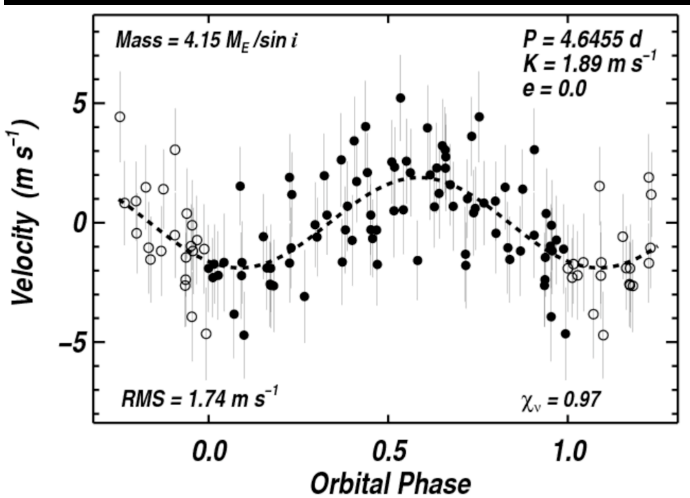
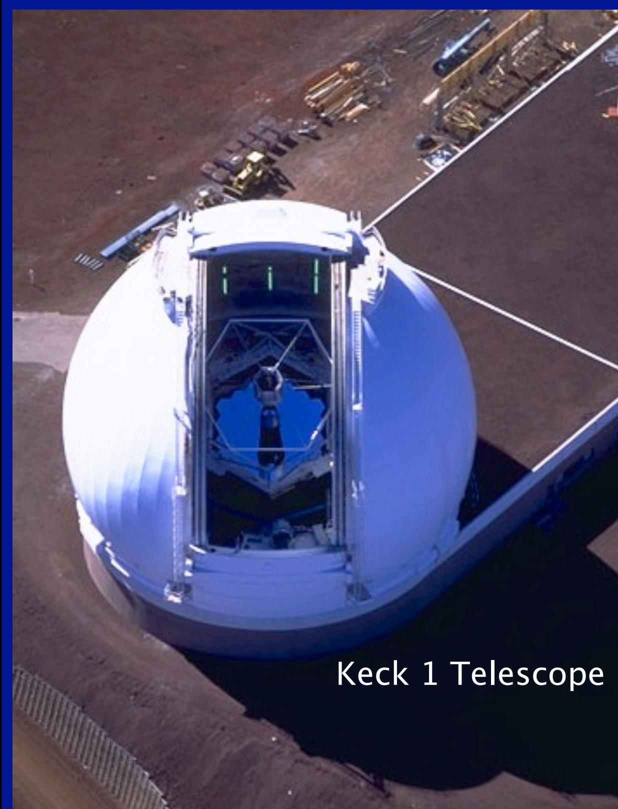
ExoPlanet Physics from the Keck Observatory

Geoff Marcy




Keck 1 Telescope

Collaborators

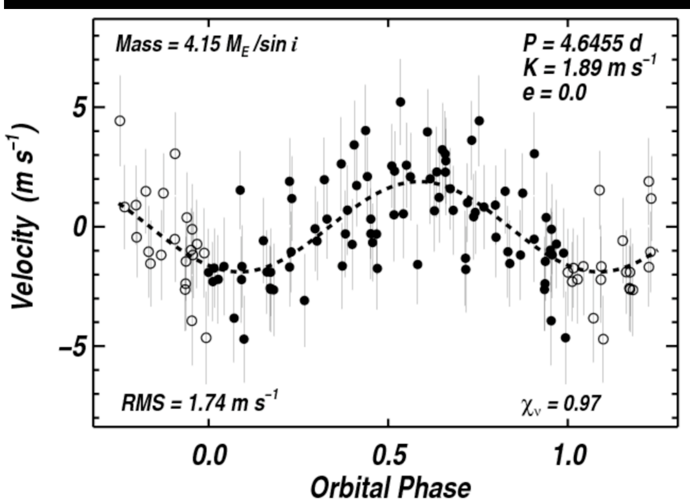
Andrew Howard
Jason Wright
Debra Fischer
John Johnson
Howard Isaacson
Greg Henry
Julien Spronck
Jeff Valenti
Jay Anderson
Nikolai Piskunov
Katie Peek
Doug Lin
Shigeru Ida
… many more!

The Kavli Institute for Theoretical Physics
University of California, Santa Barbara

The NASA-UC

Eta-Earth Survey for Low-mass Planets From Keck Observatory

- Andrew Howard & Geoff Marcy -



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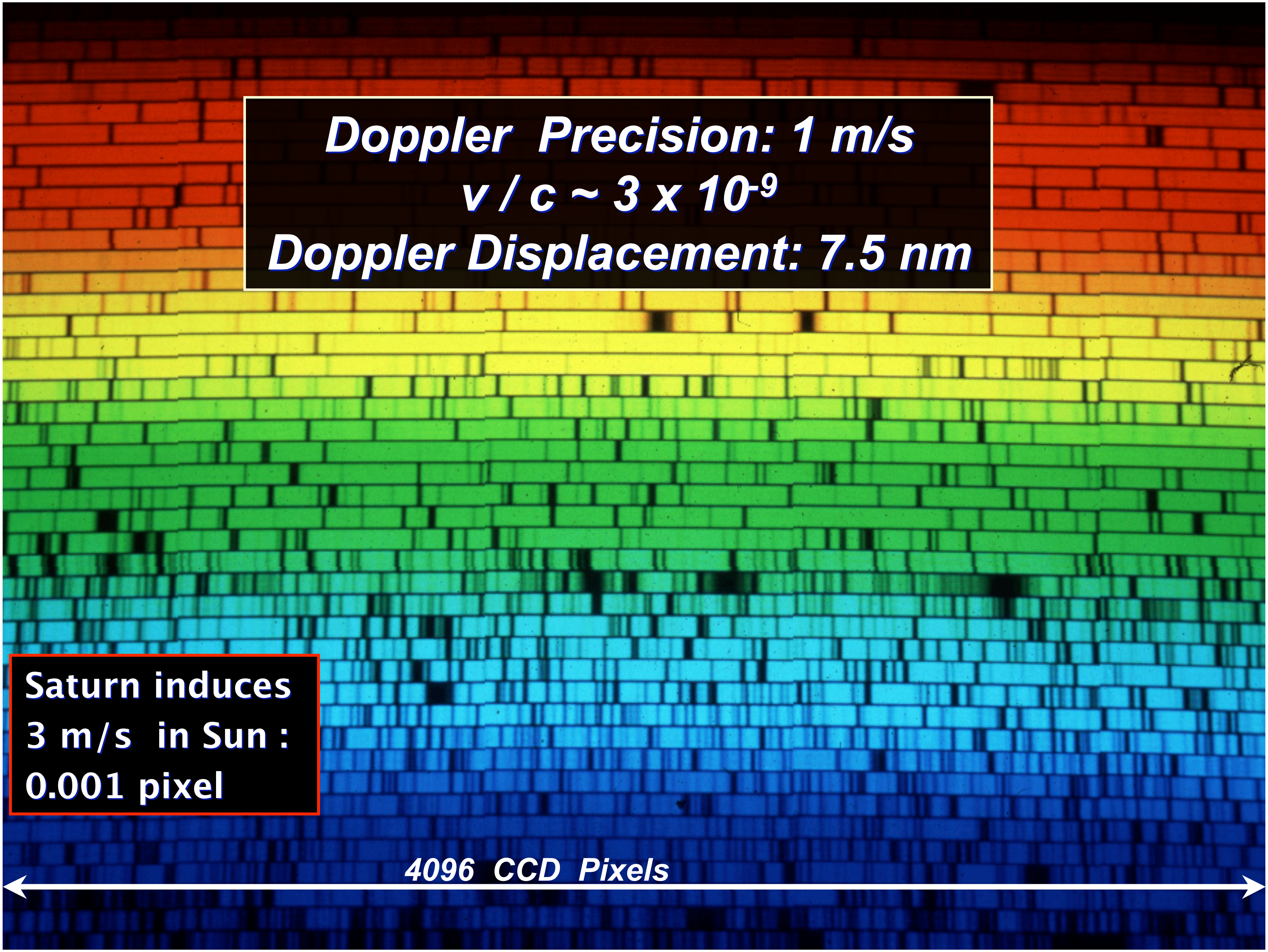
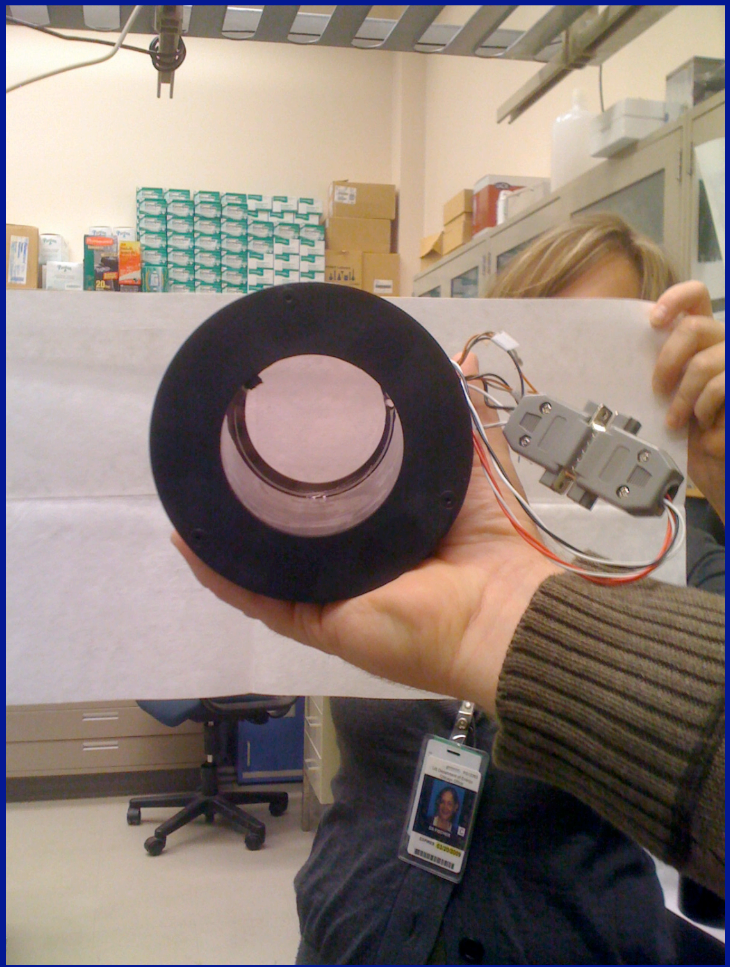
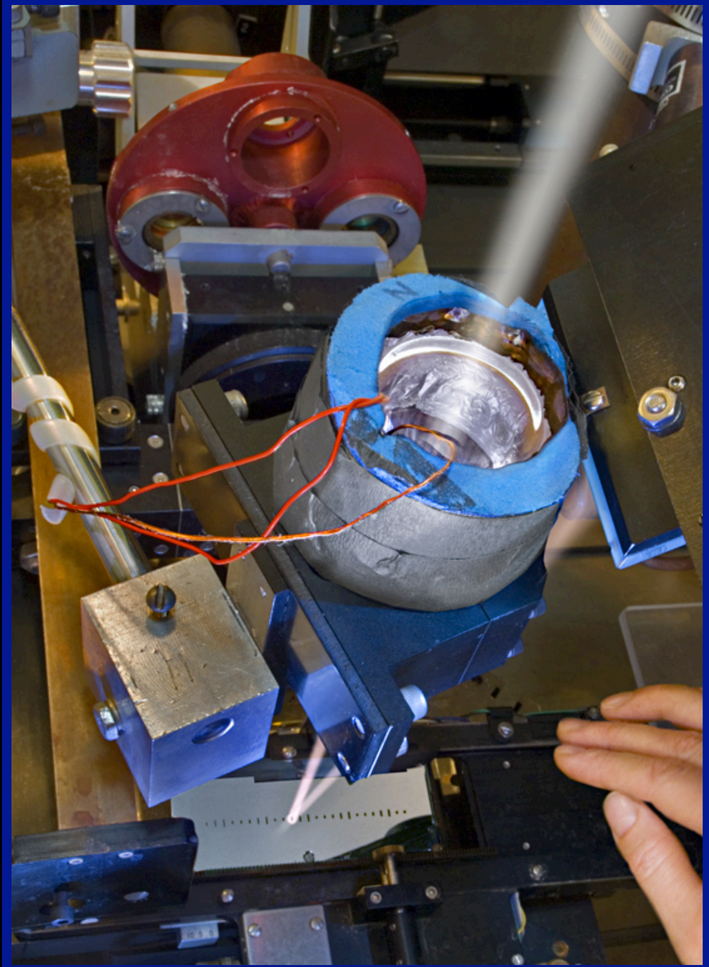
Keck Observatory


Doppler Precision: 1 m/s
$v / c \sim 3 \times 10^{-9}$
Doppler Displacement: 7.5 nm
Saturn induces
3 m/s in Sun :
0.001 pixel
4096 CCD Pixels

Iodine Cell Invention:

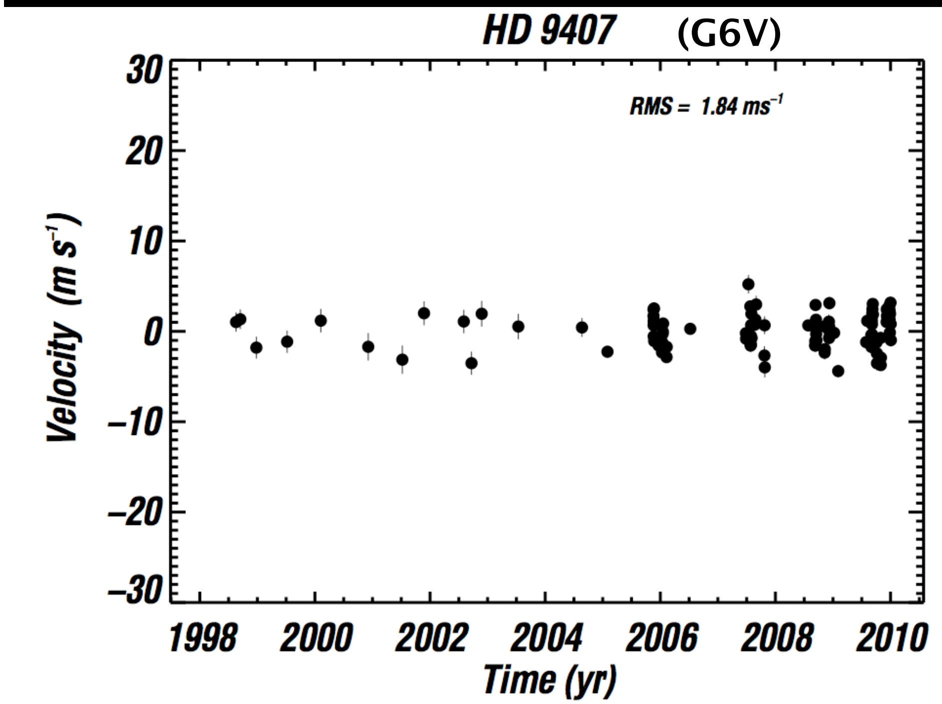
Indellible wavelengths and Instrumental Profile

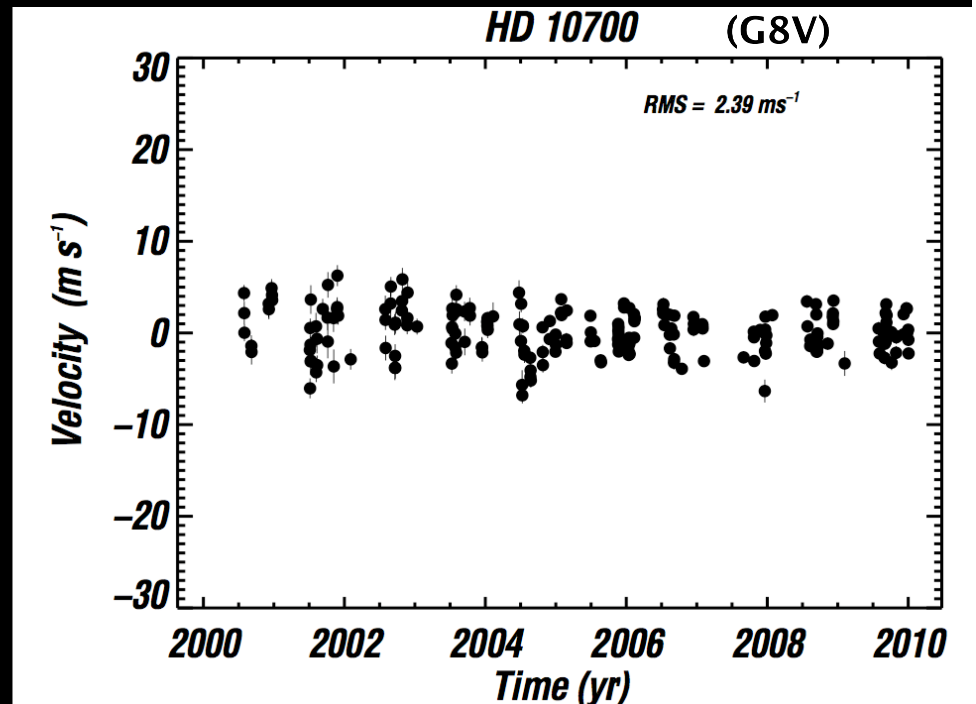




RV Standard Stars

Keck-HIRES & Iodine





10-12 years

Typical RMS: 2.0 m/s

No long-timescale noise.

