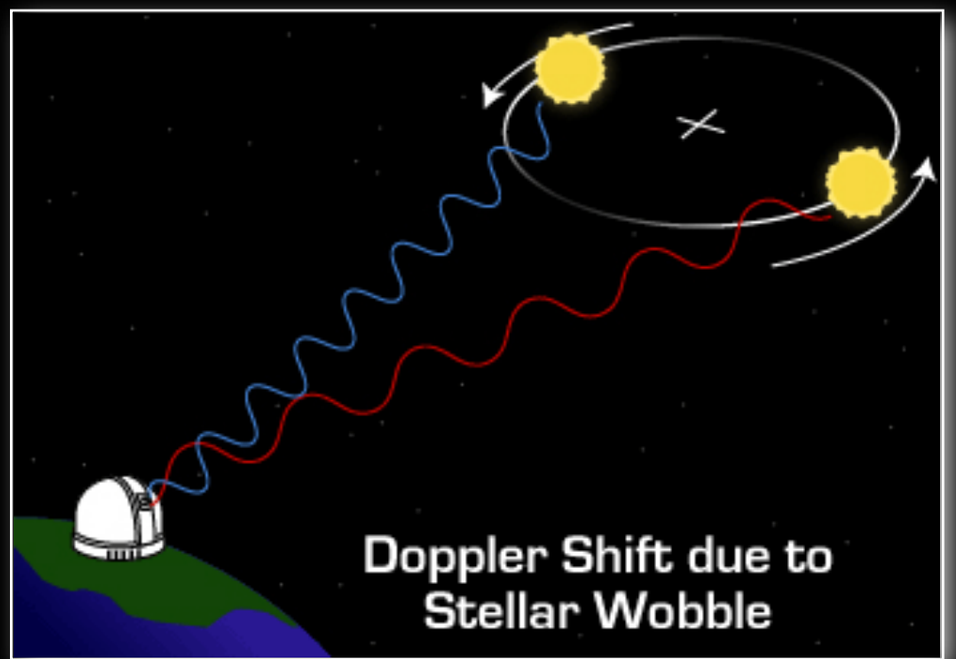


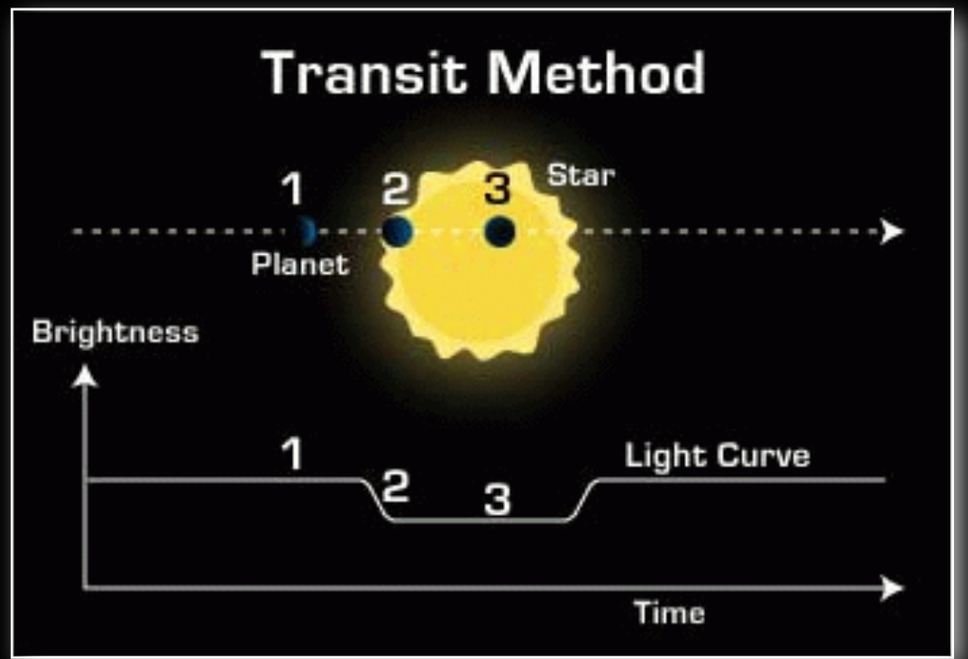
Extrasolar Planet = Exoplanet = Planet*

* The Solar System planets are just our favorite examples.

Adapted from S.Seager (2011)

Extrasolar Planet Detection Methods



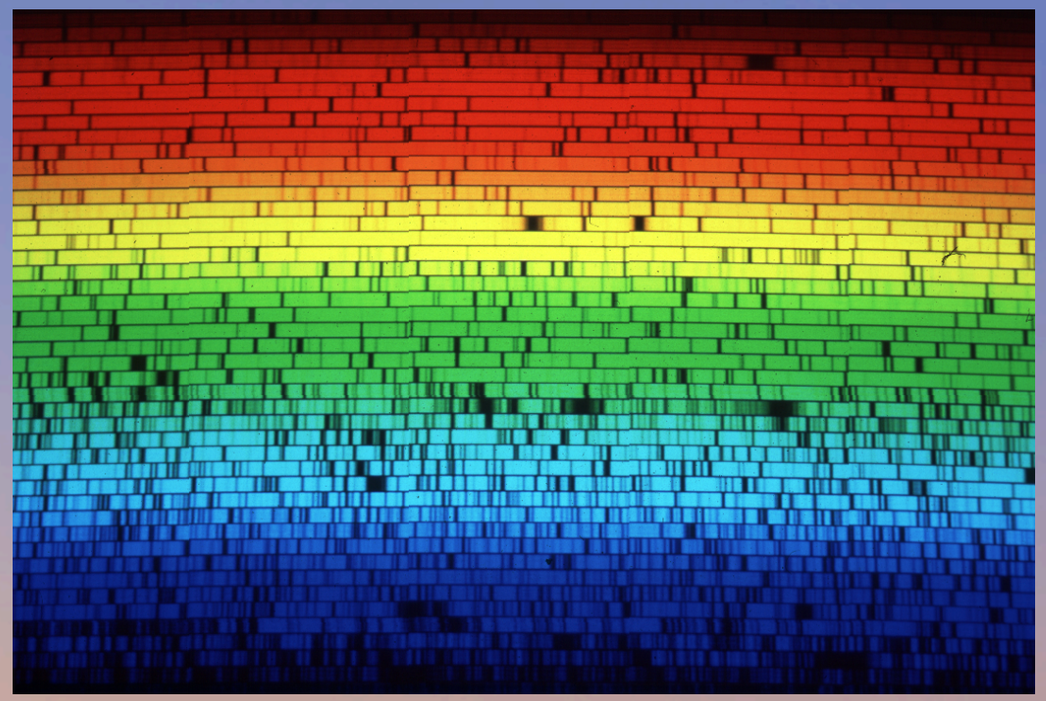


Doppler Method
Measure Planet Mass

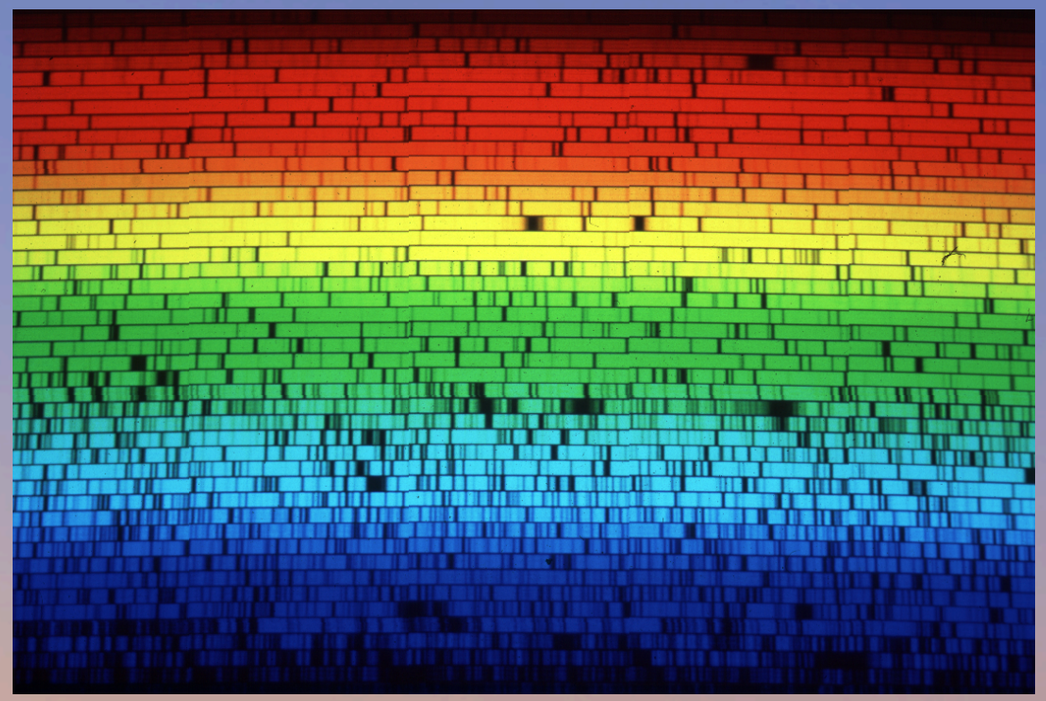
Transit Method
Measure Planet Radius

Determine Planet Density and Infer Composition

Gas giant (Jupiter), Ice Giants (Neptune),
Water Worlds (GJ 1214), Rocky Planets (Earth), More?

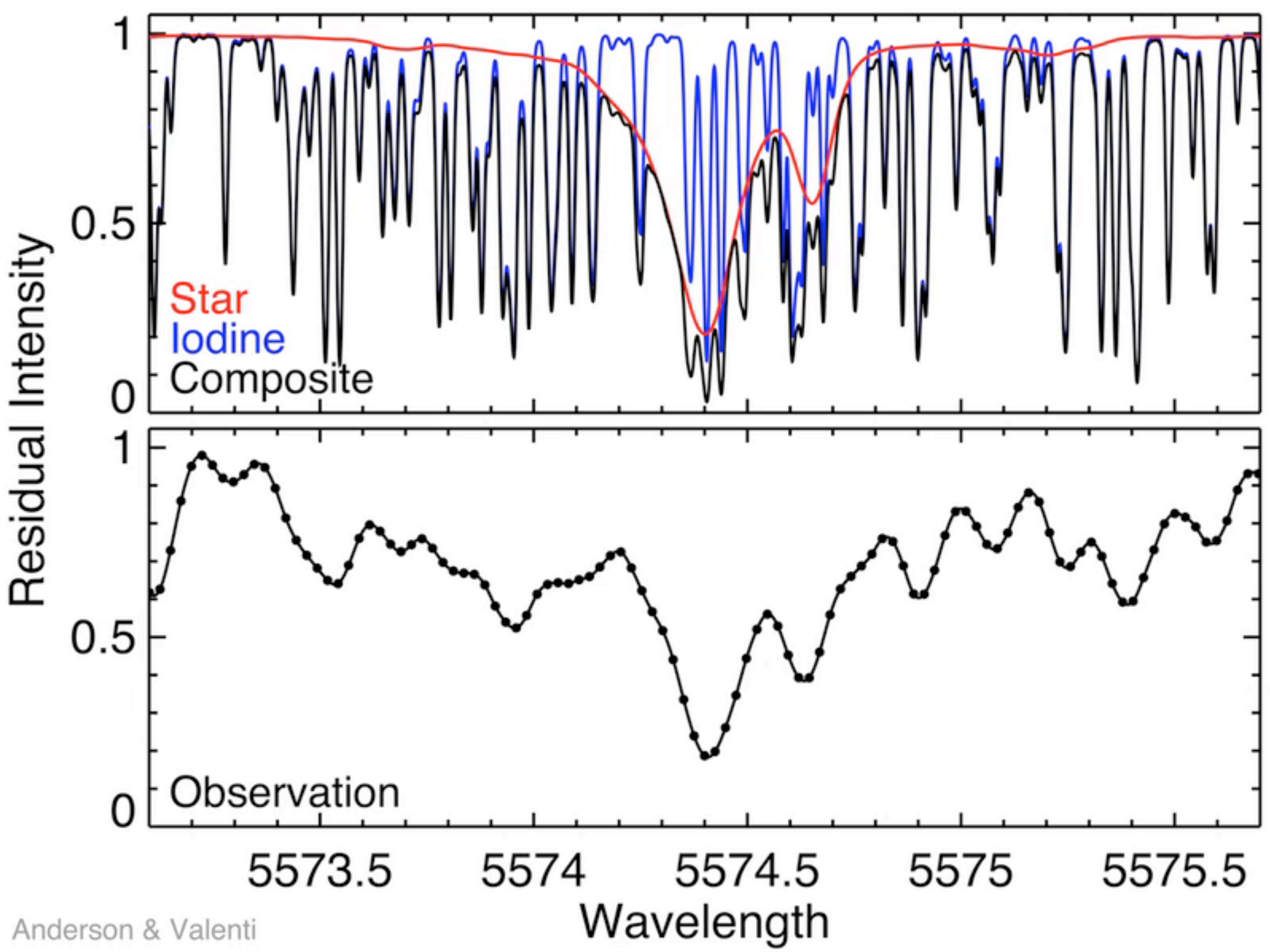


HIRES Echelle Spectrum



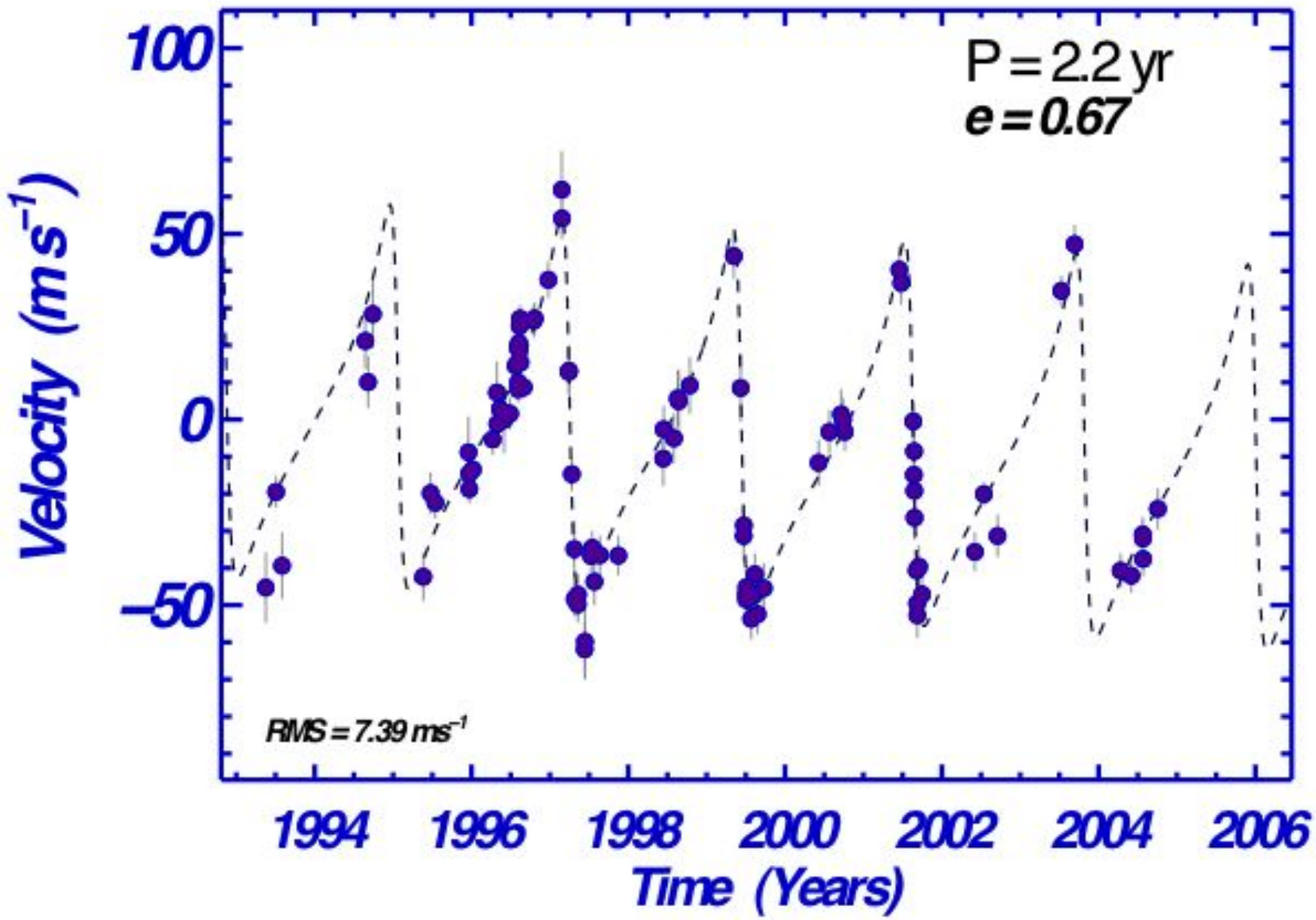
HIRES Echelle Spectrum

Iodine Absorption Cell

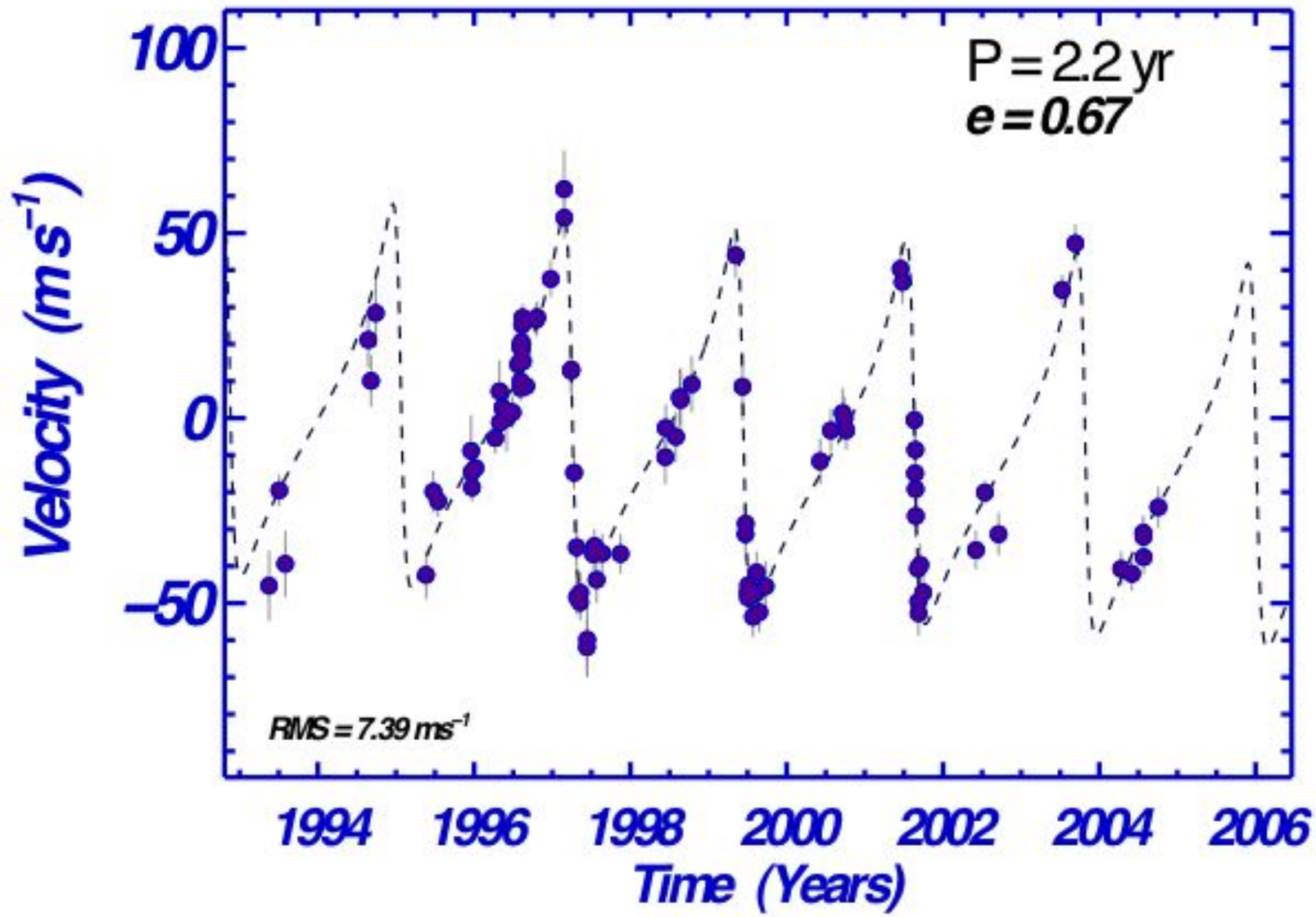


Anderson & Valenti

16 Cyg Bb

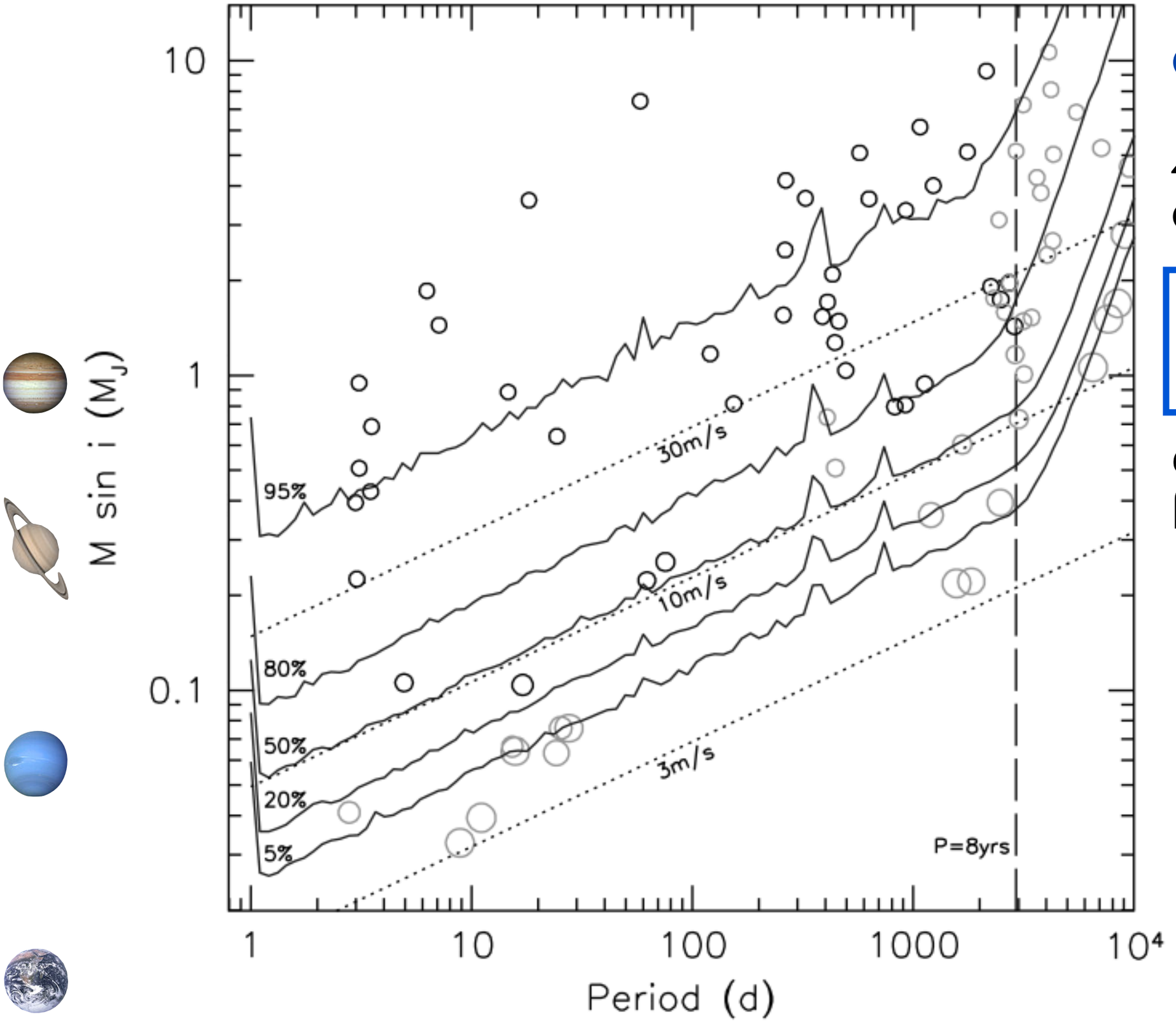

P = 2.2 yr
e = 0.67
RMS = 7.39 ms⁻¹
Velocity (m s⁻¹)
100
50
0
−50
1994
1996
1998
2000
2002
2004
2006
Time (Years)

16 Cyg Bb



Physical observables: { planet mass, orbital period, eccentricity }

Giant Planet Occurrence Rates



Cumming et al. (2008)

475 FGK dwarfs
Giant Planet Occurrence:

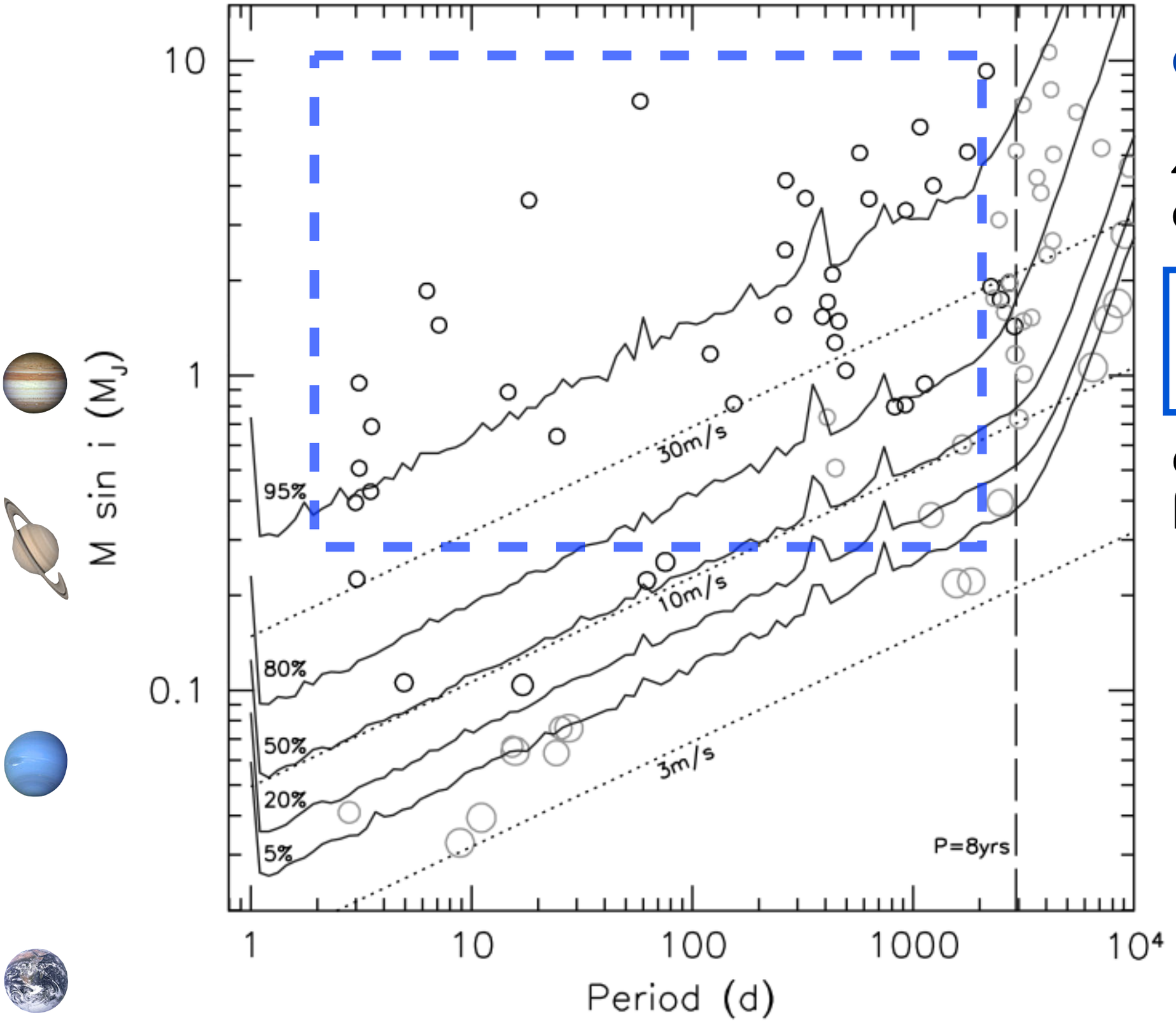
$$\frac{dN}{d\ln P\ d\ln M} = C M^{\alpha} P^{\beta}$$

$\alpha = -0.31 \pm 0.2$
$\beta = +0.26 \pm 0.1$

10.5% occurrence for
Msini = 0.3–10 M_J
P = 2–2000 days

See also, e.g., Udry et al. (2003)

Giant Planet Occurrence Rates



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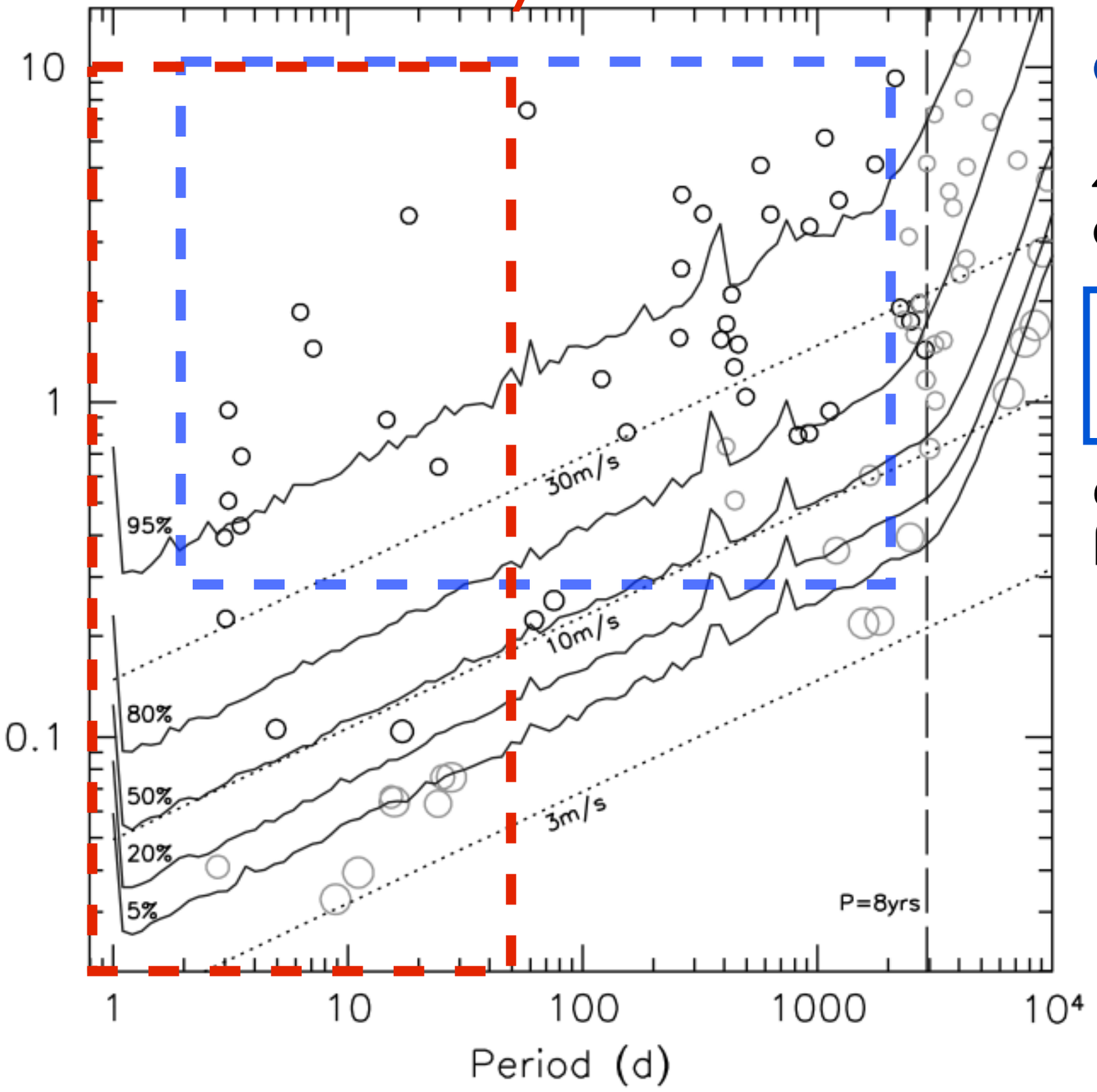
Eta-Earth Survey



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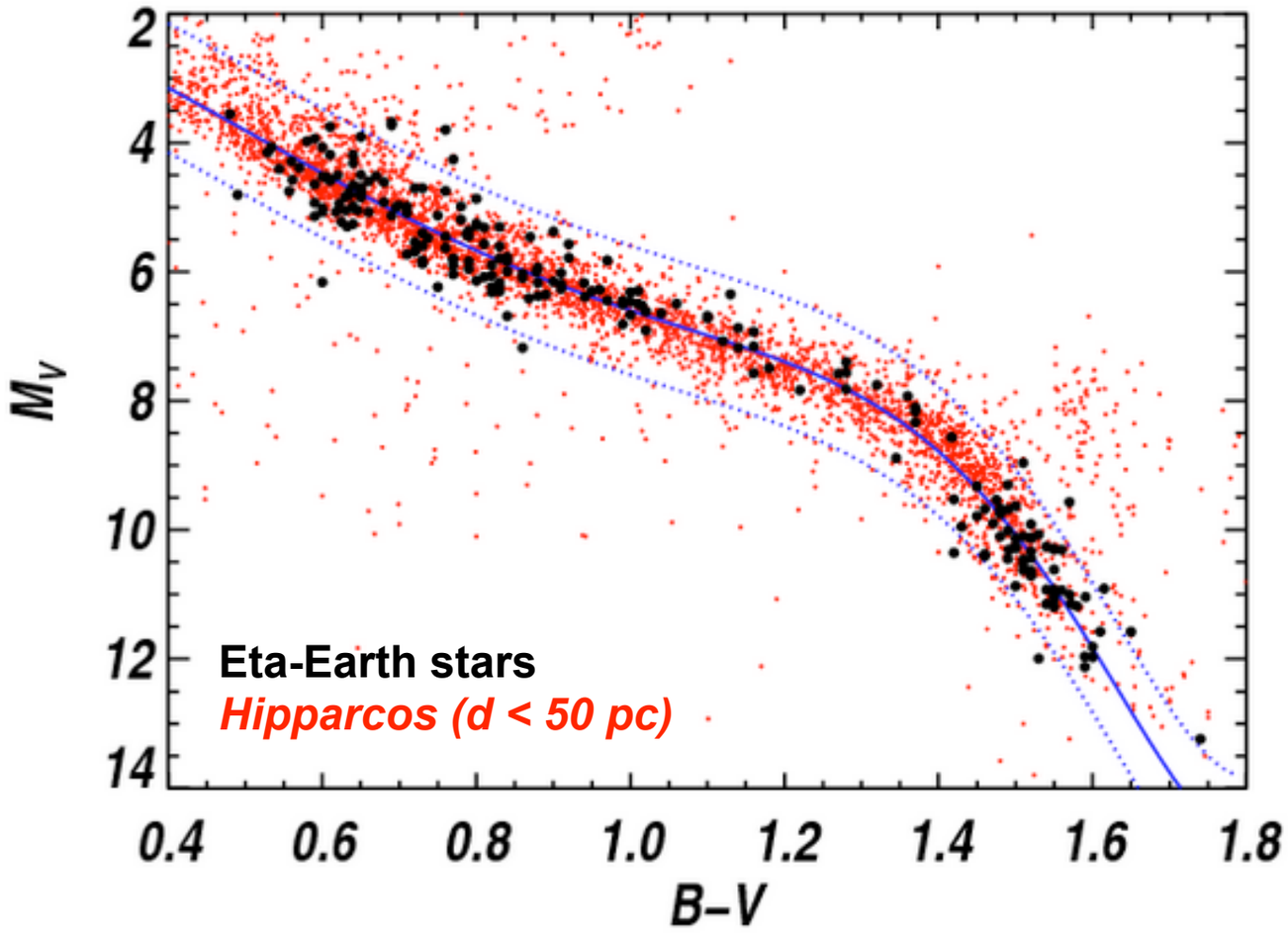
NASA-UC Eta-Earth Survey

RV survey of 238 nearby GKM dwarfs

Search for low-mass planets (Msini = 3-30 M_{Earth})

Constrain population of low-mass planets
and planet formation theory



39% G stars
33% K stars
28% M stars

Statistically unbiased (nearly) stellar population:

- V < 11
- distance < 25 pc
- log R'HK < -4.7 (inactive)

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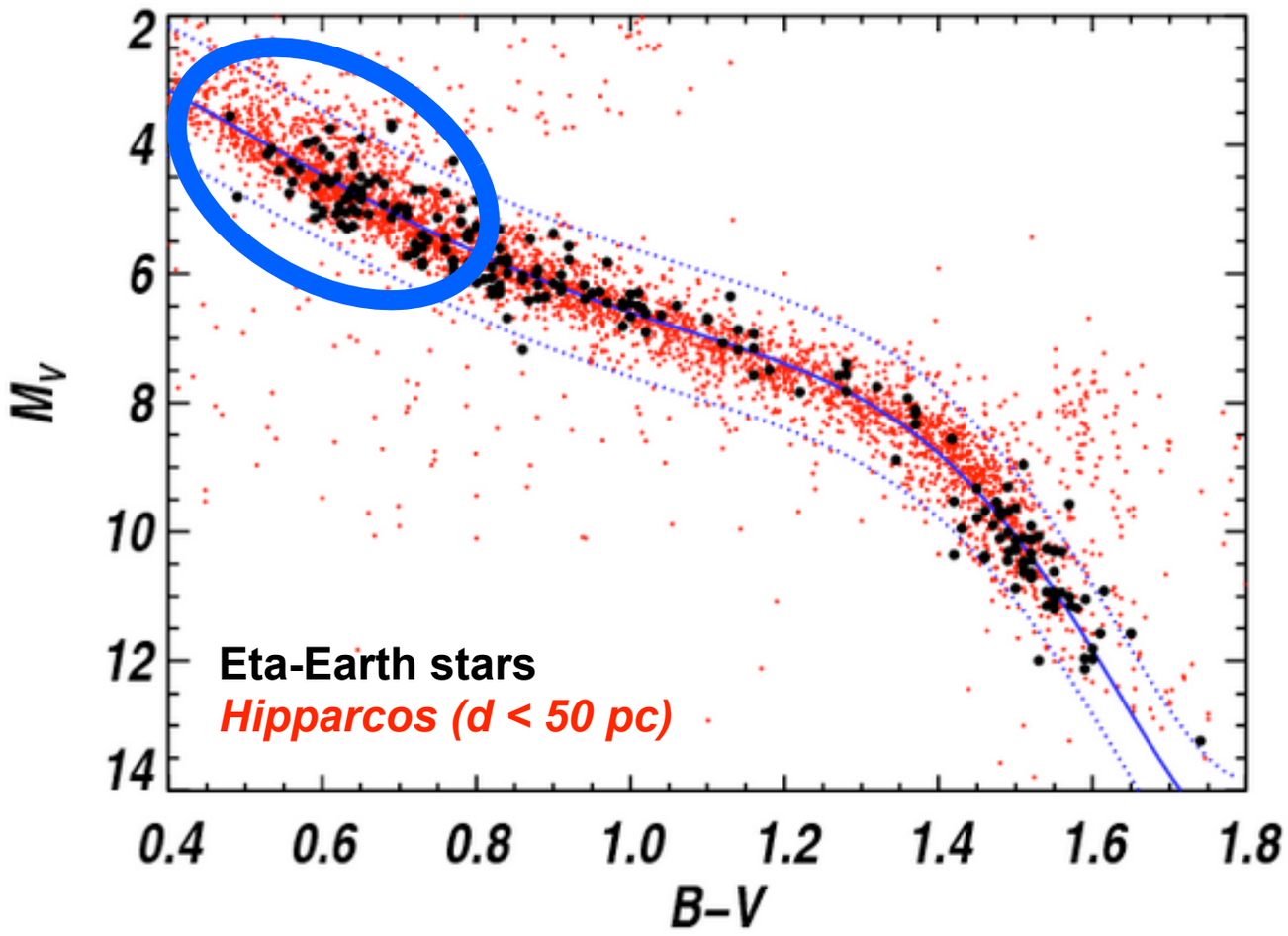
G stars



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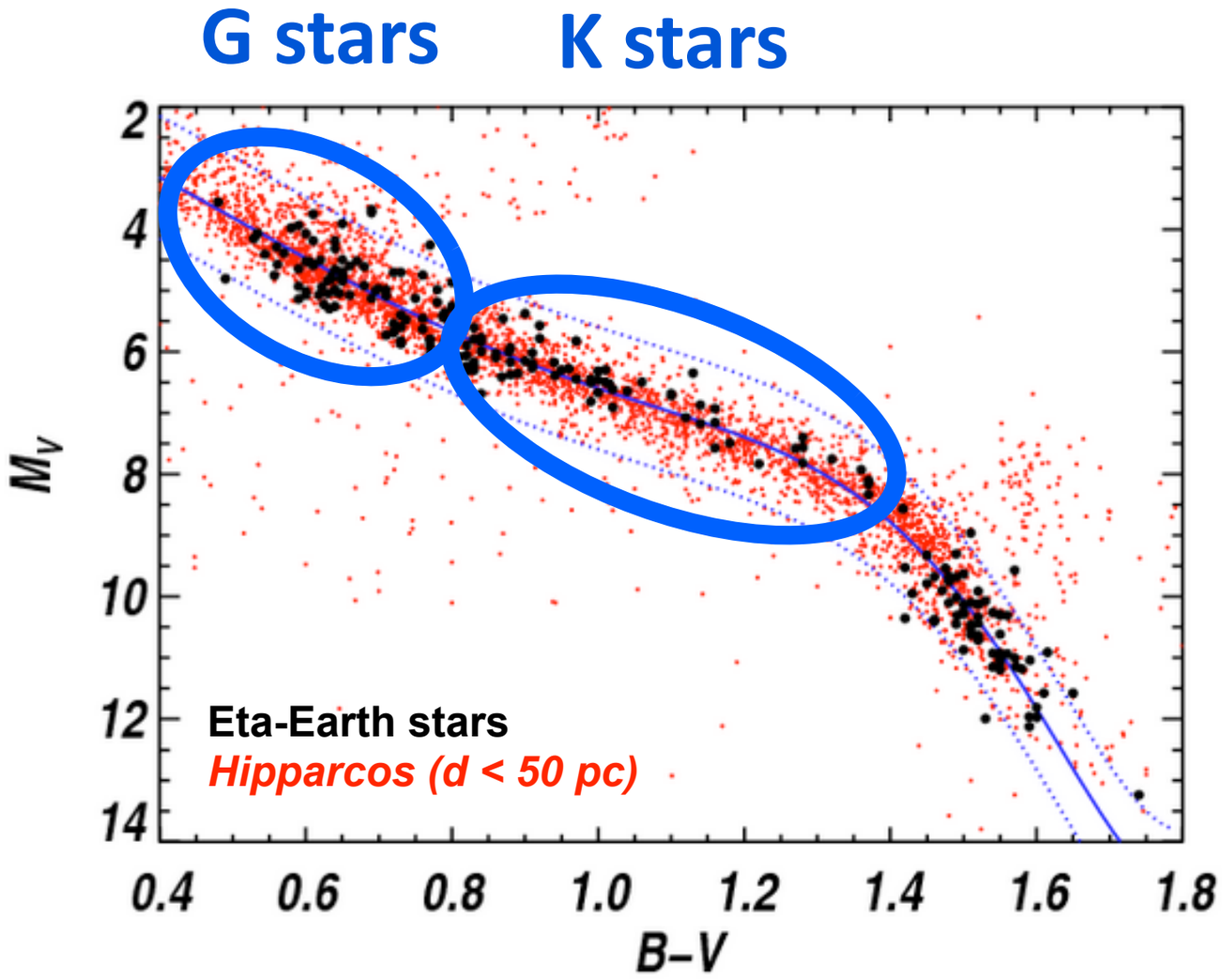

