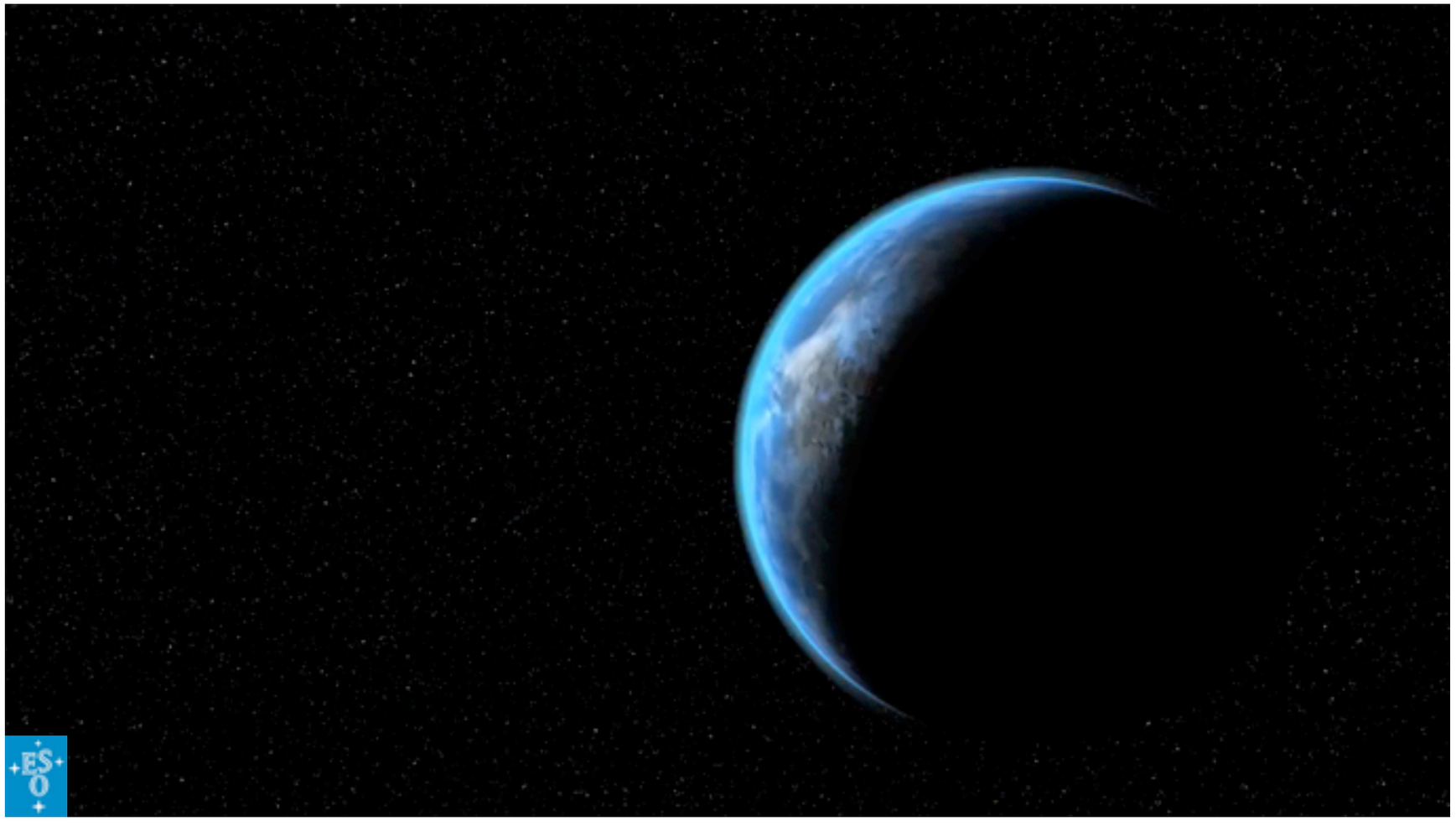
HARPS PLANETS AROUND M DWARFS
LOW-MASS / HABITABLE / TRANSITING



X. BONFILS, N. ASTUDILLO, F. BOUCHY, X. DELFOSSE, T. FORVEILLE, M. GILLON, C. LOVIS, M. MAYOR, V. NEVES, F. PEPE, C. PERRIER, D. QUELOZ, N. C. SANTOS, S. UDRY

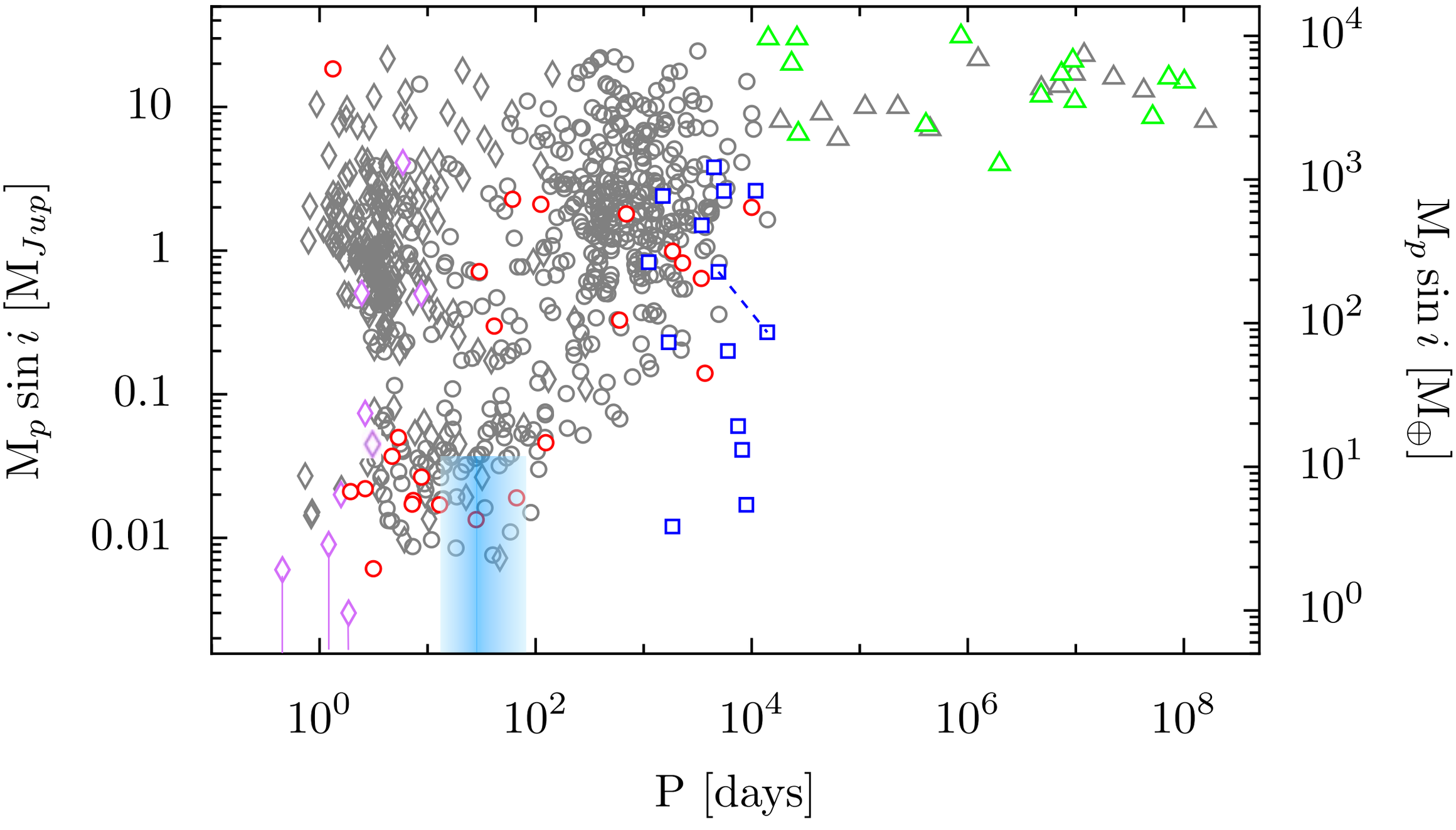
IPAG (GRENOBLE), GENEVA OBS., LIEGE OBS., CAUP (PORTO), IAP (PARIS)

Status

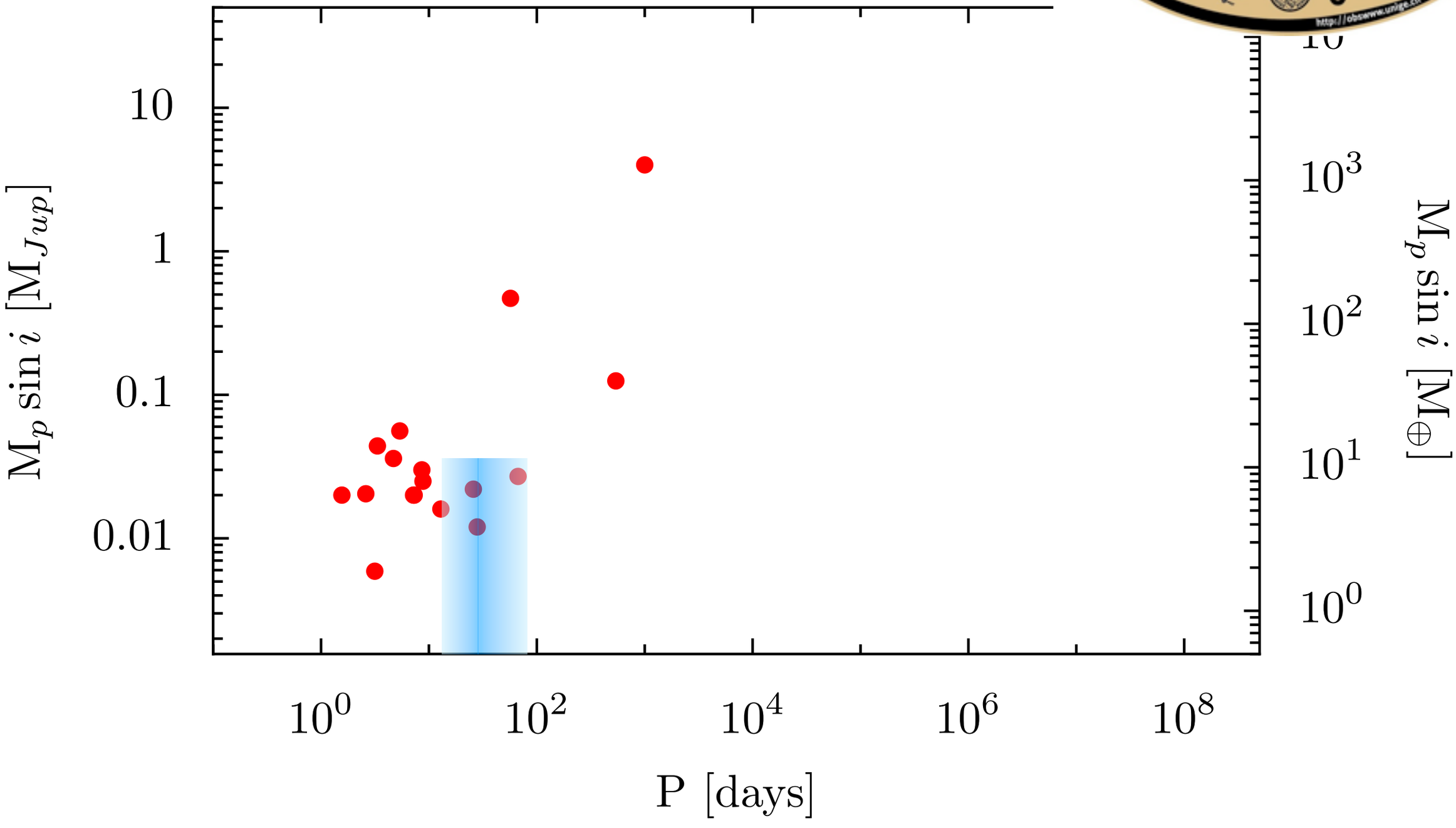
- *diversity*
- *structure*

➡ *statistical information*

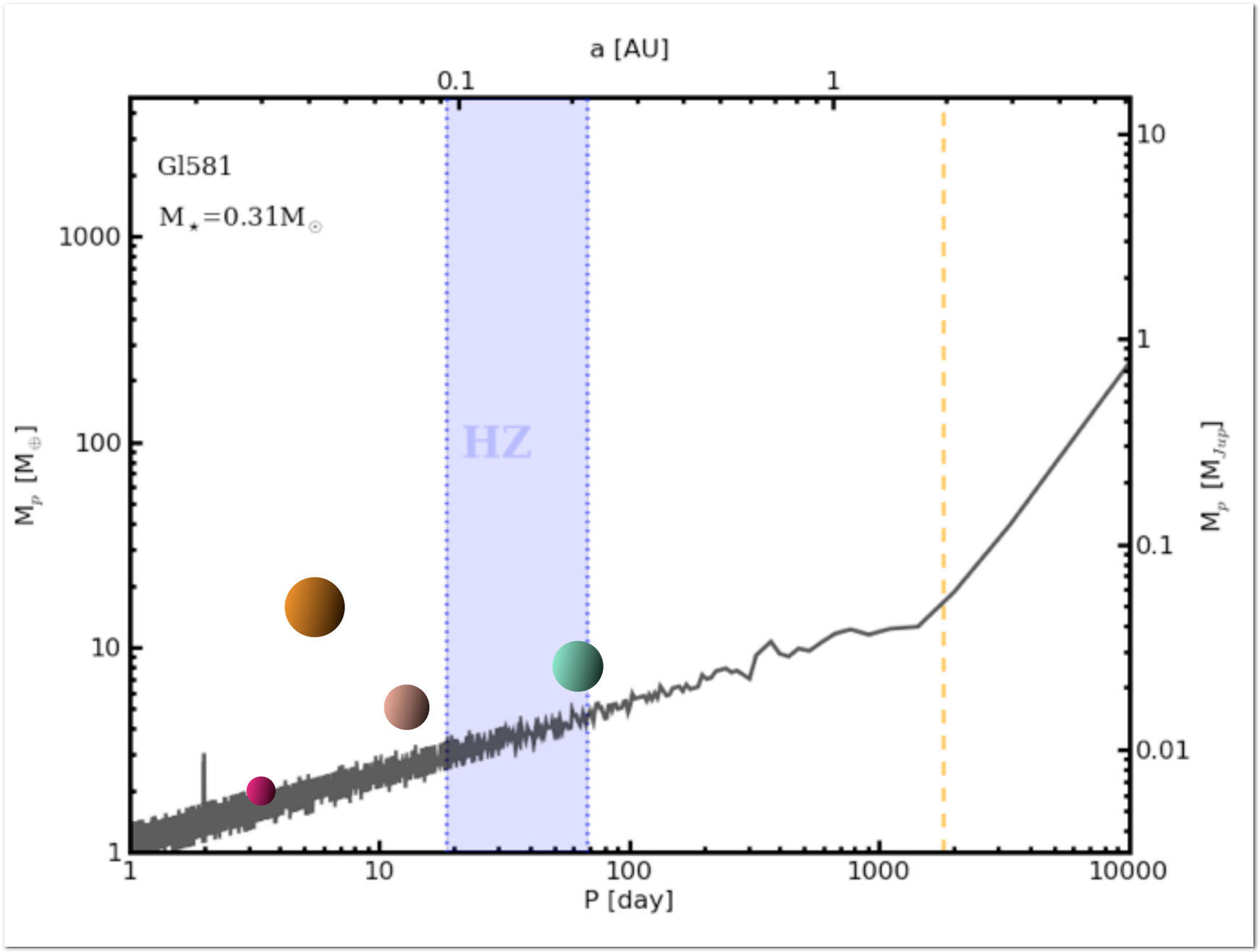
bias / need non-detection

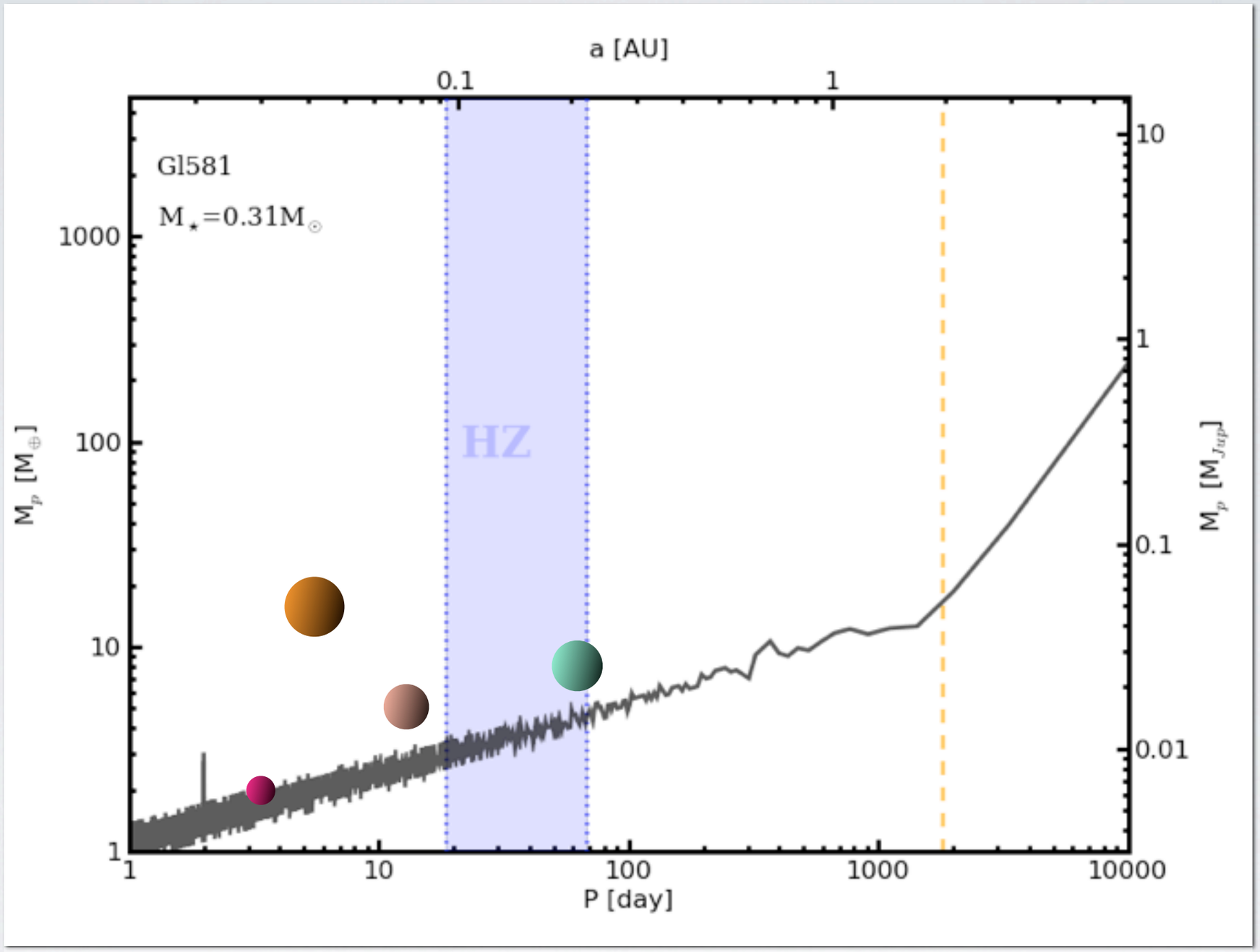


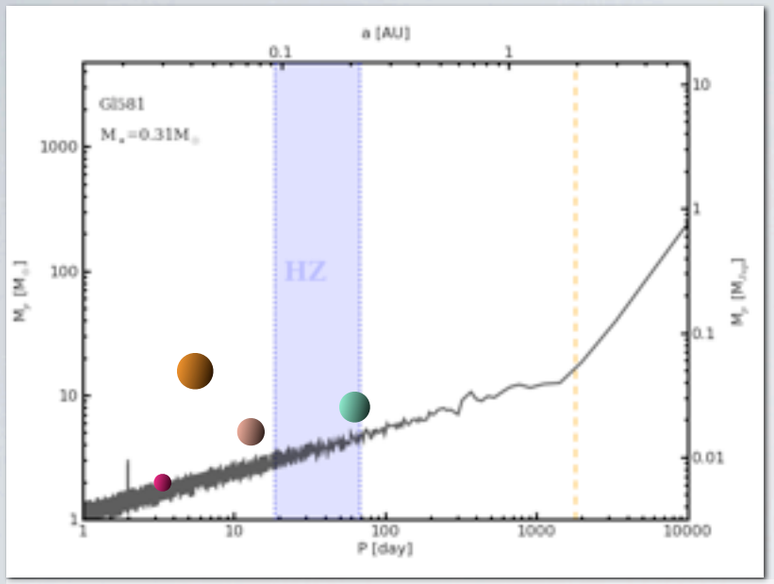
16 detections (and counting)
includes habitable-zone super-Earths
(GJ581 c&d, GJ667Cc & GJ163c)