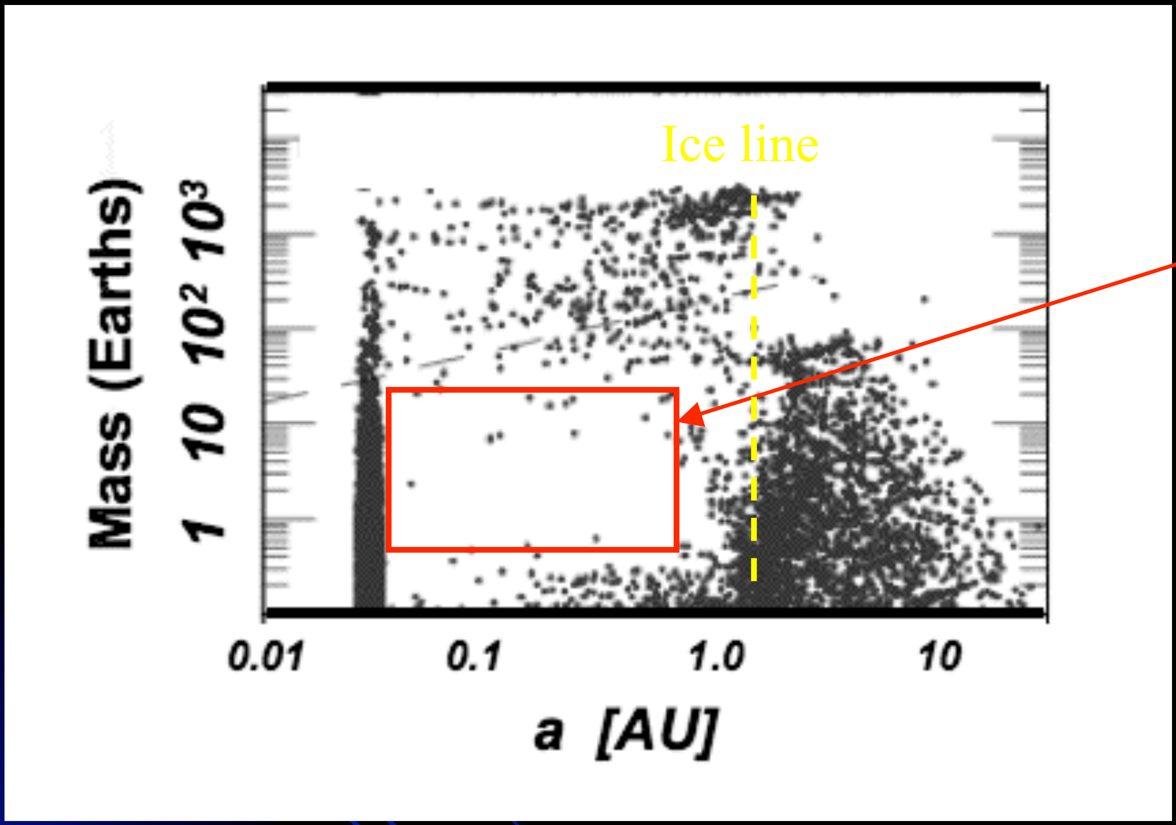
Planet Formation Theory

- Start with rocky planetesimals and gas
- They grow, migrate inward, and accrete gas
- Artistry: Migration softening (Type 1 and 2) and condensation points

Predicted

Mass vs. Orbital Distance

(Ida & Lin 2008)



Planet Desert:

a = 0.05 - 1.0 AU

M = 1 - 30 M_{Earth}

Desert: Type 1 Migration Off

Type 2 Migration Tuned down

Gas Giants grow migrate; Neptunes stall

Mordasini, Alibert, & Benz (2009)

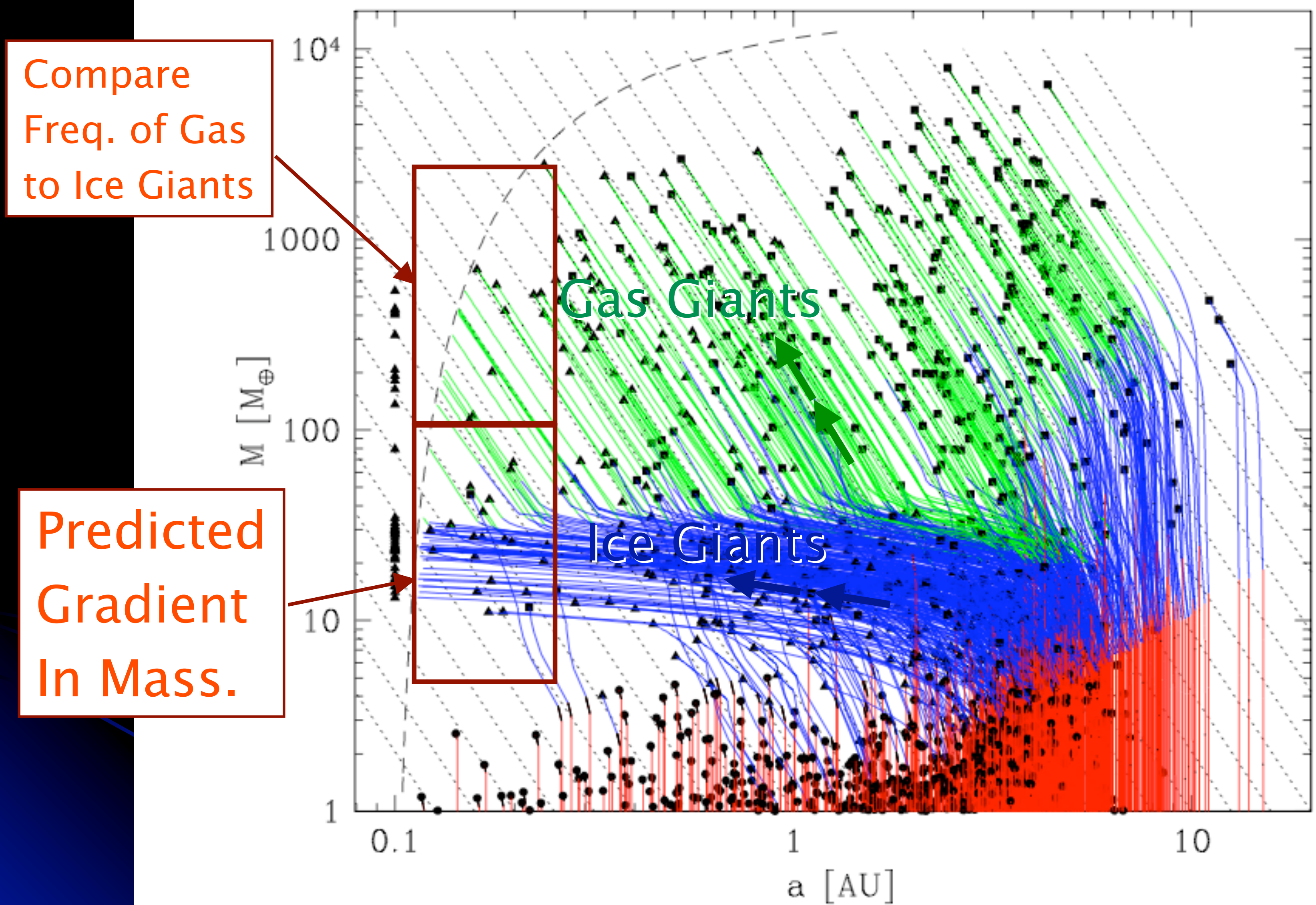


Fig. 8. Planetary formation tracks in the mass-distance plane. The large black symbols show the final position of a planet. The shape of the symbols is explained in the text. Planets reaching the feeding limit at a_{touch} (indicated by the long dashed line) have arbitrarily been set to 0.1 AU. The short 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)

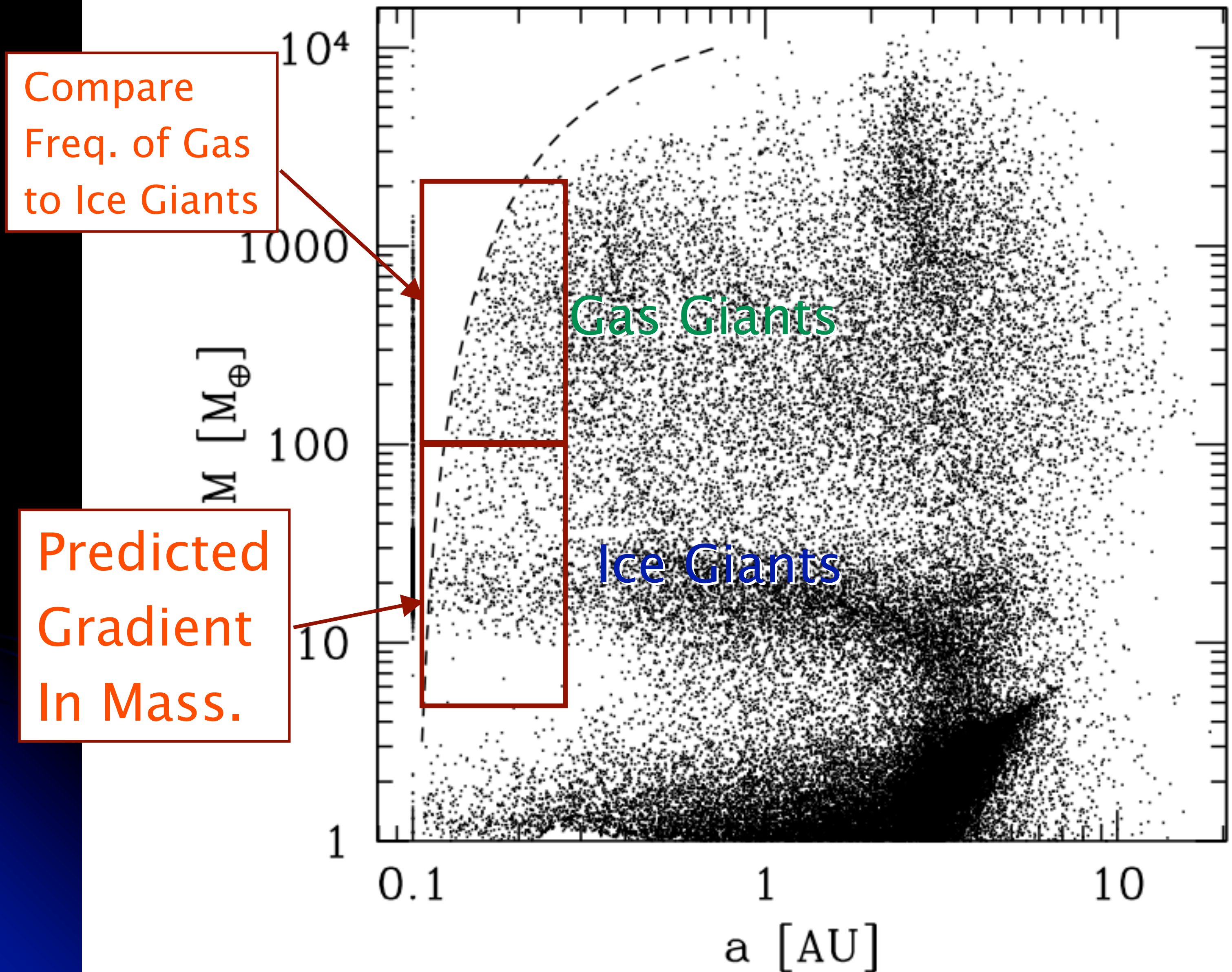


Fig. 13. Final mass M versus final distance a of $N_{synt} \approx 50\,000$ synthetic planets of the nominal planetary population. The feeding limit at a_{touch} is plotted as dashed line. Planets migrating into the feeding limit have been put to 0.1 AU. As a_{touch} gets very large for $M \gtrsim 20 M_{♃}$, 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 0.3 AU?

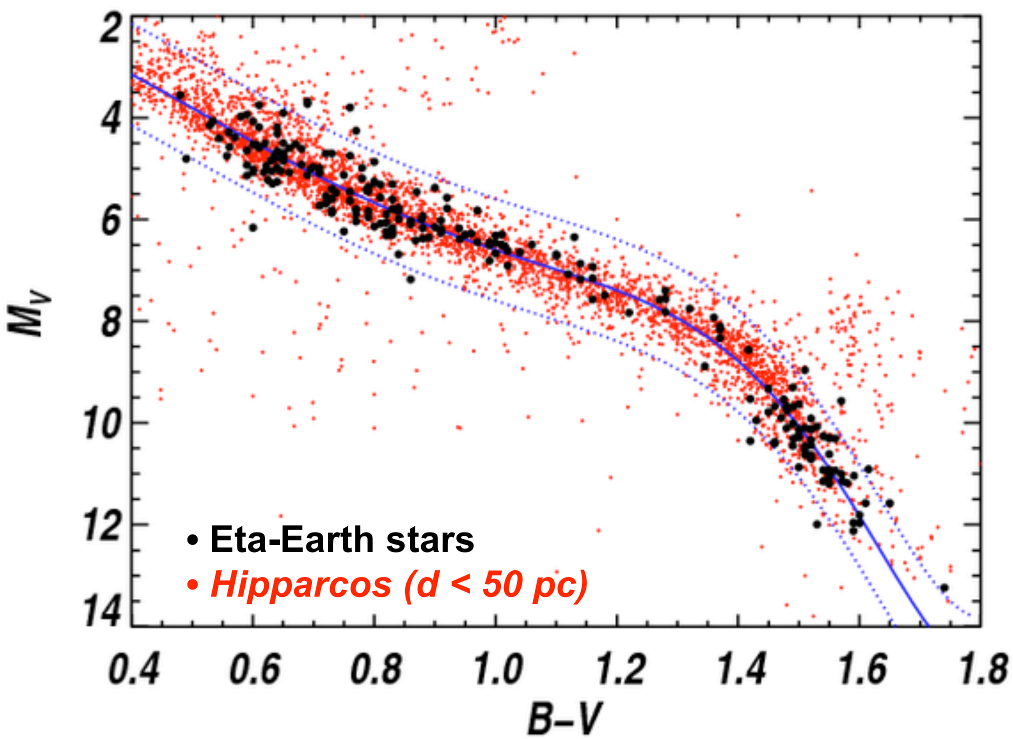
Accessible Domain of Planet-Formation Theory from 10-1000 M_{Earth}

- Theory predicts few 1-20 M_{earth} planets in short-period orbits
- Geneva group reports 50% of GK stars have rocky or Neptune planets inward of 50-day orbits

NASA-UC Eta-Earth Program

- Doppler Search for planets: M$\sin i$ = 3–30 M_{Earth}
- Stars: 238 GKM dwarfs:

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



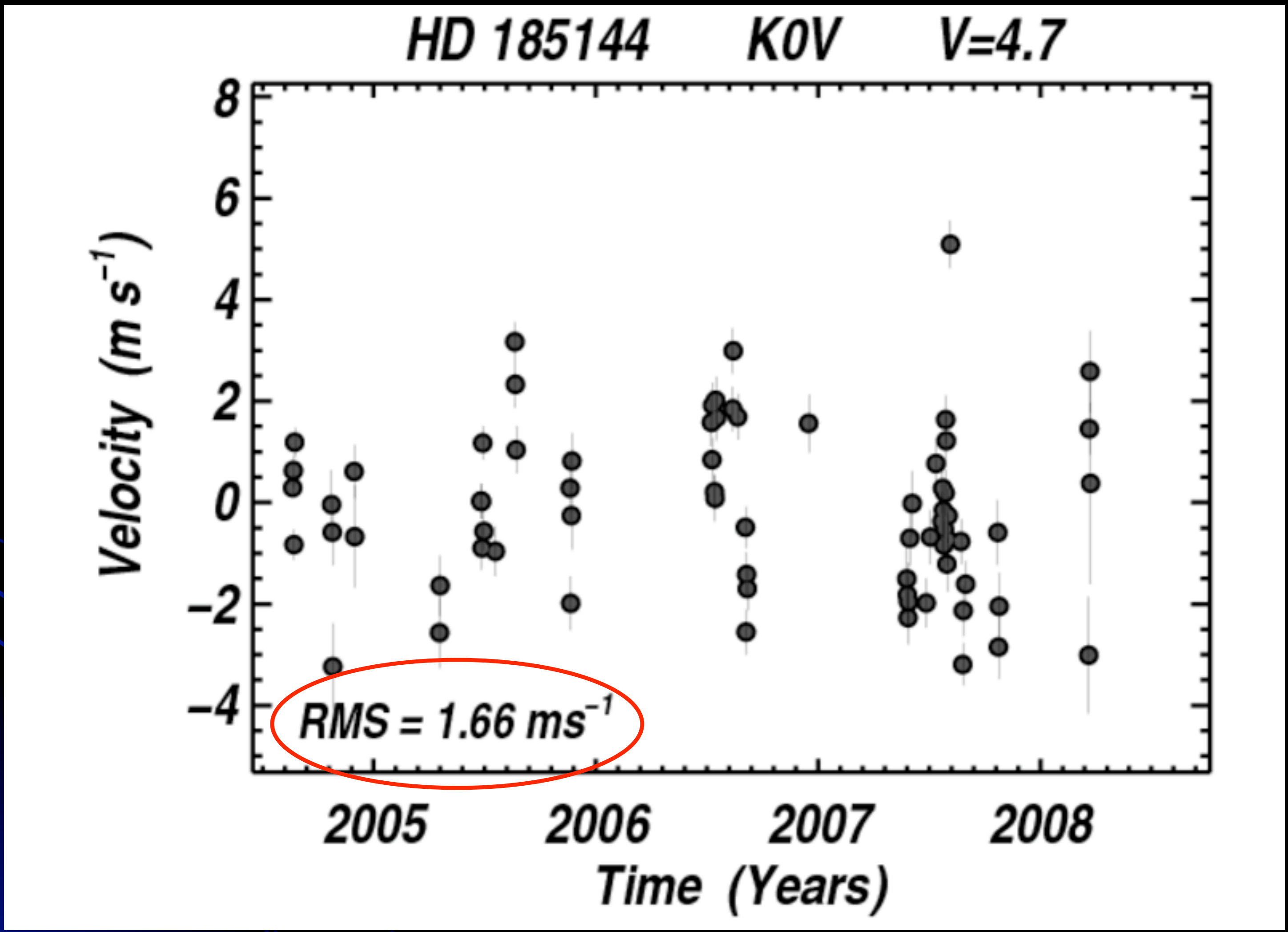
Selection Criteria:

- Distance < 25 pc
- V < 11 mag
- log R'HK < −4.7 (inactive)

