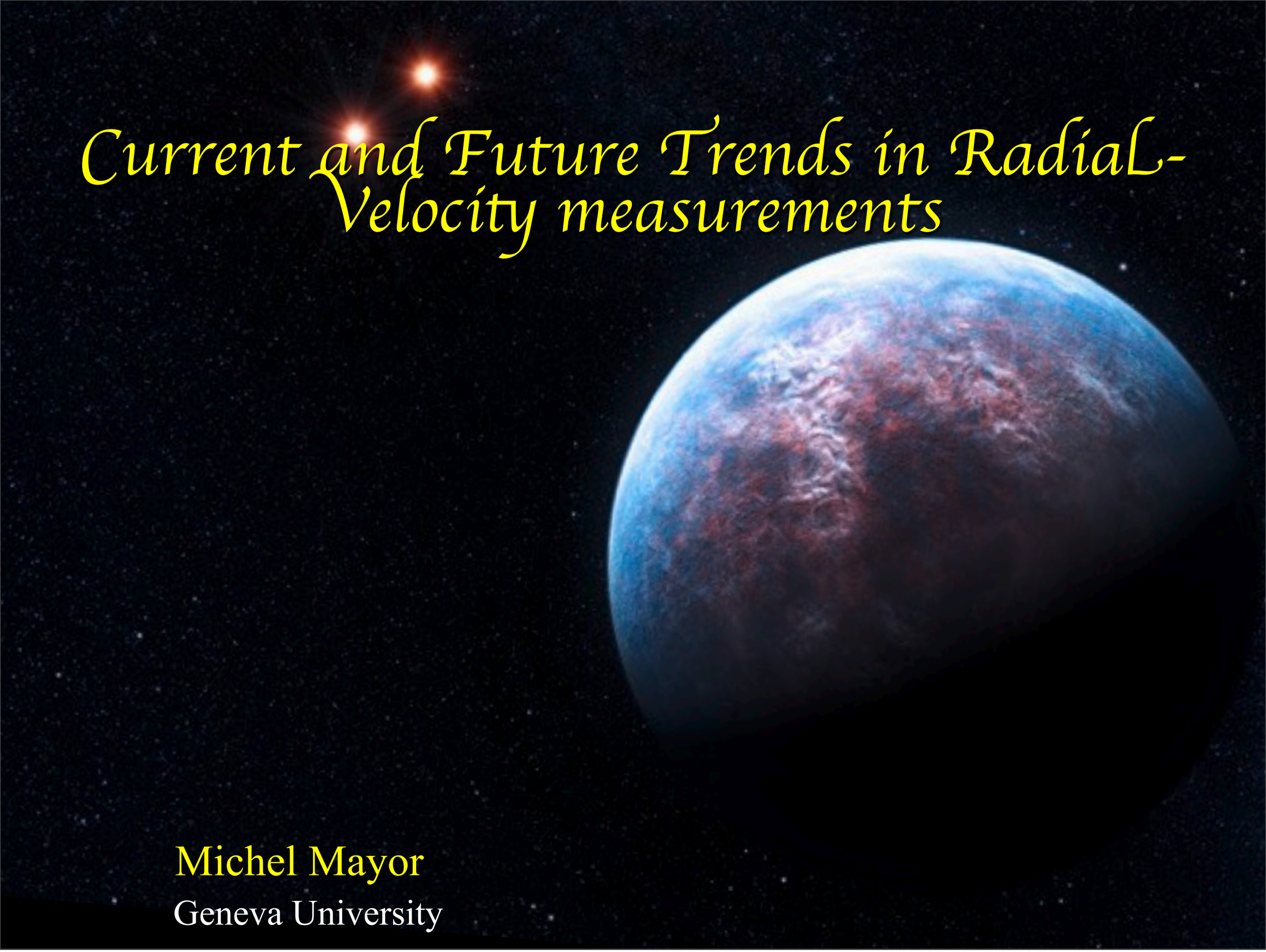
Current and Future Trends in RadiaL-Velocity measurements



Michel Mayor

Geneva University

HARPS Survey Results and Questions

Pushing down the limit of detection (F.Pepe)

Statistical properties of Super-Earths and Neptune-mass planets (M.Mayor)

A volume limited sample to revisit the gaseous giant planets (G.Locurto)

Planets hosted by M stars (X.Bonfils)

Planets orbiting metal deficient stars (N.Santos)

The HARPS Search for Southern Extra-Solar Planets

Search for Earth-analogs around nearby stars

PI: F. Pepe Cols: W. Benz, F. Bouchy, C. Lovis, M. Mayor, D. Queloz, N. C. Santos, S. Udry

Sample

10 nearby, quiet, non-rotating, stars

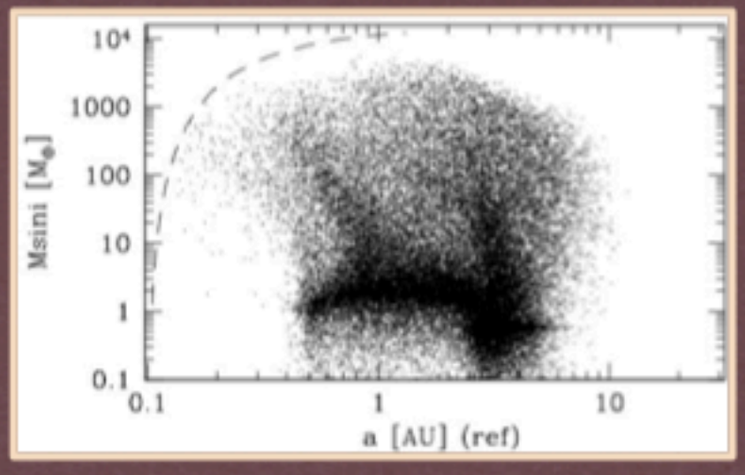
Goal

Find a planet similar to the Earth in m and P

Strategy

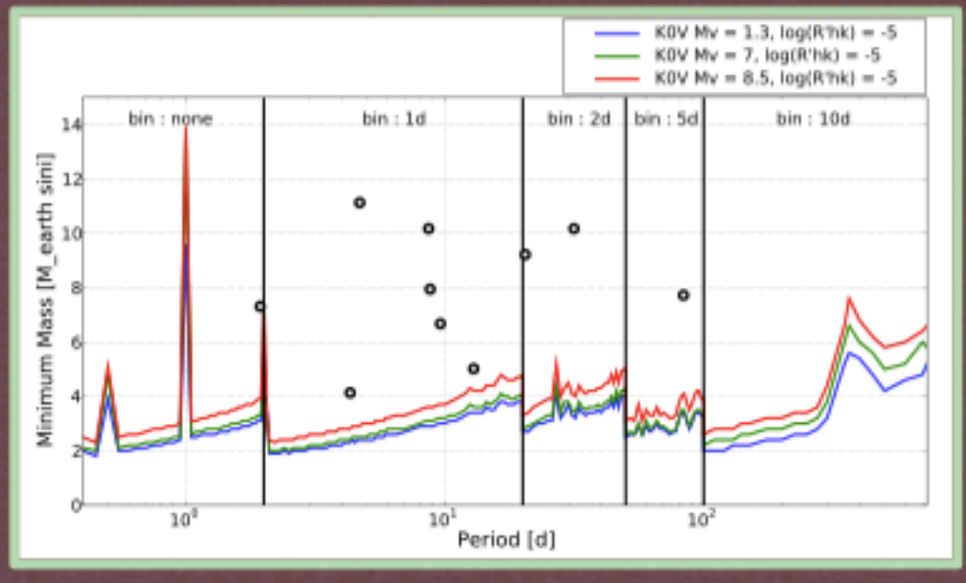
- Observe with high time sampling (3x per night) and long exposures (15 min.) to average oscillations and granulation
- Obtain at least 50 data points per season
- Observe at least 2 - 3 seasons

High expected and measured frequency of low-mass planets



Detectability

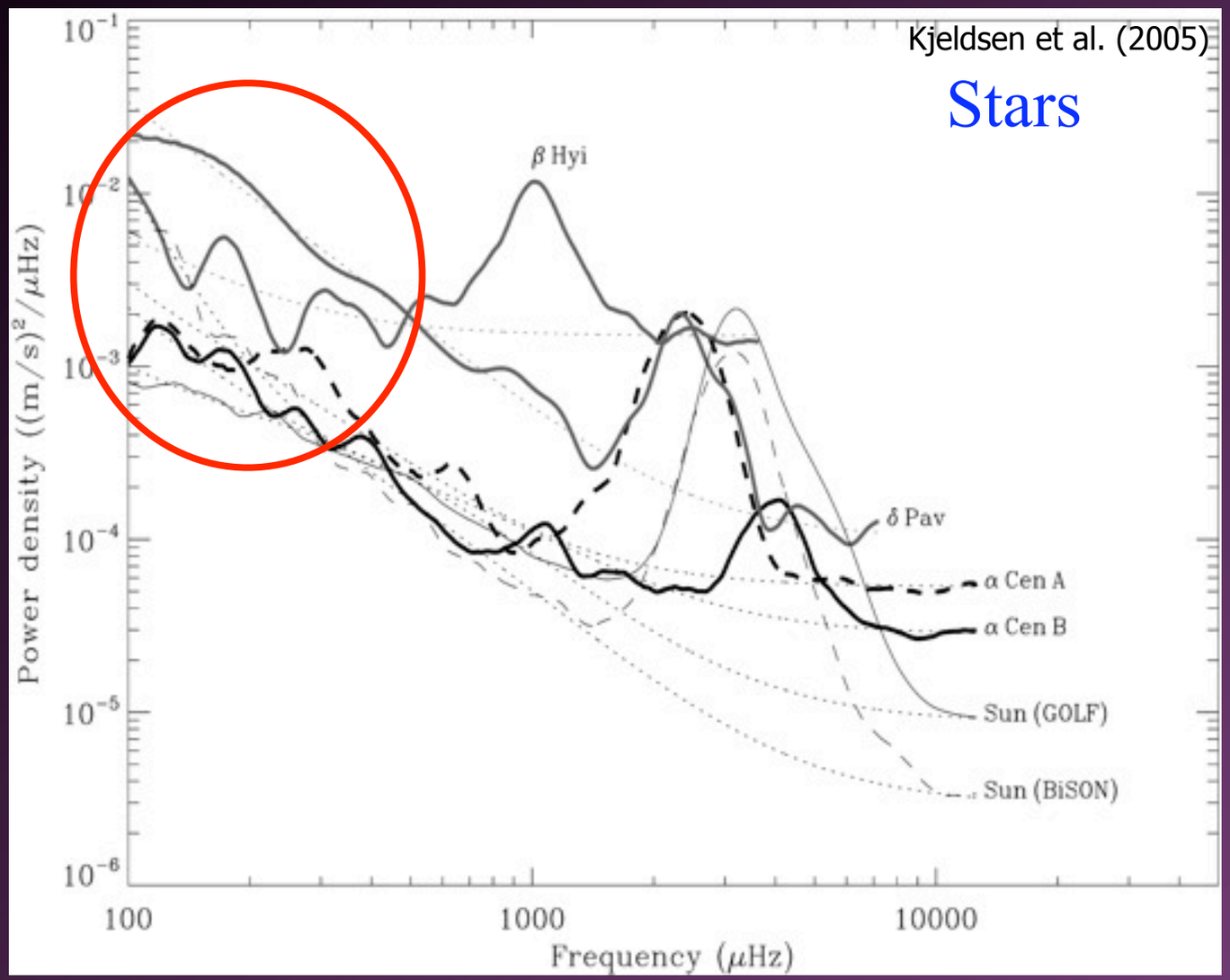
Detectable minimum planetary mass assuming ε = 0 and aiming at K/rms > 2.5 (for varying stellar magnitude and activity):



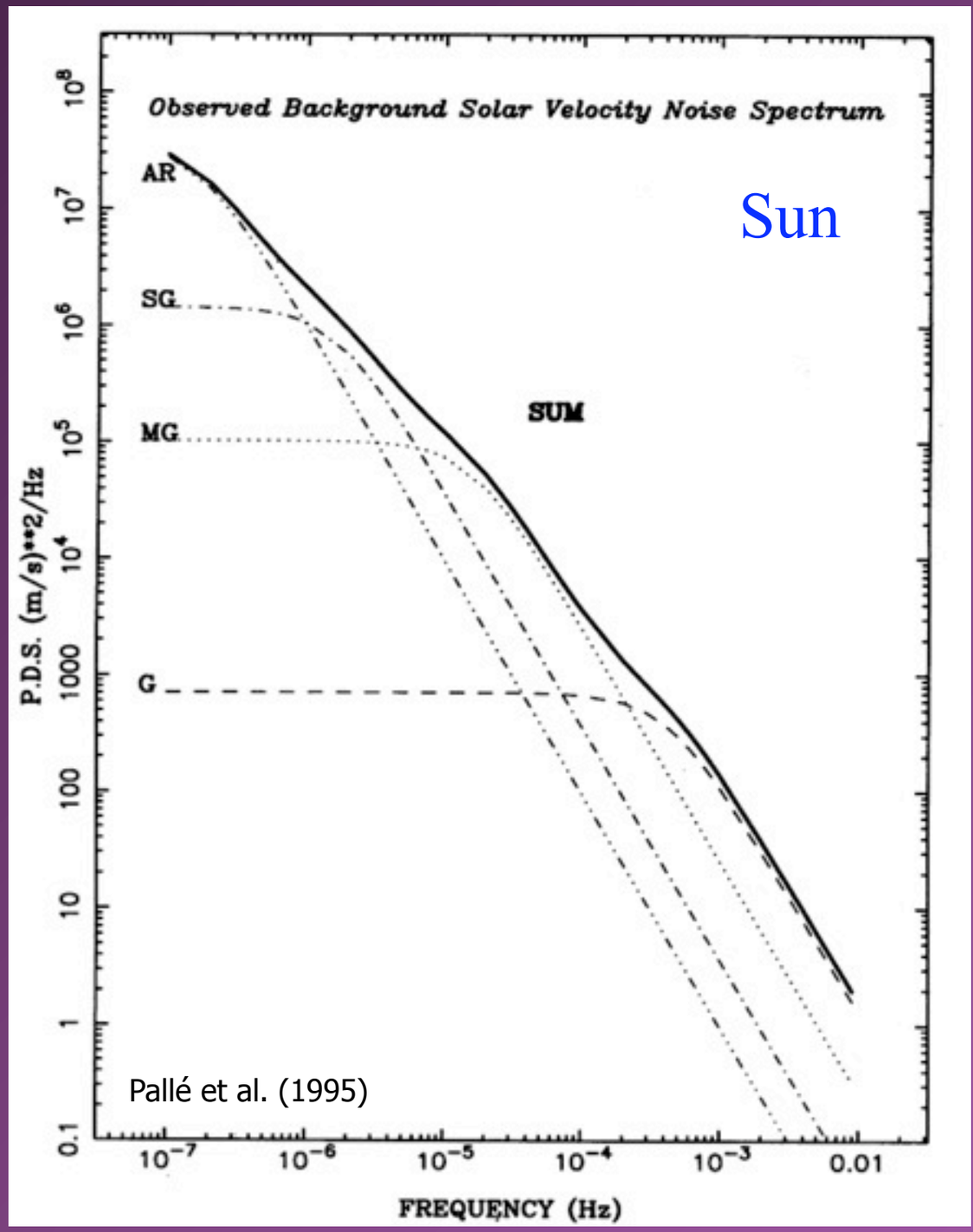
Select the «good» stars

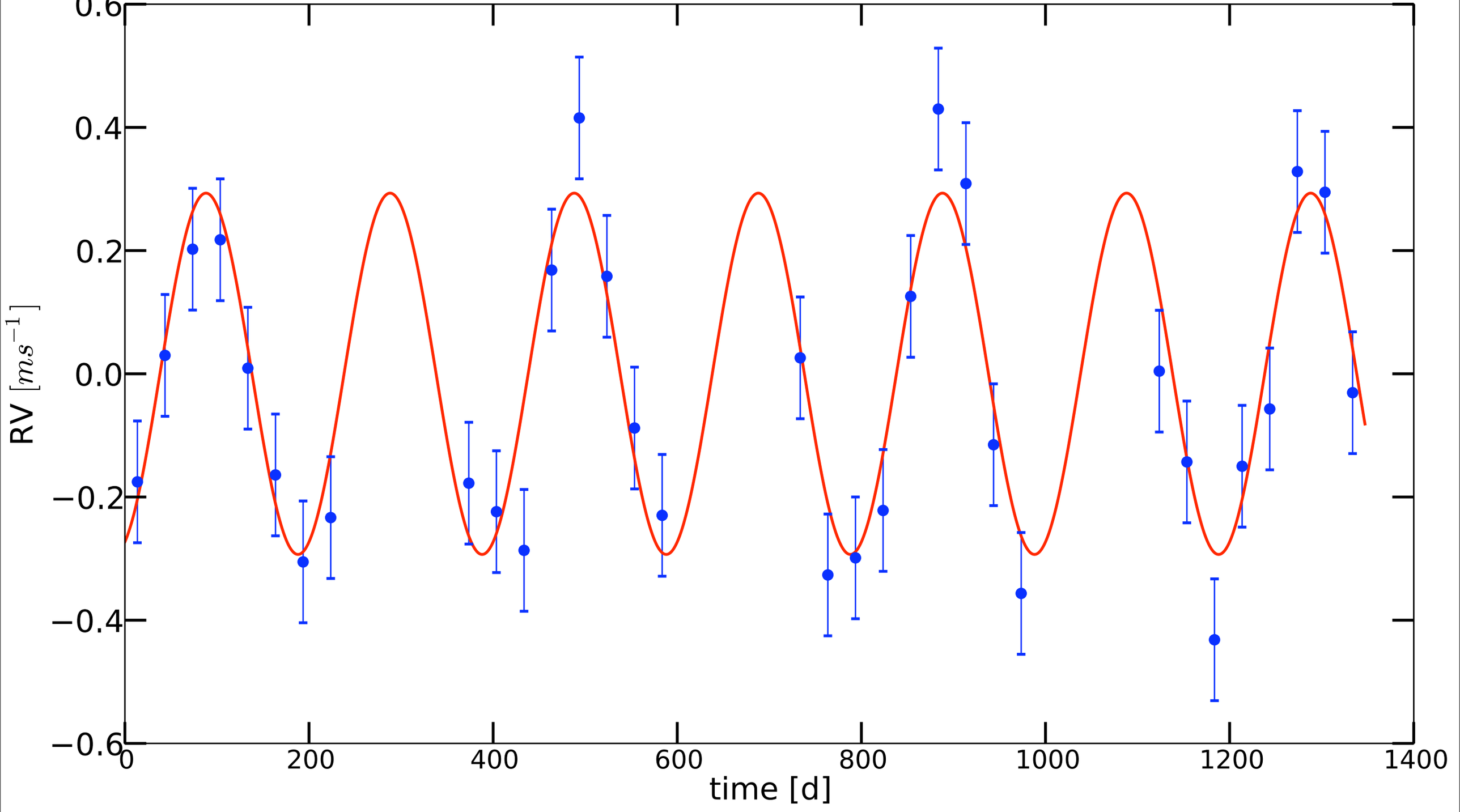
- Granulation (τ ~ 6 min)
- Mesogranulation (τ ~ 3h)
- Supergranulation (τ ~ 1 day)
- Active regions (τ ~ 10 days)