OCCURRENCE OF M-DWARF PLANETS FROM HARPS




a [AU]
0.1
1
Gl581
$M_\star$=0.31$M_\odot$
HZ
1000
100
10
1
10
1
0.1
0.01
M_p [$M_\oplus$]
M_p [M_{Jup}]
1
10
100
1000
10000
P [day]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M*=0.31M⊙
HZ
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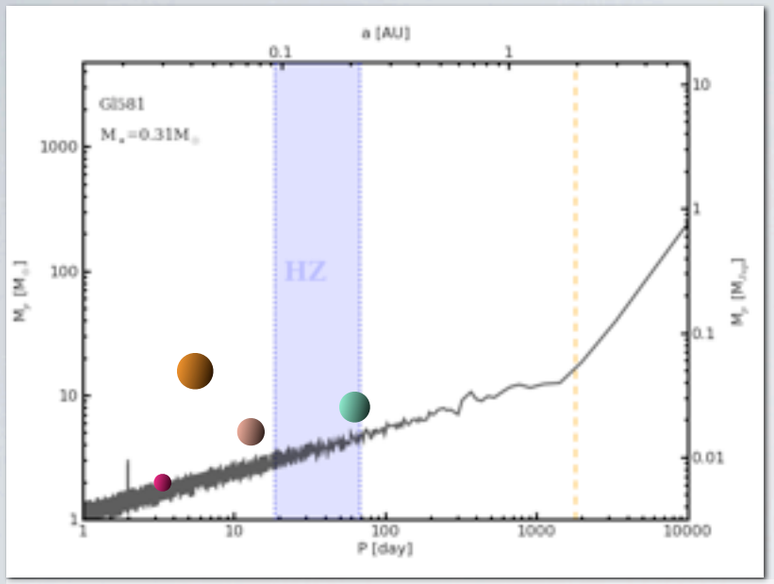
Mp [M⊕]
Mp [MJup]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M*=0.31M⊙
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M_p [M⊕]
M_p [M_Jup]
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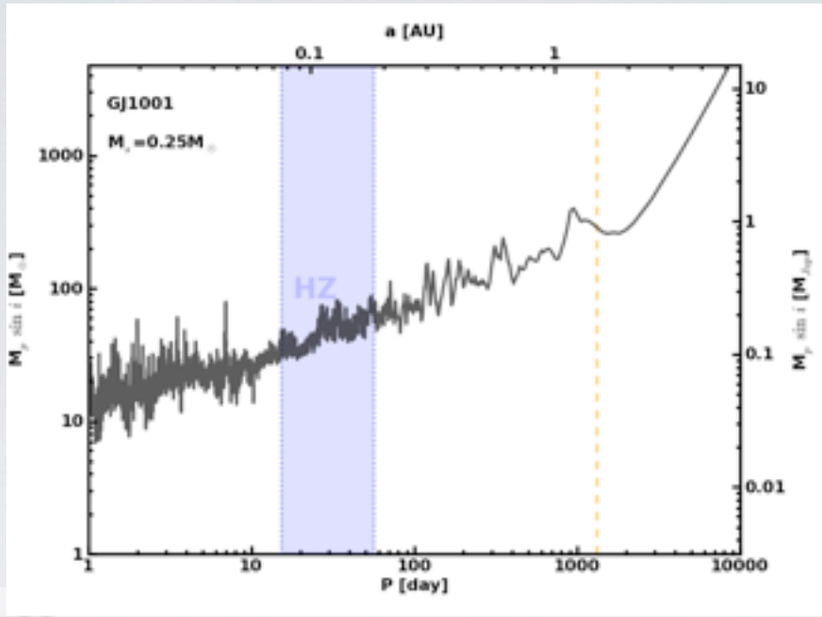
P [day]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GJ1001
M*=0.25M⊙
HZ
1000
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M_p sin i [M⊕]
M_p sin i [M_Jup]
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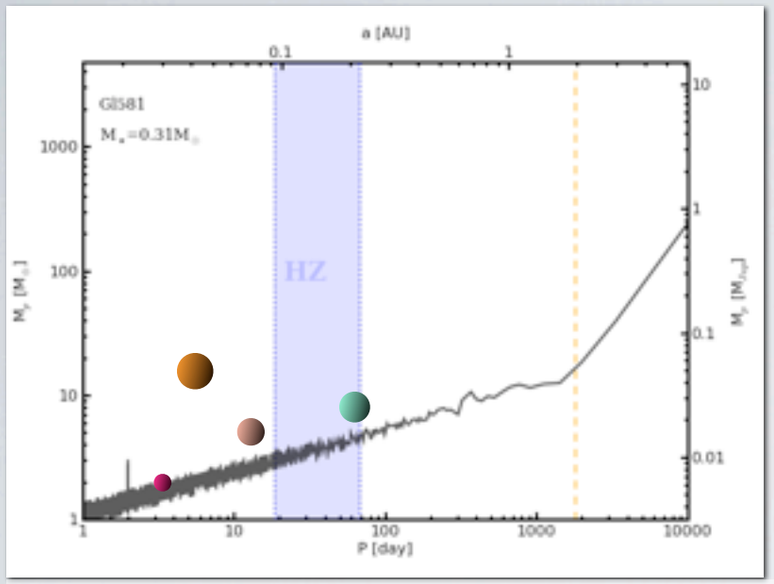
100
1000
10000
P [day]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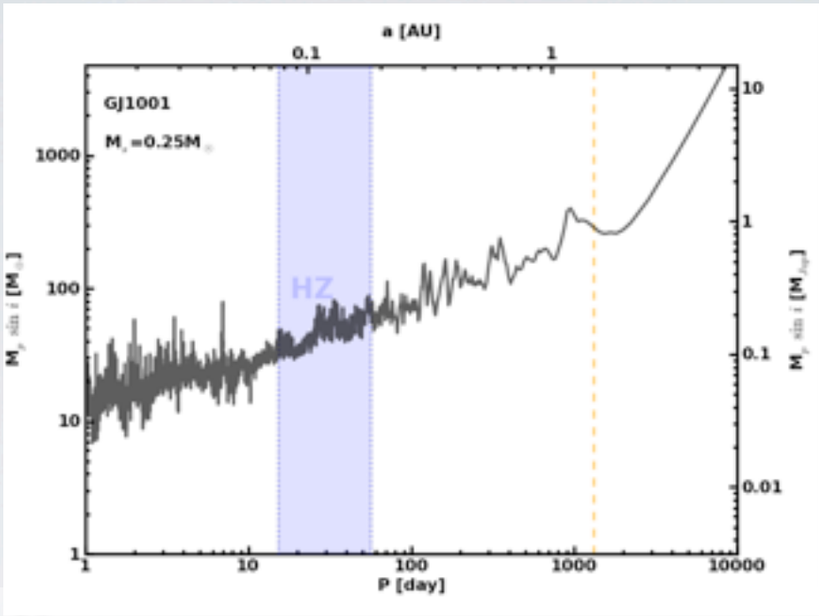
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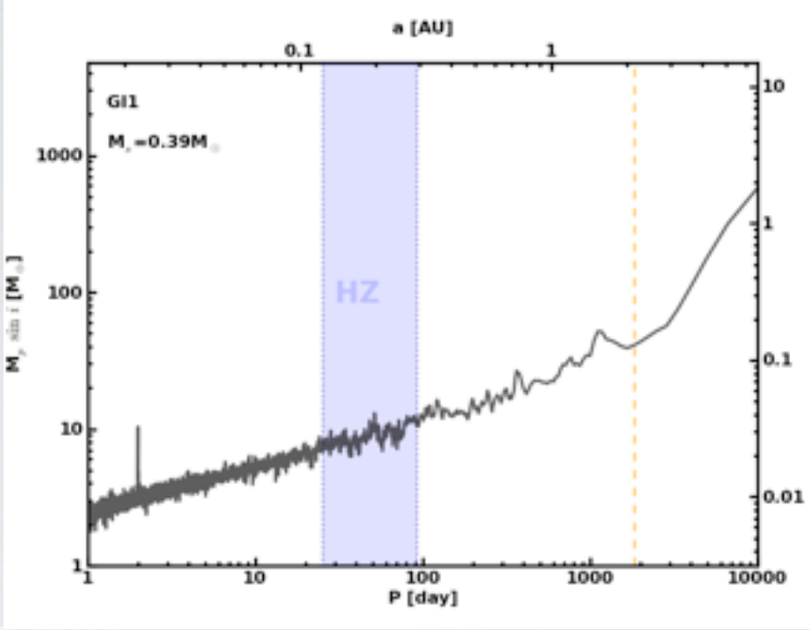
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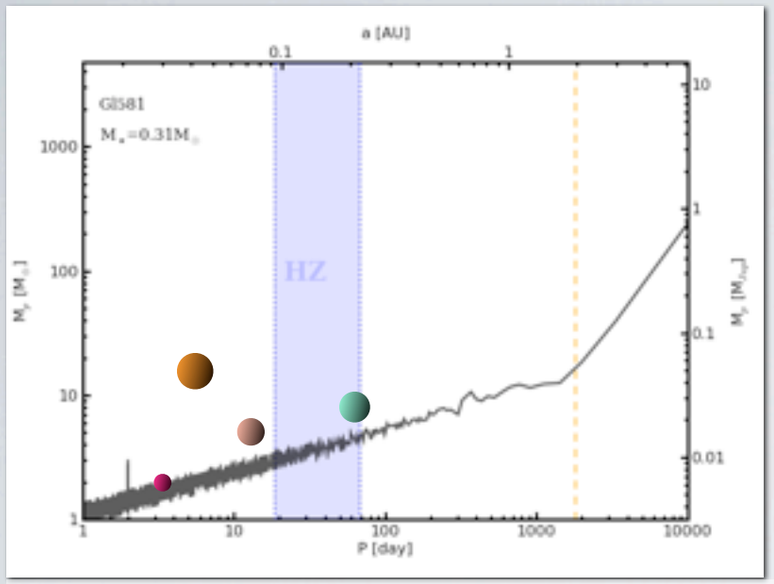
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0.1
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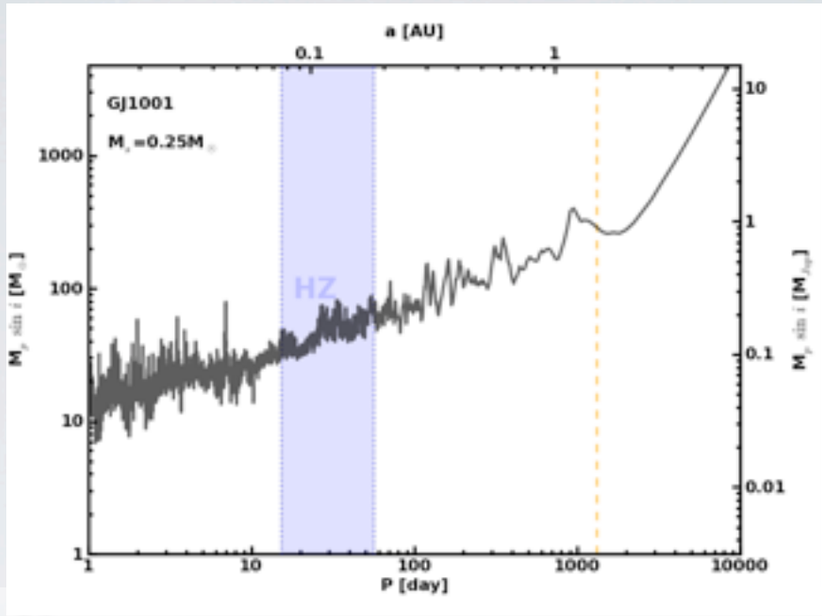
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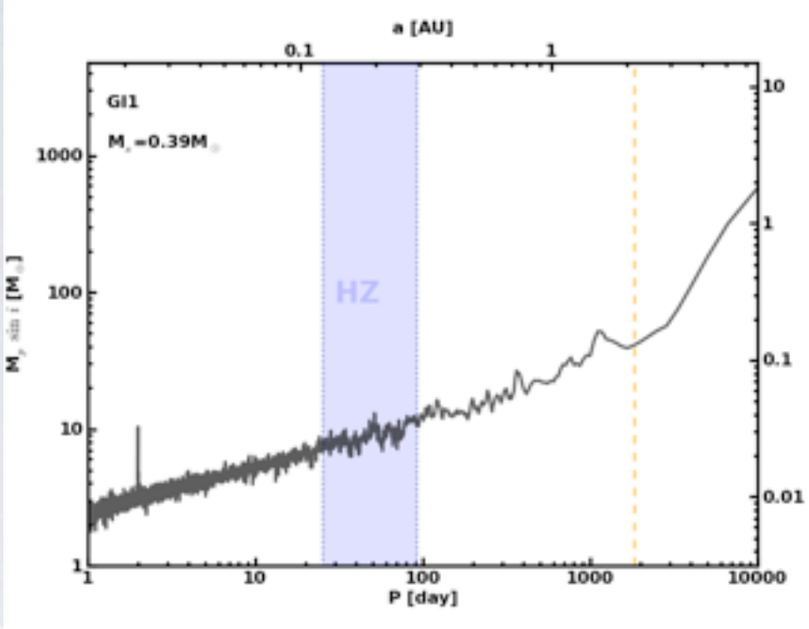
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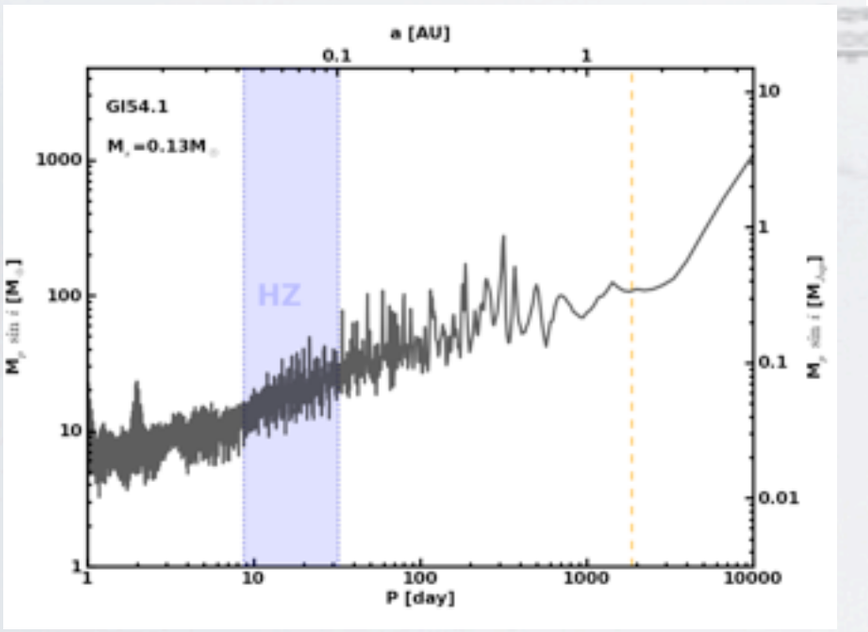
0.01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GI54.1
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HZ
1000
100
10
1
10
100
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10000
P [day]
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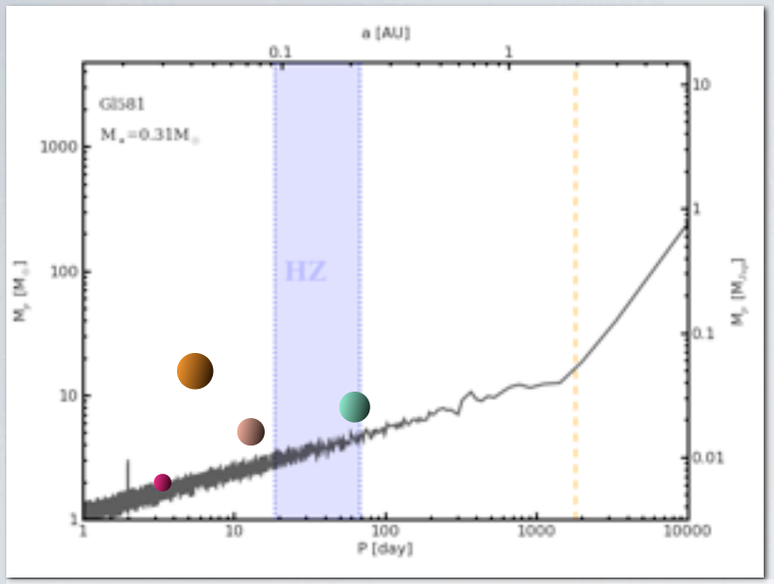
1
0.1
0.01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0.1
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GI581
M* =0.31M⊙
HZ
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100
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1
10
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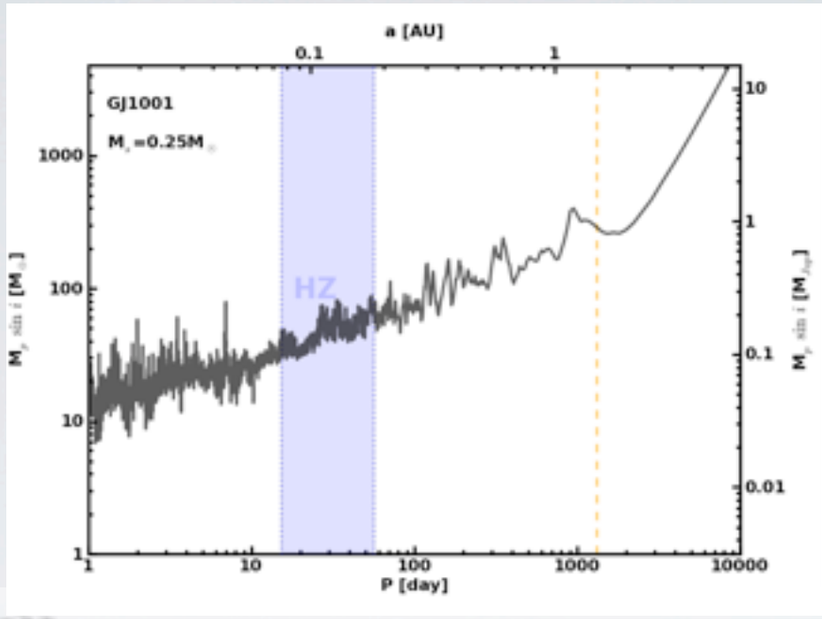
10000
P [day]
Mp sin i [M⊕]
Mp sin i [MJup]
10
1
0.1
0.01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Mp sin i [M⊕]
Mp sin i [MJup]
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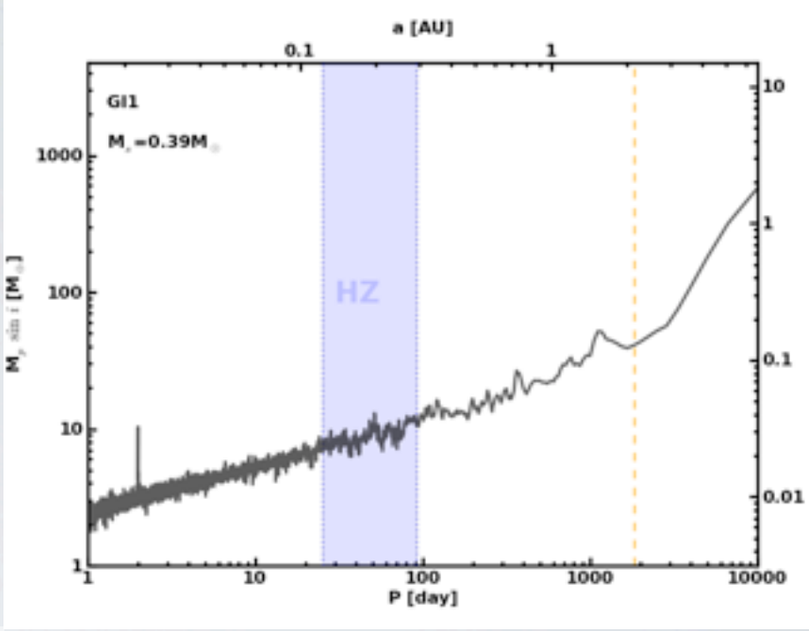
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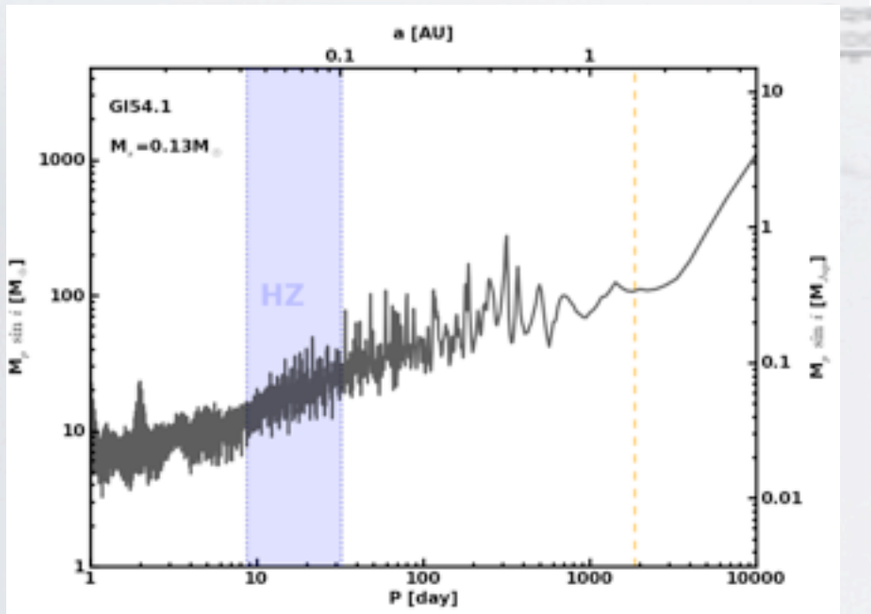
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HZ
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Mp sin i [MJup]
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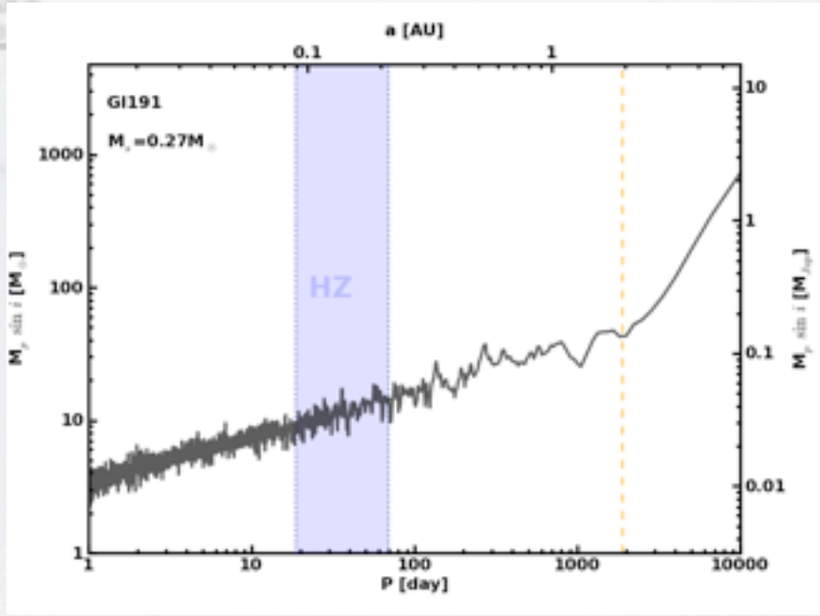
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Mp sin i [M⊕]
Mp sin i [MJup]
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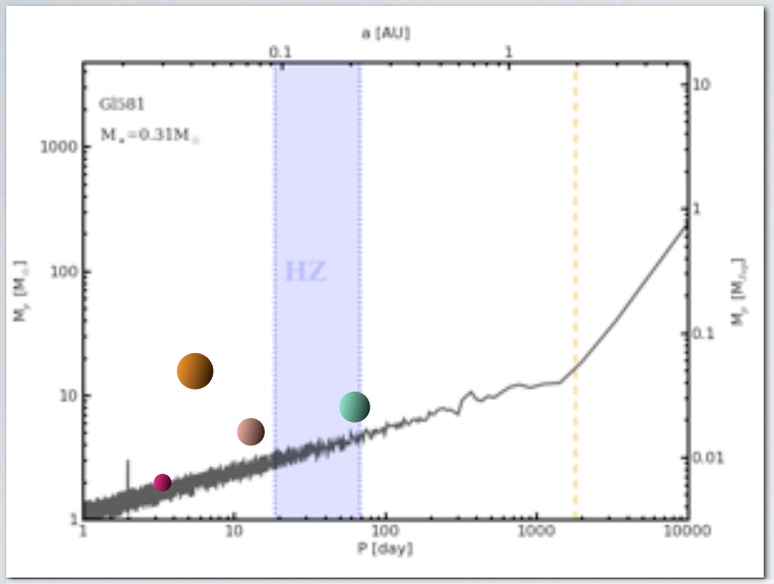
1
0.1
0.01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M* =0.31M⊙
HZ
Mp sin i [M⊕]
Mp sin i [MJup]
