The Occurrence and Mass Distribution of Super-Earths, Neptunes, and Jupiters

Andrew W. Howard
UC Berkeley

California Planet Search Team:

Geoff Marcy, Debra Fischer, John Johnson, Jason Wright, Howard Isaacson, Julien Spronck, Jeff Valenti, Jay Anderson, Nikolai Piskunov, more!

NASA-UC Eta-Earth Survey

Exo-surprises

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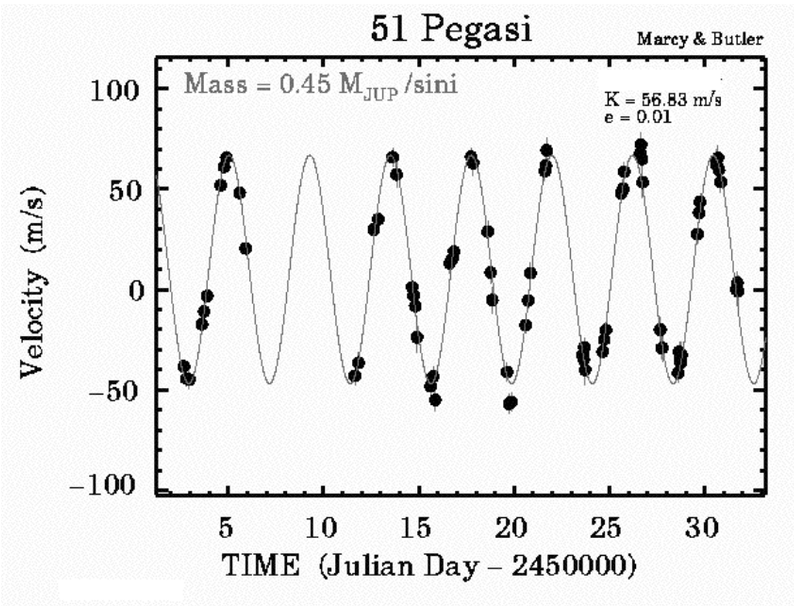
Hot Jupiters



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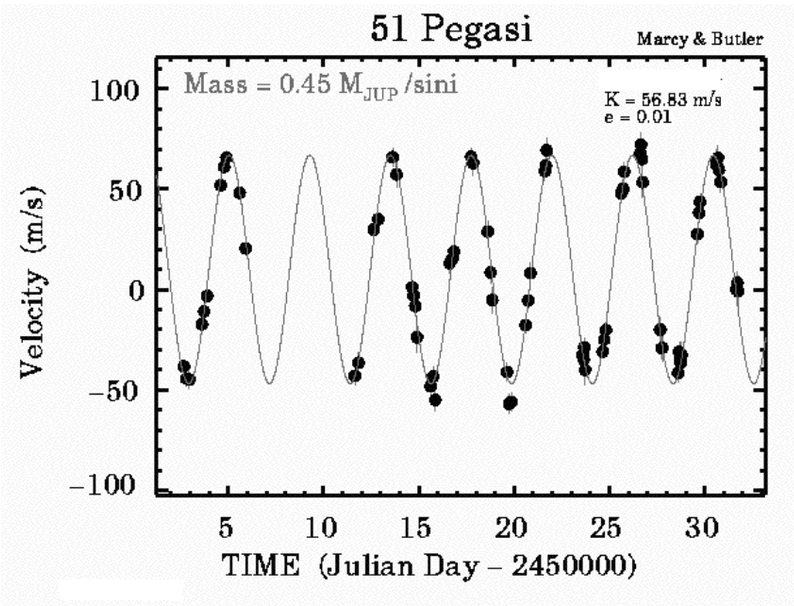
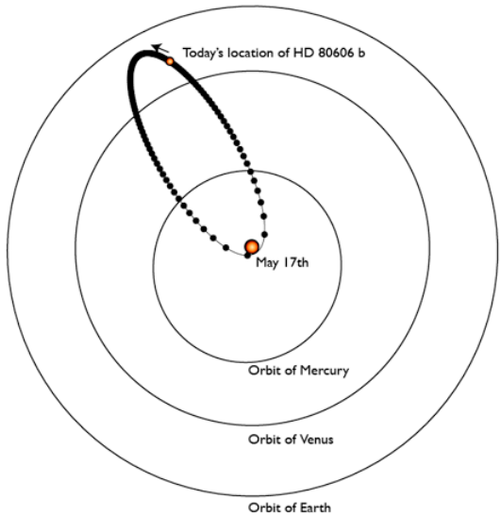


Eccentric Orbits



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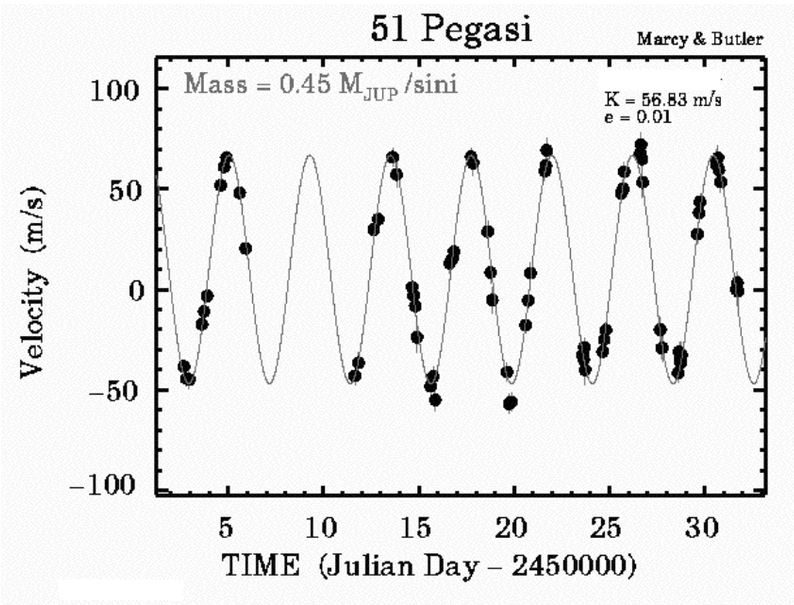

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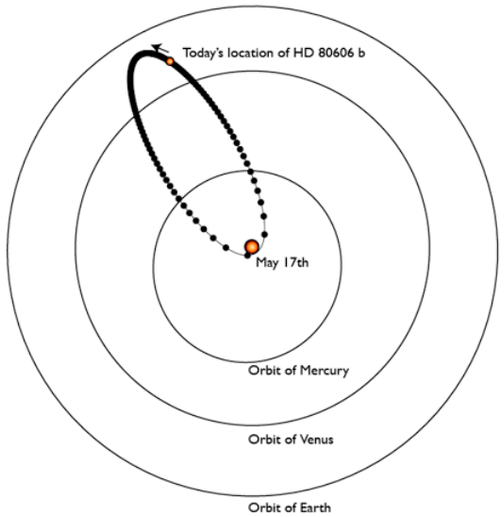

Inflated Transiting Planets

Exo-surprises

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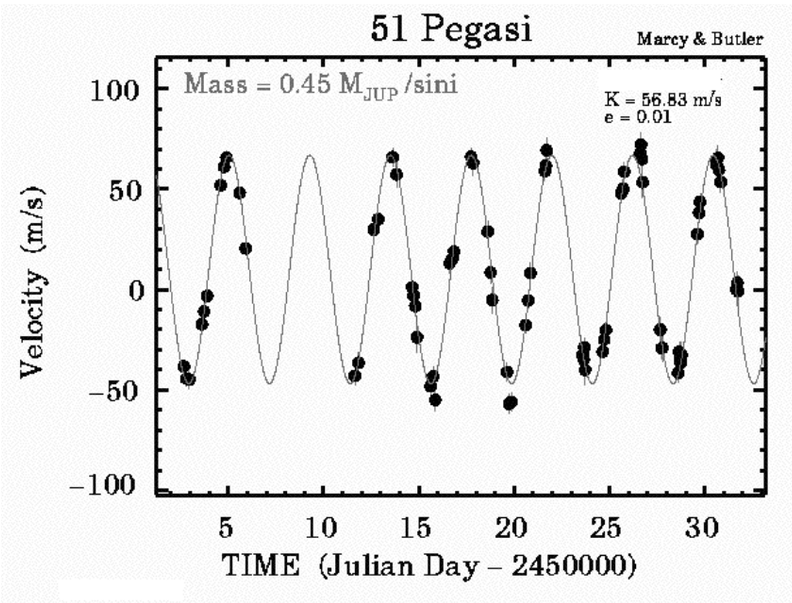

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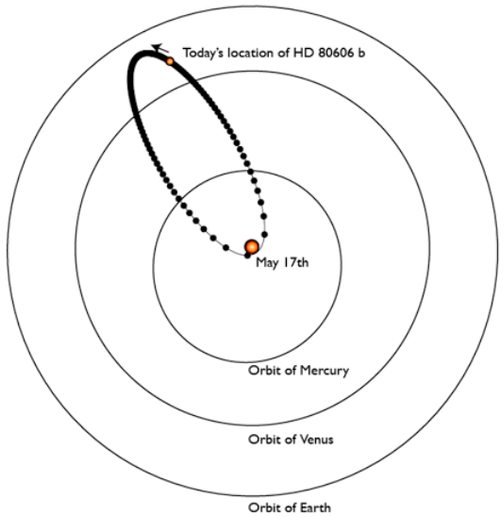

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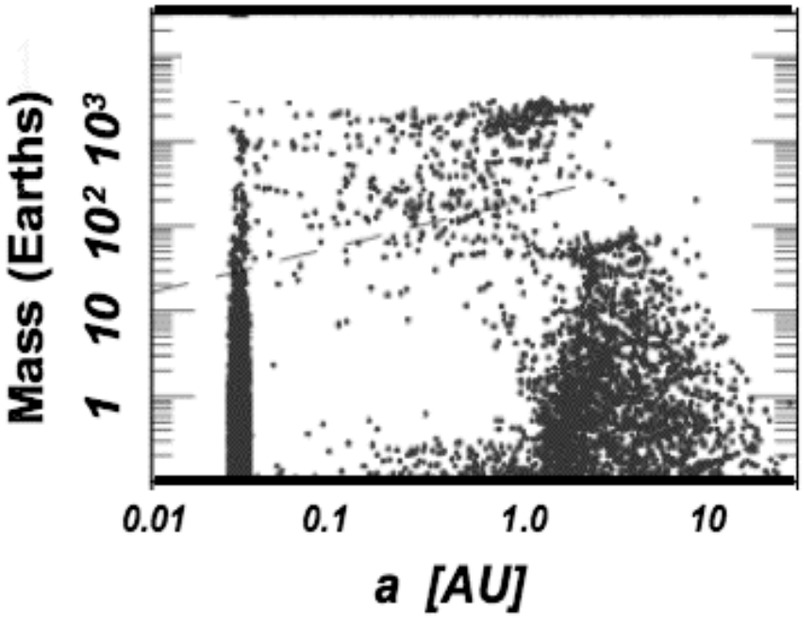
No Planet Desert



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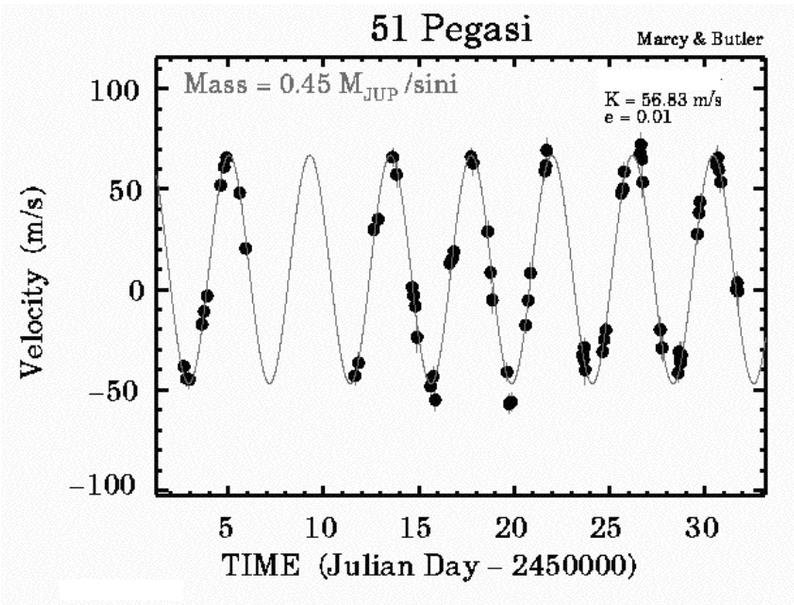

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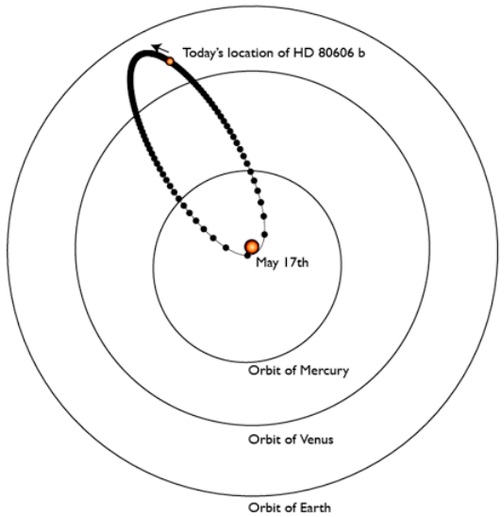

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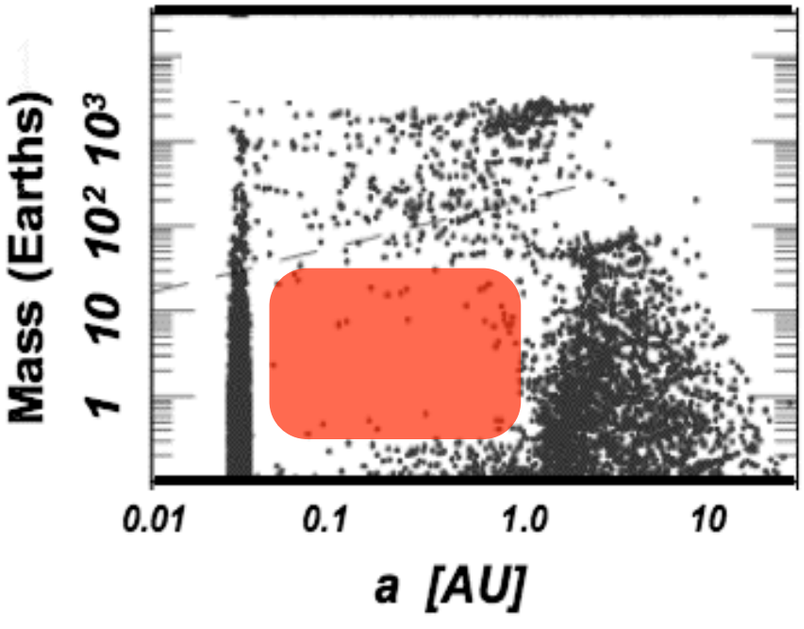
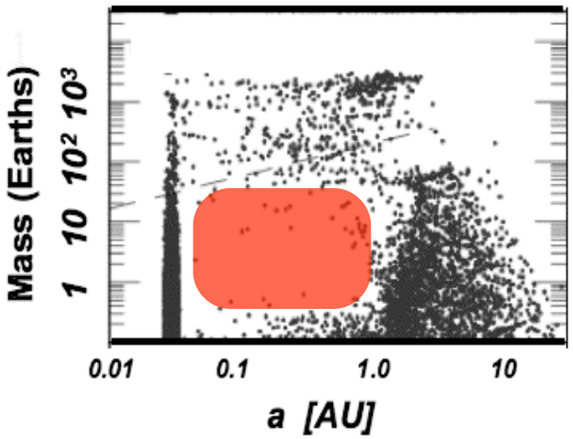
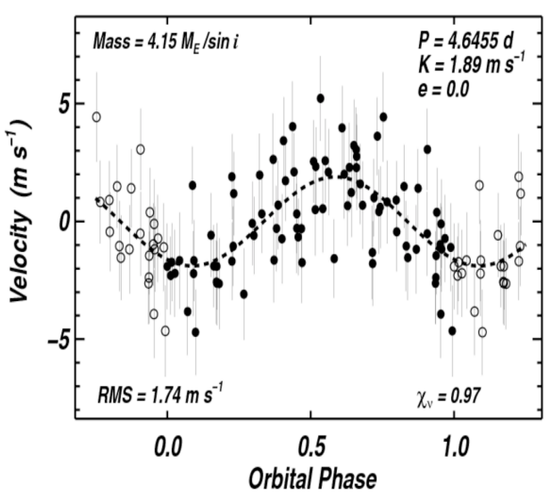




Outline:

1. A Prediction from Planet Formation
2. The Eta-Earth Survey from Keck
3. Planet Detections and Non-detections
4. The Planet Mass Distribution and η_{Earth}
5. Planet Formation Theory Revisited



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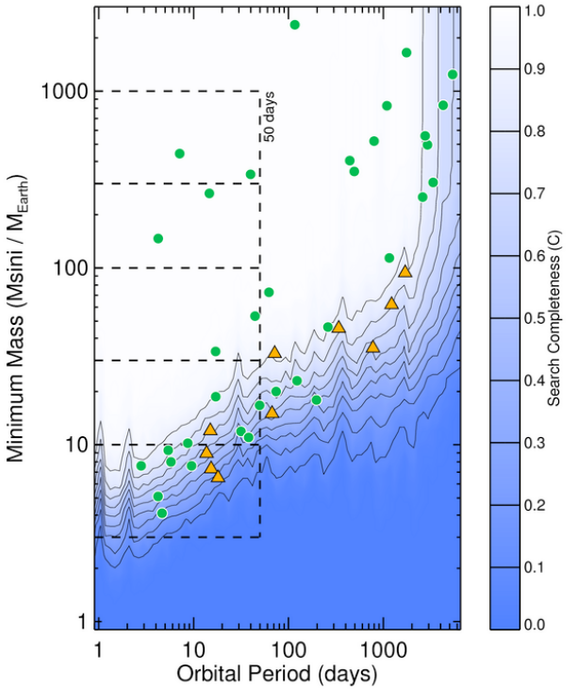
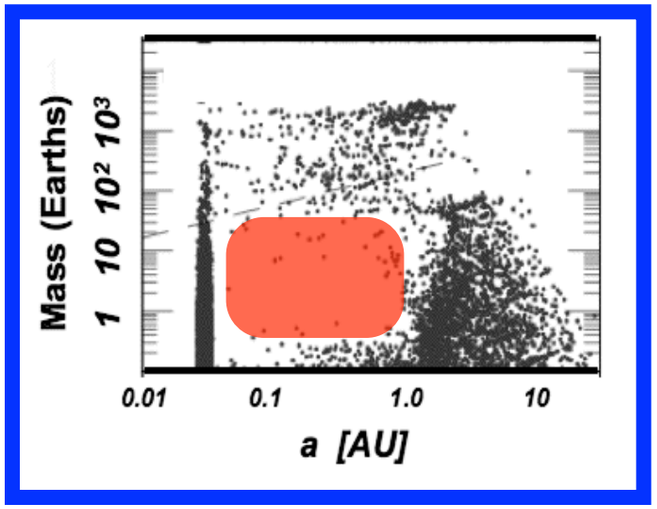
- Super-Earth detections
- Mass distribution down to 3 M_{Earth}
- η_{Earth}
- Constraints on planet formation





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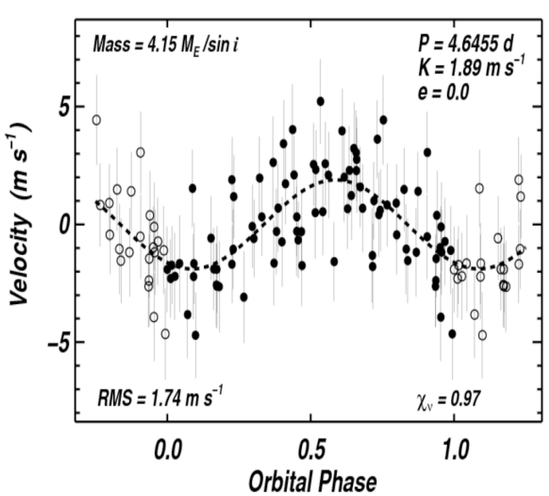

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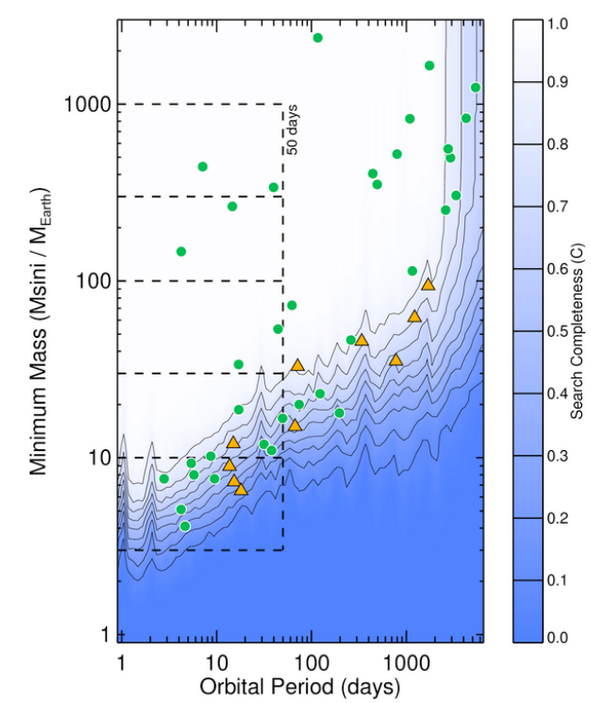
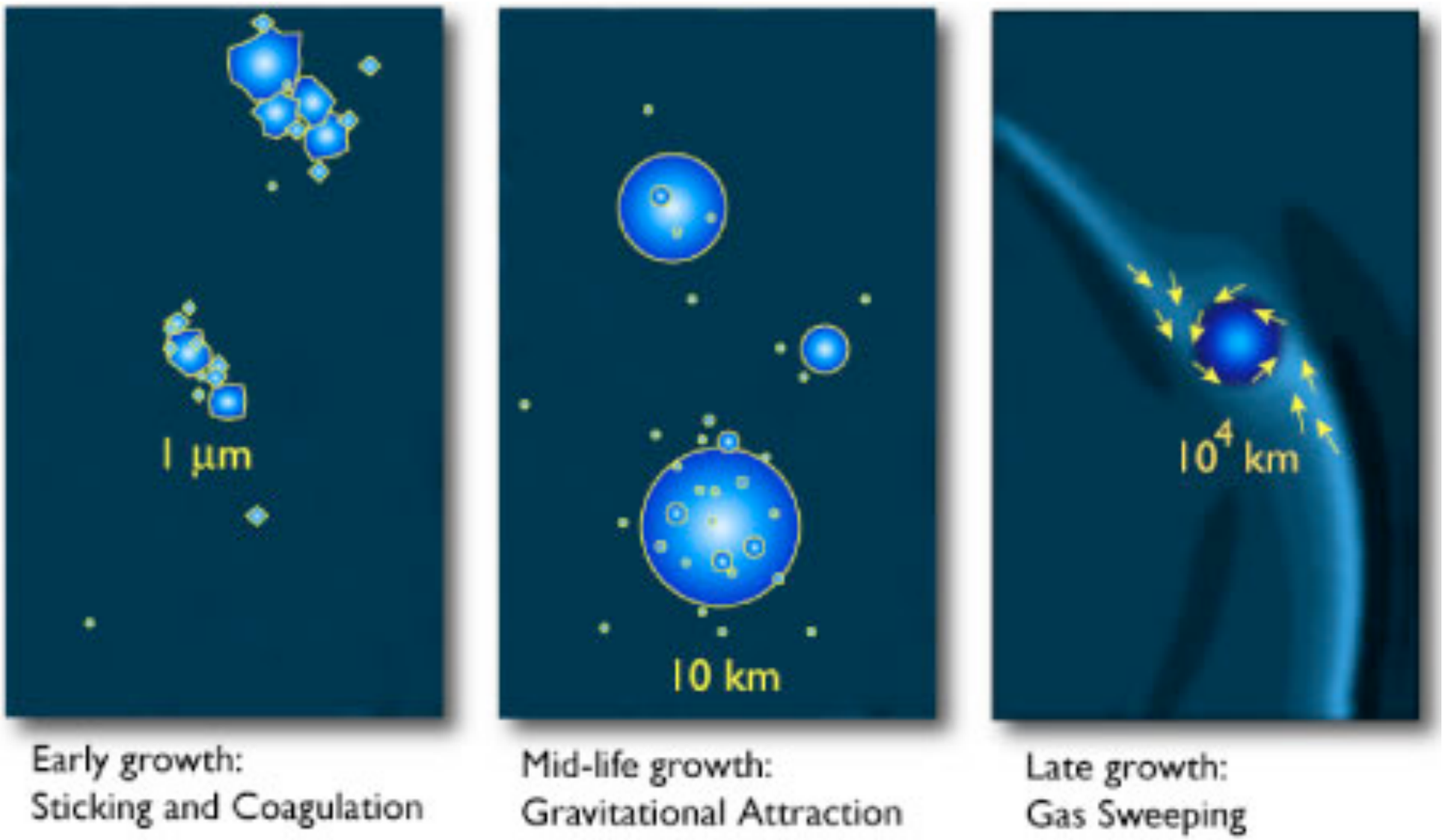


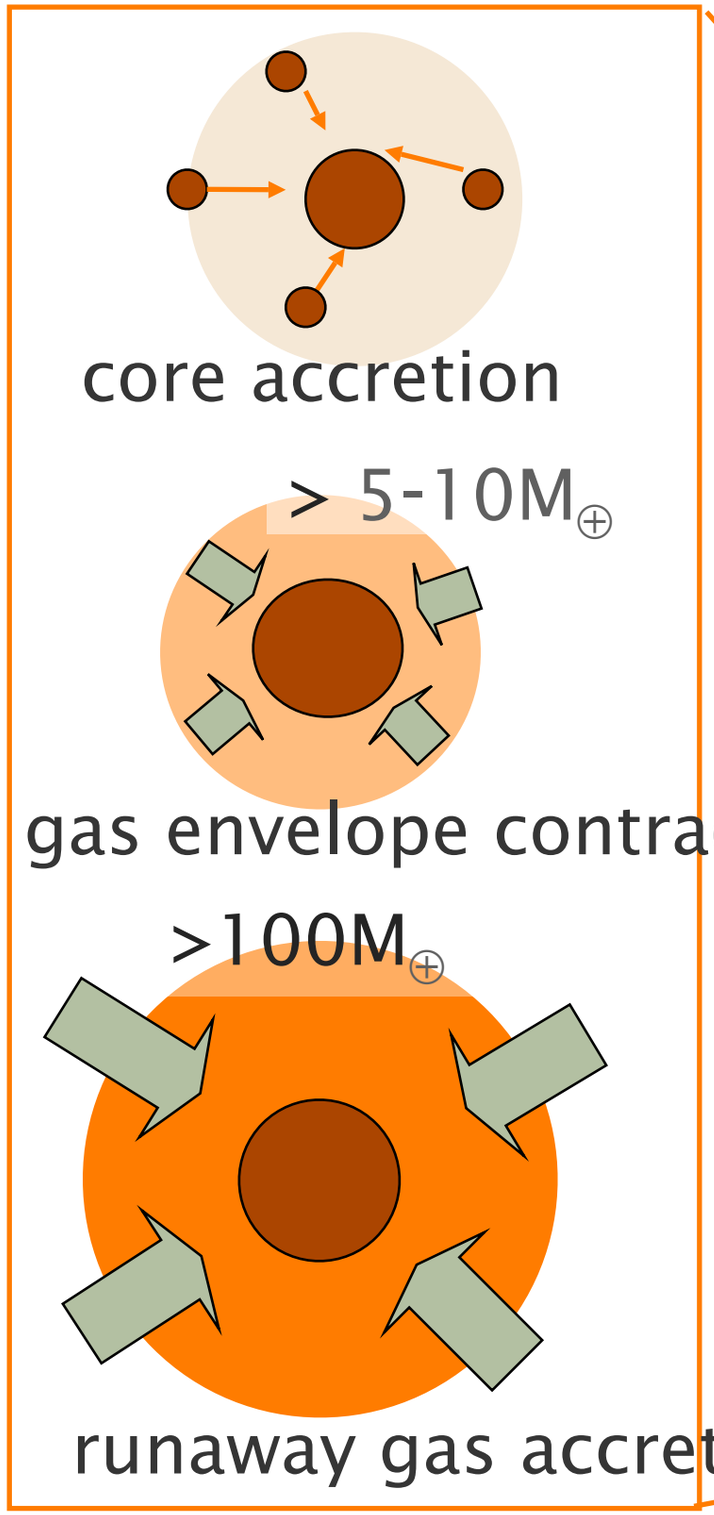
Core Accretion Model:

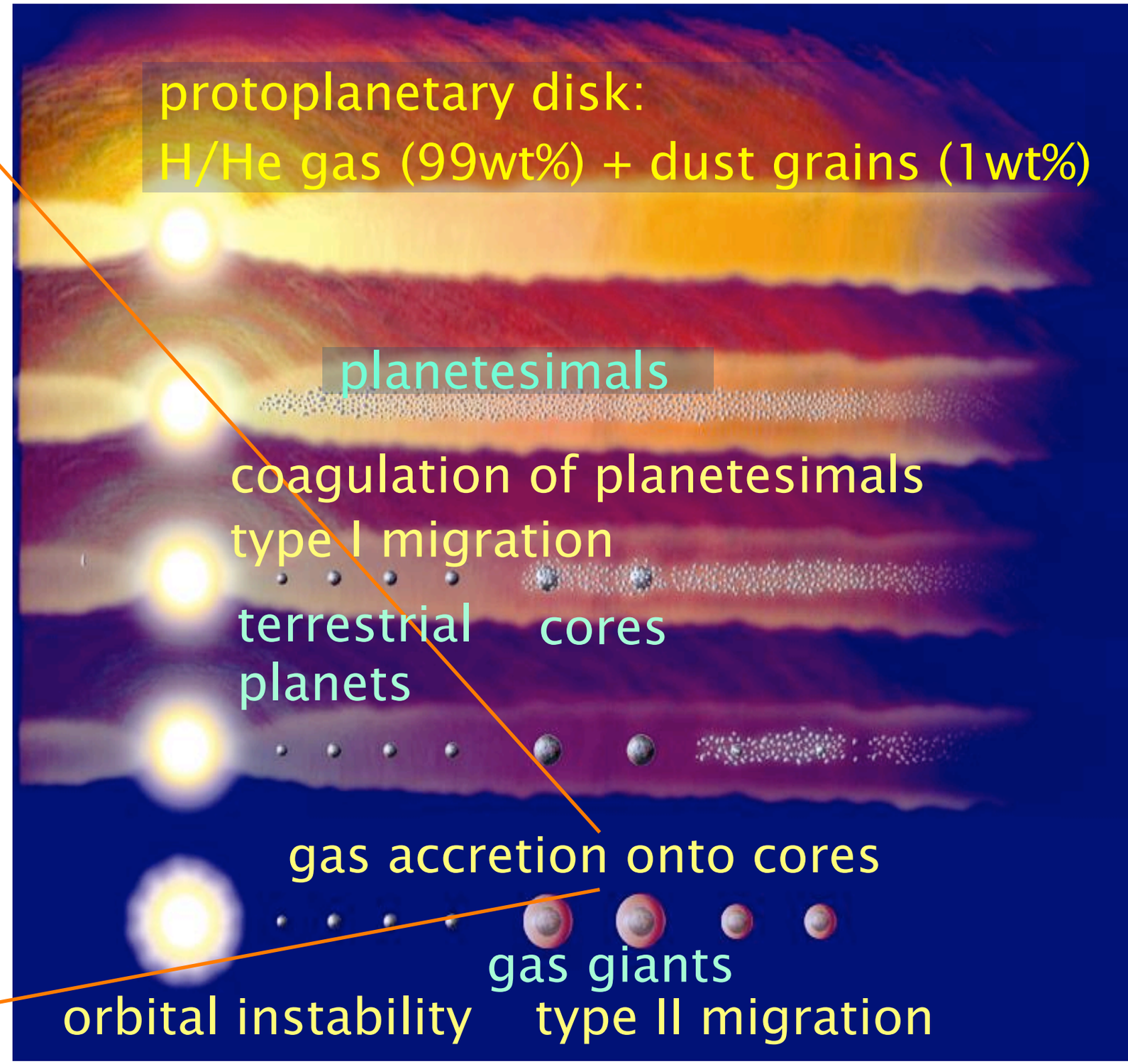


oklo.org

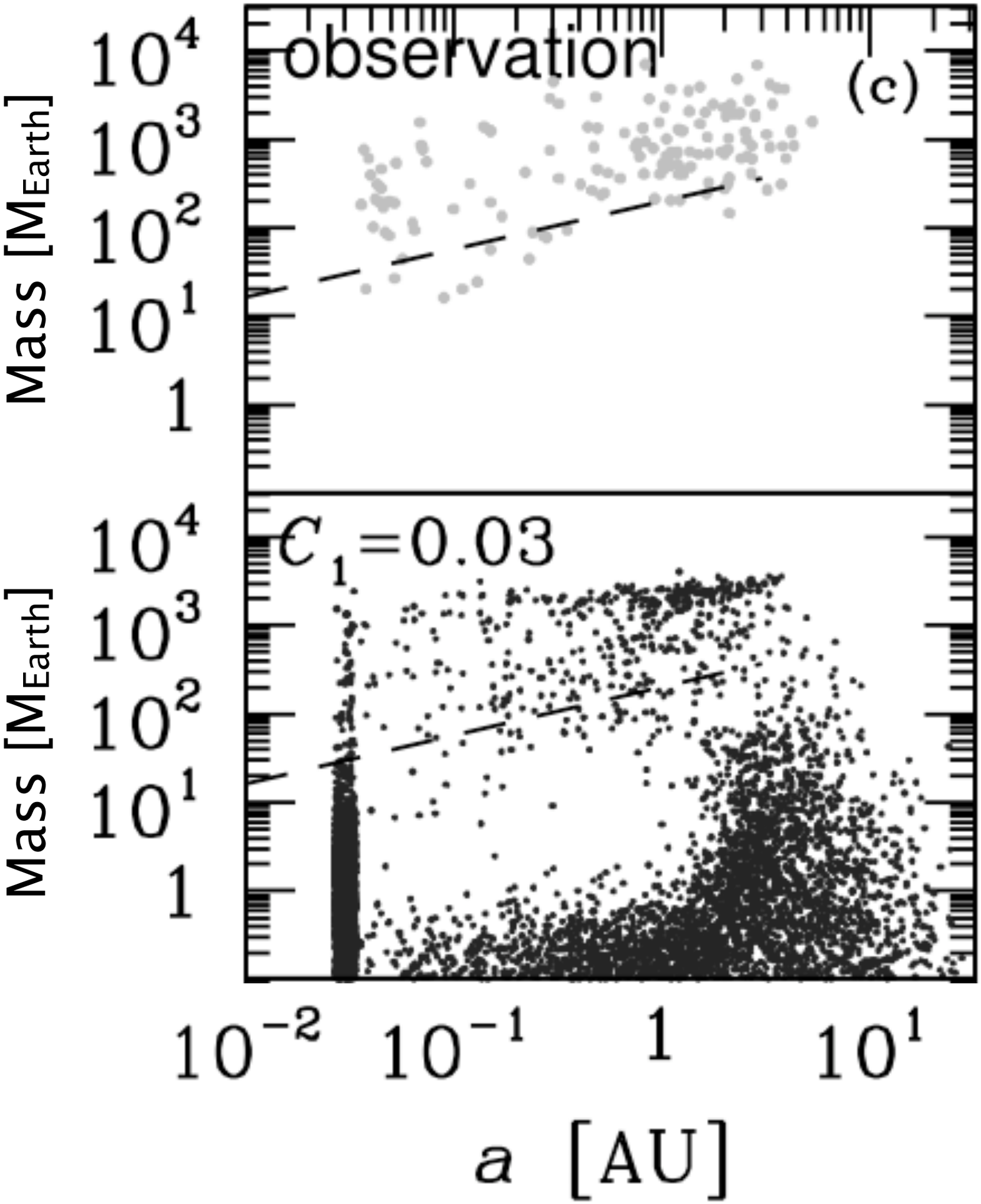
Population Synthesis Models of Core Accretion

simulate planet formation → predict M-a distribution





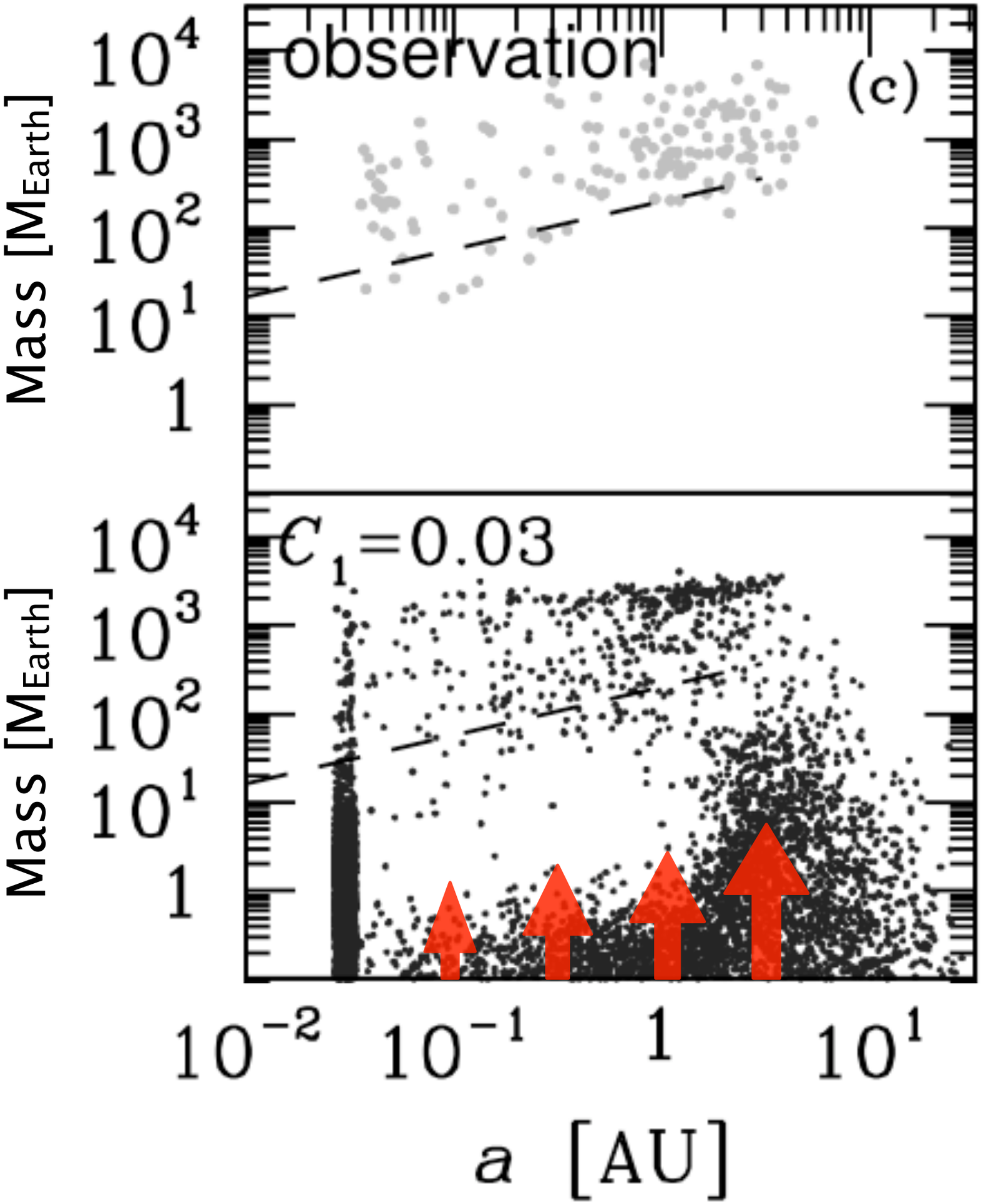
Slide from S. Ida



RV Observations

Ida/Lin Theory

Ida & Lin 2008, ApJ, 685, 584



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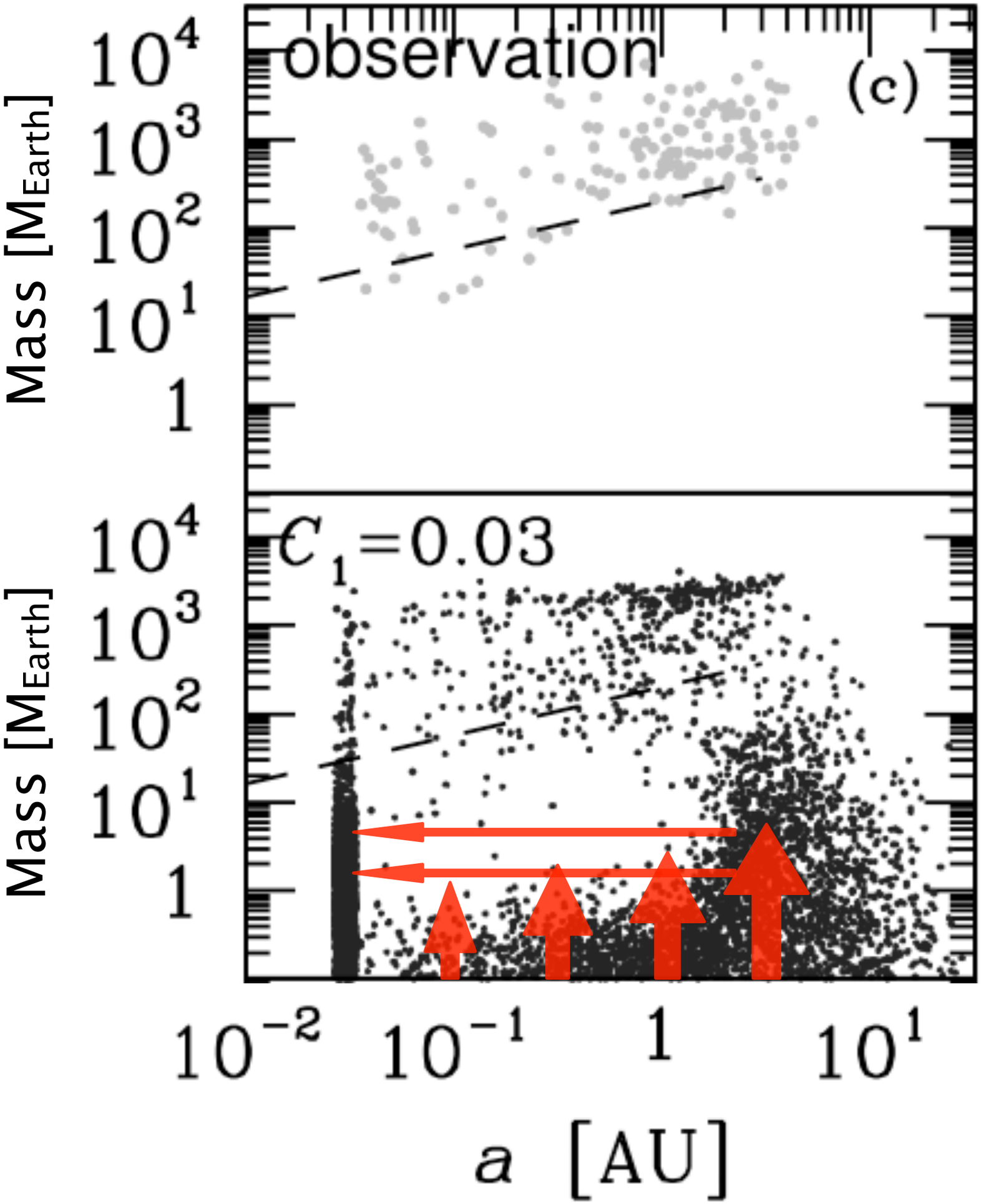

