Survey Statistics
(Planet Occurrence)

Andrew Howard
UC Berkeley → IfA/Hawaii

Sagan Summer Workshop - July 23-27, 2012

2003 Michelson Interferometry Summer School

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Outline

Planet Occurrence - what can we measure?

Planet-Metallicity Correlation

Doppler Surveys - Eta-Earth Survey

Transit Survey Completeness

Kepler Planet Occurrence

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Planet Occurrence - what can we measure?

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Planet Occurrence

Apparently simple measurement:

$$\text{Occurrence} = \frac{\text{Number of Planets}}{\text{Number of Stars}}$$

Driven by Science Questions

High planet occurrence →

planets of particular types

commonly

form *and* evolve

under particular conditions

Driven by Science Questions

High planet occurrence →

planets of particular types

{ mass / radius / temp
orbital characteristics
degree of multiplicity }

commonly

form *and* evolve

under particular conditions

Driven by Science Questions

High planet occurrence →

planets of particular types

commonly

form *and* evolve

under particular conditions

{ initial conditions:
stellar mass
stellar metallicity
stellar multiplicity
implied disk properties }

{ evolutionary conditions:
planetary dynamics
planet/disk dynamics
star/planet interactions
stellar evolution }

Driven by Science Questions

High planet occurrence →

planets of particular types

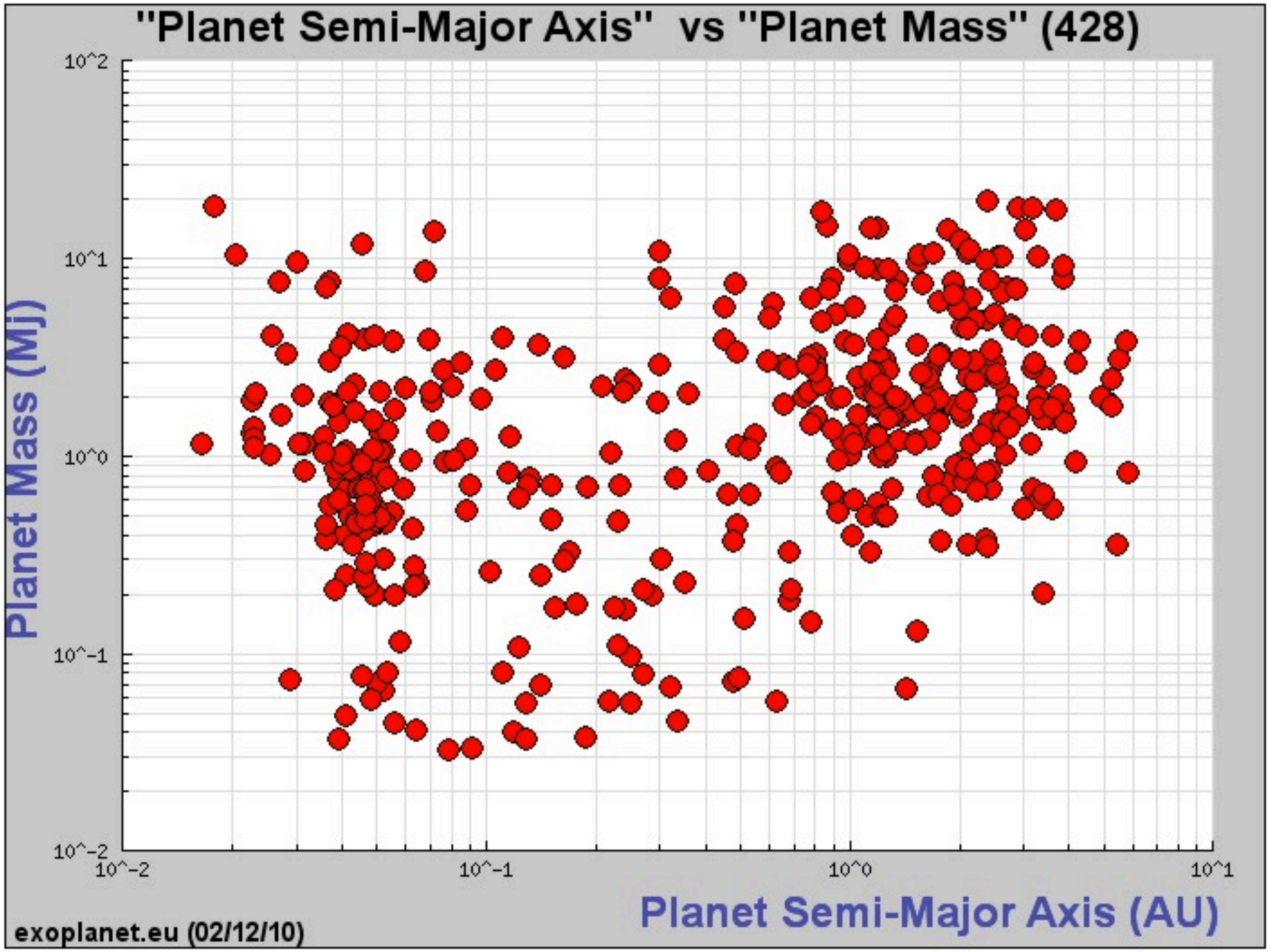
commonly

form *and* evolve

under particular conditions

difficult to disentangle formation and evolution

Planet Distribution - Msini-Period



Exoplanet.eu:

- all planets

"RV+Astrometry"

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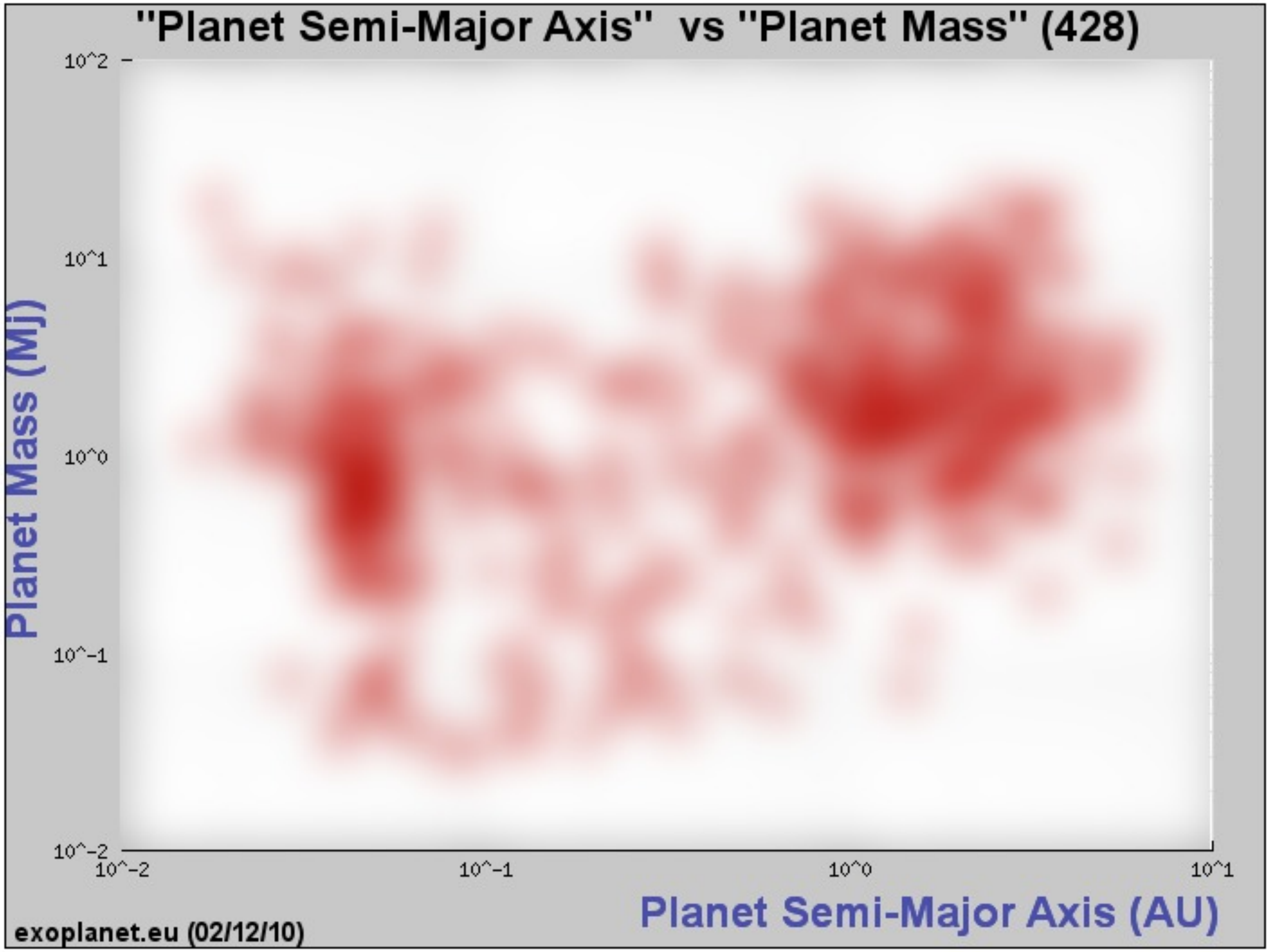

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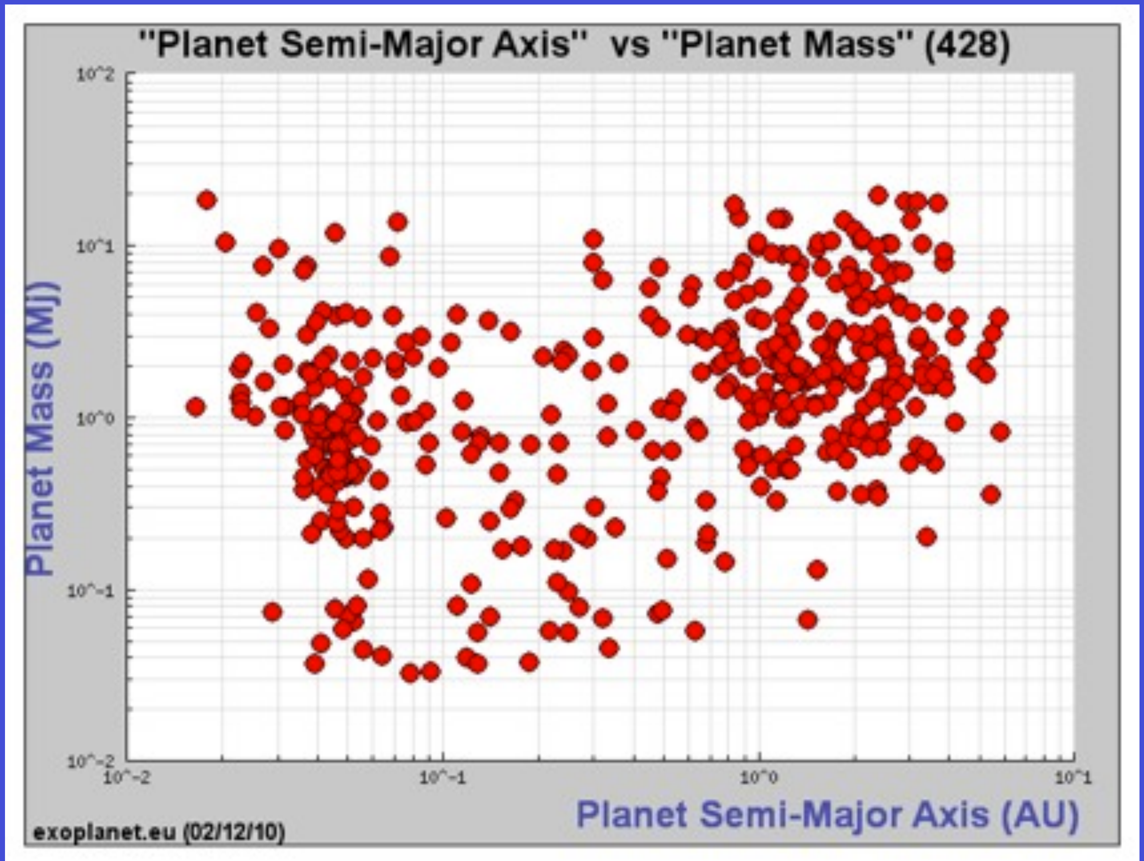
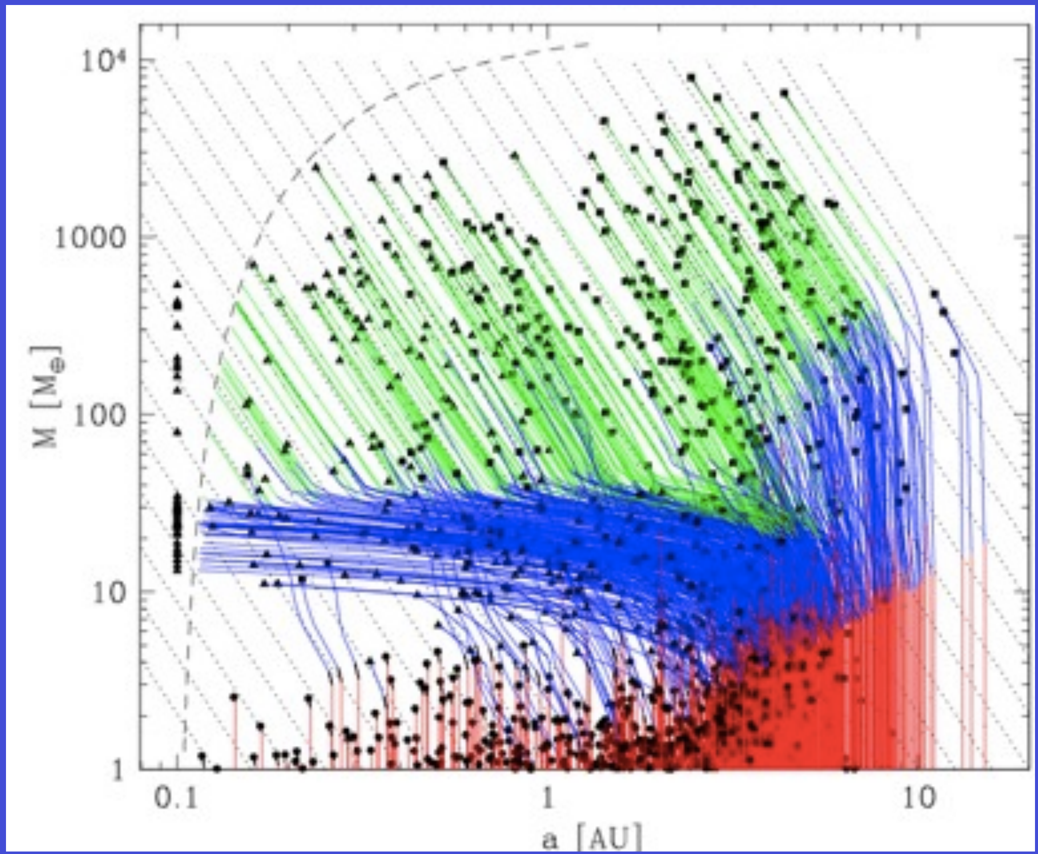
"RV+Astrometry"

Inferring Planet Formation Mechanisms from Planet Population Statistics

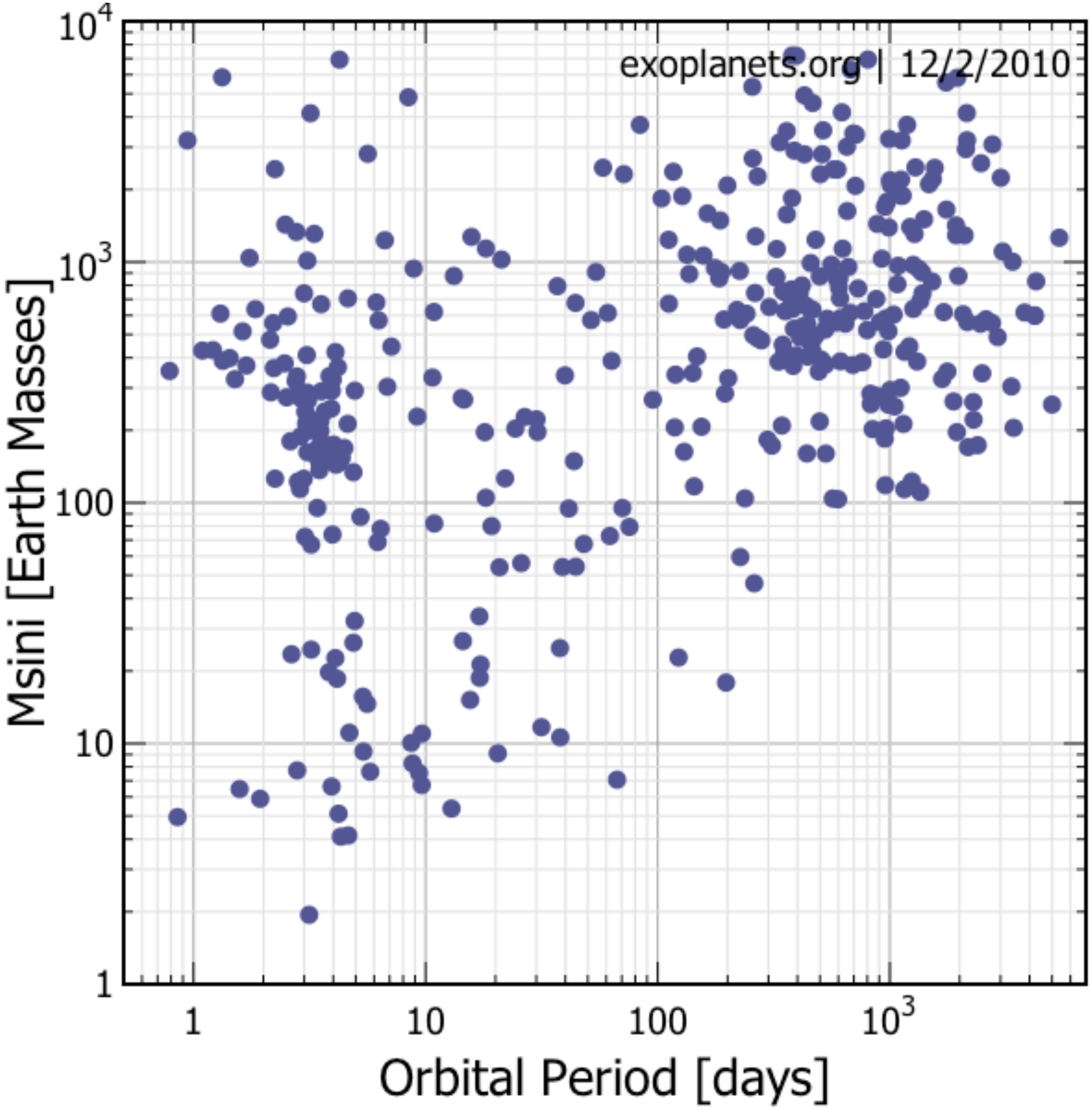
Measurements



Models



Exoplanet Distribution - Msini-Period



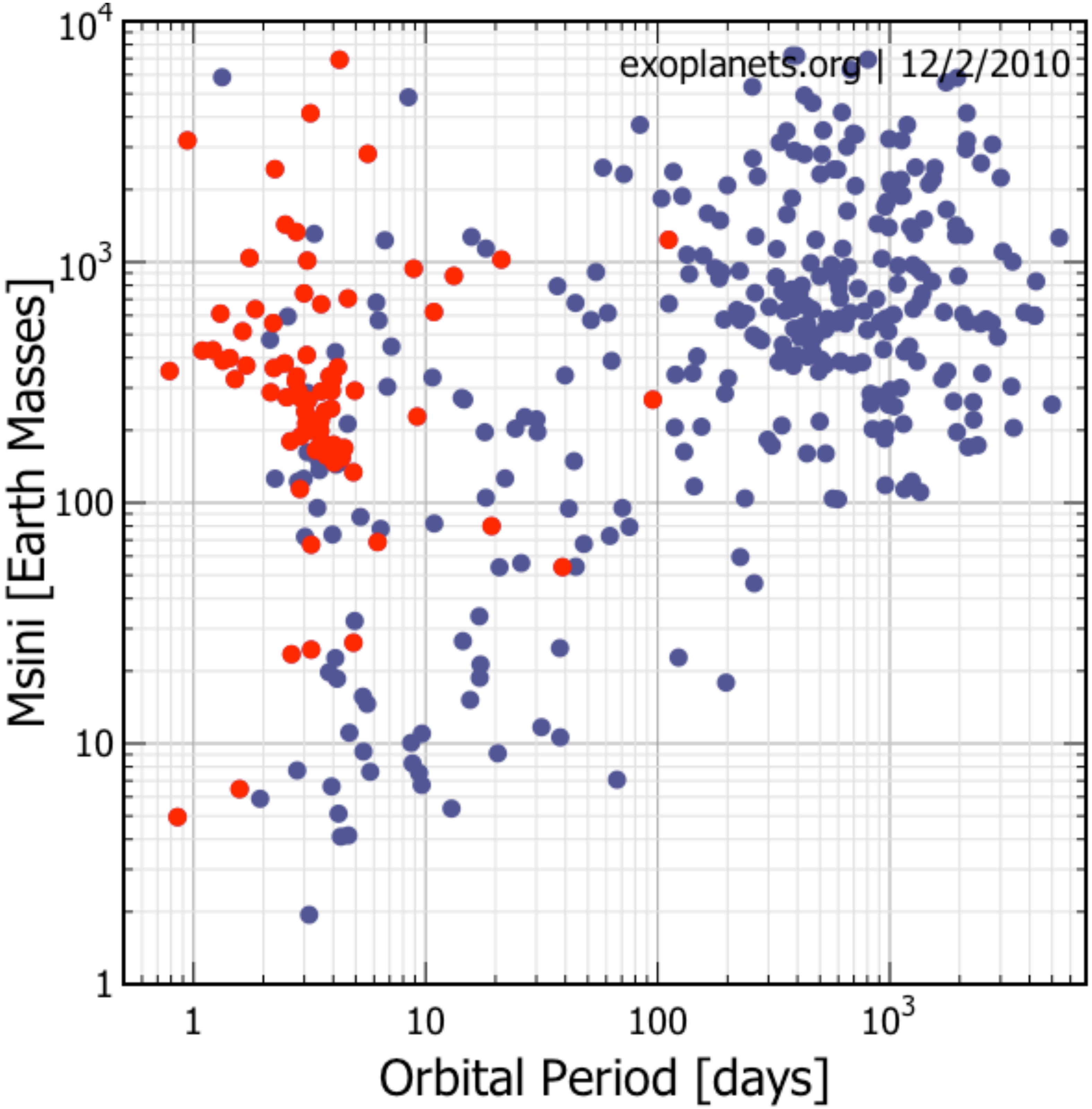
Exoplanets.org:

- all planets RV+Transit

Exoplanet.eu:
clearinghouse of planet claims

Exoplanets.org:
curated orbit database

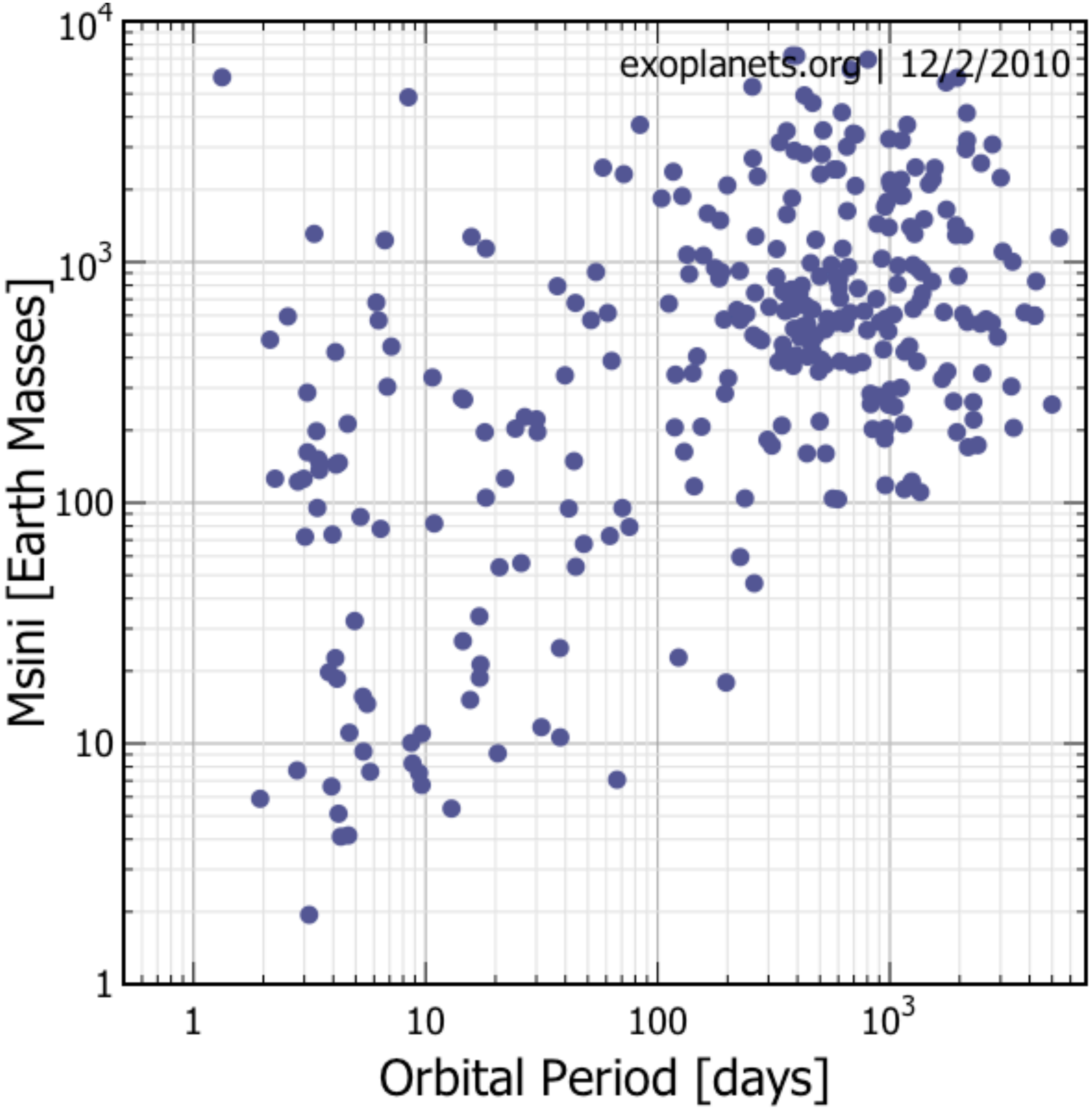
Exoplanet Distribution - Msini-Period



Exoplanets.org:

- RV-detected
- Transit-detected

Exoplanet Distribution - Msini-Period

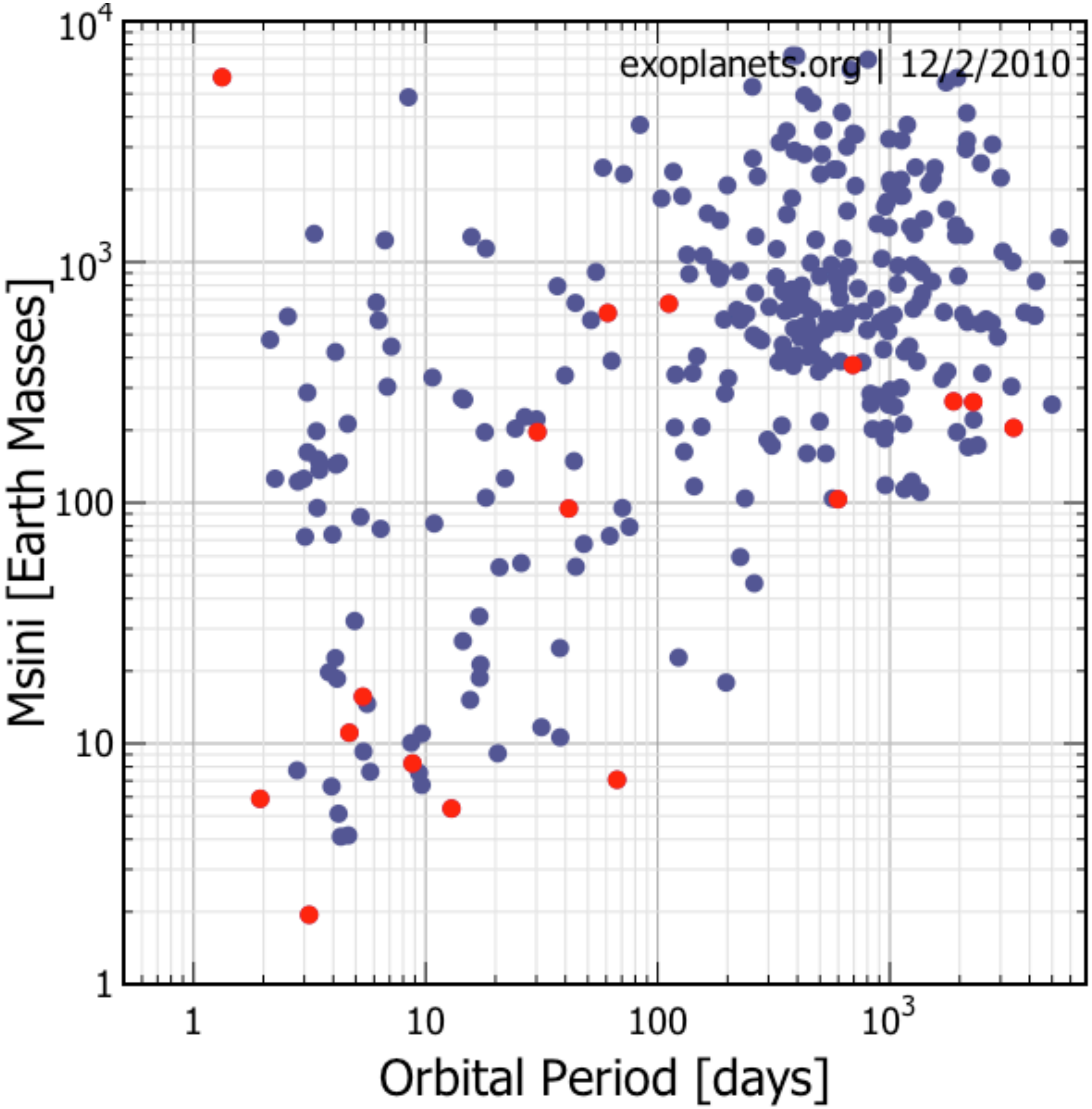


Exoplanets.org:

- RV-detected

Monday, July 23, 2012

Exoplanet Distribution - Msini-Period

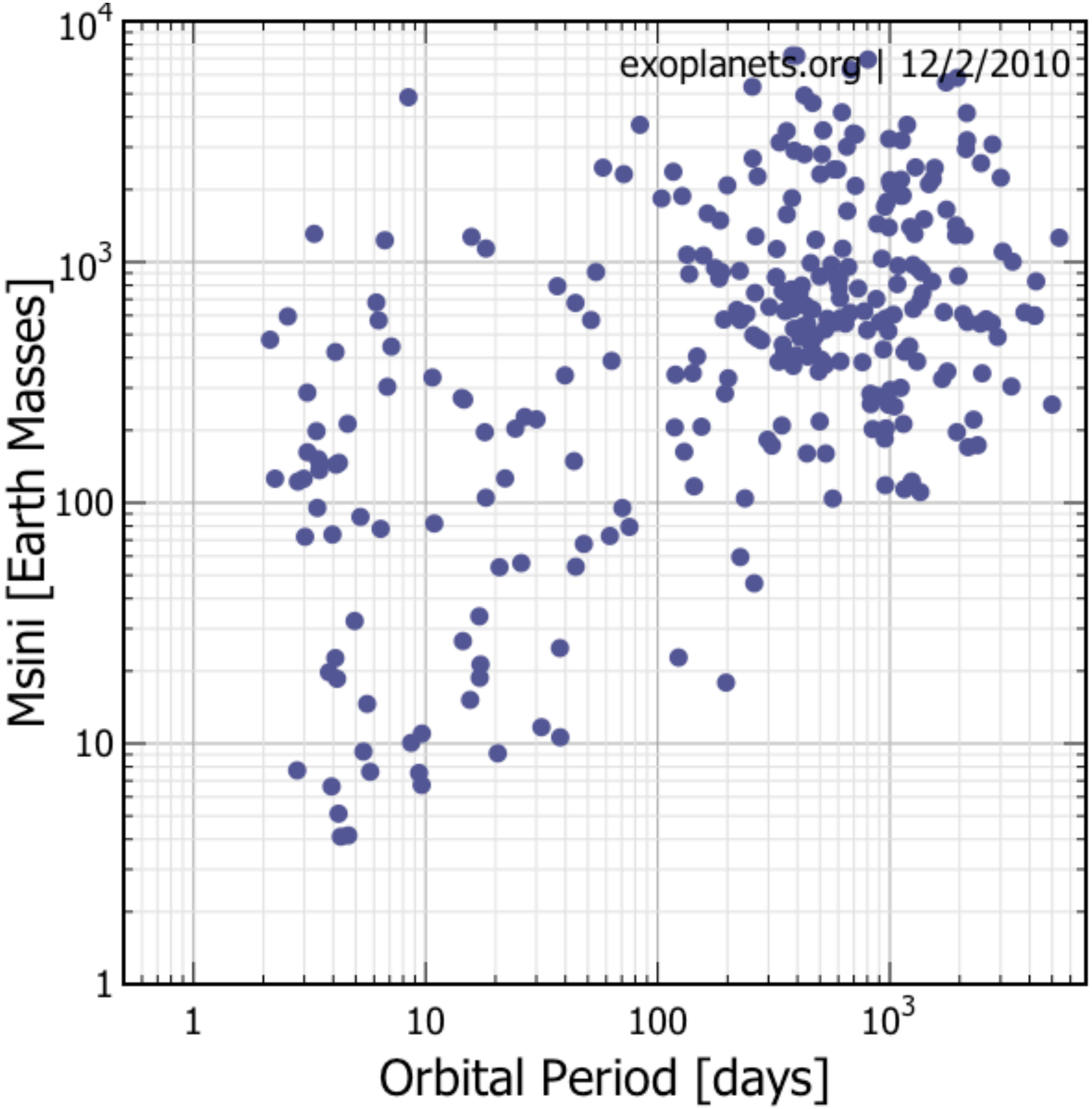


Exoplanets.org:

RV-detected and:

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

Exoplanet Distribution - Msini-Period



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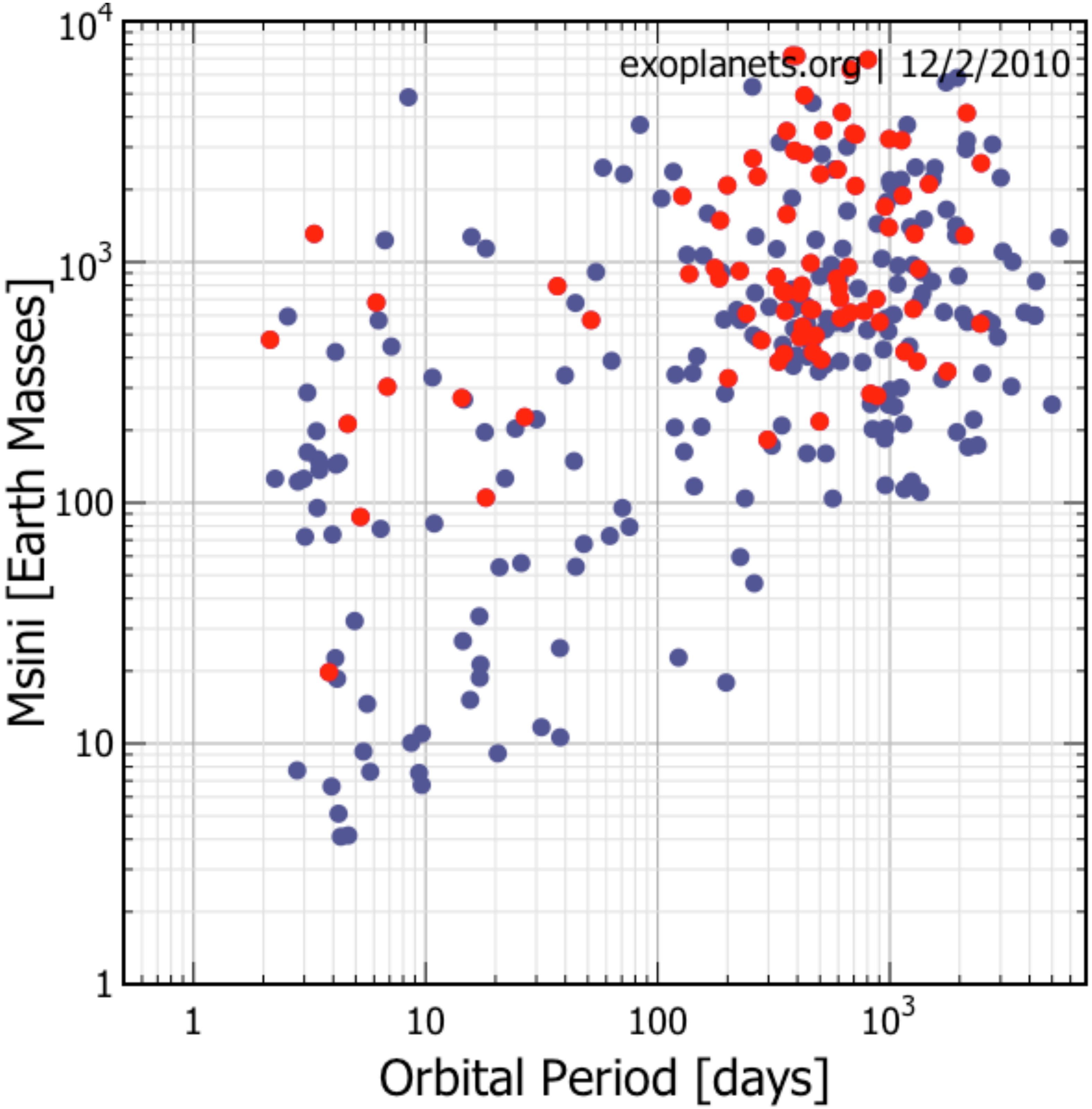
Exoplanet Distribution - Msini-Period