Granulation

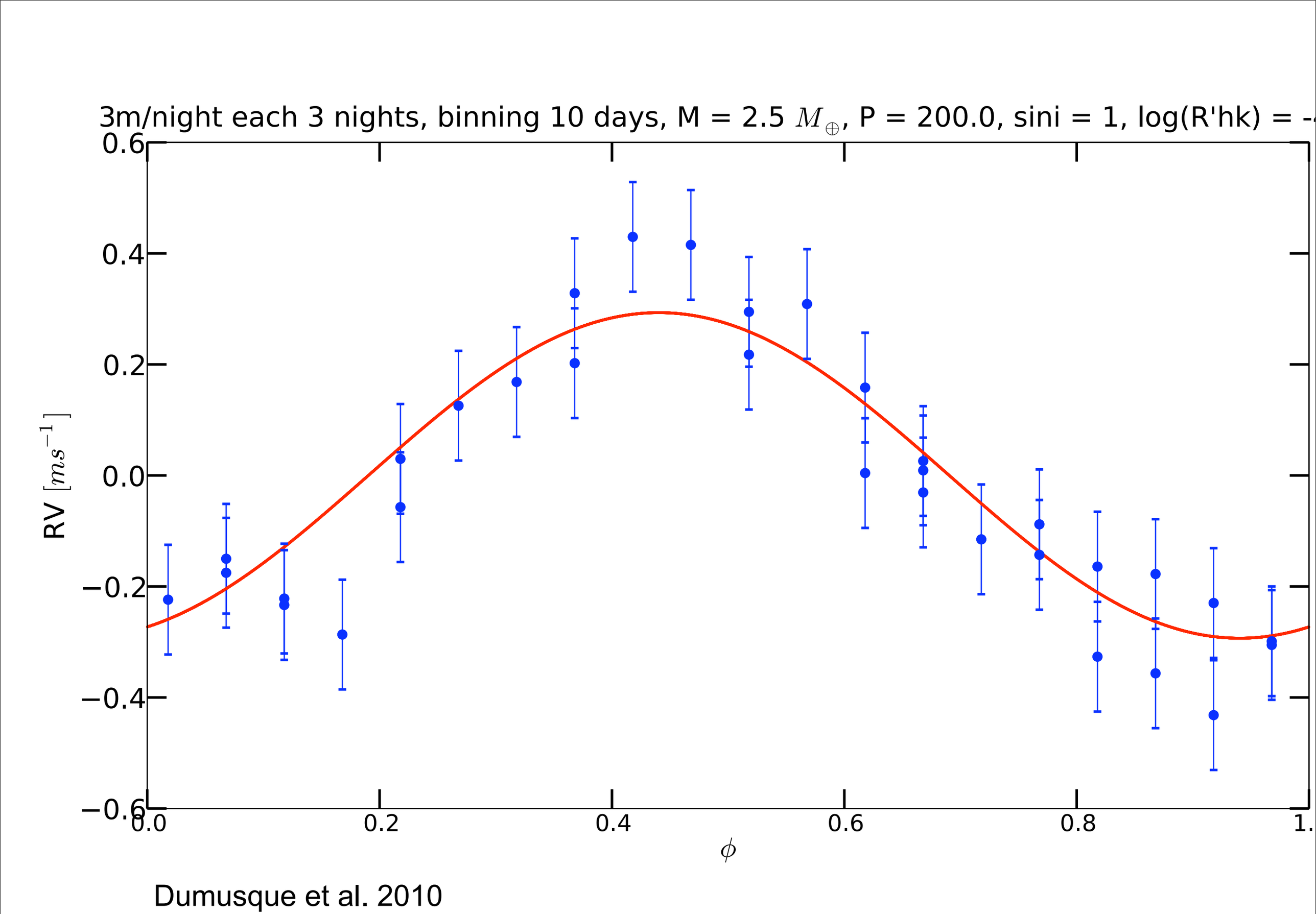


- Other sources of noise at lower frequencies

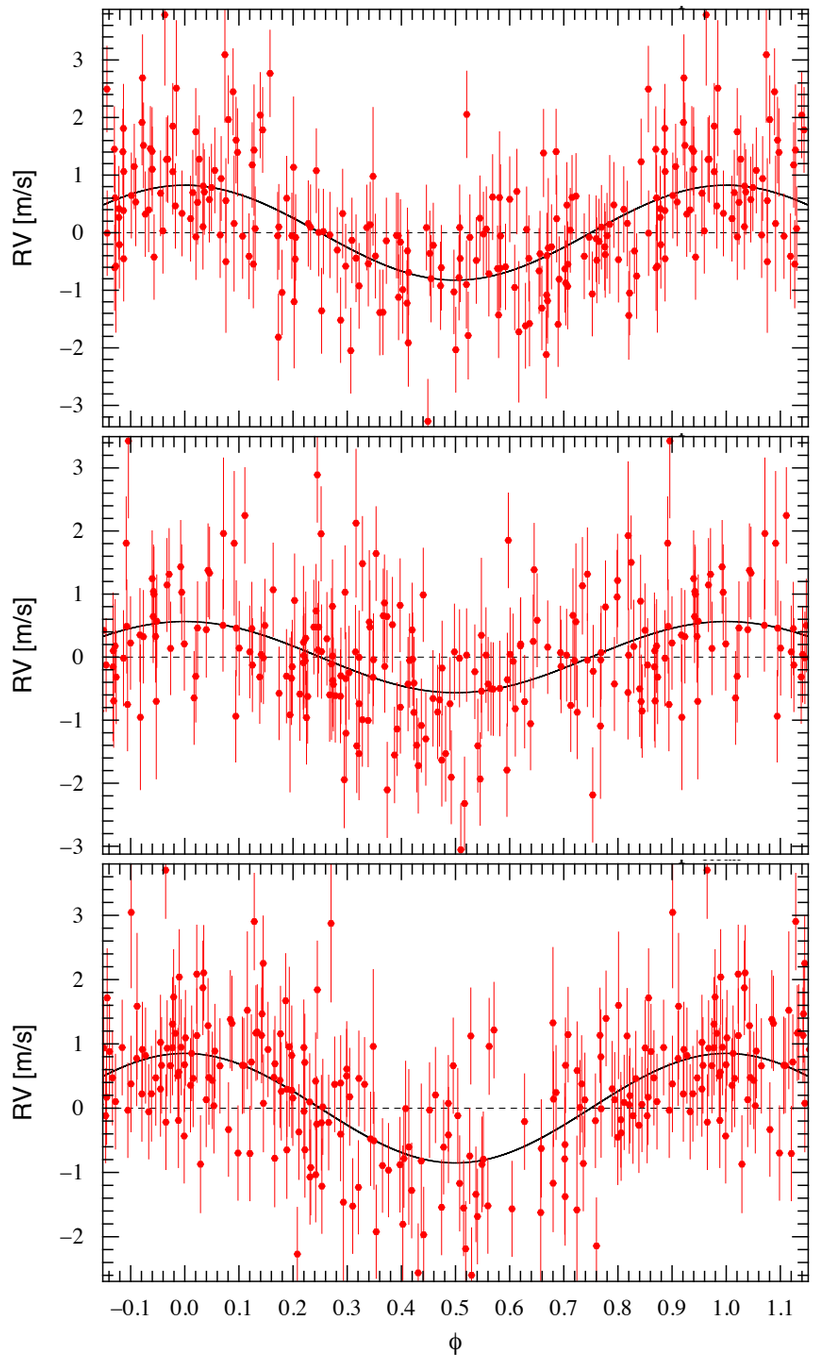




Dumusque et al. 2010

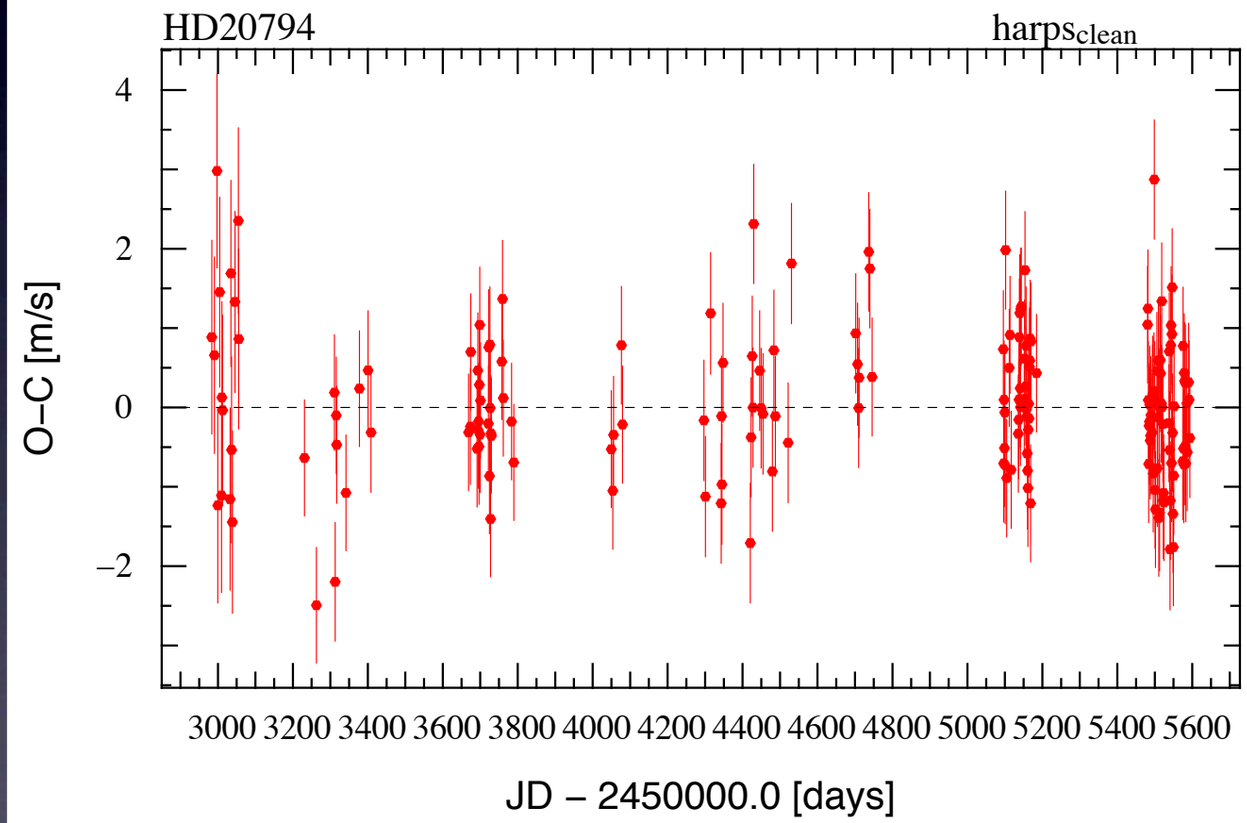

3m/night each 3 nights, binning 10 days, M = 2.5 $M_\oplus$, P = 200.0, sini = 1, log(R'hk) = -
0.6
0.4
0.2
0.0
−0.2
−0.4
−0.6
RV $[ms^{-1}]$
0.0
0.2
0.4
0.6
0.8
1.
ϕ
Dumusque et al. 2010

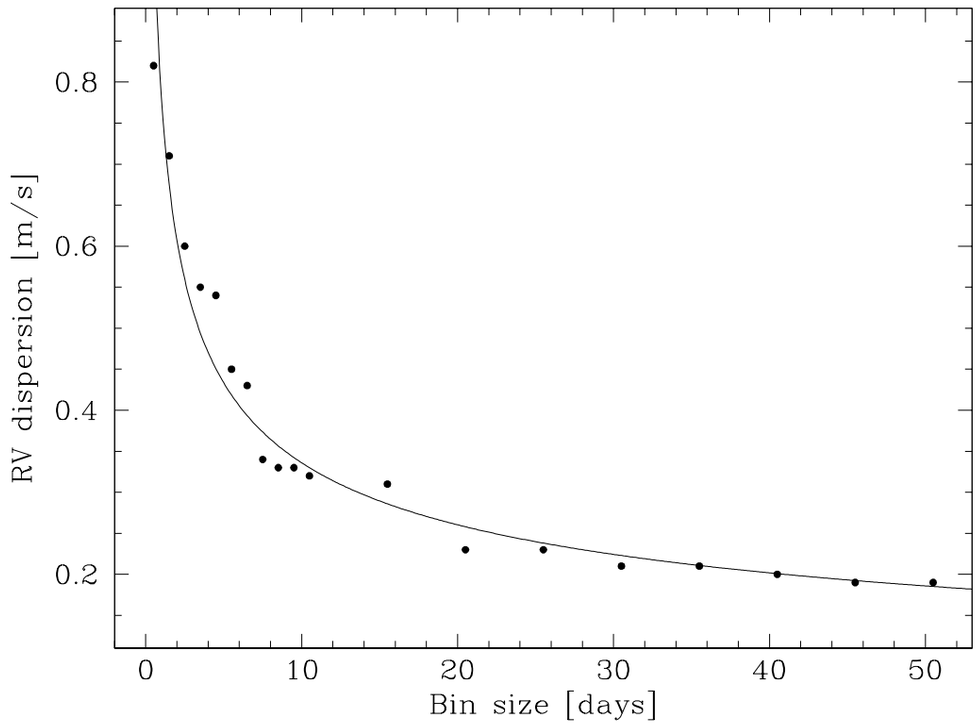
HD20794: Three Earth-mass planets



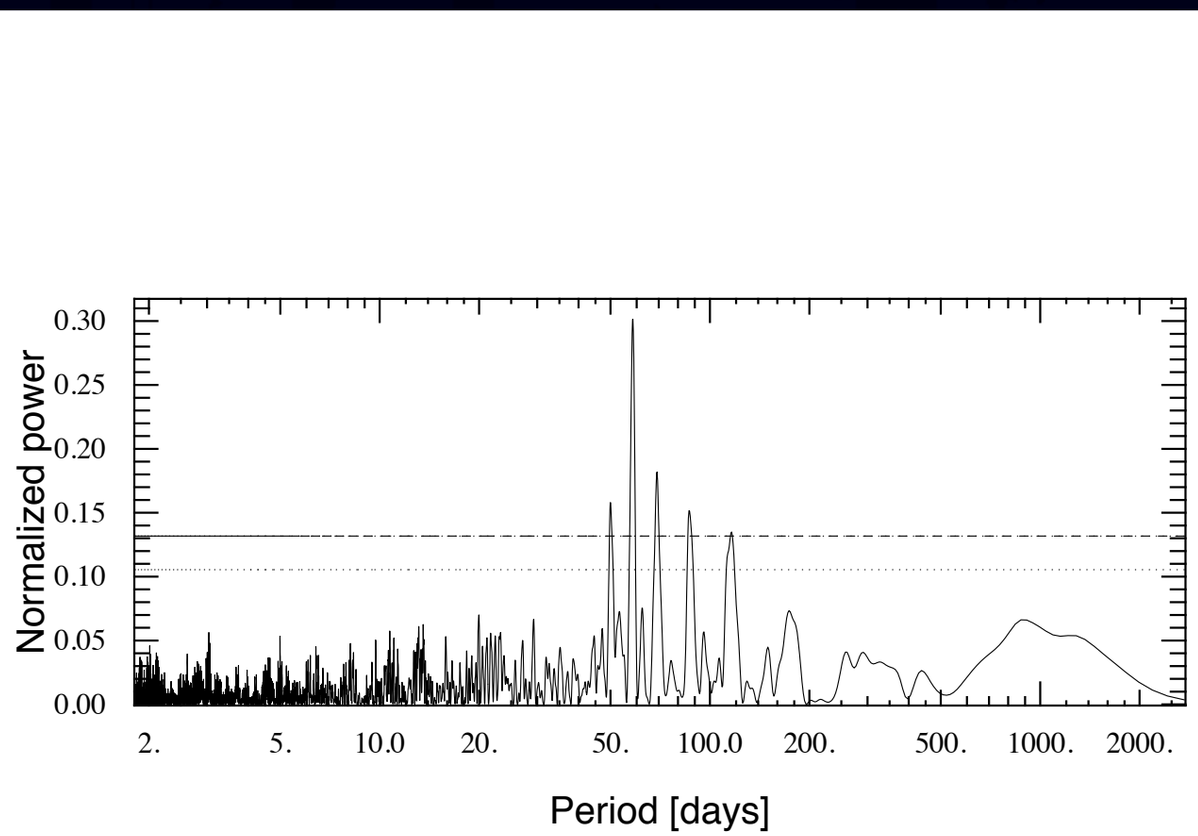
Parameter	[unit]	HD 20794 b	HD 20794 c	HD 20794 d
Epoch	[BJD]	2'454'783.40362208		
i	[deg]	90 (fixed)		
V	[km s^{-1}]	87.9525 (±0.0001)		
P	[days]	18.315	40.114	90.309
		(±0.008)	(±0.053)	(±0.184)
λ	[deg]	169.0	149.4	16.2
		(±6.7)	(±10.0)	(±6.8)
e		0.0	0.0	0.0
		(fixed)	(*fixed*)	(*fixed*)
ω	[deg]	0.0	0.0	0.0
		(fixed)	(*fixed*)	(*fixed*)
K	[m s^{-1}]	0.83	0.56	0.85
		(±0.09)	(±0.10)	(±0.10)
$m \sin i$	[$M_\oplus$]	2.7	2.4	4.8
		(±0.3)	(±0.4)	(±0.6)
a	[AU]	0.1207	0.2036	0.3499
		(±0.0020)	(±0.0034)	(±0.0059)
T_{eq}	[K]	660	508	388
N_{meas}			187	
Span	[days]		2610	
rms	[m s^{-1}]		0.82	
χ^2_r			1.39	

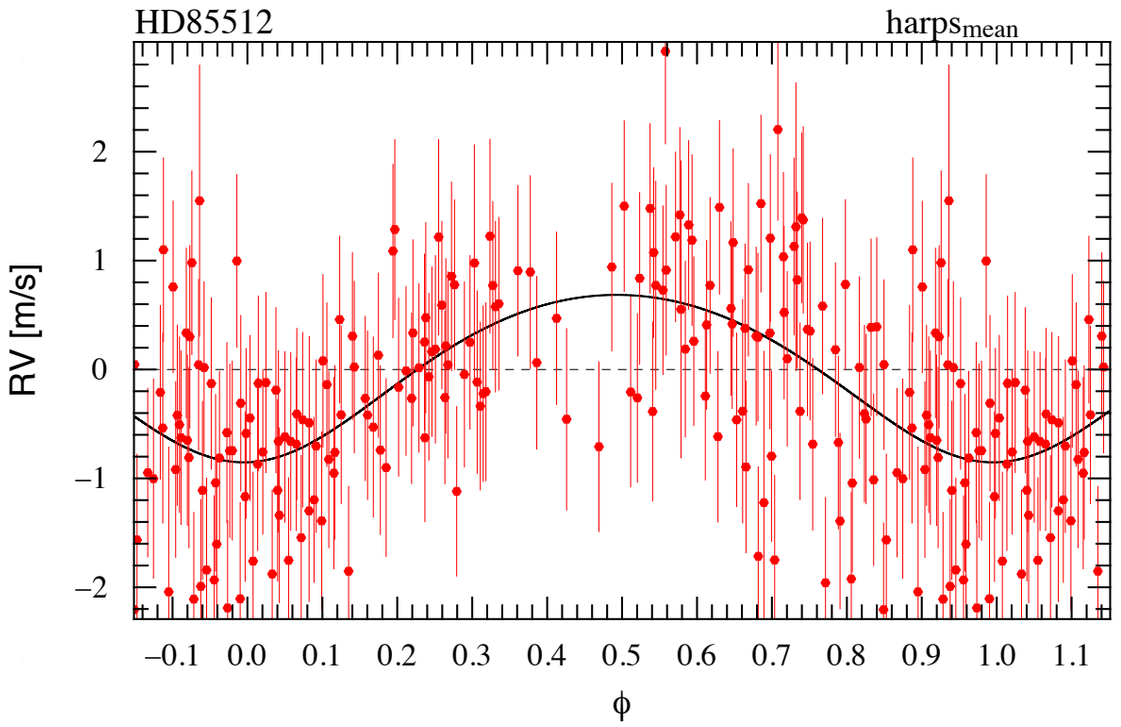
HD20794: Three Earth-mass planets





HD85512b: Rocky planet in HZ





HD 85512 b (Pepe et al.2011)

P = 58.4 days, m2sini= 3.6 M Earth

185 measurements

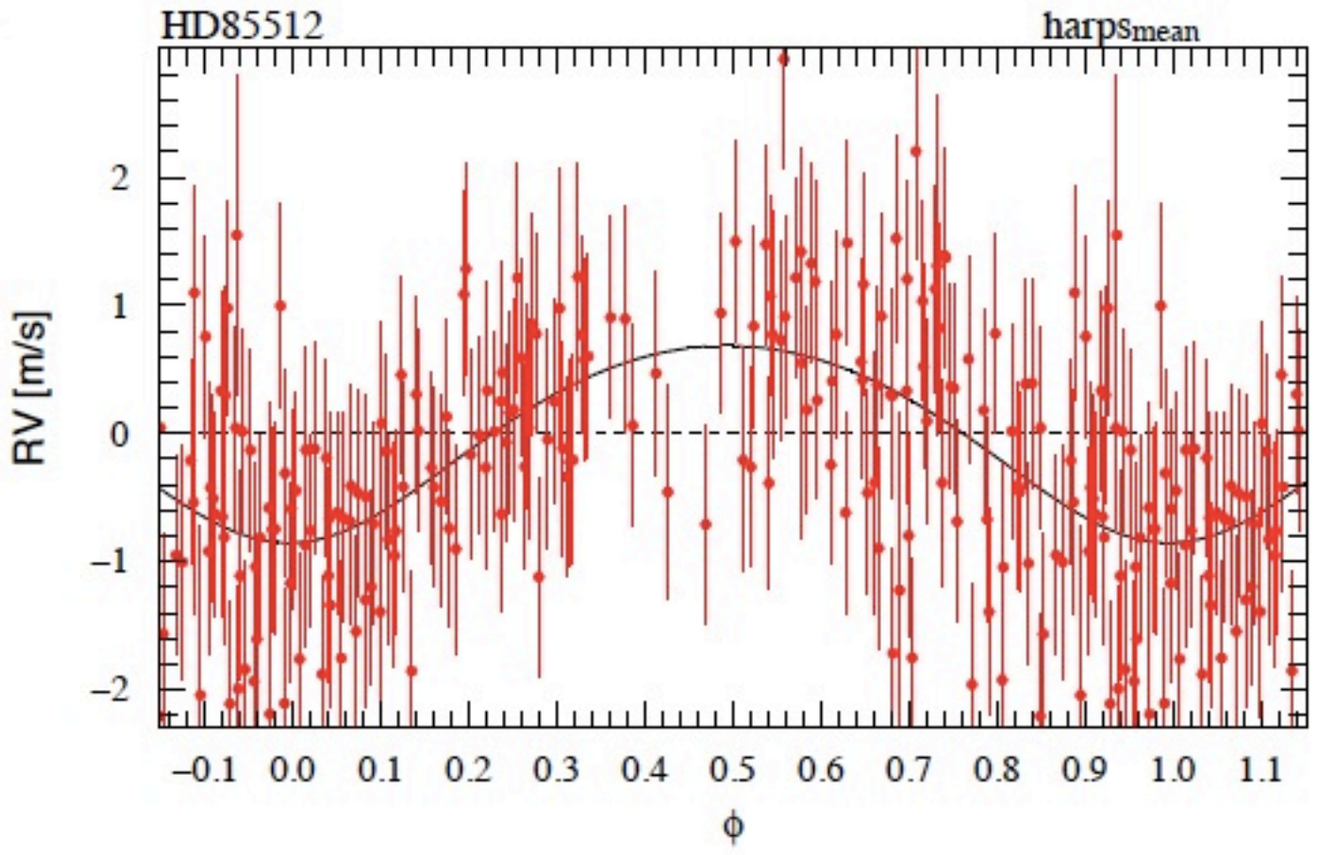


Fig. 13. Phase-folded RV data of HD 85512 and fitted Keplerian solution. The dispersion of the residuals is 0.75 m s^{-1} *rms*.

Super-Earths in the Habitable Zone

Sun

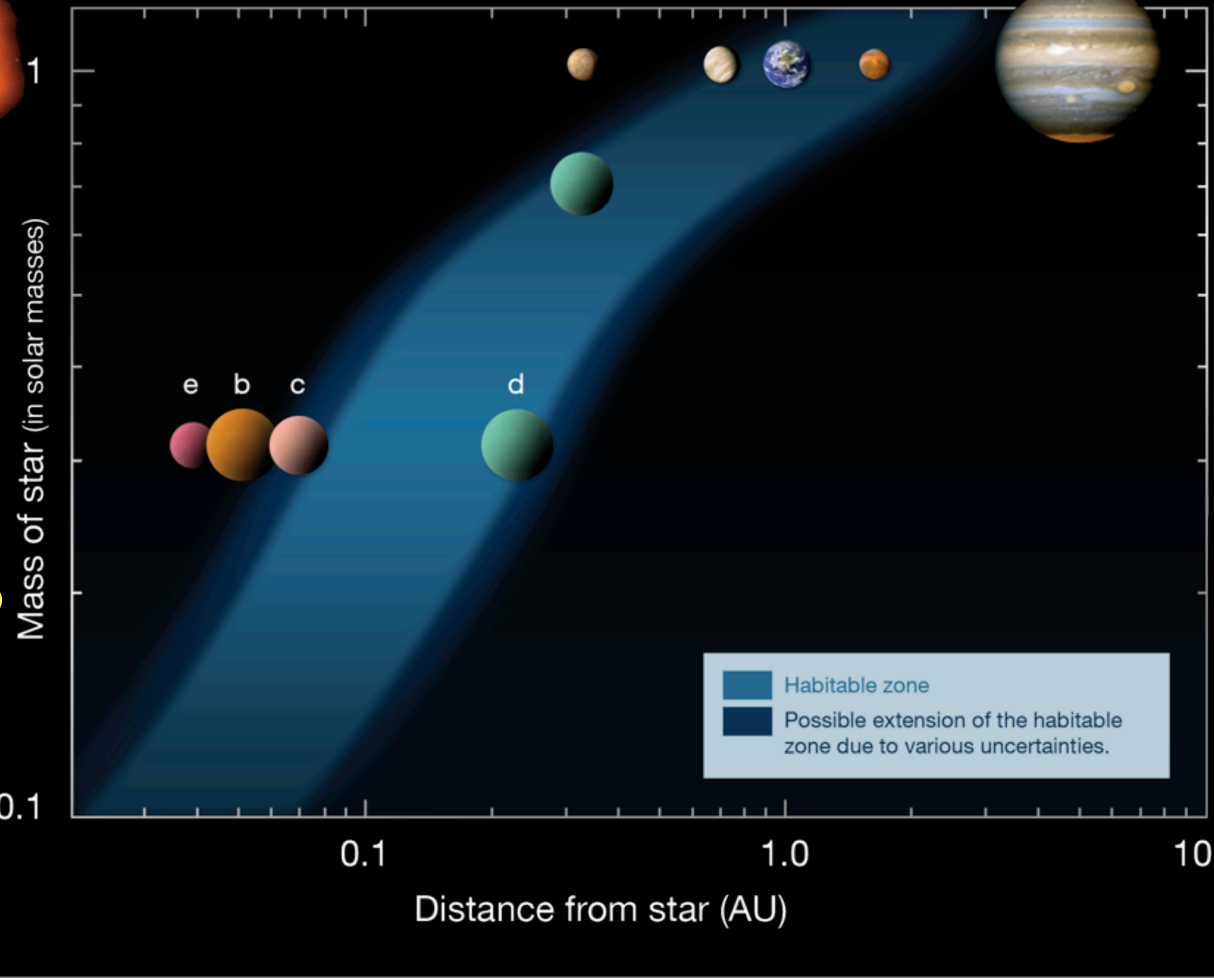
HD 85512

Pepe et al. 2011

Gliese 581

Udry et al. 2007

Mayor et al. 2009



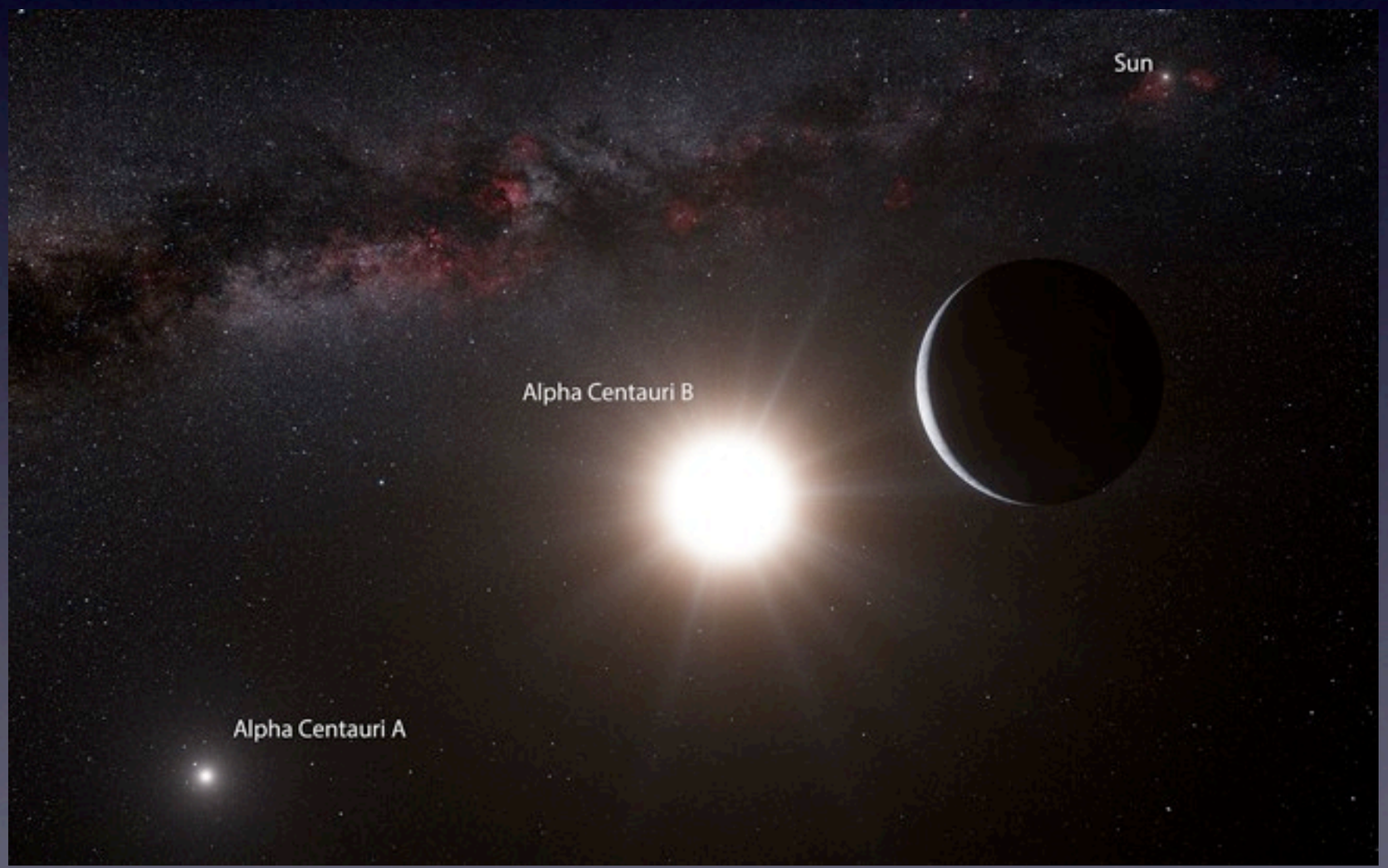
Discovery of Alpha Cen B b

An Earth mass planet orbiting one of our closest star, Alpha Cen B, at only 4 light years
Dumusque et al. 2012 , Nature

Planet discovered by a European team:X.Dumusque, F. Pepe, C. Lovis, J. Sahlmann, W. Benz, F. Bouchy, M. Mayor, D. Queloz, N. Santos, S. Udry (Geneva, Bern, Paris & Porto)

This detection have been made using the Radial-velocity technique, with HARPS

Alpha Cen B is a “quiet” star, as our Sun, that present extremely small perturbing stellar signals, however their are observed at this level of precision.