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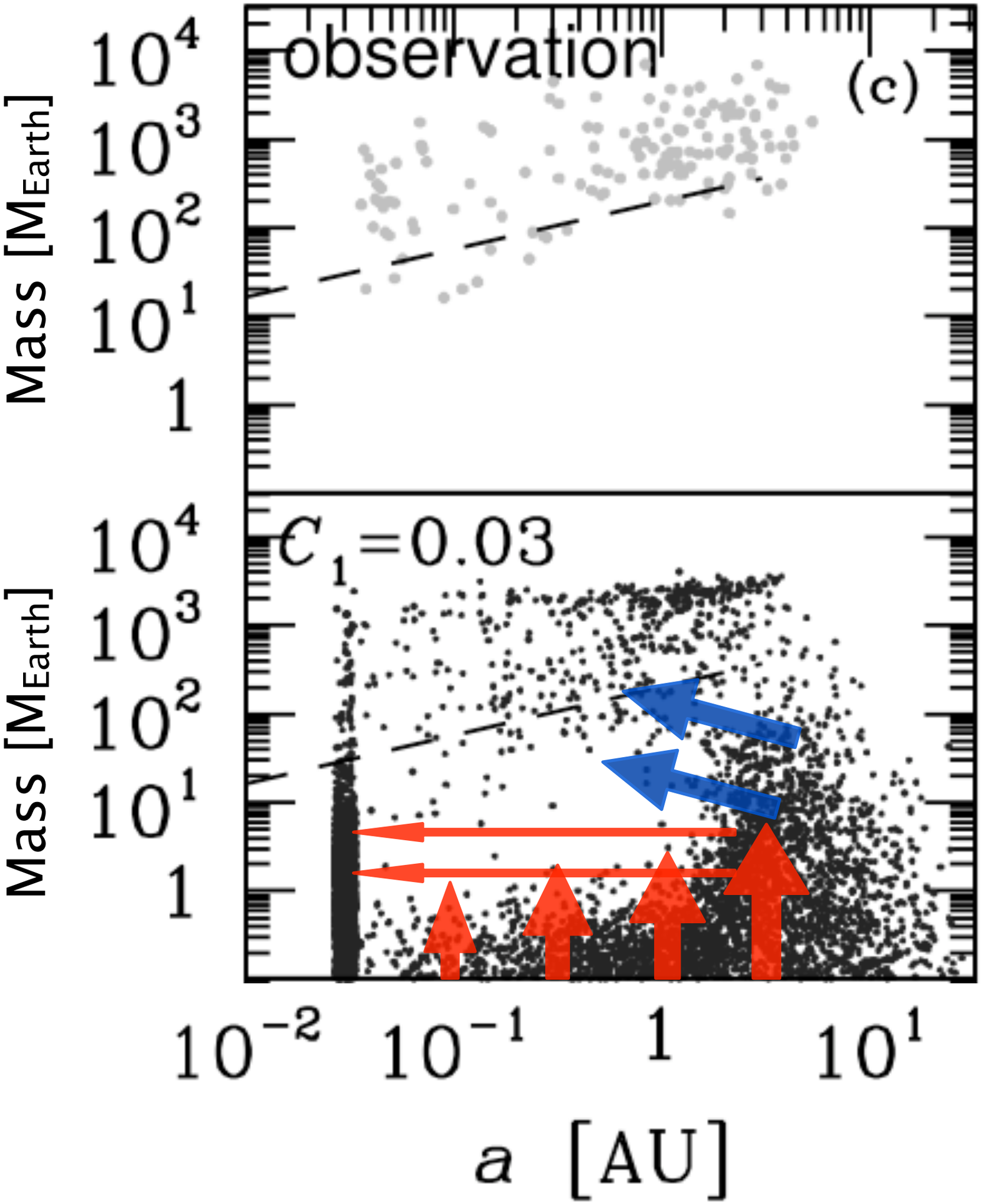

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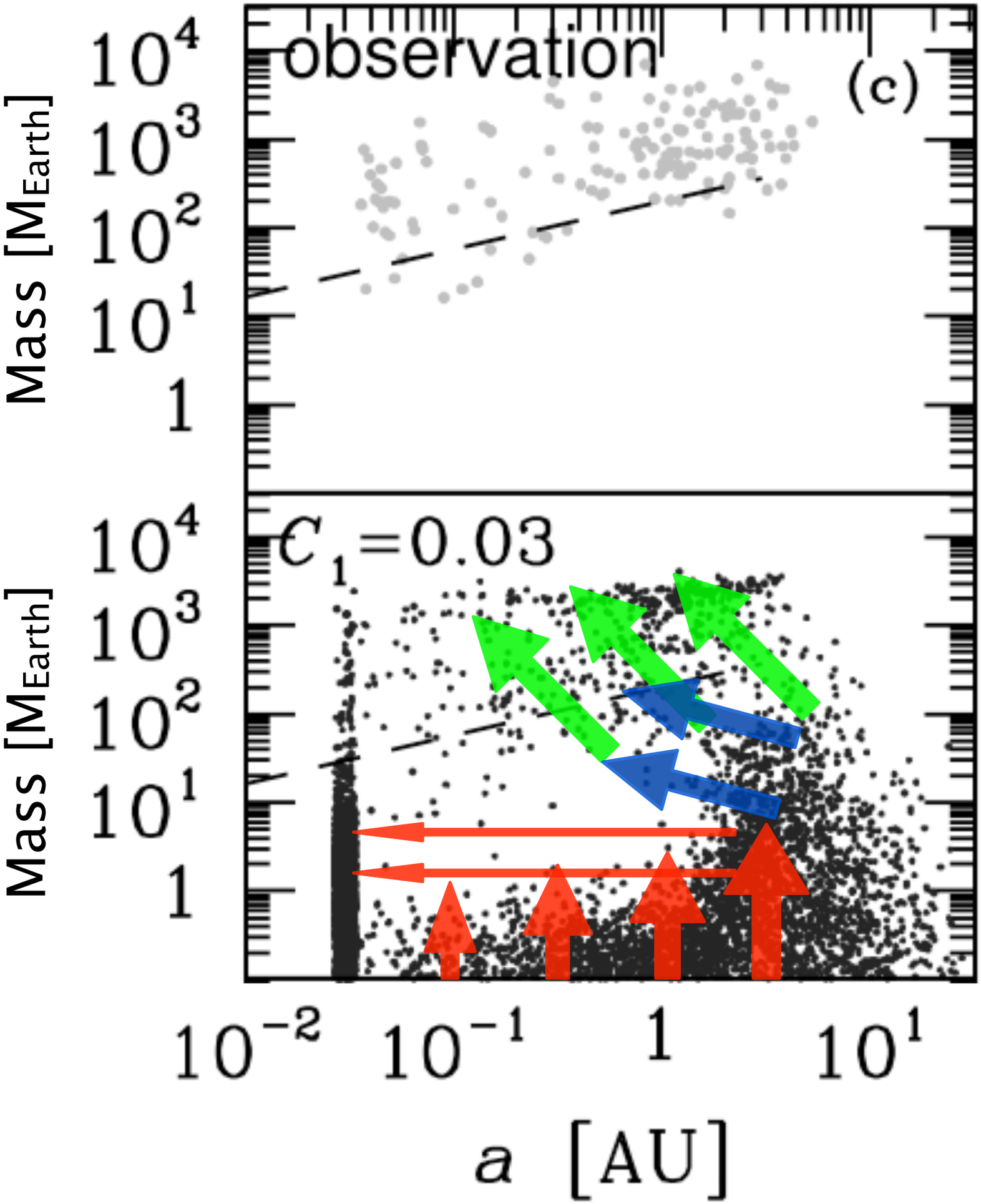

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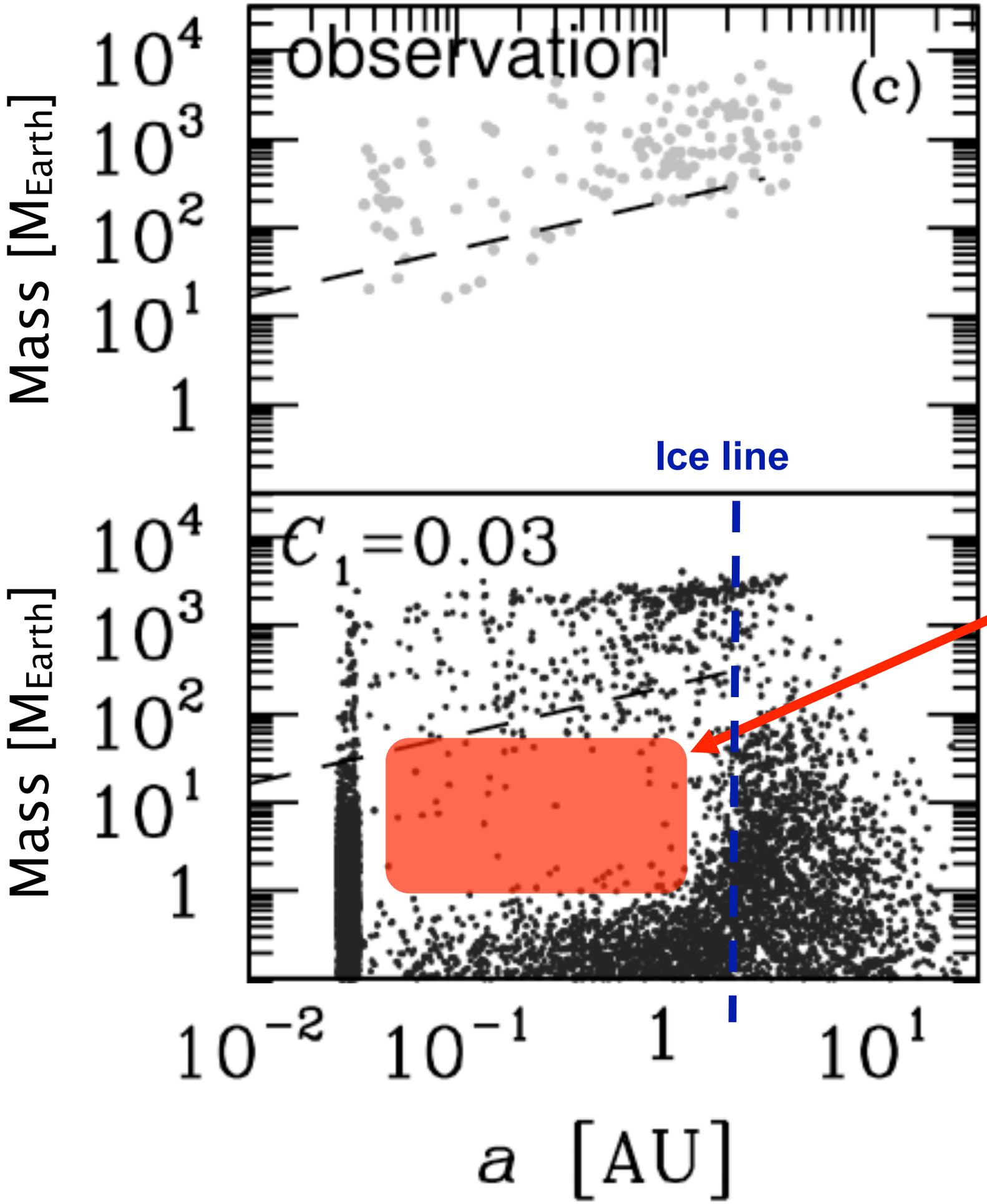

RV Observations

Planet Desert:
a = 0.05 - 1.0 AU
M = 1 - 30 M_{Earth}

Ida/Lin Theory

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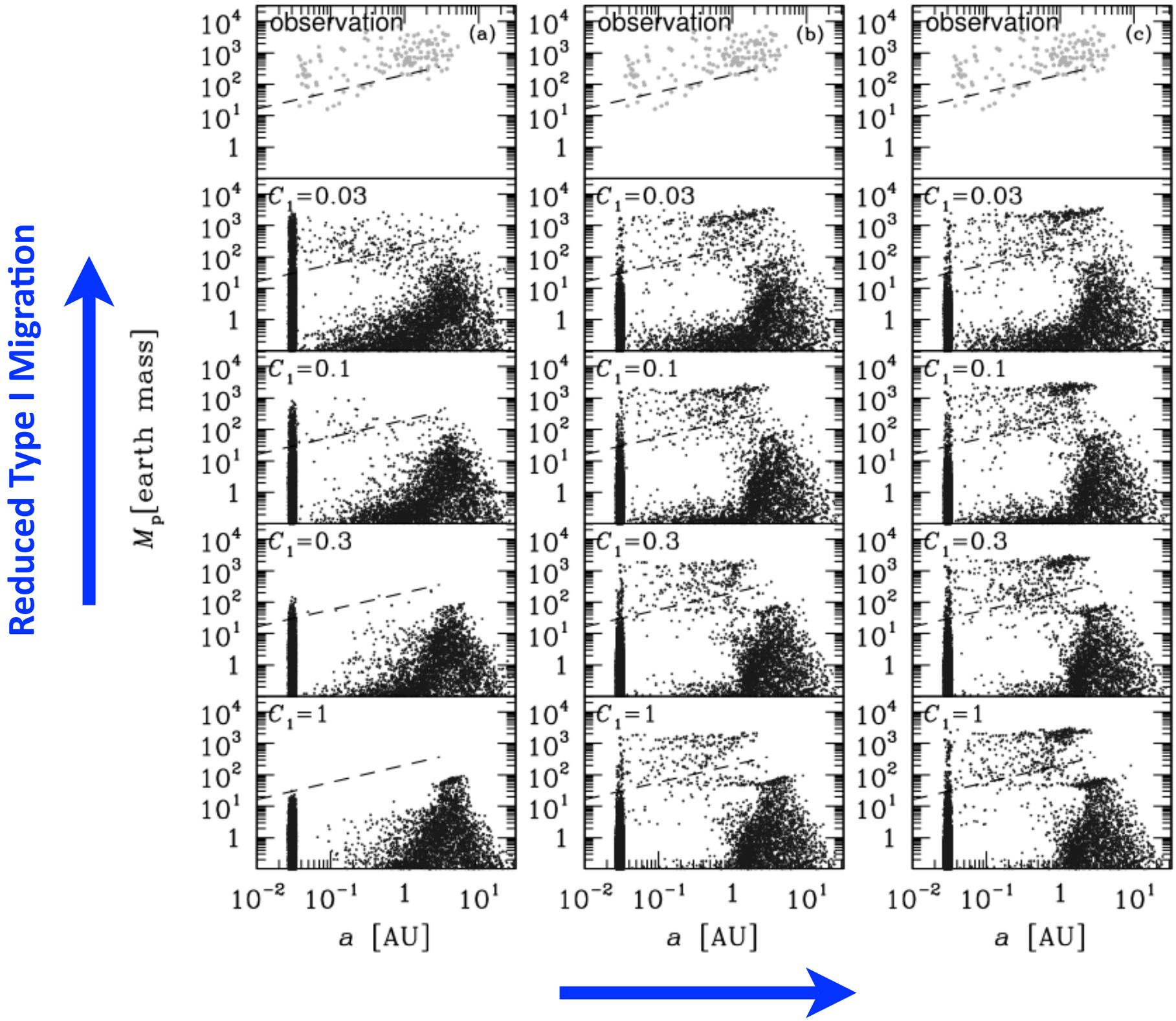
Parameter Adjustments - Pop. Synth. Models



Pop. Synth. Model Knobs:

- Type I & II migration efficiency
- dust-to-gas ratio
- density "bumps" near ice line
- ...

Ida & Lin 2008, ApJ, 685, 584

Mordasini, Alibert, & Benz (2009)

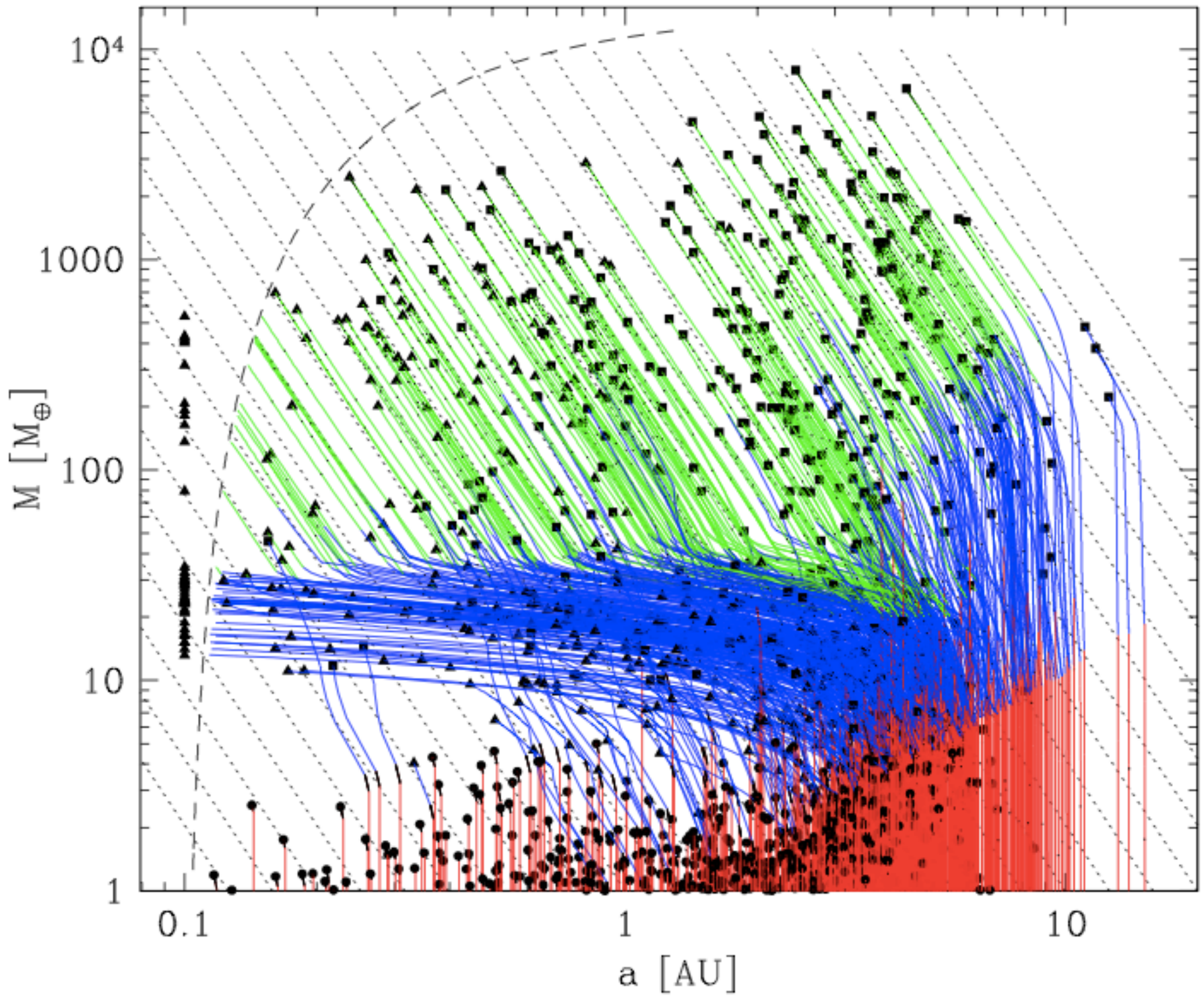
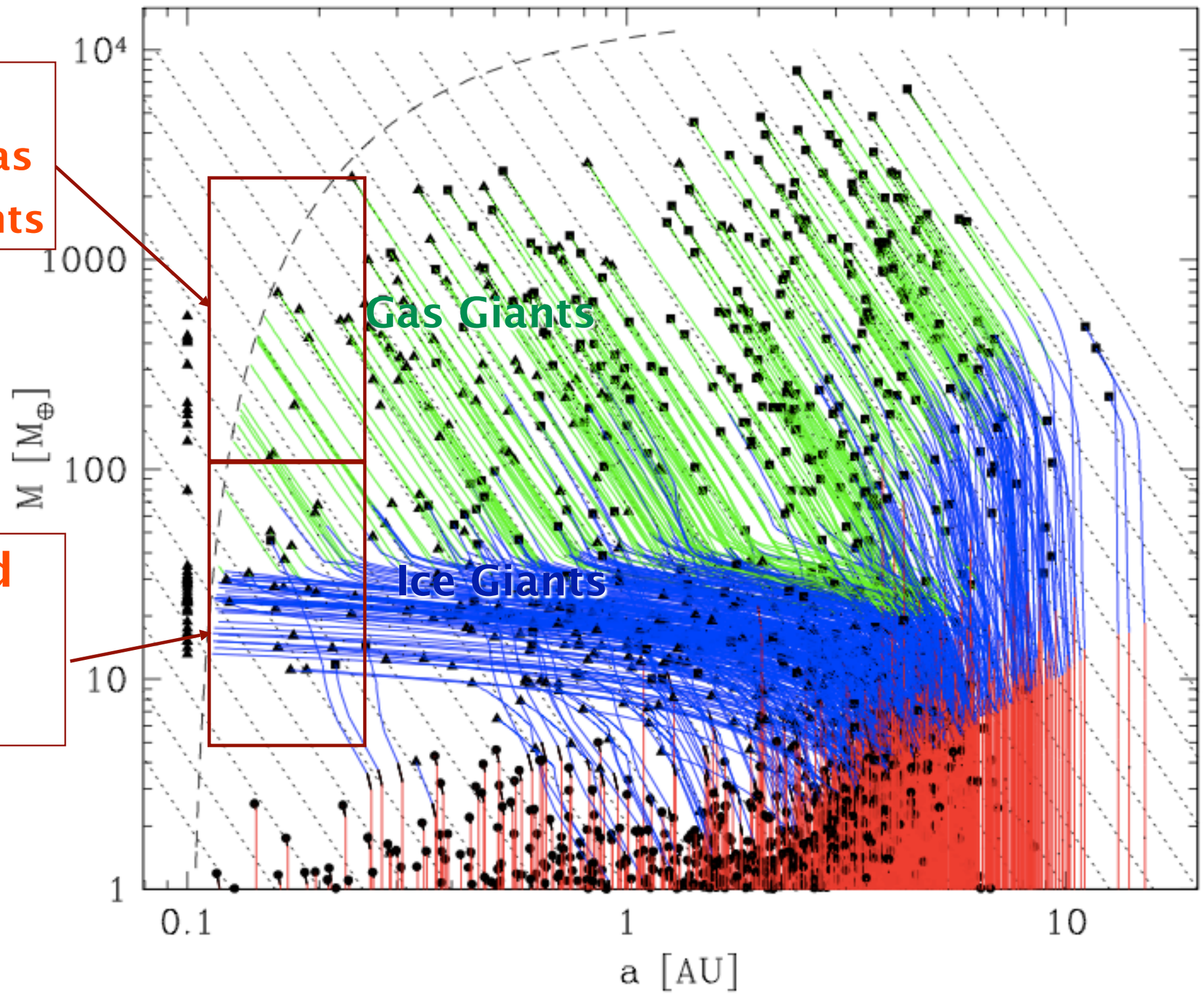


Fig. 8. Planetary formation tracks in the mass-distance plane. The large black symbols show the final position of a planet. The shape of the symbols is explained in the text. Planets reaching the feeding limit at $a_{\rm touch}$ (indicated by the long dashed line) have arbitrarily been set to 0.1 AU. The short dashed lines have a slope of $-\pi$ (discussion in §5.1.3). Each track is color-coded according to the migration mode, and small black dots are plotted on the tracks all 0.2 Myr to indicate the temporal evolution of a planet.

Mordasini, Alibert, & Benz (2009)

Compare Freq. of Gas to Ice Giants

Predicted Gradient In Mass.



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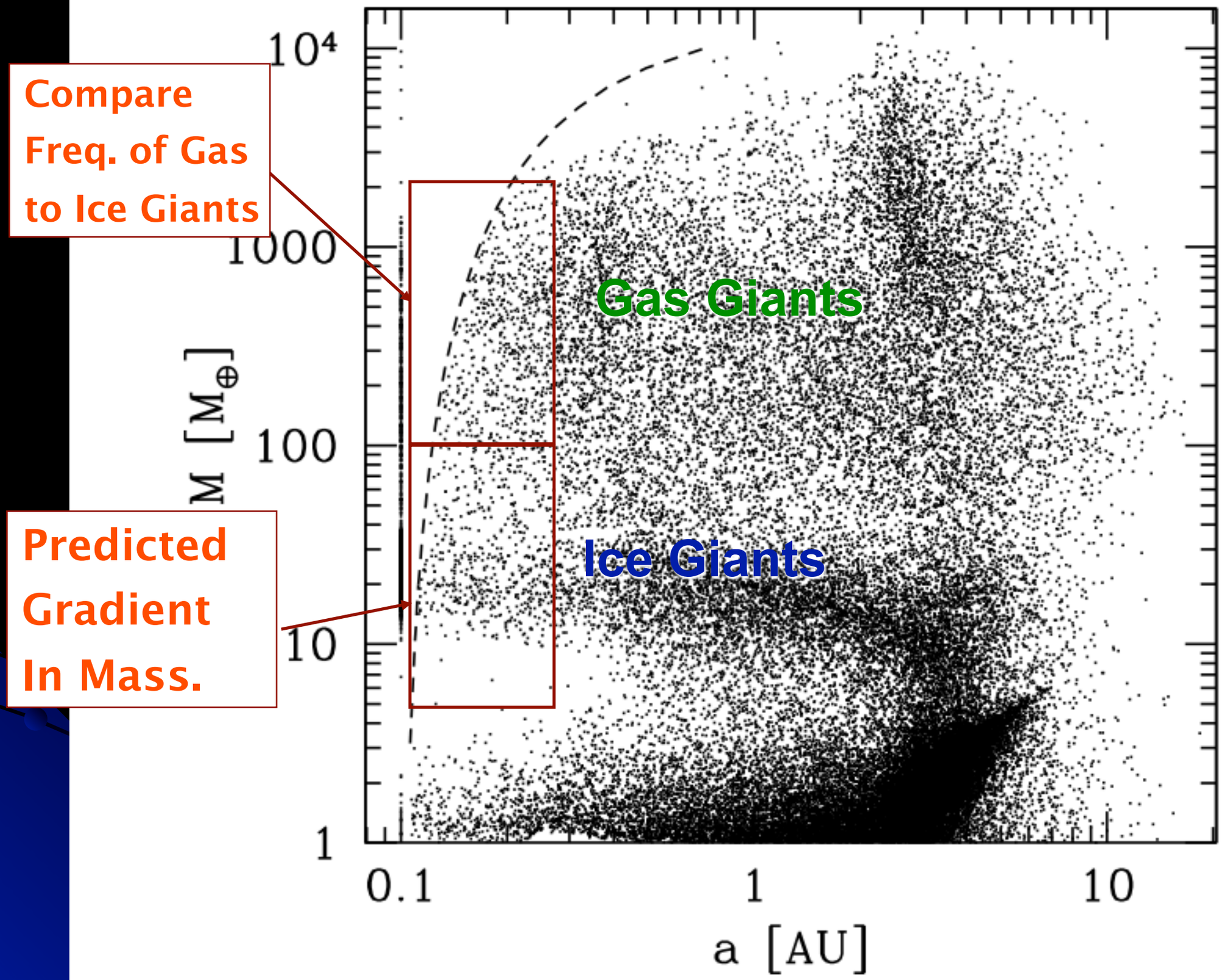
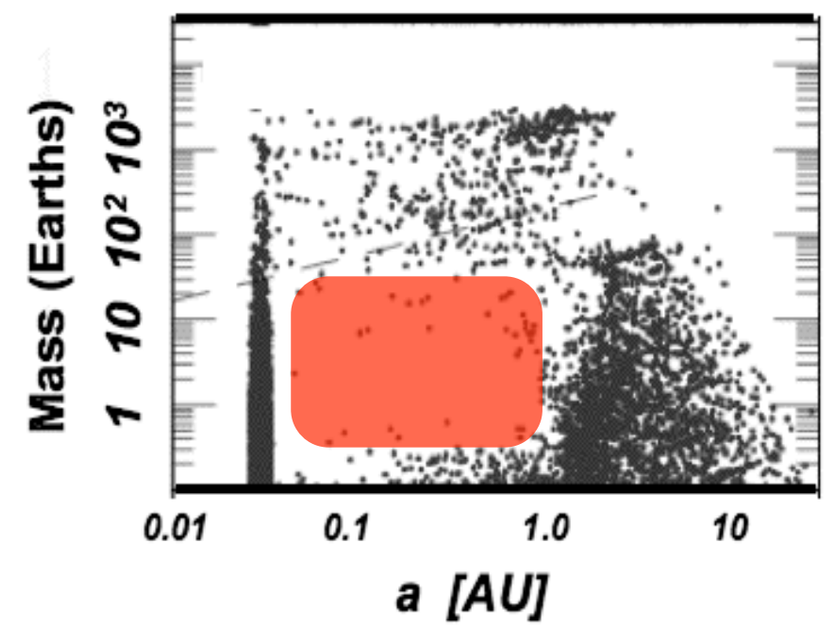


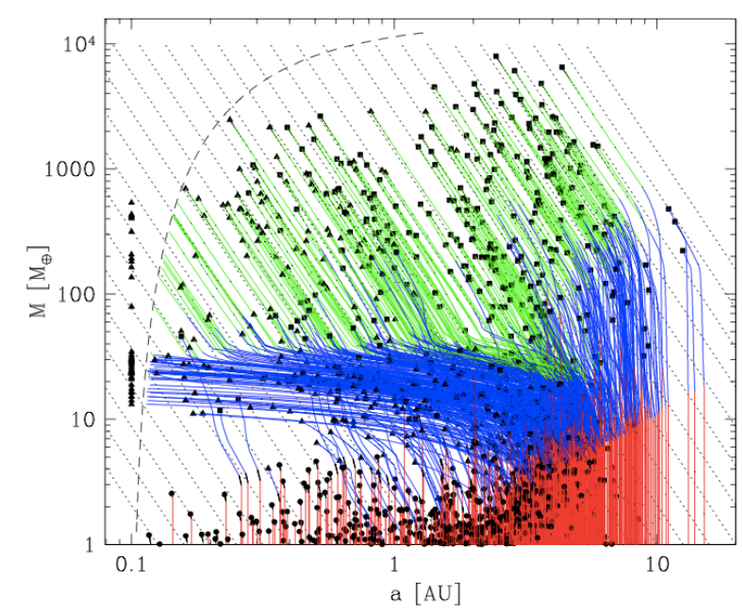
Fig. 13. Final mass M versus final distance a of $N_{\rm synt} \approx 50\,000$ synthetic planets of the nominal planetary population. The feeding limit at $a_{\rm touch}$ is plotted as dashed line. Planets migrating into the feeding limit have been put to 0.1 AU. As $a_{\rm touch}$ gets very large for $M \gtrsim 20 M_{♃}$, also a few extremely massive planets are in the feeding limit which should however be regarded as a simulation artifact because our simplification of putting planets that reach the feeding limit to 0.1 AU ceases to be justified.

Occurrence of Planets within 0.25 AU?

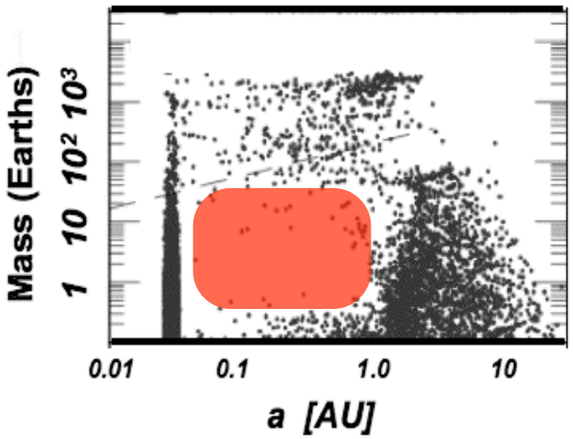
Accessible Domain of Planet-Formation Theory from 3-1000 M_{Earth}



Theory predicts few 1-20 M_{Earth} planets in short-period orbits



Geneva group reports 30% or 50% of GK stars have rocky or Neptune planets inward of 50-day orbits



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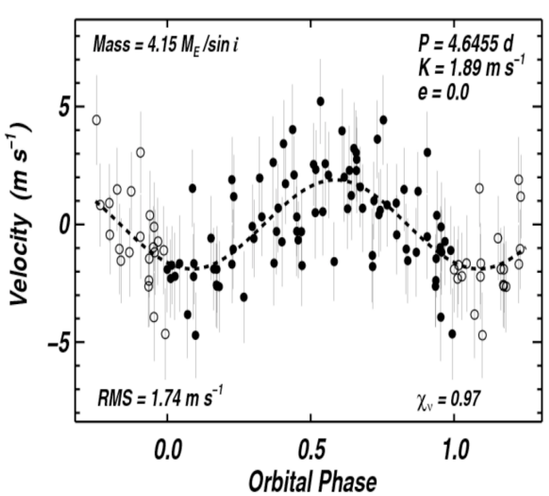
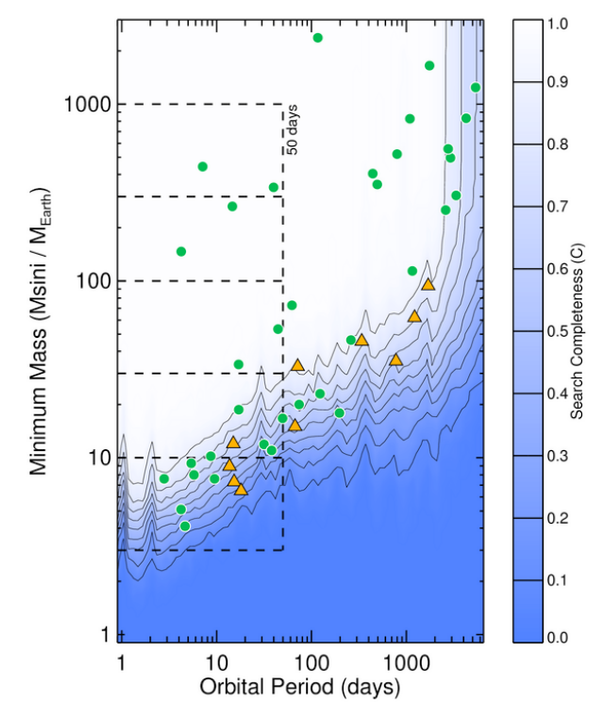


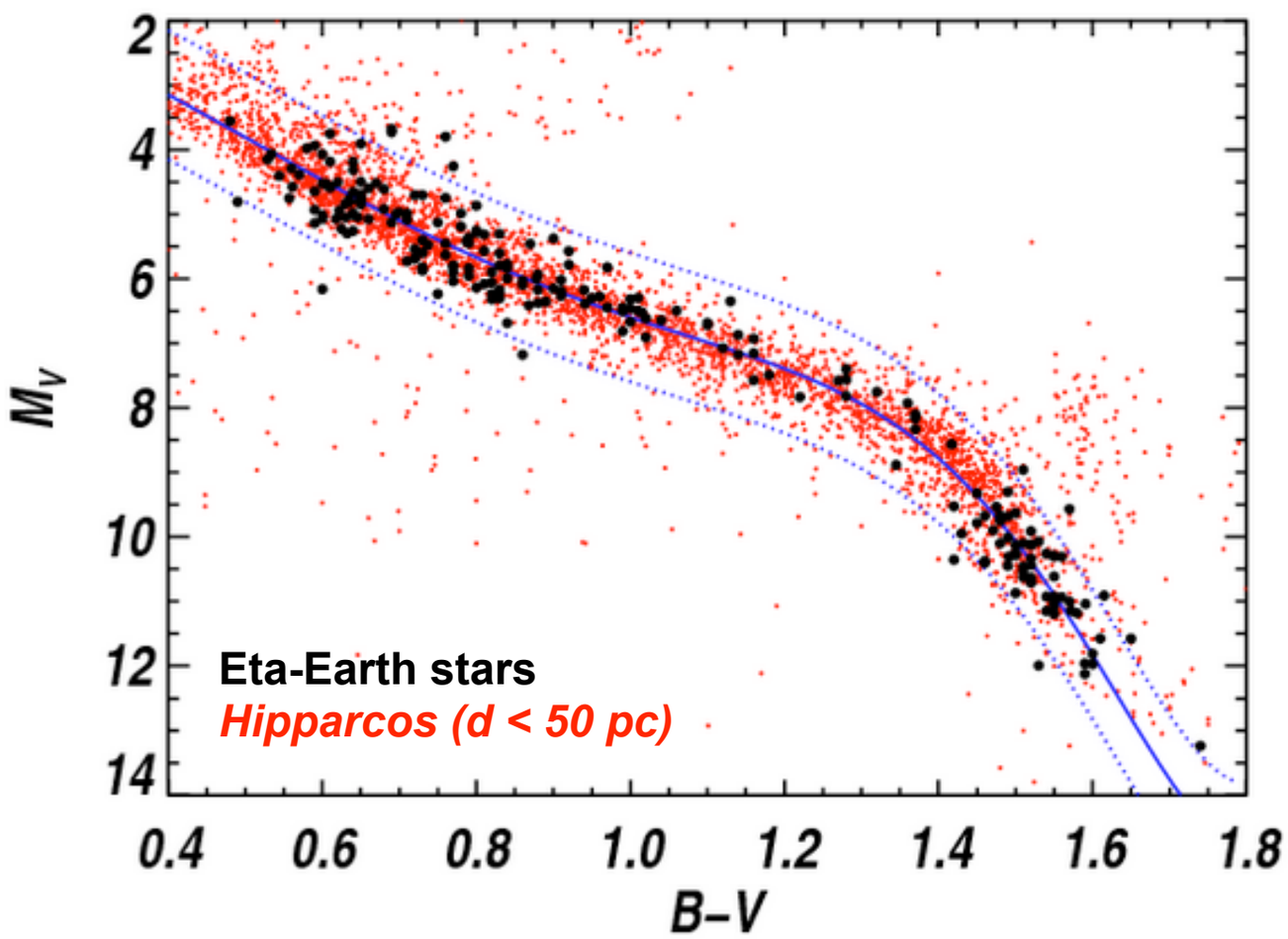


NASA-UC Eta-Earth Program

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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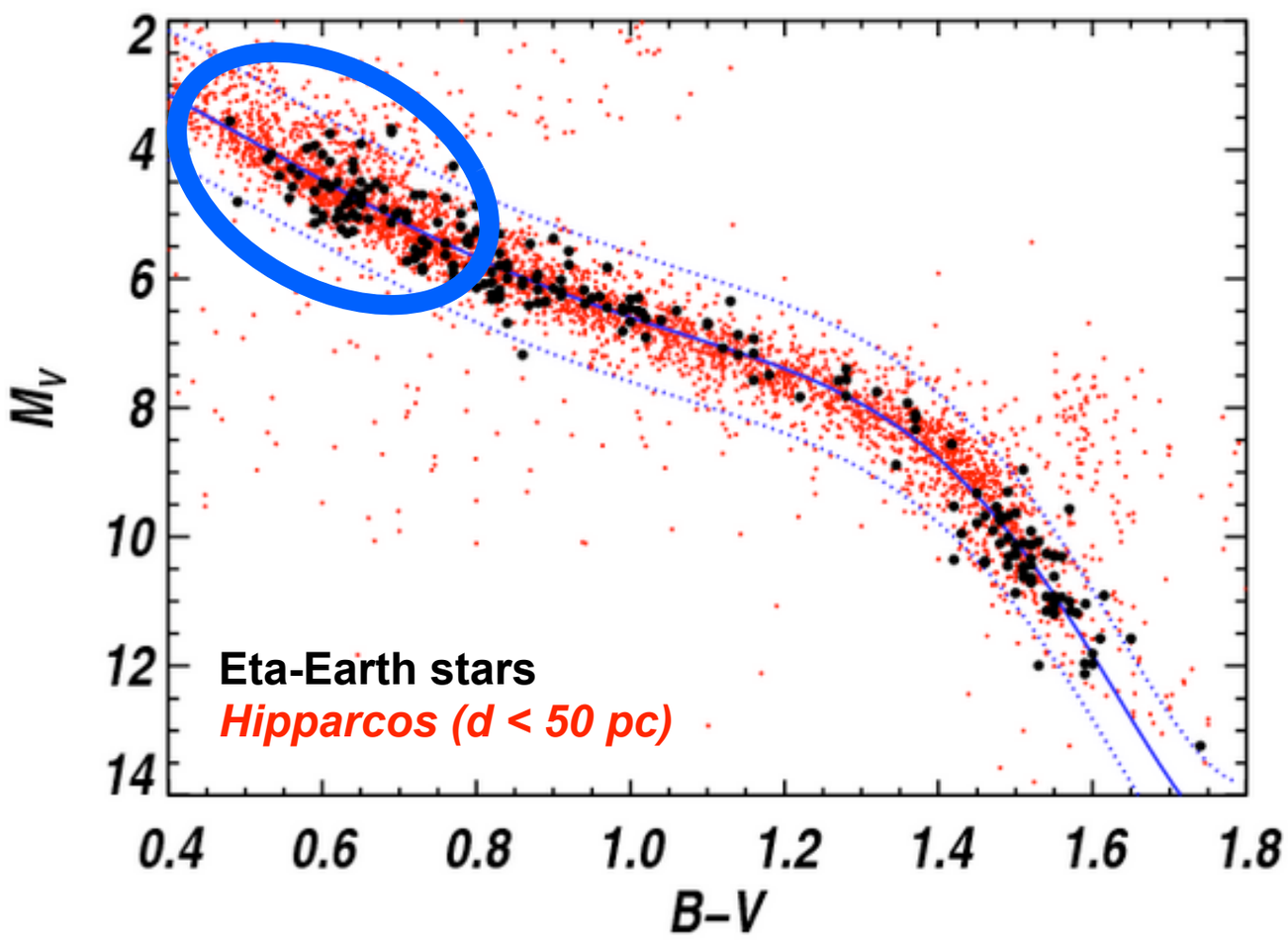