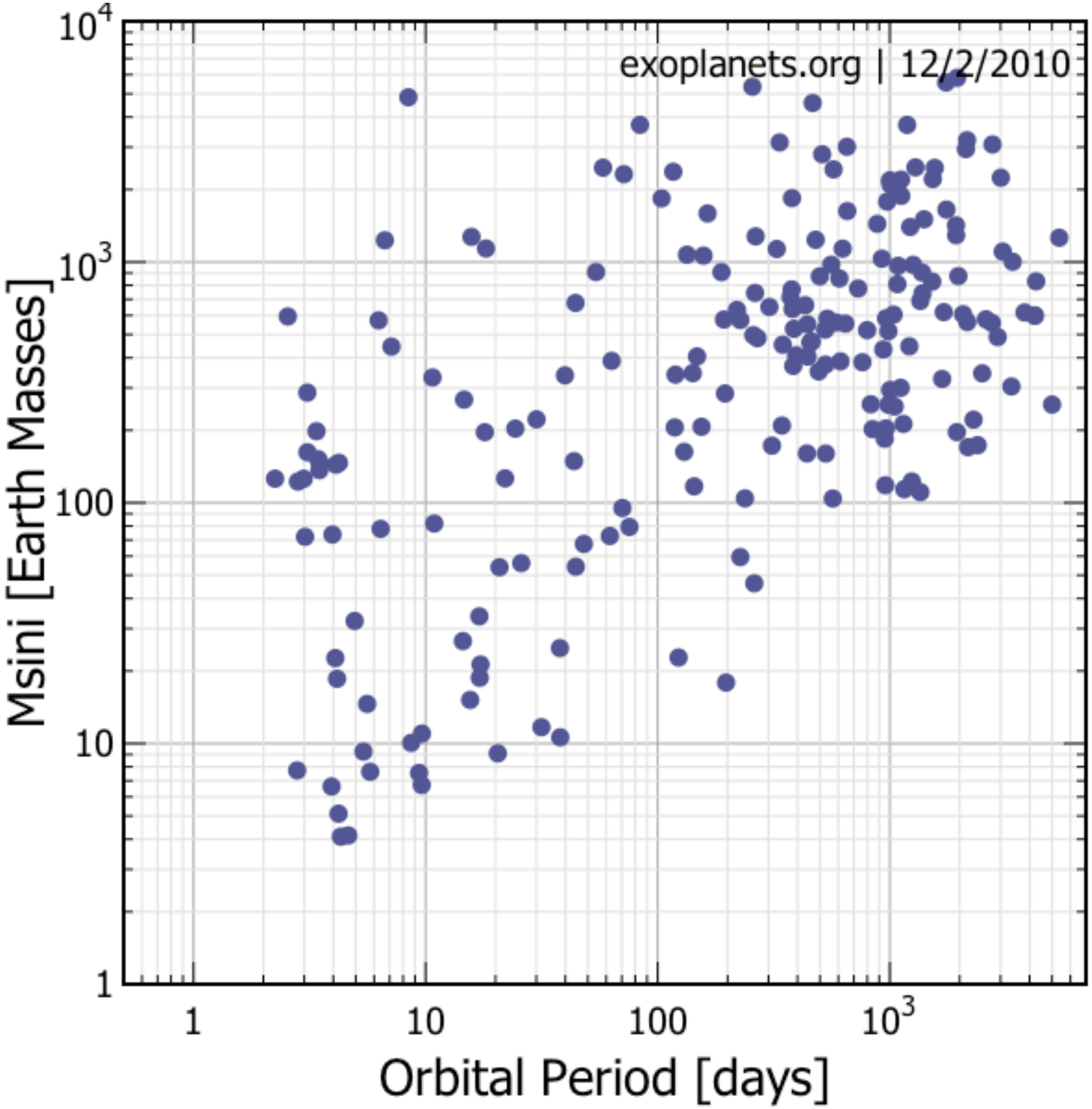
<u>Exoplanets.org:</u>

RV-detected,

M_{star} > 0.6 M_{sun} and:

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

Exoplanet Distribution - Msini-Period

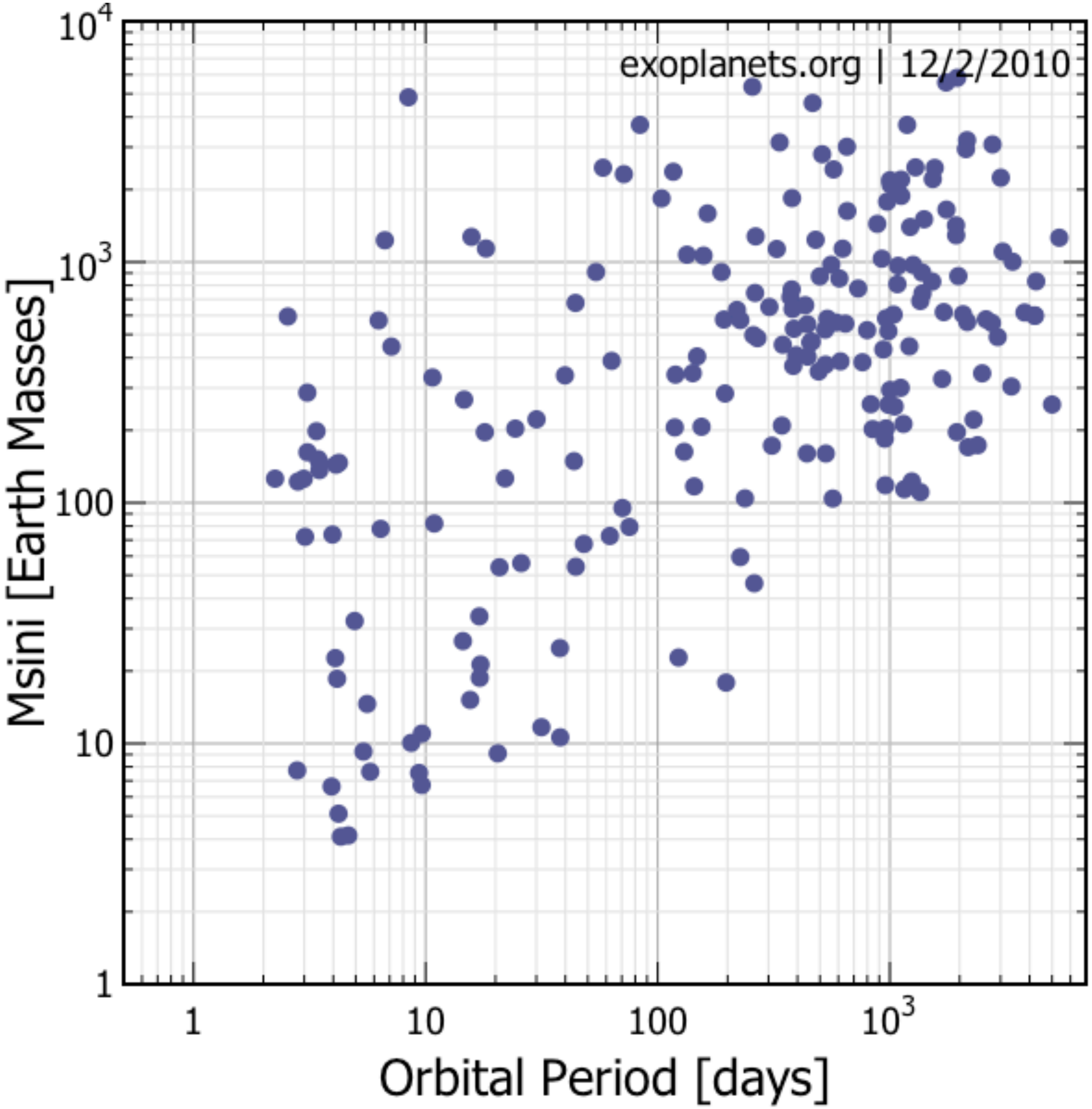


<u>Exoplanets.org:</u>

RV-detected and:

- M_{star} =0.6-1.2 M_{sun}

Exoplanet Distribution - Msini-Period



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How do you compute?

$$\frac{\#\text{ of Planets}}{\#\text{ of Stars}}$$

Planet Occurrence

Apparently simple measurement requires careful treatment of numerator and denominator:

$$\text{Occurrence} = \frac{\text{Number of Planets}}{\text{Number of Stars}}$$

Planet Occurrence

Apparently simple measurement requires careful treatment of numerator and denominator:

- Define planet parameters of measurement (M, R, P, e, etc.)
- Set planet detection threshold
- Incompleteness — correct for missed planets

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- Define stellar parameters of measurement (*M*, *R*, *Fe/H*, *Teff*, *logg*, etc.)

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Pause ....

... questions so far?

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Early Observation:

4/4 Jupiter host stars are iron-rich (Gonzalez et al. 1997)

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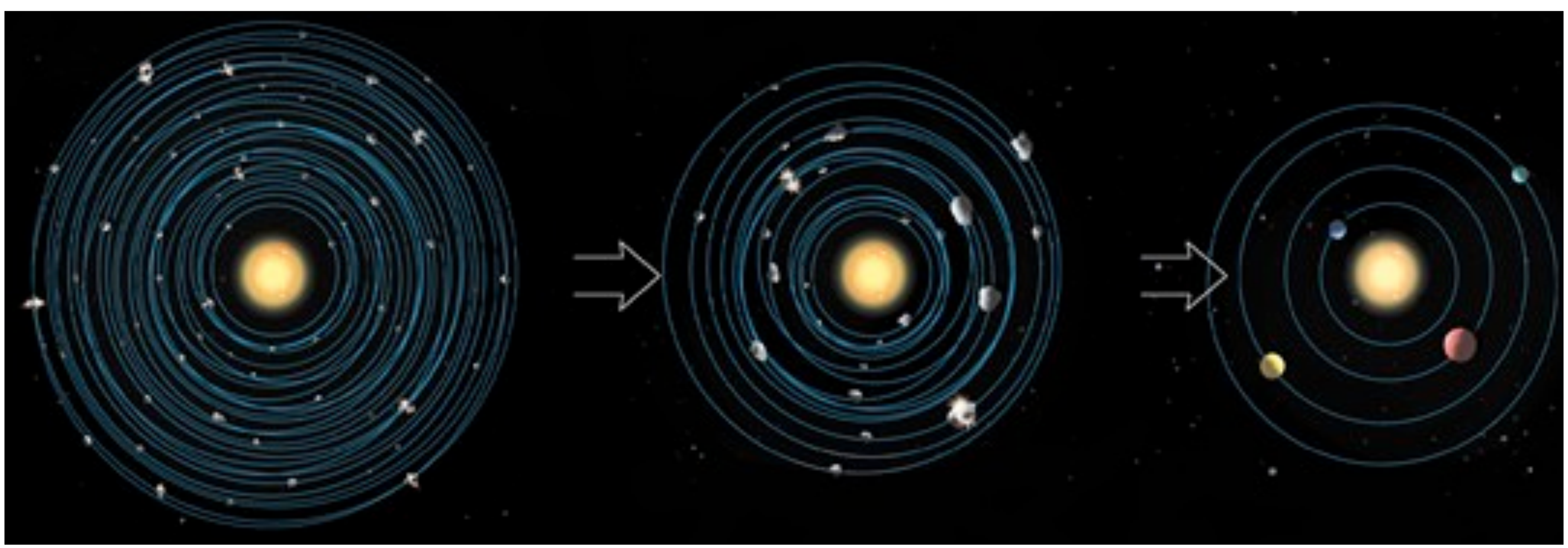
Core Accretion



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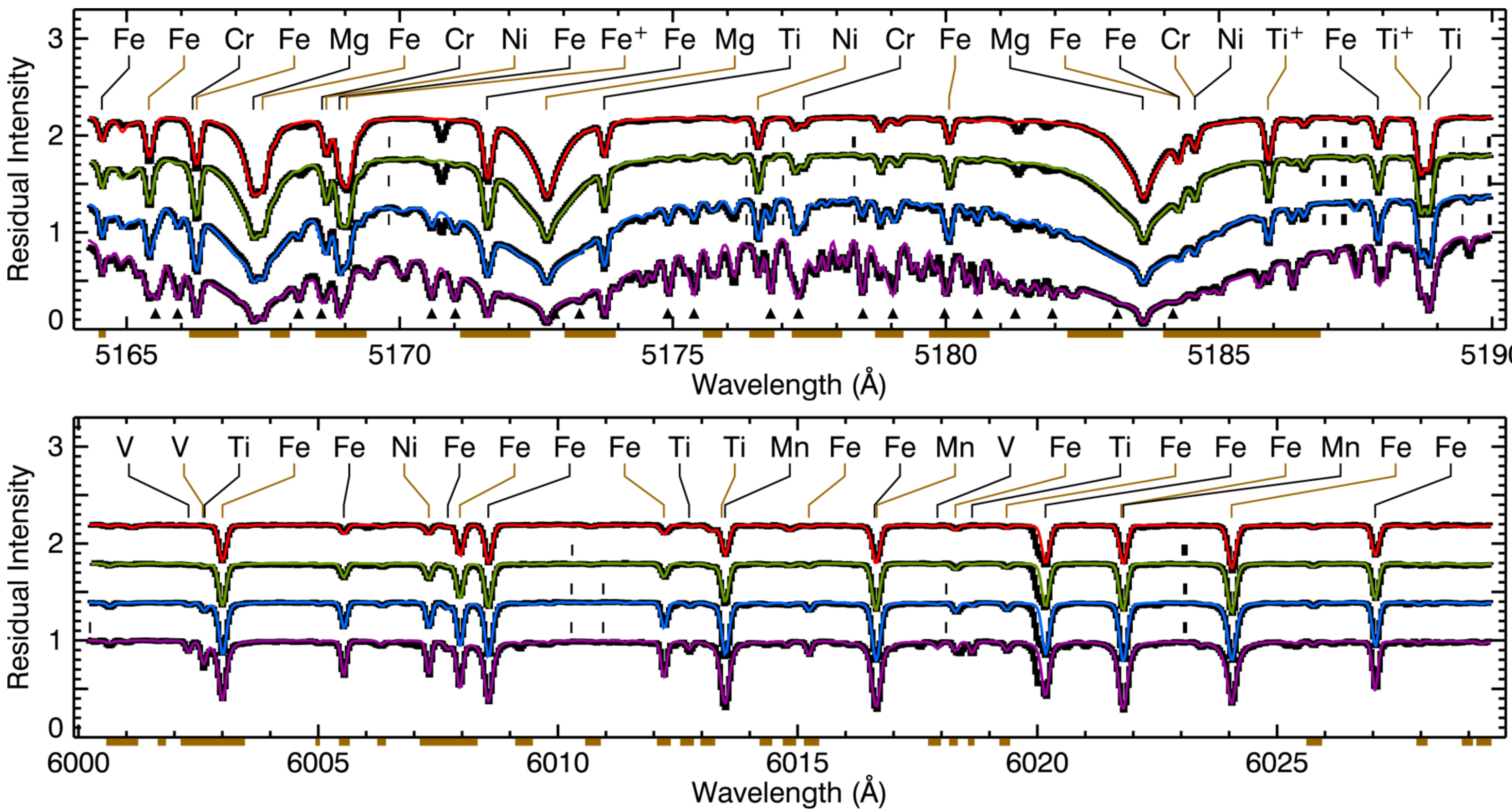
Many responses:

Focus on Fischer & Valenti (2005)

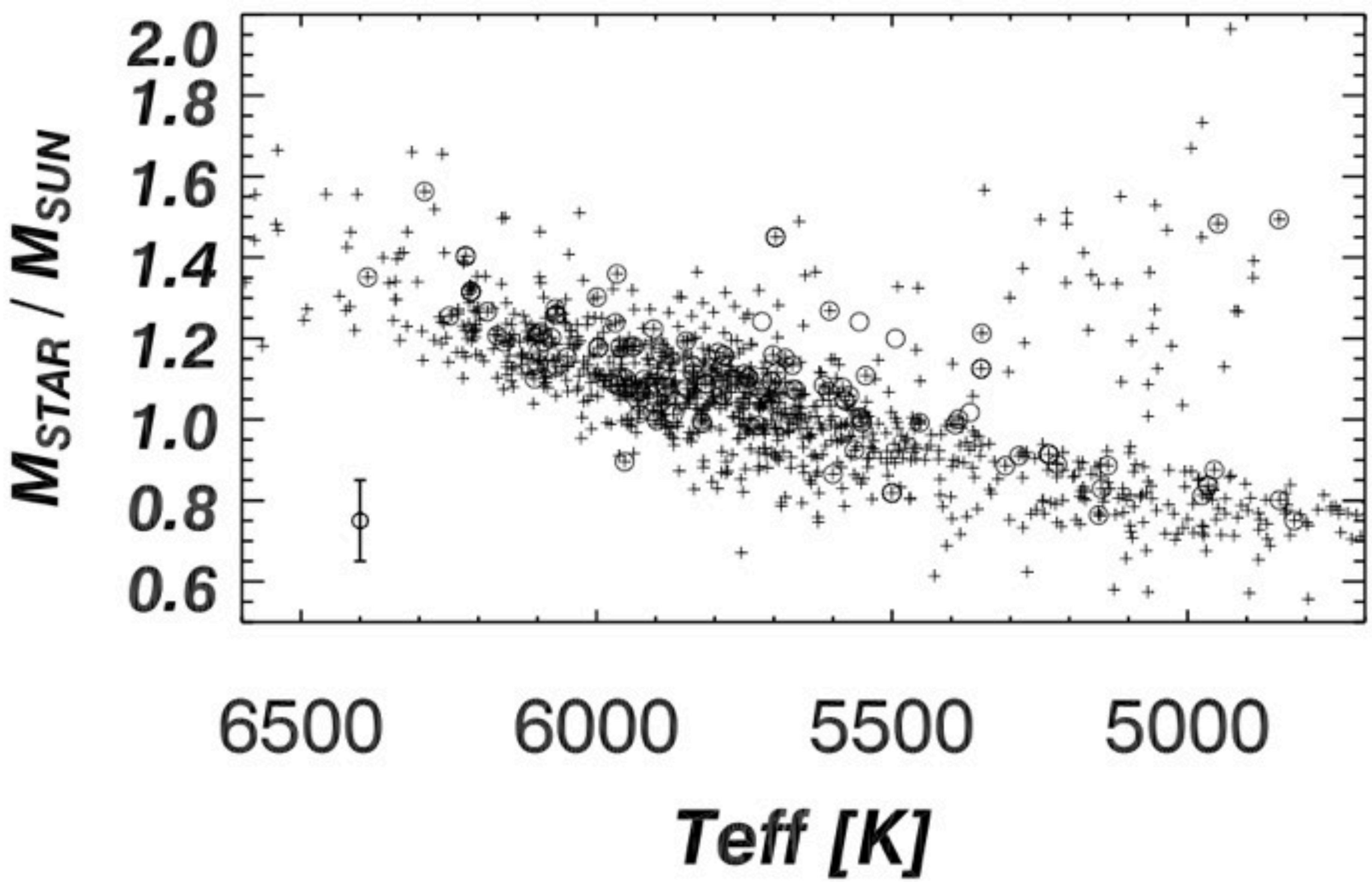
Measure [Fe/H] using Spectroscopy Made Easy (SME)

Valenti & Fischer (2005) — measure stellar parameters (SME)
Fischer & Valenti (2005) — planet-metallicity correlation



Define the Sample

1040 nearby dwarfs and subgiants in planet search programs at Keck/Lick/AAT — nearly unbiased sample



Compute Planet Occurrence

- Define planet parameters of measurement (*M*, *R*, *P*, e, etc.)
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- Incompleteness — correct for missed planets

$$\text{Occurrence} = \frac{\text{Number of Planets}}{\text{Number of Stars}}$$

- FGK dwarfs and subgiants — nearby; nearly unbiased (Hipparcos)

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- [Fe/H] and other stellar params measured uniformly by SME

Compute Planet Occurrence

- Period < 4 years, ~Jovian mass (depending on period)
- K > 30 m/s
- Assume 100% planet detection completeness (reasonable)

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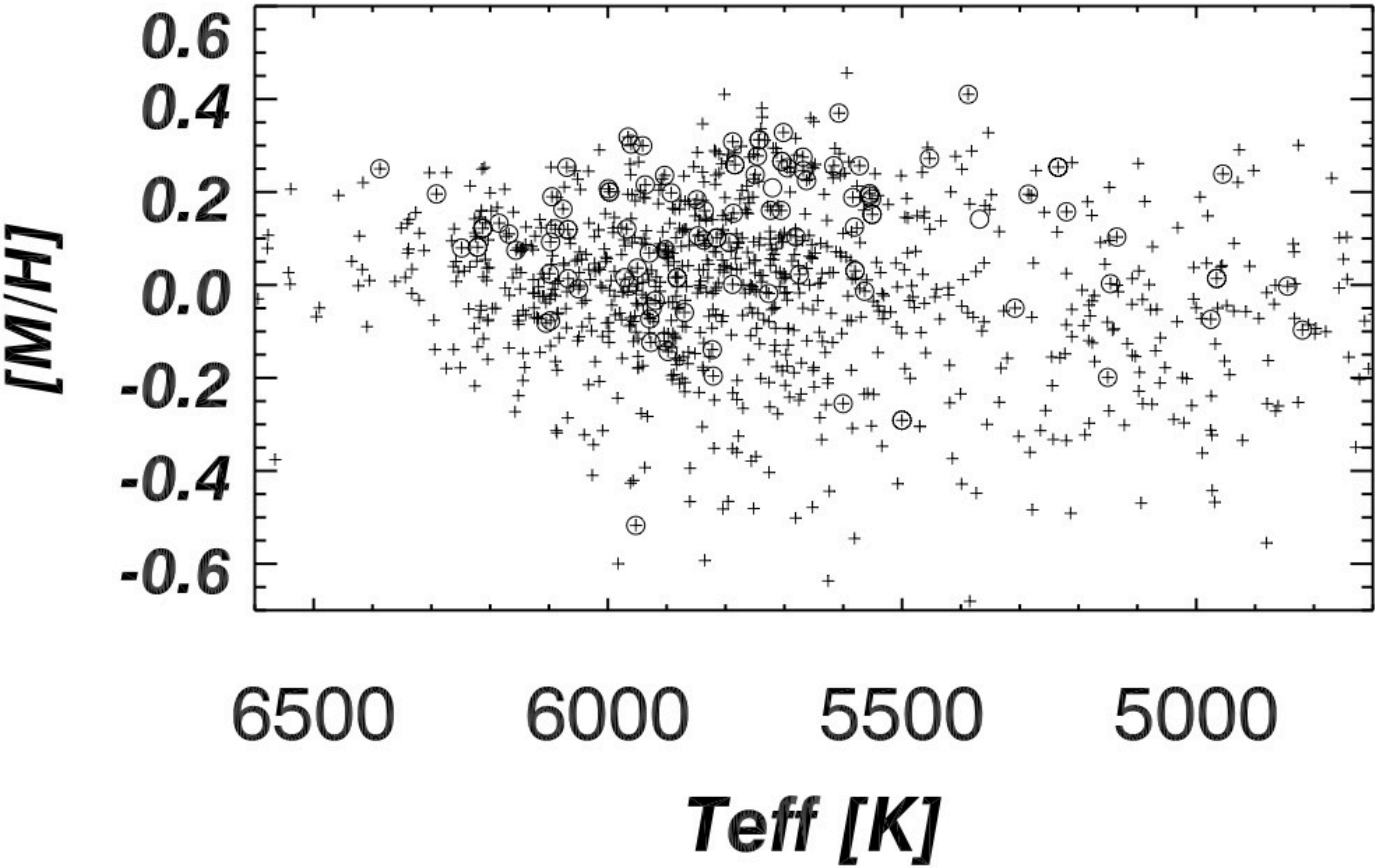
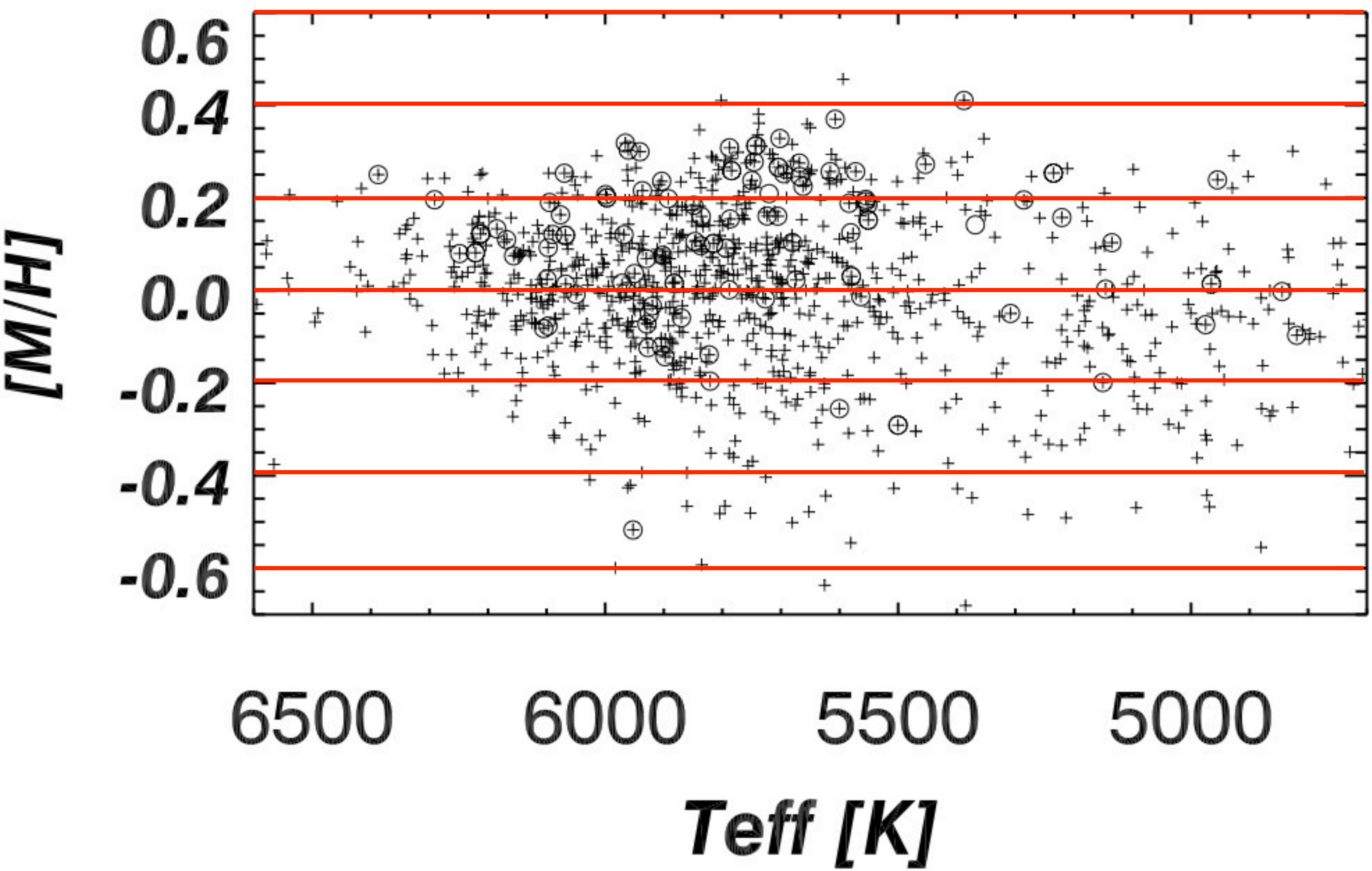

0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
[M/H]
6500
6000
5500
5000
Teff [K]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5000
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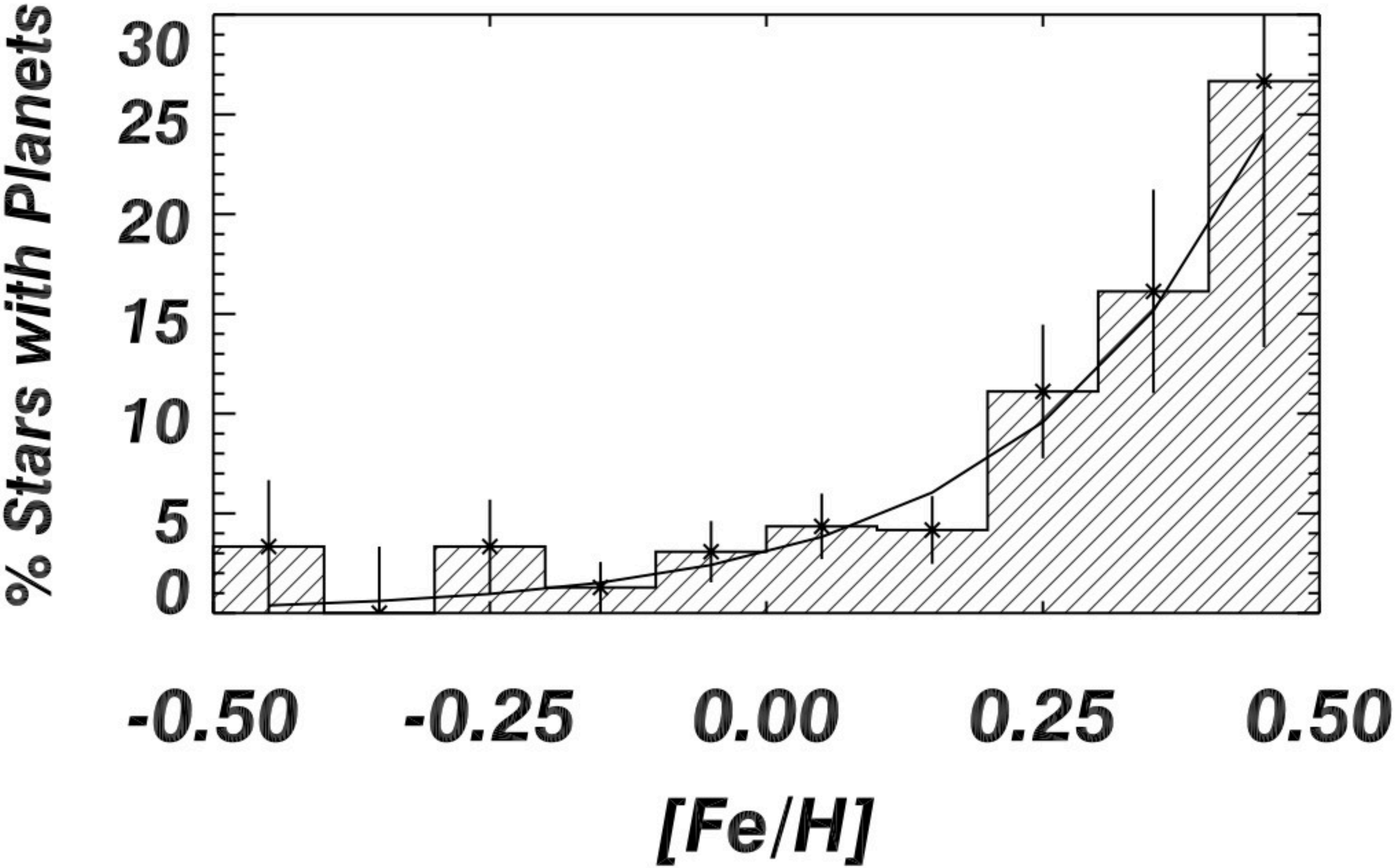
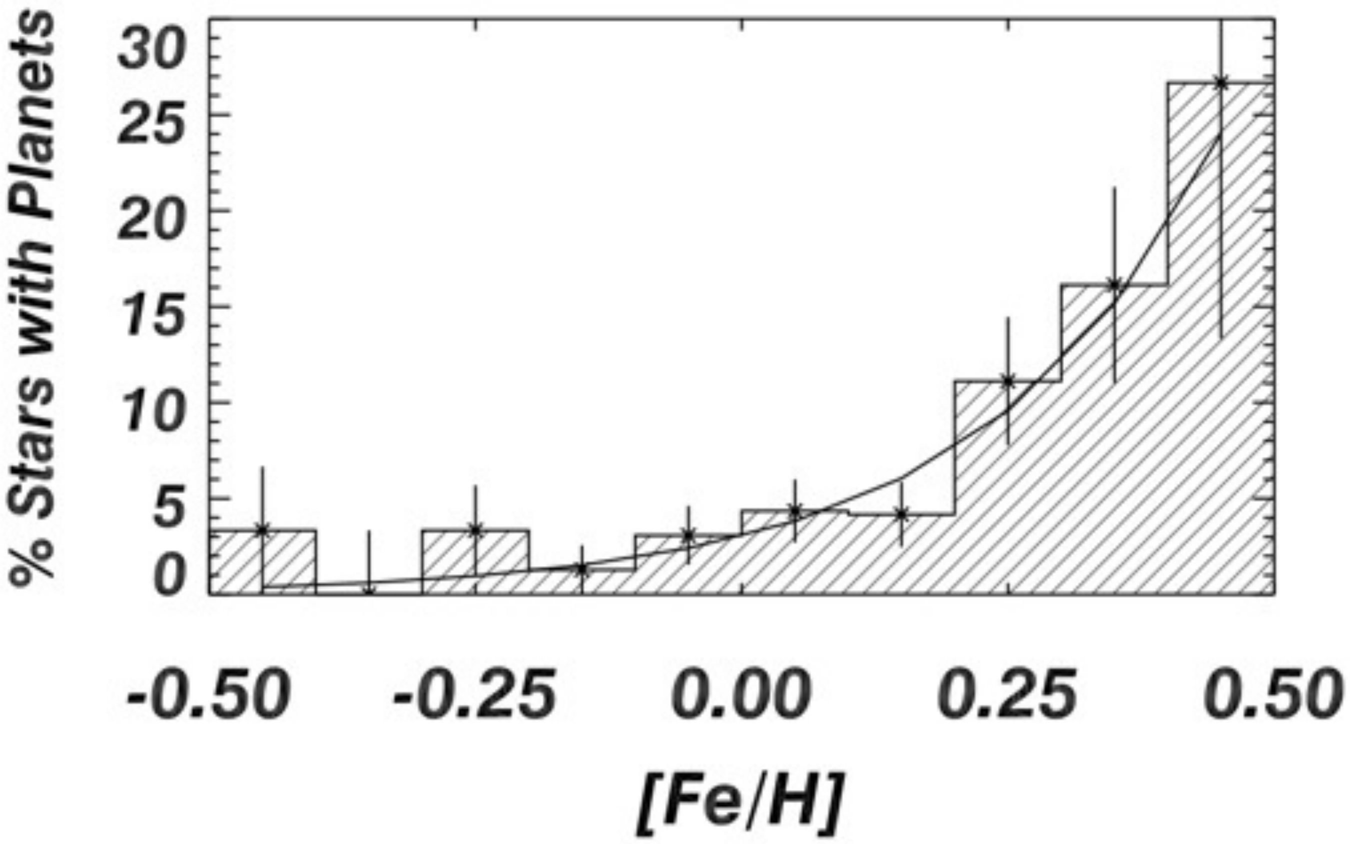
Planet-Metallicity Correlation



Fit to Model



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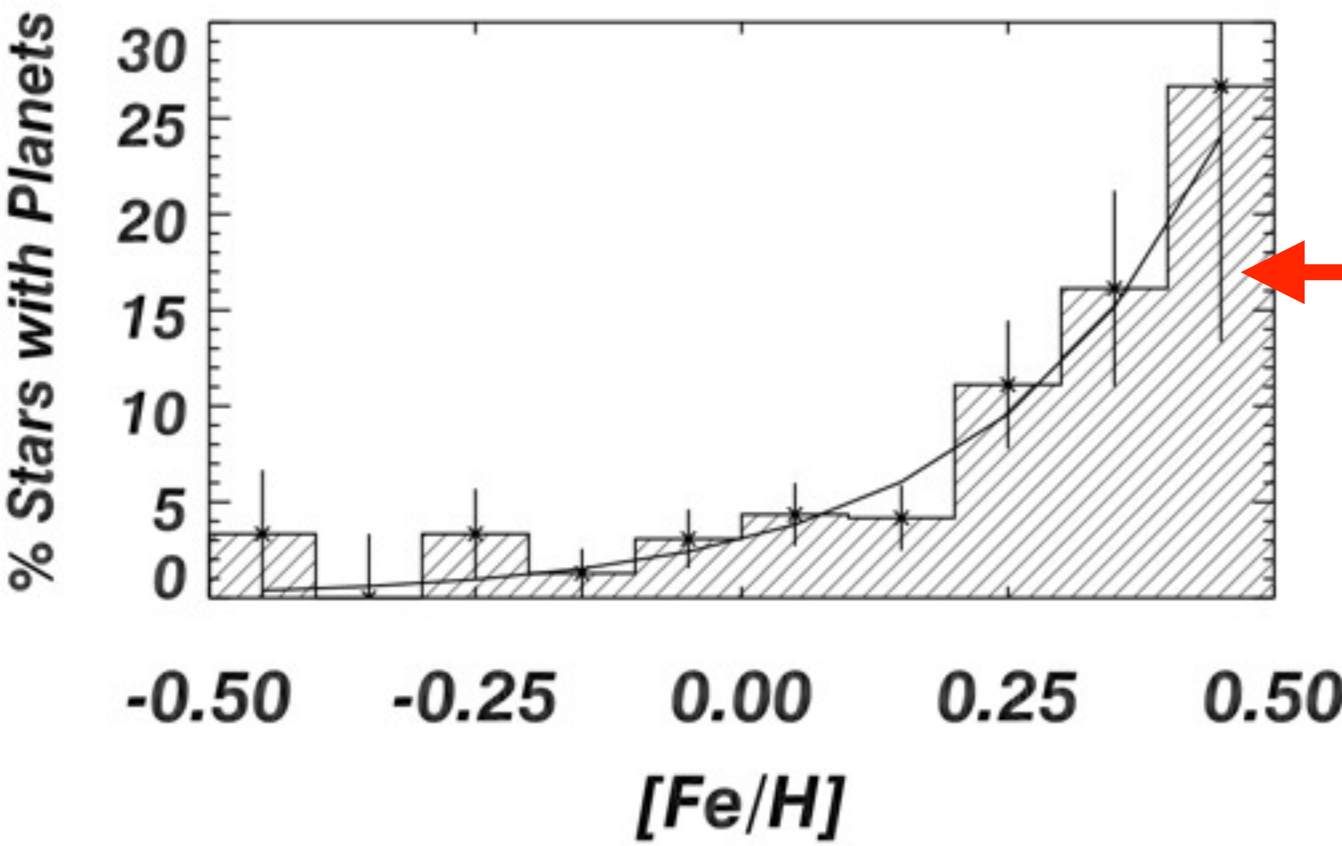
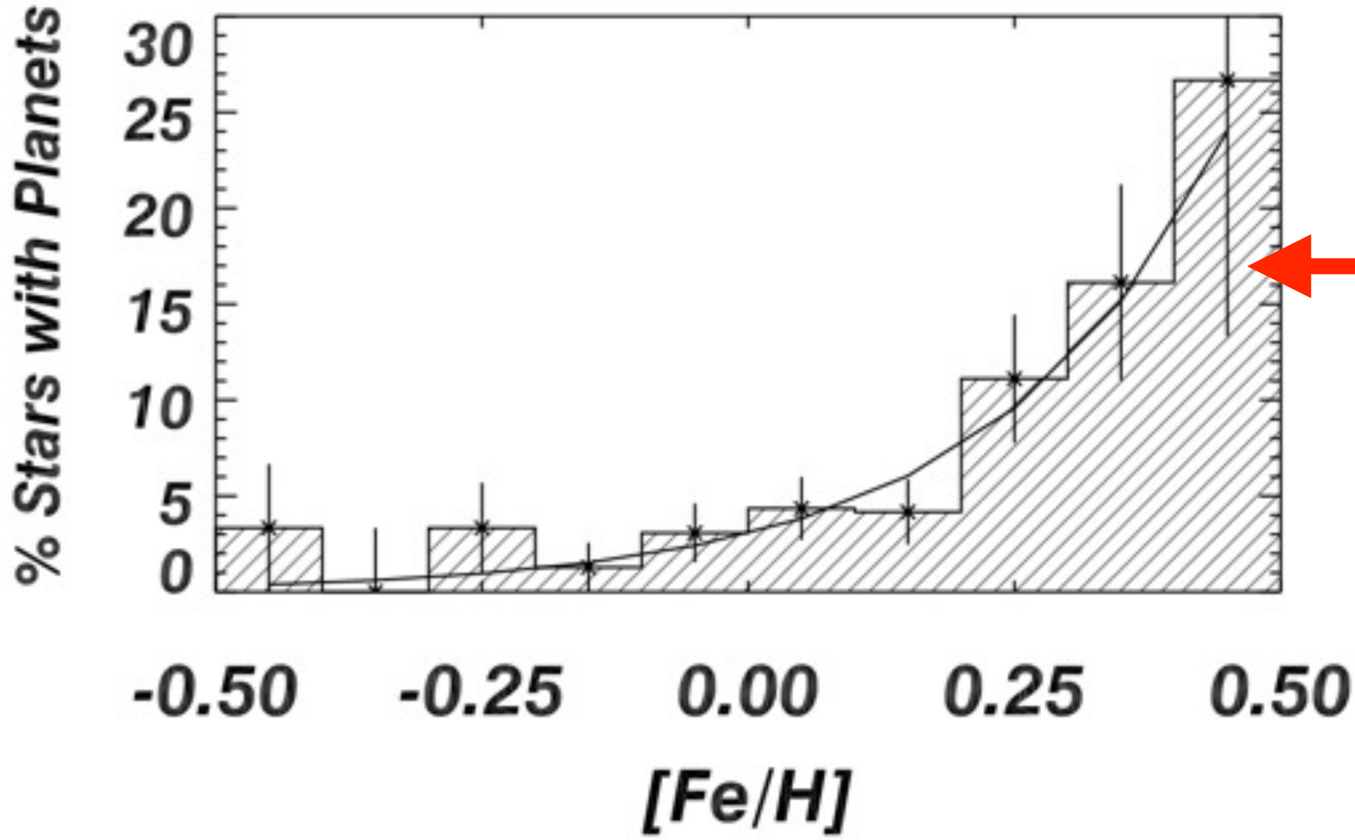


Poisson errors ∝ sqrt(N_{pl})

Fit to Model



Poisson errors ∝ sqrt(N_{pl})

Fit to Power Law Model

Free params

$$\mathcal{P}(\text{planet}) = 0.03 \times 10^{2.0[\text{Fe/H}]}$$

$$\mathcal{P}(\text{planet}) = 0.03 \left[\frac{N_{\text{Fe}}/N_{\text{H}}}{(N_{\text{Fe}}/N_{\text{H}})_{\odot}} \right]^2$$

Planet-Metallicity Correlation

Statistical Question:

Are jovian planets more commonly found orbiting metal-rich stars? What is the occurrence of jovian planets as a function of stellar metallicity?