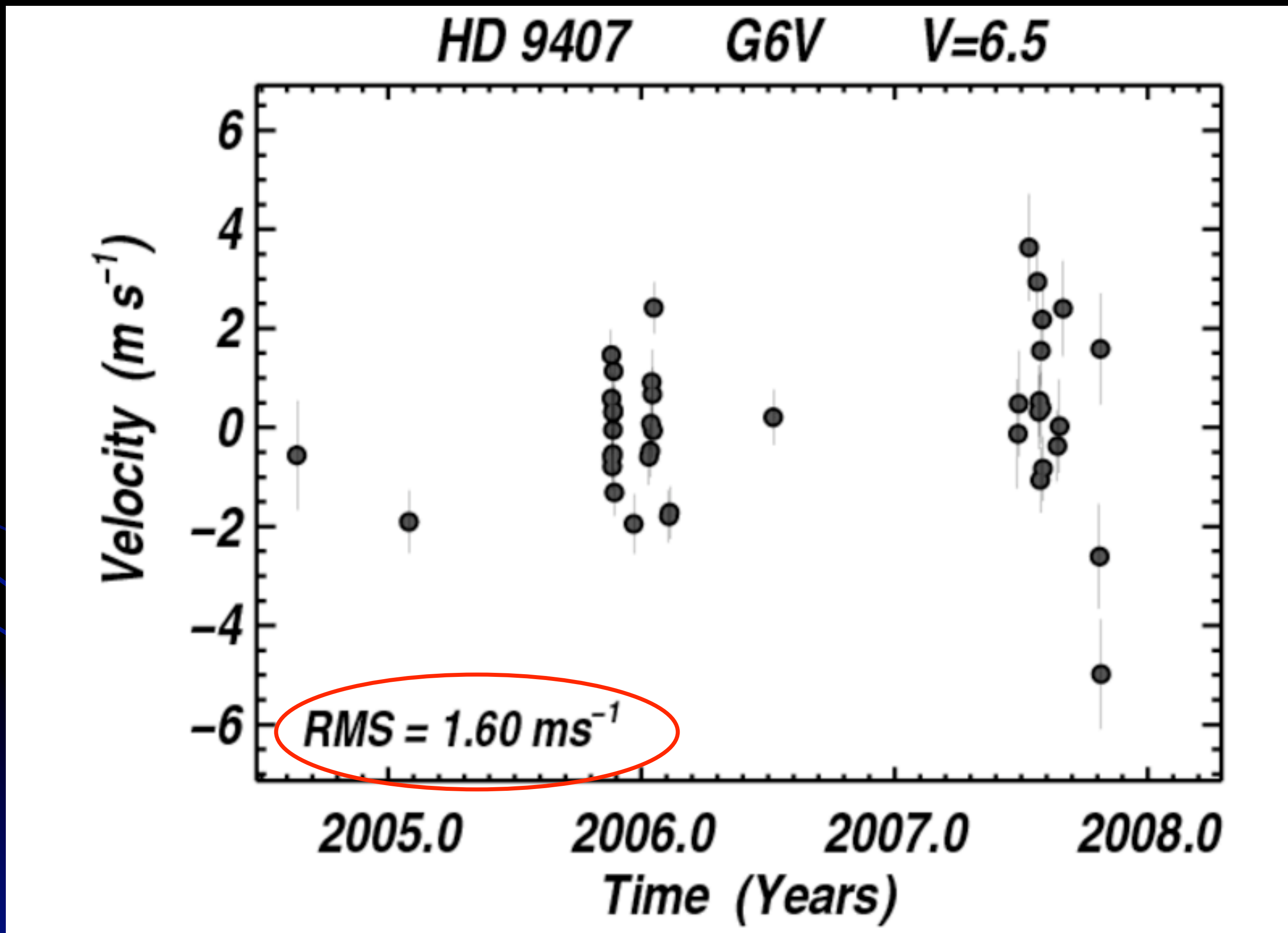
Solar Neighborhood Population

Howard & Marcy 2010

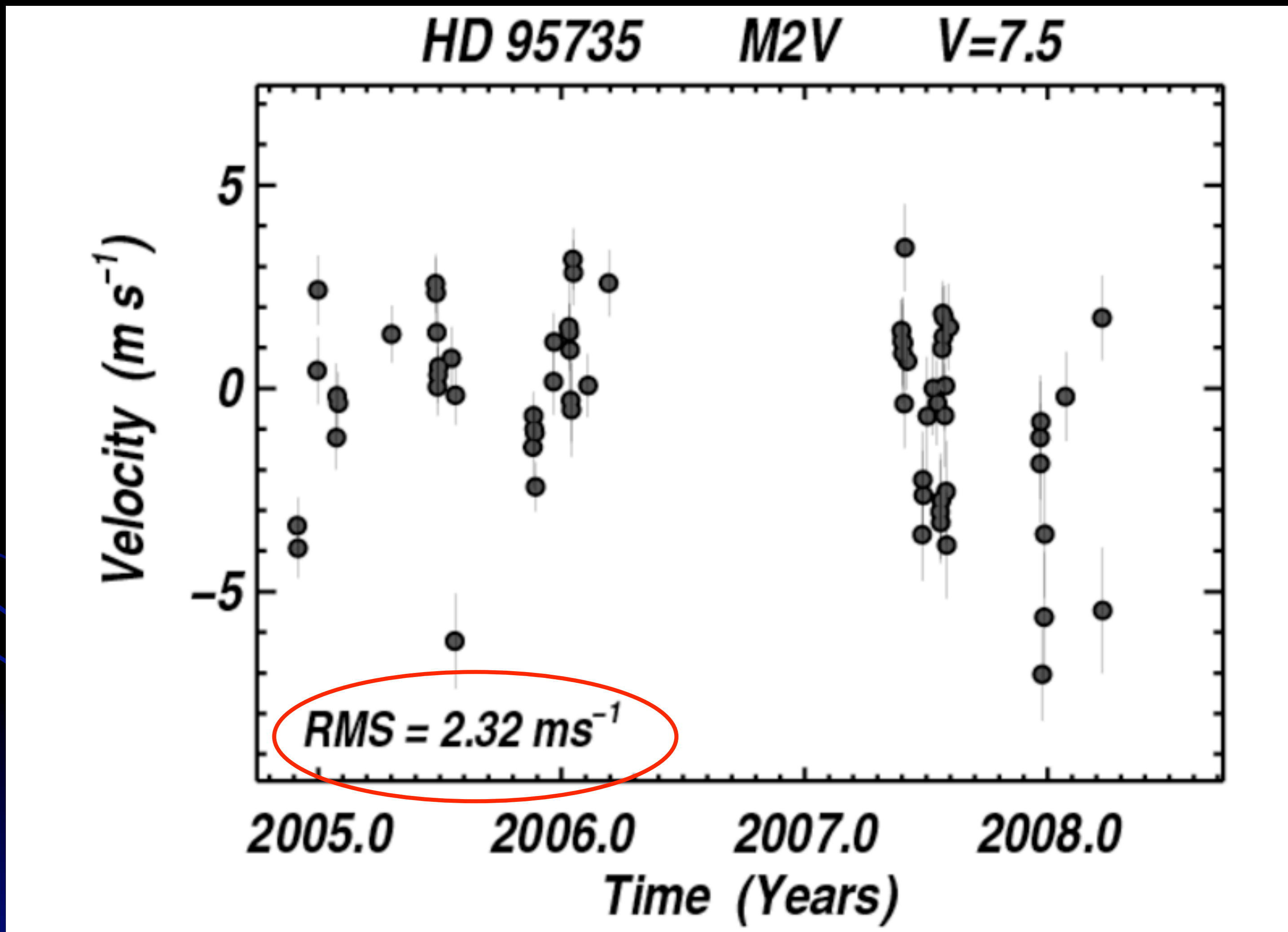
Eta-Earth Doppler Results



Eta-Earth Doppler Results



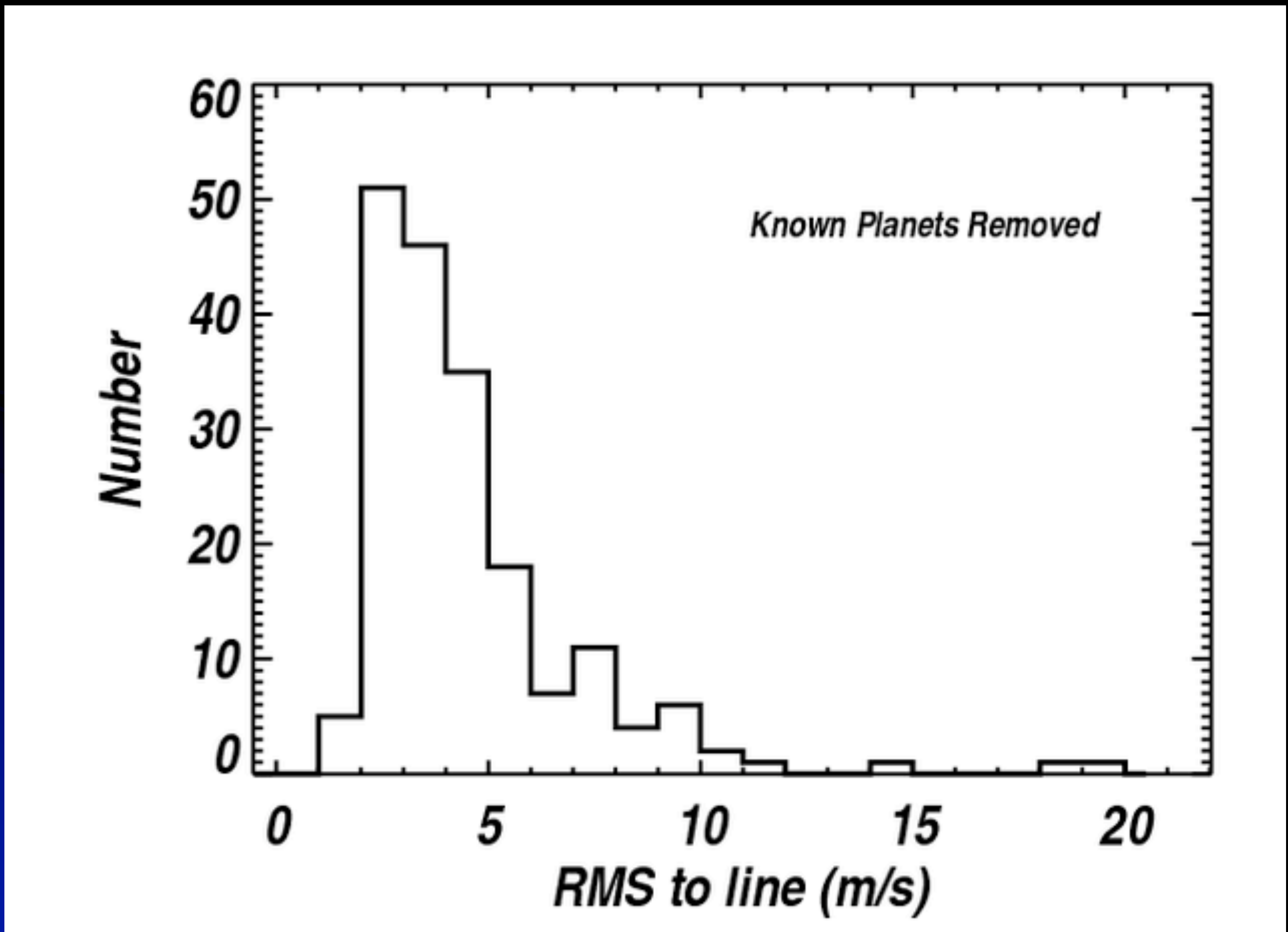
Eta-Earth Doppler Results



Eta-Earth

Doppler Precision

Velocity RMS of Eta-Earth stars

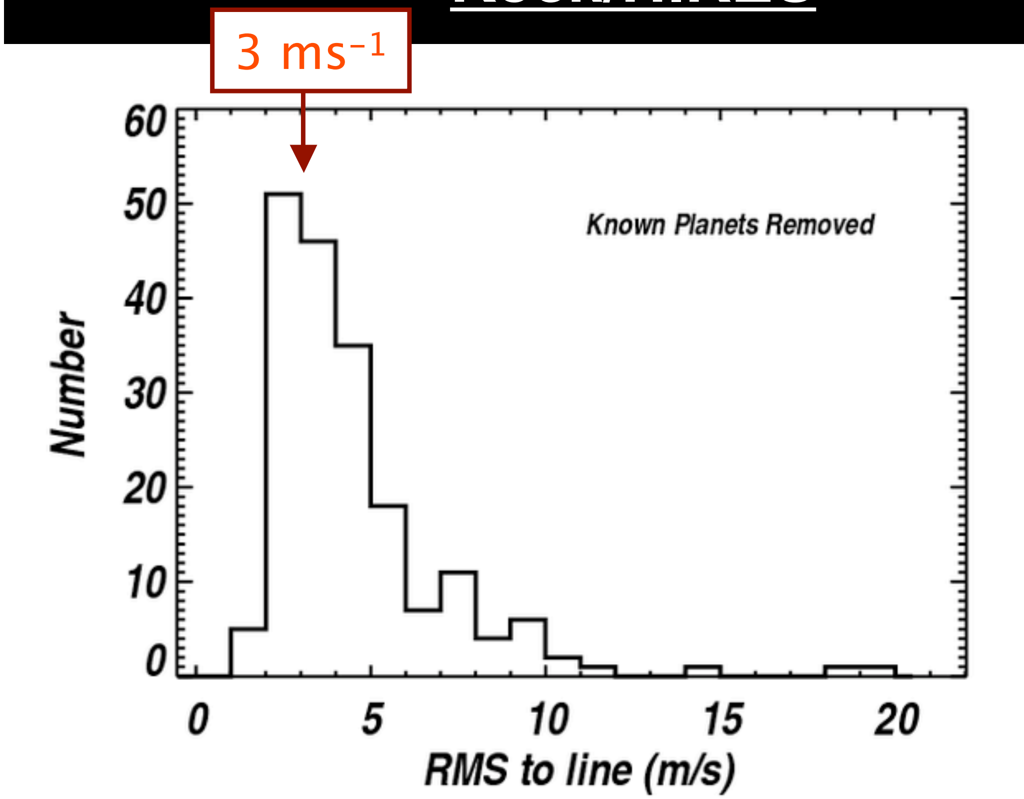


Limited by:

- Stellar jitter
- Photon noise
- Spectrometer PSF

Doppler Noise

Keck/HIRES



Eta-Earth GKM stars:
Chromospherically quiet
20-100 observations each

HARPS

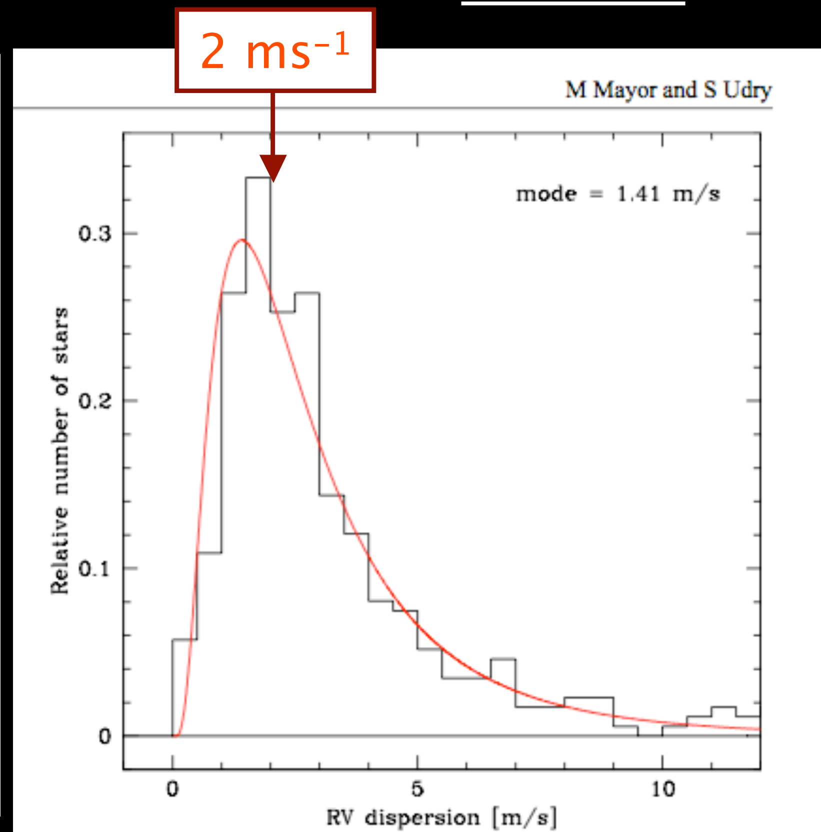


Figure 2. Histogram of radial-velocity rms for the stars in the high-precision HARPS subprogramme aiming at detecting very low-mass planets. Part of the 'large' rms observed in the tail of the distribution results from stellar activity or from still undetected planetary systems.

Mayor and Udry, 2008,
Phys. Scr. T130, 014010

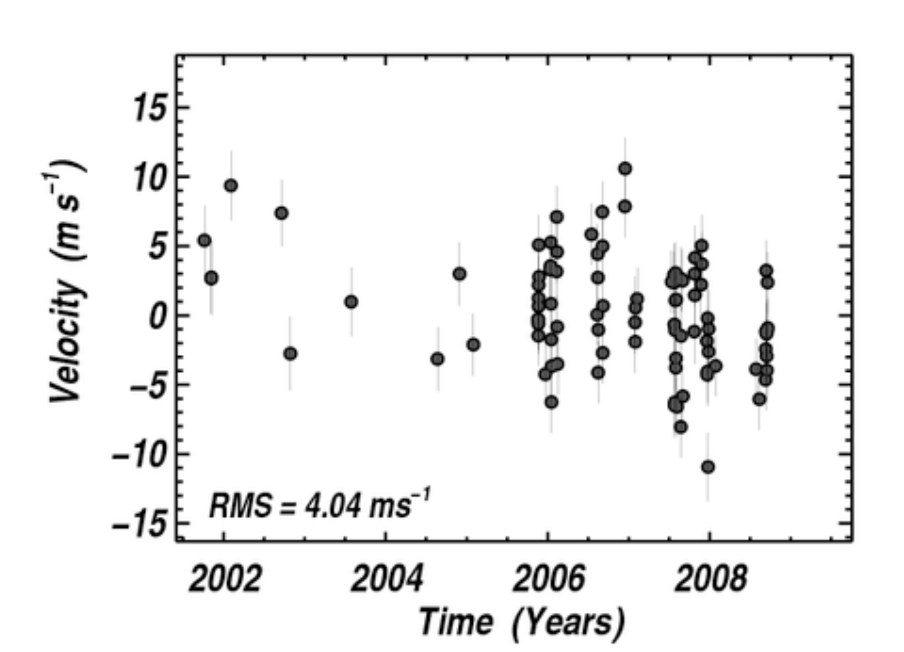
HD 7924b - Super-Earth Detection

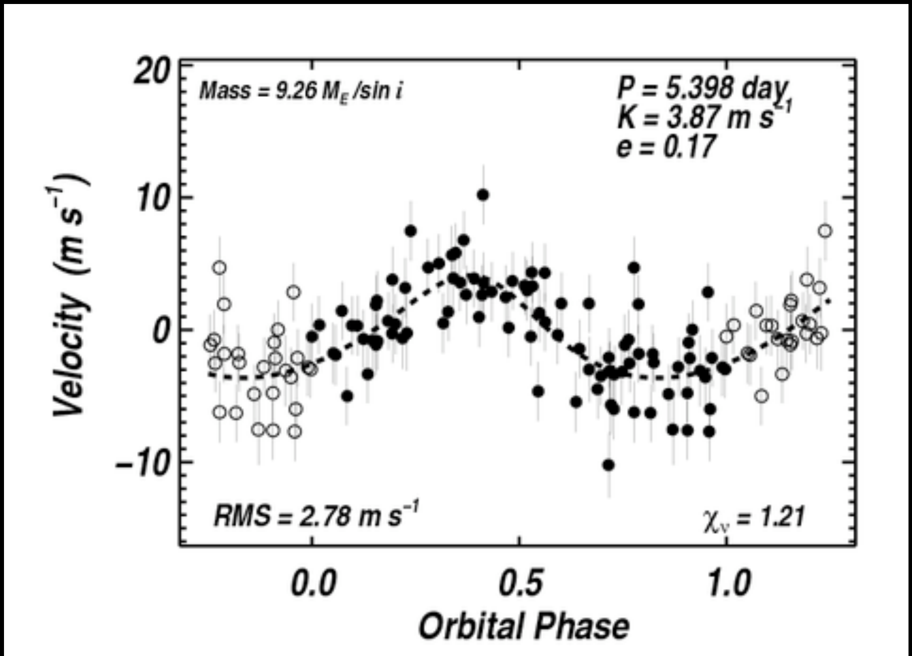
Star: HD 7924 (K0V)