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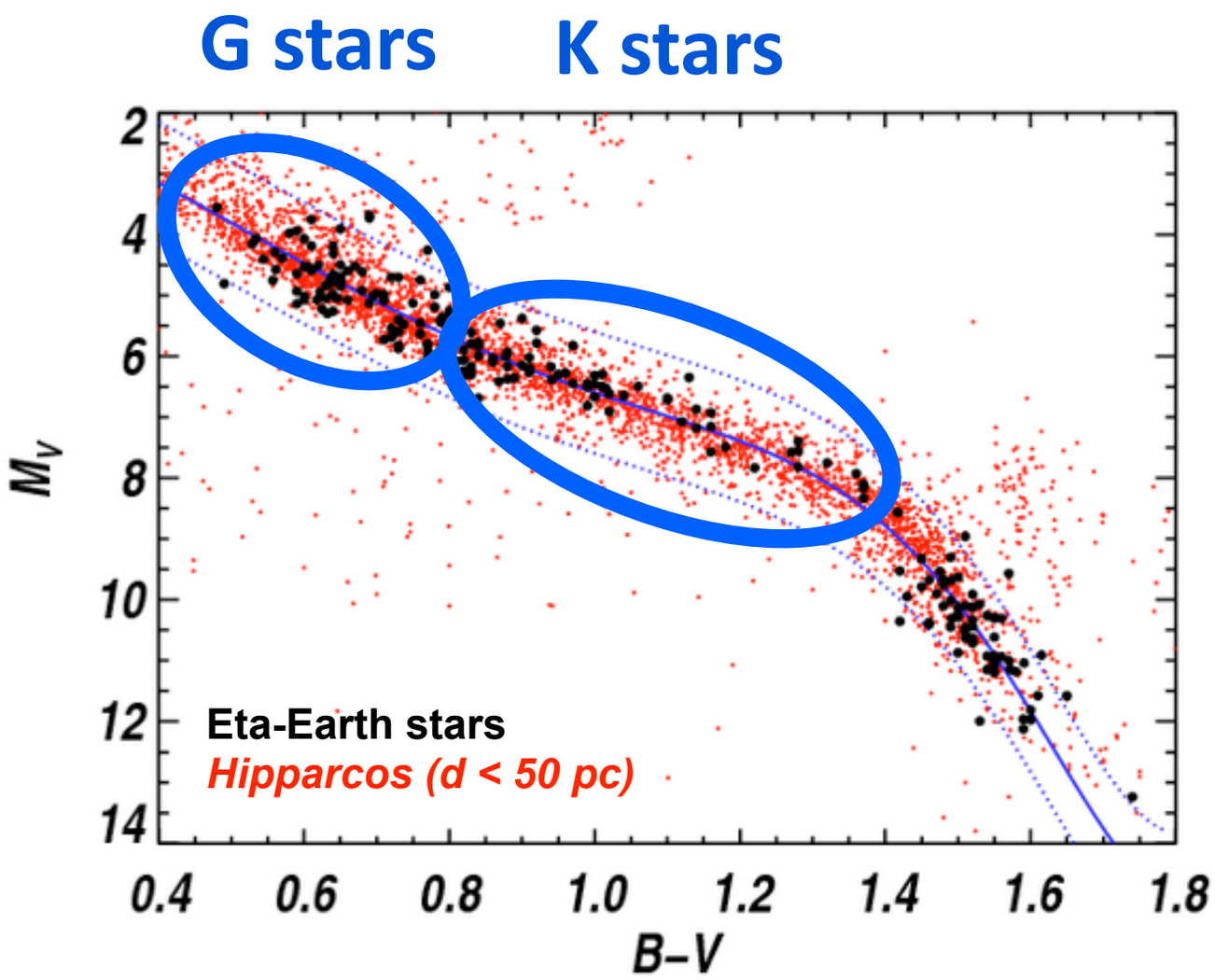

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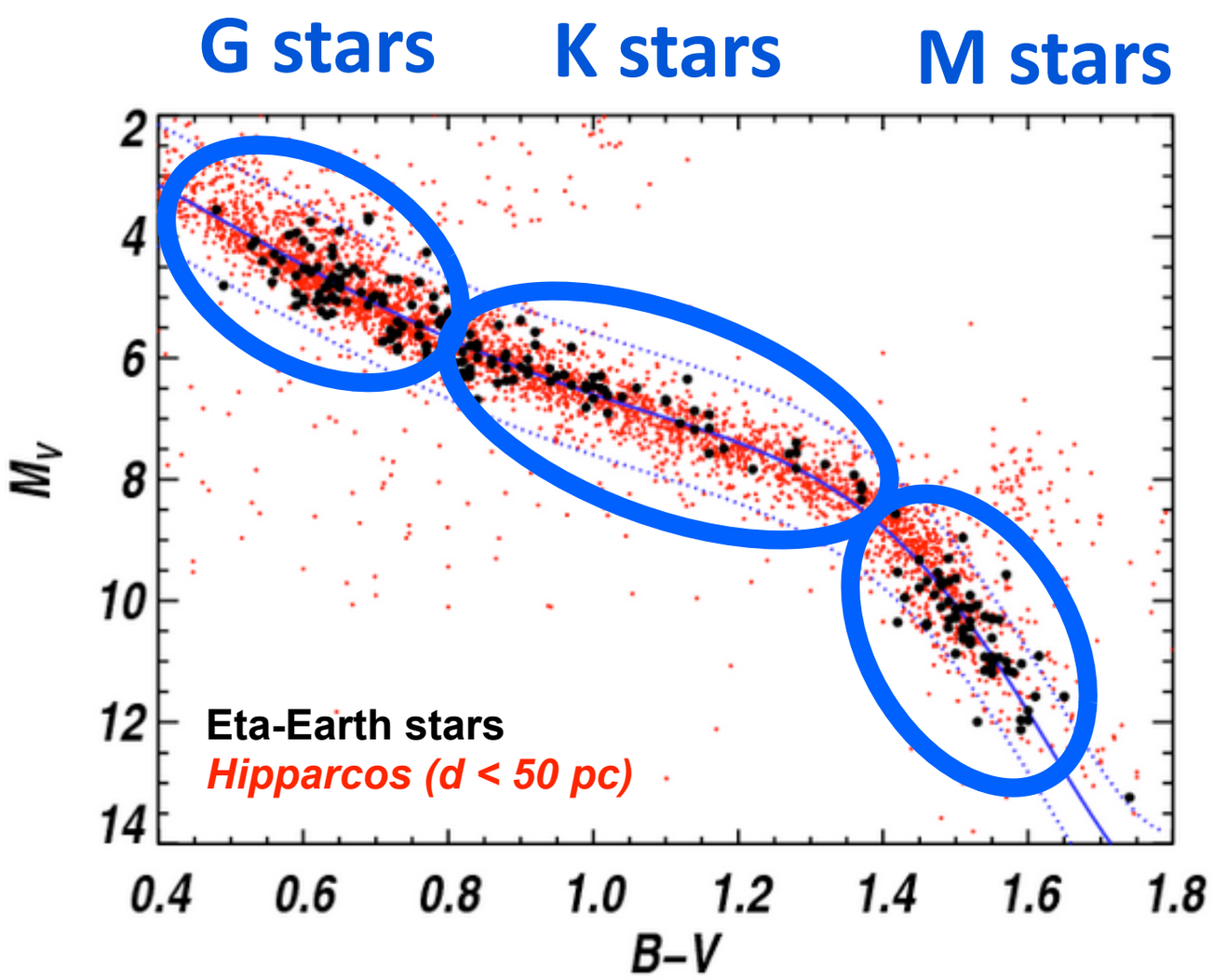

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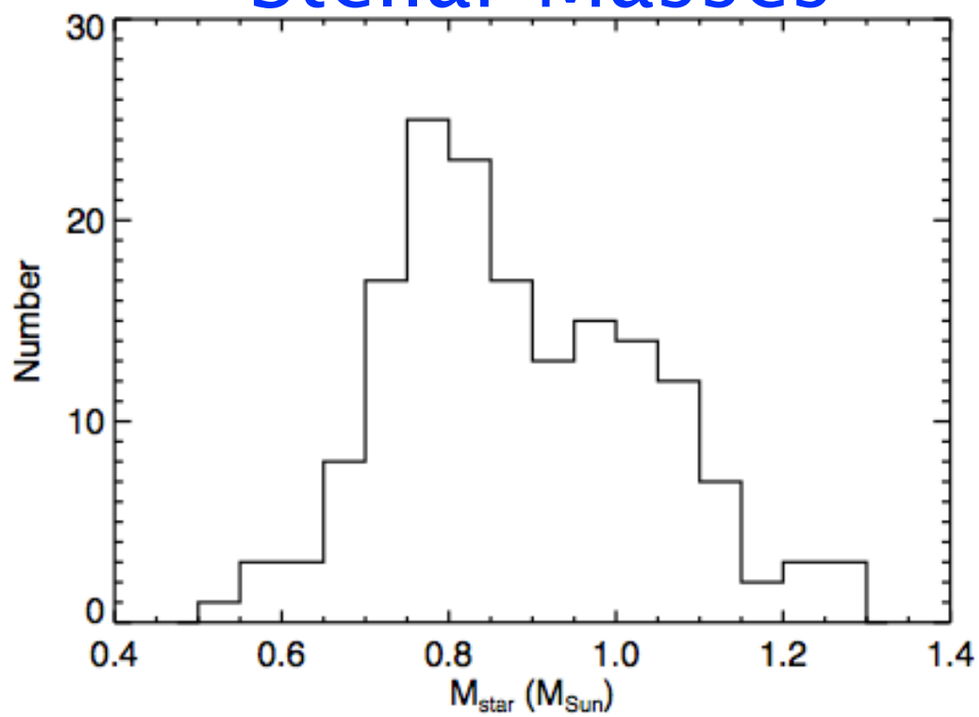
Stellar Masses



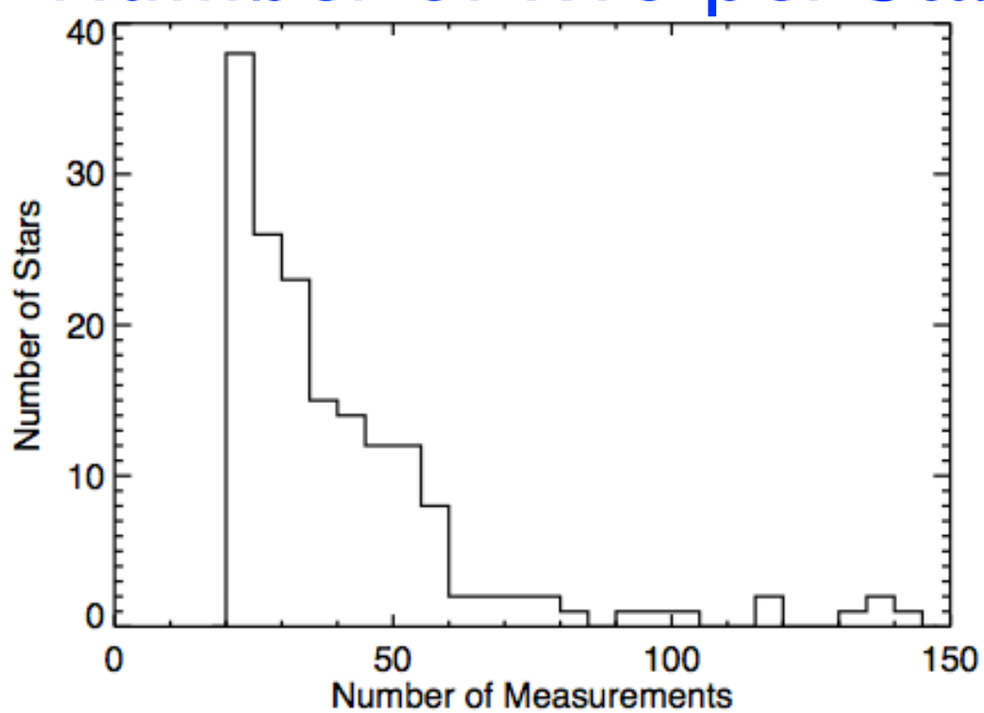
Histogram of stellar masses for Eta-Earth stars.

G & K Main Sequence:

All have parallaxes &

Stellar evolution Tracks

Number of RVs per Star



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

Median: 35 Keck RVs per star

All have high cadence run during 10 Keck nights

166 GK Target 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

Table S1—Continued

Name	Spec. Type	Mass ($M_\odot$)	Num. Obs.
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

Table S1—Continued

Name	Spec. Type	Mass ($M_\odot$)	Num. Obs.
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

Table S1—Continued

Name	Spec. Type	Mass ($M_\odot$)	Num. Obs.
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

Table S1—Continued

Name	Spec. Type	Mass ($M_\odot$)	Num. Obs.
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

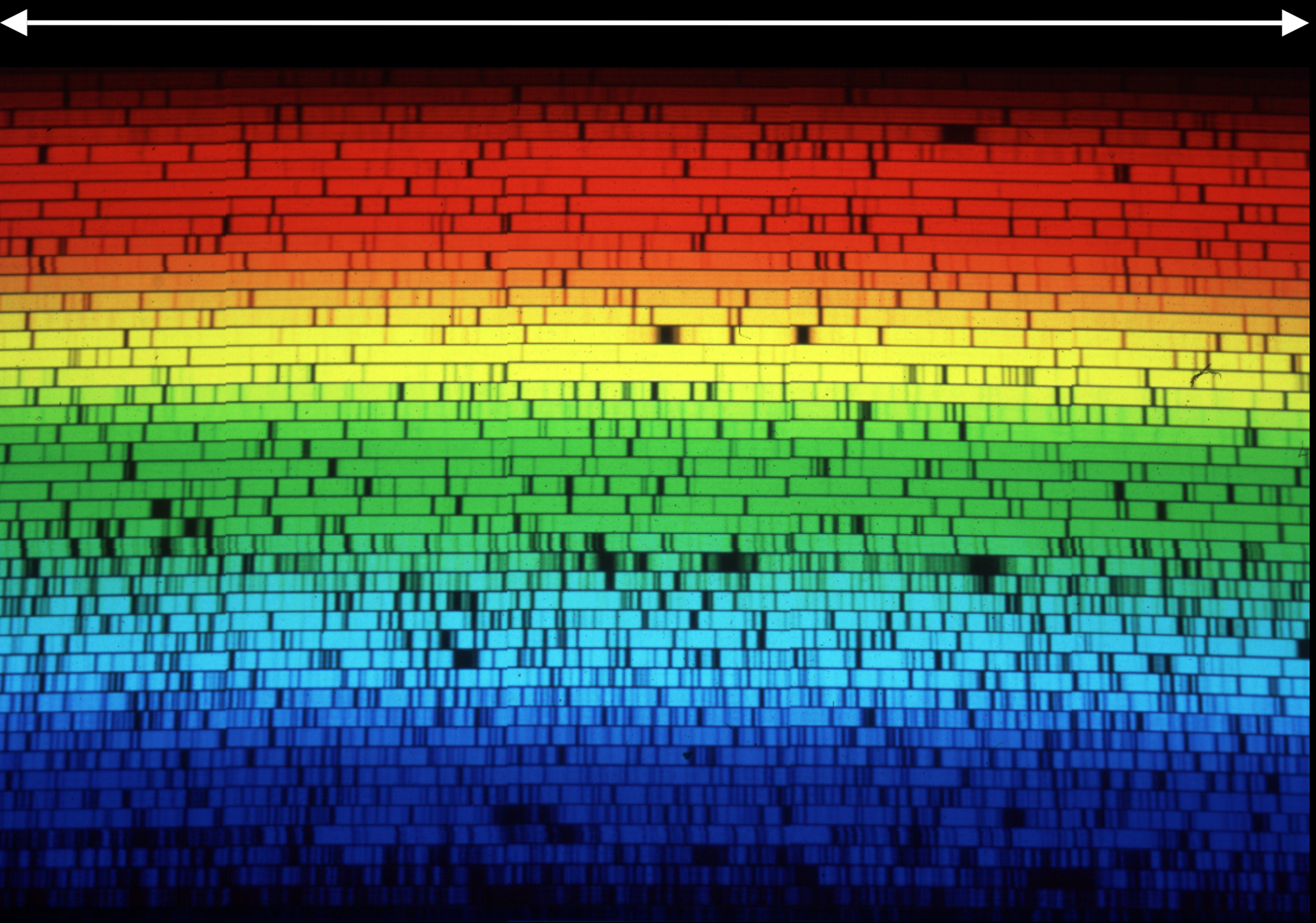
Table S1—Continued

Name	Spec. Type	Mass ($M_\odot$)	Num. Obs.
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

Iodine Absorption Cell

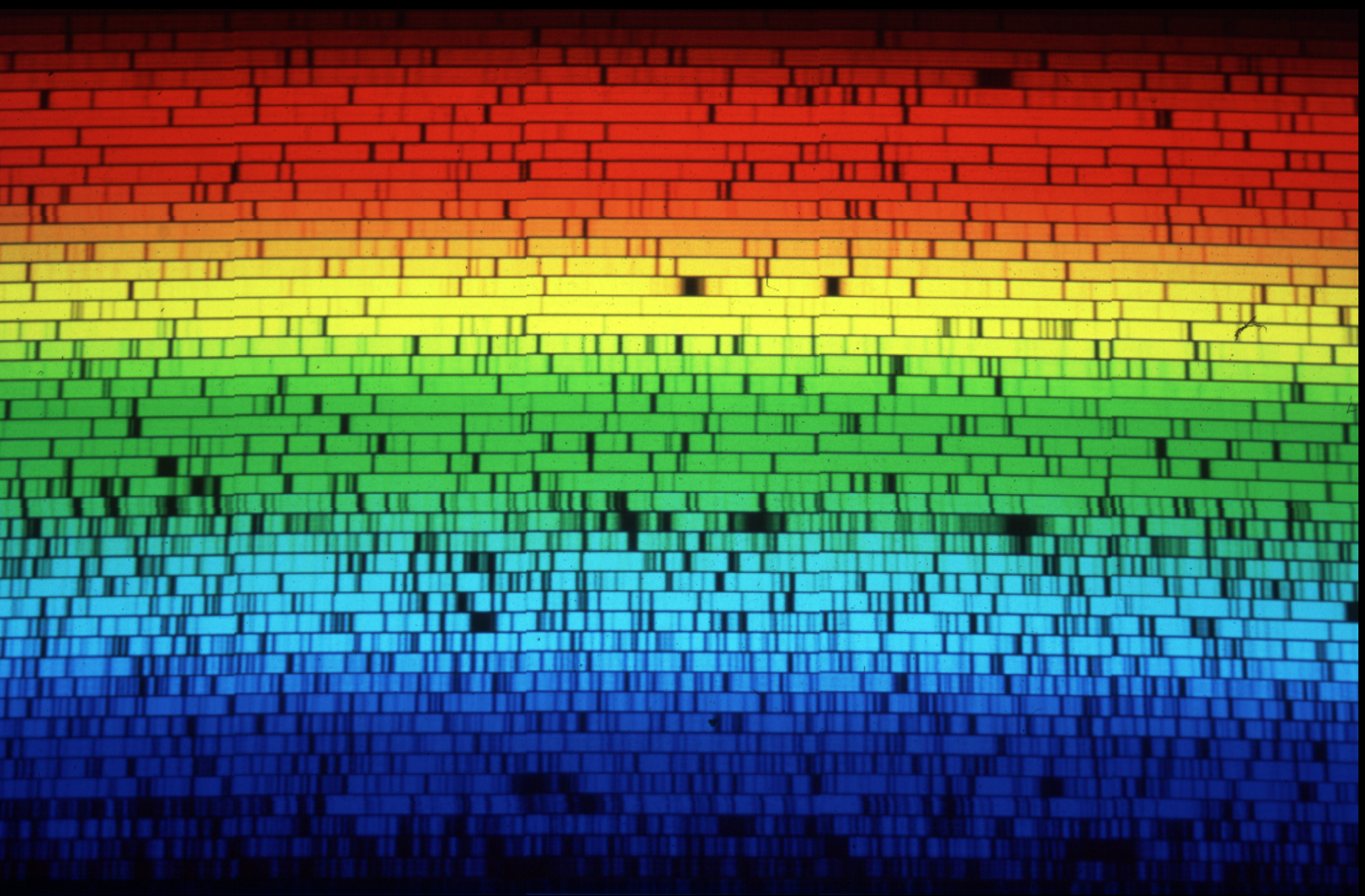
Stellar Spectrum: Echelle

4000 Pixels on CCD



Stellar Spectrum: Echelle

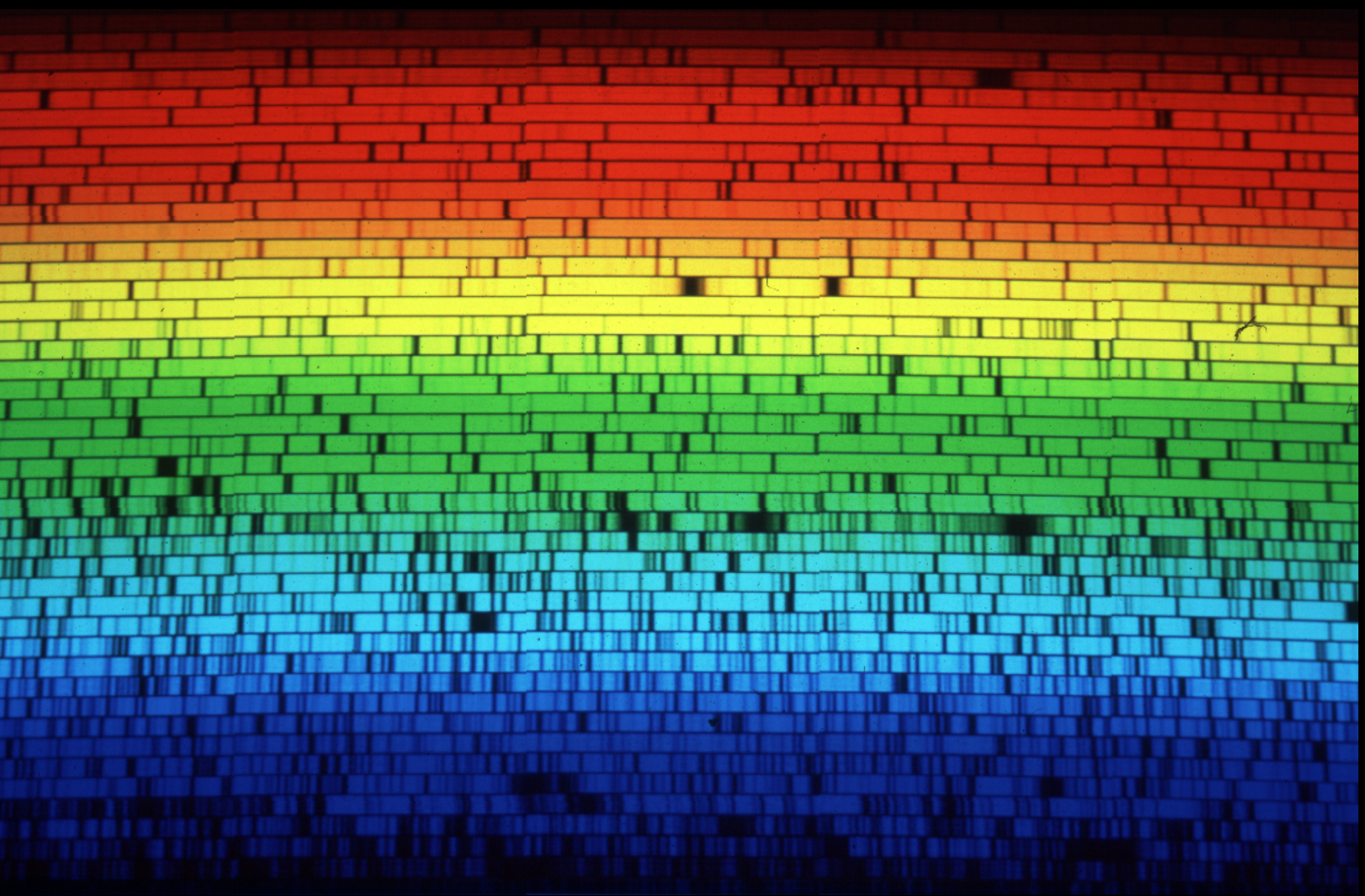
4000 Pixels on CCD



2 m/s ➔
0.001 pixel
(80 Si atoms)

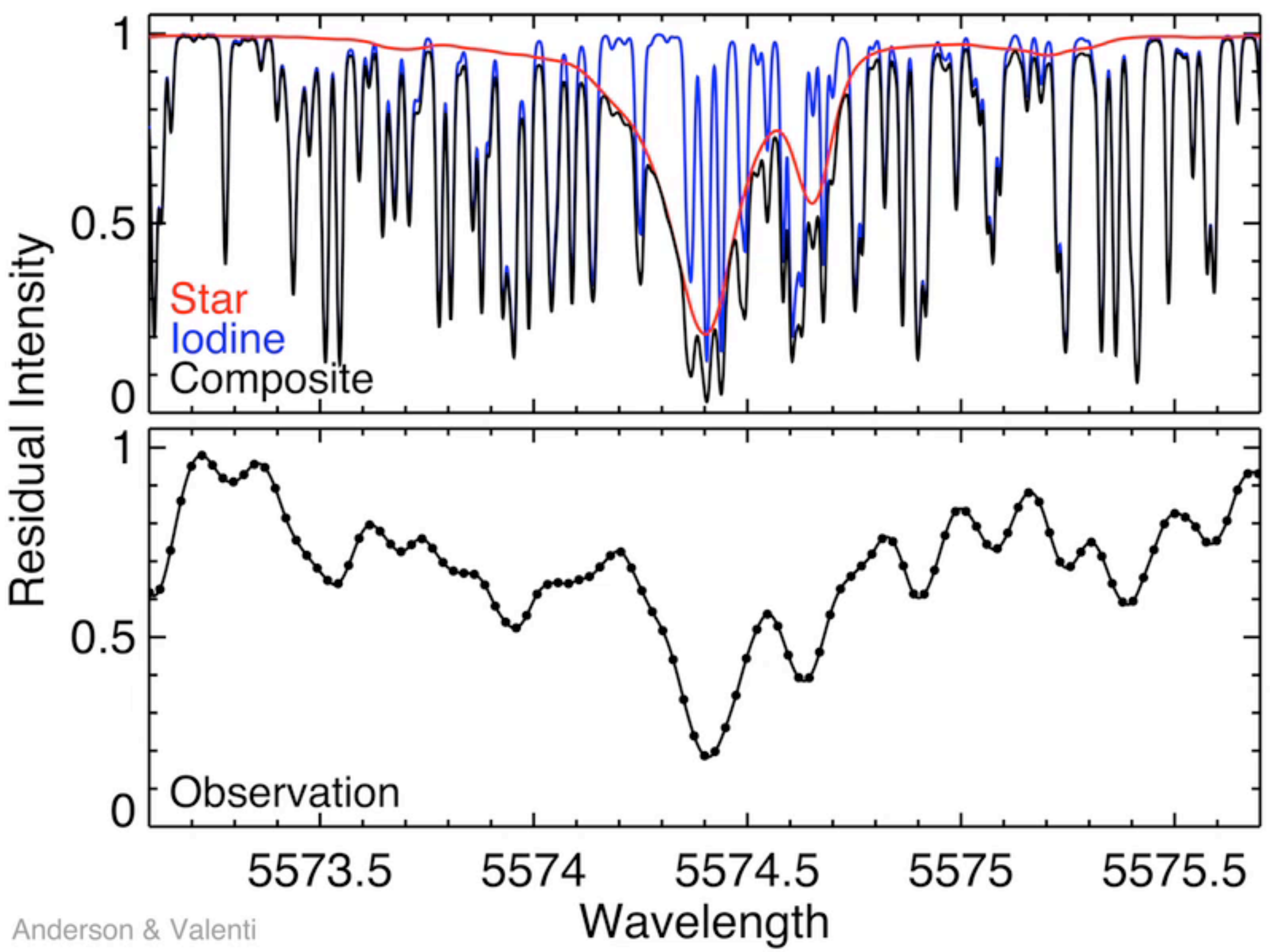
Stellar Spectrum: Echelle

4000 Pixels on CCD

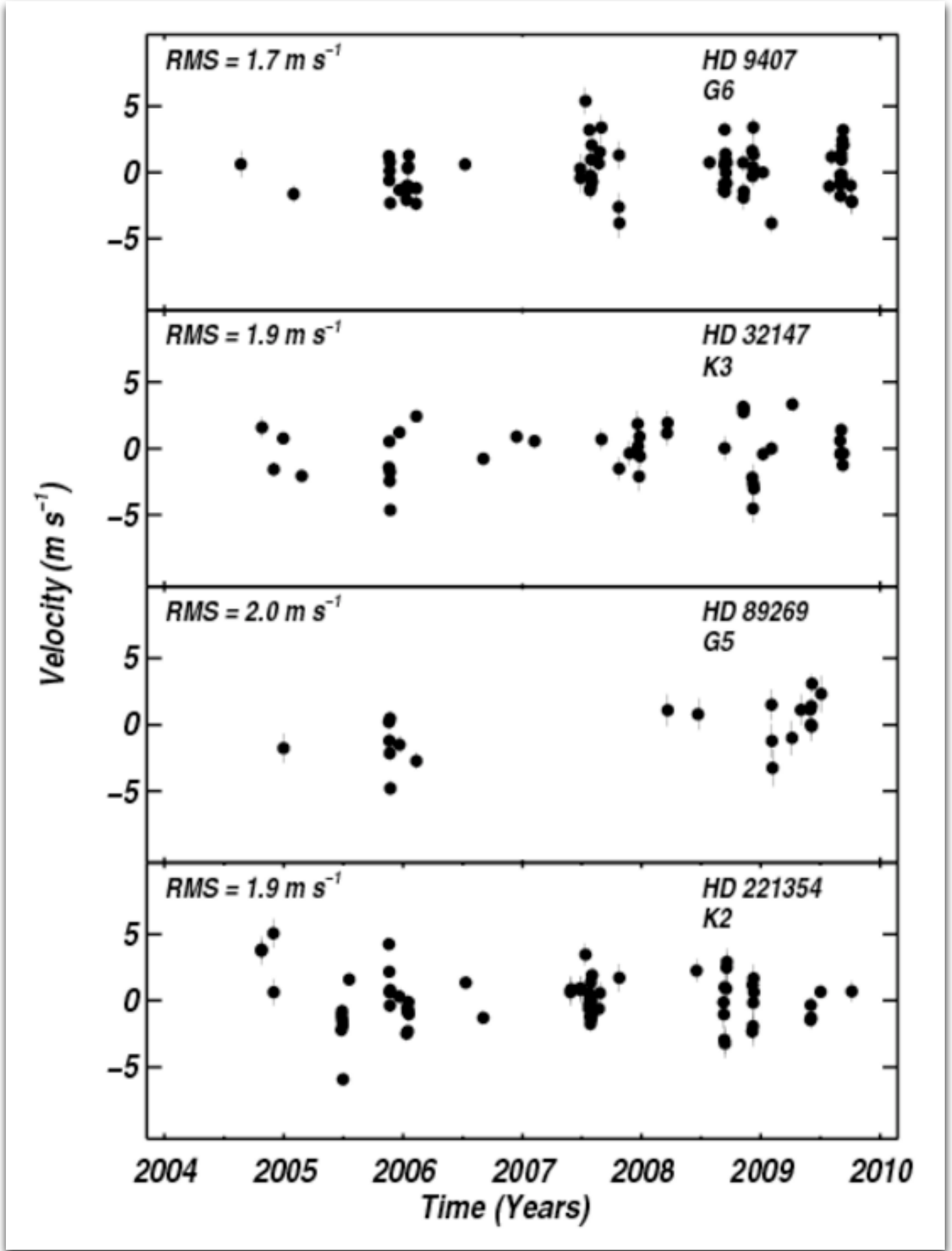


2 m/s ➔
0.001 pixel
(80 Si atoms)

λ Calib:
8 sig. fig.
(v/c).