Answer:

Yes, metal-rich stars are more commonly planet hosts.
Jovian planet occurrence scales as the square of the number of iron atoms

Science Question:

Are jovian planets formed by core accretion, which depends critically on quickly accreting a ~10 Earth-mass core out of metals from the protoplanetary disk?

Answer:

The planet-metallicity correlation supports the core accretion mechanism, both qualitatively and quantitatively.

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- Assume 100% planet detection completeness (reasonable)

↓

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↑

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Well-defined sample

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Uniform [Fe/H] Catalog

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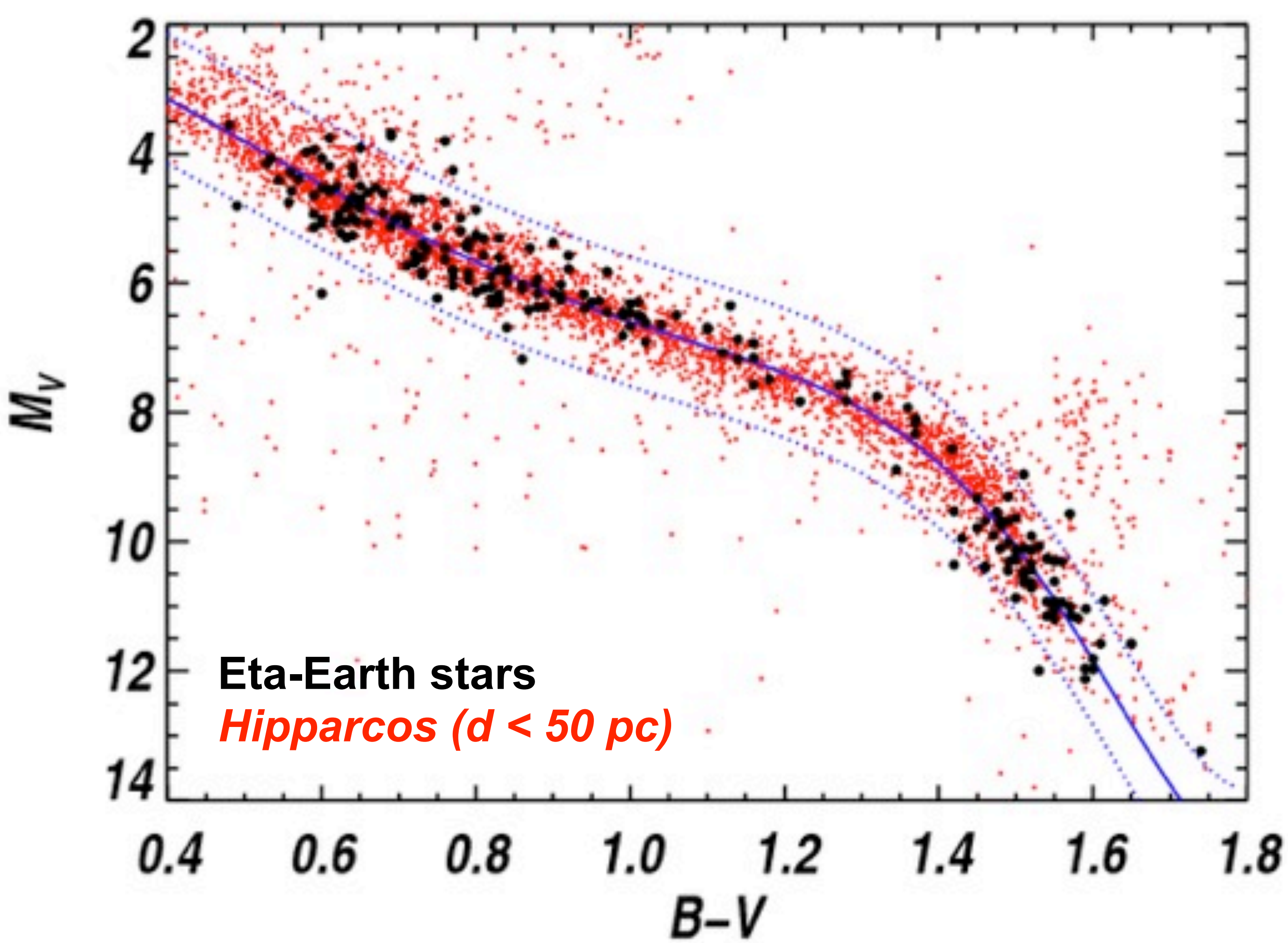
NASA-UC Eta-Earth Program

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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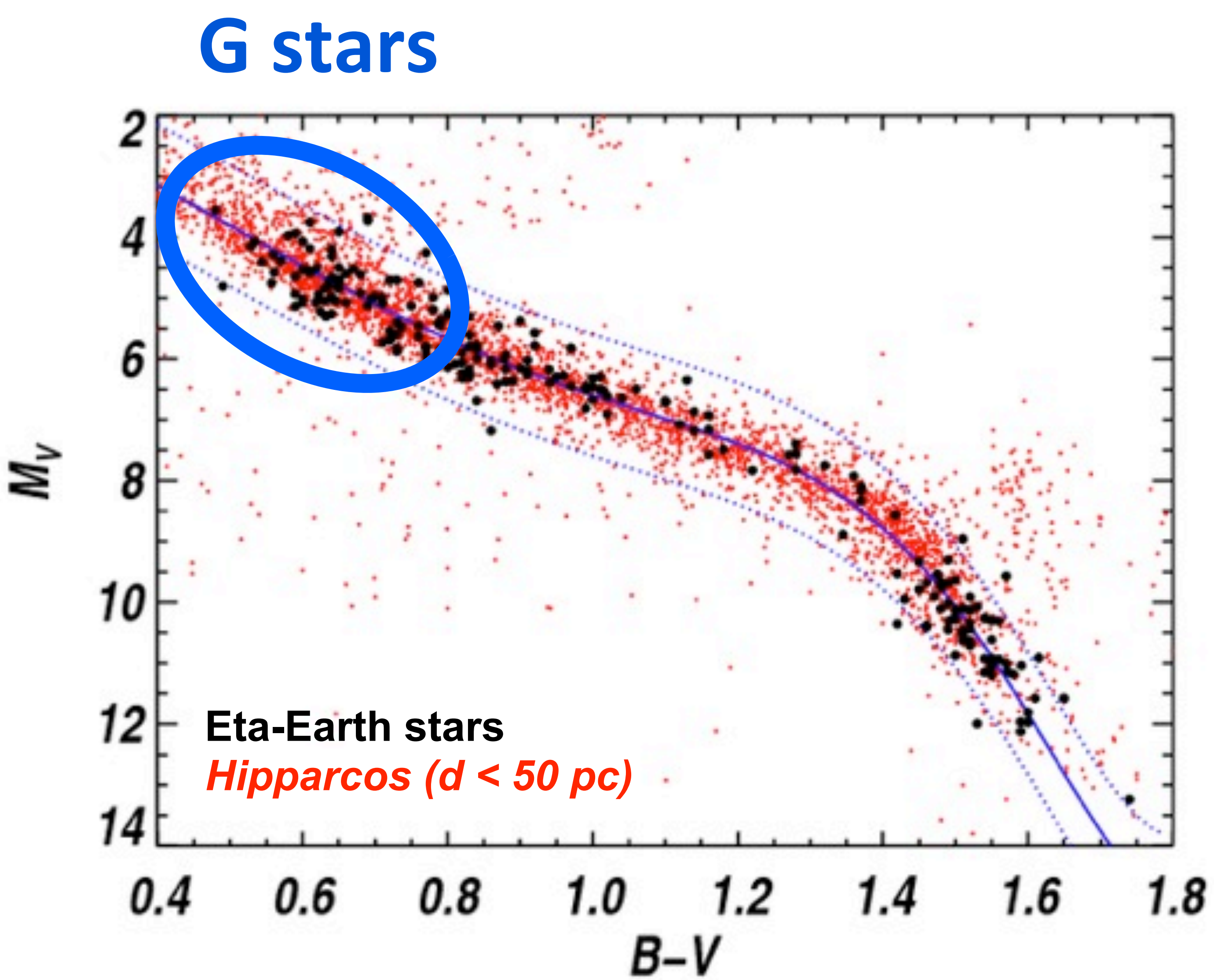

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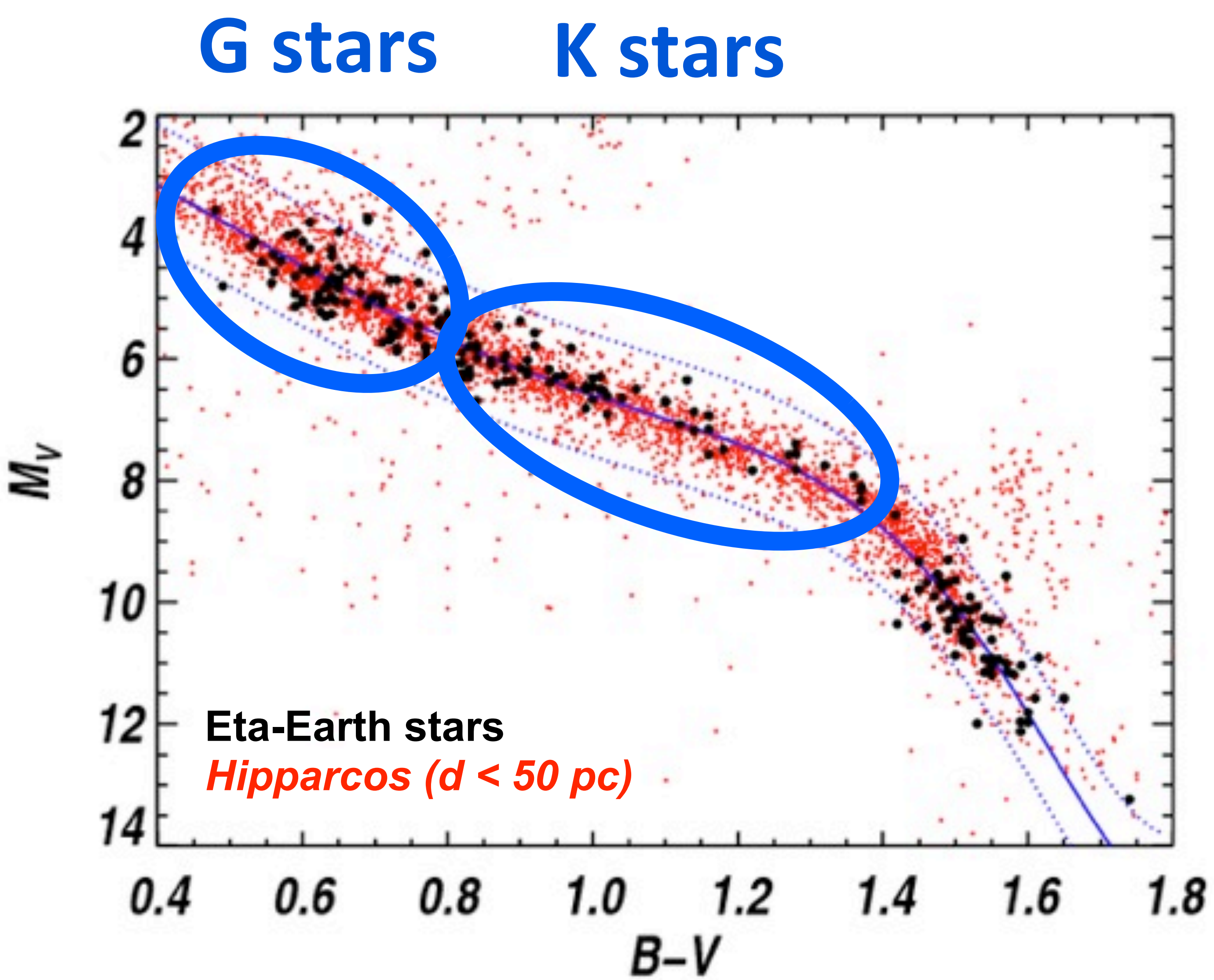

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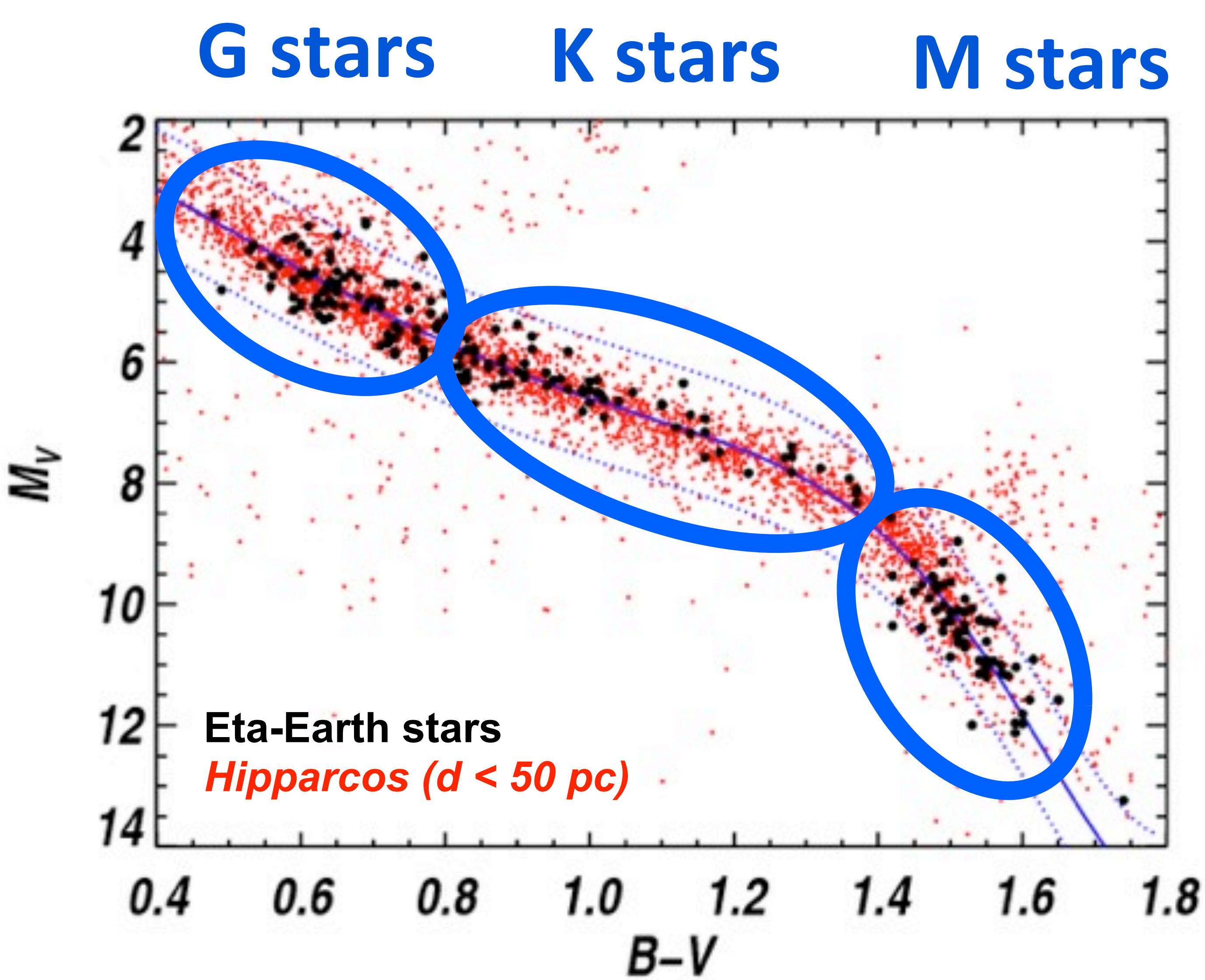

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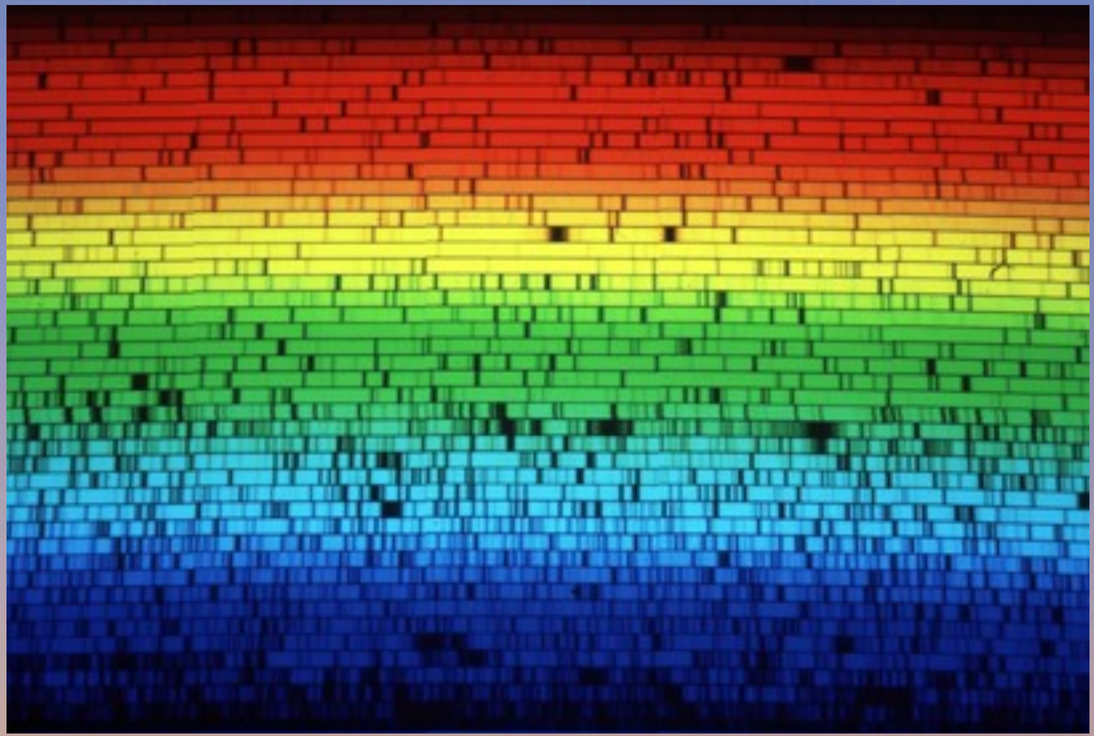
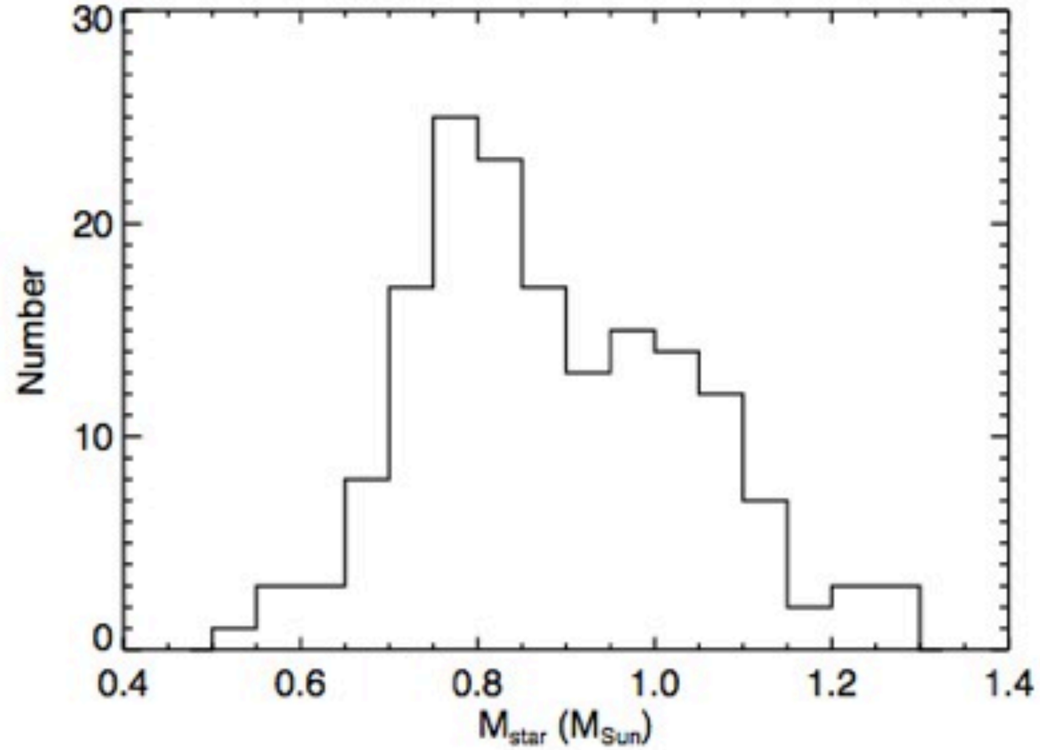
HIRES Echelle Spectrum



HIRES Echelle Spectrum

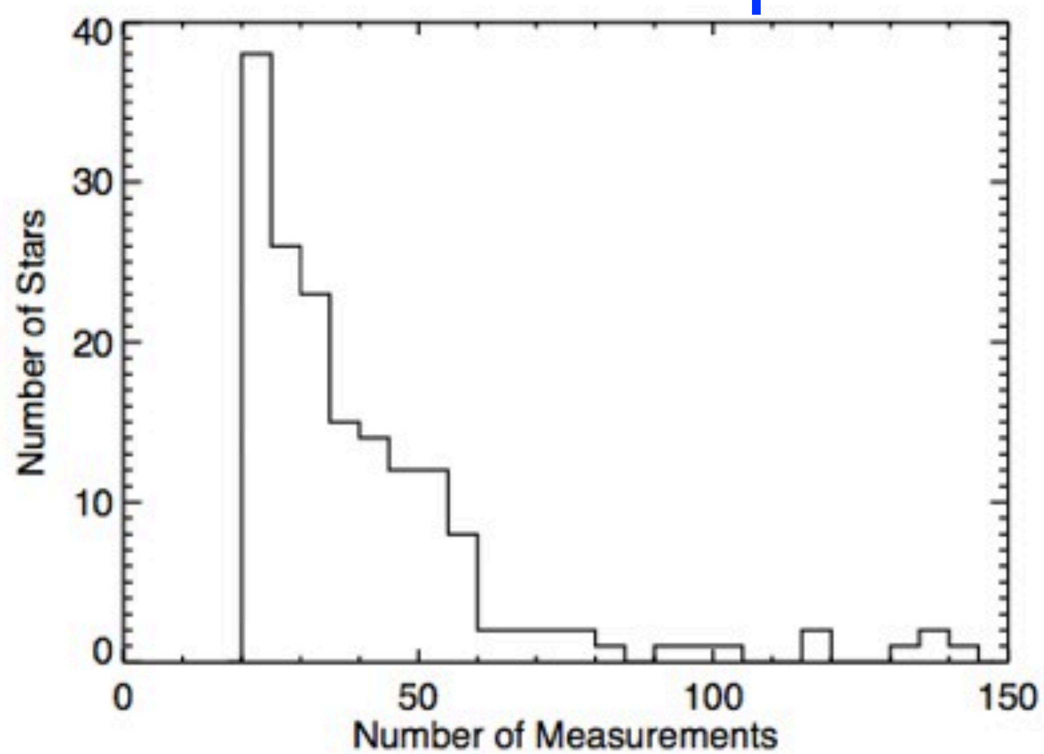
Iodine Absorption Cell

Stellar Masses



Histogram of stellar masses for Eta-Earth stars.

Number of RVs per Star



Histogram of number of RV measurements per Eta-Earth star.

G & K Main Sequence:

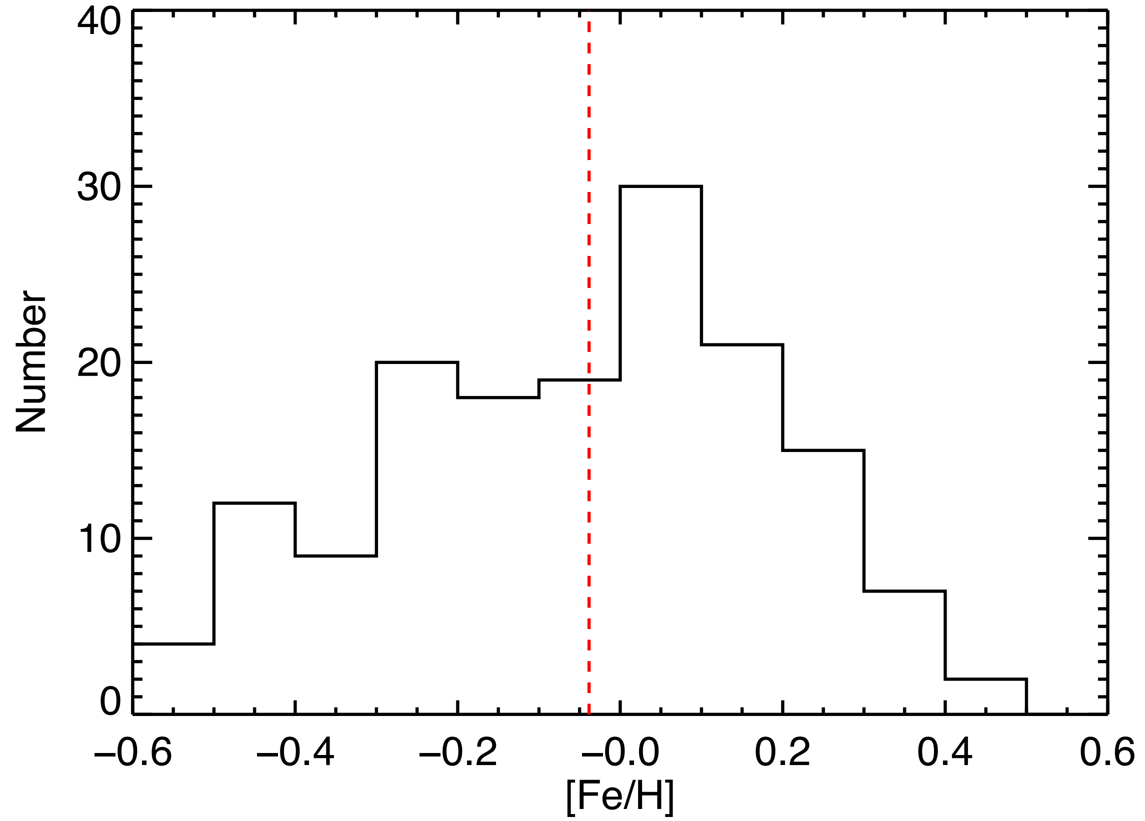
All have parallaxes &

Stellar evolution Tracks

Median: 35 Keck RVs per star

All have high cadence run during 10 Keck nights

Stellar Metallicities

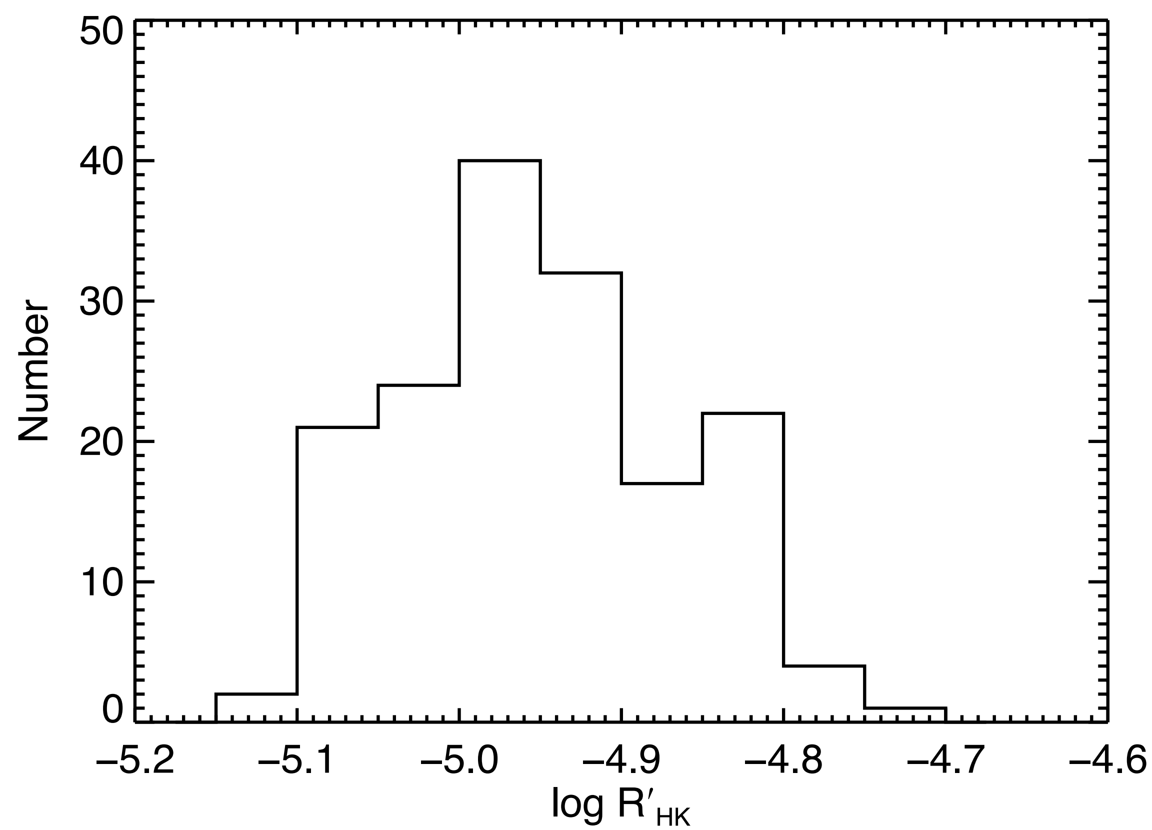


Unbiased Metallicity:

Volume-limited survey

median [Fe/H] = −0.04

Stellar Activity – $\log R'_{HK}$



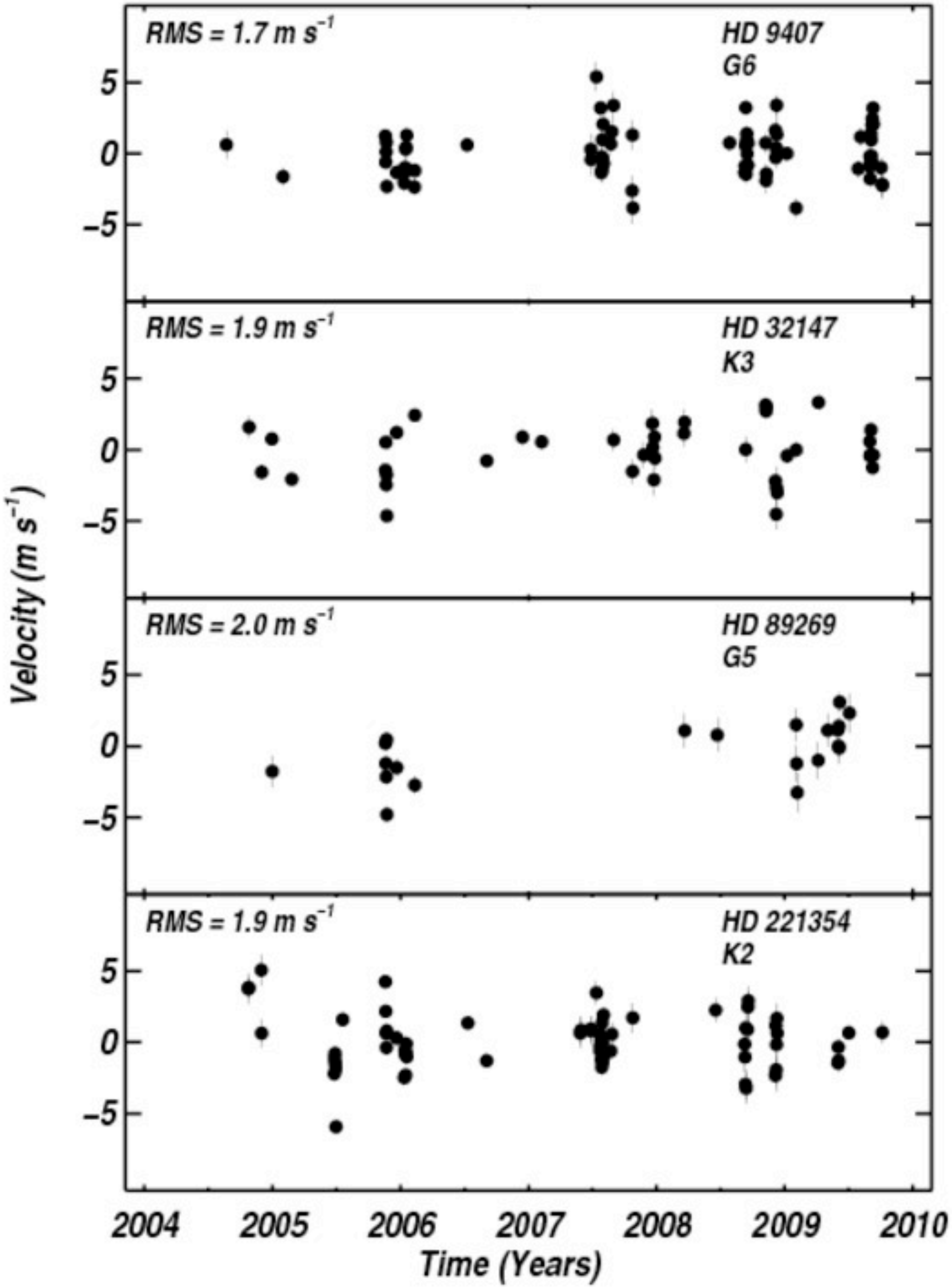
Activity:

$\log R'_{HK} < -4.7$

166 GK Stars in Eta-Earth Survey

Table S1. G and K-type Target Stars in the Eta-Earth

Name	Spec. Type	Mass ($M_\odot$)	Num. Obs.
HD 1461	G0	1.08	154
HD 3651	K0	0.89	29
HD 3765	K2	0.84	35
HD 4256	K2	0.85	36
HD 4614	G0	0.99	30
HD 4614 B	K7	0.57	28
HD 4628	K2	0.72	49
HD 4747	G8	0.82	22
HD 4915	G0	0.90	37
HD 7924	K0	0.83	135
HD 9407	G6	0.98	97
HD 10476	K1	0.83	56
HD 10700	G8	0.95	133
HD 12051	G5	0.99	52
HD 12846	G2	0.88	36
HD 14412	G5	0.78	37
HD 16160	K3	0.76	47
HD 17230	K5	0.69	31
HD 18143	G5	0.90	35
HD 18803	G8	1.00	32
HD 19373	G0	1.20	47
HD 20165	K1	0.82	26
HD 20619	G1	0.91	35
HD 22879	F9	0.79	22
HD 23356	K2	0.78	22
HD 23439	K1	0.67	26
HD 24238	K0	0.73	29
HD 24496	G0	0.94	47
HD 25329	K1	0.83	34
HD 25665	G5	0.78	21
HD 29883	K5	0.76	23
HD 32147	K3	0.83	52
HD 32923	G4	1.03	26
HD 34721	G0	1.12	21
HD 34411	G0	1.13	40
HD 36003	K5	0.73	42
HD 37008	K2	0.73	22
HD 38230	K0	0.83	24
HD 38858	G4	0.92	35
HD 40397	G0	0.92	23
HD 42618	G4	0.96	59
HD 45184	G2	1.04	46
HD 48682	G0	1.17	27
HD 50692	G0	1.00	37
HD 51419	G5	0.86	40
HD 51866	K3	0.78	32
HD 52711	G4	1.02	46
HD 55575	G0	1.26	32
HD 62613	G8	0.94	24
HD 65277	K5	0.72	21
HD 65583	G8	0.76	26
HD 68017	G4	0.85	43
HD 69830	K0	0.87	46
HD 72673	K0	0.78	23
HD 73667	K1	0.72	22
HD 75732	G8	0.91	96
HD 84035	K5	0.73	22
HD 84117	G0	1.15	22
HD 84737	G0	1.22	24
HD 86728	G3	1.08	28
HD 87883	K0	0.80	30
HD 89269	G5	0.89	29
HD 90156	G5	0.90	28
HD 92719	G2	1.10	24
HD 95128	G1	1.08	22
HD 97101	K8	0.60	21
HD 97343	G8	0.89	35
HD 97658	K1	0.78	61
HD 98281	G8	0.85	46
HD 99491	K0	1.01	71
HD 99492	K2	0.86	47
HD 100180	G0	1.10	24
HD 100623	K0	0.77	32
HD 103932	K5	0.76	44
HD 104304	G9	1.02	23
HD 109358	G0	1.00	41
HD 110315	K2	0.70	37
HD 110897	G0	1.23	29
HD 114613	G3	1.28	21
HD 114783	K0	0.86	45
HD 115617	G5	0.95	61
HD 116442	G5	0.76	25
HD 116443	G5	0.73	55
HD 117176	G4	1.11	30
HD 120467	K4	0.71	20
HD 122064	K3	0.80	43
HD 122120	K5	0.71	36
HD 125455	K1	0.79	20
HD 126053	G1	0.86	30
HD 127334	G5	1.10	24
HD 130992	K3	0.77	36
HD 132142	K1	0.77	21
HD 136713	K2	0.84	79
HD 139323	K3	0.89	91
HD 140538 A	G2	1.06	58
HD 141004	G0	1.14	68
HD 143761	G0	1.00	29
HD 144579	G8	0.75	30
HD 145675	K0	1.00	59
HD 145958 A	G8	0.91	44
HD 145958 B	K0	0.88	31
HD 146233	G2	1.02	52
HD 146362 B	G1	1.07	29
HD 148467	K5	0.67	22
HD 149806	K0	0.94	28
HD 151288	K5	0.59	22
HD 151541	K1	0.83	29
HD 154088	G8	0.97	67
HD 154345	G8	0.88	53
HD 154363	K5	0.64	25
HD 155712	K0	0.79	39
HD 156668	K2	0.77	93
HD 156985	K2	0.77	34
HD 157214	G0	0.91	25
HD 157347	G5	0.99	46
HD 158633	K0	0.78	20
HD 159062	G5	0.94	29
HD 159222	G5	1.04	55
HD 161797	G5	1.15	22
HD 164922	K0	0.94	50
HD 166620	K2	0.76	35
HD 168009	G2	1.02	24
HD 170493	K3	0.81	33
HD 172051	G5	0.87	28
HD 176377	G0	0.92	32
HD 179957	G4	1.01	39
HD 179958	G4	1.03	38
HD 182488	G8	0.96	45
HD 182572	G8	1.14	27
HD 185144	K0	0.80	122
HD 185414	G0	1.07	27
HD 186408	G1	1.07	35
HD 186427	G3	0.99	44
HD 190067	G7	0.80	50
HD 190360	G6	1.01	45
HD 190404	K1	0.70	21
HD 190406	G1	1.09	32
HD 191785	K1	0.83	22
HD 191408	K3	0.69	36
HD 192310	K0	0.82	45
HD 193202	K5	0.67	38
HD 196761	G8	0.83	27
HD 197076	G5	0.99	86
HD 201091	K5	0.66	64
HD 201092	K7	0.54	62
HD 202751	K2	0.75	42
HD 204587	K5	0.68	20
HD 208313	K0	0.80	23
HD 210277	G0	1.01	49
HD 210302	F6	1.28	23
HD 213042	K5	0.74	37
HD 215152	K0	0.78	27
HD 216520	K2	0.83	60
HD 216259	K0	0.69	50
HD 217014	G2	1.09	26
HD 217107	G8	1.10	41
HD 218868	K0	0.99	53
HD 219134	K3	0.78	74
HD 219538	K2	0.81	30
HD 219834 B	K2	0.82	24
HD 220339	K2	0.73	36
HD 221354	K2	0.85	79
HIP 18280	K7	0.59	22
HIP 19165	K4	0.70	21
HIP 41689	K7	0.62	20

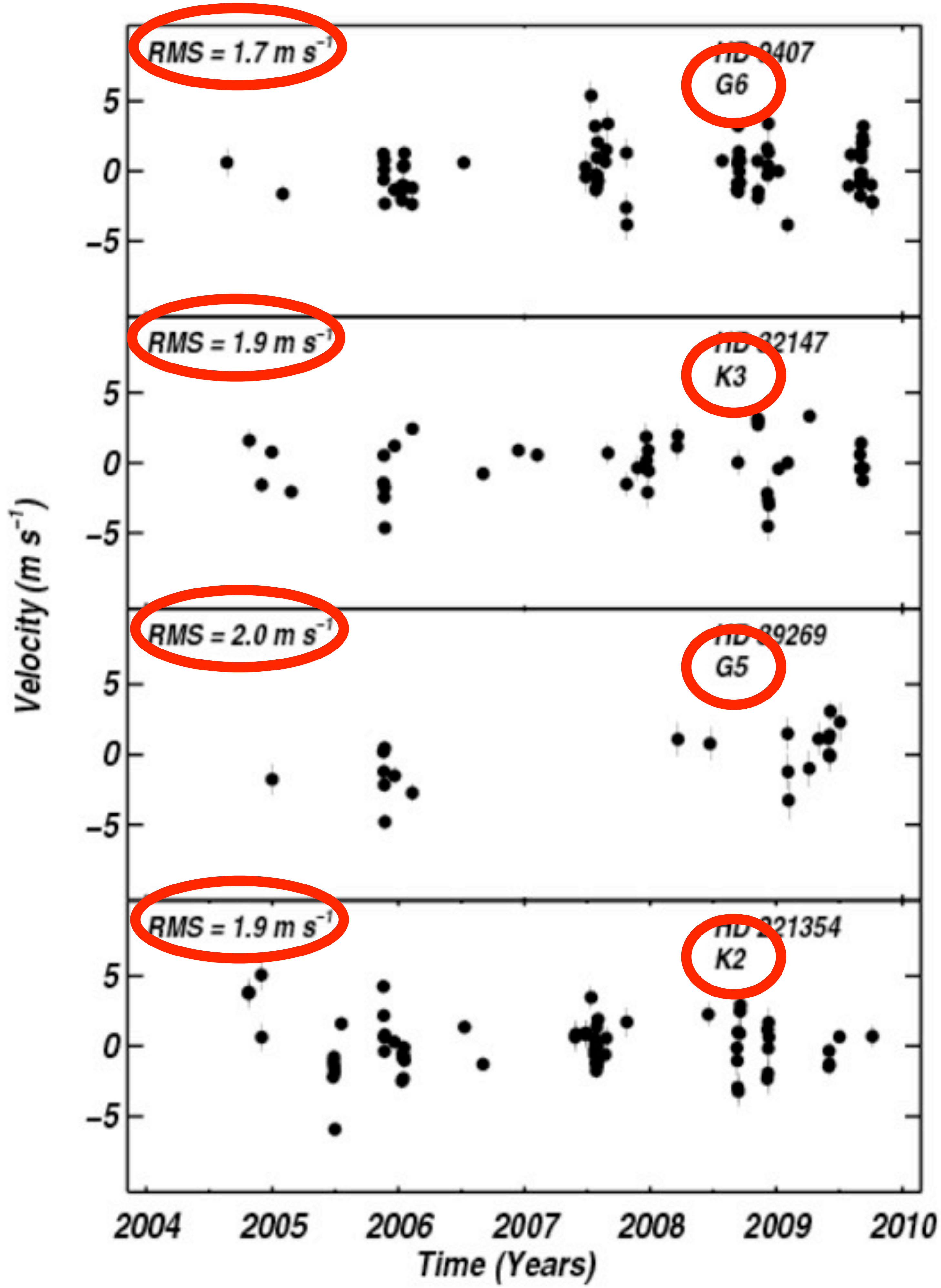


Standard Stars

The best standards have an RMS of 1.5-2.0 m/s.

These are almost always late G / early K dwarfs.

We do not explicitly average over P-modes; T_{exp} ~ 1-5 min



Standard Stars

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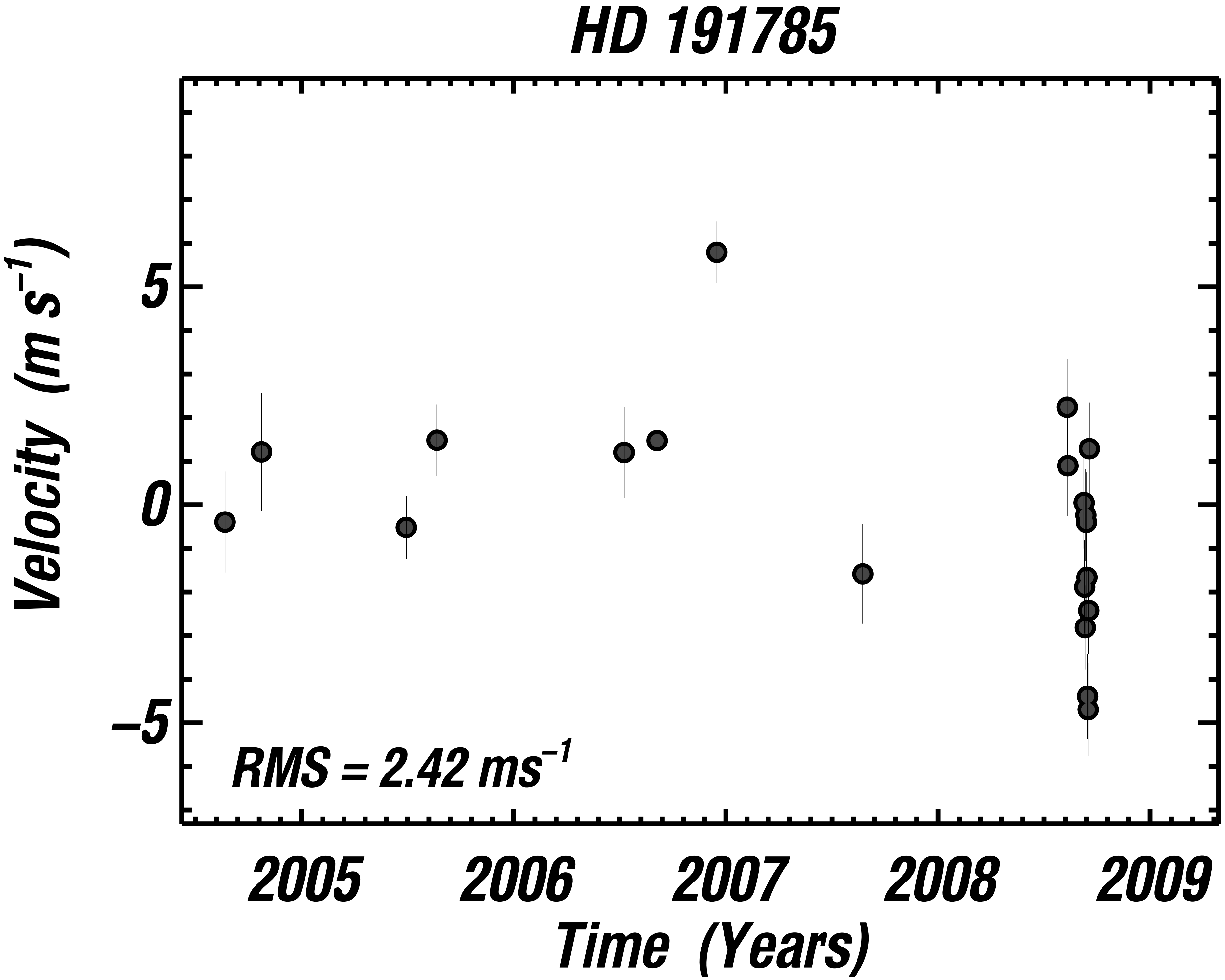
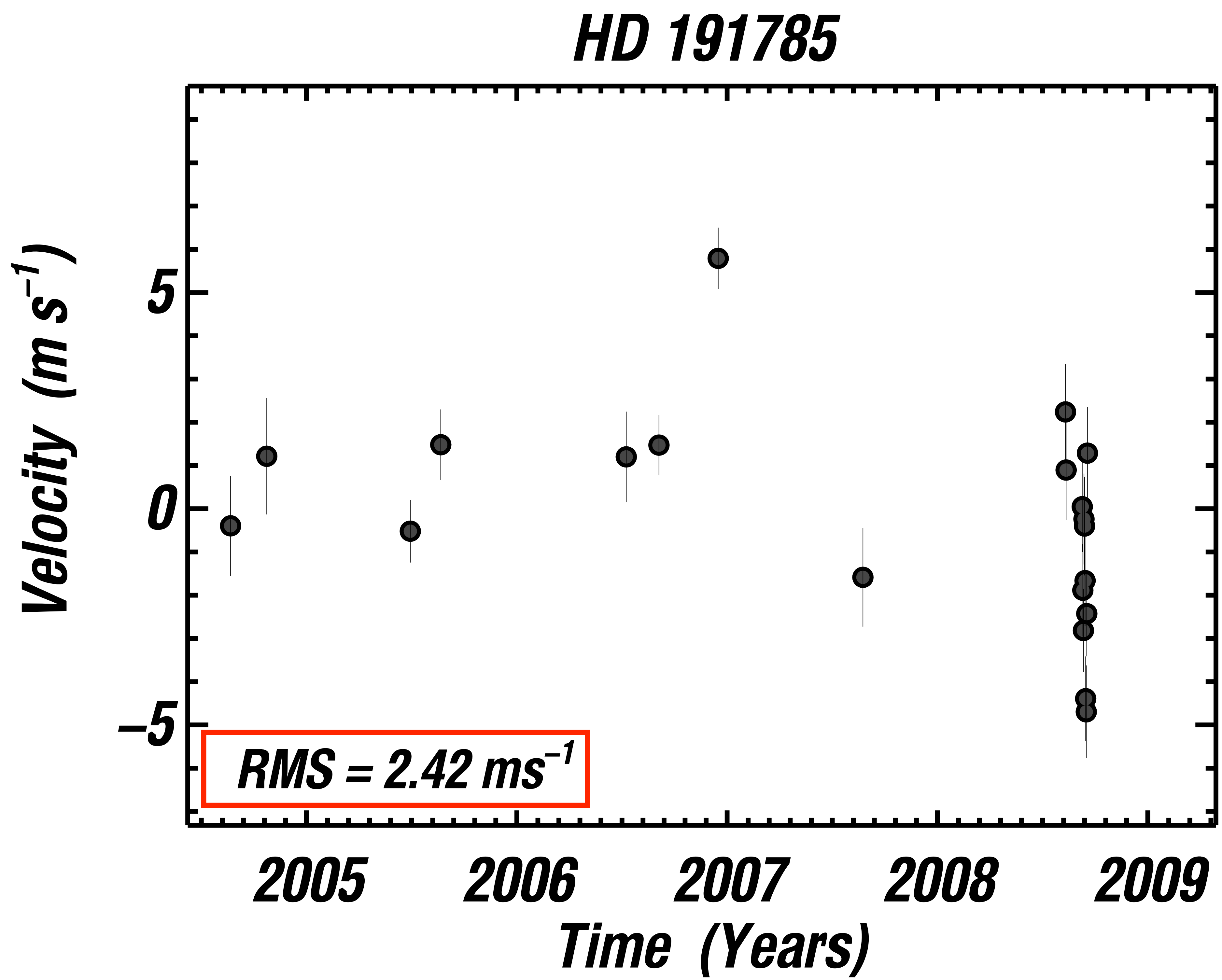
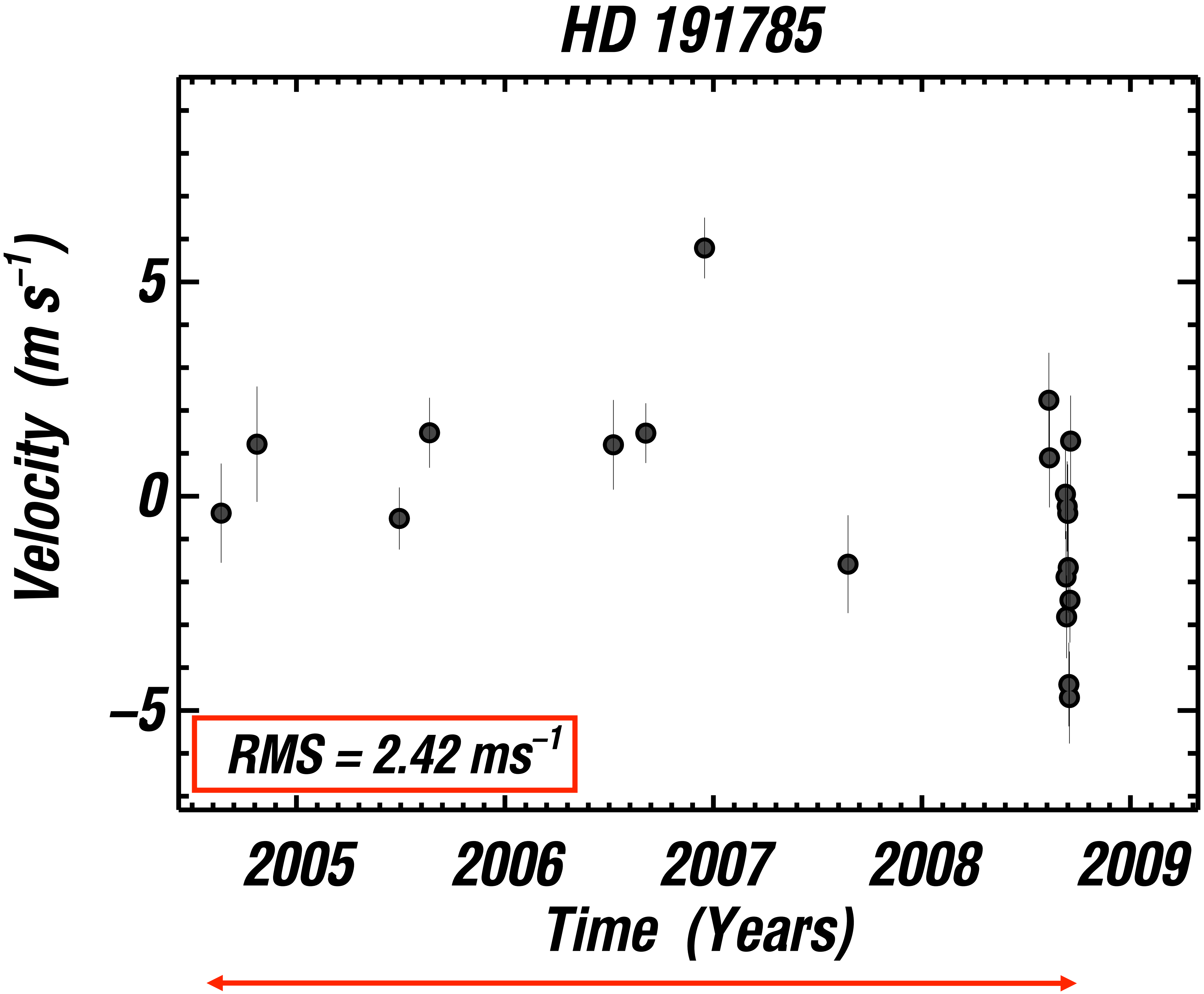
Minimum RV Observations for Eta-Earth Star



Minimum RV Observations for Eta-Earth Star

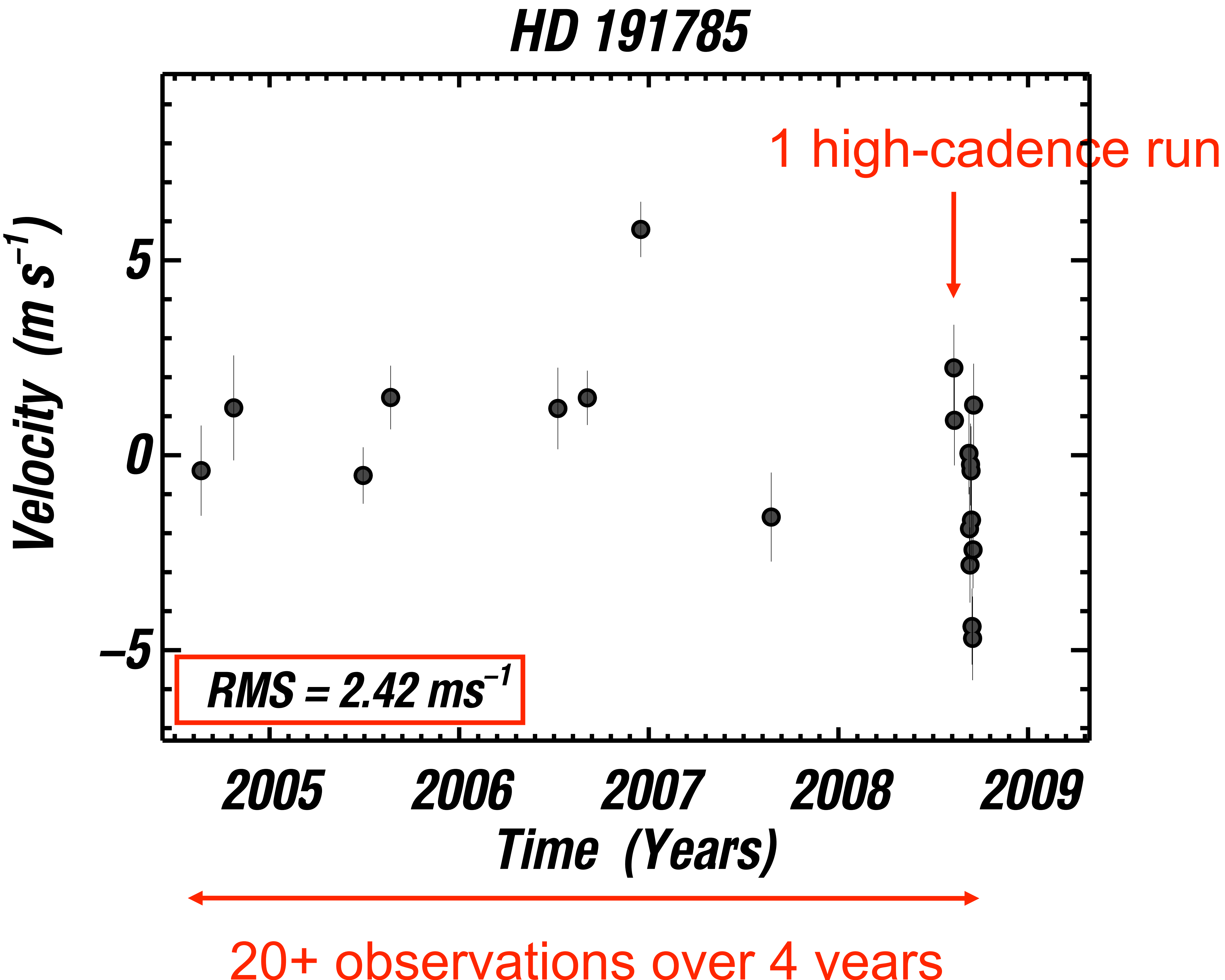


Minimum RV Observations for Eta-Earth Star

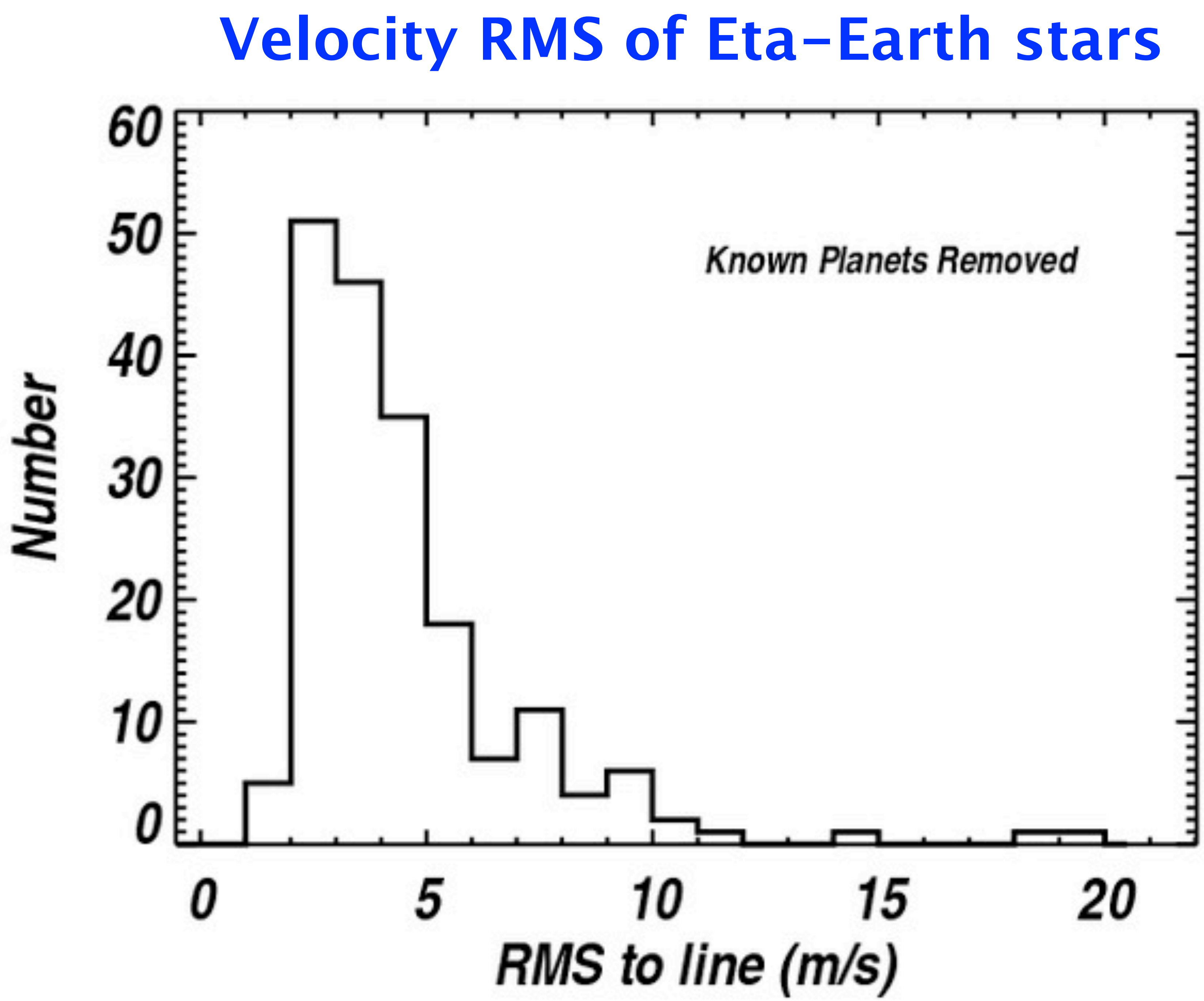


20+ observations over 4 years

Minimum RV Observations for Eta-Earth Star

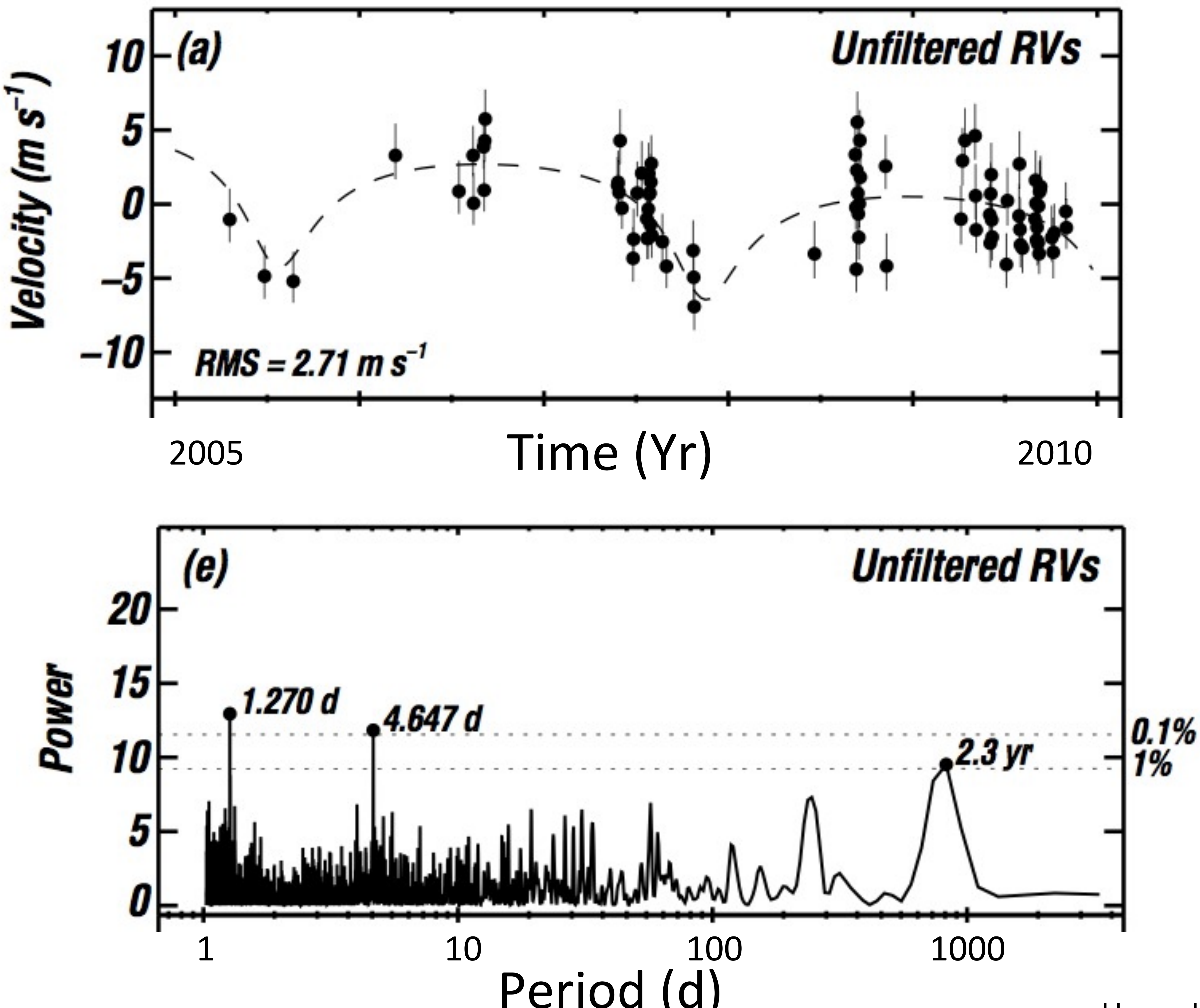


Precision of Eta-Earth Observations



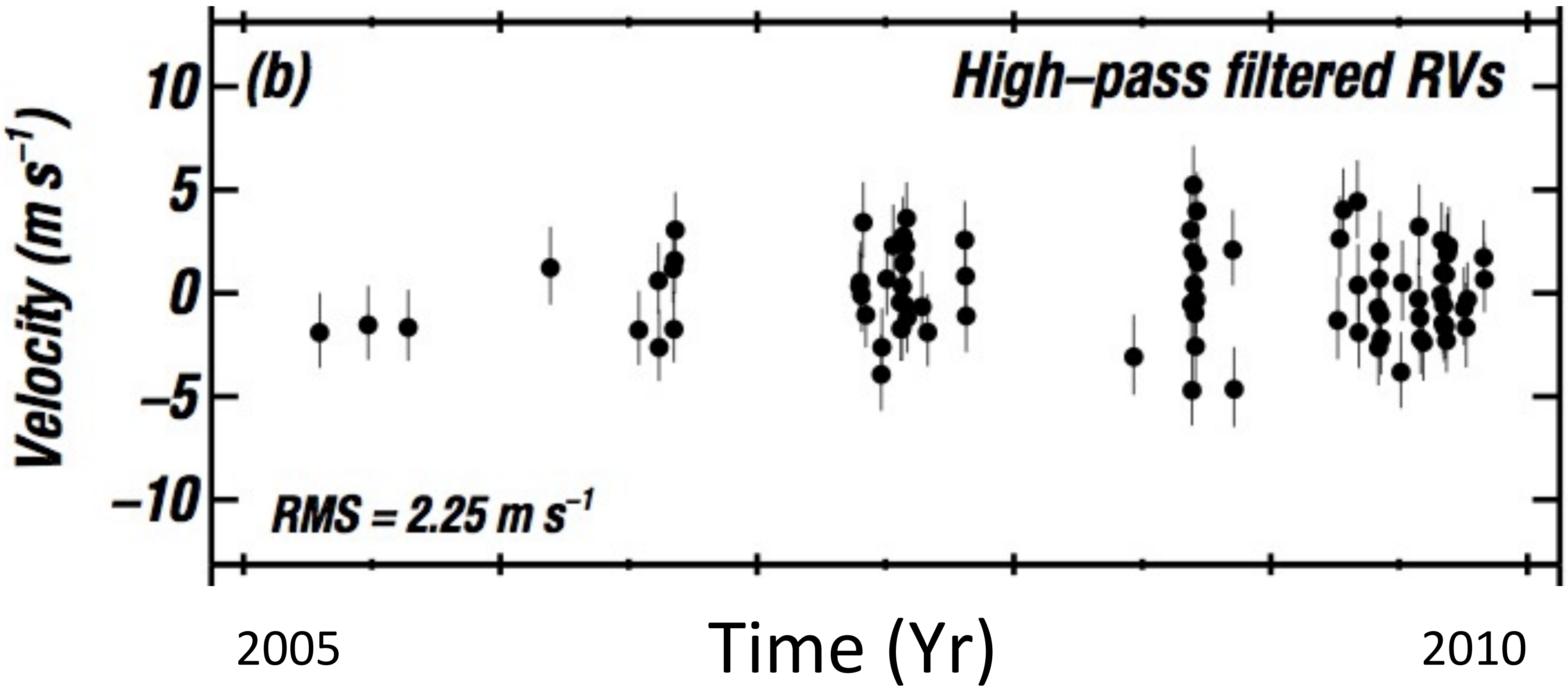
<u>Limited by:</u>
Stellar jitter
Guiding
Inst. Stability
Photon Noise