Planet: $M \sin i = 9.3\ M_{Earth}$

$P = 5.398$ d

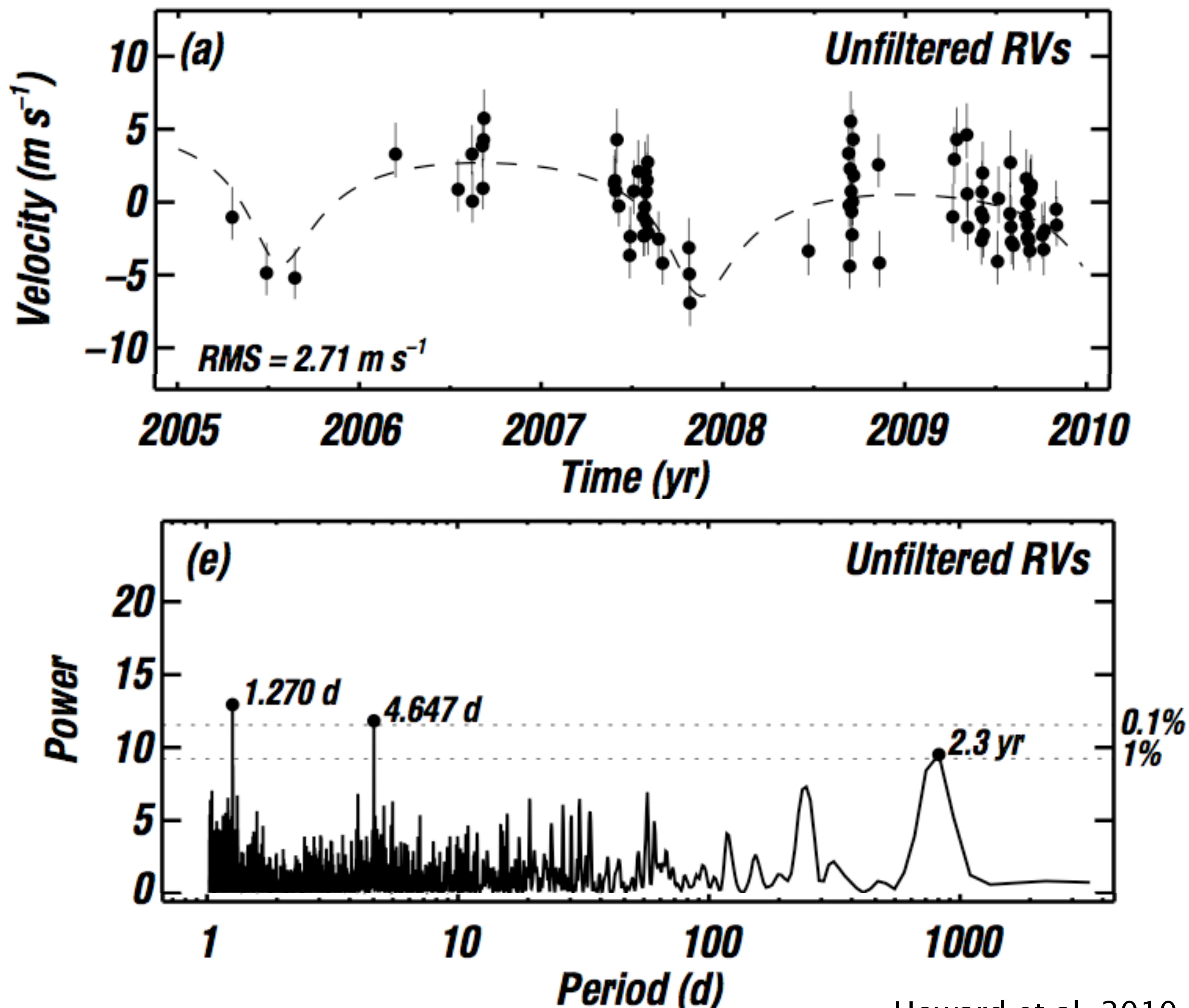
$e = 0.17$ (consistent with circular)





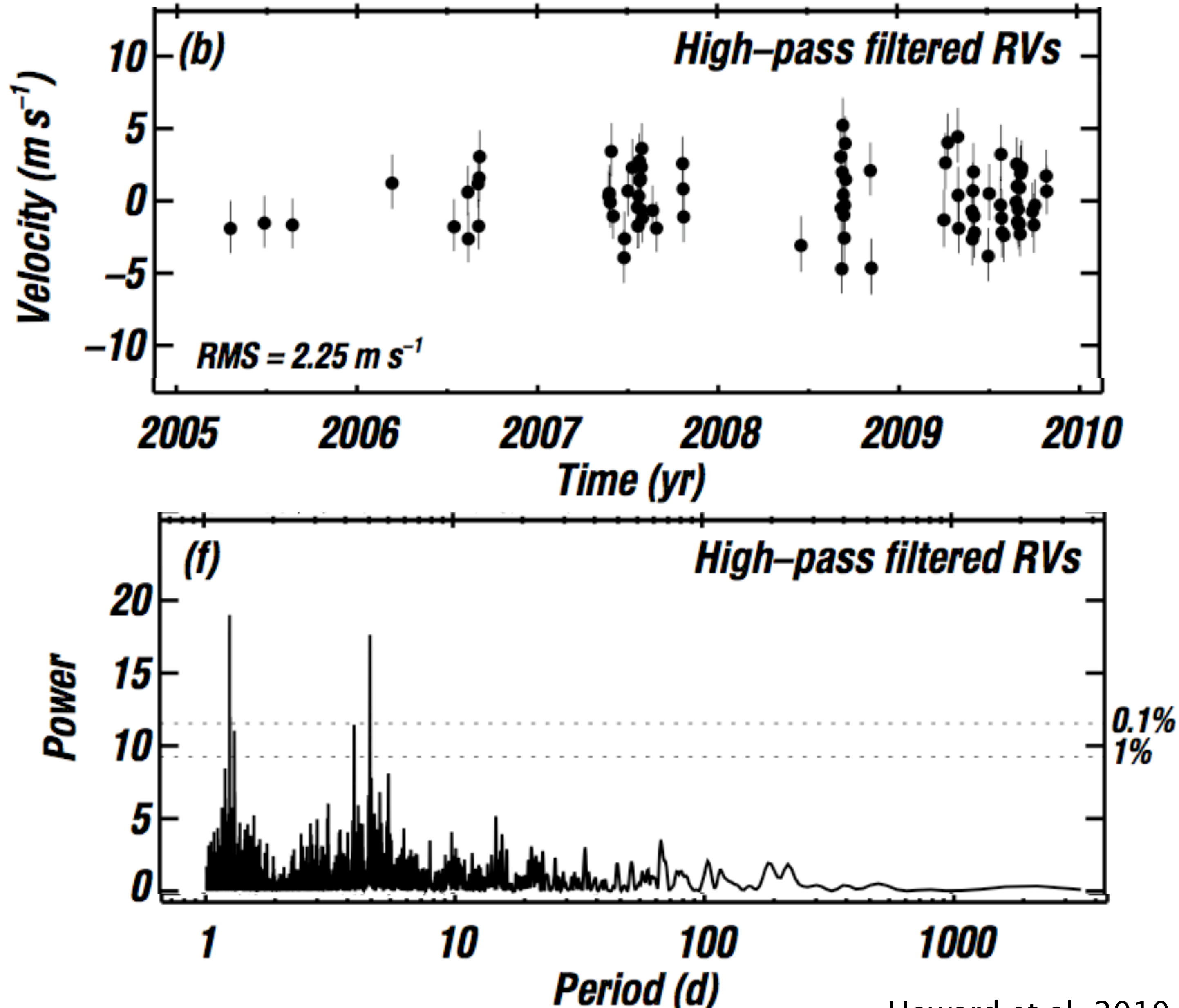
Howard et al. 2009, ApJ, 696, 75

HD 156668b - Discovery RVs



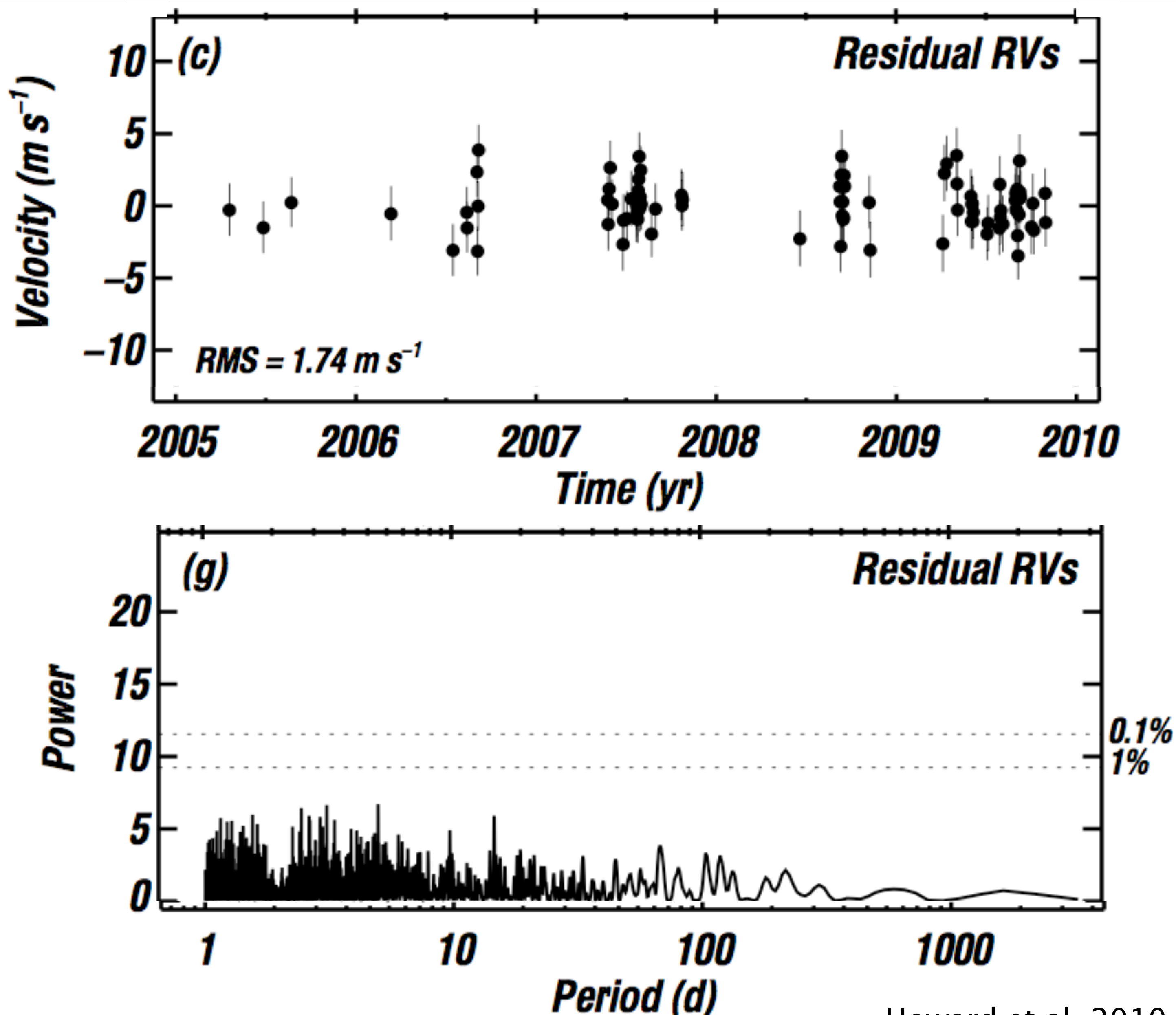
Howard et al. 2010

HD 156668b - Discovery RVs



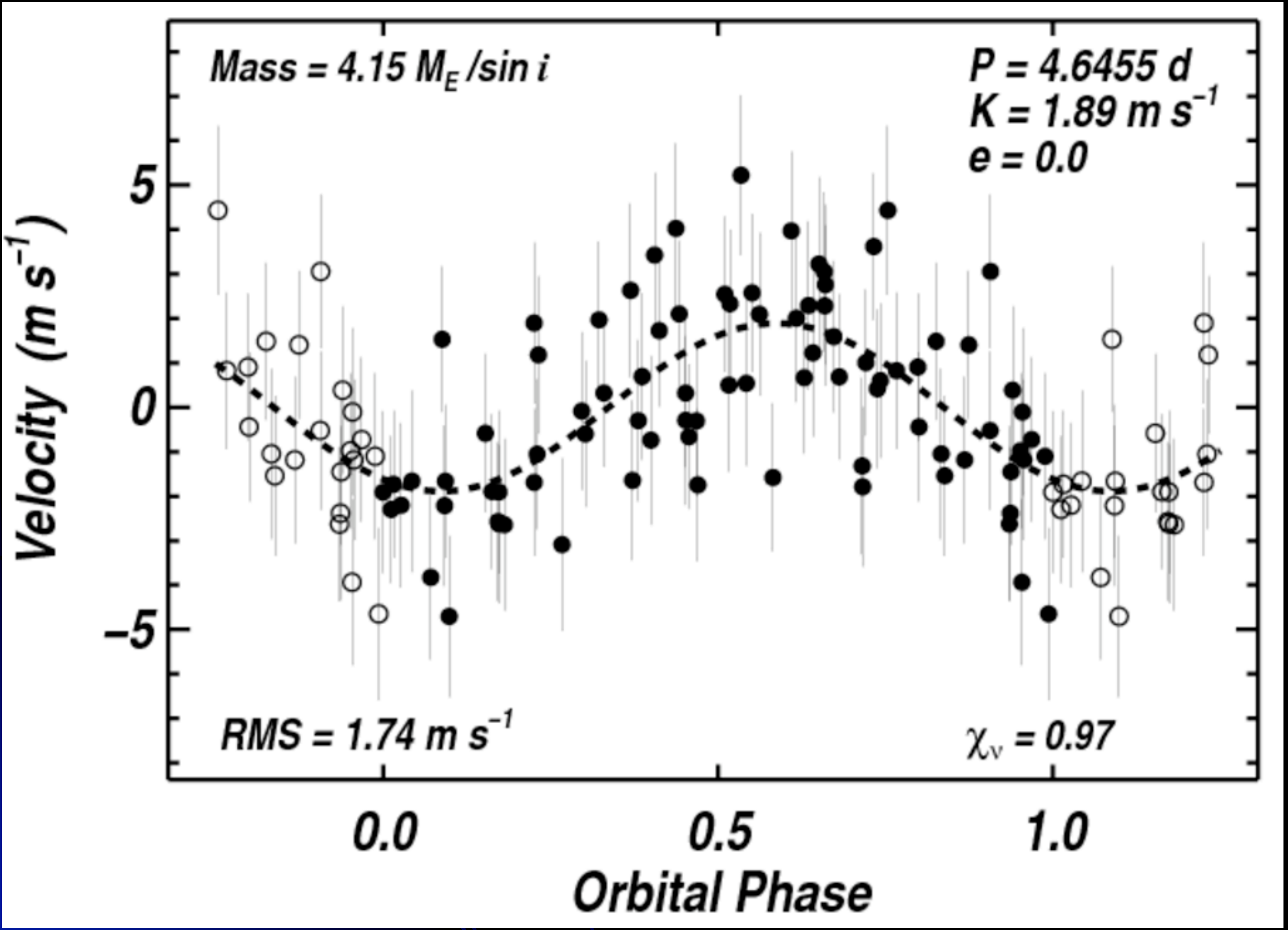
Howard et al. 2010

HD 156668b - Discovery RVs



Howard et al. 2010

HD 156668b - Super-Earth Detection



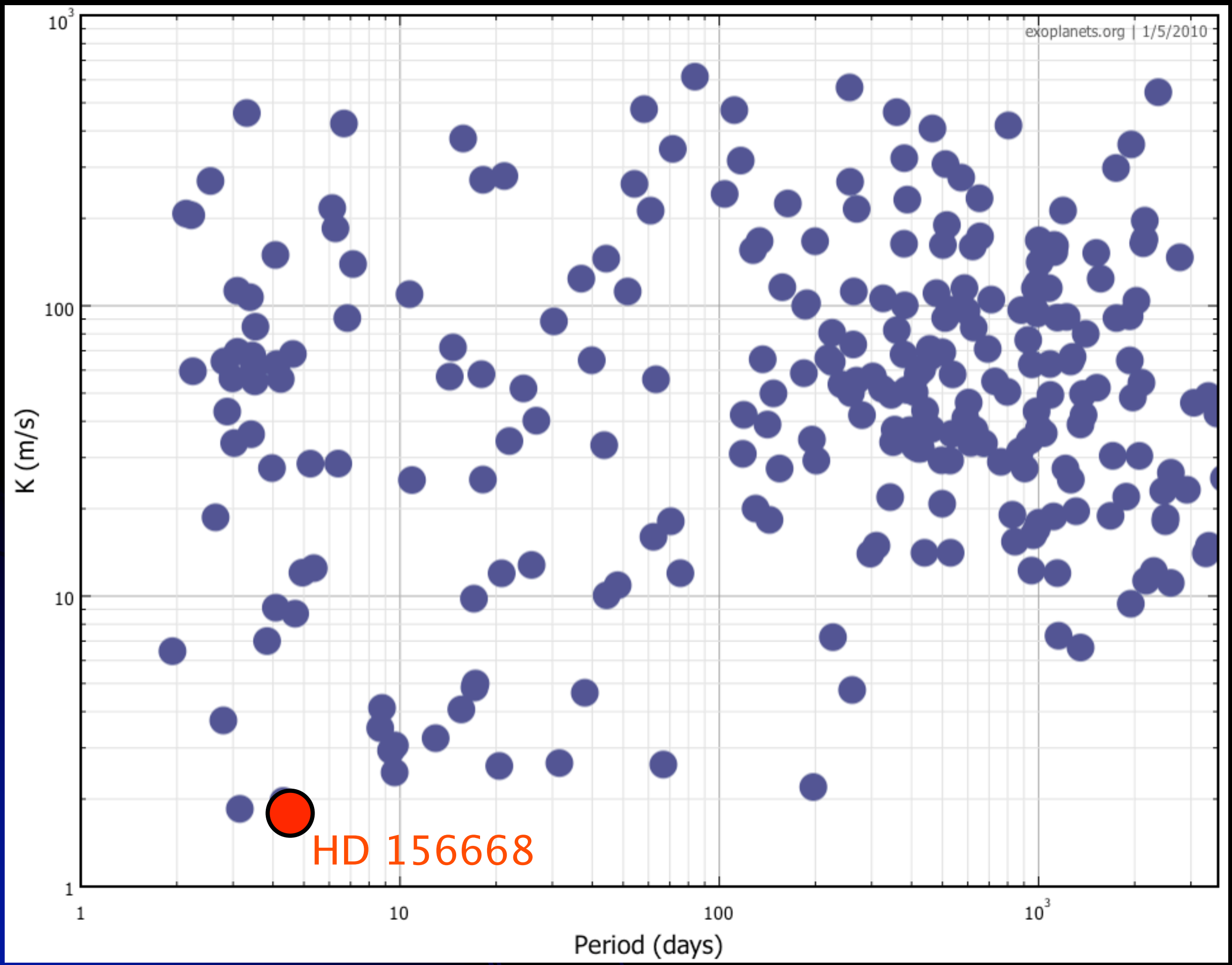
Star:
HD 156668 (K3V)
distance = 24 pc
V = 8.3
[Fe/H] = +0.05
Magnetically quiet

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

Howard et al. 2010, ApJ, submitted

Doppler: Lowest Amplitude (K)

K (m/s)   vs.   P (days)



K = 1.89 m/s

Smallest Doppler Amplitude (tied with GJ 581e)