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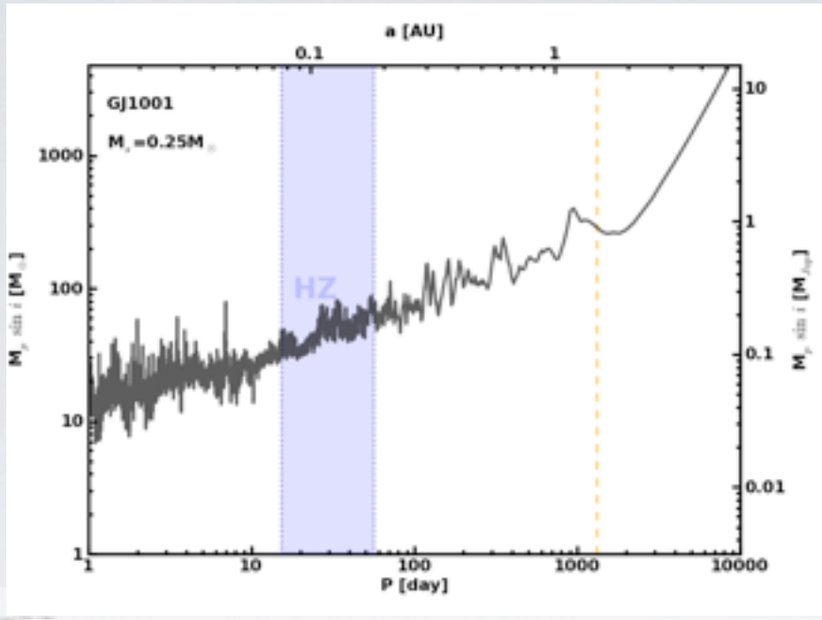
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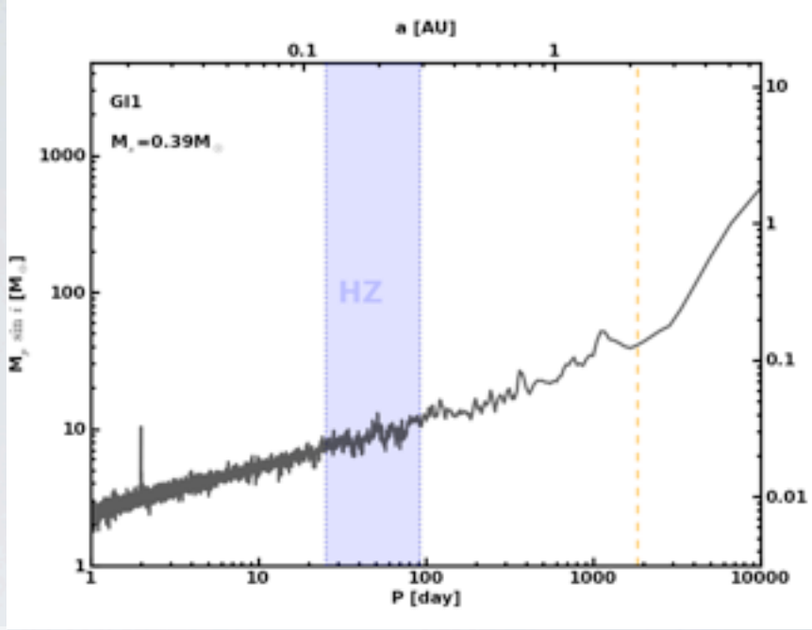
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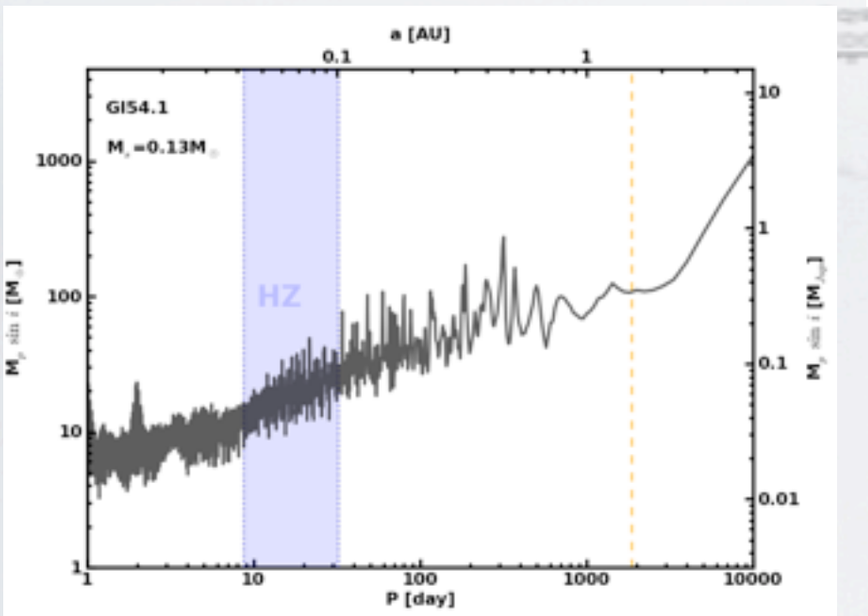
Mp sin i [MJup]
P [day]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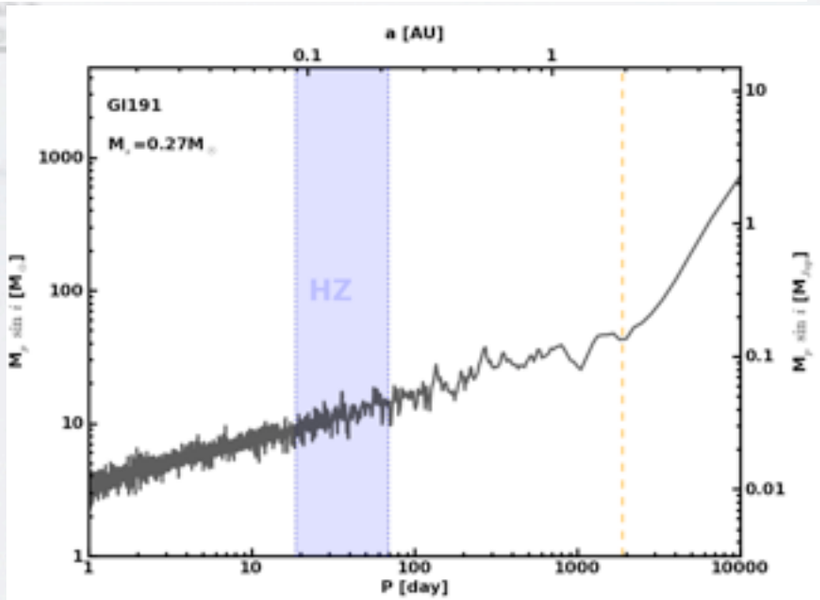
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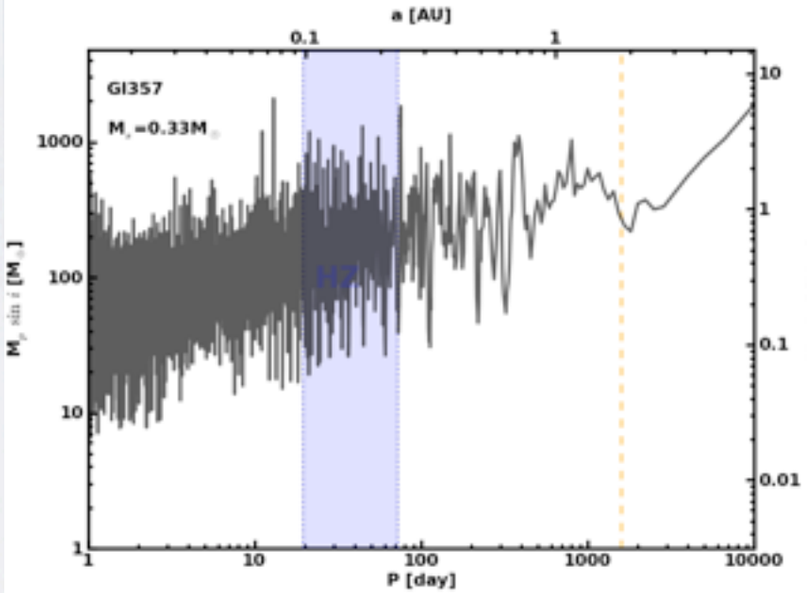
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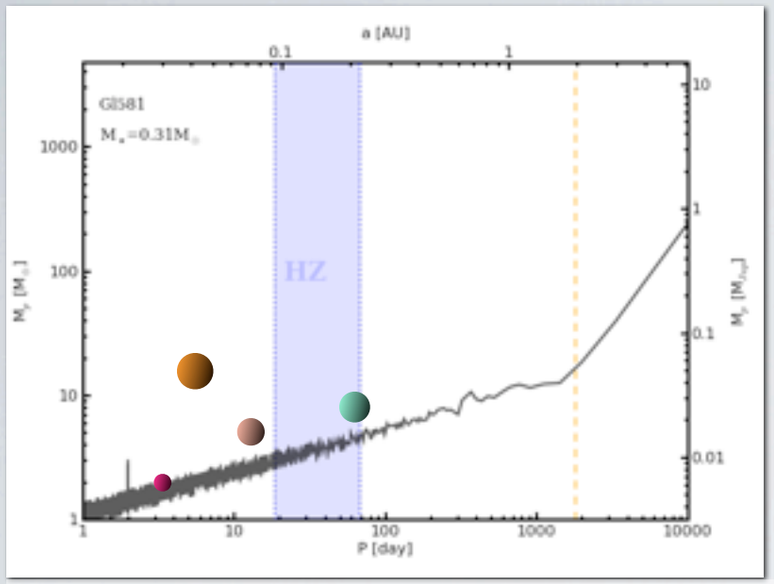
Mp sin i [MJup]
P [day]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GI581
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HZ
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1000
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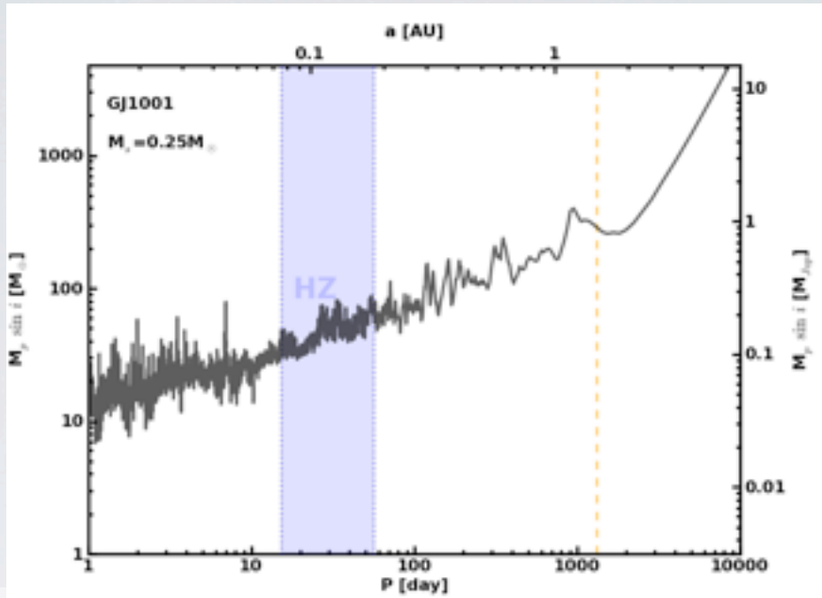
Mp sin i [M⊕]
Mp sin i [MJup]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GJ1001
M* =0.25M⊙
HZ
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100
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100
1000
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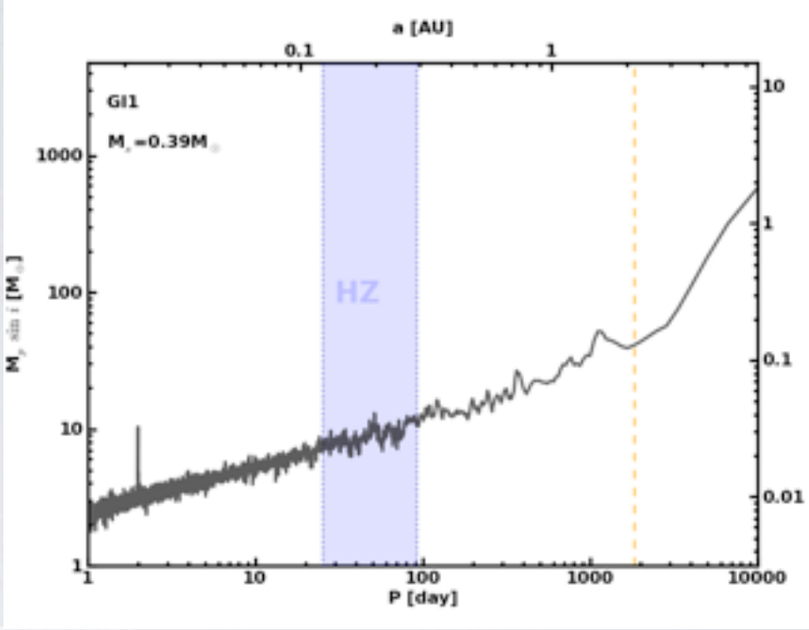
Mp sin i [M⊕]
Mp sin i [MJup]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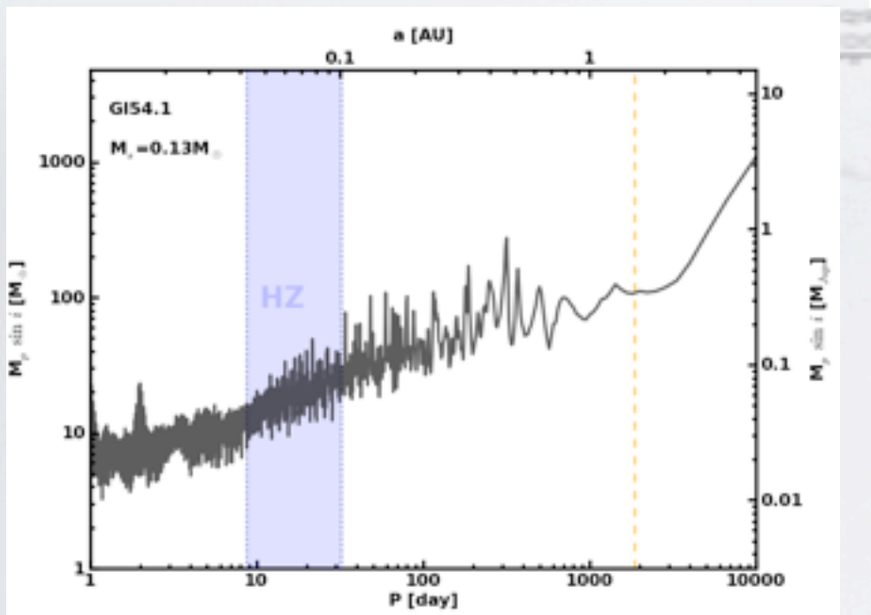
Mp sin i [M⊕]
Mp sin i [MJup]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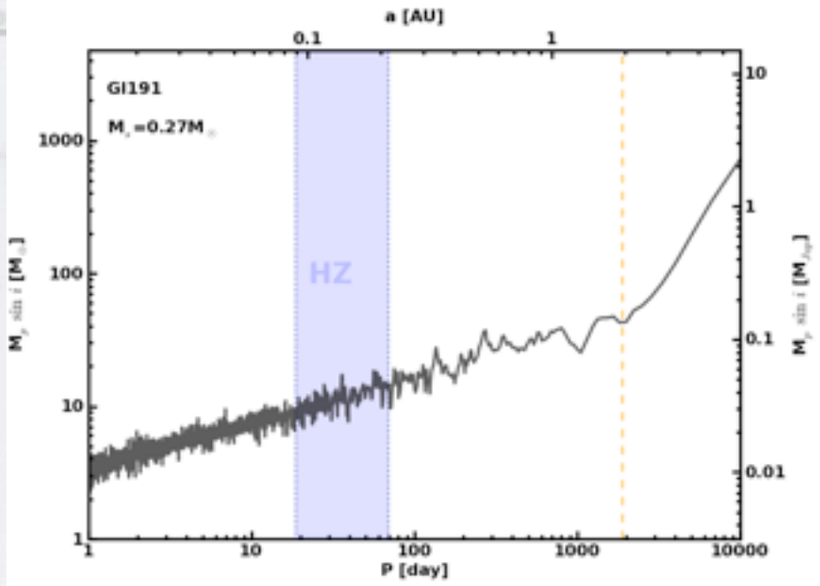
Mp sin i [M⊕]
Mp sin i [MJup]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GI191
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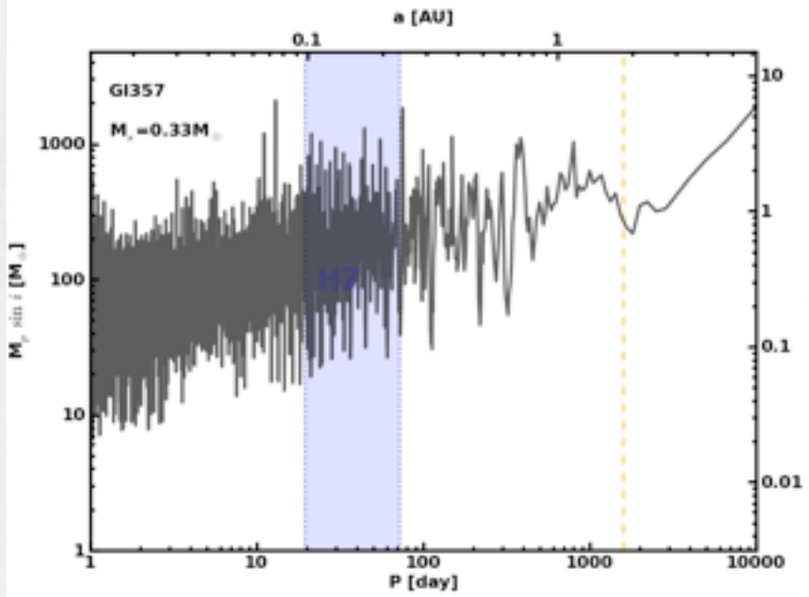
P [day]
Mp sin i [M⊕]
Mp sin i [MJup]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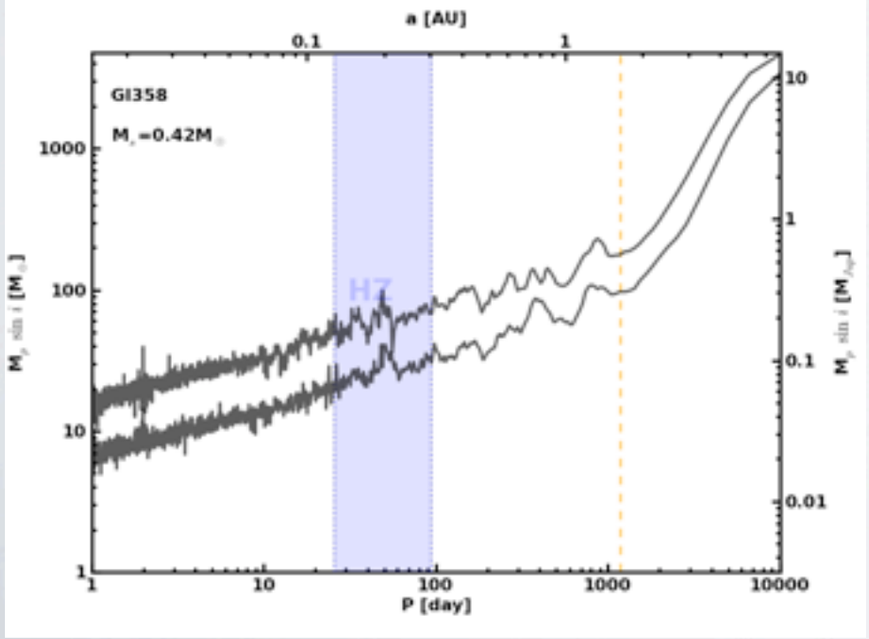
Mp sin i [M⊕]
Mp sin i [MJup]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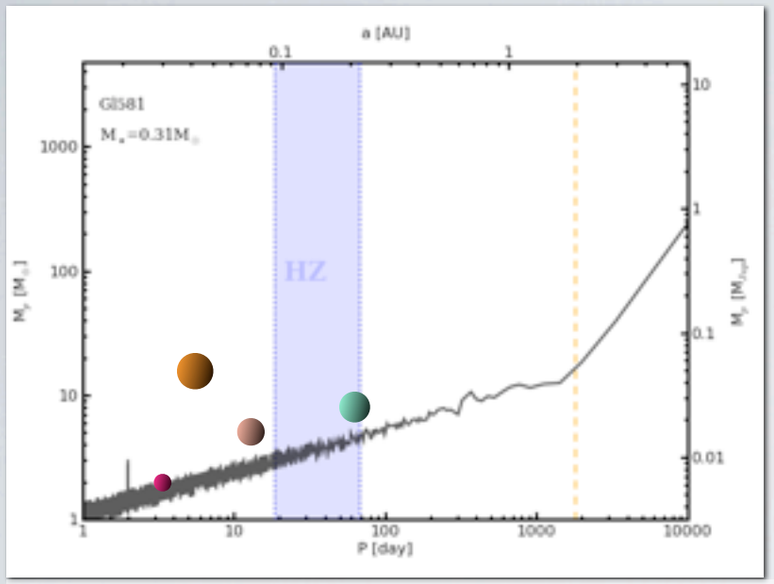
Mp sin i [MJup]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P [day]
Mp sin i [M⊕]
Mp sin i [MJup]
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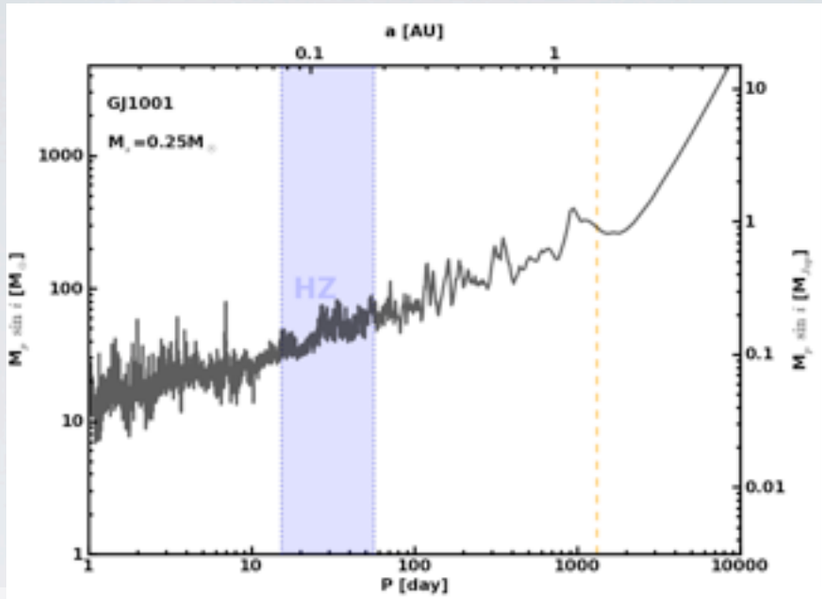
1
10
0.01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GJ1001
M*=0.25M⊙
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P [day]
Mp sin i [M⊕]
Mp sin i [MJup]
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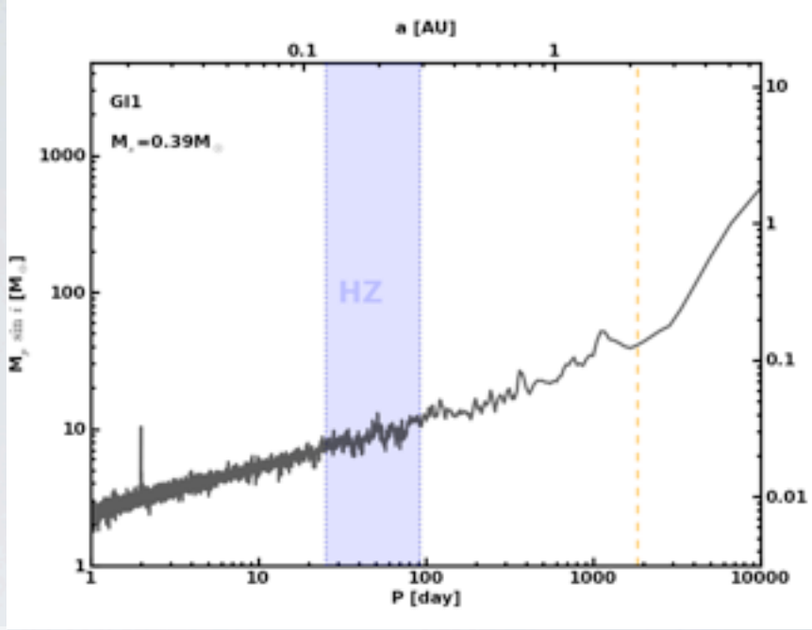
10
0.01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GI1
M*=0.39M⊙
HZ
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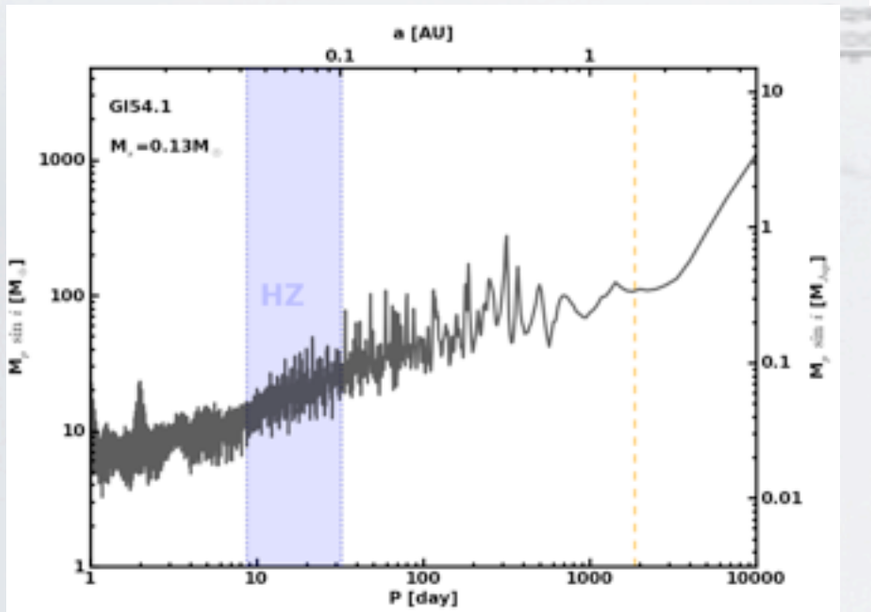
10000
P [day]
Mp sin i [M⊕]
Mp sin i [MJup]
0.1
1
10
0.01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GI54.1
M*=0.13M⊙
HZ
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10000
P [day]
Mp sin i [M⊕]
Mp sin i [MJup]
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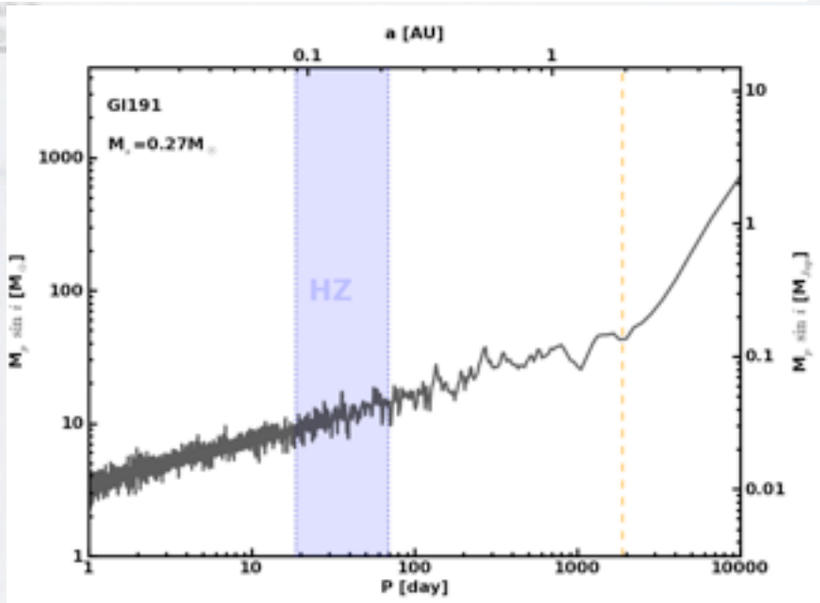
1
10
0.01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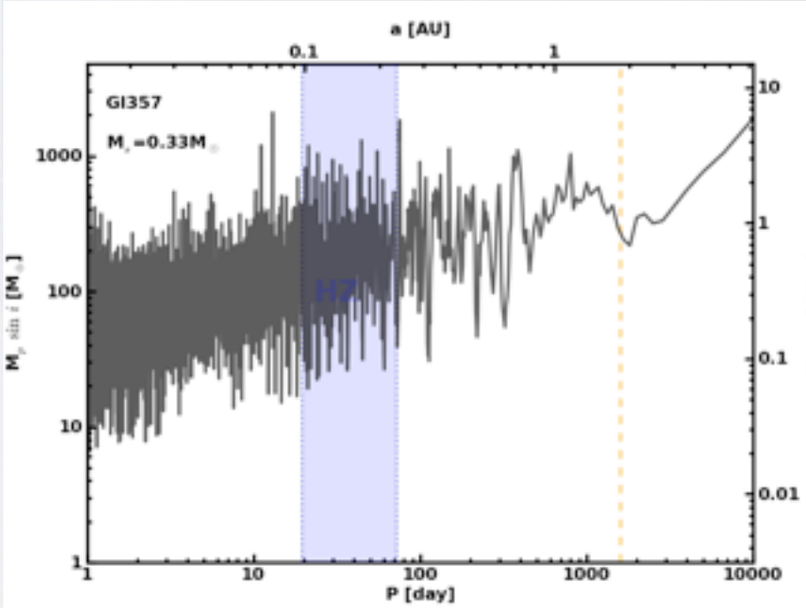
100
10
1
10
100
1000
10000
P [day]
Mp sin i [M⊕]
Mp sin i [MJup]
0.1
1
10
0.01