Anderson & Valenti

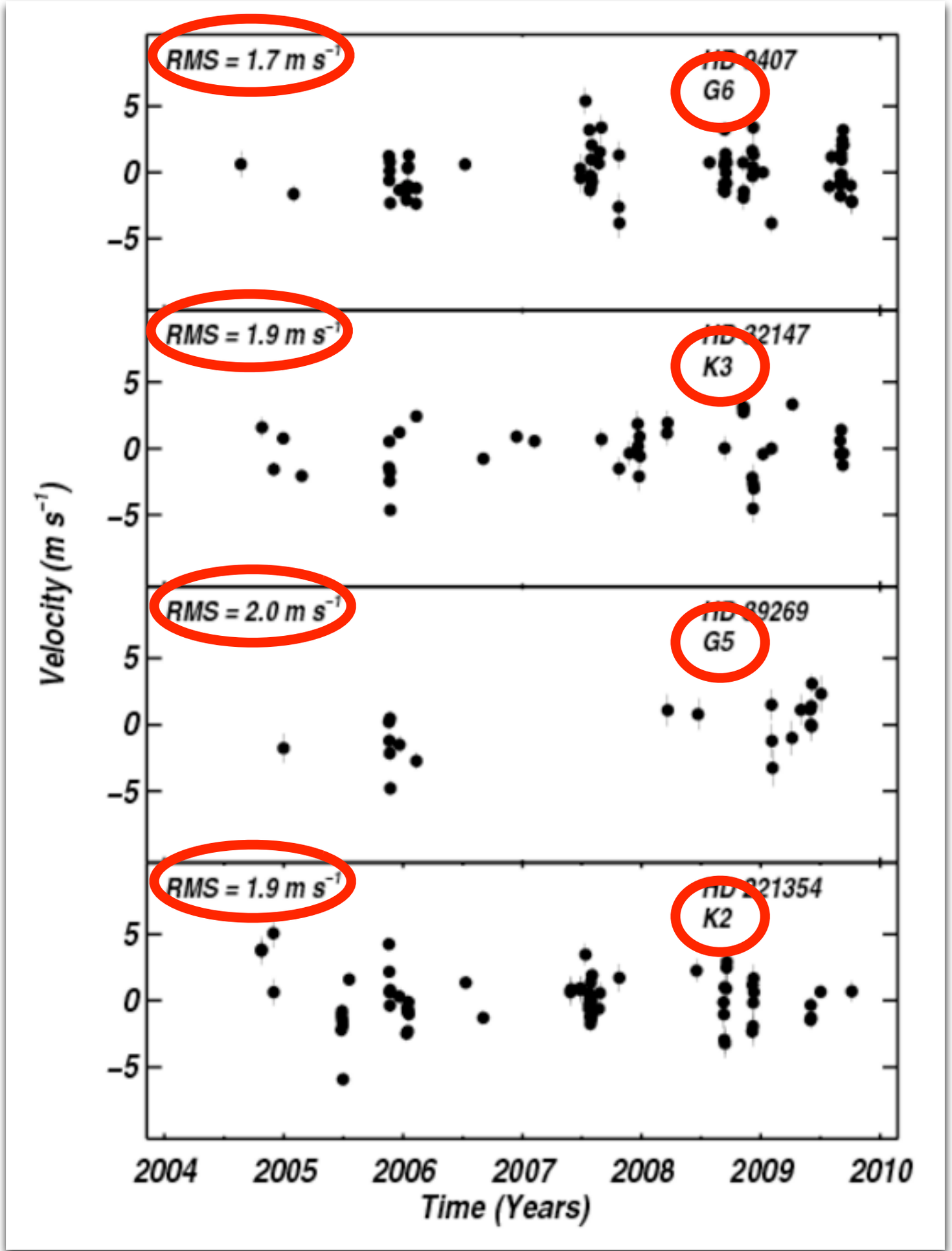


Standard Stars

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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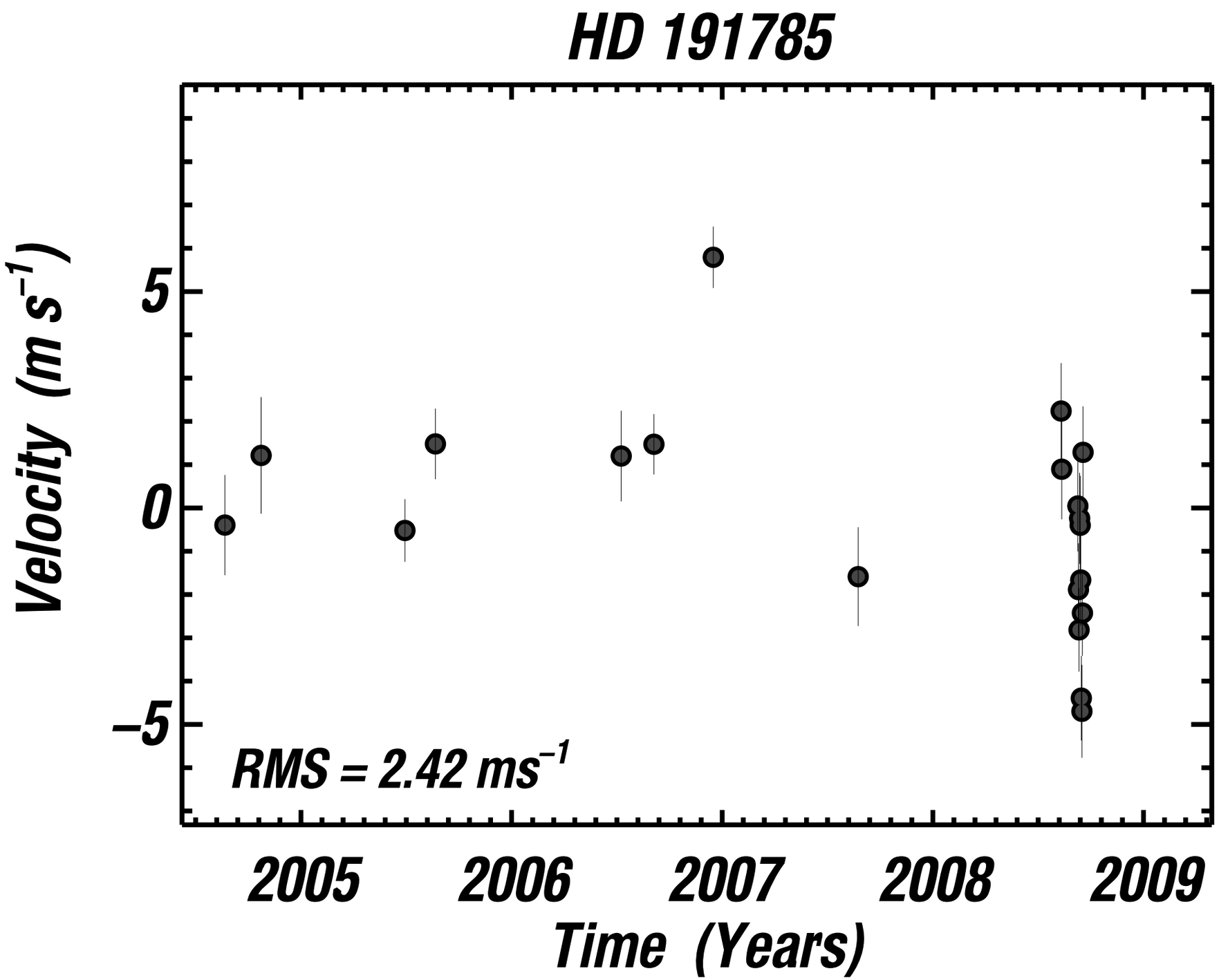
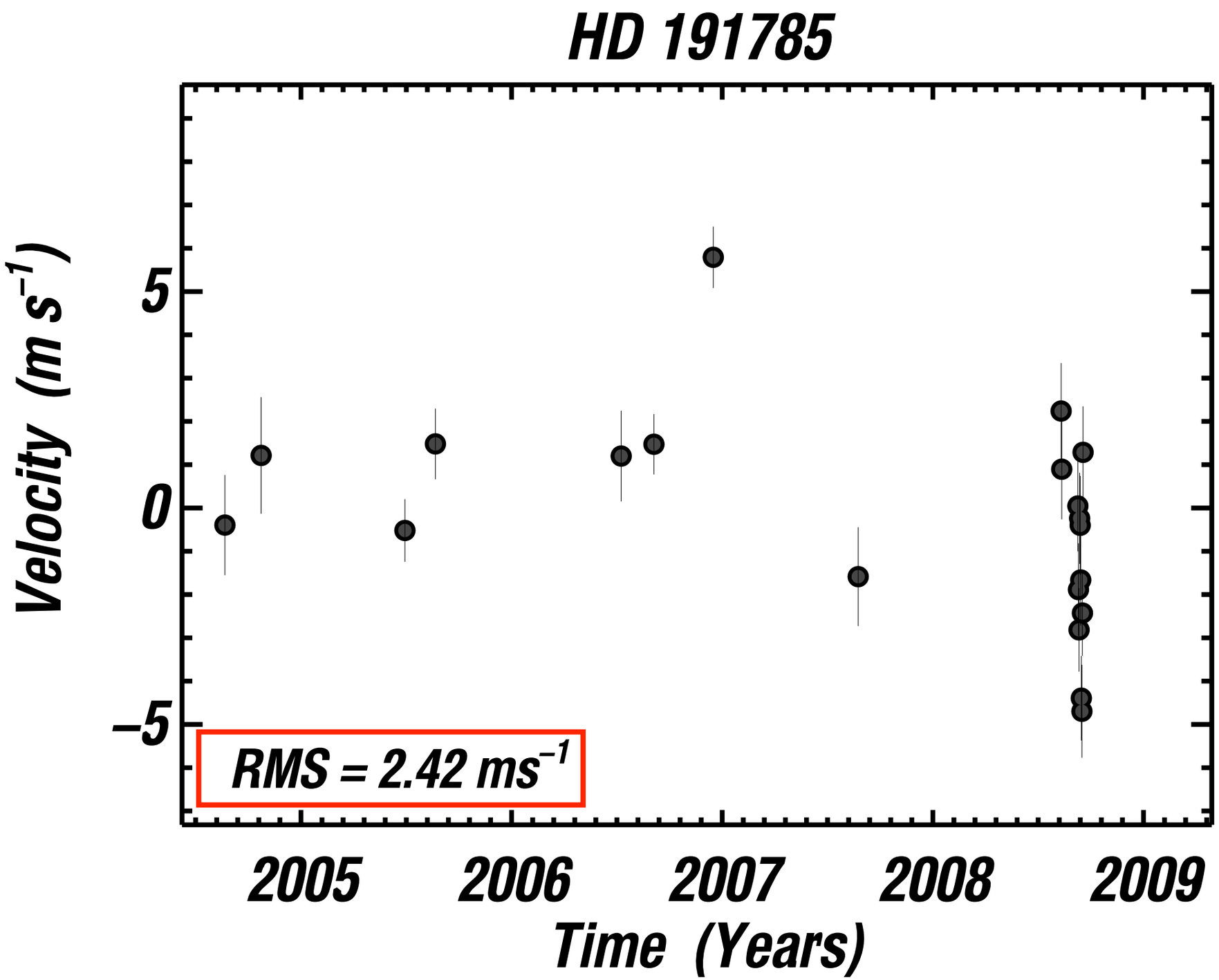
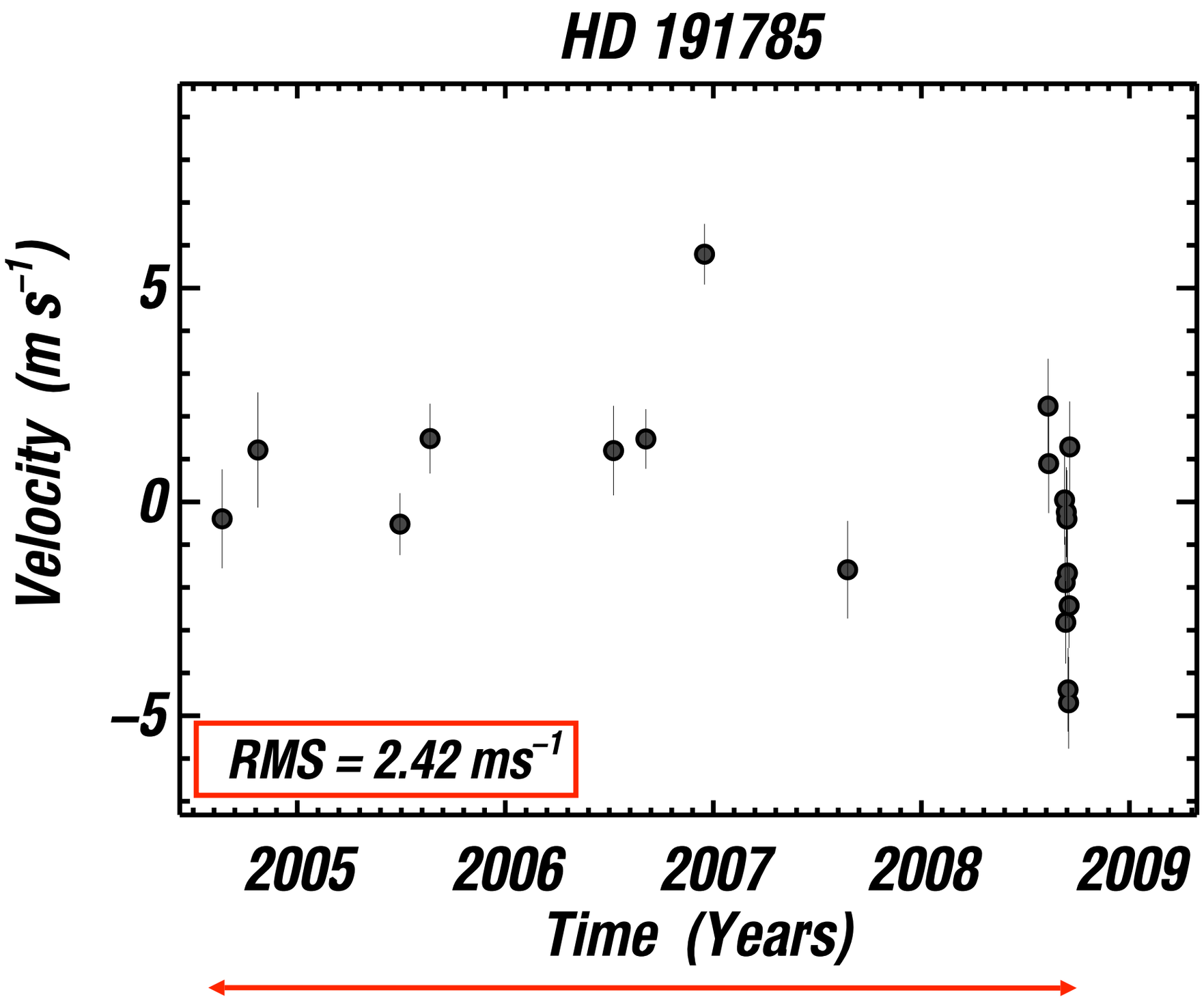
Minimum RV Observations for Eta-Earth Star



Minimum RV Observations for Eta-Earth Star

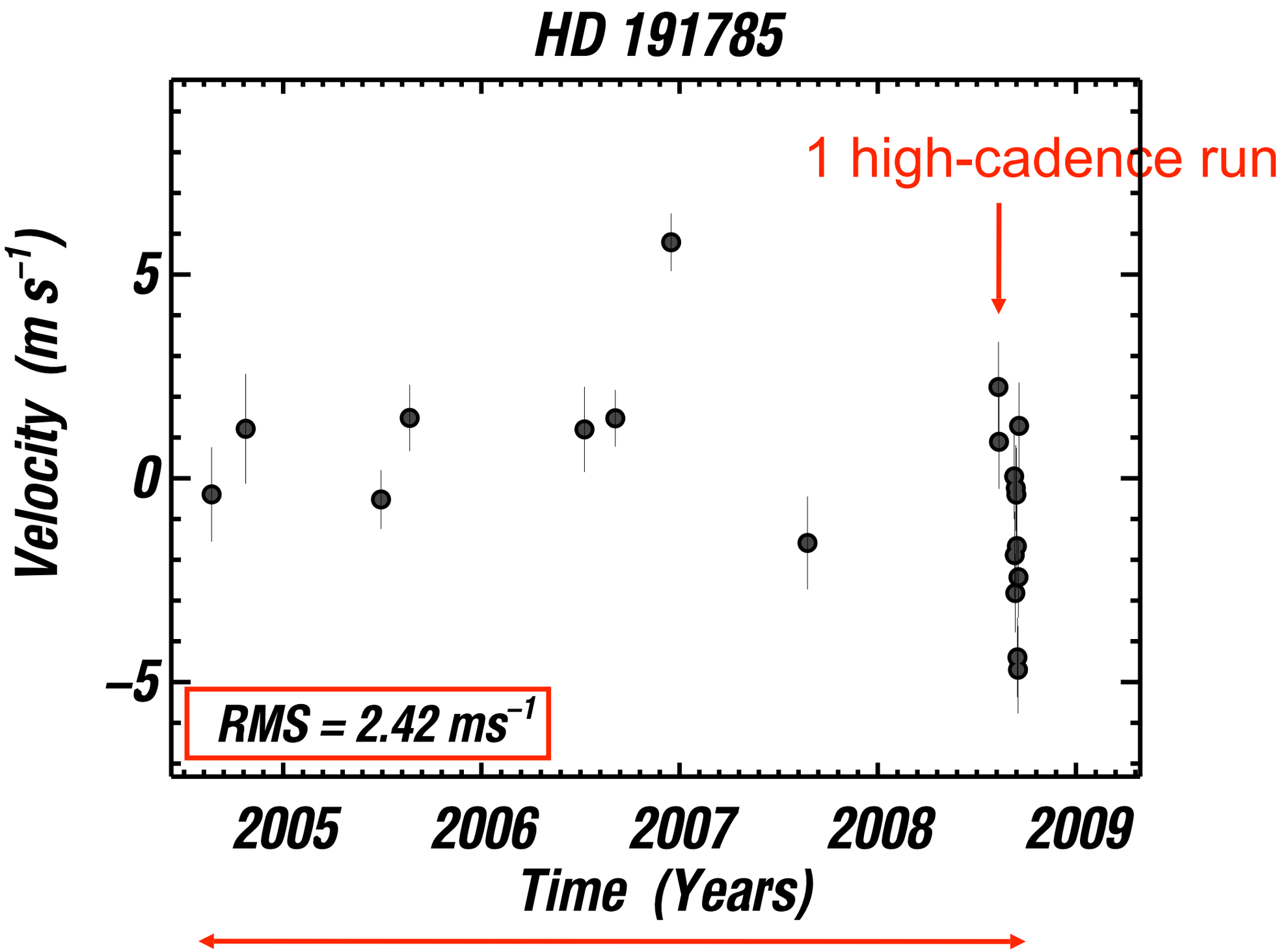


Minimum RV Observations for Eta-Earth Star



20+ observations over 4 years

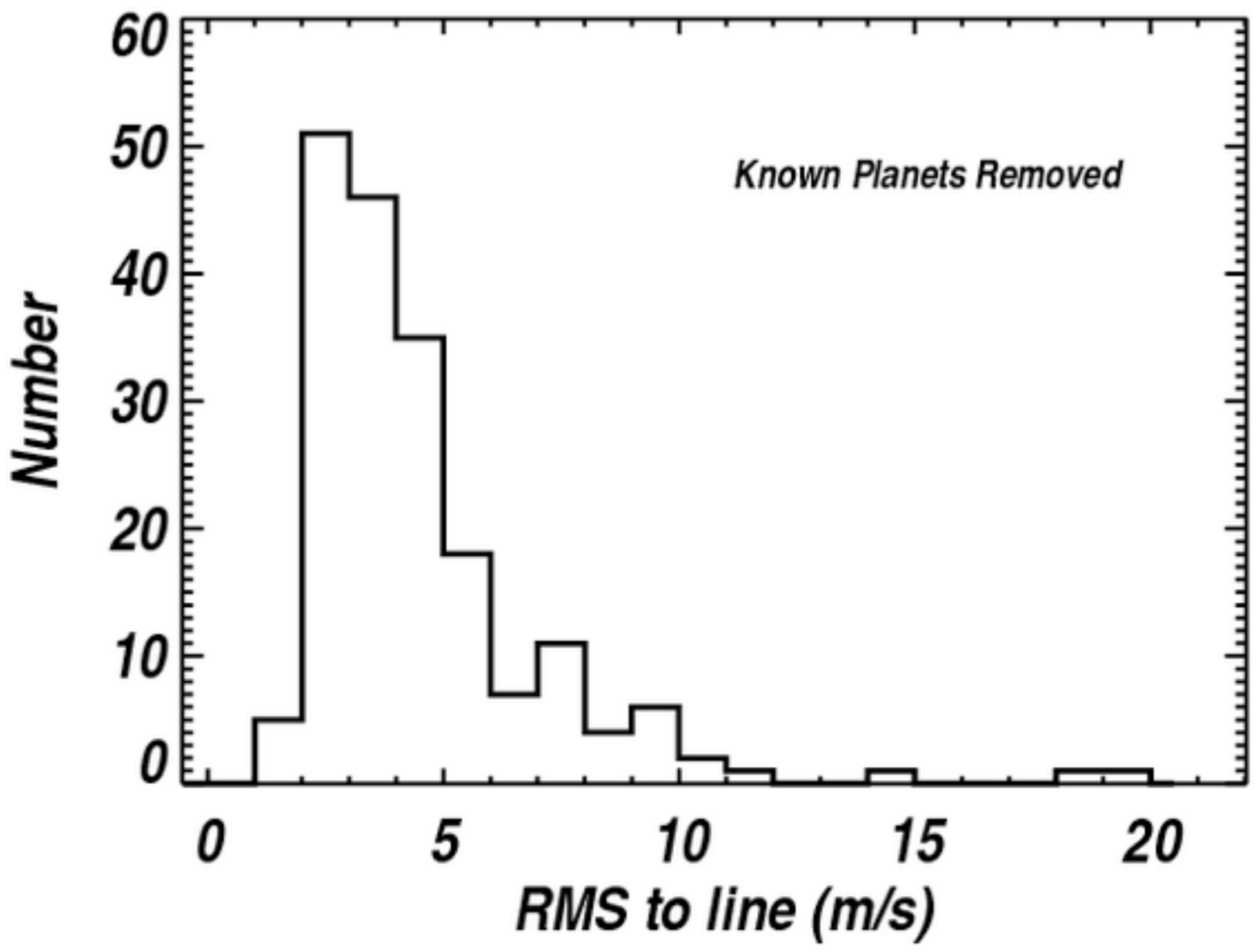
Minimum RV Observations for Eta-Earth Star



20+ observations over 4 years

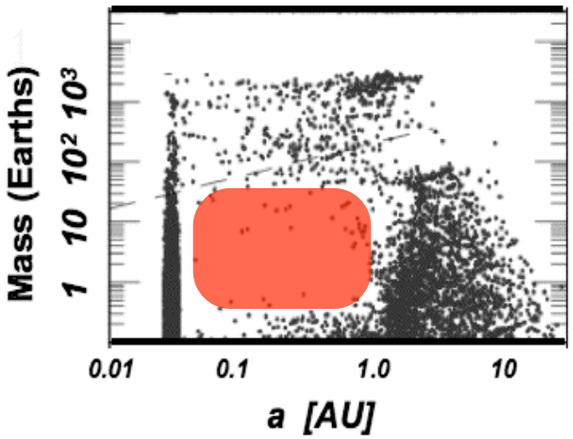
Precision of Eta-Earth Observations

Velocity RMS of Eta-Earth stars



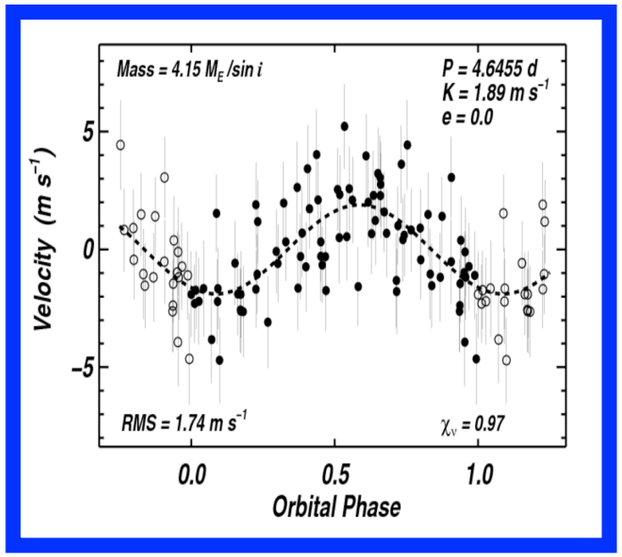
Limited by:

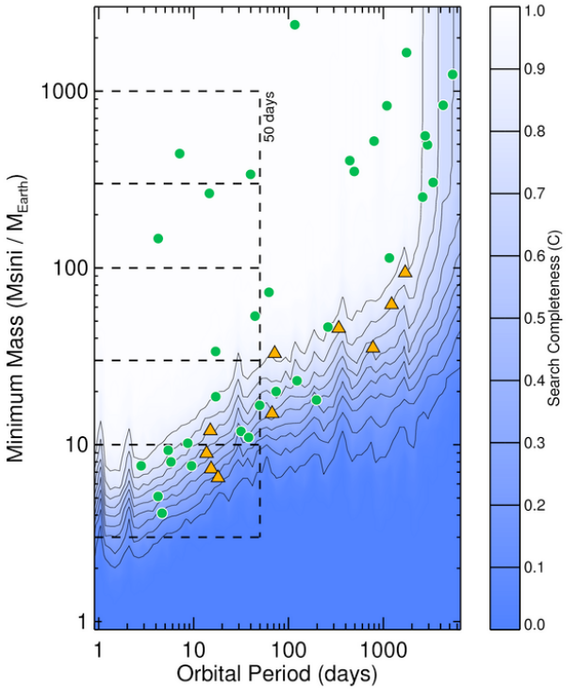
Stellar jitter
Guiding
Inst. Stability
Photon Noise



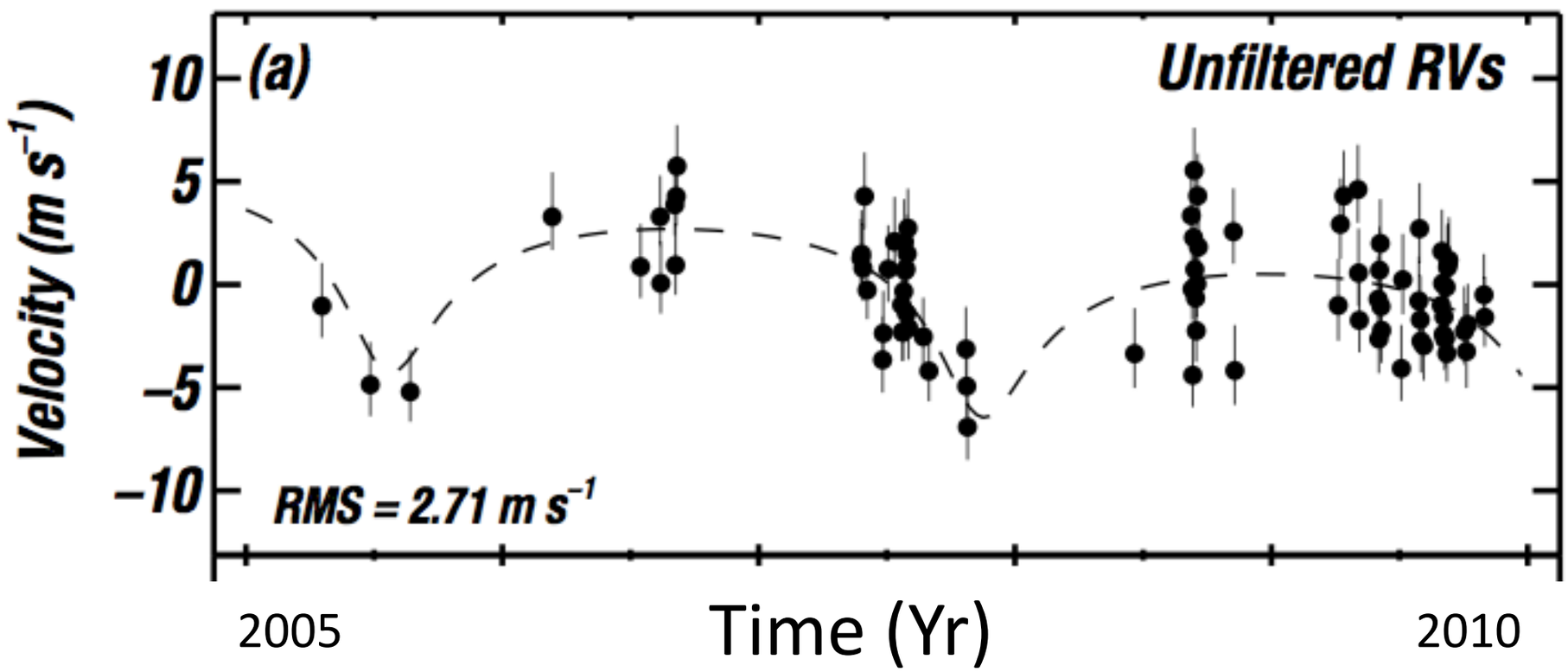
Outline:

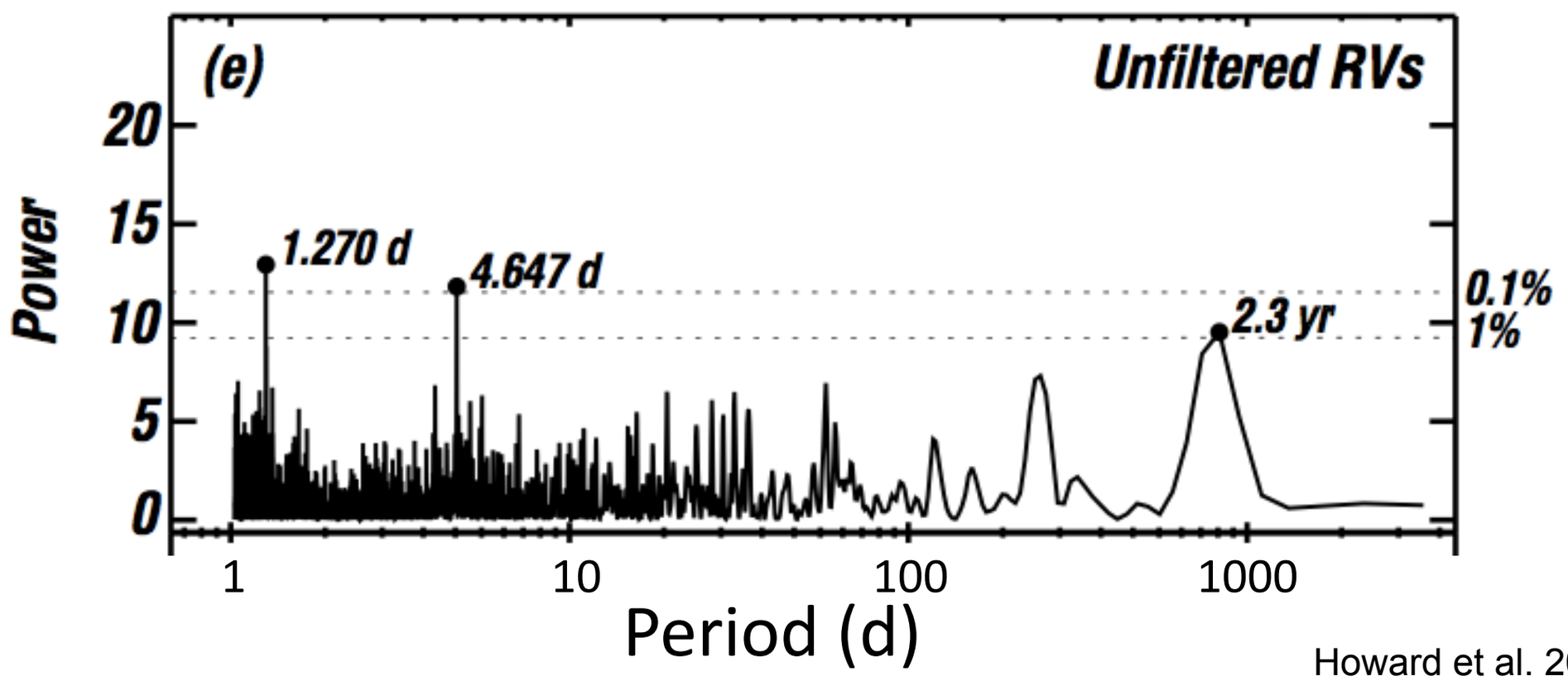
1. A Prediction from Planet Formation
2. The Eta-Earth Survey from Keck
3. **Planet Detections and Non-detections**
4. The Planet Mass Distribution and $\eta_{\mathbf{Earth}}$
5. Planet Formation Theory Revisited





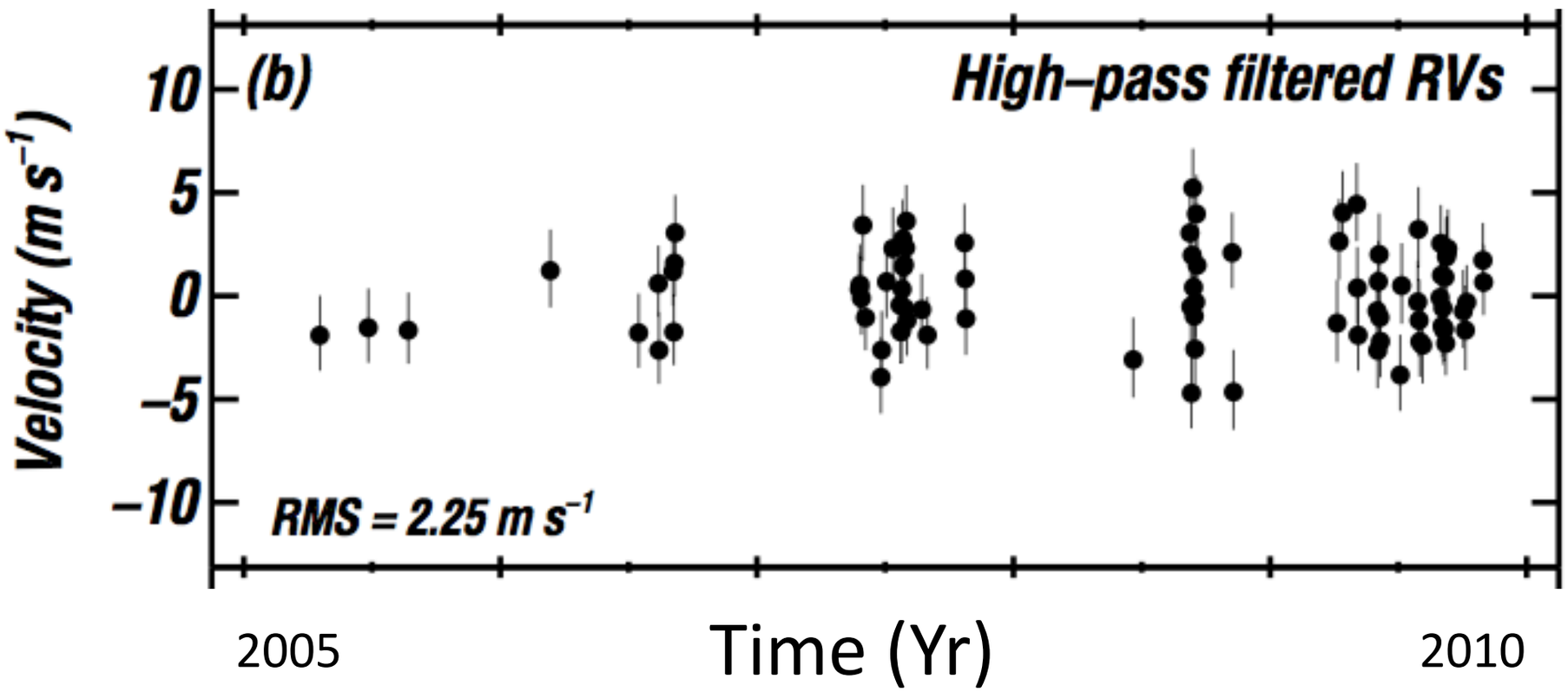
HD 156668 - Discovery RVs

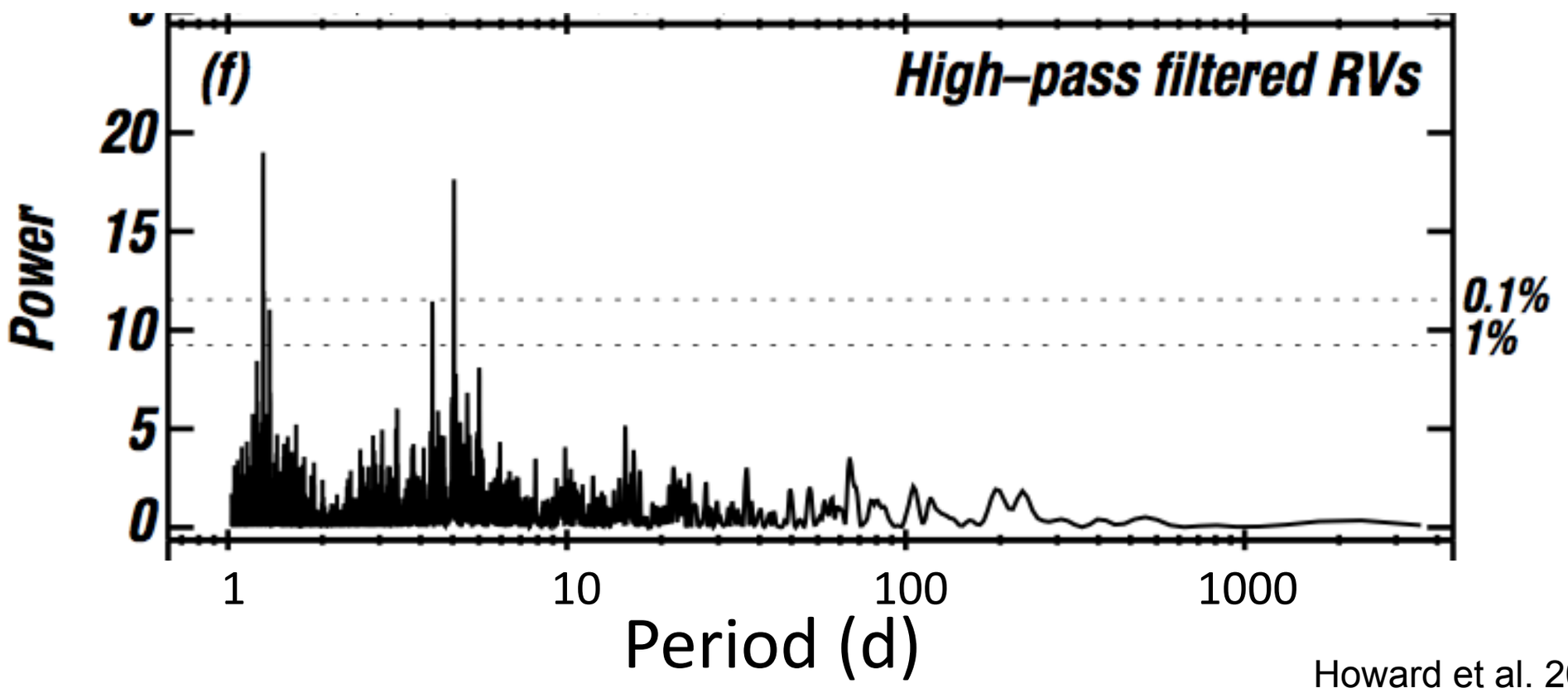




Howard et al. 2010a, ApJ,

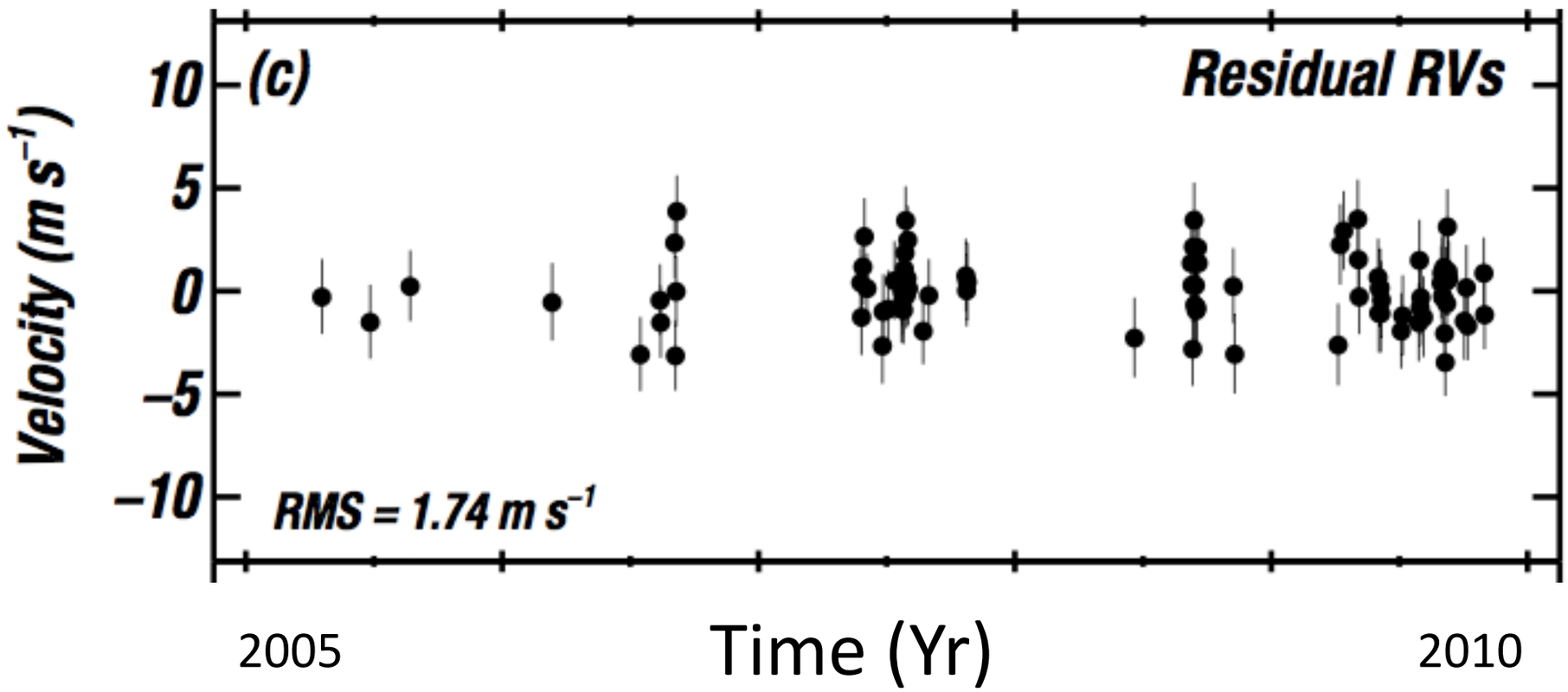
HD 156668 - High-pass Filtered RVs

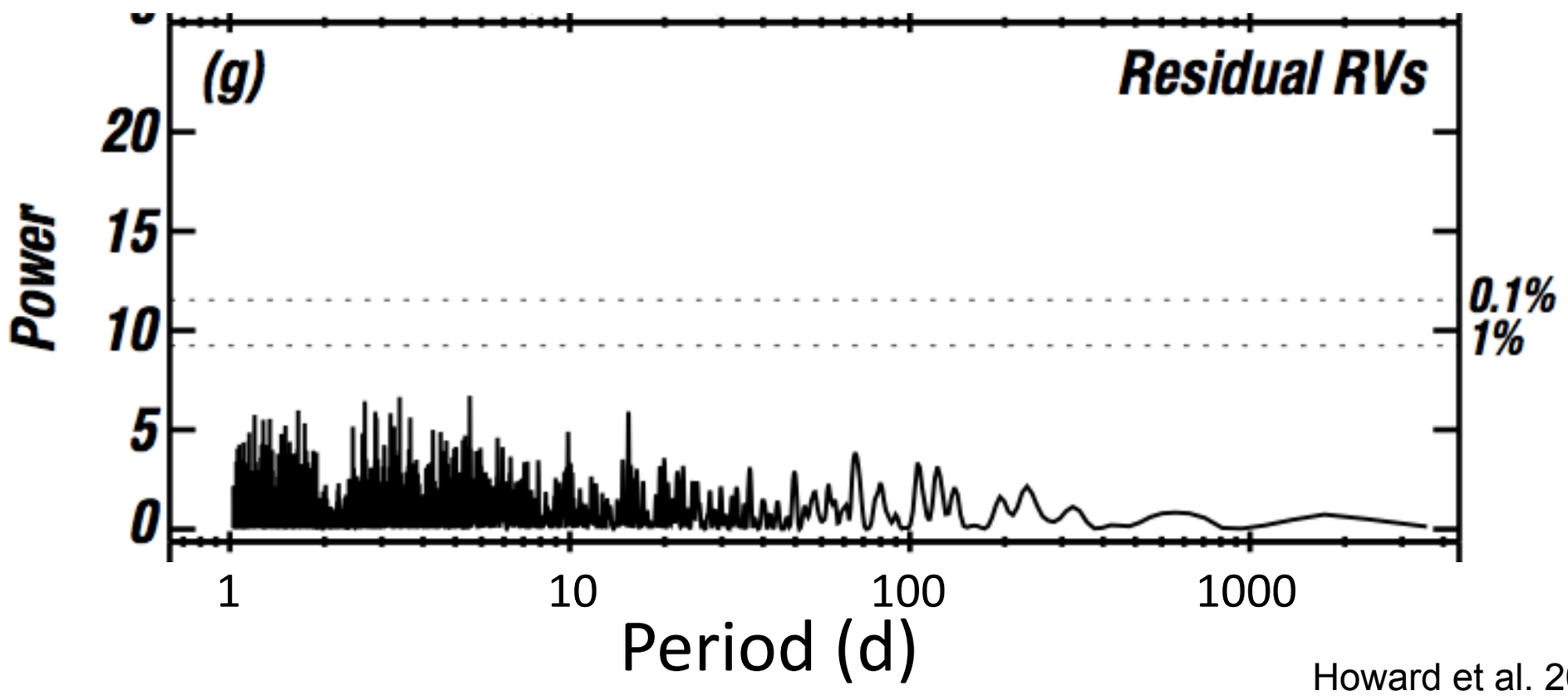




Howard et al. 2010a, ApJ,

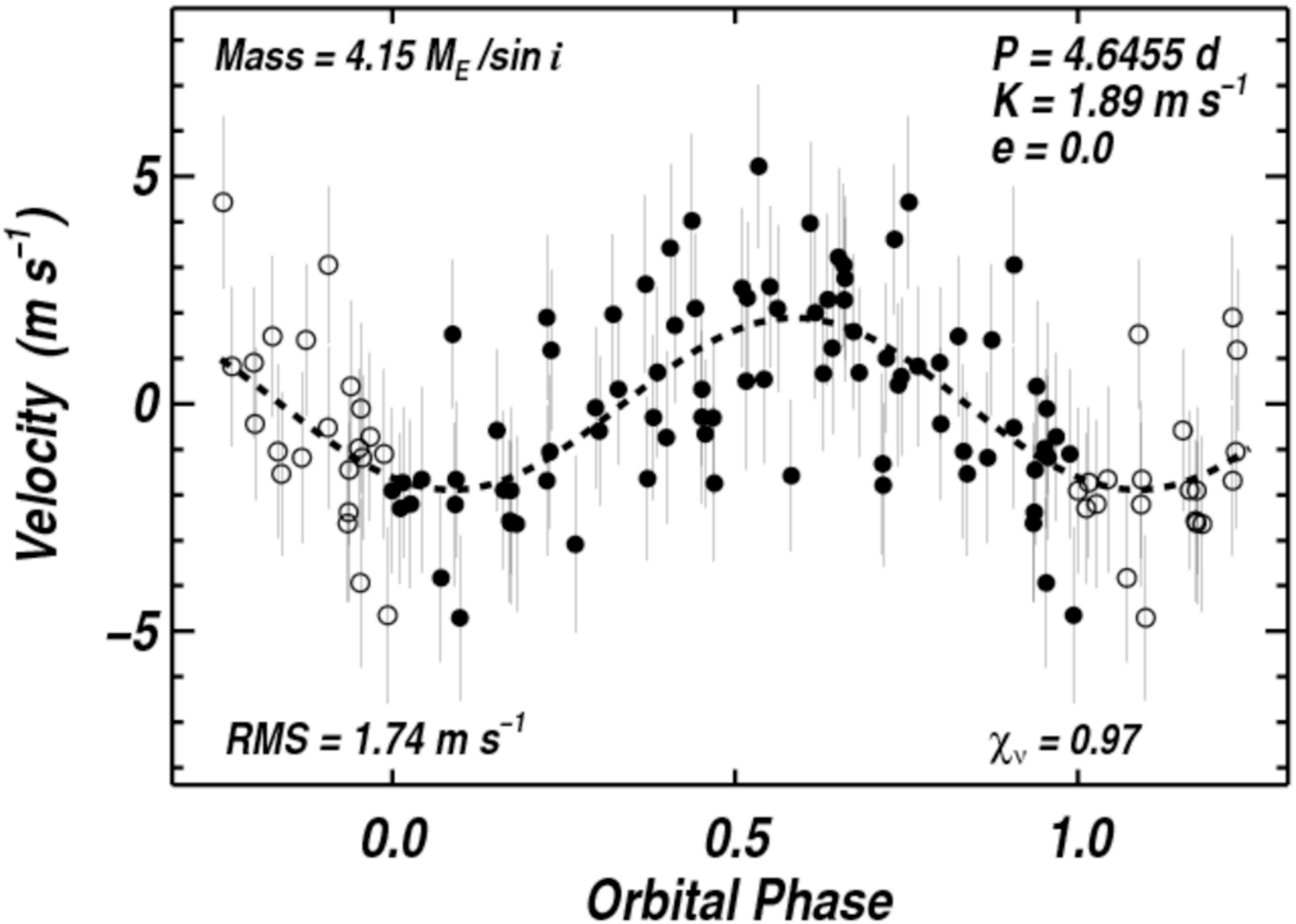
HD 156668 - Residual RVs





Howard et al. 2010a, ApJ,

HD 156668b - Detected Super-Earth!