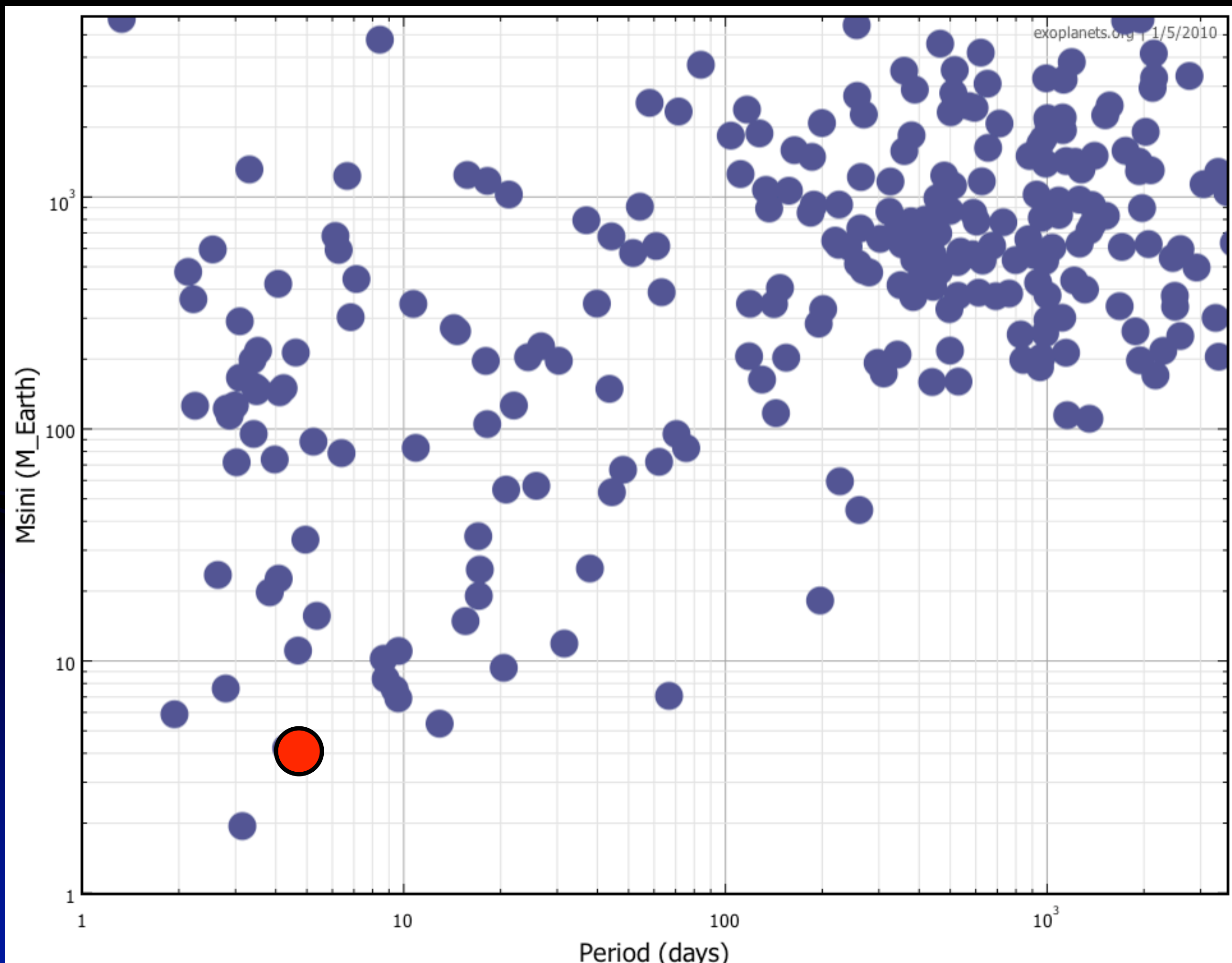
Pushing down to the RV limit

Howard et al. 2010

To make plots like this, see exoplanet.org (Jason Wright)

Among Lowest Msin$i$

Msin$i$ (M_{Earth}) vs. P (days)



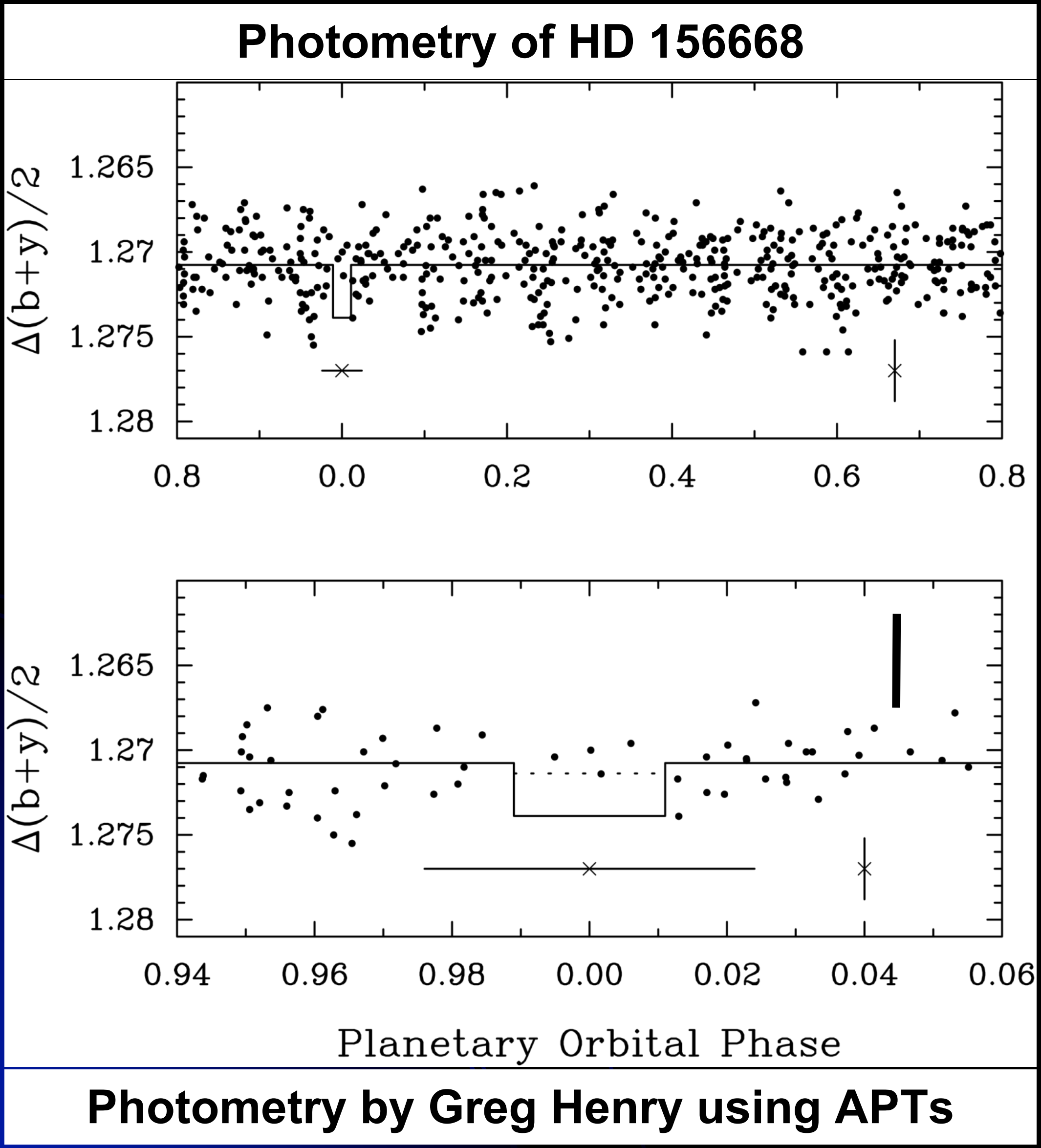
Msin$i$ = 4.15 M_{Earth}

2nd smallest Msini ever!
(GJ 581e has Msini = 1.9 M_{Earth})

Pushing down to the RV limit to the lowest masses

To make plots like this: exoplanets.org (Jason Wright)

Transit Search



5% transit probability

V=8.4 – Easy follow-up

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

Can rule out 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	0.35 mmag

Eta-Earth Survey: 41 Detected Planets

P < 10d:

HD 156668 b P = 4.646 days, Msini = 0.01 M_J, Msini = 4.1 M_E
55 Cnc e P = 2.797 days, Msini = 0.02 M_J, Msini = 7.6 M_E (multiplanet system)
HD 1461 b P = 5.77 days, Msini = 0.02 M_J, Msini = 8 M_E
HD 7924 b P = 5.398 days, Msini = 0.03 M_J, Msini = 9.3 M_E
HD 69830 b P = 8.667 days, Msini = 0.03 M_J, Msini = 10.2 M_E (multiplanet system)
51 Peg b P = 4.231 days, Msini = 0.46 M_J, Msini = 146.6 M_E
HD 217107 b P = 7.127 days, Msini = 1.39 M_J, Msini = 442.9 M_E (multiplanet system)

10d < P < 50d:

HD 69830 c P = 31.560 days, Msini = 0.04 M_J, Msini = 11.9 M_E (multiplanet system)
HD 90156 b P = 49.6 days, Msini = 0.05 M_J, Msini = 16.7 M_E
HD 190360 c P = 17.111 days, Msini = 0.06 M_J, Msini = 18.7 M_E (multiplanet system)
HD 99492 b P = 17.043 days, Msini = 0.11 M_J, Msini = 33.7 M_E
55 Cnc c P = 44.379 days, Msini = 0.17 M_J, Msini = 53.4 M_E (multiplanet system)
55 Cnc b P = 14.651 days, Msini = 0.83 M_J, Msini = 263.9 M_E (multiplanet system)
rho CrB b P = 39.845 days, Msini = 1.06 M_J, Msini = 338.2 M_E

50d < P < 1yr:

HD 69830 d P = 197. days, Msini = 0.06 M_J, Msini = 17.9 M_E (multiplanet system)
55 Cnc f P = 260.6 days, Msini = 0.15 M_J, Msini = 46.3 M_E (multiplanet system)
HD 3651 b P = 62.2 days, Msini = 0.23 M_J, Msini = 72.8 M_E
70 Vir b P = 116.6 days, Msini = 7.46 M_J, Msini = 2371.6 M_E

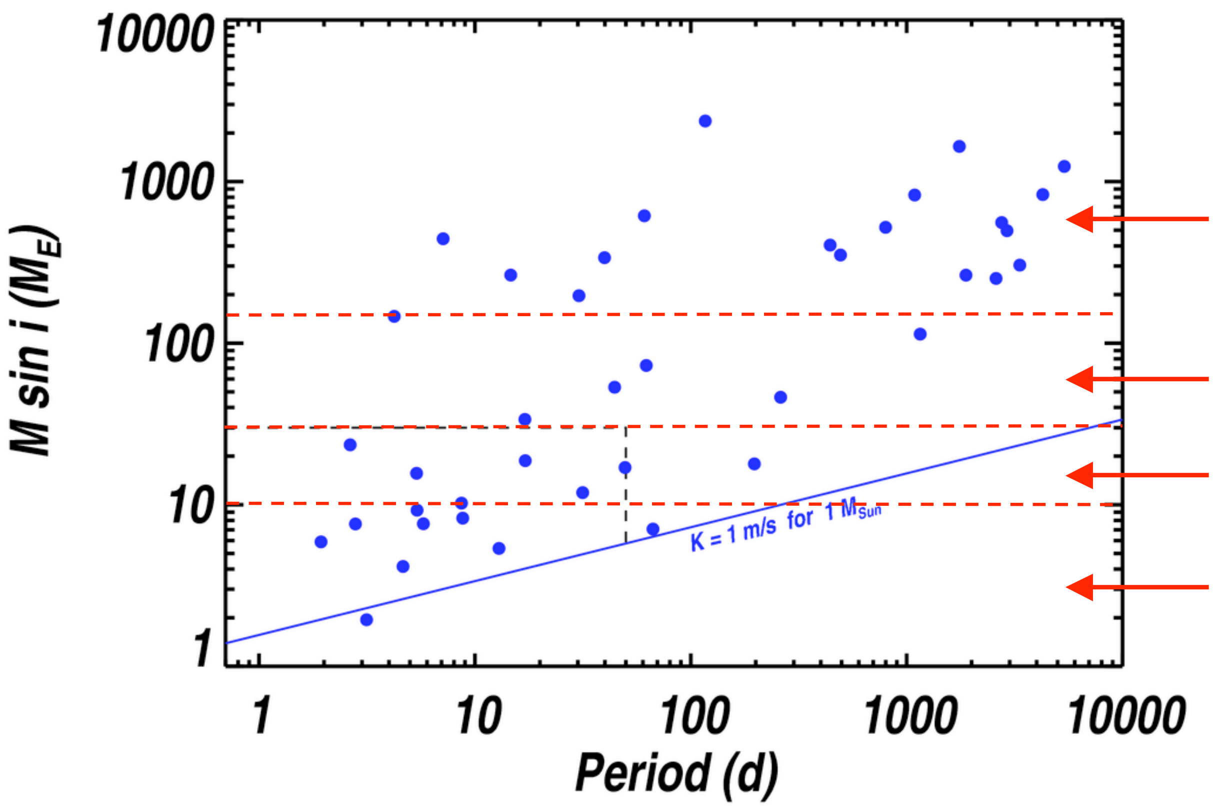
P > 1yr:

HD 164922 b P = 1155. days, Msini = 0.36 M_J, Msini = 113.8 M_E
47 UMa c P = 2594. days, Msini = 0.79 M_J, Msini = 251.6 M_E (multiplanet system)
HD 154345 b P = 3341. days, Msini = 0.96 M_J, Msini = 304.2 M_E
HD 114783 b P = 493. days, Msini = 1.11 M_J, Msini = 351.2 M_E
HD 210277 b P = 442. days, Msini = 1.27 M_J, Msini = 404.5 M_E
HD 190360 b P = 2915. days, Msini = 1.56 M_J, Msini = 496.6 M_E (multiplanet system)
16 Cyg B b P = 798. days, Msini = 1.64 M_J, Msini = 521.3 M_E
HD 87883 b P = 2754. days, Msini = 1.76 M_J, Msini = 558.1 M_E
47 UMa b P = 1089. days, Msini = 2.60 M_J, Msini = 826.0 M_E (multiplanet system)
HD 217107 c P = 4270. days, Msini = 2.62 M_J, Msini = 831.3 M_E (multiplanet system)
55 Cnc d P = 5371. days, Msini = 3.91 M_J, Msini = 1241.4 M_E (multiplanet system)
14 Her b P = 1754. days, Msini = 5.19 M_J, Msini = 1651.0 M_E

41 Known Planets in Eta-Earth Survey

Orbiting 27 stars

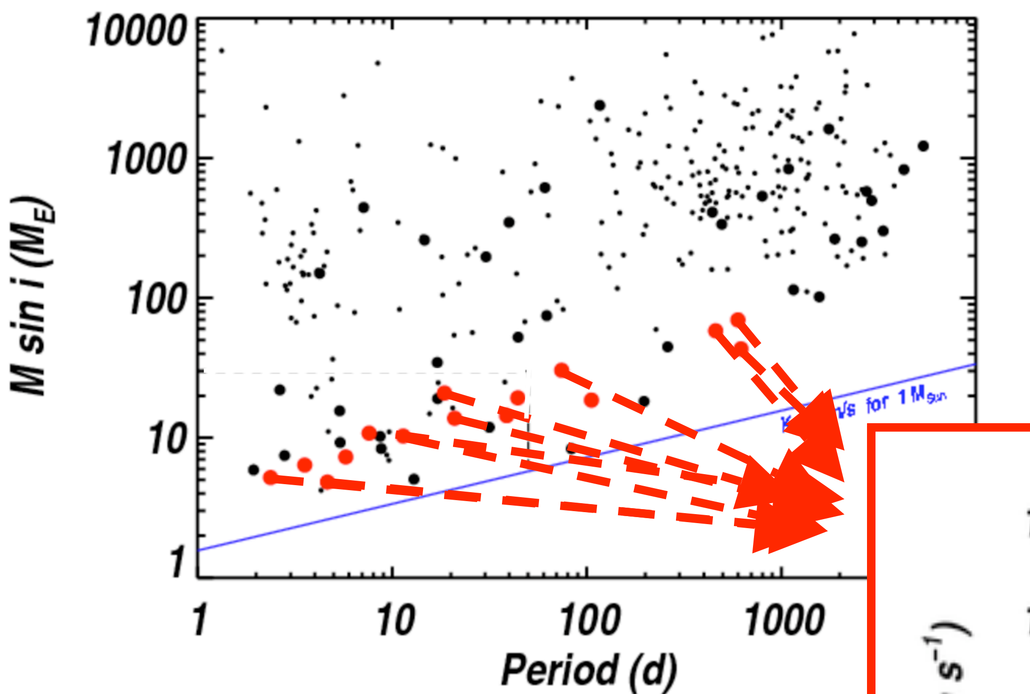
out of 238 stars in Eta-Earth Survey



Known Eta-Earth Planets By Mass:

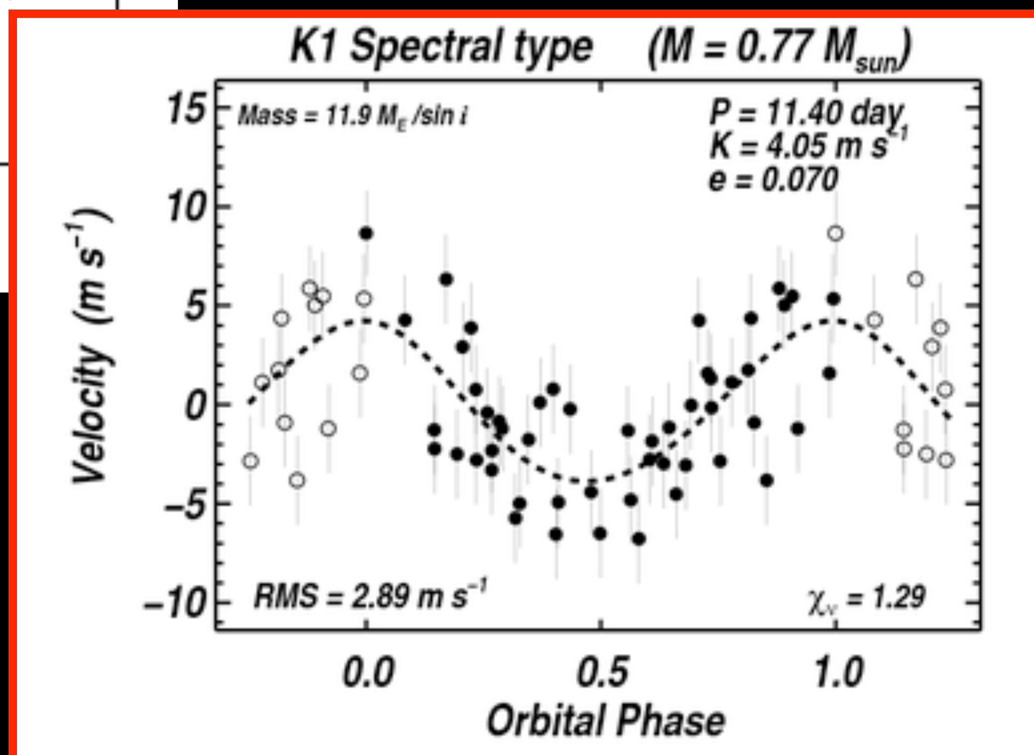
- **19 Jupiters**
- **6 Saturns**
- **7 Neptunes**
- **9 Super-Earths**