a [AU]
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GI357
M*=0.33M⊙
HZ
1000
100
10
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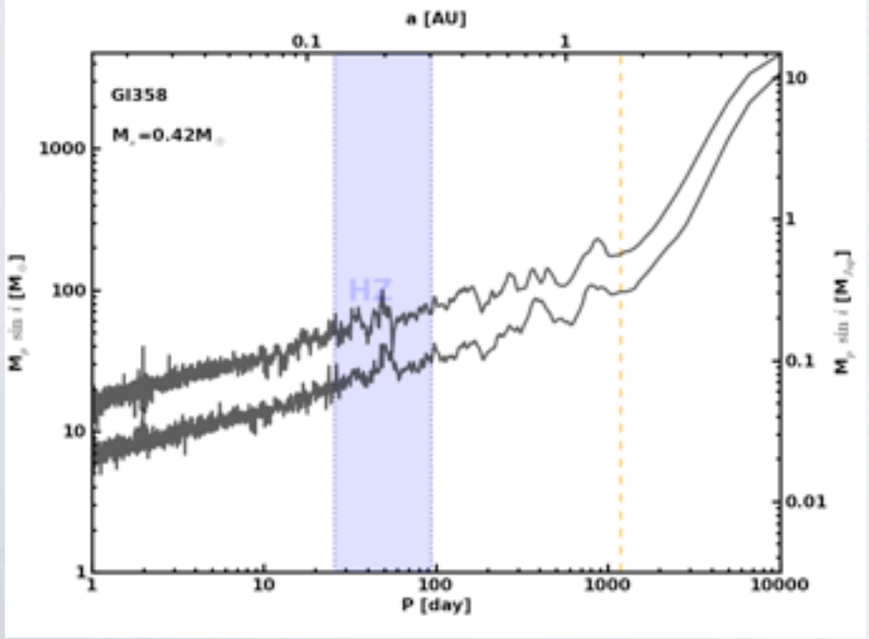
10
100
1000
10000
P [day]
Mp sin i [M⊕]
Mp sin i [MJup]
0.1
1
10
0.01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M*=0.42M⊙
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100
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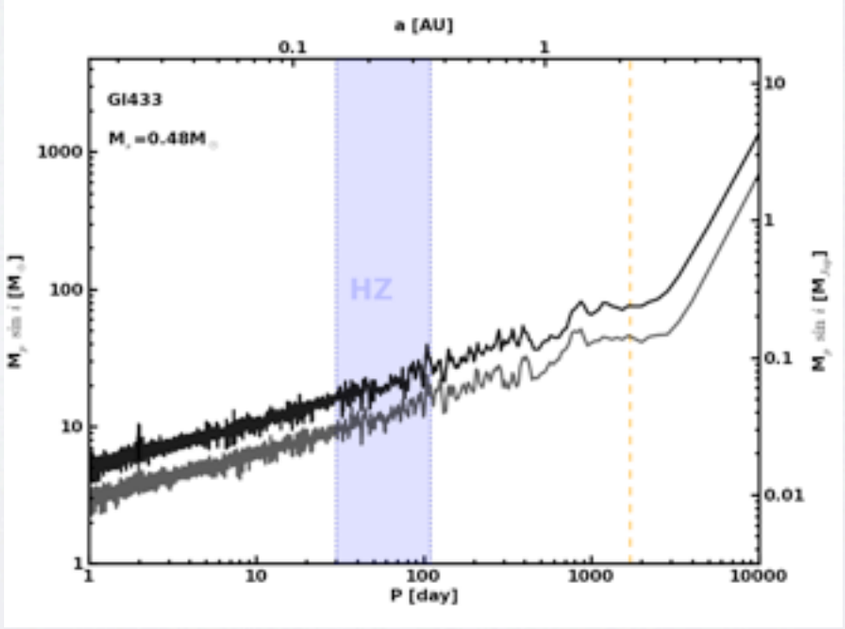
P [day]
Mp sin i [M⊕]
Mp sin i [MJup]
0.1
1
10
0.01