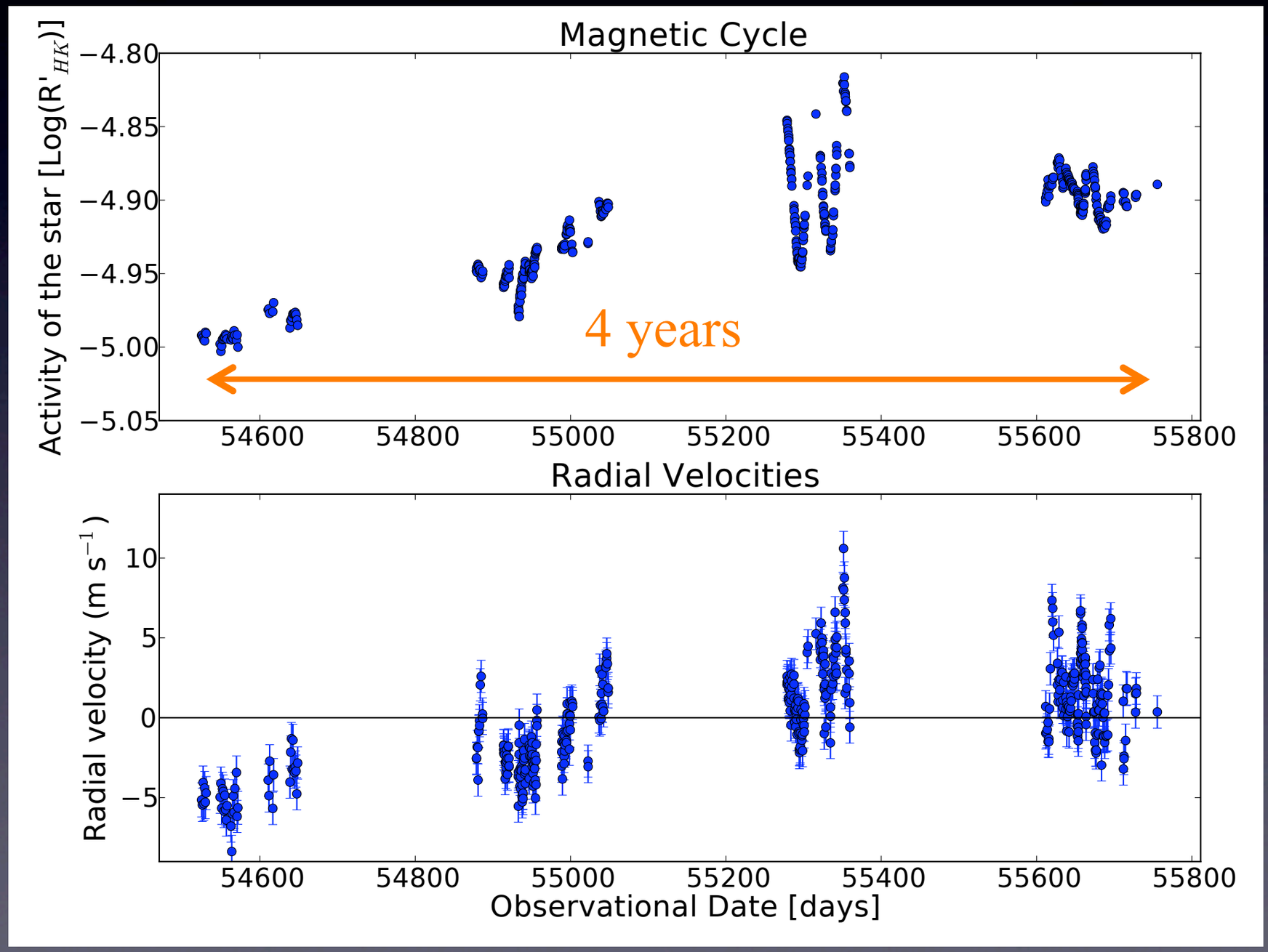
HARPS RV data

One of the most intensive campaign to search for extra-solar planets

More than 450 measurements

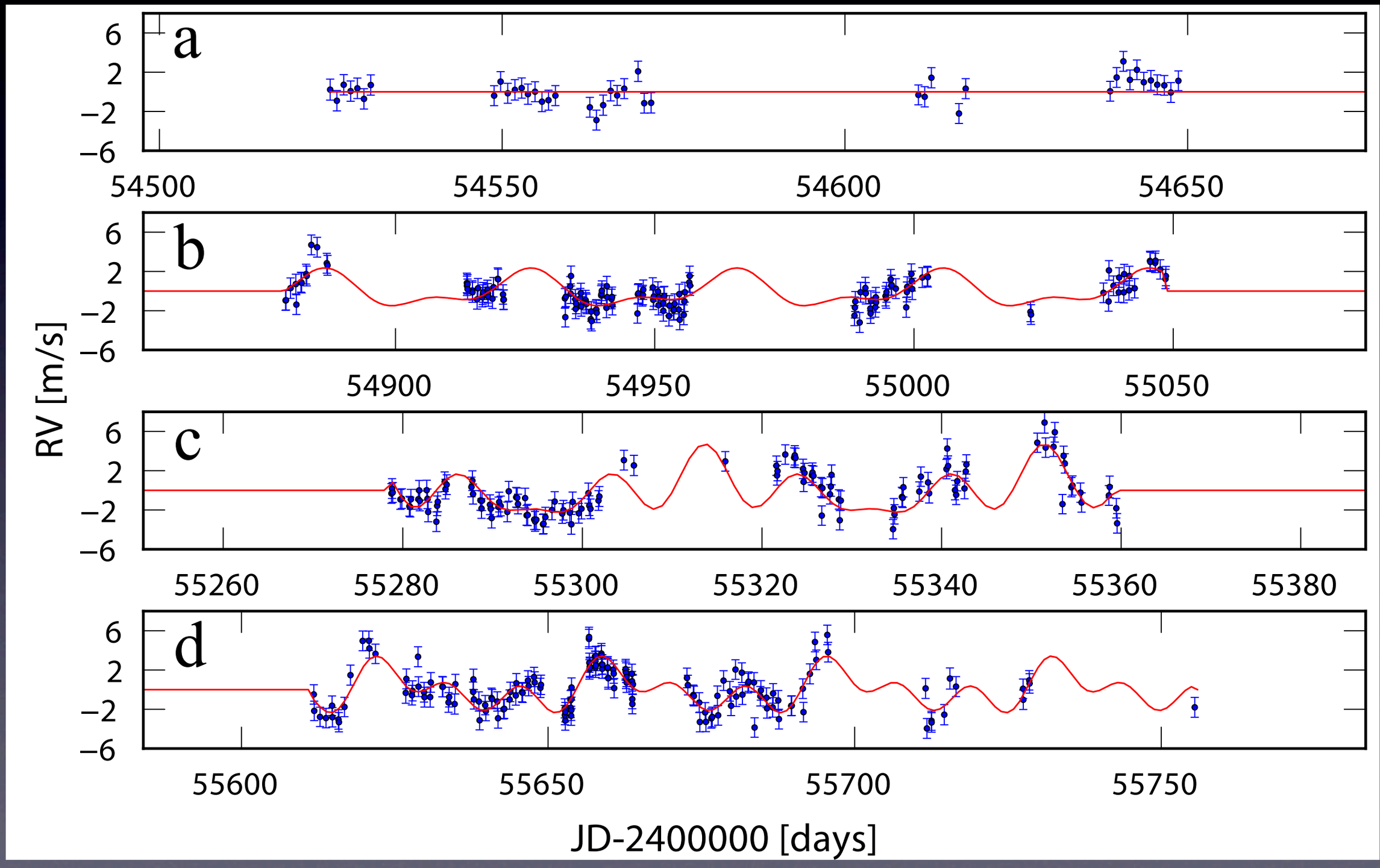
Instrument with the best precision in radial-velocity (HARPS)

Methods to mitigate stellar signals

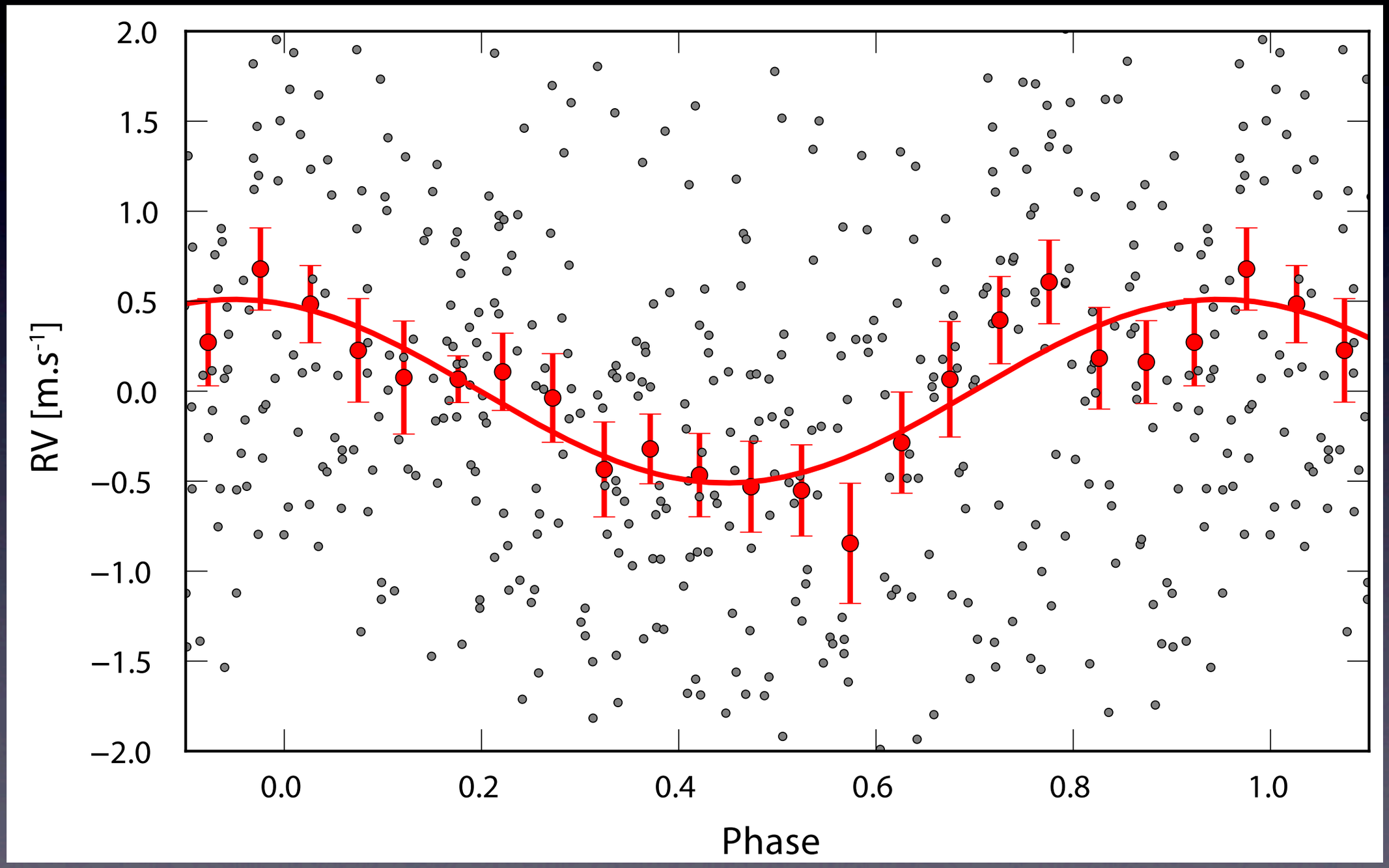


Activity-related RV effects

Stellar rotational period from b to d: 40, 38, and 37 days → Differential rotation



Smallest amplitude ever detected



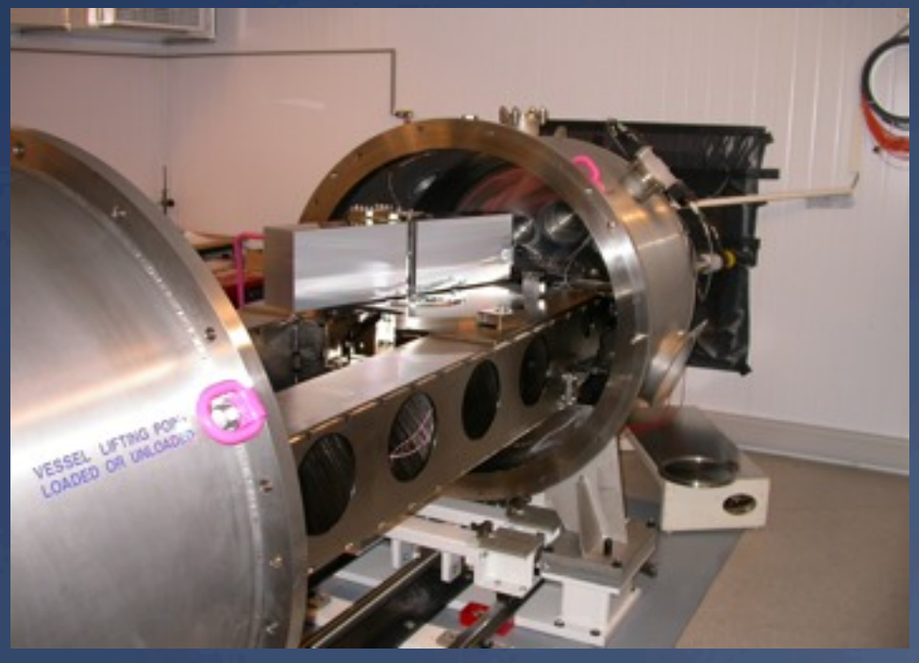
Summary of that programme

- Follow-up of 10 stars for 3 years
- 4 out of 10 stars have planets (at least)
- 1 Neptune, 5 Super Earths, 1 Earth-mass planet
- Among which HD85512 b and Alpha Cen B b
- Detected semi-amplitude as low as 40-50 cm/s

Future searches …

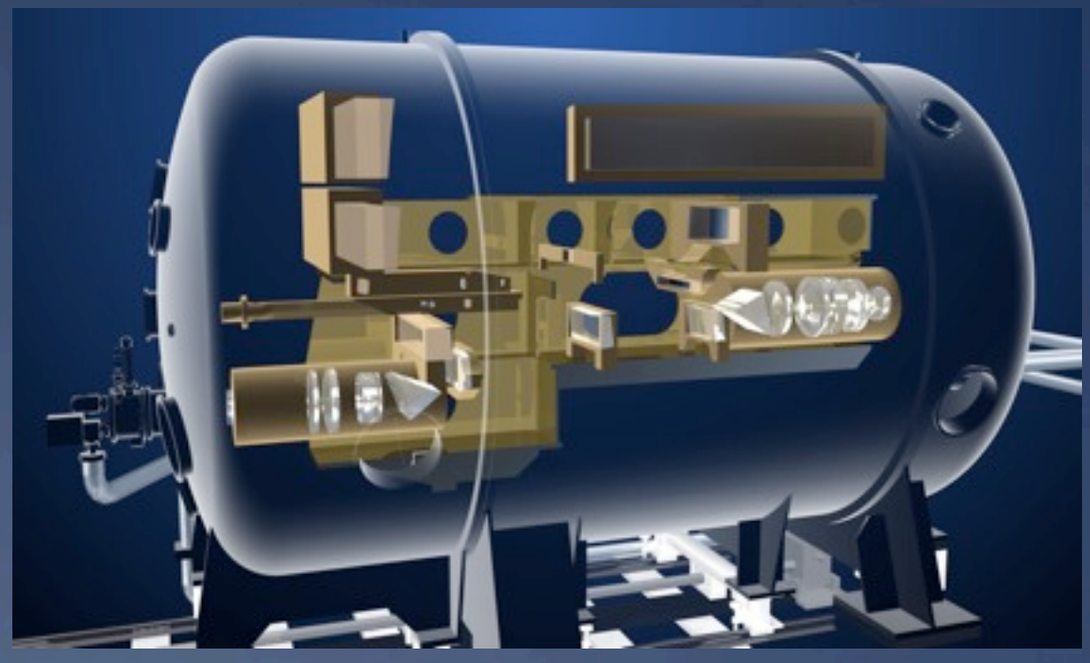
HARPS-N

* HARPS copy for northern hemisphere
* Follow-up of KEPLER candidates
* Search for Earth analogs
* Etc.



ESPRESSO@VLT

* Better precision on larger telescope
* Aim: 10 cm/s instrumental and photon noise
* Search for Rocky planets in habitable zone & variability of fundamental constants, etc.
* Up to 4 UTs incoherently



Statistical Properties of Super-Earths and Neptune-Mass Planets from the HARPS Survey

Unbiased exoplanet populations from the HARPS surveys

Mayor, Marmier, Lovis et al. astro-ph

HARPS survey for the southern hemisphere
(La Silla Observatory)

Since 2004

250 observing nights (GTO, Mayor et al.)
240 observing nights (continuation, Udry et al.)

Stellar sample

CORALIE volume-limited sample:

- distance < 50 pc
- log R'_{HK} < -4.75 (F,G); -4.70 (K)
- no binaries
- measurement precision ~5 m/s

822 FGK stars (1998 to present)

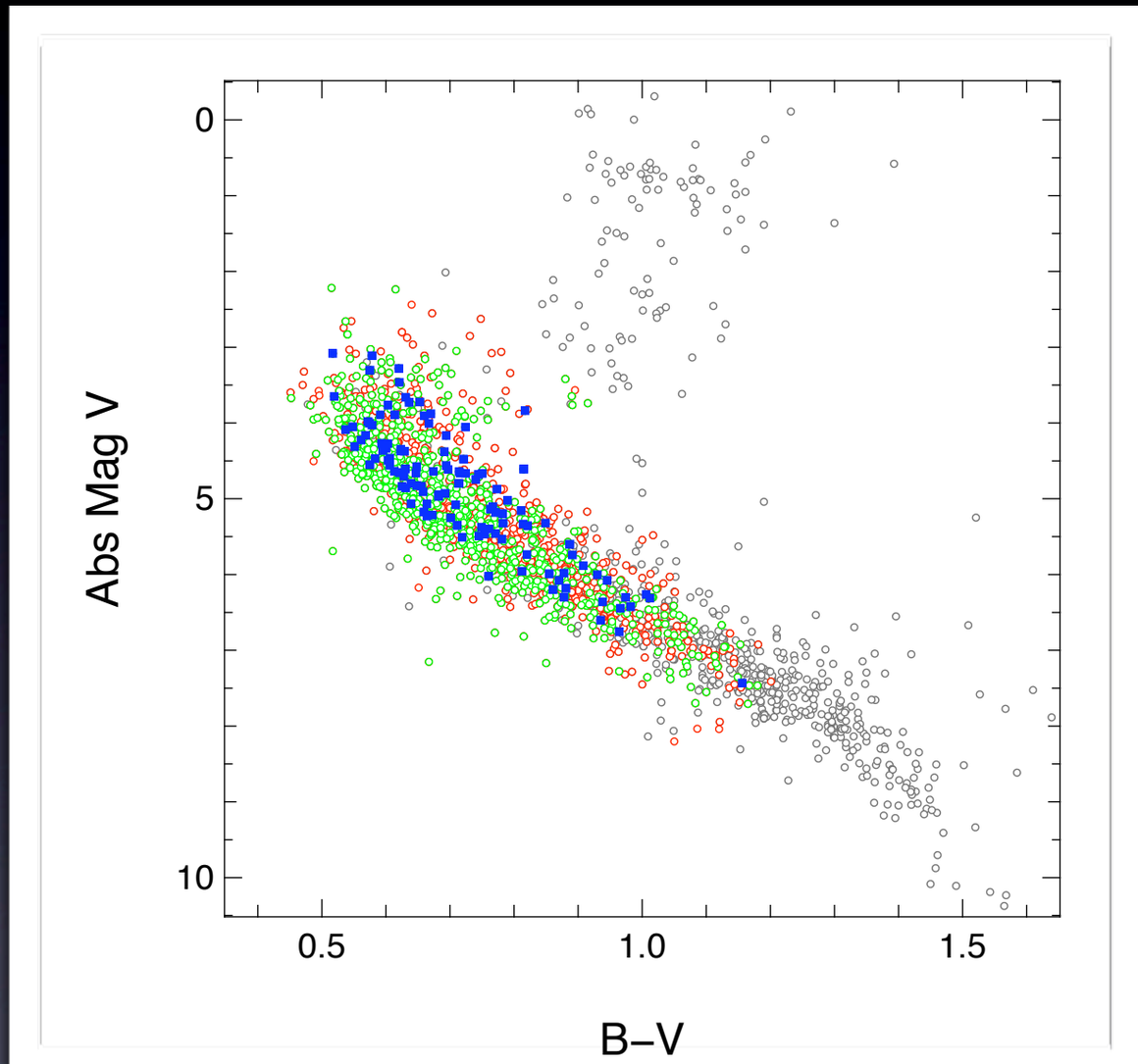
Focus on gaseous giant planets, long periods

HARPS subsample:

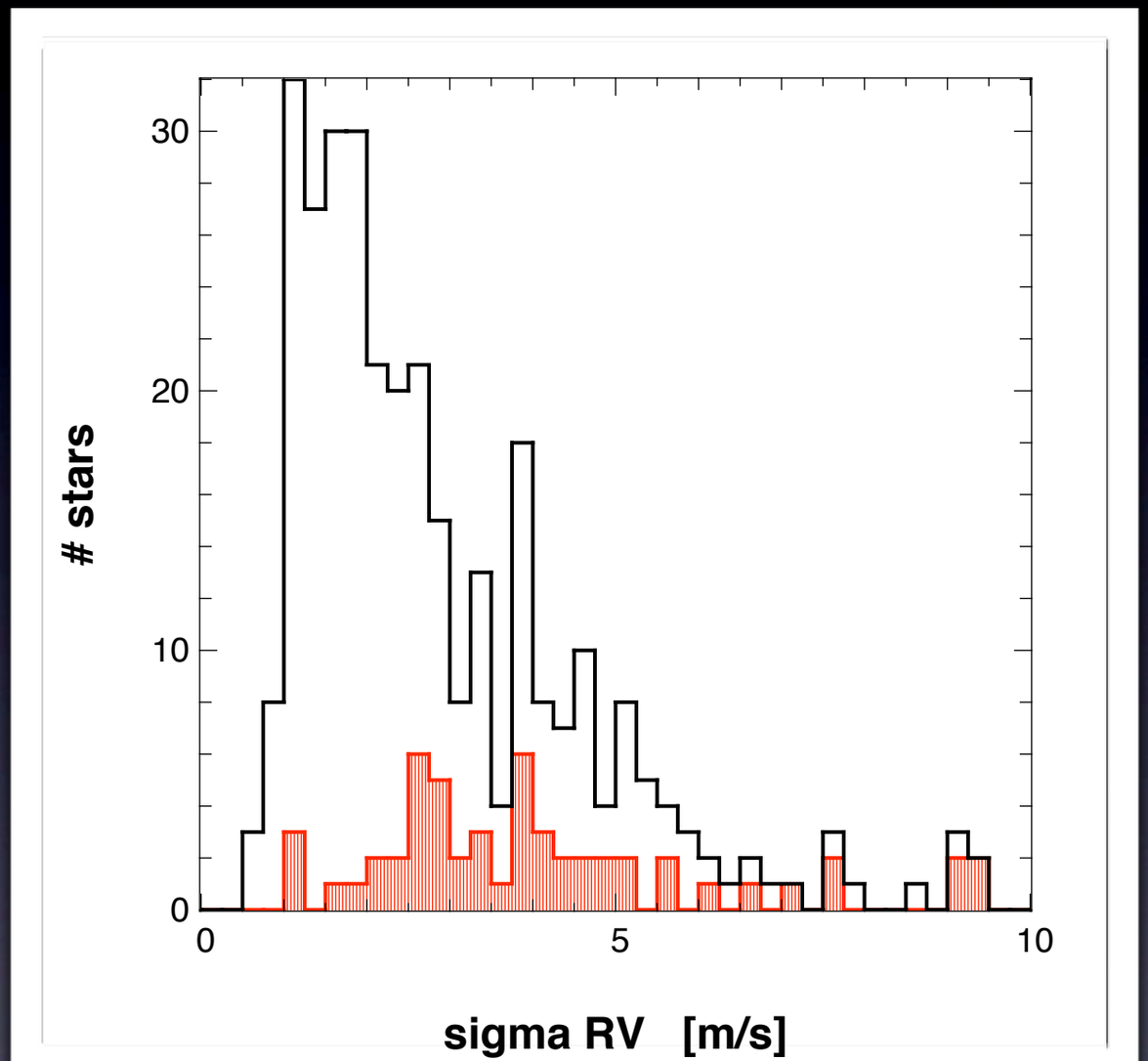
- measurement precision ~0.5 m/s

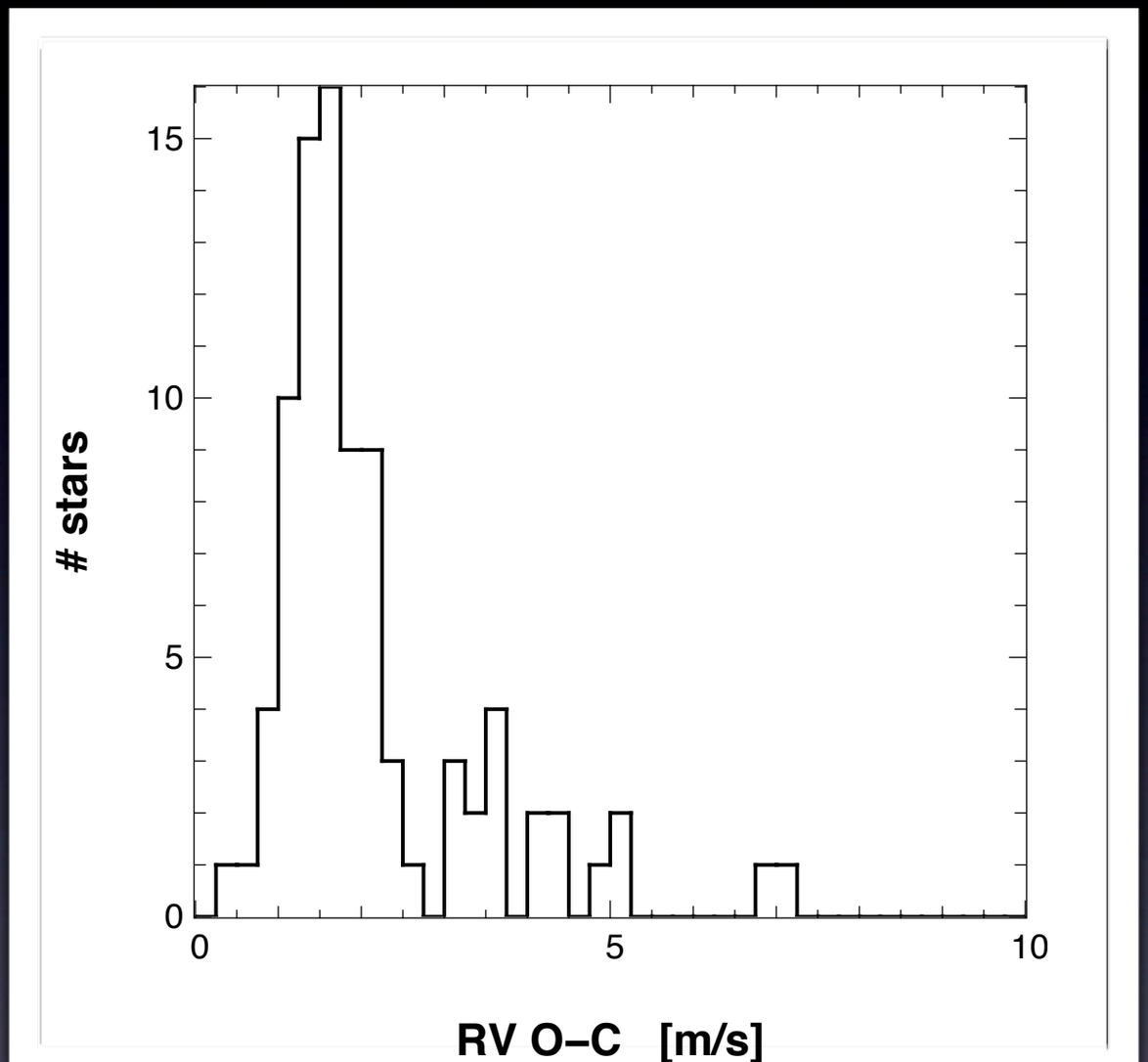
376 FGK stars (2003 to present)

Focus on super-Earths and Neptune-mass planets



Radial velocity dispersion & precision



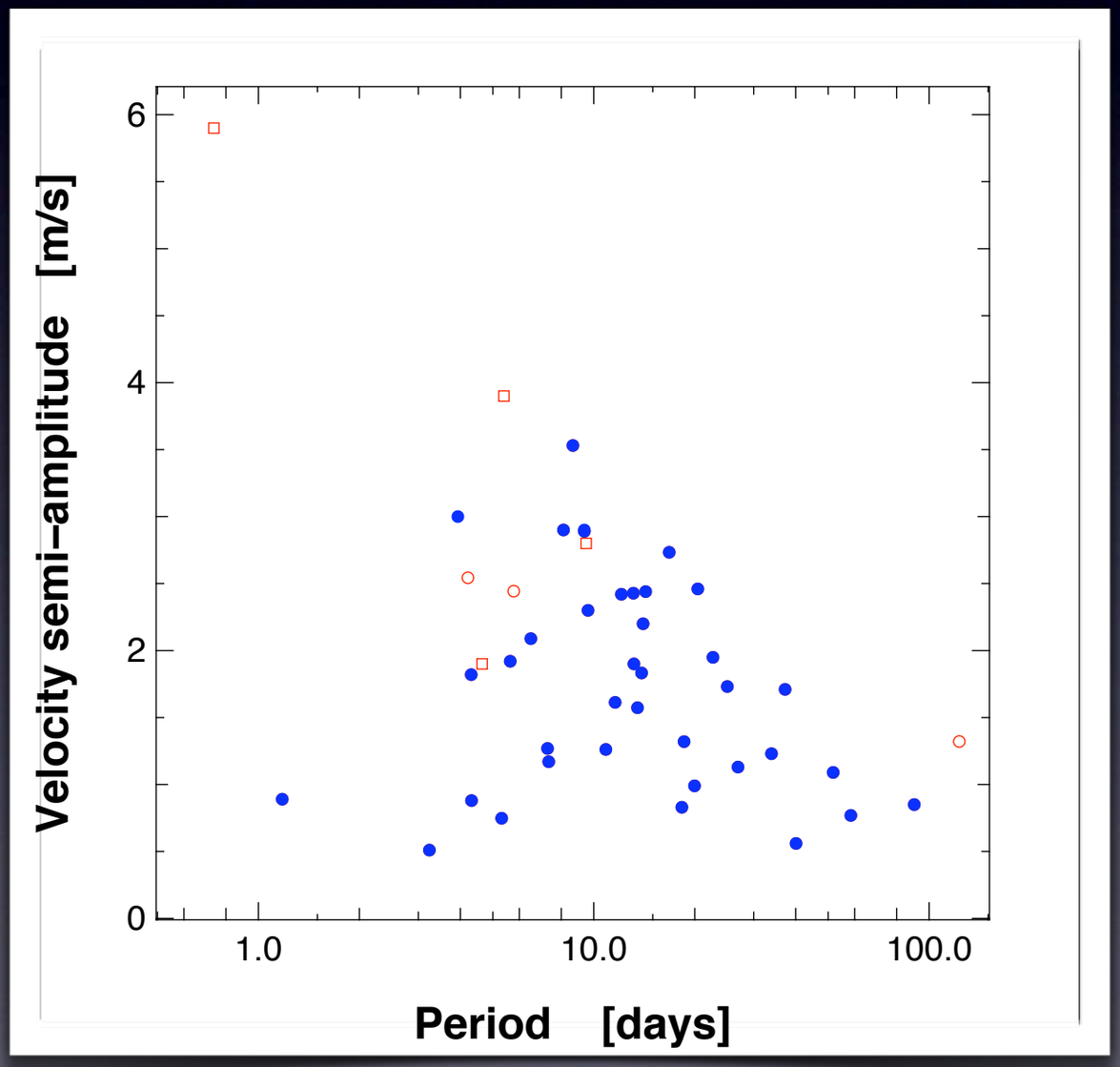


Stars with RV rms as low as 2 m/s may host a planetary system...

The radial velocity precision : a key parameter to detect Super-Earths (1-10 Earth-masses)

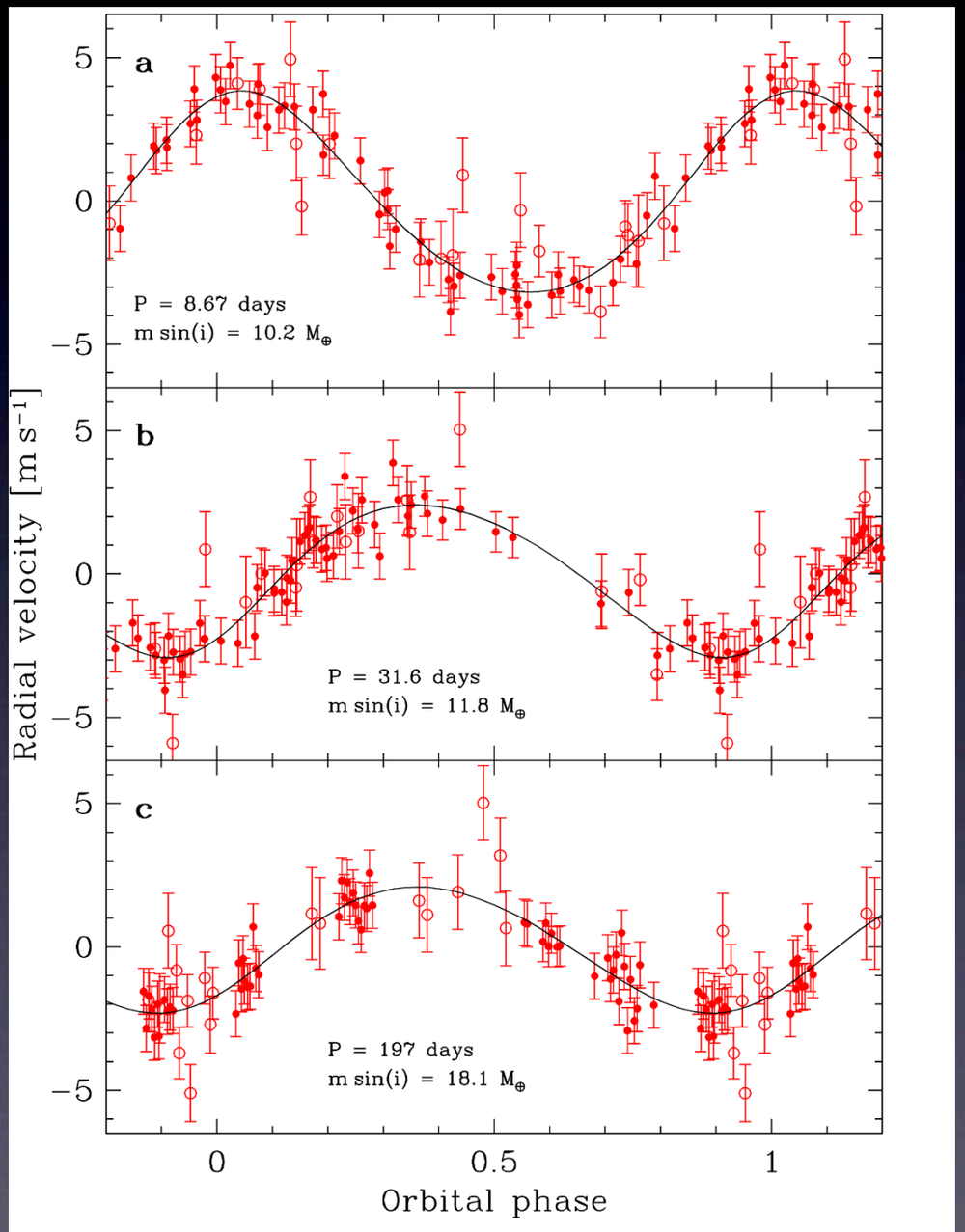
HARPS Super-Earths

Other sources in litterature



Today : smallest amplitude K= 0.50 m/s

HD 69830: a trio of Neptunes



Lovis et al. 2006

HD 69830 b

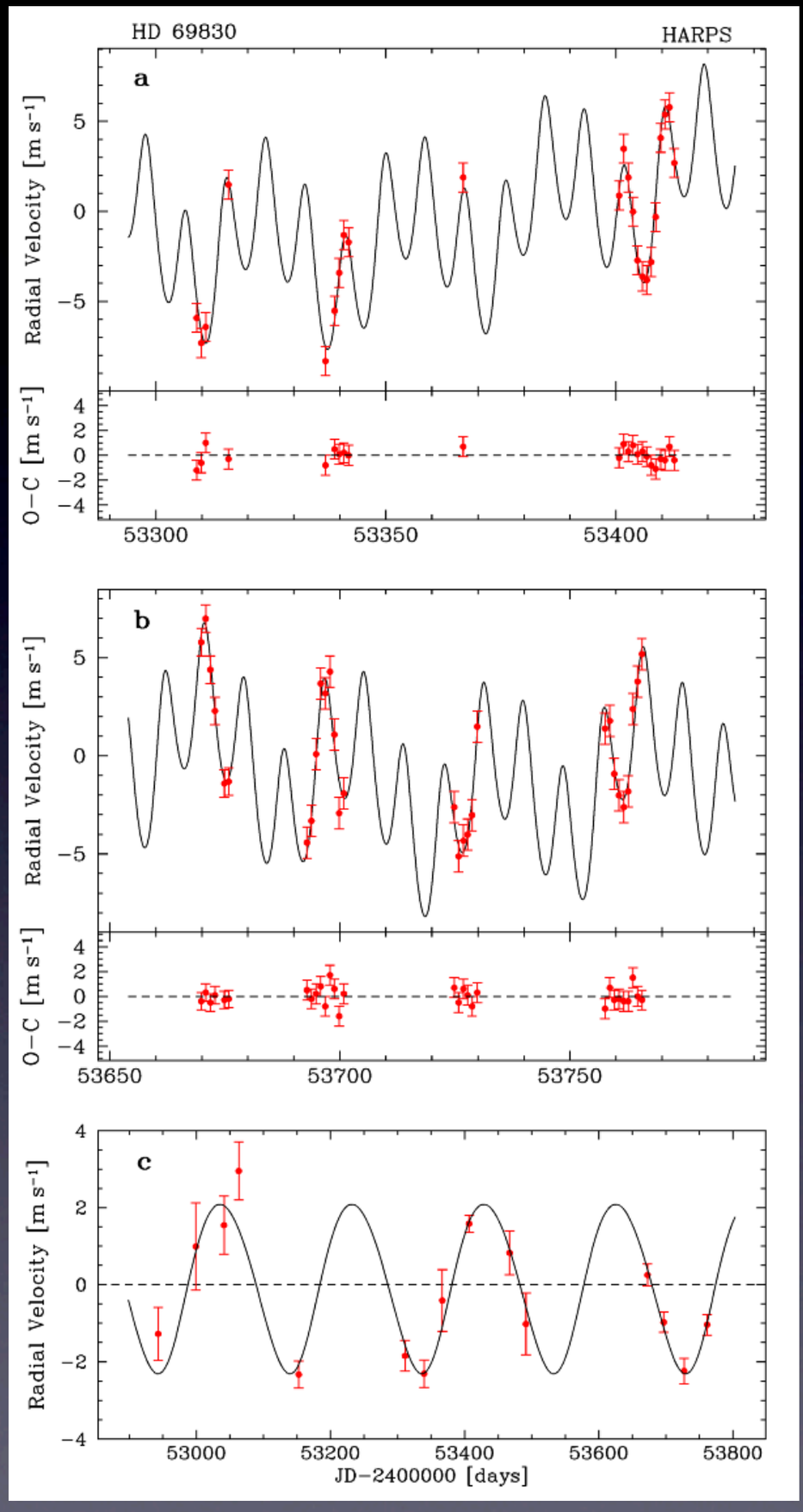
P = 8.67 days
K = 3.5 m s^{-1}
m sin(i) = 10.2 $M_\oplus$

HD 69830 c

P = 31.6 days
K = 2.7 m s^{-1}
m sin(i) = 11.8 $M_\oplus$

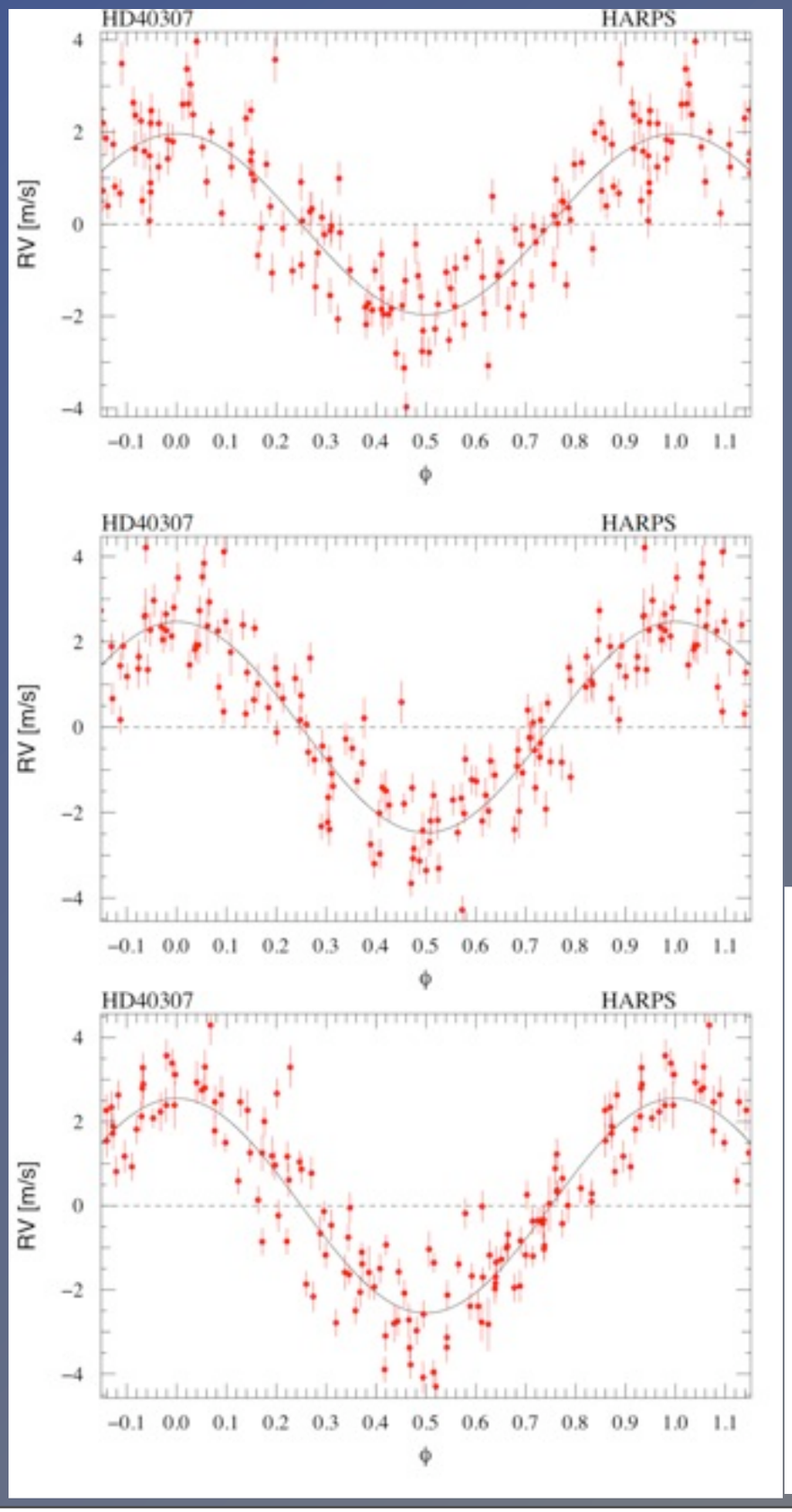
HD 69830 d

P = 197 days
K = 2.2 m s^{-1}
m sin(i) = 18.1 $M_\oplus$



HD 40307 : A trio of Super-Earths

Mayor et al. A&A 2009



P_1 = 4.31 days
e_1 = 0.02
m_1 sini = 4.3 $M_\oplus$

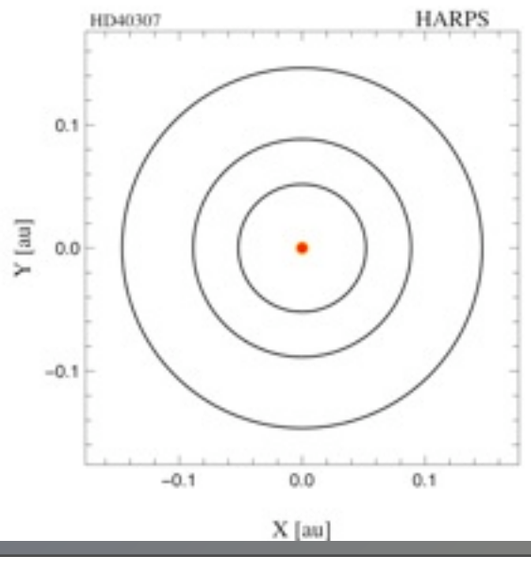
P_2 = 9.62 days
e_2 = 0.03
m_2 sini = 6.9 $M_\oplus$

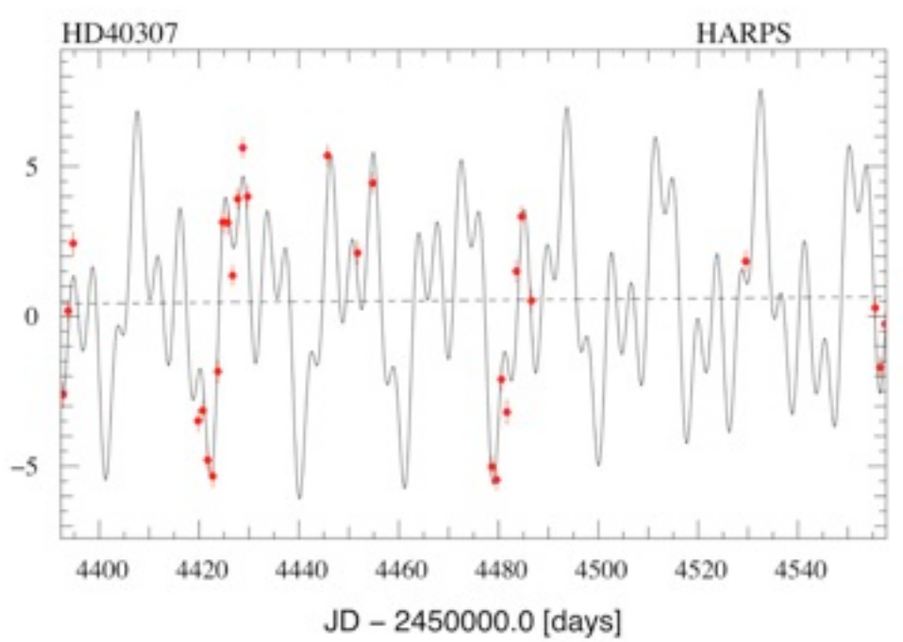
P_3 = 20.5 days
e_3 = 0.04
m_3 sini = 9.7 $M_\oplus$