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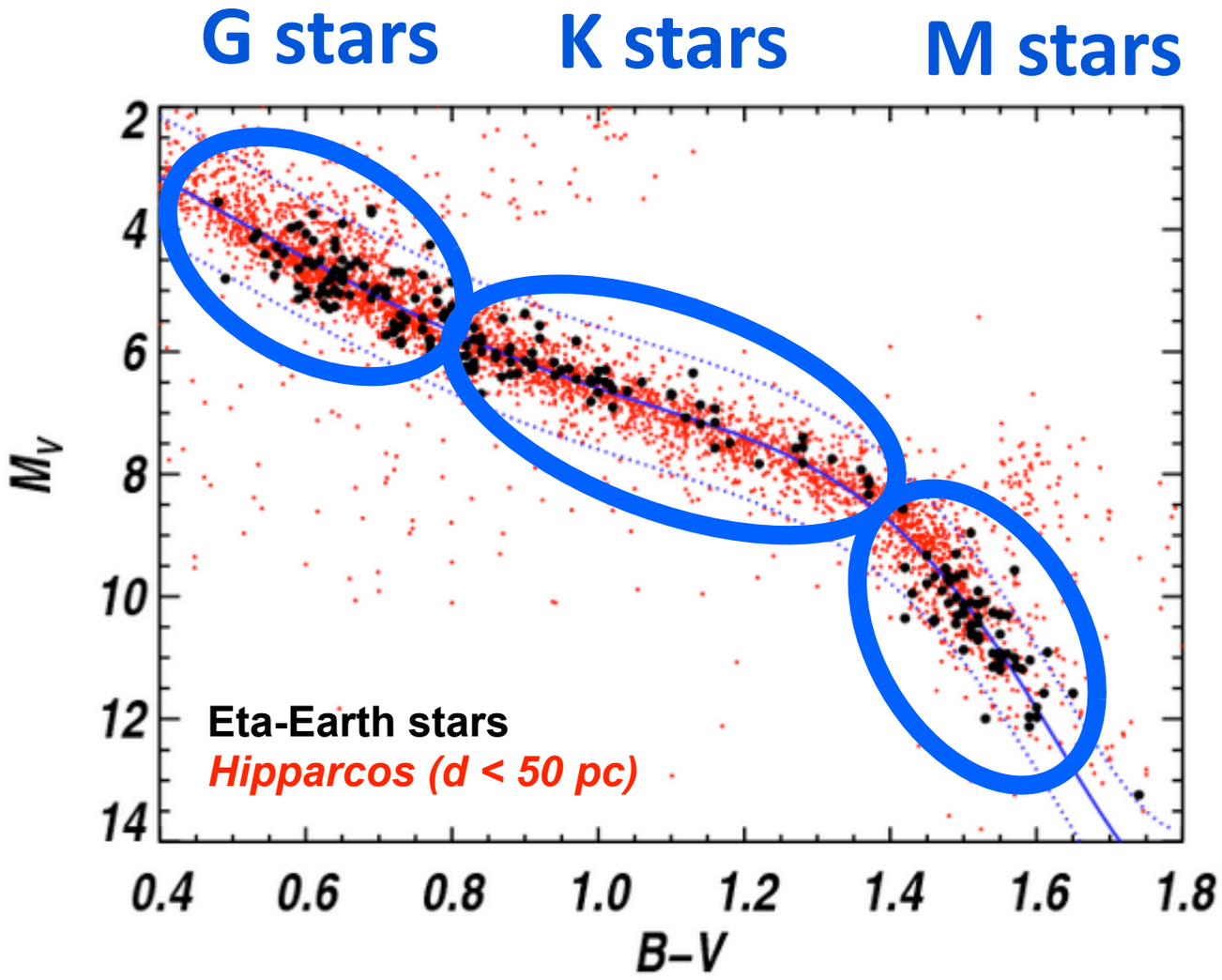

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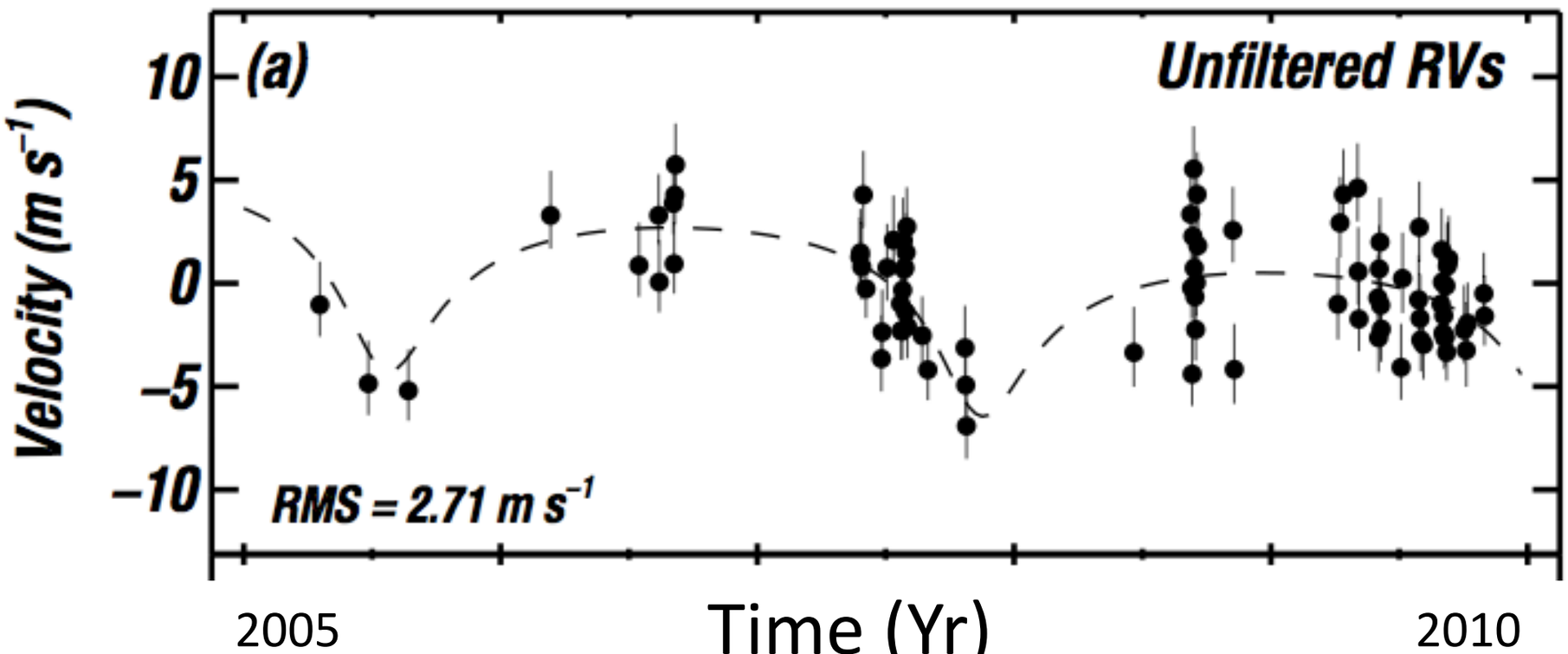
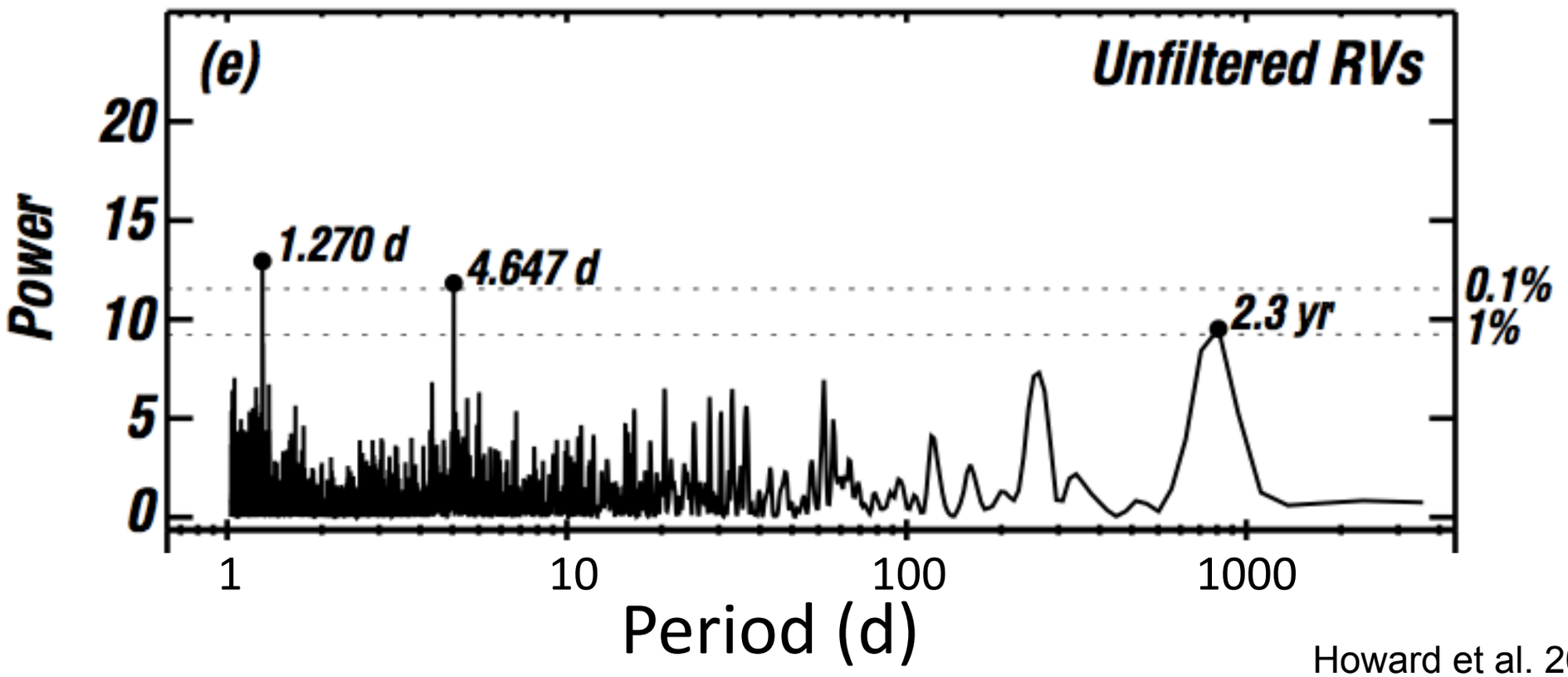
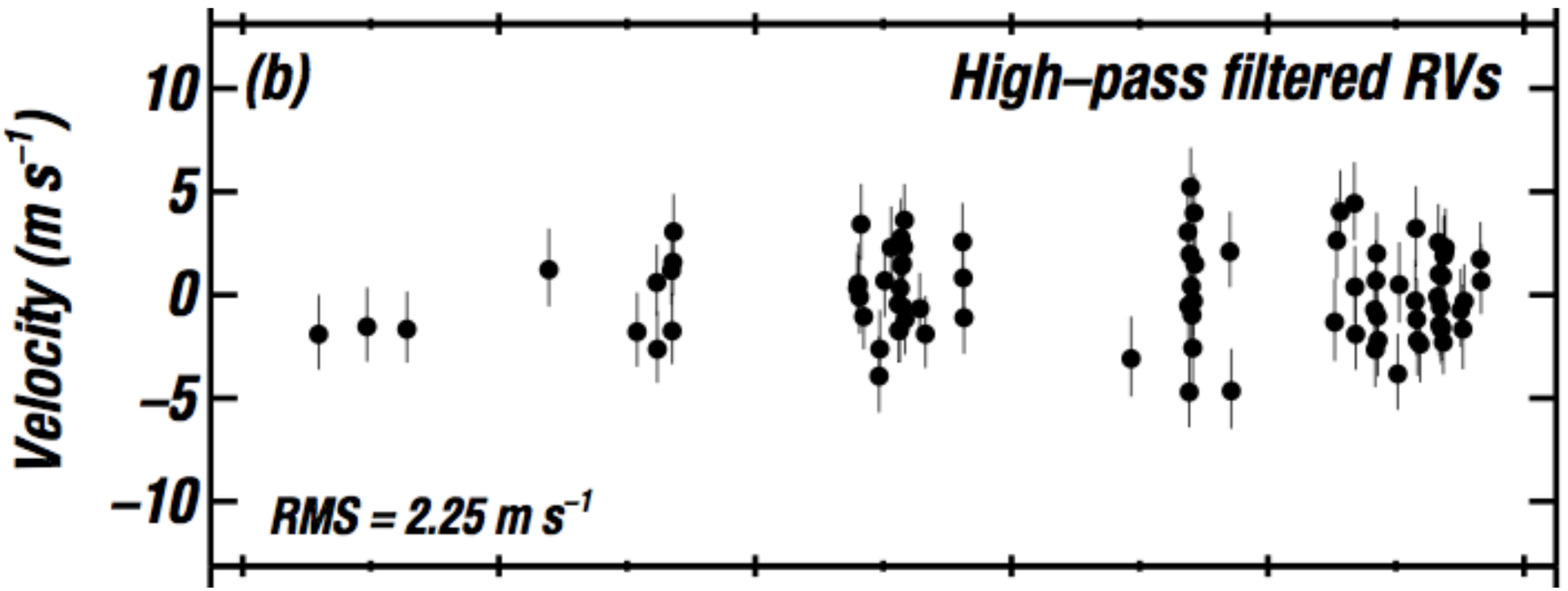
HD 156668 - Discovery RVs

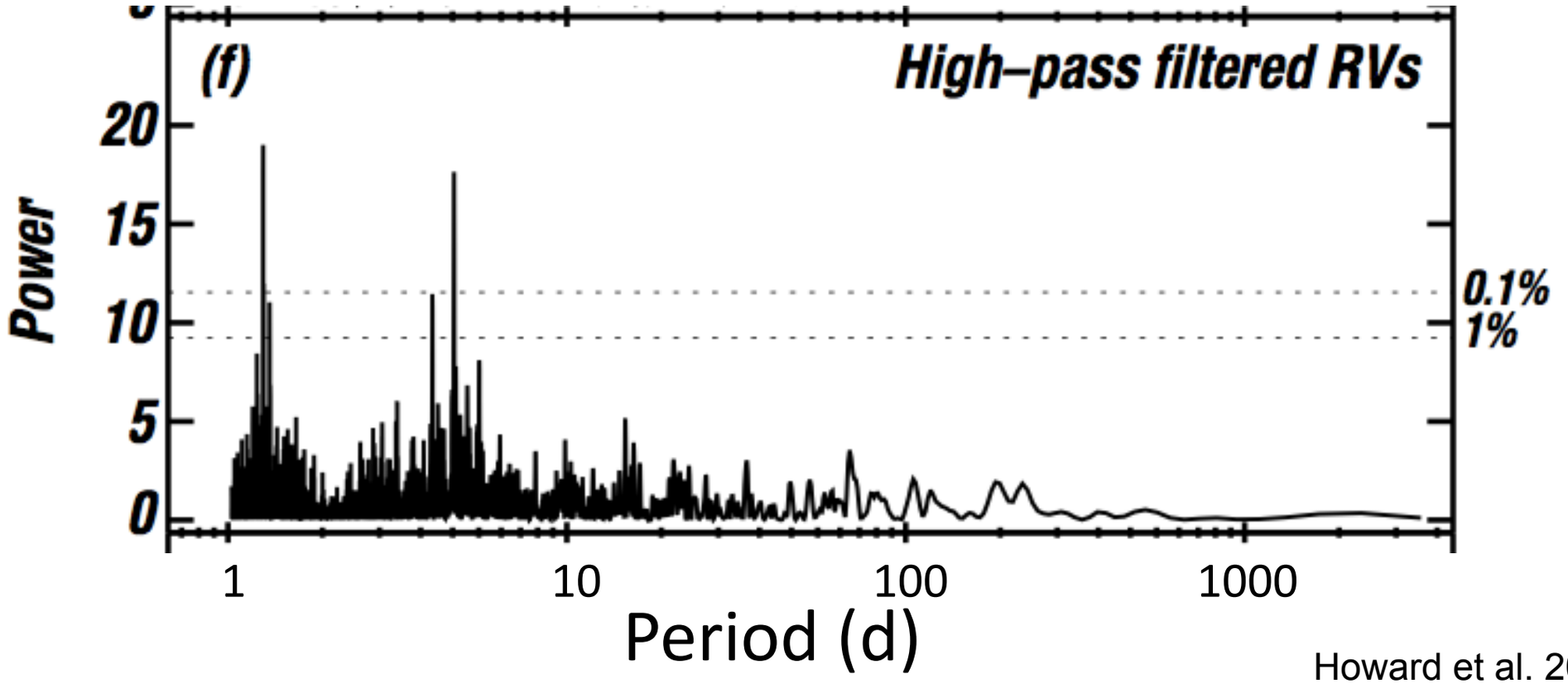




Howard et al. 2011b, ApJ

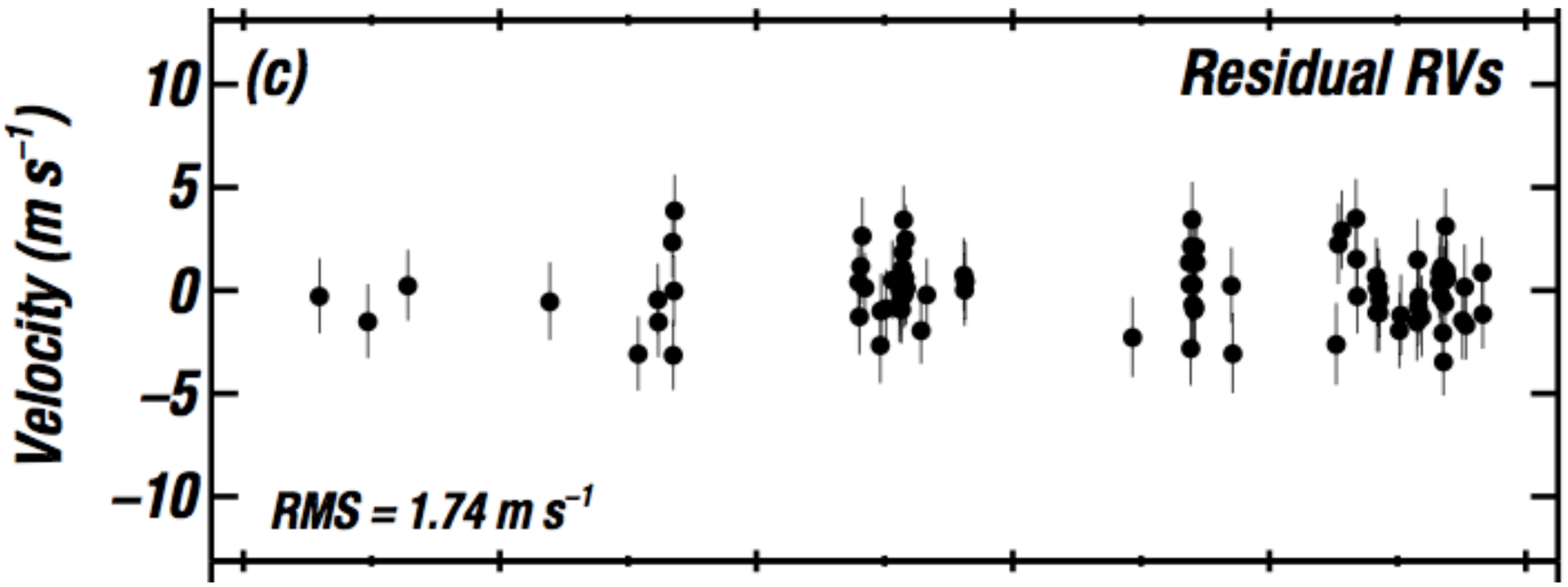
HD 156668 - High-pass Filtered RVs

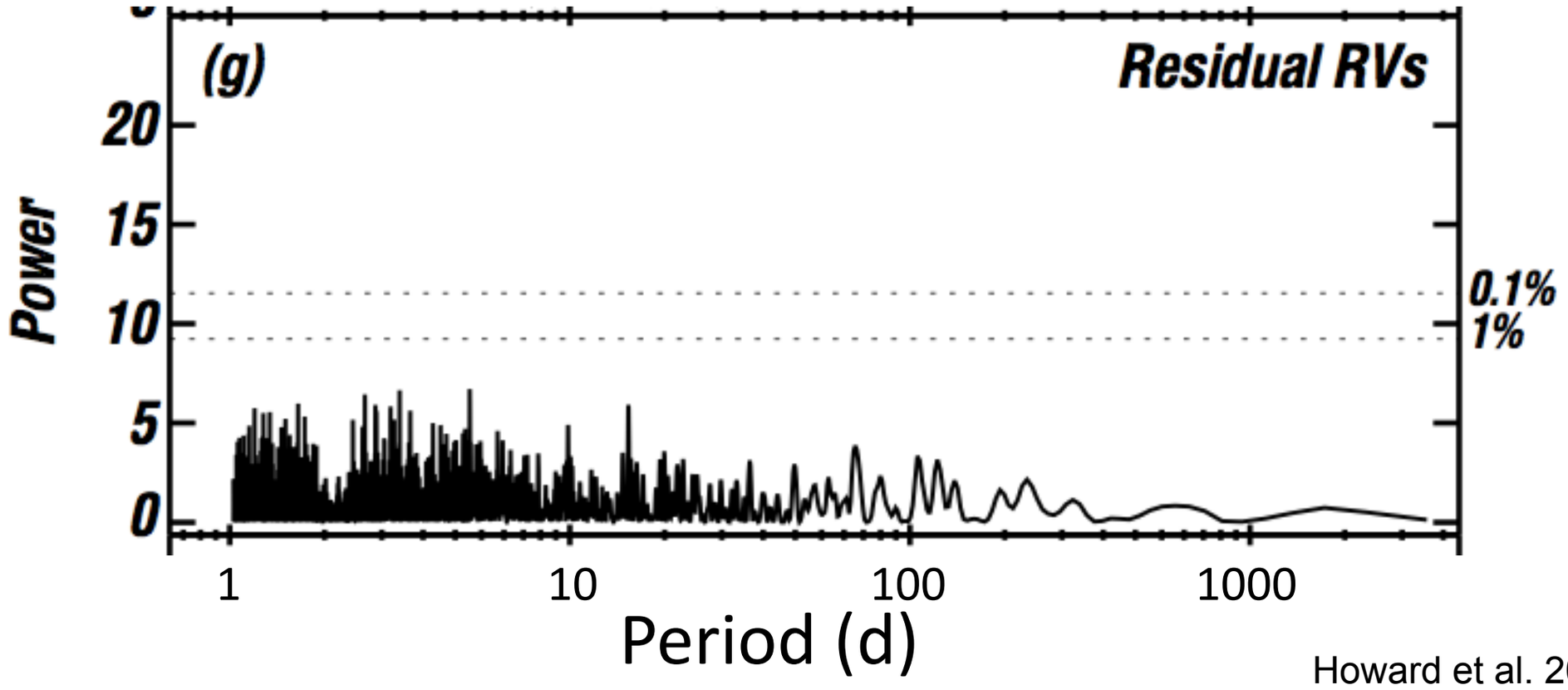




Howard et al. 2011b, ApJ

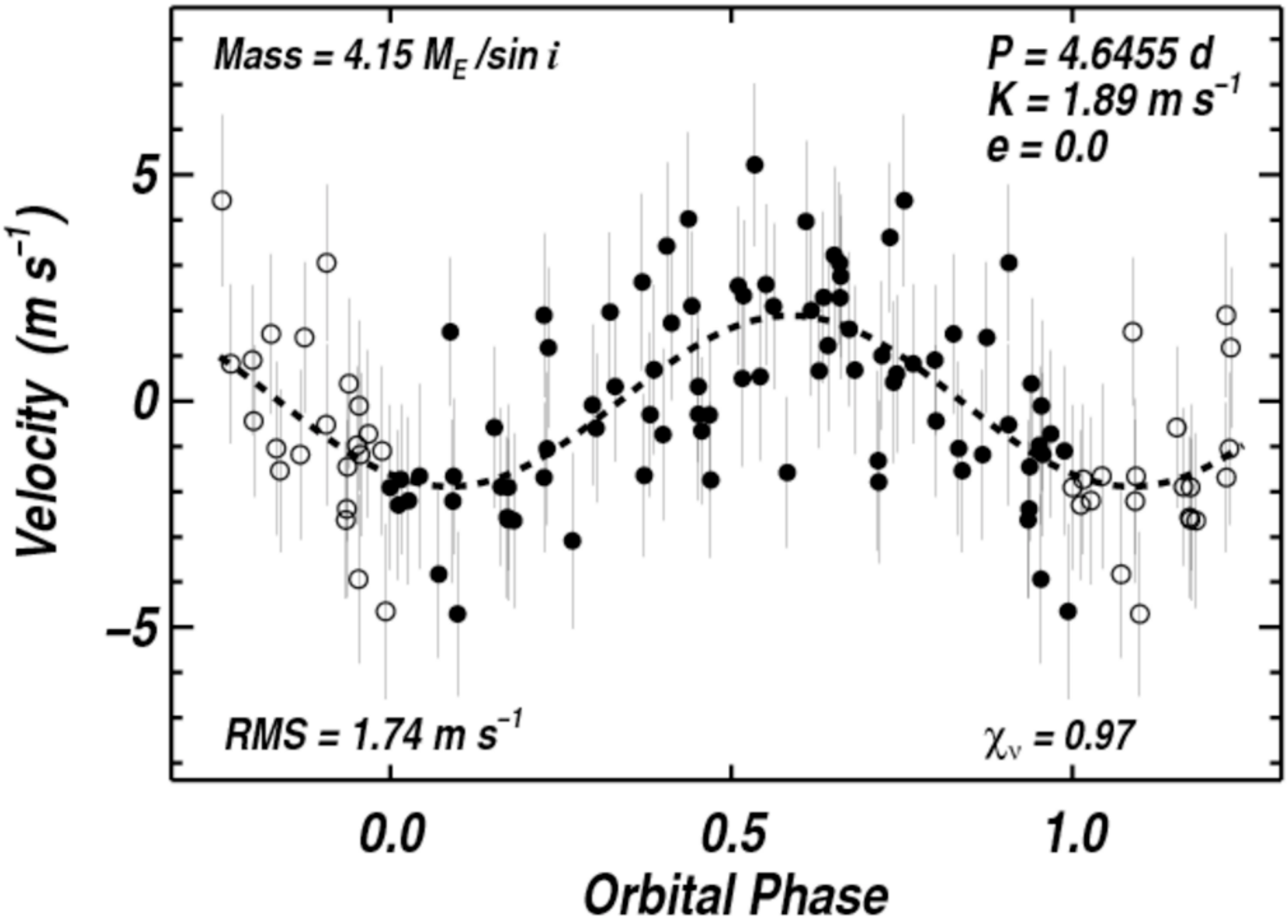
HD 156668 - Residual RVs





Howard et al. 2011b, ApJ

HD 156668b - Detected Super-Earth!



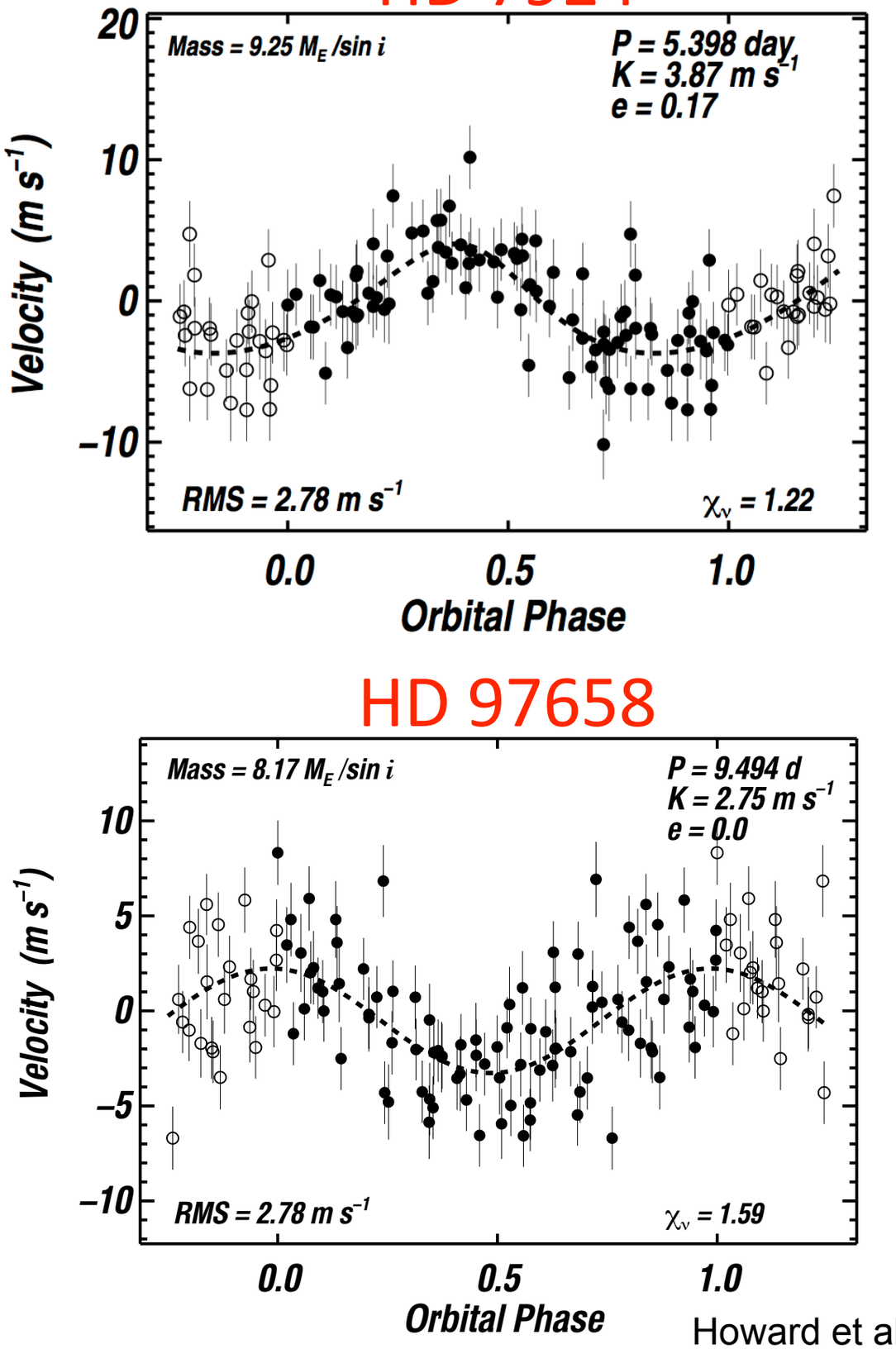
Star:
HD 156668 (K3V)
distance = 24 pc
V = 8.3
[Fe/H] = 0.05
quiet

Planet:
M sin i = 4.15 M_E
P = 4.6455 d
e = 0 (fixed)

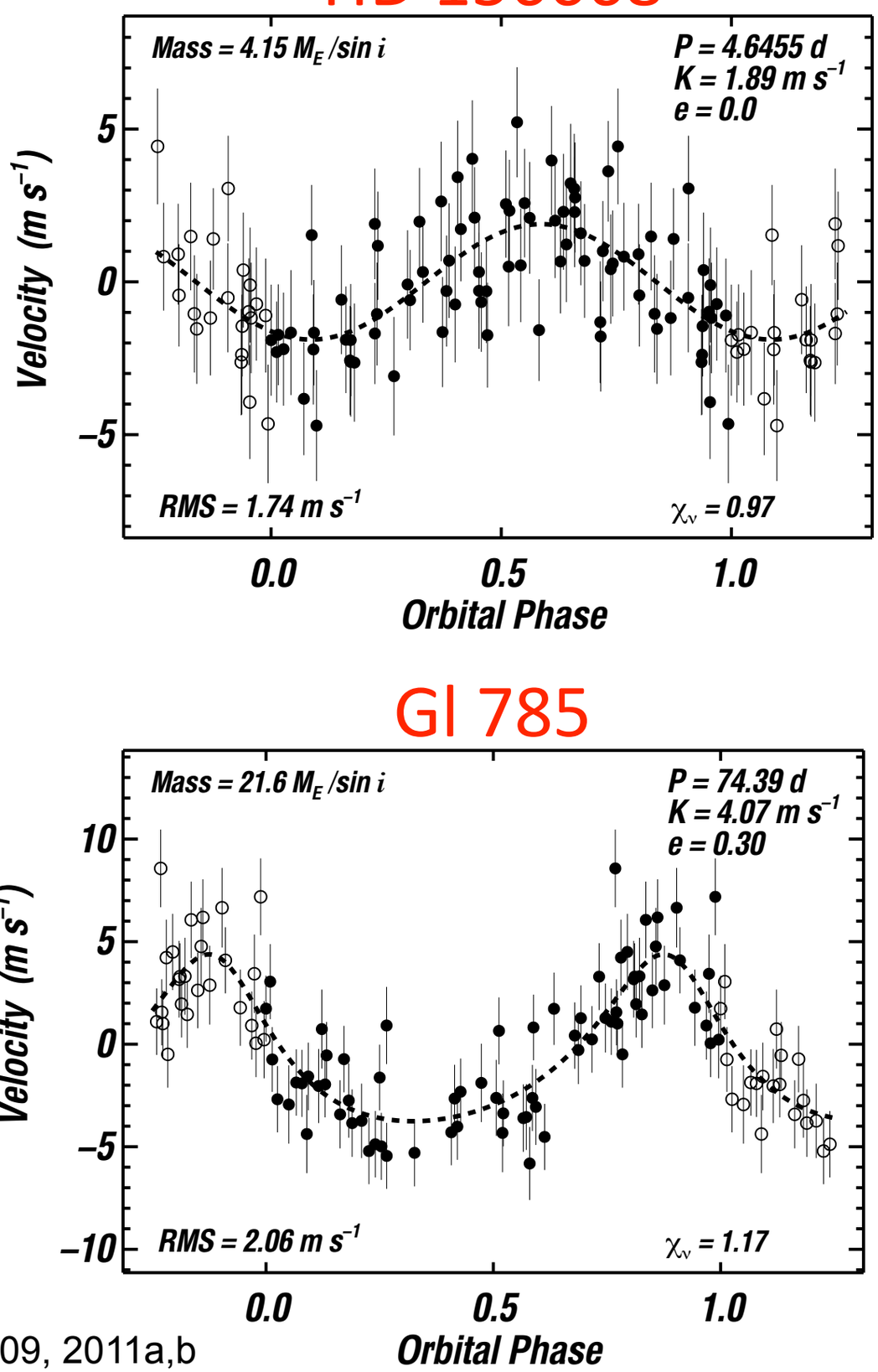
Howard et al. 2011b, ApJ

A Sample of Eta-Earth Survey Planets from Keck-HIRES

HD 7924



HD 156668

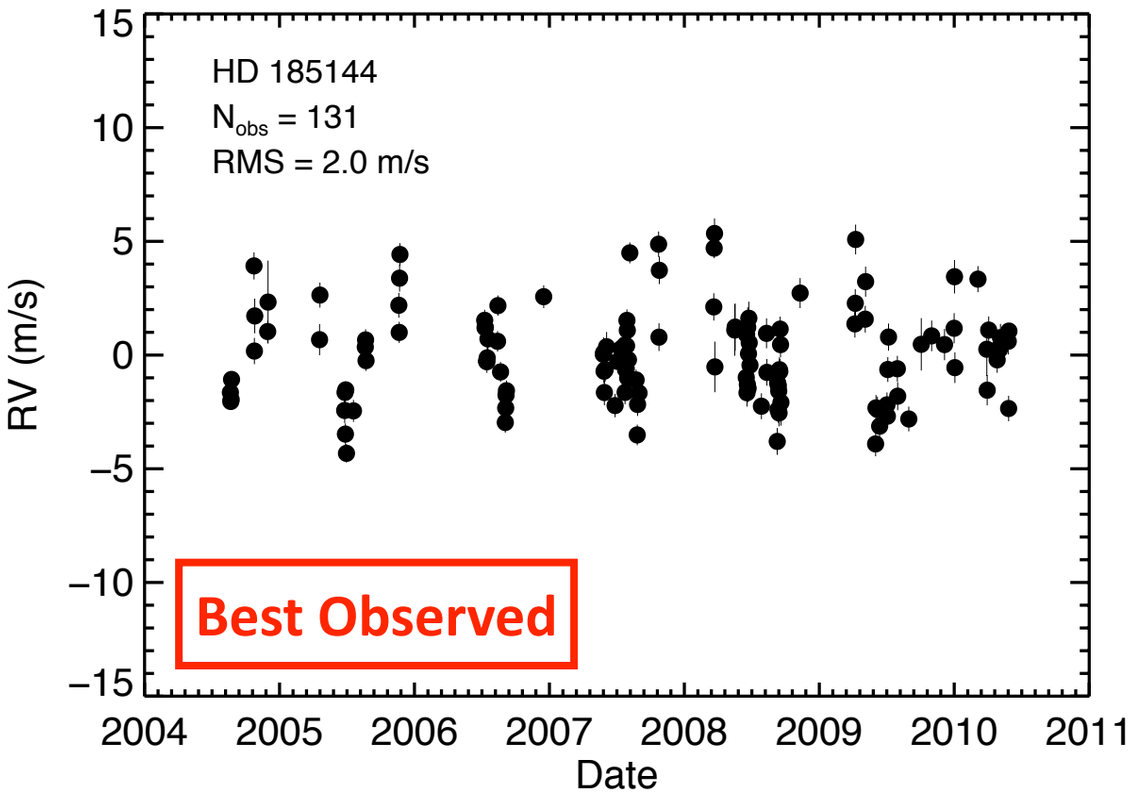


HD 97658

Gl 785

Howard et al. 2009, 2011a,b

Limits on Non-detections of Planets



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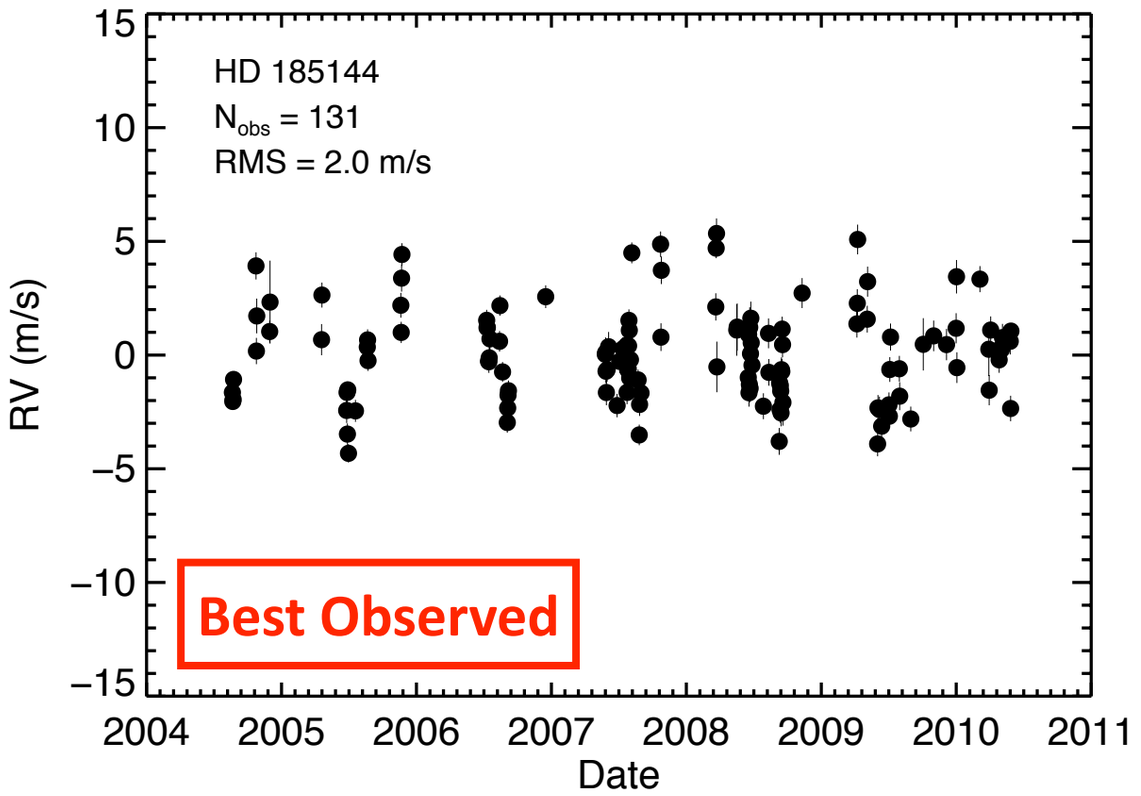