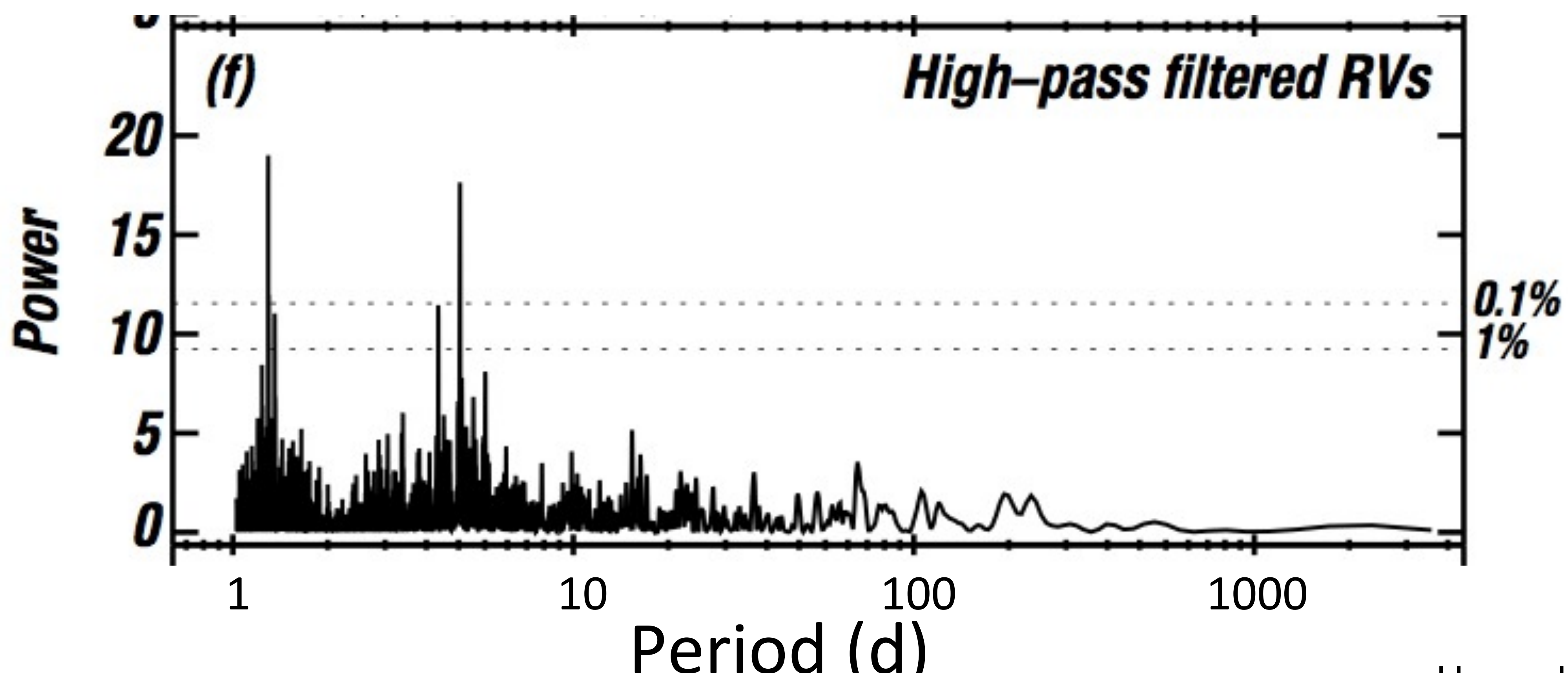
HD 156668 - Discovery RVs



Howard et al. 2011

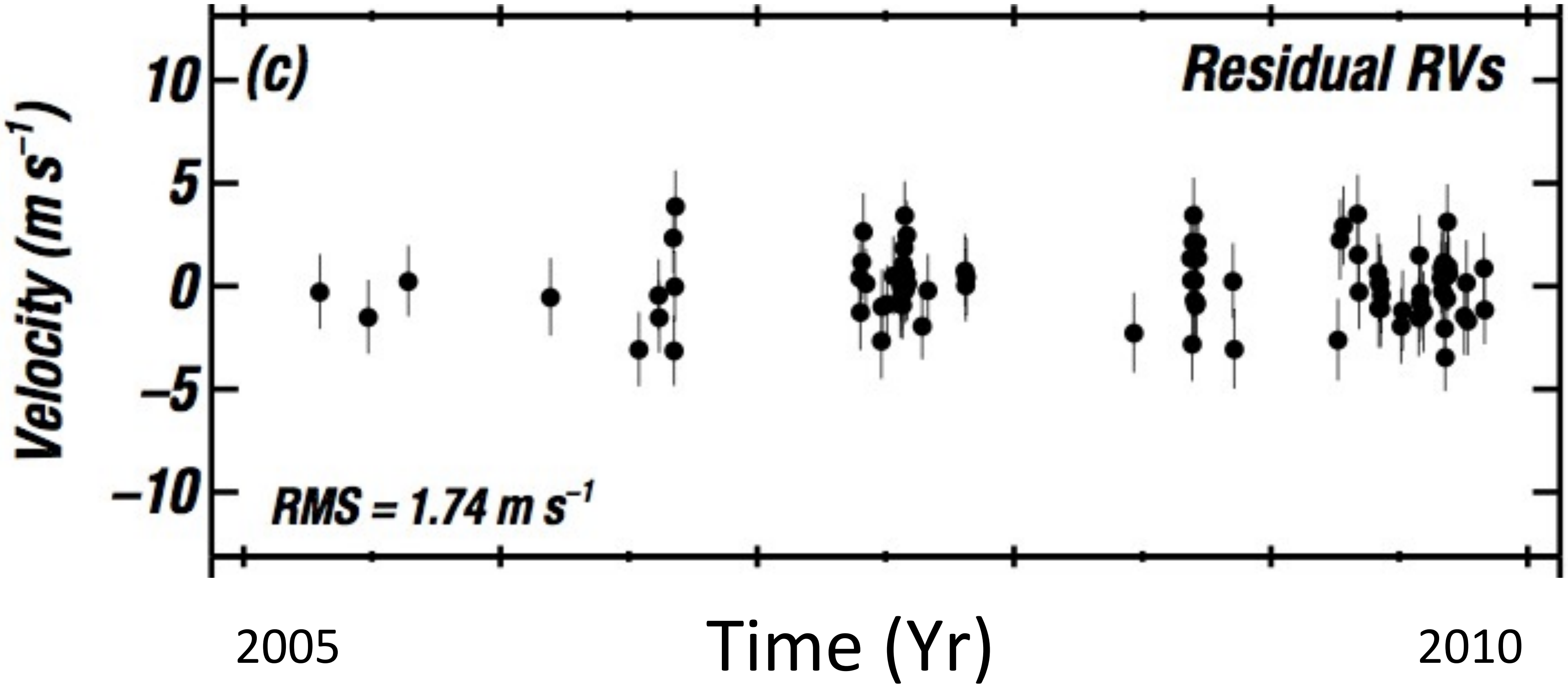
HD 156668 - High-pass Filtered RVs

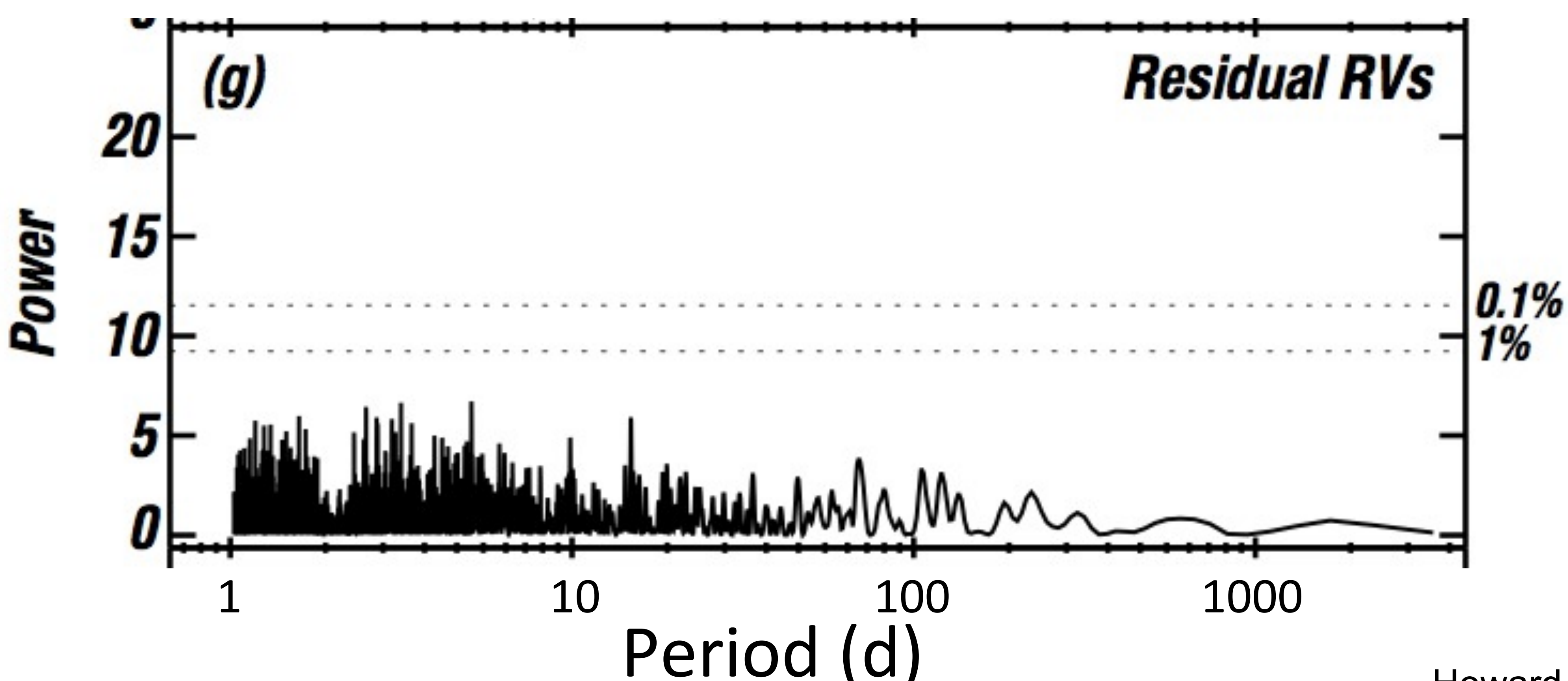




Howard et al. 2011

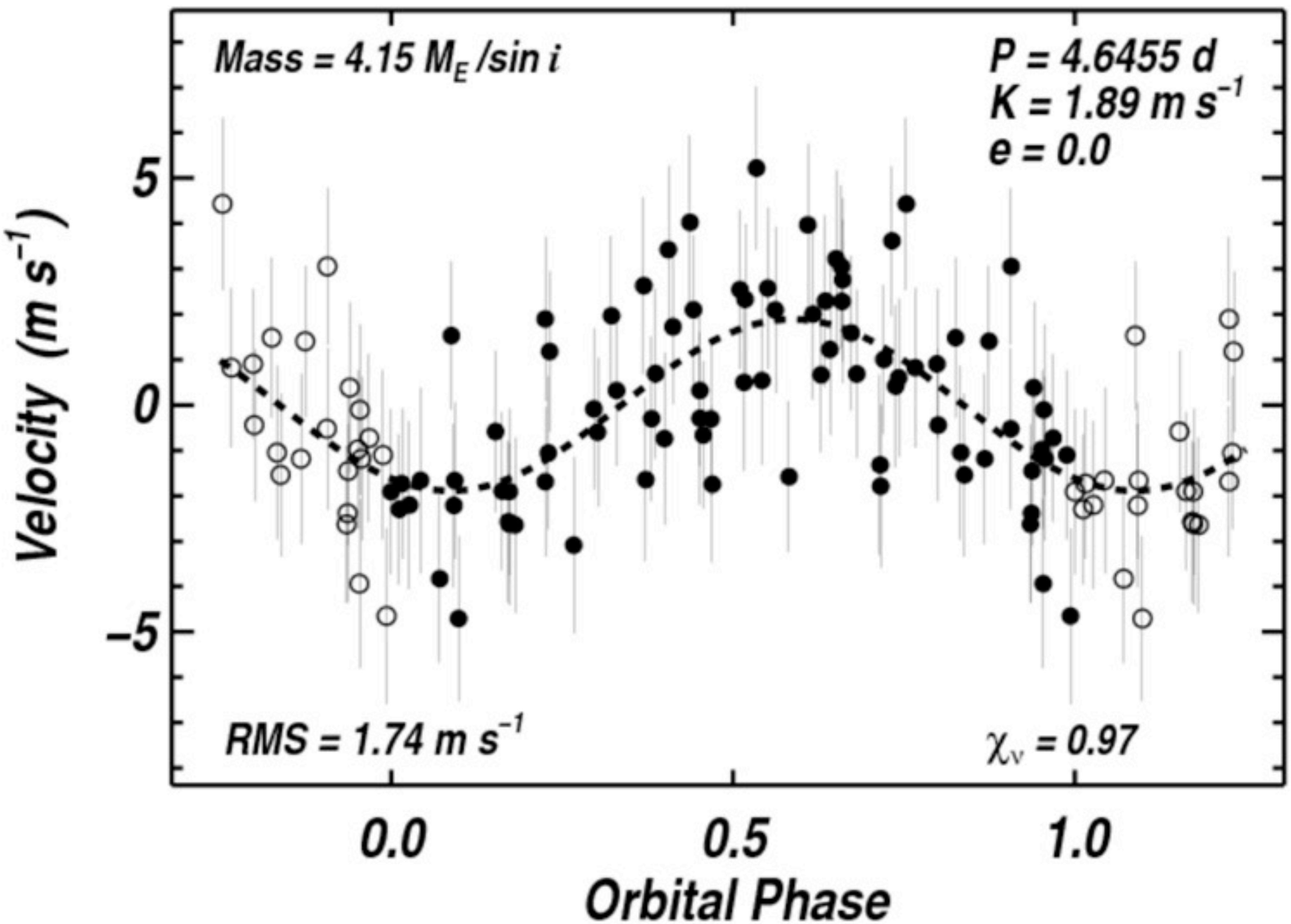
HD 156668 - Residual RVs





Howard et al. 2011

HD 156668b - Detected Super-Earth!

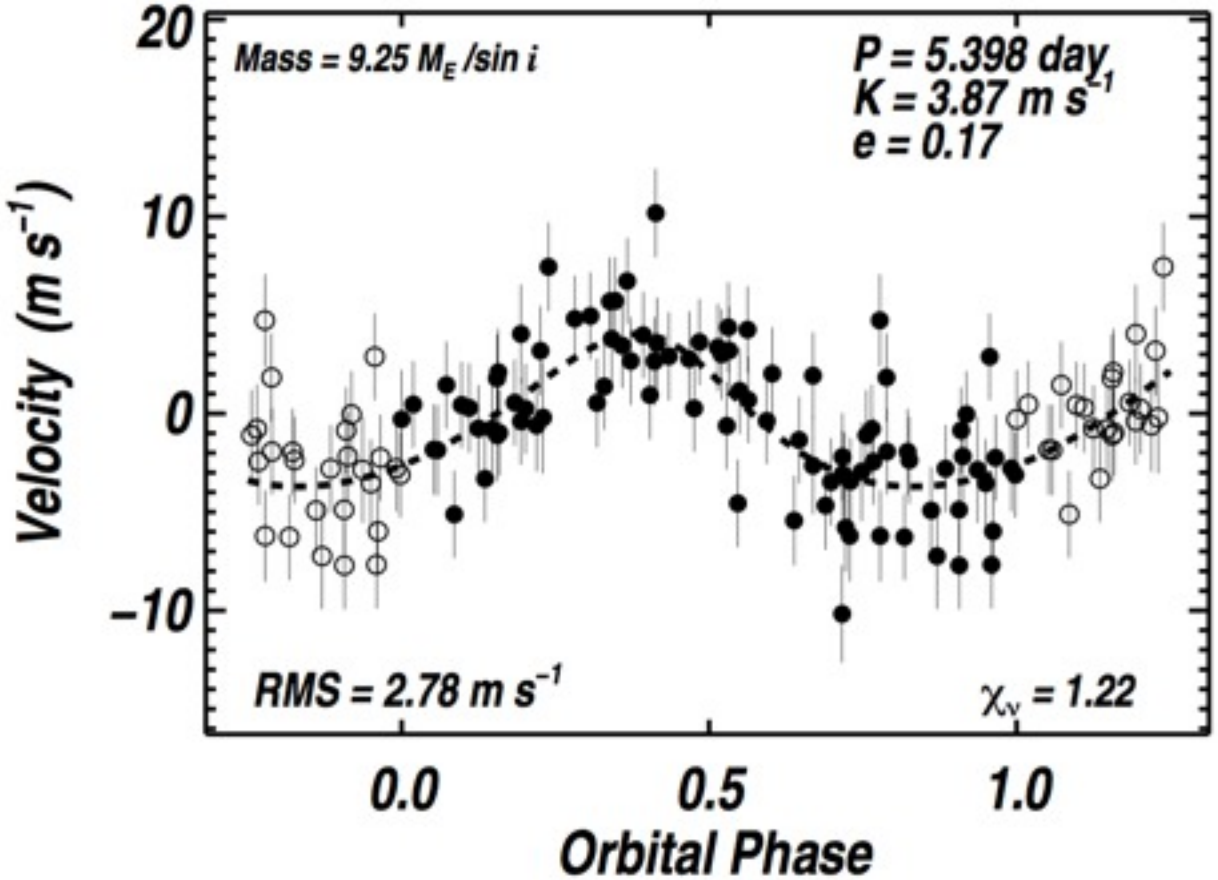


Star:
HD 156668 (K3V)
distance = 24 pc
V = 8.3
[Fe/H] = 0.05
quiet

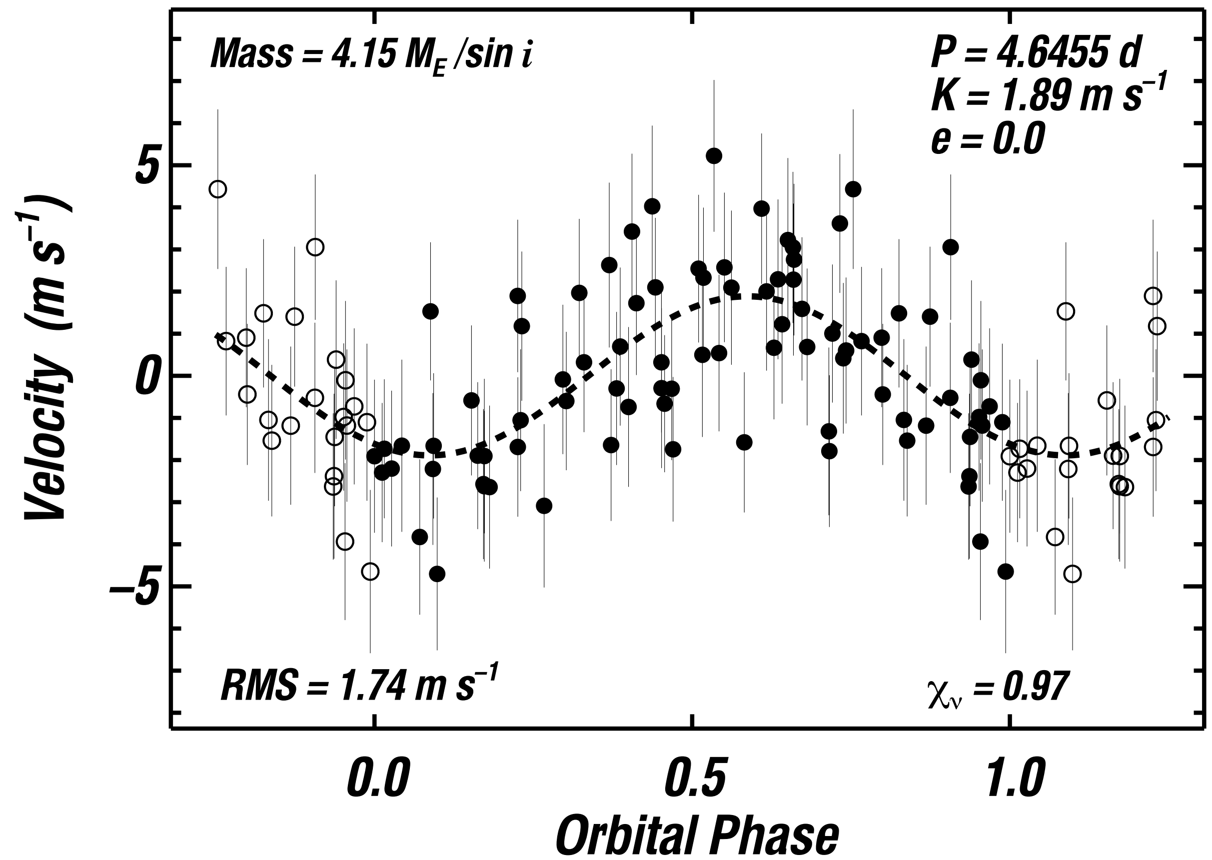
Planet:
M sin i = 4.15 M_E
P = 4.6455 d
e = 0 (fixed)

Howard et al. 2011

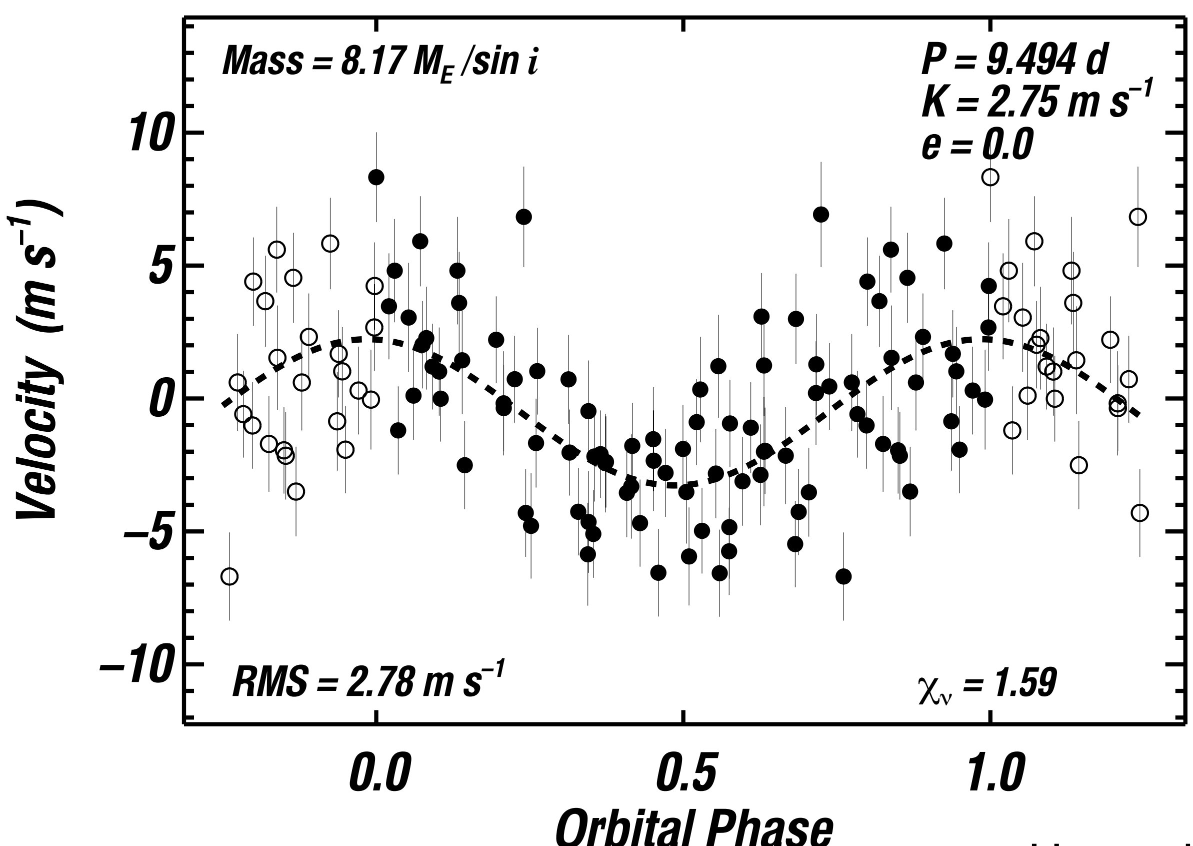
HD 7924 b



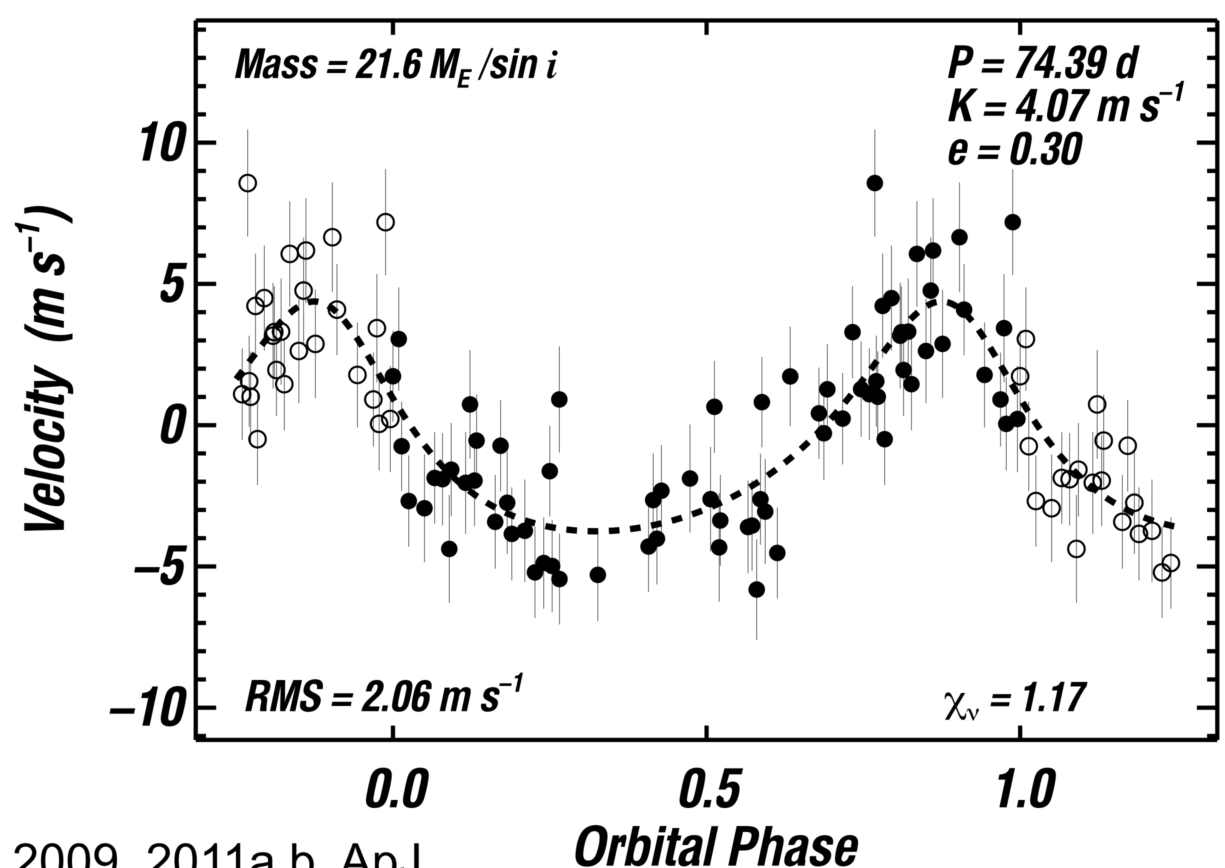
HD 156668 b



HD 97658 b



Gl 785 b



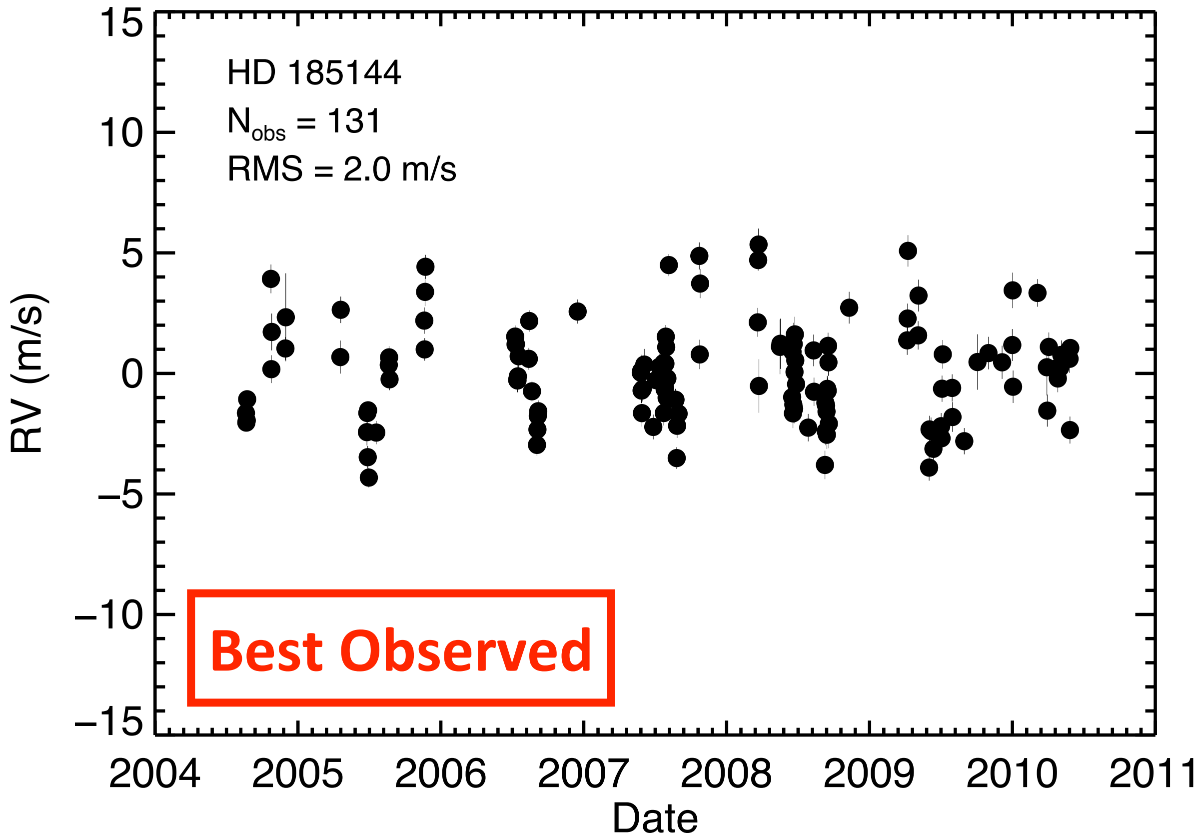
Howard et al. 2009, 2011a,b, ApJ

33 Detected Planets in the Survey

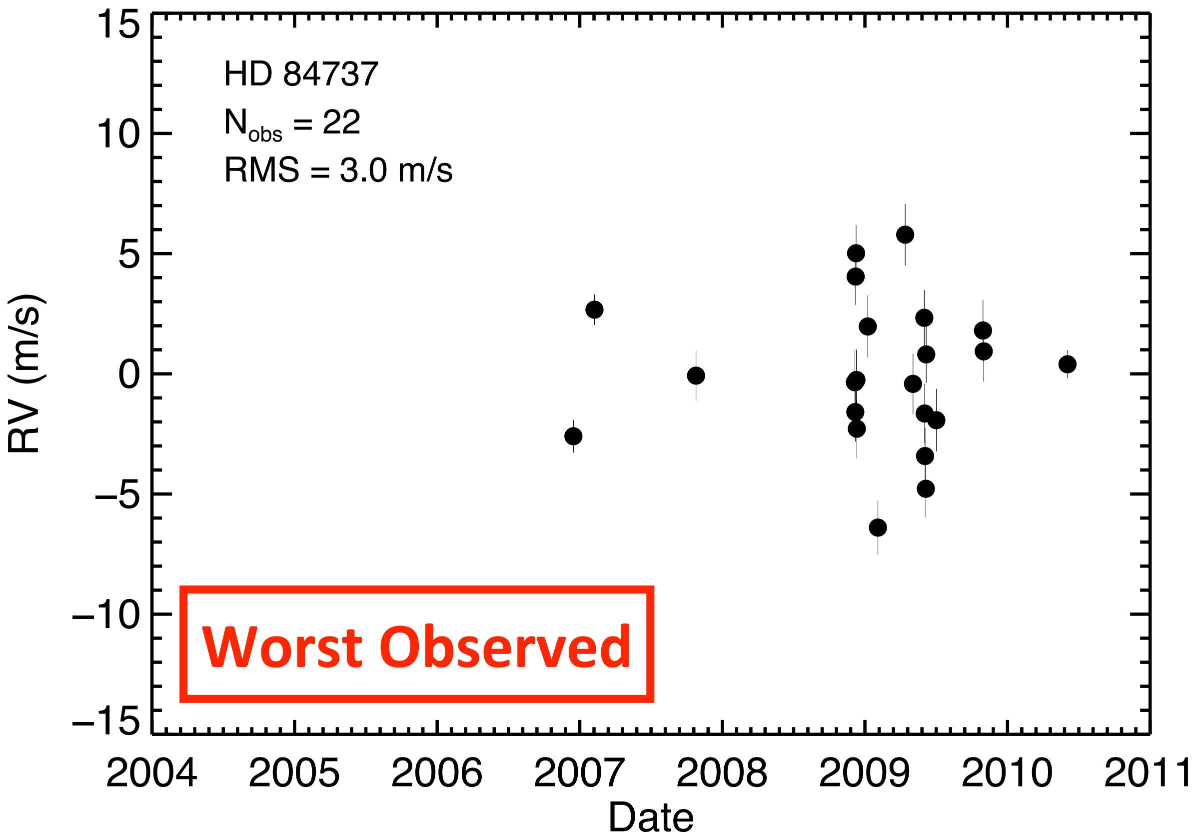
Planet	Star	Period (d)	$M \sin i$ ($M_\oplus$)	Reference
14 Her b	HD 145675	1754	1651	(15)
16 Cyg b	HD 186427	798	521	(15)
47 UMa b	HD 95128	1090	826	(16)
47 UMa c	HD 95128	2590	252	(16)
51 Peg b	HD 217014	4.2	147	(17)
55 Cnc b	HD 75732	14.7	264	(18)
55 Cnc c	HD 75732	44.4	53.4	(18)
55 Cnc d	HD 75732	5371	1241	(18)
55 Cnc e	HD 75732	2.8	7.6	(18)
55 Cnc f	HD 75732	261	46.3	(18)
61 Vir b	HD 115617	4.2	5.1	(19)
61 Vir c	HD 115617	38.0	11	(19)
61 Vir d	HD 115617	123	23	(19)
70 Vir b	HD 117176	116	2372	(20)
HD 1461 b	HD 1461	5.8	8	(21)
HD 3651 b	HD 3651	62.2	72.8	(22)
HD 7924 b	HD 7924	5.5	9.3	(6)
HD 69830 b	HD 69830	8.7	10.2	(23)
HD 69830 c	HD 69830	31.6	11.9	(23)
HD 69830 d	HD 69830	197	17.9	(23)
HD 87883 b	HD 87883	2754	558	(24)
HD 90156 b	HD 90156	49.6	16.7	(25)
HD 99492 b	HD 99492	17.0	33.7	(15)
HD 114783 b	HD 114783	493	351	(26)
HD 154345 b	HD 154345	3341	304	(27)
HD 156668 b	HD 156668	4.6	4.1	(28)
HD 164922 b	HD 164922	1155	114	(15)
HD 190360 b	HD 190360	2915	497	(29)
HD 190360 c	HD 190360	17.1	18.7	(29)
HD 210277 b	HD 210277	442	405	(15)
HD 217107 b	HD 217107	7.1	443	(30)
HD 217107 c	HD 217107	4270	831	(30)
ρ CrB b	HD 143761	39.8	338	(15)

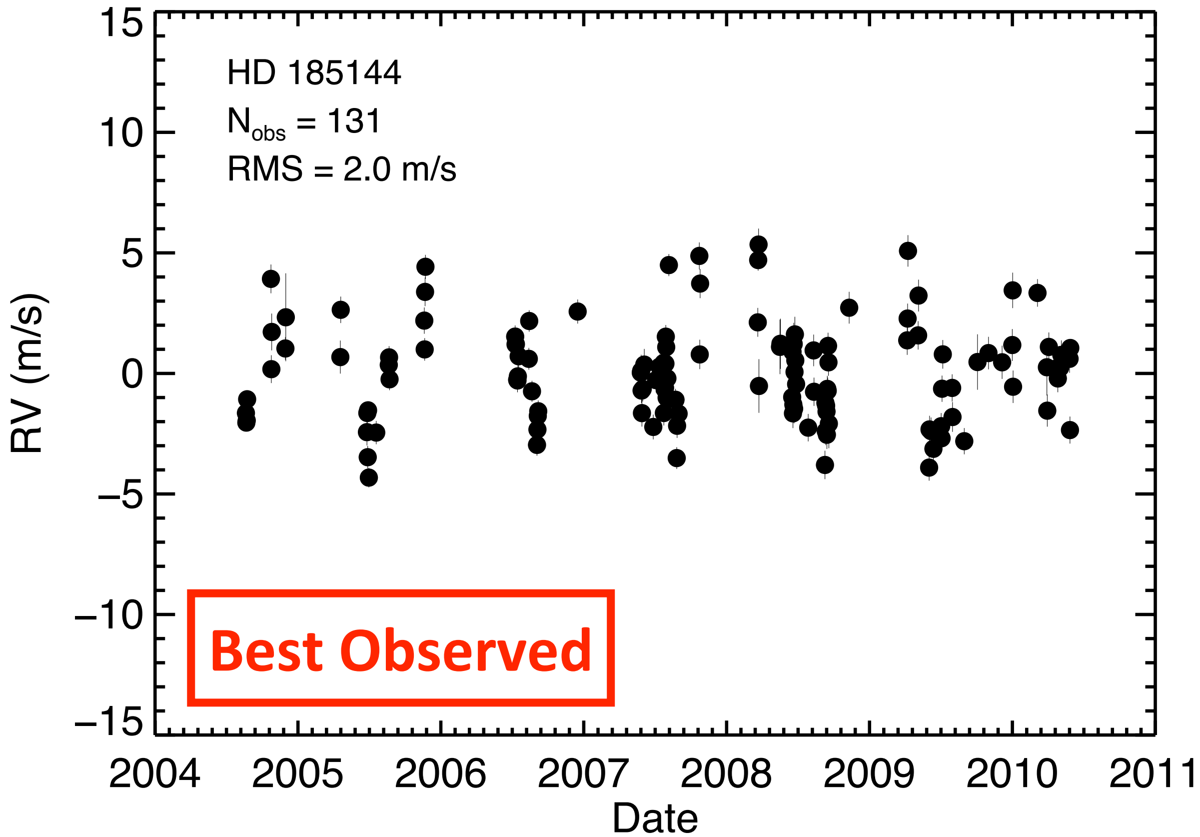
- **Some found by others; confirmed here**
- **Firm Period, Msin*i***
- **All published**