a [AU]
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M*=0.48M⊙
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1000
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P [day]
Mp sin i [M⊕]
Mp sin i [MJup]
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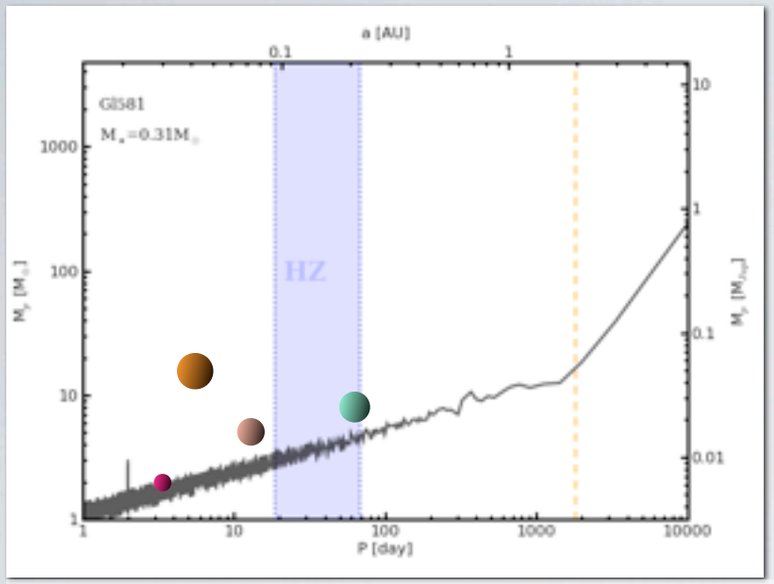
1
10
0.01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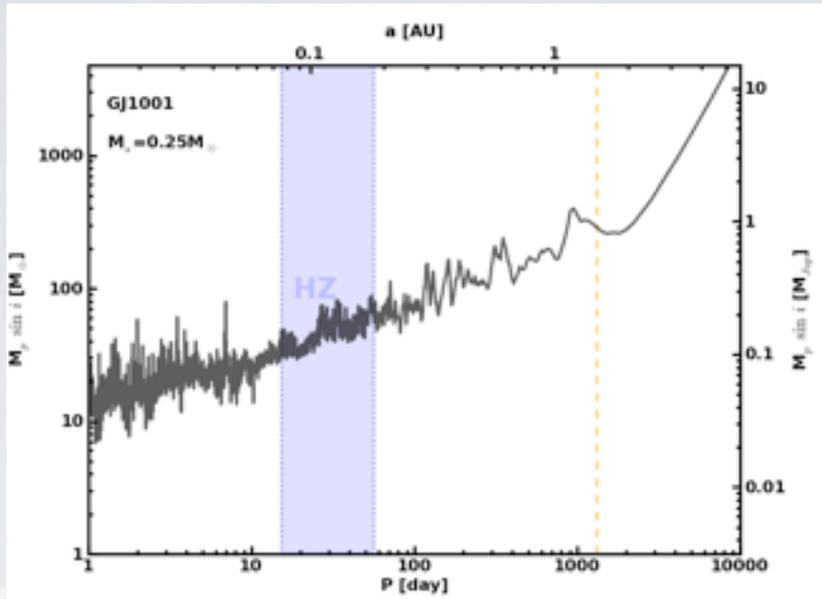
Mp sin i [MJup]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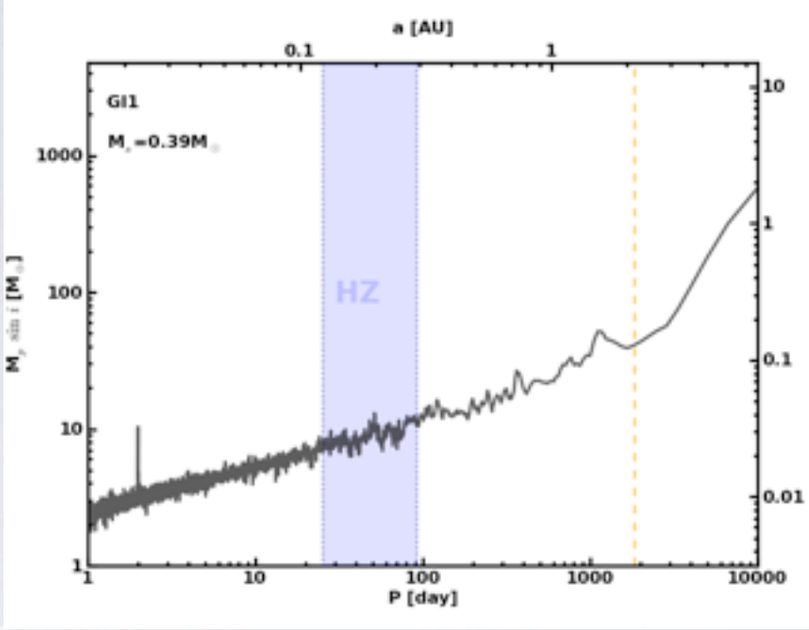
Mp sin i [M⊕]
Mp sin i [MJup]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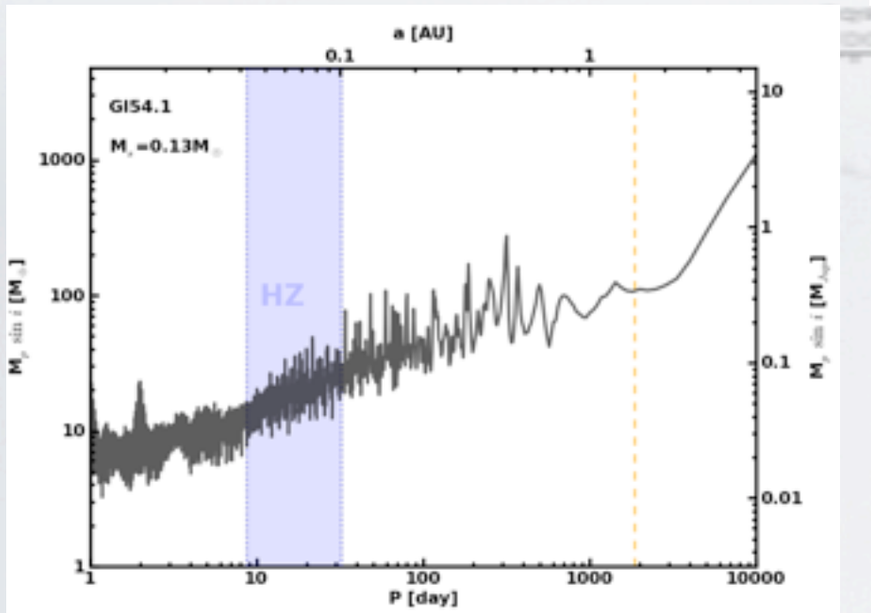
100
10
1
10
0.1
0.01
1
10
100
1000
10000
P [day]
Mp sin i [M⊕]
Mp sin i [MJup]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10
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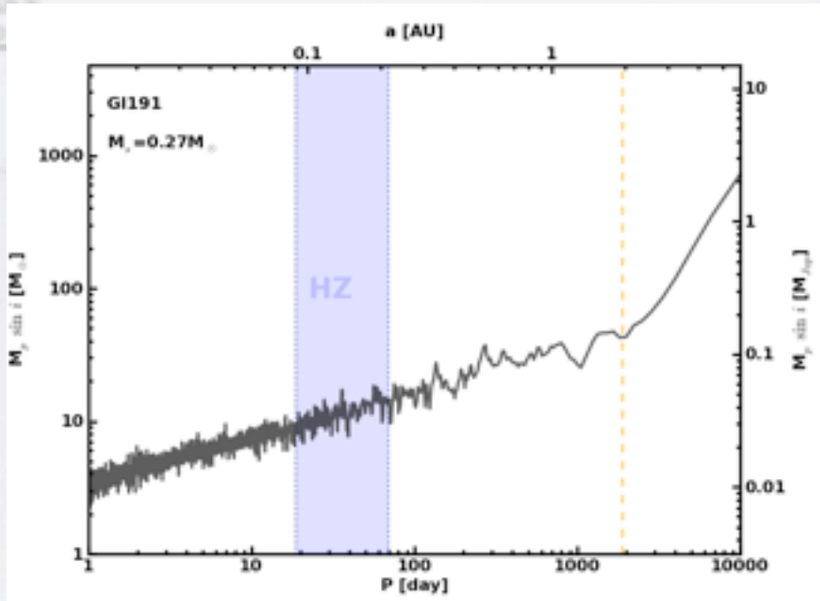
0.01
1
10
100
1000
10000
P [day]
Mp sin i [M⊕]
Mp sin i [MJup]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HZ
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100
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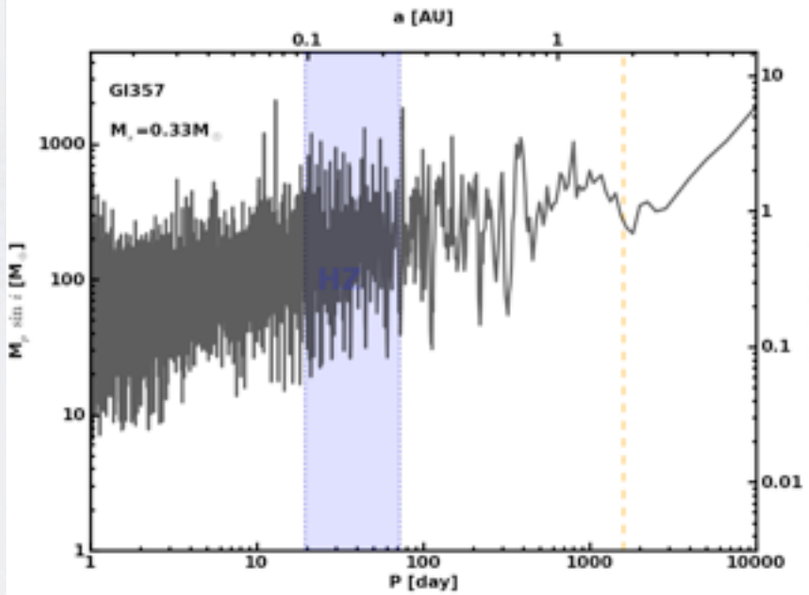
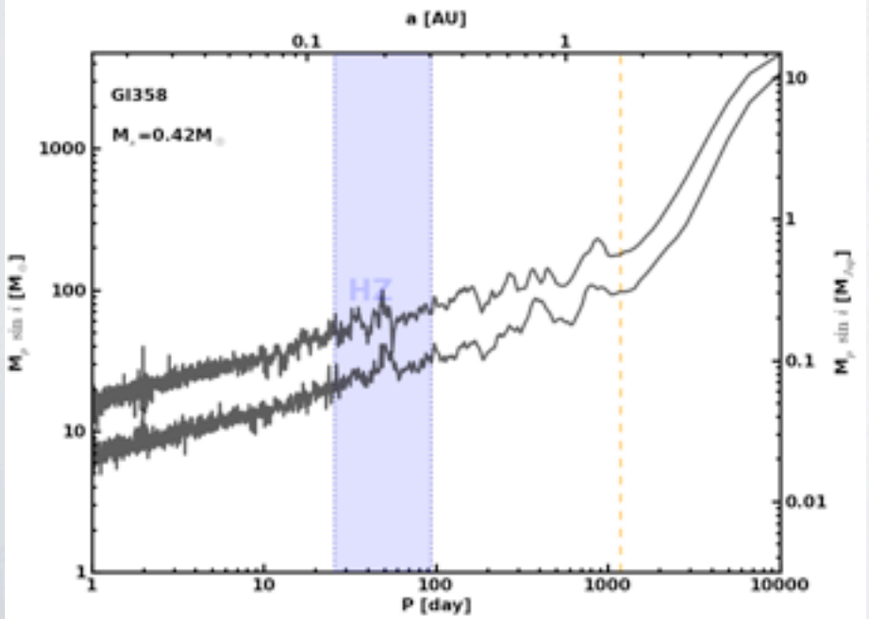
0.1
0.01
1
10
100
1000
10000
P [day]
Mp sin i [M⊕]
Mp sin i [MJup]


a [AU]
0.1
1
GI357
M*=0.33M⊙
HZ
1000
100
10
1
10
0.1
0.01
1
10
100
1000
10000
P [day]
Mp sin i [M⊕]
Mp sin i [MJup]


a [AU]
0.1
1
GI358
M*=0.42M⊙
HZ
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100
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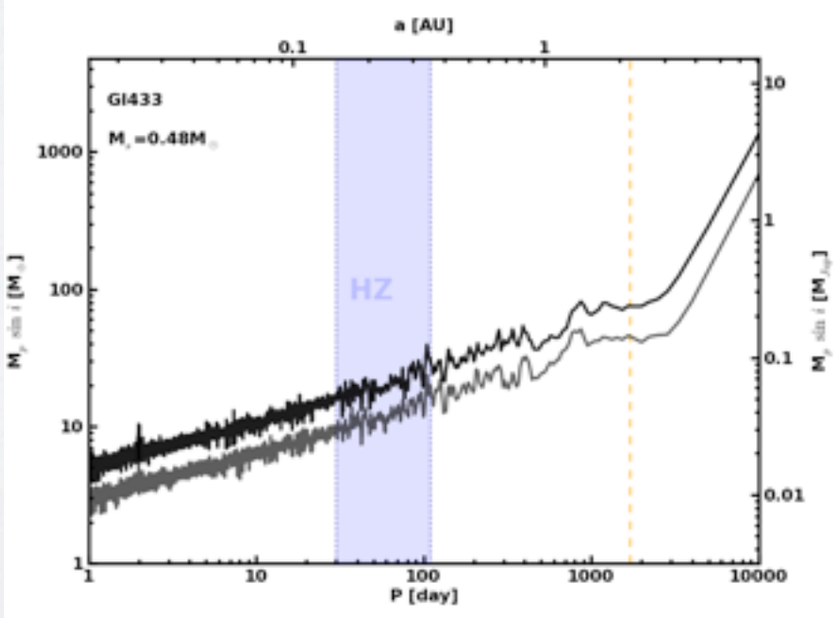
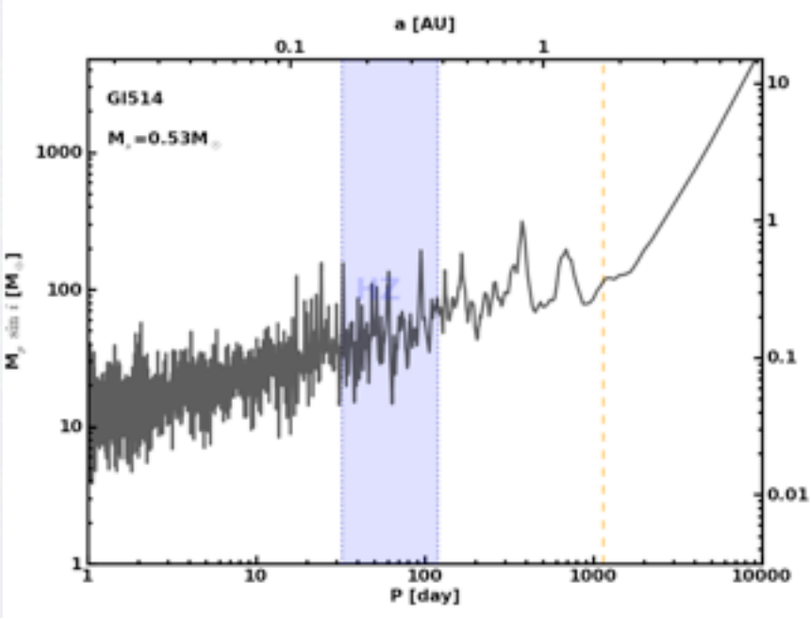
0.01
1
10
100
1000
10000
P [day]
Mp sin i [M⊕]
Mp sin i [MJup]


a [AU]
0.1
1
GI433
M*=0.48M⊙
HZ
1000
100
10
1
10
0.1
0.01
1
10
100
1000
10000
P [day]
Mp sin i [M⊕]
Mp sin i [MJup]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HZ
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0.1
0.01
1
10
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1000
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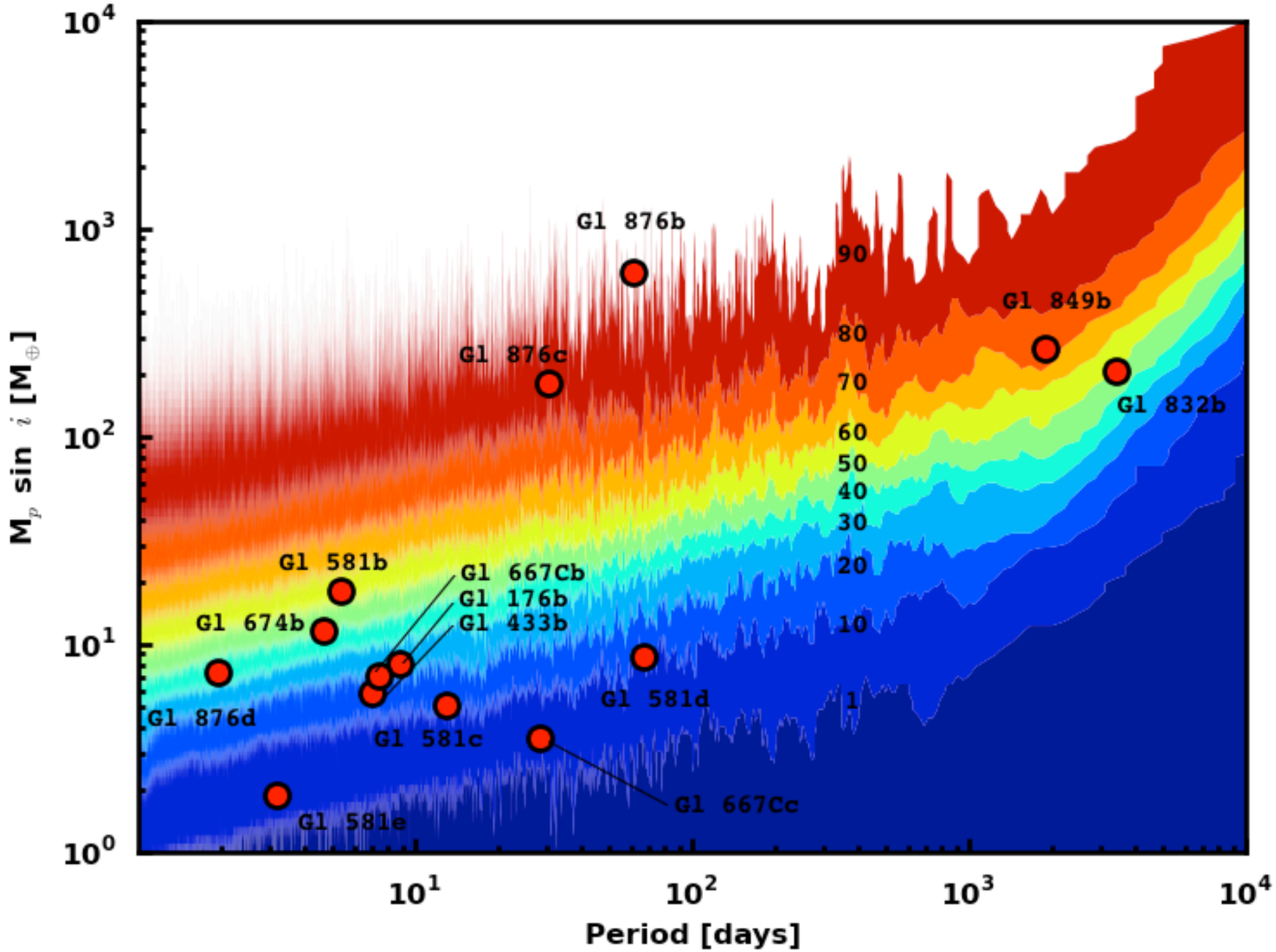
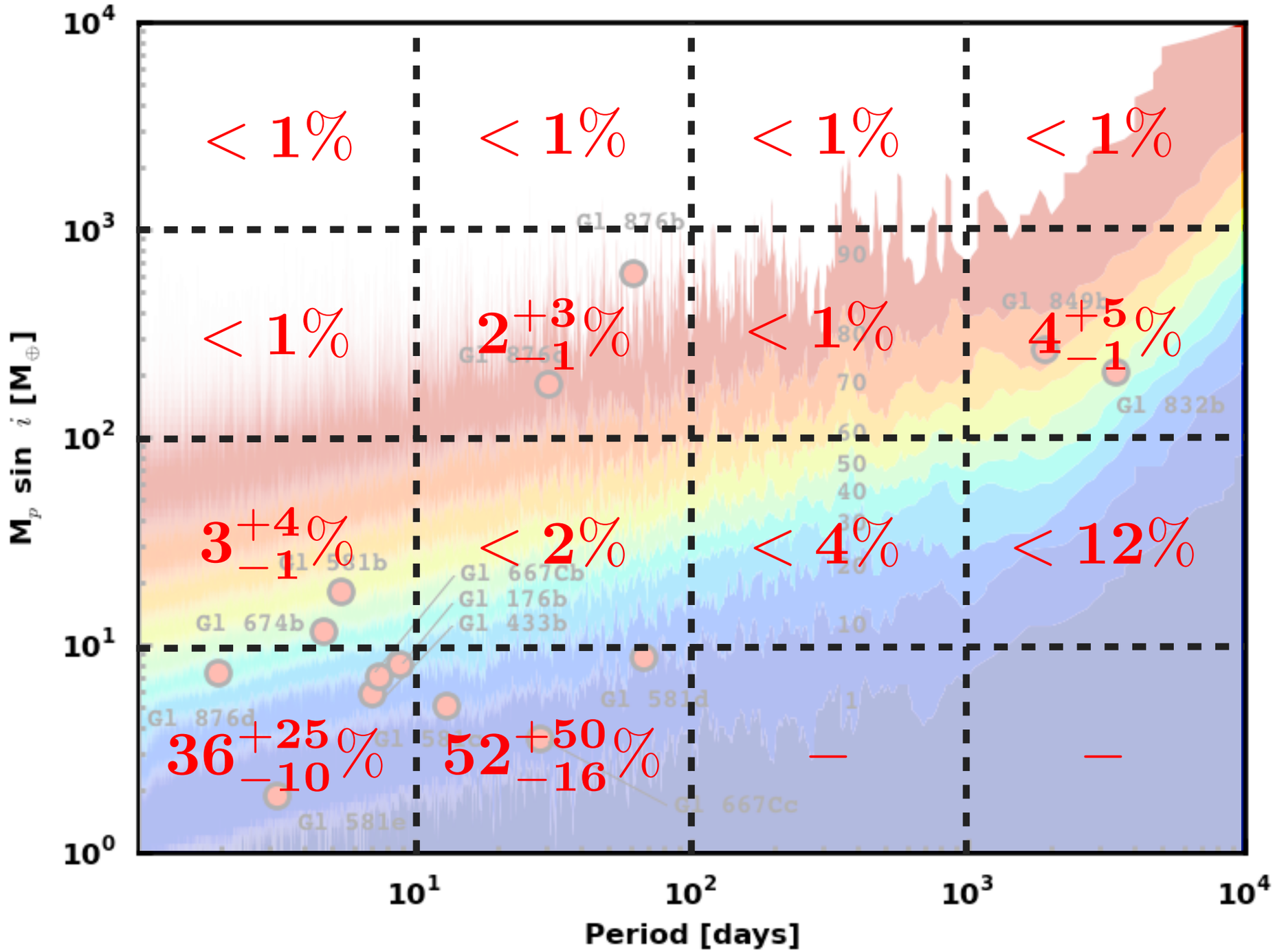
P [day]
Mp sin i [M⊕]
Mp sin i [MJup]