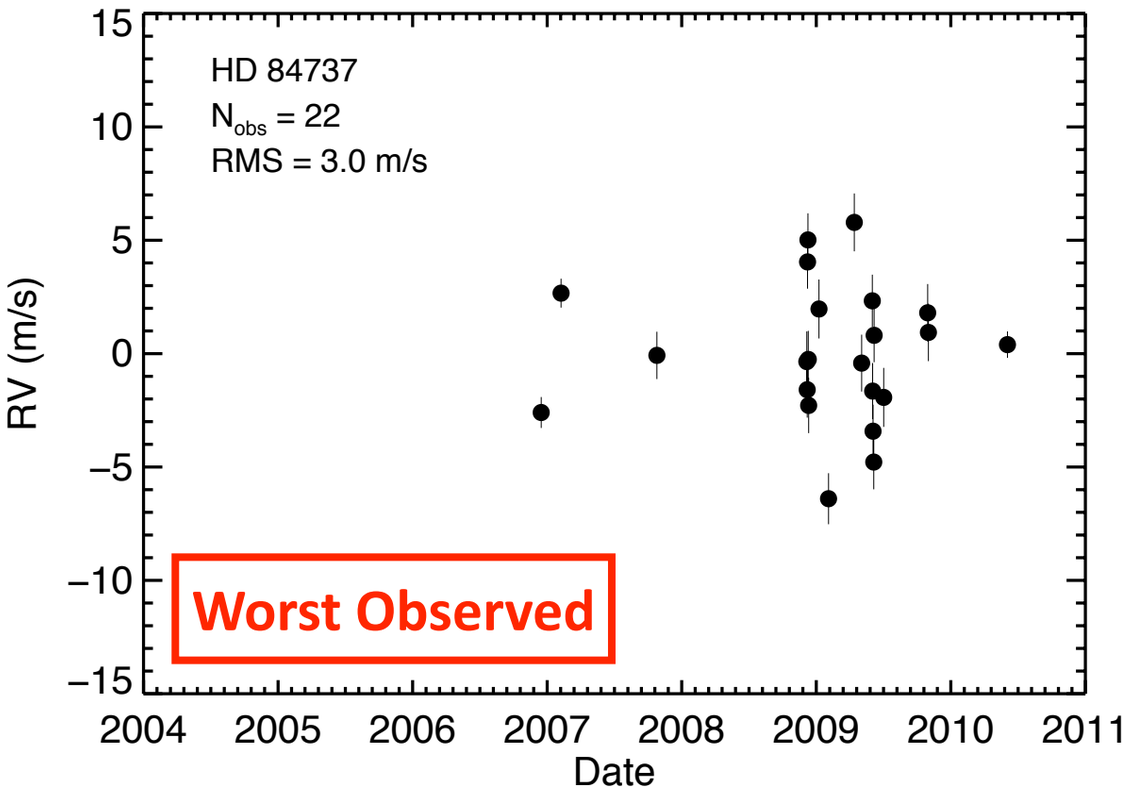

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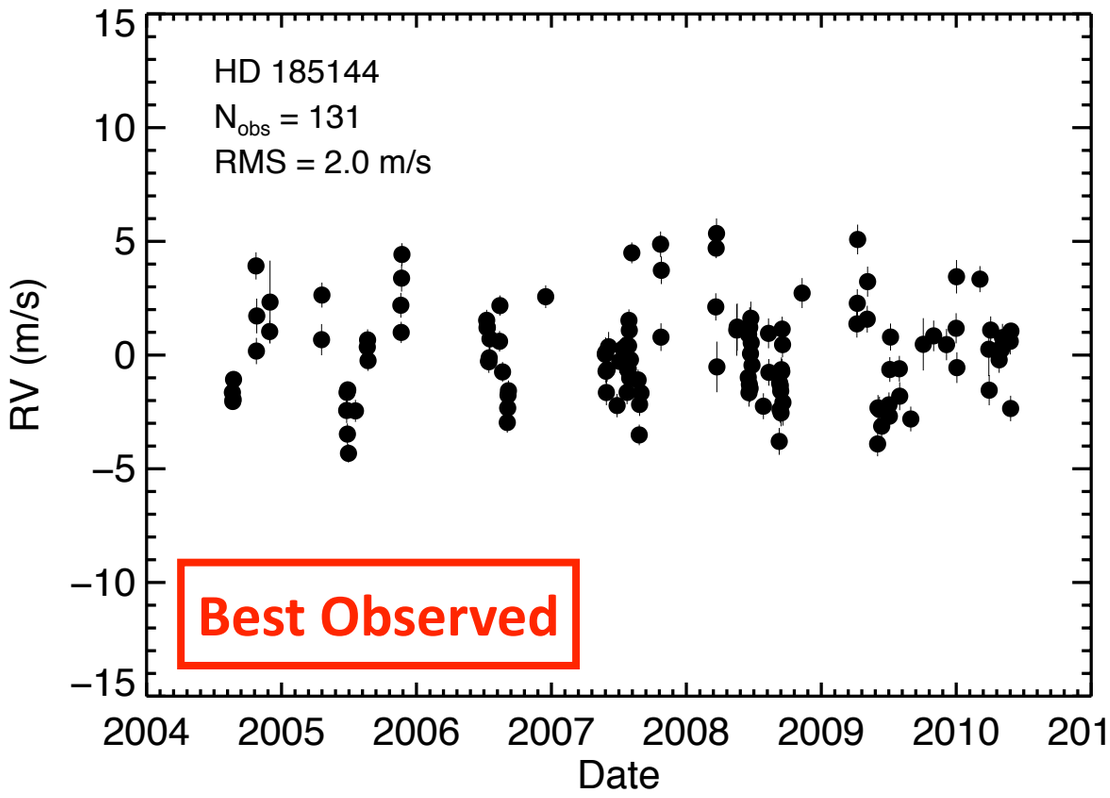

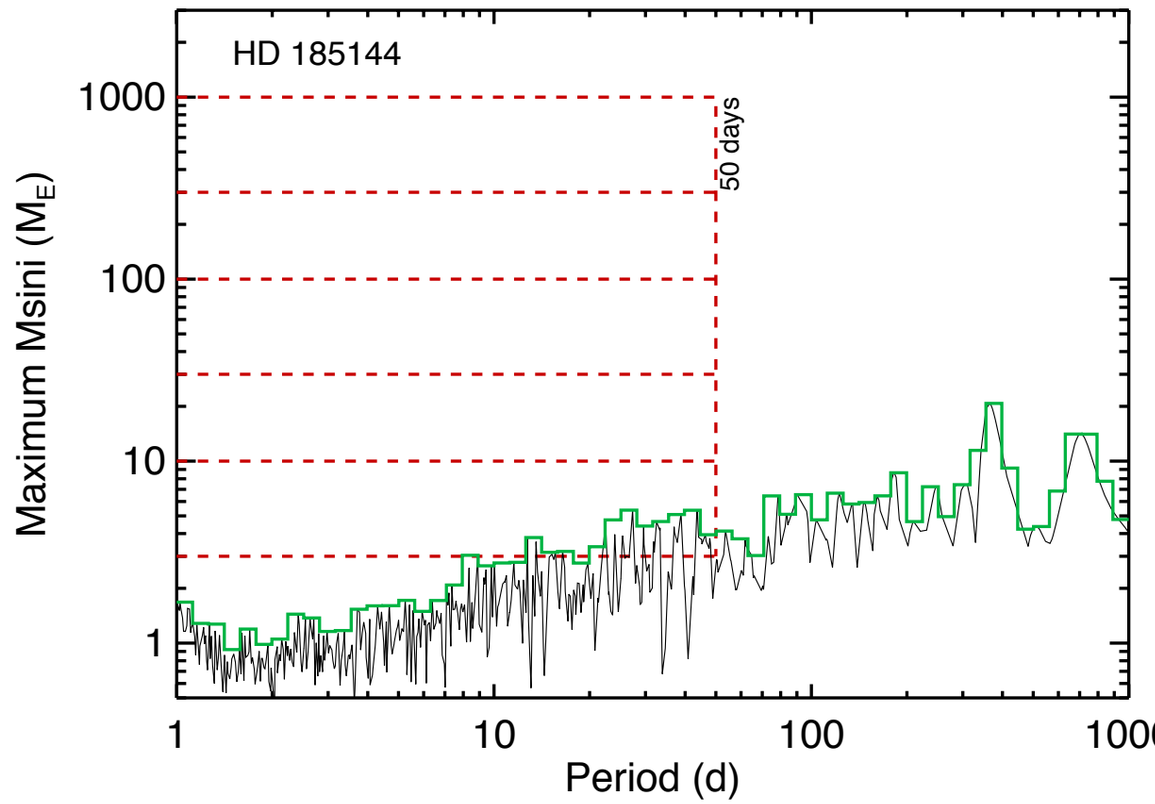

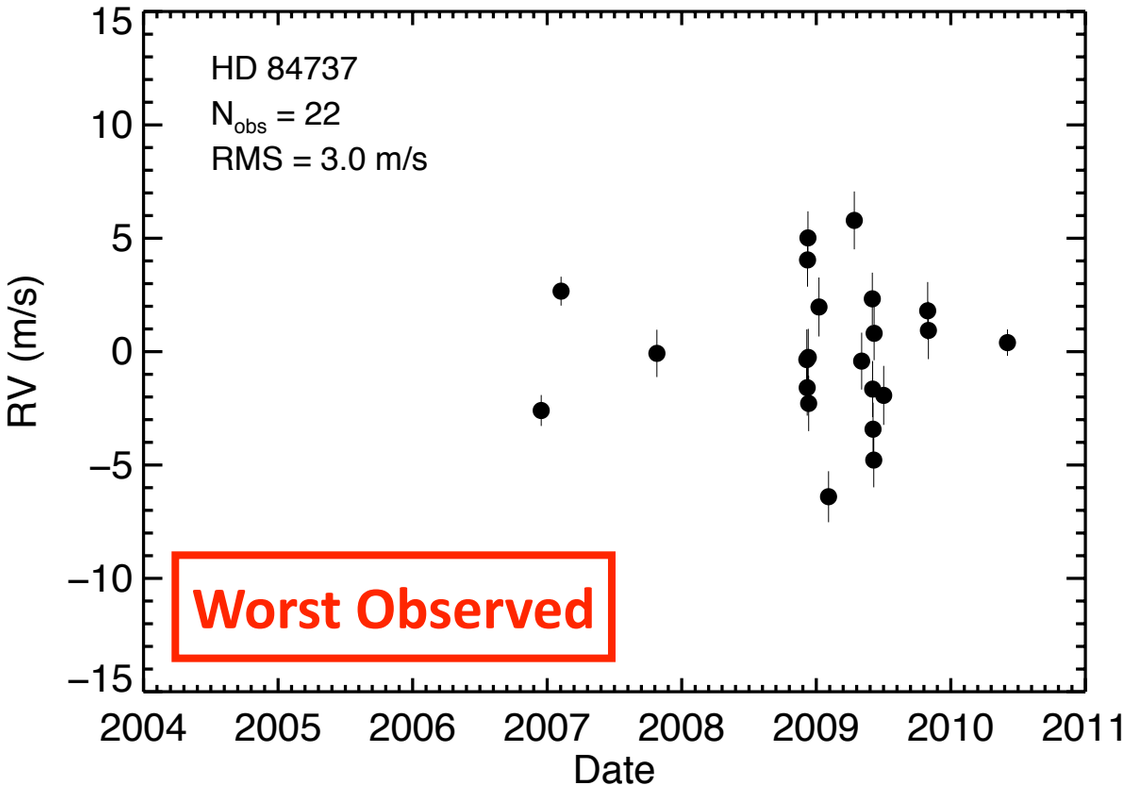

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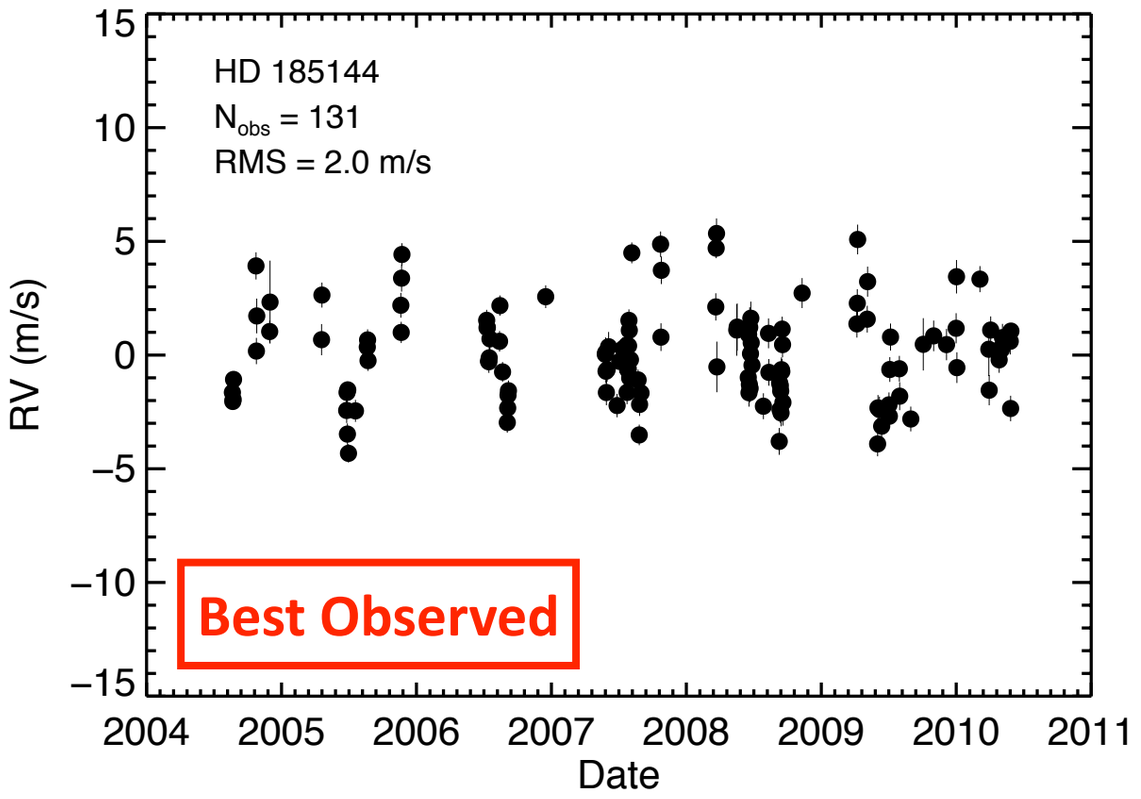
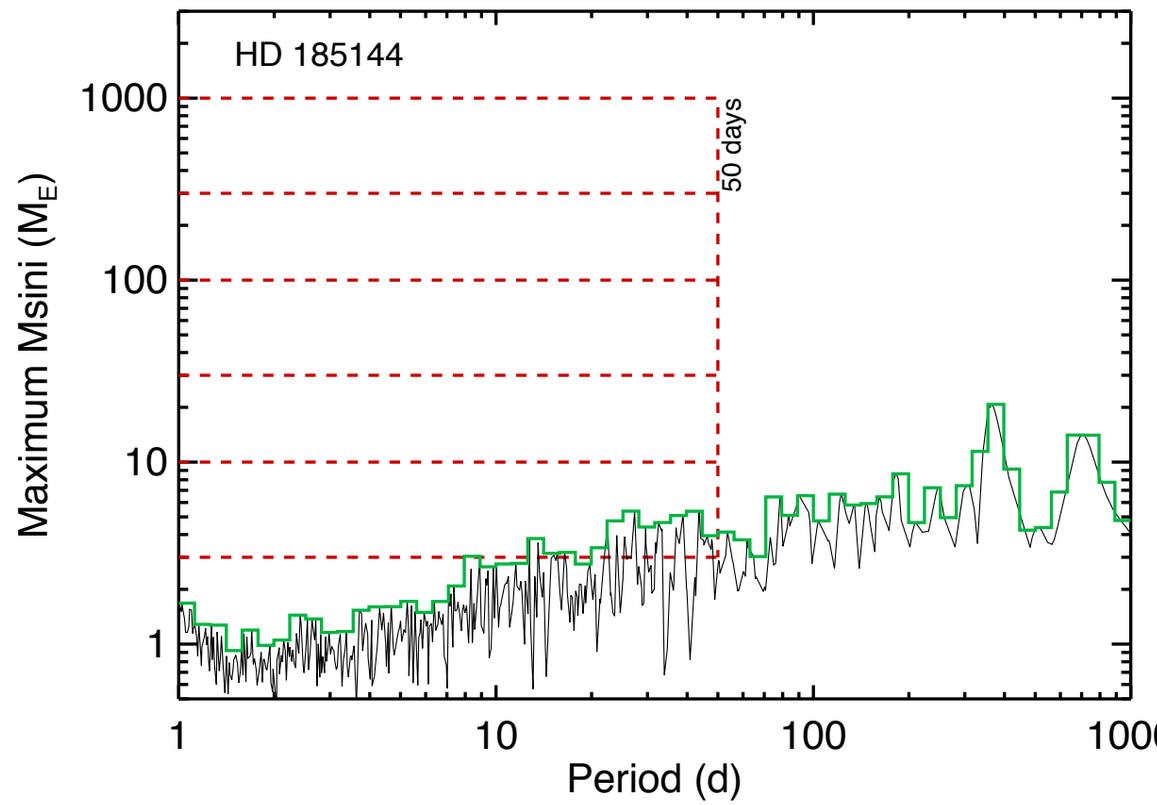
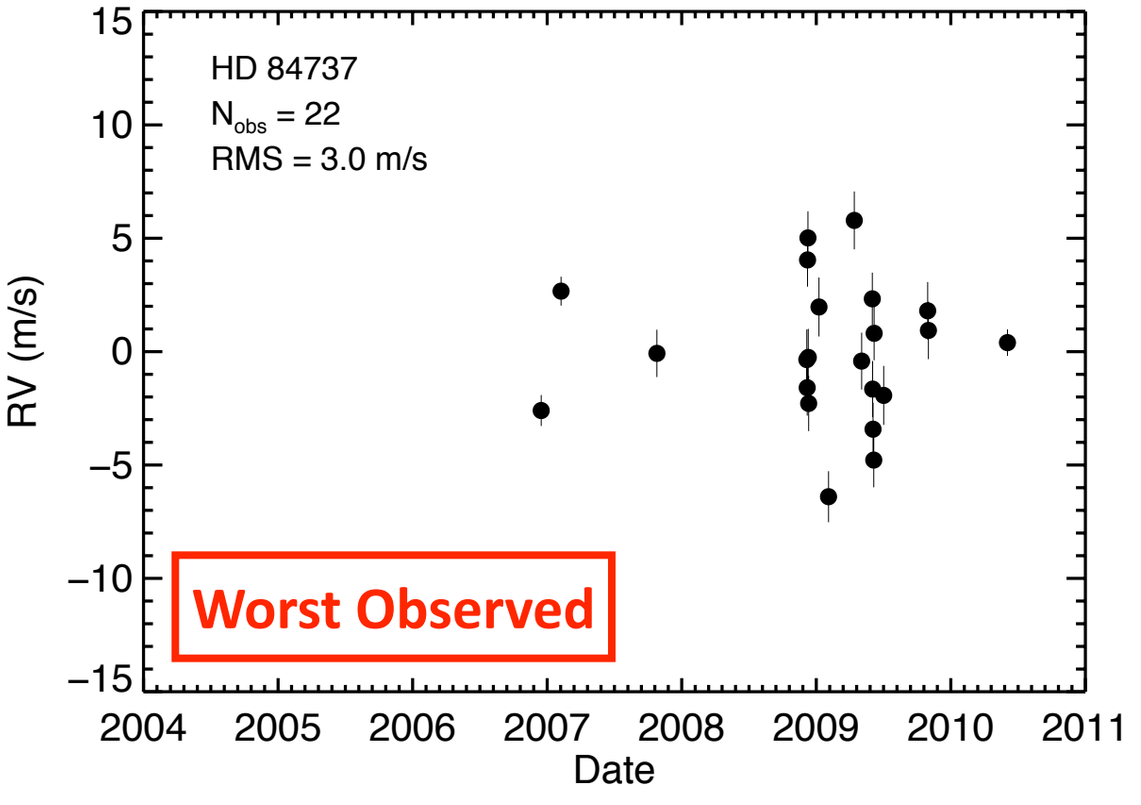
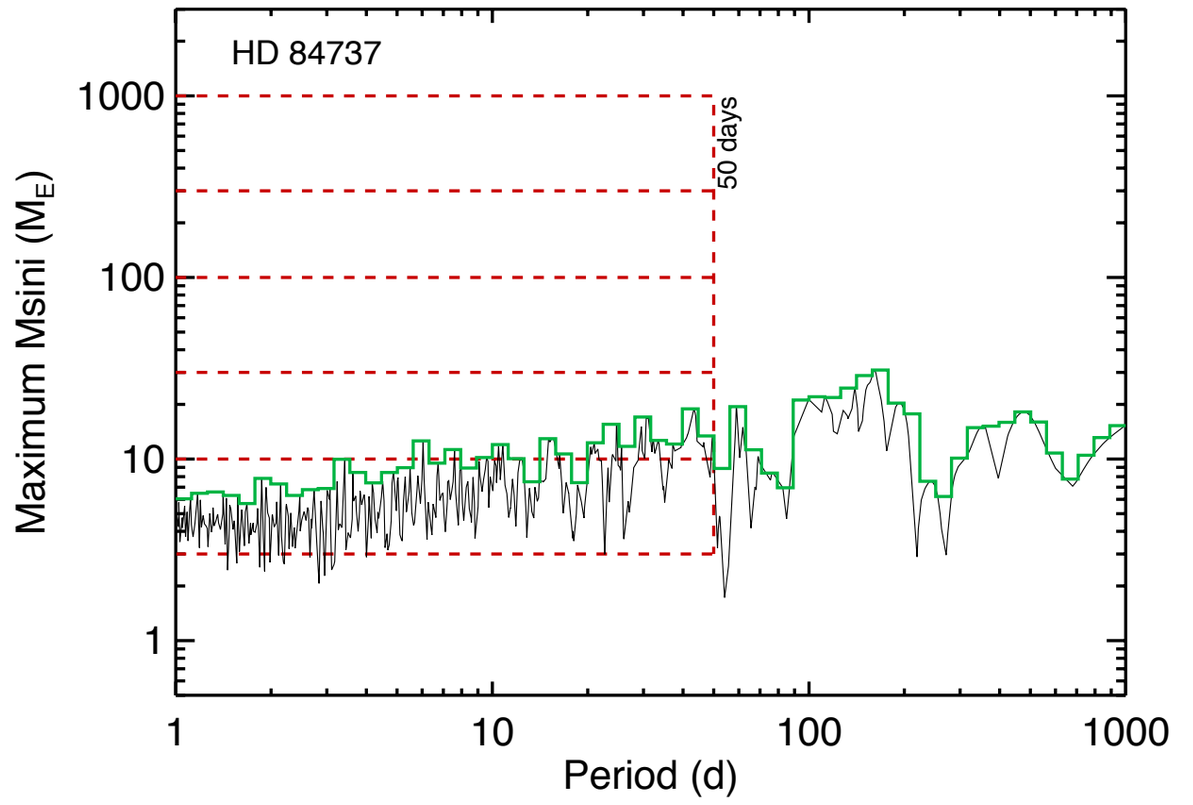
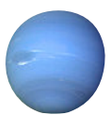


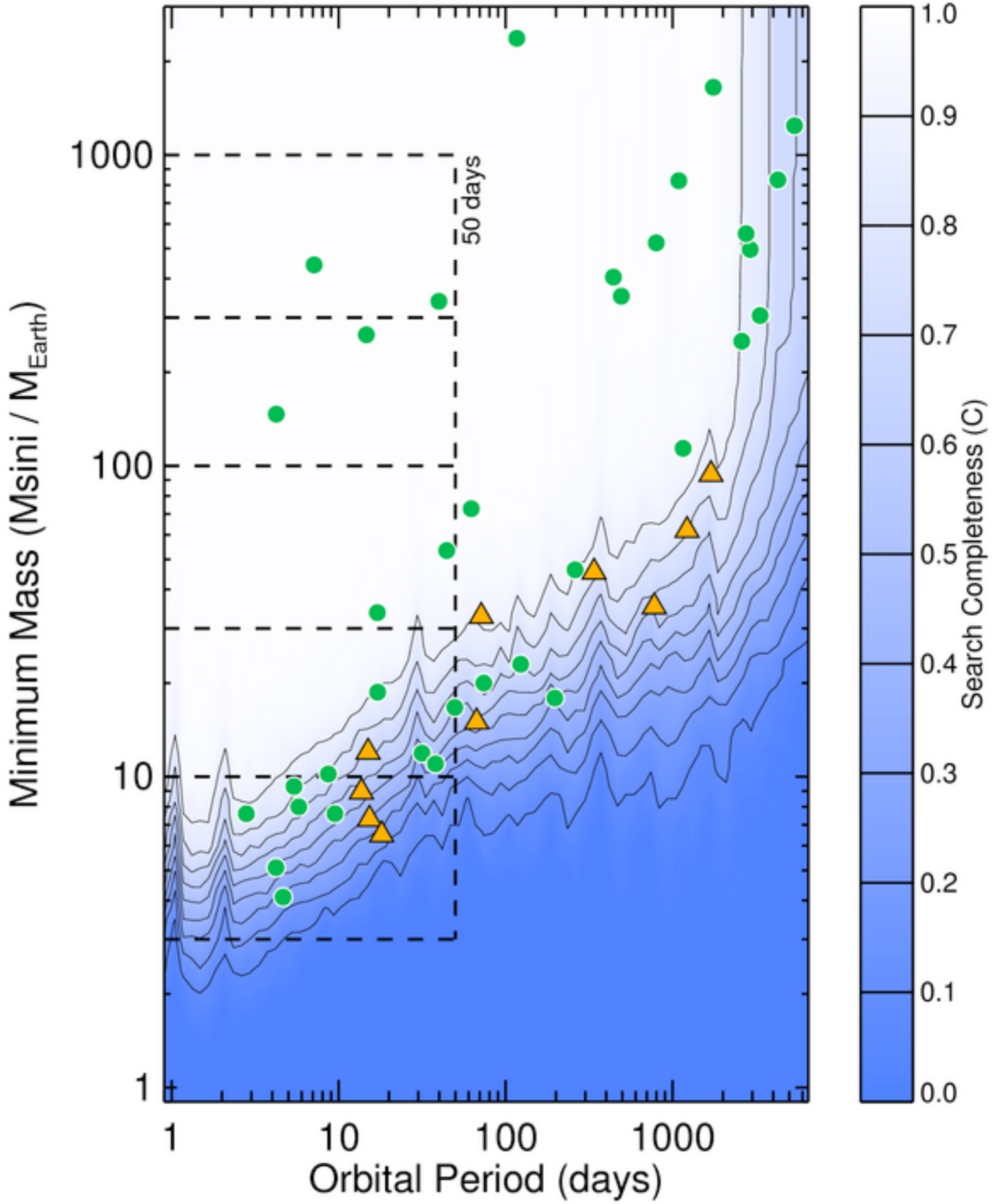






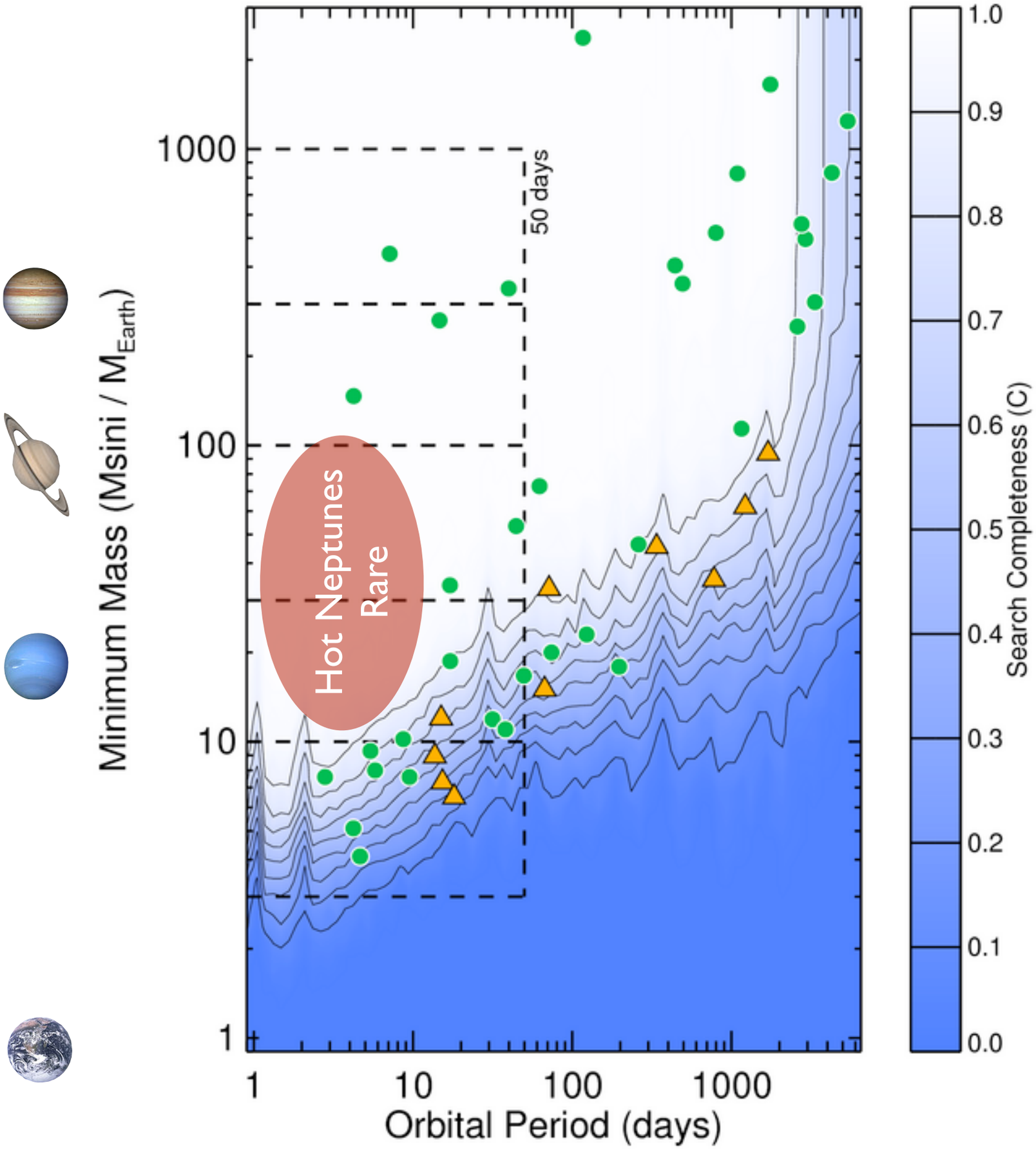
Howard et al. 2010, Science, 330, 653





- Detected planets
- Candidate planets (FAPs ~ 1-5%)

Howard et al. 2010, Science, 330, 653



1. Hot Neptunes rare
   Msini=10-100 M_E, P < 20 days

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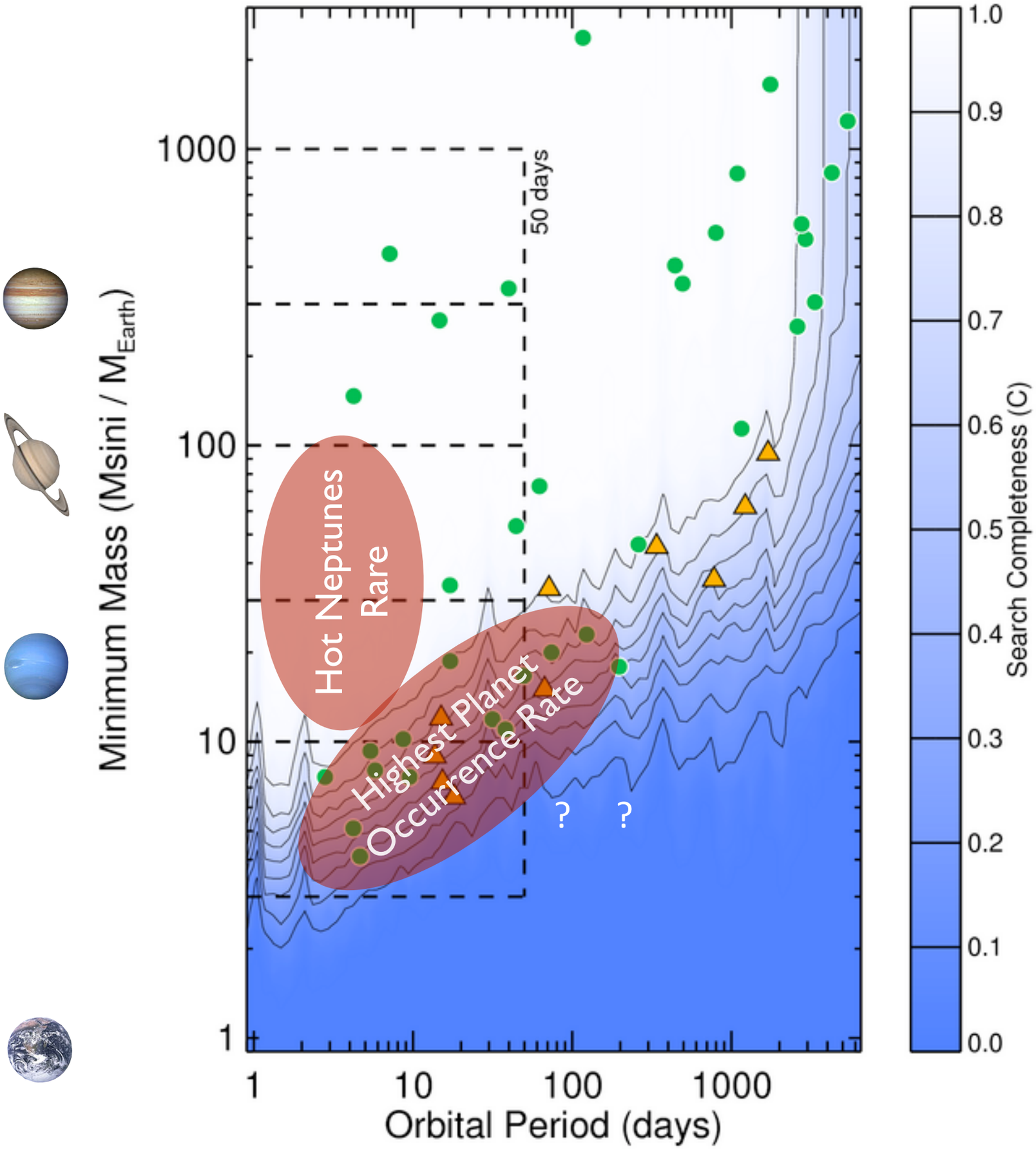
Howard et al. 2010, Science, 330, 653



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   Msini=10-100 M_E, P < 20 days

2. Highest planet occurrence rate:
   - Msini=10-30 M_E, P > ~20 days
   - Msini=3-10 M_E, P > ~5 days

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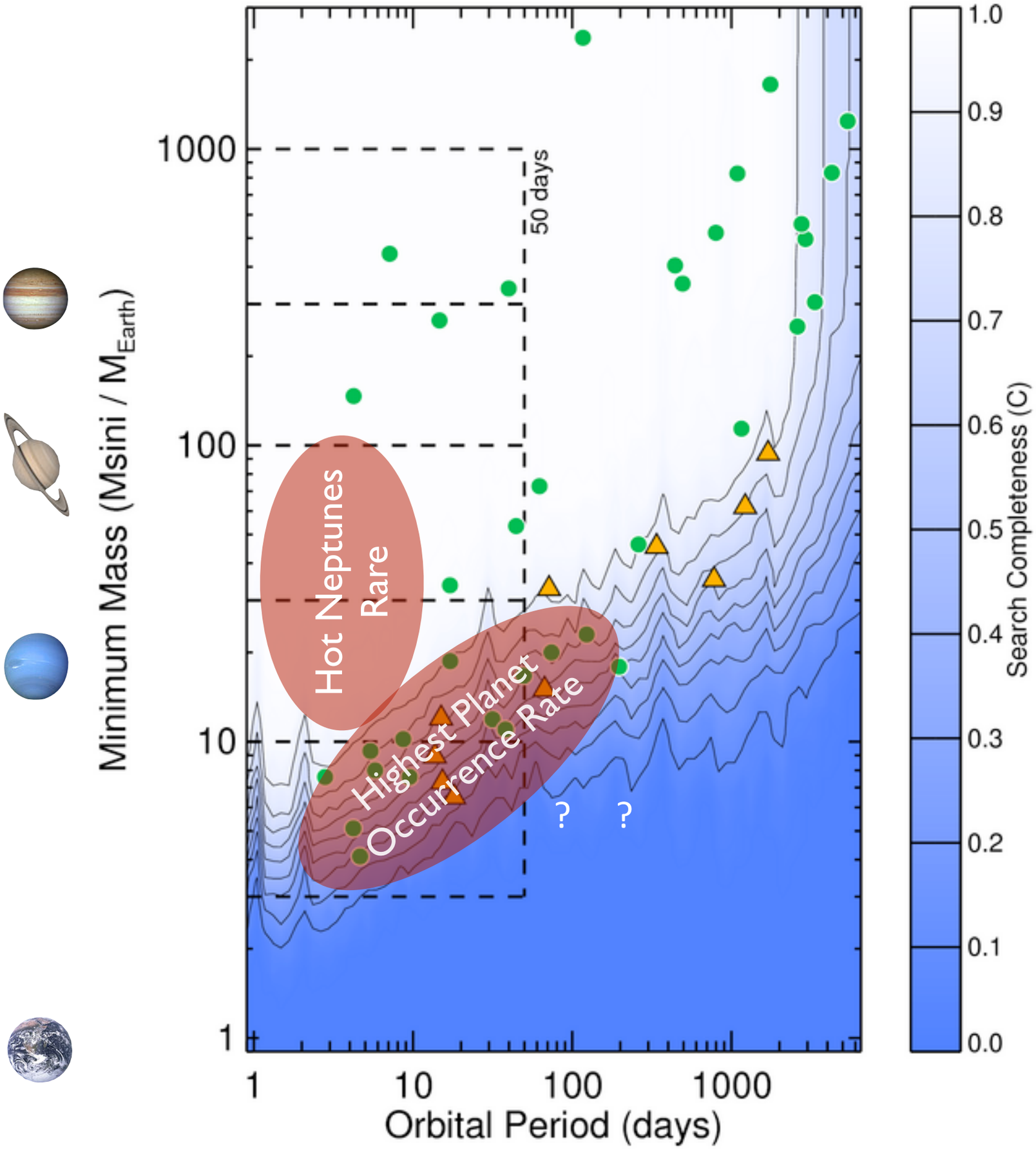
- Candidate planets (FAPs ~ 1-5%)

Howard et al. 2010, Science, 330, 653



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3. Low-mass planets:
   No short-period pileup

- Detected planets
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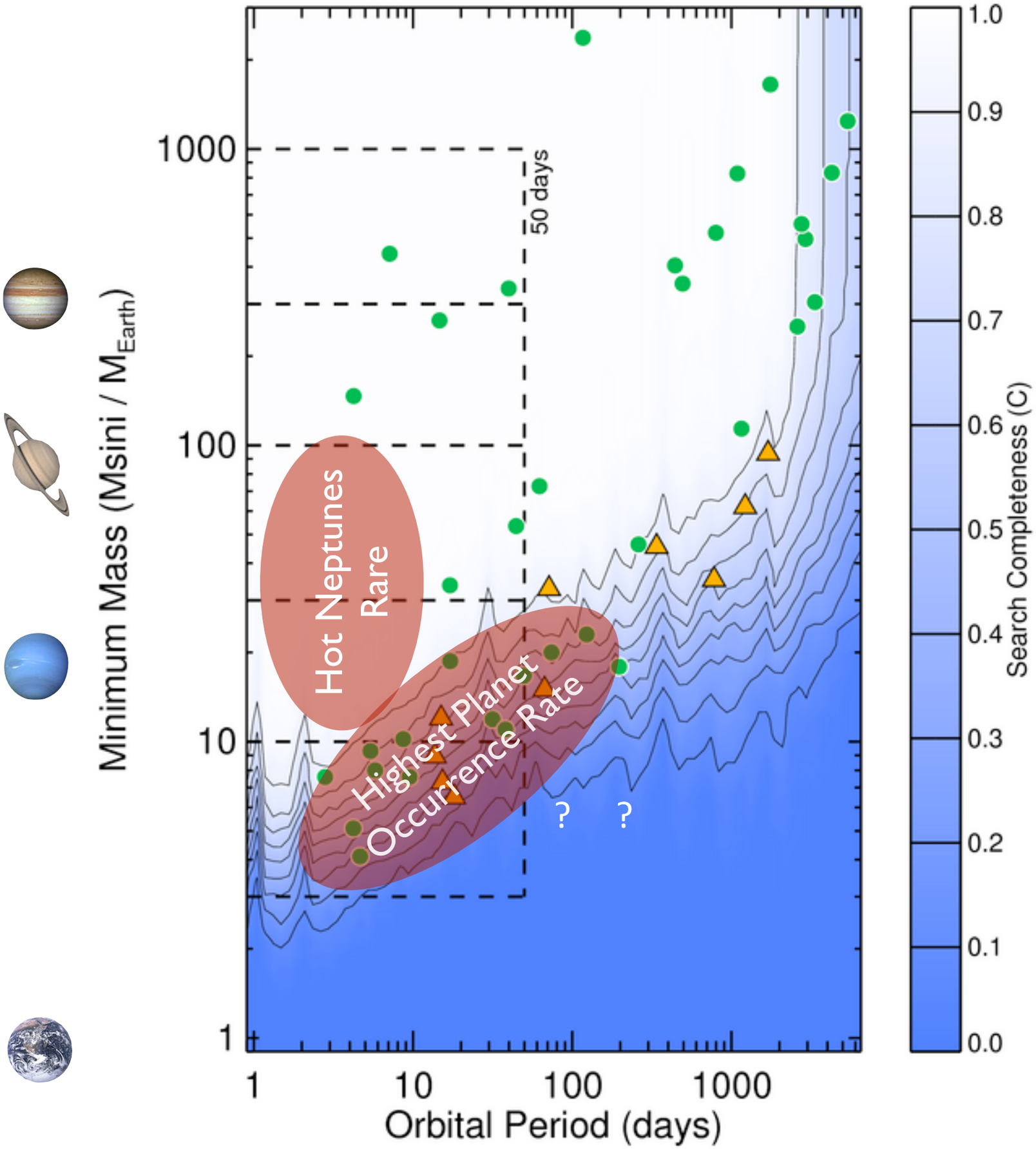
Howard et al. 2010, Science, 330, 653



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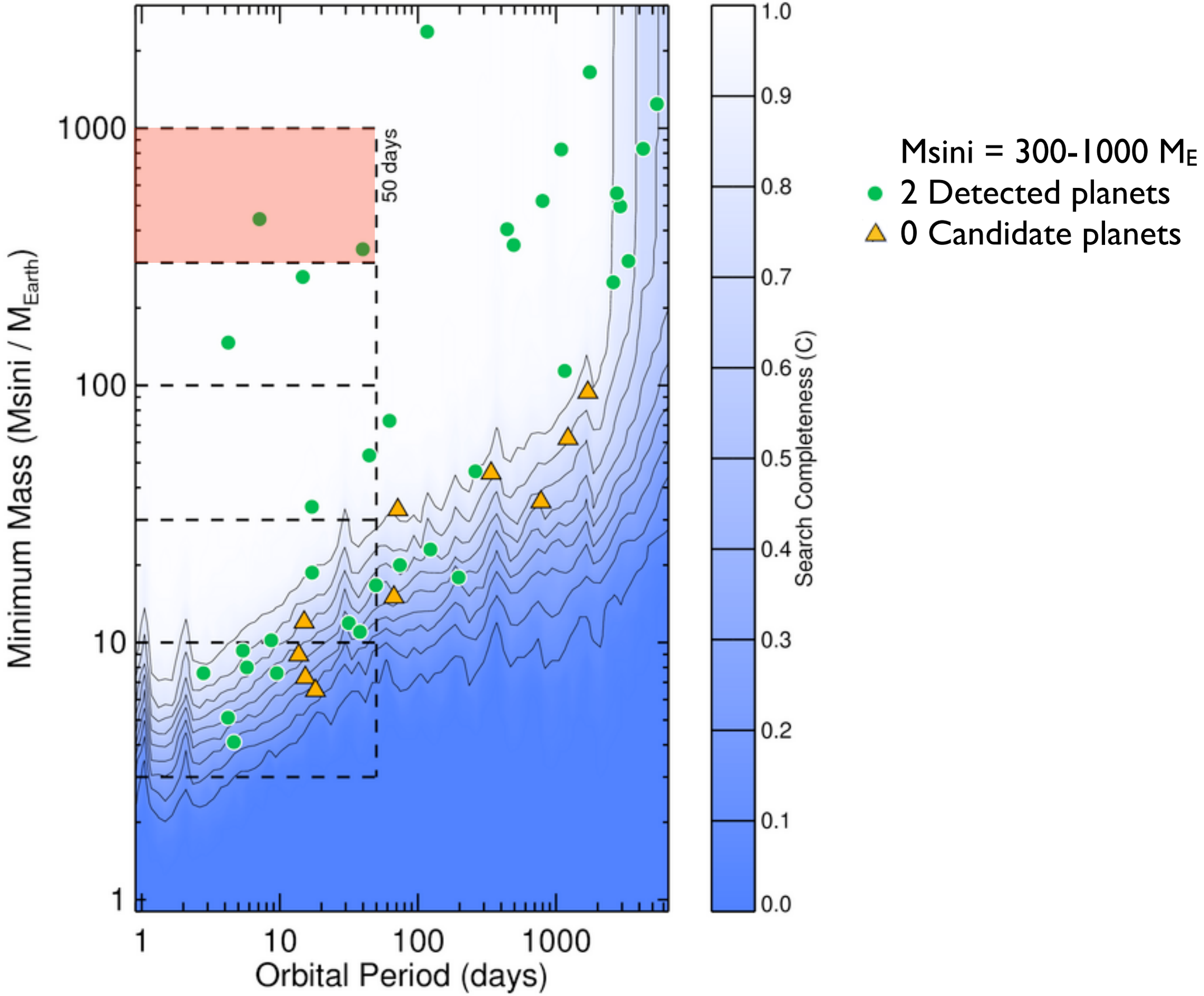
3. Low-mass planets:
   No short-period pileup

