Patterns of Low-mass Planet Occurrence from Kepler and Doppler Planet Searches

Andrew W. Howard - UC Berkeley

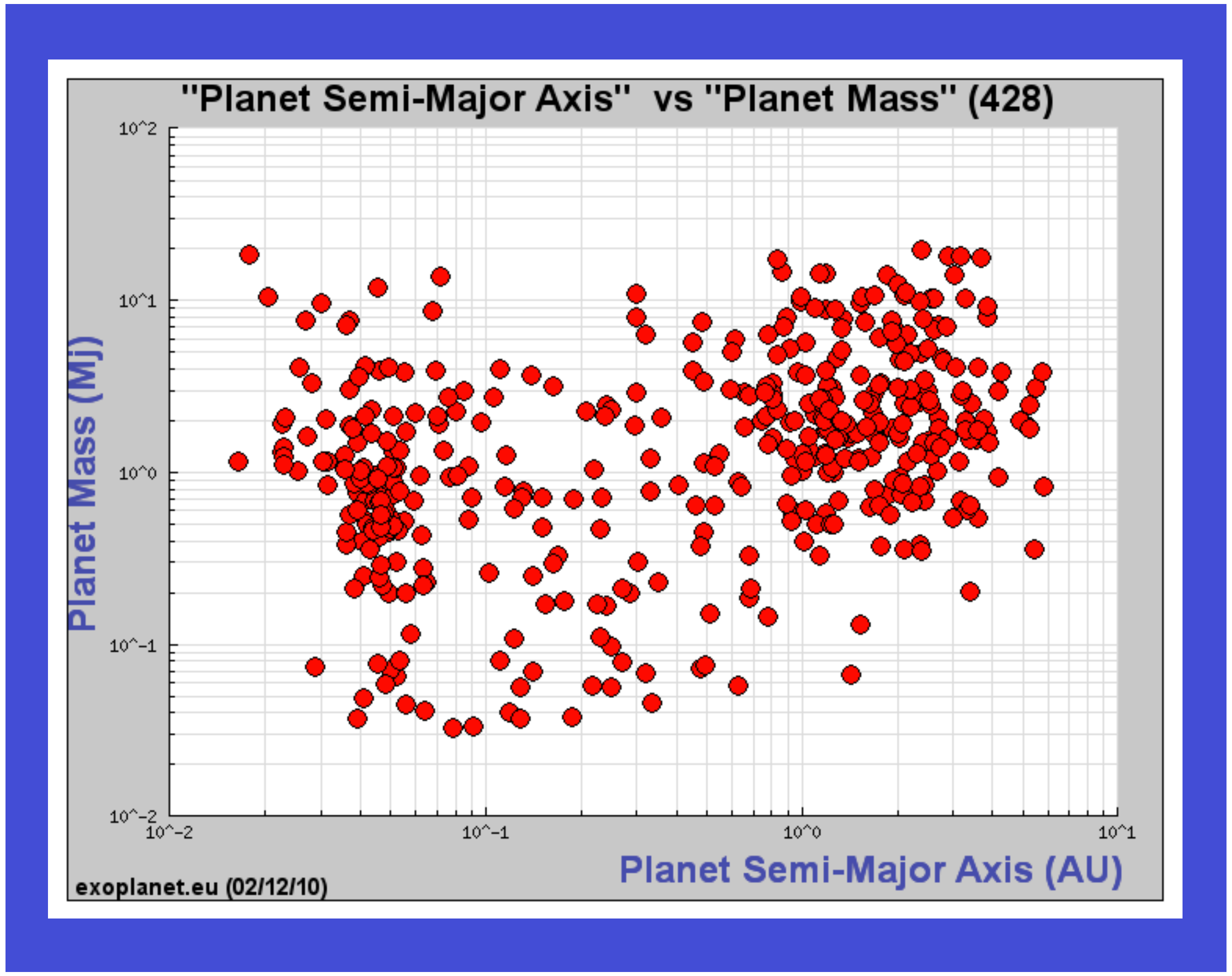
California Planet Search (CPS):
Geoff Marcy, Debra Fischer, John Johnson, Jason Wright, Howard Isaacson, more!

Kepler Team

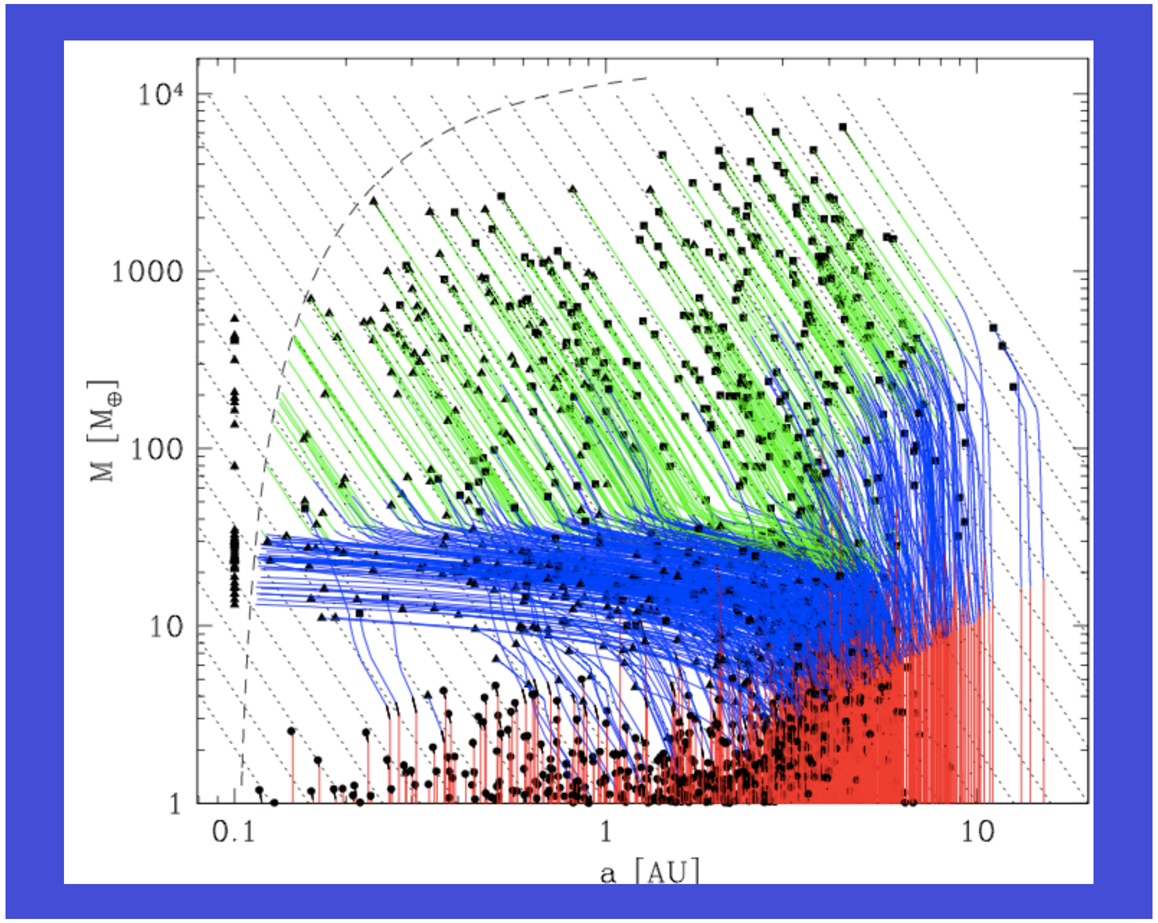
William J. Borucki, David G. Koch, Geoffrey W. Marcy, Natalie M. Batalha, Edward W. Dunham, Thomas N. Gautier III, Jon M. Jenkins, Stephen T. Bryson, Jason F. Rowe, Jeffrey Van Cleve, William D. Cochran, David W. Latham, Jack J. Lissauer, Guillermo Torres, Timothy M. Brown, Ronald L. Gilliland, Lars A. Buchhave, Douglas A. Caldwell, Jørgen Christensen-Dalsgaard, David Ciardi, Francois Fressin, Michael R. Haas, Steve B. Howell, Hans Kjeldsen, Sara Seager, Leslie Rogers, Dimitar D. Sasselov, Jason H. Steffen, Gibor S. Basri, David Charbonneau, Jessie Christiansen, Bruce Clarke, Andrea Dupree, Daniel C. Fabrycky, Debra A. Fischer, Eric B. Ford, Jonathan J. Fortney, Jill Tarter, Forrest R. Girouard, Matthew J. Holman, John Asher Johnson, Todd C. Klaus, Pavel Machalek, Althea V. Moorhead, Robert C. Morehead, Darin Ragozzine, Peter Tenenbaum, Joseph D. Twicken, Samuel N. Quinn, Howard Isaacson, Avi Shporer, Philip W. Lucas, Lucianne M. Walkowicz, William F. Welsh, Alan Boss, Edna Devore, Alan Gould, Jeffrey C. Smith, Robert L. Morris, Andrej Prsa,...... more !

Inferring Planet Formation Mechanisms from Planet Population Statistics

Measurements

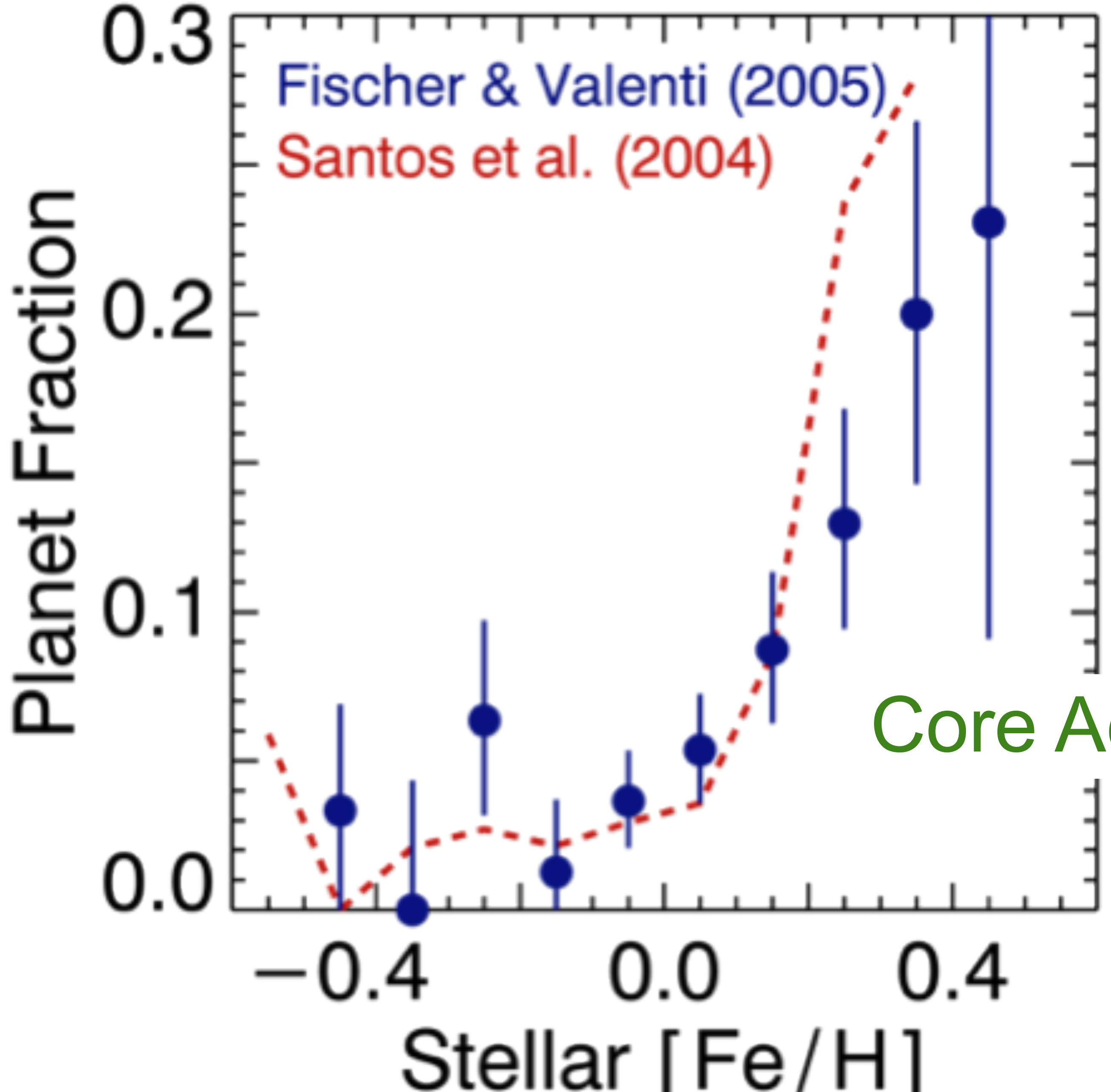


Models



Correlations between planet occurrence and planet/star properties reveal mechanisms of planet formation and evolution

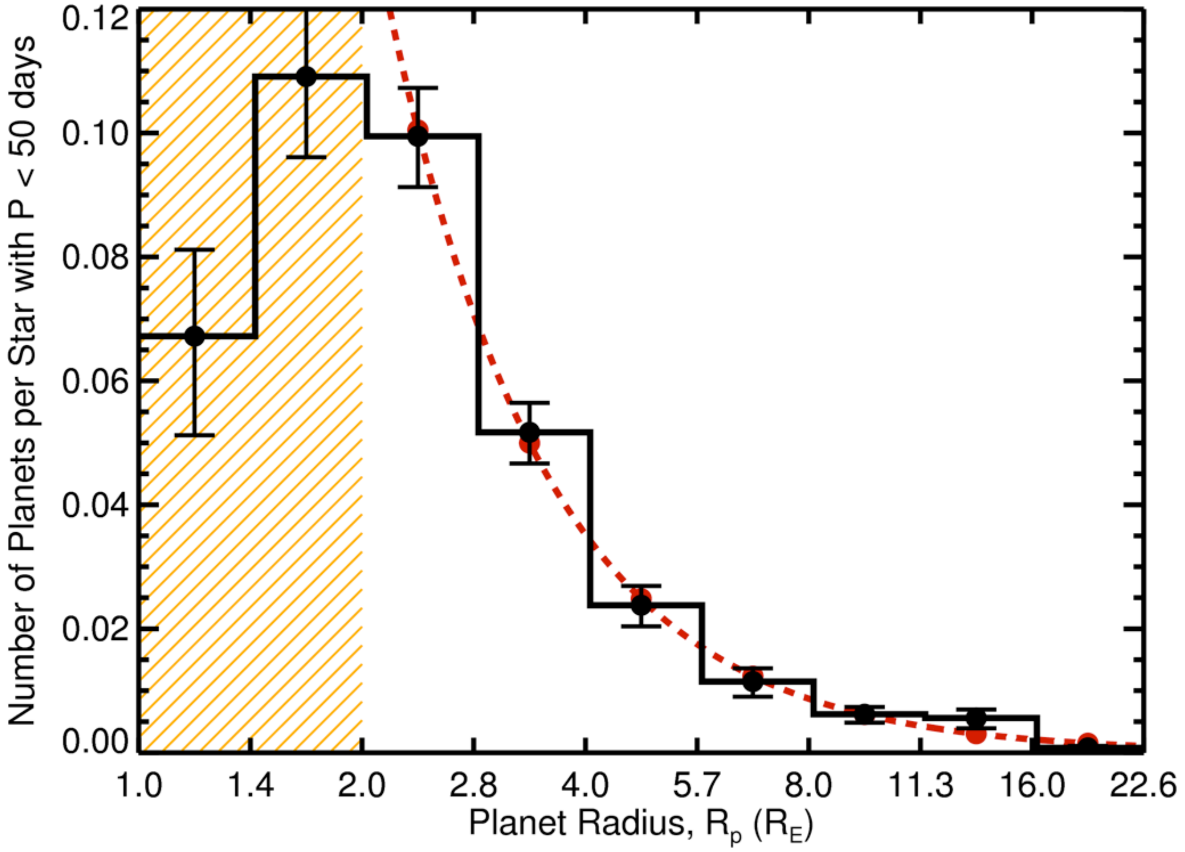
Planet-Metallicity Correlation for *Giant* Planets



Core Accretion!

Inferring Planet Formation Mechanisms from Planet Population Statistics

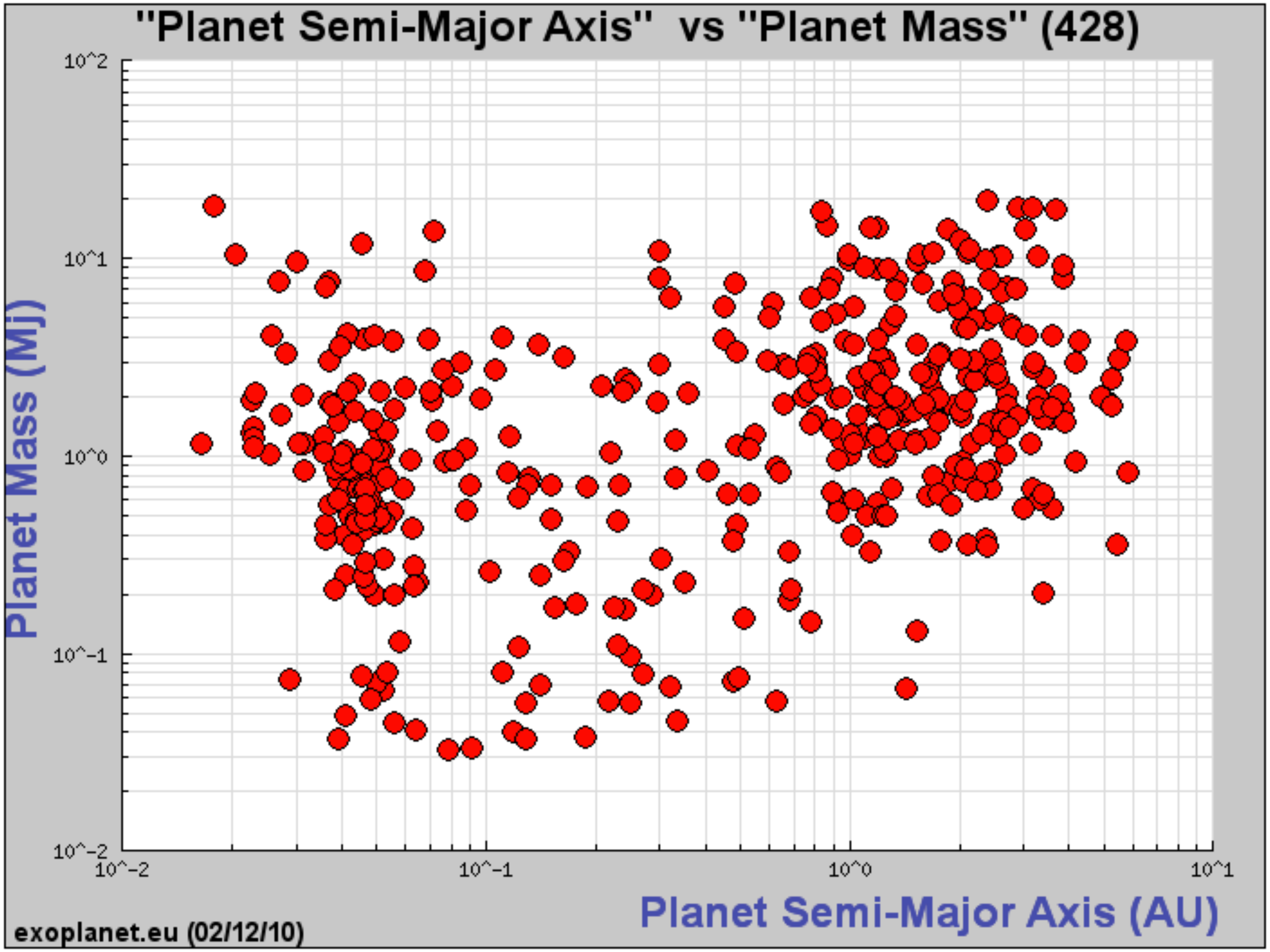
$$\text{Planet Occurrence} = \frac{\text{\# of Detected Planets}}{\text{\# of Stars Searched}}$$



<u>Challenges:</u>

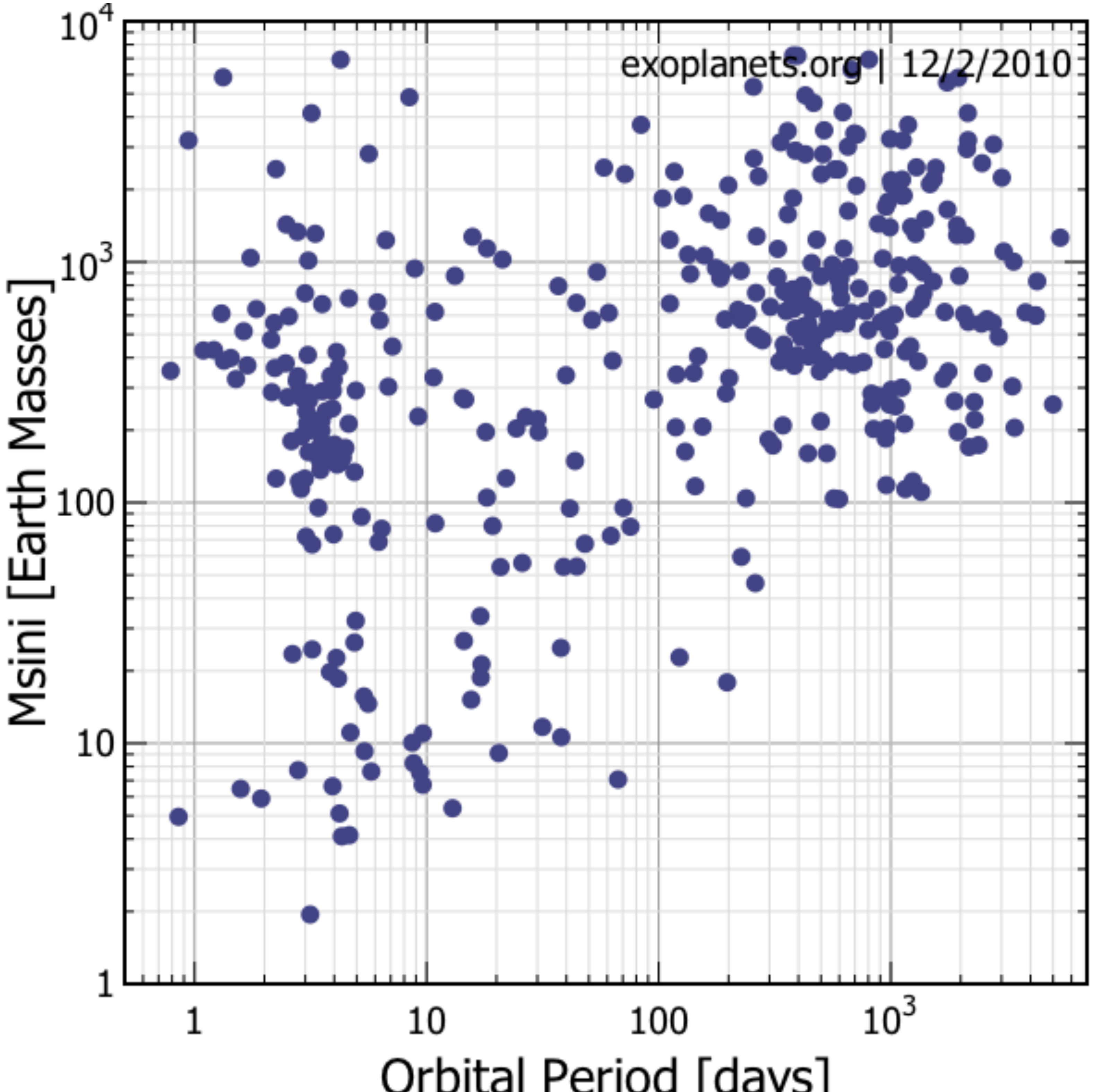
- small number statistics
- completeness corrections