Candidate Planets in Eta-Earth Survey



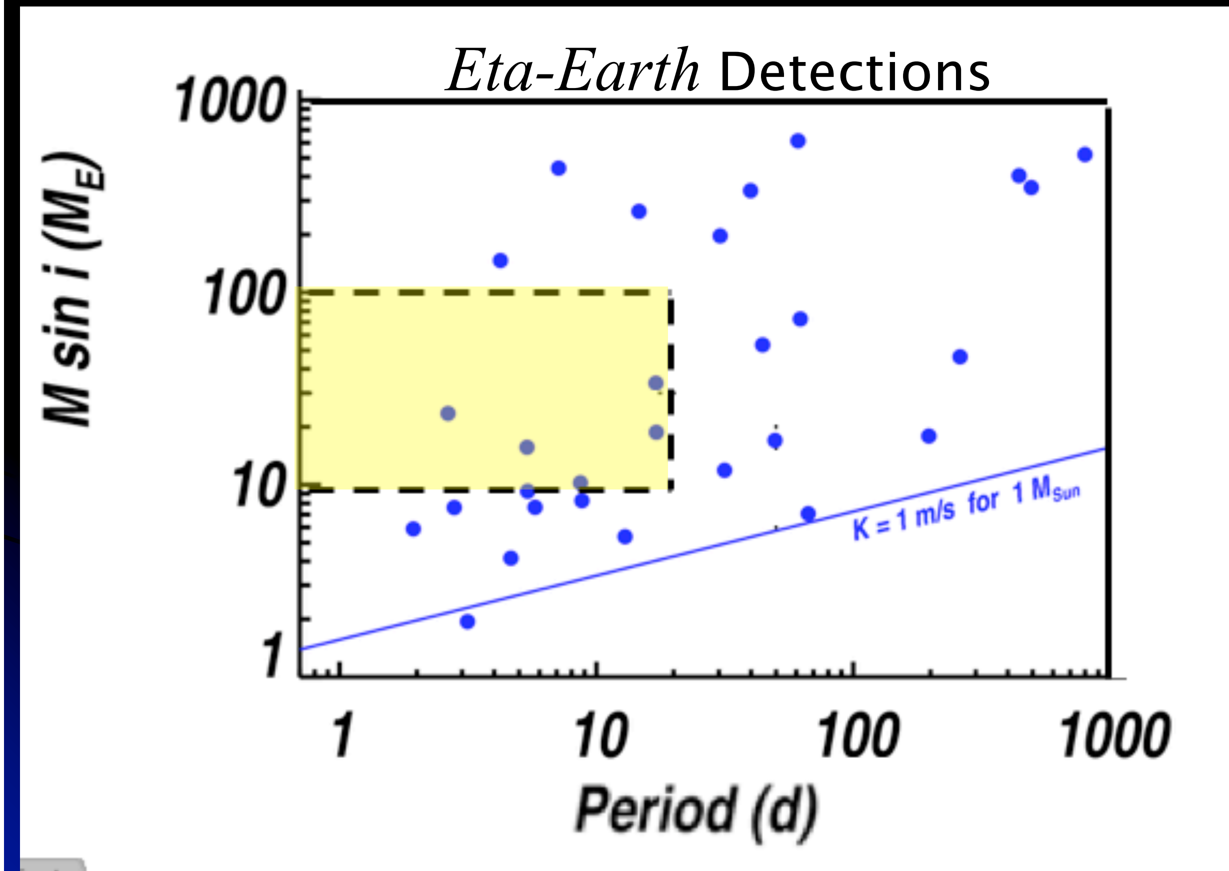
Candidates planets need additional observations because:

- Non-unique orbital solution
- Multiple planets in system
- False Alarm Probability (FAP) too high



- Planets in Eta-Earth
- *Candidate* Planets
- All RV Exoplanets

Frequency of Planets:
10-100 M_{Earth} and Period < 20 d



171 G + K Stars

6 Secure Planets

4 Candidate Planets

10 Total Planets

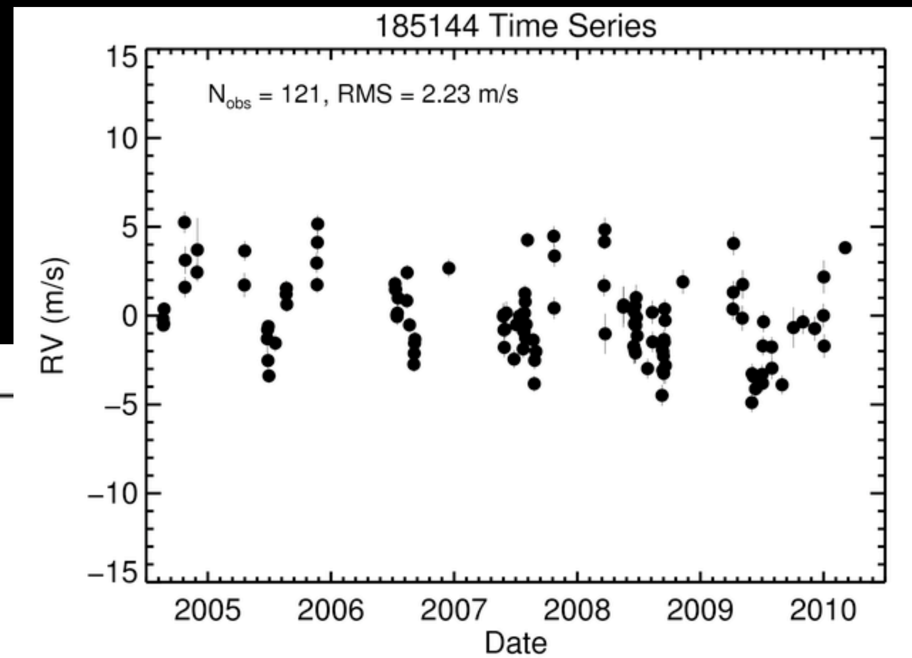
Frequency:

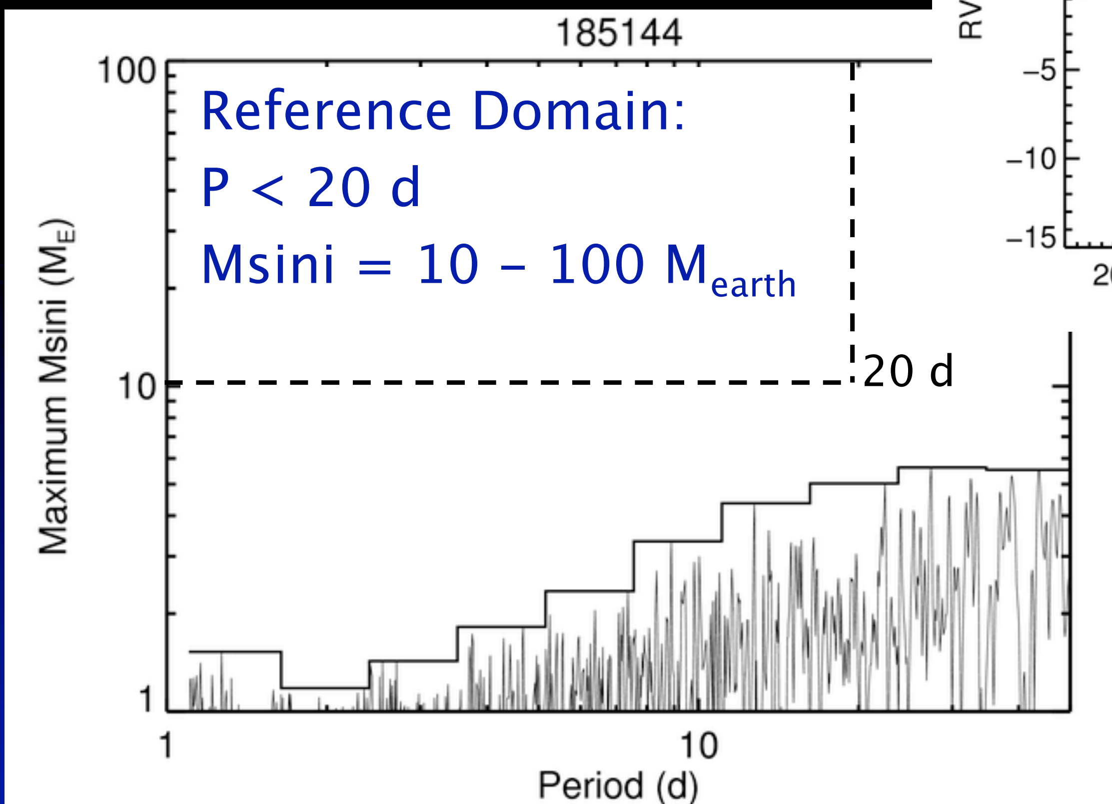
10 / 171 = 5.8 %

Incompleteness:

Poorly Observed Stars

Limits on Planets Mass in Well-Observed Star



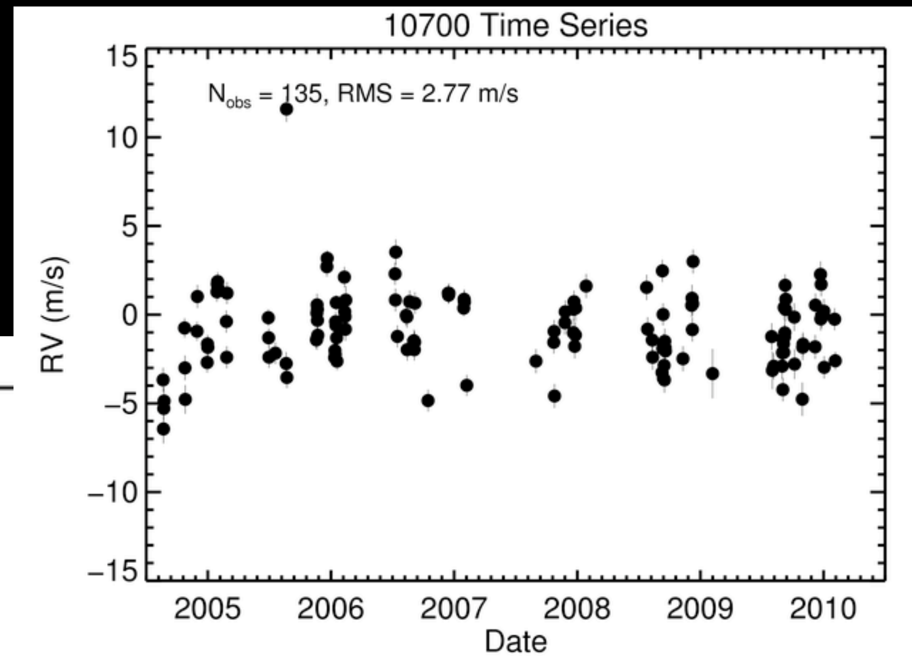


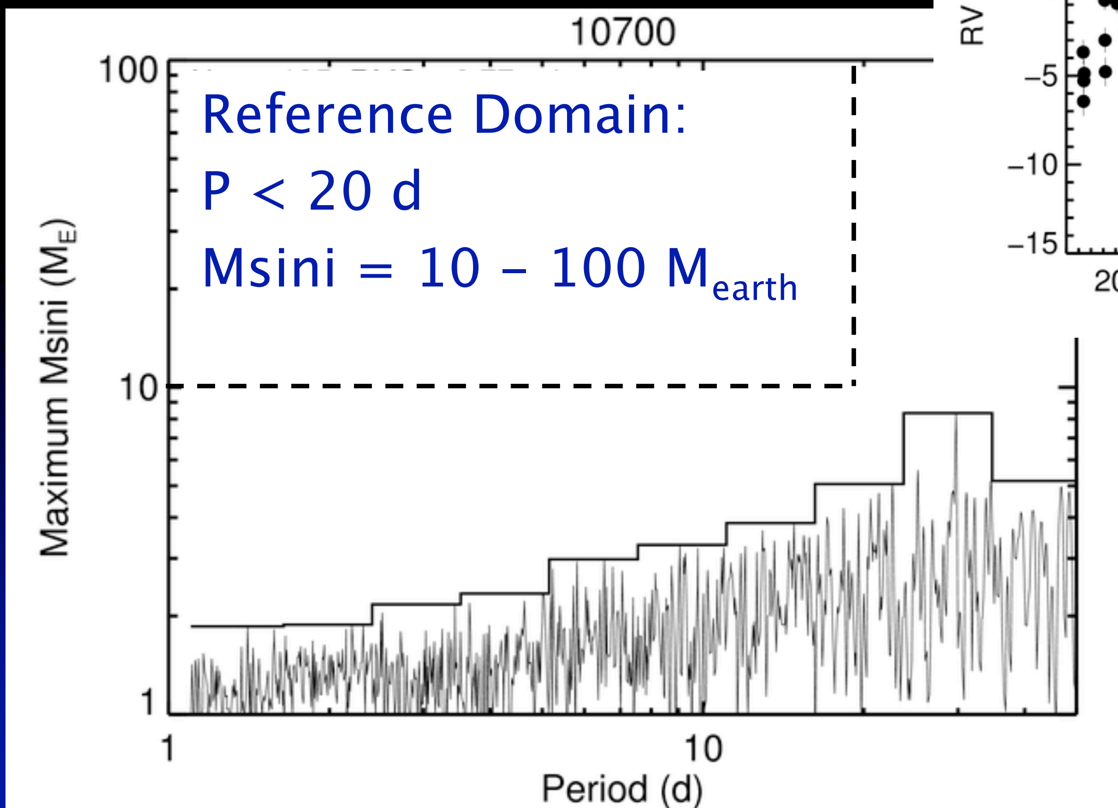
Reference Domain:

P < 20 d

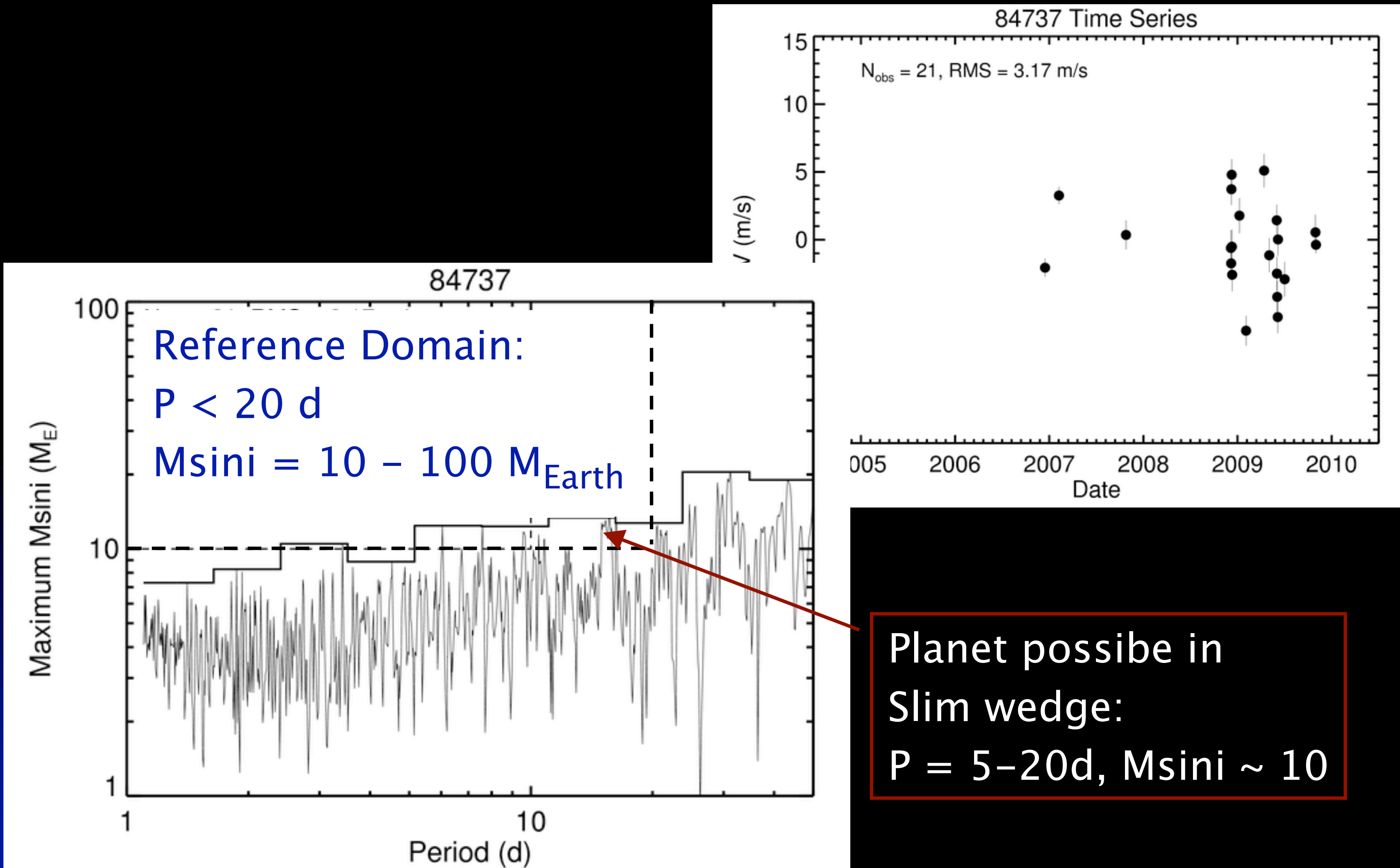
Msini = 10 – 100 M_{earth}

Limits on Planets Mass in Well-Observed Star



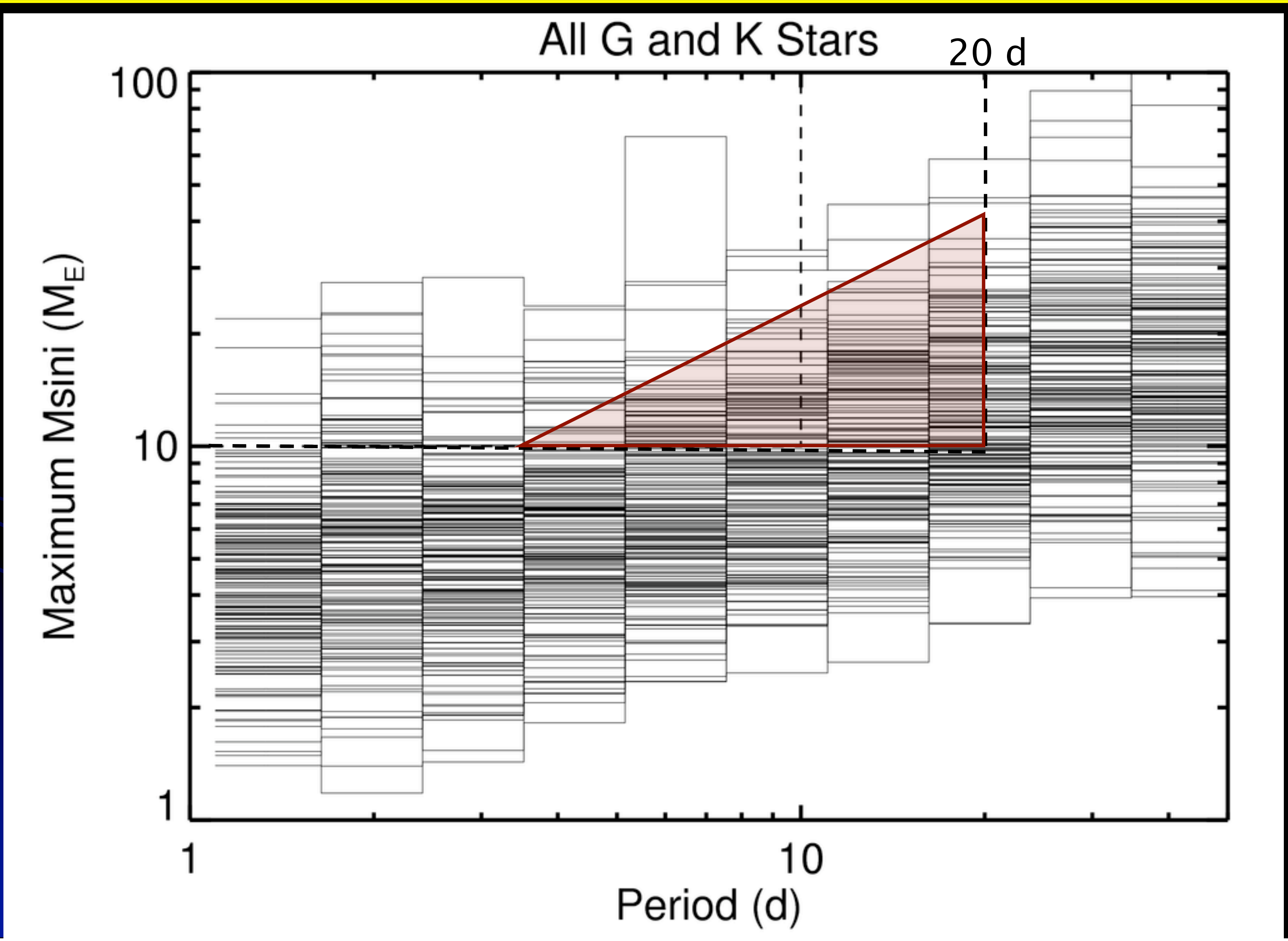


Planet Mass Limits in Poorly Observed Star

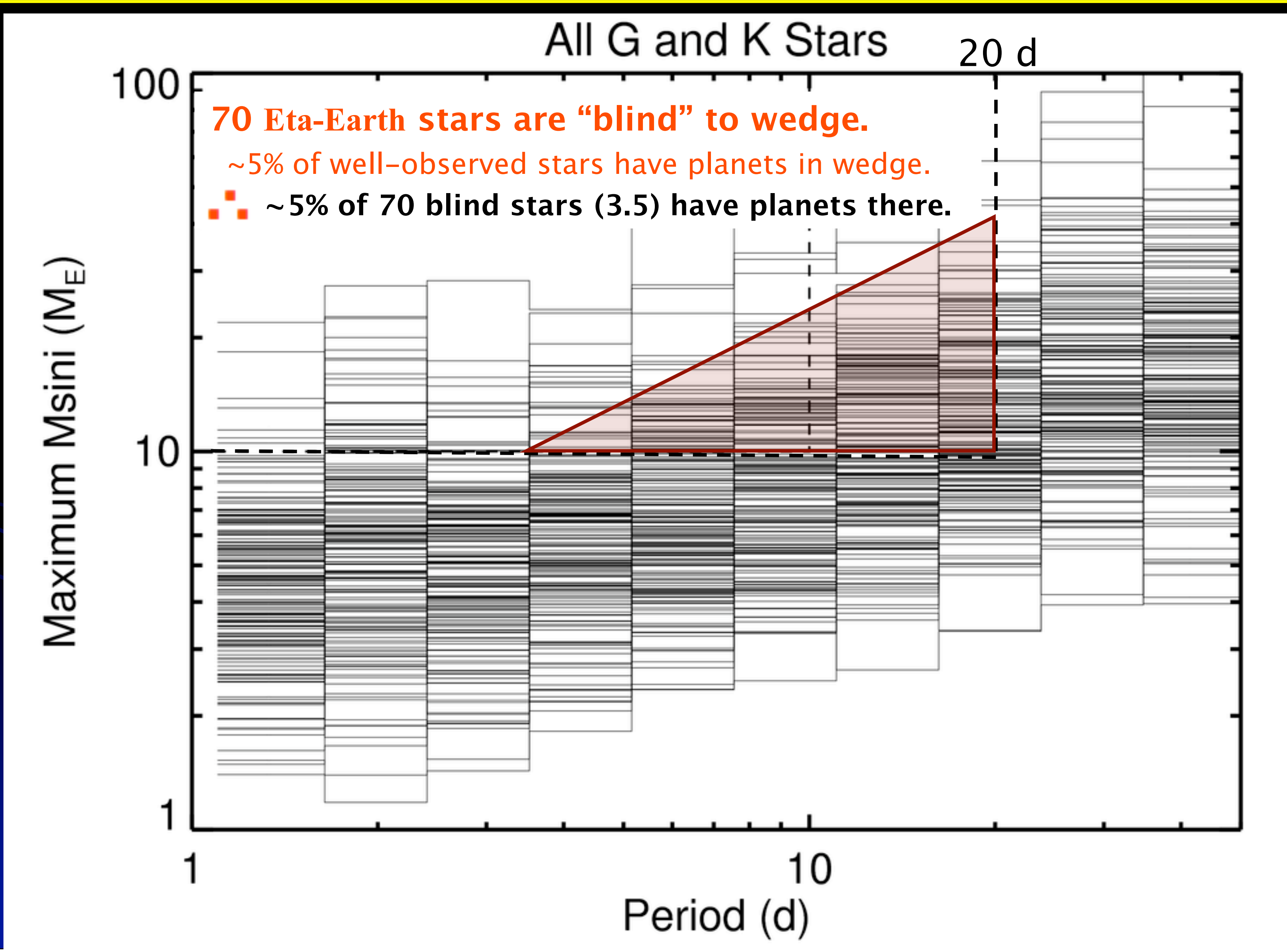


Planet possibe in
Slim wedge:
P = 5-20d, Msini ~ 10

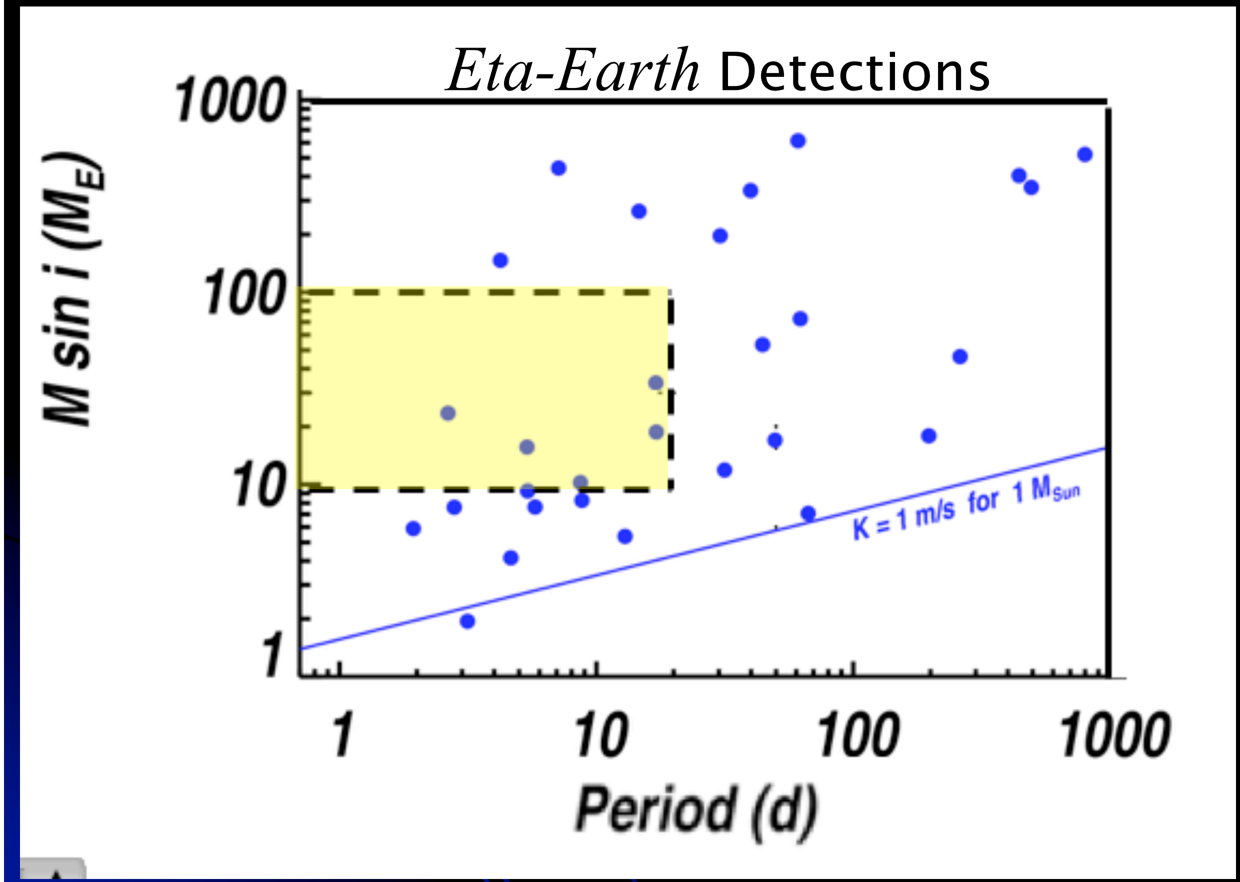
Limits on Msin$i$ for All Non-Detections



Limits on Msini for All Non-Detections



Frequency of Planets: 10-100 M_{Earth} and Period < 20 d



171 G + K Stars

6 Secure Planets

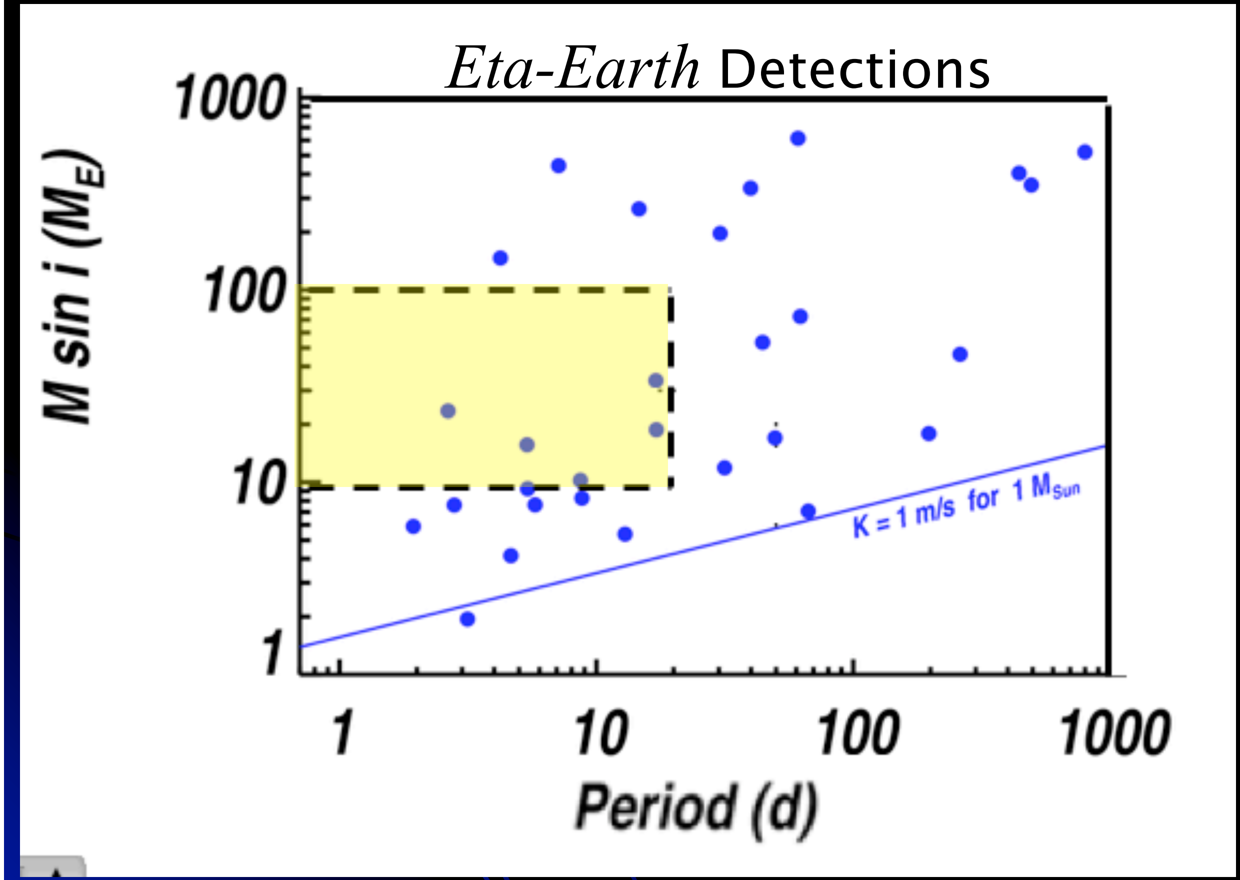
4 Candidate Planets

10 Total Planets

Frequency:
10 / 171 = 5.8 %

Incompleteness:
~3.5 Missed planets.

Frequency of Planets: 10-100 M_{Earth} and Period < 20 d



171 G + K Stars

6 Secure Planets

4 Candidate Planets

3.5 Missed Planets

13.5 Total Planets

Frequency:
13.5 / 171 = 7.9 %

Doppler Periodicities from Starspots:

RMS Doppler Velocity = 0.5 Δmag V_{eq} sin i

STARSPOT JITTER IN PHOTOMETRY, ASTROMETRY AND RADIAL VELOCITY MEASUREMENTS

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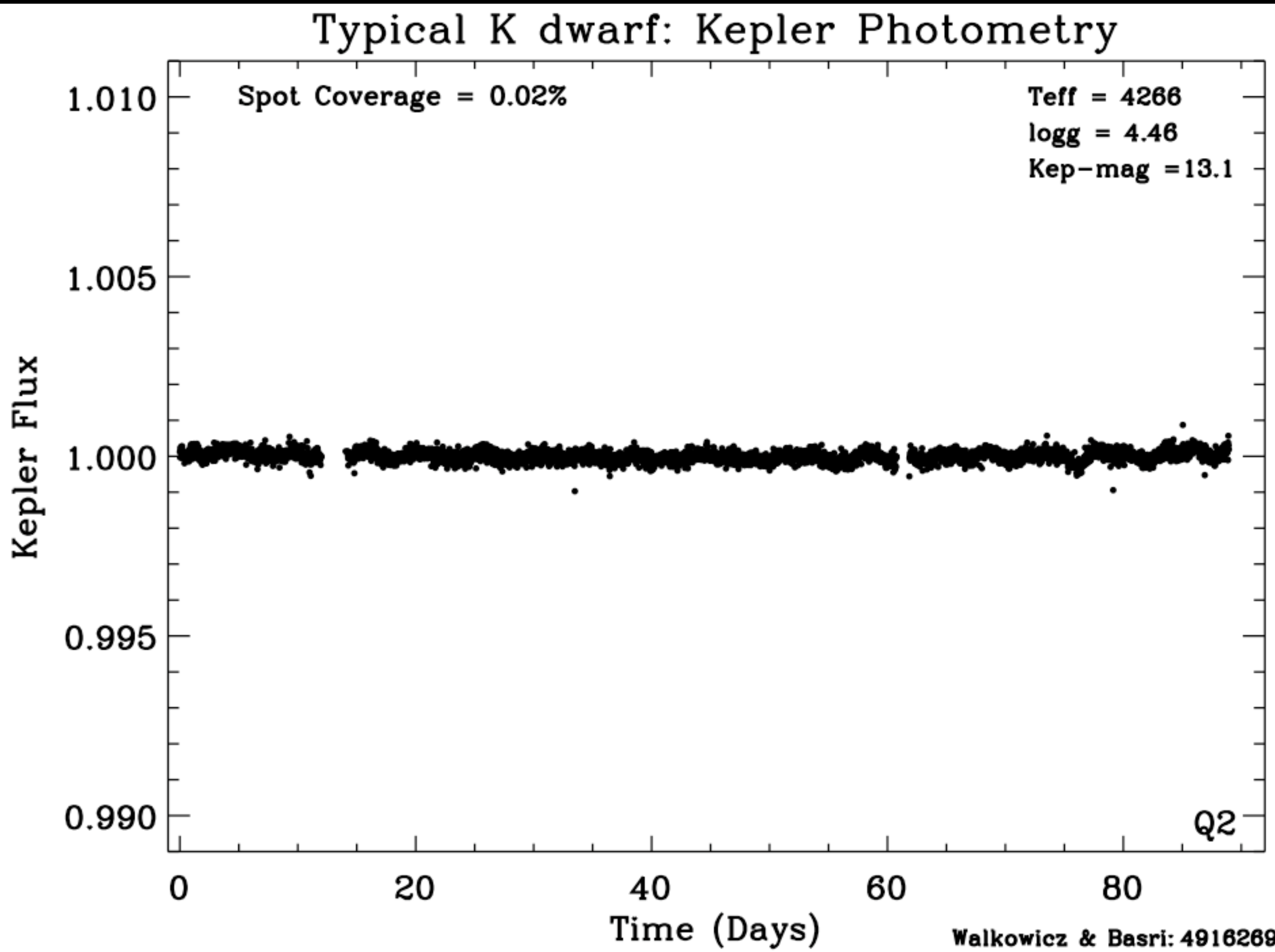
ABSTRACT

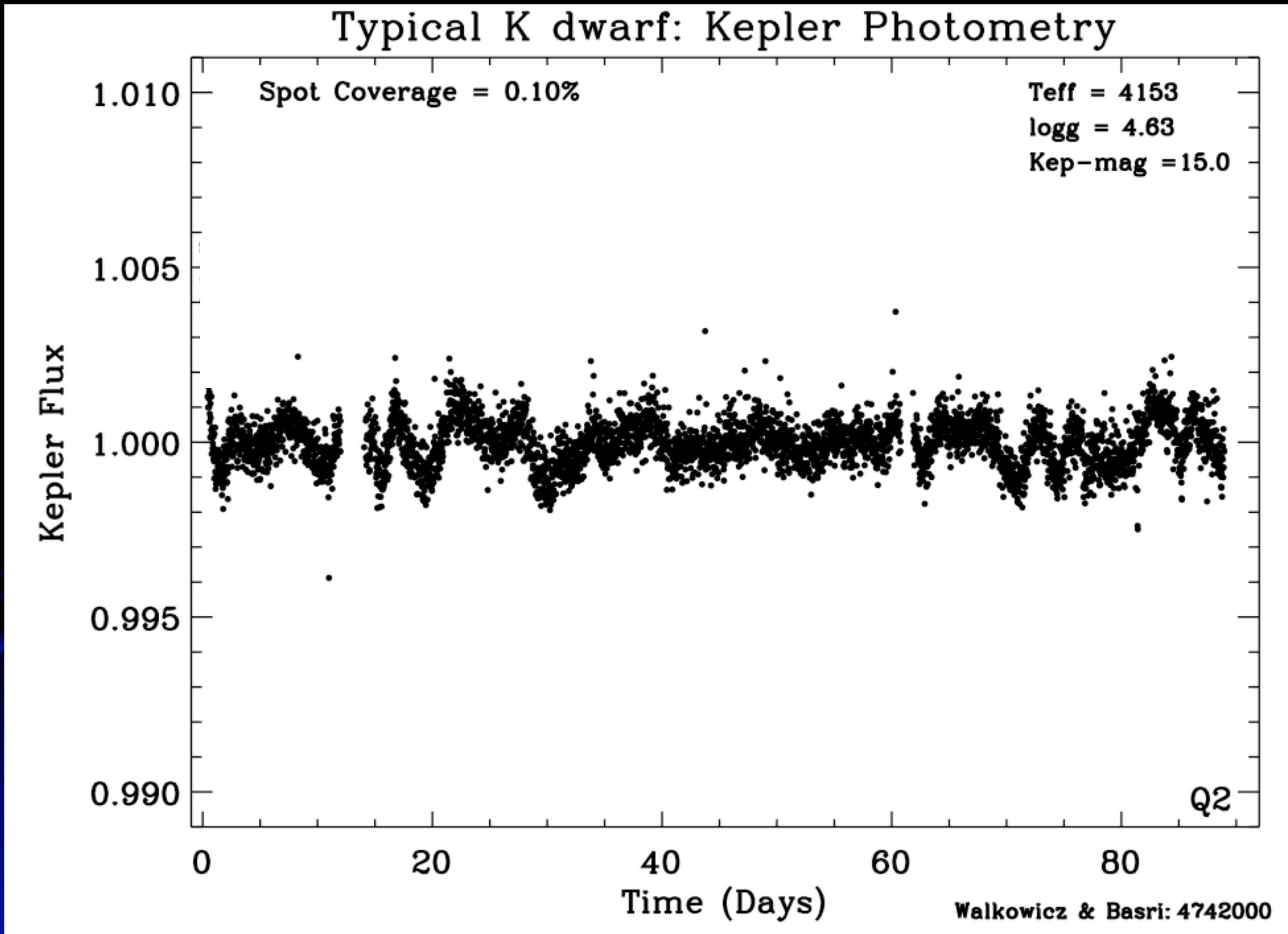
Analytical relations are derived for the amplitude of astrometric, photometric and radial velocity perturbations caused by a single rotating spot. The relative power of the star spot jitter is estimated and compared with the available data for κ^1 Ceti and HD 166435, as well as with numerical simulations for κ^1 Ceti and the Sun. A Sun-like star inclined at $i = 90°$ at 10 pc is predicted to have a RMS jitter of 0.087 μas in its astrometric position along the equator, and 0.38 m s^{-1} in radial velocities. If the presence of spots due to stellar activity is the ultimate limiting factor for planet detection, the sensitivity of SIM Lite to Earth-like planets in habitable zones is about an order of magnitude higher that the sensitivity of prospective ultra-precise radial velocity observations of nearby stars.