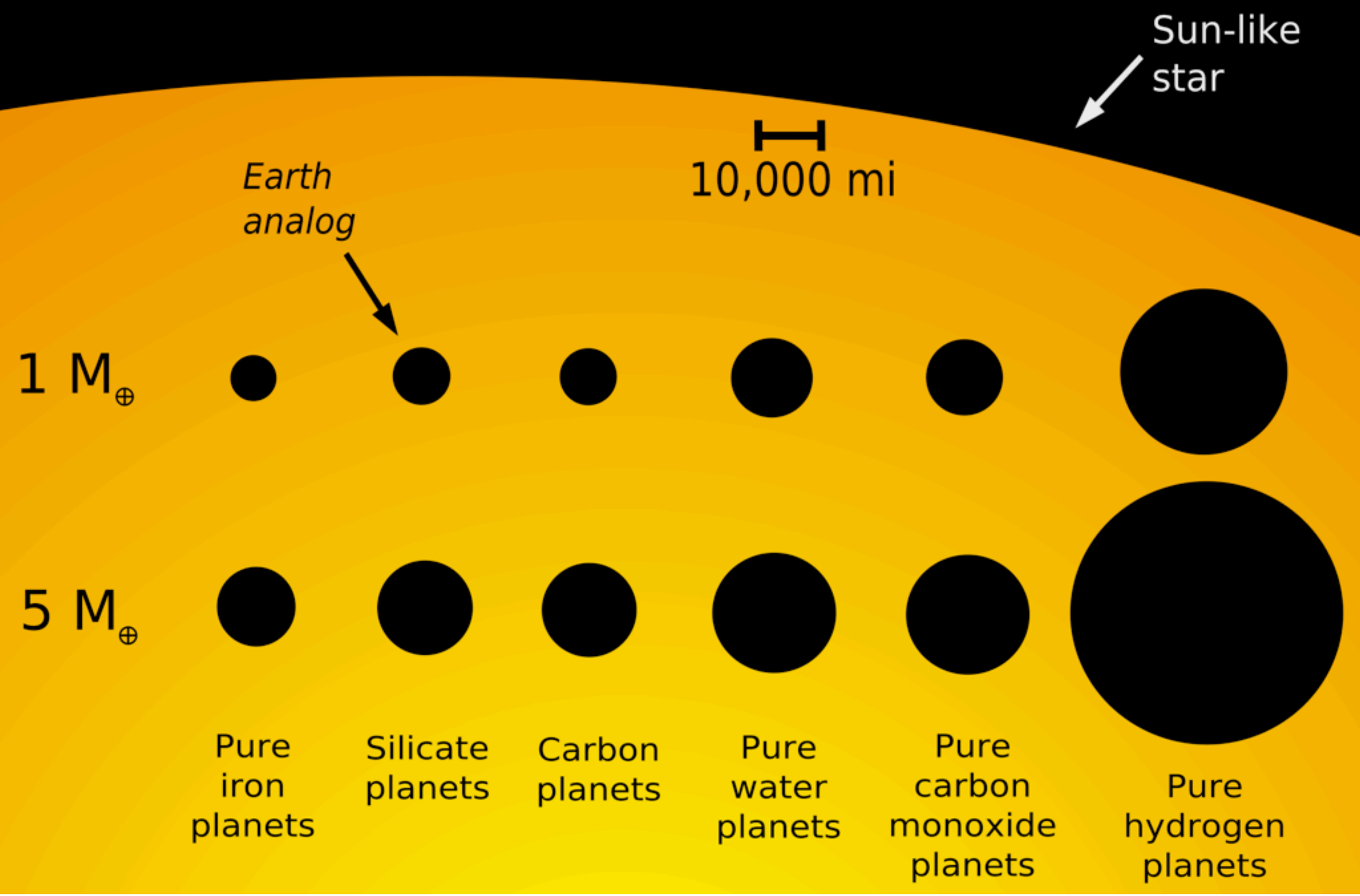


Star:
HD 156668 (K3V)
distance = 24 pc
V = 8.3
[Fe/H] = 0.05
quiet

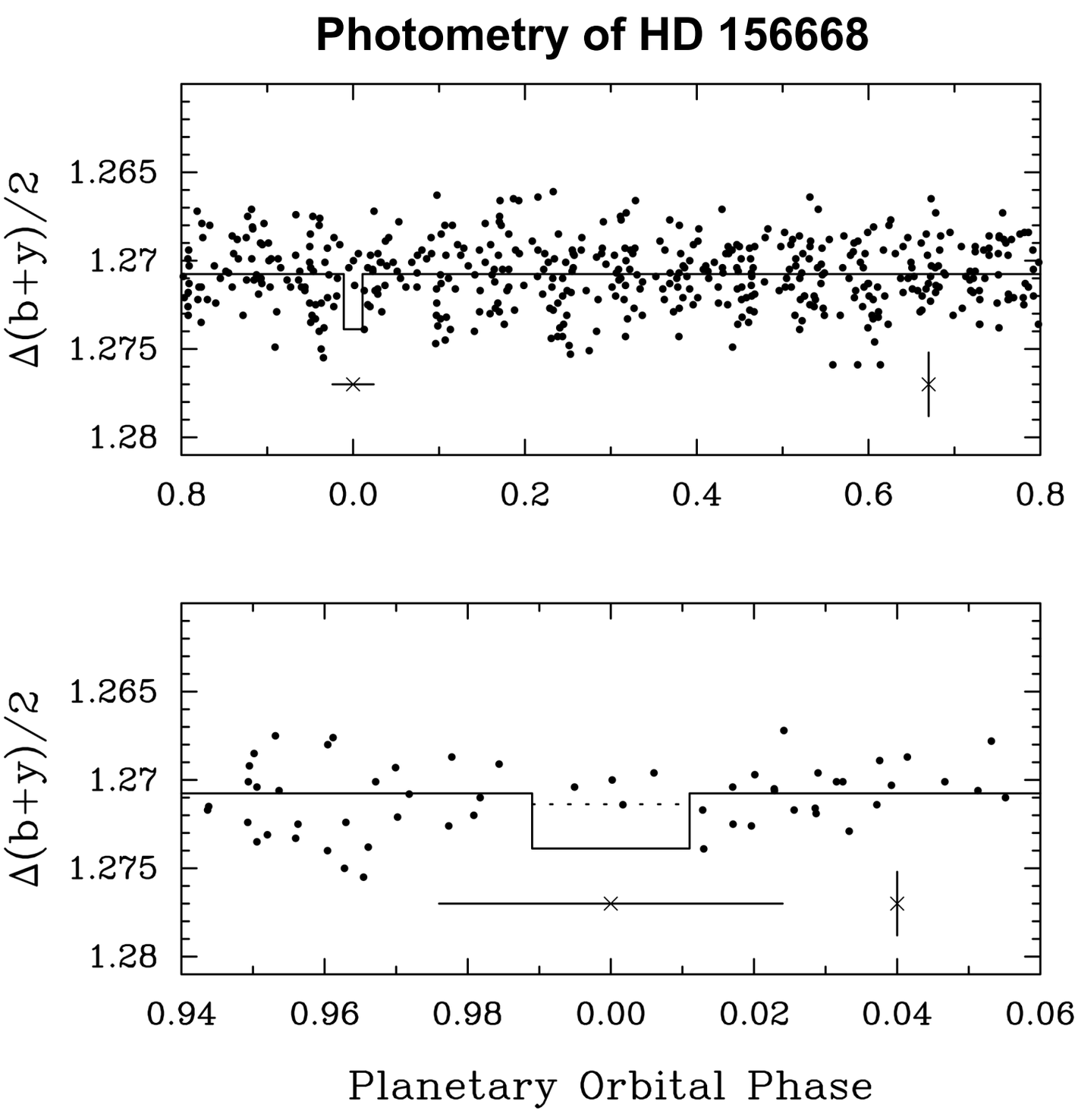
Planet:
M sin i = 4.15 M_E
P = 4.6455 d
e = 0 (fixed)

Howard et al. 2010, ApJ, accepted

Predicted sizes of different kinds of planets



HD 156668b - Transit Search



Photometry by Greg Henry using APTs

5% transit probability

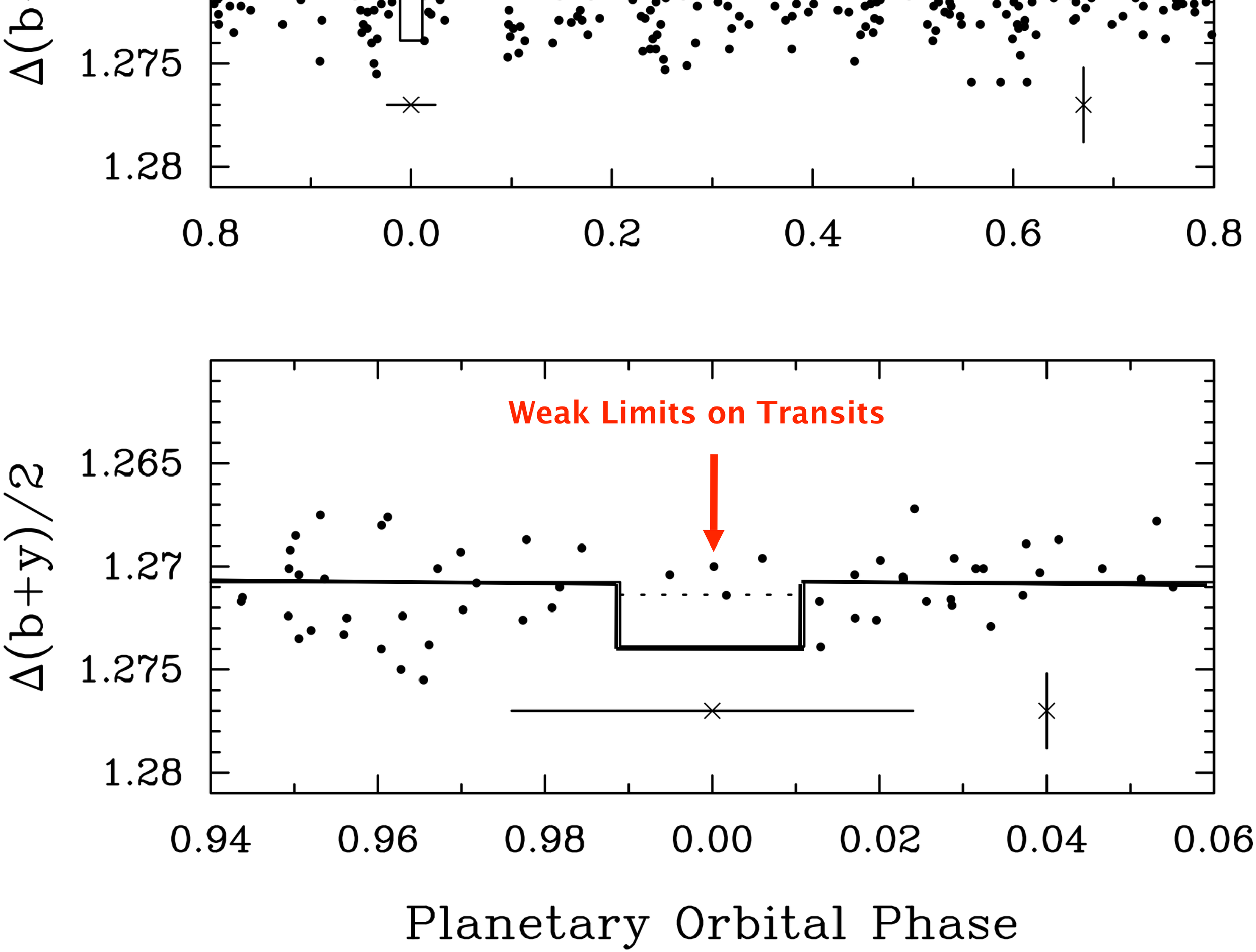
V=8.4 – great follow-up!

No transits detected, but no dedicated search, *yet!*

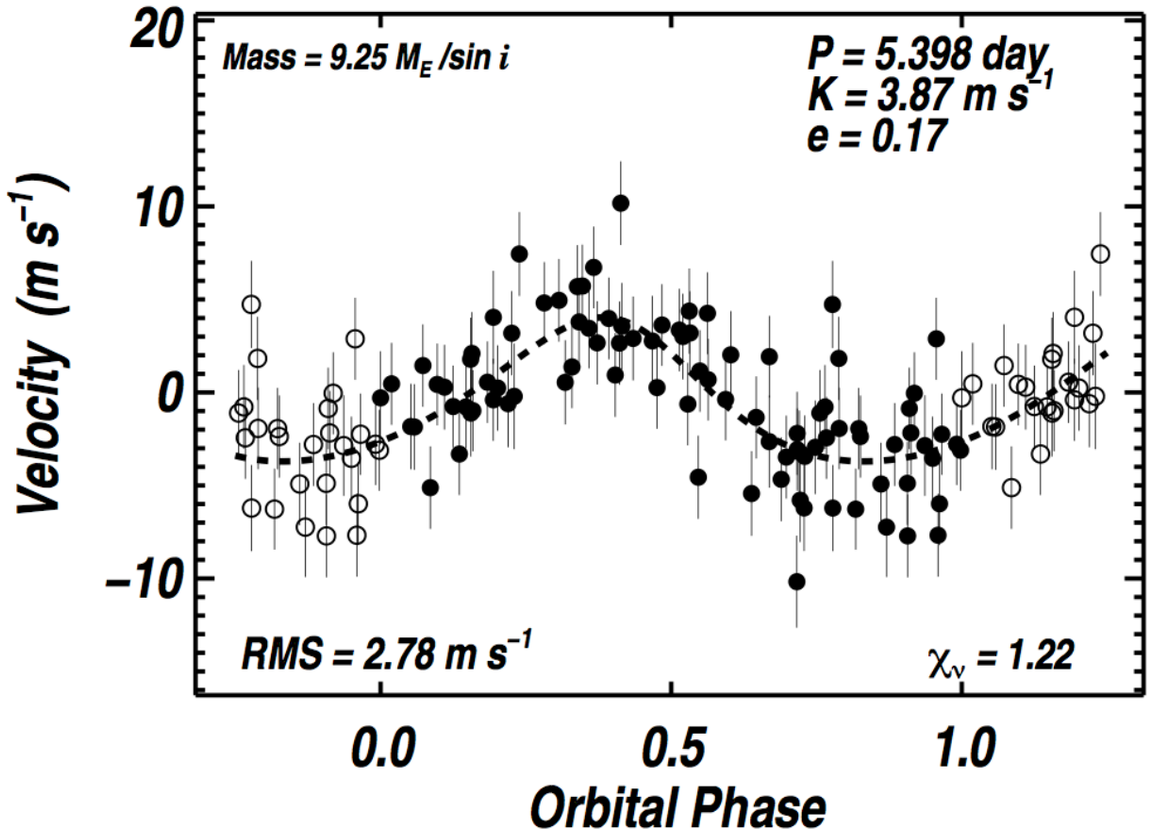
Can rule out extremely bloated planets:
depth < 3 mmag
$R < 4.5\ R_{Earth}$

Possible compositions (toy models):

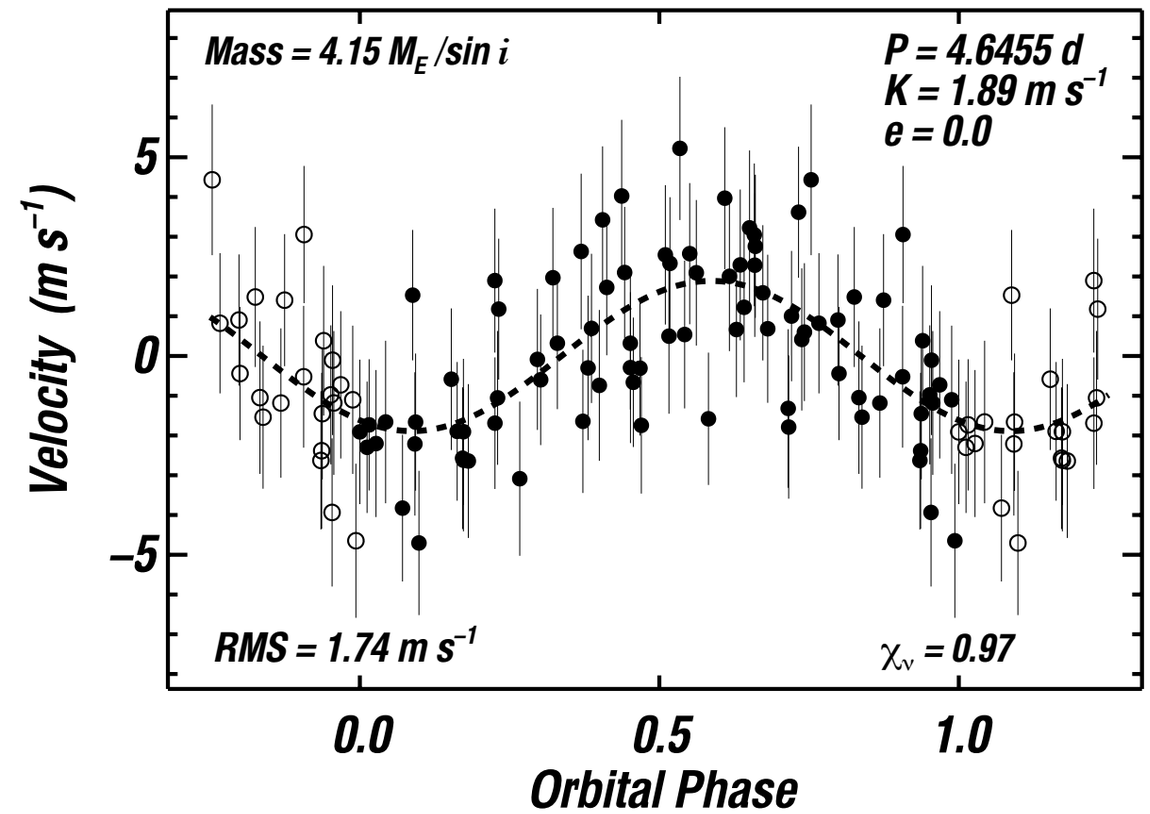
Hydrogen	$4.5\ R_E$	3.1 mmag
Water	$2.0\ R_E$	0.61 mmag
Silicate	$1.5\ R_E$	0.35 mmag
Iron	$1.2\ R_E$	0.22 mmag


Δ(b
1.275
1.28
0.8
0.0
0.2
0.4
0.6
0.8
Weak Limits on Transits
Δ(b+y)/2
1.265
1.27
1.275
1.28
0.94
0.96
0.98
0.00
0.02
0.04
0.06
Planetary Orbital Phase

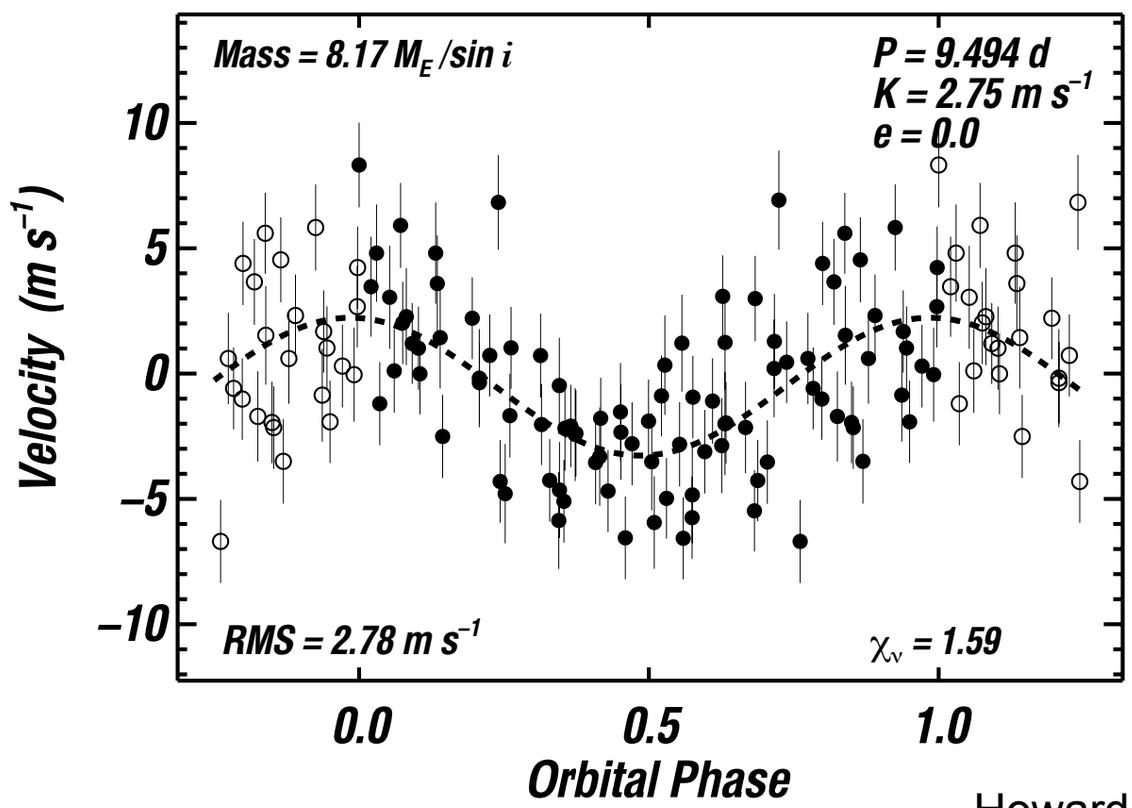
HD 7924 b



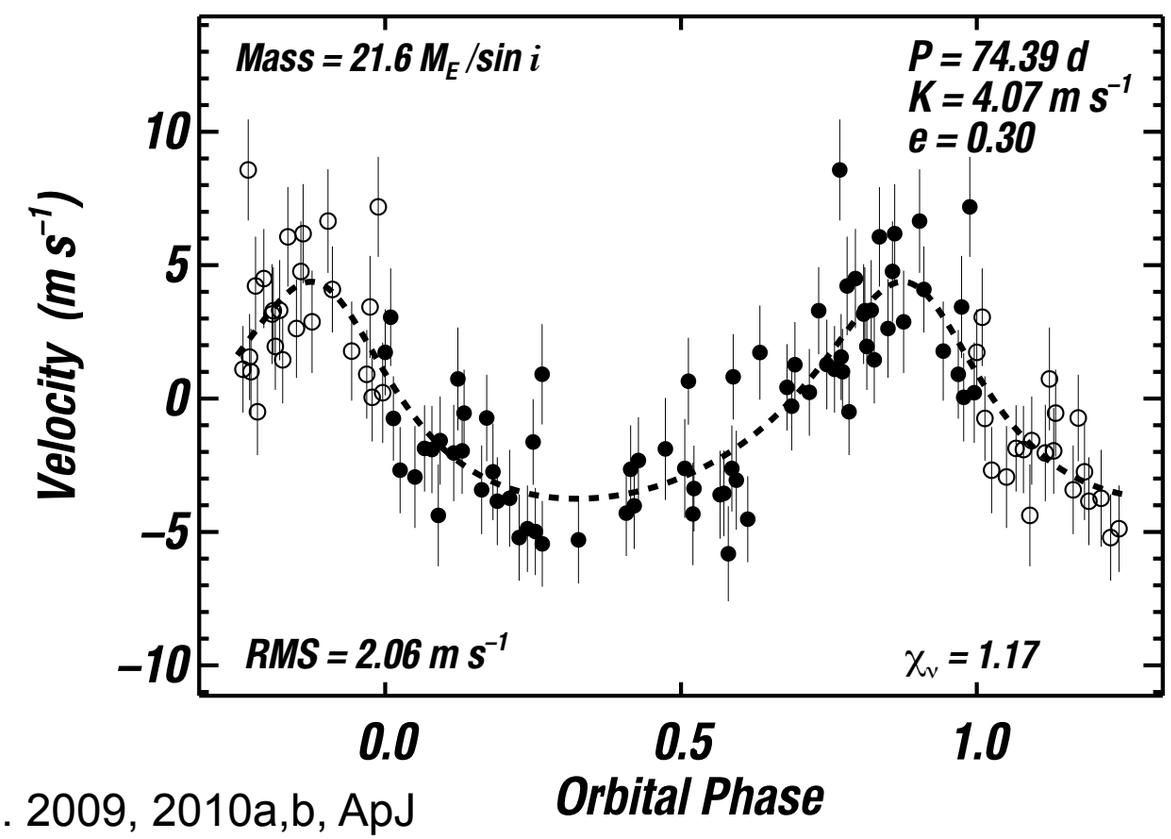
HD 156668 b



HD 97658 b



Gl 785 b



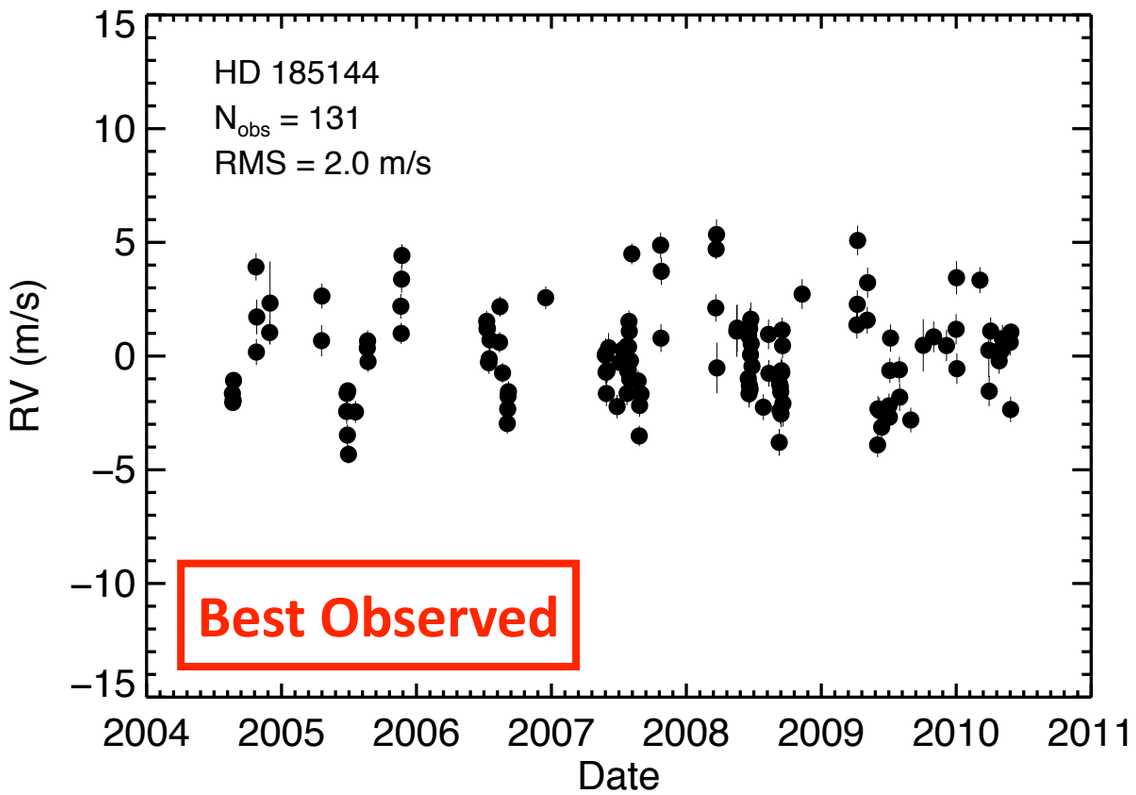
Howard et al. 2009, 2010a,b, ApJ

33 Detected Planets in the Survey

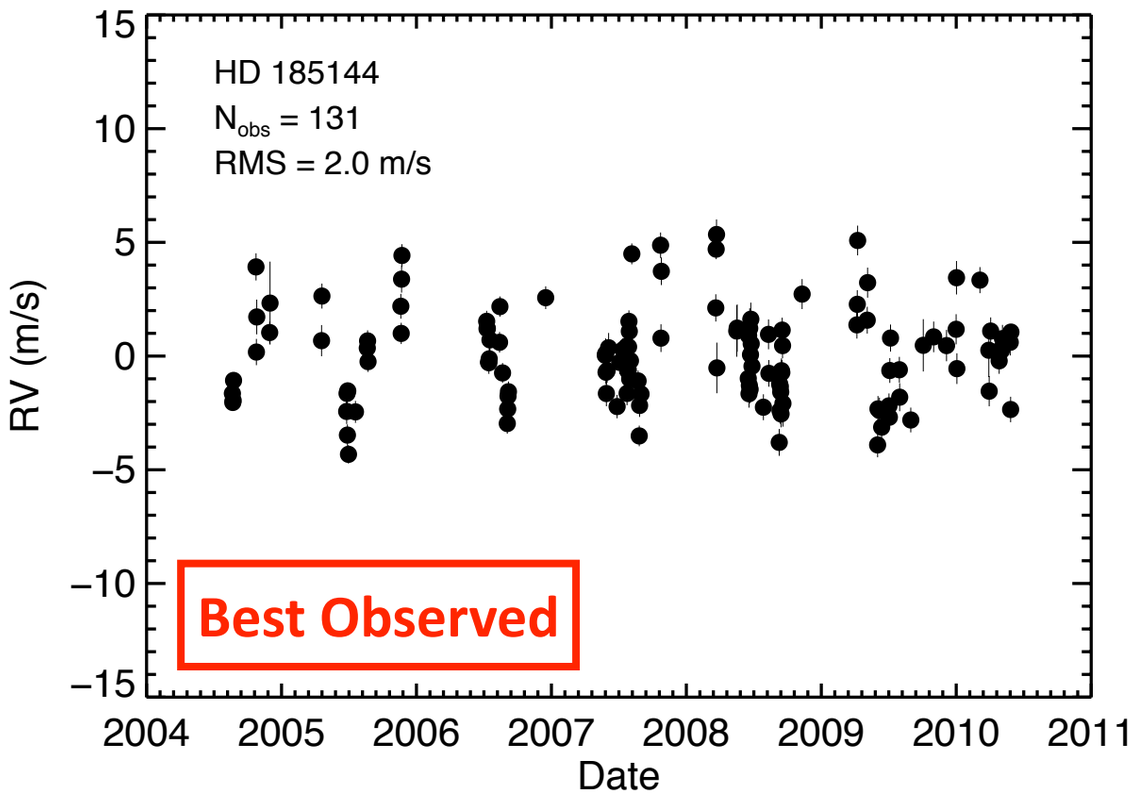
Planet	Star	Period (d)	$M \sin i$ ($M_\oplus$)	Reference
14 Her b	HD 145675	1754	1651	(*15*)
16 Cyg b	HD 186427	798	521	(*15*)
47 UMa b	HD 95128	1090	826	(*16*)
47 UMa c	HD 95128	2590	252	(*16*)
51 Peg b	HD 217014	4.2	147	(*17*)
55 Cnc b	HD 75732	14.7	264	(*18*)
55 Cnc c	HD 75732	44.4	53.4	(*18*)
55 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*)

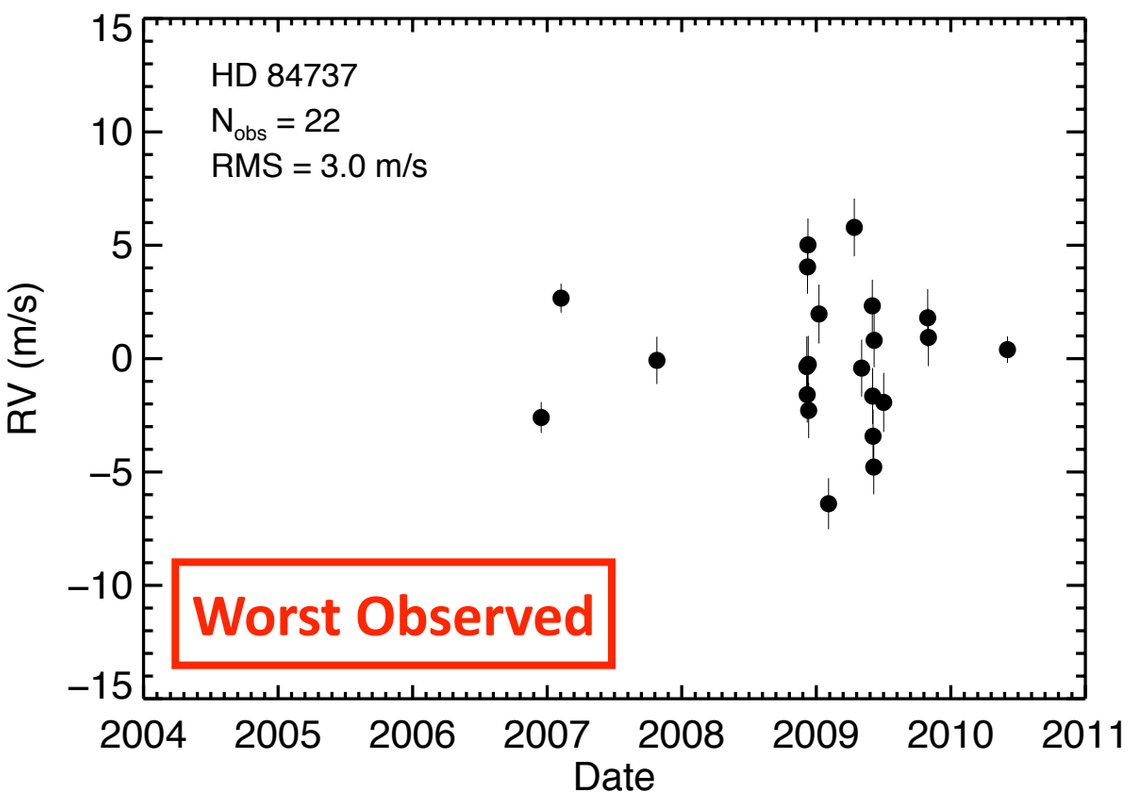
- **Some found by others; confirmed here**
- **Firm Period, Msin*i***
- **All published**