Planet Distribution - Msini-Period



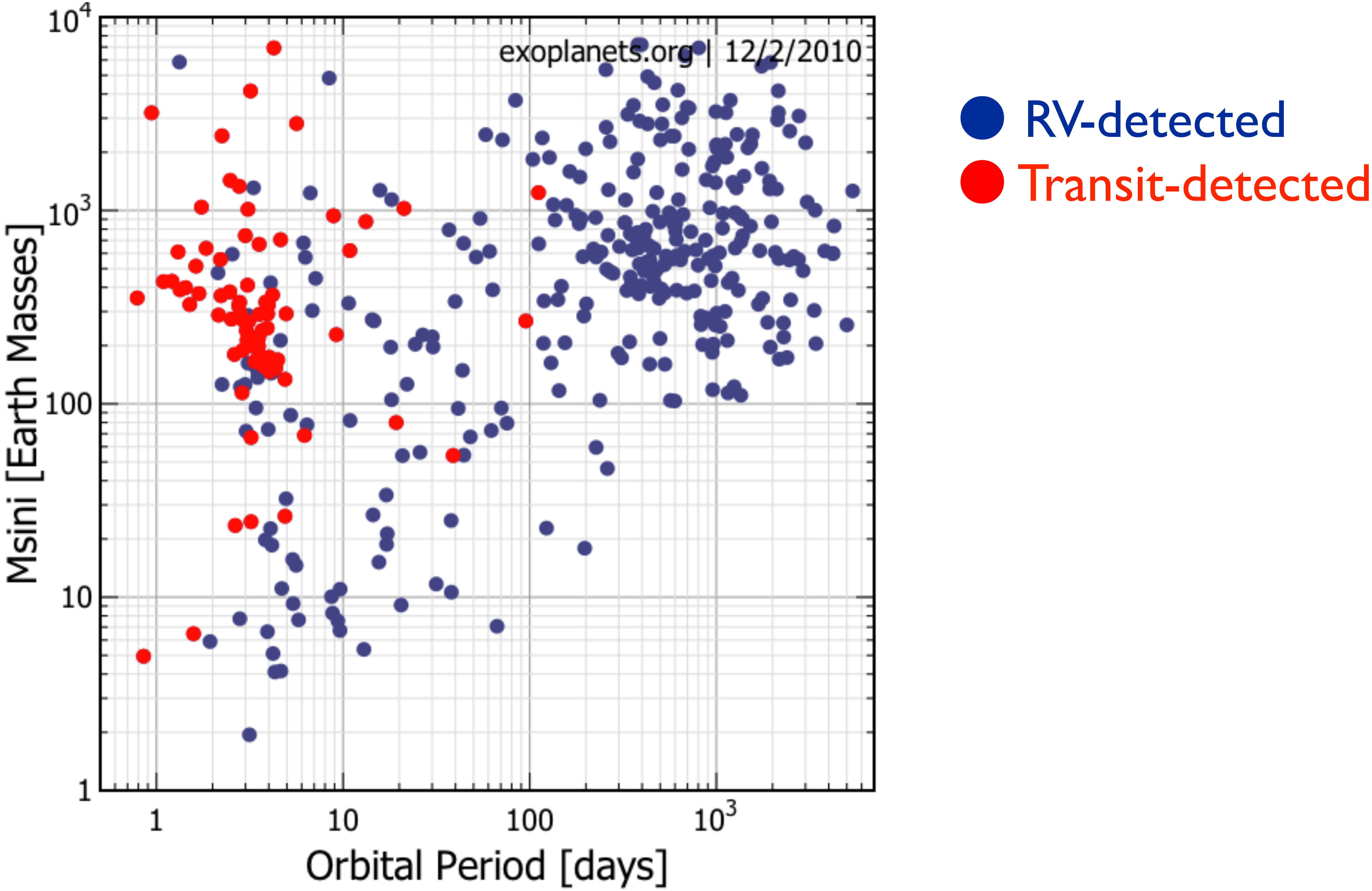
● all planets

Exoplanet Distribution - Msini-Period

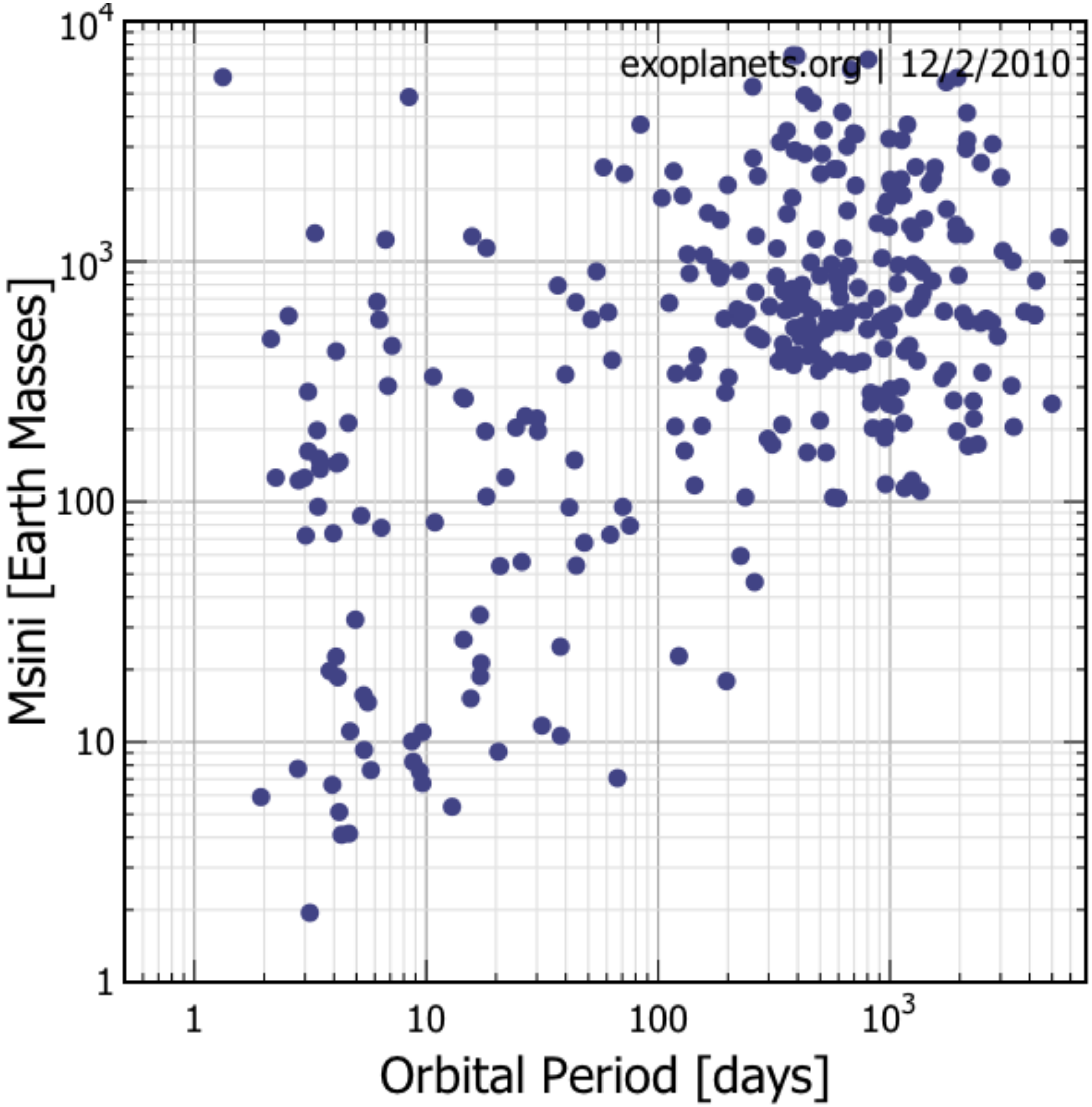


● all planets
RV+Transit

Exoplanet Distribution - Msini-Period

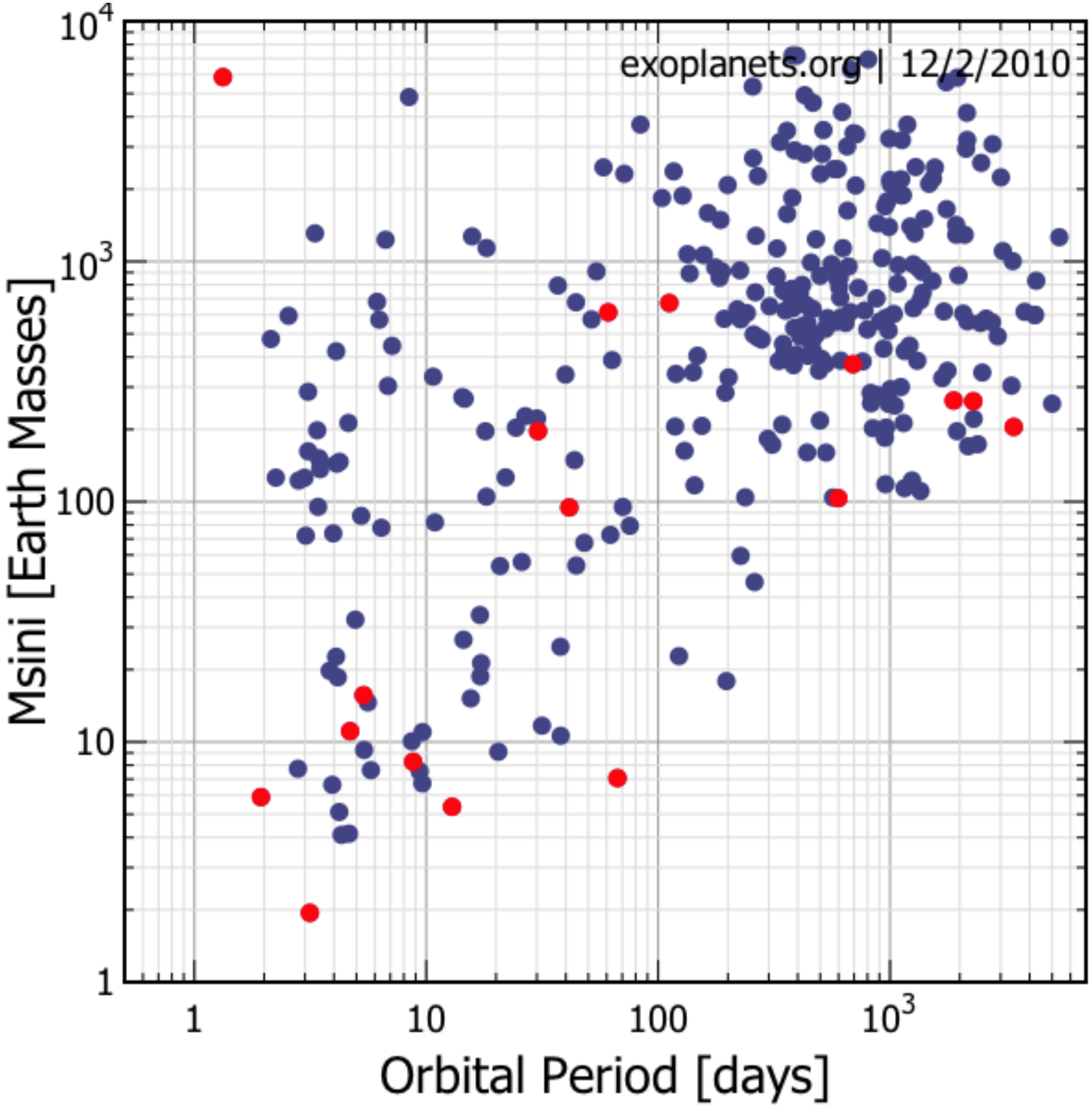


Exoplanet Distribution - Msini-Period



● RV-detected

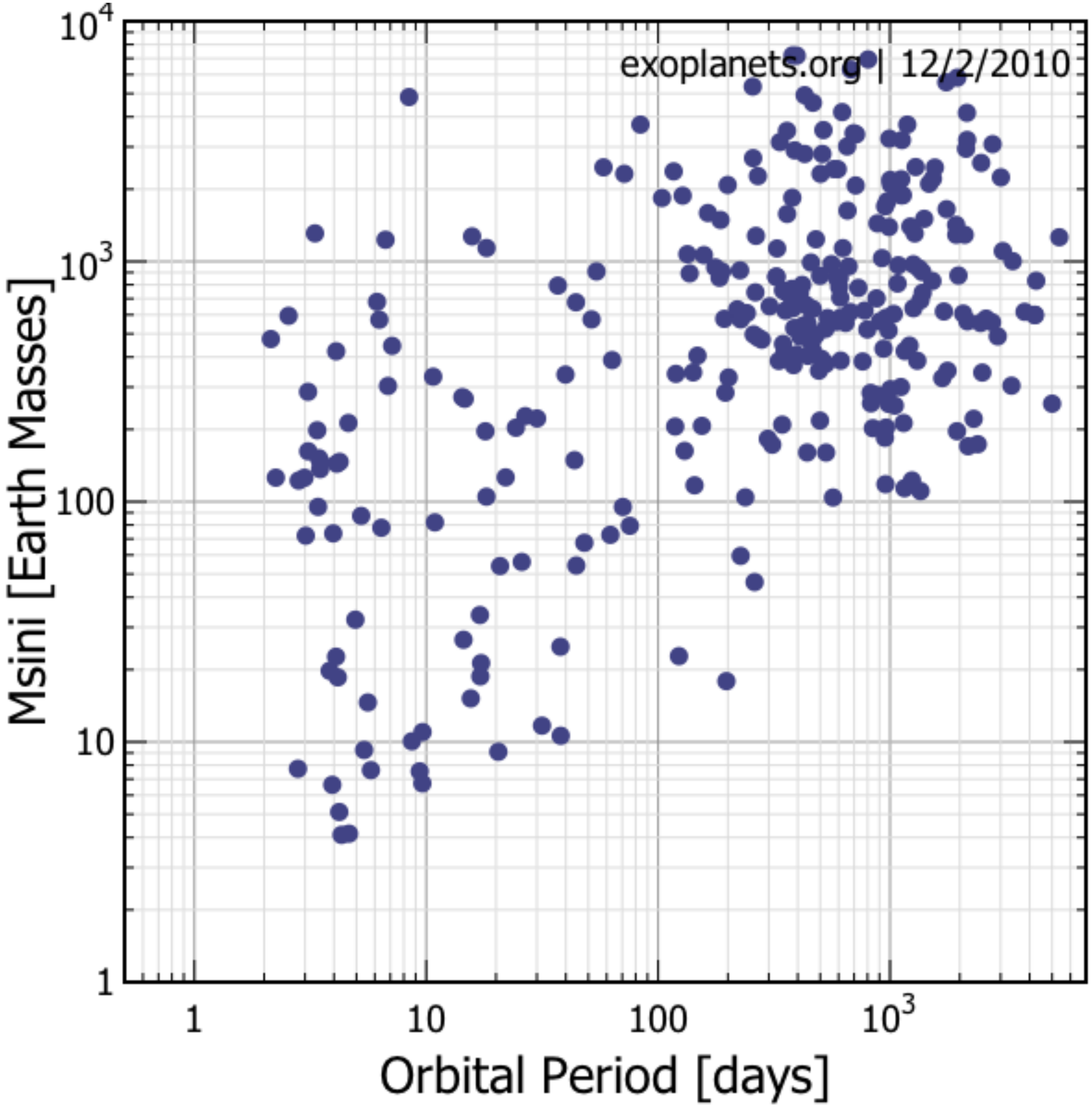
Exoplanet Distribution - Msini-Period



$M_{star} > 0.6\ M_{sun}$

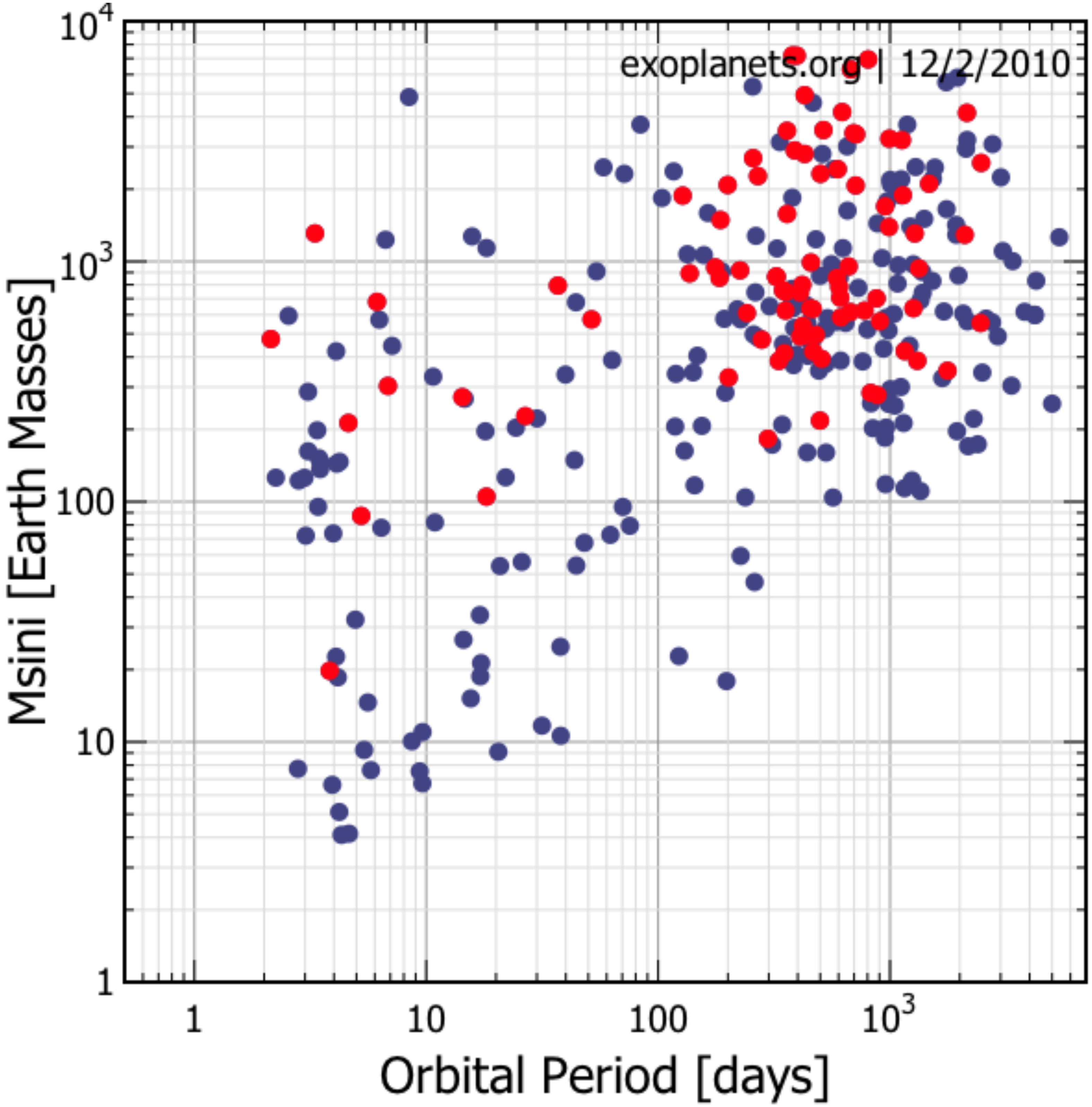
$M_{star} < 0.6\ M_{sun}$ (M dwarfs)

Exoplanet Distribution - Msini-Period



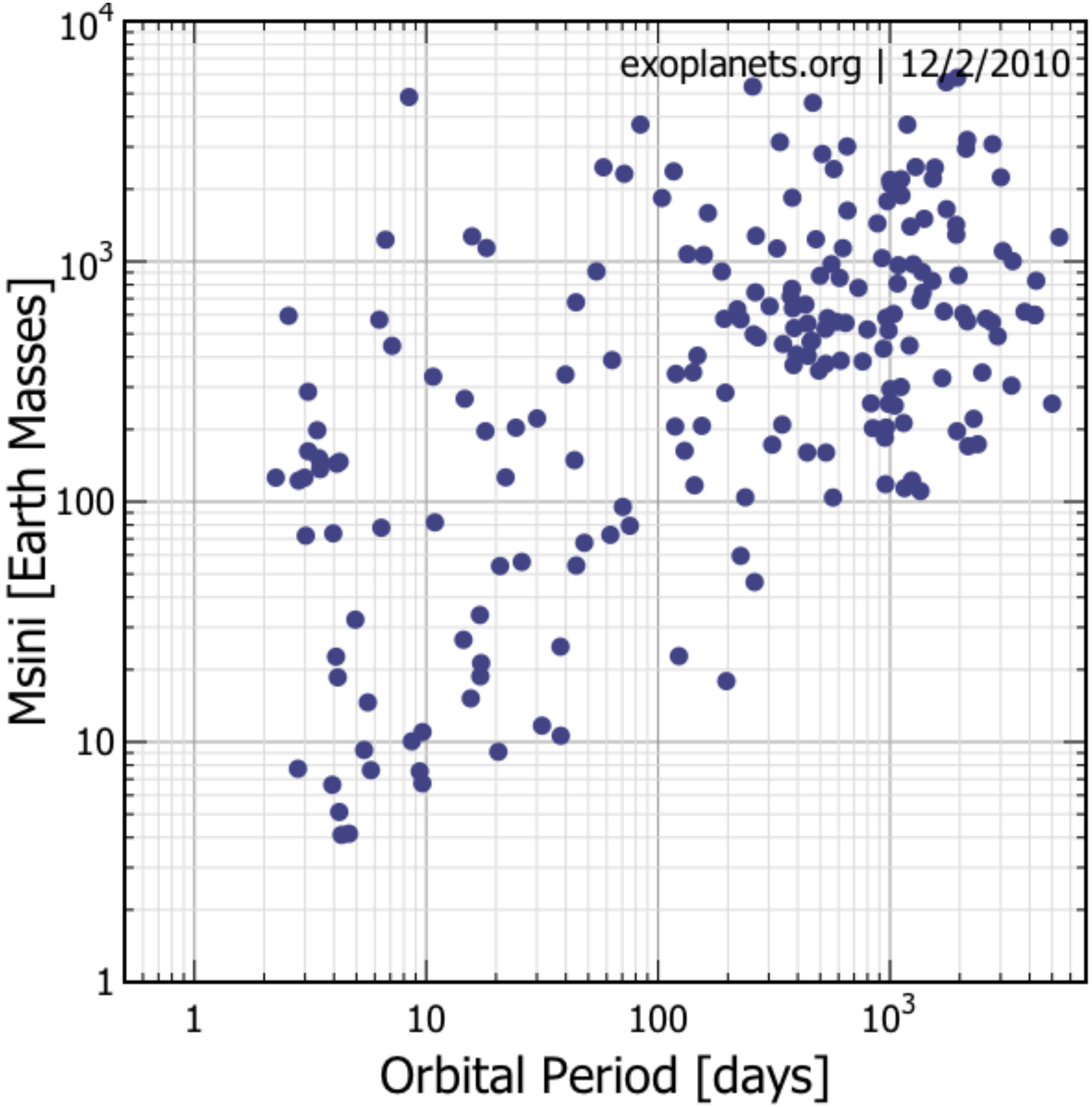
● $M_{star} > 0.6\ M_{sun}$

Exoplanet Distribution - Msini-Period



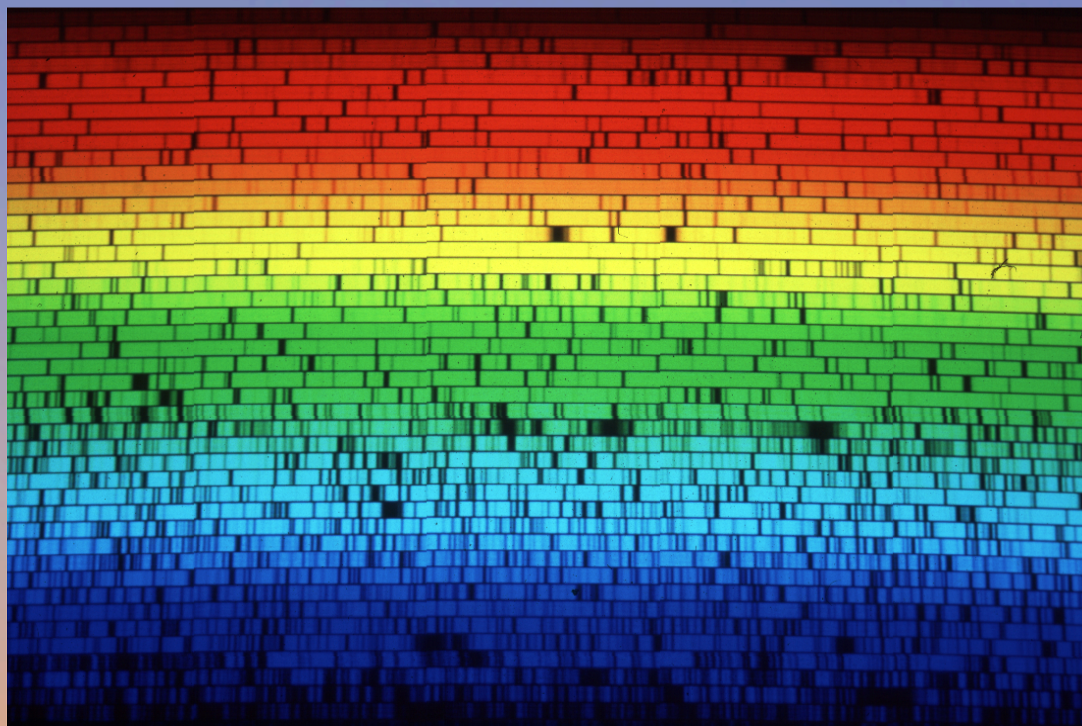
- $M_{star} < 1.2\ M_{sun}$
- $M_{star} > 1.2\ M_{sun}$ (F dwarfs, subgiants, giants)

Exoplanet Distribution - Msini-Period



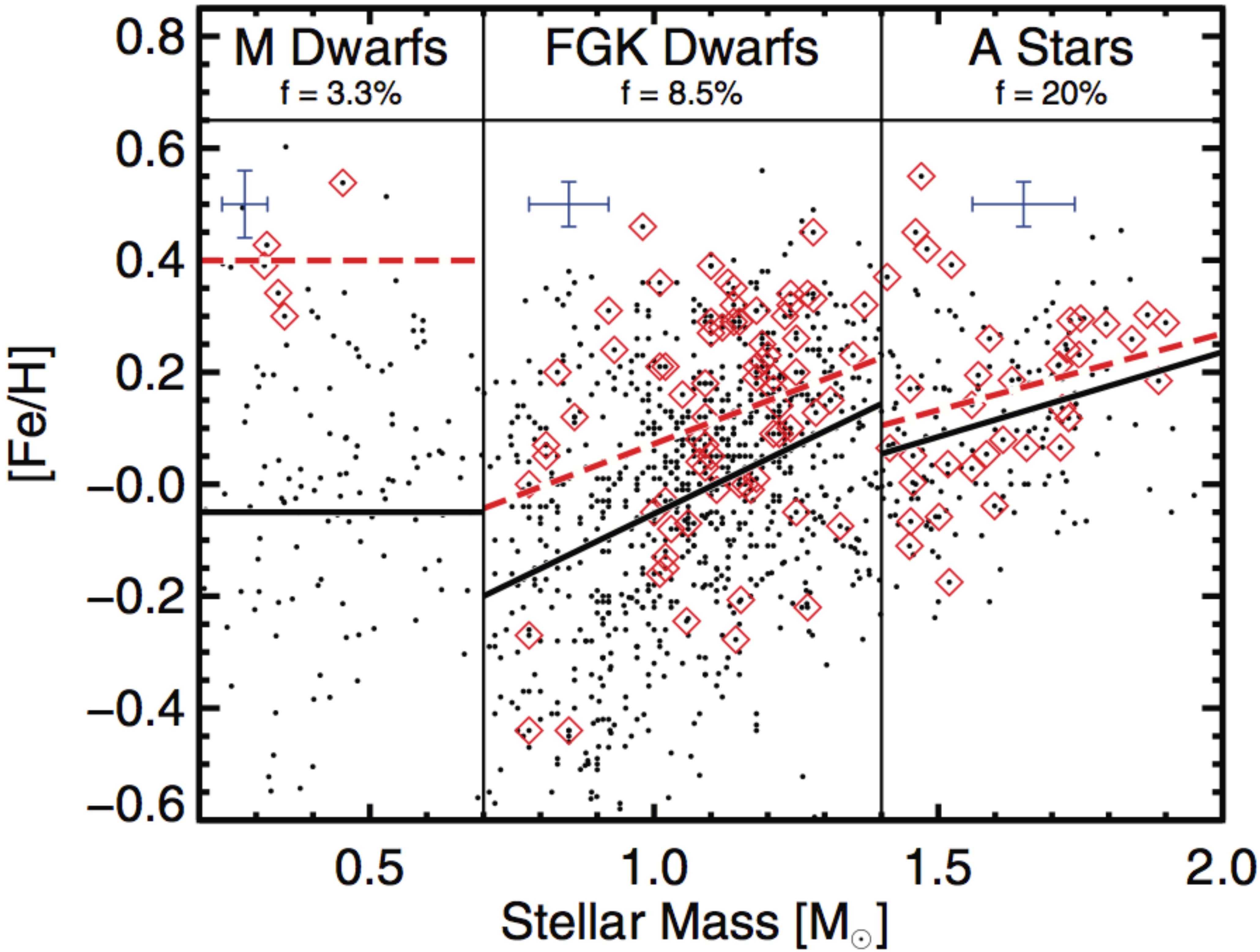
● M_{star} =0.6-1.2 M_{sun}

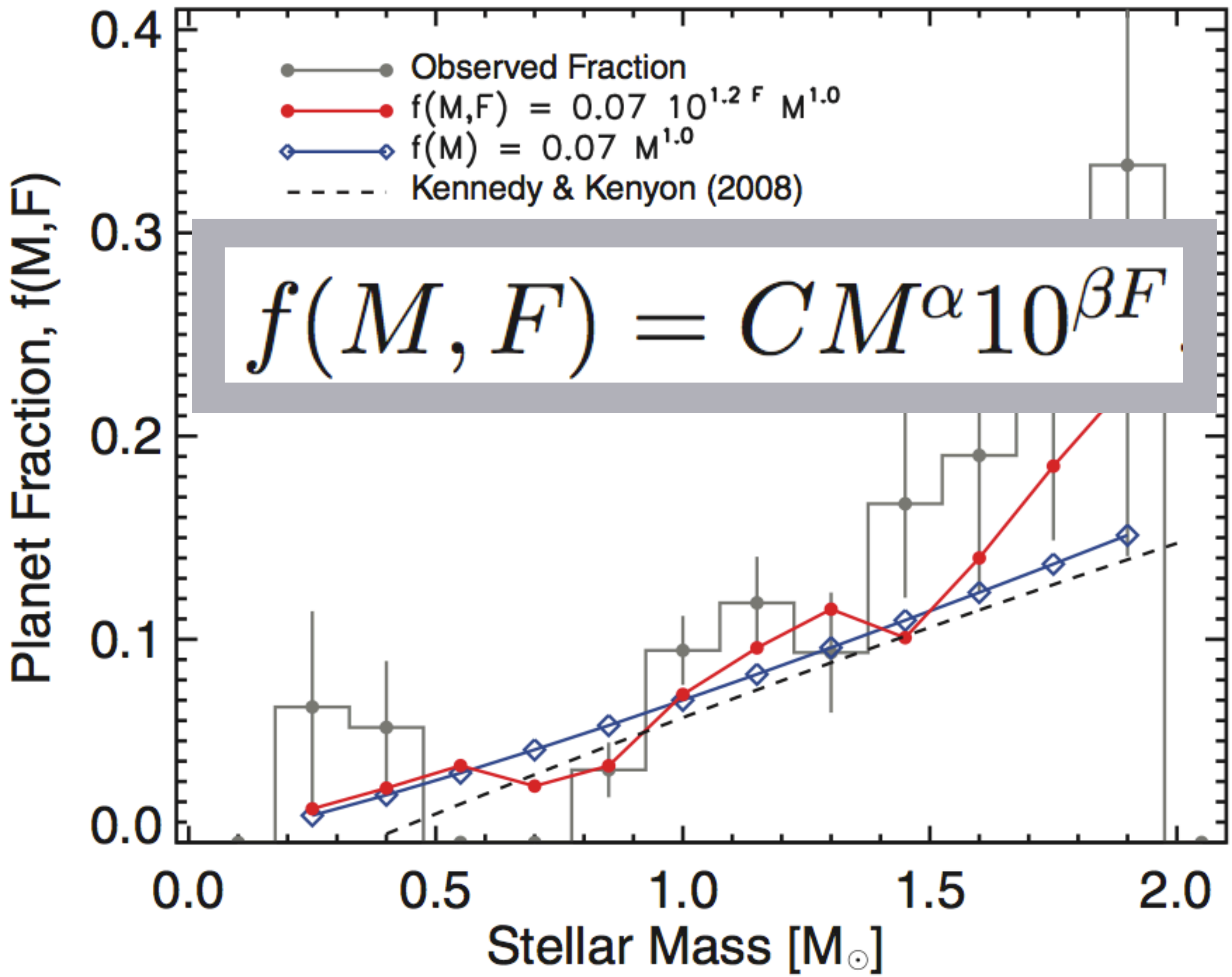
California Planet Search (CPS) — Doppler Searches from Keck



HIRES Echelle Spectrum

Iodine Absorption Cell

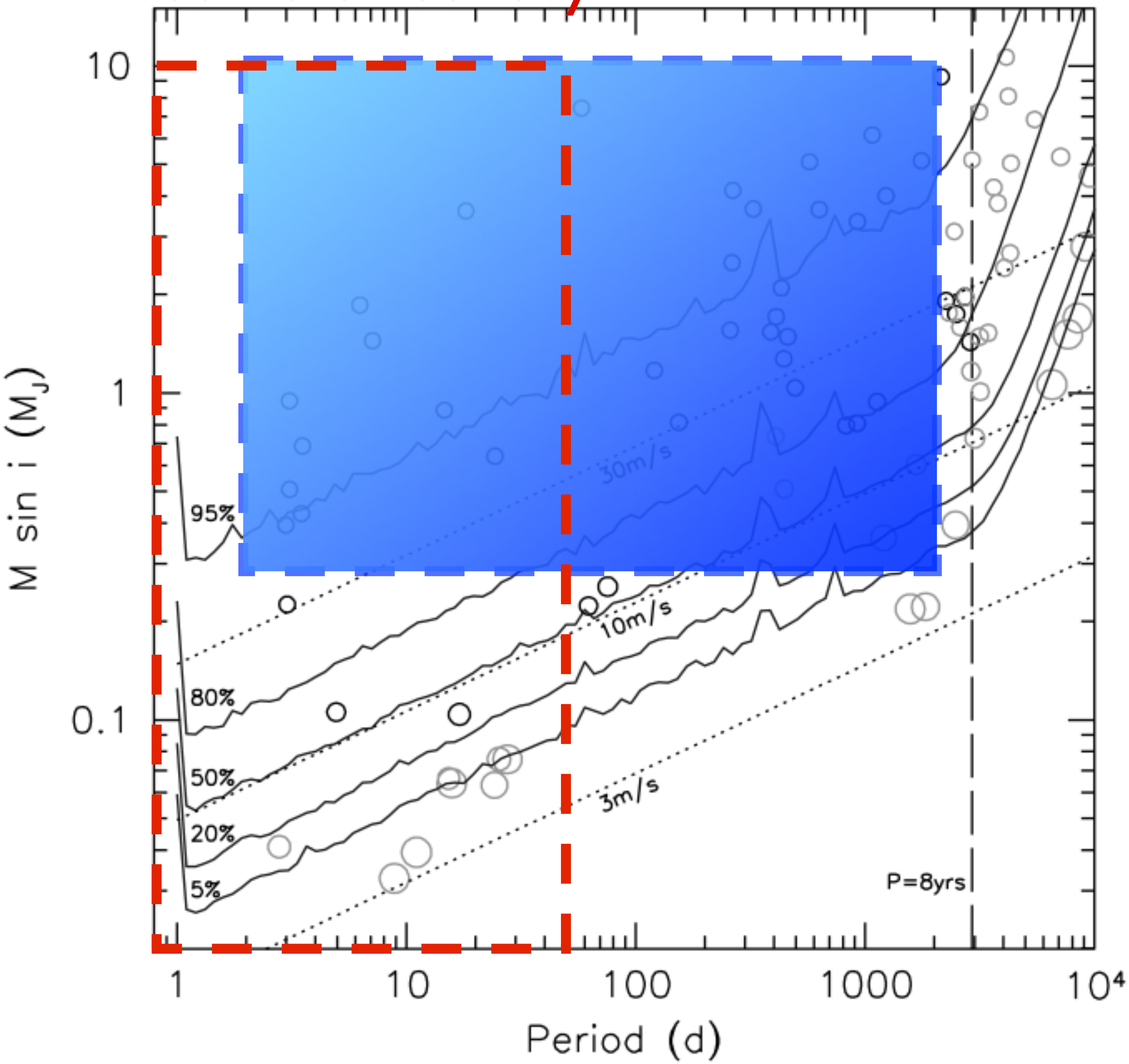

M Dwarfs
f = 3.3%
FGK Dwarfs
f = 8.5%
A Stars
f = 20%
0.8
0.6
0.4
0.2
−0.0
−0.2
−0.4
−0.6
[Fe/H]
0.5
1.0
1.5
2.0
Stellar Mass [M☉]



$$f(M, F) = C M^{\alpha} 10^{\beta F}$$

Giant Planet Occurrence Rates

Eta-Earth Survey



Cumming et al. (2008)

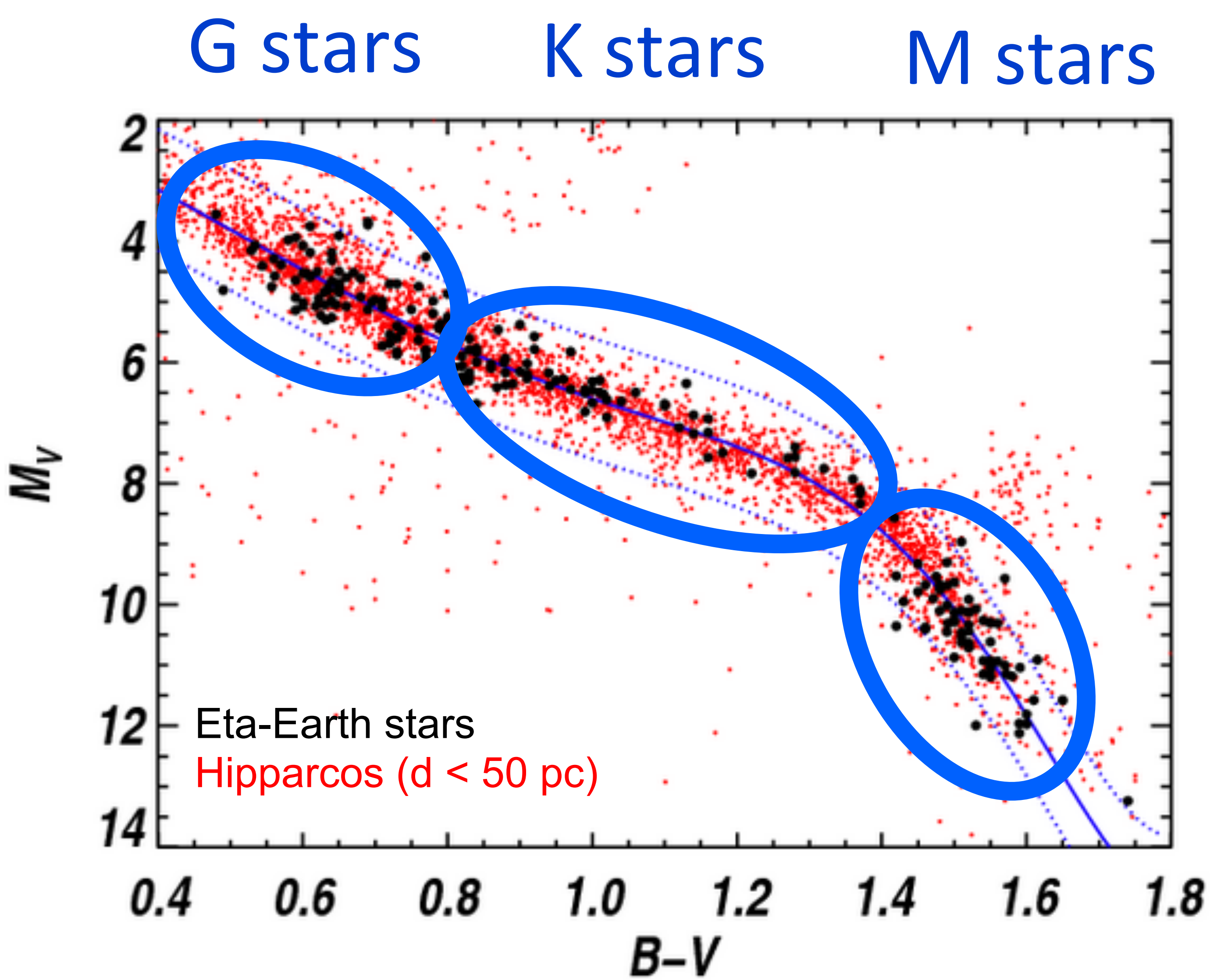
$$\frac{dN}{d\ln P\ d\ln M} = CM^{\alpha}P^{\beta}$$

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

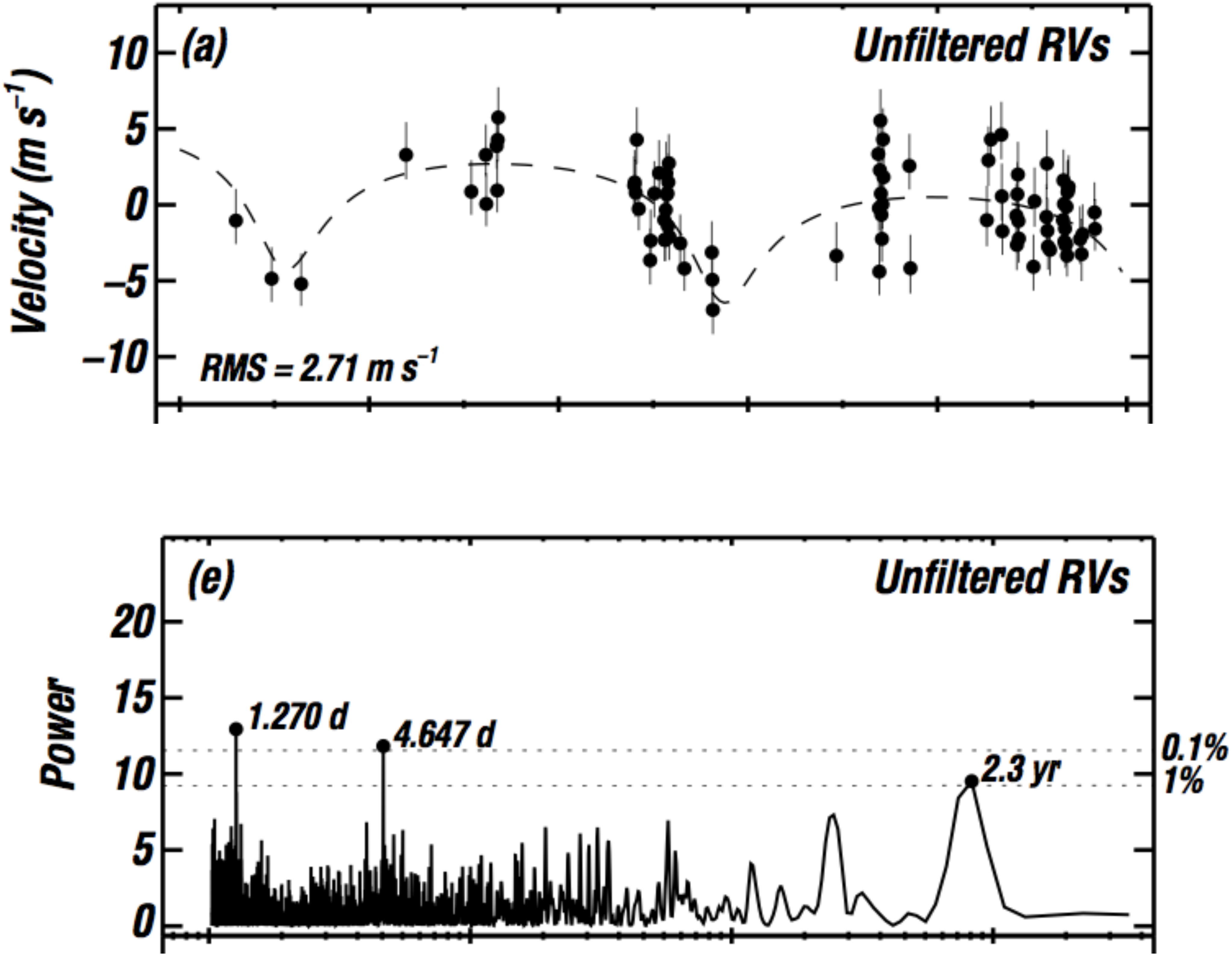


39% G stars
33% K stars
28% M stars

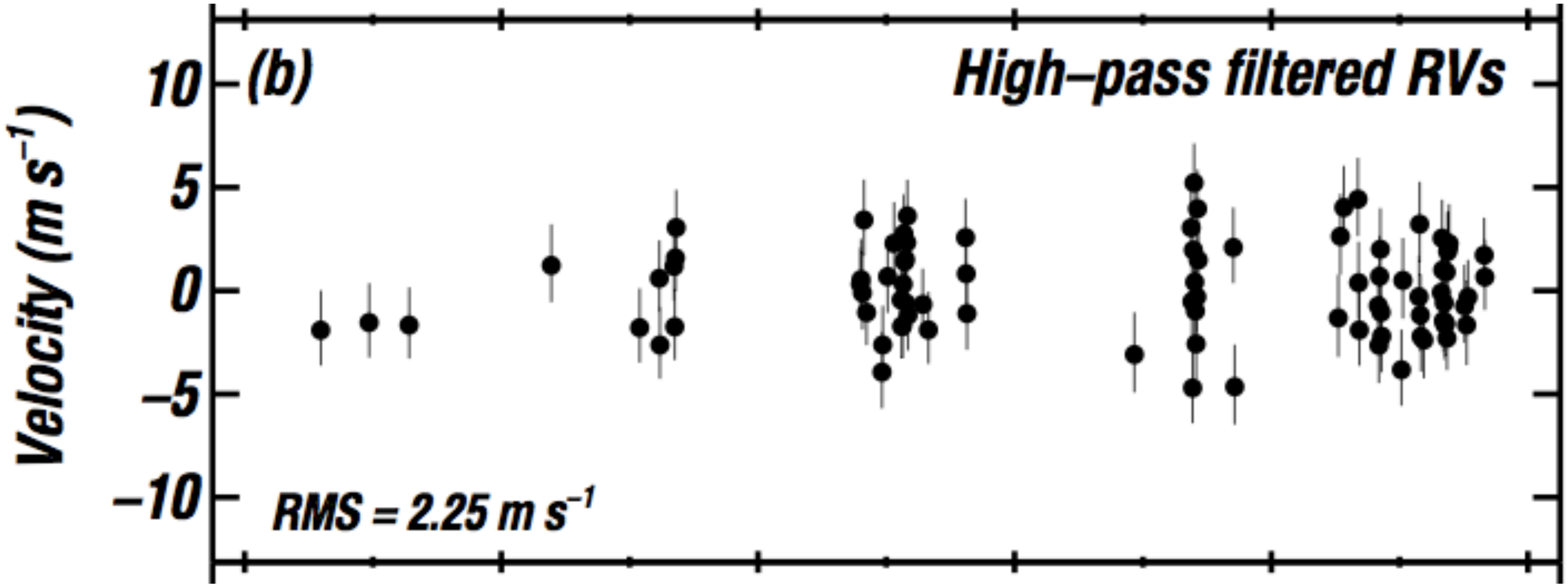
Statistically unbiased (nearly) stellar population:

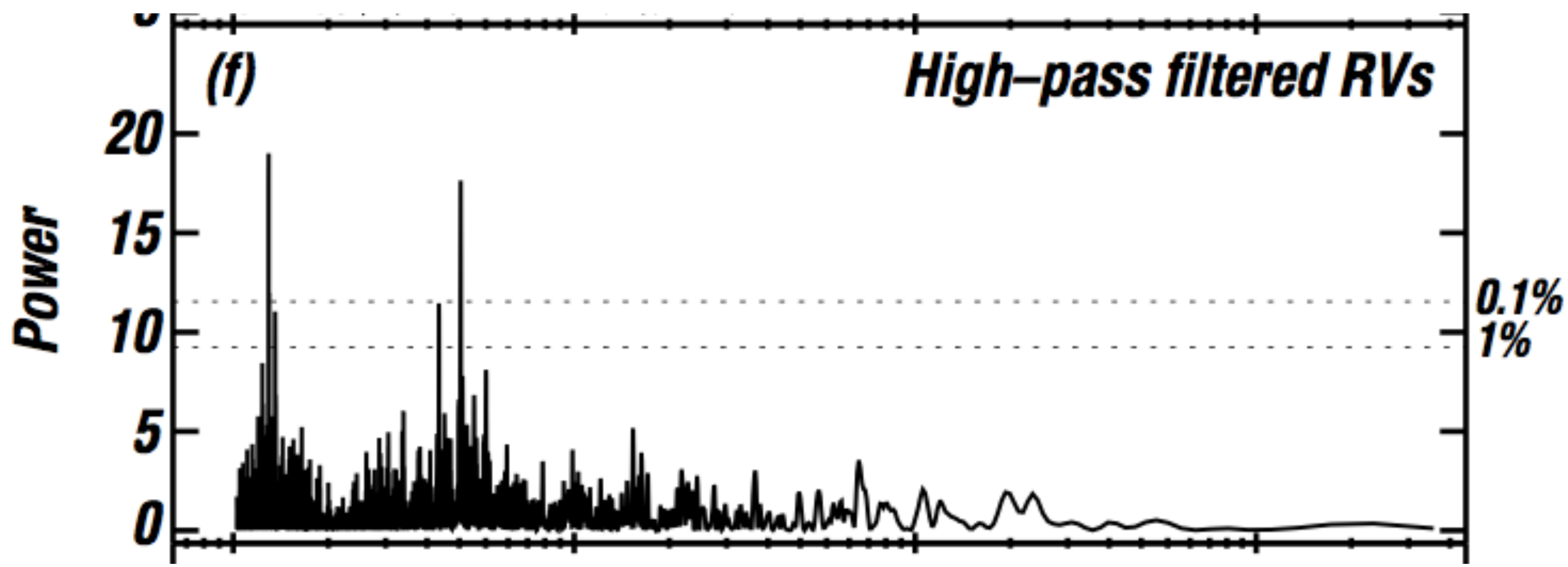
- V < 11
- distance < 25 pc
- log R'HK < –4.7 (inactive)

HD 156668 - Discovery RVs

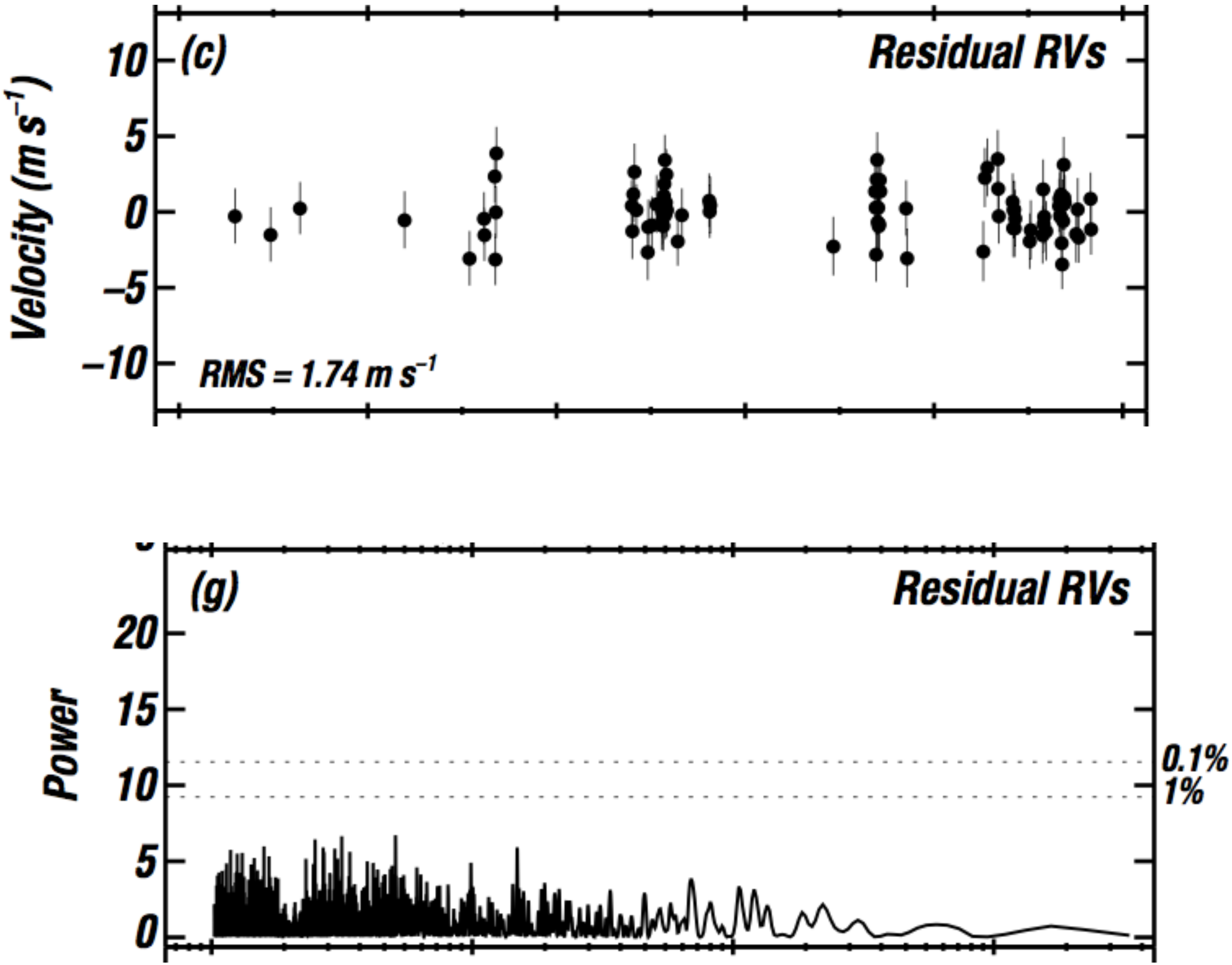


HD 156668 - High-pass Filtered RVs

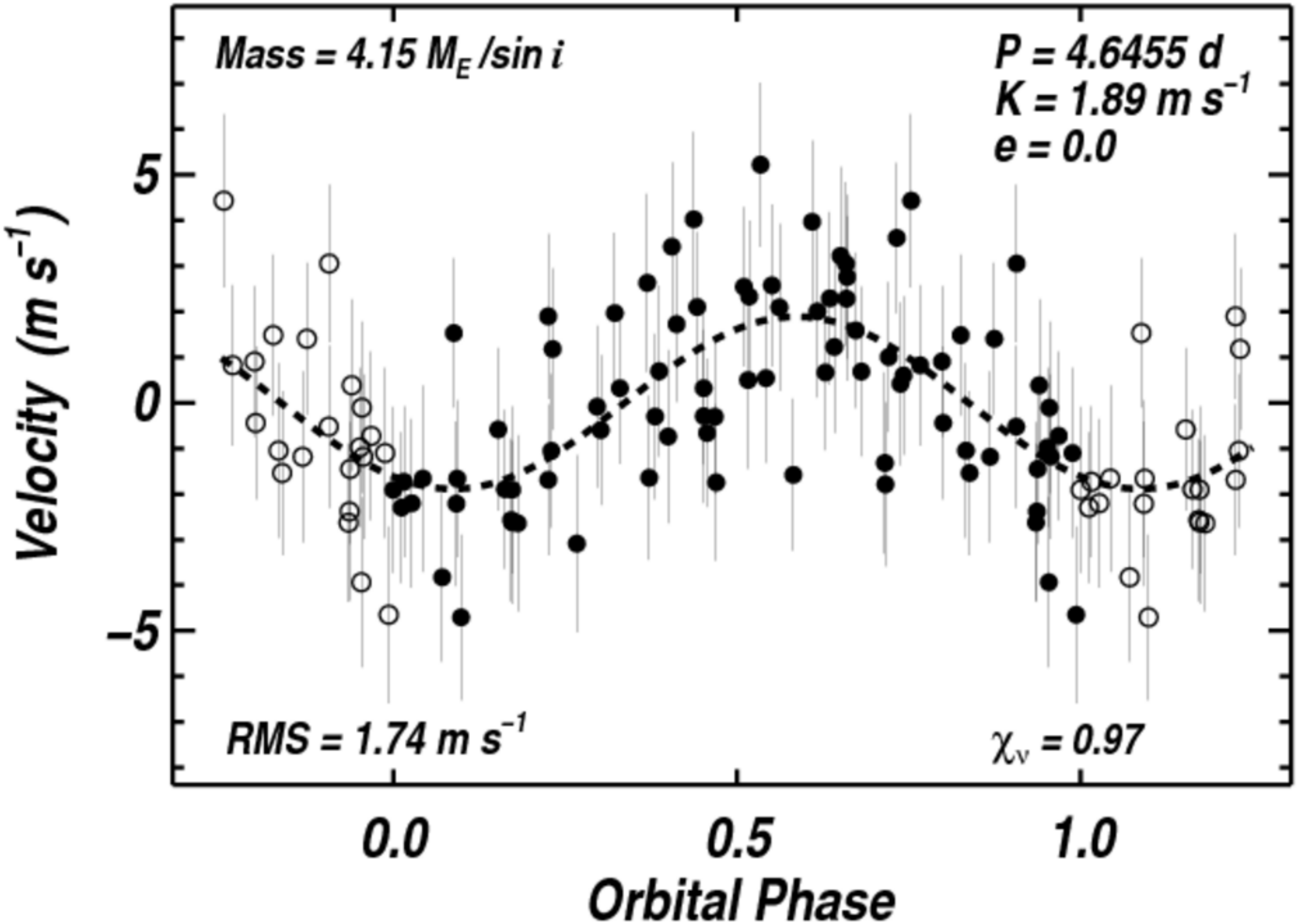




HD 156668 - Residual RVs



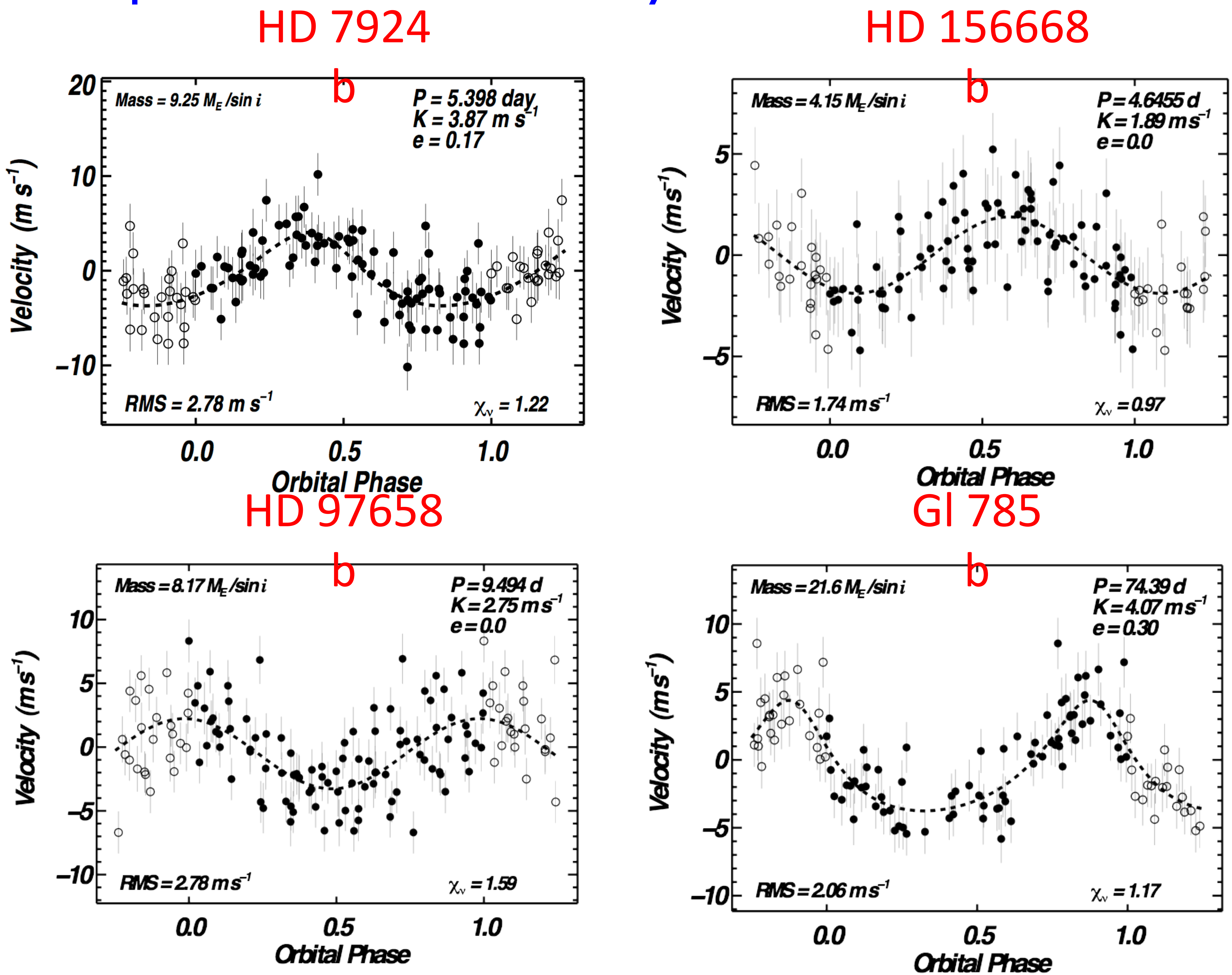
HD 156668b - Detected Super-Earth!



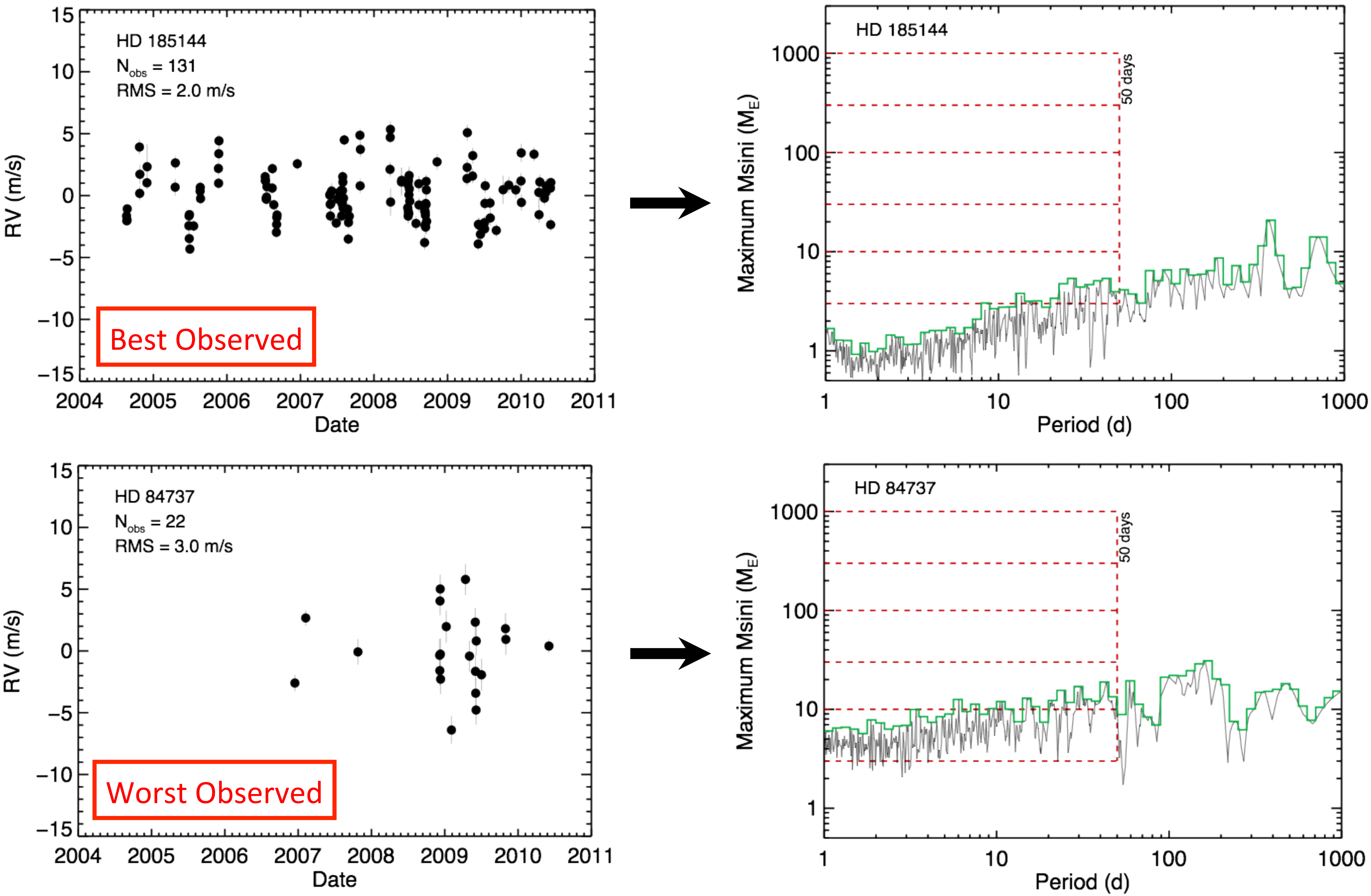
Star:

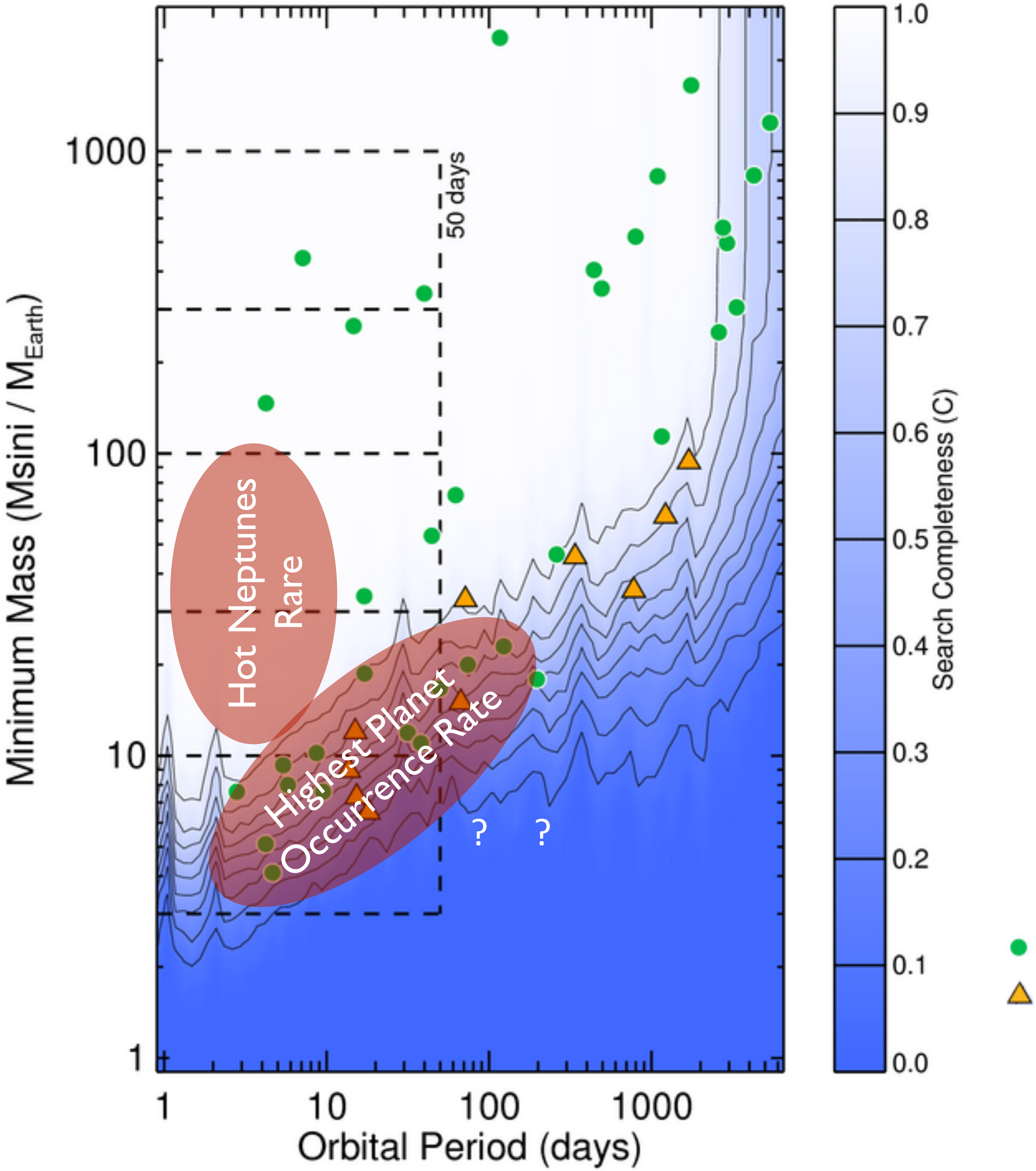
Planet:

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

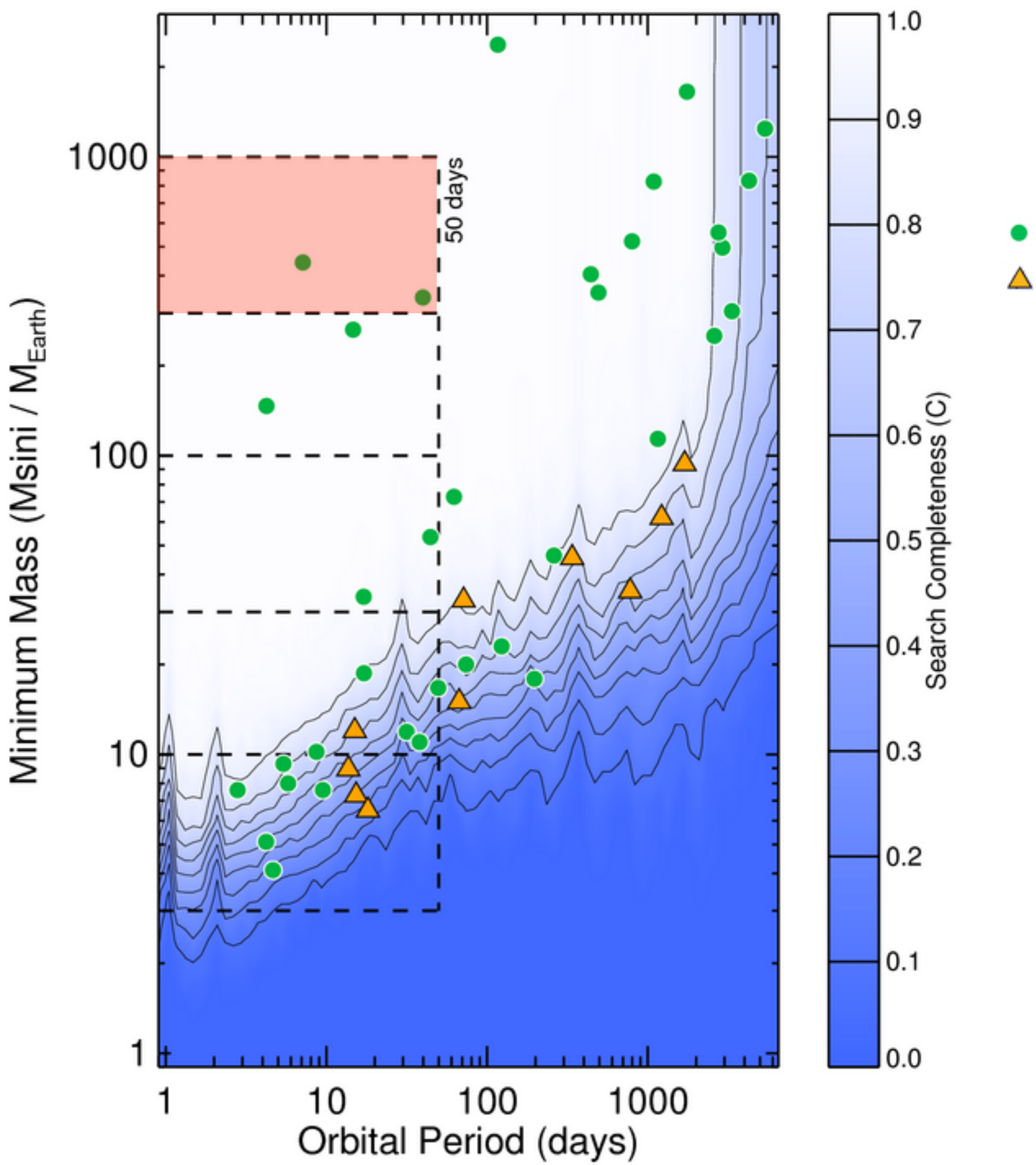


Limits on Non-detections of Planets

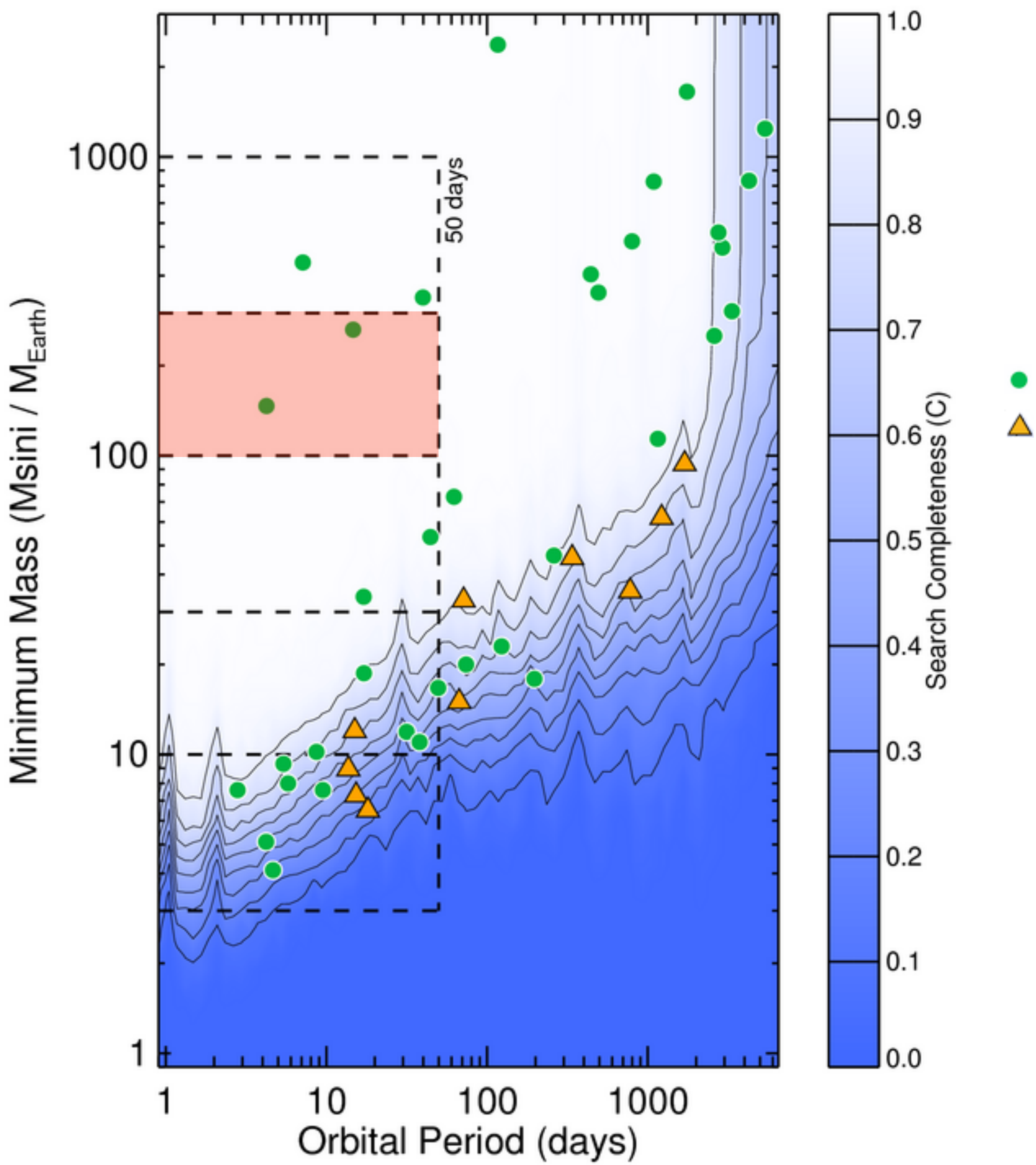




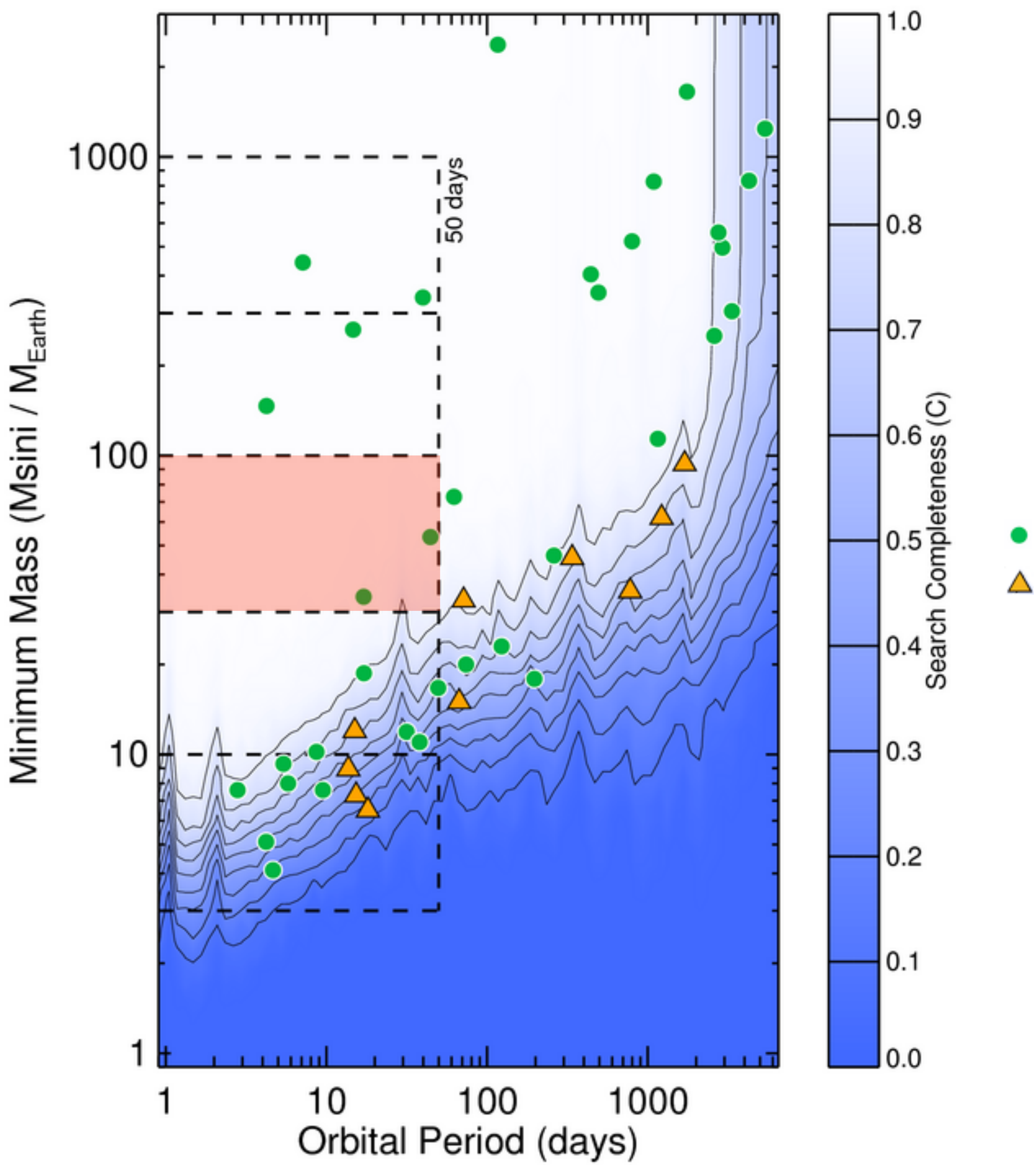
Minimum Mass (Msini / M_{Earth})
Orbital Period (days)
Search Completeness (C)
50 days
Hot Neptunes
Rare
Highest Planet
Occurrence Rate
?
?
1
10
100
1000
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0



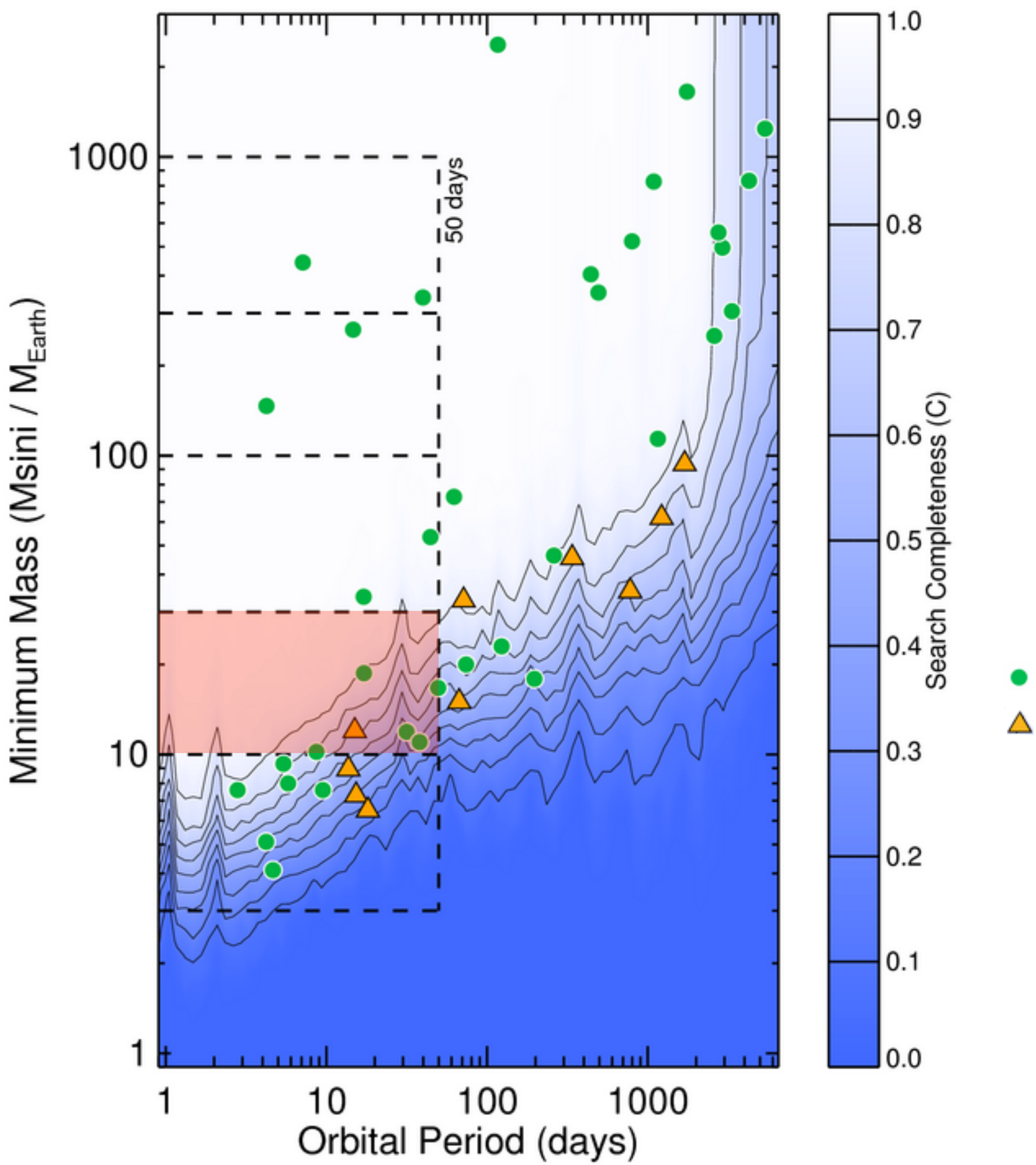
Minimum Mass (Msini / M$_{Earth}$)
1000
100
10
1
1
10
100
1000
Orbital Period (days)
50 days
Search Completeness (C)
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0