4. Low-mass planets:
   Multi-planet systems common

- Detected planets
- Candidate planets
  (FAPs ~ 1-5%)

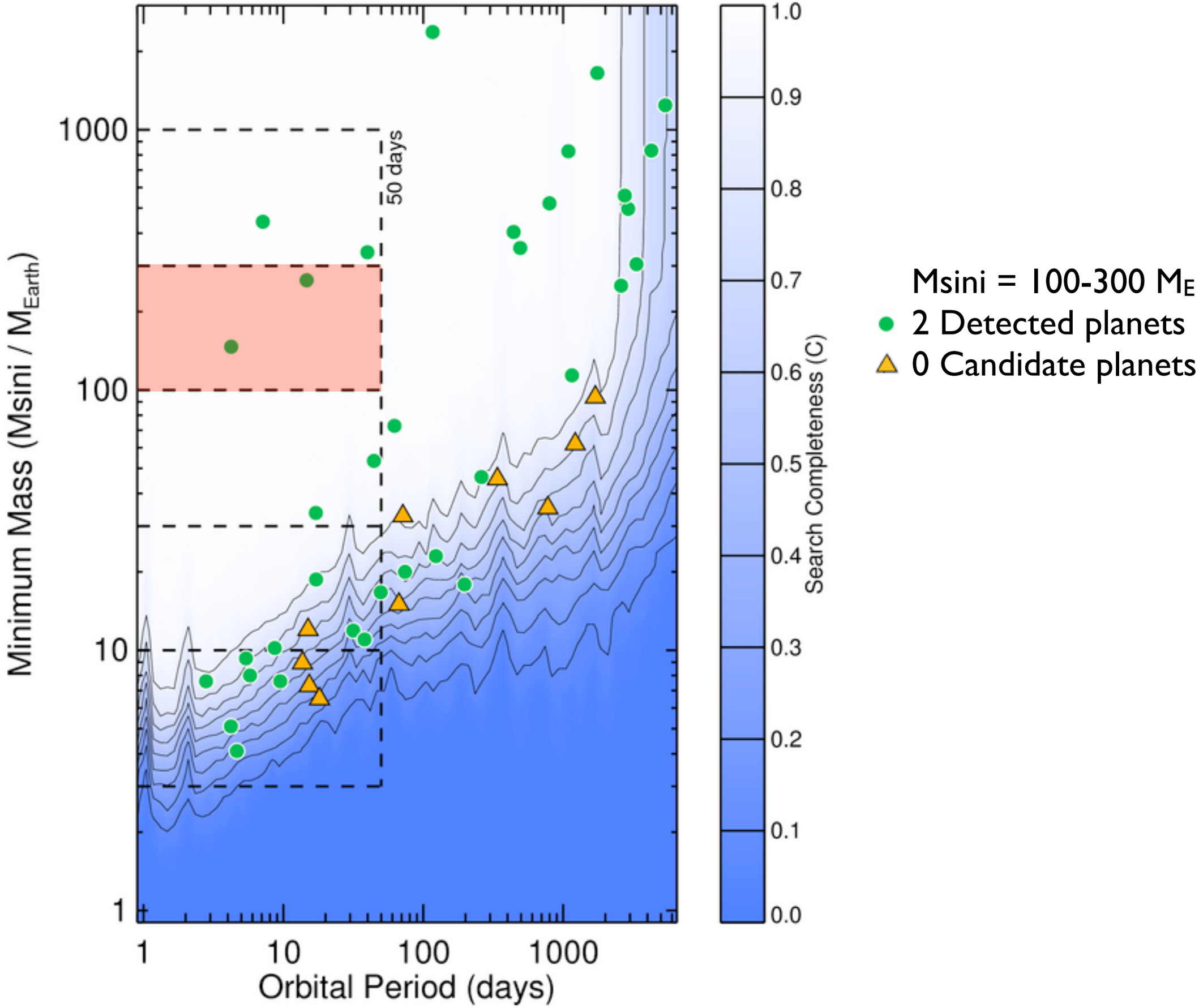
Howard et al. 2010, Science, 330, 653



Msini = 300-1000 M_E

- 2 Detected planets
- 0 Candidate planets

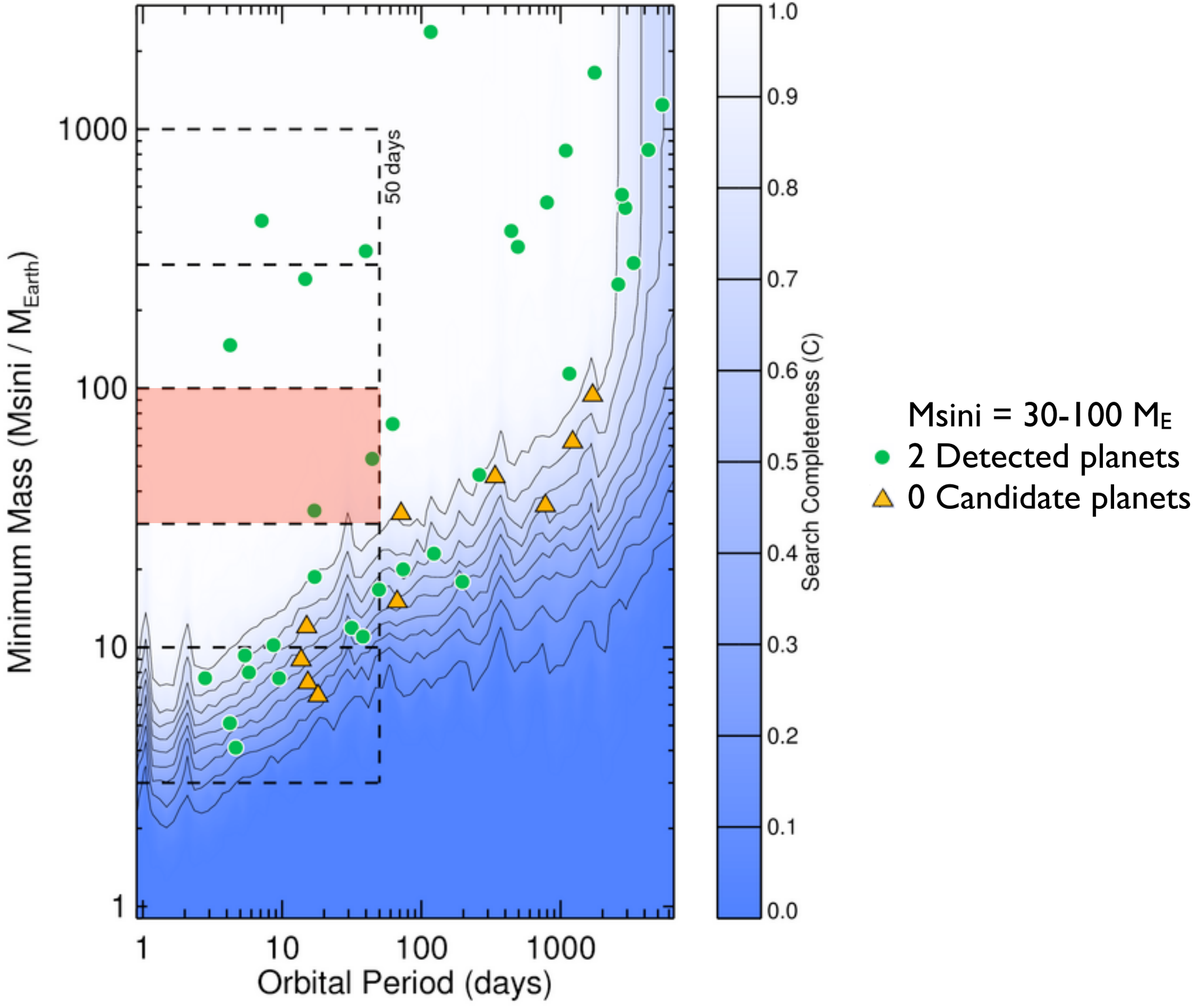
Howard et al. 2010, Science, 330, 653



Msini = 100-300 M_E

- 2 Detected planets
- 0 Candidate planets

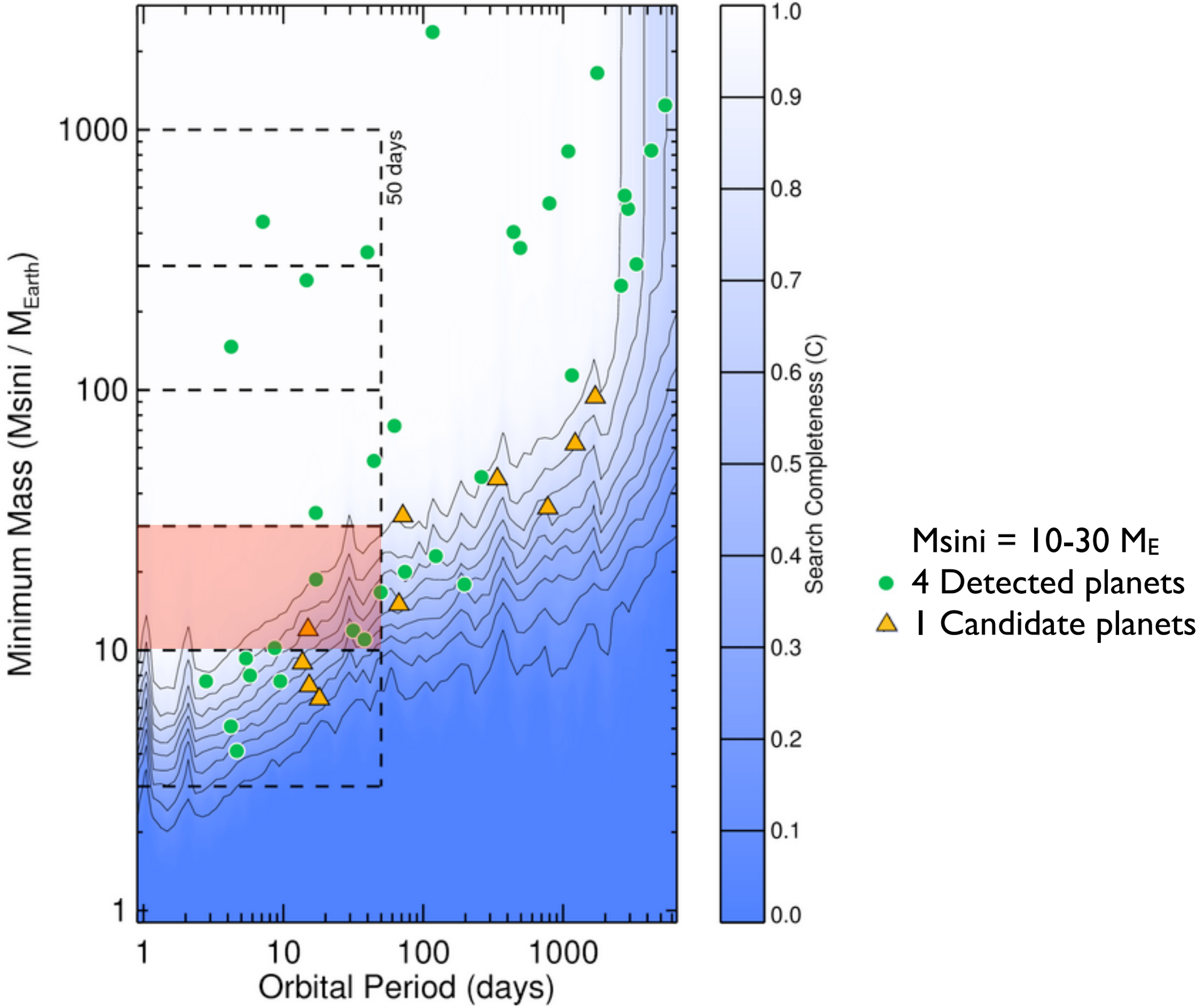
Howard et al. 2010, Science, 330, 653



Msini = 30-100 M_E

- 2 Detected planets
- 0 Candidate planets

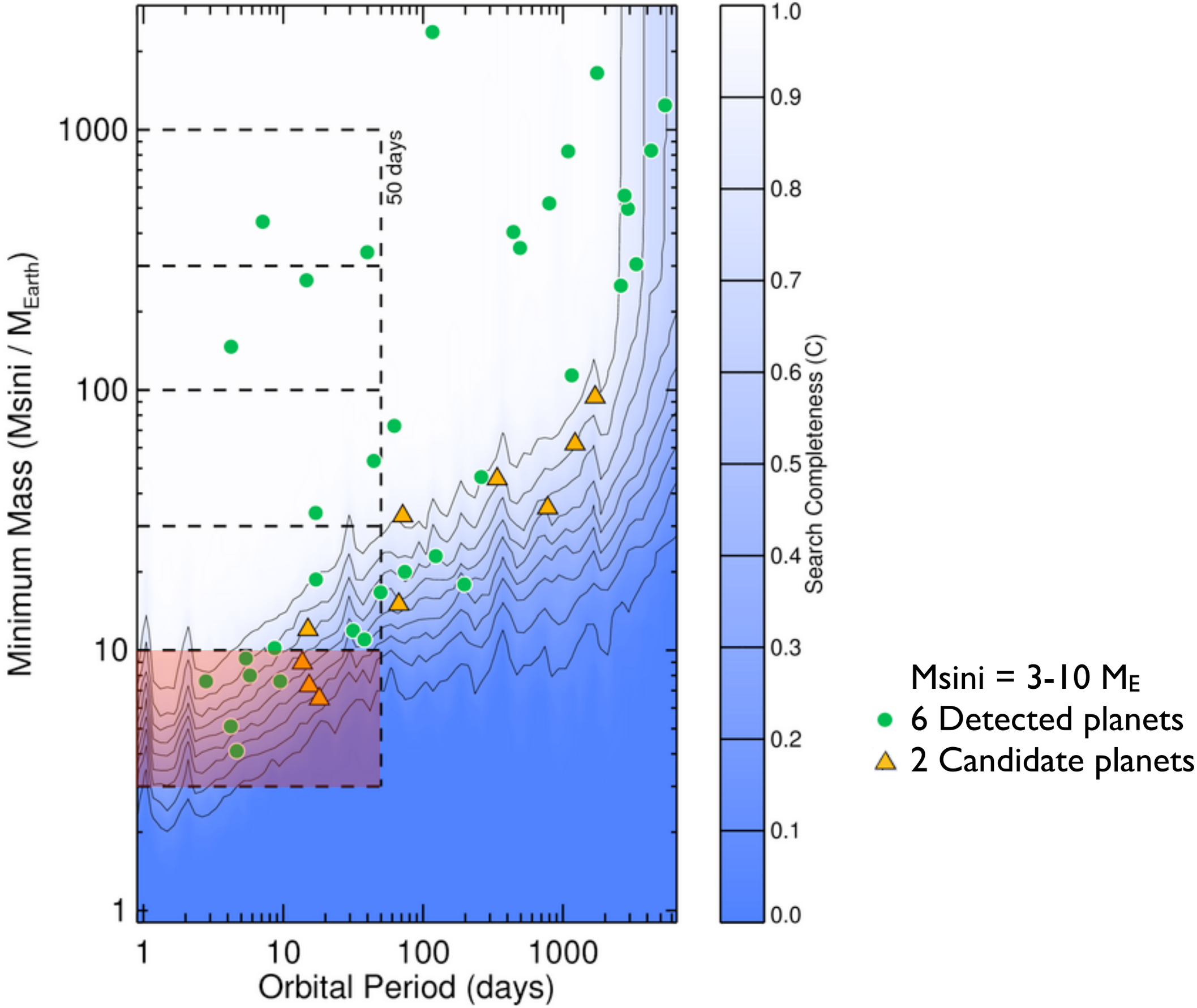
Howard et al. 2010, Science, 330, 653



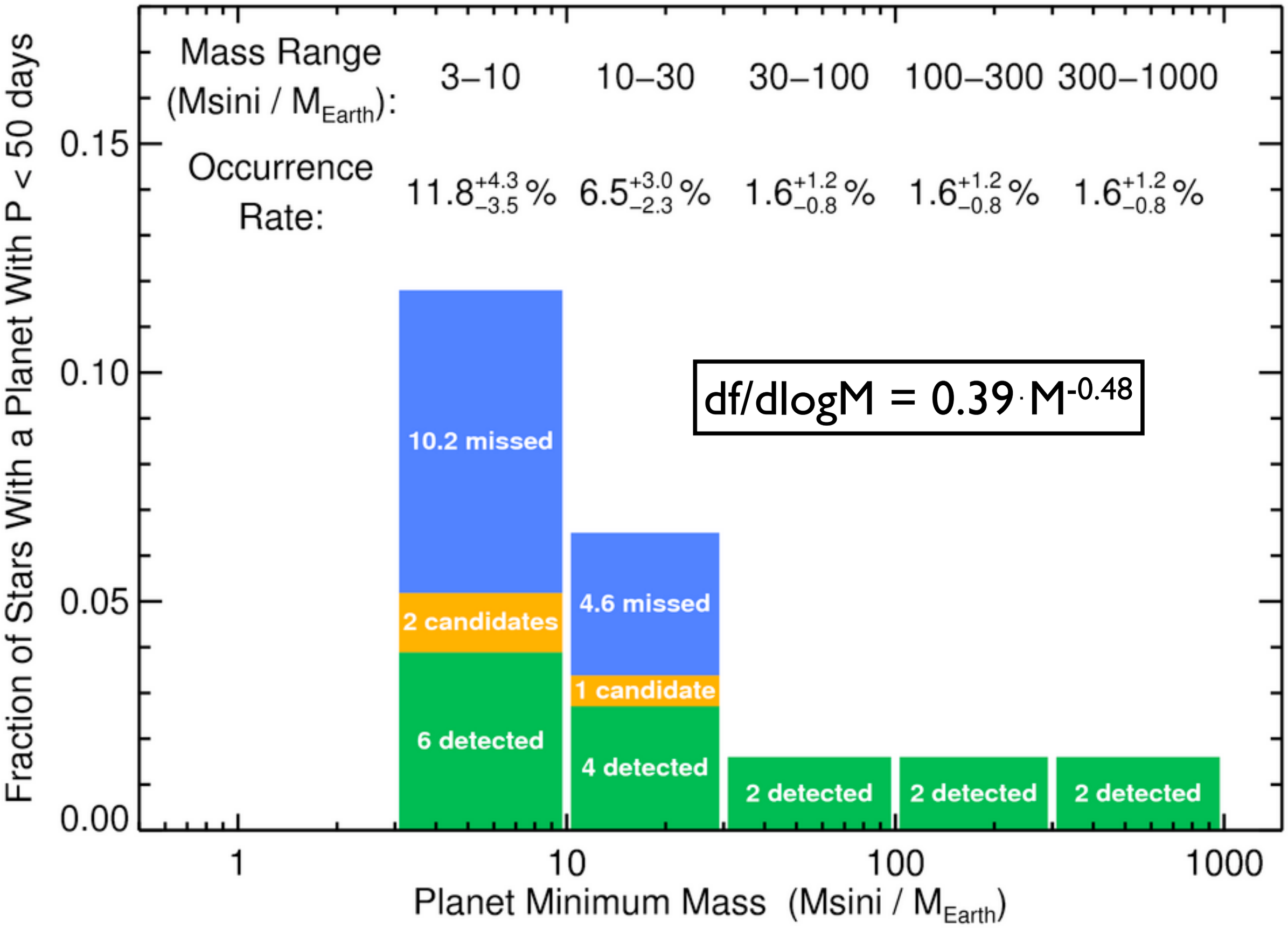
Msini = 10-30 M_E

- 4 Detected planets
- 1 Candidate planets

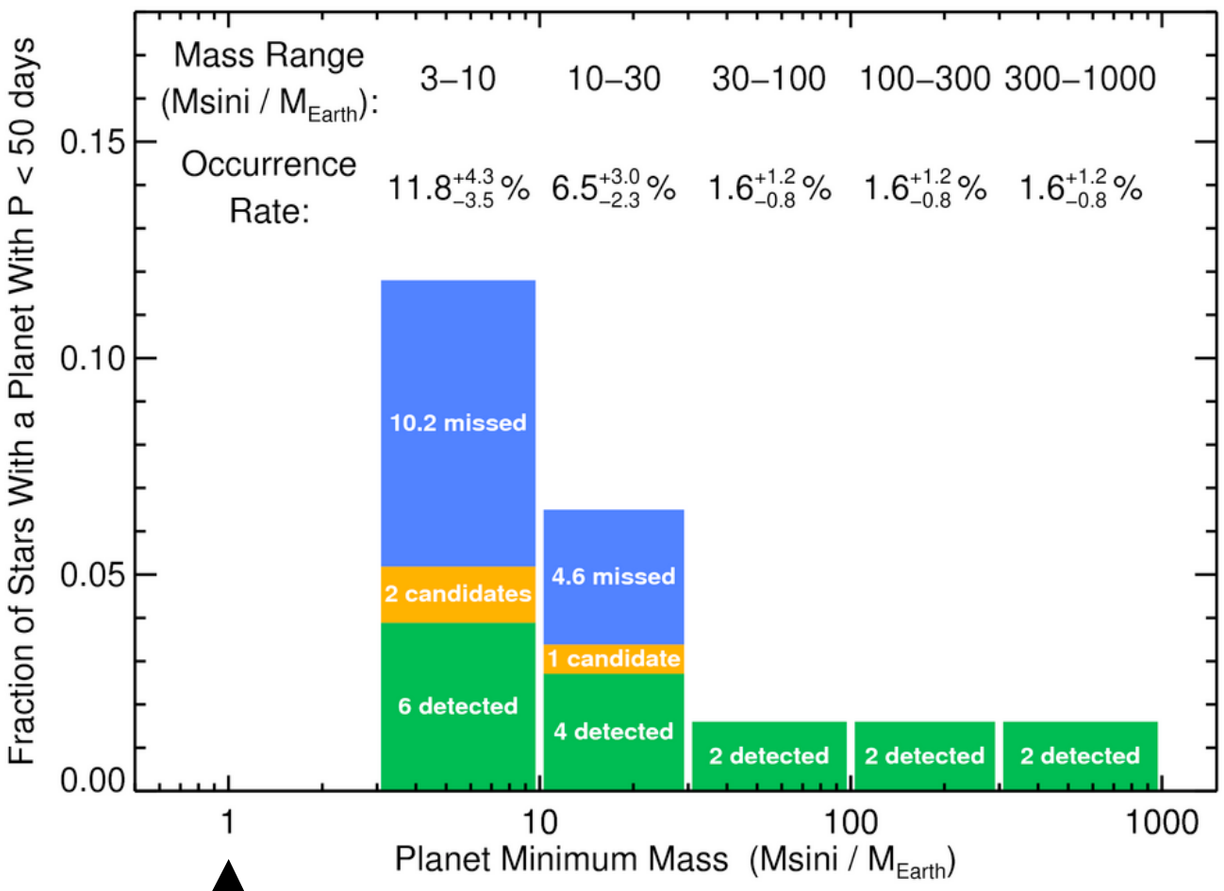
Howard et al. 2010, Science, 330, 653



Howard et al. 2010, Science, 330, 653



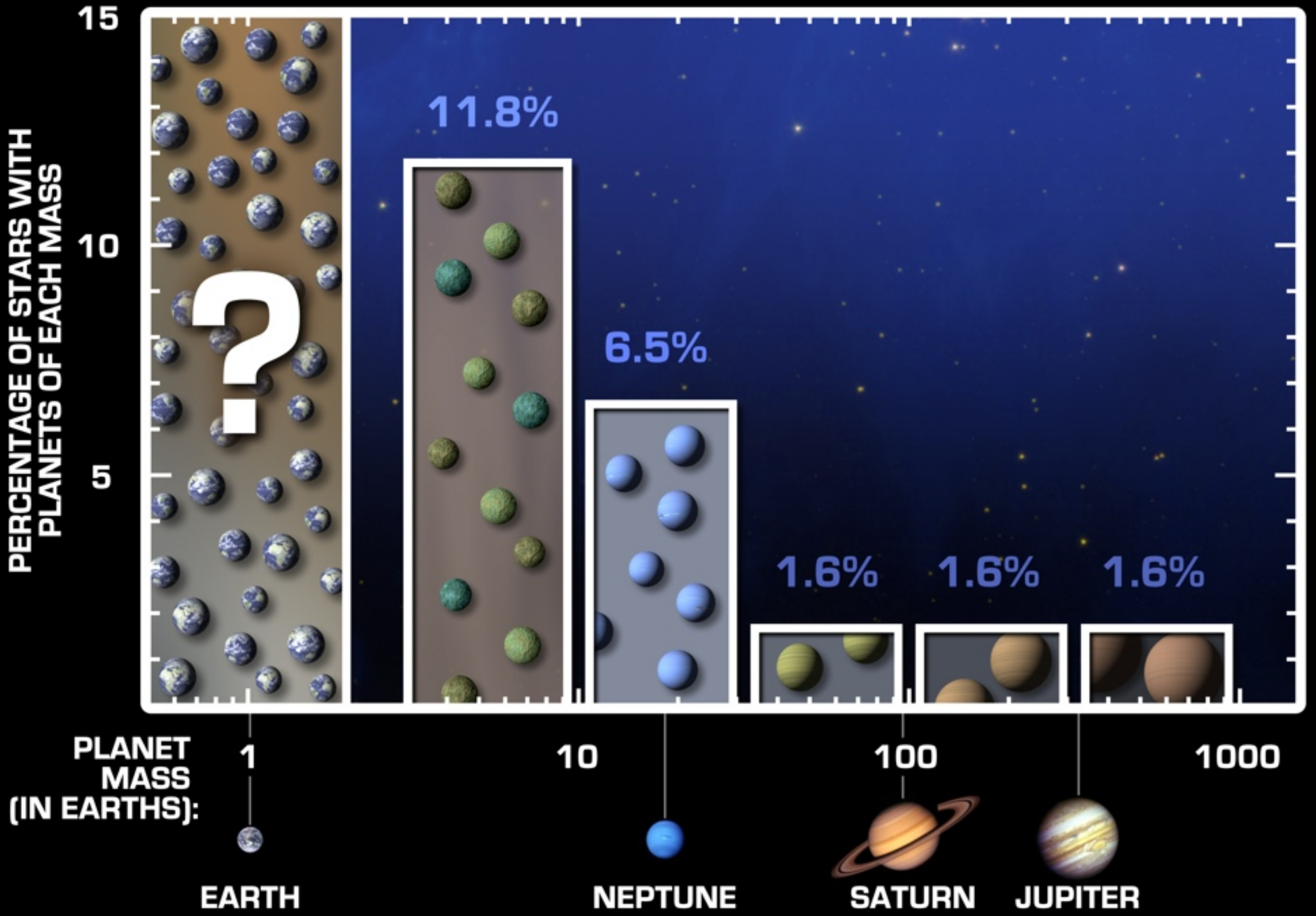
Key Result: Earth-mass Planets Common



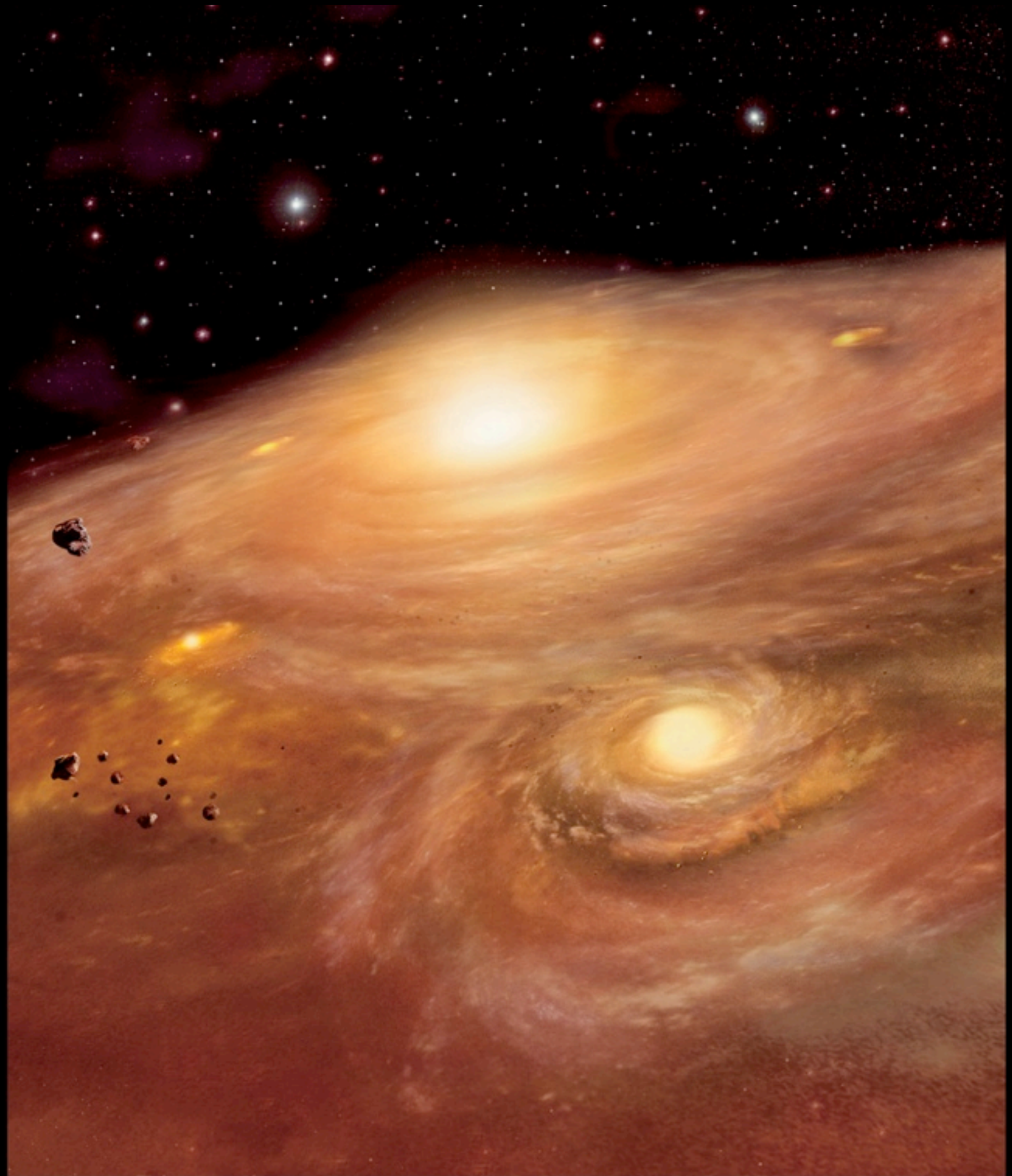
Extrapolation of Power Law Model:

$\eta_{\mathbf{Earth}} = 23^{+16}_{-10}$ % for $M\sin i$ = 0.5-2.0 M_E, P < 50 days

Howard et al. 2010, Science, 330, 653



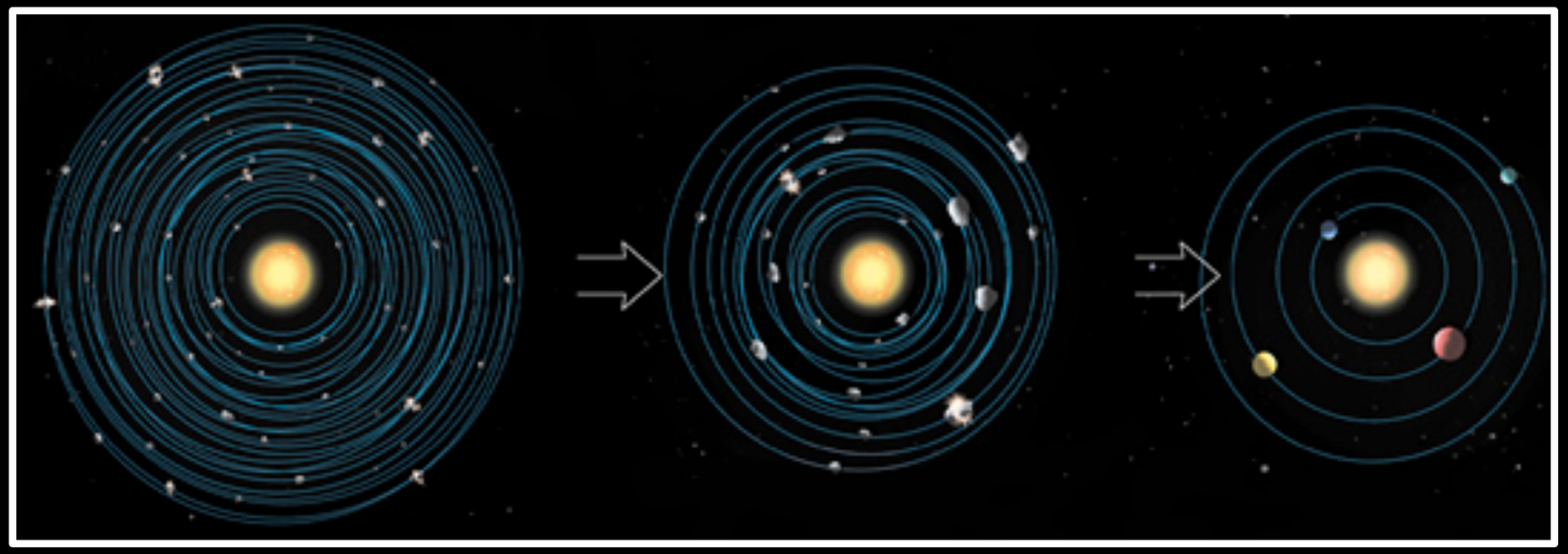
Credit: NASA/JPL-Caltech/UC Berkeley



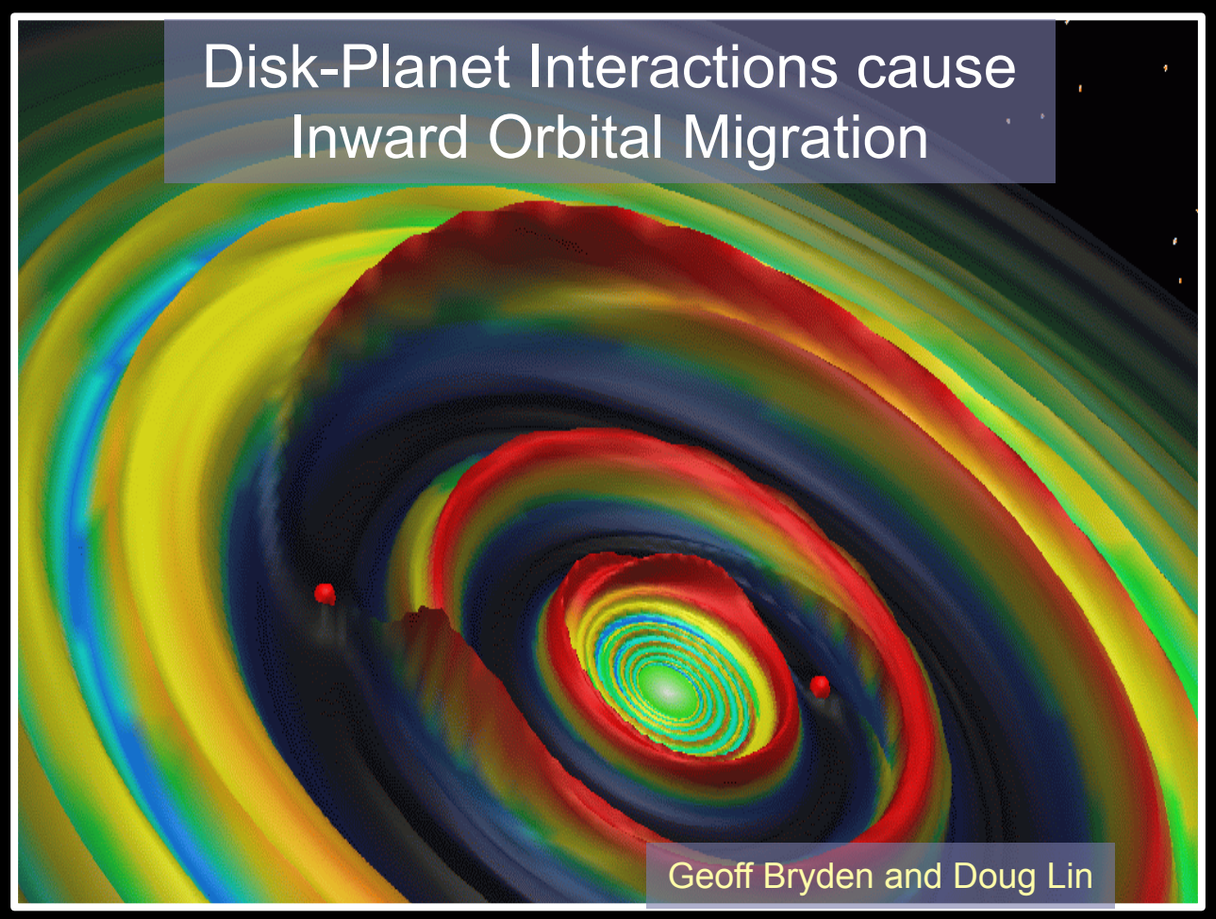
Compare with Planet Formation Models

Core Accretion Model of Planet Formation:

Planet Growth

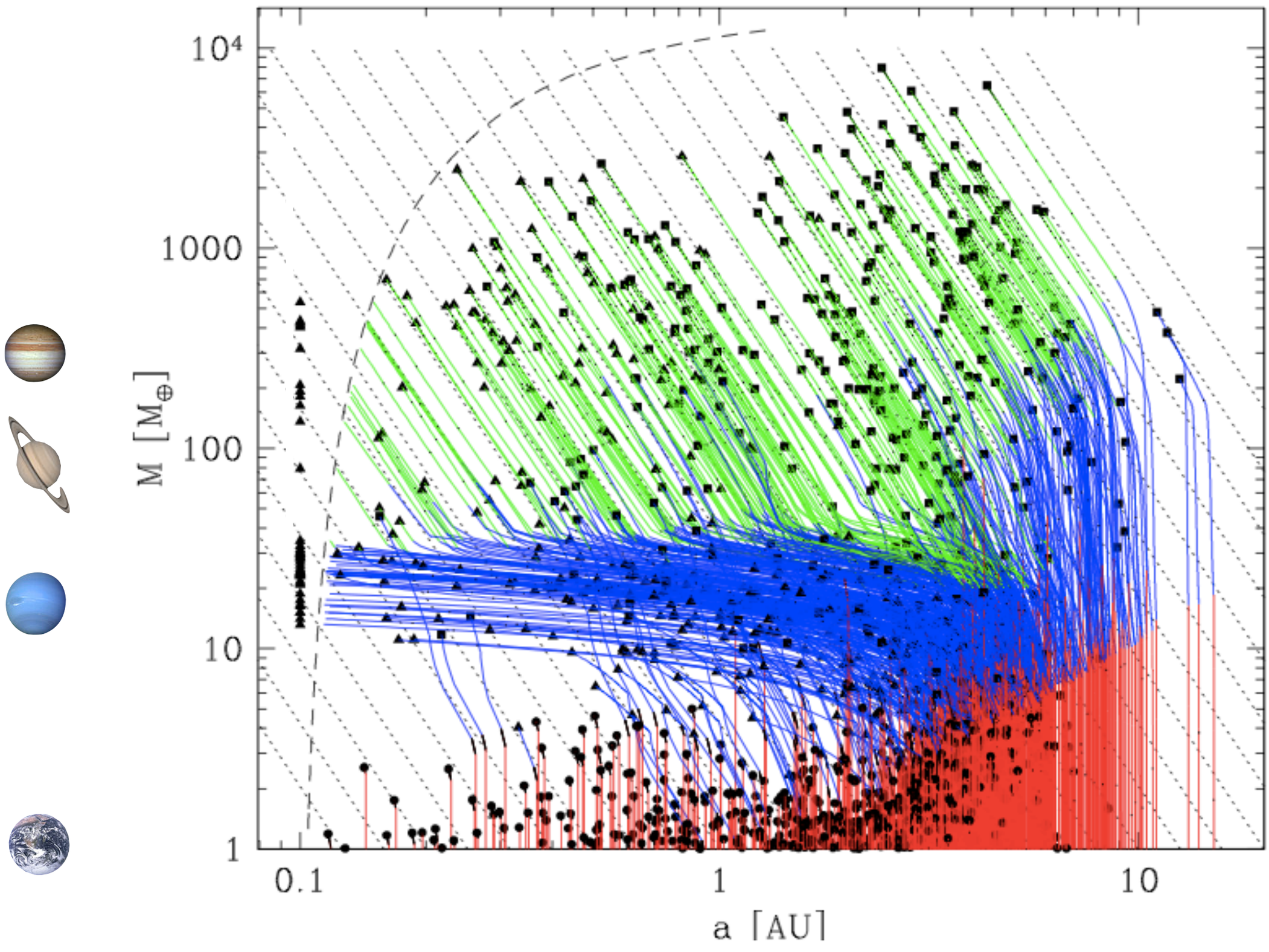


Planet Migration

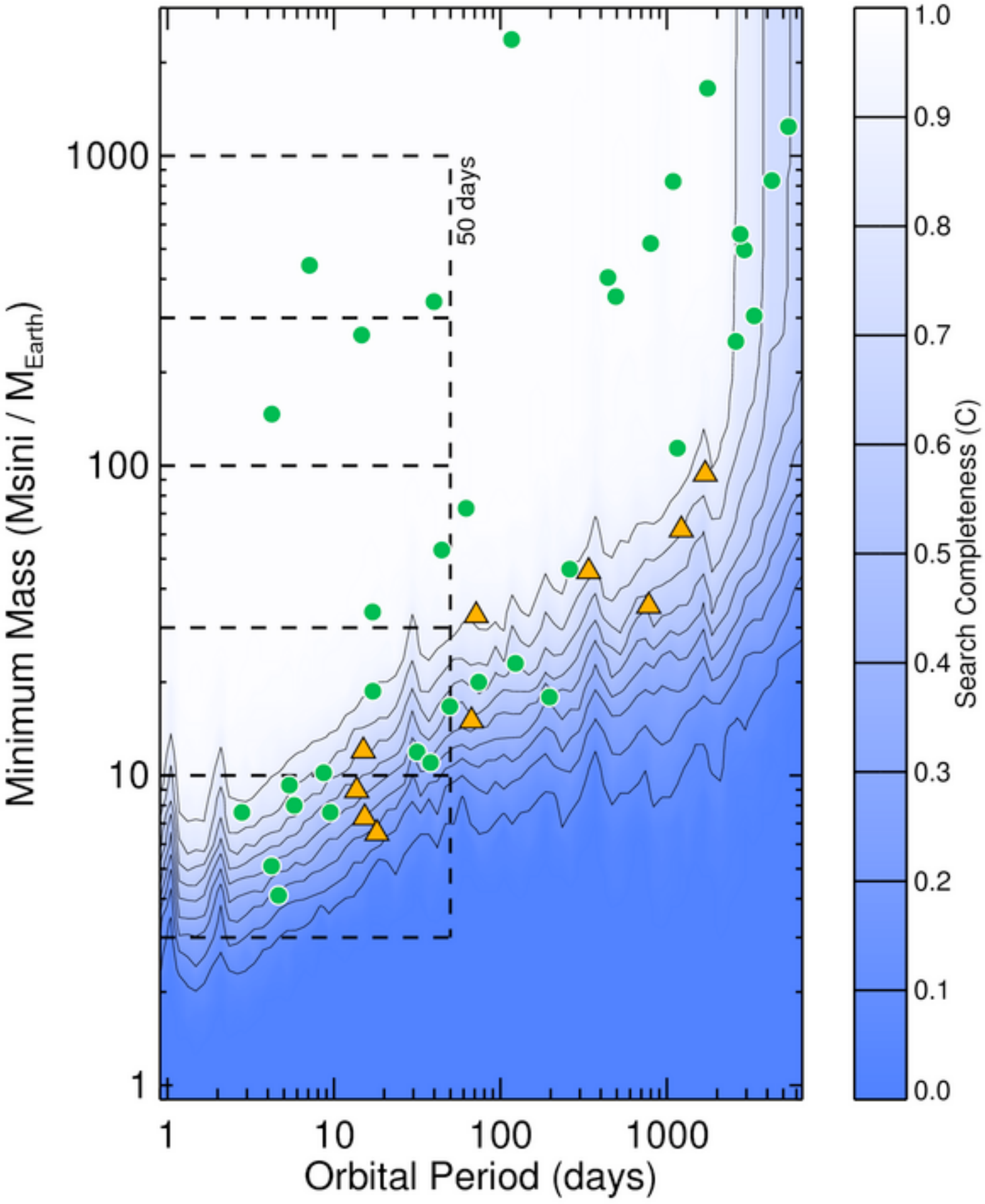


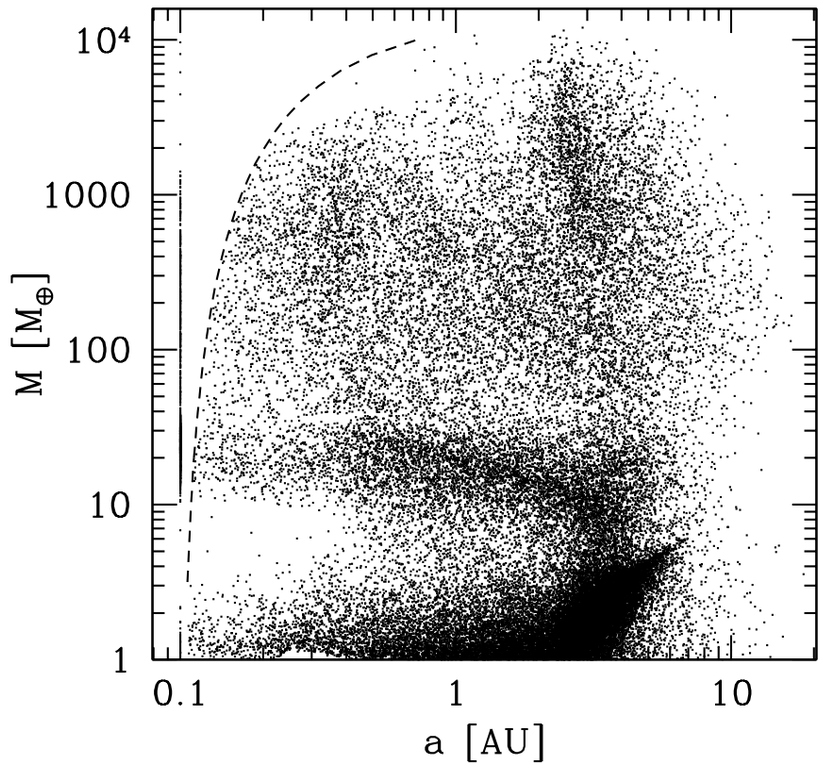
Population Synthesis Model: Planet Formation & Migration