Limits on Non-detections of Planets

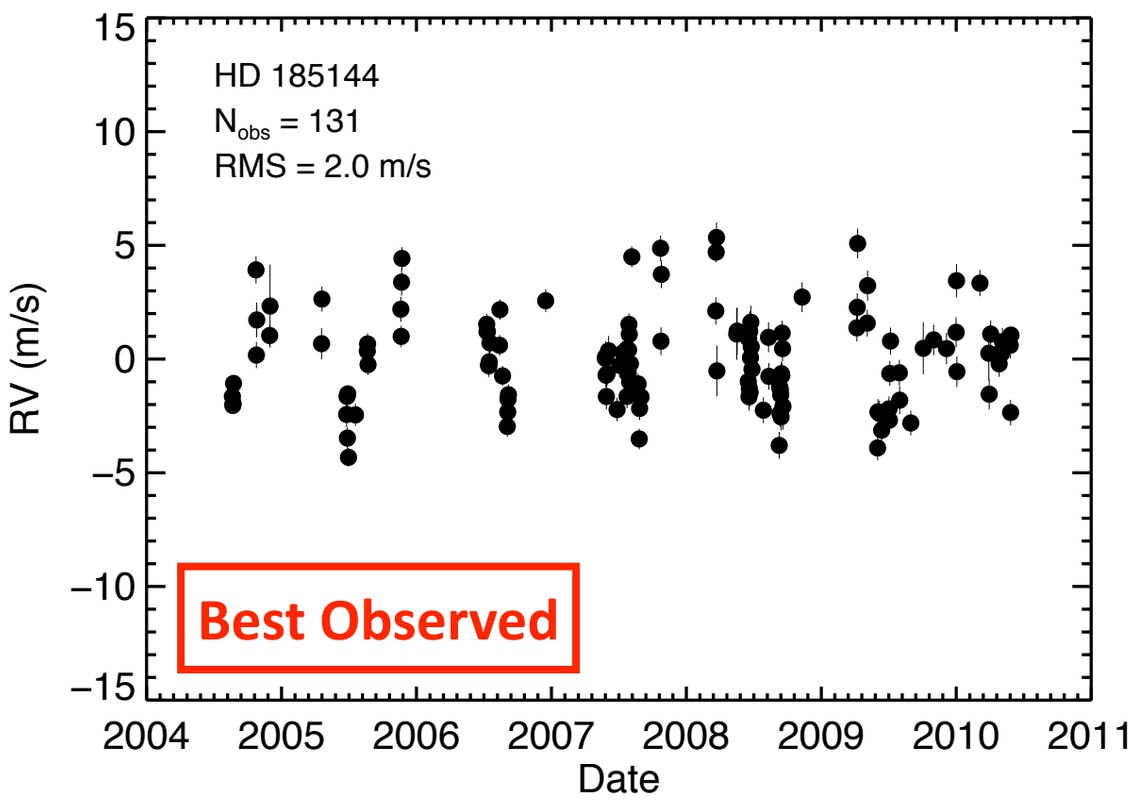


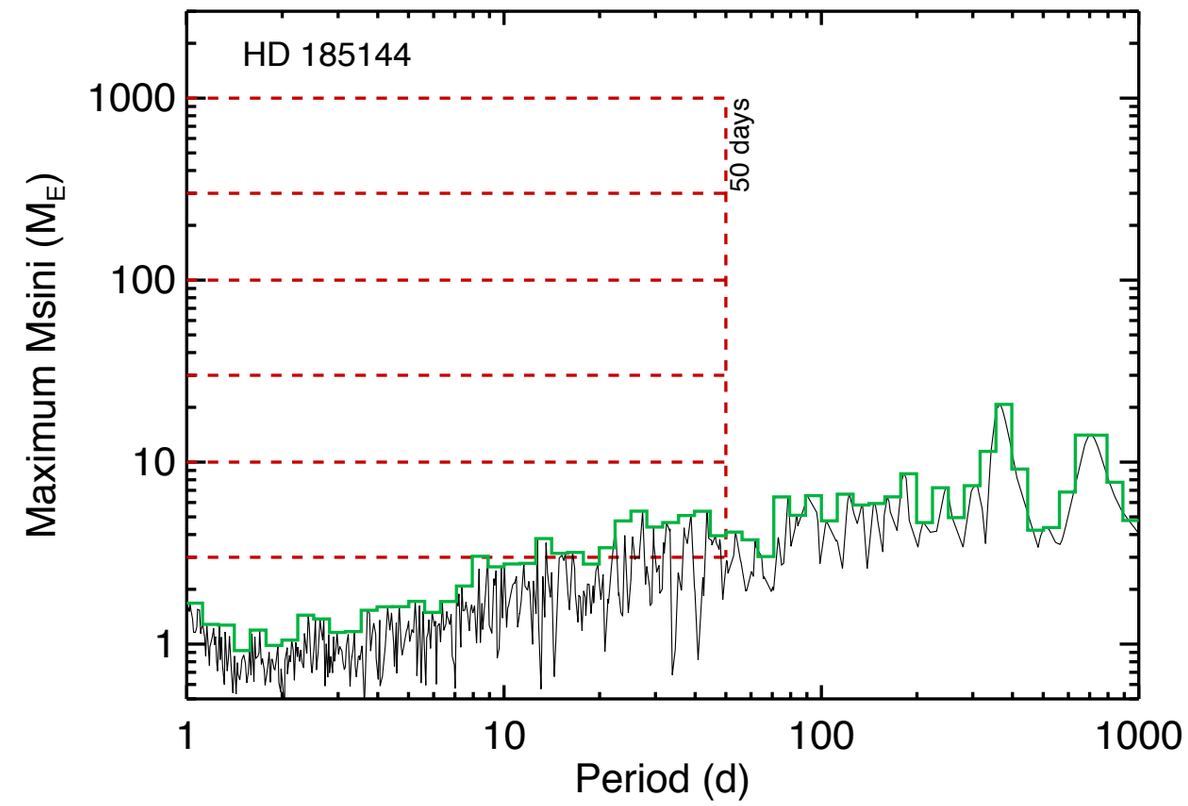
Limits on Non-detections of Planets

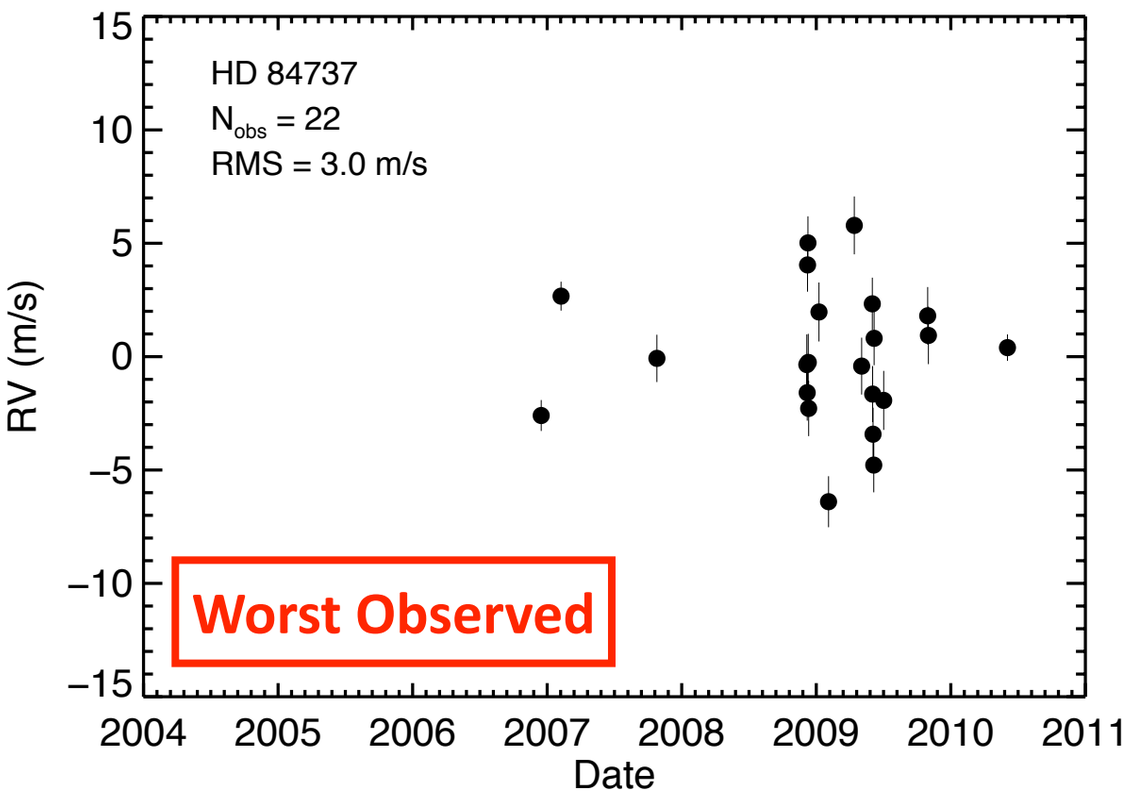




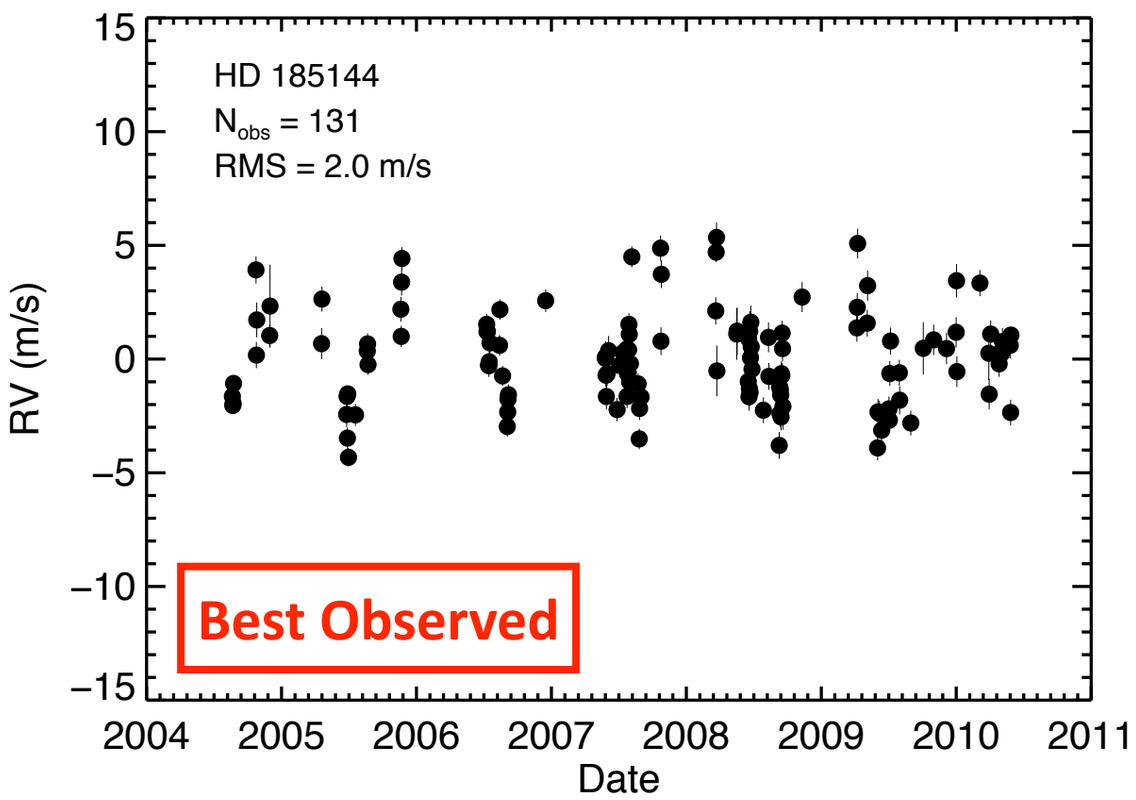
Limits on Non-detections of Planets

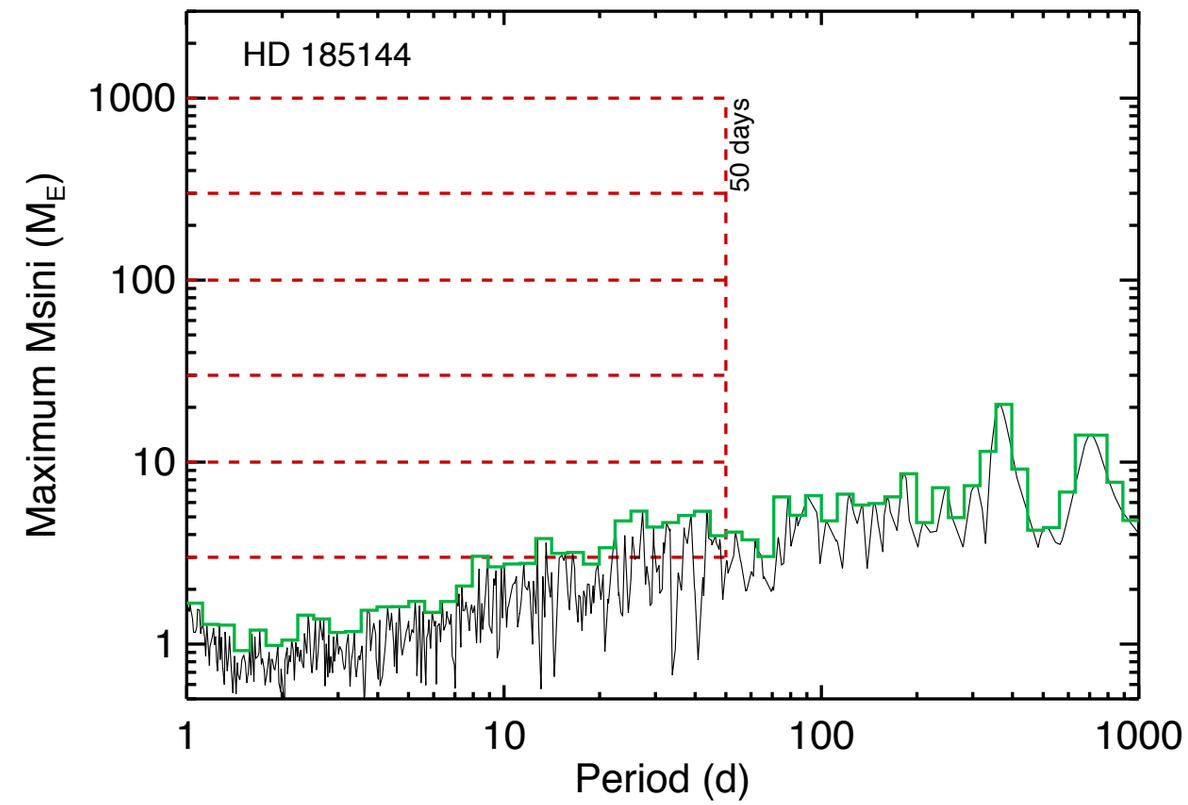


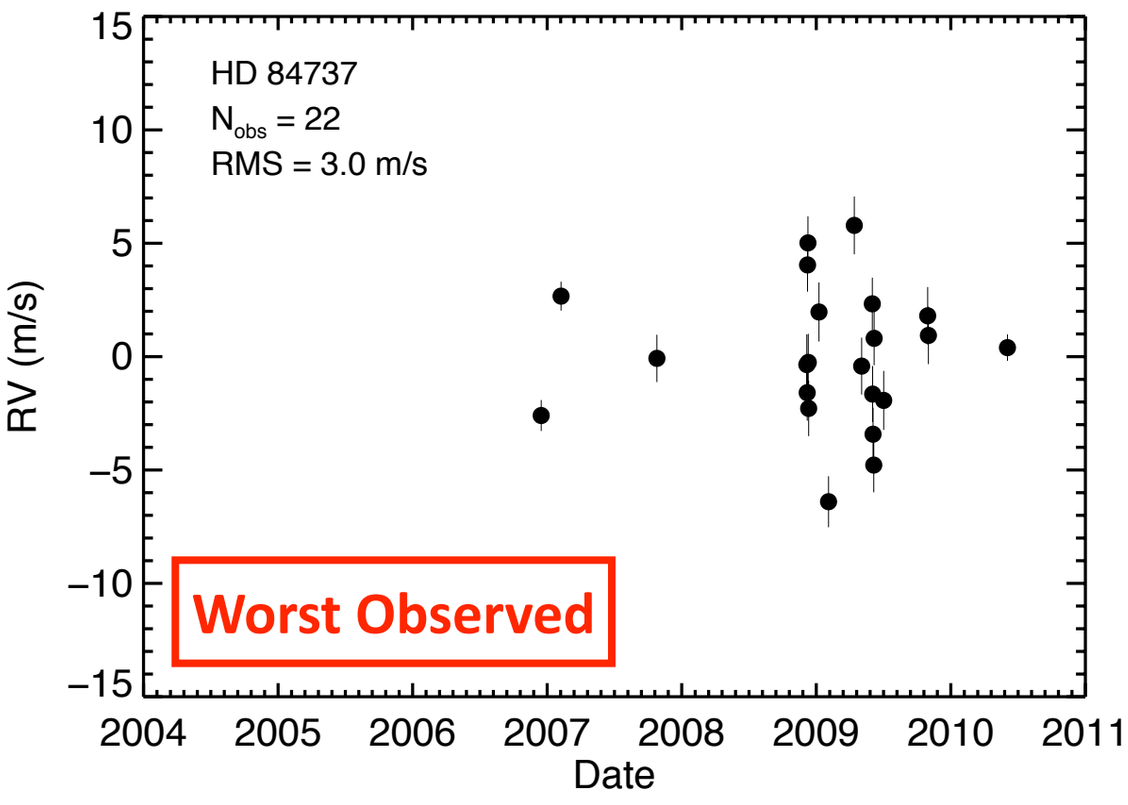


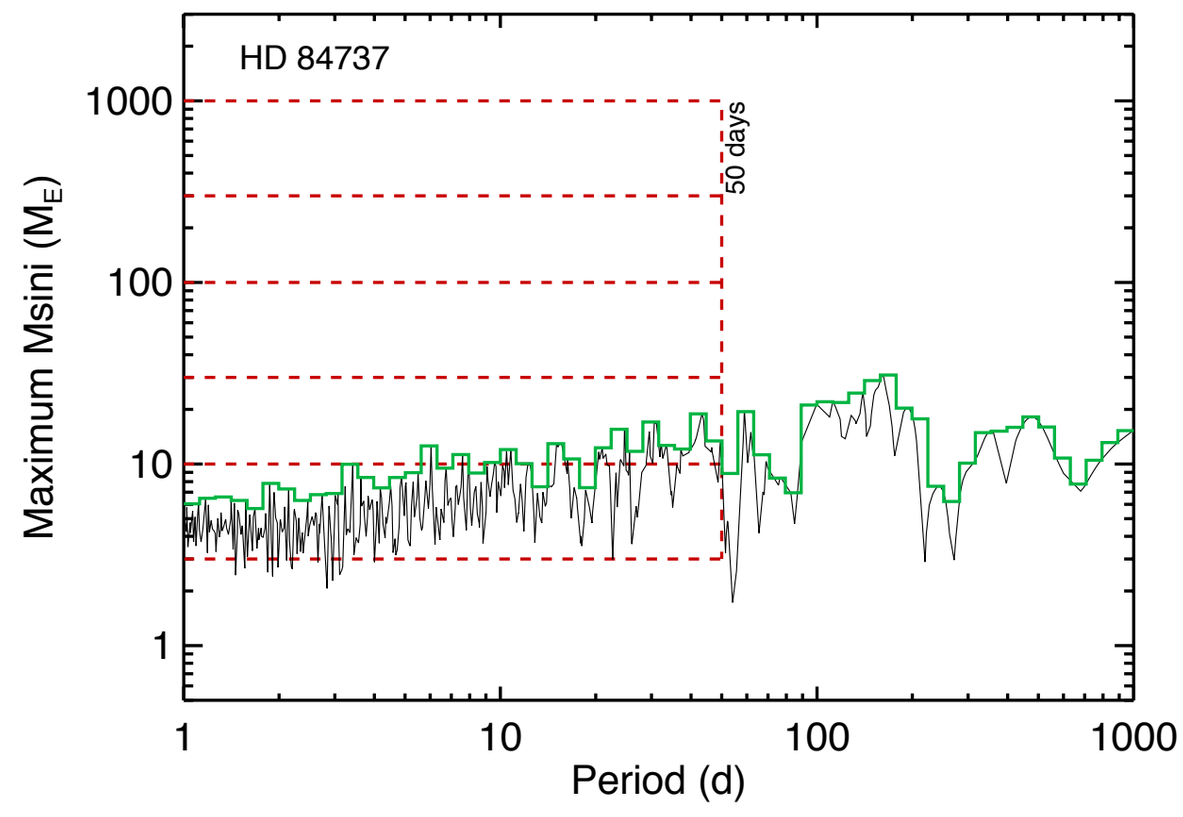


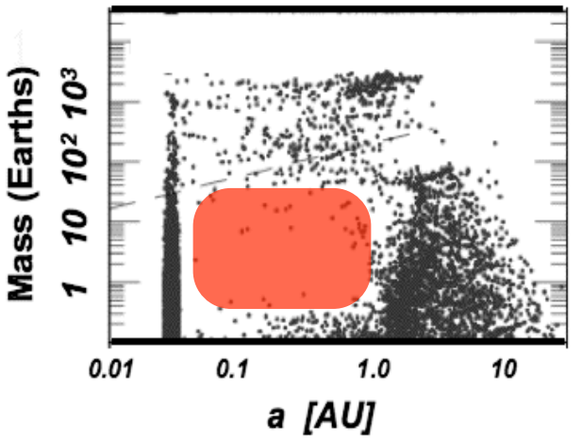
Limits on Non-detections of Planets











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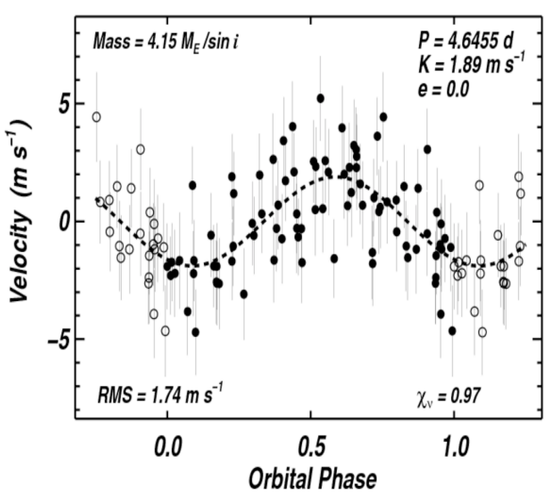
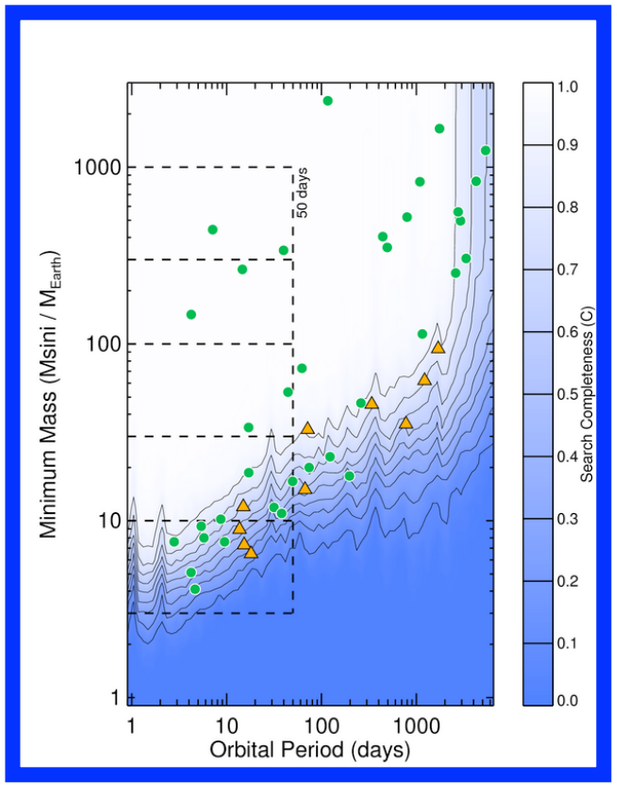
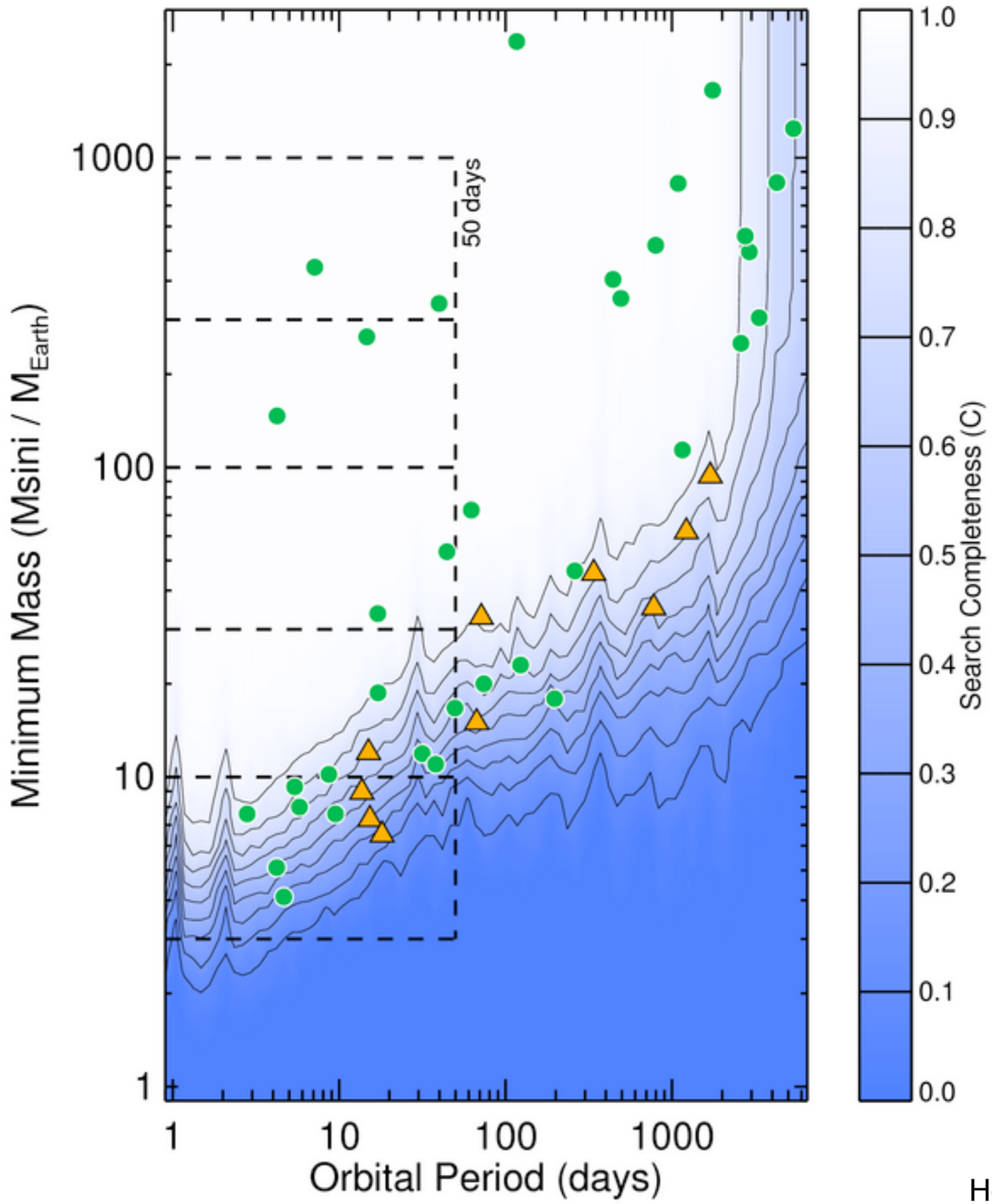




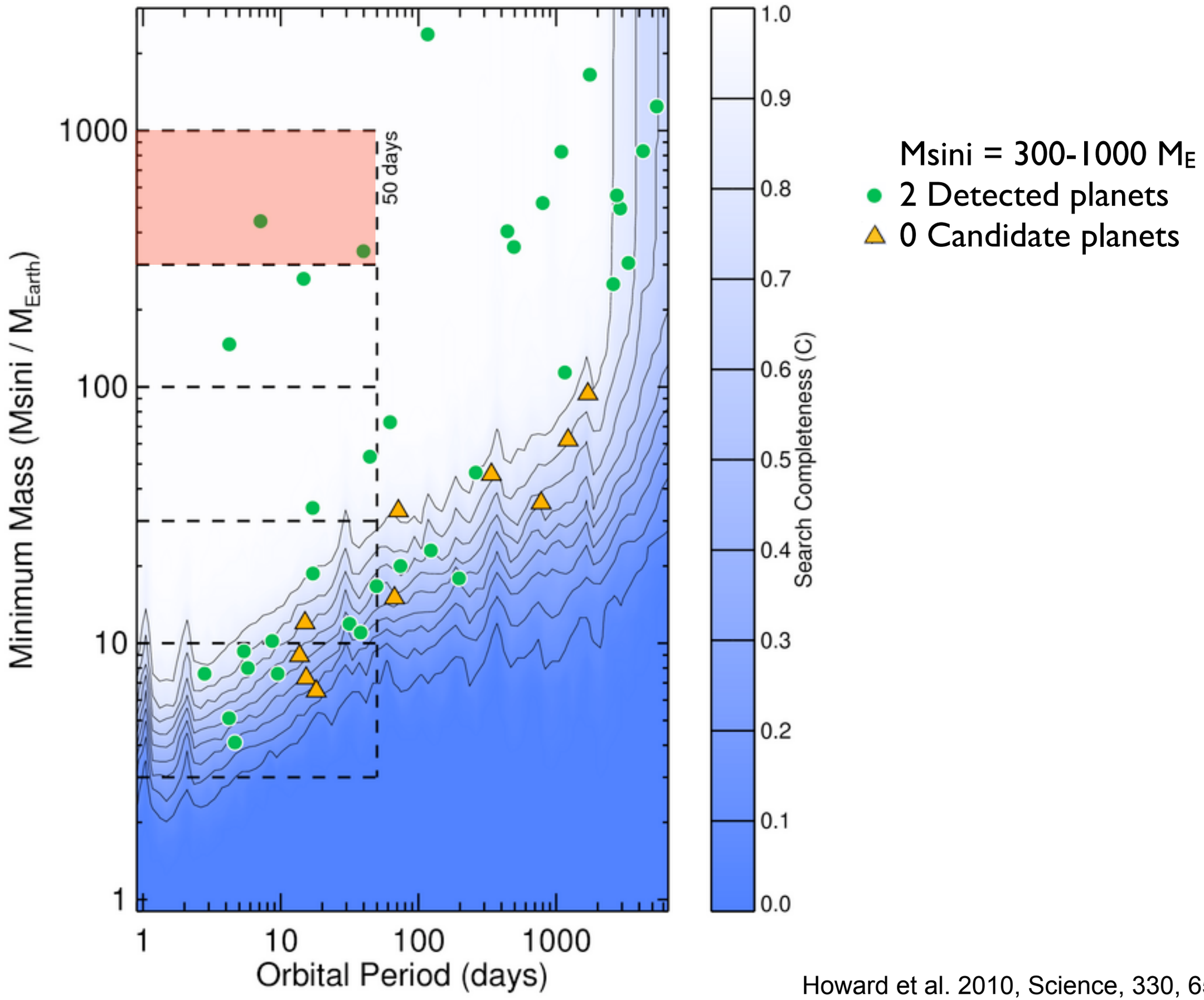


Detected planets

Candidate planets (FAPs ~ 1-5%)

Candidate planets included in counting planets.

Howard et al. 2010, Science, 330, 653



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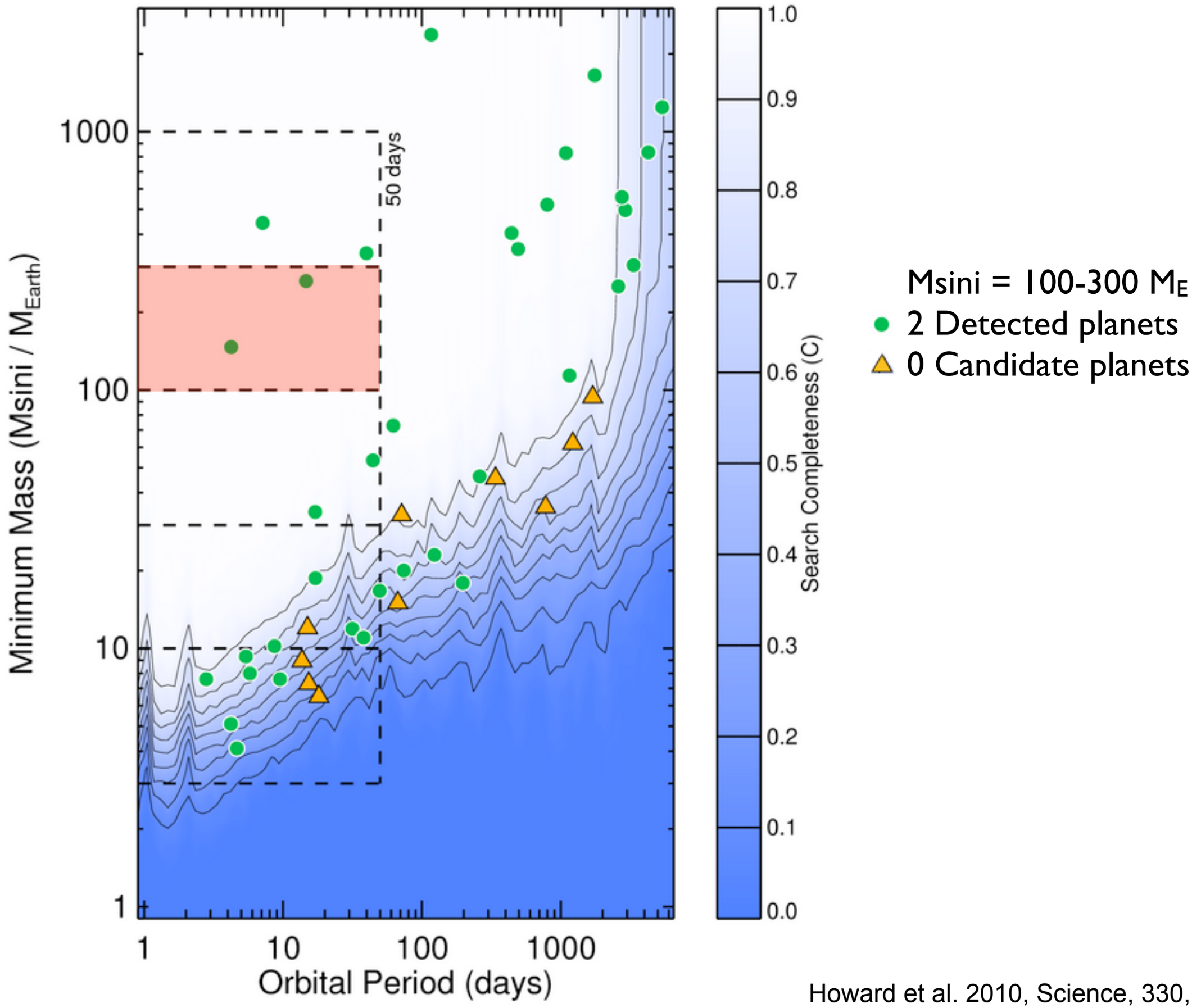

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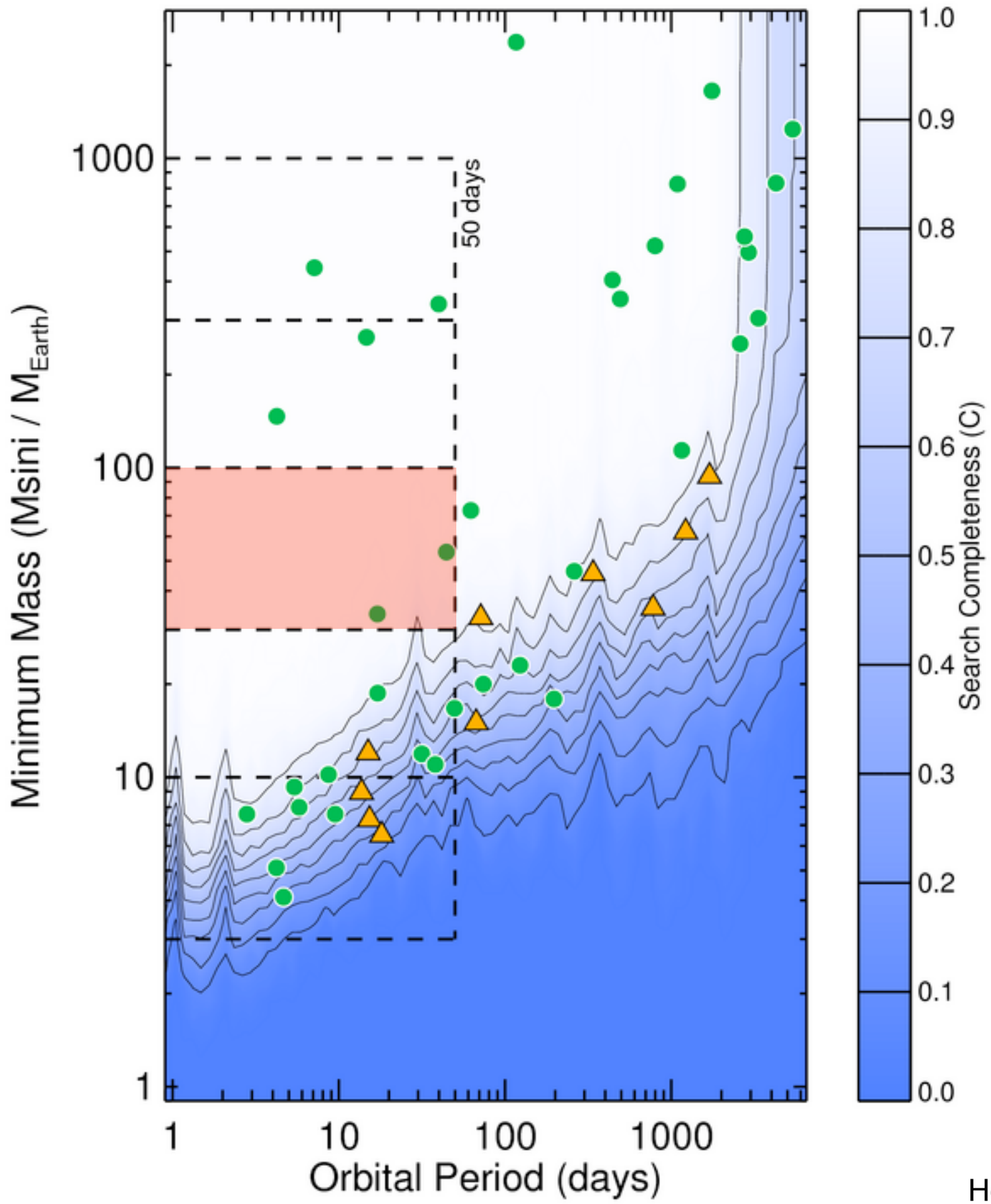
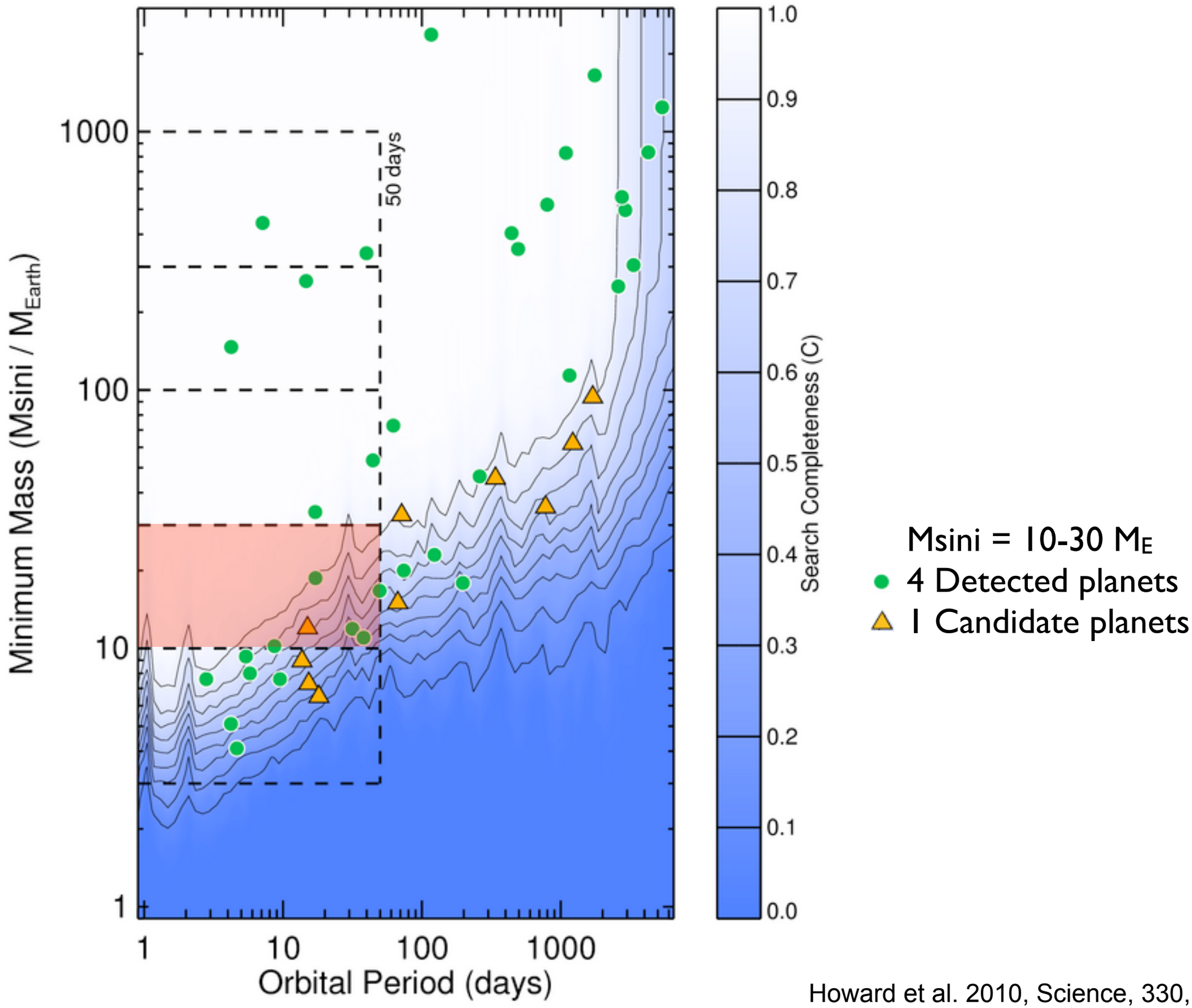


Msini = 30-100 M_E

- 2 Detected planets
- 0 Candidate planets

Howard et al. 2010, Science, 330, 653



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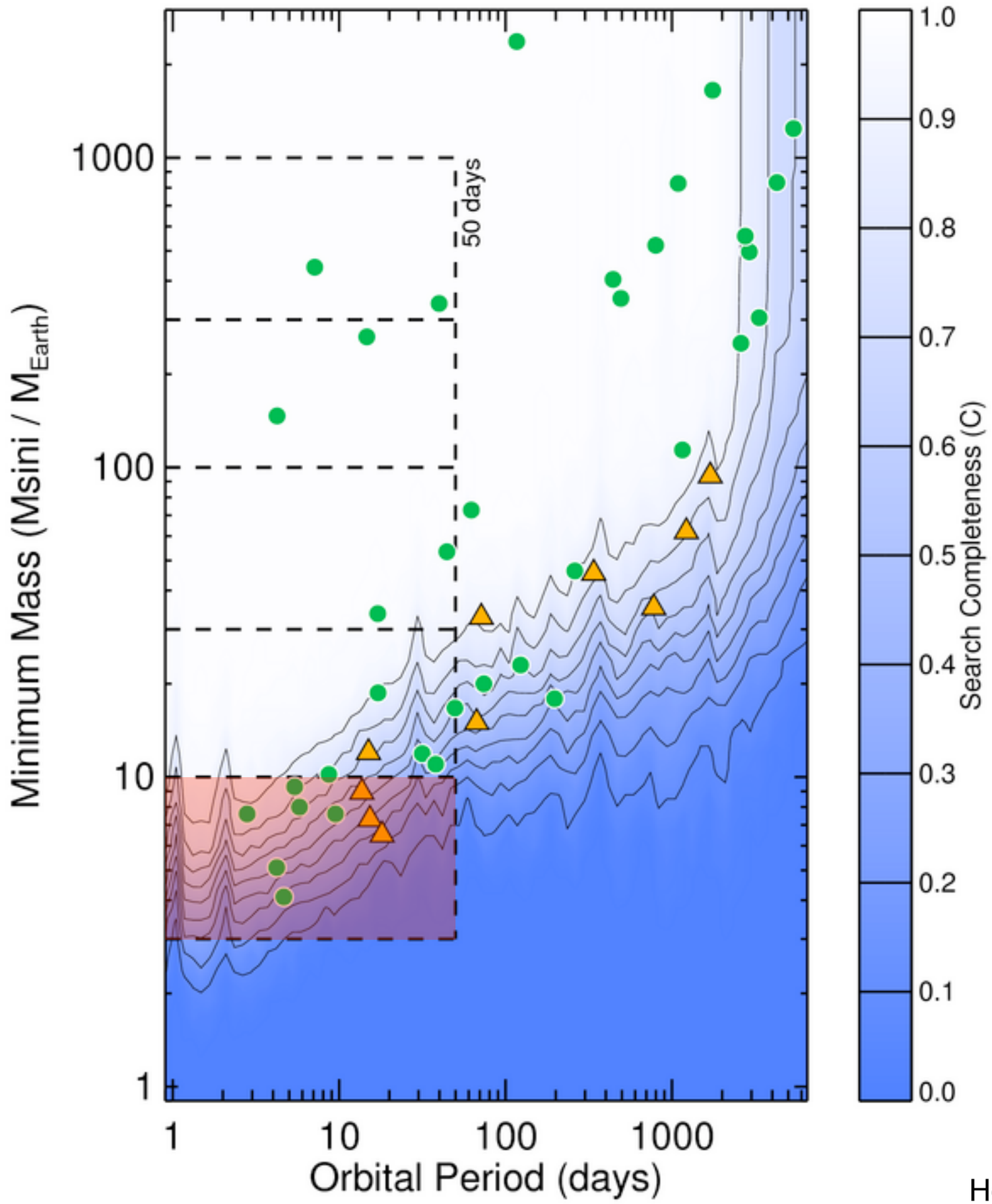
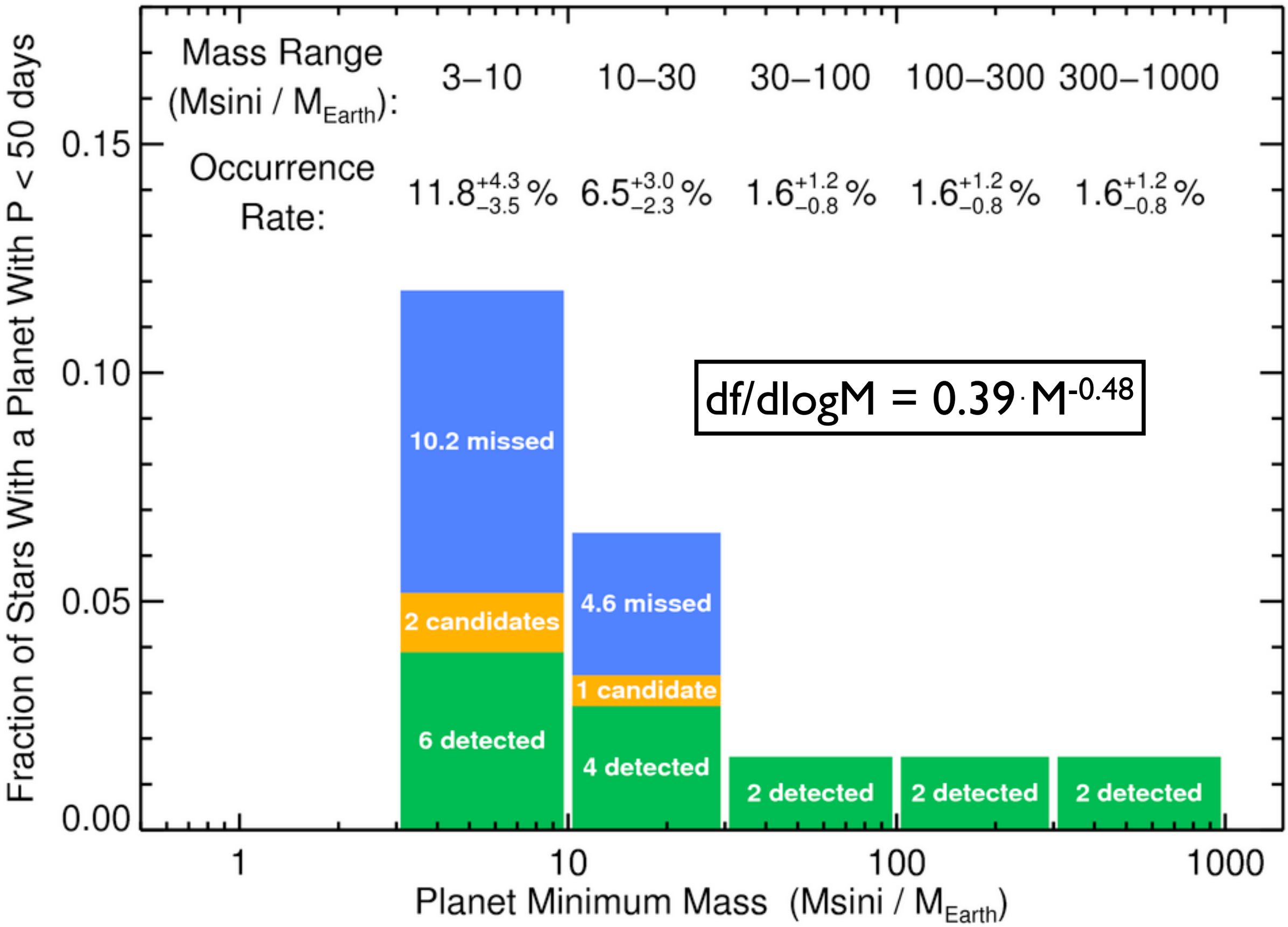