Limits on Non-detections of Planets



Limits on Non-detections of Planets





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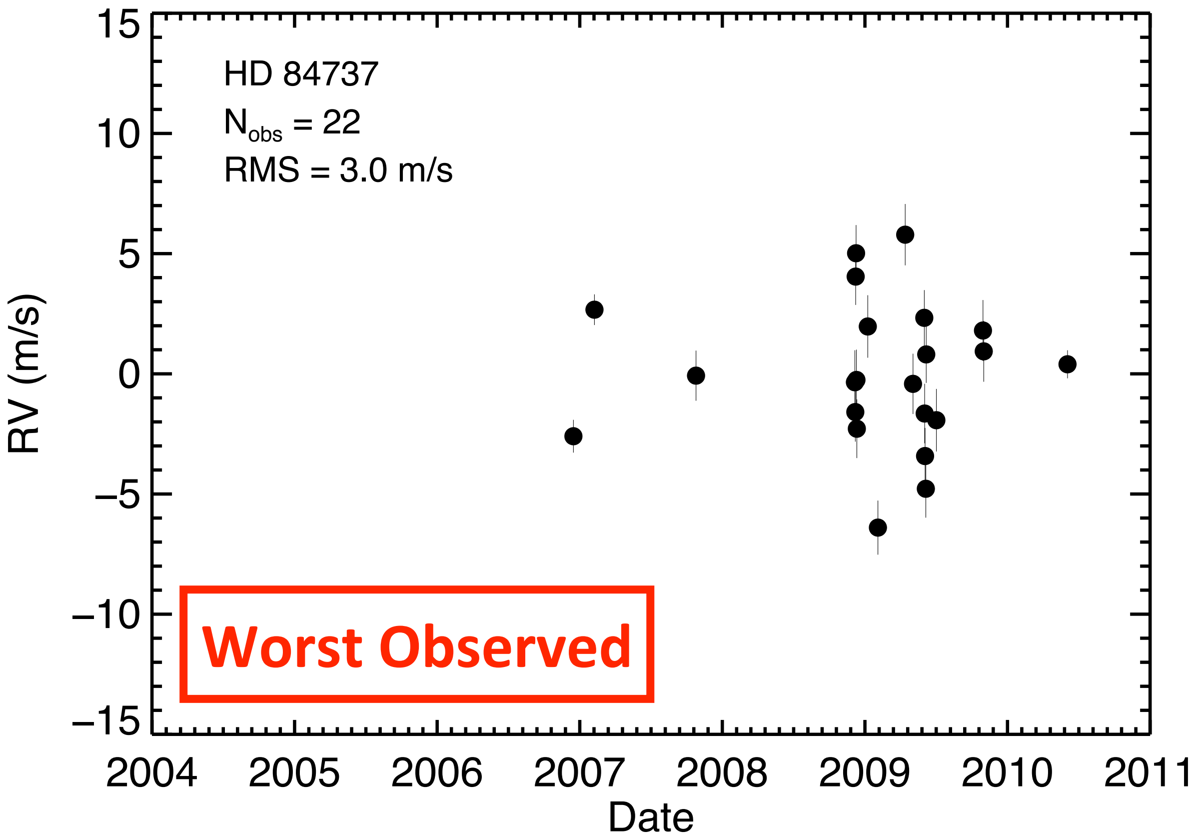
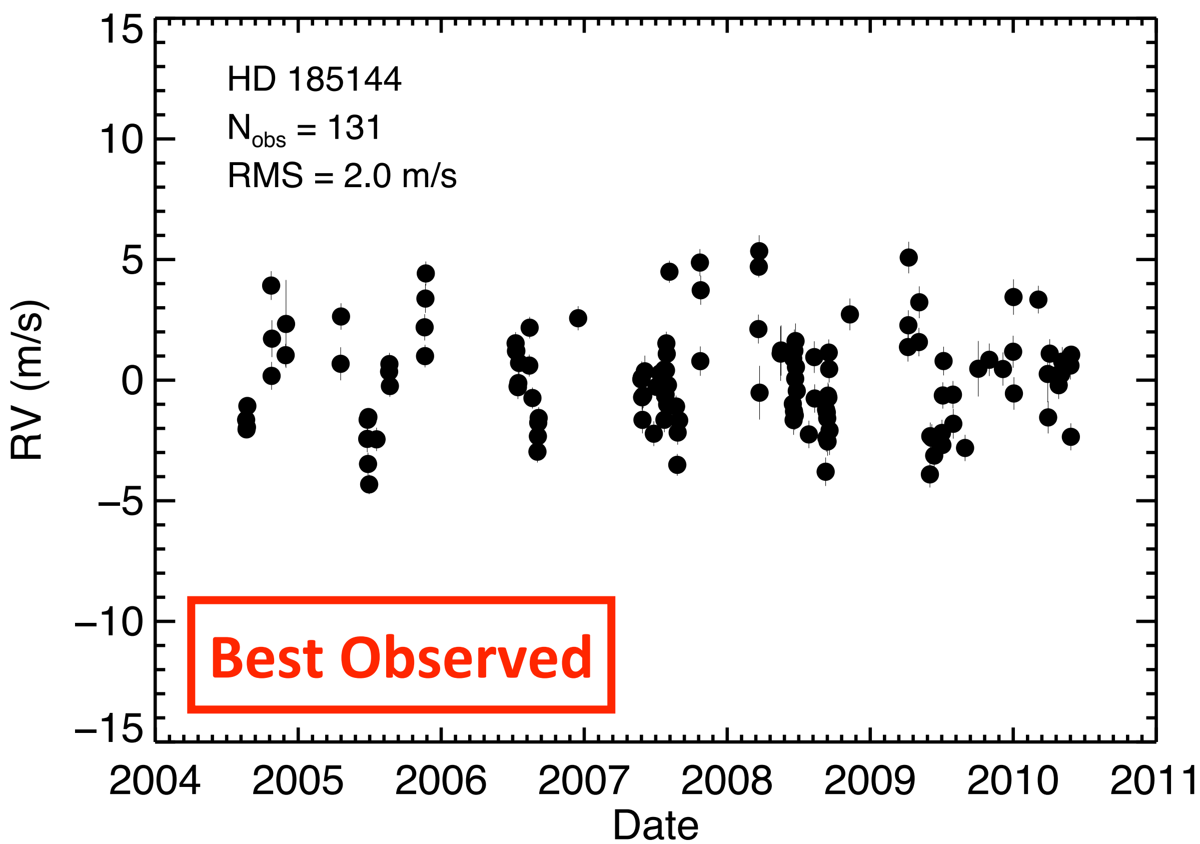
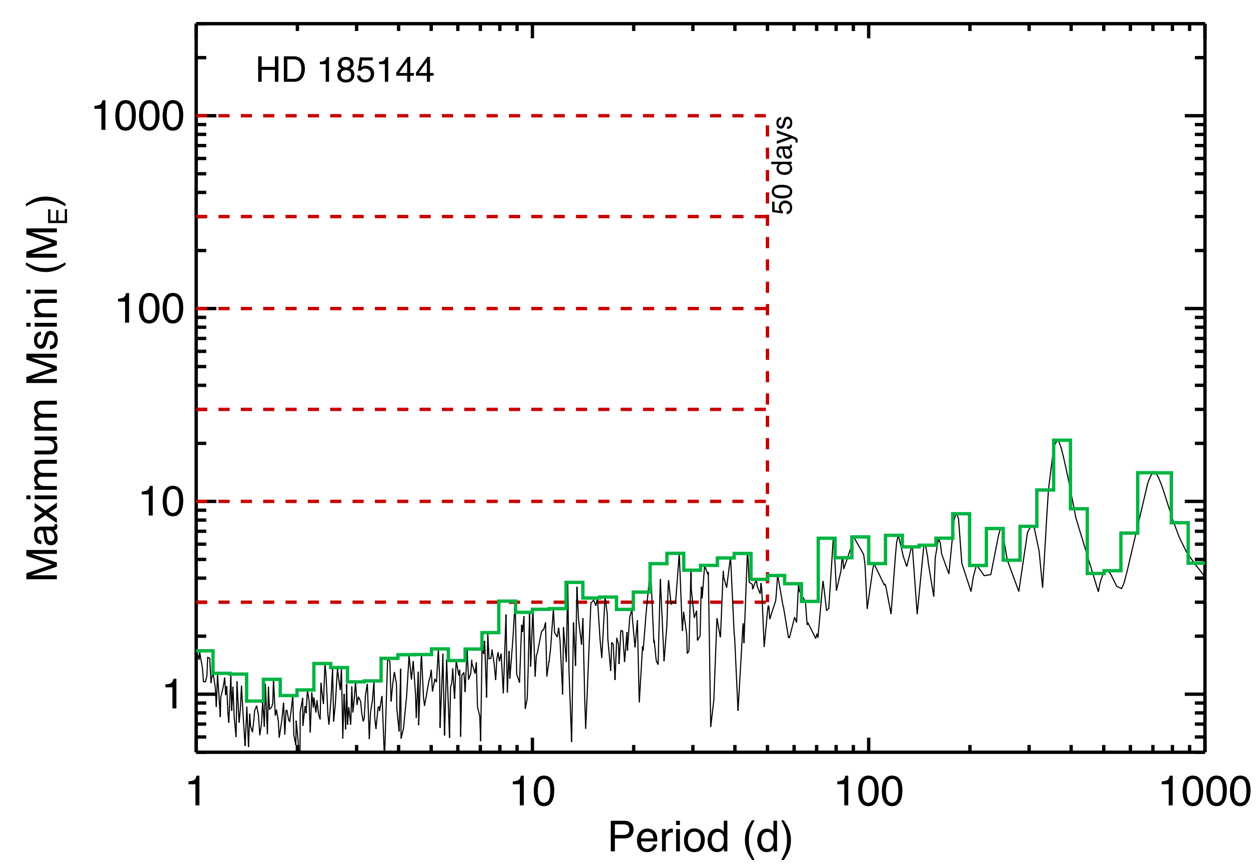
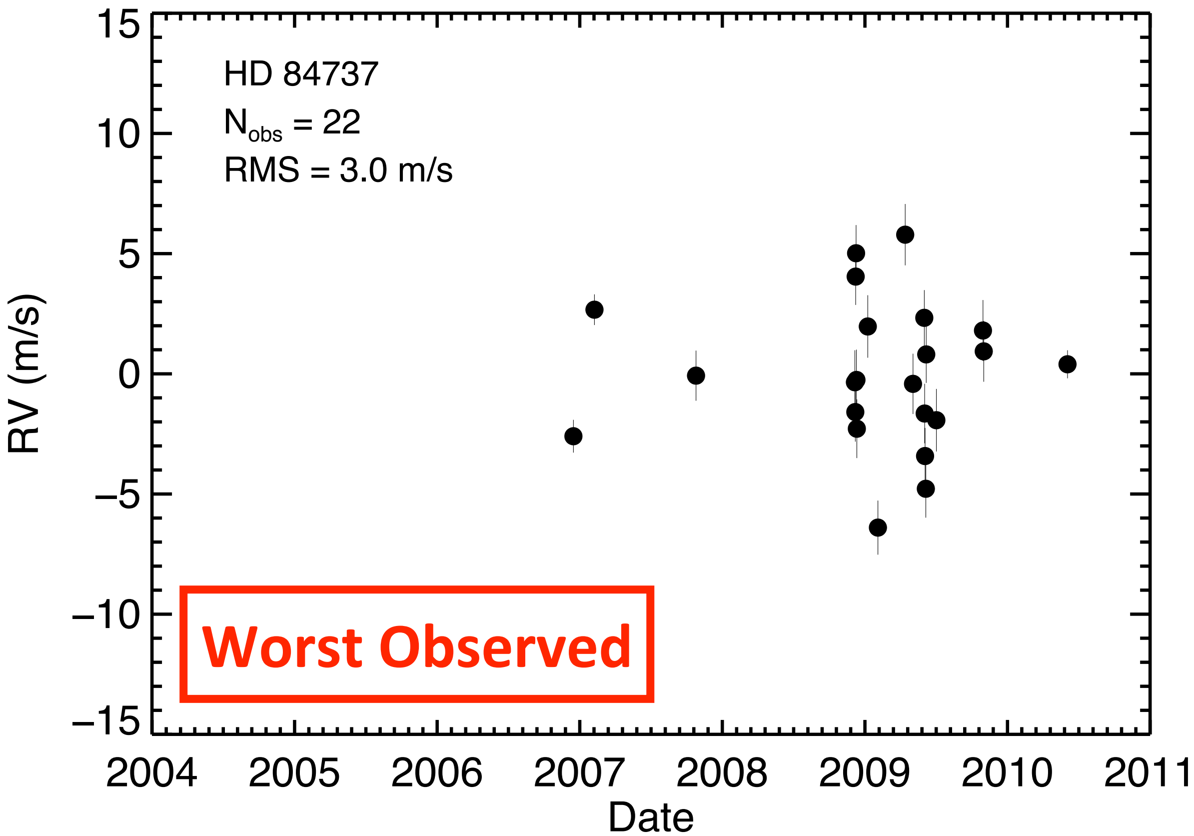
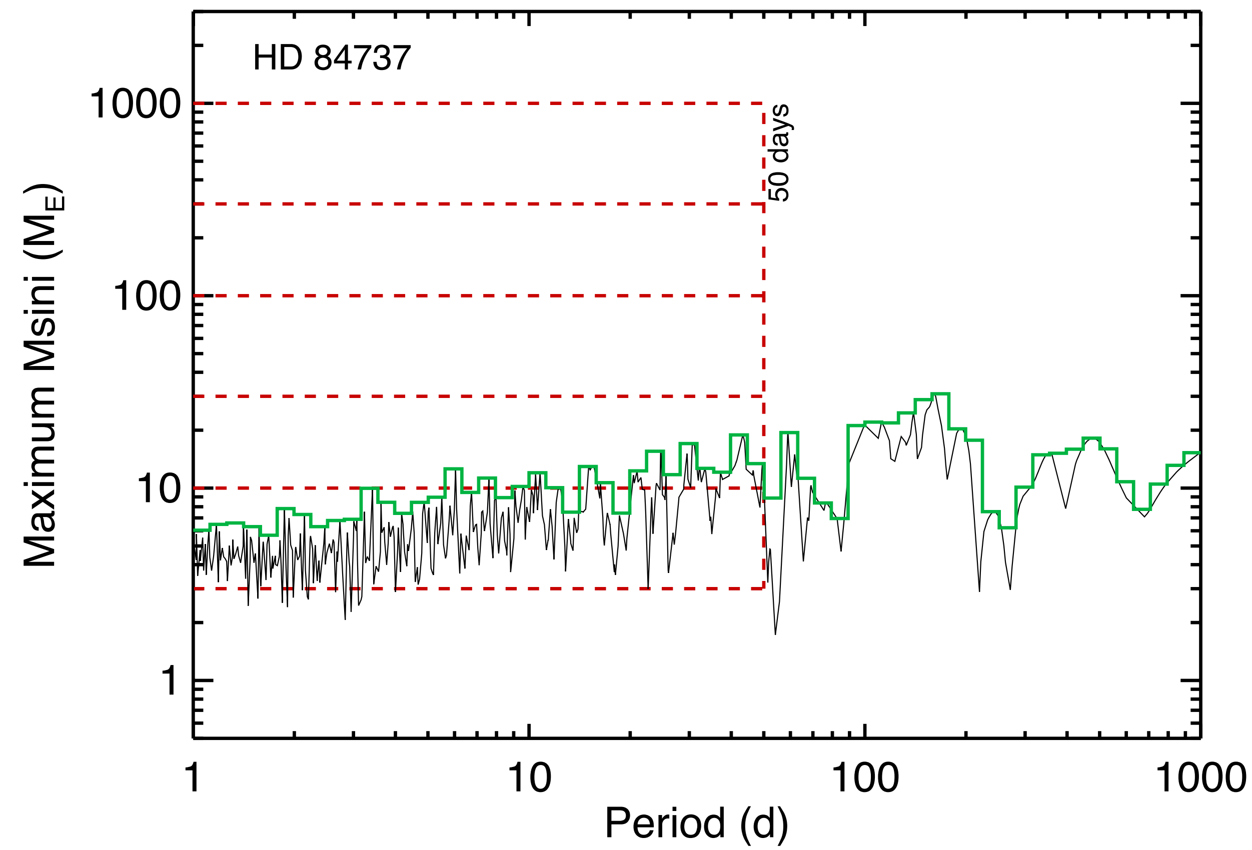


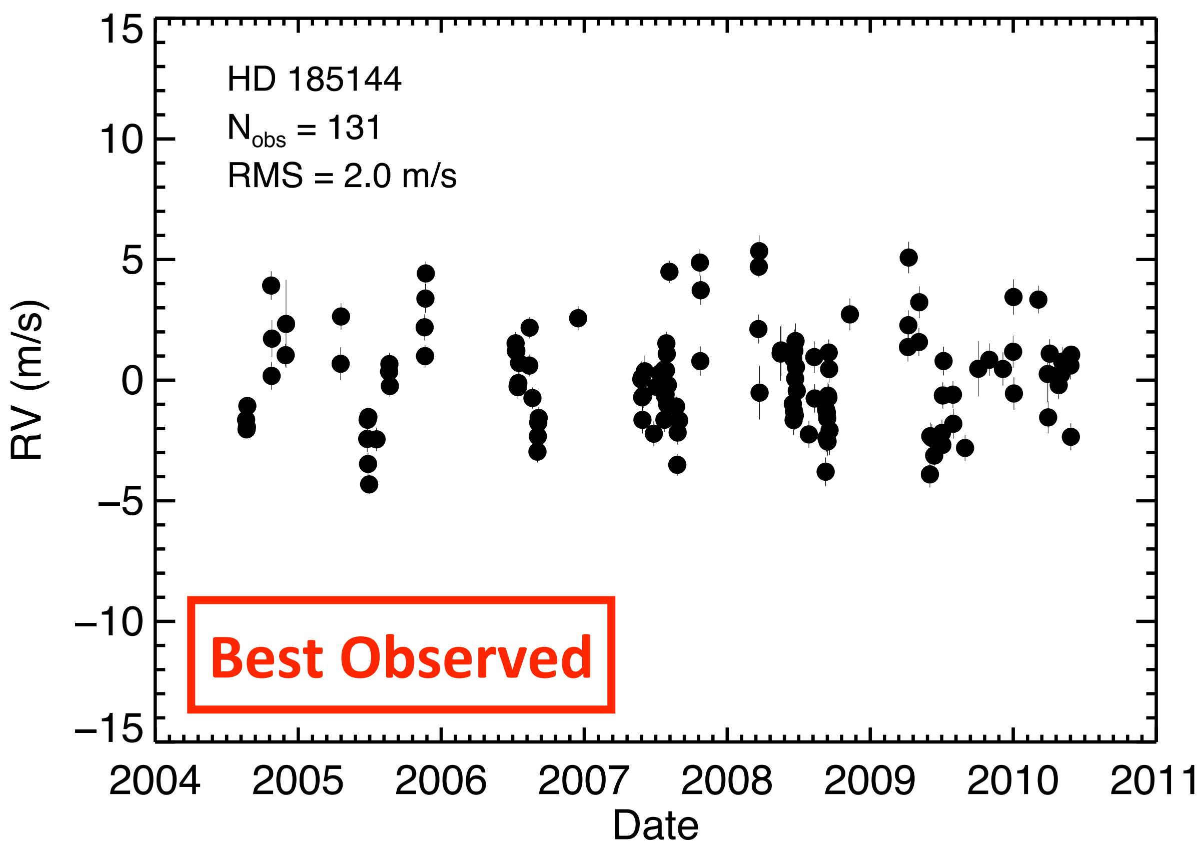


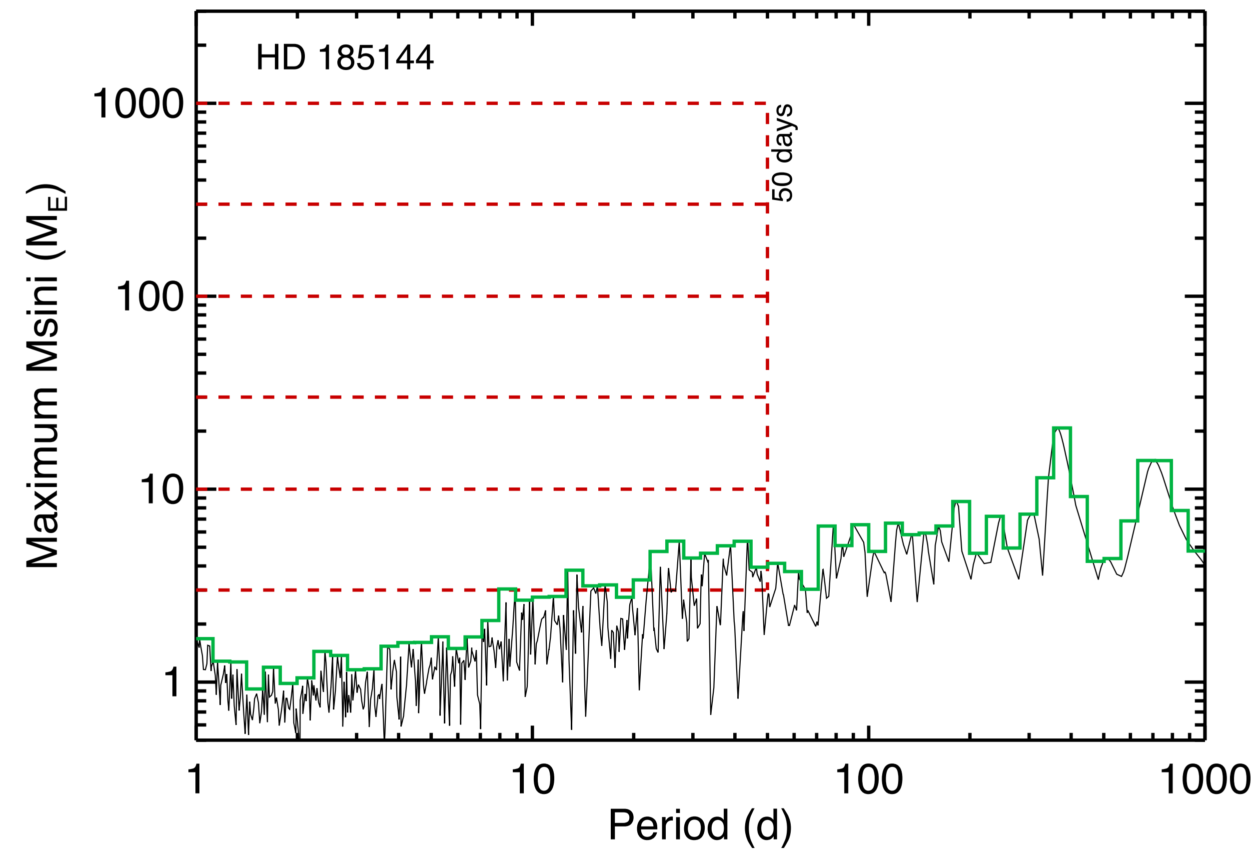


Limits on Non-detections of Planets

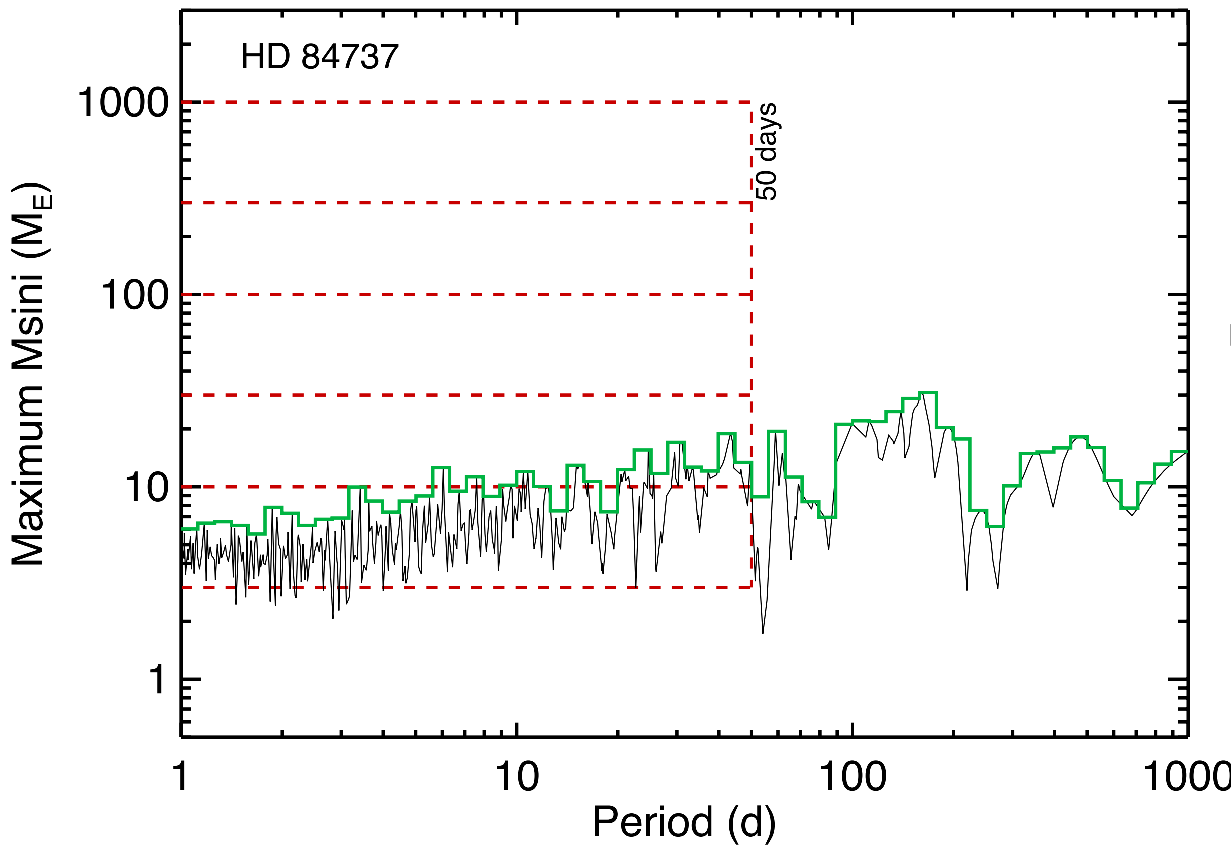


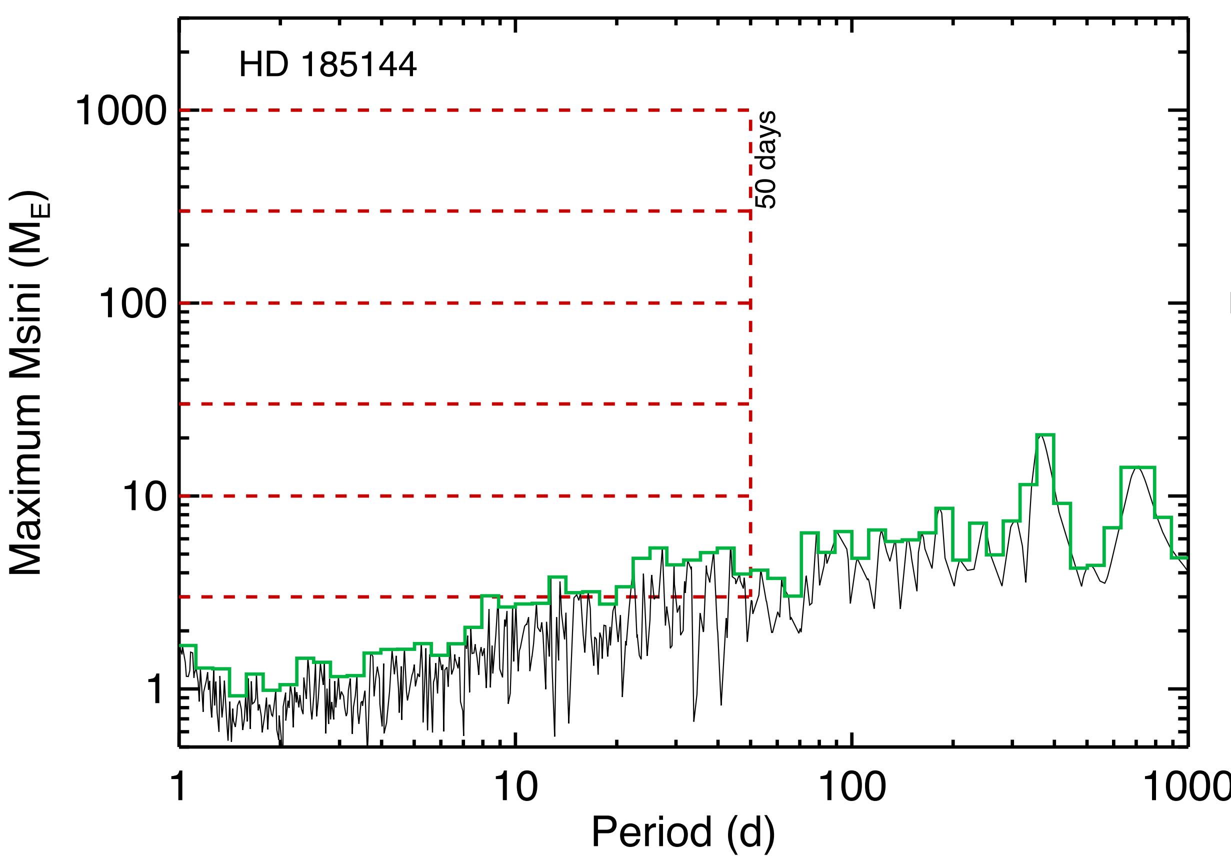


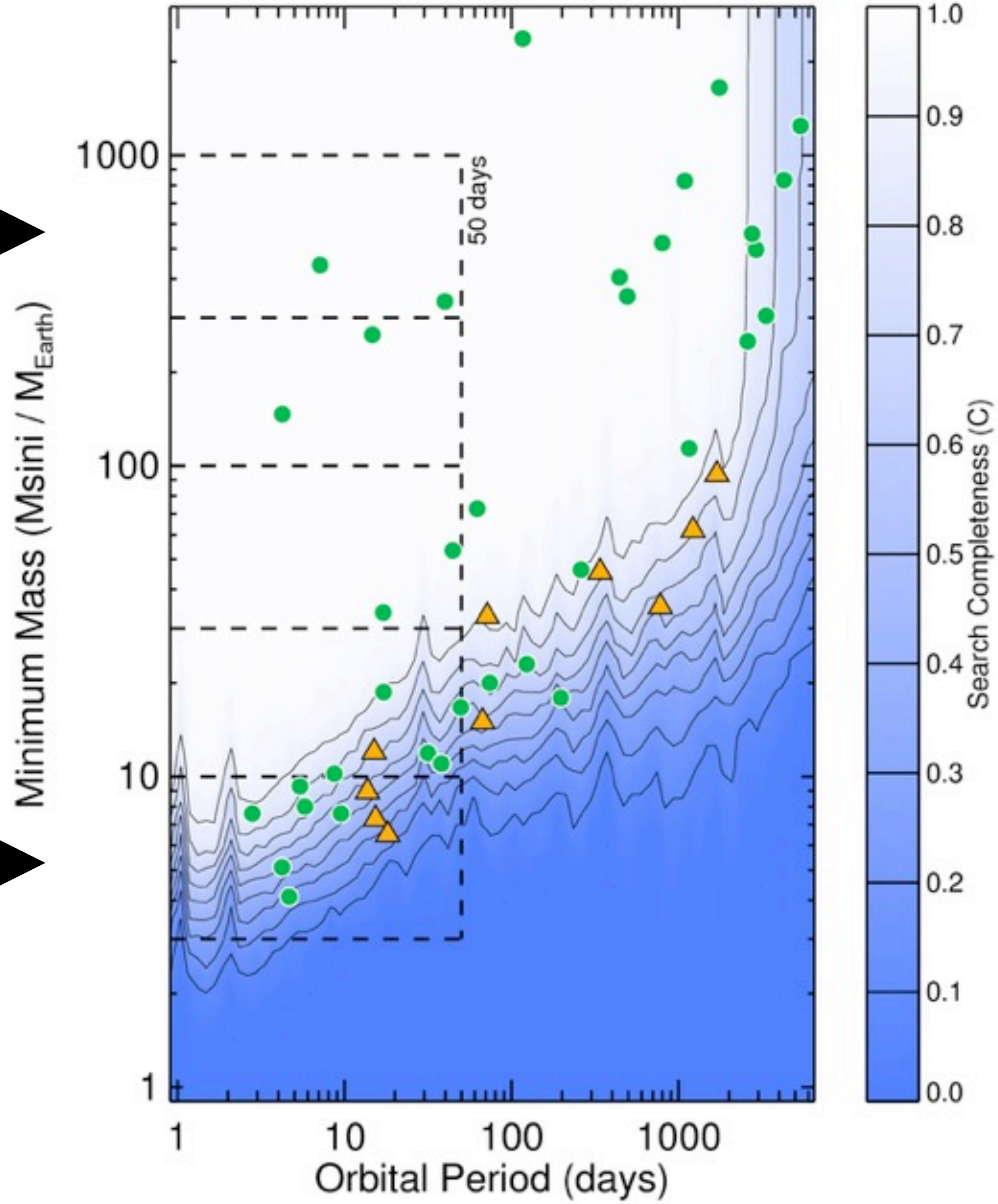


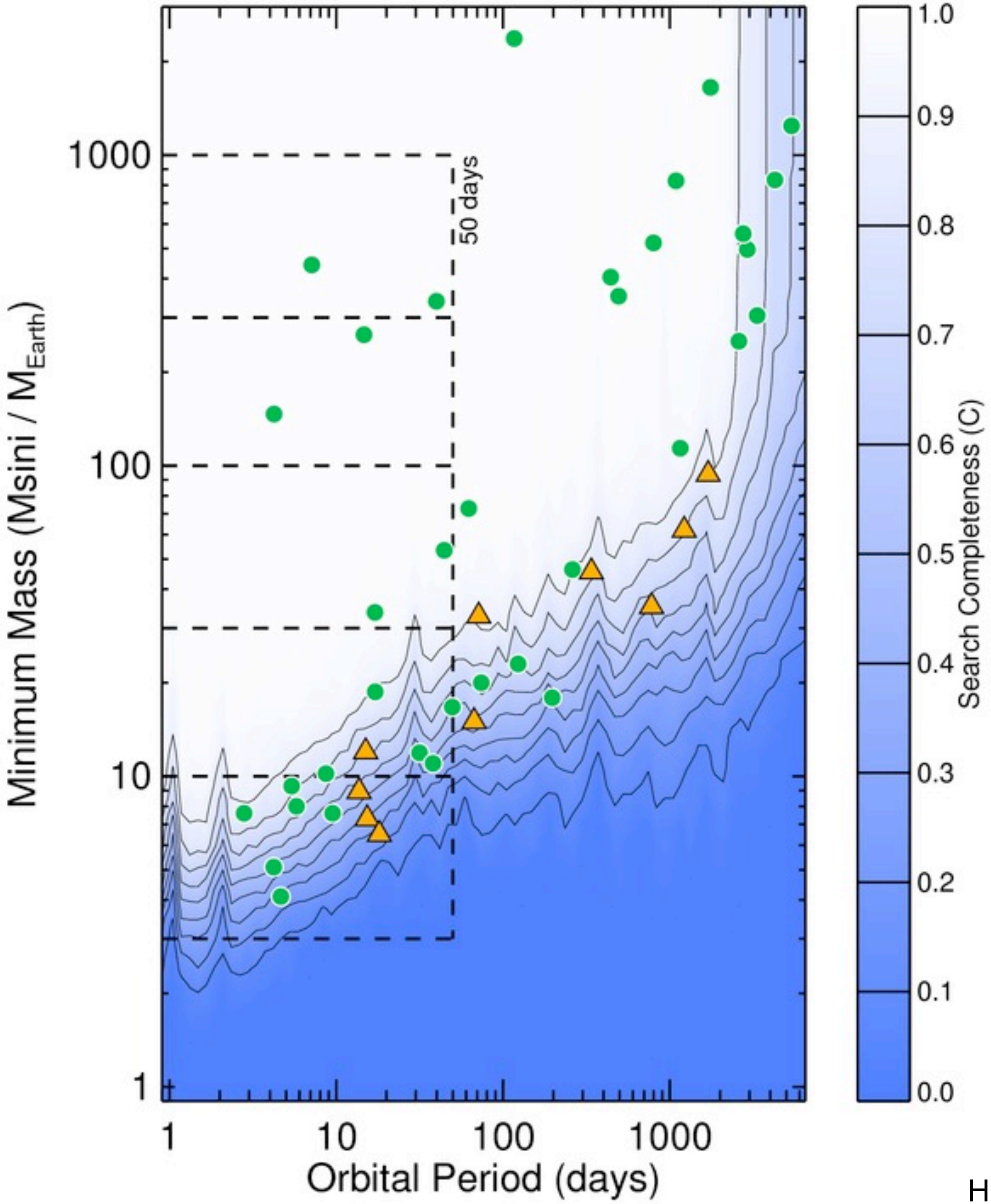


Completeness





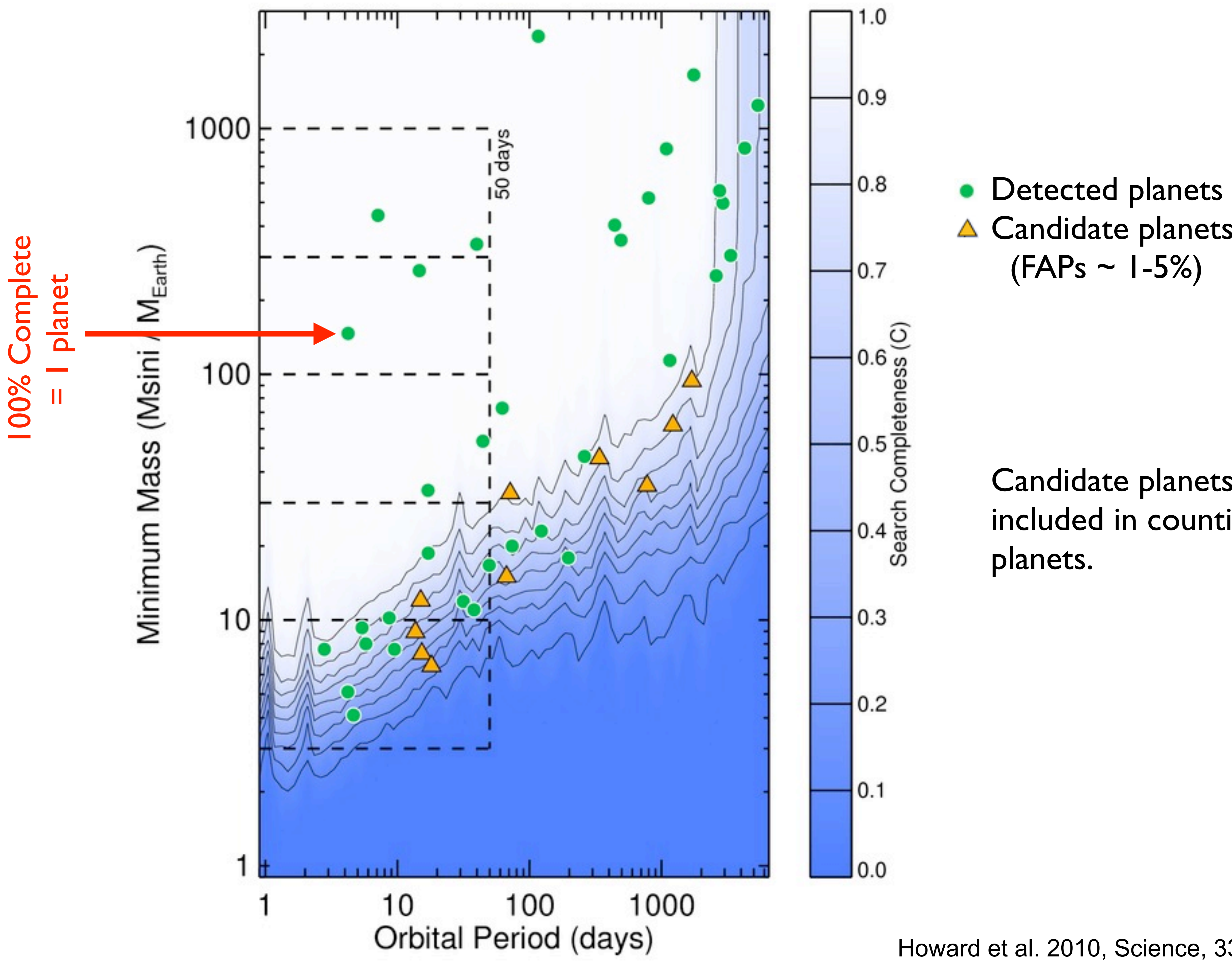




- Detected planets
- Candidate planets (FAPs ~ 1-5%)

Candidate planets included in counting planets.