Mordasini, Alibert, & Benz (2009)

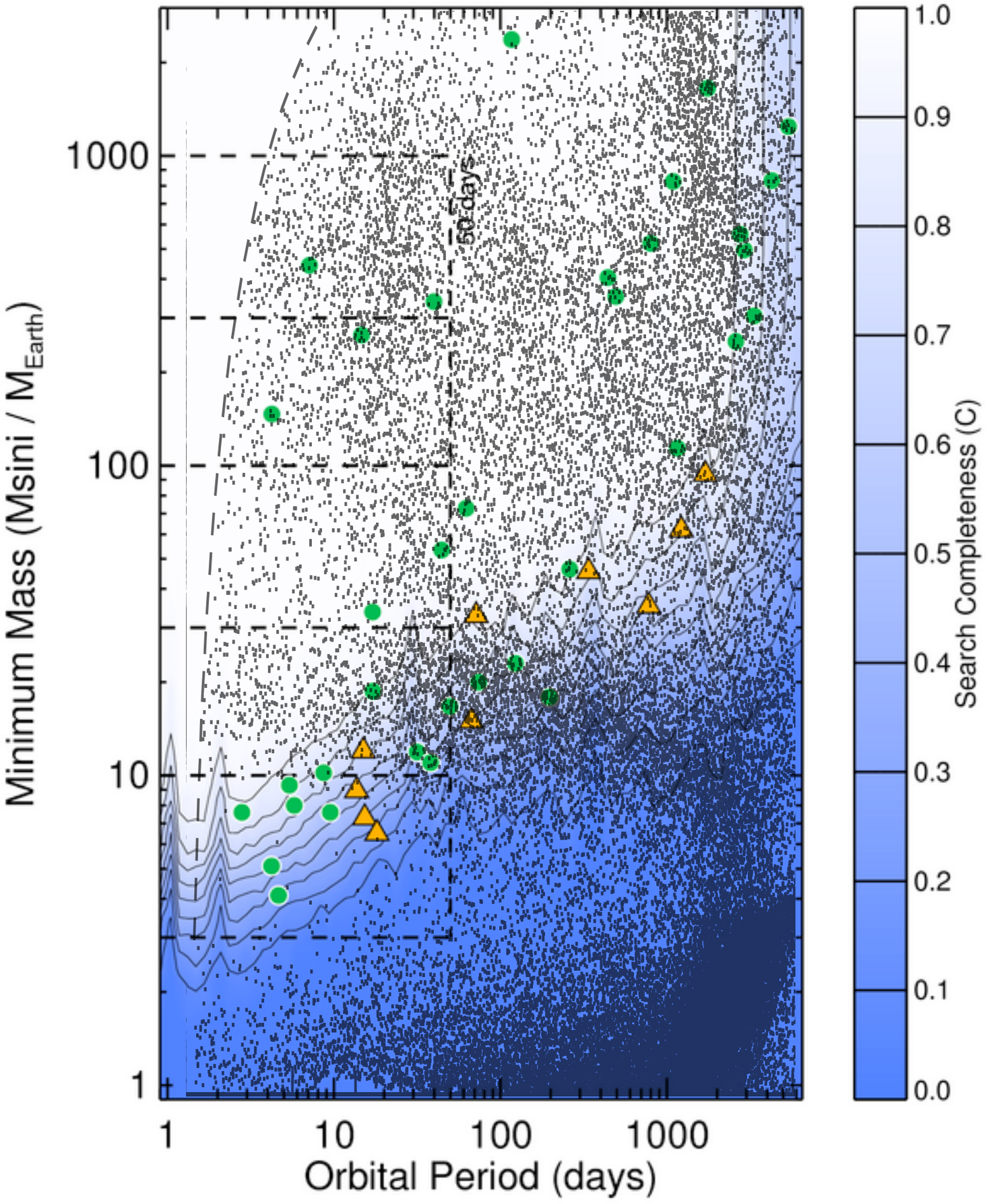


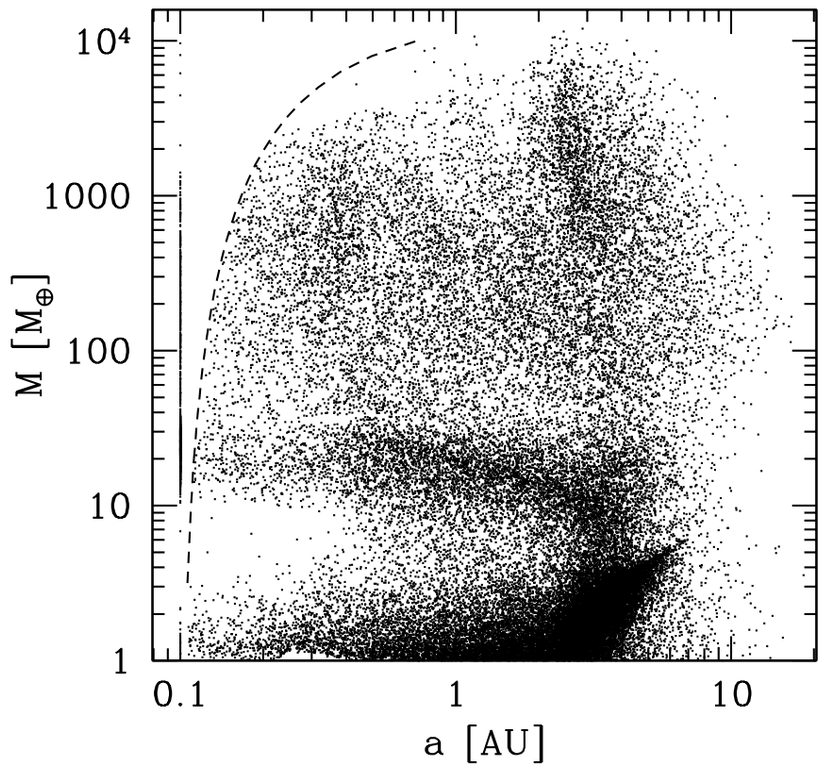
Compare with Mordasini et al. (2009)





Compare with Mordasini et al. (2009)





Migration then Assembly:
Formation of Neptune mass planets inside 1 AU

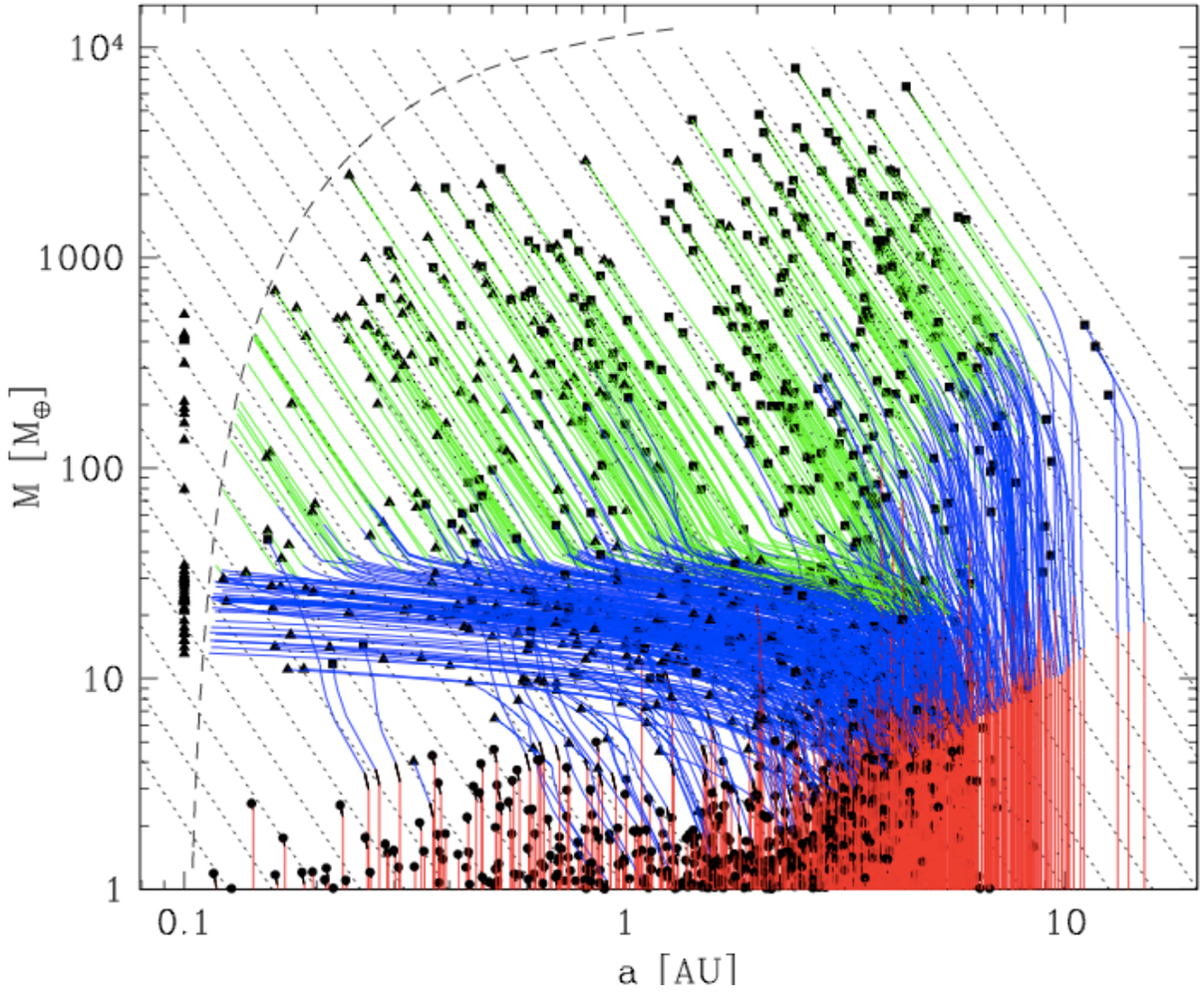
Hansen & Murray (2011, arXiv:1105.2050)

Assembly then Migration (traditional picture):

Cores form at typically ≥ 2 AU and then migrate by Type I & II

Reproduces Jovian population (mostly)

Predicts planet desert (not observed)



Migration then Assembly:
Formation of Neptune mass planets inside 1 AU

Hansen & Murray (2011, arXiv:1105.2050)

Migration then Assembly (heretical picture):

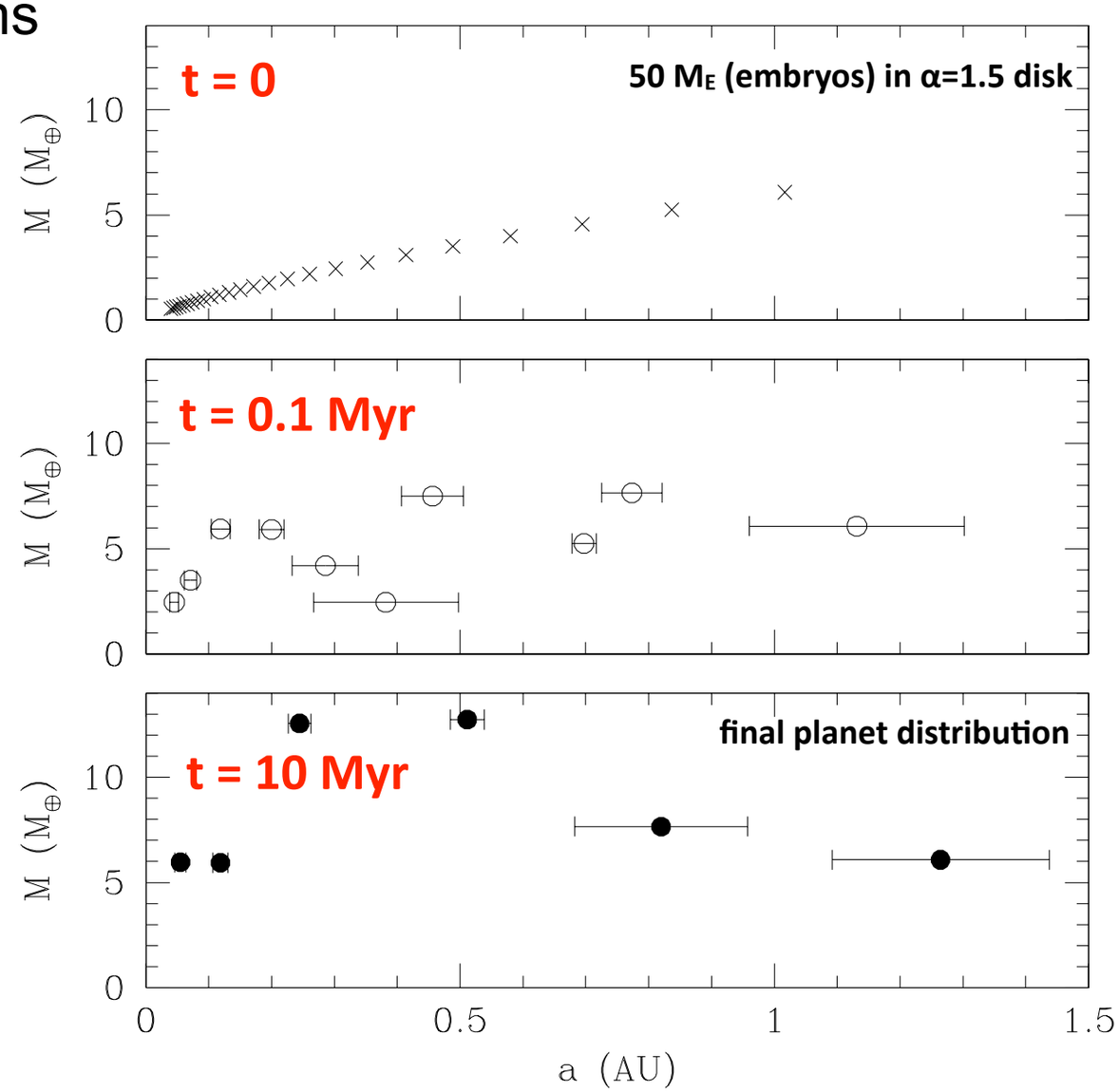
Planetesimals migrate to < 1 AU and form embryos that interact and accrete

Reproduces: distribution in mass and orbital distance of close-in planets & details of multi-planet systems

Predictions: period ratios

Goal of toy model:

see how much of the mass/period distribution can be reproduced before invoking new physics (i.e. migration)



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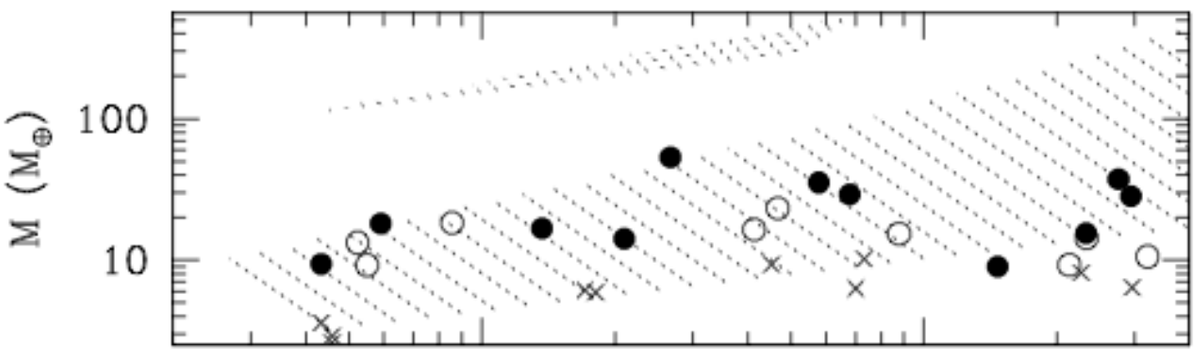
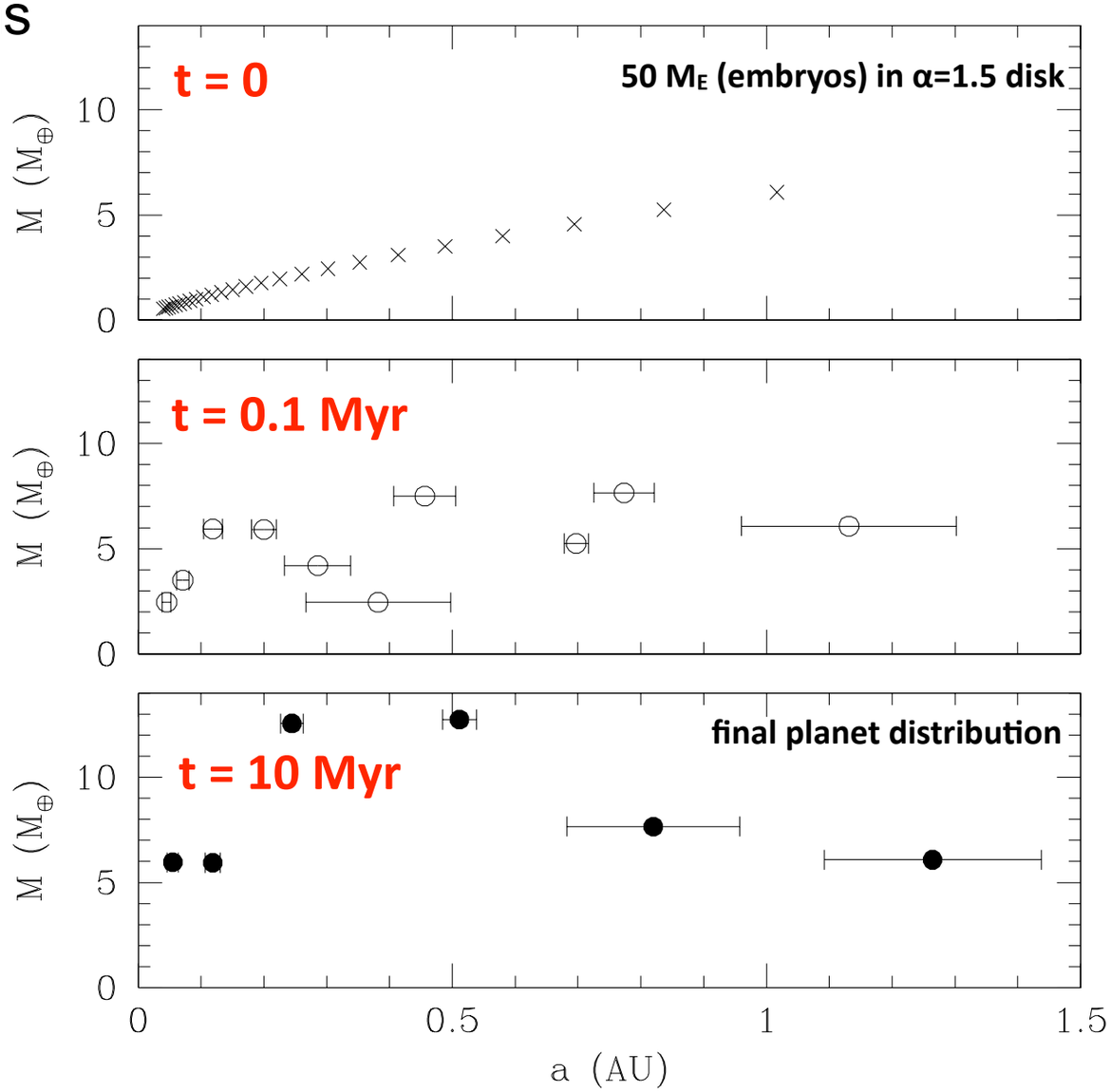
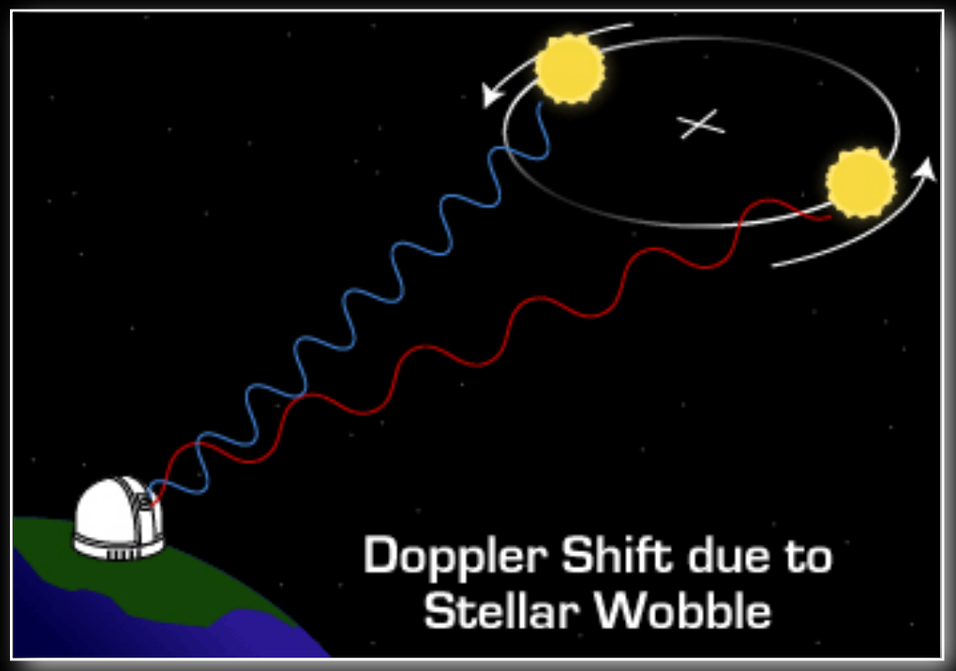
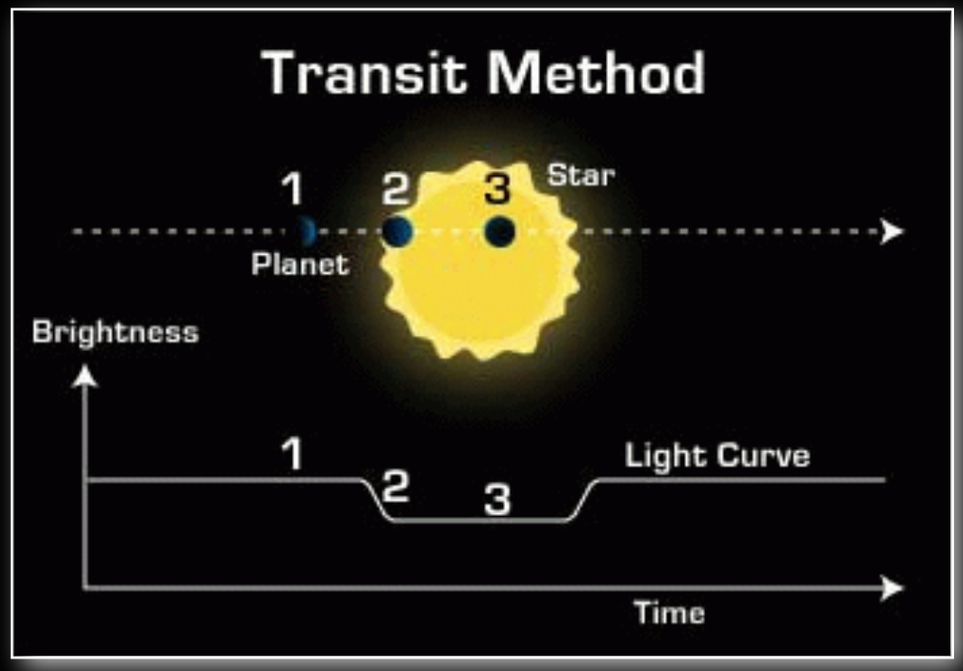


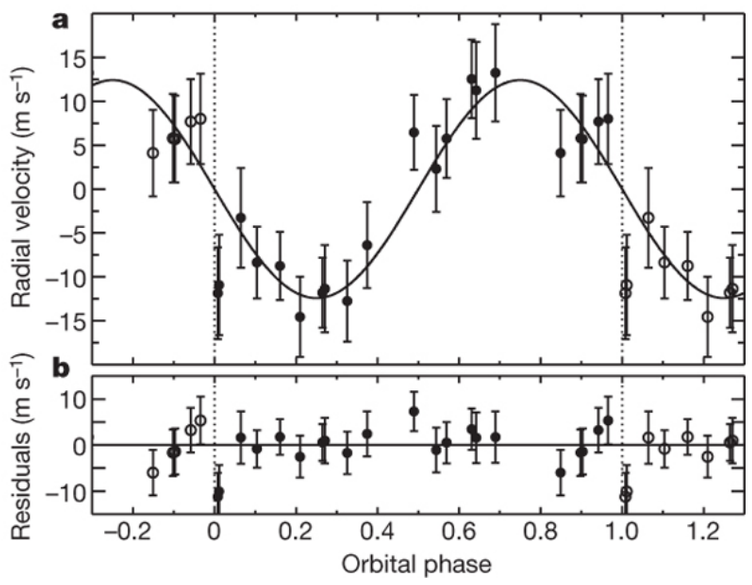


GJ 1214b: Doppler + Transit → Planet Density



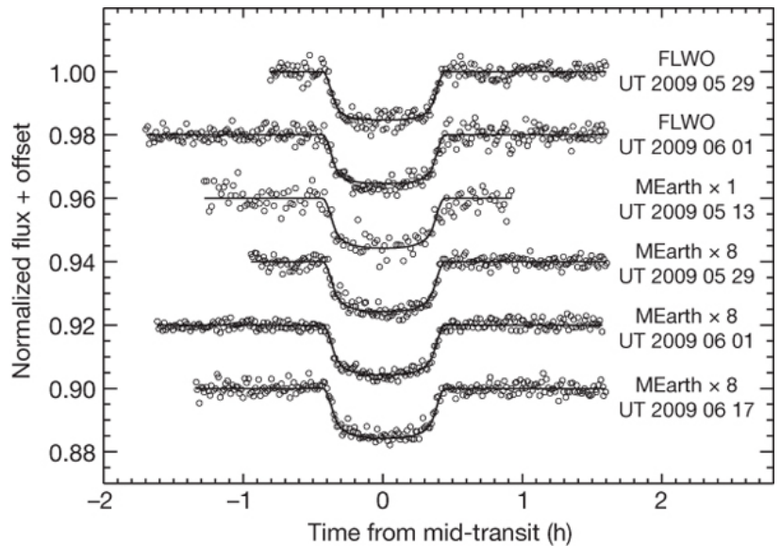


Mass = 6.5 M_E

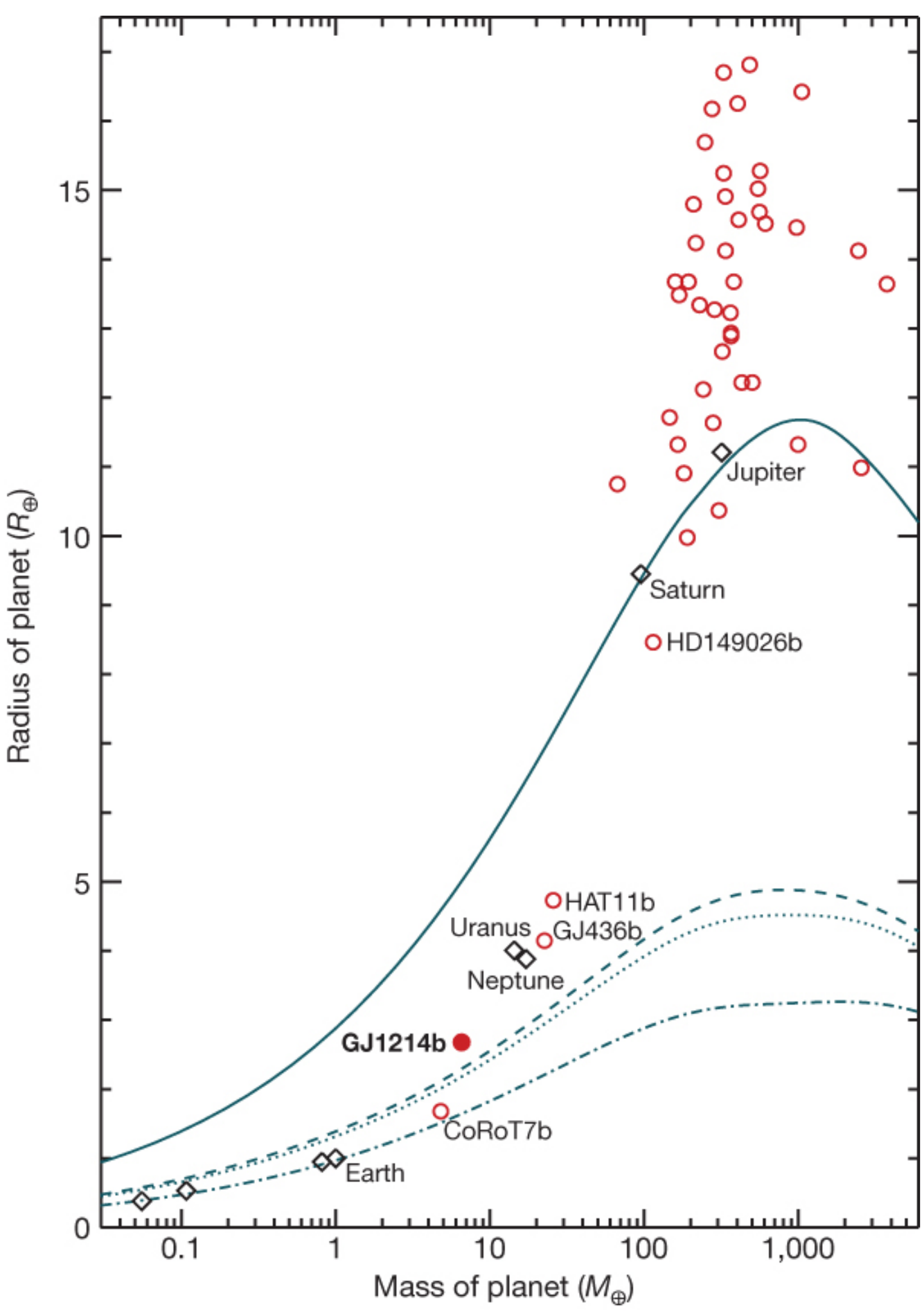


Charbonneau et al. (2009)

Radius = 2.7 R_E

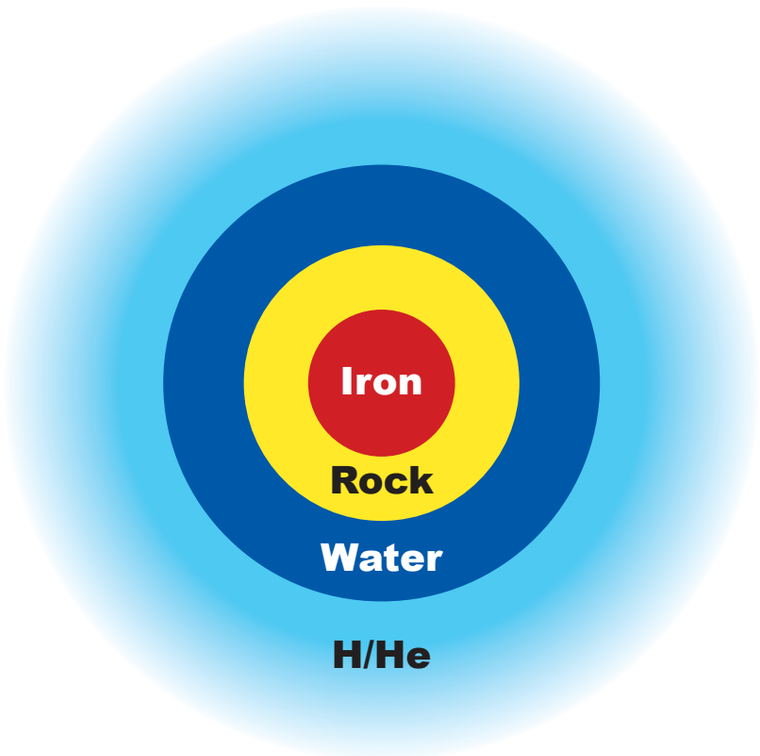


Charbonneau et al. (2009)


15
10
5
0
Radius of planet ($R_\oplus$)
Jupiter
Saturn
HD149026b
HAT11b
Uranus
GJ436b
Neptune
GJ1214b
CoRoT7b
Earth
0.1
1
10
100
1,000
Mass of planet ($M_\oplus$)

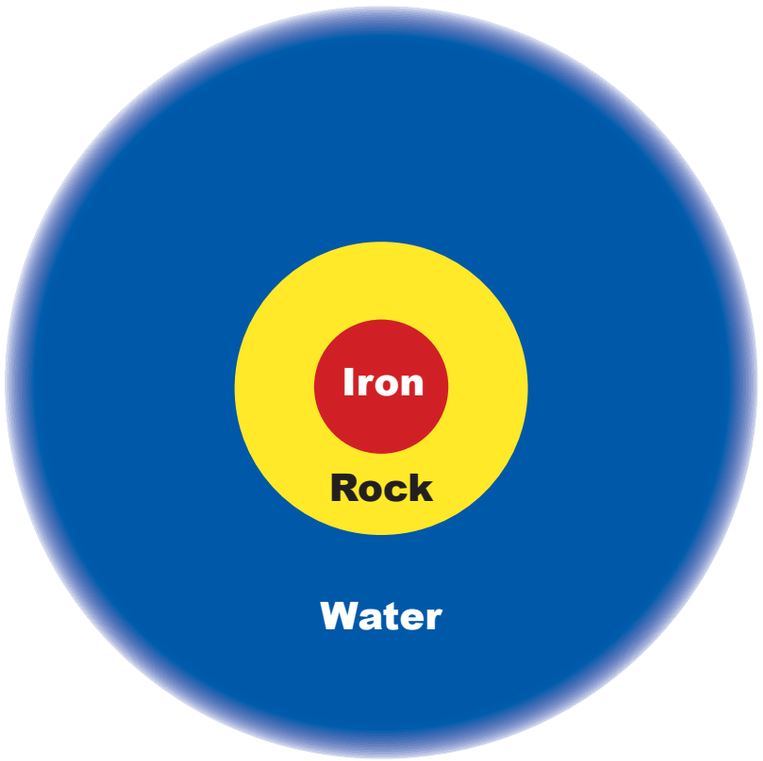
What is GJ 1214b made of?

Mini-Neptune



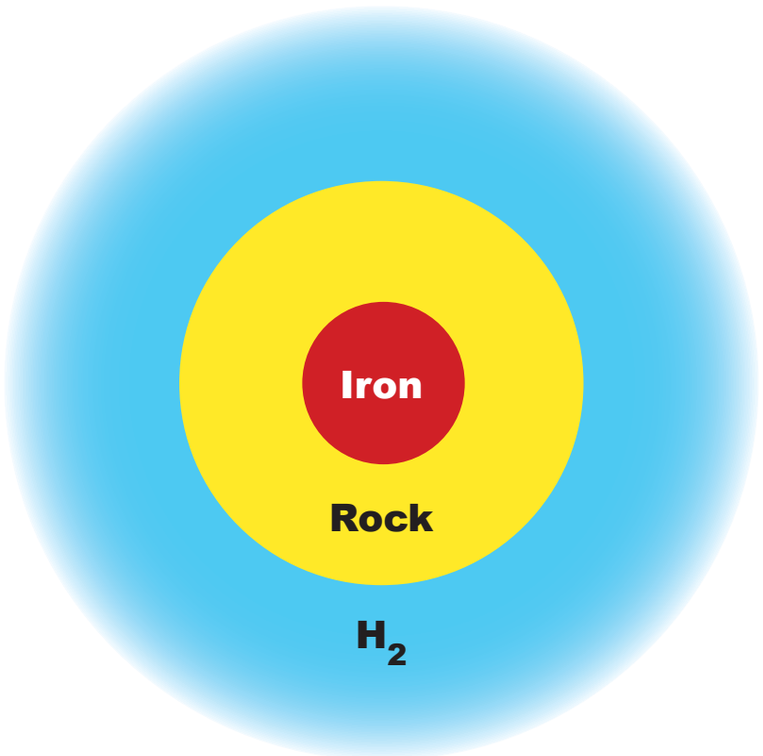
H/He mass fraction
= 10^{-4} to 6.8%

Water World



H_2O mass fraction
≥ 47%

Super-Earth

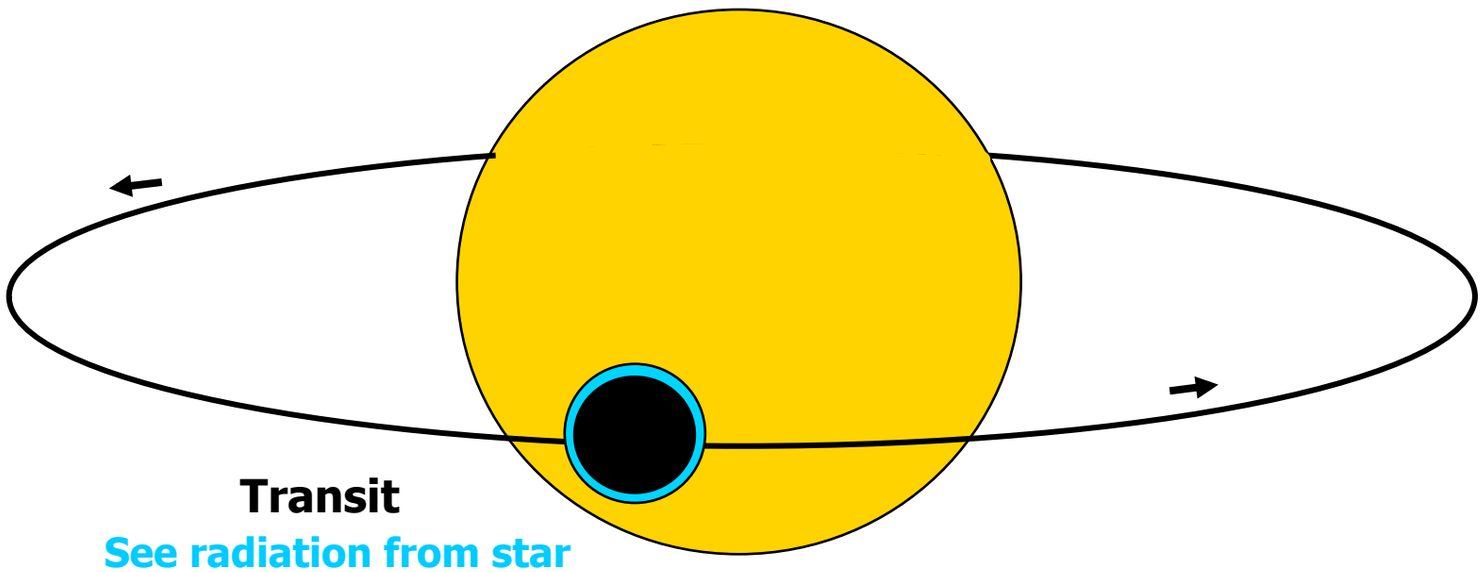


H_2 mass fraction
= 5×10^{-4} to 3%

All planets above have M = 6.5 M_E and R = 2.7 R_E

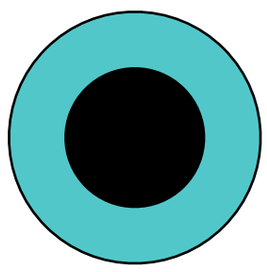
Rogers & Seager (2010)