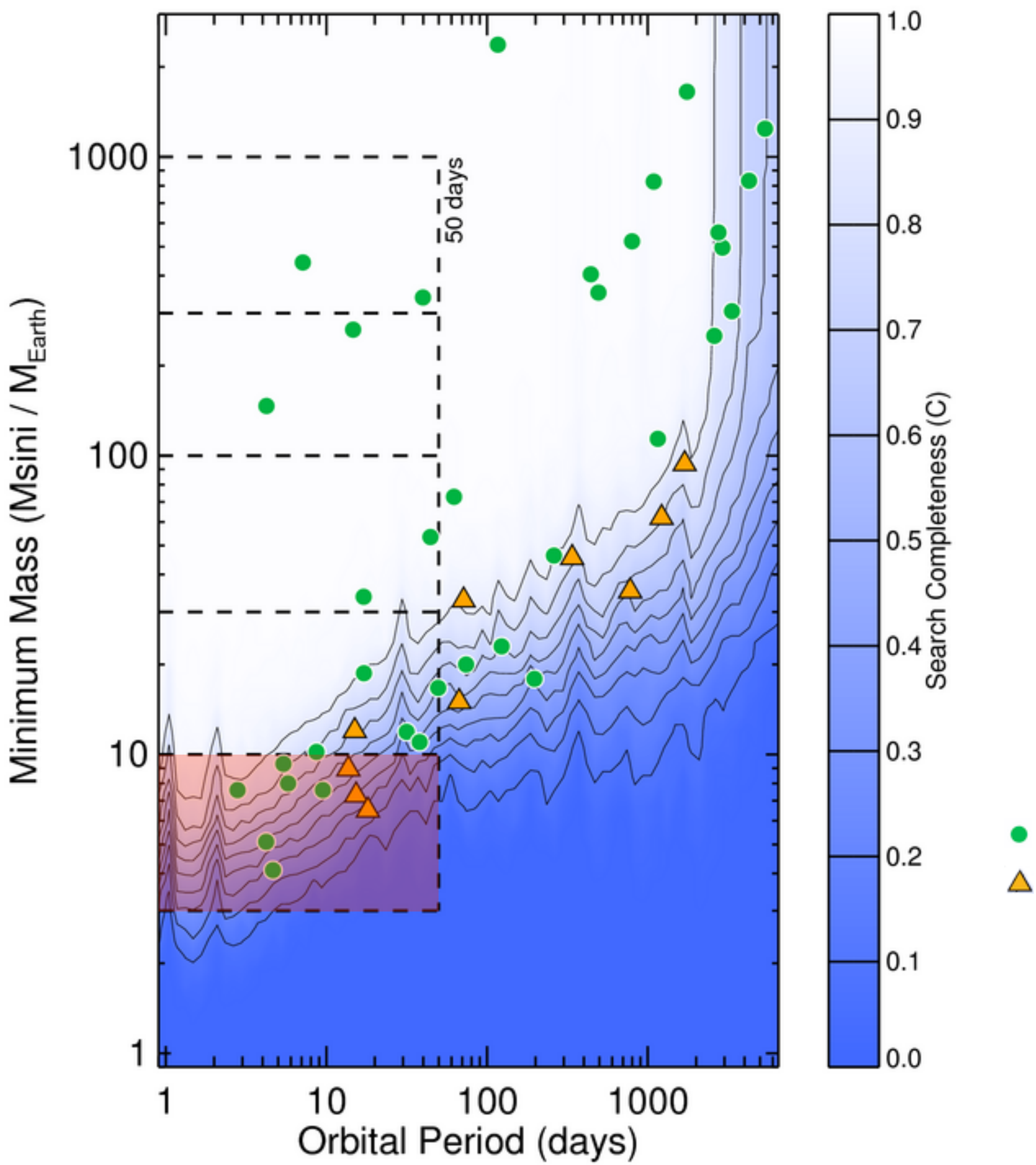
1000
100
10
1
1
10
100
1000
Orbital Period (days)
Minimum Mass (Msini / M$_{Earth}$)
50 days
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
Search Completeness (C)



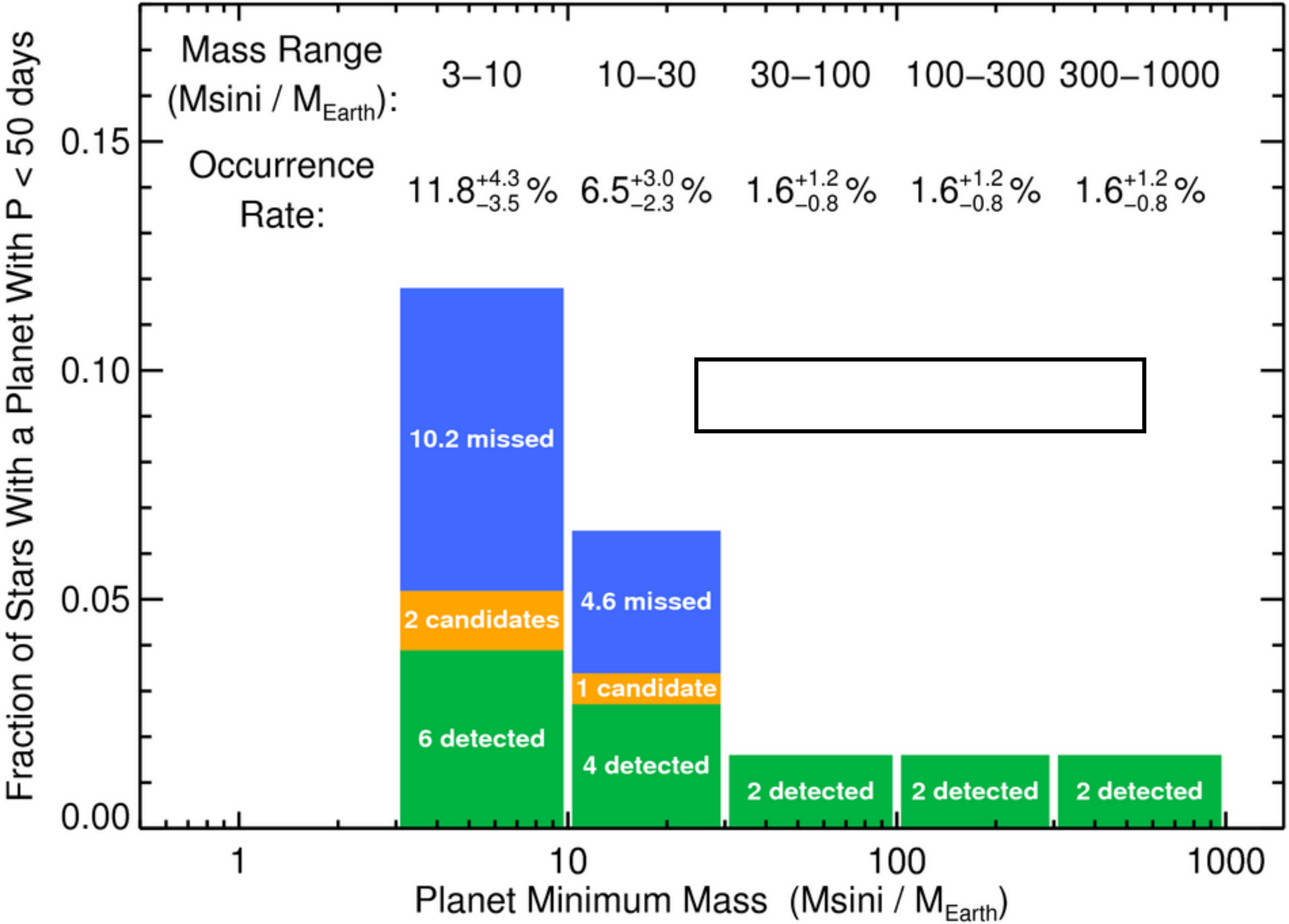
Minimum Mass (Msini / M_Earth)
1000
100
10
1
1
10
100
1000
Orbital Period (days)
50 days
Search Completeness (C)
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0



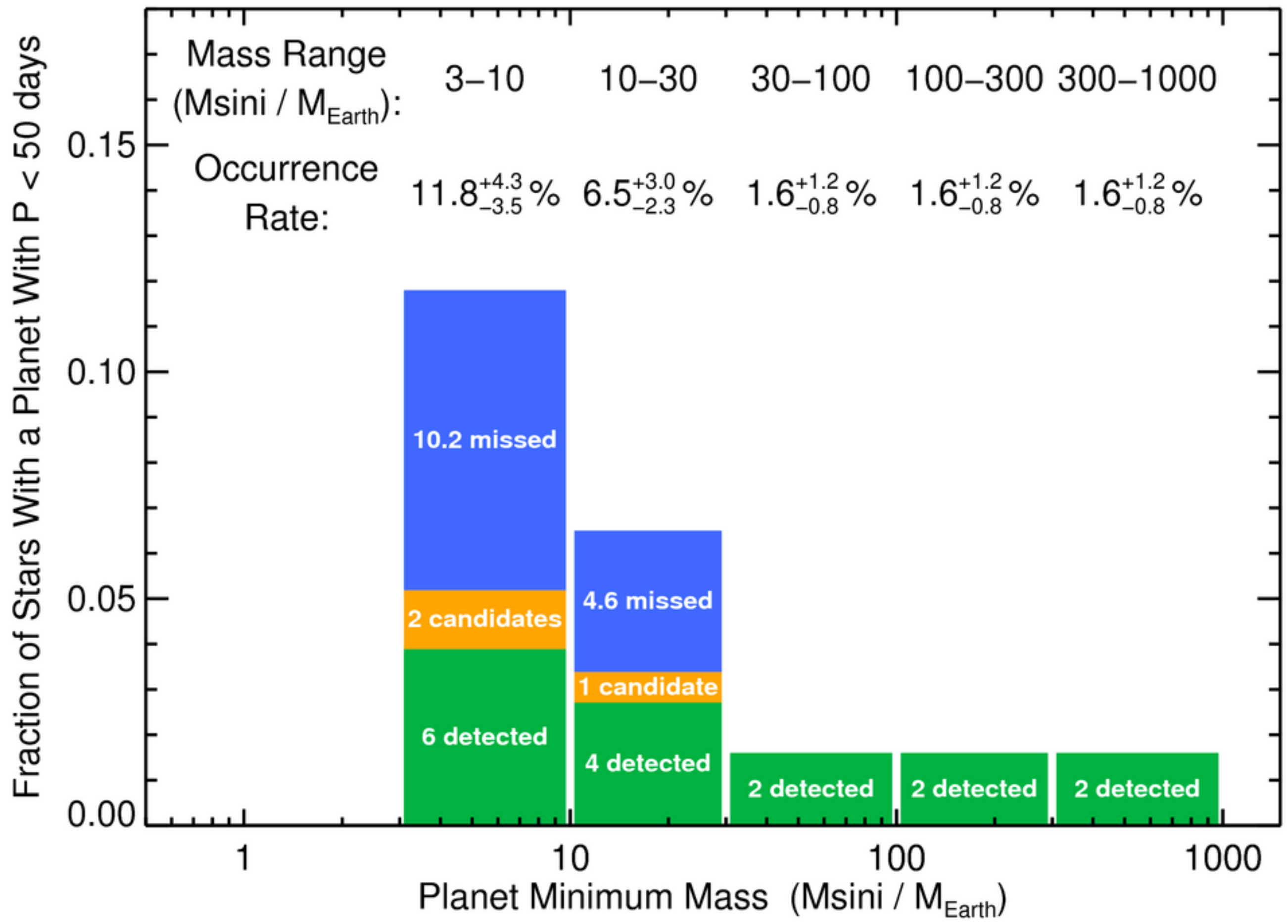
1000
100
10
1
50 days
Minimum Mass (Msini / M$_{Earth}$)
1
10
100
1000
Orbital Period (days)
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
Search Completeness (C)



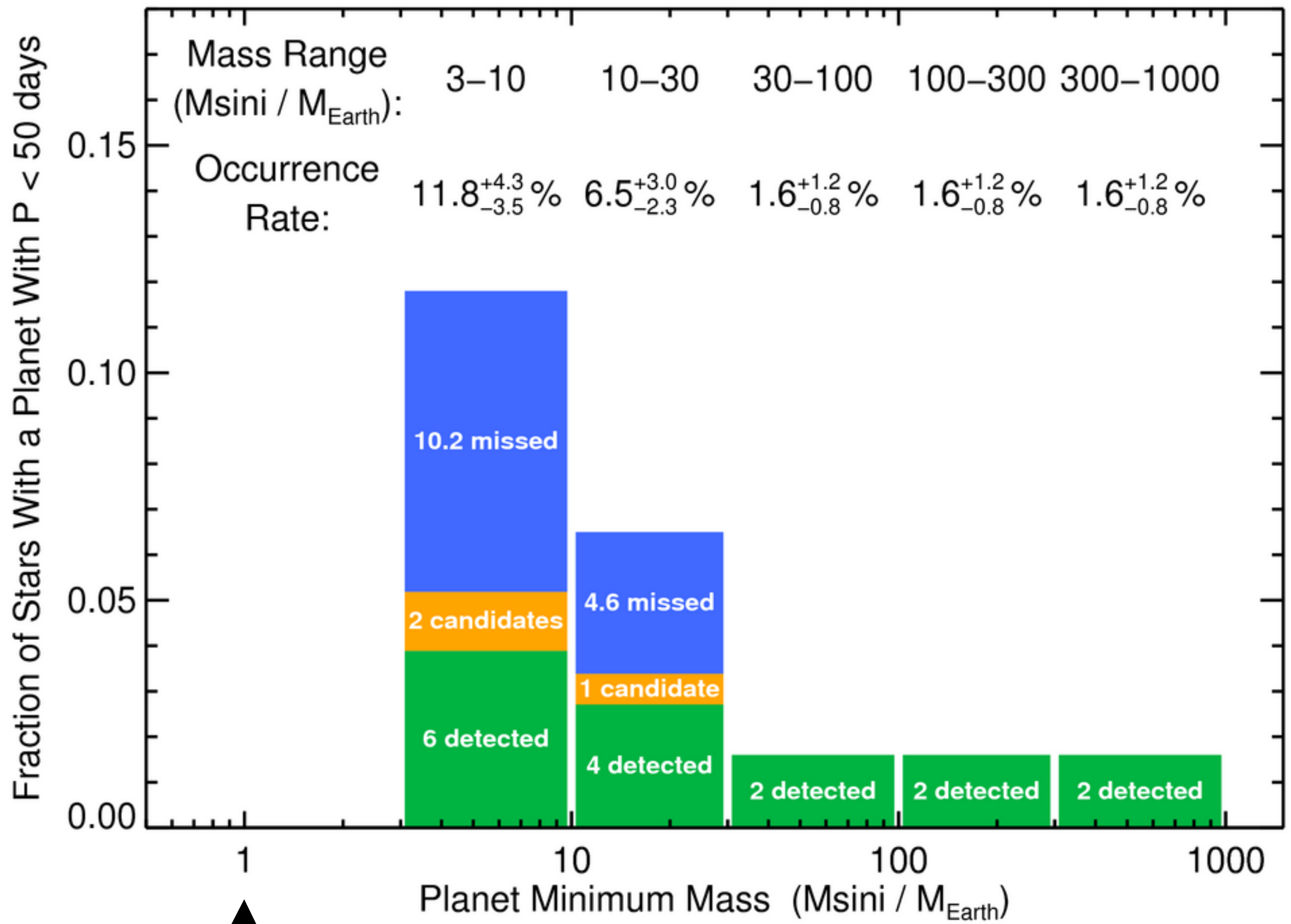
1000
100
10
1
50 days
Minimum Mass (Msini / M_Earth)
1
10
100
1000
Orbital Period (days)
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
Search Completeness (C)


Mass Range
(Msini / M_Earth):
3–10
10–30
30–100
100–300
300–1000
Occurrence
Rate:
11.8 +4.3 −3.5 %
6.5 +3.0 −2.3 %
1.6 +1.2 −0.8 %
1.6 +1.2 −0.8 %
1.6 +1.2 −0.8 %
10.2 missed
2 candidates
6 detected
4.6 missed
1 candidate
4 detected
2 detected
2 detected
2 detected
Fraction of Stars With a Planet With P < 50 days
0.00
0.05
0.10
0.15
1
10
100
1000
Planet Minimum Mass (Msini / M_Earth)

Key Result: Occurrence rate of Super-Earths + Neptunes



Key Result: Earth-mass Planets Common

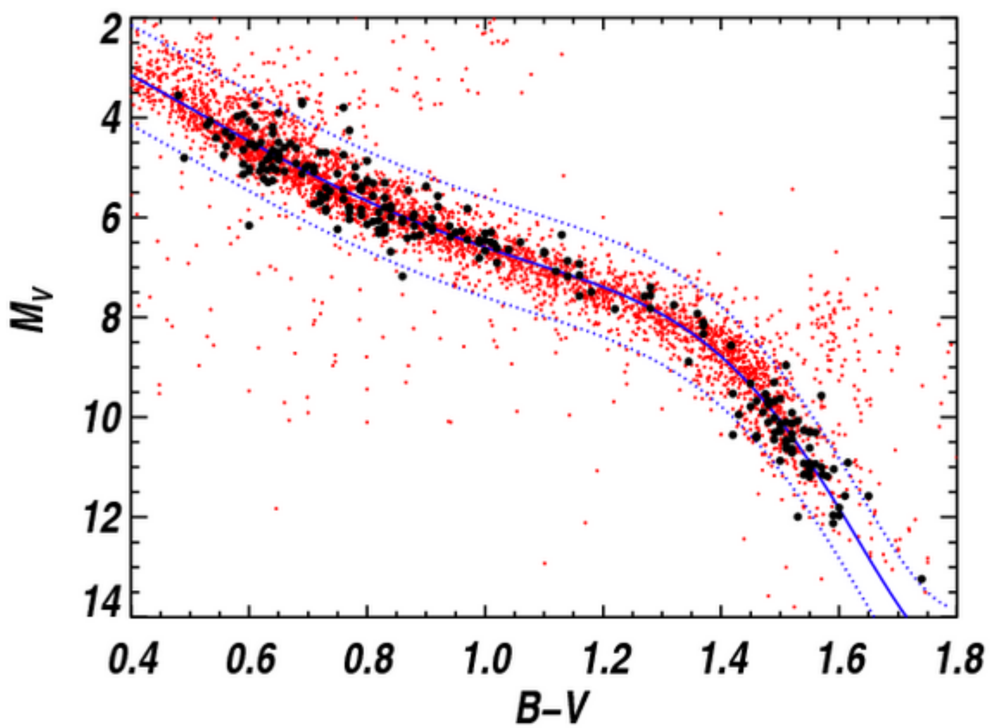


η_{Earth}

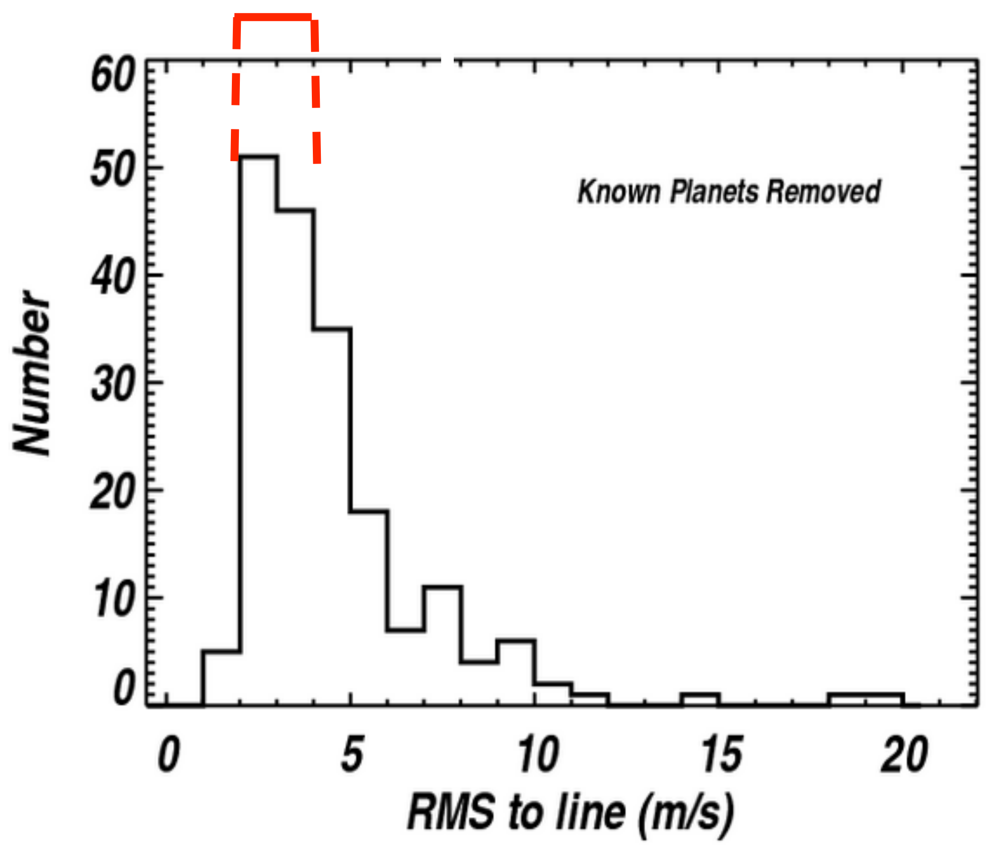
HARPS + CORALIE Volume-limited Survey

Mayor et al. (2011)

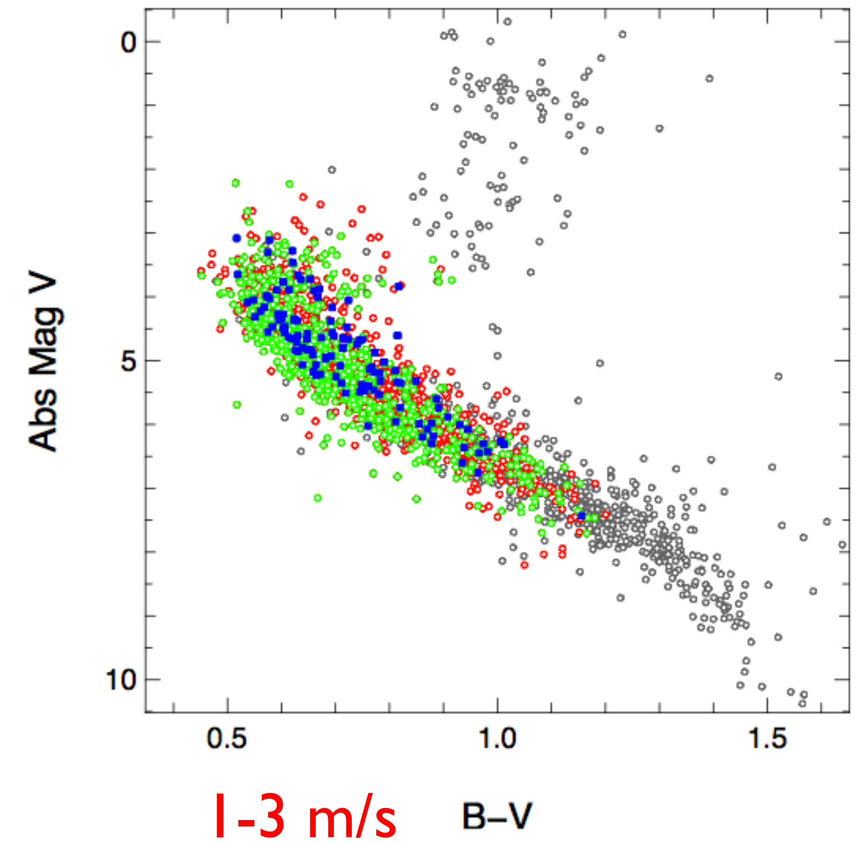
Keck/HIRES



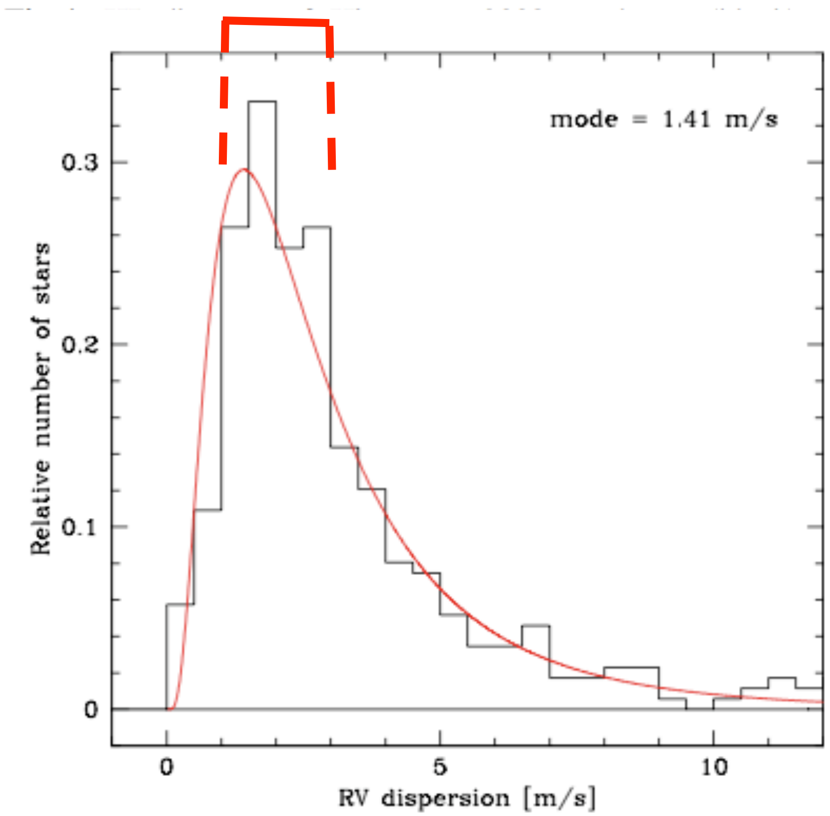
2-4 m/s



HARPS

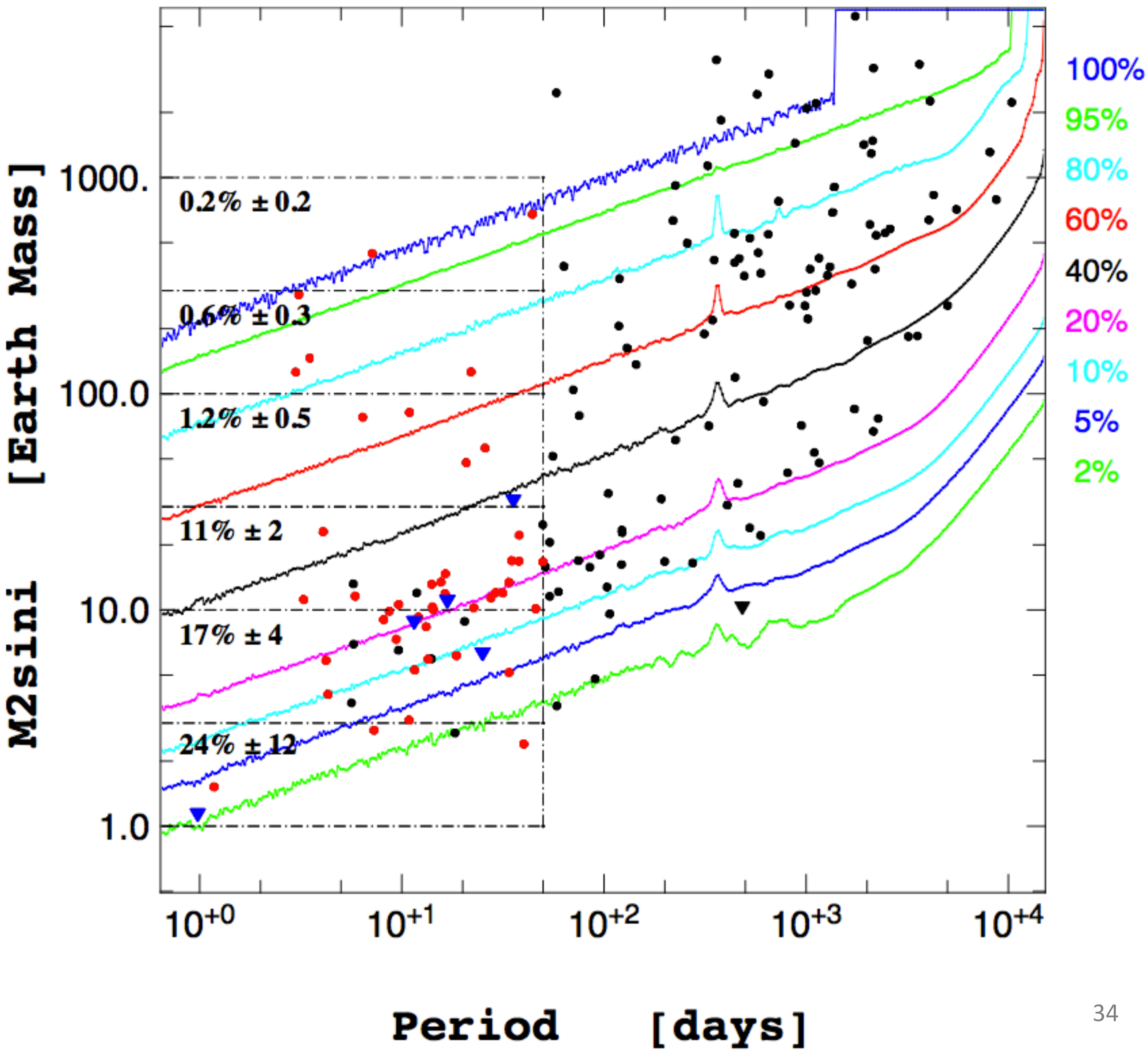


1-3 m/s



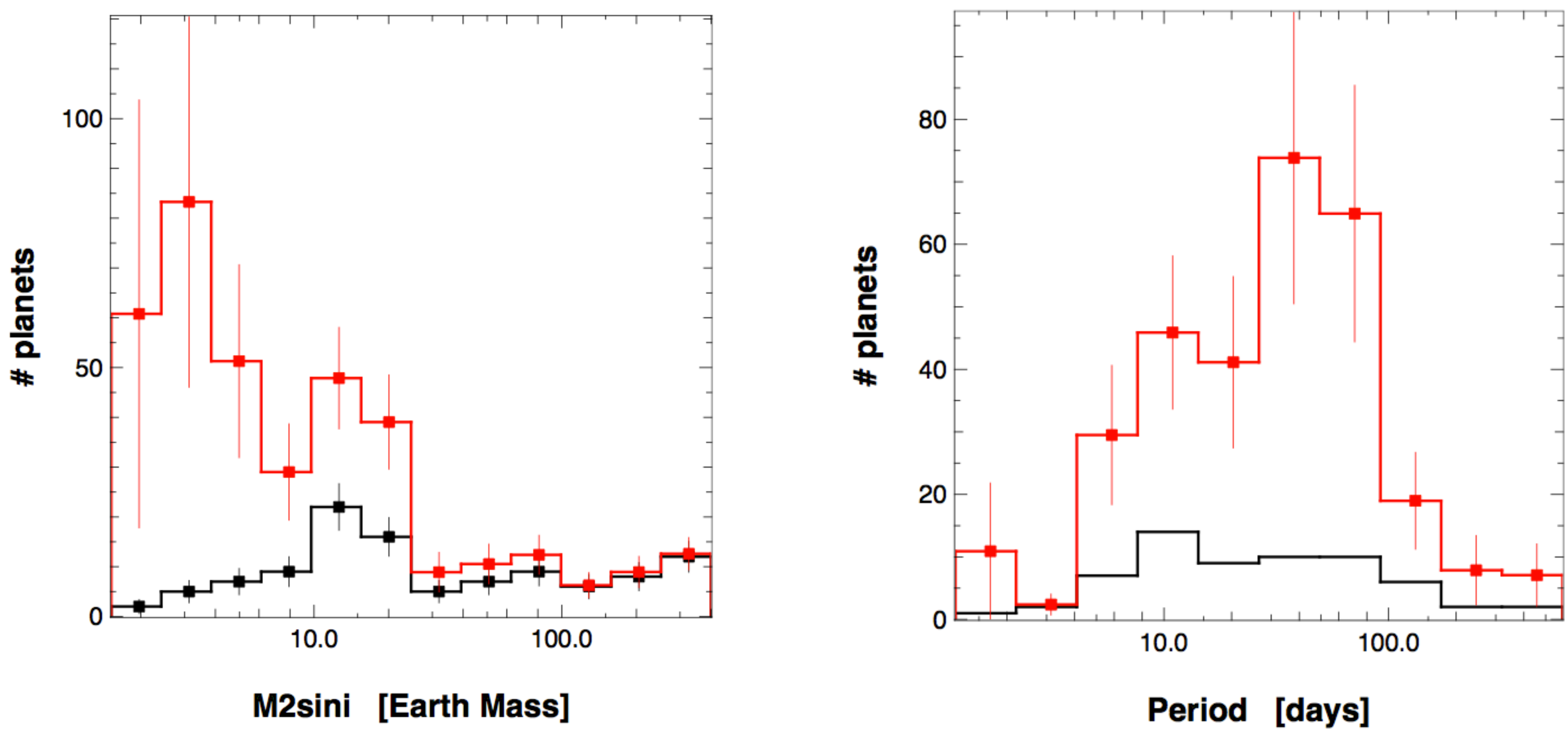
HARPS + CORALIE Volume-limited Survey

Mayor et al. (2011)



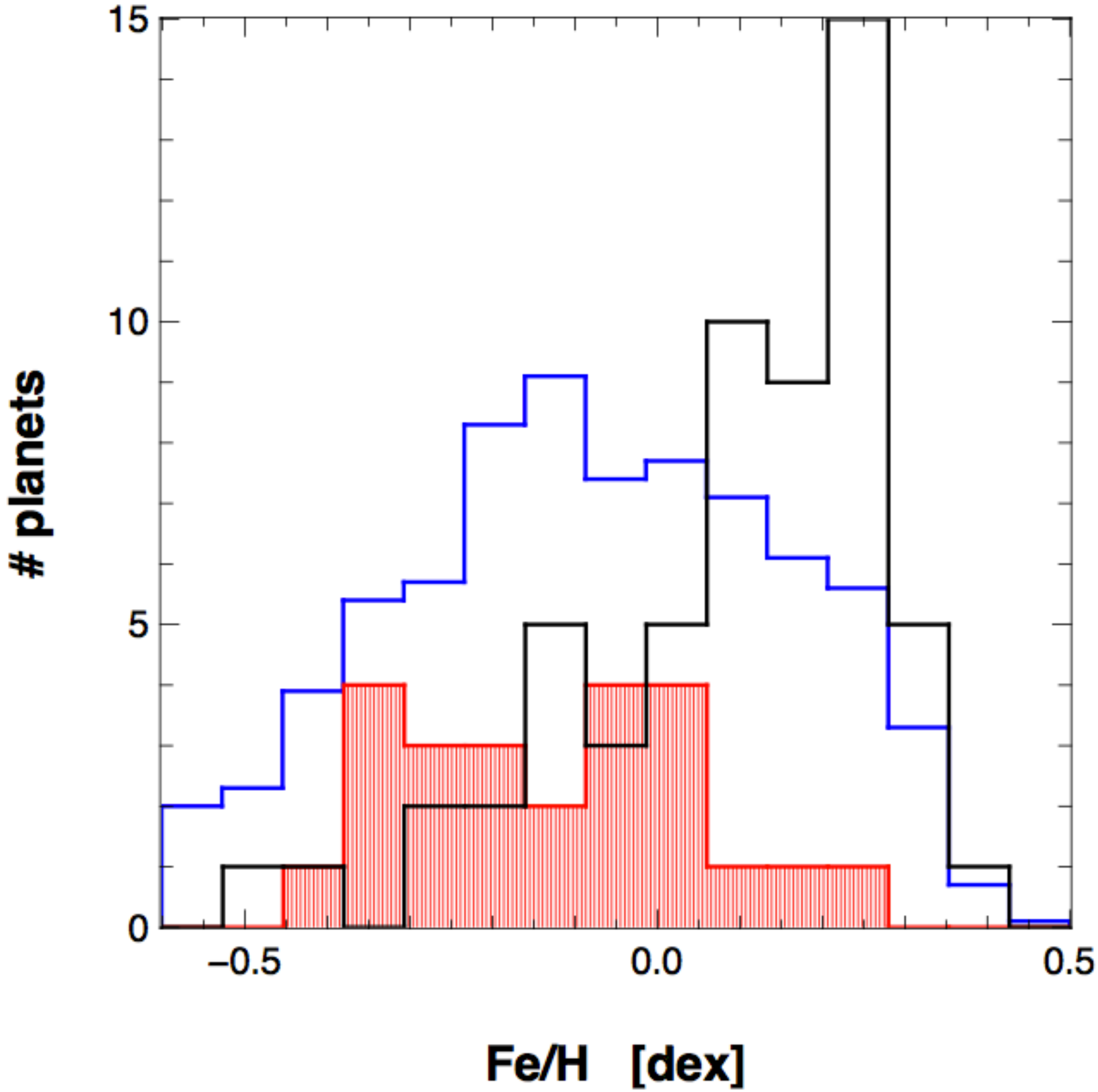
HARPS + CORALIE Volume-limited Survey

Mayor et al. (2011)