HD 40307
K2 V
Dist 12.8 pc
[Fe/H] = -0.31

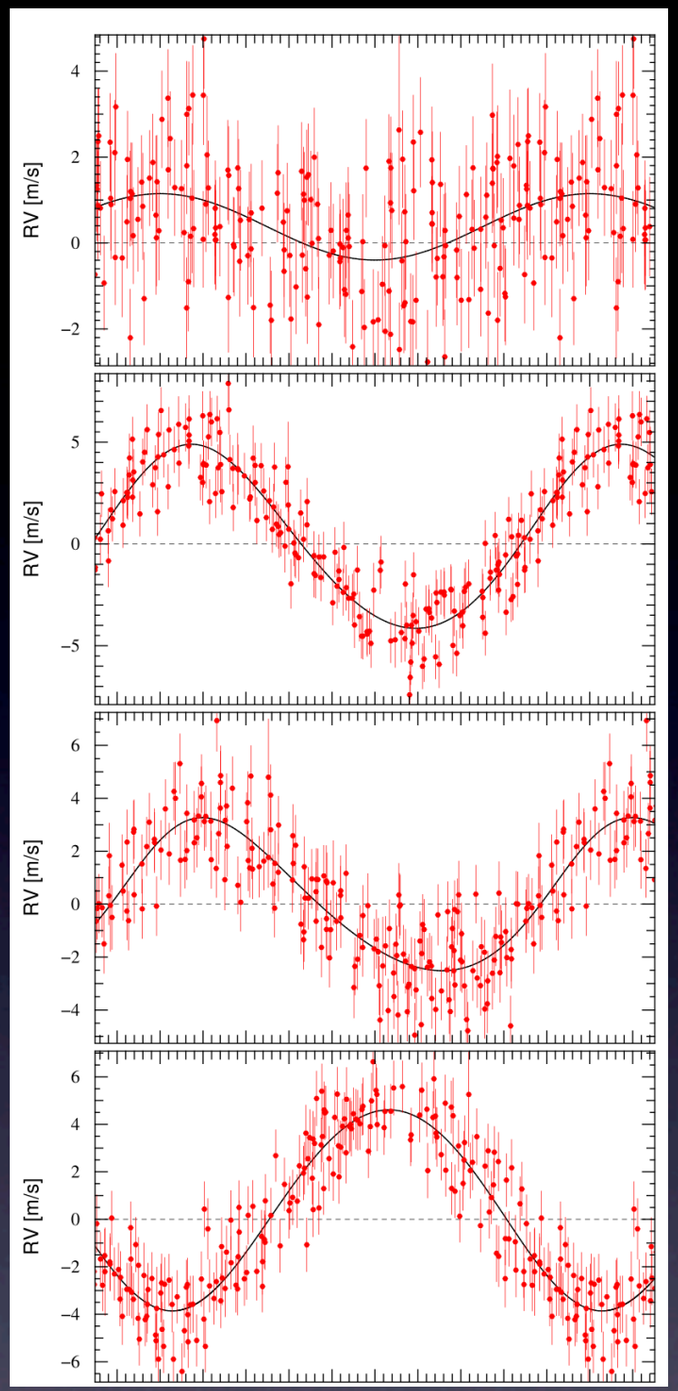
O-C = 0.85 m/s
135 observations

+ drift = 0.5 m/s/y





Up to 7 planets around HD 10180 Lovis et al. 2011



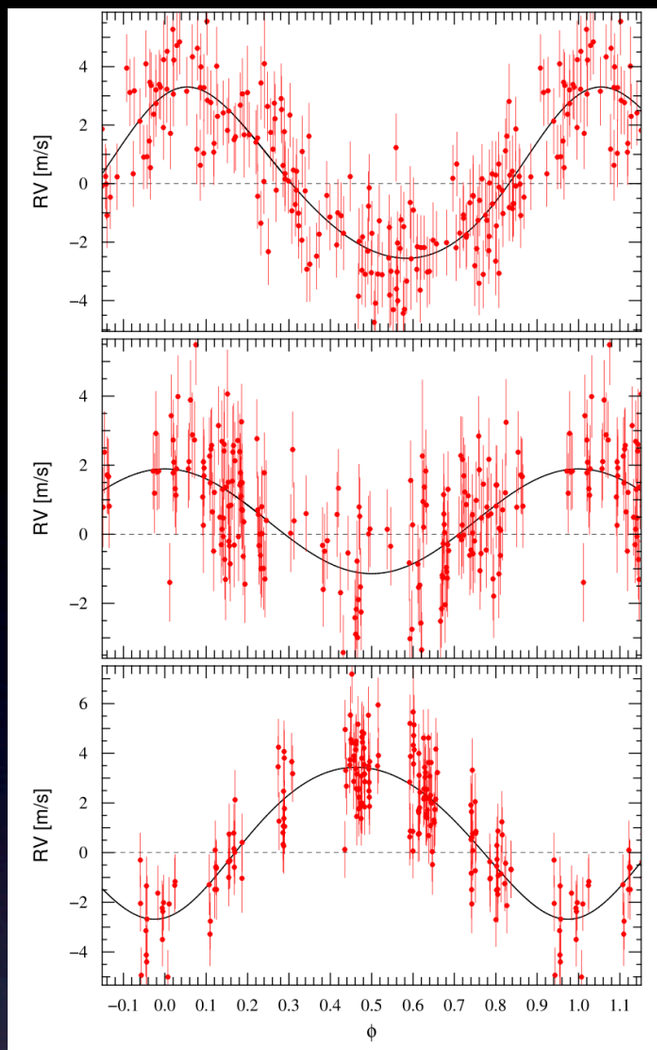


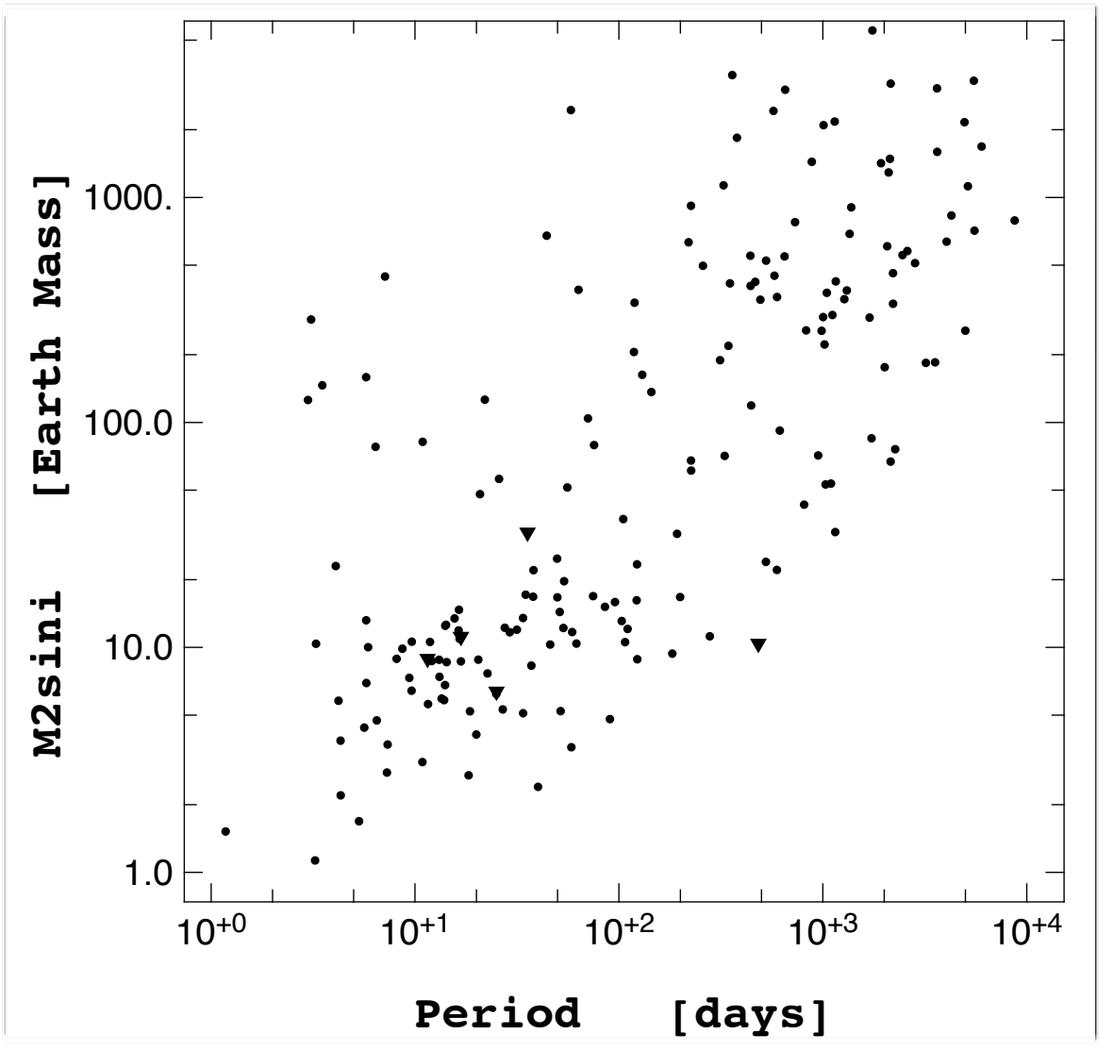
Table 3. Orbital and physical parameters of the planets orbiting HD 10180, as obtained from a 7-Keplerian fit to the data. Error bars are derived using Monte Carlo simulations. λ is the mean longitude ($\lambda = M + \omega$) at the given epoch.

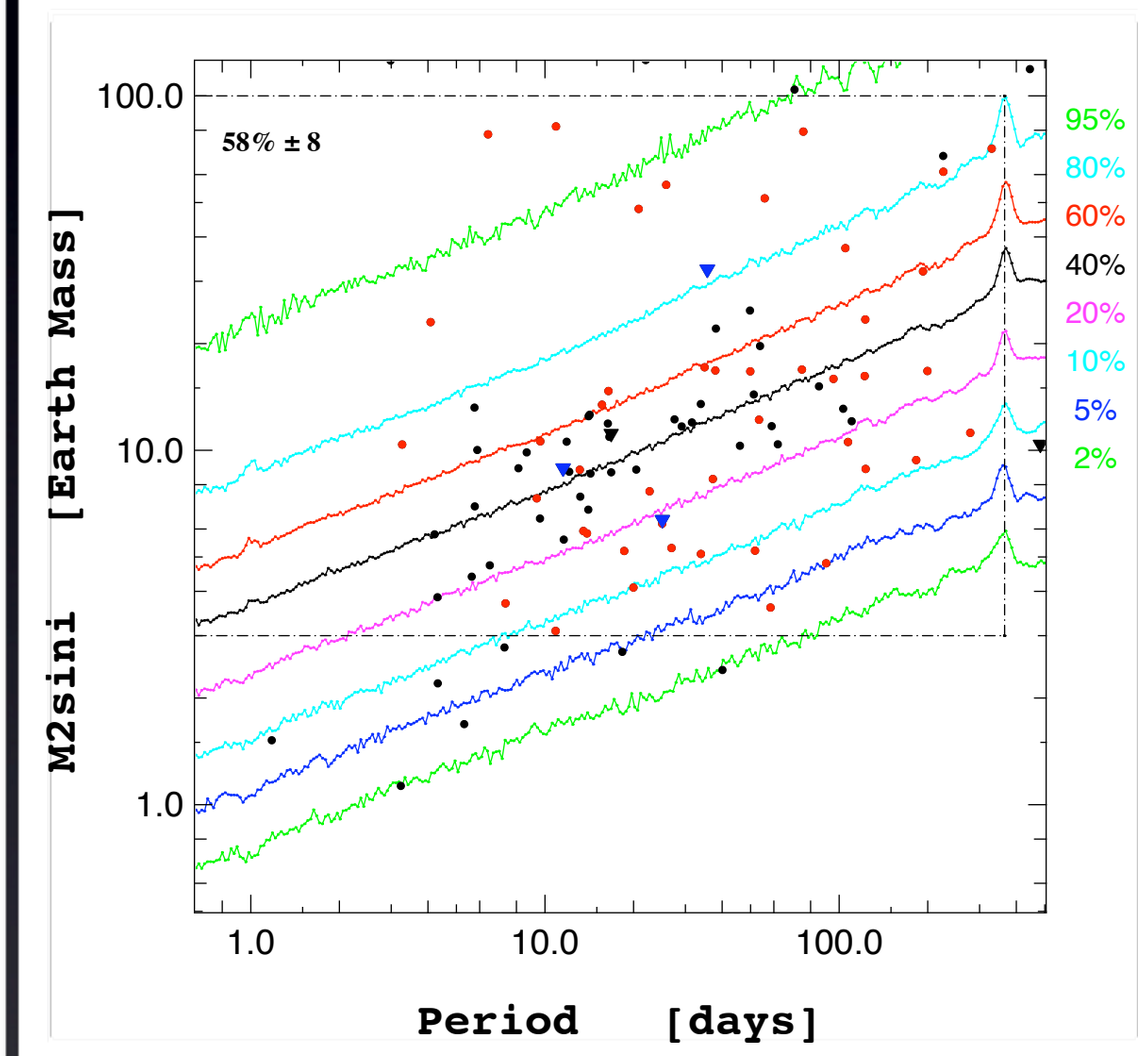
Parameter	[unit]	HD 10180 b	HD 10180 c	HD 10180 d	HD 10180 e	HD 10180 f	HD 10180 g	HD 10180 h
Epoch	[BJD]				2,454,477.878676 (fixed)			
i	[deg]				90 (fixed)			
V	[km s^{-1}]				35.53014(±0.00045)			
P	[days]	1.177662 (±0.000090)	5.75962 (±0.00029)	16.3570 (±0.0042)	49.747 (±0.023)	122.72 (±0.19)	602 (±11)	2229 (±106)
λ	[deg]	142 (±11)	29.4 (±1.9)	99.4 (±3.3)	20.9 (±2.2)	237.8 (±3.2)	253 (±11)	317.6 (±4.1)
e		0.0 (fixed)	0.077 (±0.032)	0.142 (±0.060)	0.061 (±0.036)	0.127 (±0.066)	0.0 (fixed)	0.145 (±0.073)
ω	[deg]	0.0 (fixed)	$-41\ (^{+70}_{-141})$	$-51\ (^{+43}_{-10})$	171 (±60)	$-37\ (^{+79}_{-209})$	0.0 (fixed)	−166 (±58)
K	[m s^{-1}]	0.82 (±0.14)	4.53 (±0.15)	2.92 (±0.16)	4.26 (±0.18)	2.95 (±0.18)	1.55 (±0.22)	3.11 (±0.22)
$m \sin i$	[$M_\oplus$]	1.40 (±0.25)	13.16 (±0.59)	11.91 (±0.75)	25.3 (±1.4)	23.5 (±1.7)	21.3 (±3.2)	65.2 (±4.6)
a	[AU]	0.02226 (±0.00038)	0.0641 (±0.0010)	0.1286 (±0.0021)	0.2695 (±0.0048)	0.4924 (±0.0083)	1.422 (±0.030)	3.40 (±0.12)
$N_{\rm meas}$					190			
Span	[days]				2428			
rms	[m s^{-1}]				1.27			
$\sqrt{\chi^2_\nu}$					1.23			

Multiplicity

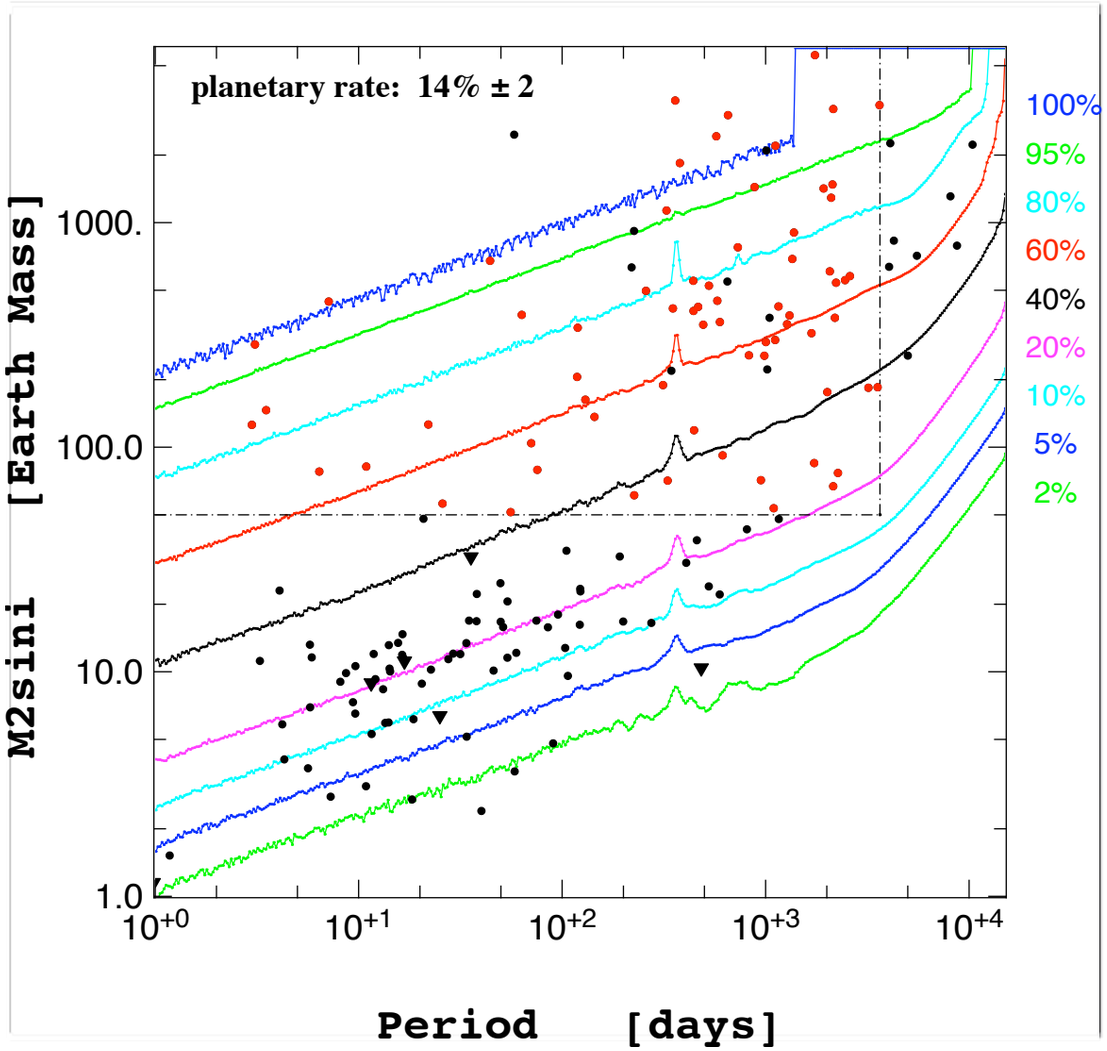
> 70 % of planetary systems
with m2sini< 30 M_{Earth}
include more than one planet

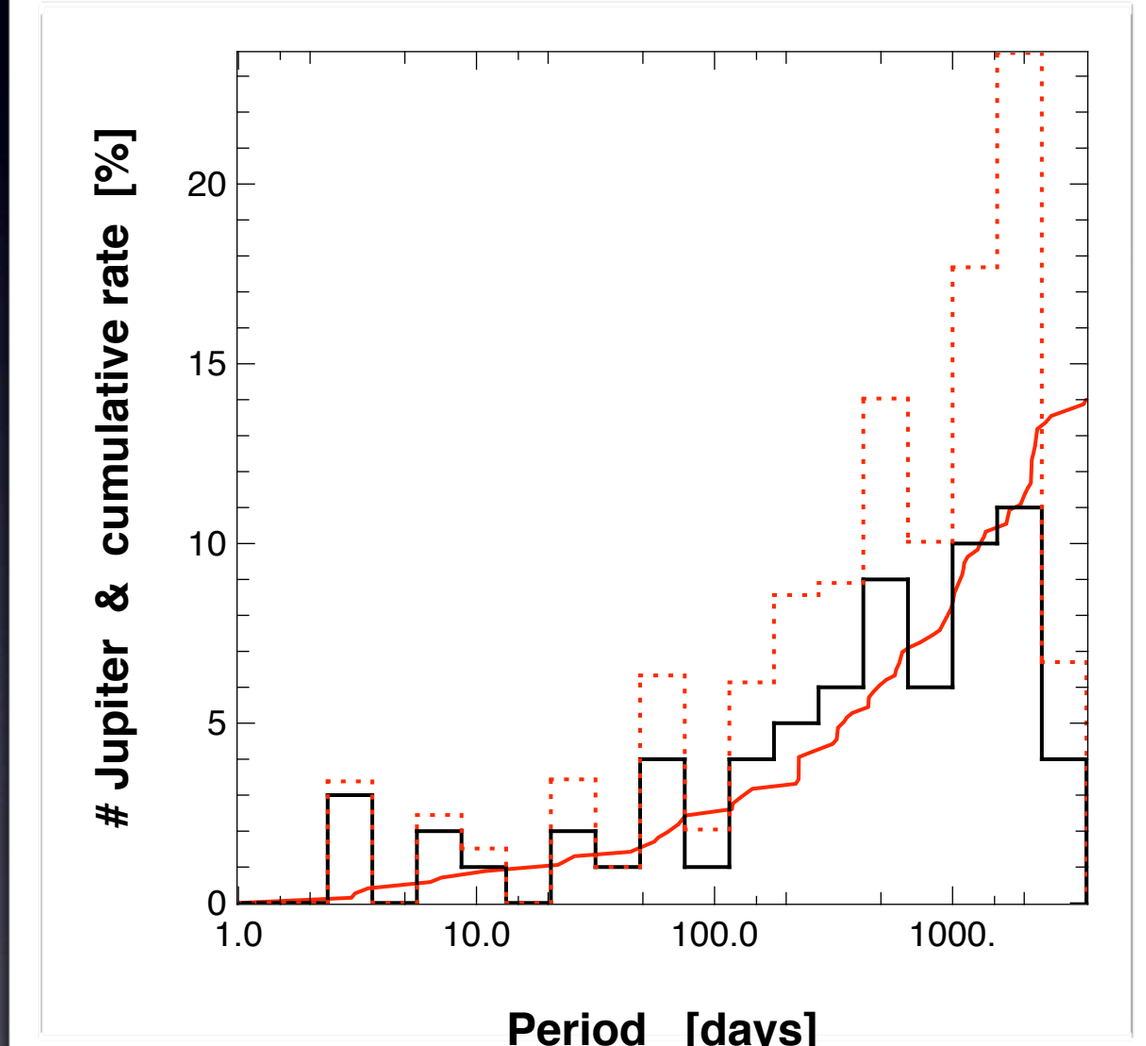
The M2sini - log P plane



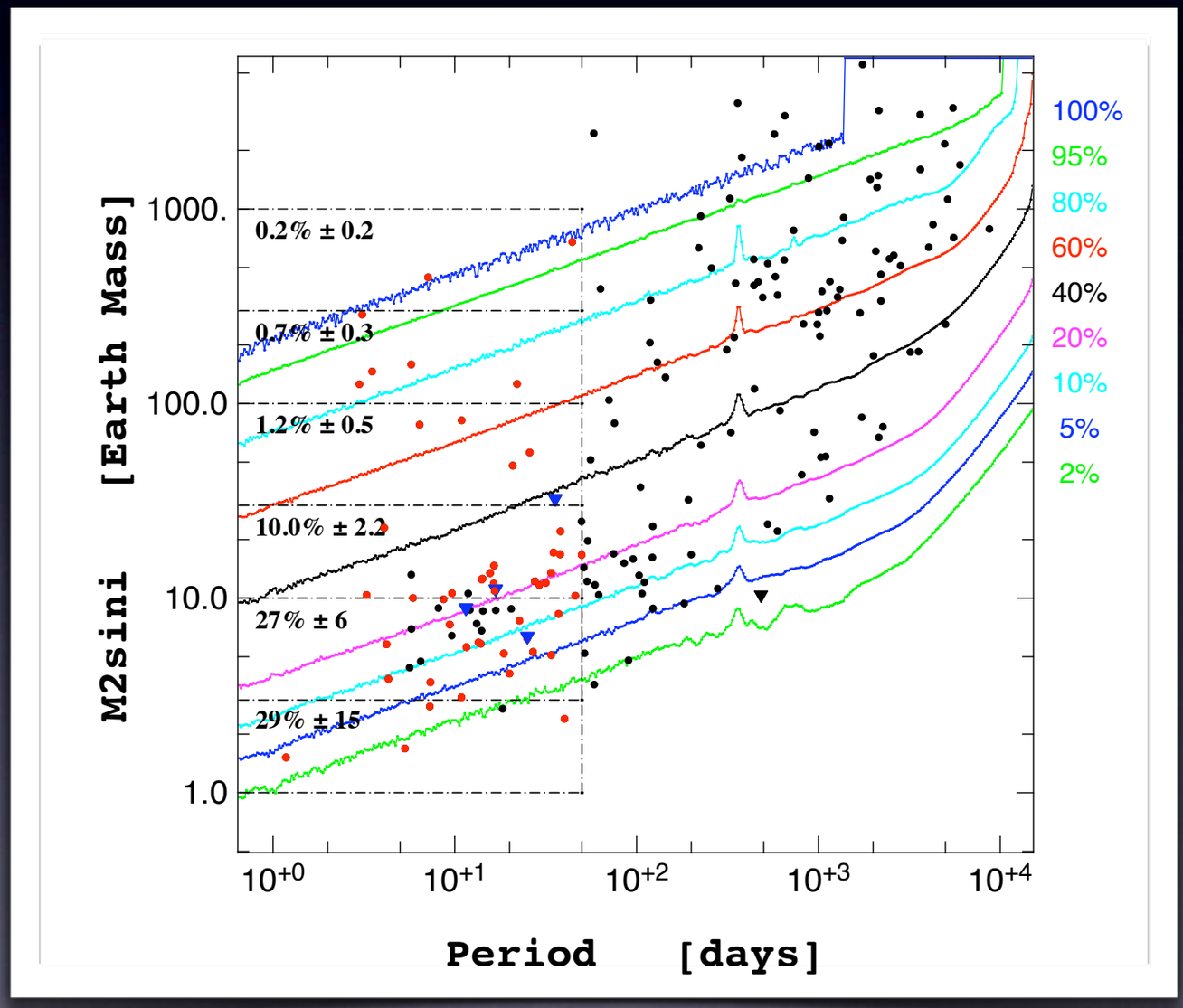


Gaseous giant planets
(Msini > 50 Earth masses)