Measure Atmospheric Scale Height

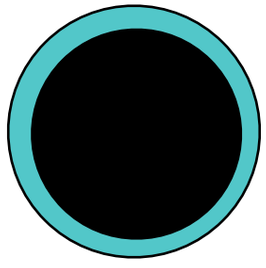


Transit

See radiation from star transmitted through the planet's atmosphere



Large
Scale Height

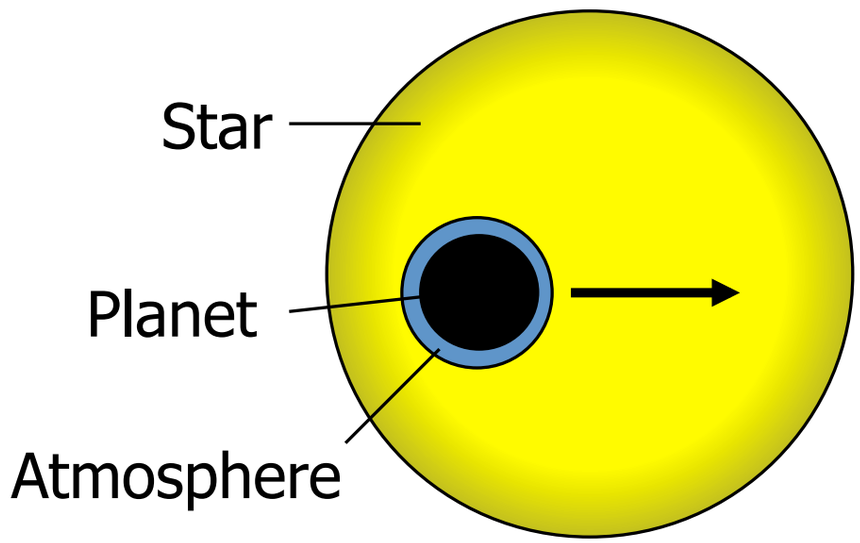


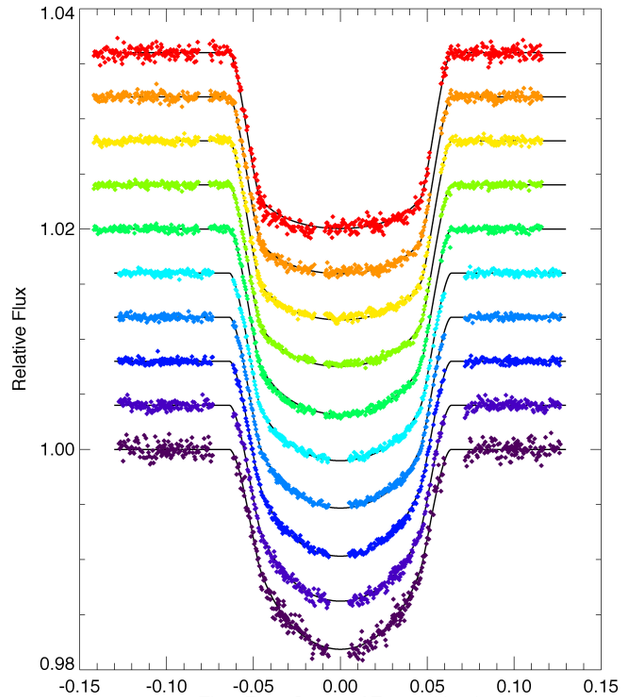
Small
Scale Height

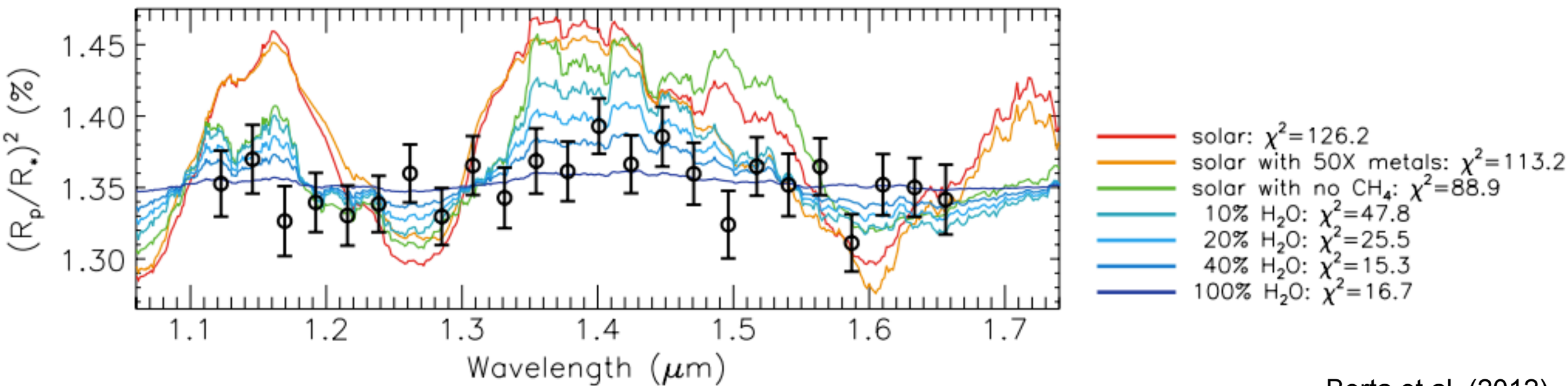
Atmospheric
Scale Height

$$H = \frac{kT}{\mu g}$$

Measure Atmospheric Scale Height

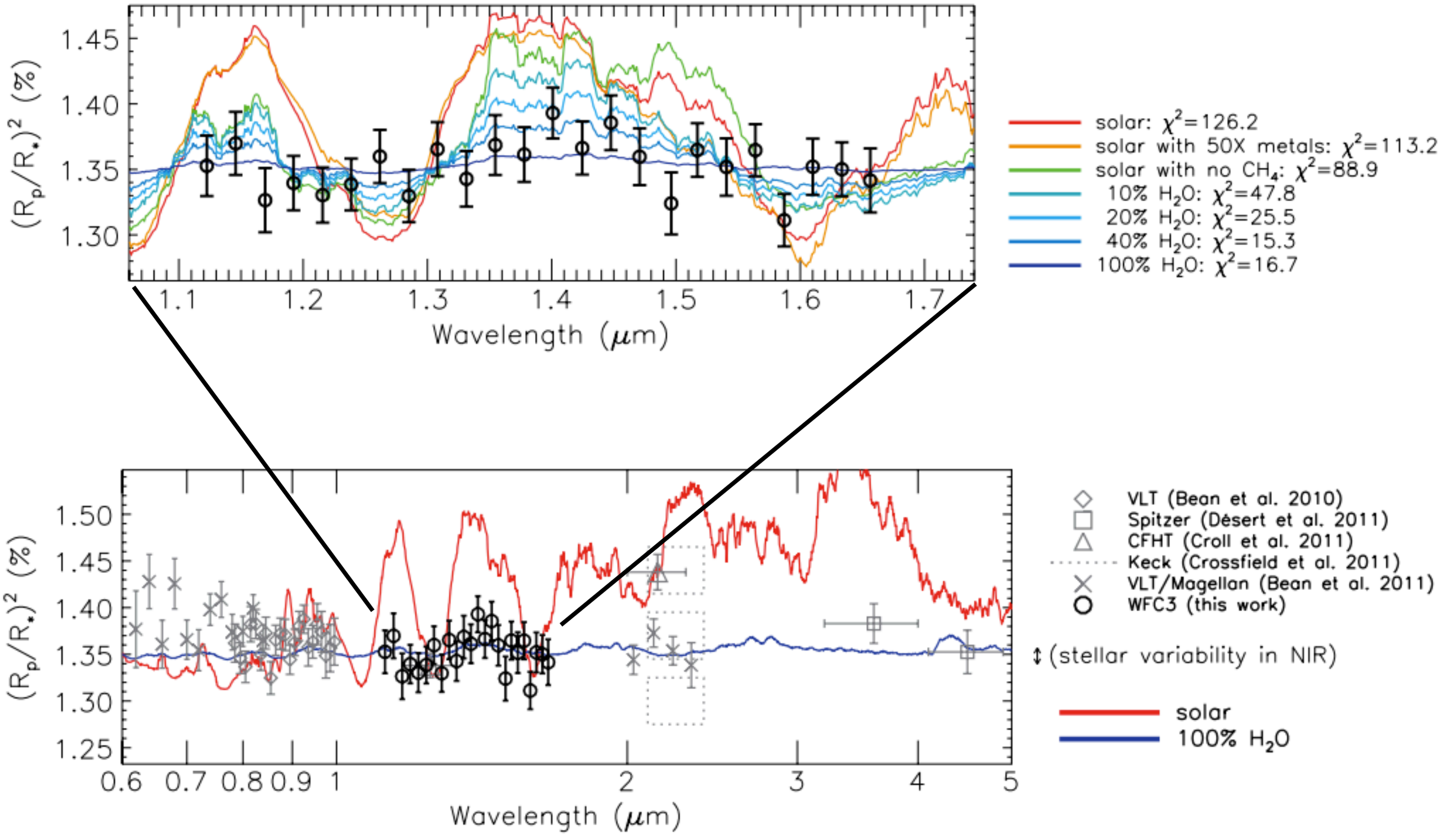






Berta et al. (2012)

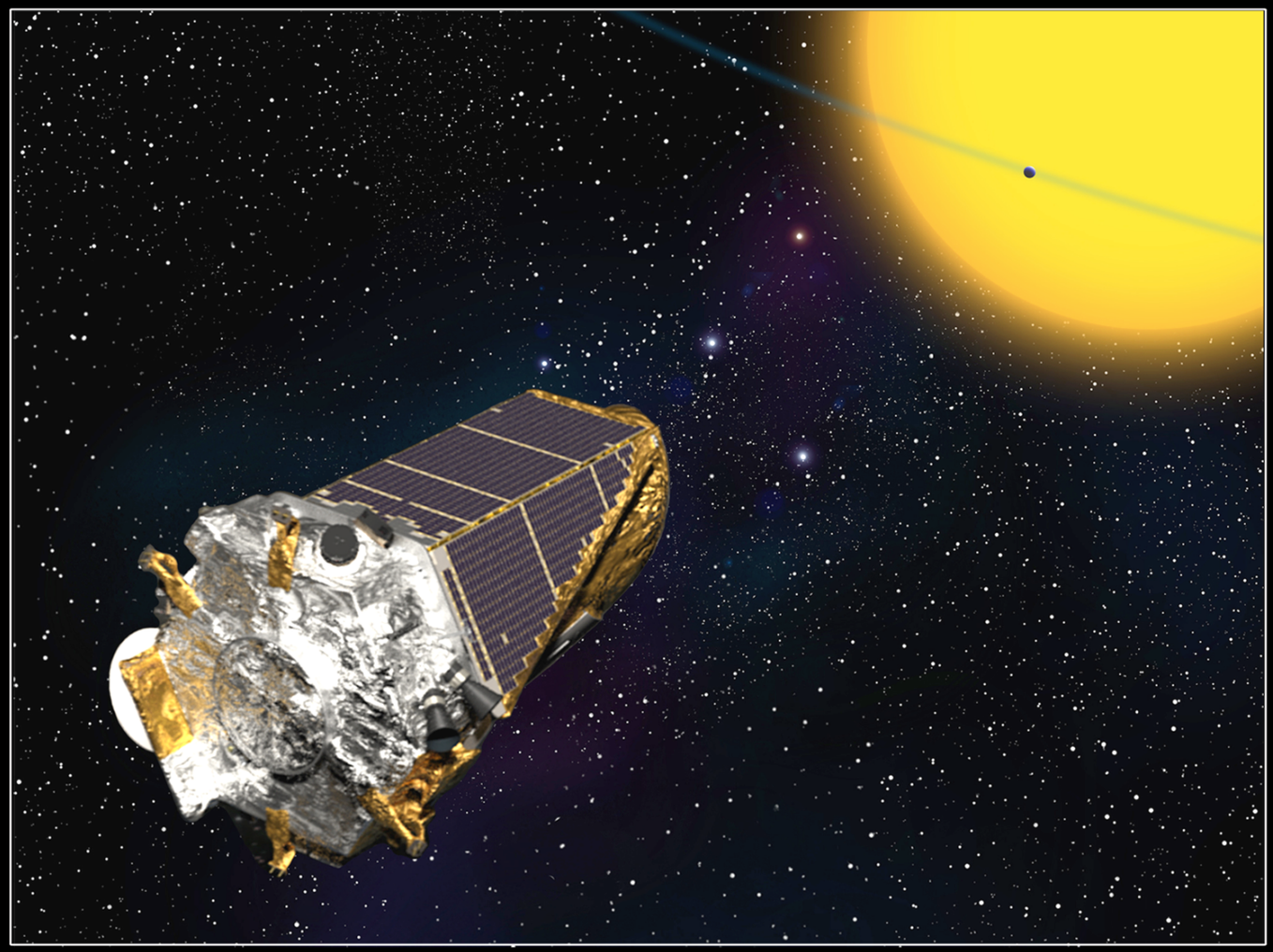
GJ 1214b - Atmospheric Transmission Specrum



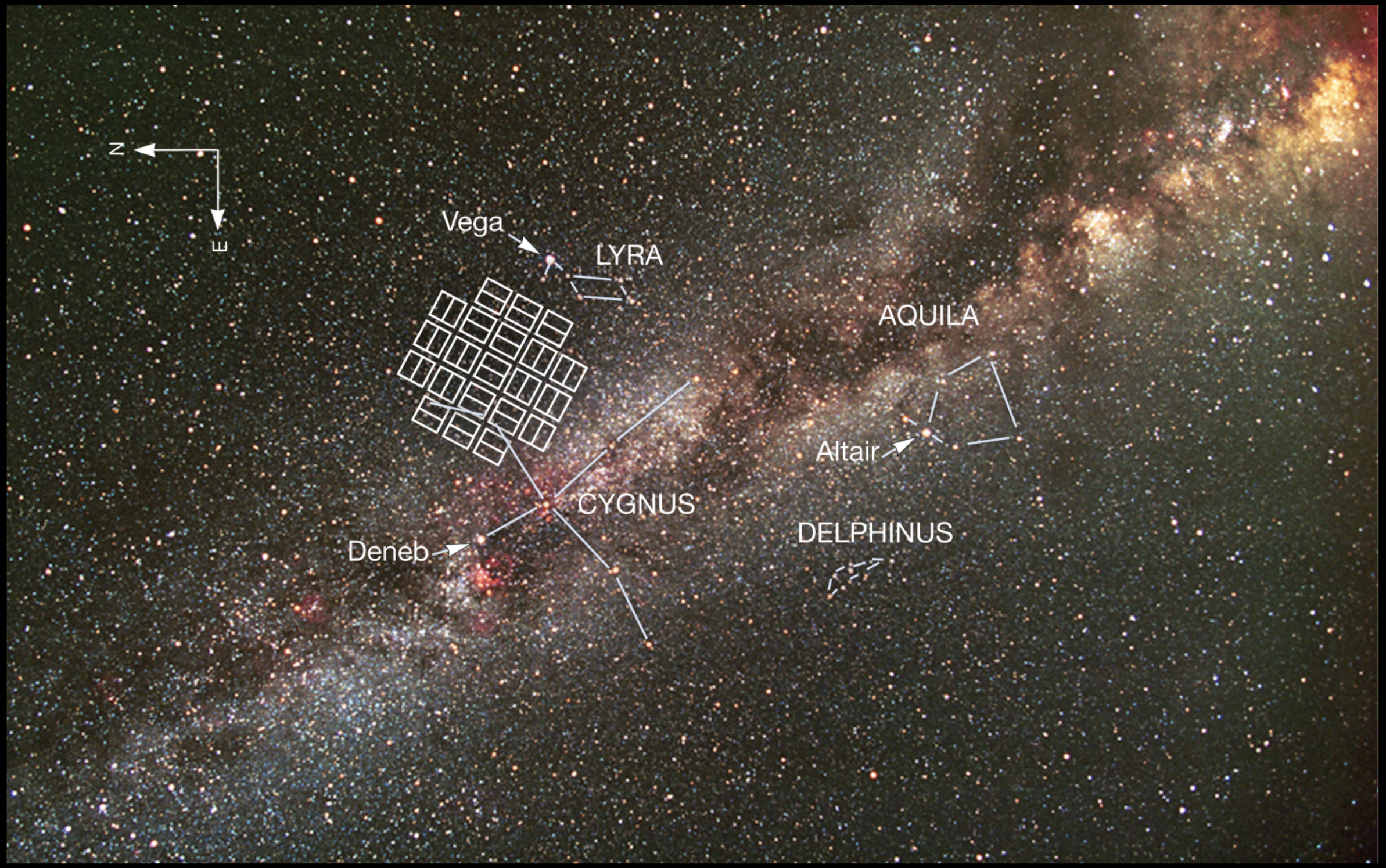
Berta et al. (2012)

NASA's Kepler Mission

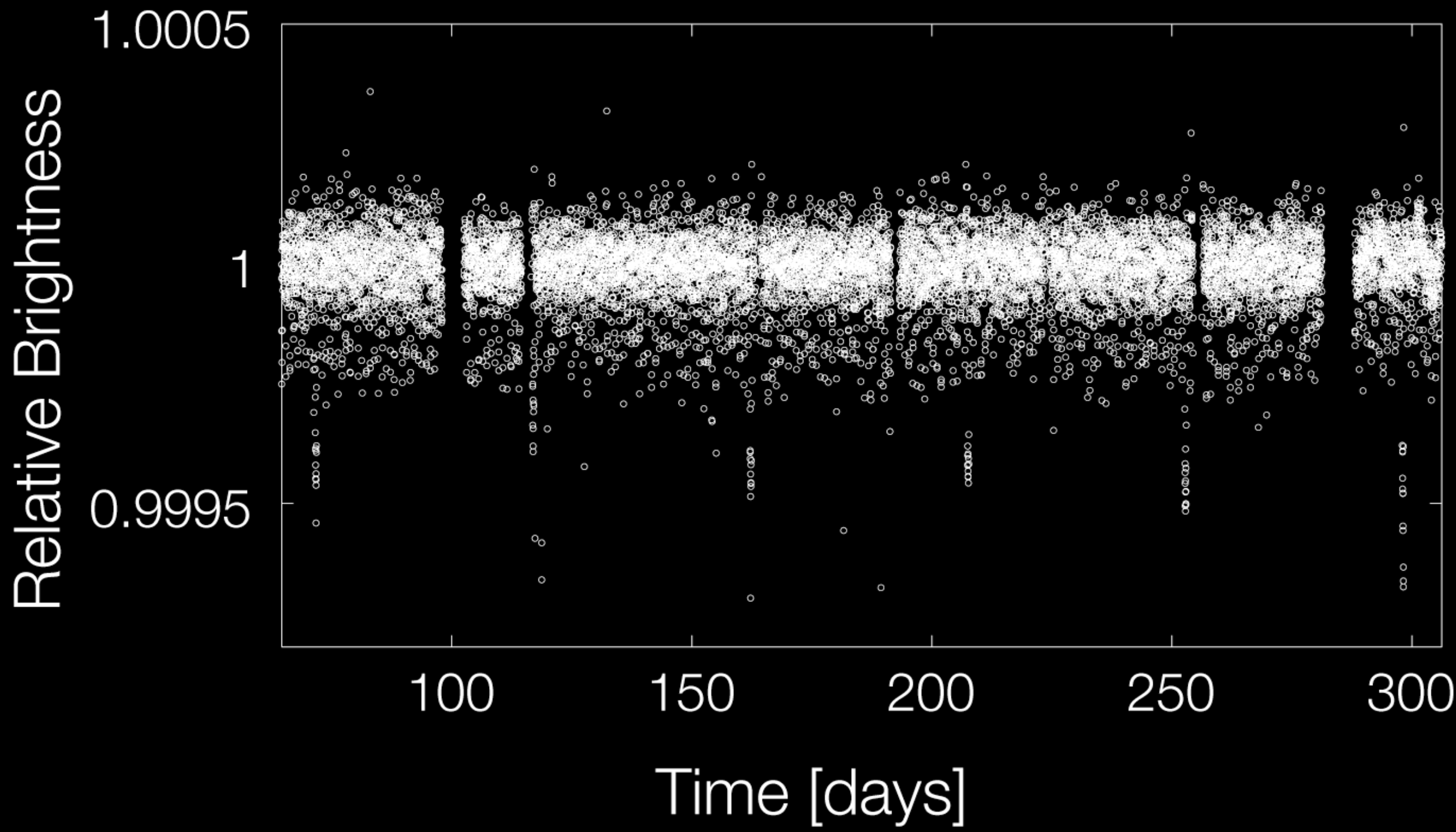
- Determine the frequency of Earth-size and larger planets in the habitable zone of sun-like stars
- Determine the size and orbital period distributions of planets