Howard et al. 2010, Science, 330, 653



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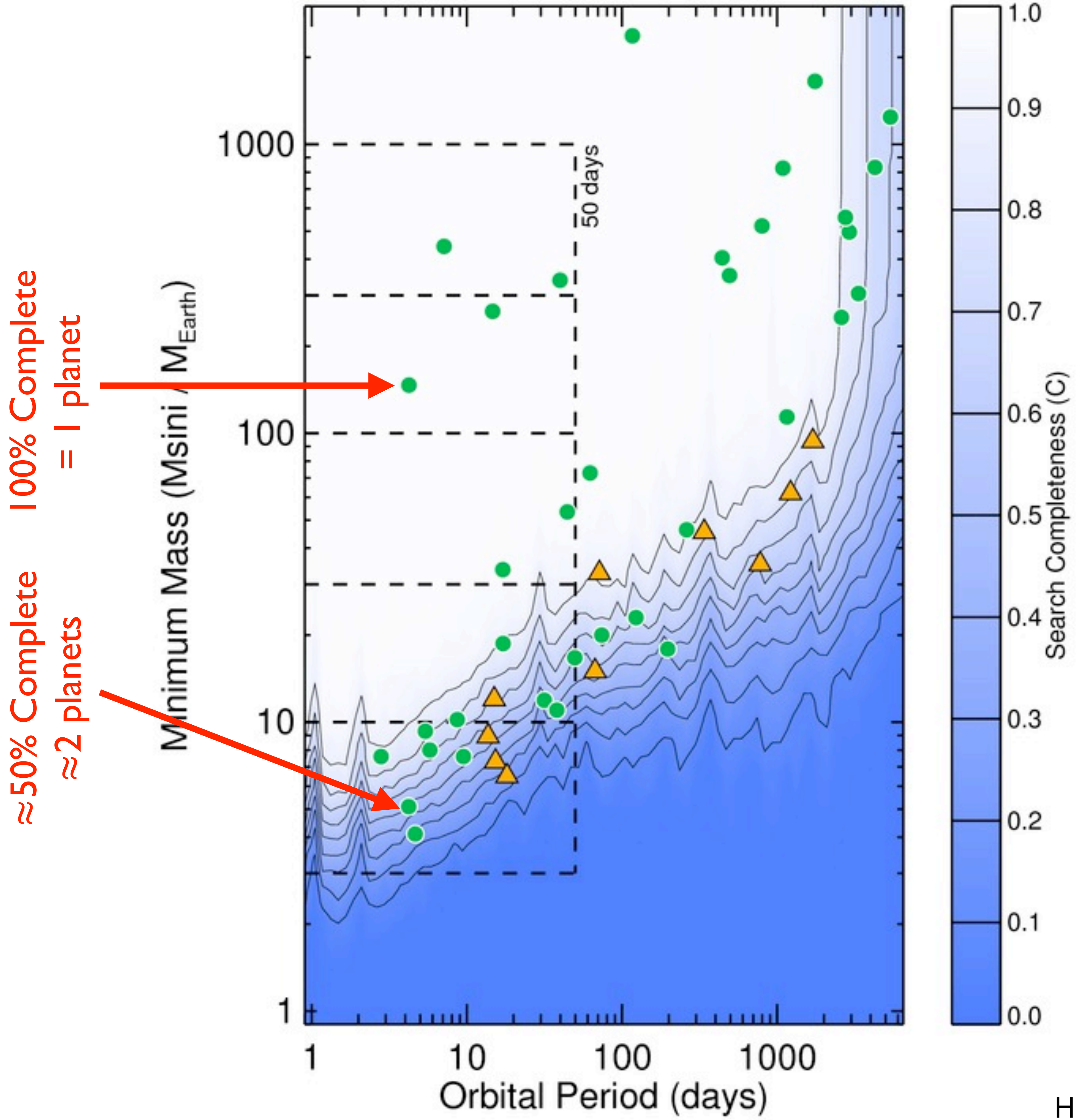
Howard et al. 2010, Science, 330, 653



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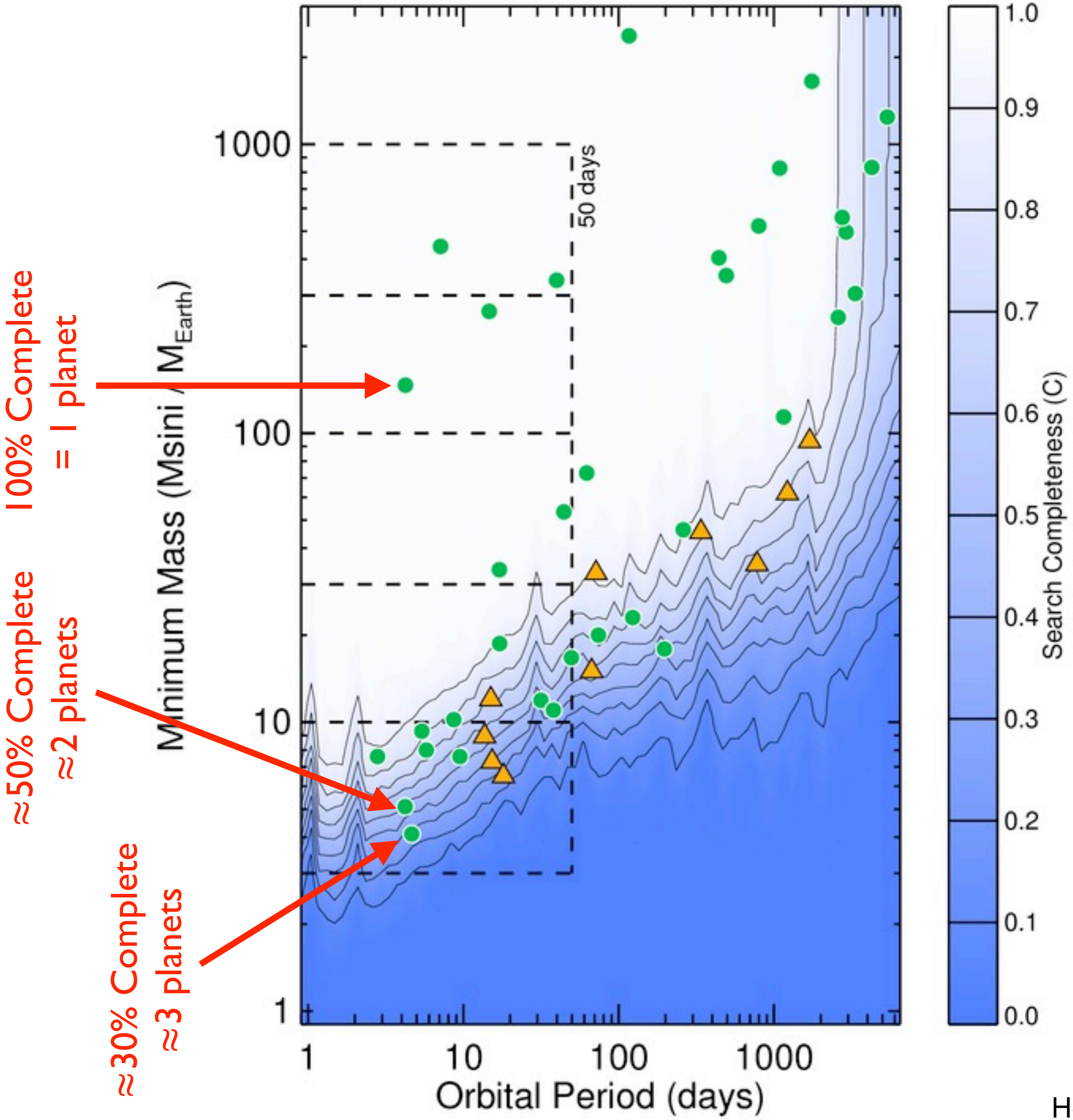
Howard et al. 2010, Science, 330, 653



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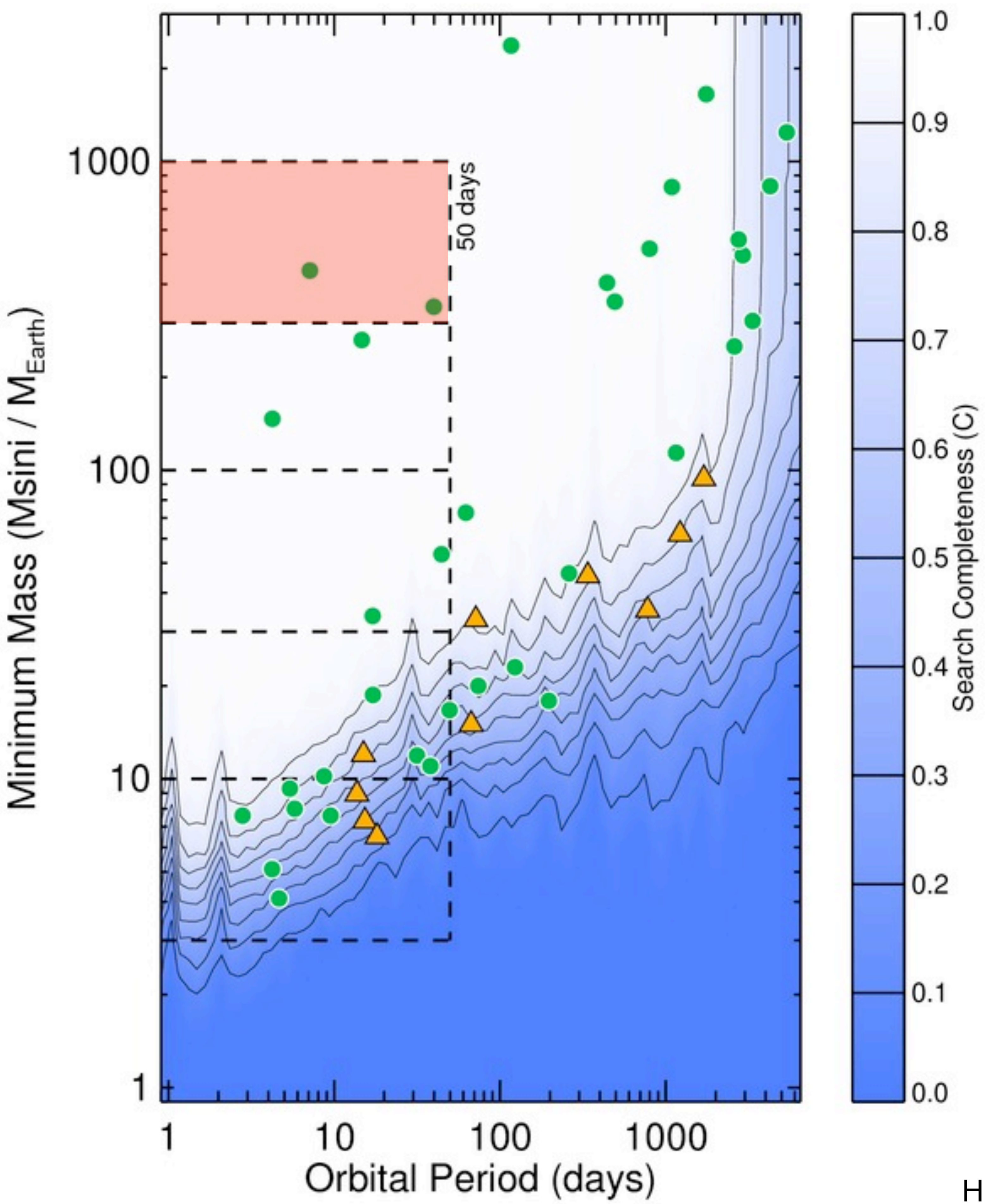
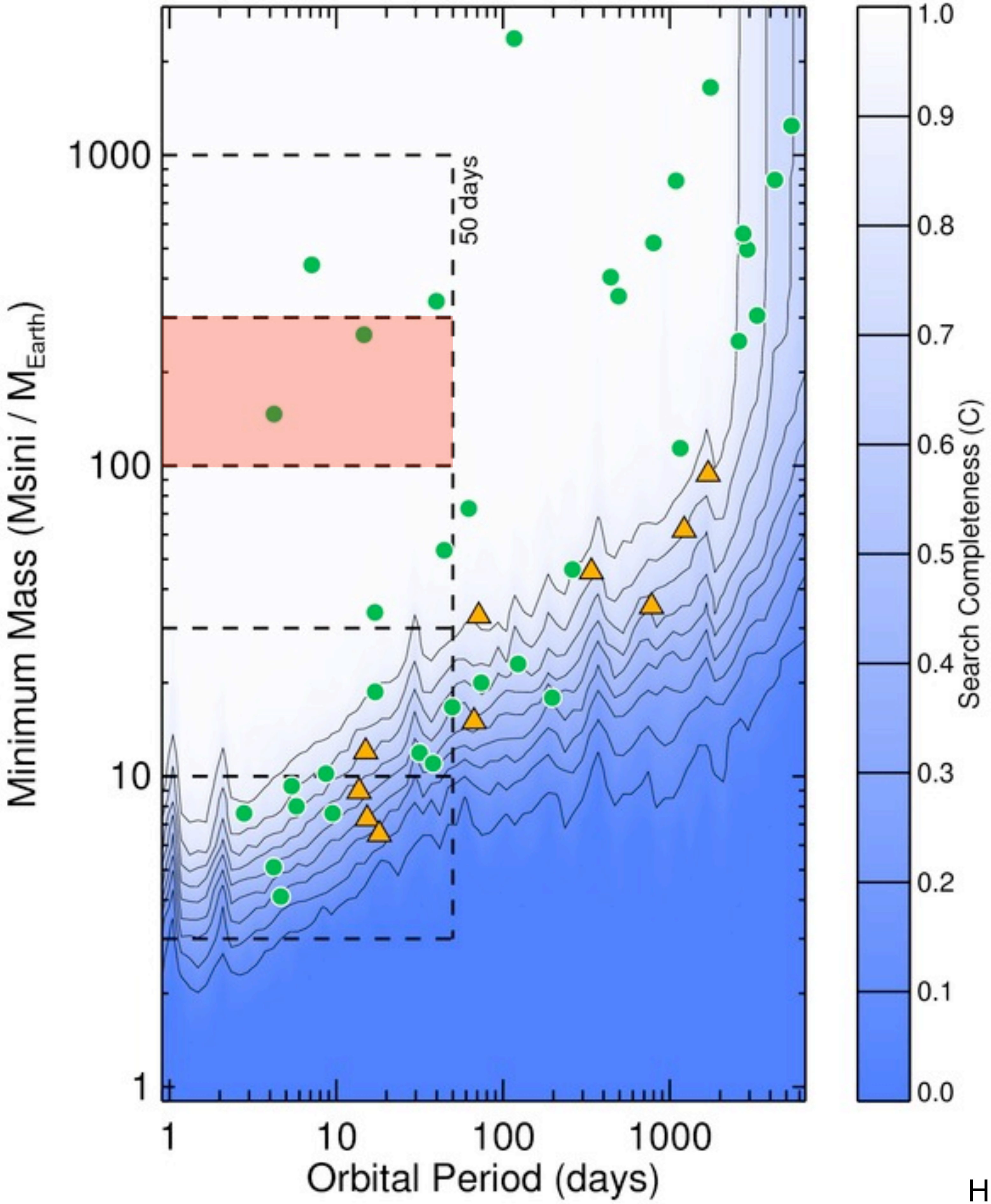
Howard et al. 2010, Science, 330, 653



Msini = 300-1000 M_E

- 2 Detected planets
- 0 Candidate planets

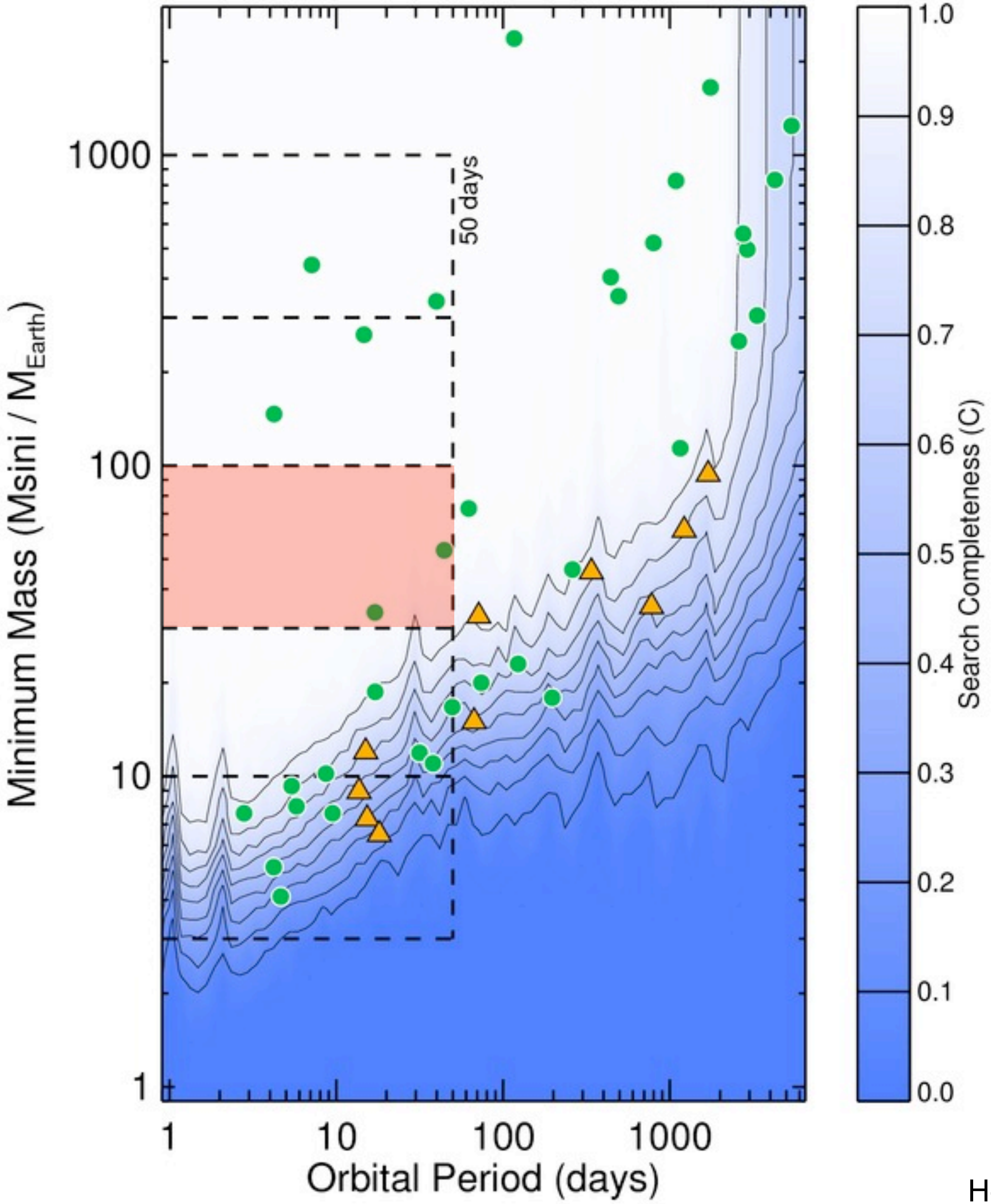
Howard et al. 2010, Science, 330, 653



Msini = 100-300 M_E

- 2 Detected planets
- 0 Candidate planets

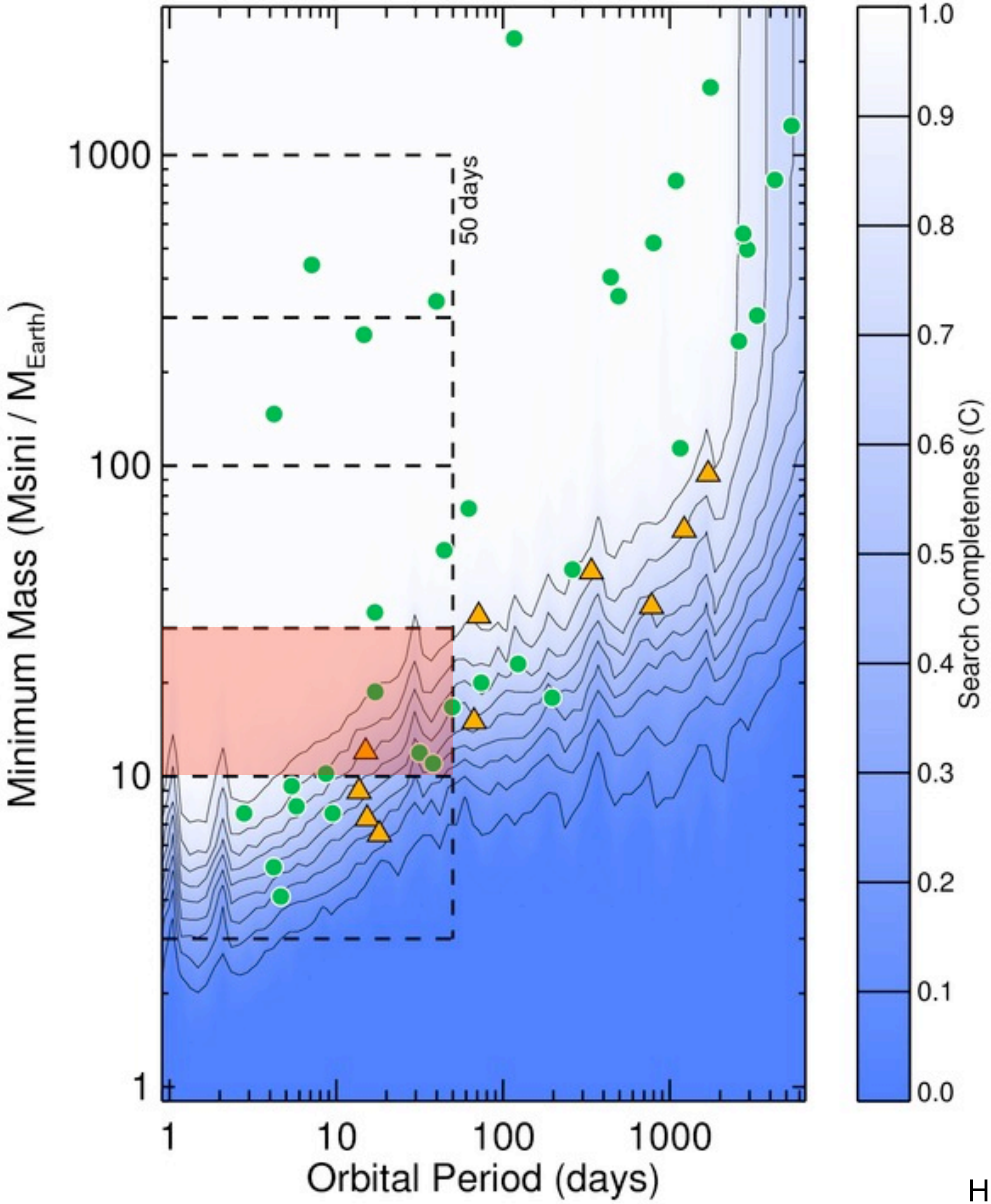
Howard et al. 2010, Science, 330, 653



Msini = 30-100 M_E

- 2 Detected planets
- 0 Candidate planets

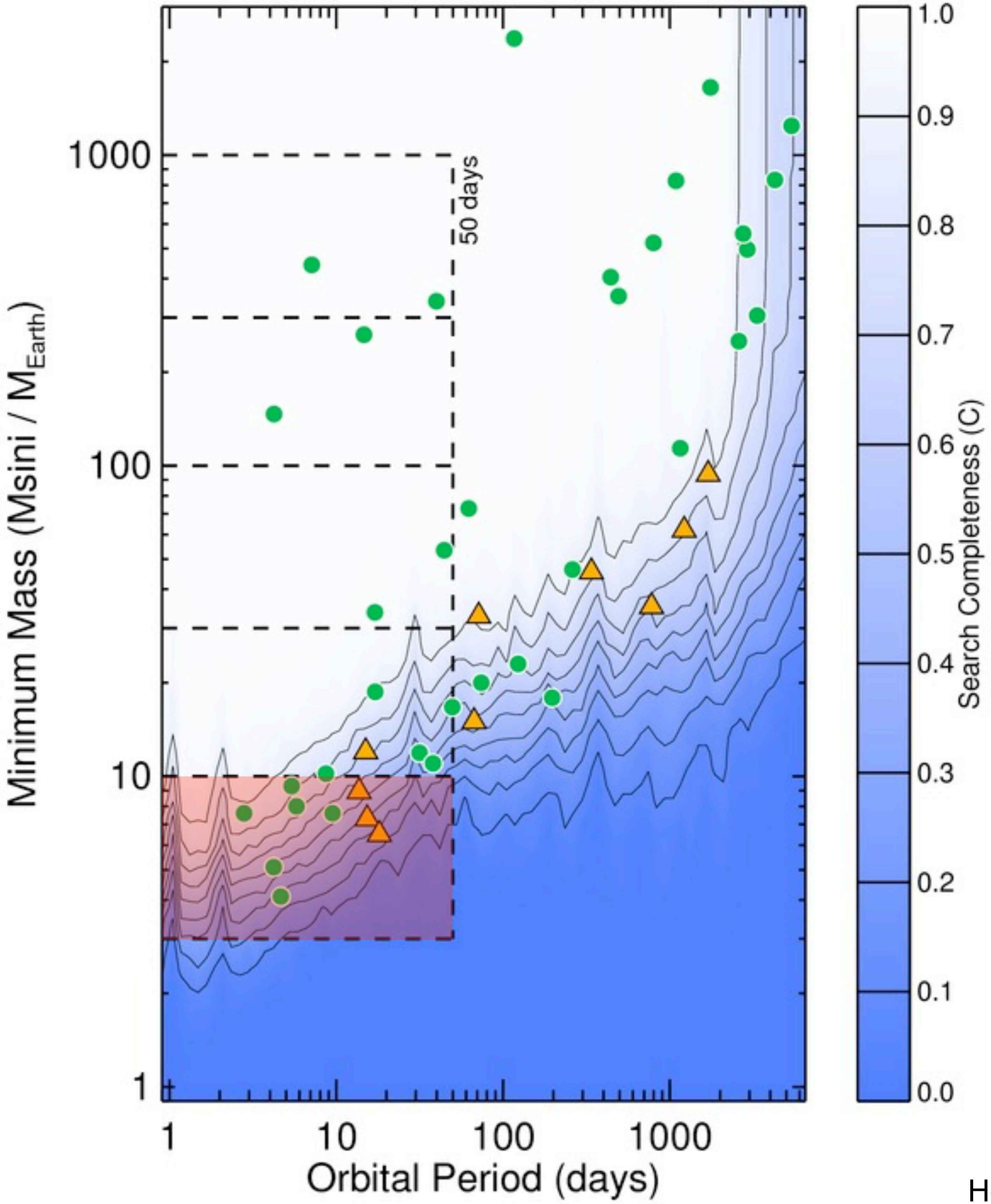
Howard et al. 2010, Science, 330, 653



Msini = 10-30 M_E

- 4 Detected planets
- 1 Candidate planets

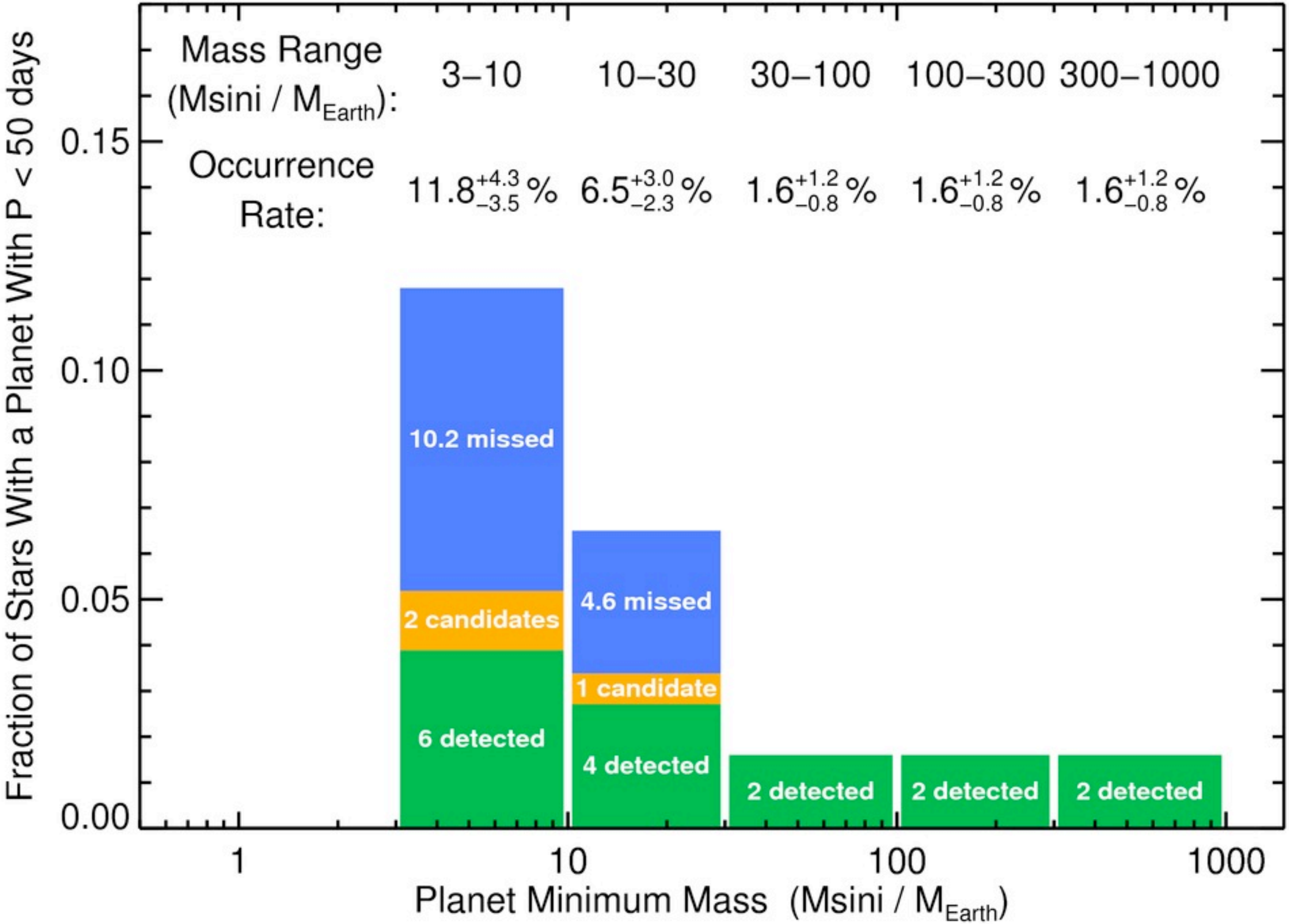
Howard et al. 2010, Science, 330, 653



Msini = 3-10 M_E

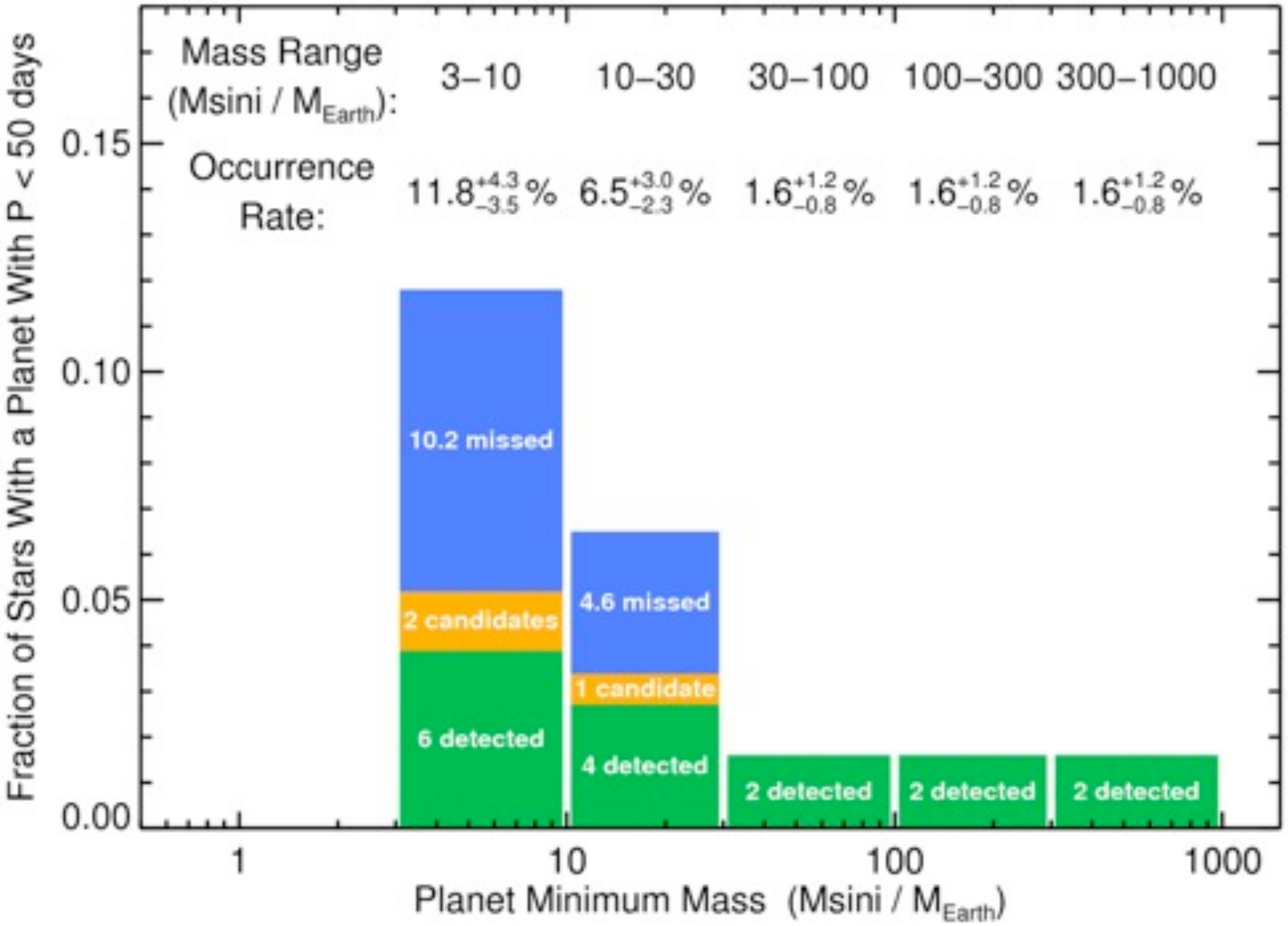
- 6 Detected planets
- 2 Candidate planets

Howard et al. 2010, Science, 330, 653



Howard et al. 2010, Science, 330, 653

Key Result: Power-law Mass Distribution



Howard et al. 2010, Science, 330, 653

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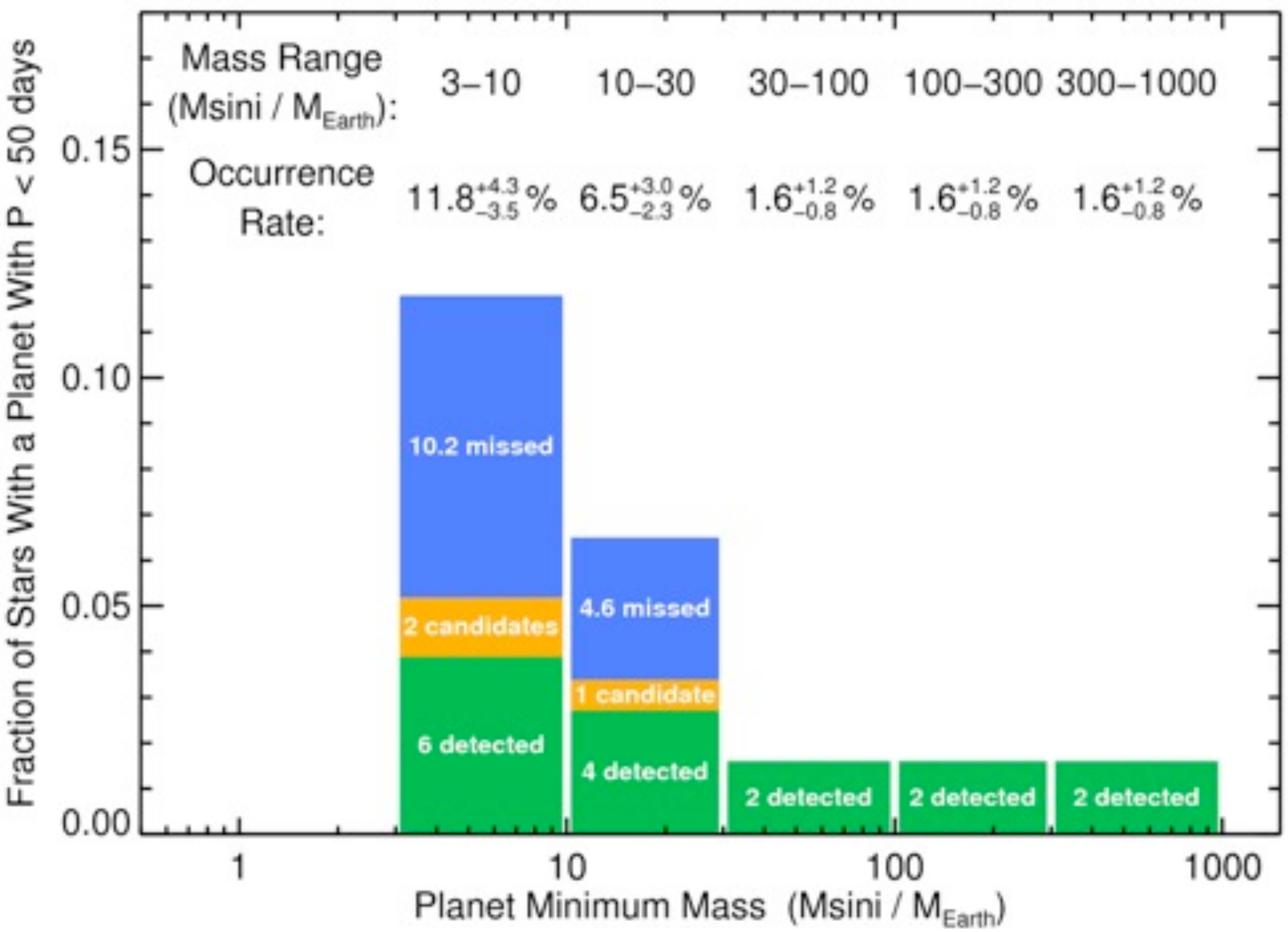
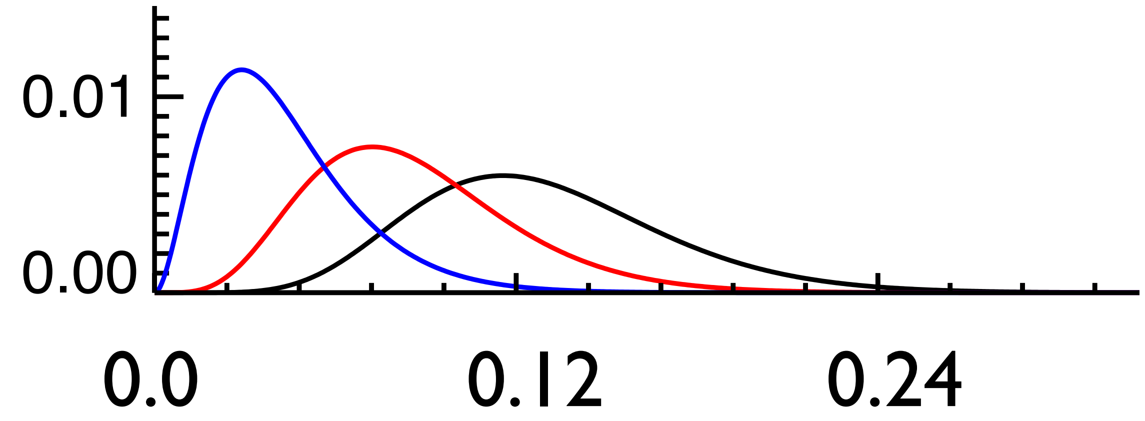