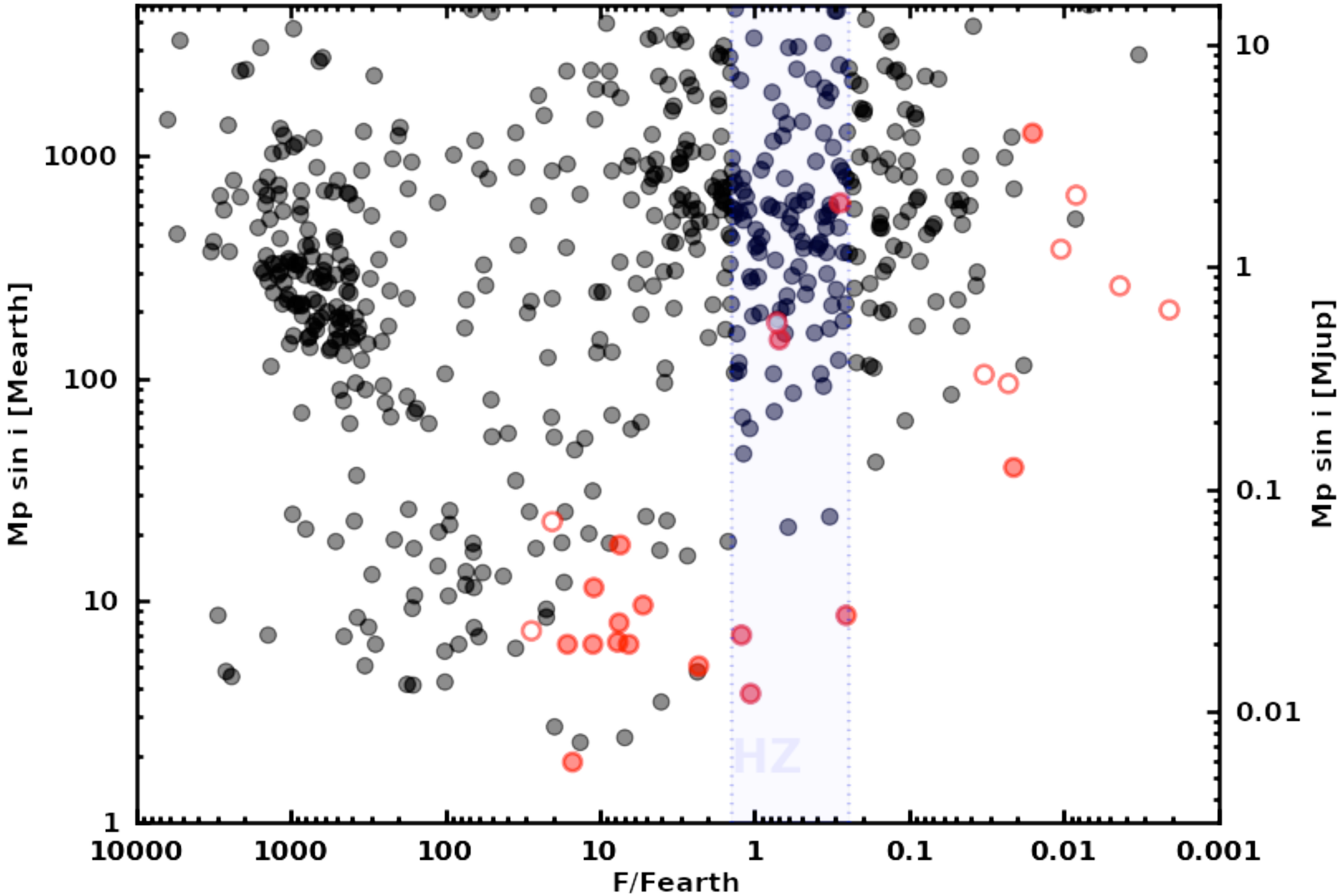


Bonfils et al. (2012, A&A in press)
astro-ph/1111.5019B



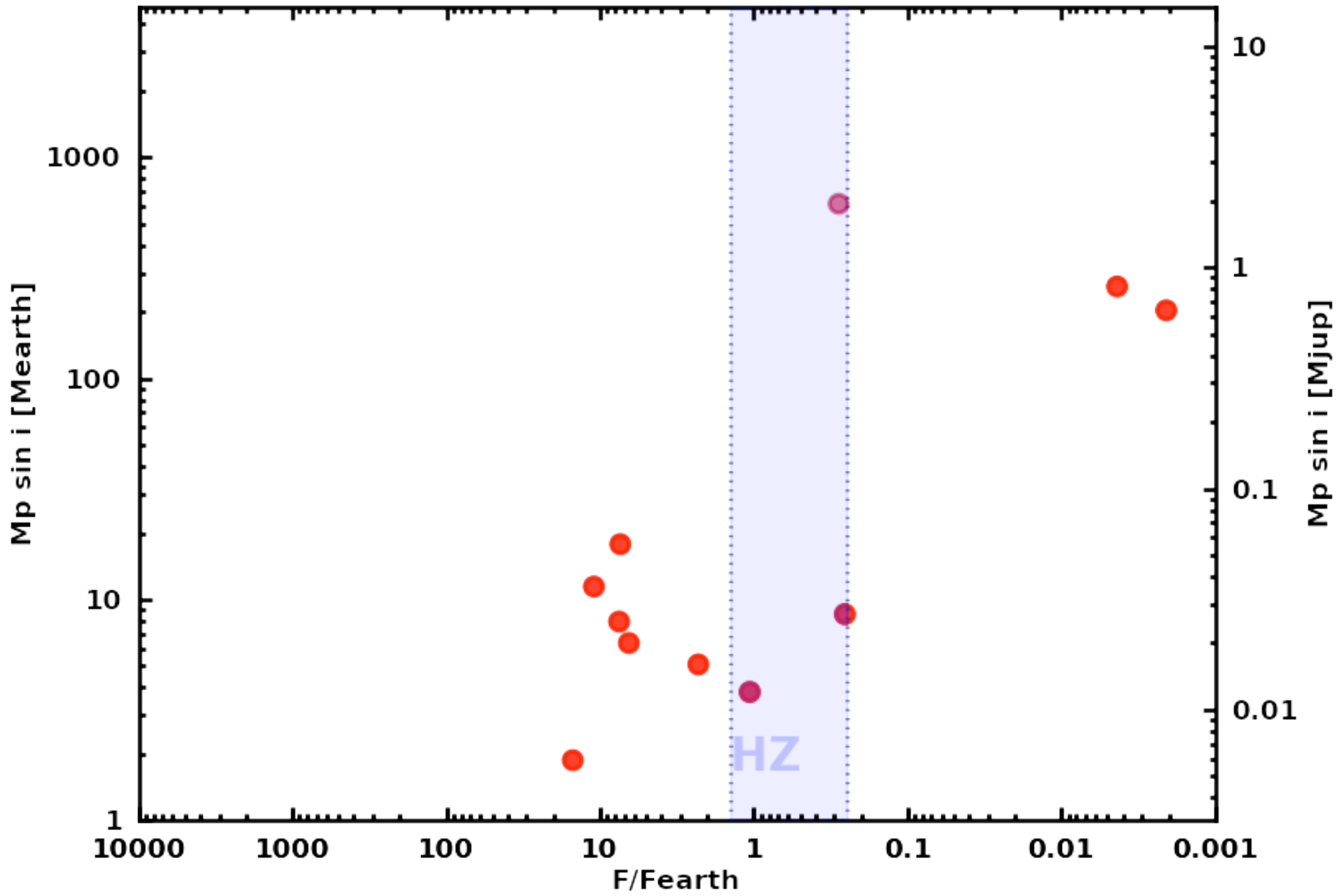
Bonfils et al. (2012, A&A in press)
astro-ph/1111.5019B

(a direct measure)



Bonfils et al. (2012, A&A in press)
astro-ph/1111.5019B

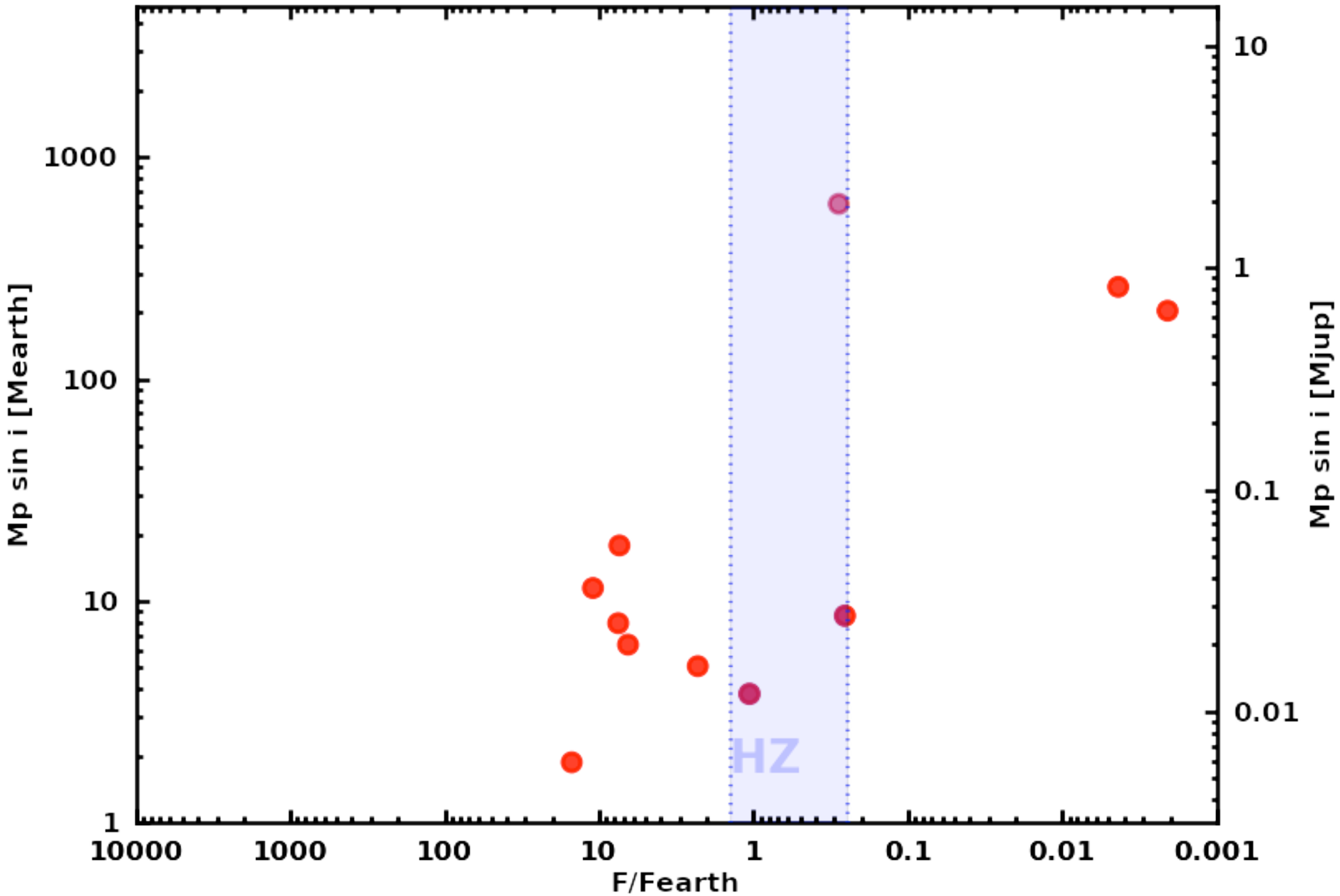
(a direct measure)



Bonfils et al. (2012, A&A in press)
astro-ph/1111.5019B

$$\eta_\oplus = 0.41^{+0.54}_{-0.13}$$

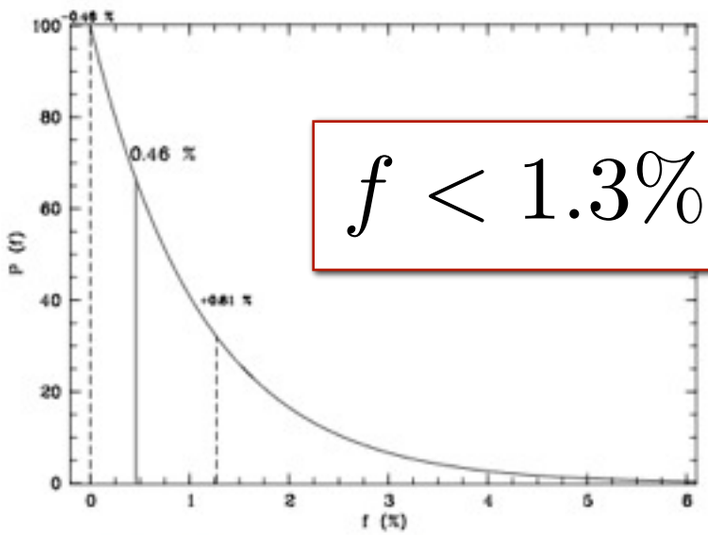
(a direct measure)



Bonfils et al. (2012, A&A in press)
astro-ph/1111.5019B

follow-up on previous radial-velocity results *(mostly for giant planets)*

Endl et al. (2006, AJ 649, 436)



$$f < 1.3\%(1\ \sigma)$$

Fig. 2.— Probability function $P(f)$ for the true companion frequency f based on all our M dwarf data (HET, VLT, HJS, and Keck: $N = 89$ stars) and $d = 0$ detections. We find $f = 0.46^{+0.81}_{-0.46}$ percent. The dashed lines delimit the area of 68% integrated probability ($\approx 1\ \sigma$ Gaussian error).

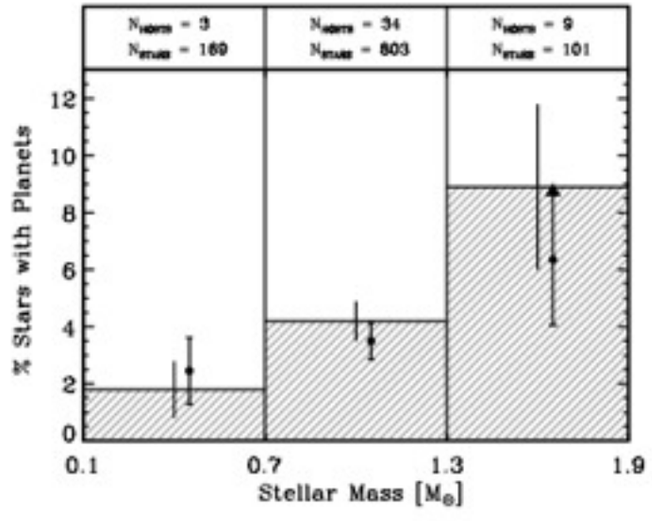
Butler et al. (2006, AJ 649, 436)

$$f = 1.8 \pm 1.2\% \ (> 0.4\ \mathrm{M_{Jup}}; < 2.5\mathrm{AU})$$

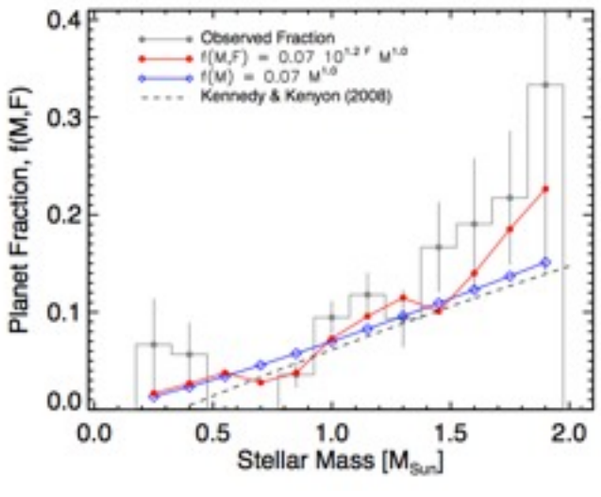
Cumming et al. (2008, PASP 120, 531)

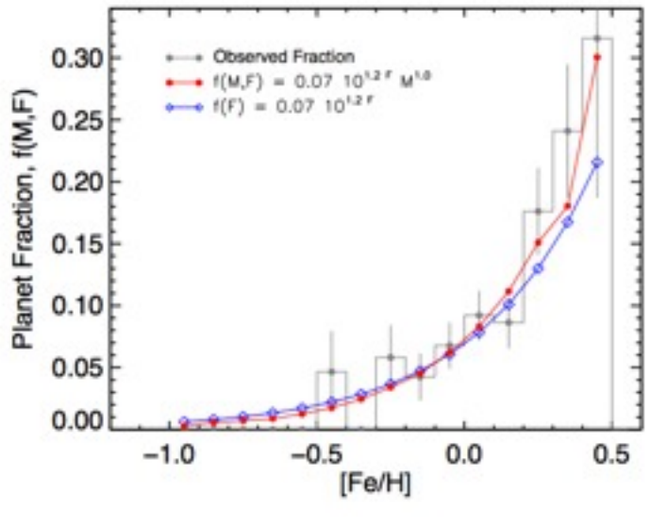
> 1 Mjup are x5-10 times under abundant compared to Sun-like stars
f~1% (<5.4% @ 2-sigma)

Johnson et al. (2007, AJ 670, 833)



Johnson et al. (2010, PASP)





Bonfils et al. (2007, A&A 474, 293)

$f_{\text{hot Nept.}} > f_{\text{hot Jup}}$ (> 97% probability)

$$f(M_\star, [Fe/H]) = 0.07 \pm 0.01 \times (M_\star/M_\odot)^{1.0\pm0.3} \times 10^{1.2\pm0.2[Fe/H]}$$

photometry (transit)

- *Kepler results*
- *Mearth*

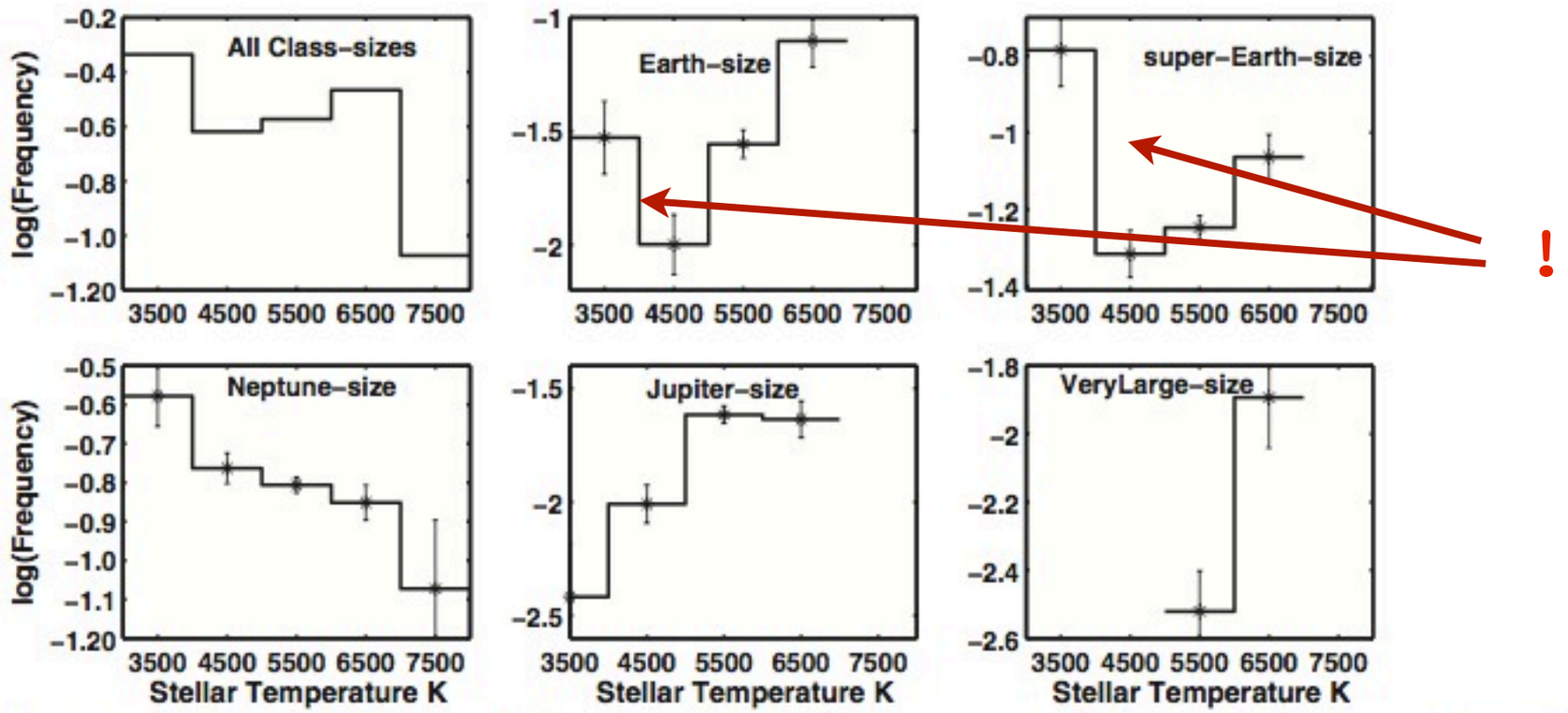


Figure 15. Logarithm of the intrinsic frequencies as a function of stellar effective temperature after implementing the sensitivity corrections described in Section 4. The bins along the *x*-axis span 3000–4000 K, 4000–5000 K, 5000–6000 K, and 6000–7000 K, with each bin labeled by the central value.

small mass planets much more abundant around (early-)M dwarfs

Howard et al. (2011, Sci 330, 653)

$$f = 0.30 \pm 0.08$$

Gaidos et al. (2012, AJ 753, 90)

$$f = 0.36 \pm 0.08$$

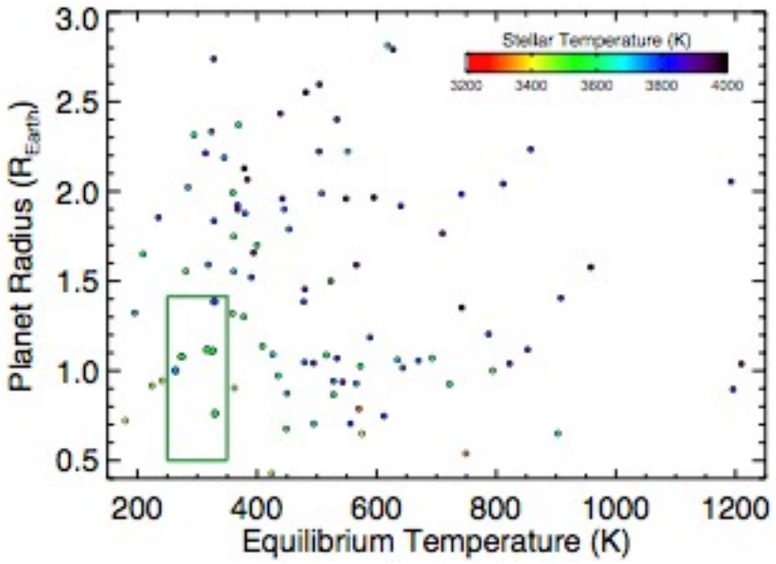
$$(3600 < T_{eff} < 4100 \text{ K};\ P < 50 \text{ d};\ \ 2 < R_p < 32 \text{ R}_\oplus)$$