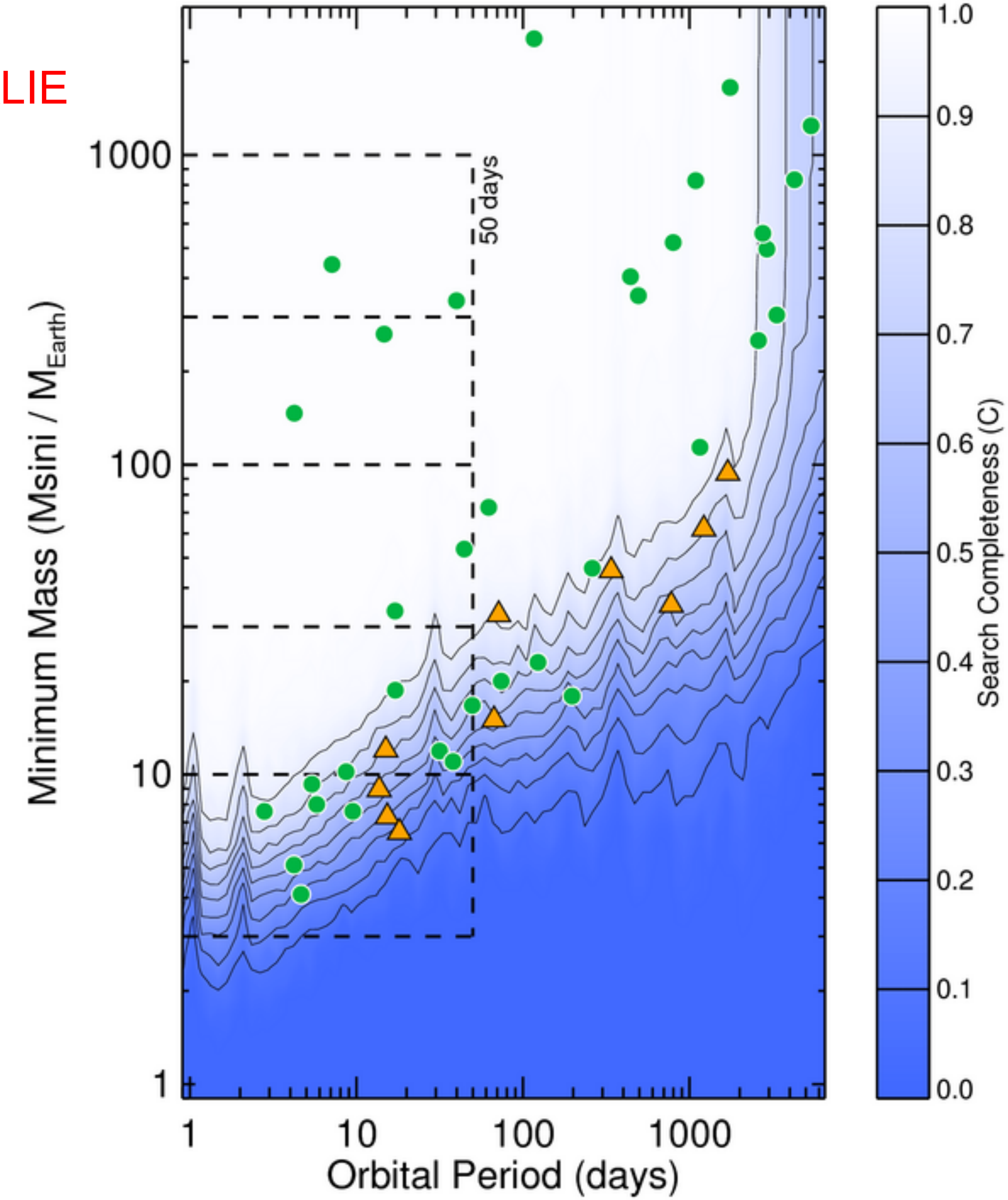


HARPS + CORALIE Volume-limited Survey

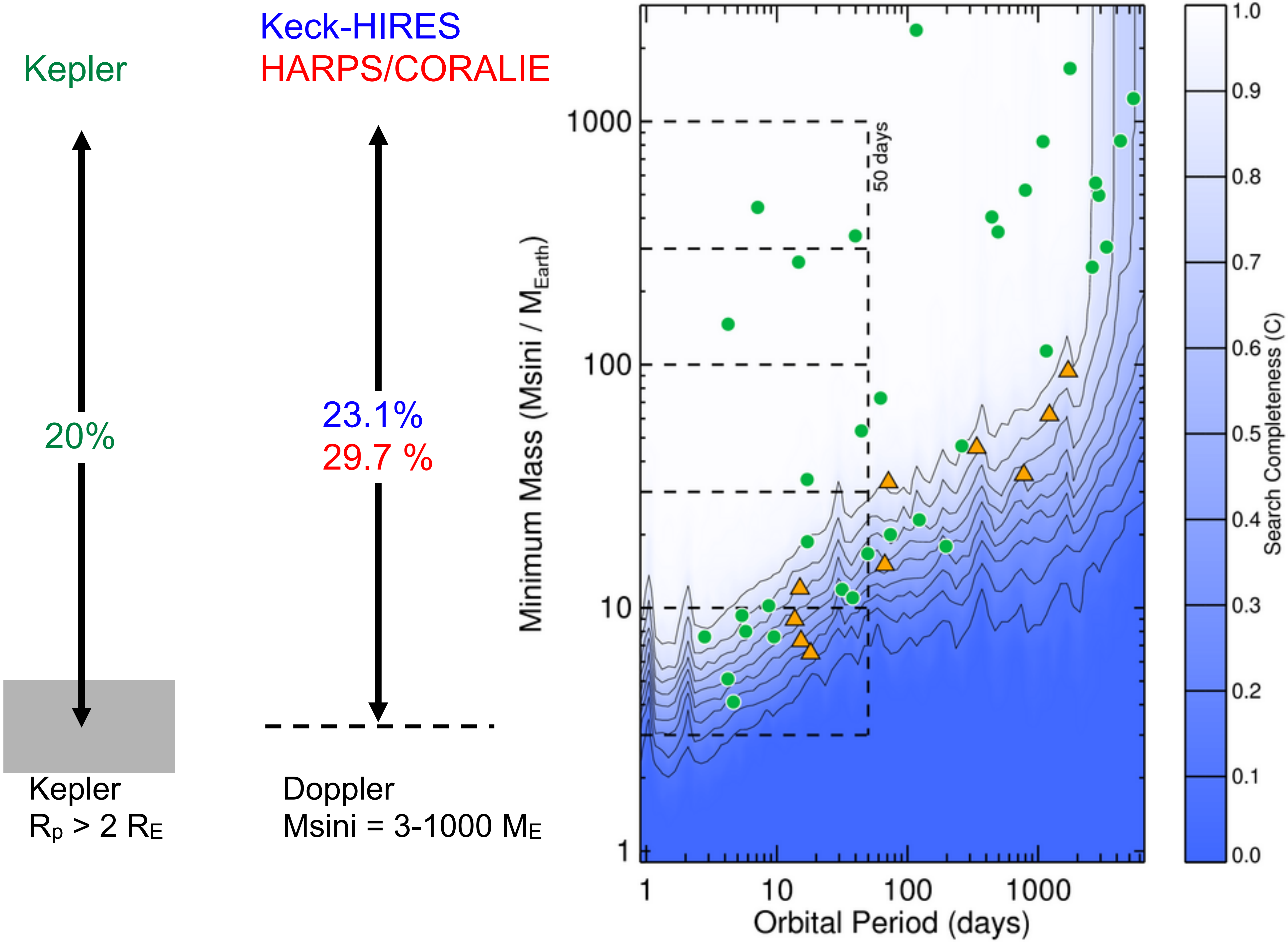
Mayor et al. (2011)



Difference	Keck-HIRES	HARPS/CORALIE
+1.1σ	1.6 ± 1.2 %	0.24 ± 0.17 %
+0.8σ	1.6 ± 1.2 %	0.58 ± 0.29 %
+0.3σ	1.6 ± 1.2 %	1.17 ± 0.52 %
+1.2σ	6.5 ± 3.0 %	11.1 ± 2.4 %
+0.8σ	11.8 ± 4.3 %	16.6 ± 4.4 %
		24 ± 12 %



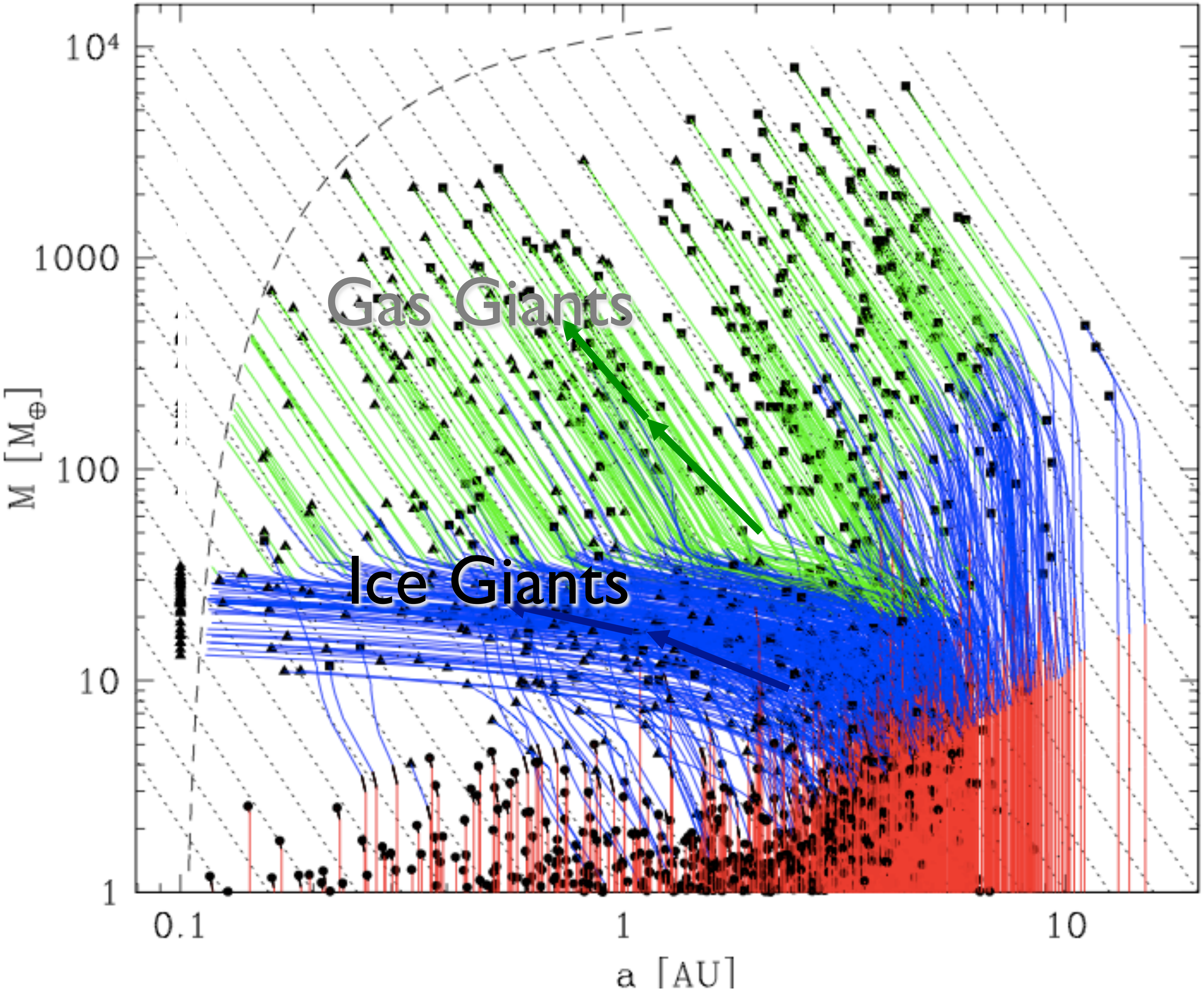
Howard et al. (2010)
Mayor et al. (2011)

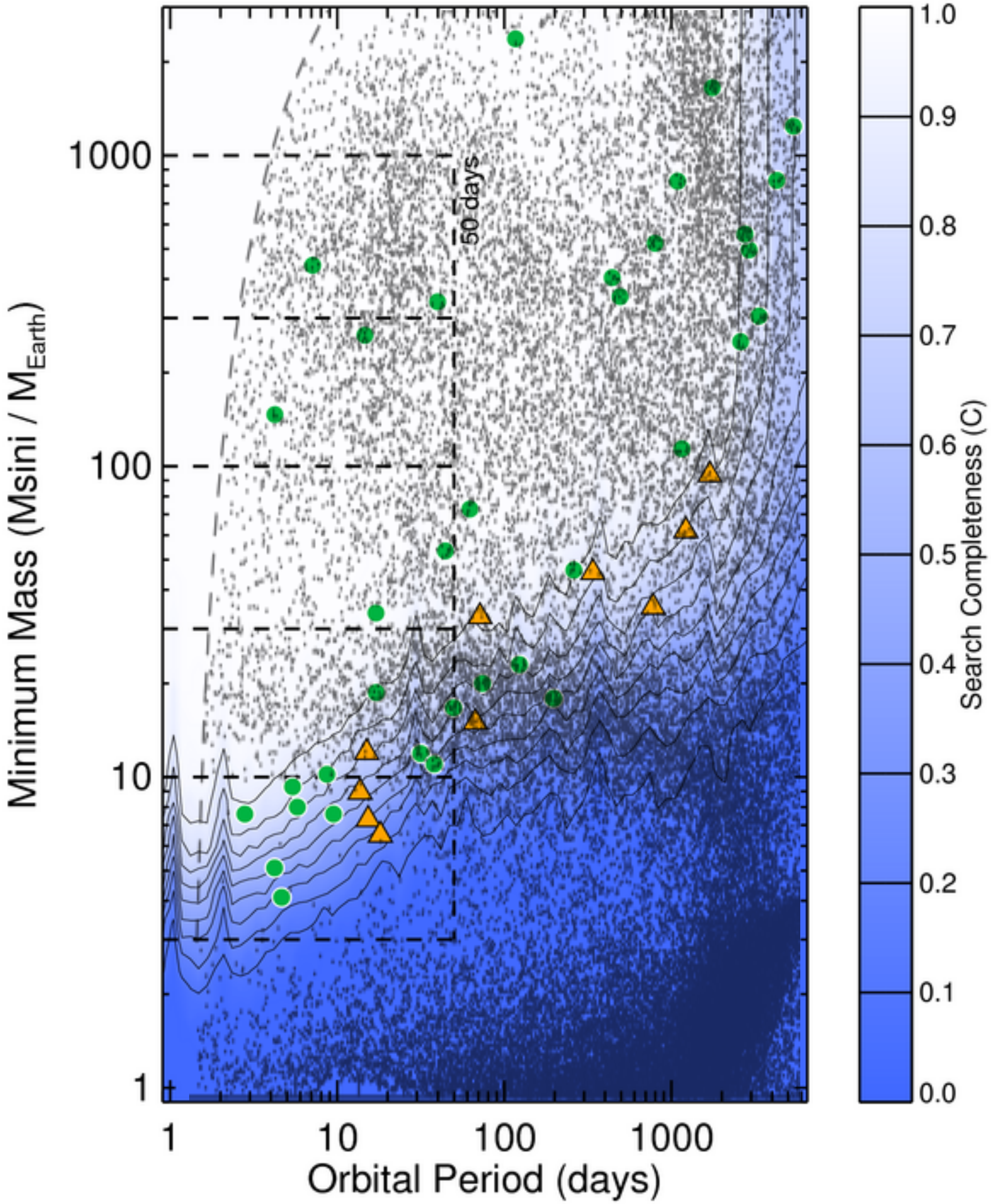


Kepler
Keck-HIRES
HARPS/CORALIE
20%
23.1%
29.7 %
Kepler
Rp > 2 RE
Doppler
Msini = 3-1000 ME
50 days
Minimum Mass (Msini / MEarth)
Orbital Period (days)
Search Completeness (C)
1
10
100
1000
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0

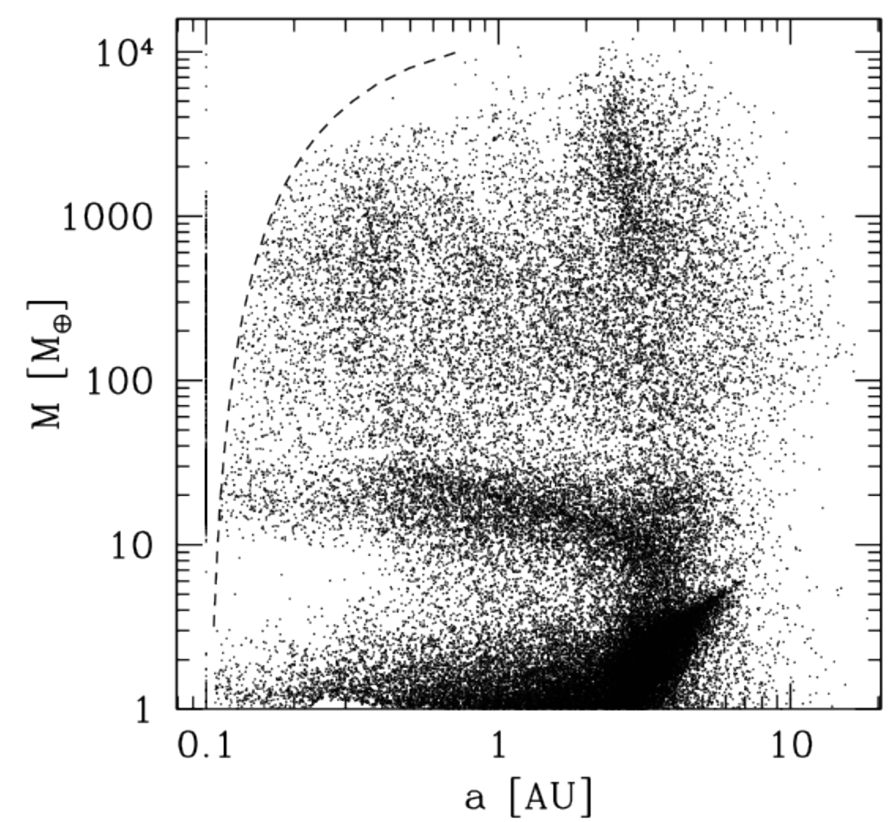
Population Synthesis Model: Planet Formation & Migration

Mordasini, Alibert, & Benz (2009)





Minimum Mass (Msini / M_{Earth})
Orbital Period (days)
Search Completeness (C)
50 days
1000
100
10
1
1
10
100
1000
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0



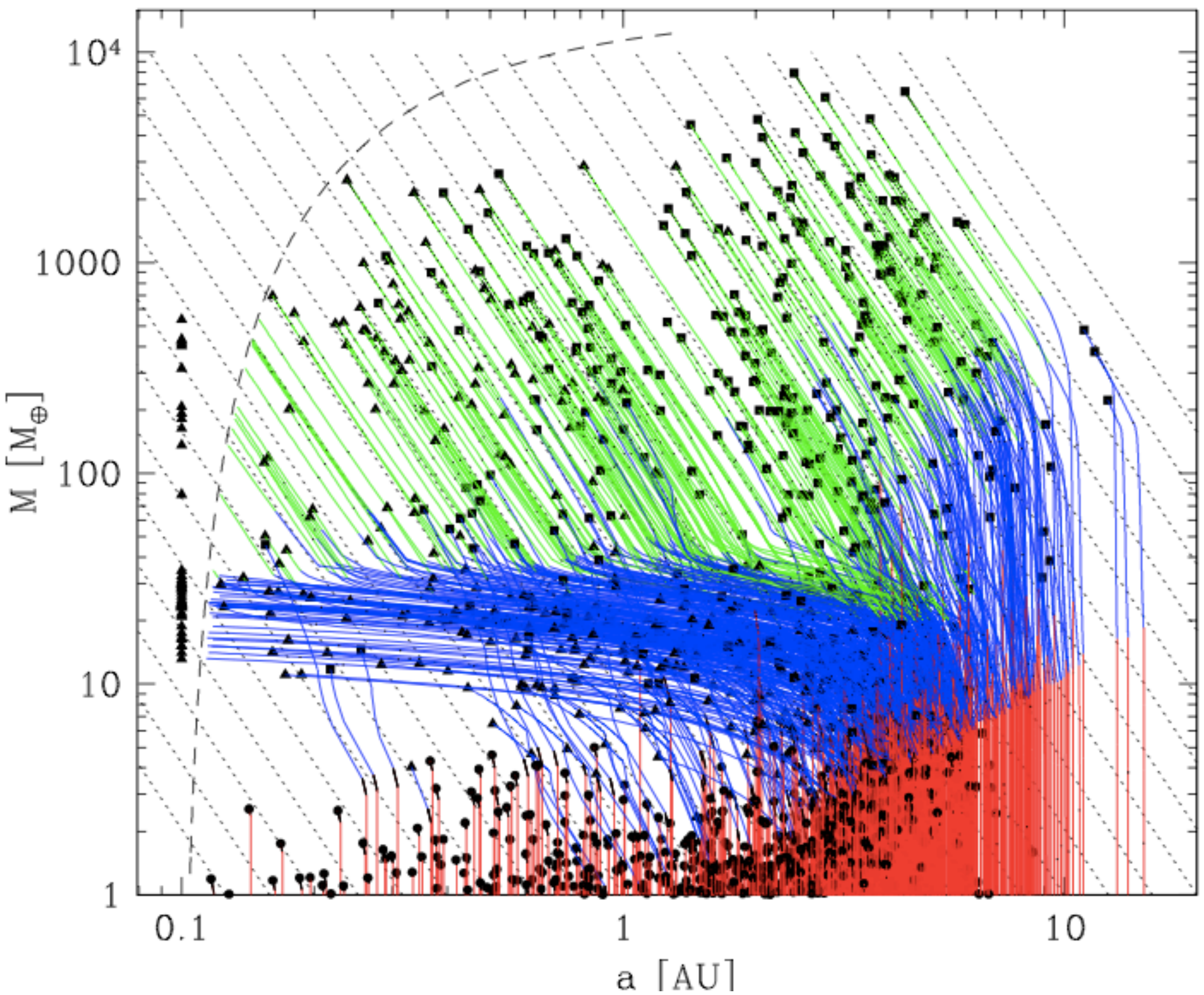
M [$M_\oplus$]
a [AU]
10^4
1000
100
10
1
0.1
1
10

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

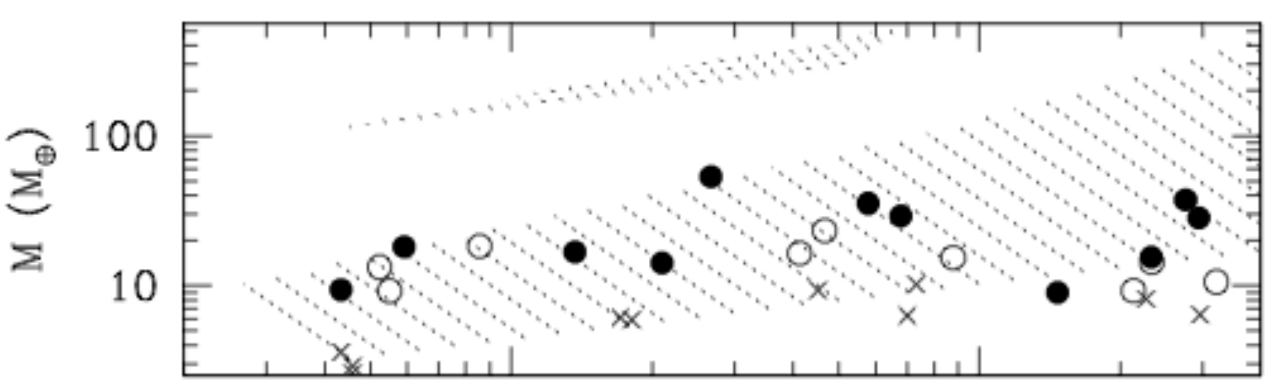
Hansen & Murray (2011, arXiv:1105.2050)

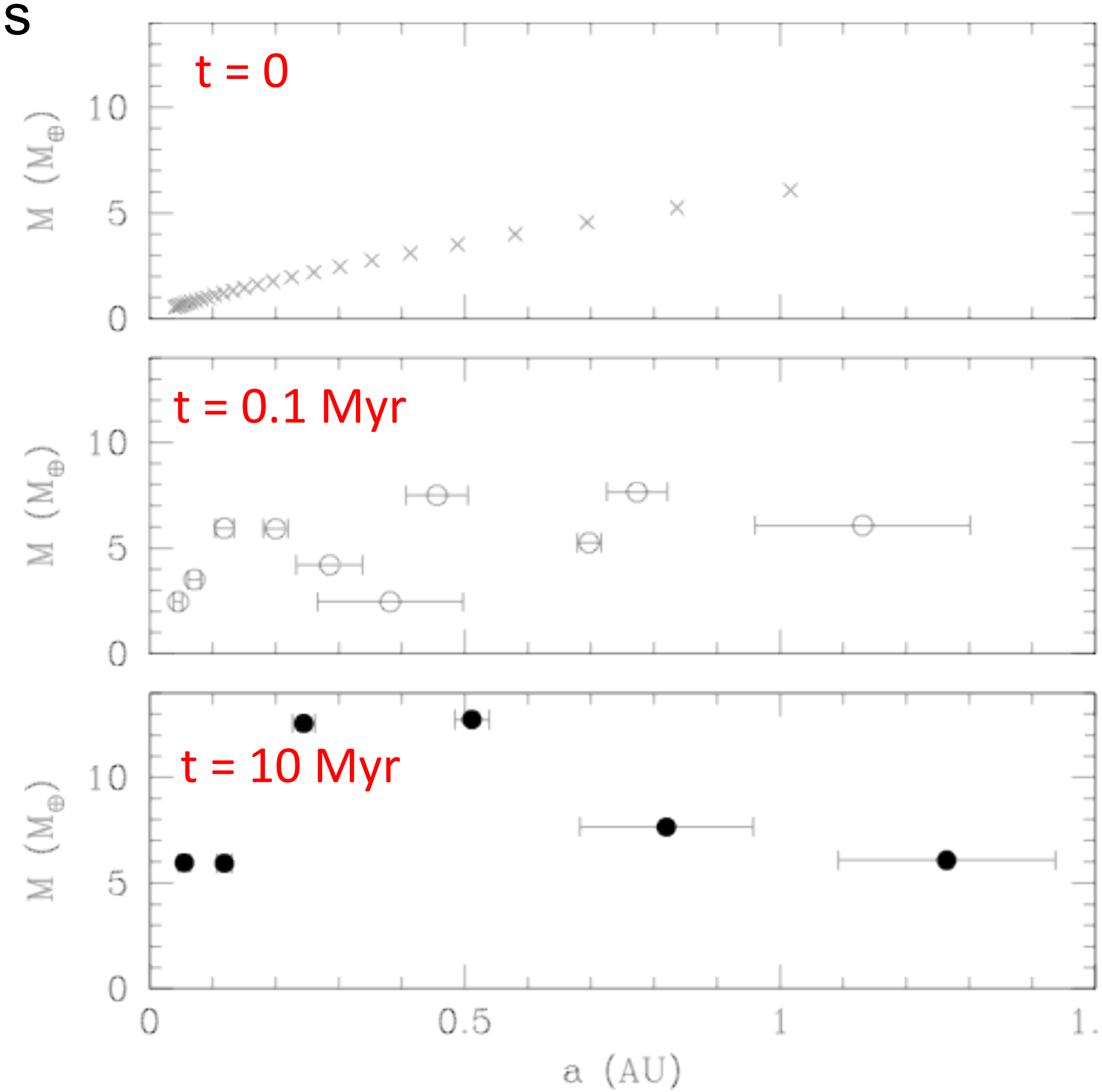
Migration then Assembly (heretical picture):

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

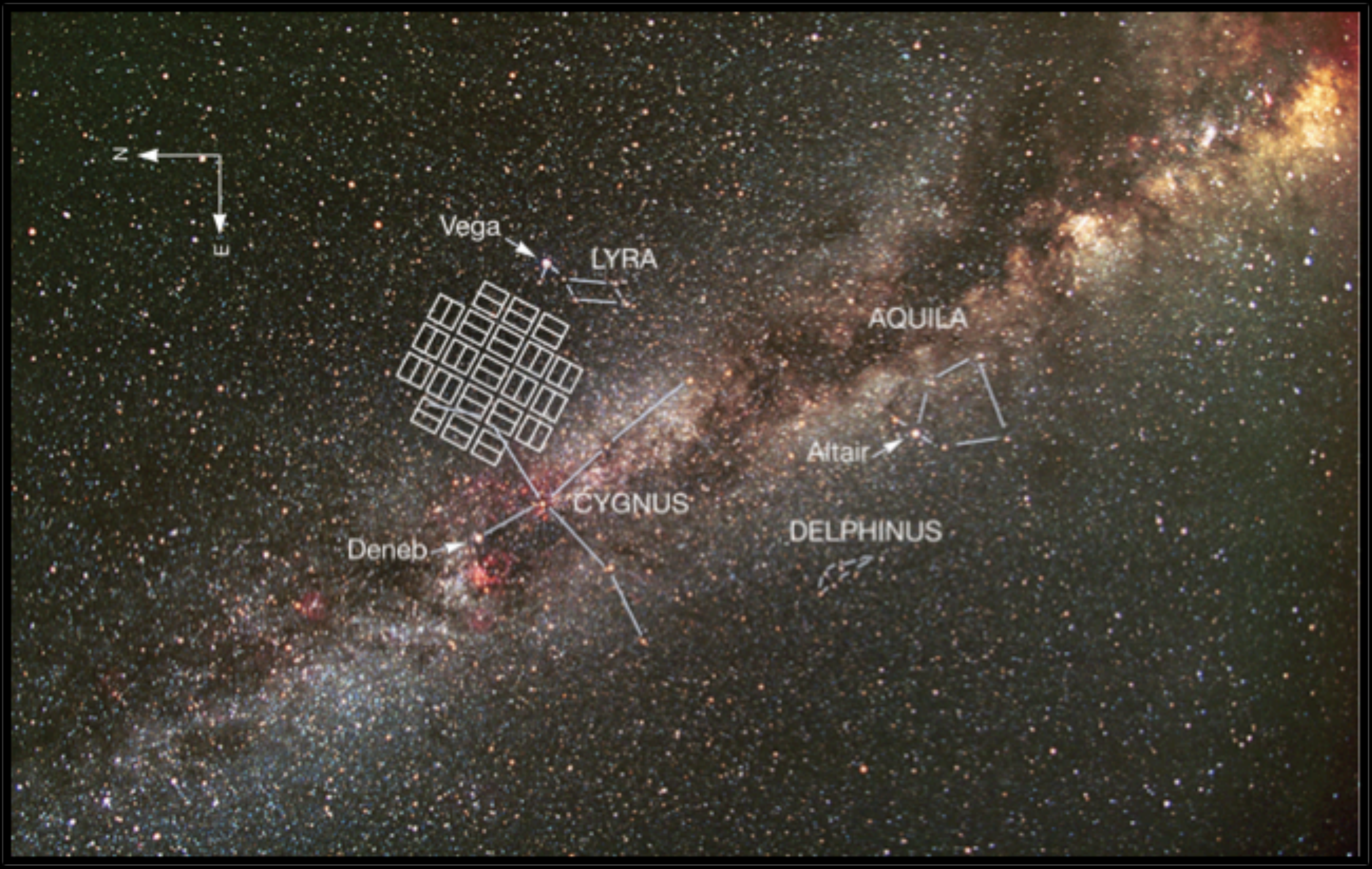
Goal of toy model:

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

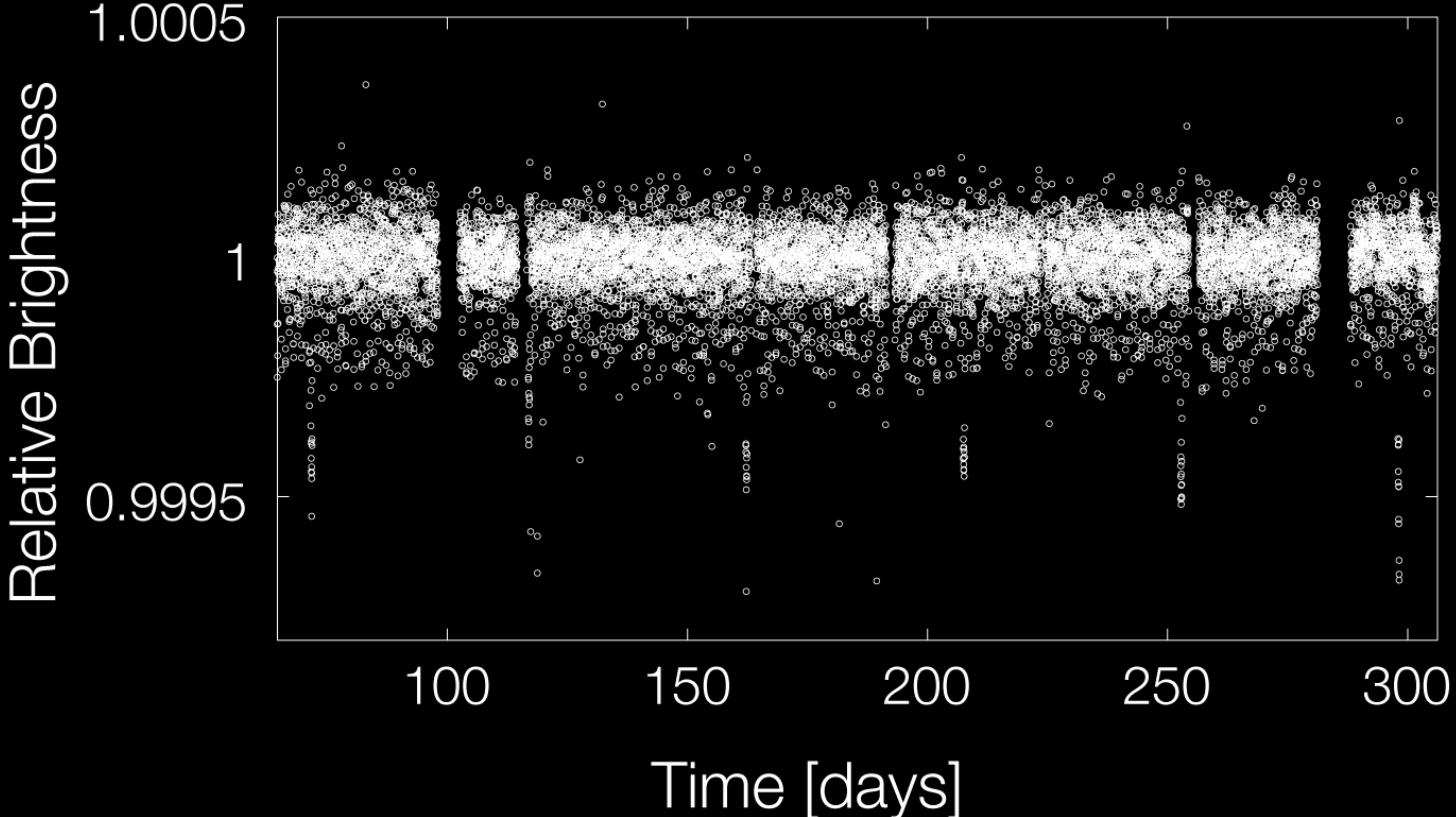




NASA's Kepler Mission

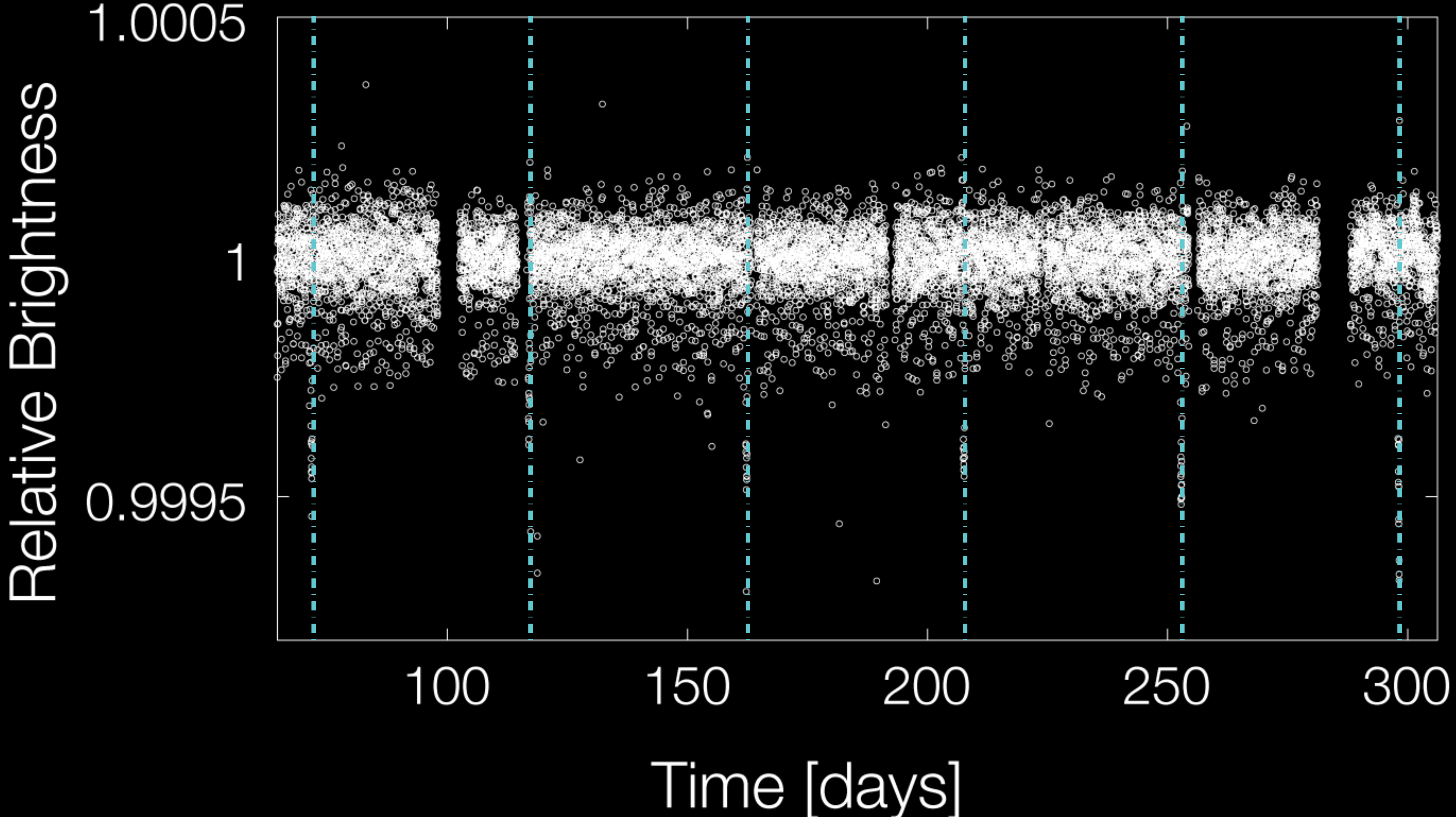


Kepler-10 Light Curve



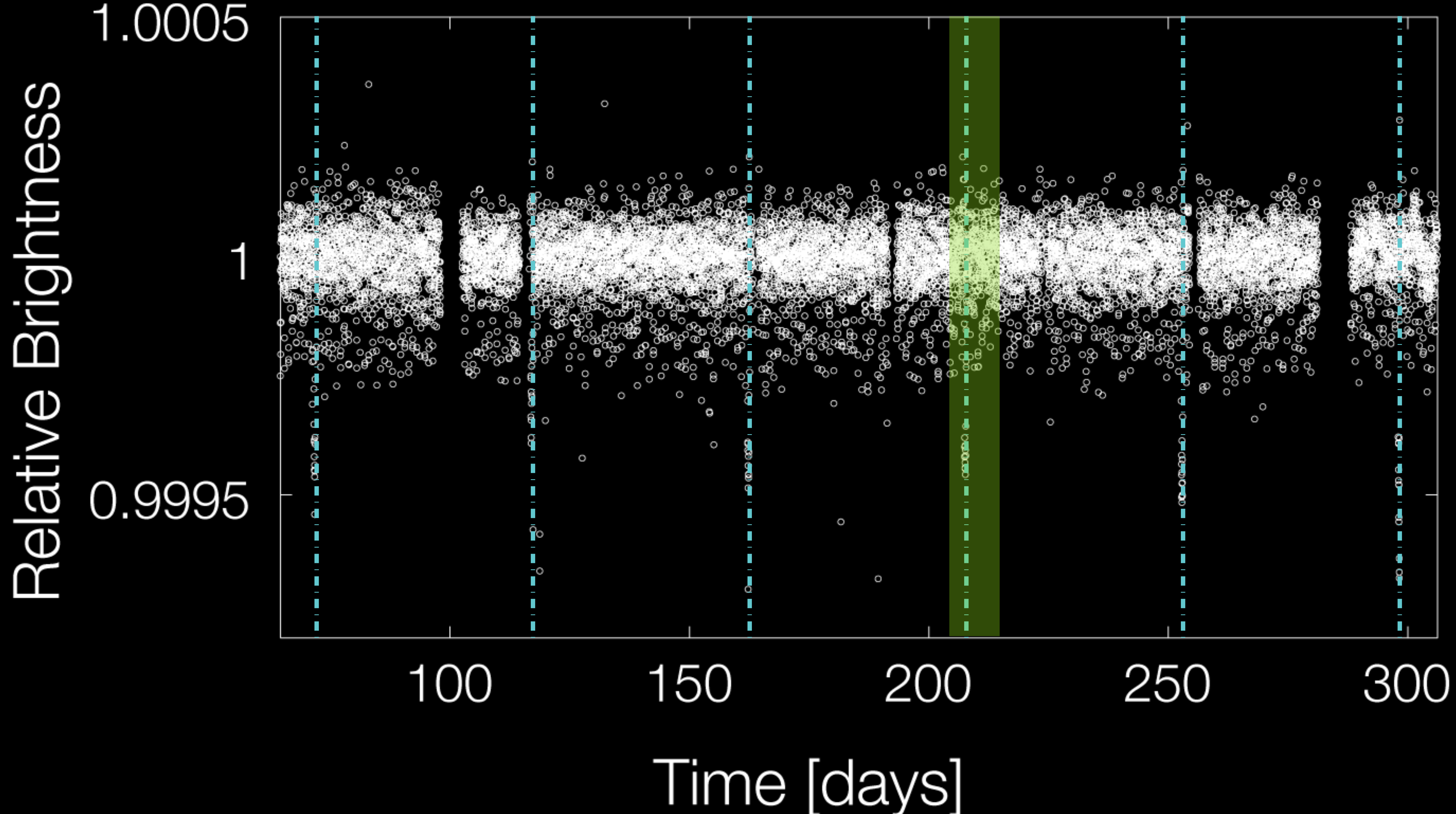
Kepler-10 Light Curve

Period = 45.29 days

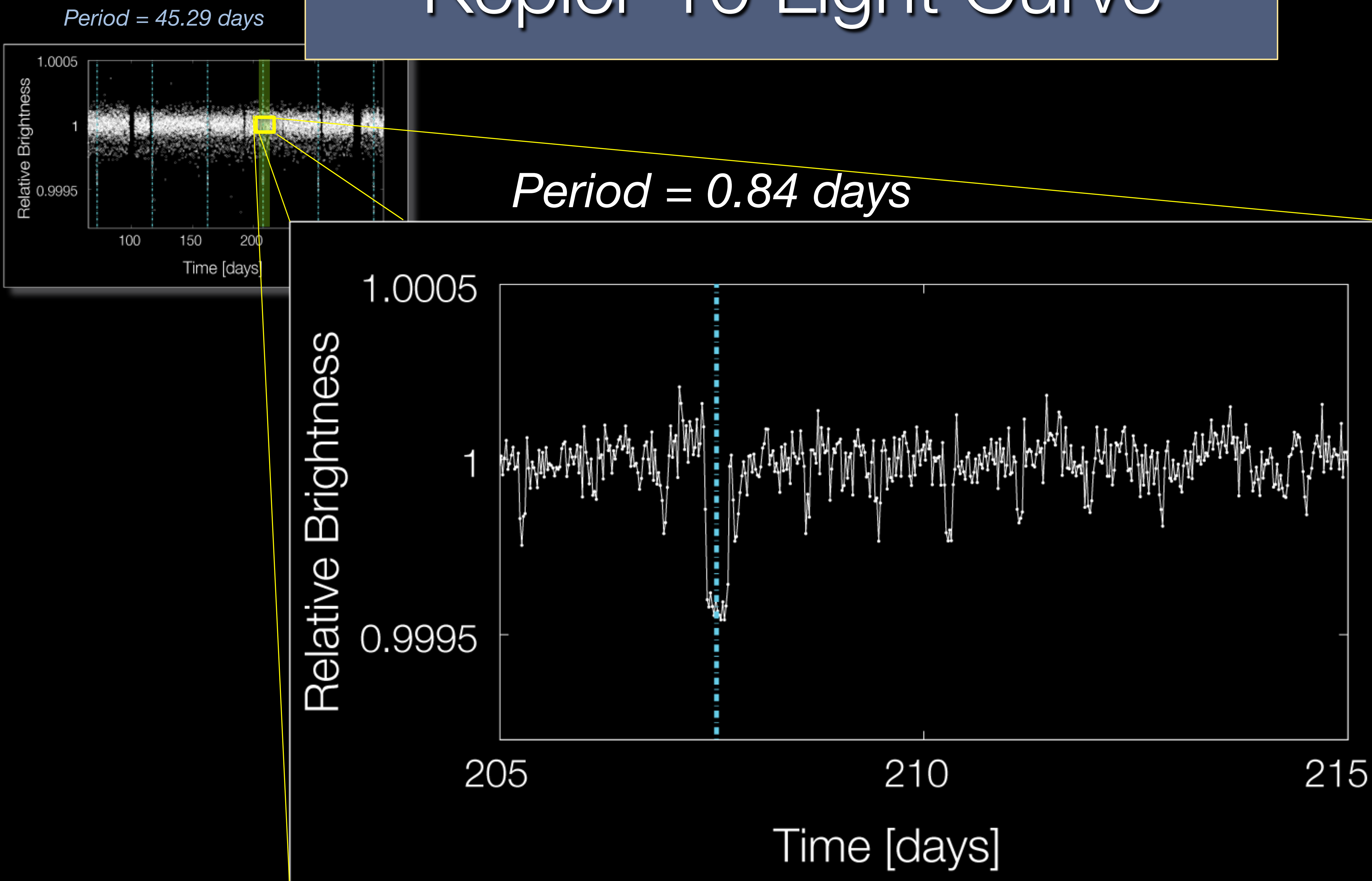


Kepler-10 Light Curve

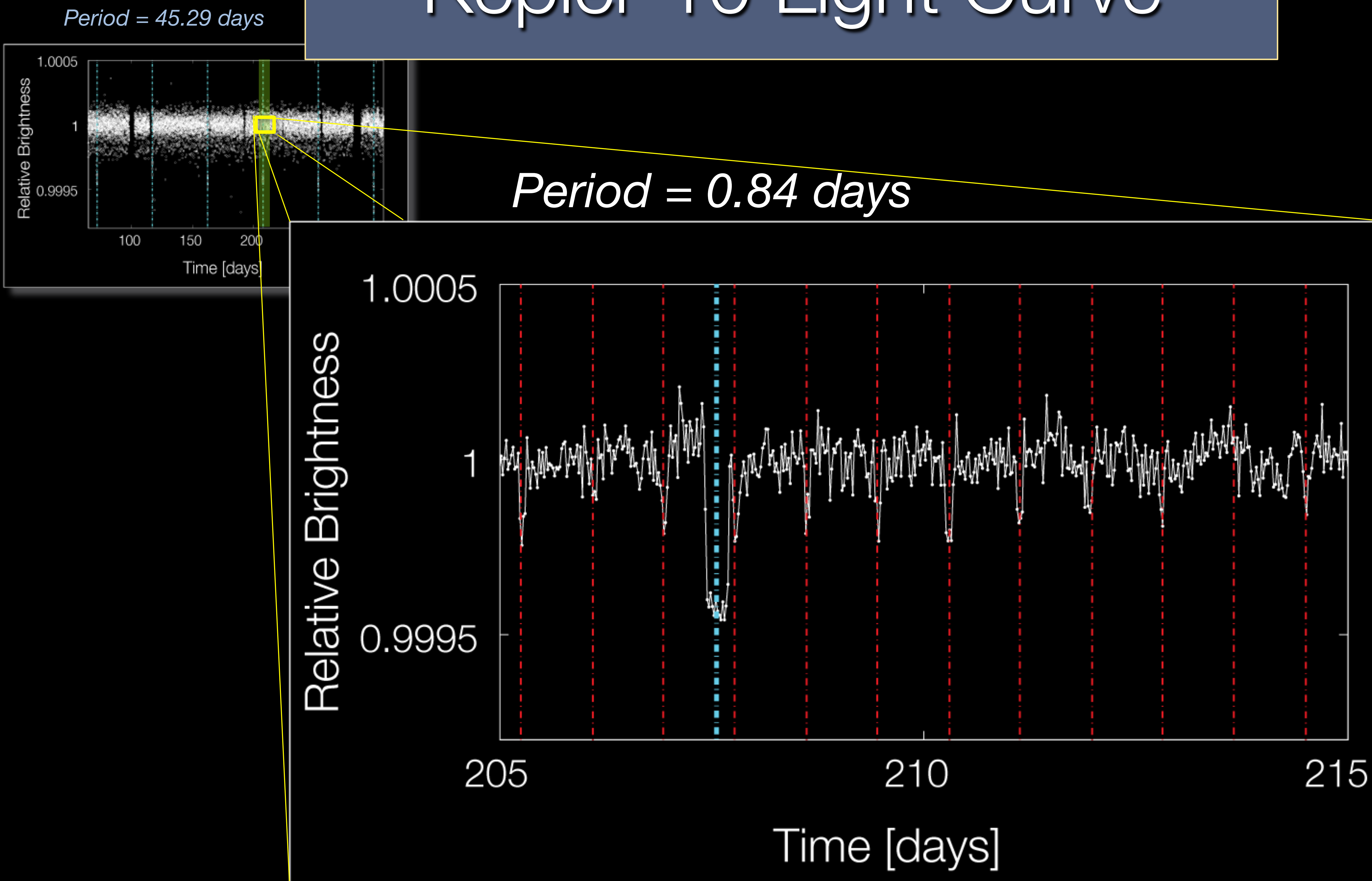
Period = 45.29 days



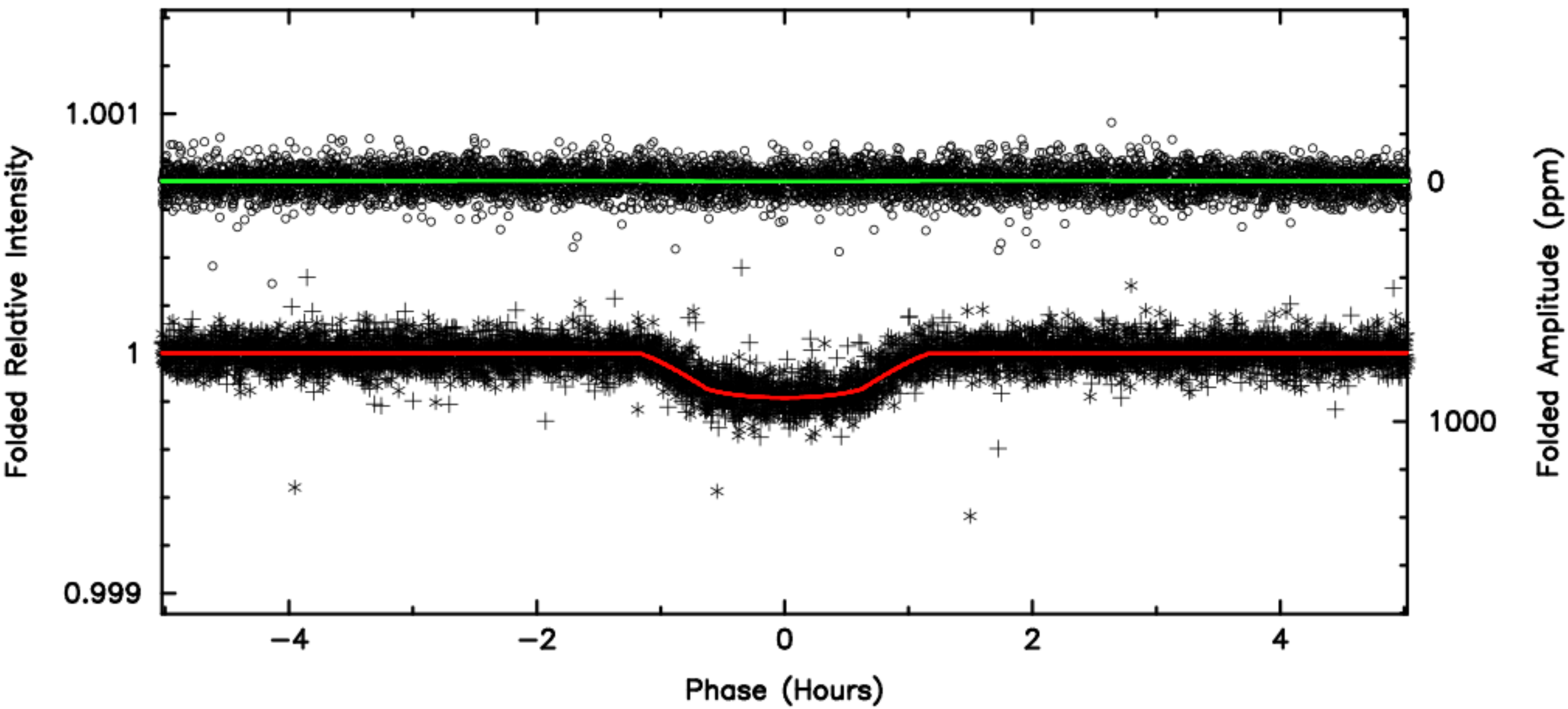
Kepler-10 Light Curve



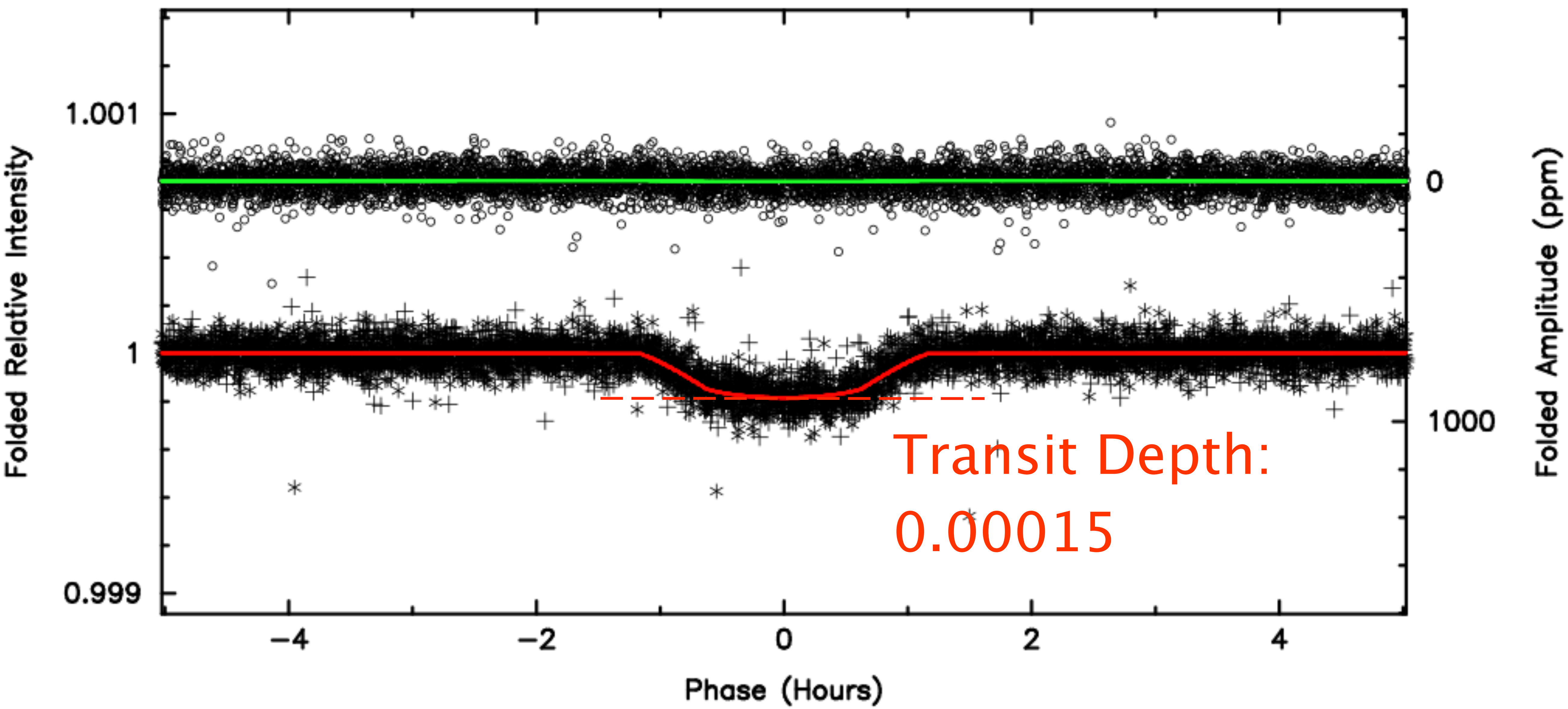
Kepler-10 Light Curve



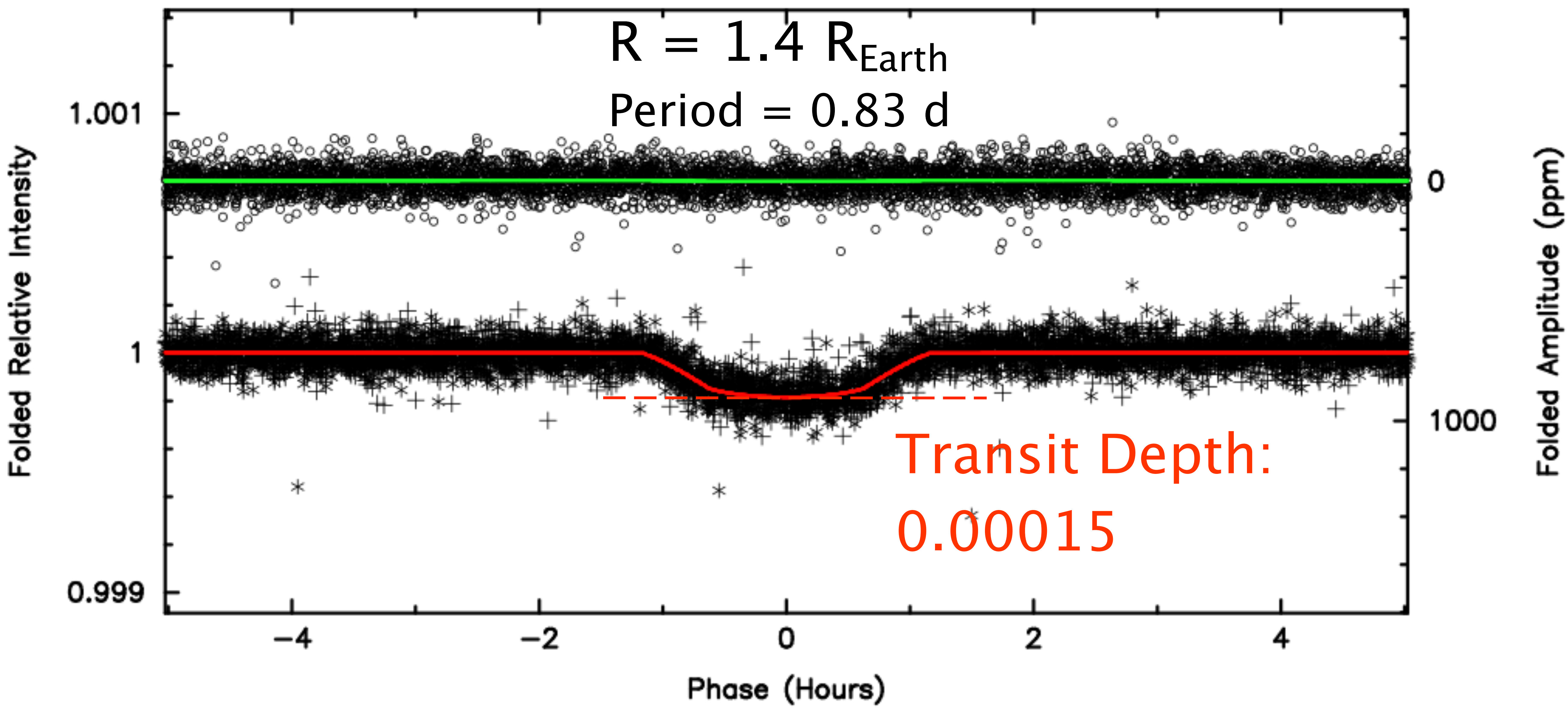
Kepler-10 Light Curve



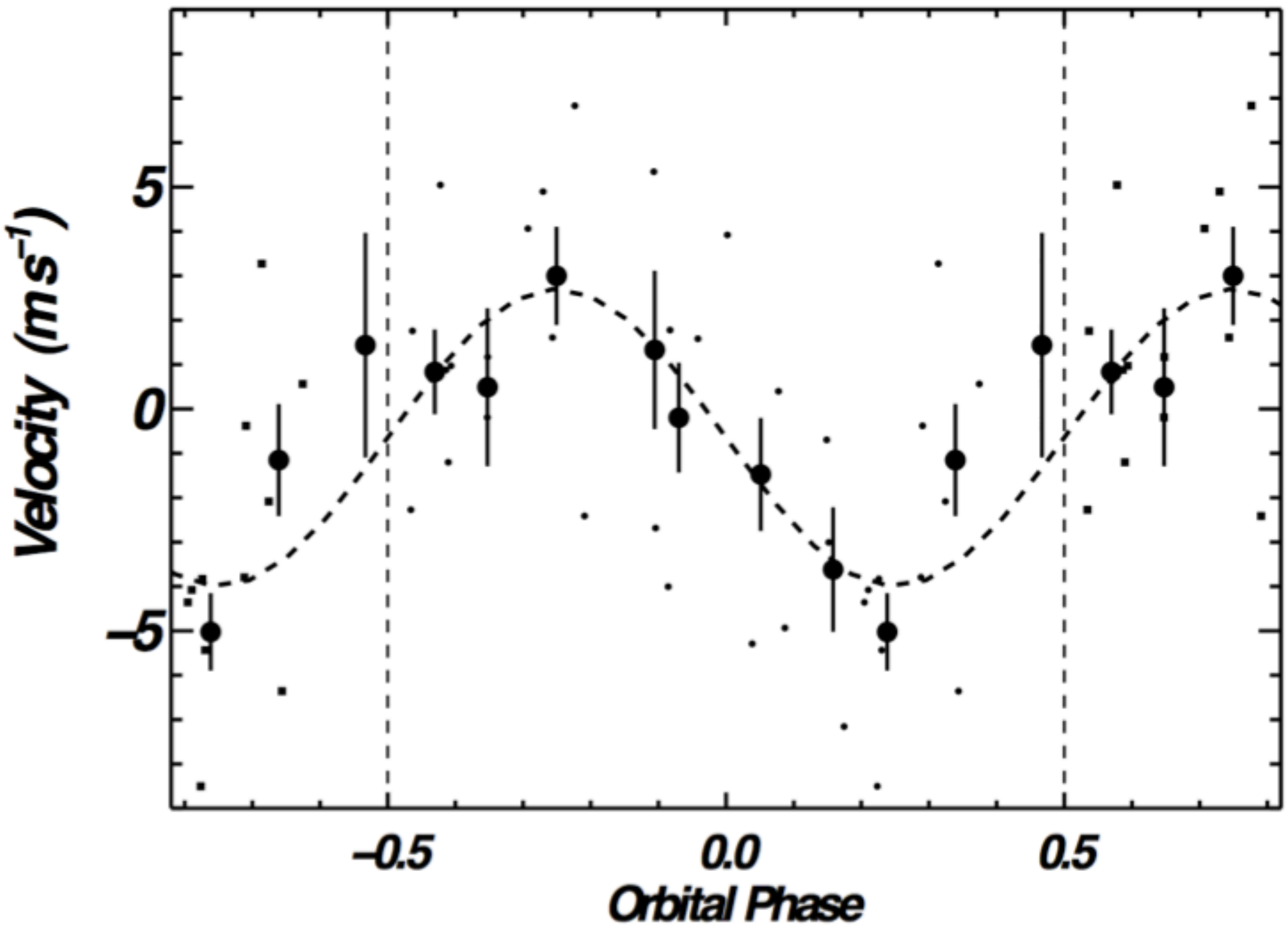
Kepler-10 Light Curve



Kepler-10 Light Curve



Kepler-10: Doppler Mass Measurement



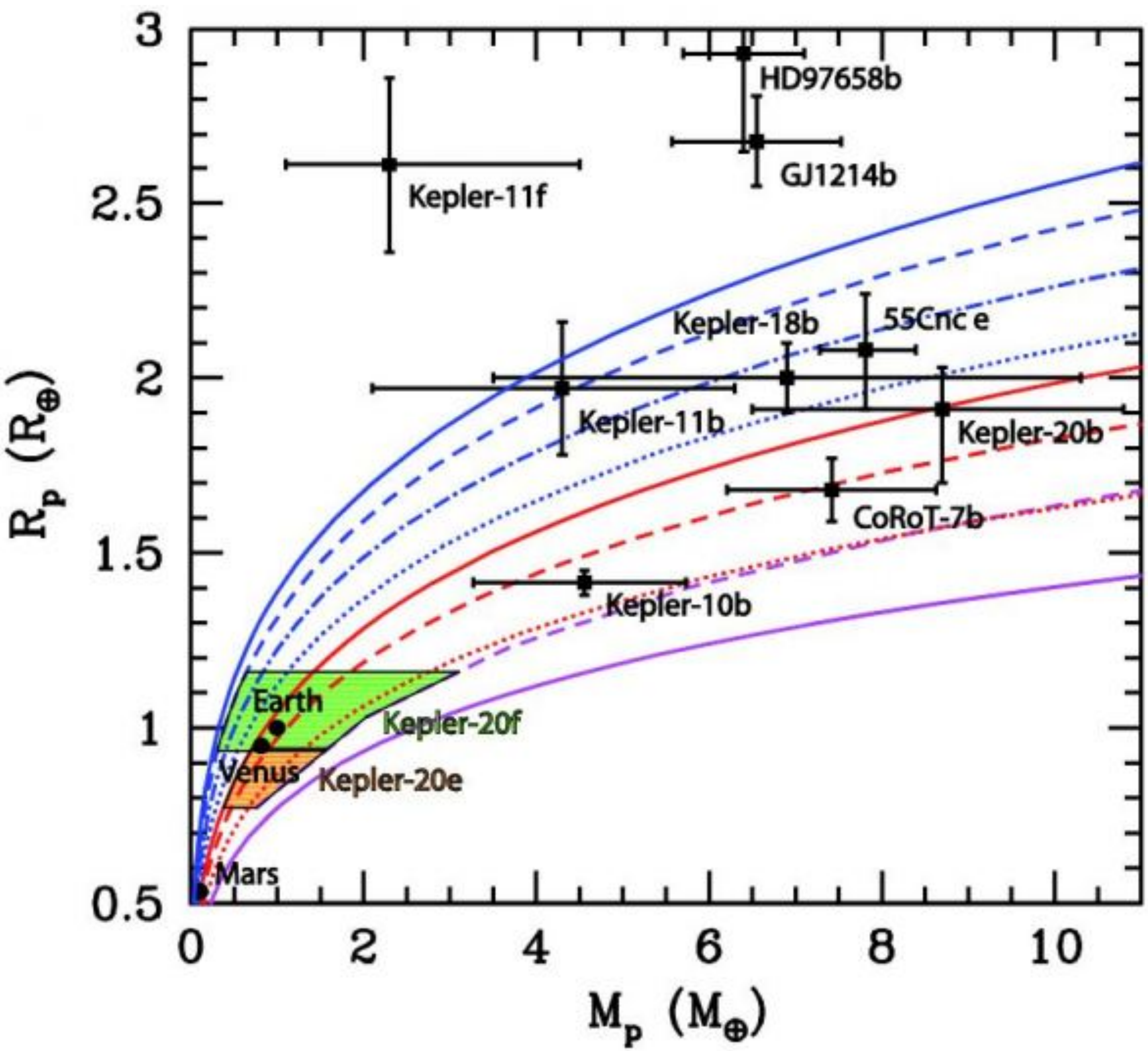
Kepler-10b

Mass = 4.6 M_{earth}

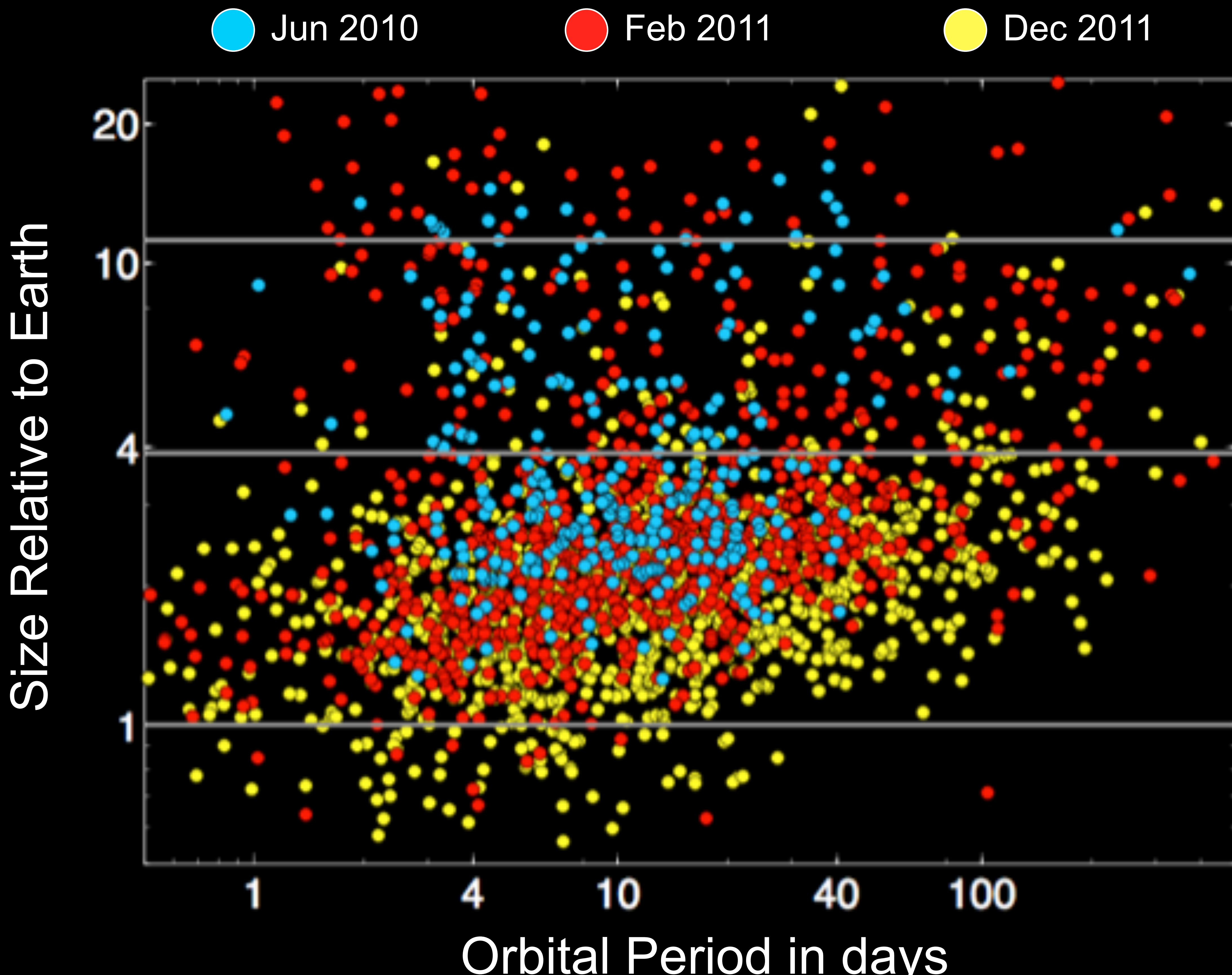
Radius = 1.4 R_{earth}

Density = 9 g cm^{-3}

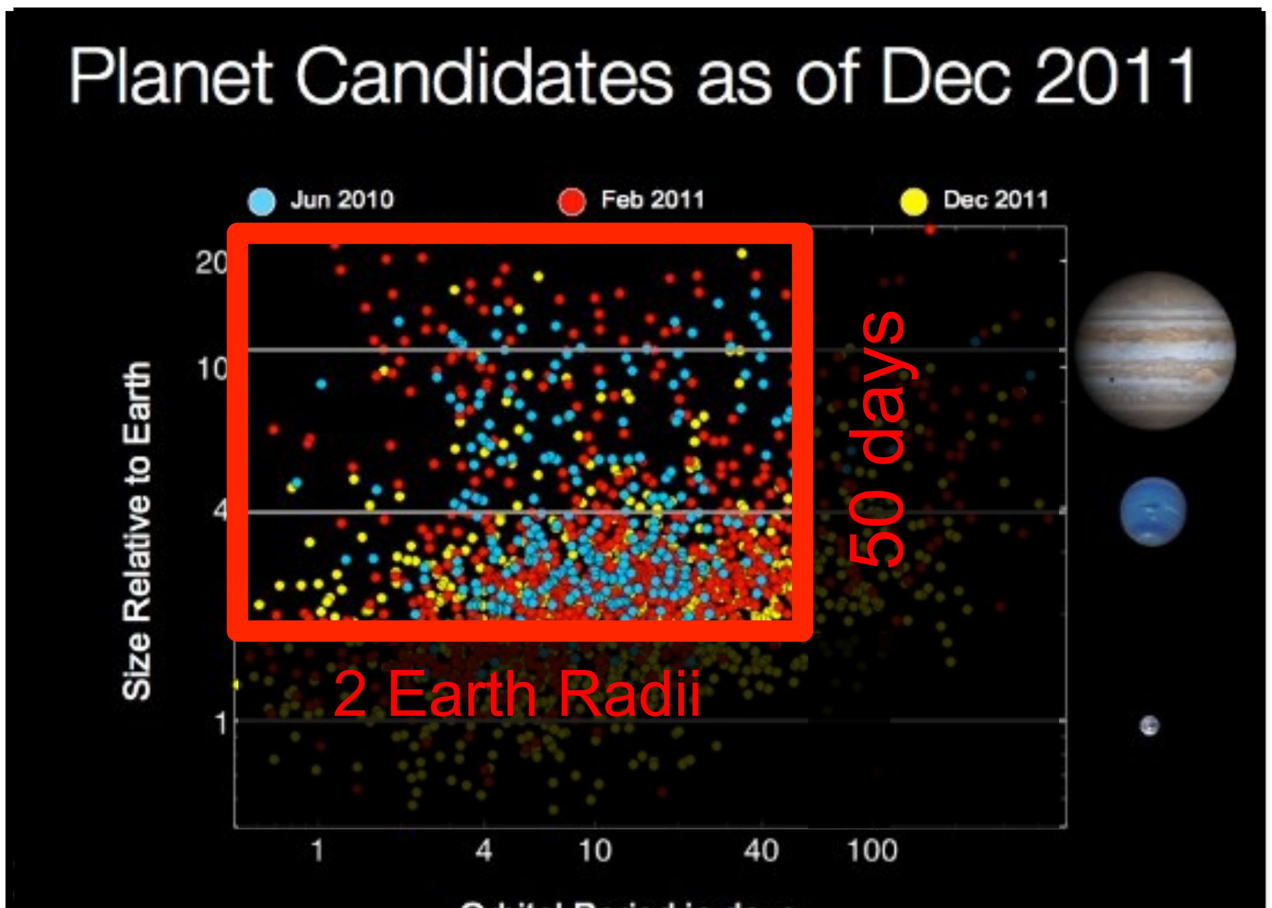
Kepler-10b is a Rocky Planet



2300 Planet Candidates as of Dec 2011



Focus on Statistics of Planet Occurrence from Kepler



95% True planets - Morton and Johnson (2011)

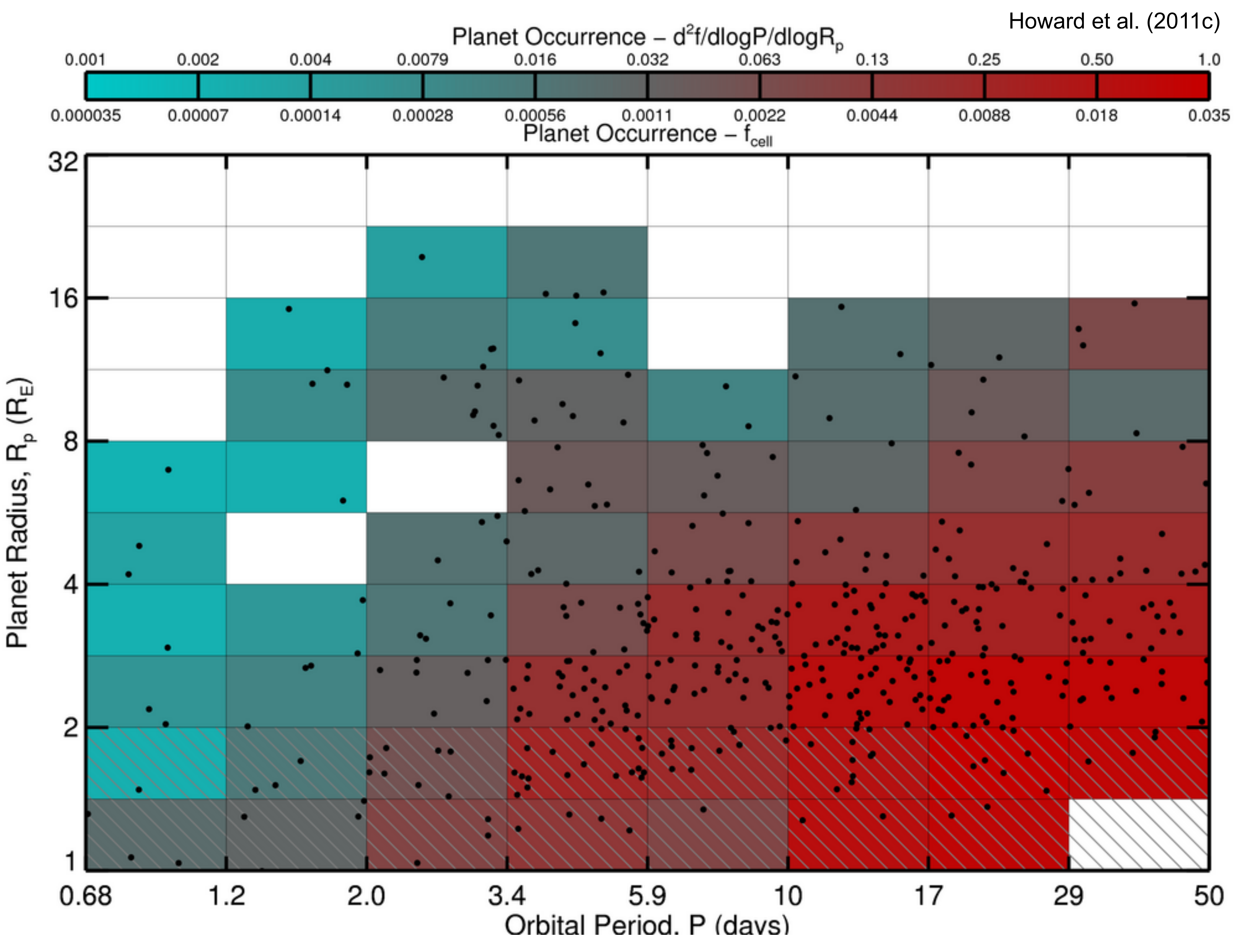
How to Compute planet occurrence:

1. Select set of planets, stars, and SNR threshold

2. Correct for transit probabilities

3. Correct for noisy stars using actual noise measurements (CDPP)

4. Compute planet occurrence in grid of cells in R_p and period

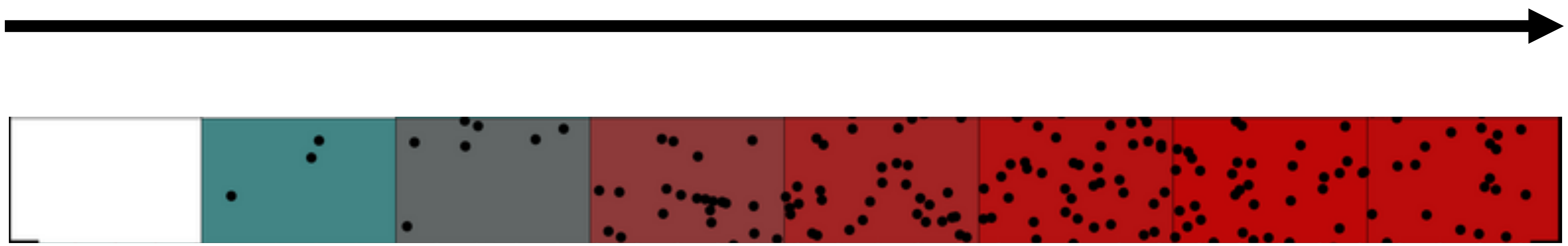


Howard et al. (2011c)