<u>Compute Errors</u>

assume binomial statistics

scale missed planets w/det + cand



Howard et al. 2010, Science, 330, 653

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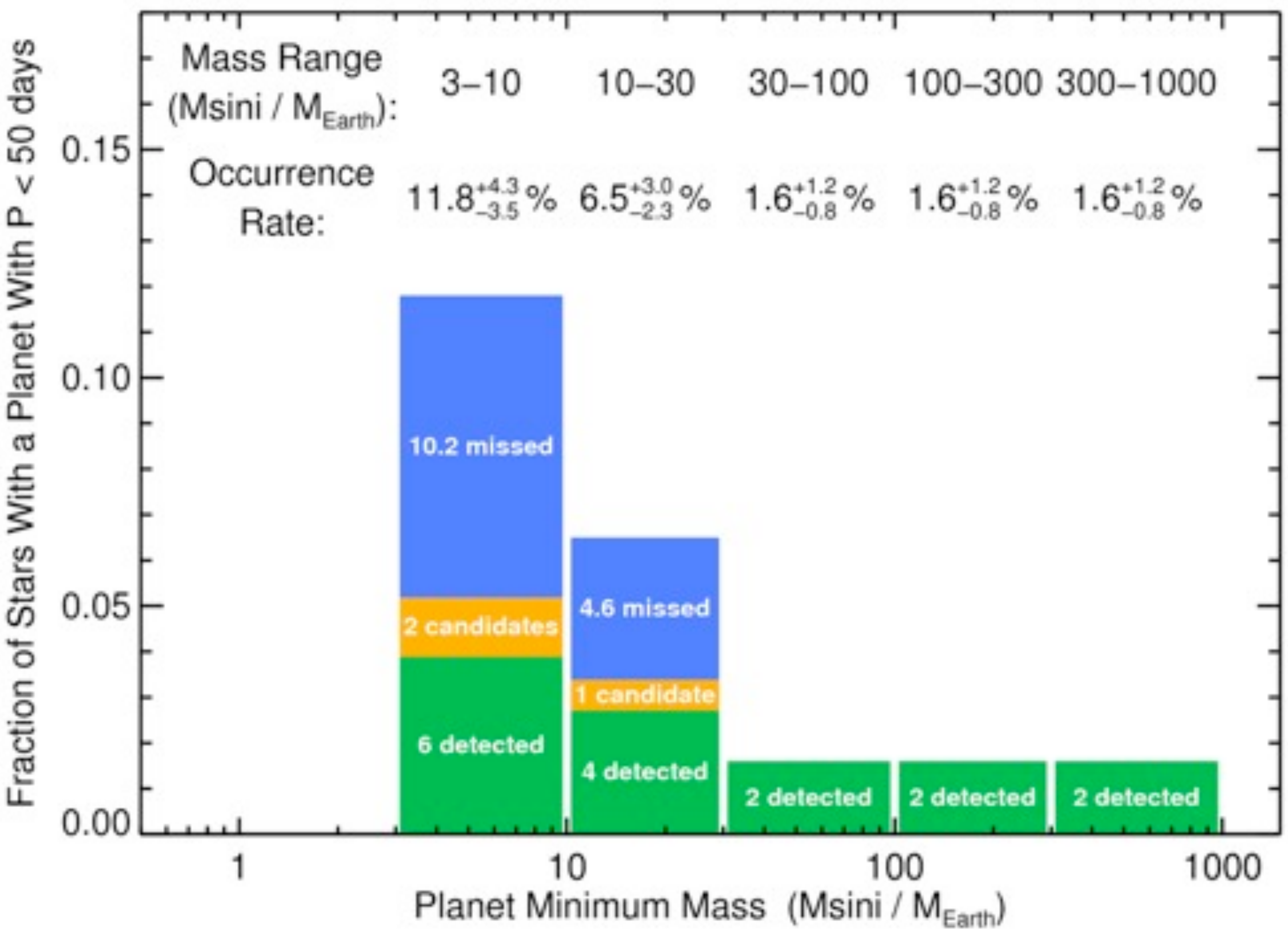

<u>Compute Errors</u>

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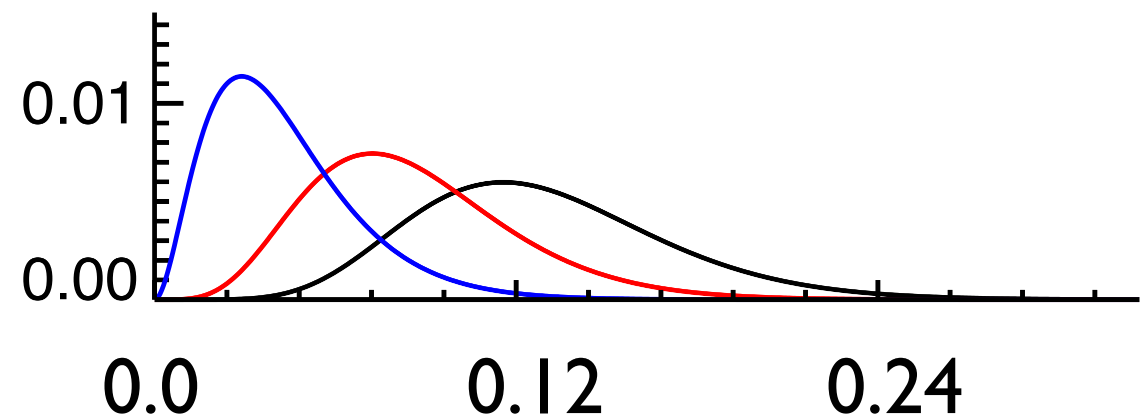
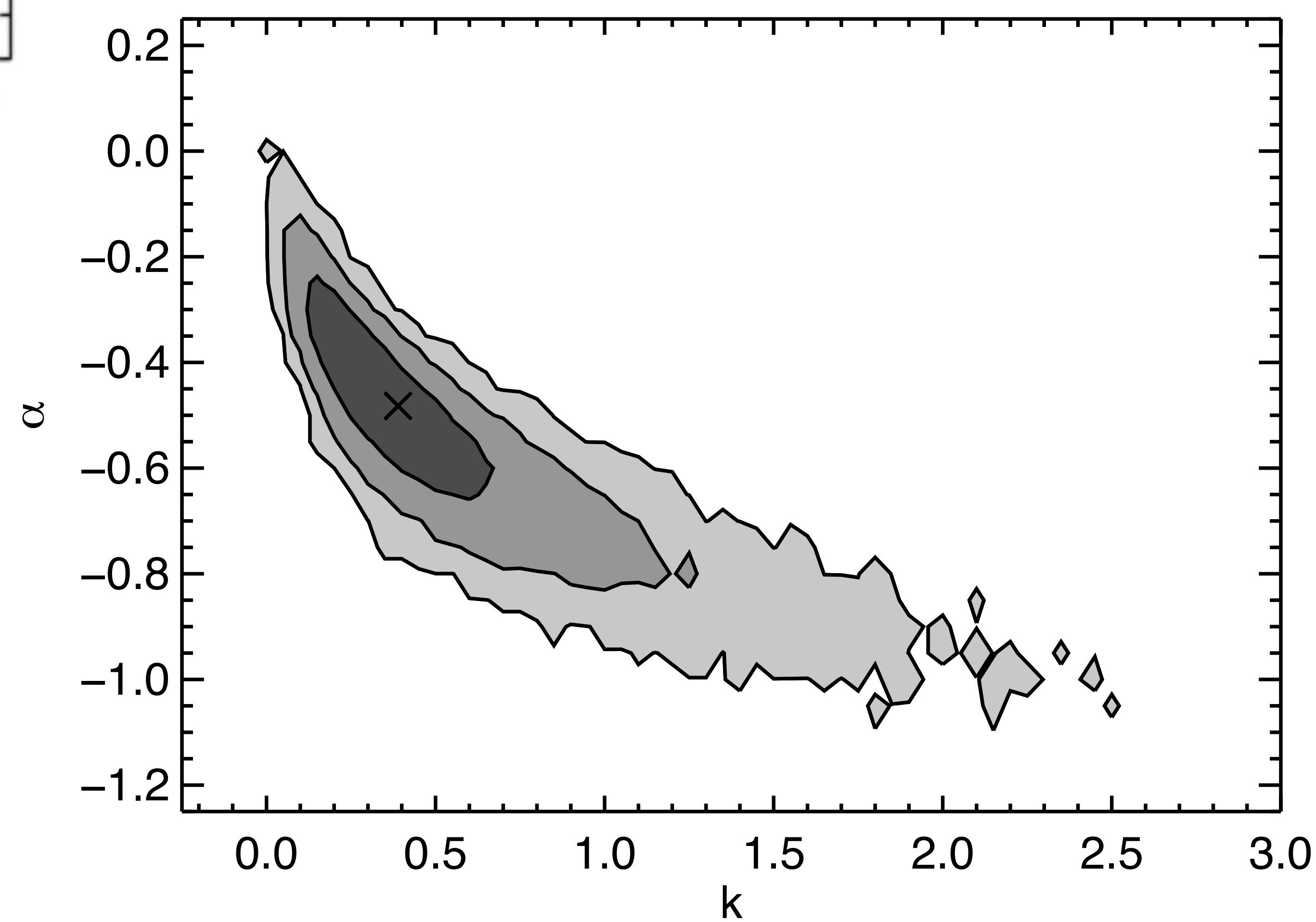


$$df/d\log M = kM^{\alpha}$$

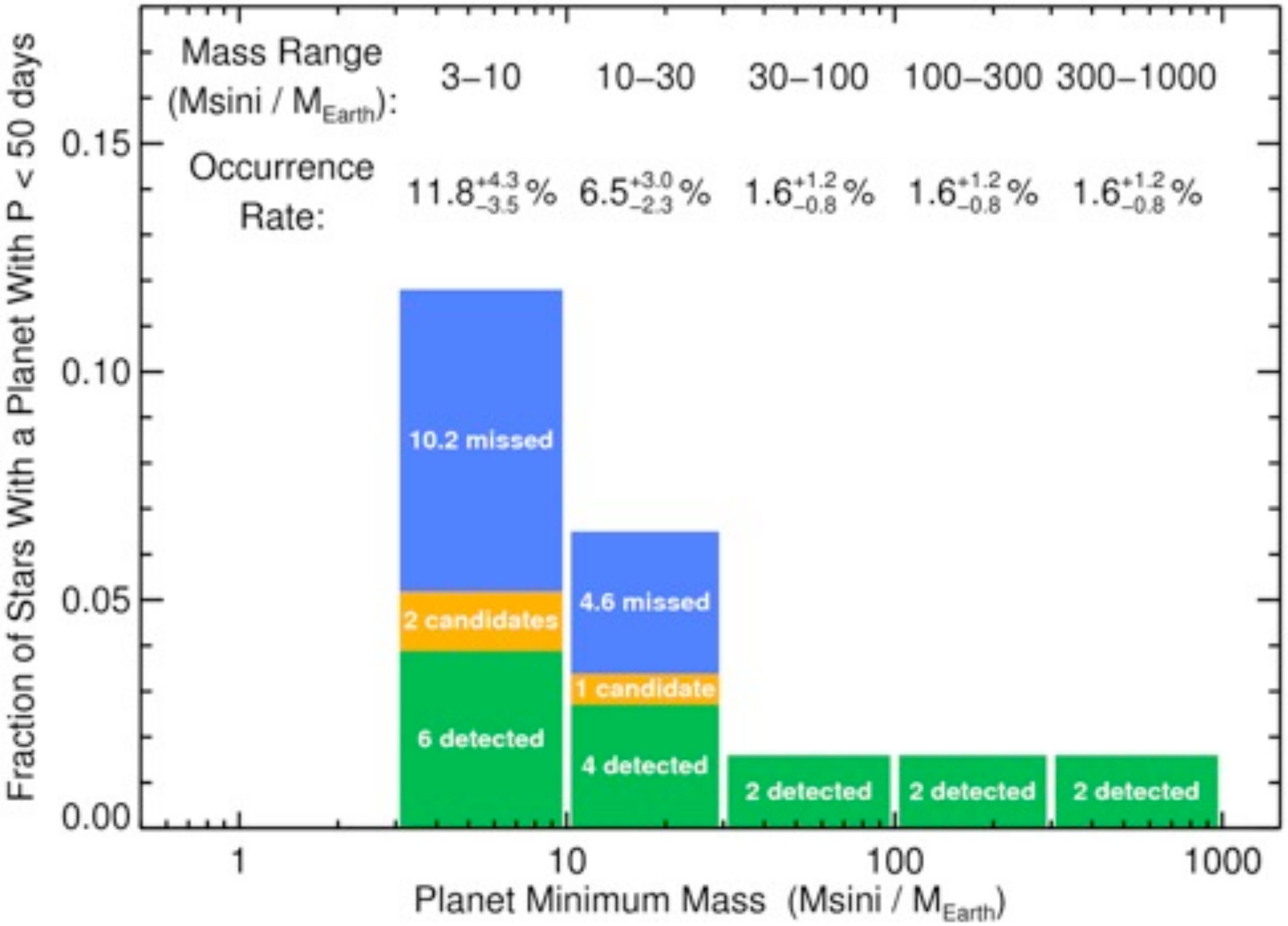
$$k = 0.39^{+0.27}_{-0.16}$$

$$\alpha = -0.48^{+0.12}_{-0.14}$$



Howard et al. 2010, Science, 330, 653

Key Result: Occurrence rate of Super-Earths + Neptunes

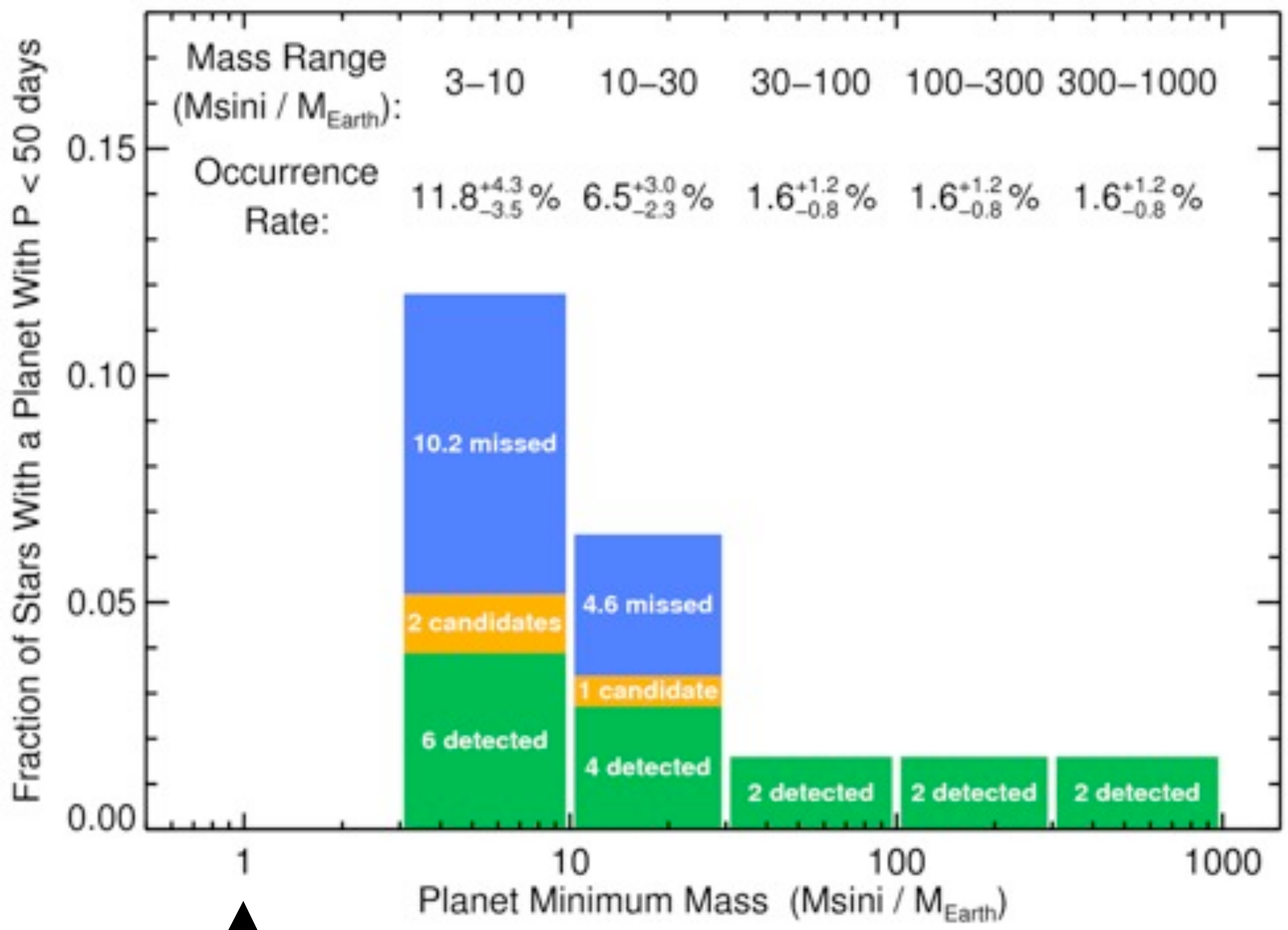


<u>Occurrence rate of super-Earths & Neptunes:</u>

15^{+5}_{-4}% occurrence $M\sin i = 3\text{-}30\ M_E$, $P < 50$ days

Howard et al. 2010, Science, 330, 653

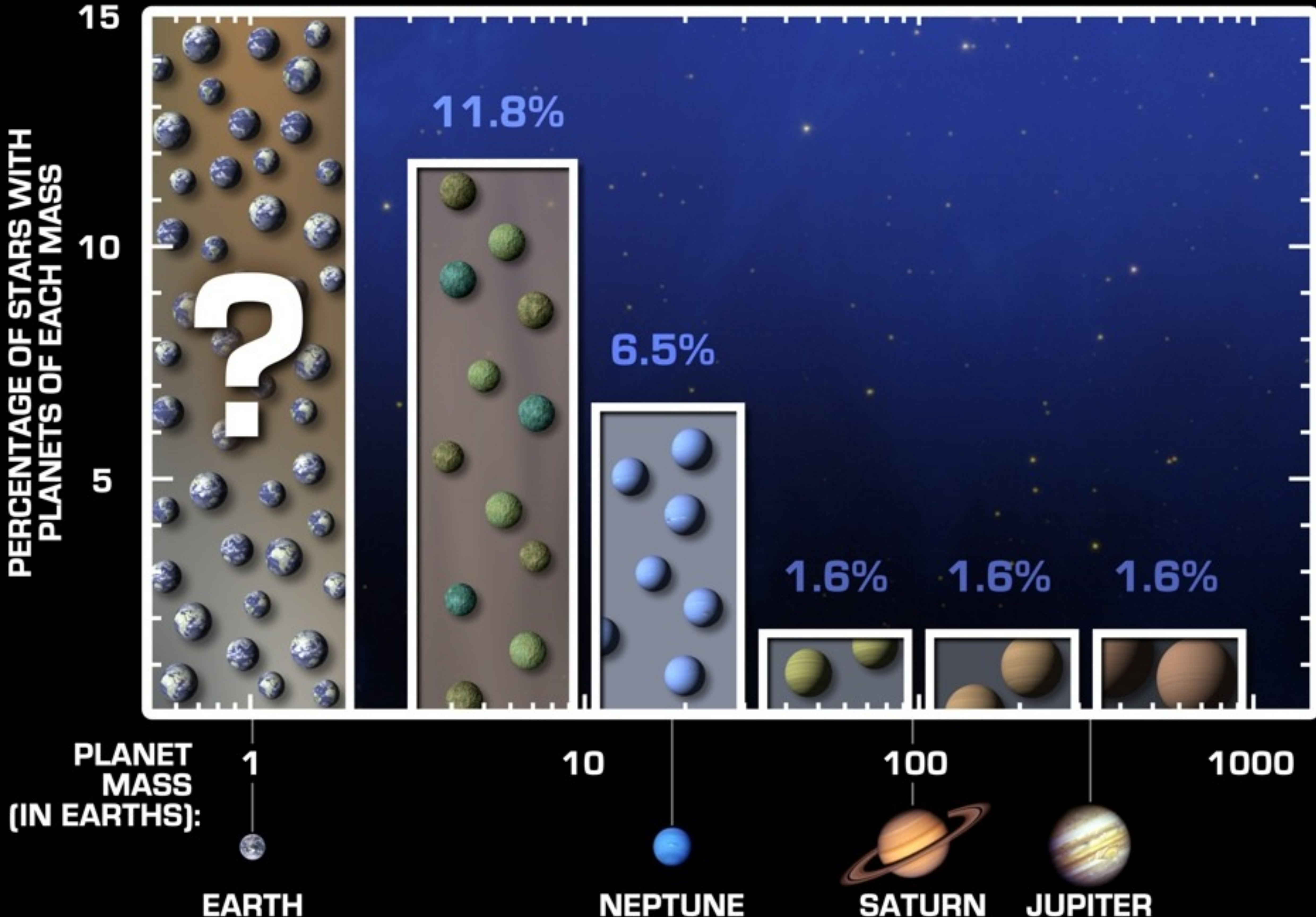
Key Result: Earth-mass Planets Common



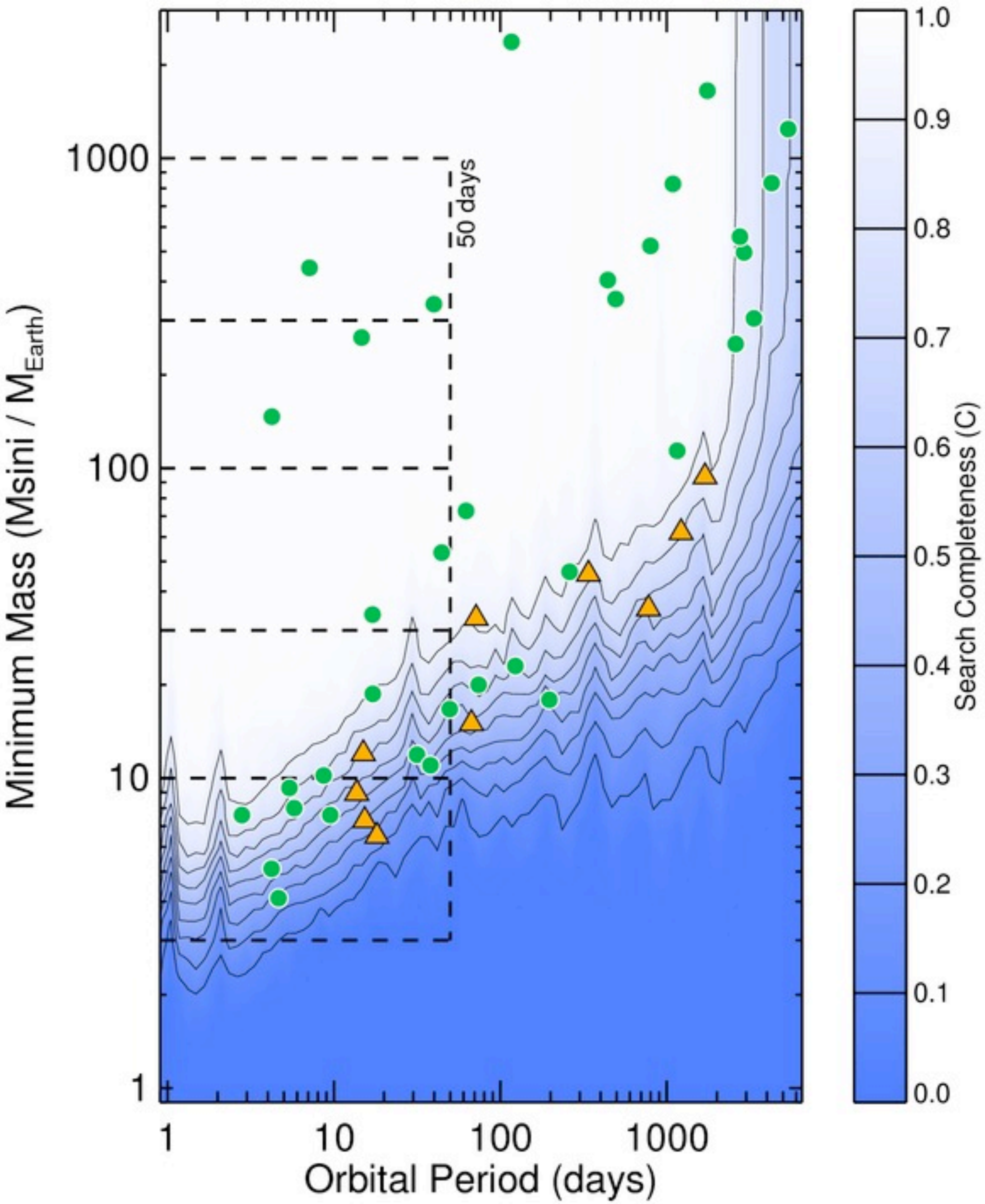
<u>Extrapolation of Power Law Model:</u>

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



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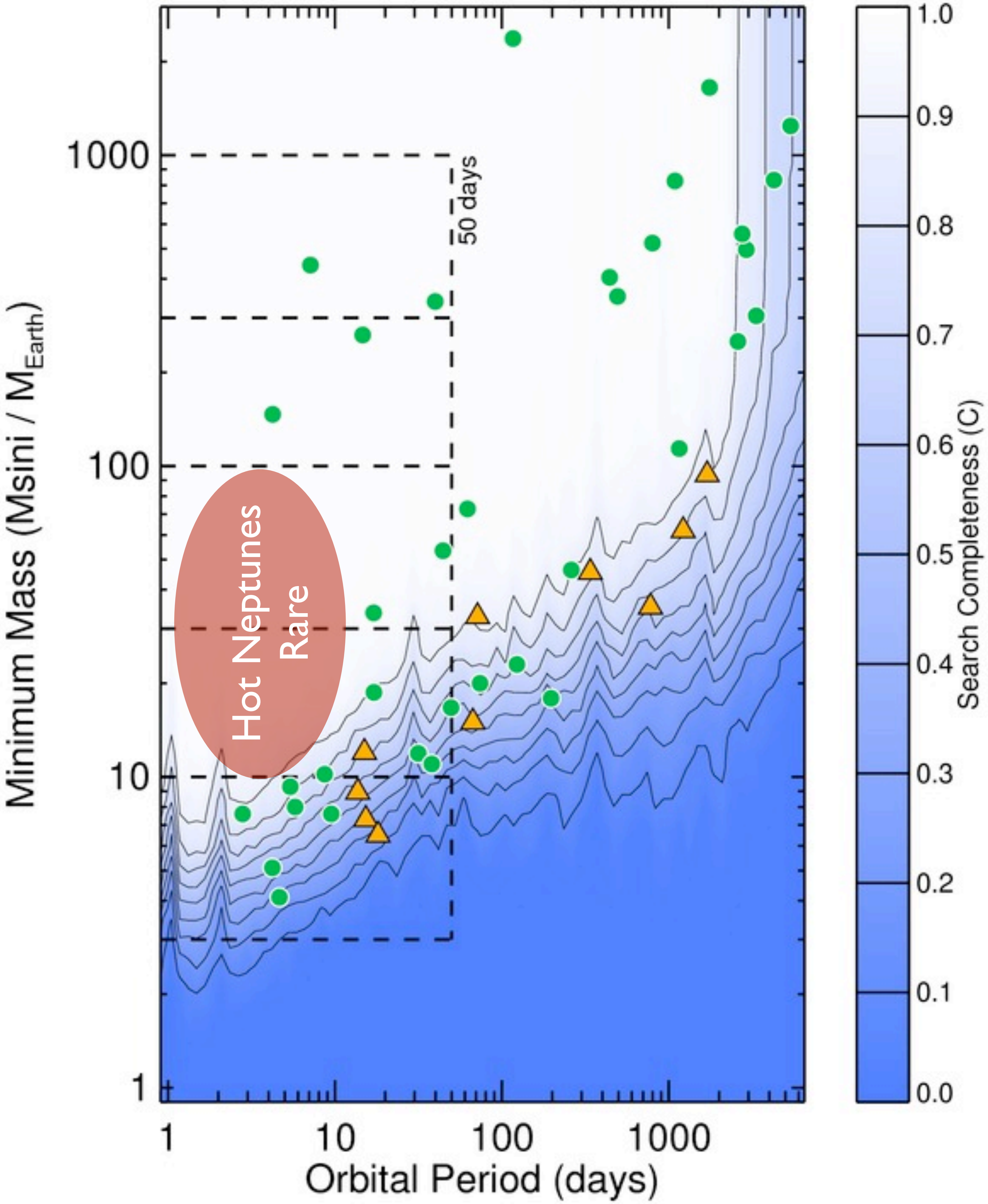

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   Msini=10-100 M_E, P < 20 days

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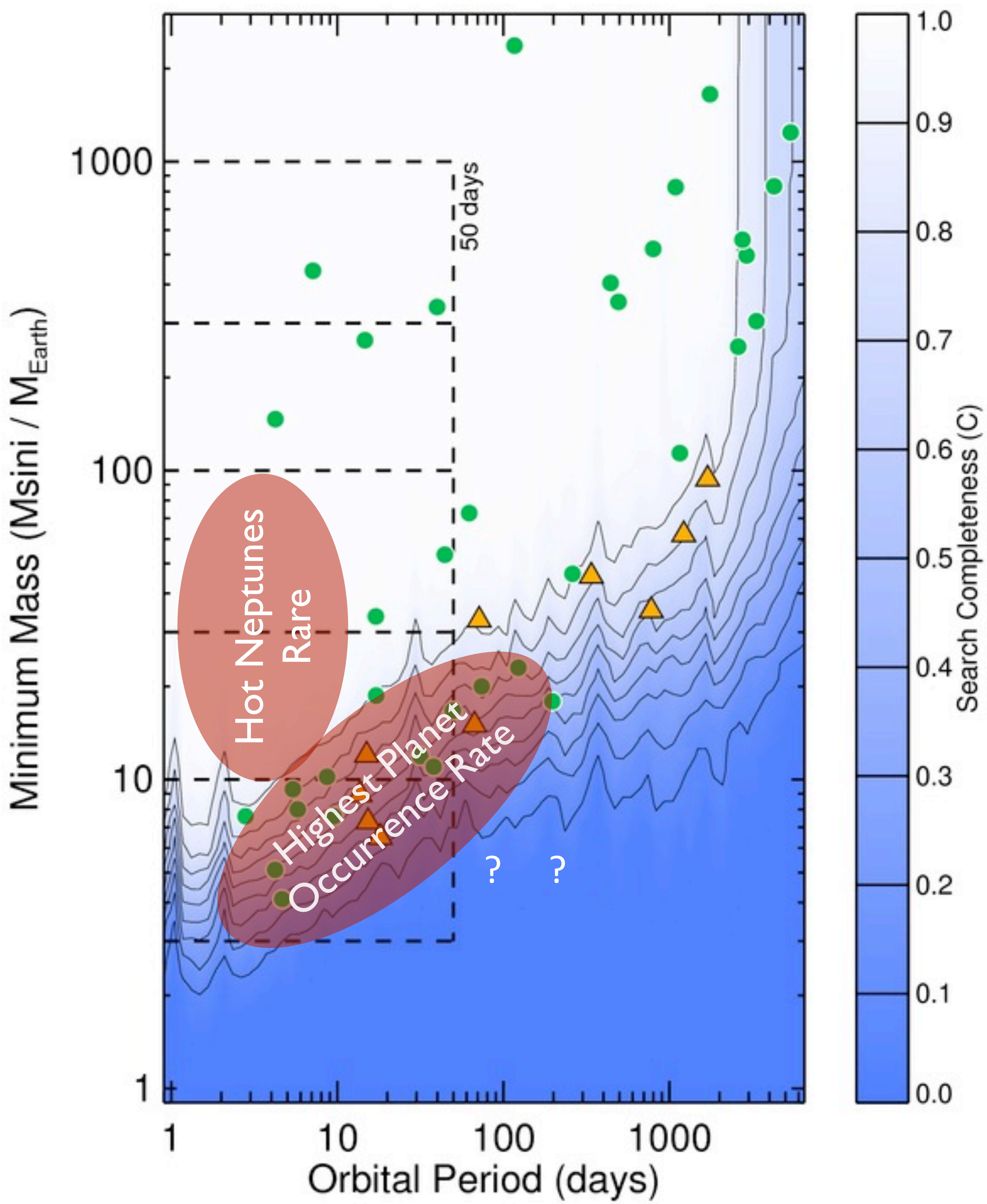

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2. Highest planet occurrence rate:
   - Msini=10-30 M_E, P > ~20 days
   - Msini=3-10 M_E, P > ~5 days

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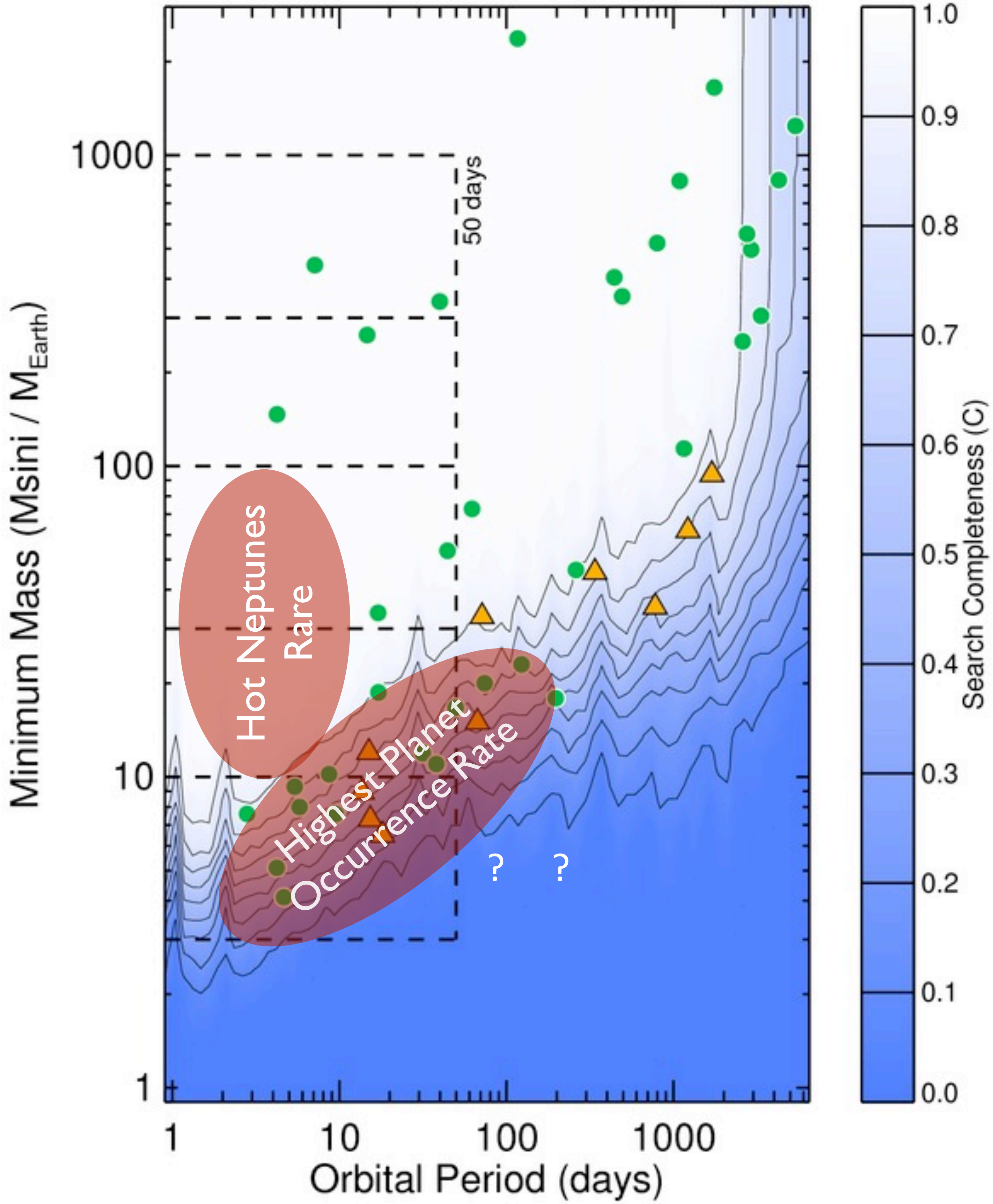

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   No short-period pileup

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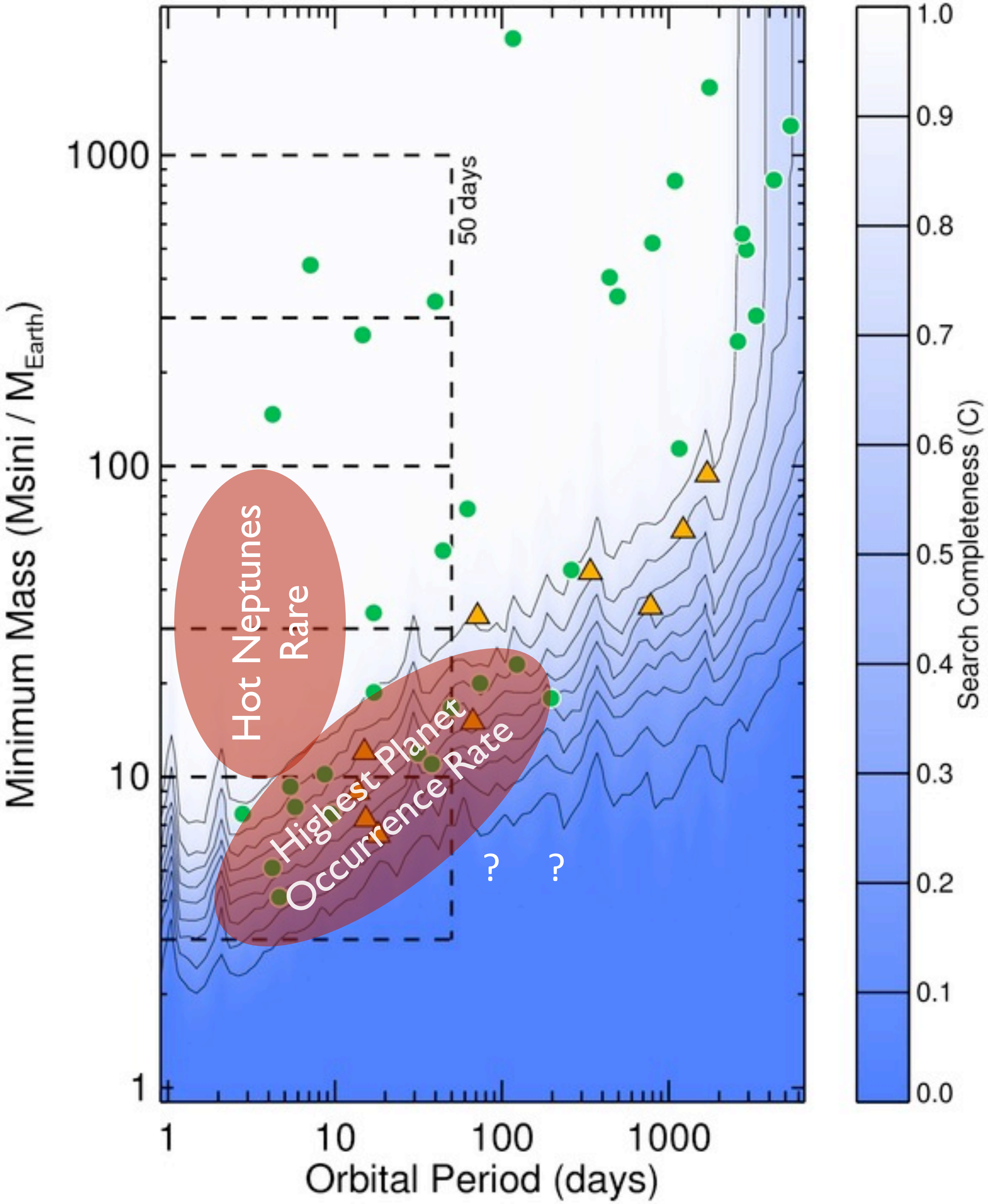

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4. Low-mass planets:
   Multi-planet systems common

Howard et al. 2010, Science, 330, 653

- Period < 50 days, Msini ≥ 3 Earth-masses
- Msini and period well-measured by Doppler signal
- Correct incompleteness with star-by-star analysis

$$\text{Occurrence} = \frac{\text{Number of Planets}}{\text{Number of Stars}}$$

- GK dwarfs — nearby; nearly unbiased (Hipparcos)

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Break ....

... questions?

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