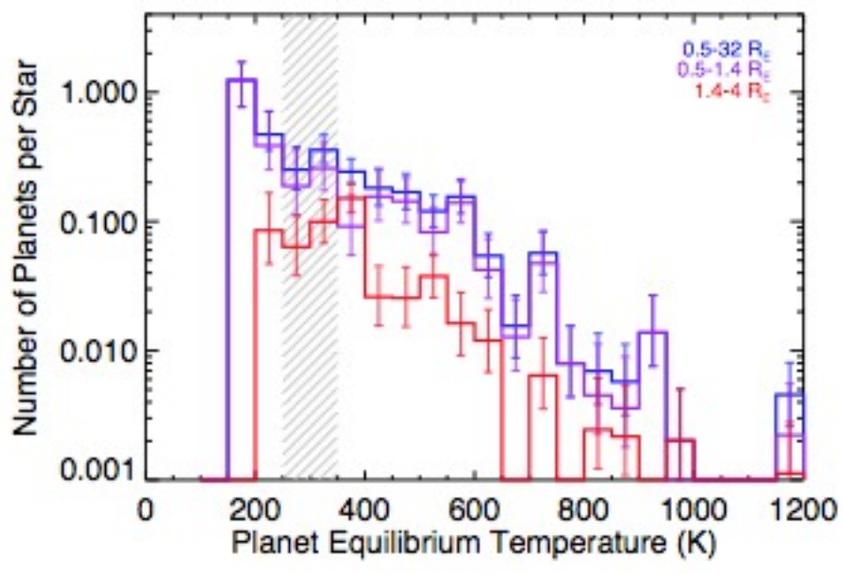
photometry (transit)

- *Kepler results*
- *Mearth*

The Occurrence Rate of Habitable Planets Around M Dwarfs from Kepler

Courtney Dressing[1,*] & David Charbonneau[1]
[1]Harvard-Smithsonian Center for Astrophysics, *cdressing@cfa.harvard.edu



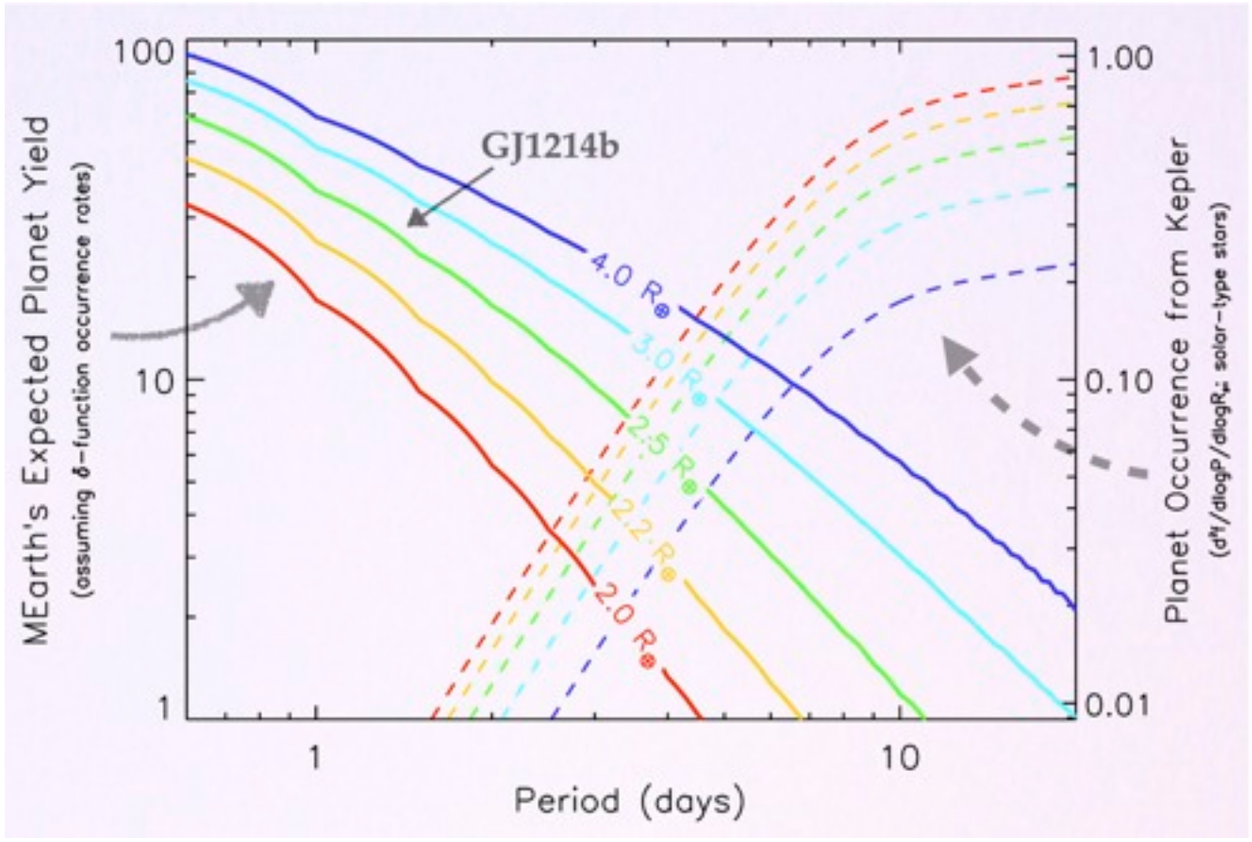


$f \sim 0.4$ habitable pl. / star

Dressing et al.

MEarth and the occurrence rate of warm super-Earths and Neptunes orbiting mid-to-late M dwarfs

Zachory K. Berta[1], Jonathan Irwin[1], David Charbonneau[1], Christopher Burke[2], Emilio Falco[3]



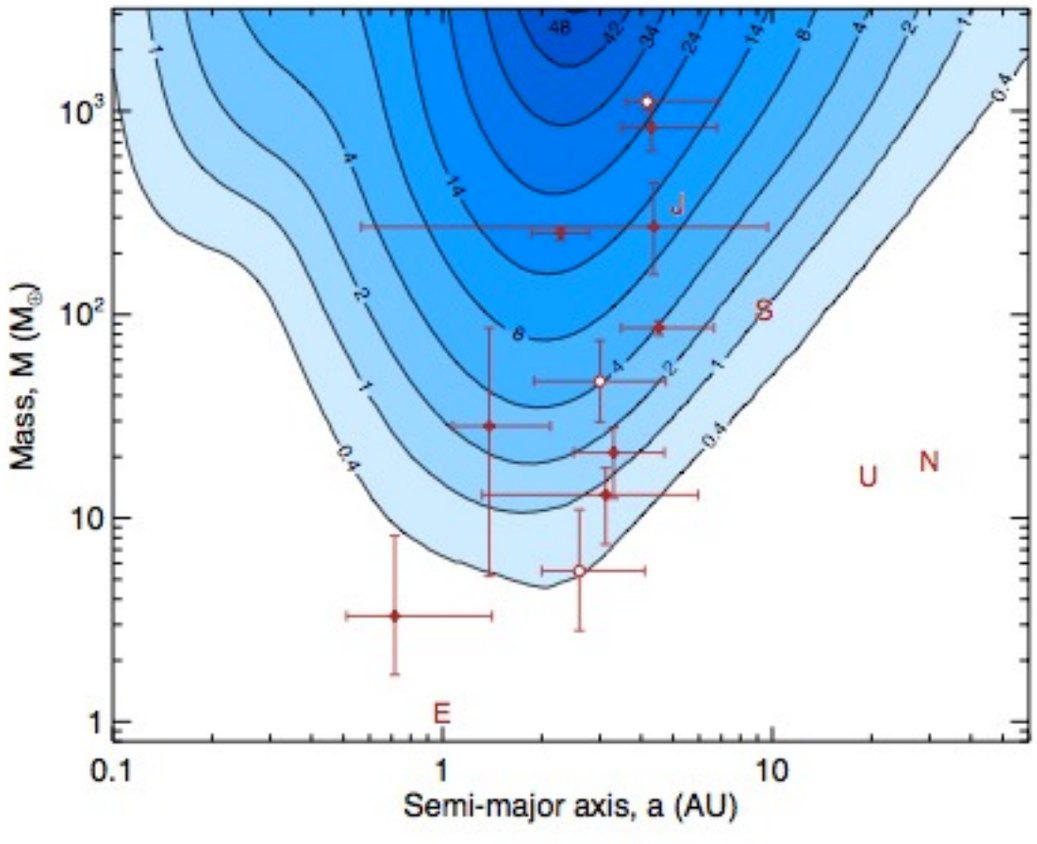
Berta et al.

$$f = 0.22^{+0.52}_{-0.06}$$

$$2 - 4\ \mathrm{R}_\oplus; P < 10\ \mathrm{d}$$

μ-lensing

- *Gould et al. (2010, ApJ 720, 1013)*
- *Cassan et al. (2011, Nature 481, 167)*



$$0.5 < a < 10\ AU$$

$$f = 19^{+6}_{-9}\% \qquad 0.3 < M_p < 10\ \mathrm{M_{Jup}}$$

$$f = 55^{+22}_{-29}\% \qquad 10 < M_p < 30\ \mathrm{M_\oplus}$$

$$f = 62^{+35}_{-37}\% \qquad 5 < M_p < 10\ \mathrm{M_\oplus}$$

PLANET OCCURRENCE

Consistent picture emerging from HARPS, Kepler, Mearth and μ-lensing surveys

- occurence of $1-10\ \mathrm{M}_\oplus$: $f \sim 30-50\%/\mathrm{dlog}P$
- ~40% habitable planets

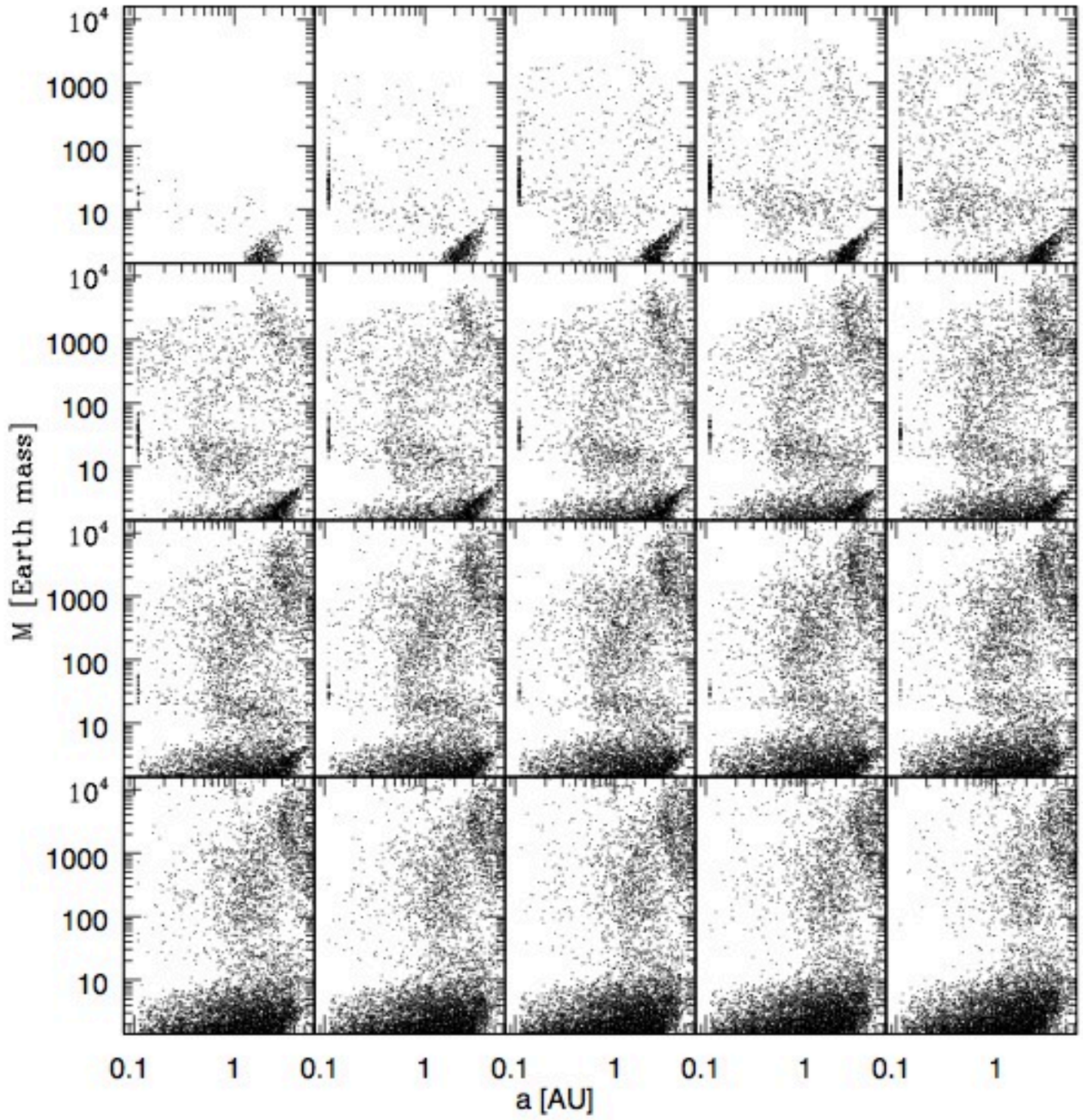


Fig. 12. Mass *versus* semi-major axis for stars between 0.1 $M_\odot$ and 2.0 $M_\odot$. The α_D parameter is equal to 1.2, and disk lifetime are reduced for stars more massive than 1.5 $M_\odot$. 30000 stars are considered in each panel. First line, from left to right, masses between 0.1 $M_\odot$ and 0.5 $M_\odot$, second line, from left to right, masses between 0.6 $M_\odot$ and 1.0 $M_\odot$, third line, from left to right, masses between 1.1 $M_\odot$ and 1.5 $M_\odot$ fourth line, from left to right, masses between 1.6 $M_\odot$ and 2.0 $M_\odot$.

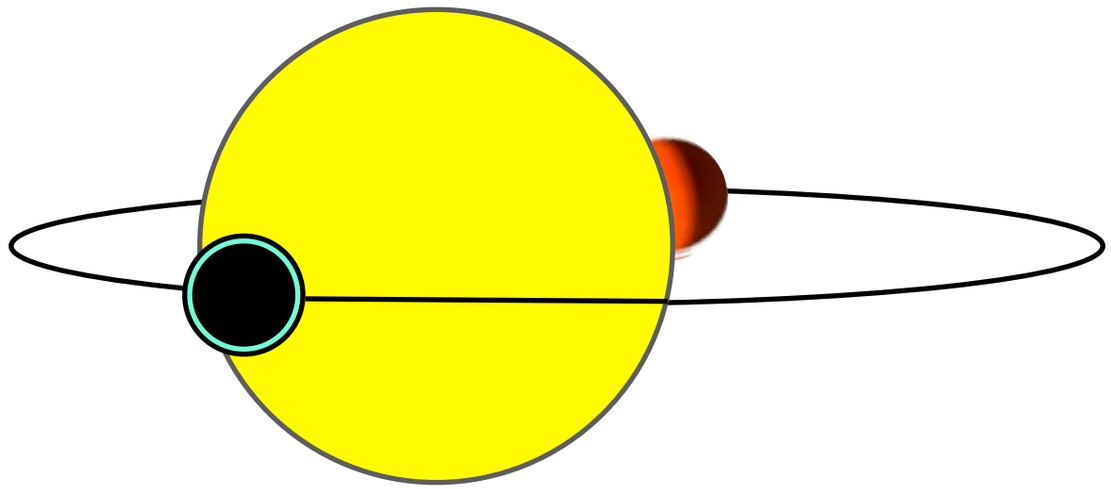
Ida & Lin (2005)

Laughlin et al. (2004)

Kennedy & Kenyon (2008)

Alibert, Mordasini & Benz (2011)

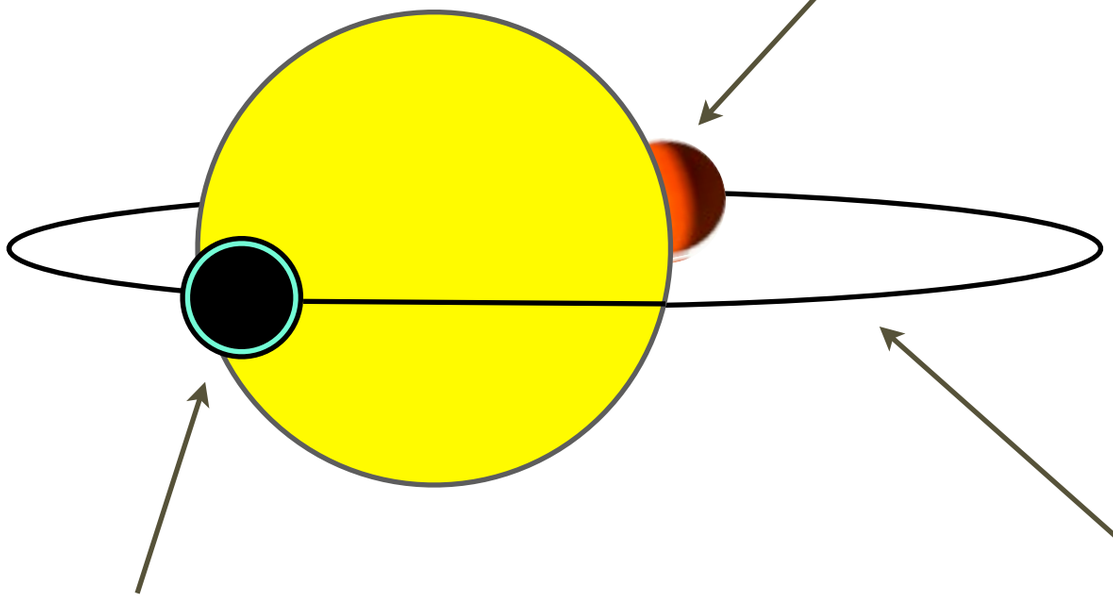
=>matches only roughly the theoretical predictions



Transit

Occultations

- IR emission, Tp
- emission spectra (IR)
- reflected light (Visible)



} Chronometry

- eccentricity
- detection method

Eclipses

- radius
- transmission spectroscopy

+ RV

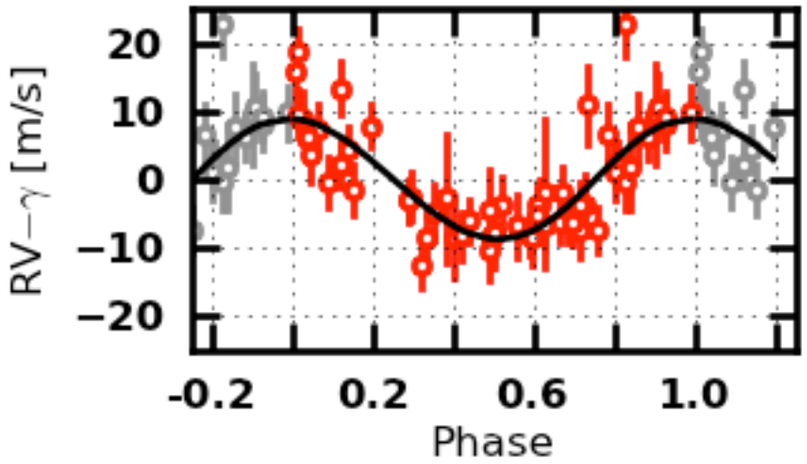
- mass, density, inclination
- tilt orbit / star rotation axis

Phase

- heat redistribution (IR)
- Albedo (Visible)

GJ3470b

HARPS RVs : (TOTEMS)