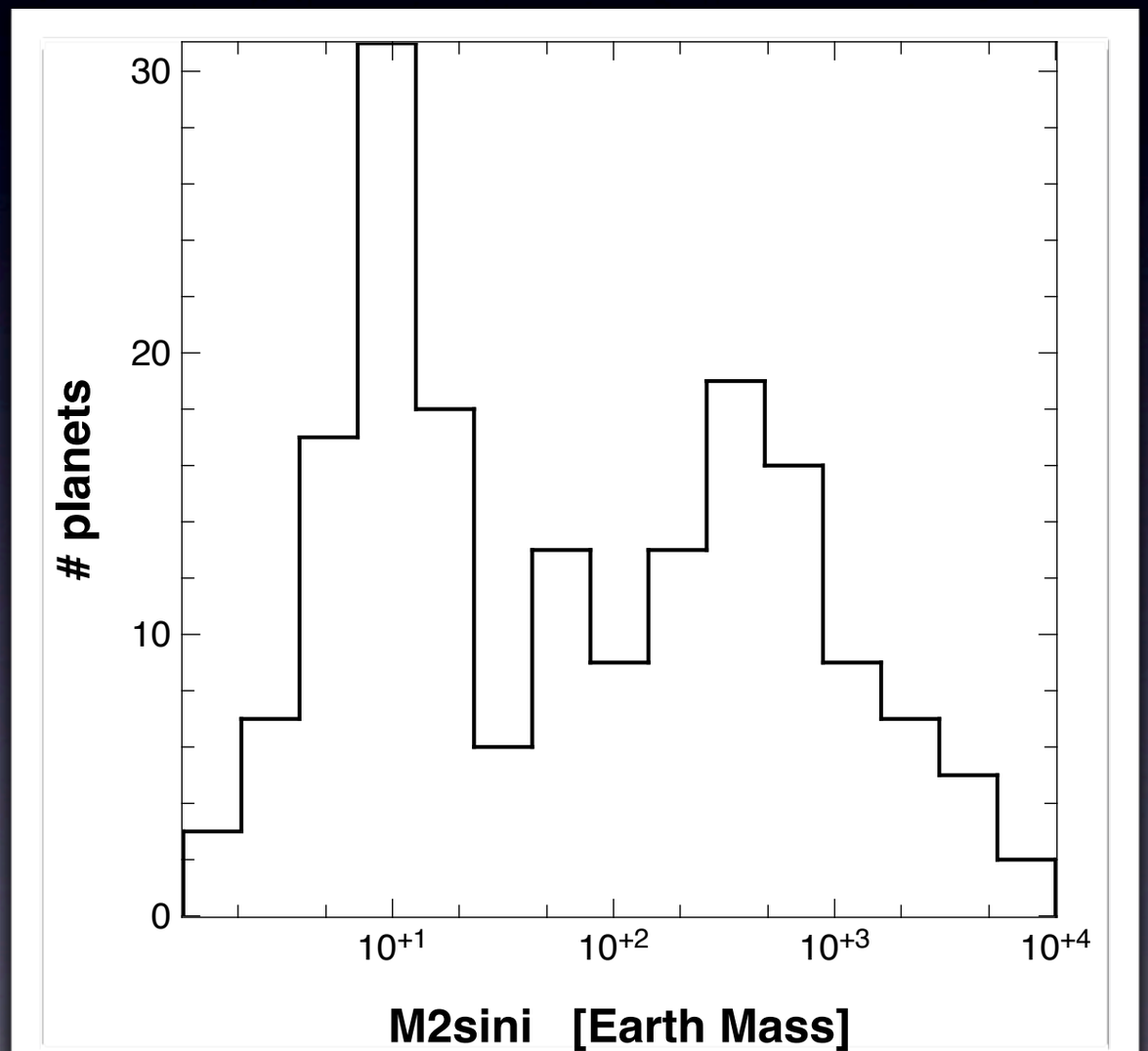


Orbital periods < 50 days

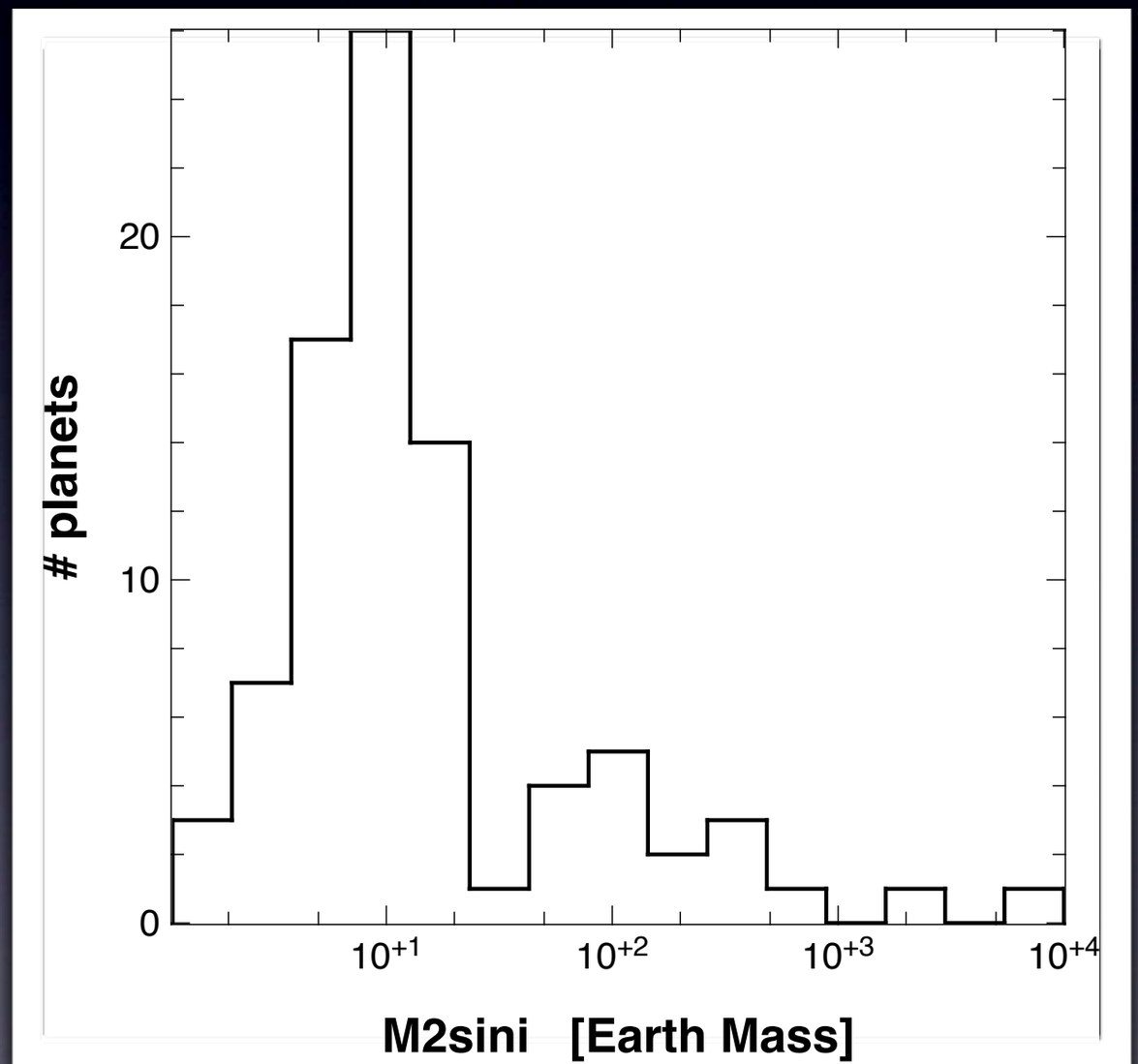


Mass distribution

Detections in the global sample

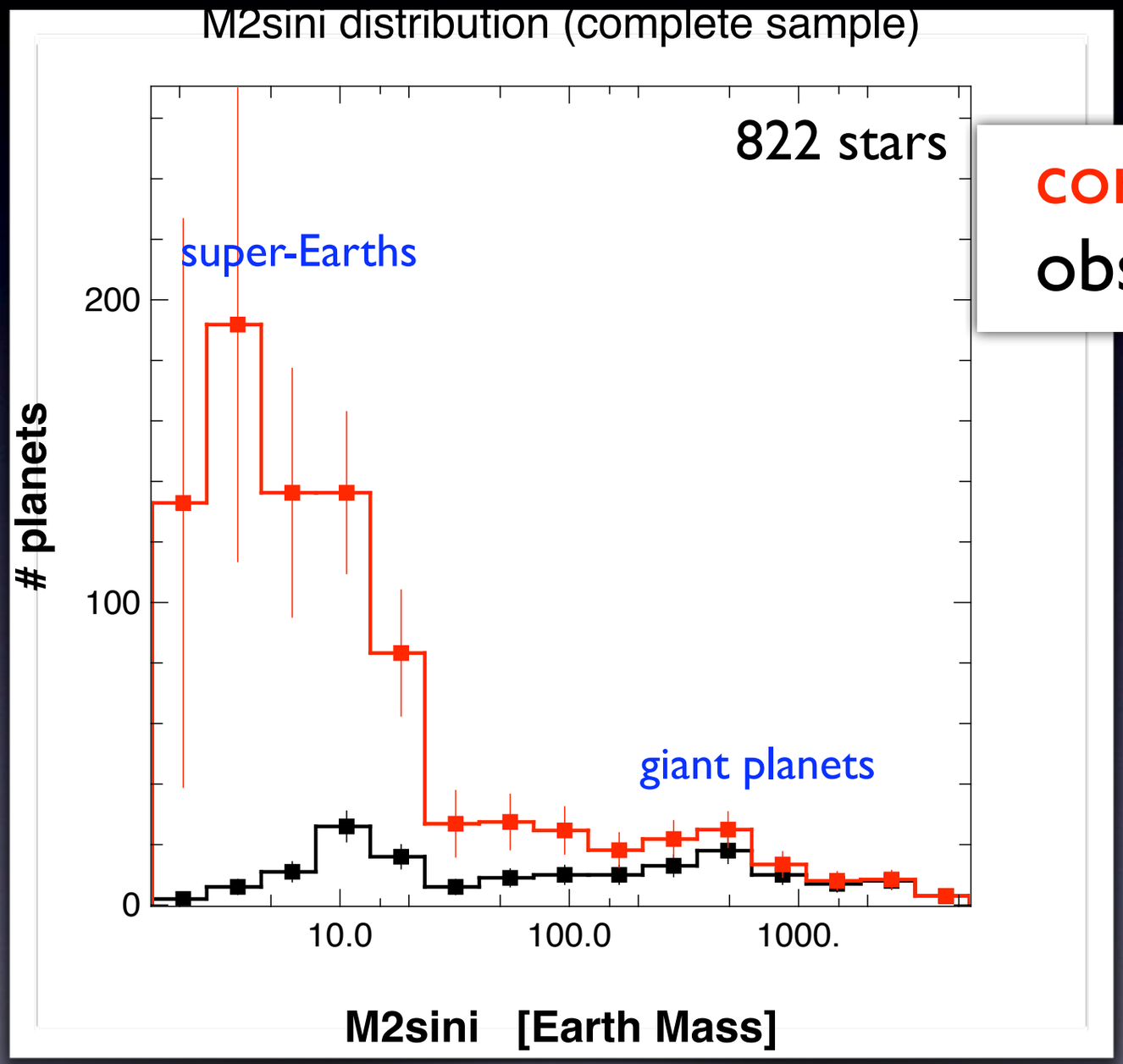


...and for P < 100 days
huge occurence of
planets with m2sin < 30
Earth-masses



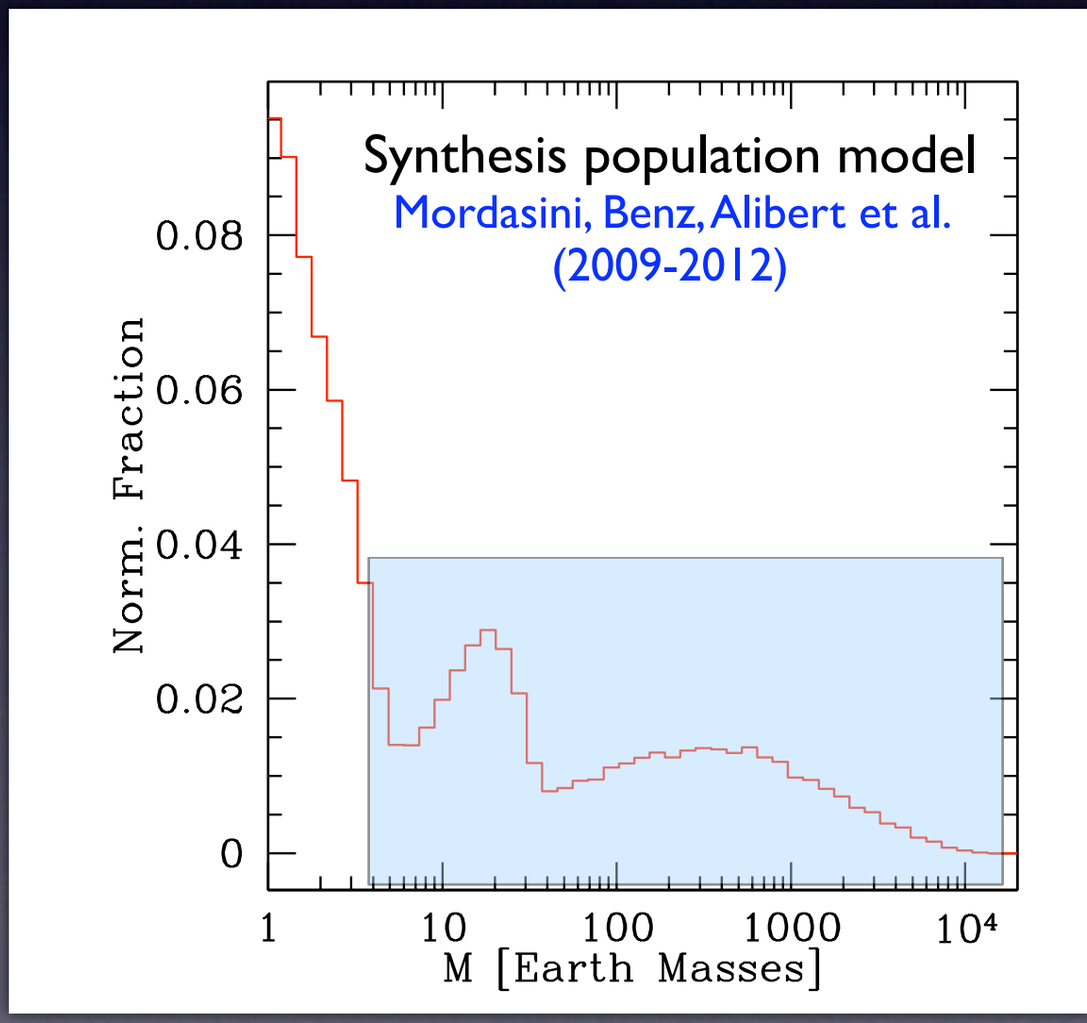
Mass distribution

with incompleteness correction

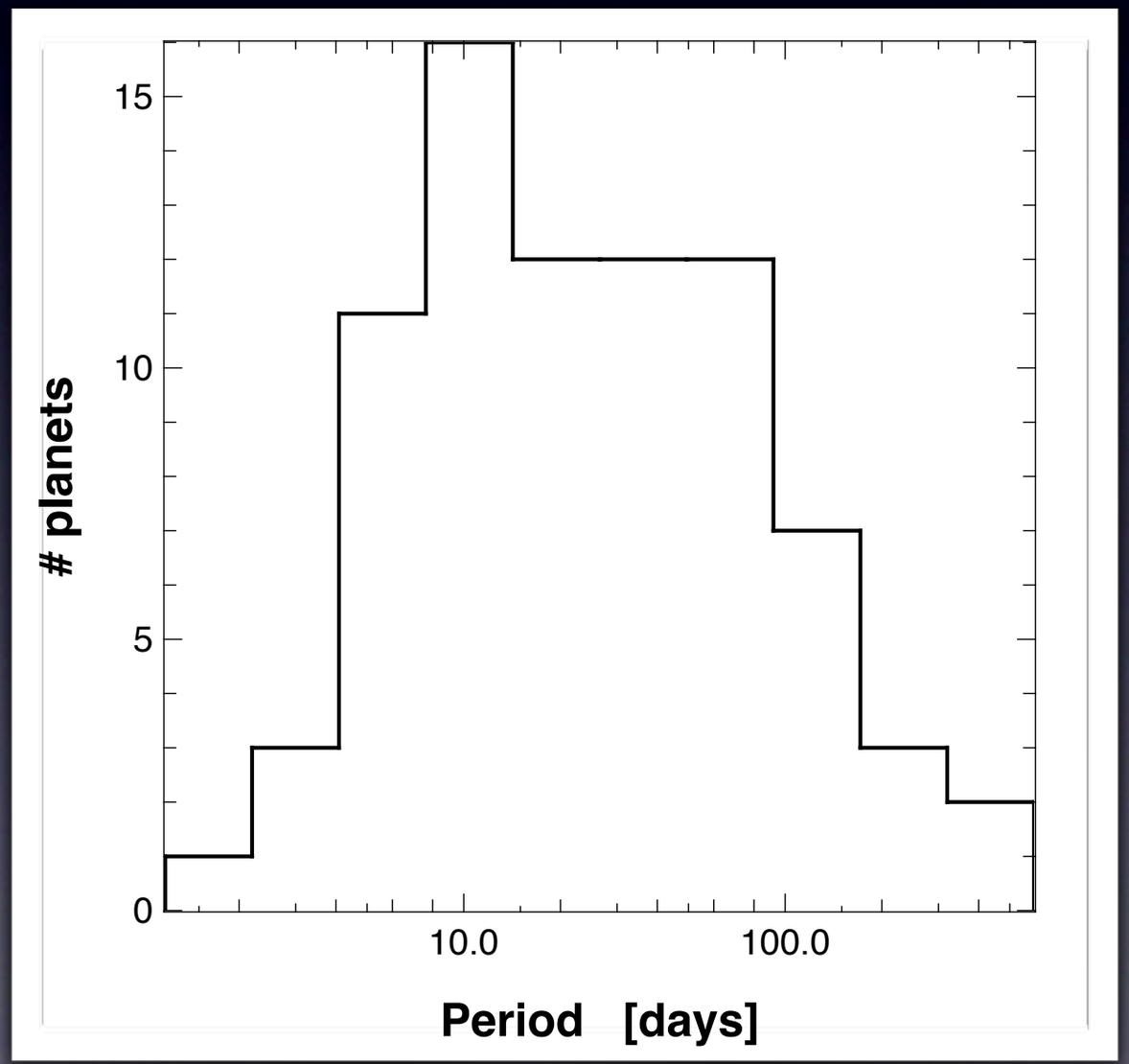


corrected

observed



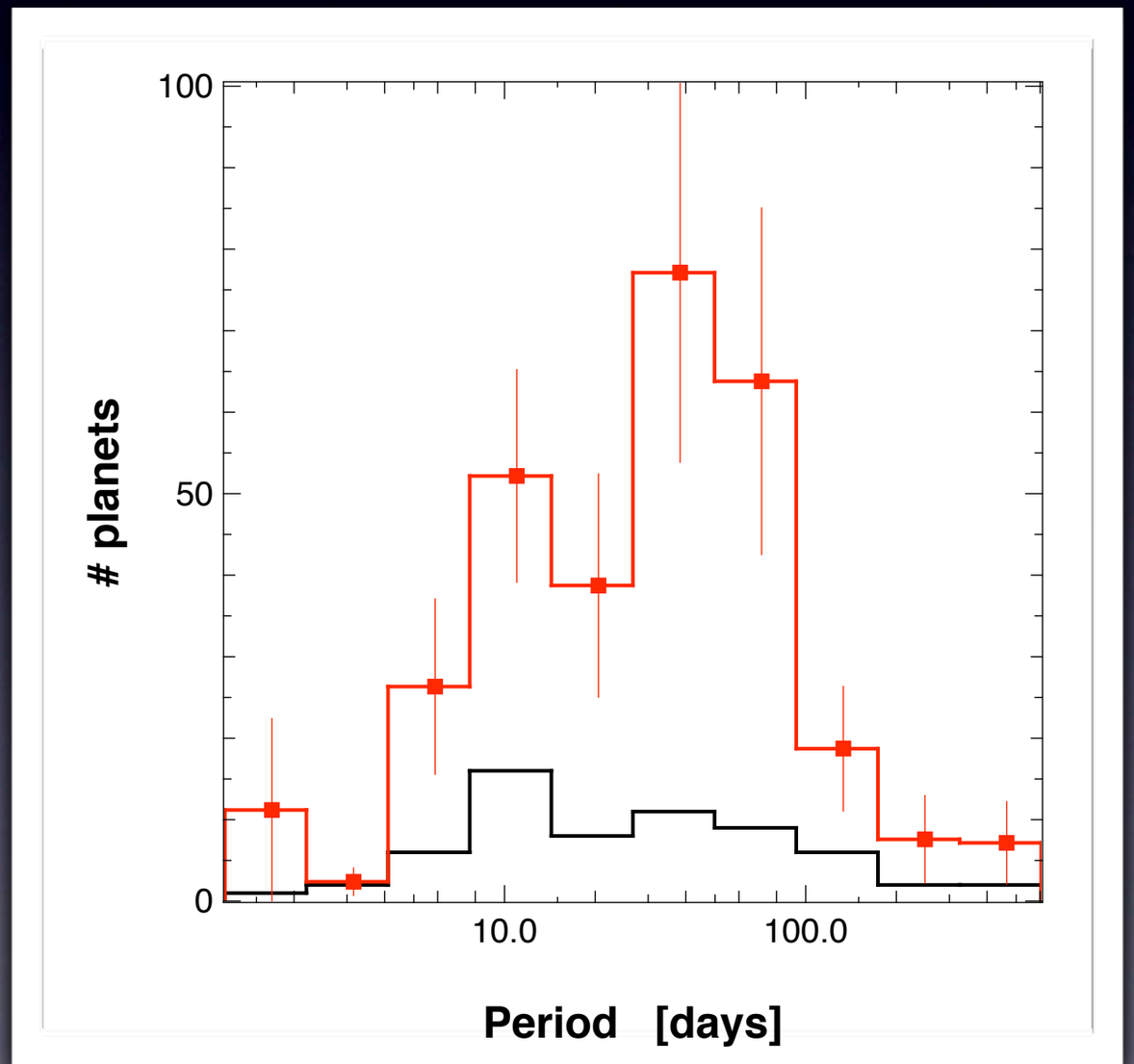
Observed Period distribution for M2sini < 30 Earth-masses