Msini = 3-10 M_E

● 6 Detected planets

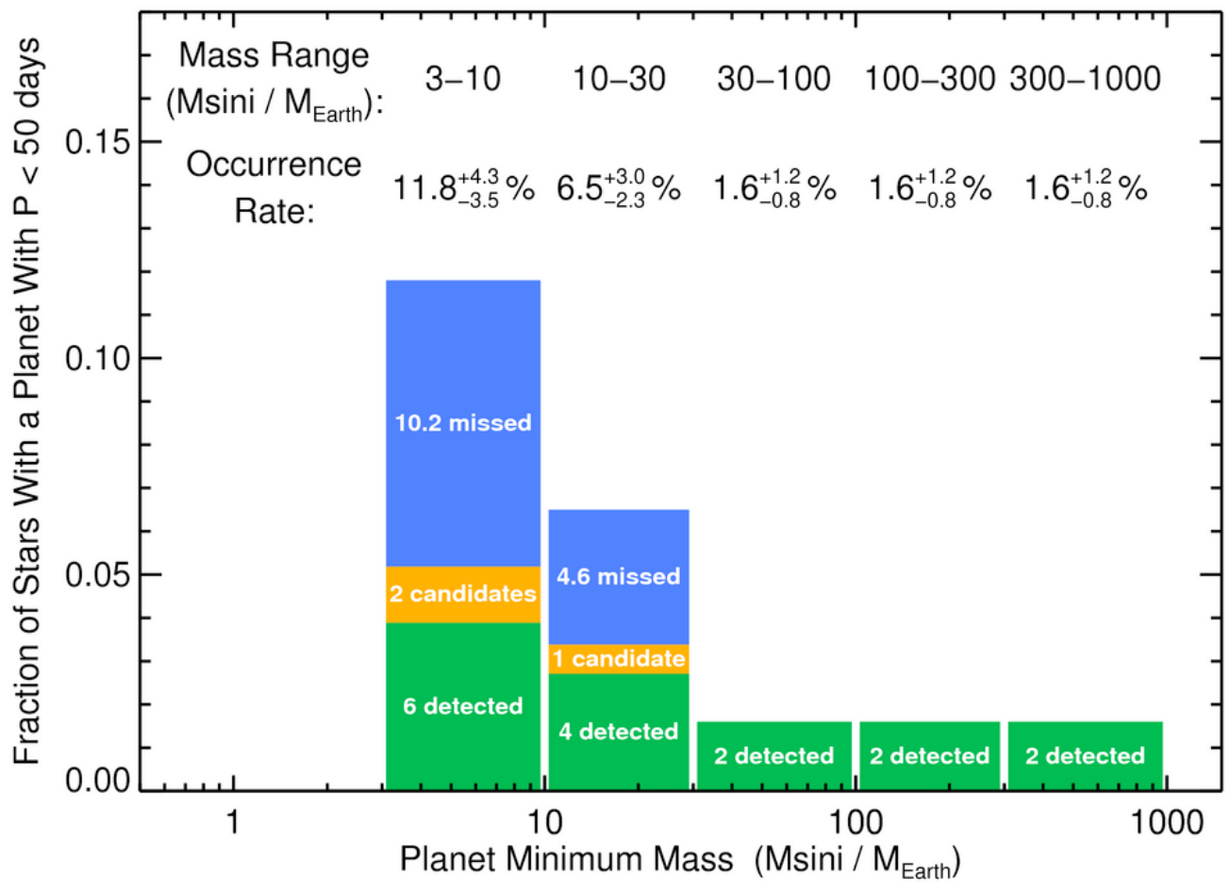
△ 2 Candidate planets

Howard et al. 2010, Science, 330, 653



Howard et al. 2010, Science, 330, 653

Key Result: Power-law Mass Distribution



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

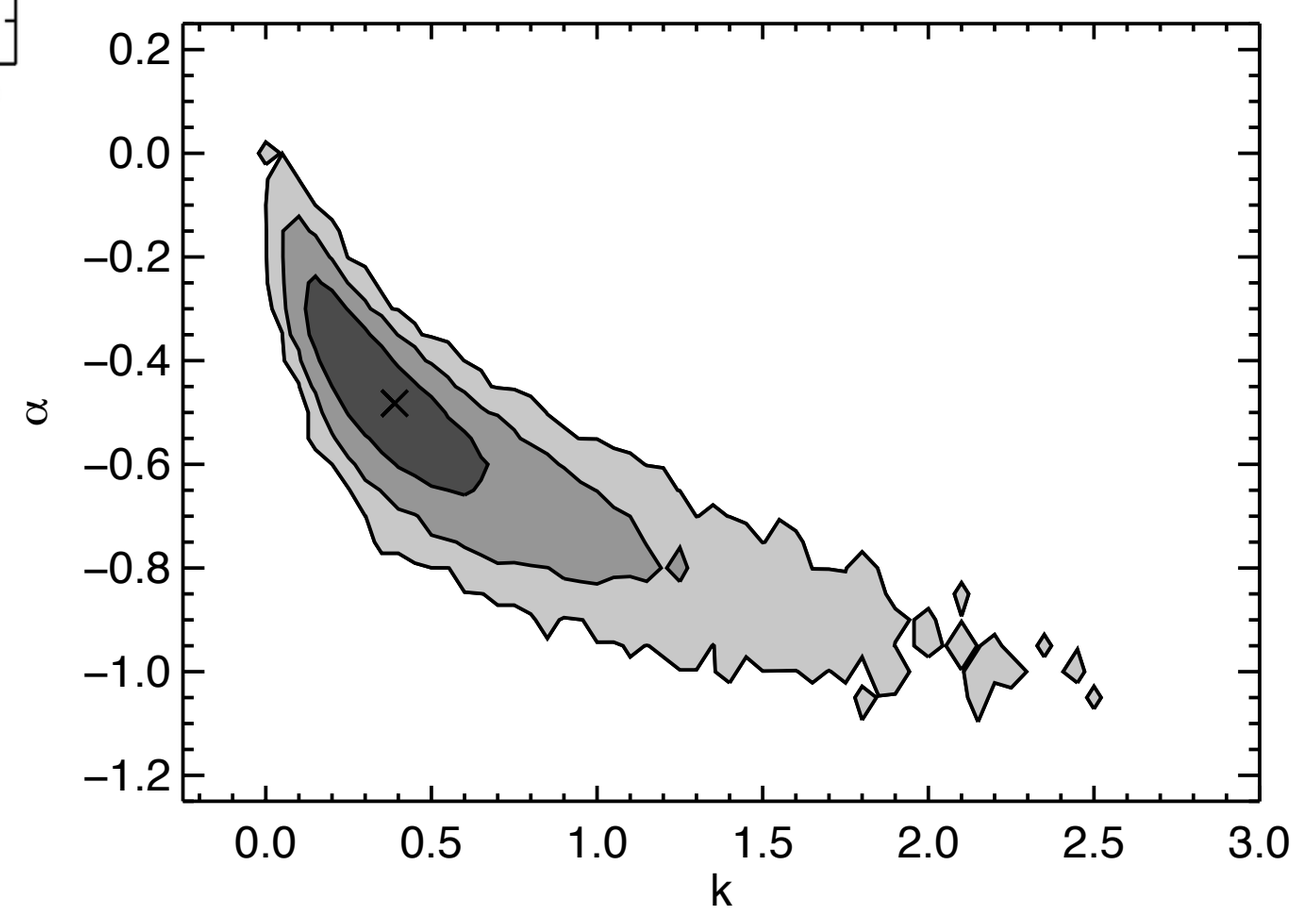
$$k = 0.39^{+0.27}_{-0.16}$$

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

<u>Compute Errors</u>

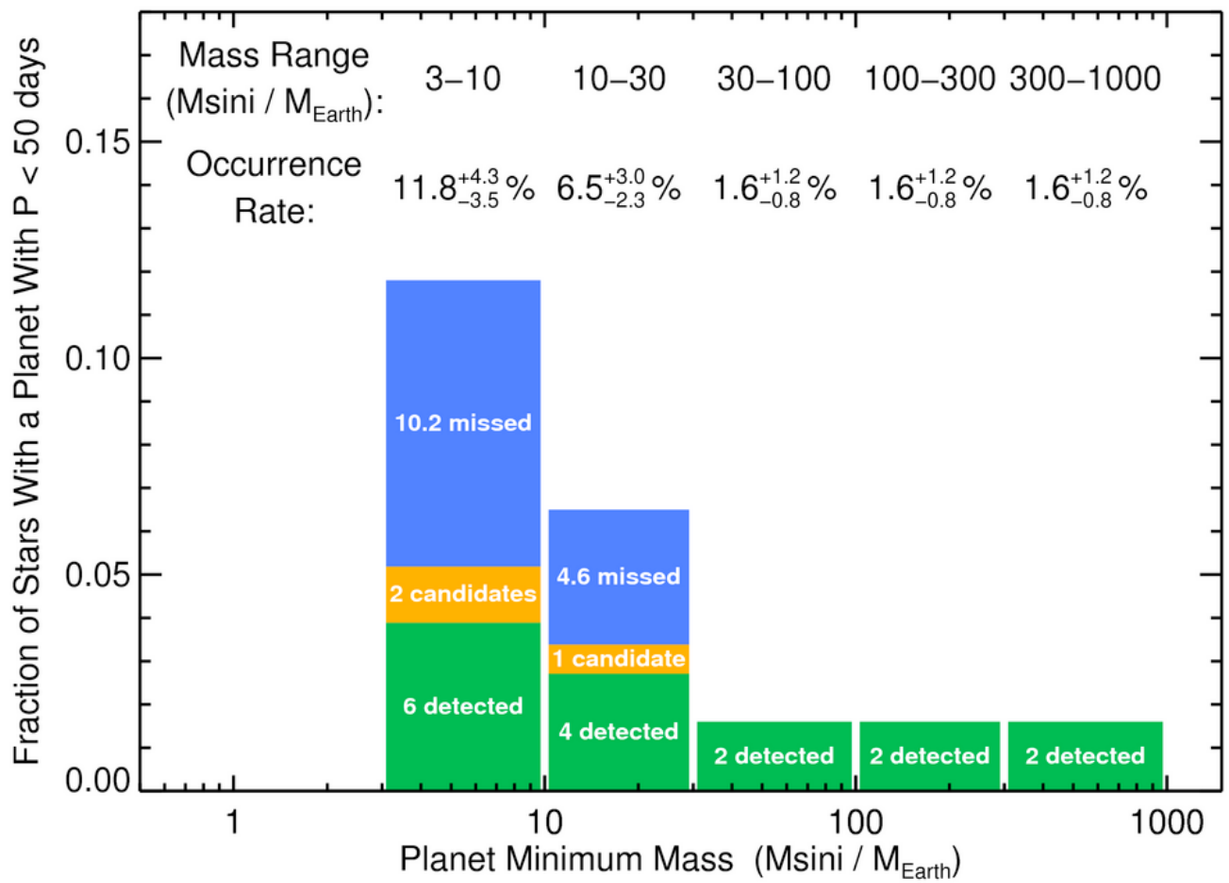
assume binomial statistics

scale missed planets w/det + cand



Howard et al. 2010, Science, 330, 653

Key Result: Occurrence rate of Super-Earths + Neptunes

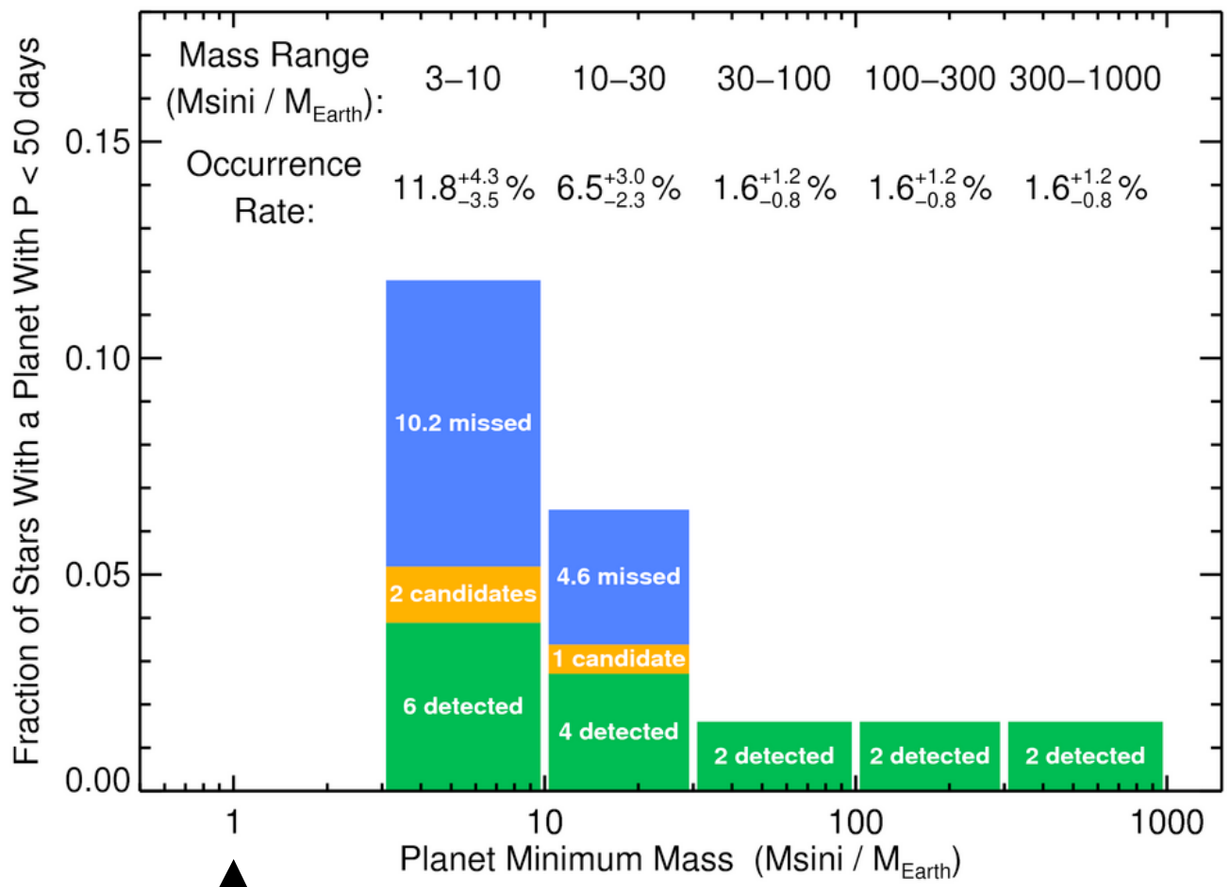


<u>Occurrence rate of super-Earths & Neptunes:</u>

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

Howard et al. 2010, Science, 330, 653

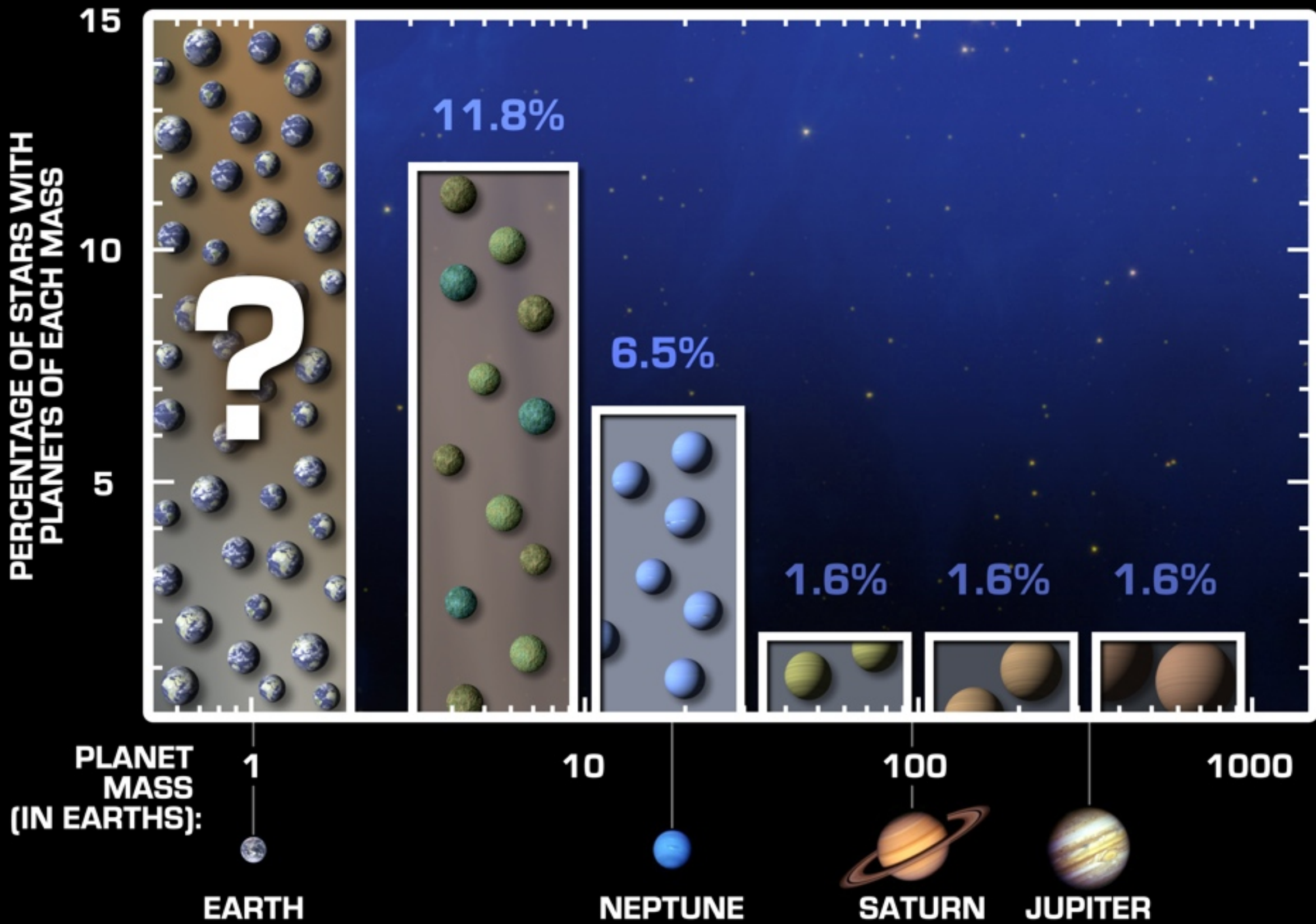
Key Result: Earth-mass Planets Common



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

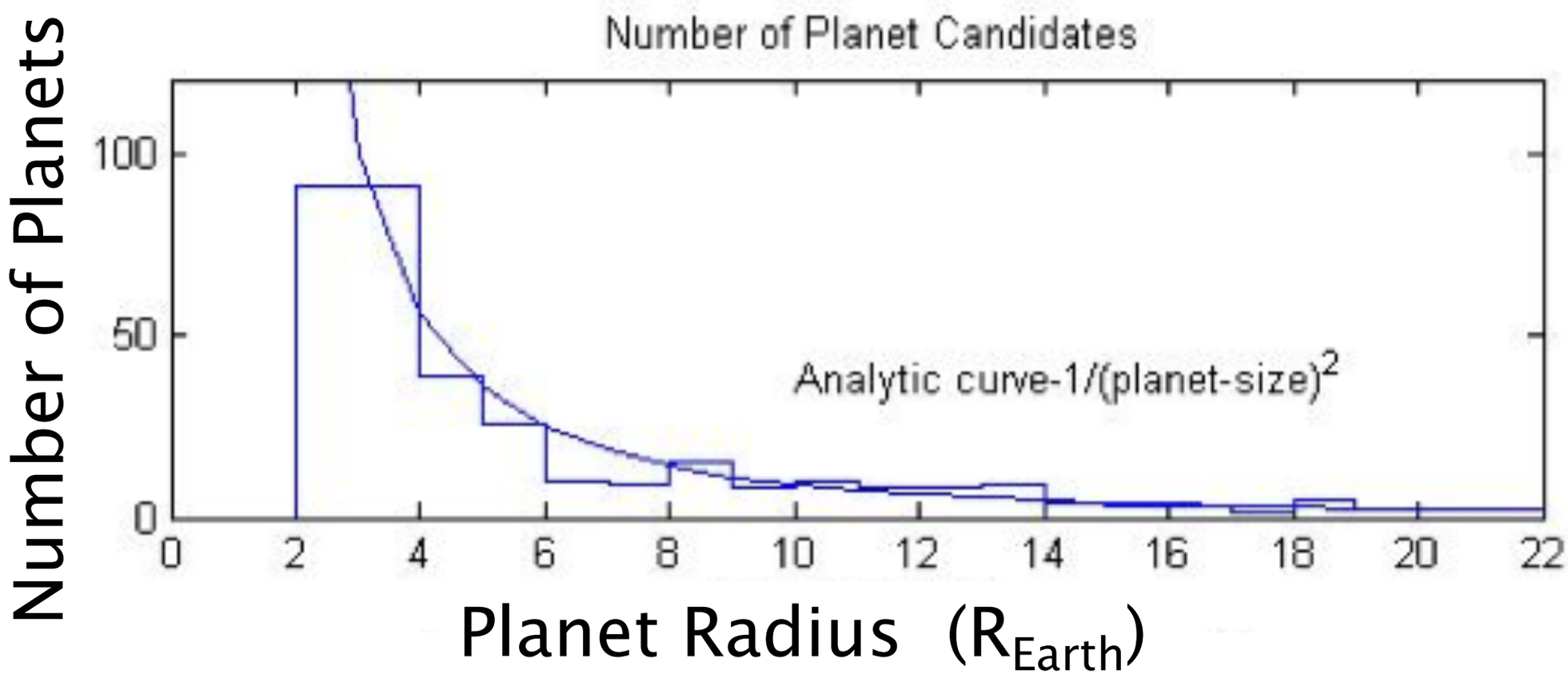
$\eta_{\mathbf{Earth}} = 23^{+16}_{-10}\%$ for $M\sin i = 0.5\text{-}2.0\ M_E$, $P < 50$ days

Howard et al. 2010, Science, 330, 653



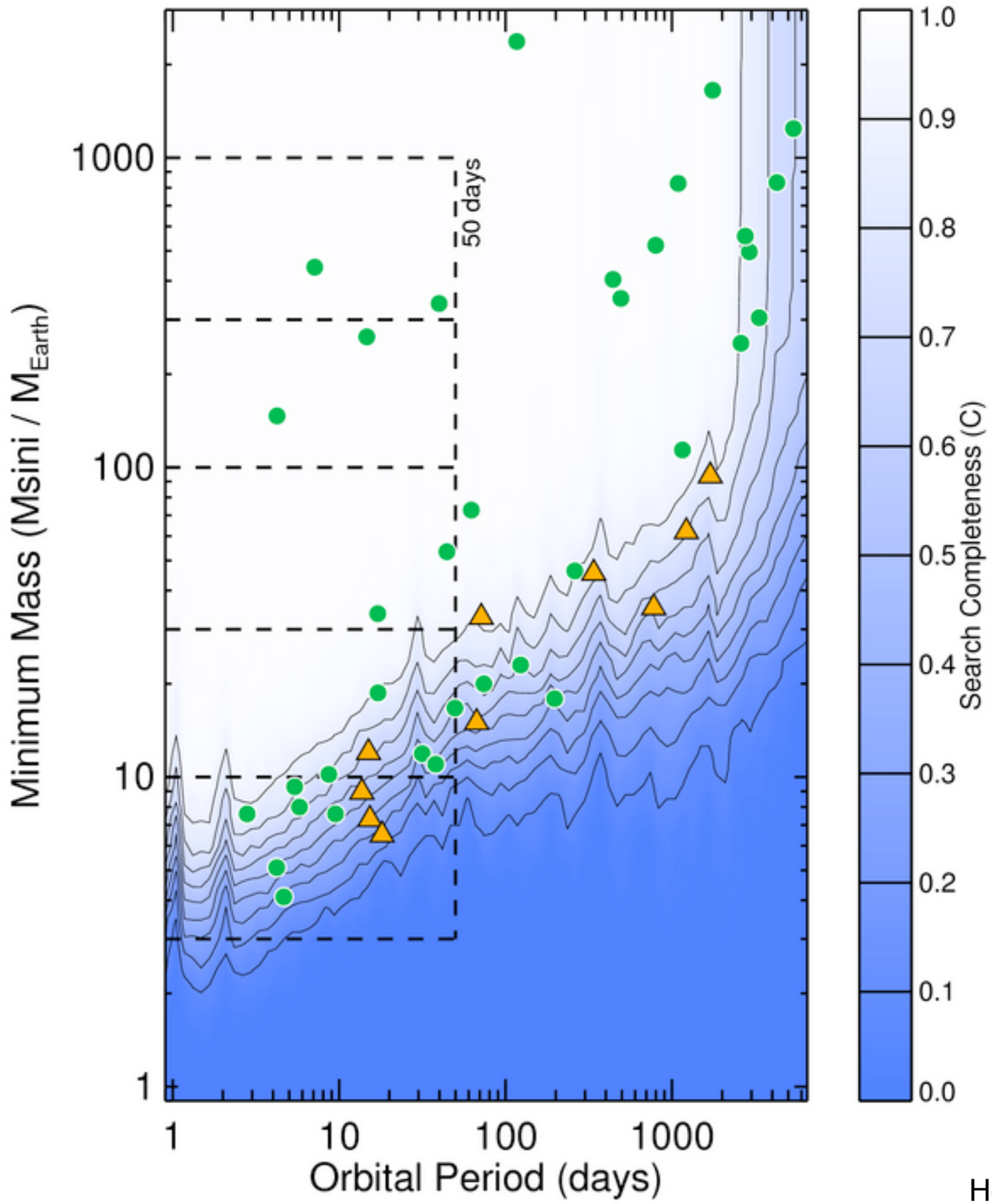
Credit: NASA/JPL-Caltech/UC Berkeley

Kepler:
Planet Candidate Occurrence Rises with Decreasing Planet Radius



Mapping R -> M
requires densities

Borucki et al. (2010)



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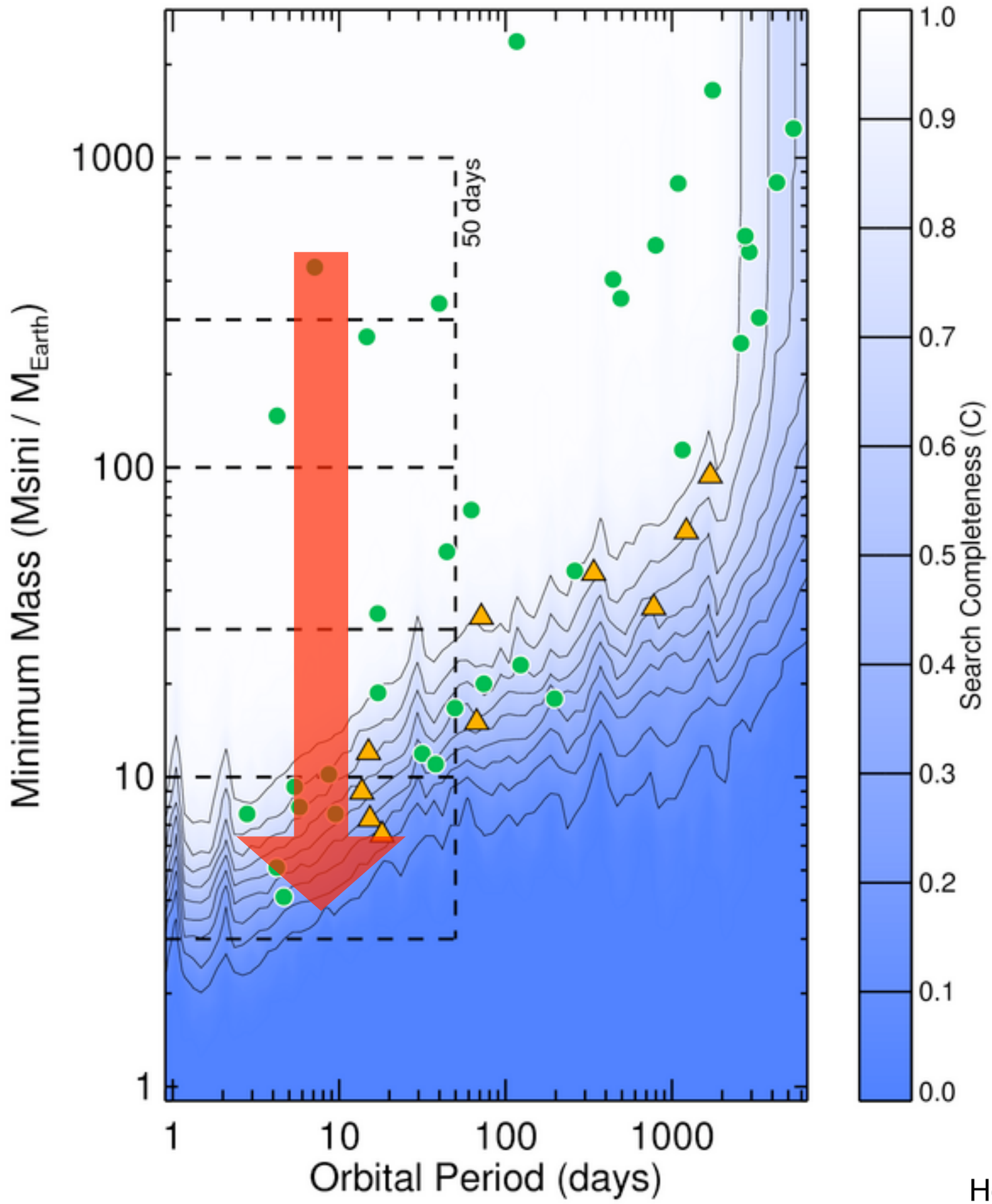

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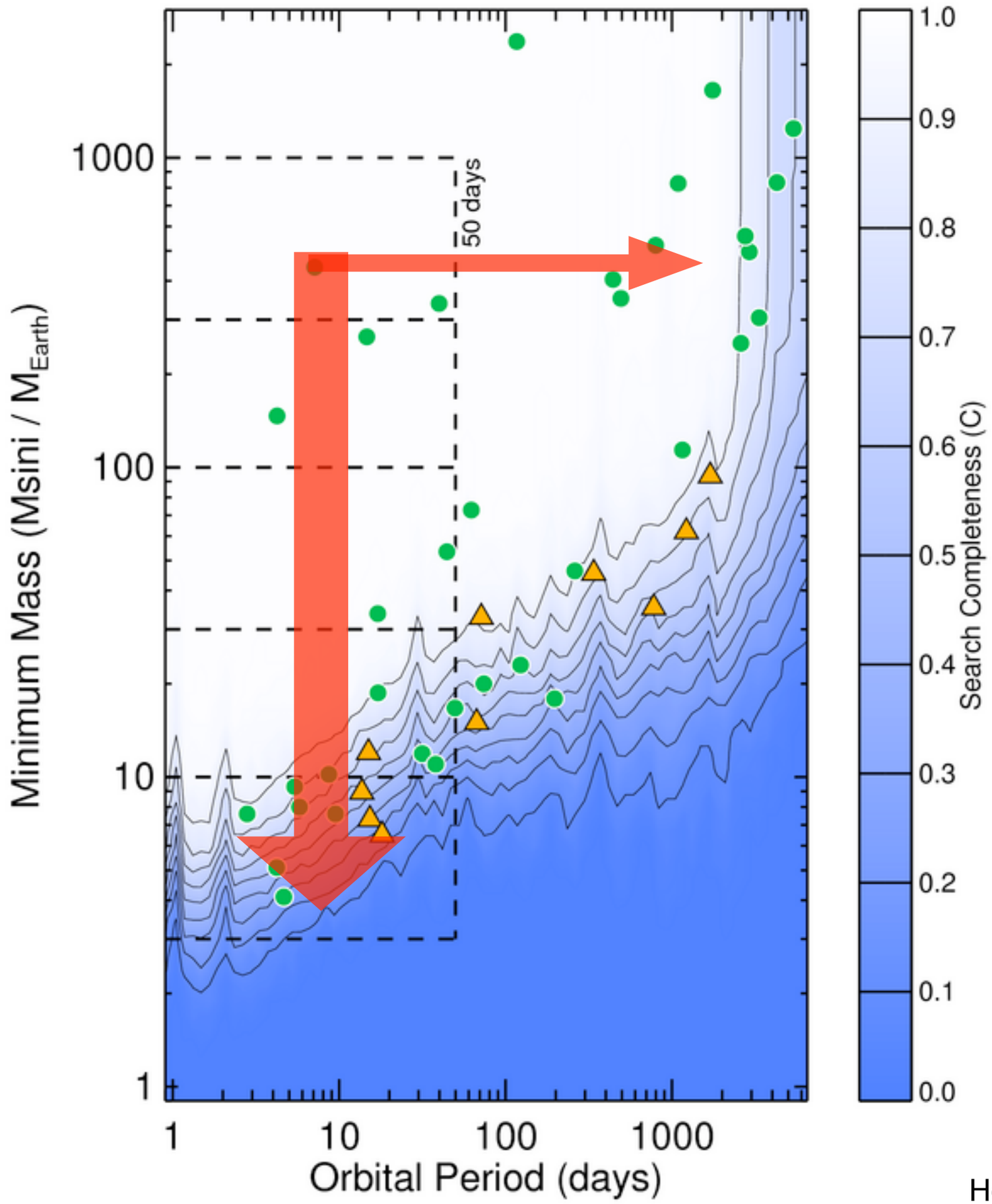

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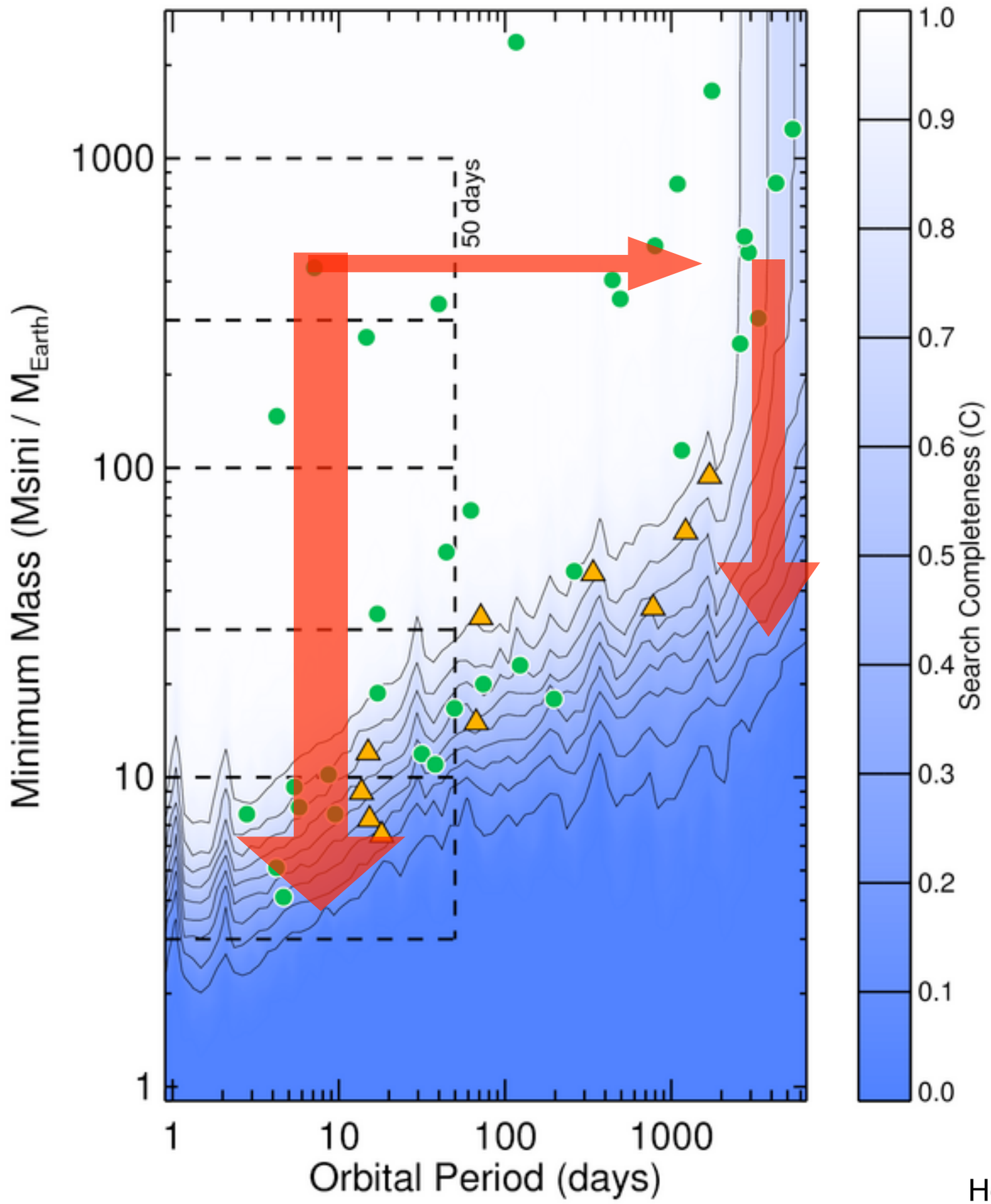

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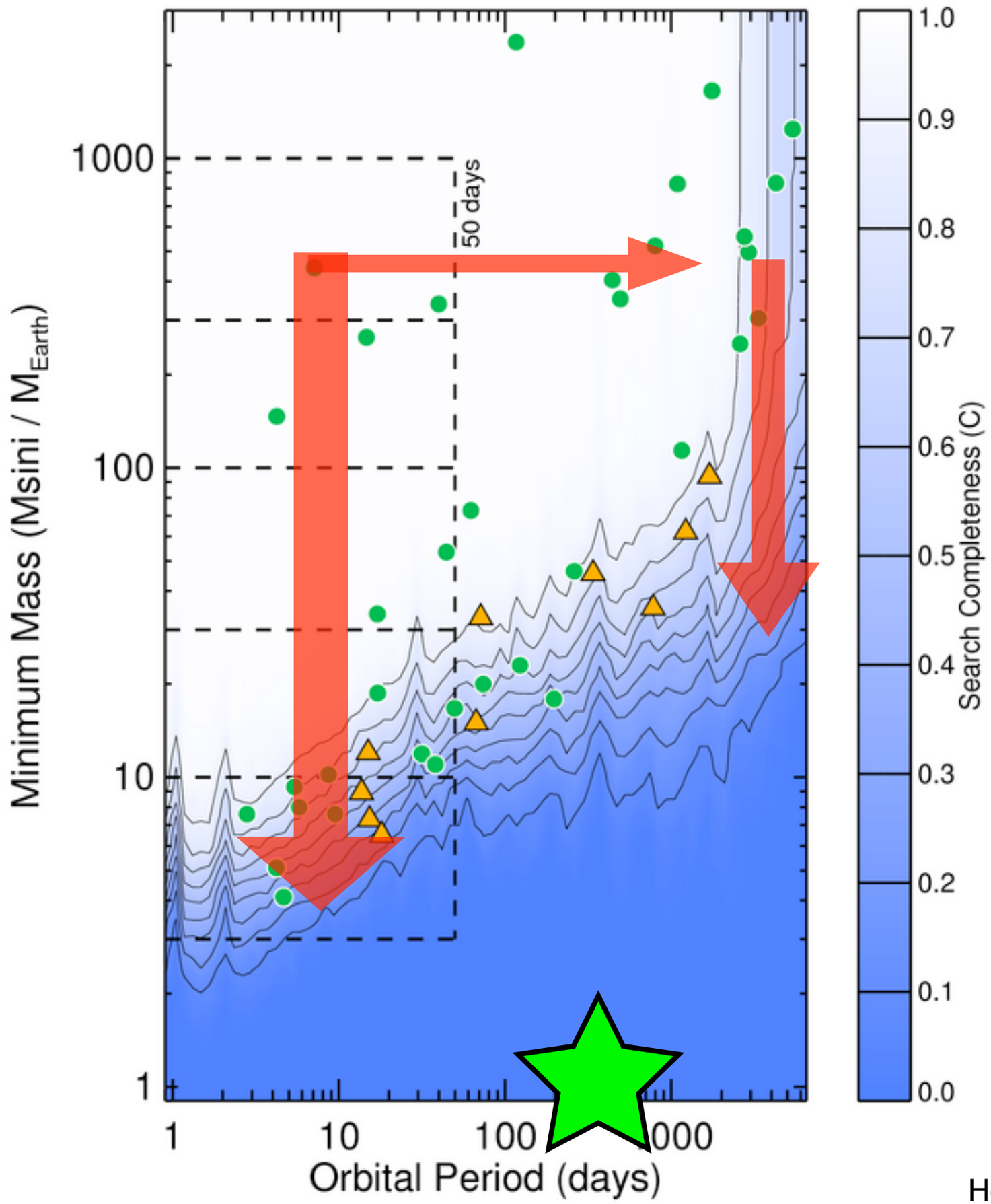

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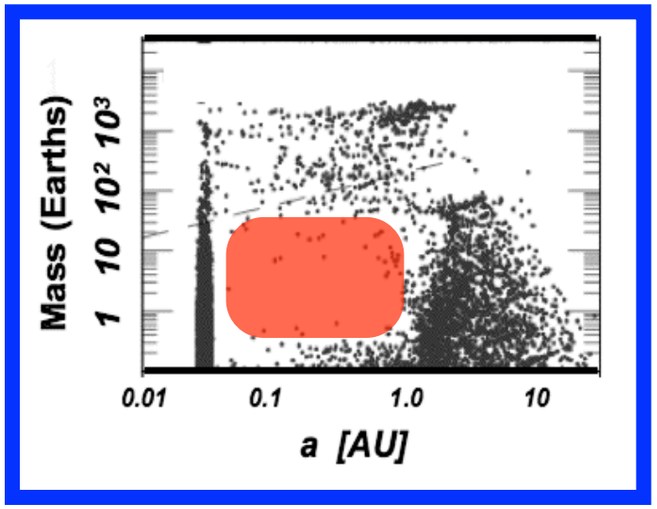