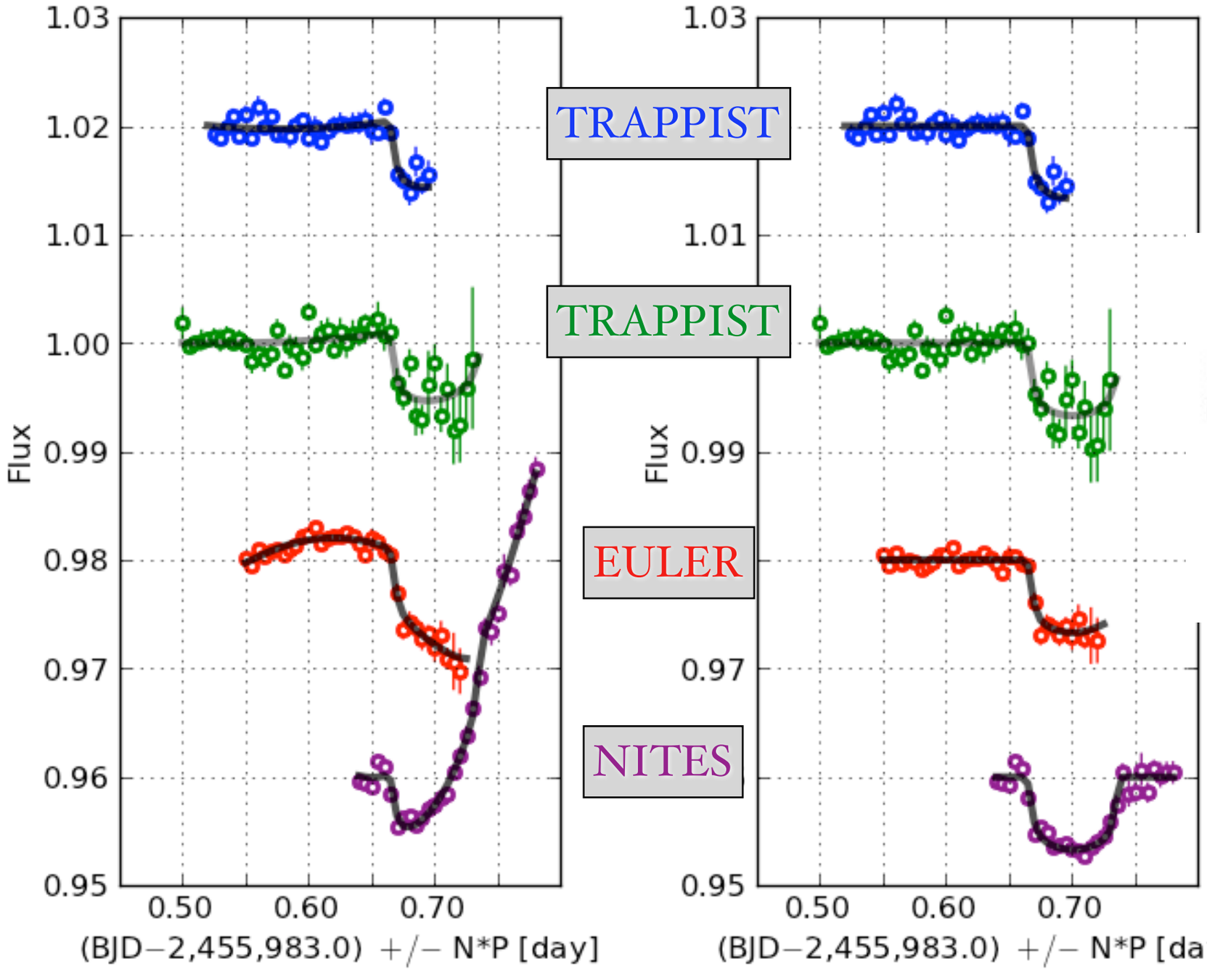


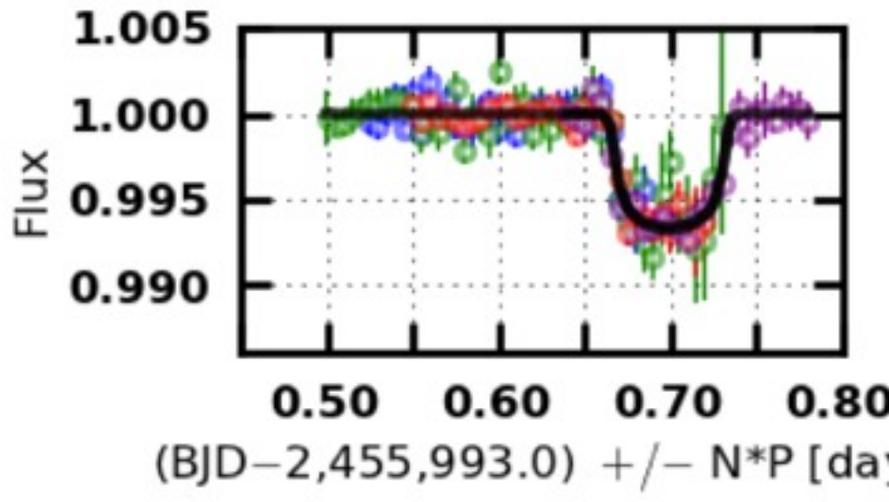
TRAPPIST

TRAPPIST

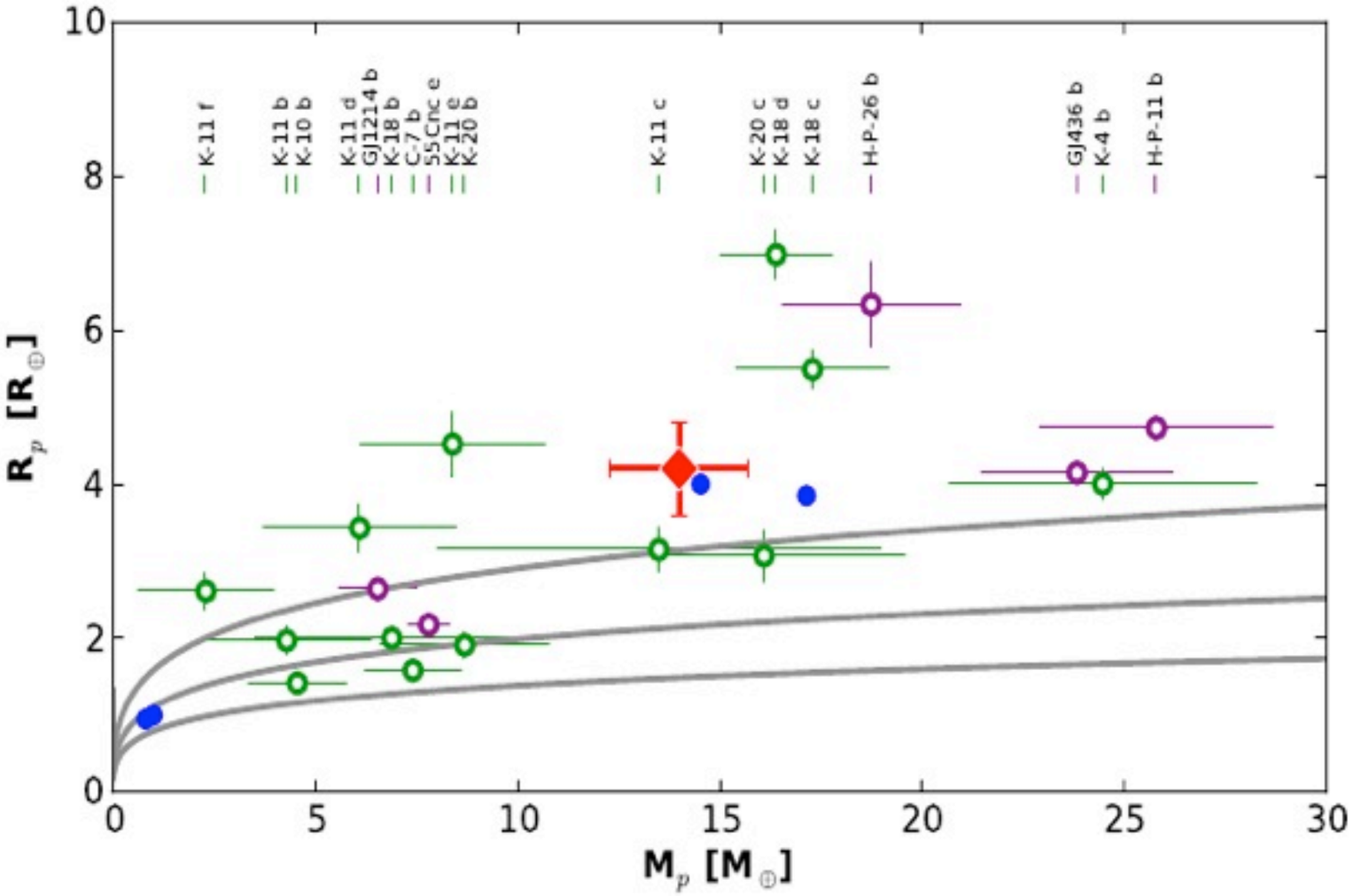
EULER

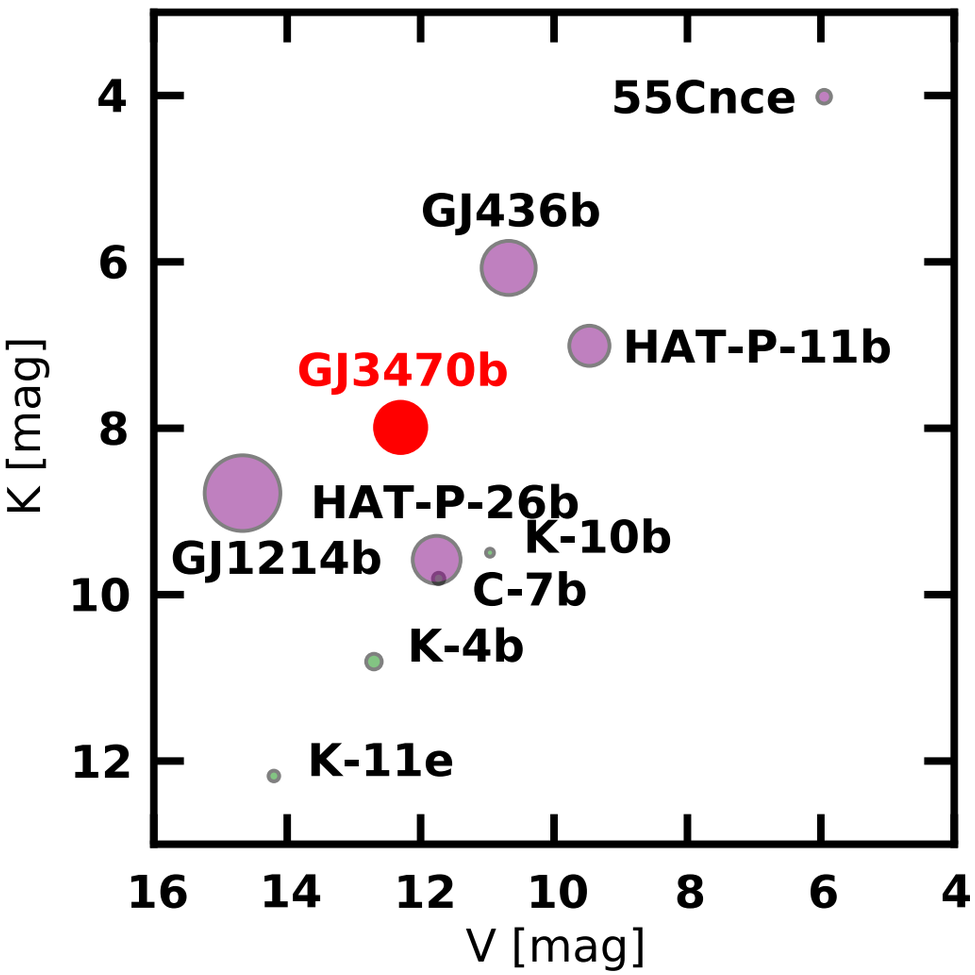
NITES





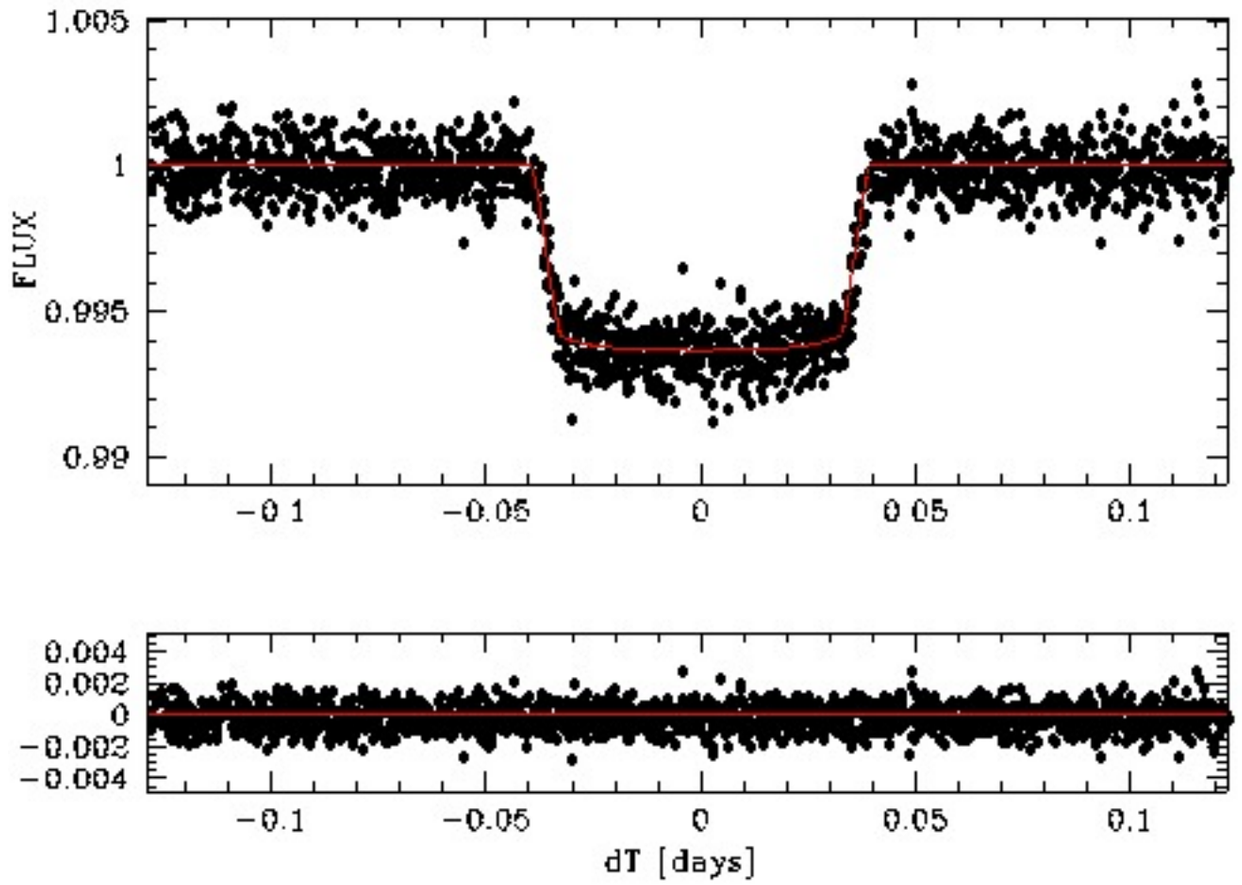
GJ3470b





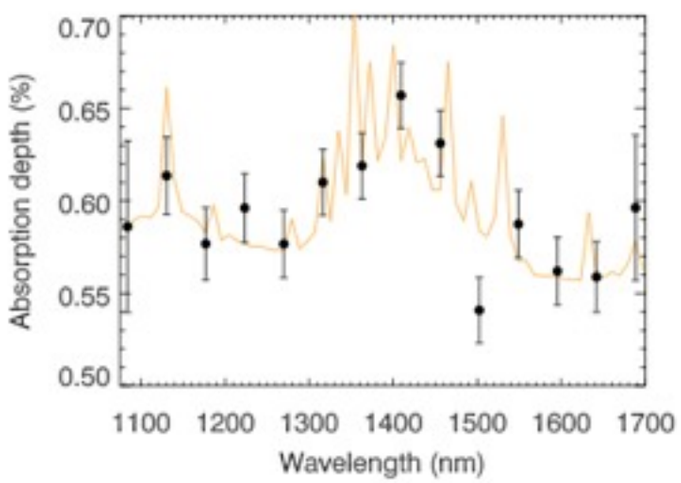
- a cornerstone between super-Earths and ice giants
- favorable for follow-up characterization (large transit depth and bright in the IR)

Spitzer

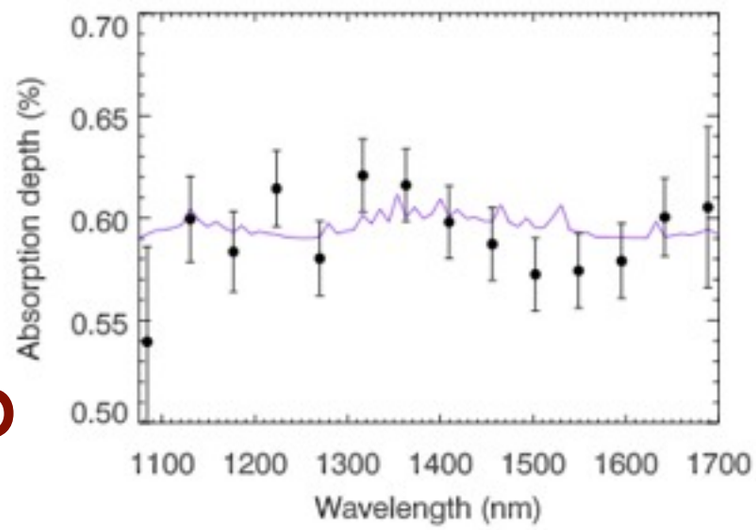


Demory et al.

HST

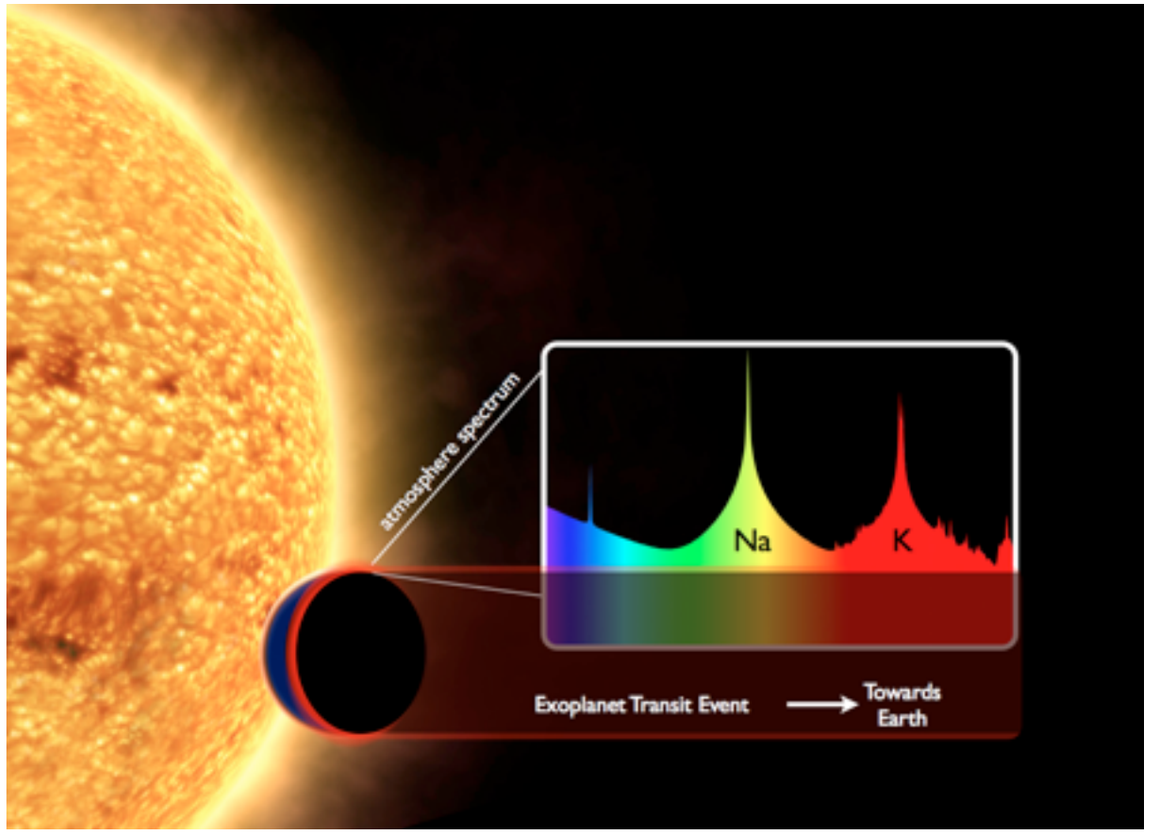


GJ3470b



13064 - **David Ehrenreich**

Investigating the nature of GJ 3470b, the missing link between super-Earths and Neptunes



2-year post-doc position @ IPAG / Grenoble

on the characterization of transiting planet

in coll. w/ A. Lecavelier (IAP), D. Ehrenreich (Geneva)...

CONCLUSIONS

HARPS survey uncovered

- most of the RV M-dwarf planets,
- and most of the M-dwarf low-mass planets

(all techniques included)

- first possibly habitable planets

(GJ581c & d, GJ667Cc and GJ163c)

- detection of a transiting Uranus

favorable for follow-up characterization

- statistical picture of low-mass planet occurrence

(coherent picture w/ Kepler, Mearth and μ-lensing)

- direct measure of eta_earth (~40% habitable planets)

Next ? Exploring the Earth-mass regime for 30 M dwarfs...

Transposing HARPS precision to IR spectrographs