Planet Occurrence – $d^2f/d\log P/d\log R_p$
0.001 0.002 0.004 0.0079 0.016 0.032 0.063 0.13 0.25 0.50 1.0
0.000035 0.00007 0.00014 0.00028 0.00056 0.0011 0.0022 0.0044 0.0088 0.018 0.035
Planet Occurrence – f_{cell}
Planet Radius, R_p (R_E)
32 16 8 4 2 1
0.68 1.2 2.0 3.4 5.9 10 17 29 50
Orbital Period, P (days)

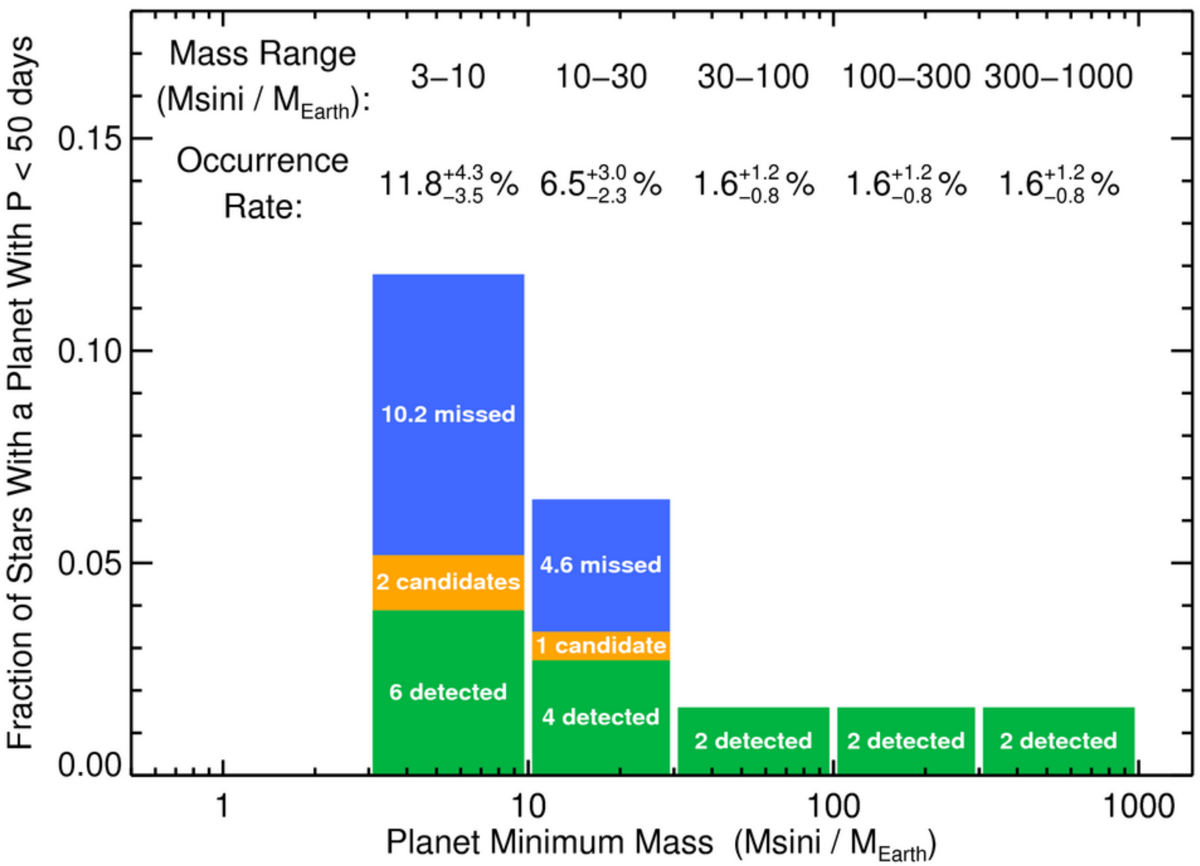
Howard et al. (2011c)

Compute Occurrence vs. Planet Radius

Sum Occurrence
for all Periods
in R + ΔR



Planet Mass Distribution
Eta-Earth Survey (Doppler)



Power Law Mass Function

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

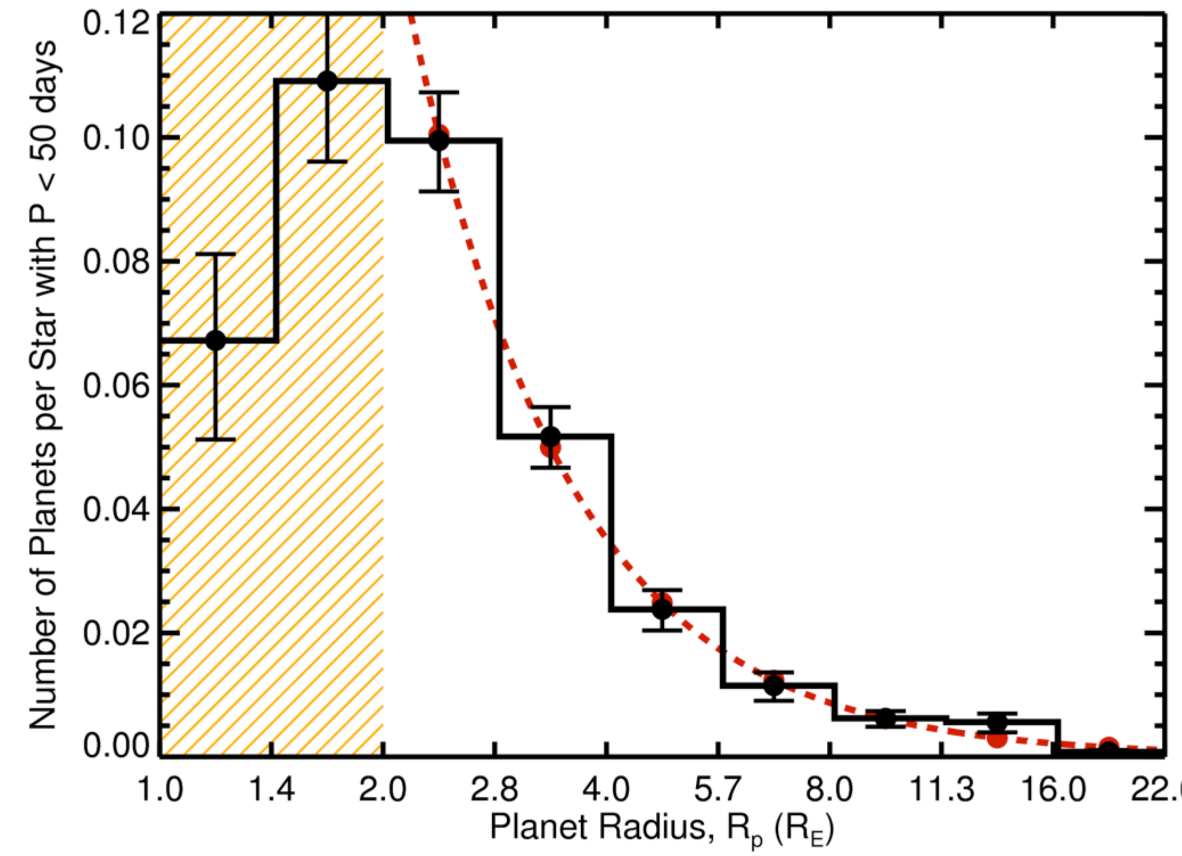
$k = 0.39^{+0.27}_{-0.16}$, $\alpha = -0.48^{+0.12}_{-0.14}$

Extrapolate:

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

Msini = 0.5-2.0 M_E, P < 50 days

Planet Radius Distribution
Kepler



Power Law Radius Function

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

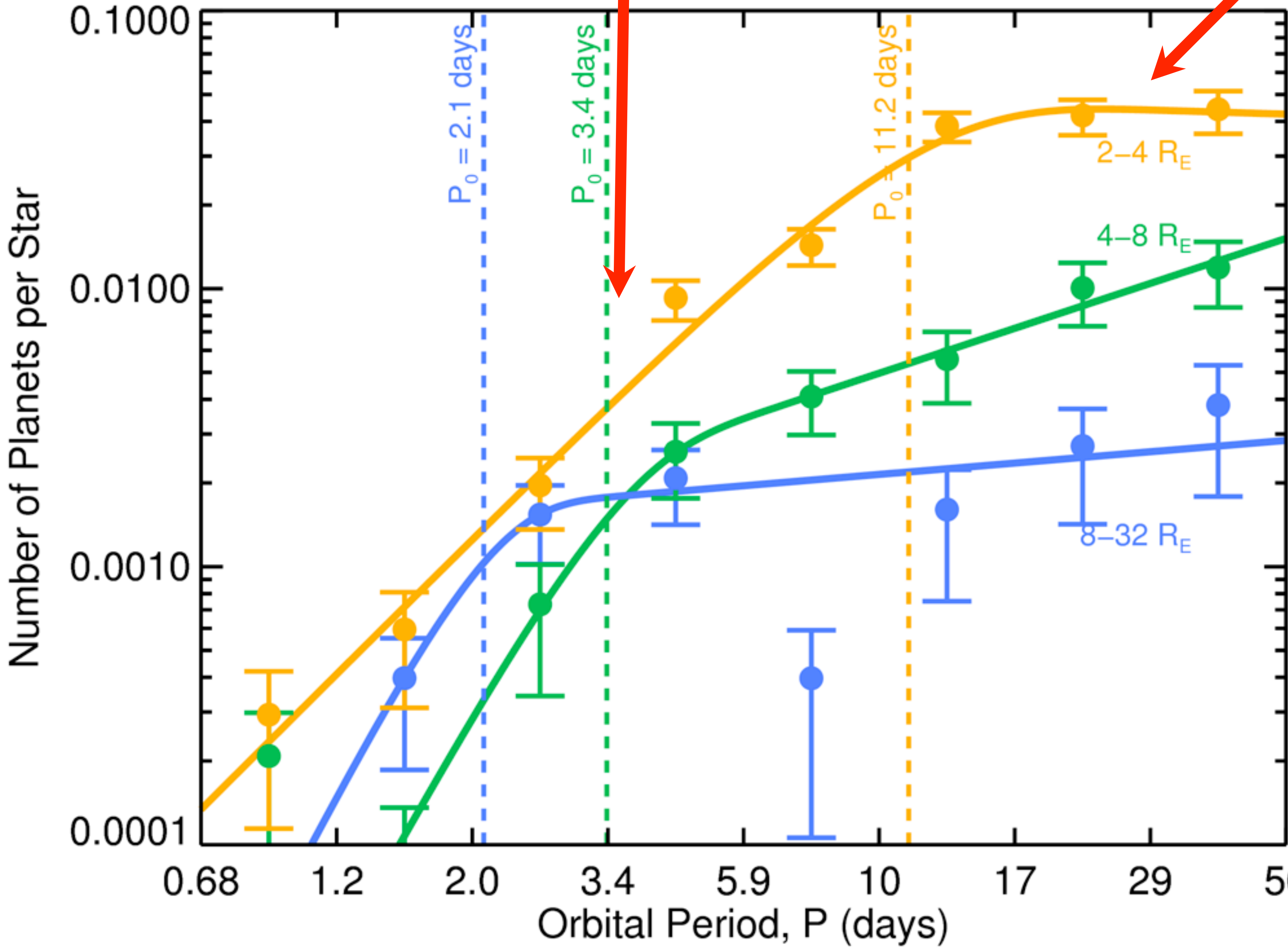
$k = 2.9 \pm 0.5$, $\alpha = -1.92 \pm 0.11$

Howard et al. (2011c)

Planet Period Distribution

Exponential Cutoff

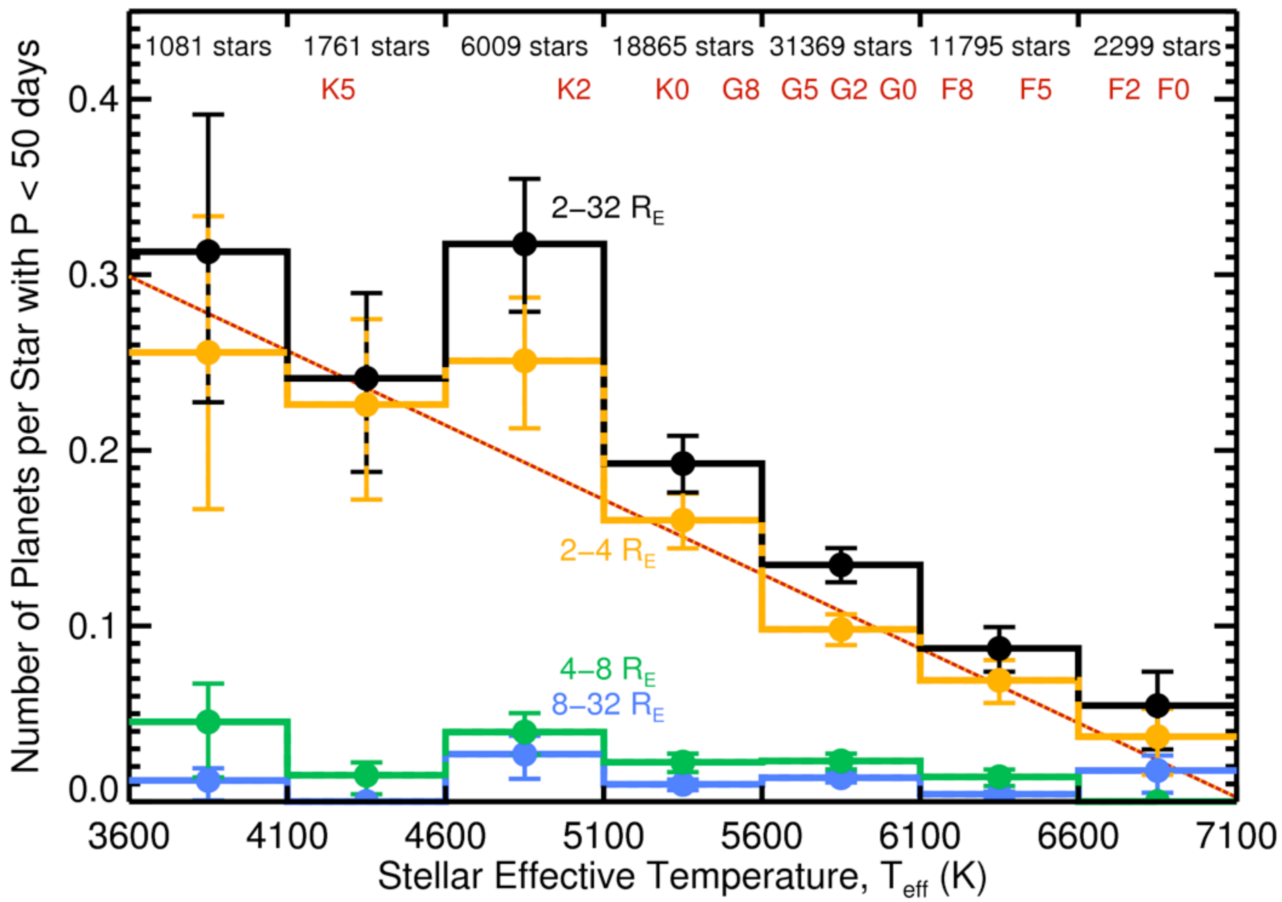
Power Law

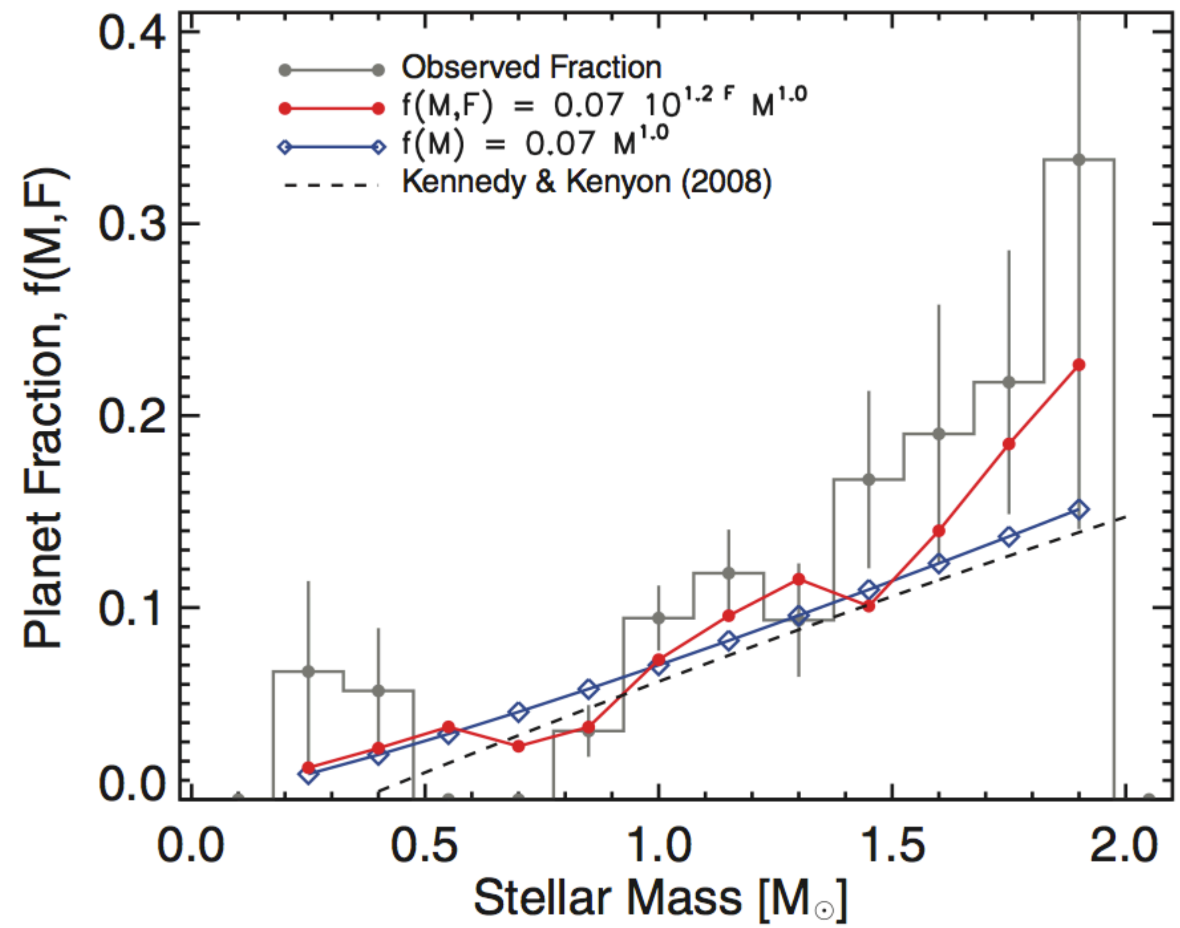


Increasing
Planet Occurrence
per log P bin

$$dN/d\log P = kP^{\beta} (1-\exp((P/P)^{\gamma}))$$

Planet Occurrence vs. $M_\star$



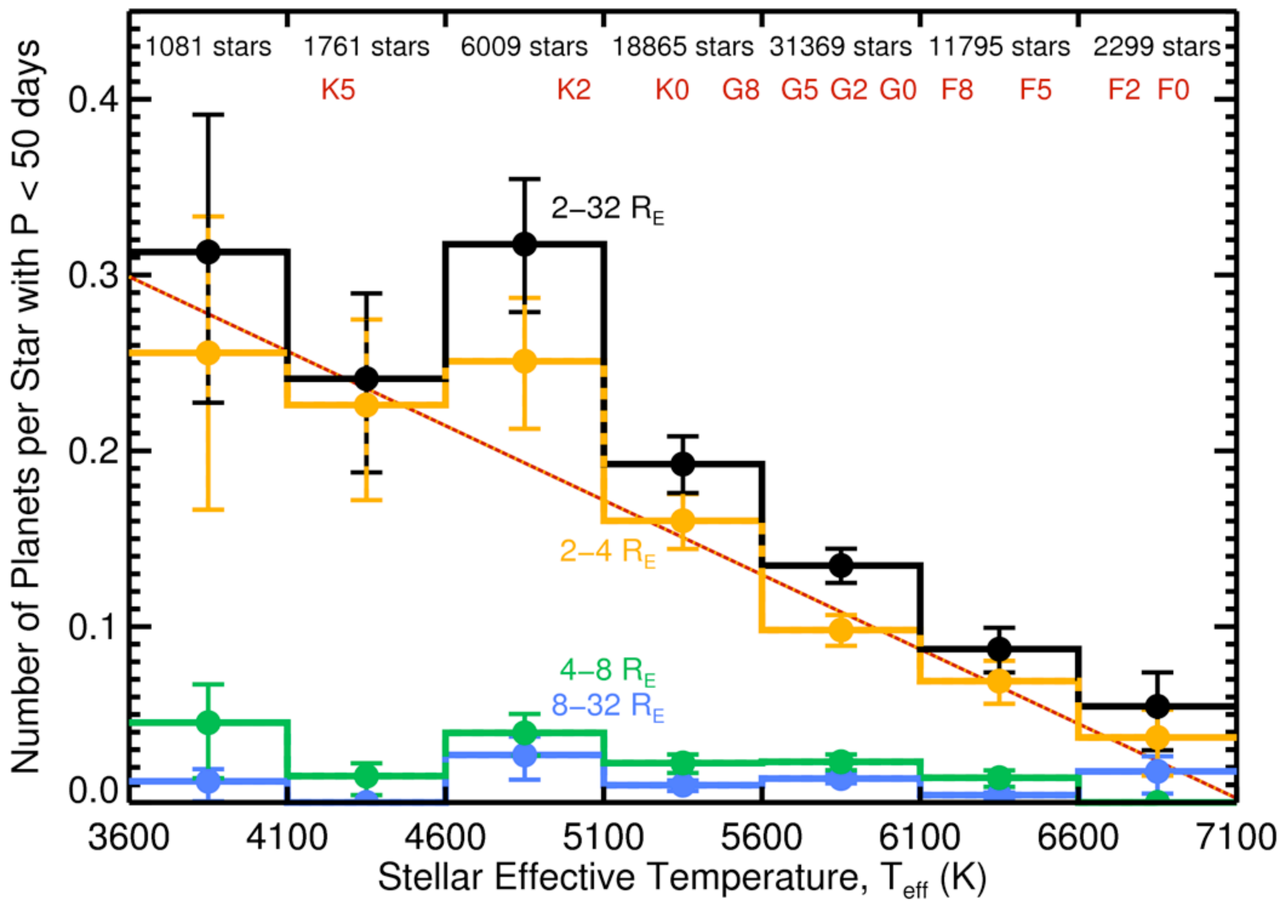


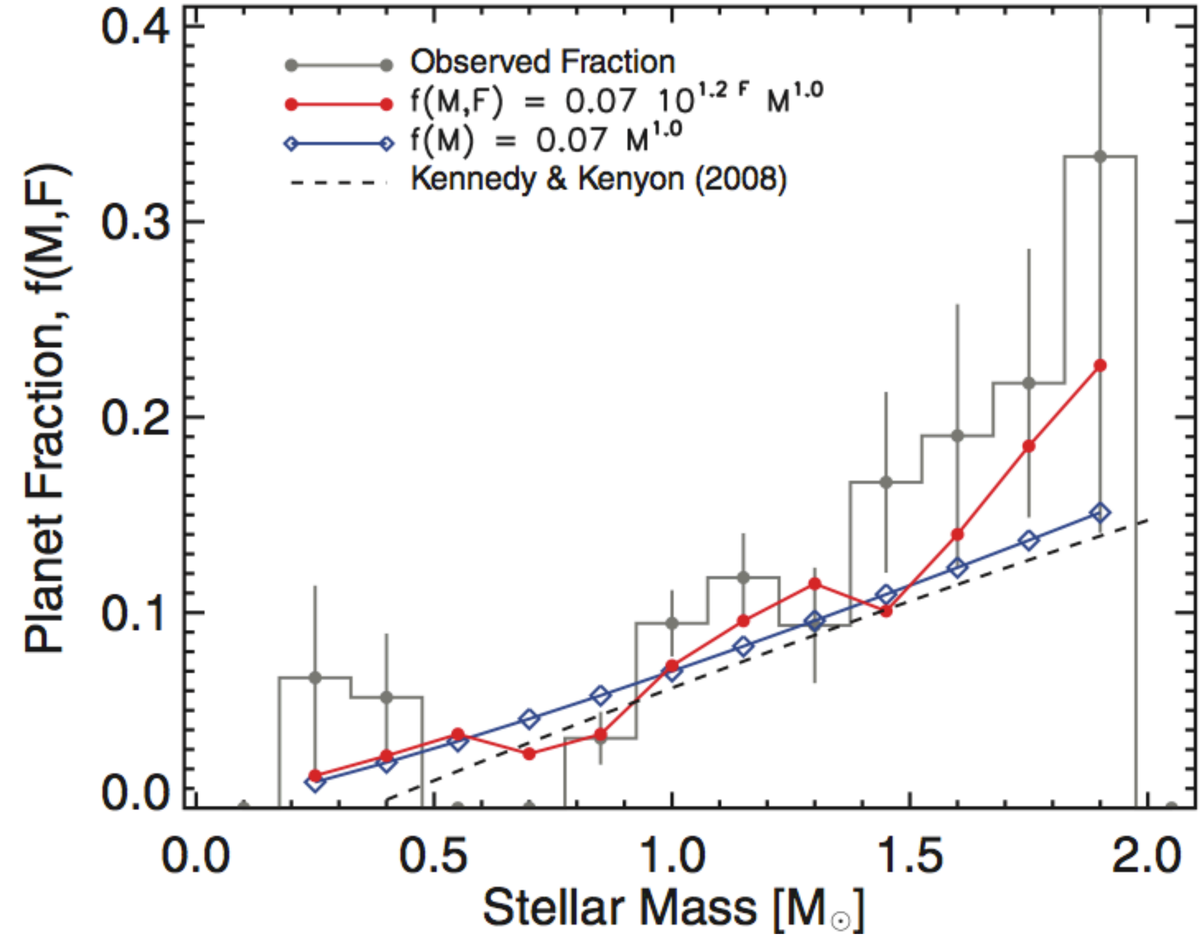
Occurrence within 0.25 AU of small planets decreases with $M_\star$