Period distribution

M2sini < 30 Earth-masses

With detection probability correction

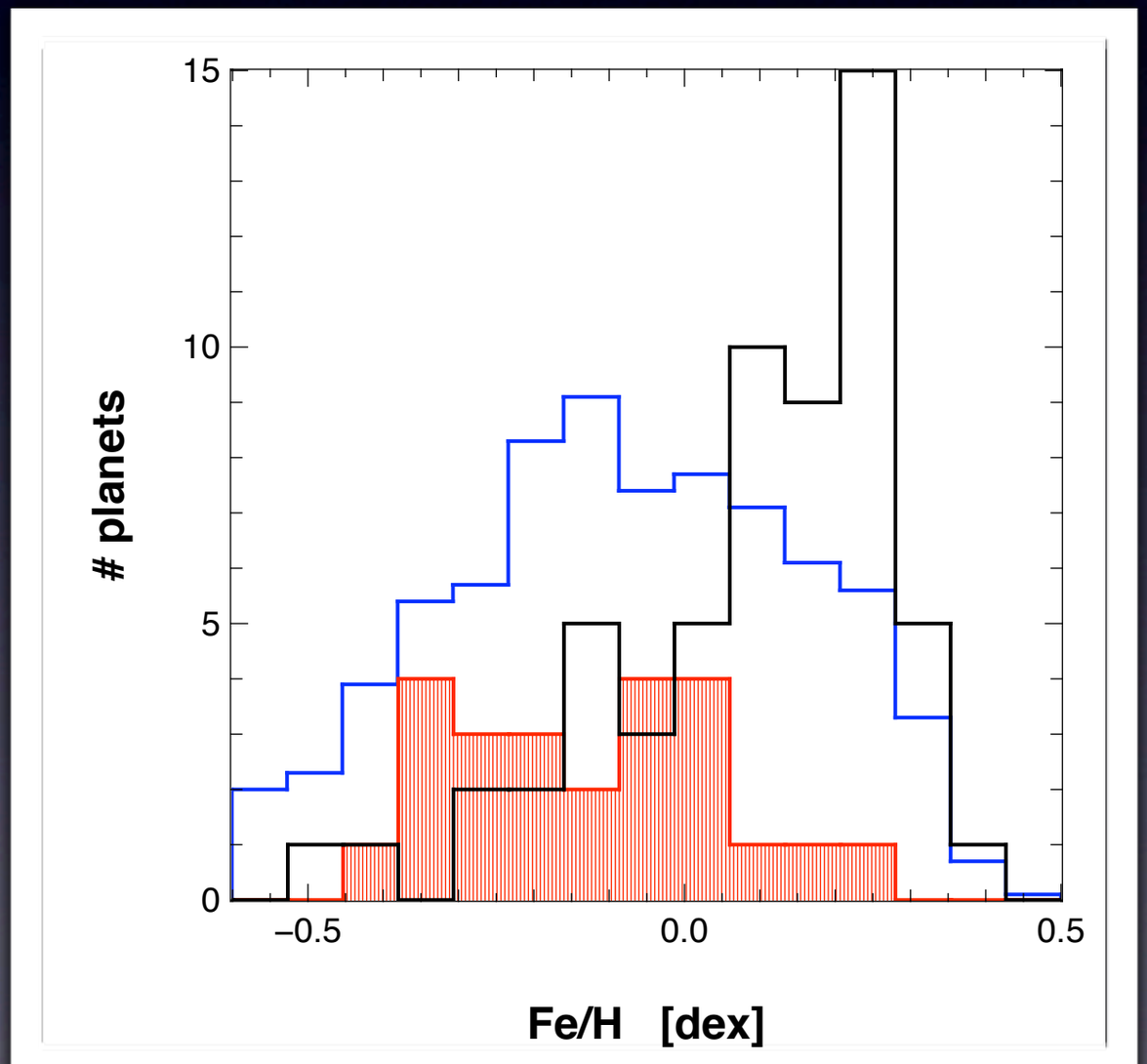


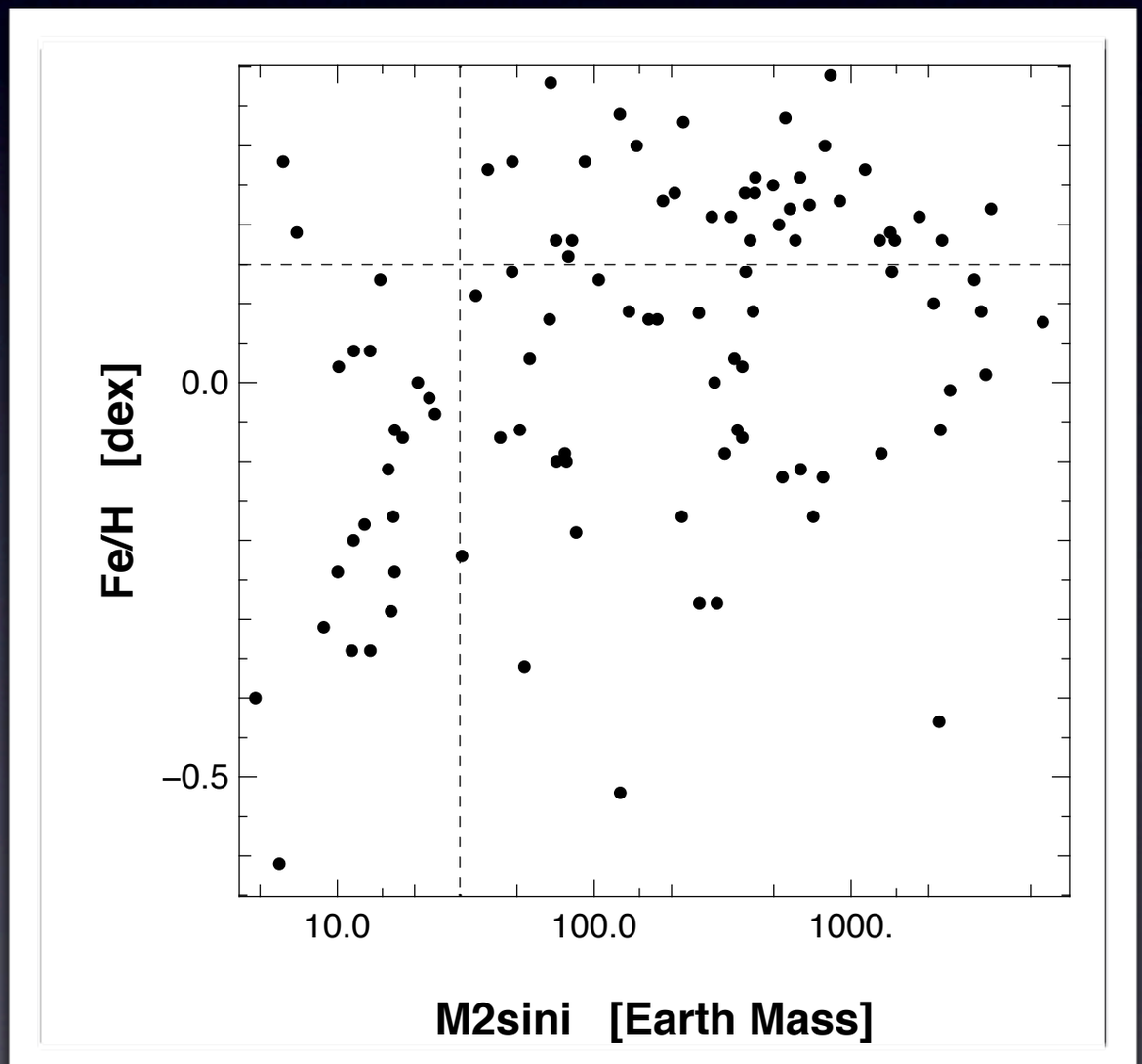
Host star metallicities

Blue : Entire sample

Black : Msini > 50 Earth-masses

Red : Msini < 30 Earth-masses





Two planetary populations with distinct properties
(and well separated in the mass histogramme)

Planetary systems with all masses smaller than 30 Mearth

Multiplicity > 70 %

Frequency not correlated with Fe/H

Frequency decreasing with log P

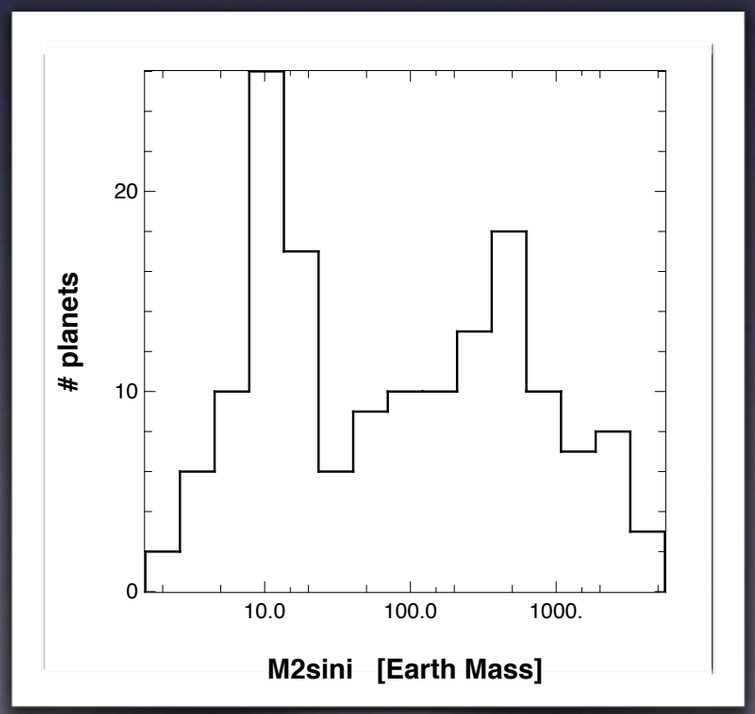
Planetary systems with gaseous giant planets

Multiplicity of about 25%

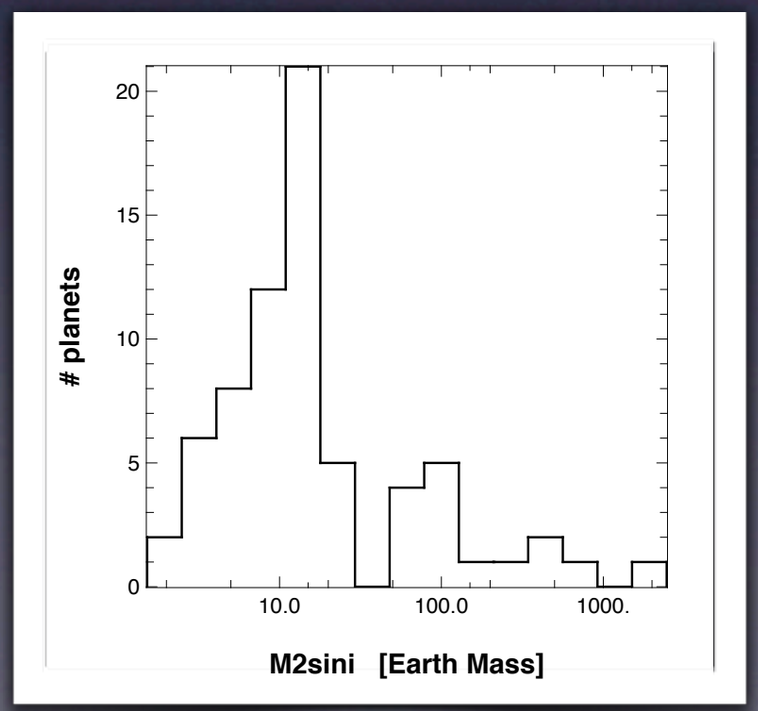
Frequency strongly correlated with Fe/H

Frequency increasing with log P

Detections in the global sample

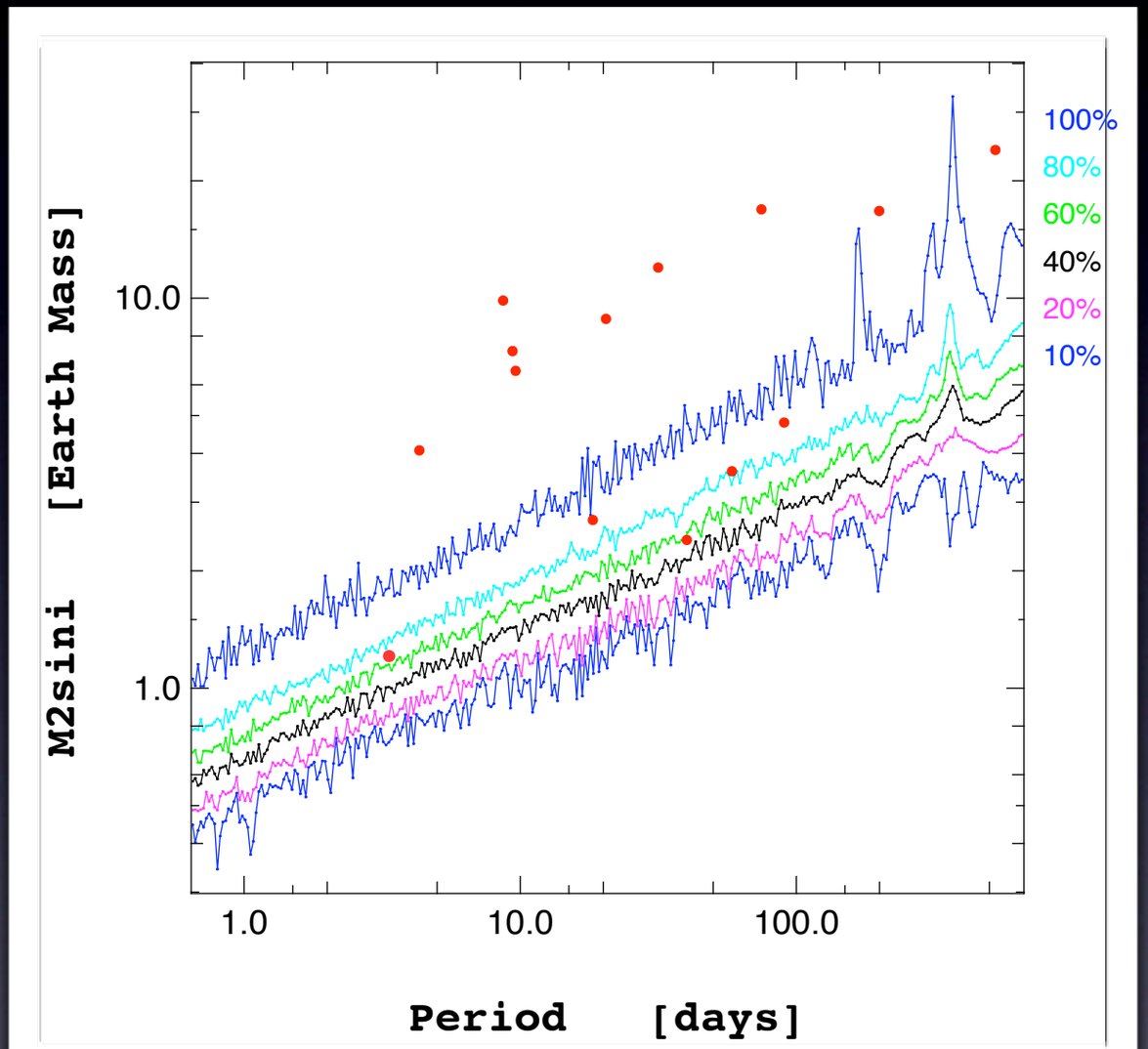


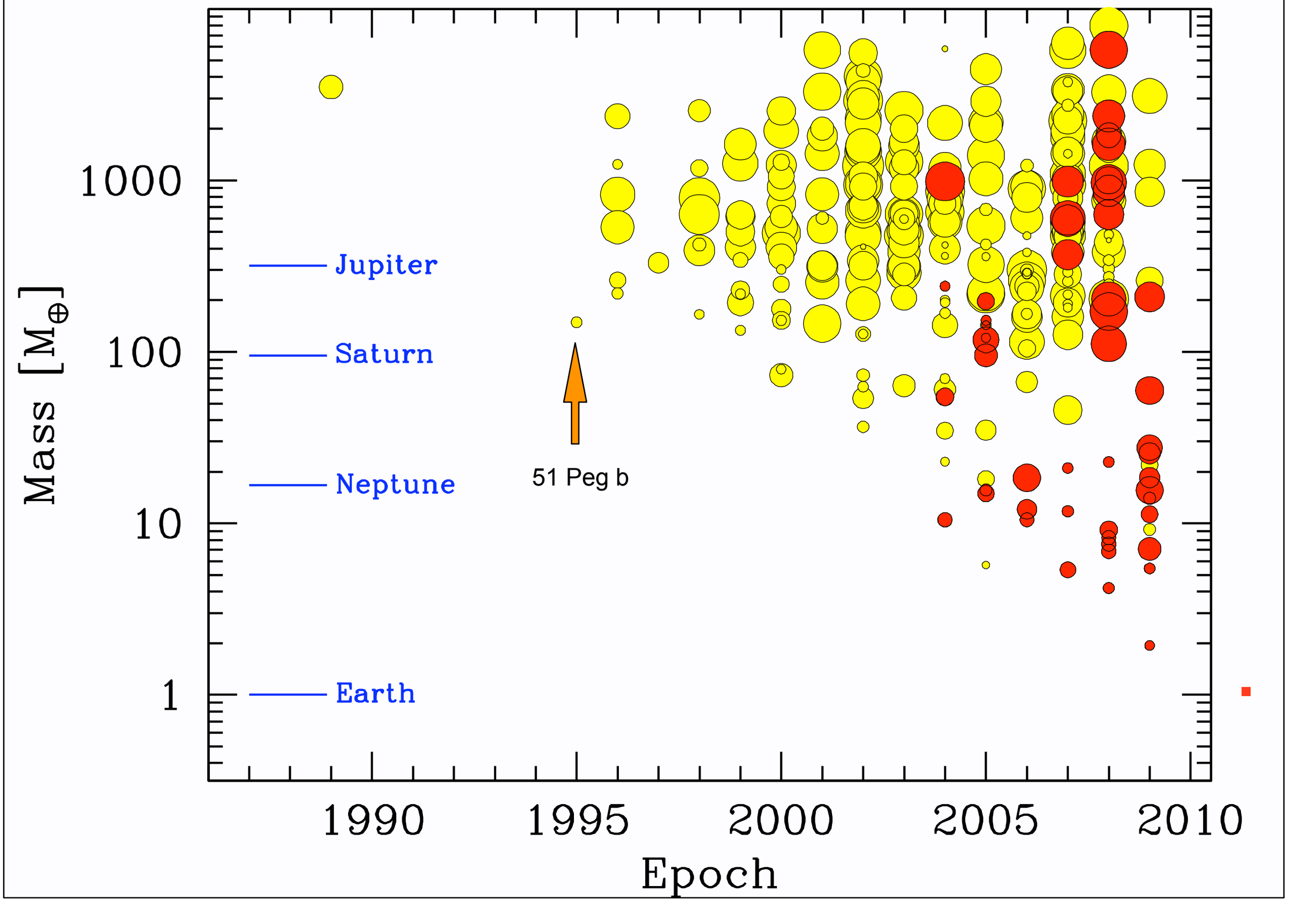
...and for P < 100 days



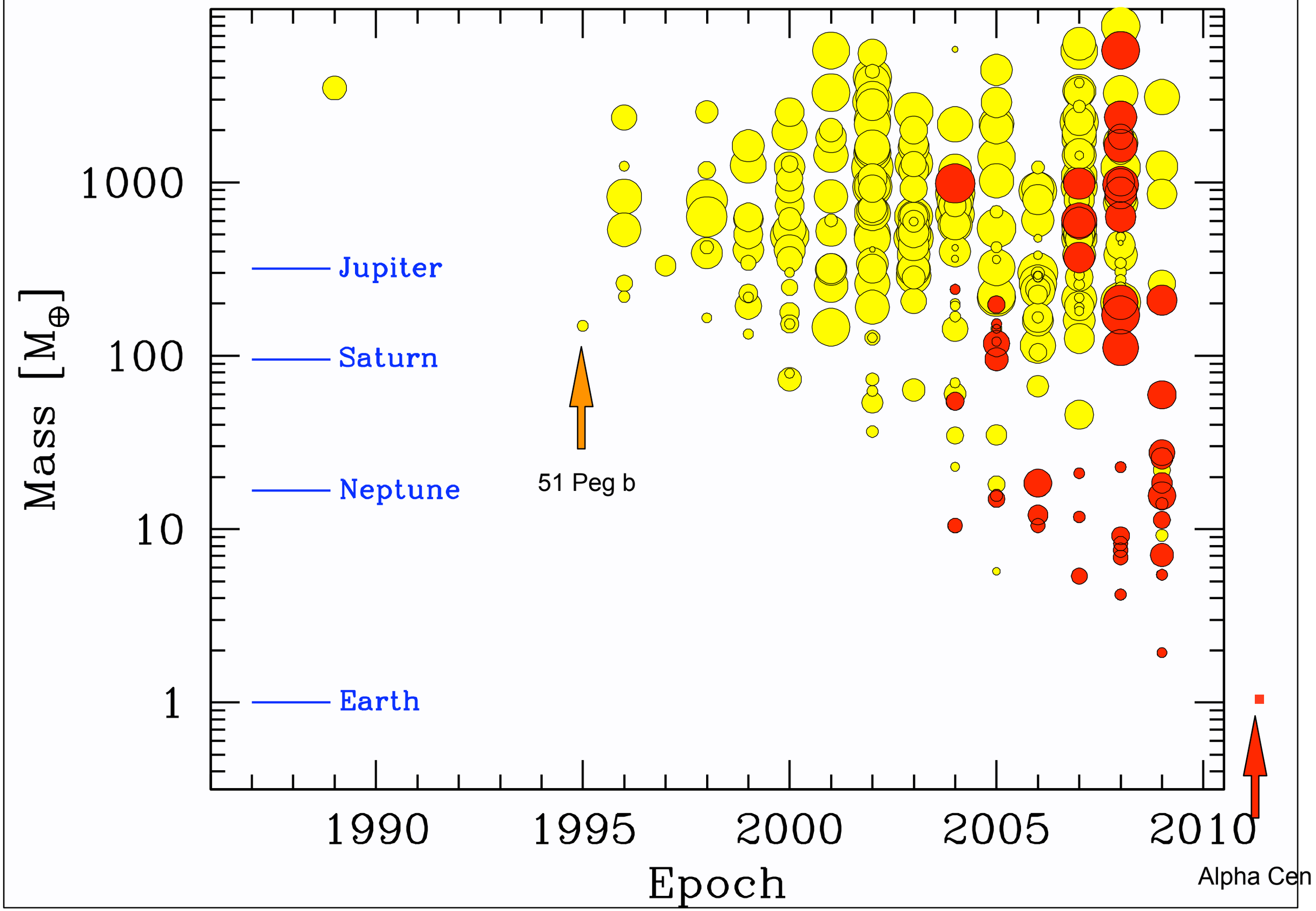
Pushing down the limits

- Detection limits for the 11 stars with the largest number of HARPS measurements (N > 165)
- 16 planets hosted by these 11 stars
- Super-Earths are detectable up to a period of 1 year





Planètes découvertes par spectroscopie Doppler



Planètes découvertes par spectroscopie Doppler

Super-Earths in the Habitable zone

Sun

HD 85512

Pepe et al. 2011

Gliese 581

Udry et al.2007

Mayor et al. 2009

Gl667C b

e b c d

Mass of star (in solar masses)

1

0.1

0.1 1.0 10

Distance from star (AU)

Habitable zone

Possible extension of the habitable zone due to various uncertainties.