NASA's Kepler Mission

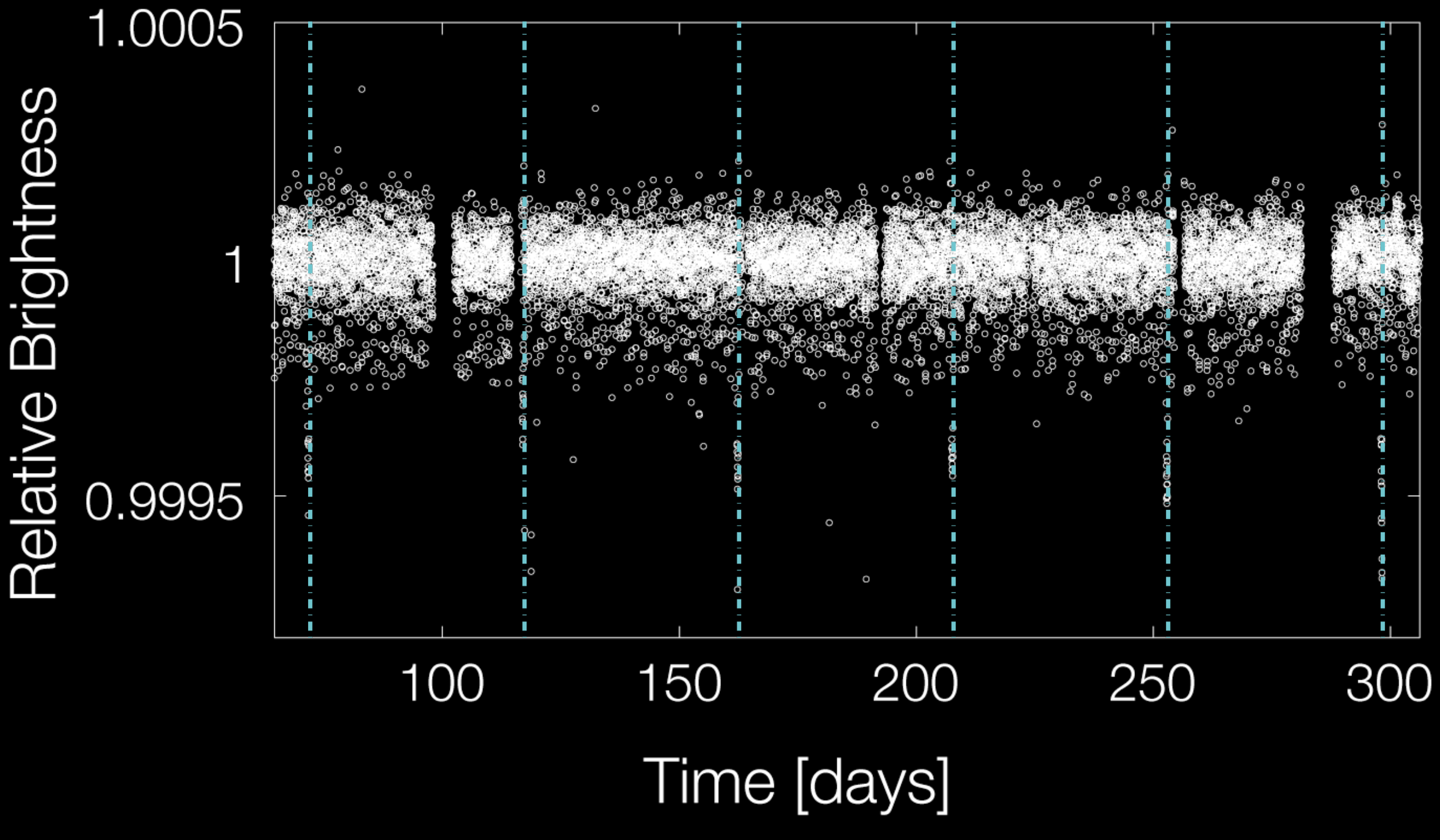


Kepler-10 Light Curve



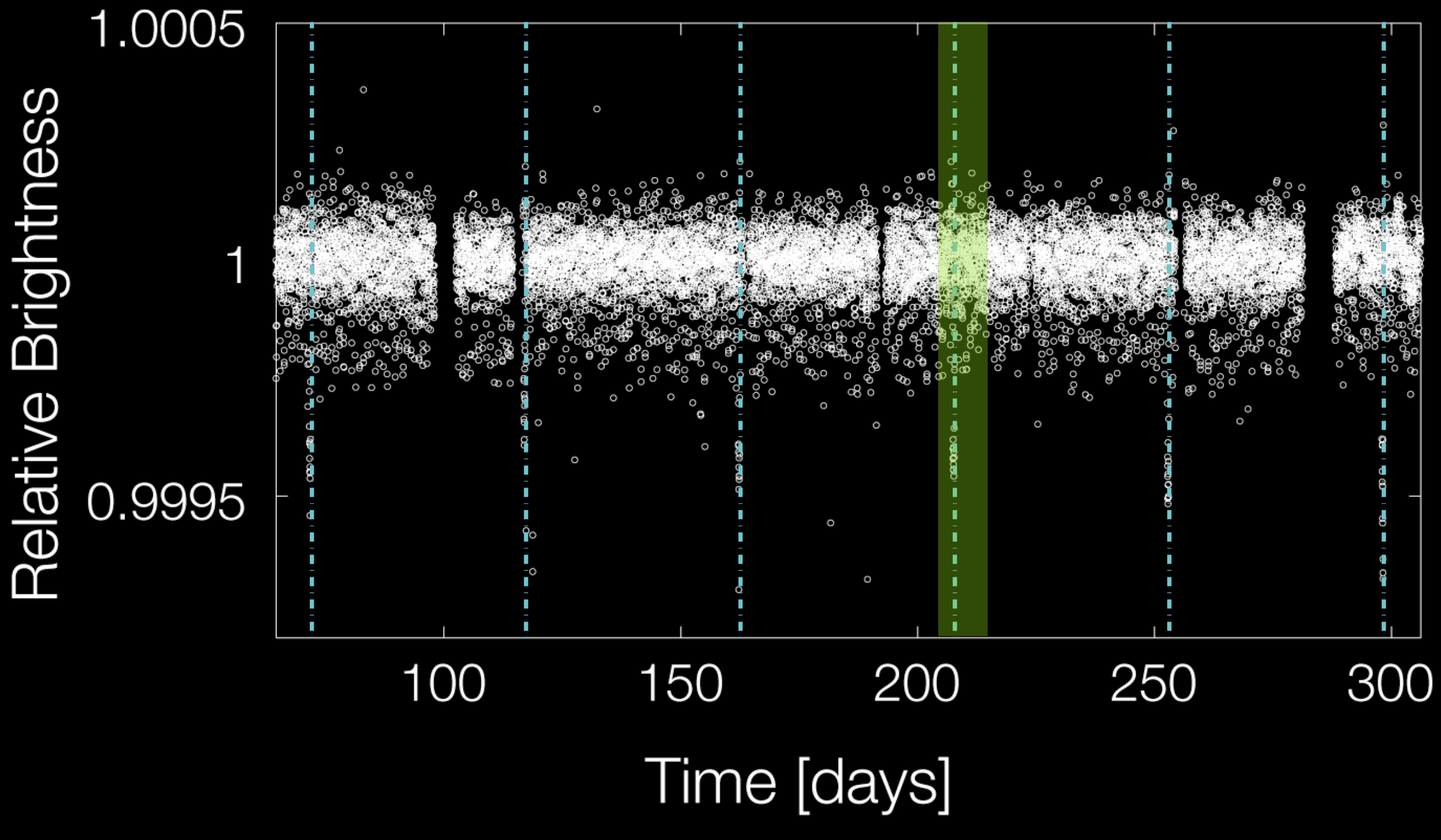
Kepler-10 Light Curve

Period = 45.29 days



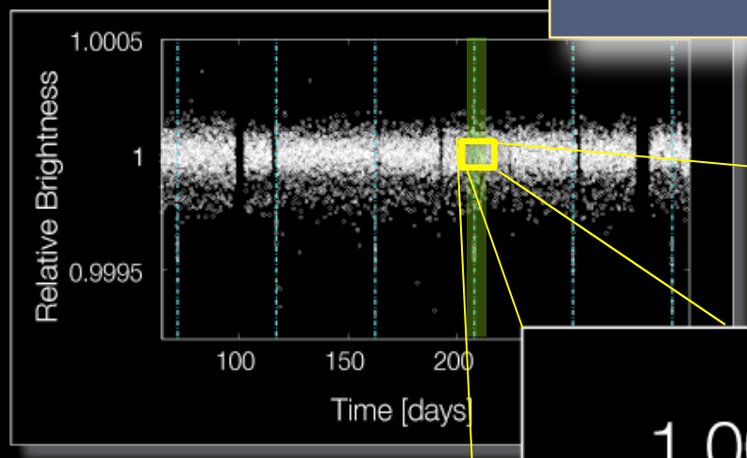
Kepler-10 Light Curve

Period = 45.29 days

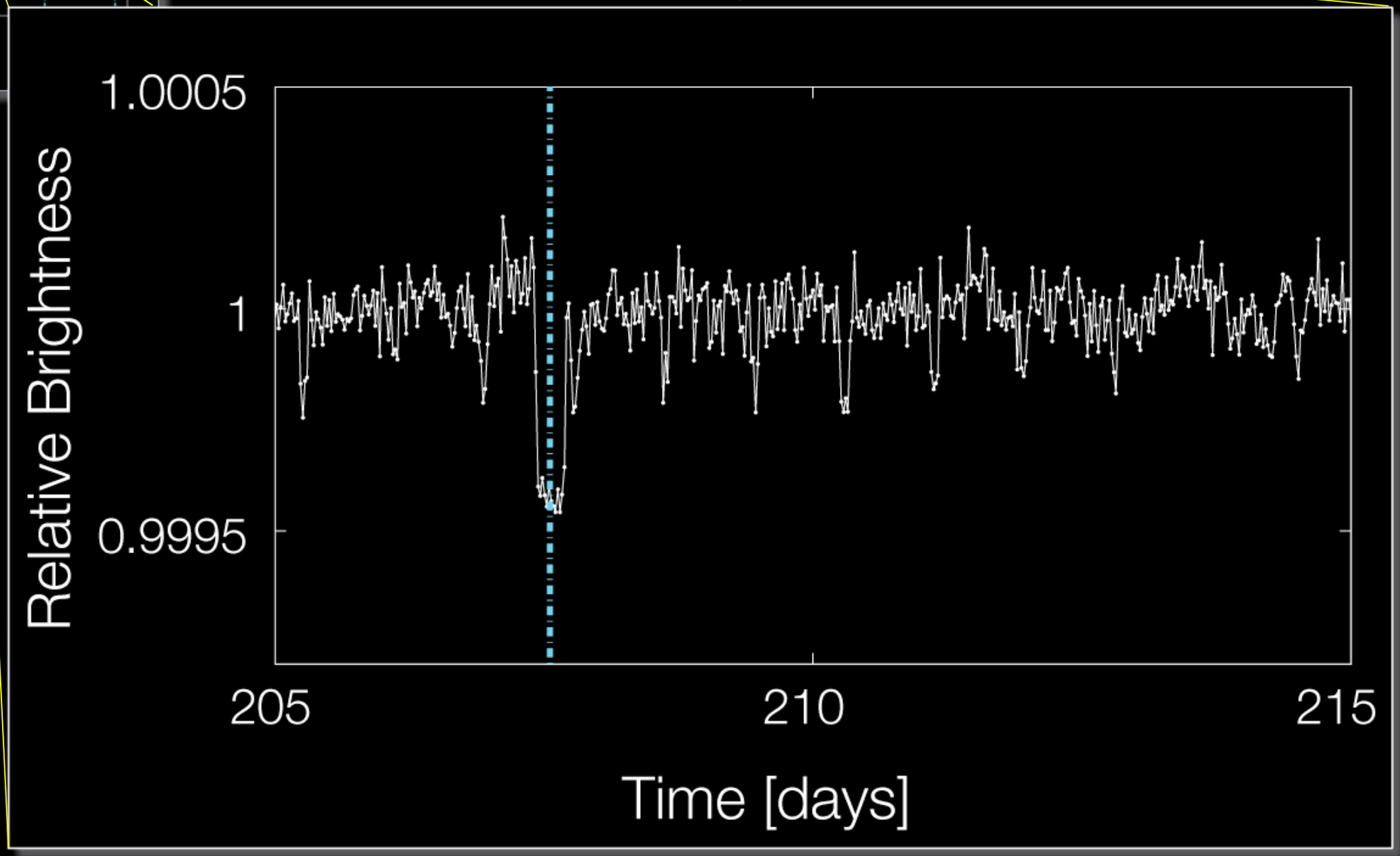


Kepler-10 Light Curve

Period = 45.29 days

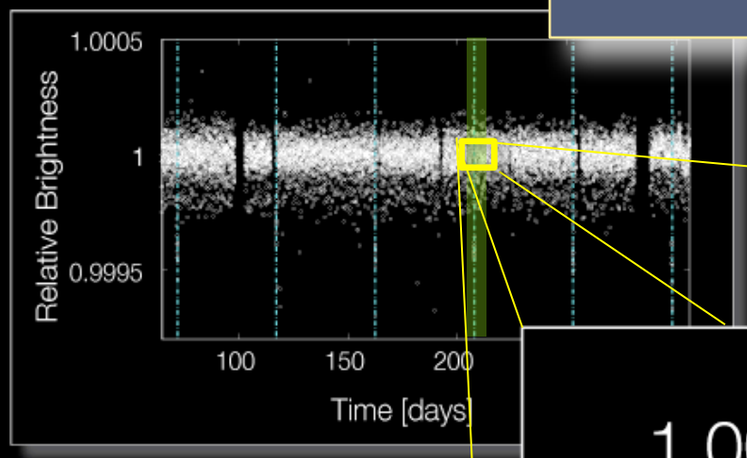


Period = 0.84 days

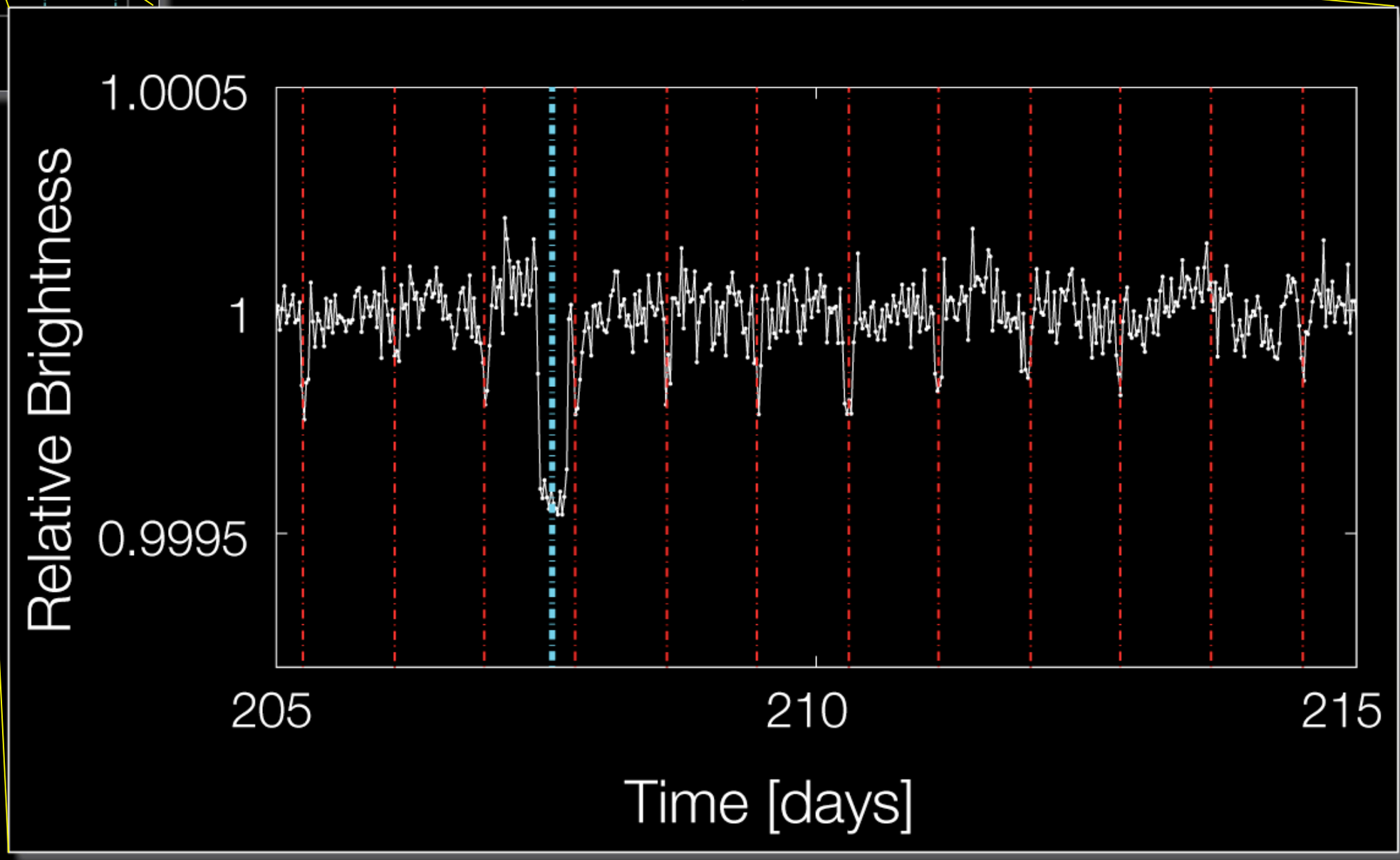


Kepler-10 Light Curve

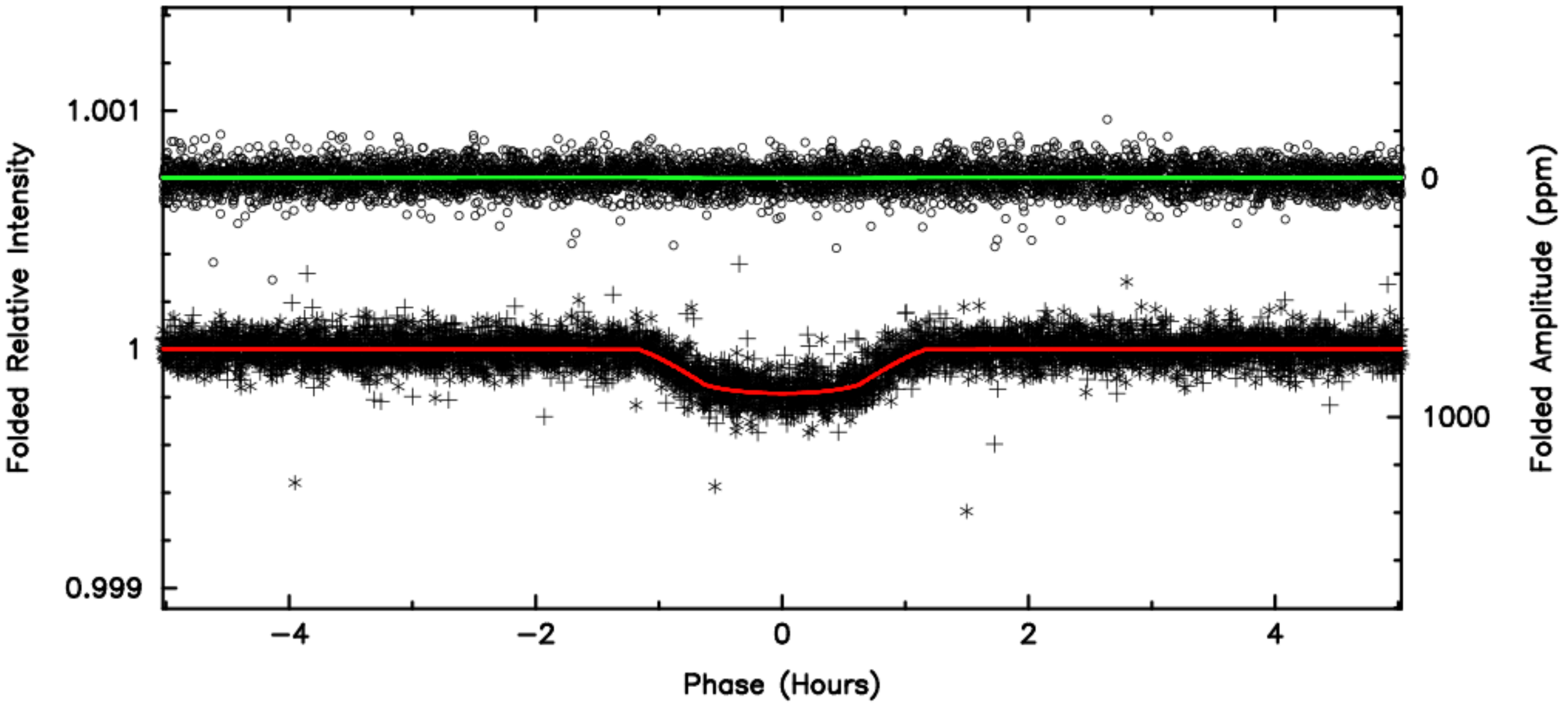
Period = 45.29 days



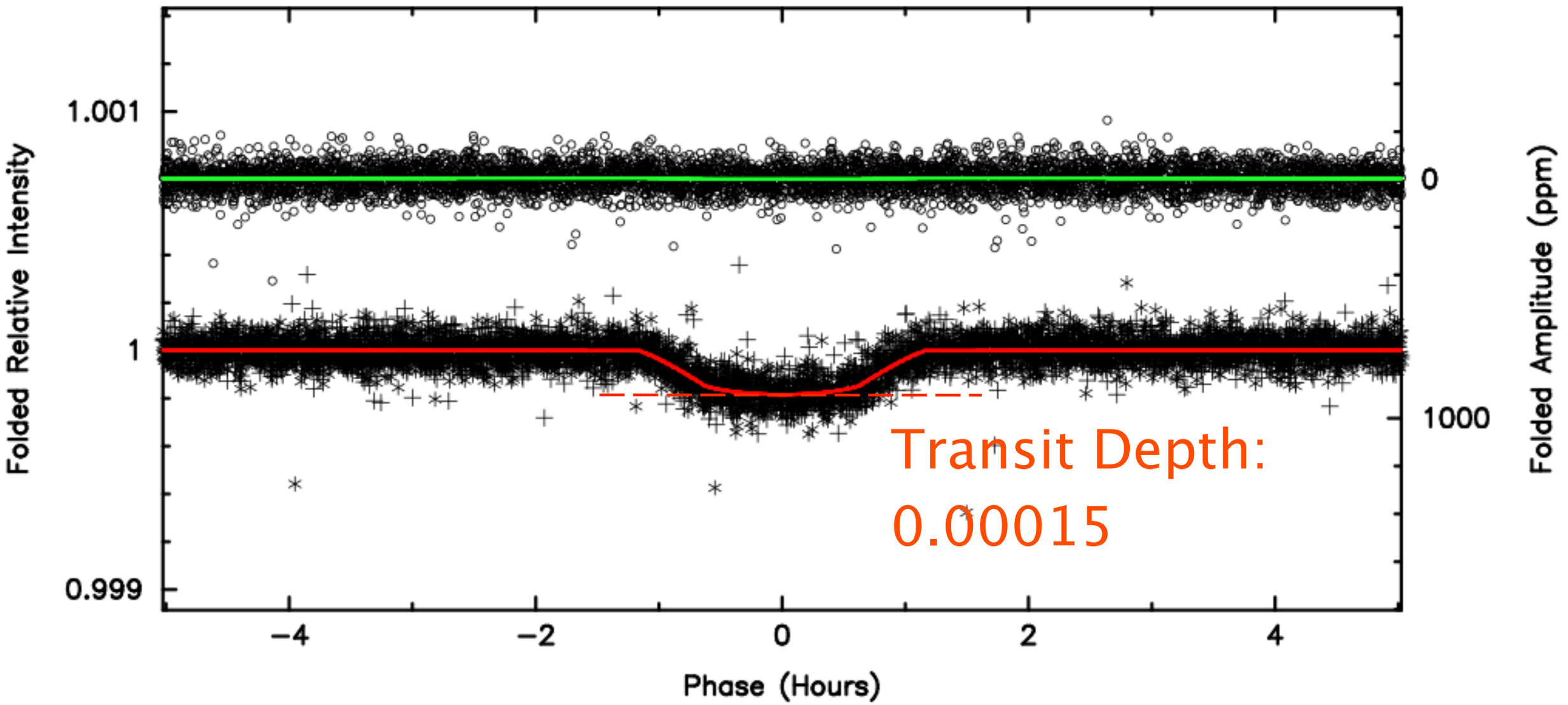
Period = 0.84 days



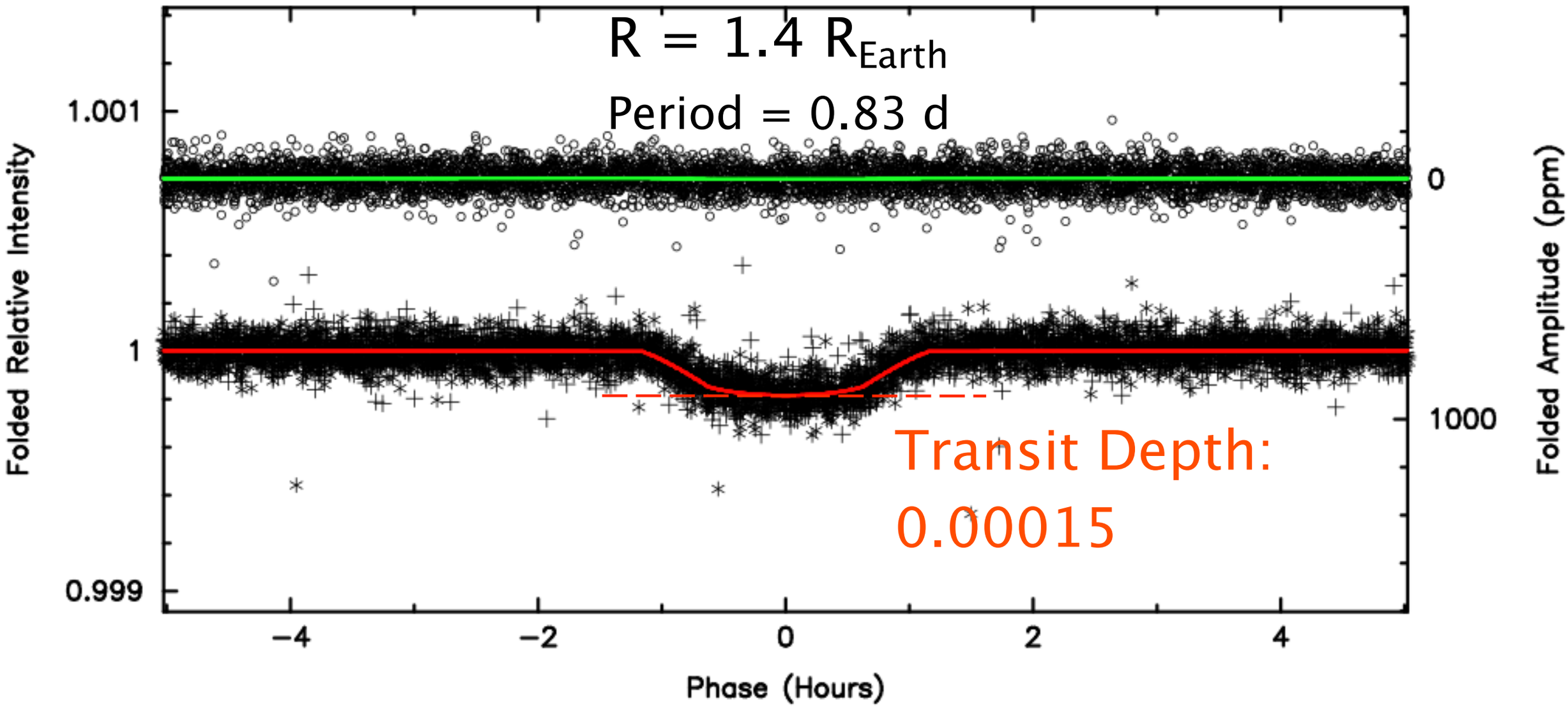
Kepler-10 Light Curve



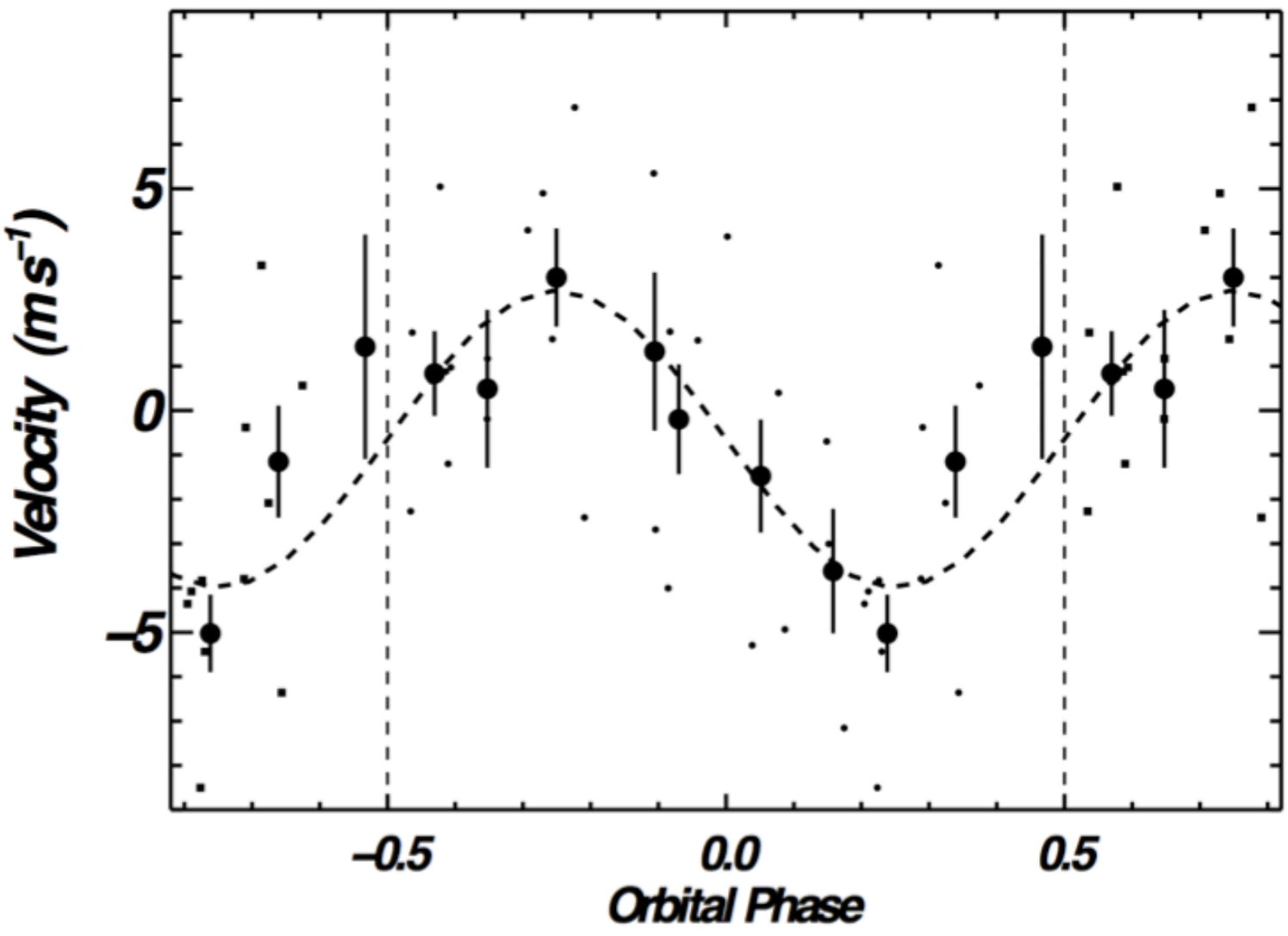
Kepler-10 Light Curve



Kepler-10 Light Curve



Kepler-10: Doppler Mass Measurement



Kepler-10b

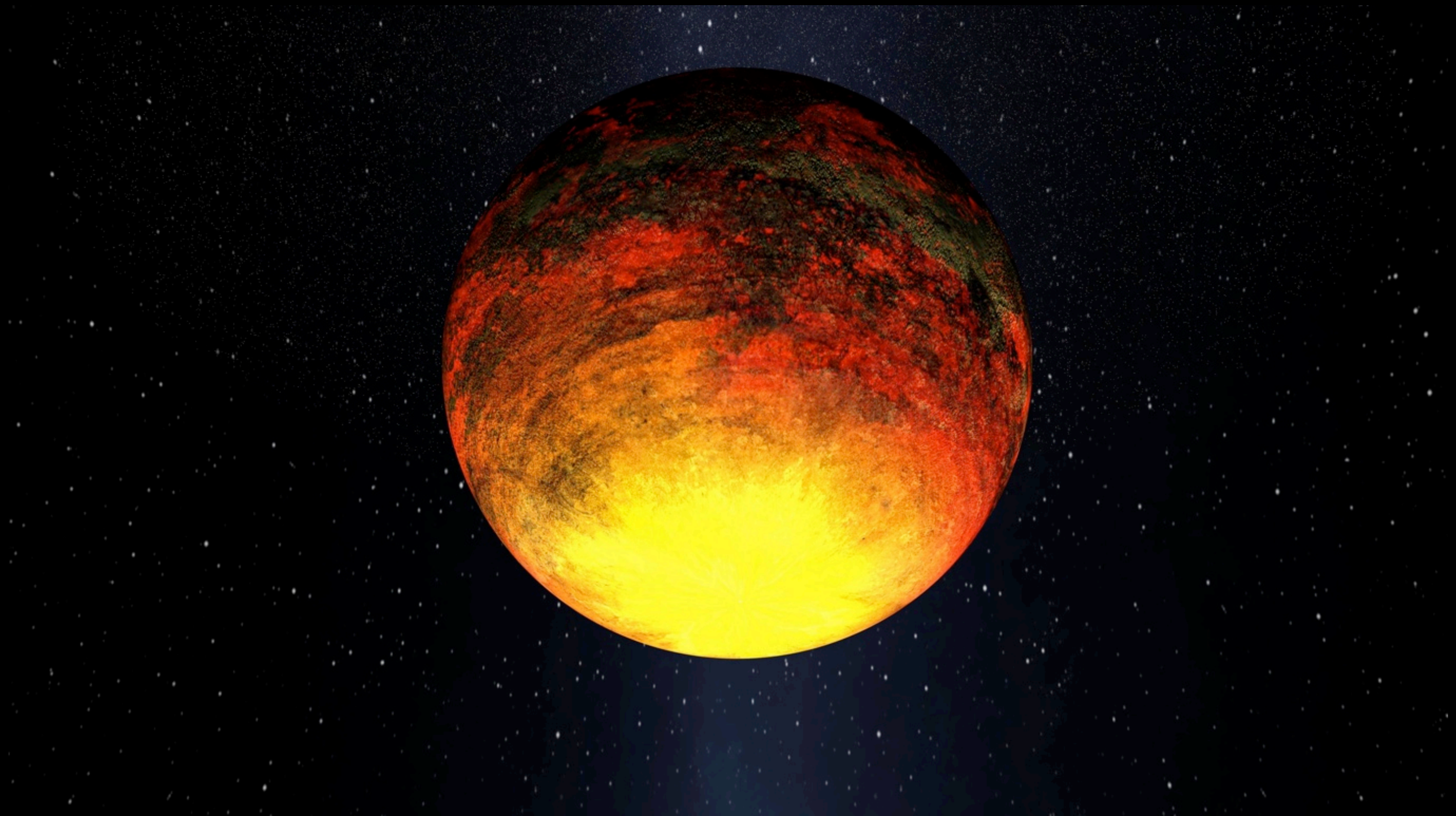
Mass = 4.6 M_{earth}

Radius = 1.4 R_{earth}

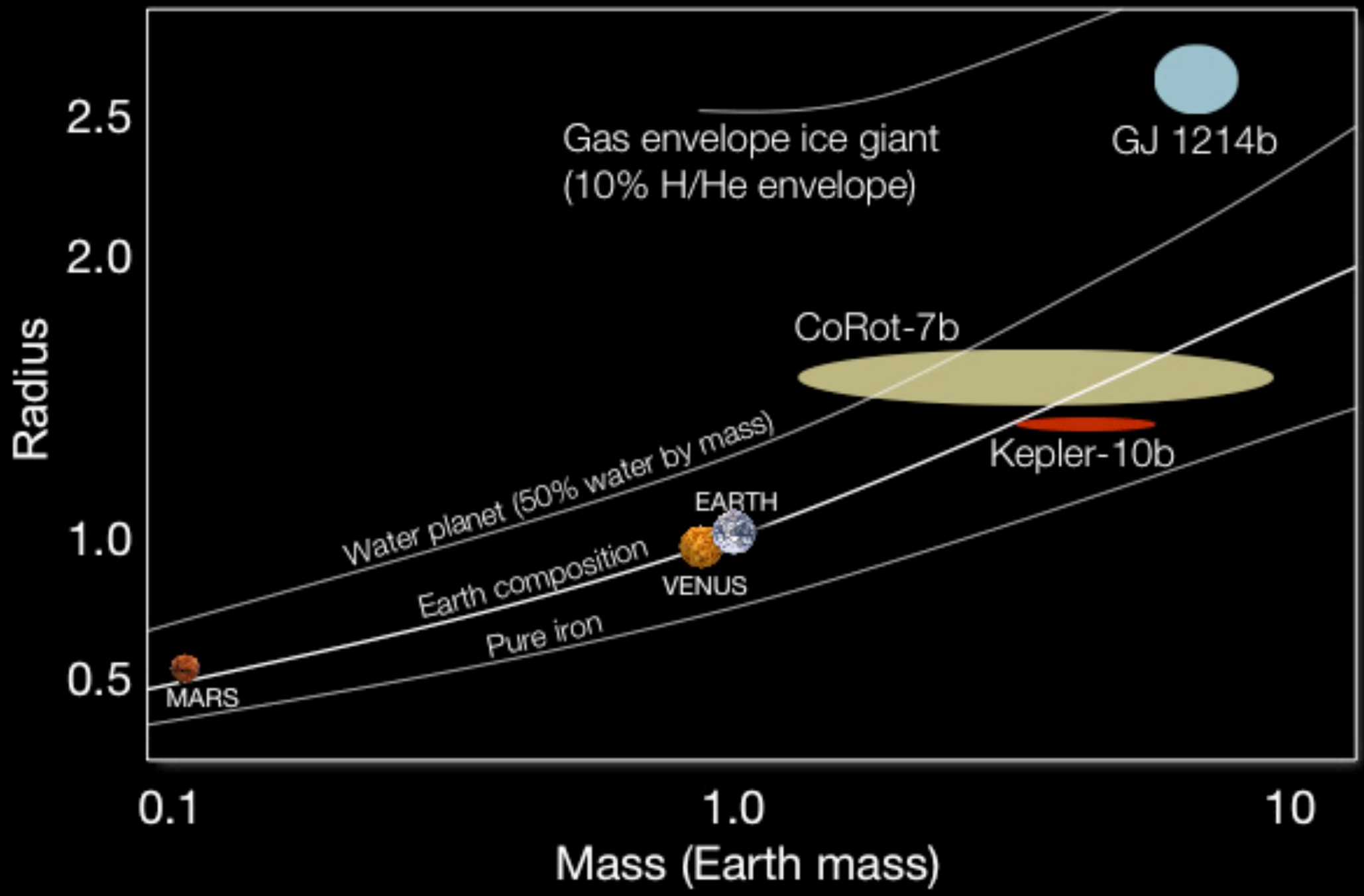
Density = 9 g cm^{-3}

Batalha et al. (2011)

Kepler-10

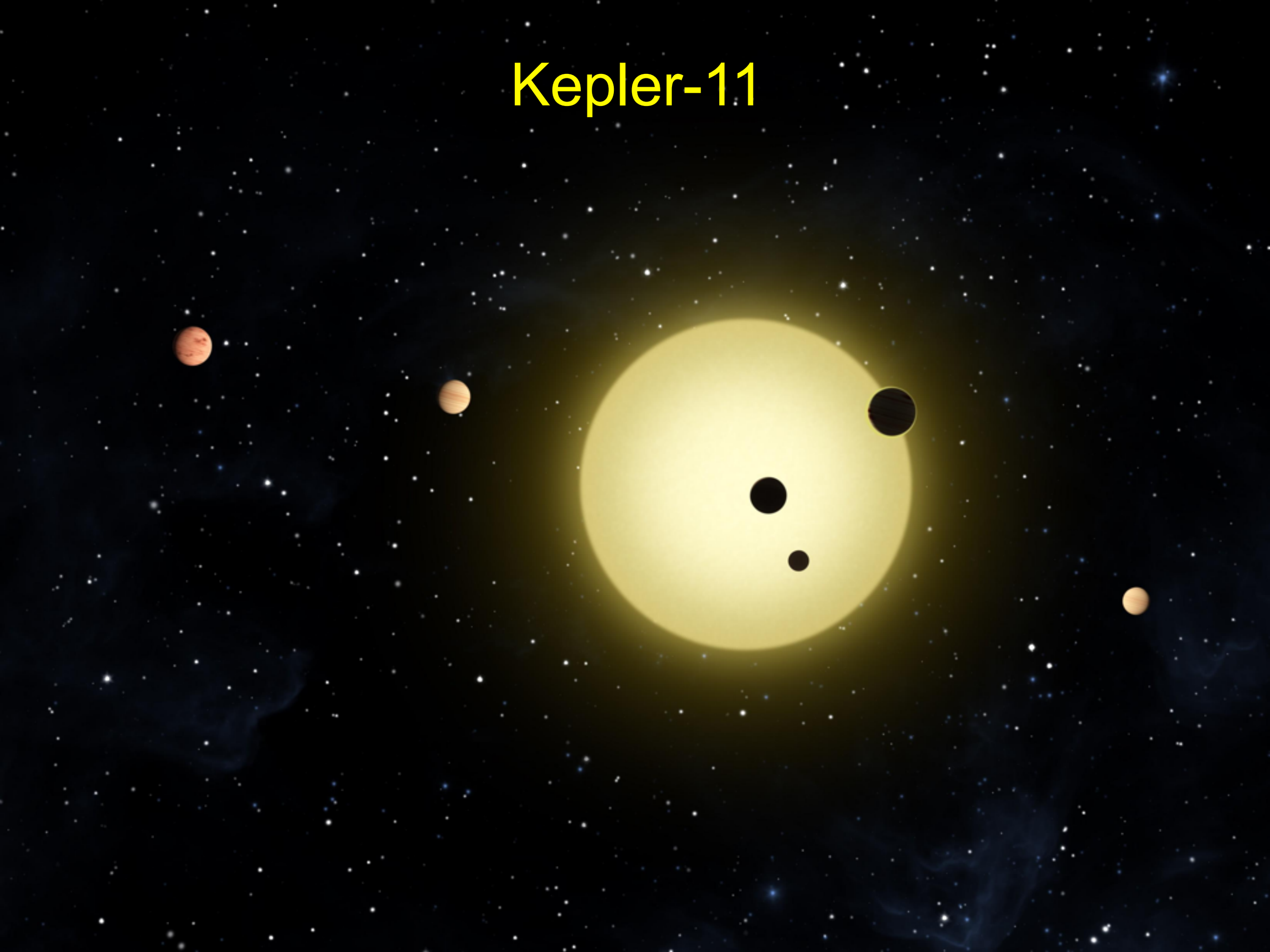


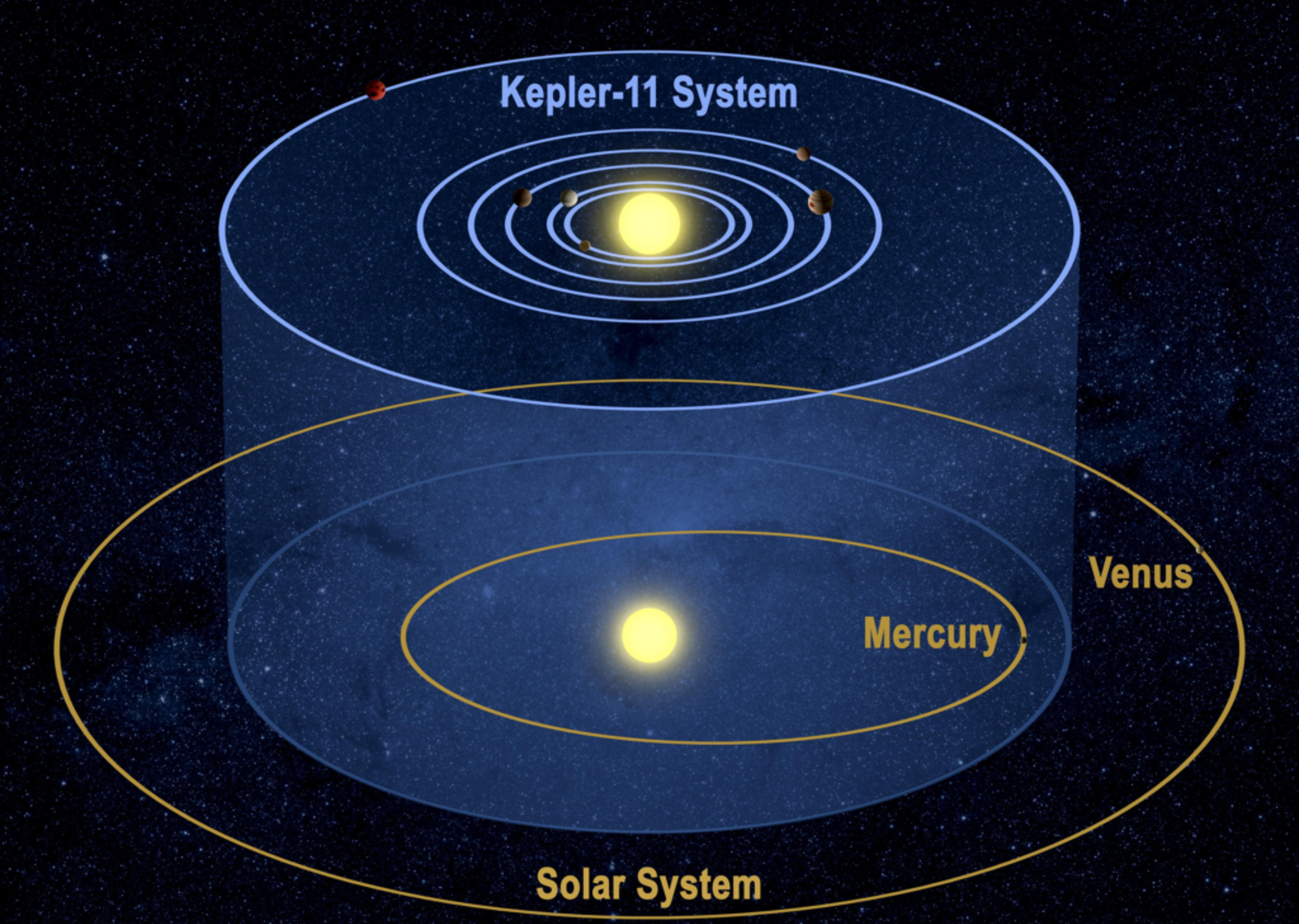
Composition of Kepler-10b



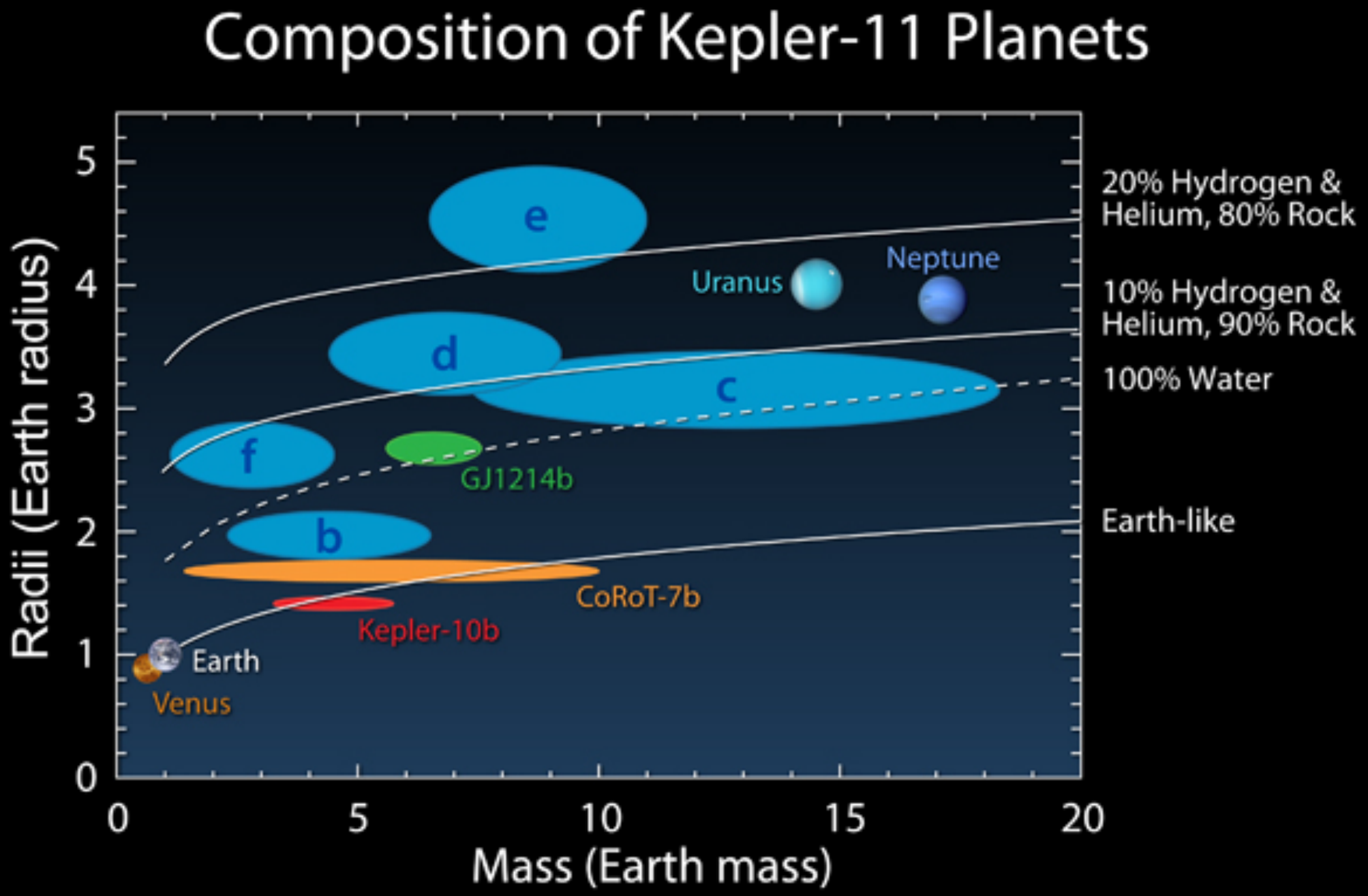
Batalha et al. (2011)

Kepler-11

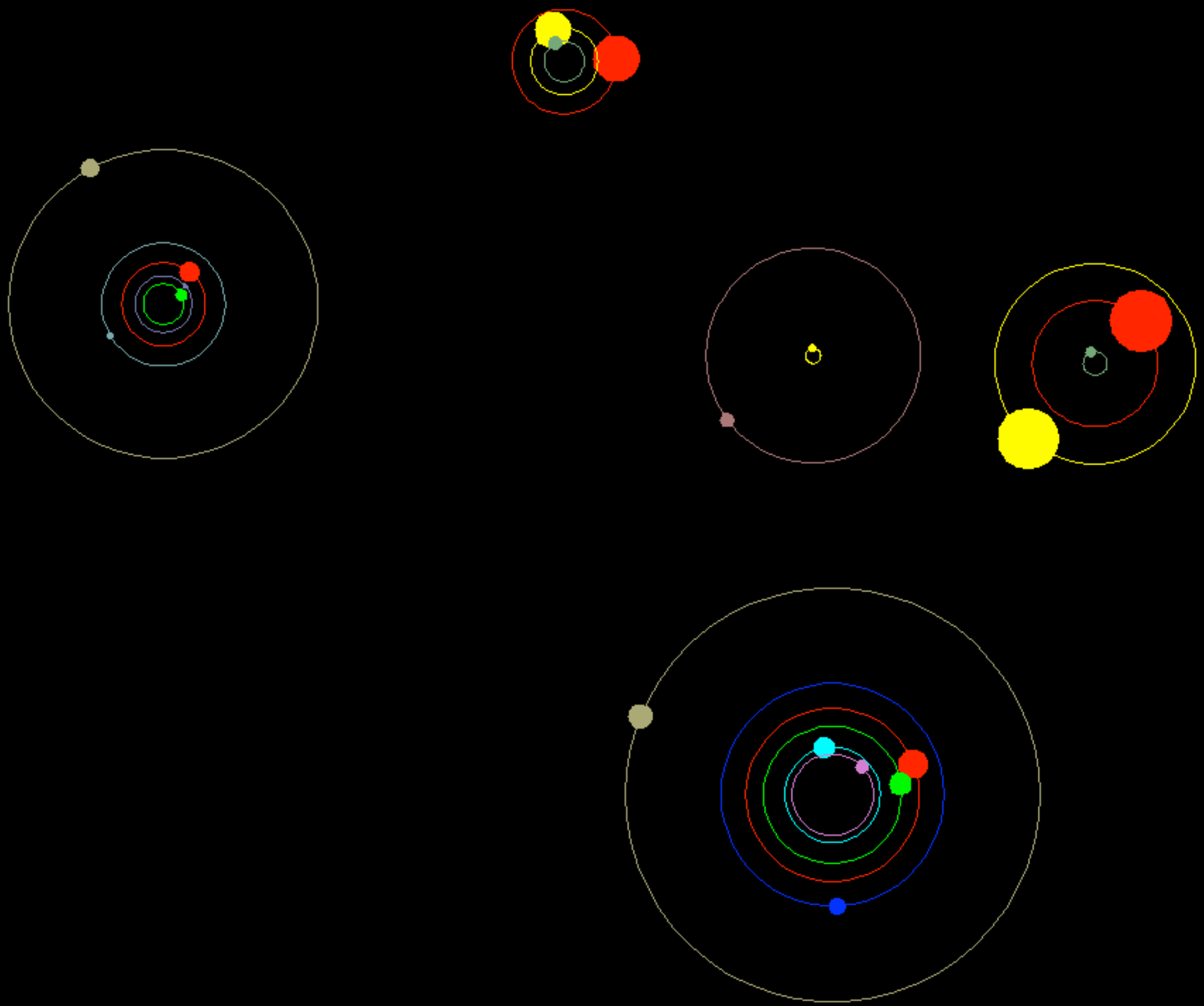



Kepler-11 System
Venus
Mercury
Solar System

Kepler-11


Composition of Kepler-11 Planets
Radii (Earth radius)
Mass (Earth mass)
0
1
2
3
4
5
0
5
10
15
20
e
d
c
f
b
GJ1214b
CoRoT-7b
Kepler-10b
Uranus
Neptune
Earth
Venus
20% Hydrogen & Helium, 80% Rock
10% Hydrogen & Helium, 90% Rock
100% Water
Earth-like

Dynamically Interacting Multi-transiting Systems



Kepler-22 System

Habitable Zone

Solar System

Kepler-22b

Mercury

Venus

Earth

Mars

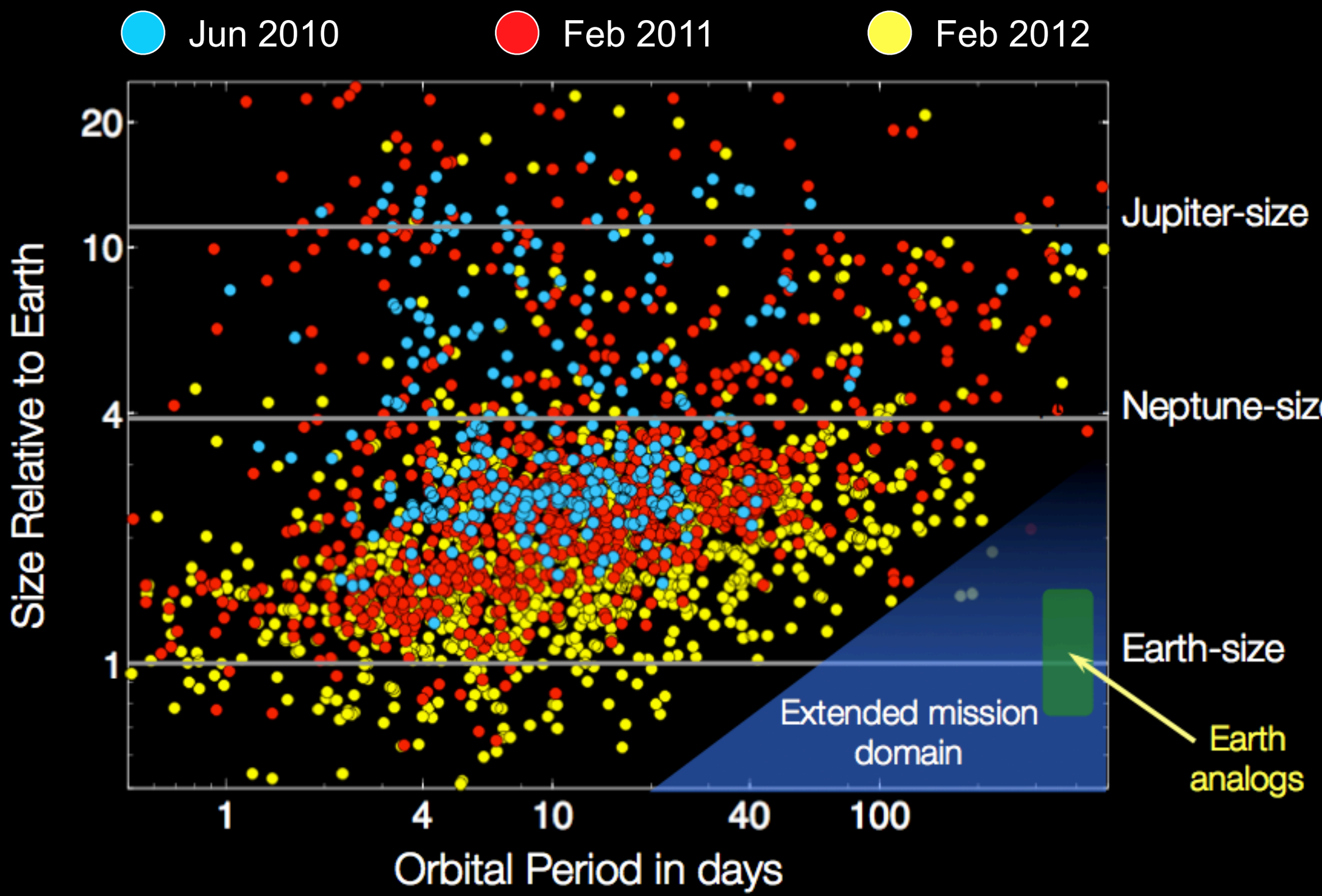
Planets and orbits to scale

Earth-size and Mars-size Planets

Mars | KOI-961.03 | KOI-961.02 | KOI-961.01 | Kepler-20e | Earth | Kepler-20f

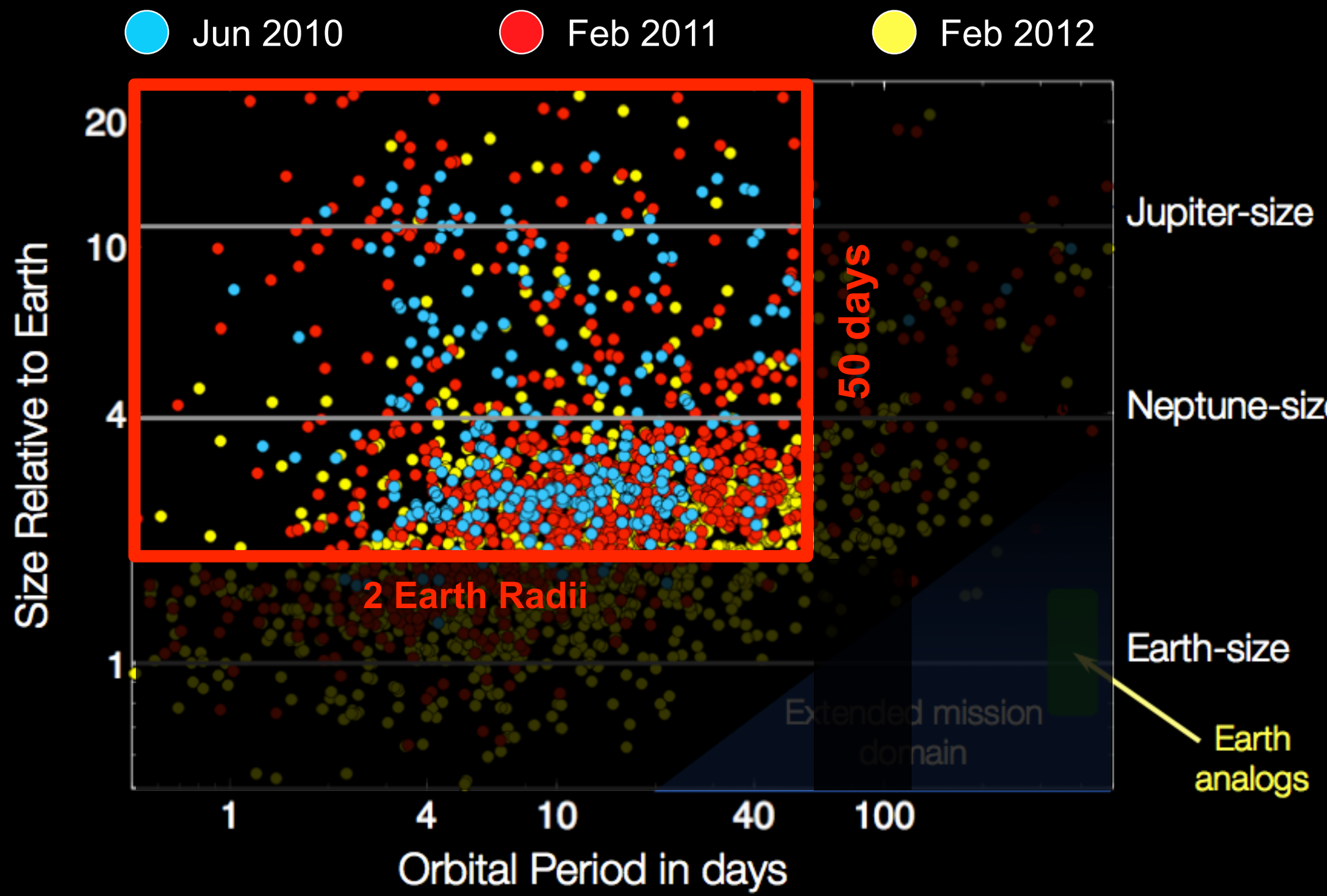
Johnson et al. (2012); Fressin et al. (2012)

2300 Planet Candidates as of Feb 2012



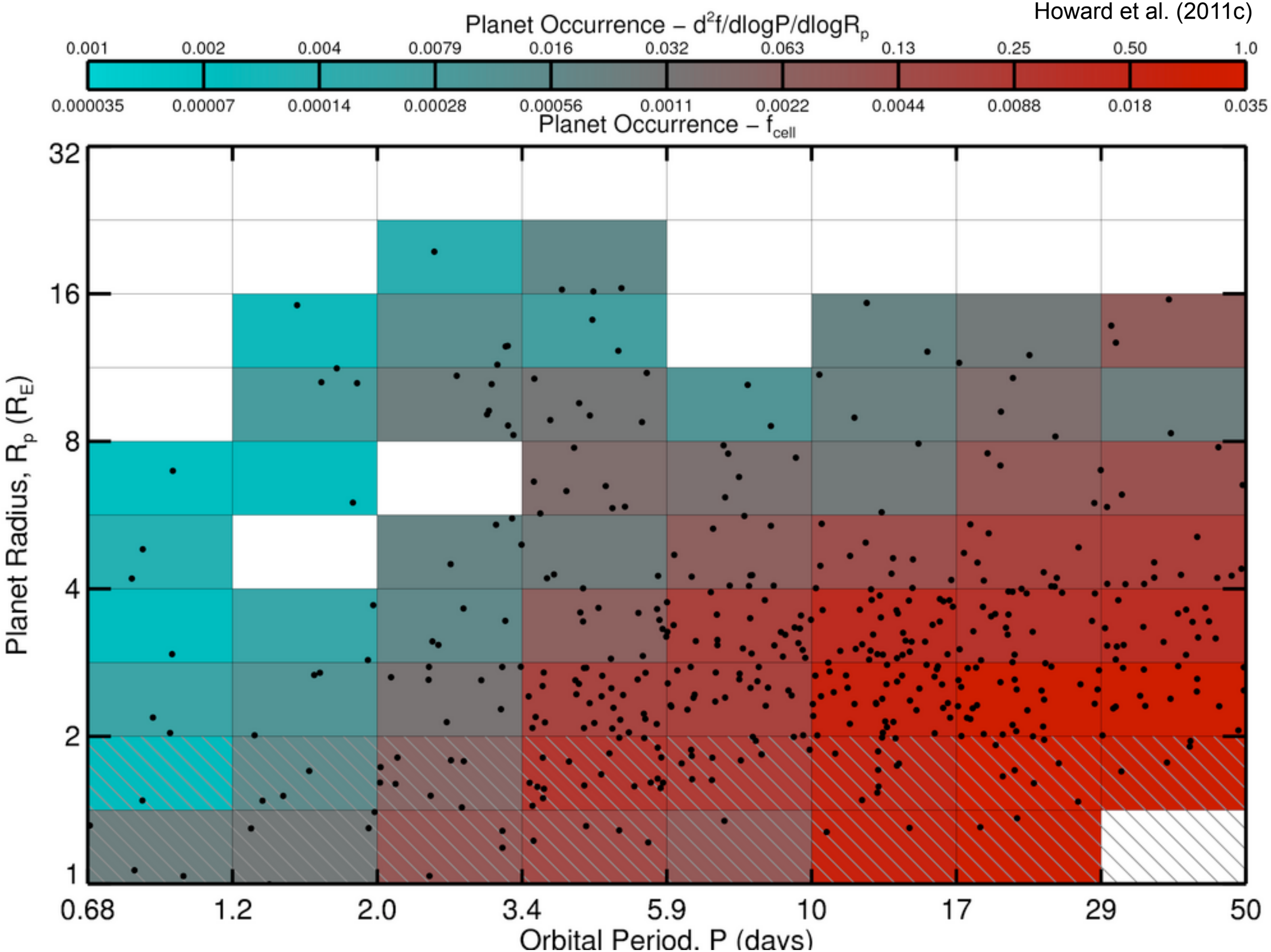
95% True planets - Morton and Johnson (2011)

2300 Planet Candidates as of Feb 2012



95% True planets - Morton and Johnson (2011)

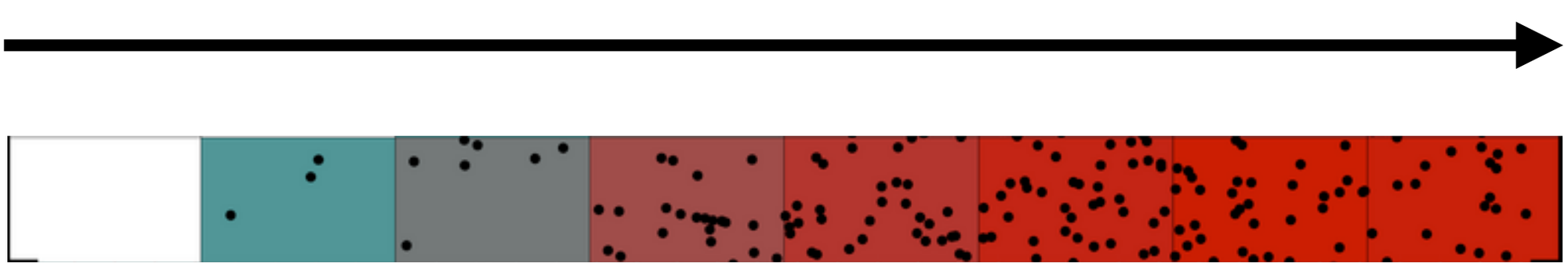
Howard et al. (2011c)



Howard et al. (2011c)