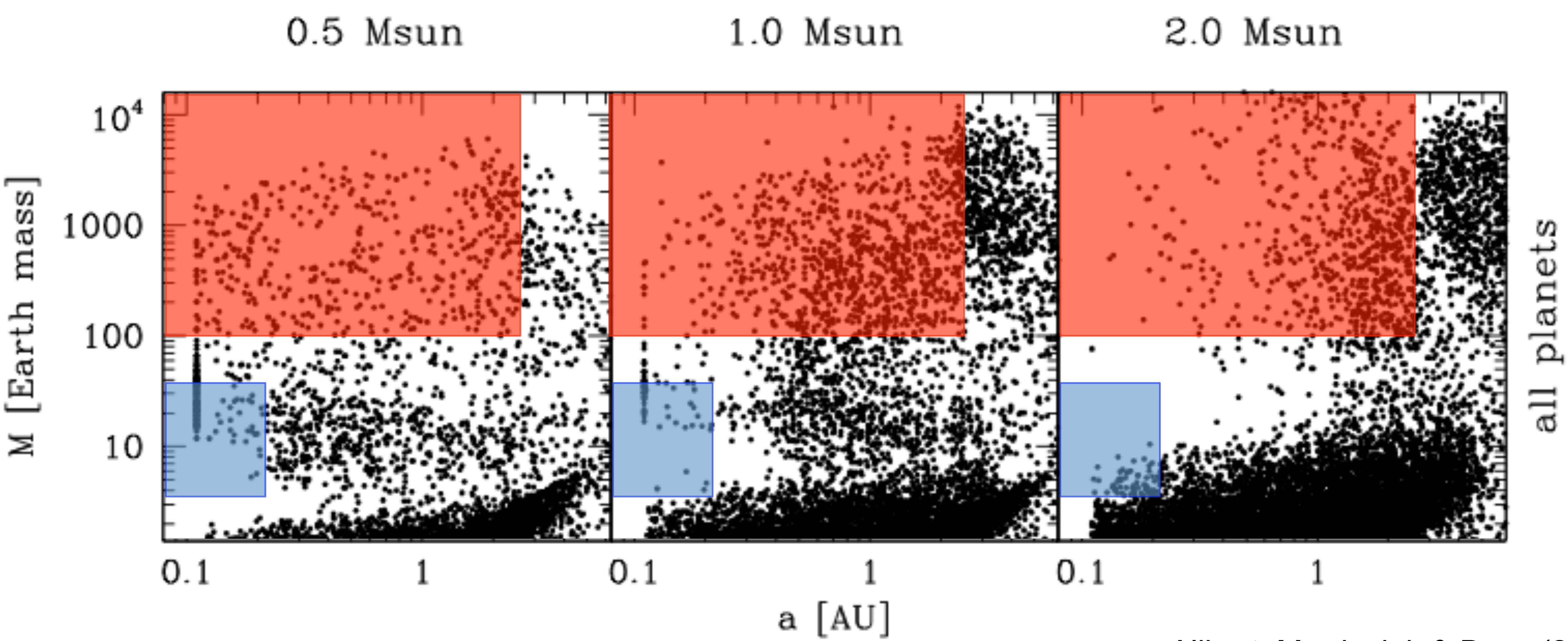
Occurrence within 2.5 AU of giant planets increases with $M_\star$

Howard et al. (2011c)

Johnson et al. (2010)

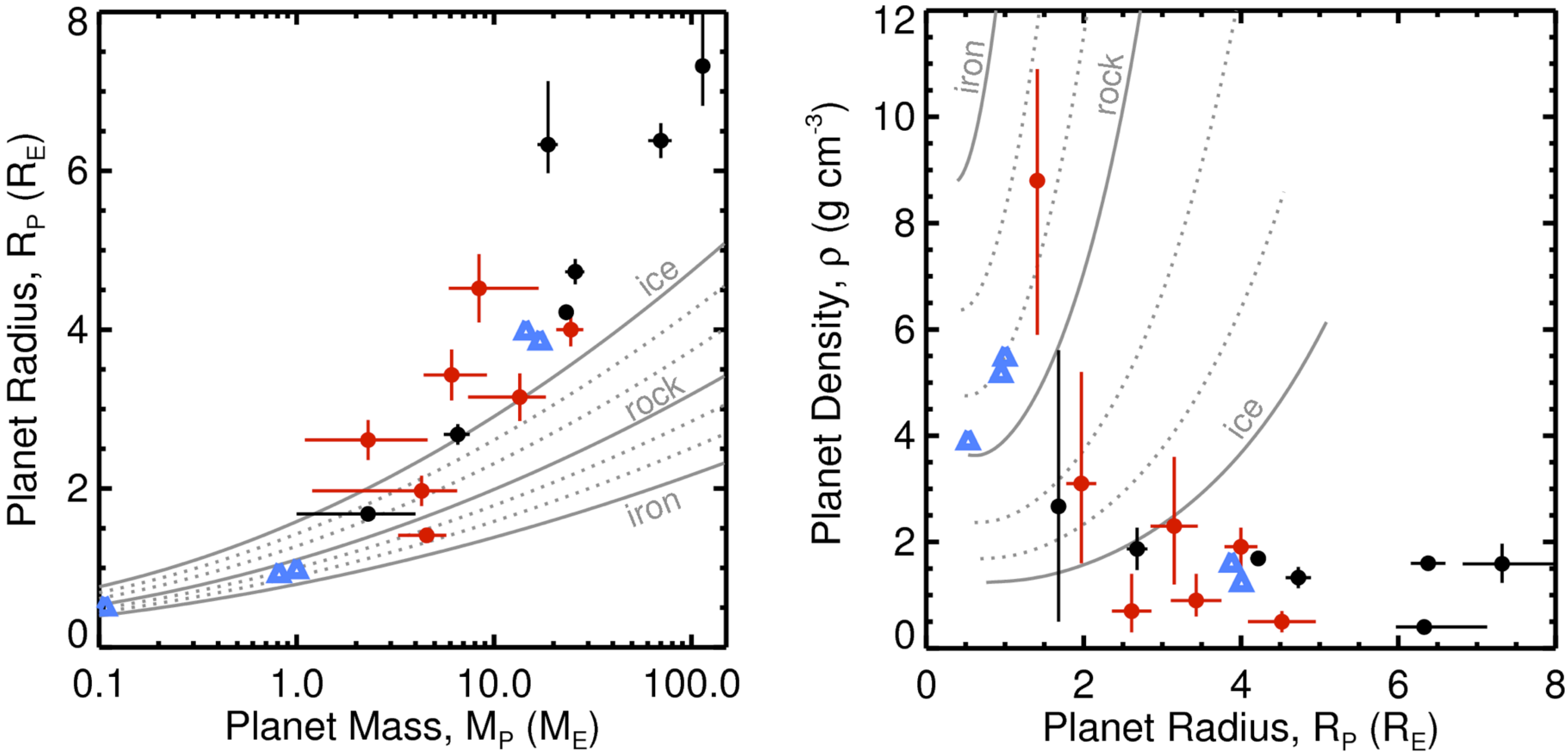






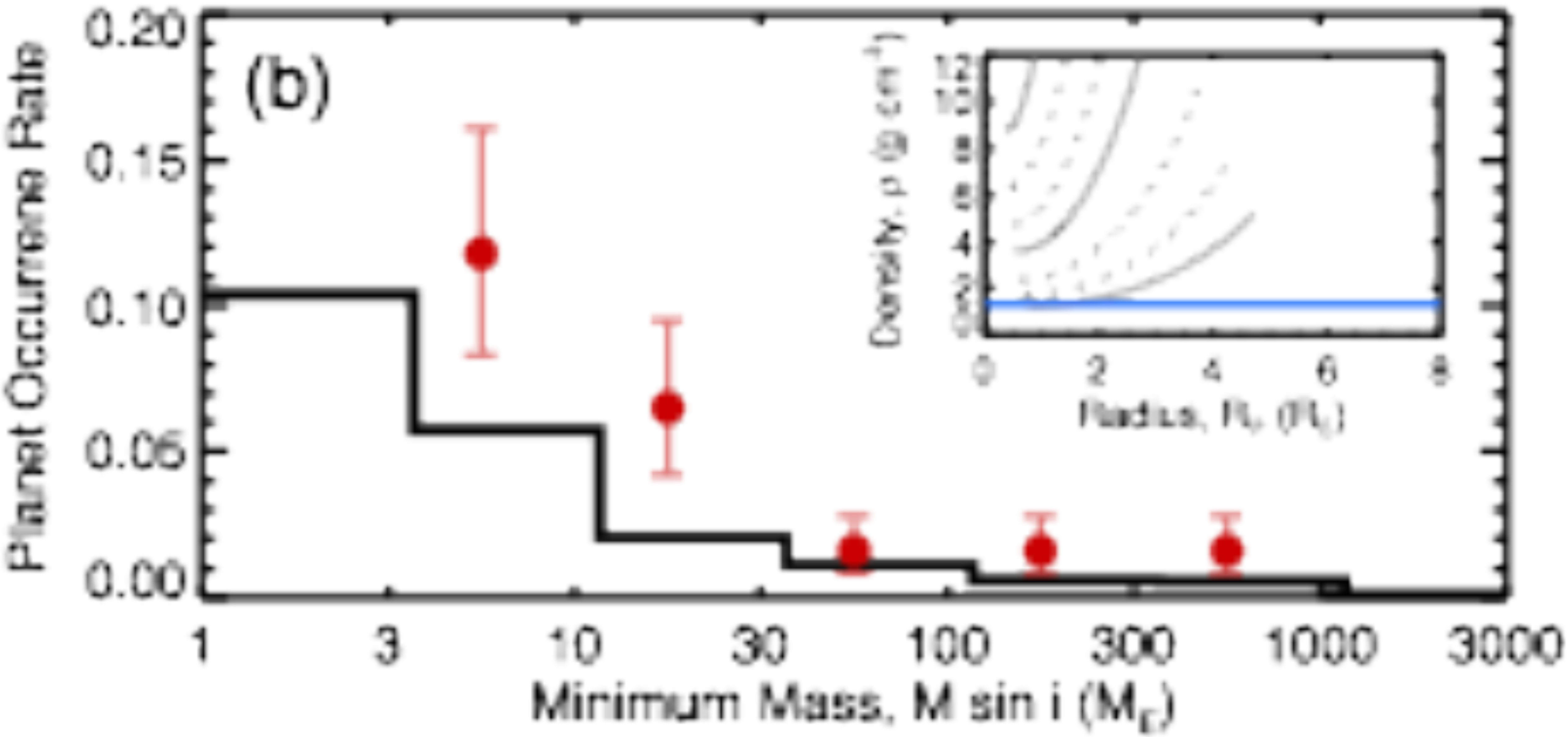
Alibert, Mordasini, & Benz (2011)

Planet Densities



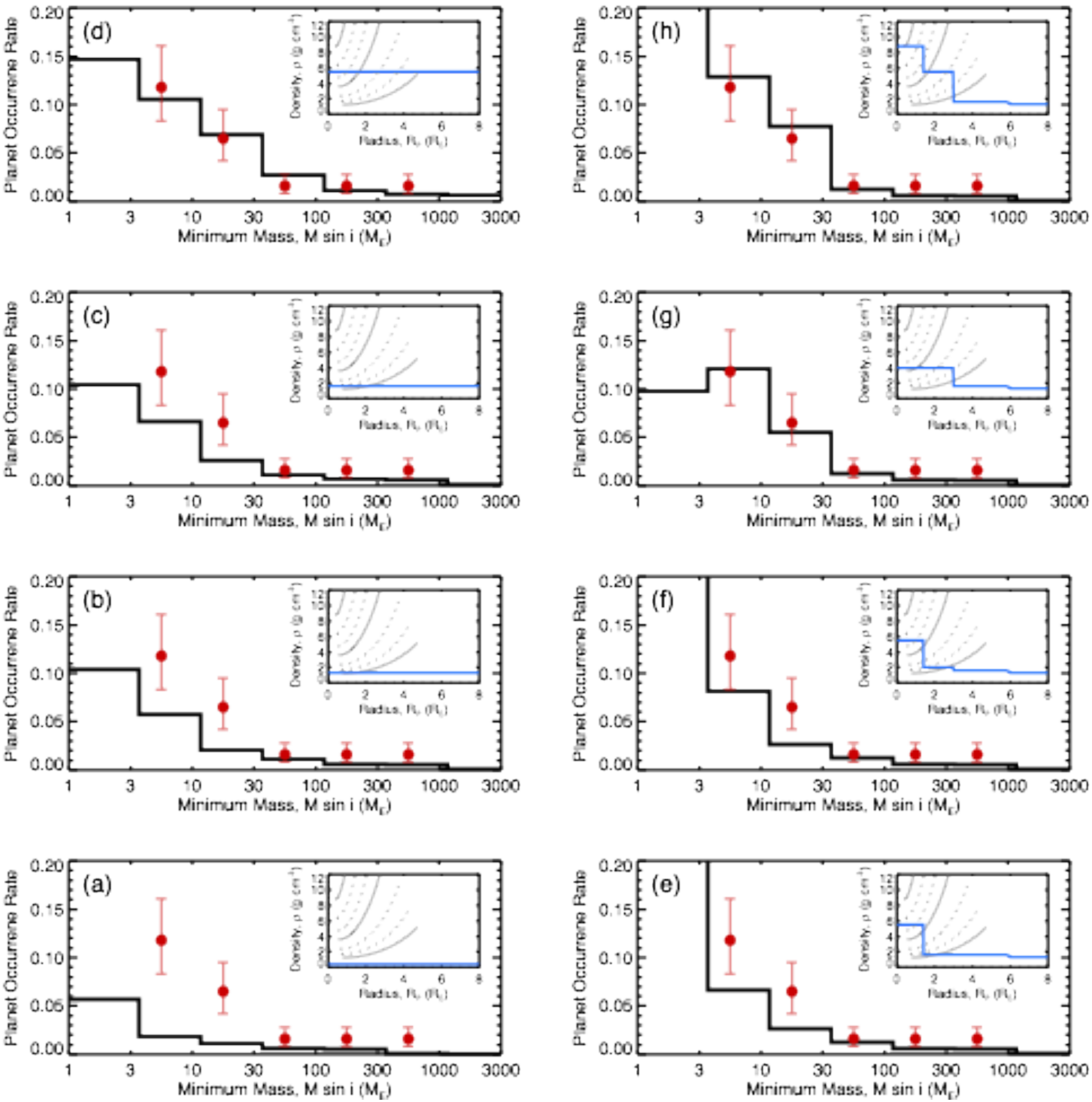
Howard et al. (2011c) arXiv:1103.2541

Planet Densities



Howard et al. (2011c)
arXiv:1103.2541

Planet Densities



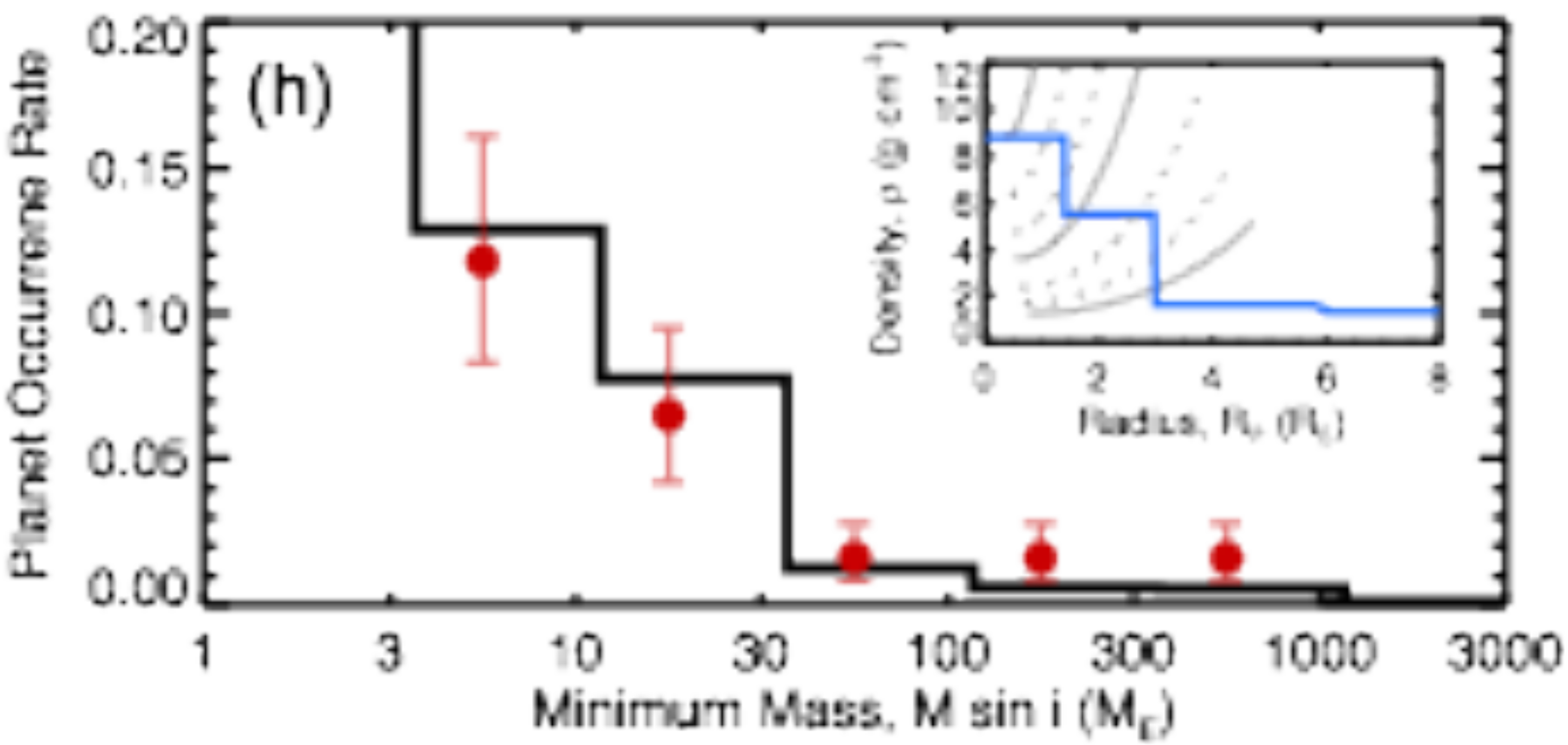
Howard et al. (2011c)
arXiv:1103.2541

Face Value Conclusions:

- On average, planets smaller than 3 R_E have bulk densities > 4 g cm^{-3}
- Terrestrial composition ?!

Complications:

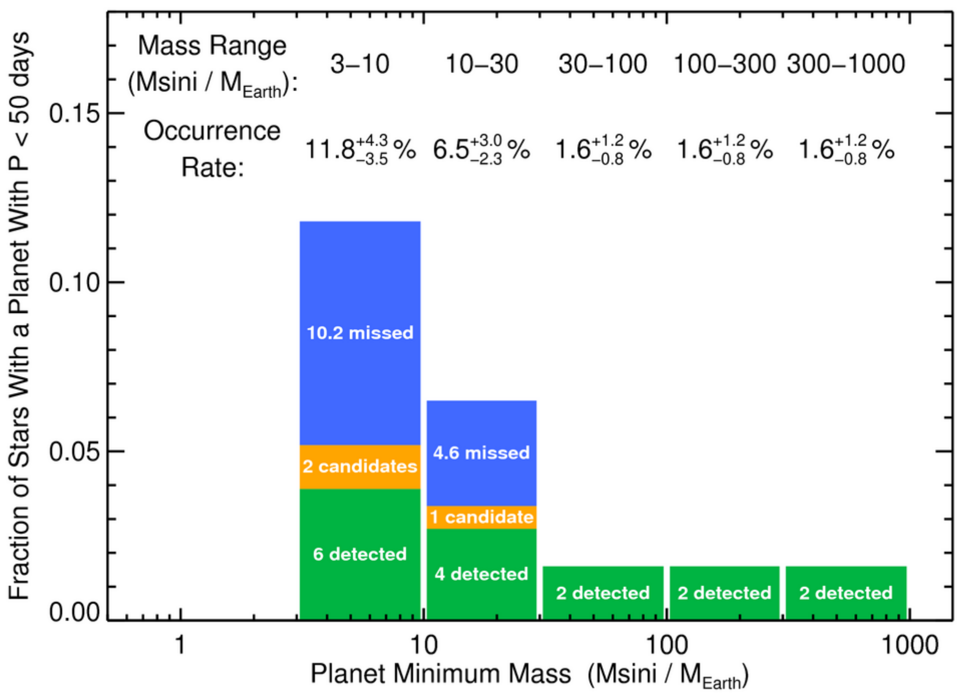
- Multiple planets per system
- Different stellar samples?
- Not one-to-one mapping from radius to mass

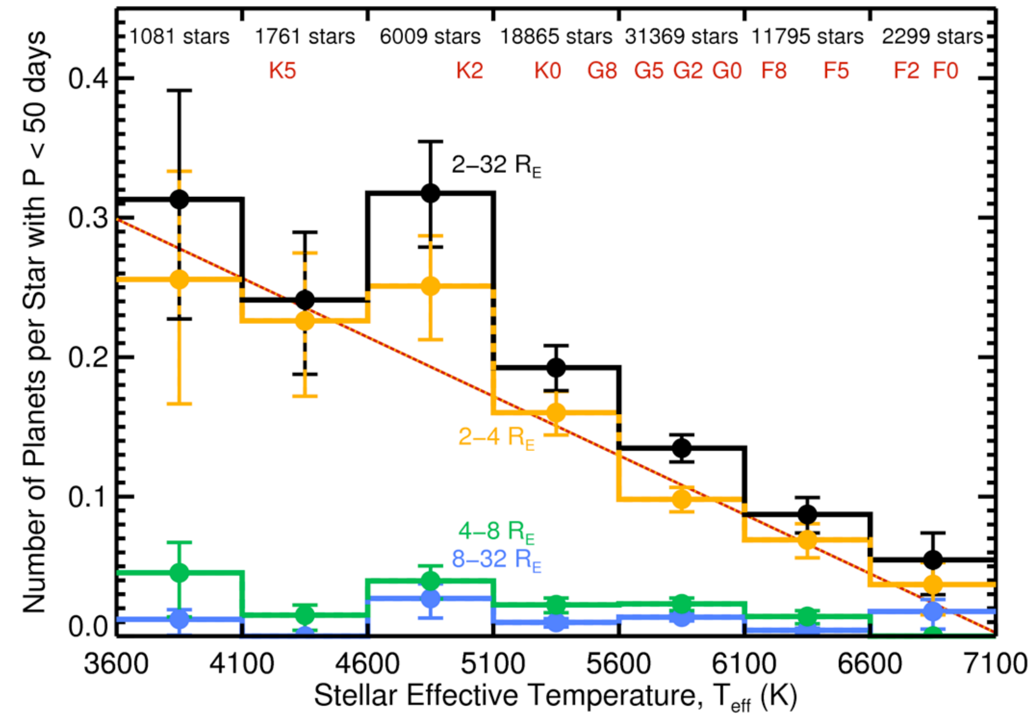


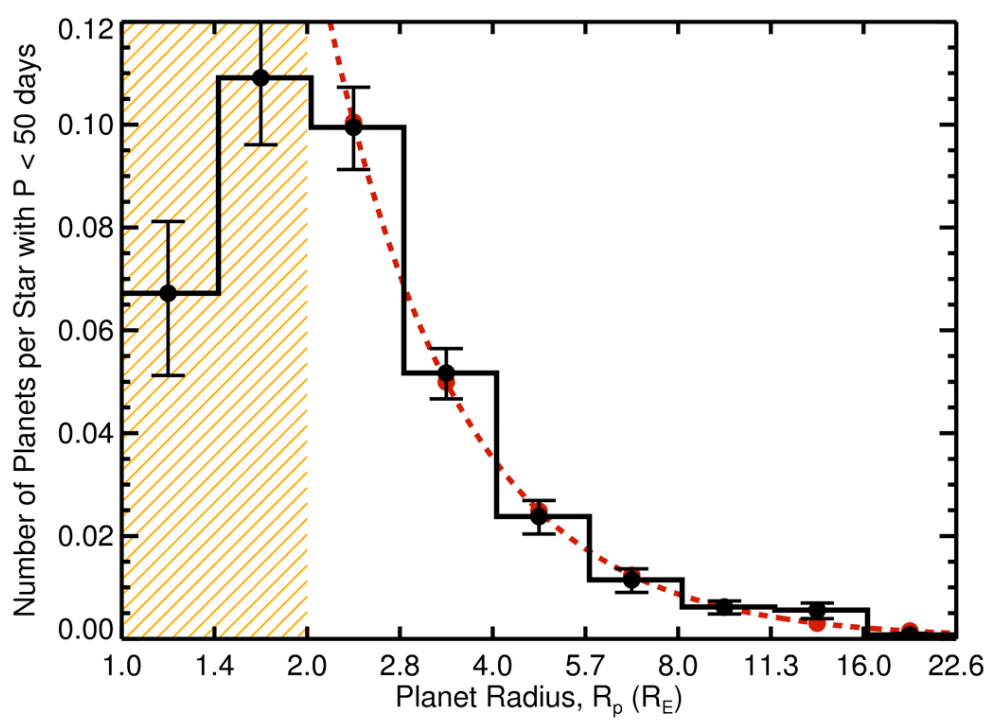
ρ(R) rises with decreasing R

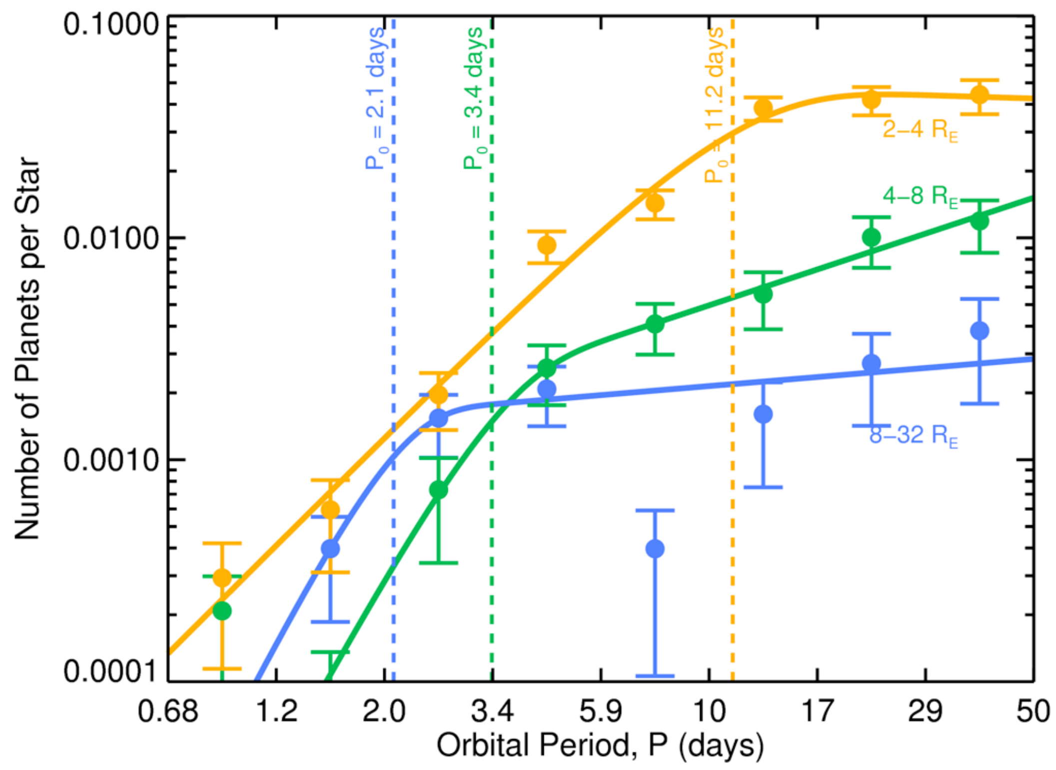
Howard et al. (2011c) arXiv:1103.2541

Patterns of Planet Occurrence

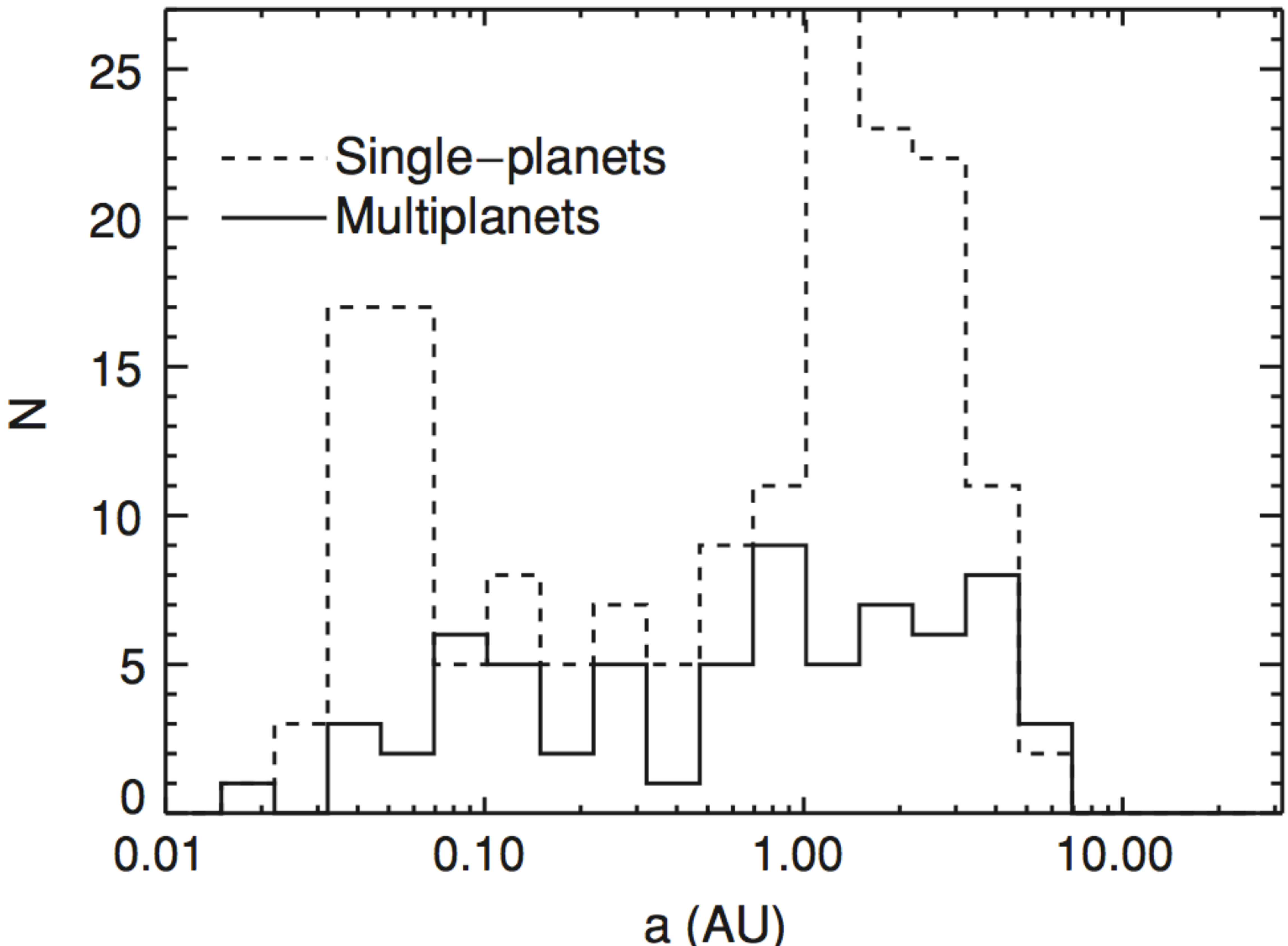








Jovian Planets



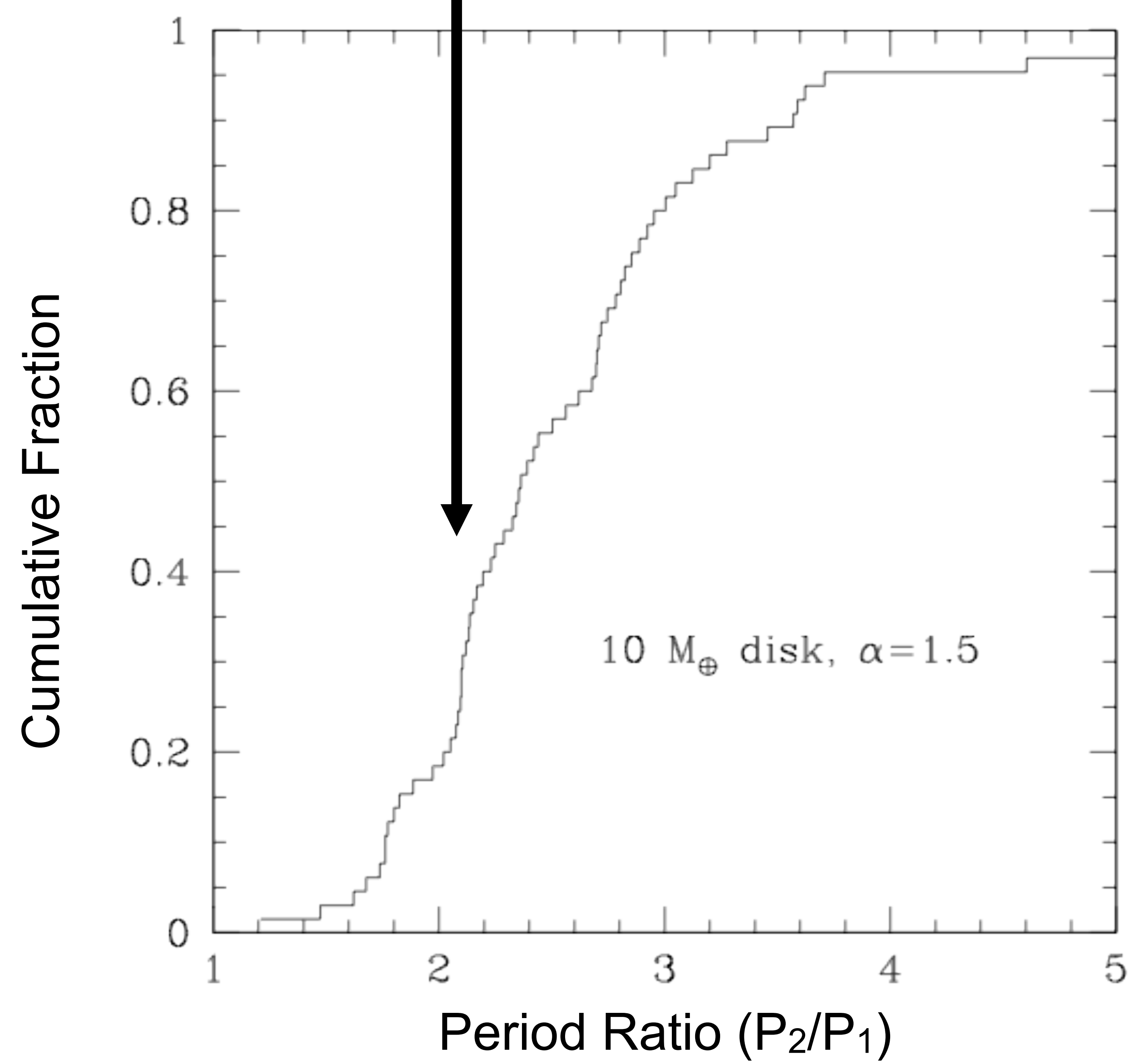
Wright et al. (2009)

In Situ Planet Formation (Hansen & Murray)

Hansen & Murray (2011) focused on M_{disk} > 25 M_E to explain close-in Neptunes

For M_{disk} < 25 M_E it it produces super-Earths with period ratios on right.

Just outside 2:1 period ratio
Consistent with Lissauer et al. (2011)



Hansen & Murray (2011)