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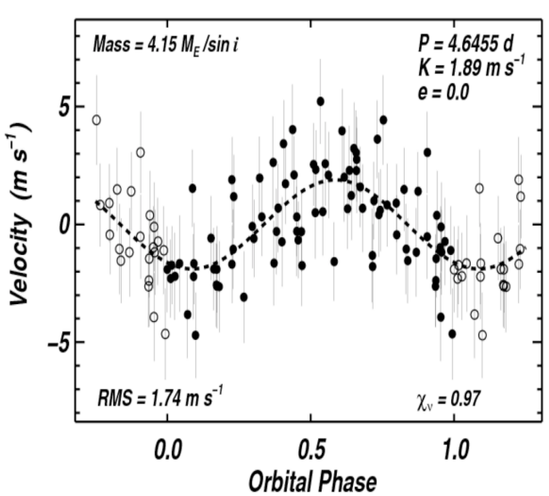
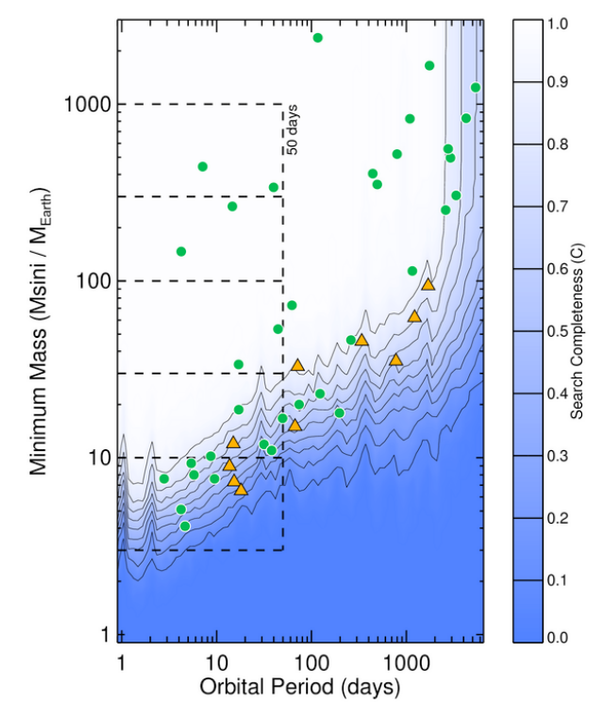
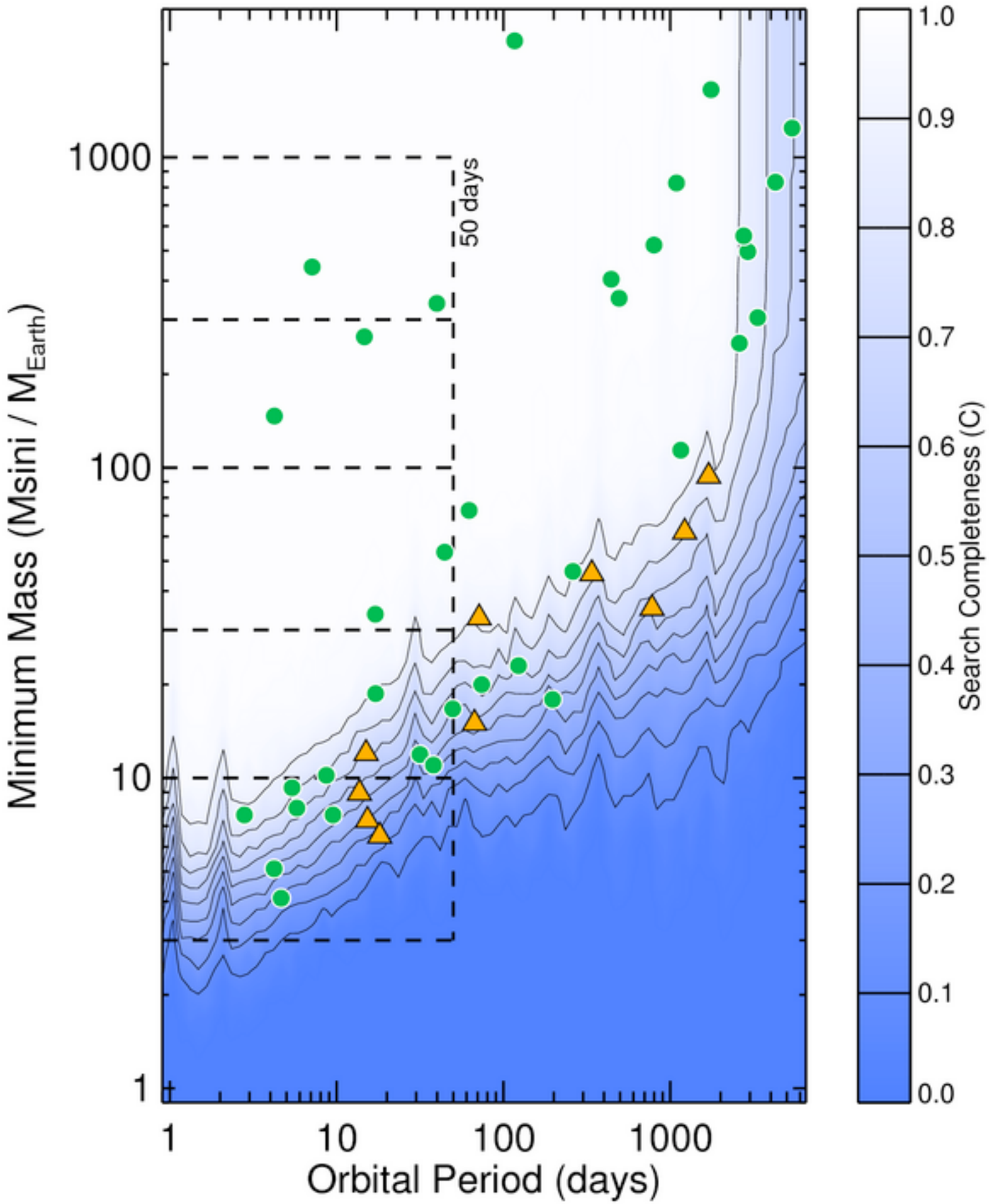
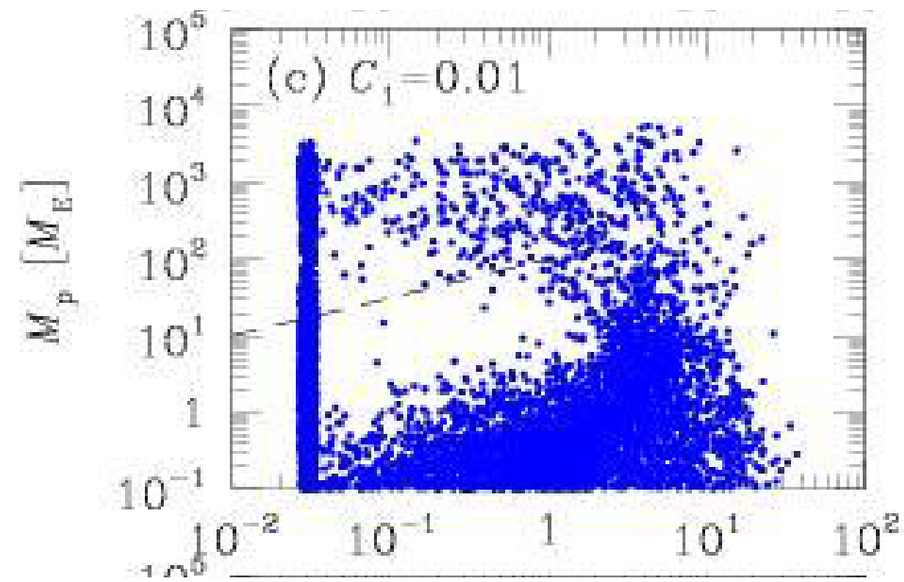
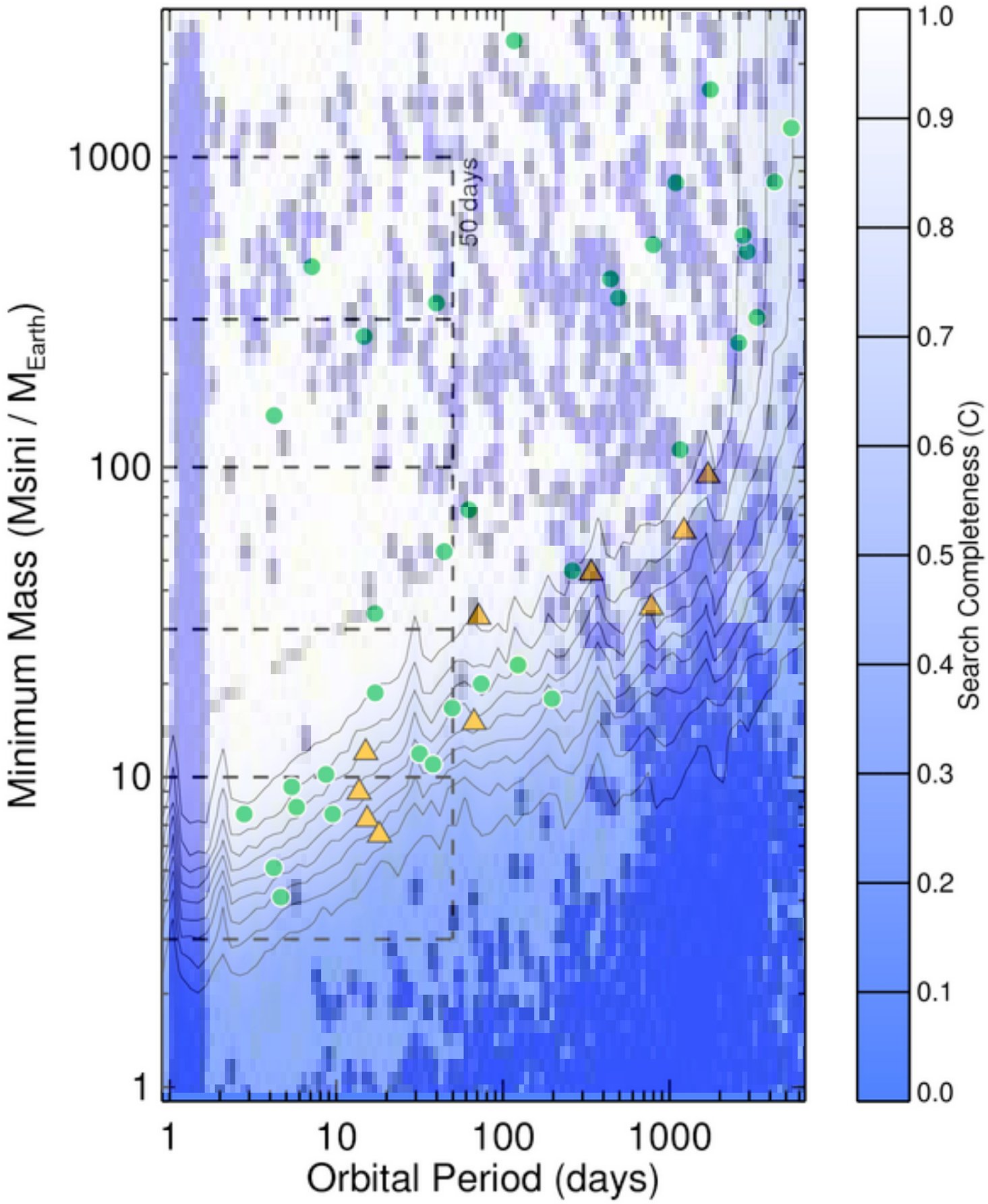






Compare with Ida & Lin:





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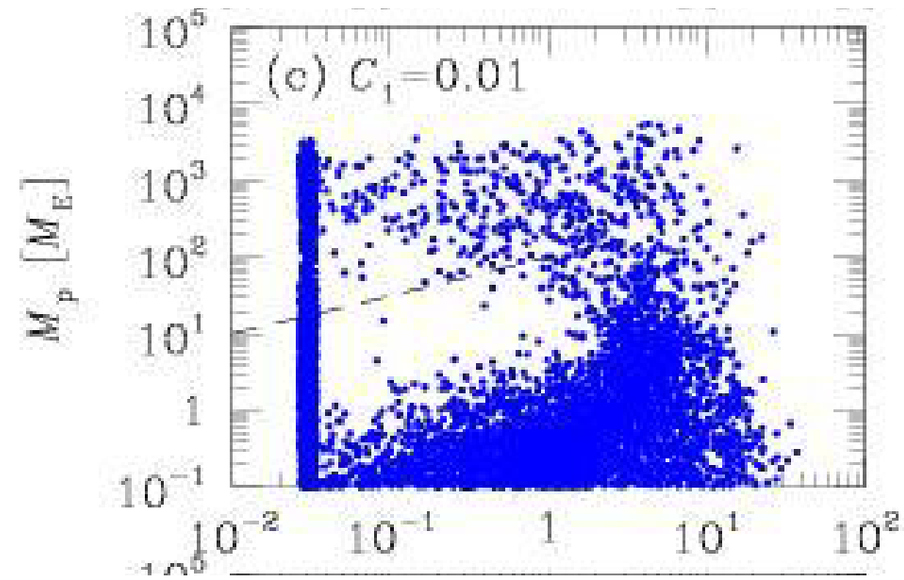
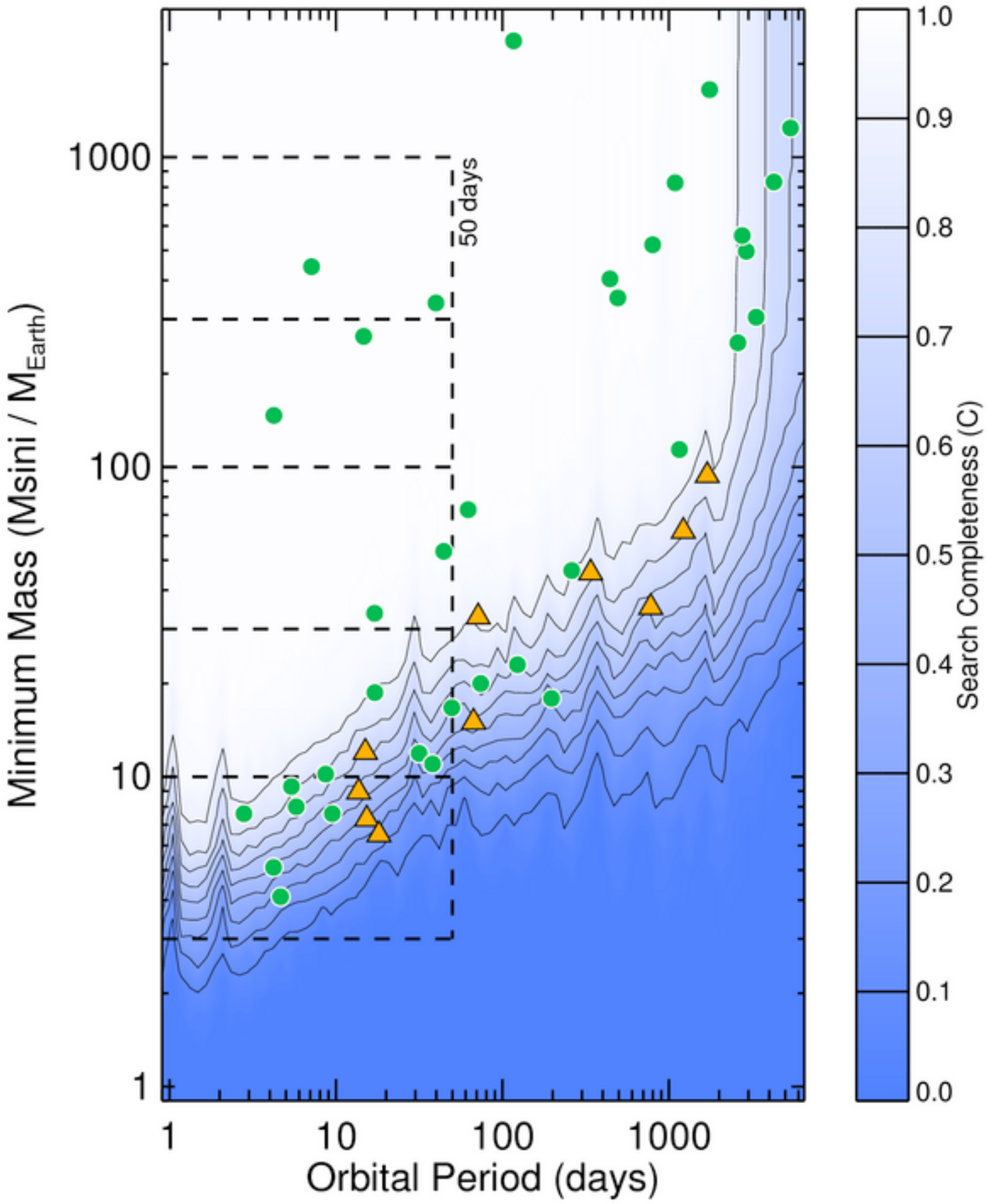
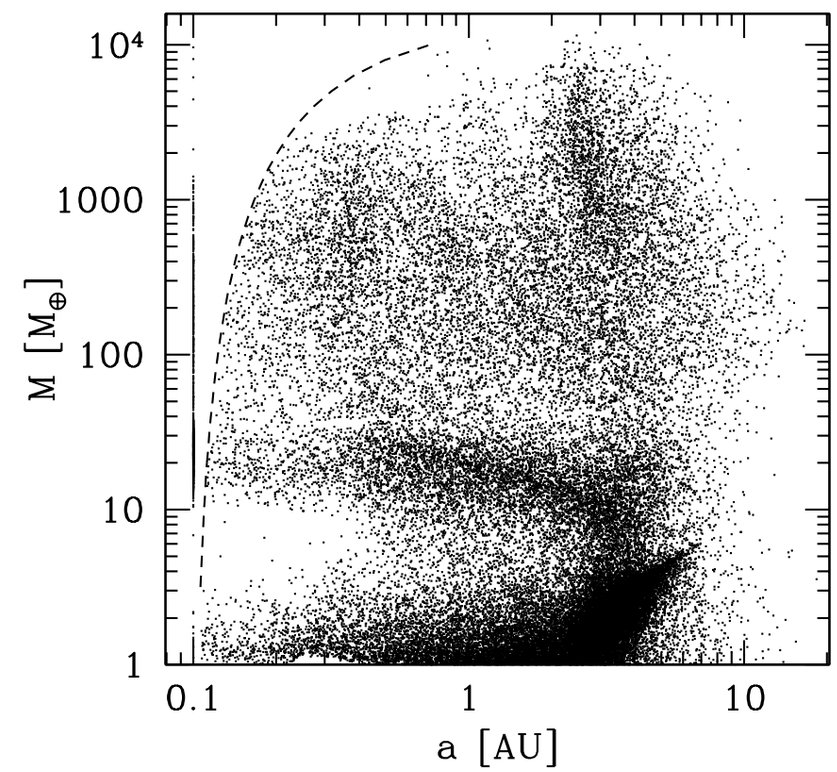


Compare with Mordasini et al.





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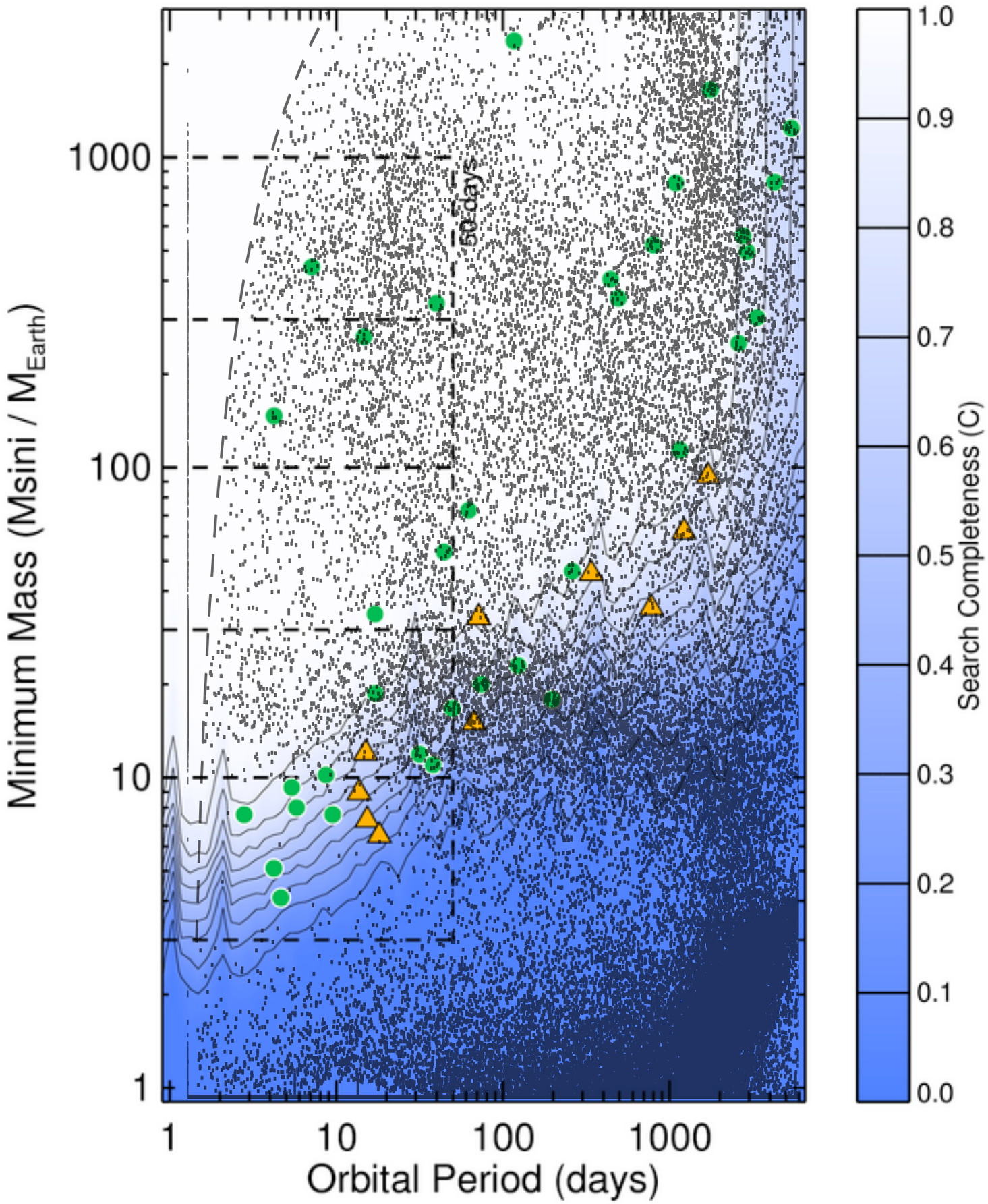

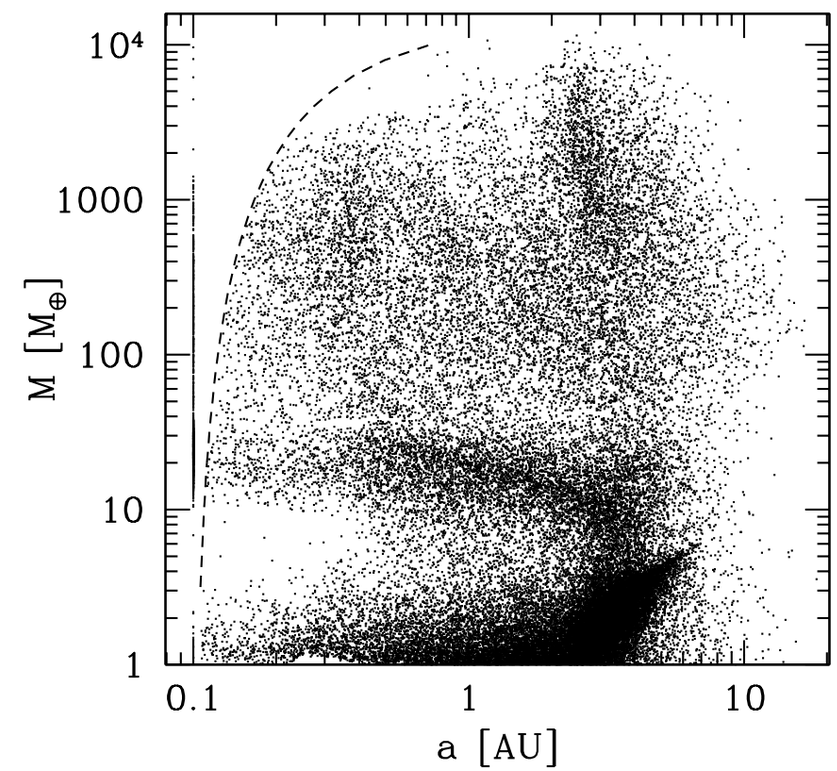

Solutions?

How are close-in low-mass planets made?

Ideas:

1. Improved Disk Migration
   non-isothermal disk alters migration behavior (Mordasini, Paardekooper, others)

Movie courtesy C. Mordasini

2. Planet-planet scattering/growth
   after gas clears in ~10 Myr (Ida & Lin, others)

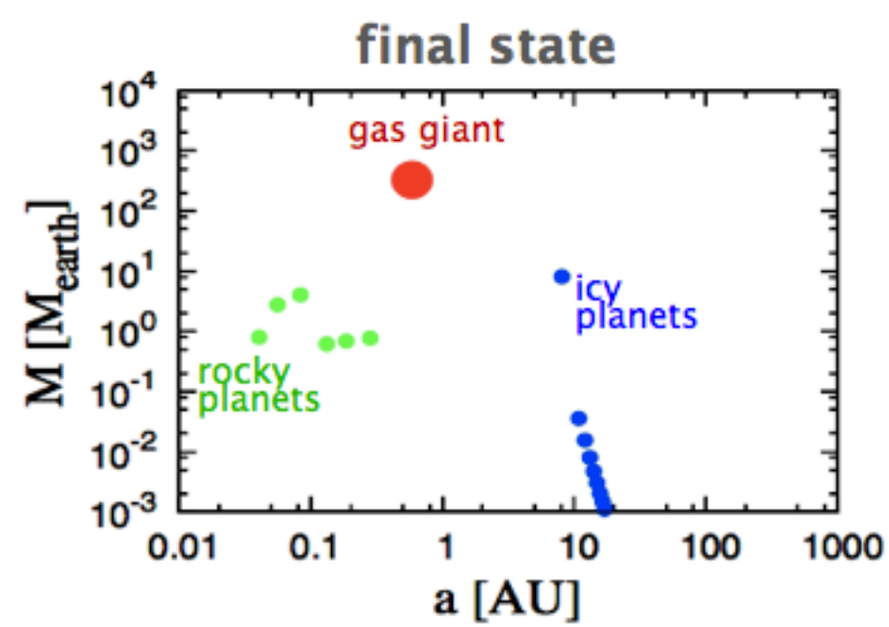

Figure courtesy S. Ida

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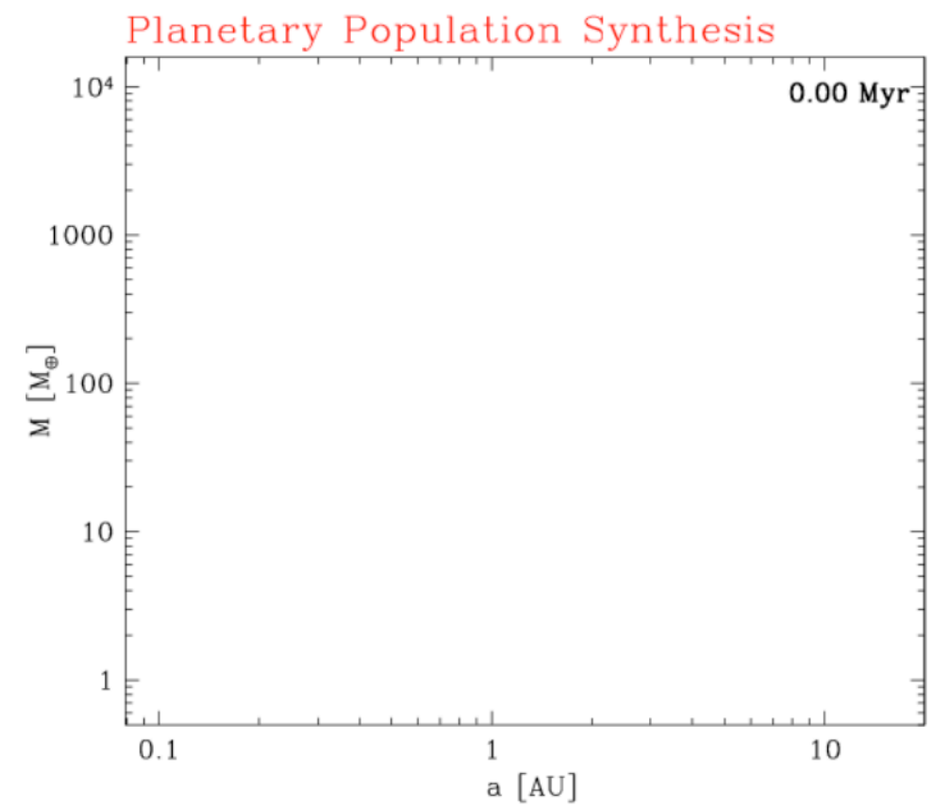

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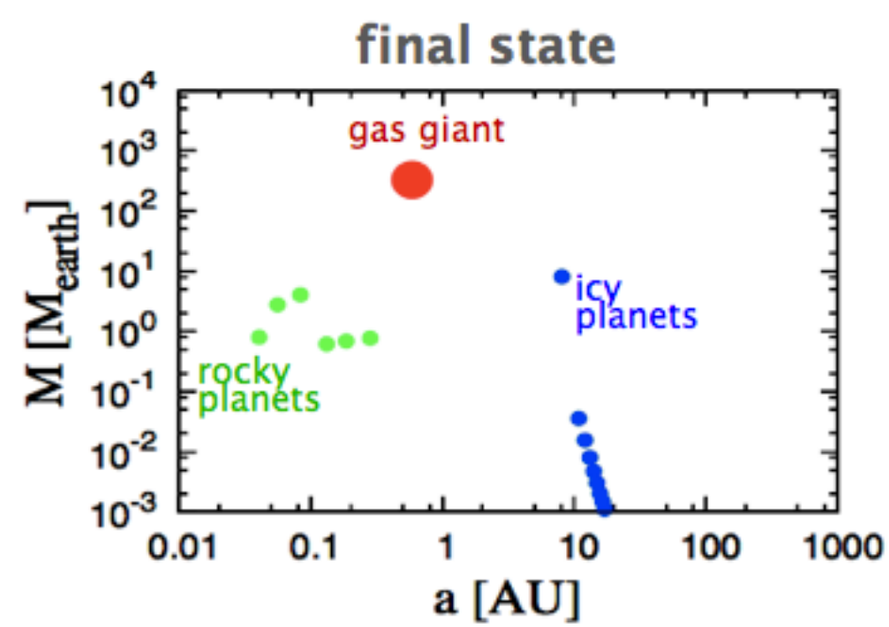

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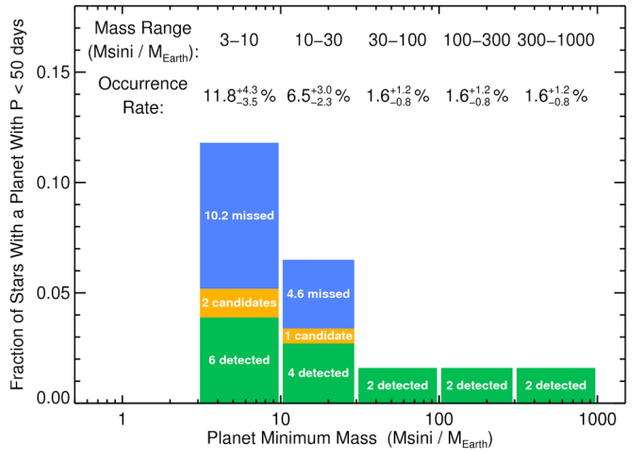

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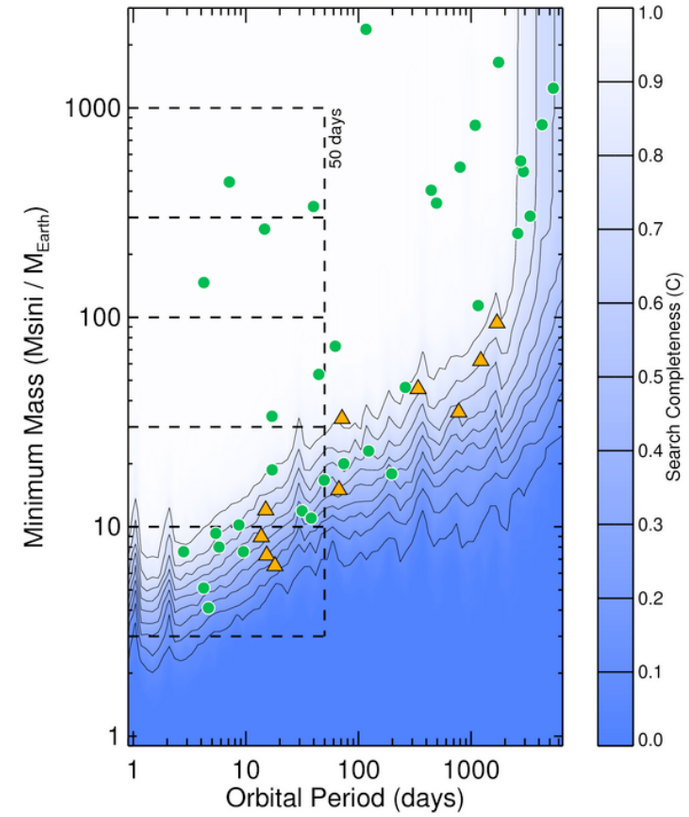
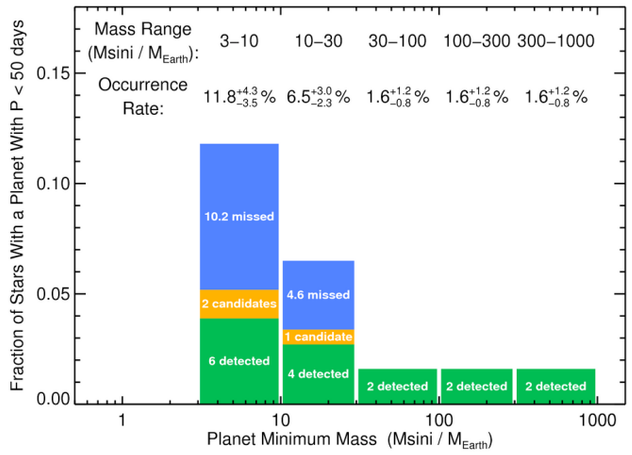


1. Planet Mass Distribution

$$df/d\log M = 0.39 \cdot M^{-0.48}$$



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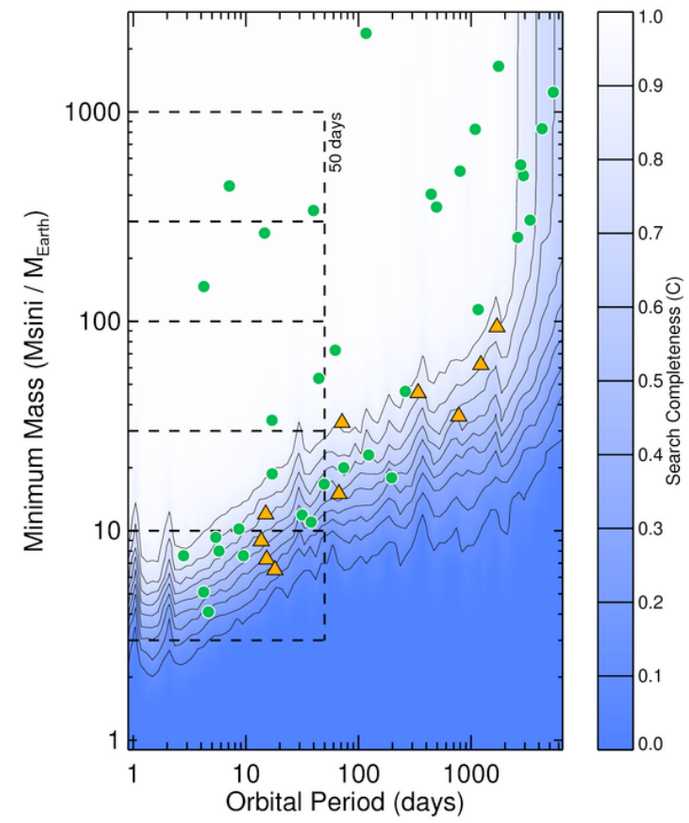

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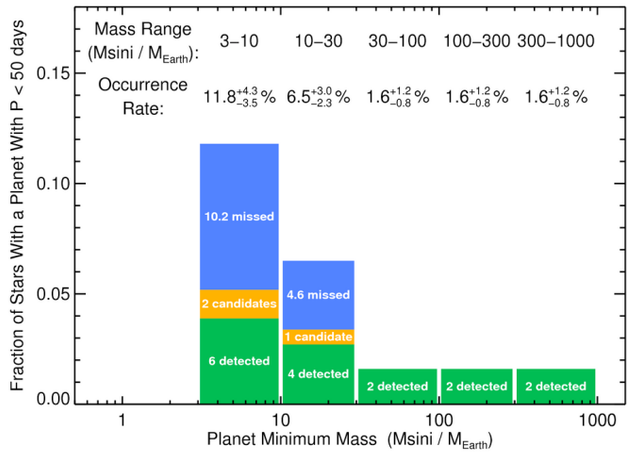
2. 15% of Solar-type stars have planets with $M\sin i$ = 3-30 M_{Earth} and P < 50 days



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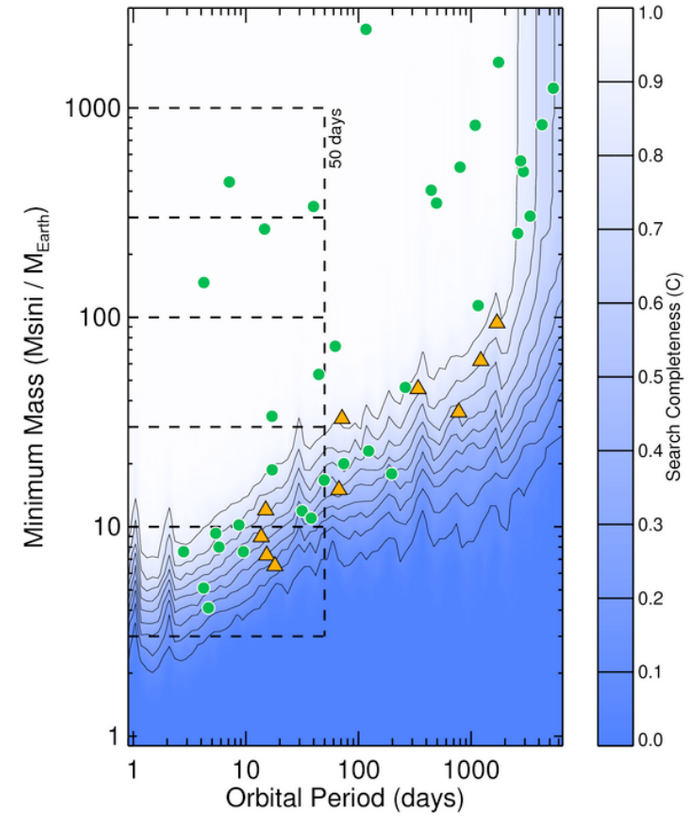

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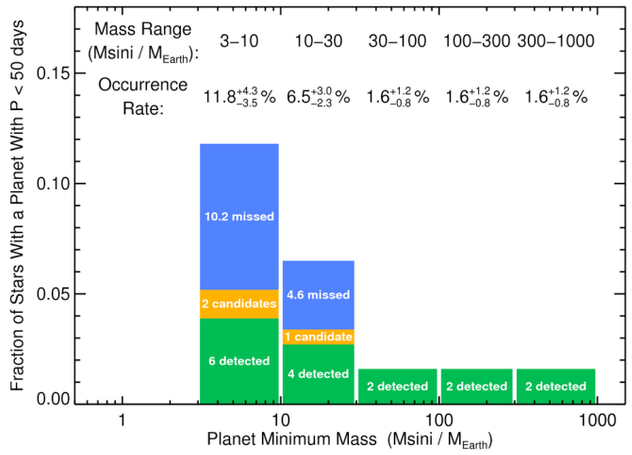

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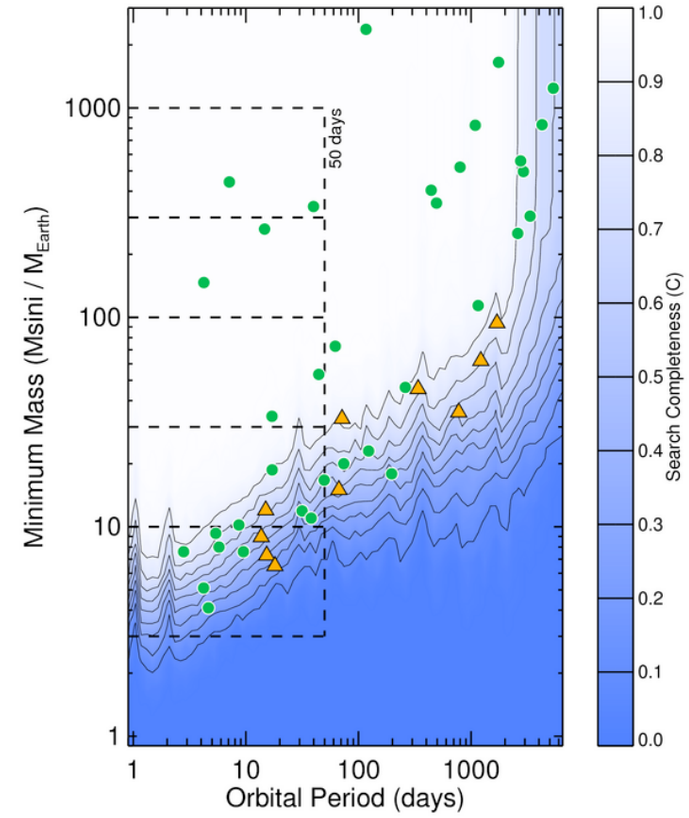

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4. Type I and Type II migration in a gas disk is not well supported by observations

Questions?