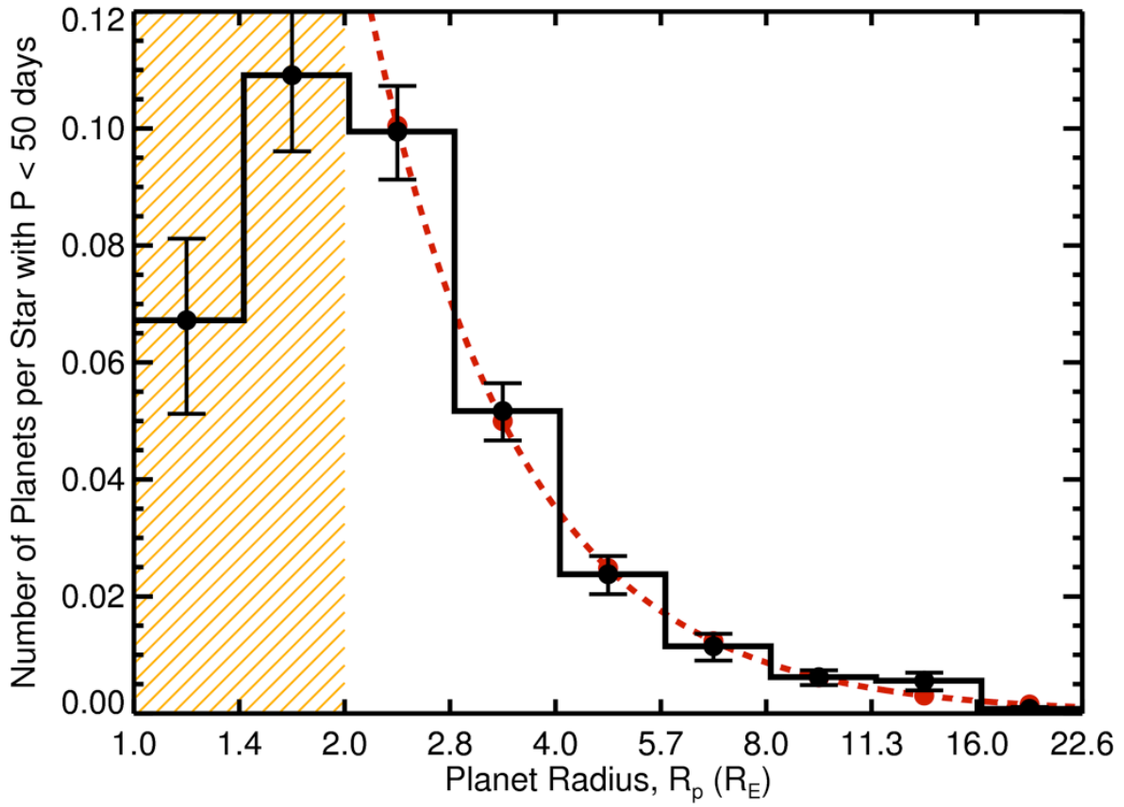
Compute Occurrence vs. Planet Radius

Sum *Occurrence*
for all Periods
in R + ΔR



Planet Radius Distribution
Kepler

Howard et al. 2011c, ApJ submitted, arXiv:1103.2541



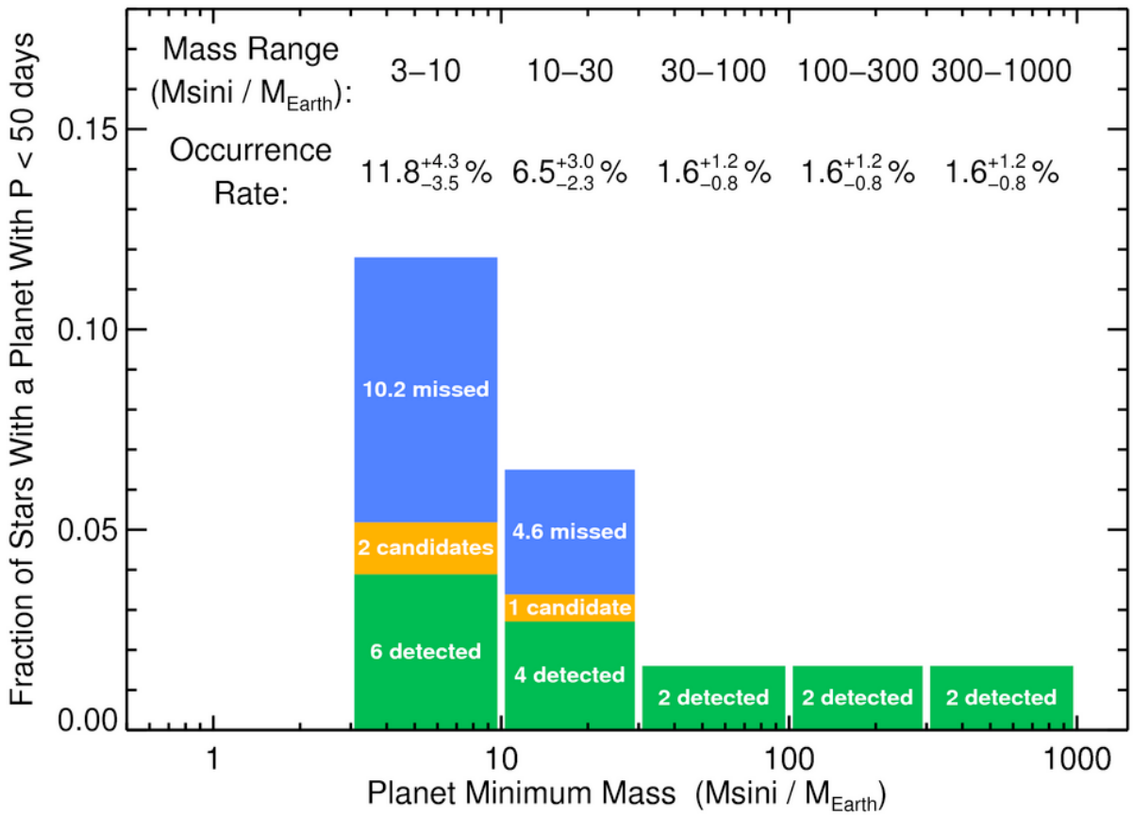
Power Law Radius Function

$df/d\log R = kR^{\alpha}$

$k = 2.9 \pm 0.5$, $\alpha = -1.92 \pm 0.11$

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

Howard et al. 2010, Science, 33, 653



Power Law Mass Function

$df/d\log M = kM^{\alpha}$

$k = 0.39^{+0.27}_{-0.16}$, $\alpha = -0.48^{+0.12}_{-0.14}$

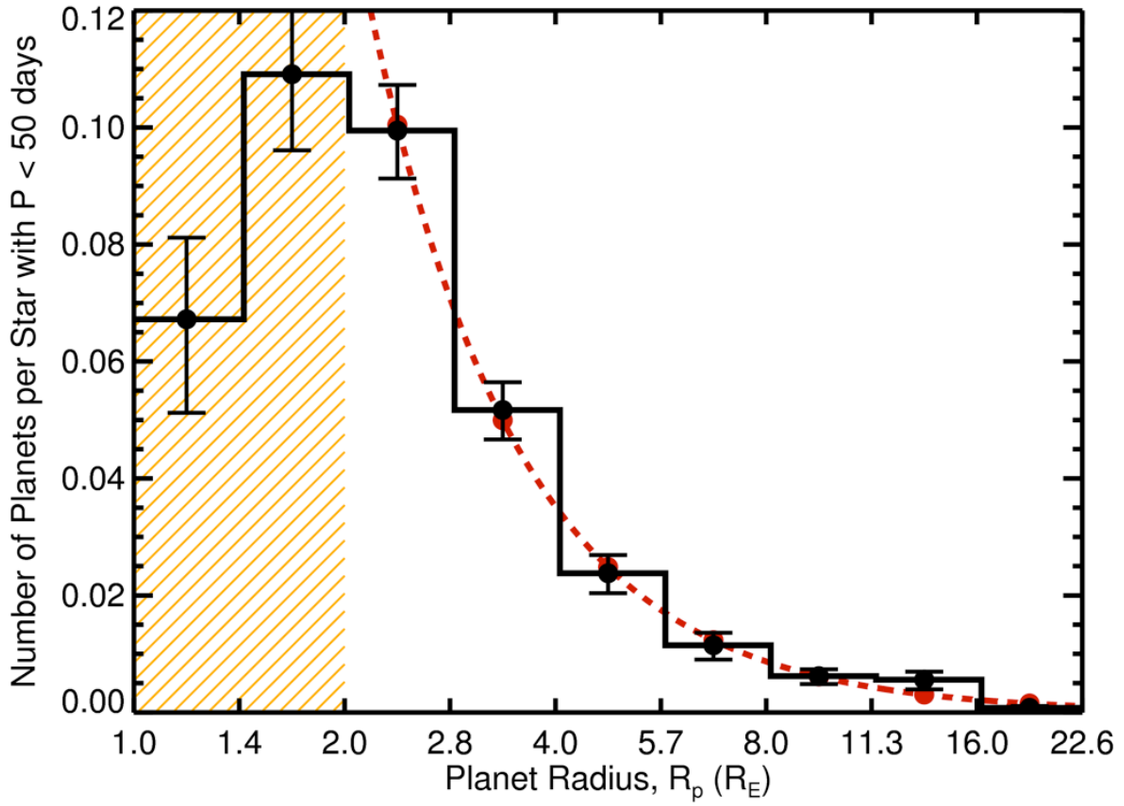
Extrapolate:

$\eta_{\oplus} = 23^{+16}_{-10}\%$

$M\sin i = 0.5\text{-}2.0\ M_E$, $P < 50$ days

Planet Radius Distribution
Kepler

Howard et al. 2011c, ApJ submitted, arXiv:1103.2541



Power Law Radius Function

$df/d\log R = kR^{\alpha}$

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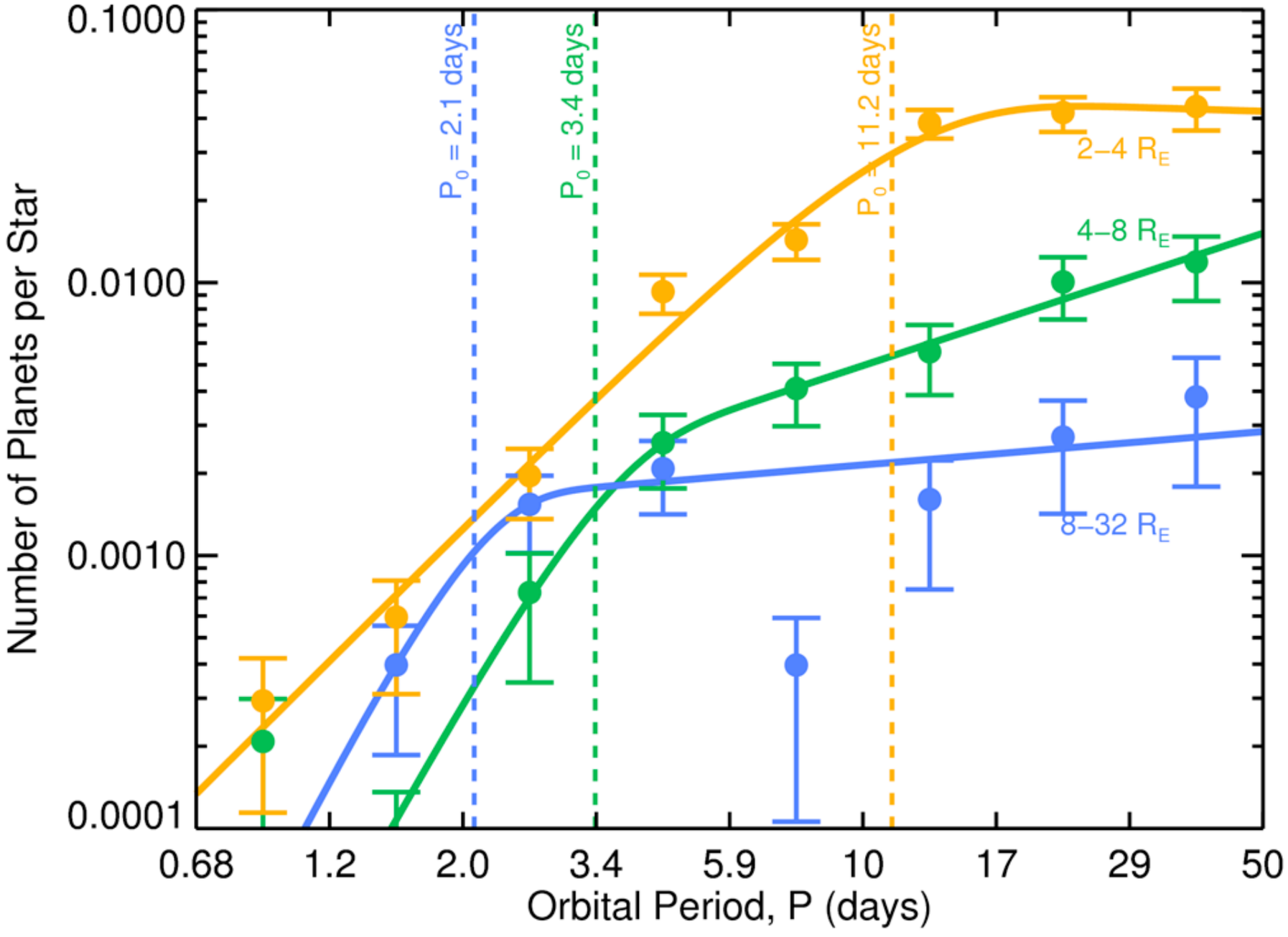
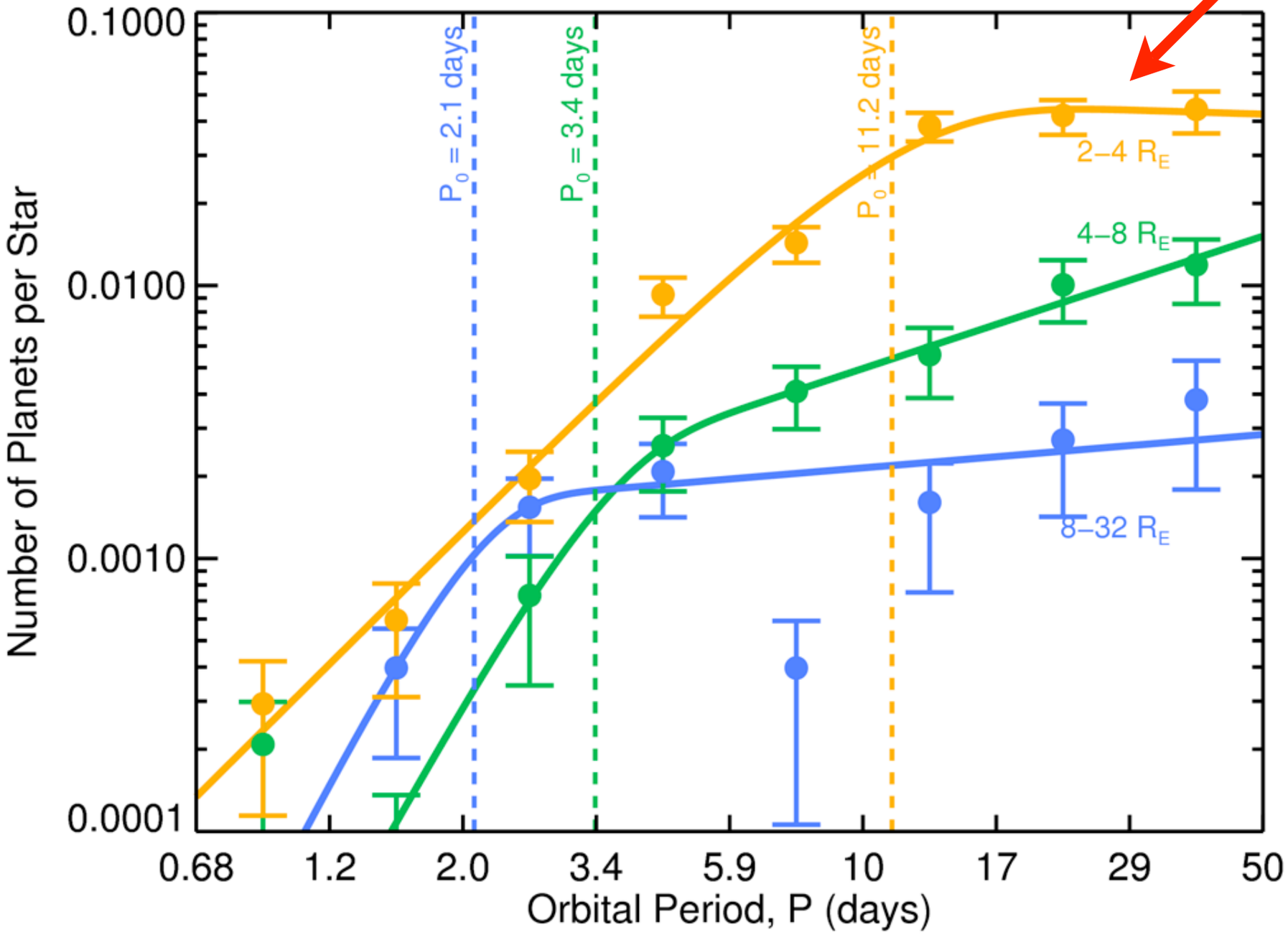
Howard et al. (2011c)

Planet Period Distribution



Howard et al. (2011c)

Power Law

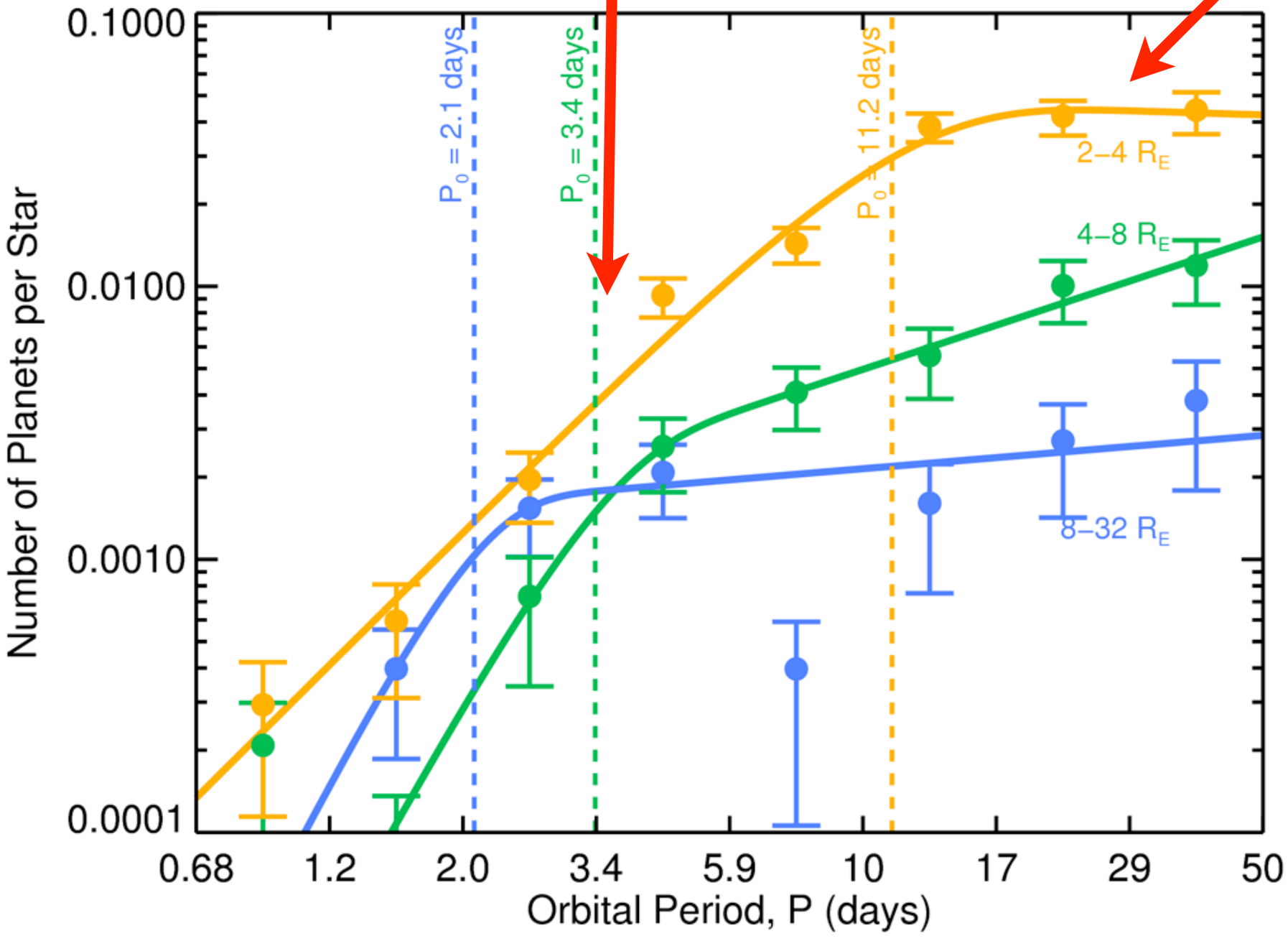


Increasing
Planet Occurrence
per log *P* bin

Howard et al. (2011c)

Exponential Cutoff

Power Law

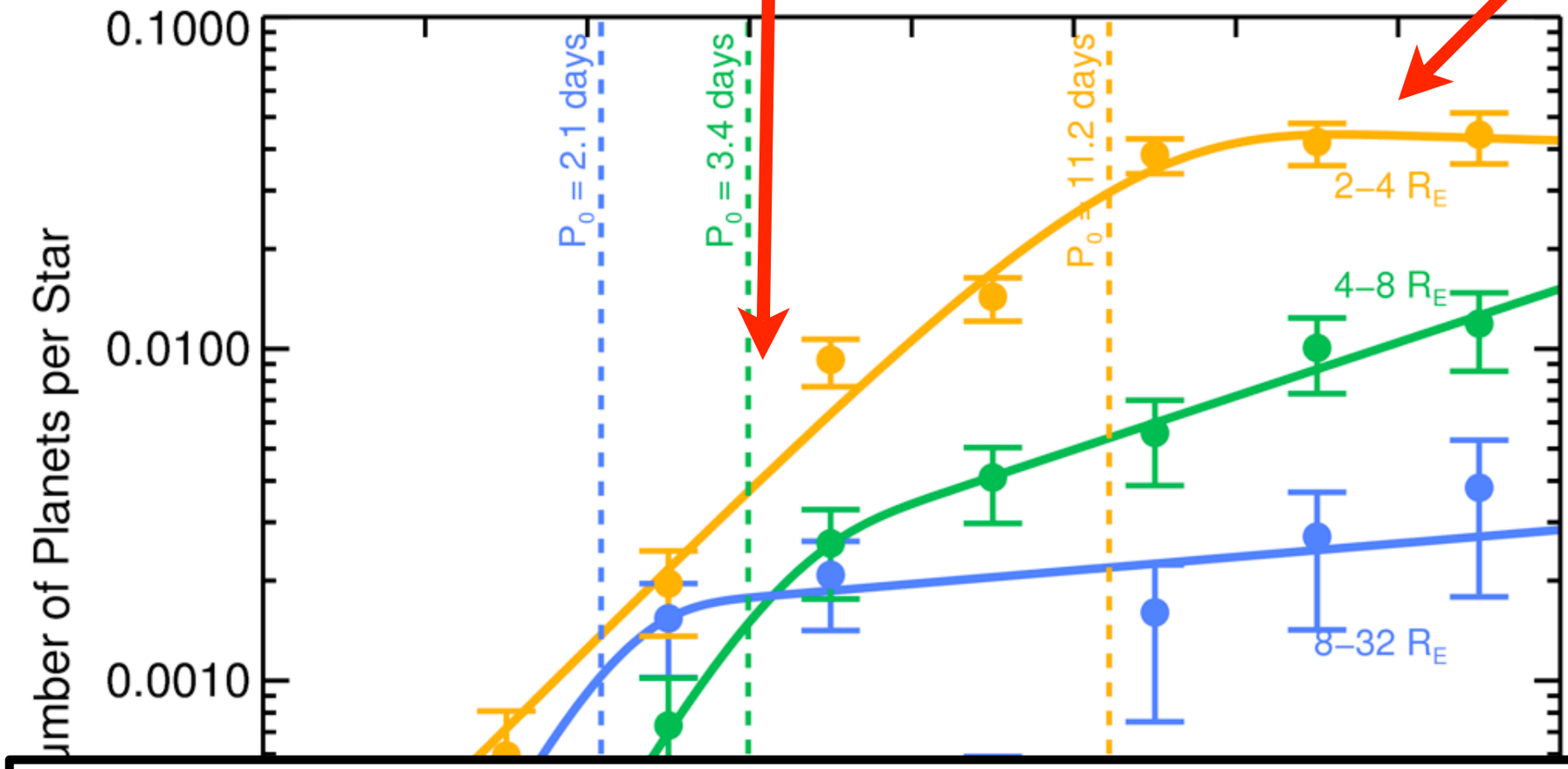


Increasing
Planet Occurrence
per log *P* bin

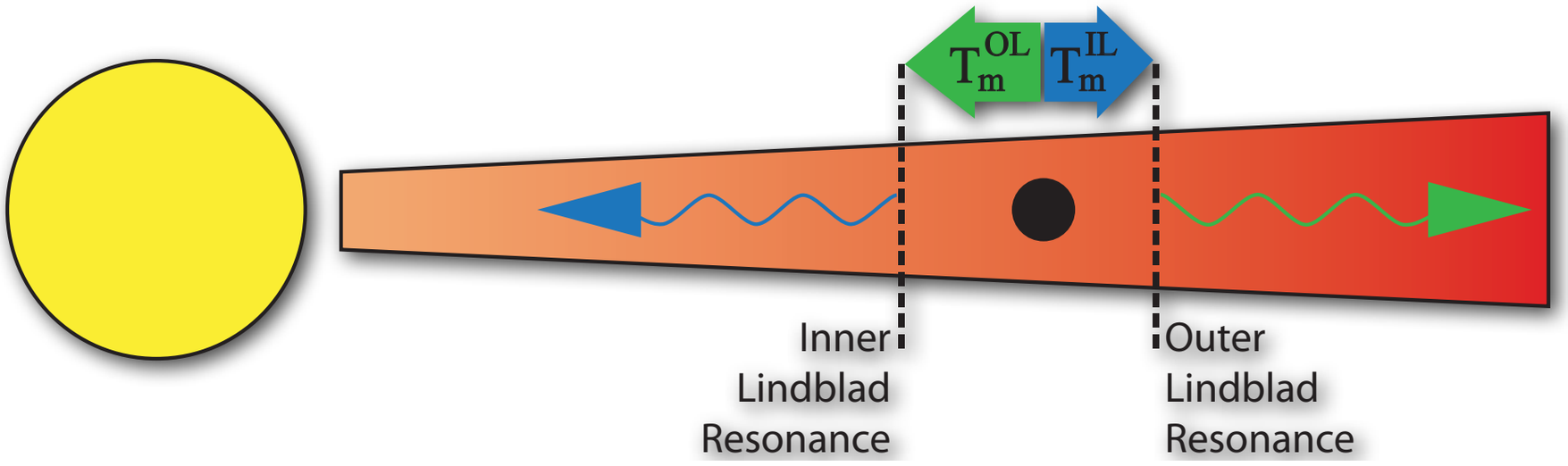
Howard et al. (2011c)

Exponential Cutoff

Power Law

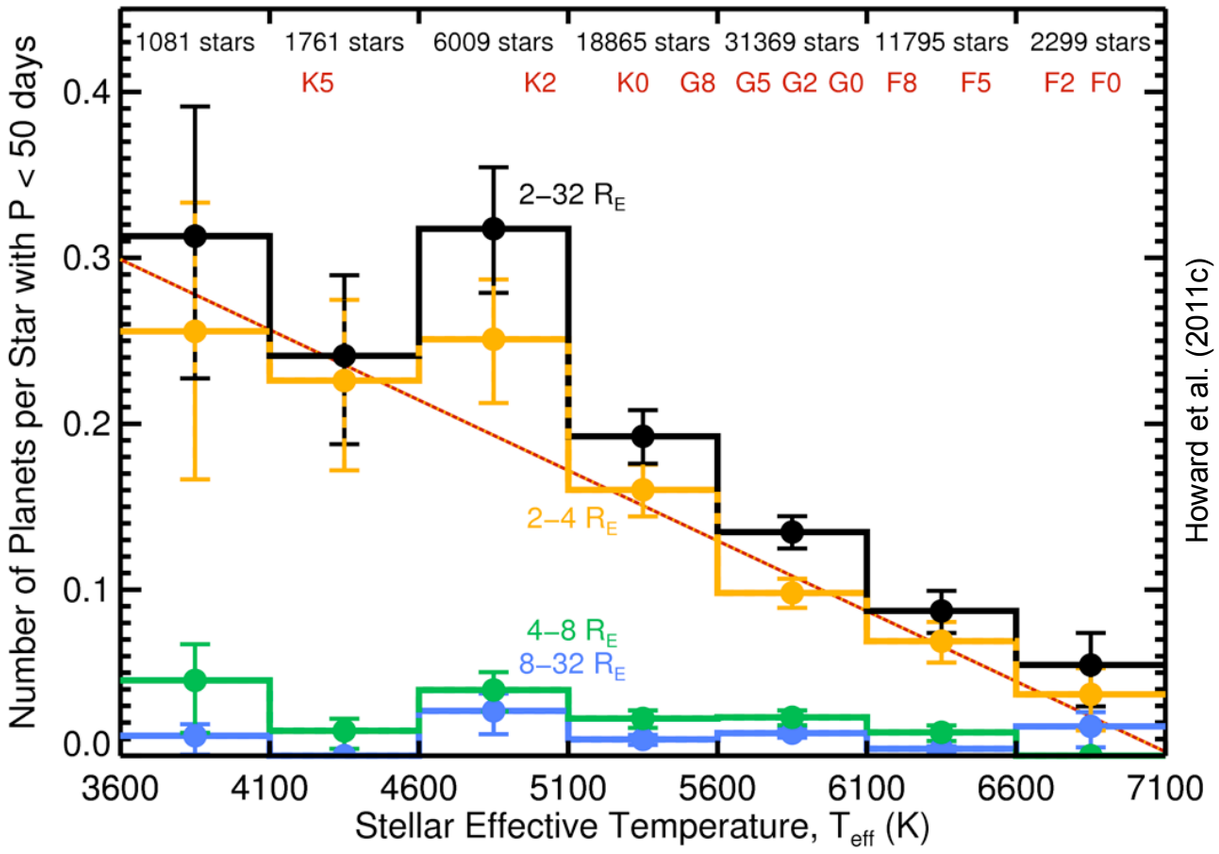


Increasing Planet Occurrence per log *P* bin

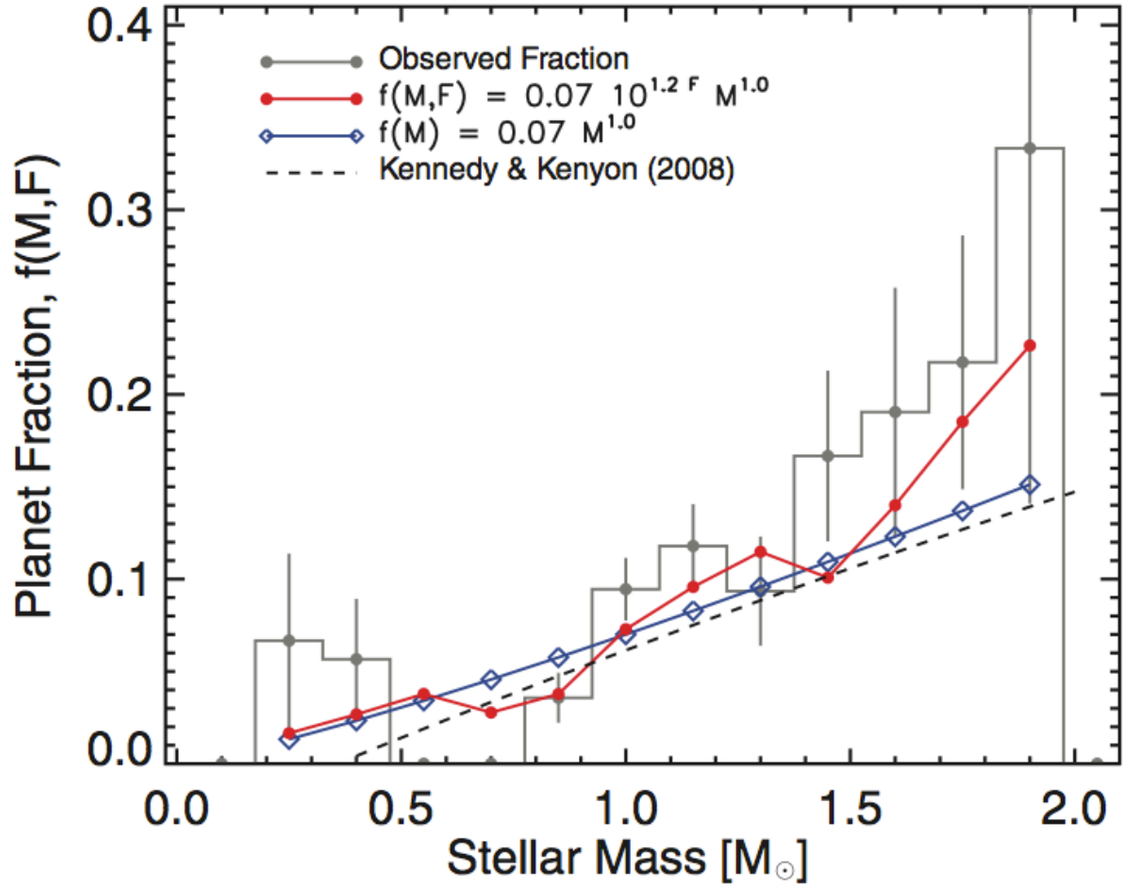


Trapping Small Planets in Disk Resonances?

See paper by D. Tsang (2011, ApJ, 741, 109)



Howard et al. (2011c)

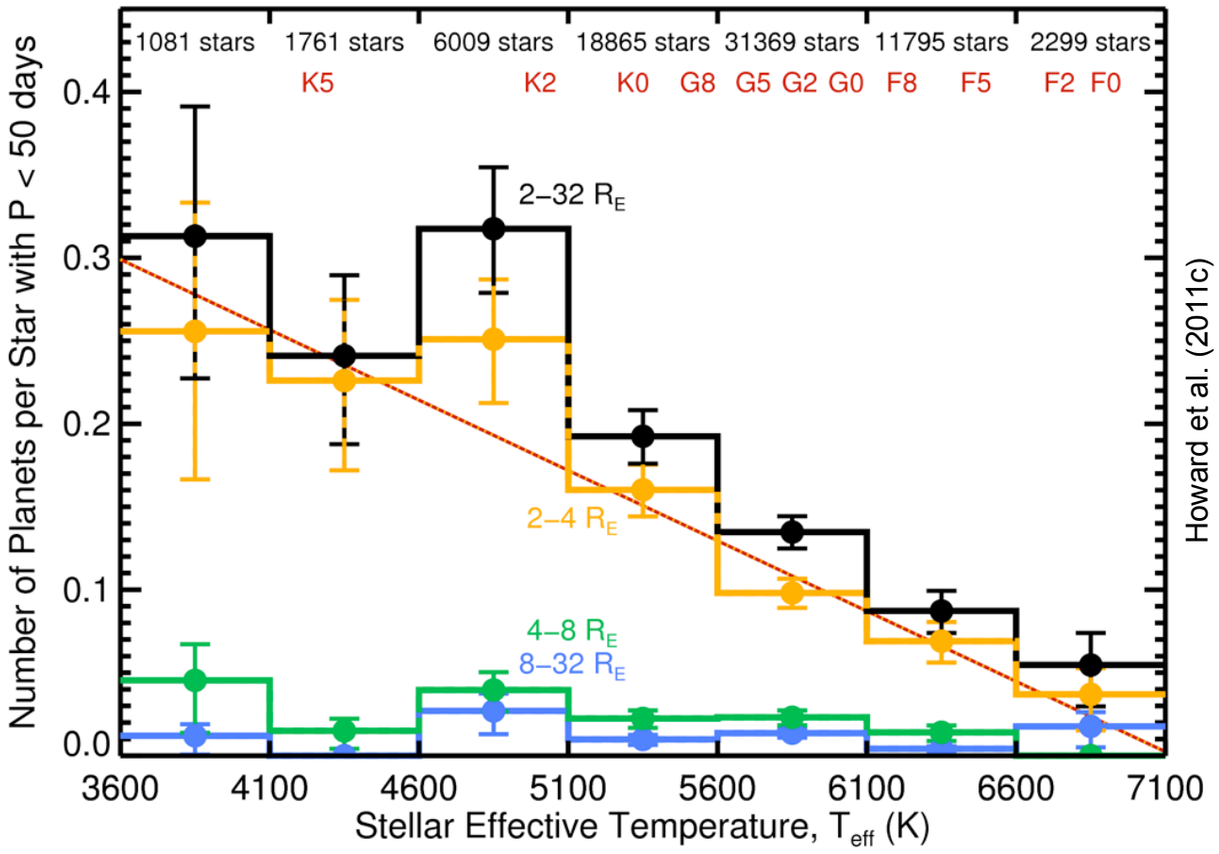


Johnson et al. (2010)

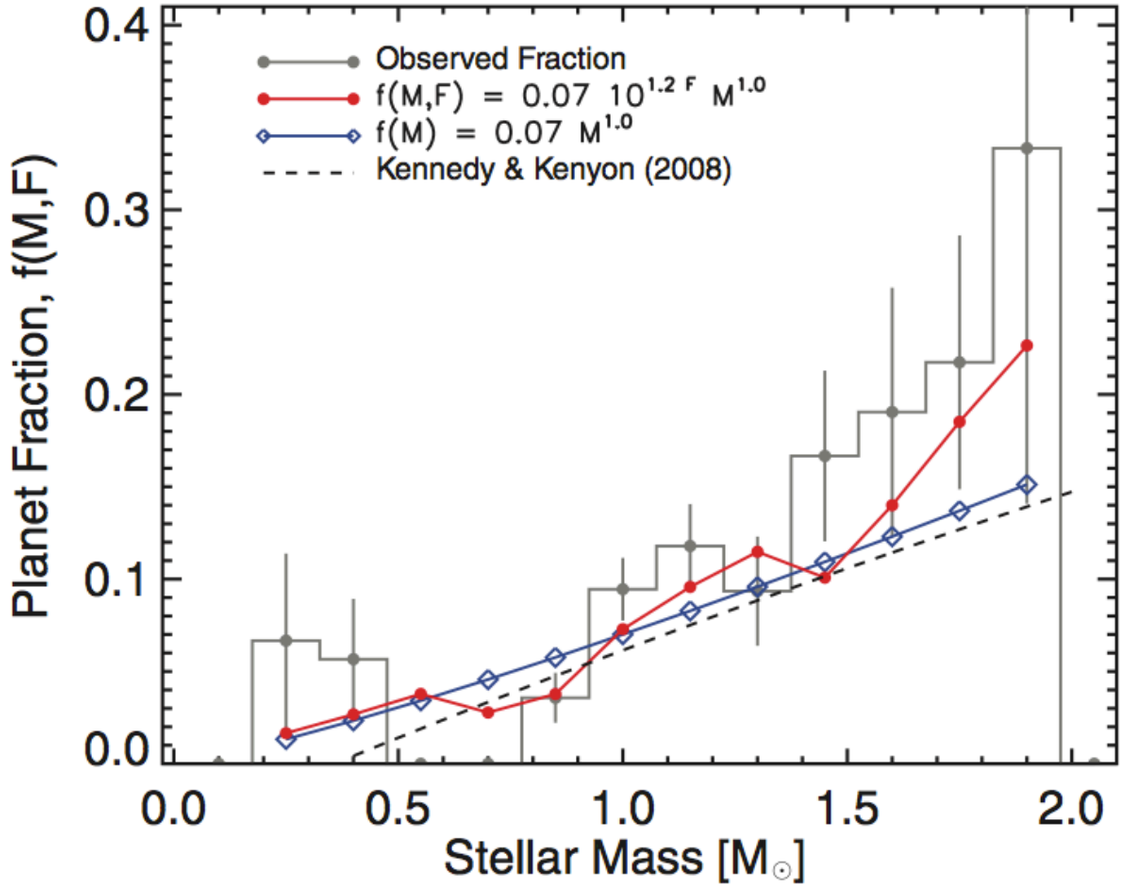
Occurrence within 0.25 AU of small planets *decreases* with M★

Occurrence within 2.5 AU of giant planets *increases* with M★

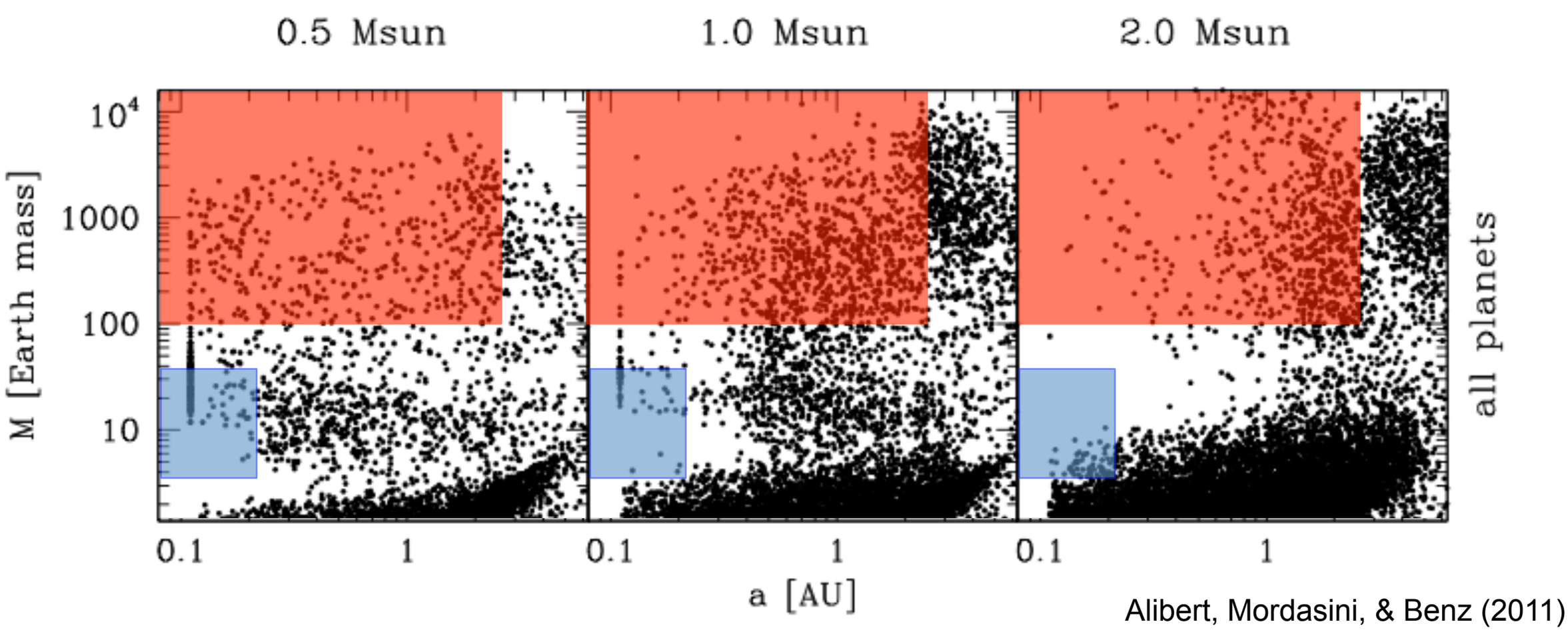
Planet Occurrence vs. M★



Howard et al. (2011c)



Johnson et al. (2010)



Alibert, Mordasini, & Benz (2011)

Questions?