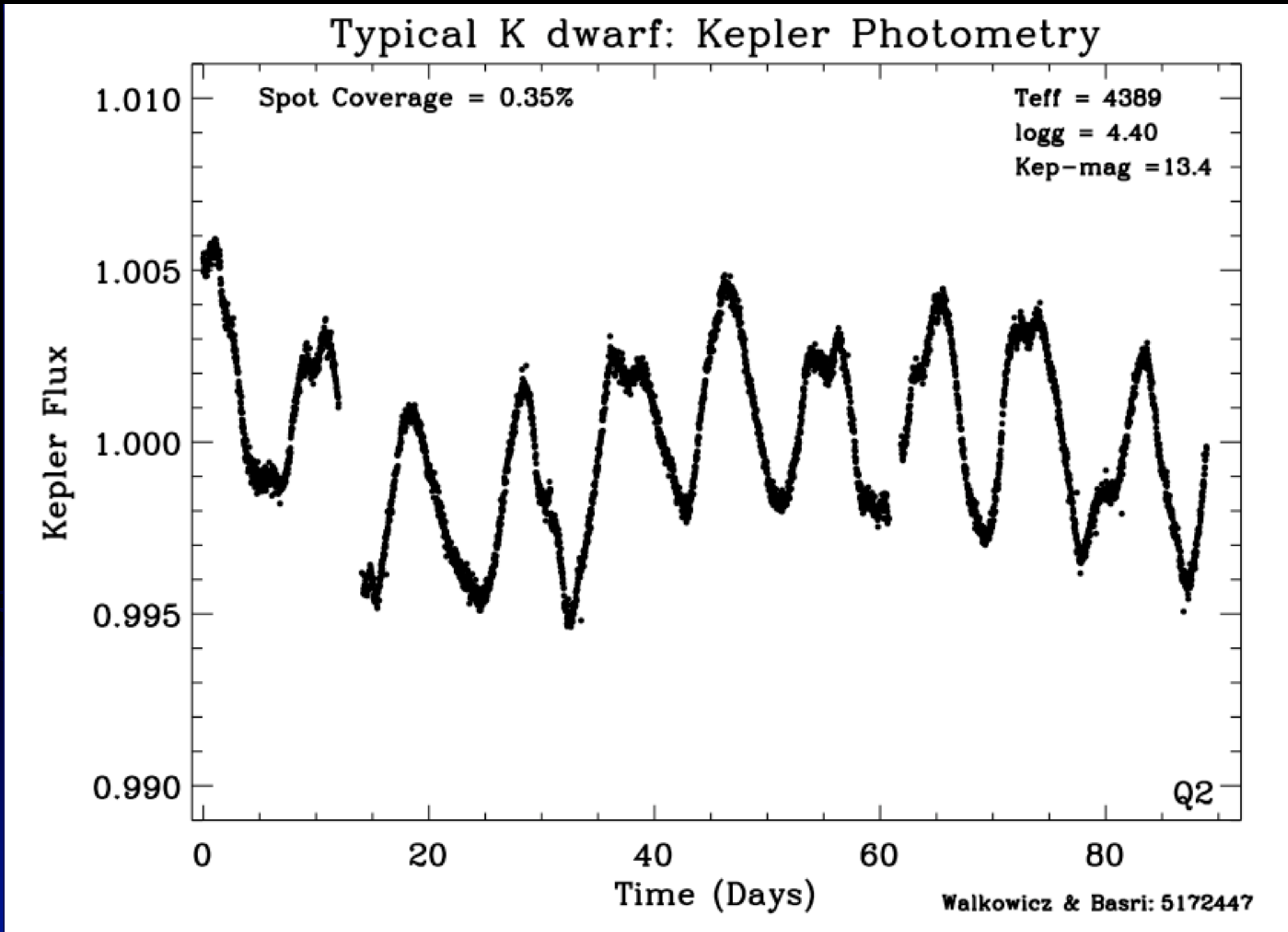
Makarov et al. 2010

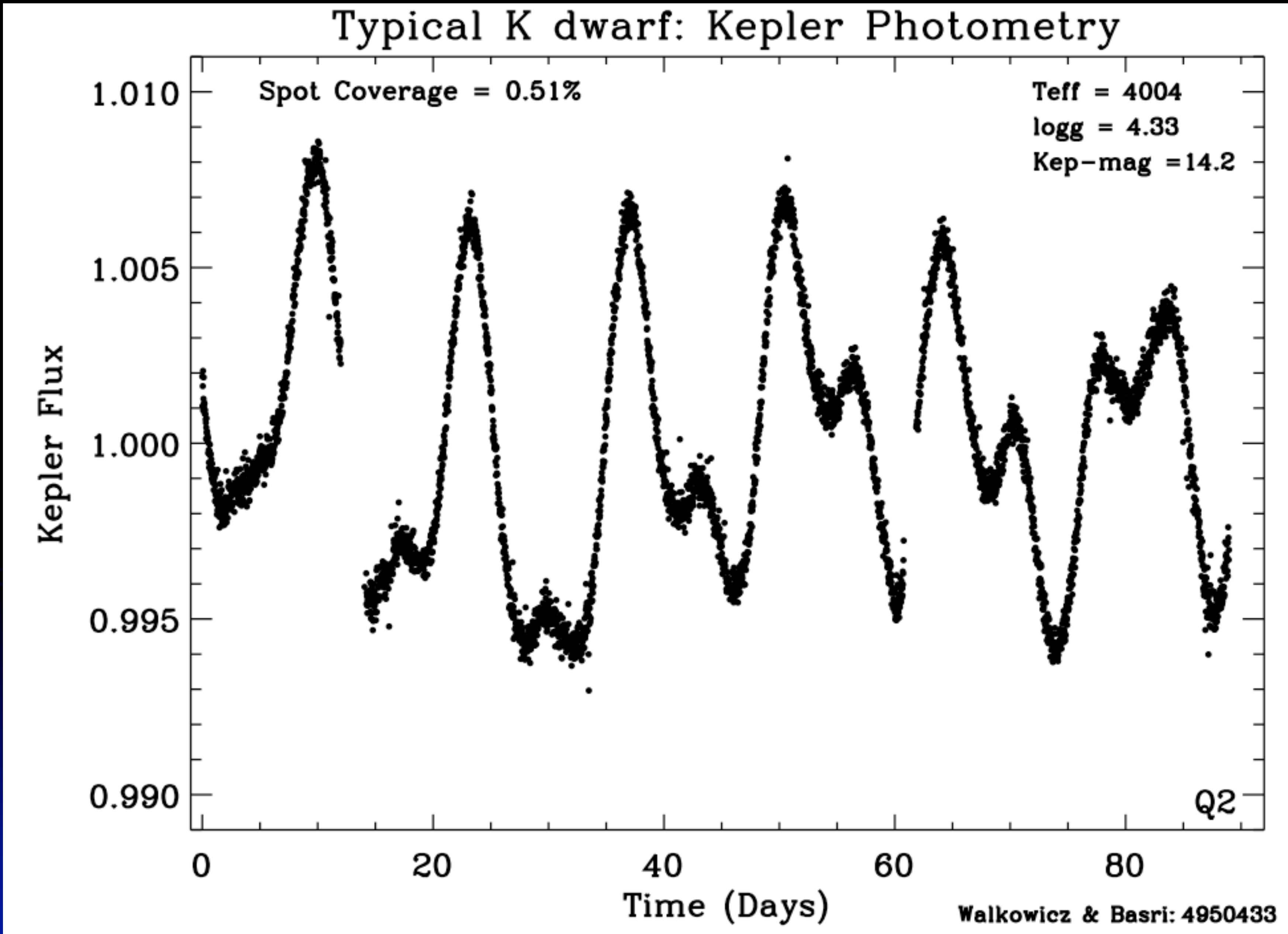
Sun, $V_{eq} = 2$ km s^{-1} and $R_\odot = 4650$ μAU. We estimate a relative flux variability of the Sun of RMS($\Delta F/F$) $= 3.24 \cdot 10^{-4}$ after subtracting a 10-yr period solar cycle light curve from the solar irradiance PMOD data (Fröhlich & Lean 1998). Therefore, the sunspot-related jitter is not greater than $\Delta m\, R$ (1.5 μAU for the Sun) in position and than $\Delta m\, V_{eq}$ (0.65 m s^{-1} for the Sun) in radial velocities, where Δm is the characteristic magnitude jitter.

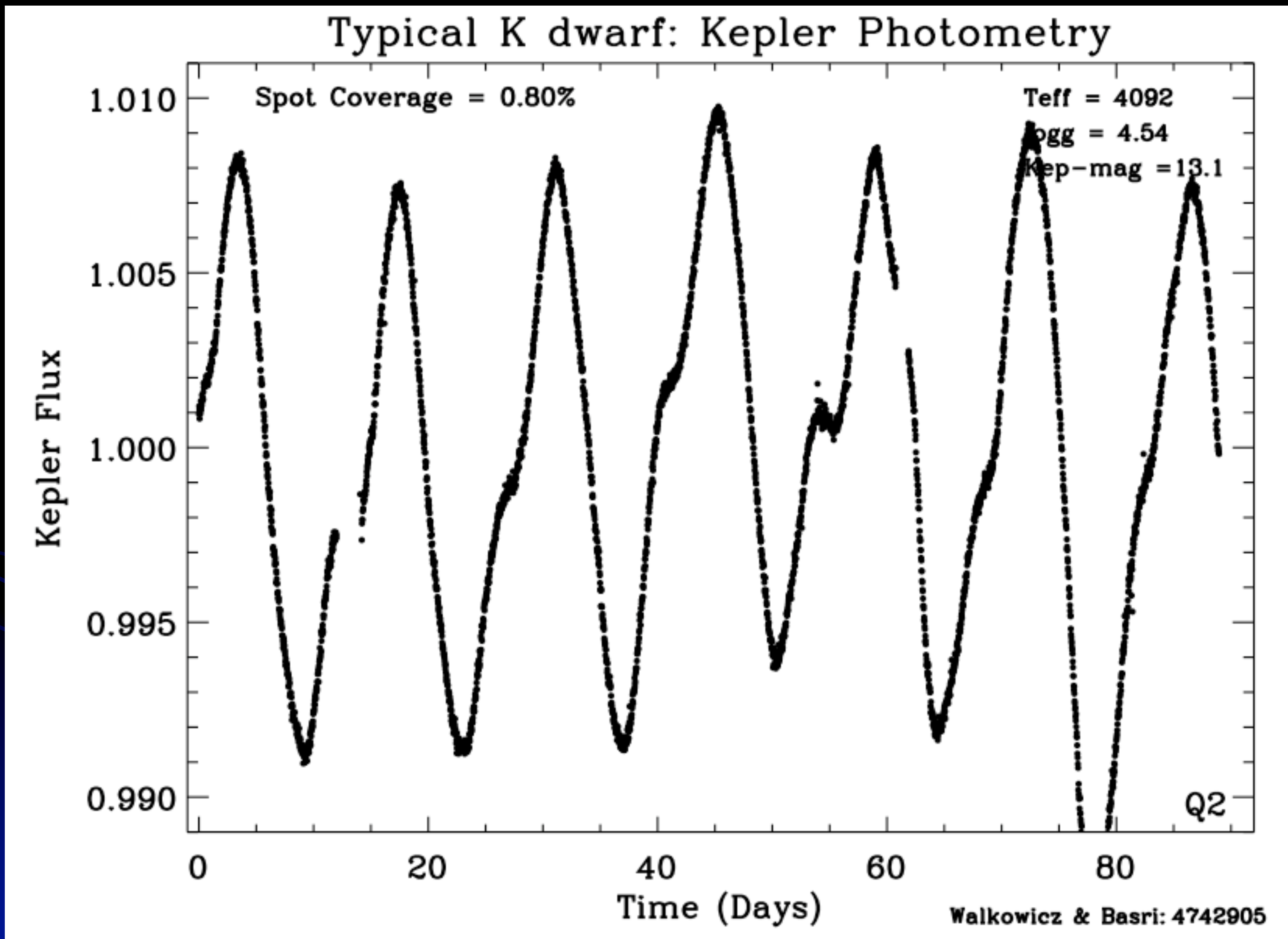


Typical K dwarf: Kepler Photometry
Spot Coverage = 0.02%
Teff = 4266
logg = 4.46
Kep−mag =13.1
Kepler Flux
1.010
1.005
1.000
0.995
0.990
Q2
0
20
40
60
80
Time (Days)
Walkowicz & Basri: 4916269

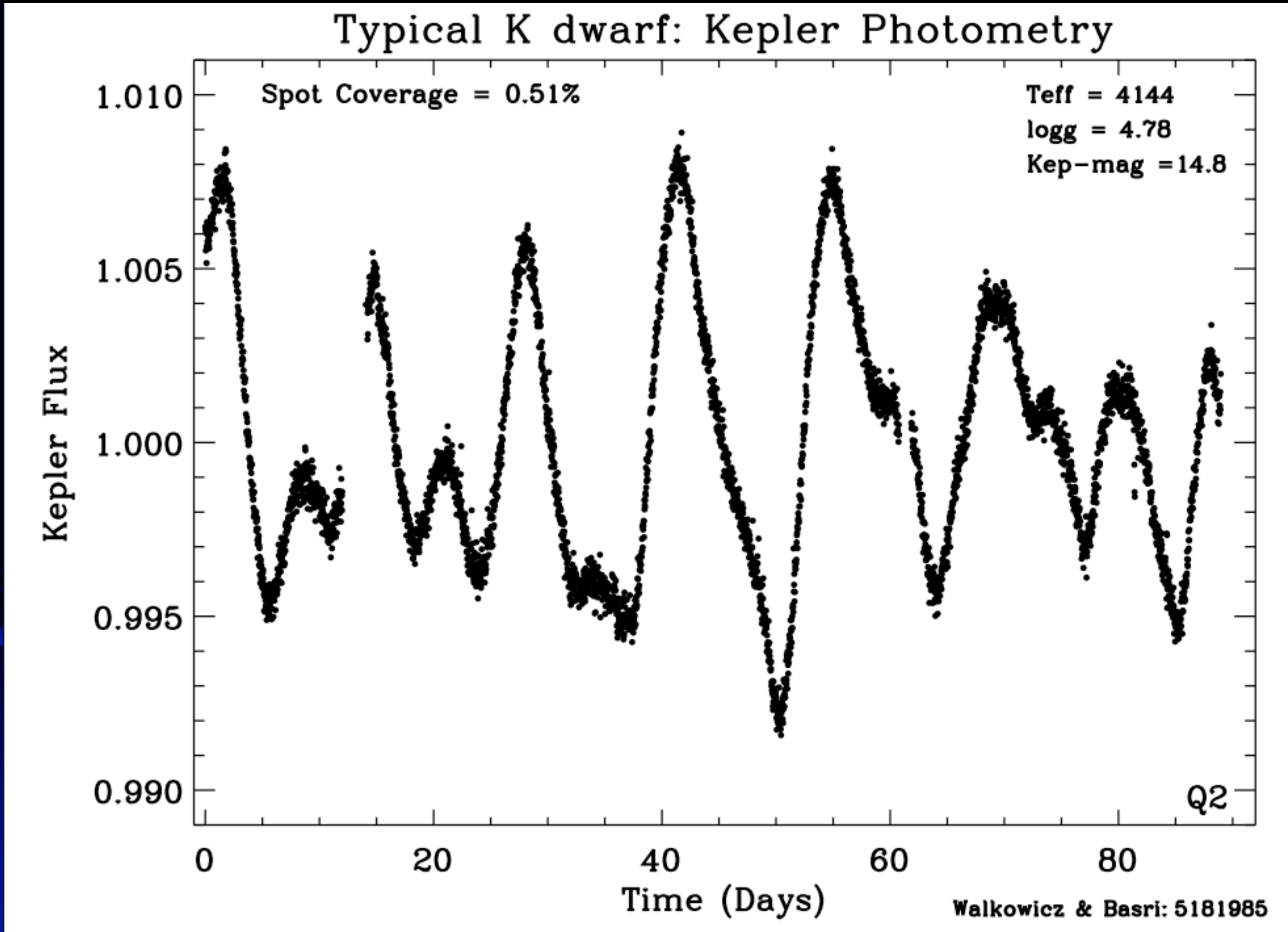

Typical K dwarf: Kepler Photometry
Spot Coverage = 0.10%
Teff = 4153
logg = 4.63
Kep-mag =15.0
Kepler Flux
1.010
1.005
1.000
0.995
0.990
Q2
0
20
40
60
80
Time (Days)
Walkowicz & Basri: 4742000


Typical K dwarf: Kepler Photometry
Spot Coverage = 0.35%
Teff = 4389
logg = 4.40
Kep-mag =13.4
Q2
1.010
1.005
1.000
0.995
0.990
Kepler Flux
0
20
40
60
80
Time (Days)
Walkowicz & Basri: 5172447


Typical K dwarf: Kepler Photometry
Spot Coverage = 0.51%
Teff = 4004
logg = 4.33
Kep-mag =14.2
Kepler Flux
1.010
1.005
1.000
0.995
0.990
0
20
40
60
80
Time (Days)
Q2
Walkowicz & Basri: 4950433



Typical K dwarf: Kepler Photometry
Spot Coverage = 0.80%
Teff = 4092
logg = 4.54
Kep-mag =13.1
Q2
Kepler Flux
1.010
1.005
1.000
0.995
0.990
0
20
40
60
80
Time (Days)
Walkowicz & Basri: 4742905


Typical K dwarf: Kepler Photometry
Spot Coverage = 0.51%
Teff = 4144
logg = 4.78
Kep-mag =14.8
Q2
Kepler Flux
1.010
1.005
1.000
0.995
0.990
0
20
40
60
80
Time (Days)
Walkowicz & Basri: 5181985

Summary:
Eta-Earth Survey

1. Doppler Planet Search of 171 GK Stars: Complete
2. 65 M Dwarfs Still Incomplete
3. Examine Domain: $P < 20$ d, Msini=10–100 M_{Earth}
4. 6 Planets + 4 Candidates + 3.5 Likely Missed

8 % of Solar-Type Stars have 10–100 M_{Earth} Planets with Periods < 20 days

Thanks: Andrew Howard, U.C., NASA