Super-Earths in the Habitable zone

Sun

HD 85512

Pepe et al. 2011

Gliese 581

Udry et al.2007

Mayor et al. 2009

Mass of star (in solar masses)

1

0.1

e b c d

Gl667C b

- Super-Earths (3.6 - 8 M_{Earth})
- Missing radius
  -> no composition information
  -> habitability?

Habitable zone

Possible extension of the habitable zone due to various uncertainties.

0.1 1.0 10

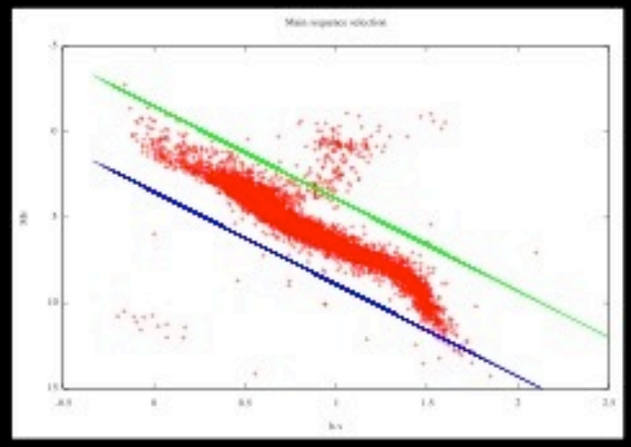
Distance from star (AU)

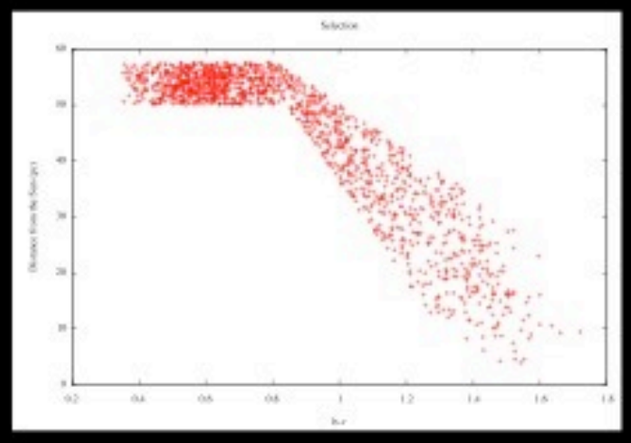
A volume limited sample :
Toward a better statistics of gaseous giant stars.

G.Locurto, W.Benz, F.Bouchy, G.Hébrard, C.Lovis, M.Mayor, C.Moutou, D.Naef, F.Pepe, D.Queloz, N.C.Santos, D.Segransan, S.Udry

The sample selection

- HIPPARCOS catalog
- F2-M0 spectral types
- Main sequence stars
- Declination < 0
- 50 pc < dist. < 57.5 pc
- Complement to the CORALIE sample

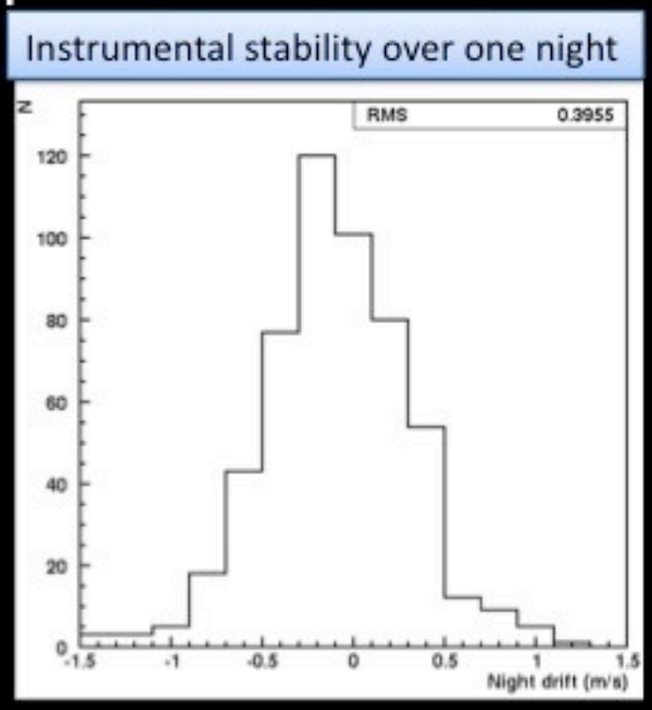




1

Observing strategy

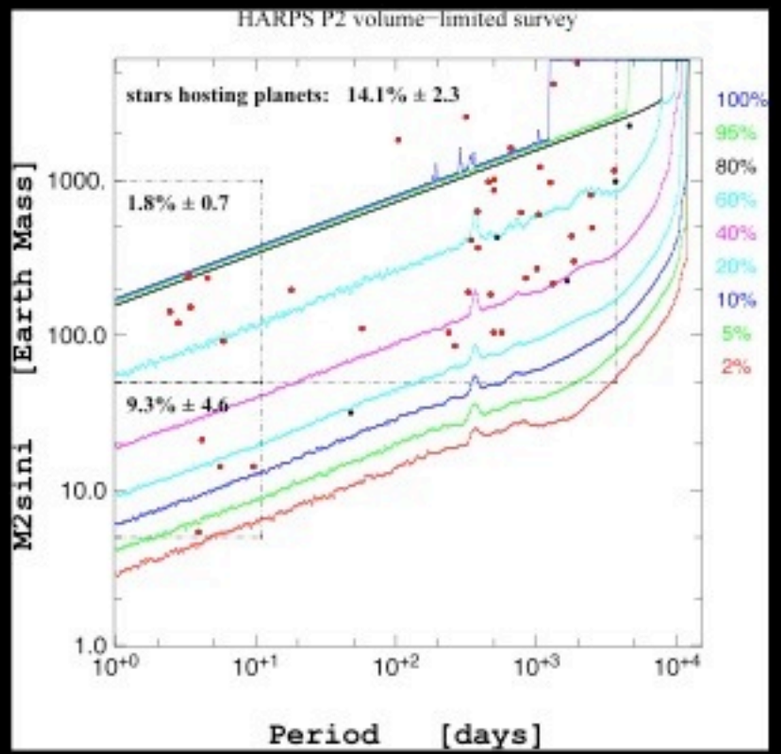
- Limit to 2-3m/s RV precision
- S/N ~ 40 (@ 550nm)
- No simult. Th-Ar reference
  - Night drift is low:
    - drift<0.5m/s : 83%
    - drift<1.0m/s : 98%
- Single exposures
- Telescope time ~8'/exp.
- Follow up if RV varying over 5m/s



Main results from the survey so far

RV drifts (long period planets ?) => 57

Confirmed orbits => 48
- Stars => 1
- Brown dwarfs => 2
- Planets => 45
  - in multiple systems => 13 (29%)
  - Super-Earth => 2
  - Neptun mass planet => 5
  - Jupiters (M>0.1MJ) => 38



All super-Earth and 4 out of 5 Neptune mass Planets are in multiple systems.

Eccentiricity is on average higher in multi-planet systems.

Stars hosting Jupiter mass planets are metal rich

One Neptune-mass planet in the habitable zone of a K7 dwarf (paper submitted).

The HARPS Search for Southern Extra-Solar Planets
The M-dwarf sample

X. BONFILS, 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

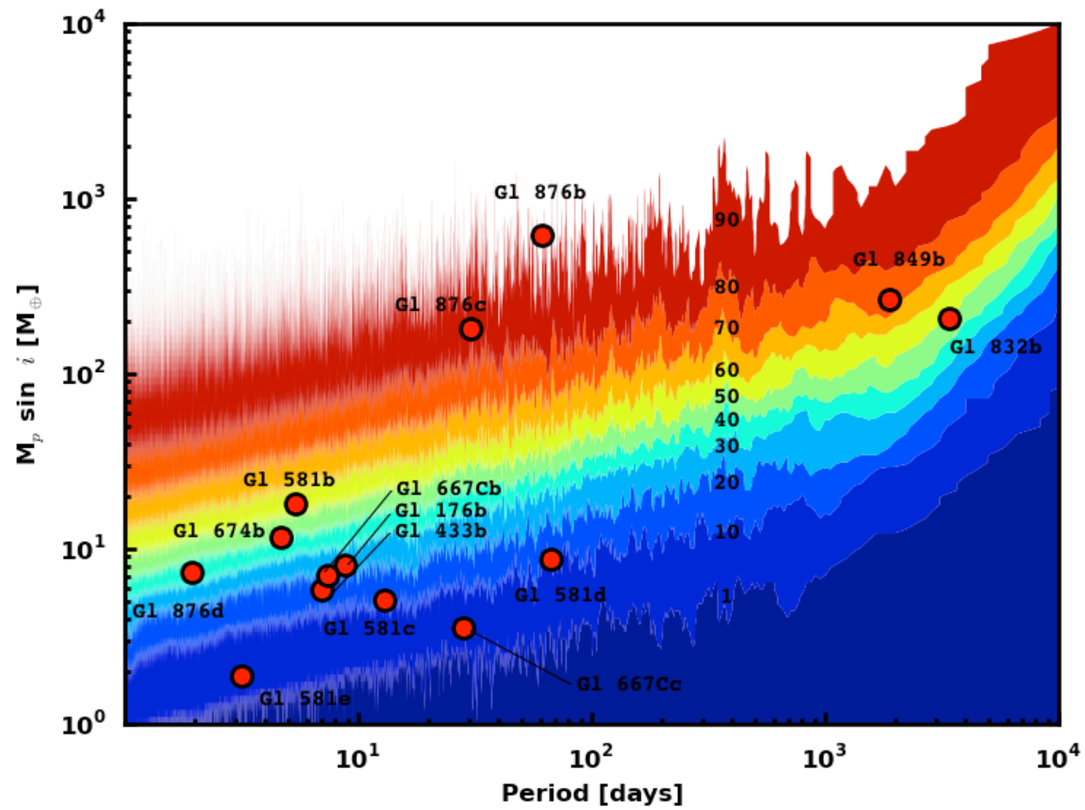
Sample:
~400 brightest M dwarfs

Highlights:
- 90% of M-dwarfs planets w/ $m \sin i < 20$ Mearth
- lowest-mass planets (GJ 581e; $m \sin i$ = 1.9 Mearth)
- first possibly habitable planets :
  GJ 581 c&d, GJ667Cc, GJ163c
- a transiting Uranus-like exoplanet (GJ3470b)
- statistical results :
  - few Jupiter-mass planets

$$f < 1\% \quad \text{for} \quad 1 < P < 10 \text{ day}$$
$$f = 0.02^{+0.03}_{-0.01} \quad \text{for} \quad 10 < P < 100 \text{ day}$$

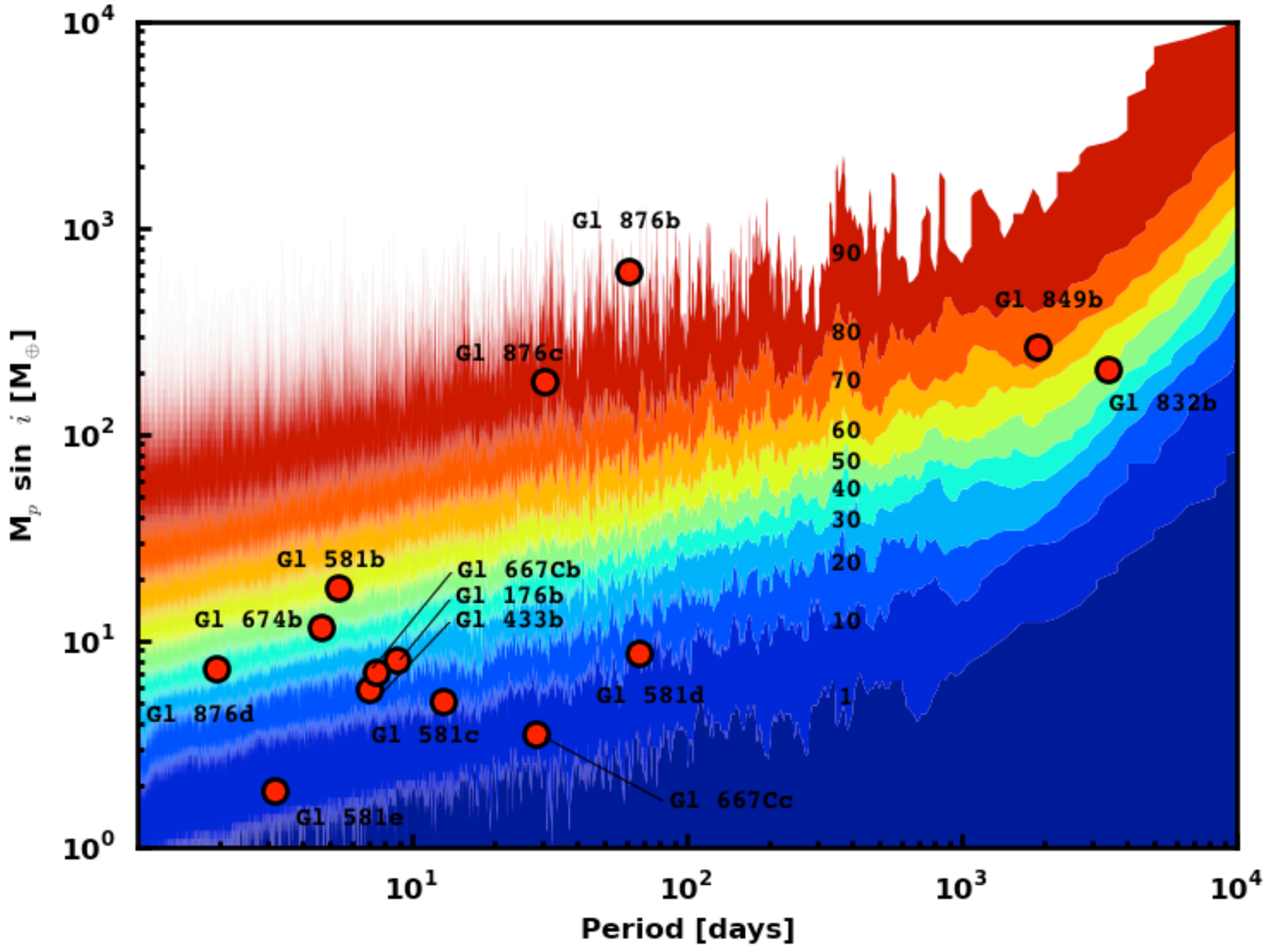
  - super-Earth are common (>30%)

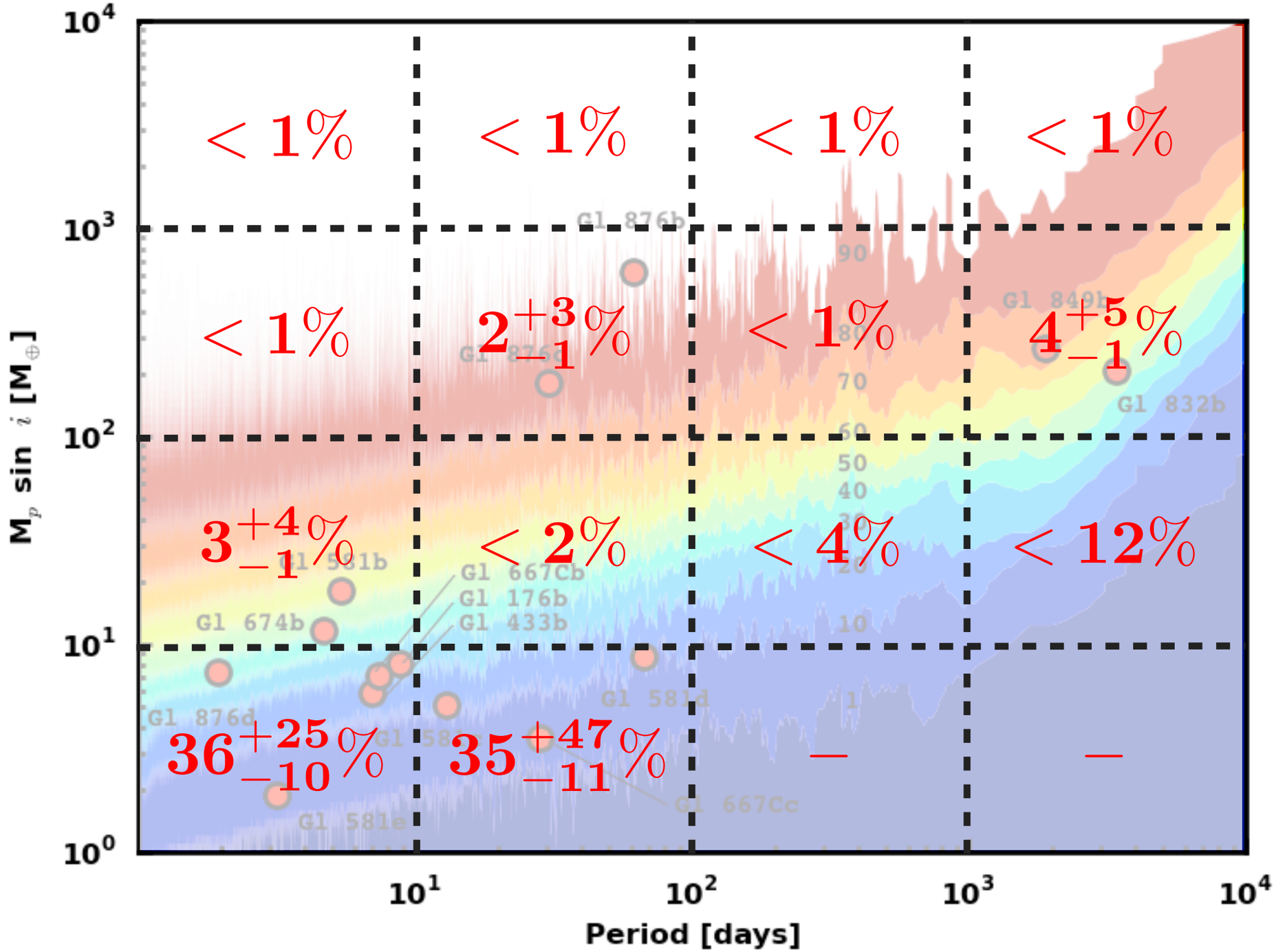
$$f = 0.36^{+0.25}_{-0.10} \quad \text{for} \quad 1 < P < 10 \text{ day}$$
$$f = 0.52^{+0.50}_{-0.16} \quad \text{for} \quad 10 < P < 100 \text{ day}$$



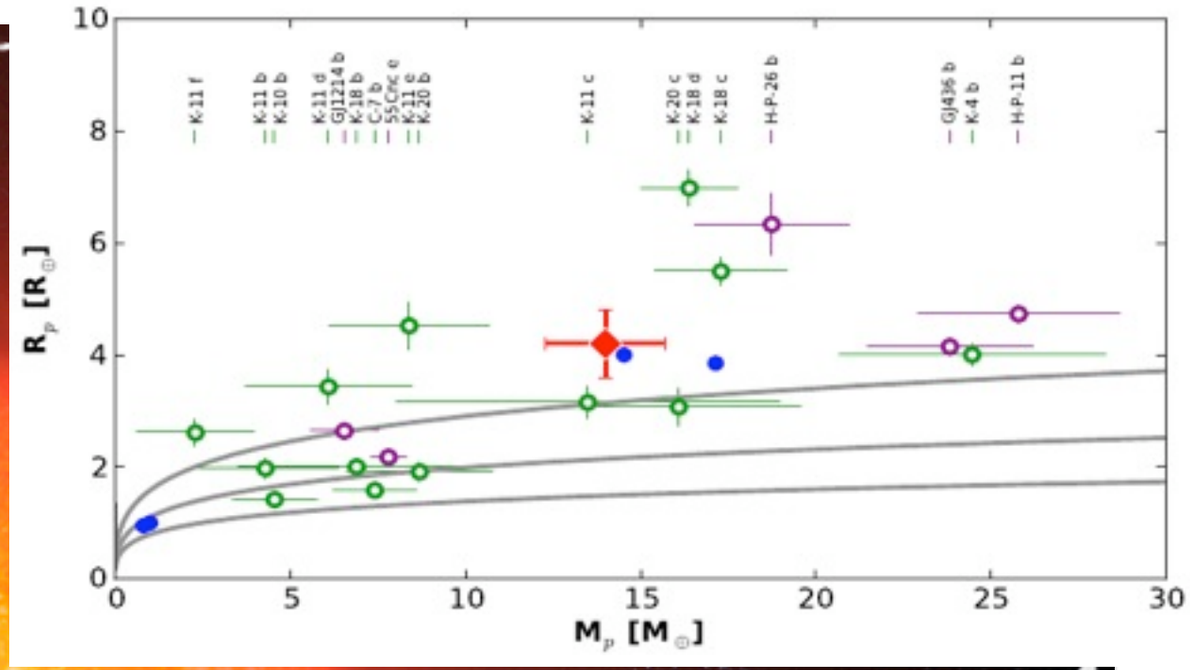
$$\eta_\oplus = 0.41^{+0.54}_{-0.13}$$

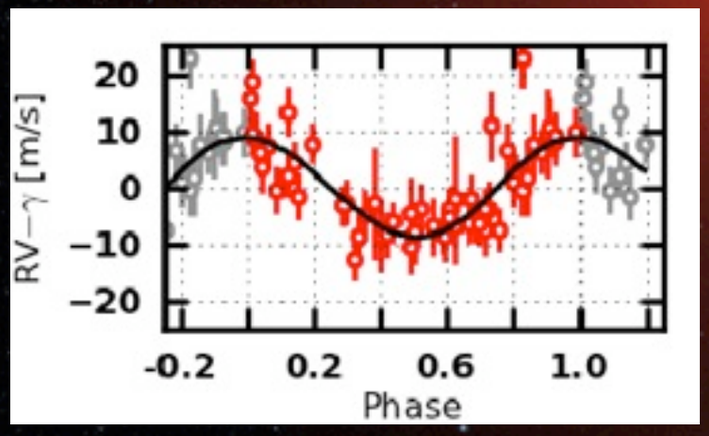
(a direct measure)

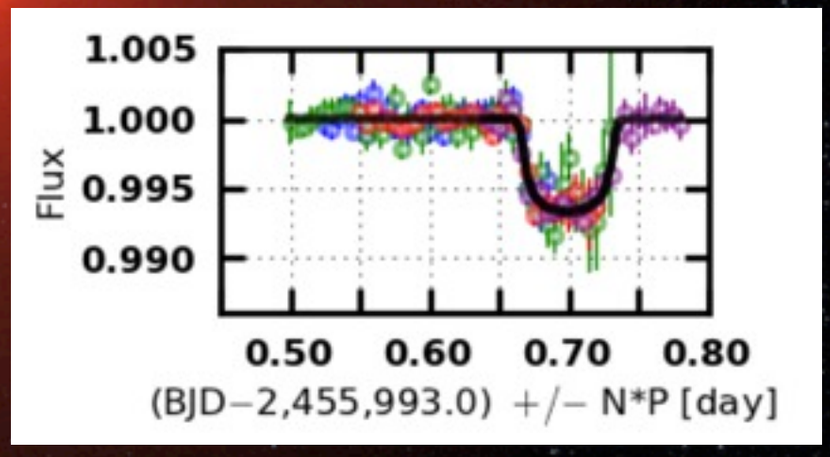

10^4
10^3
10^2
10^1
10^0
$M_p \sin i$ [$M_\oplus$]
Gl 876b
Gl 876c
Gl 849b
Gl 832b
Gl 581b
Gl 667Cb
Gl 176b
Gl 433b
Gl 674b
Gl 581d
Gl 876d
Gl 581c
Gl 667Cc
Gl 581e
90
80
70
60
50
40
30
20
10
1
10^1
10^2
10^3
10^4
Period [days]


$< 1\%$
$< 1\%$
$< 1\%$
$< 1\%$
$< 1\%$
$2^{+3}_{-1}\%$
$< 1\%$
$4^{+5}_{-1}\%$
$3^{+4}_{-1}\%$
$< 2\%$
$< 4\%$
$< 12\%$
$36^{+25}_{-10}\%$
$35^{+47}_{-11}\%$
—
—
Gl 876b
Gl 849b
Gl 832b
Gl 581b
Gl 667Cb
Gl 176b
Gl 433b
Gl 674b
Gl 876d
Gl 581d
Gl 581c
Gl 667Cc
Gl 581e
90
80
70
60
50
40
30
20
10
1
10^4
10^3
10^2
10^1
10^0
$M_p \sin i$ [$M_\oplus$]
10^1
10^2
10^3
10^4
Period [days]

GJ3470b







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

The HARPS Search for Southern Extra-Solar Planets
The metal-deficient sample

N.Santos et al.

Sample:

~100 FGK dwarfs with -0.5<[Fe/H]<-2.0

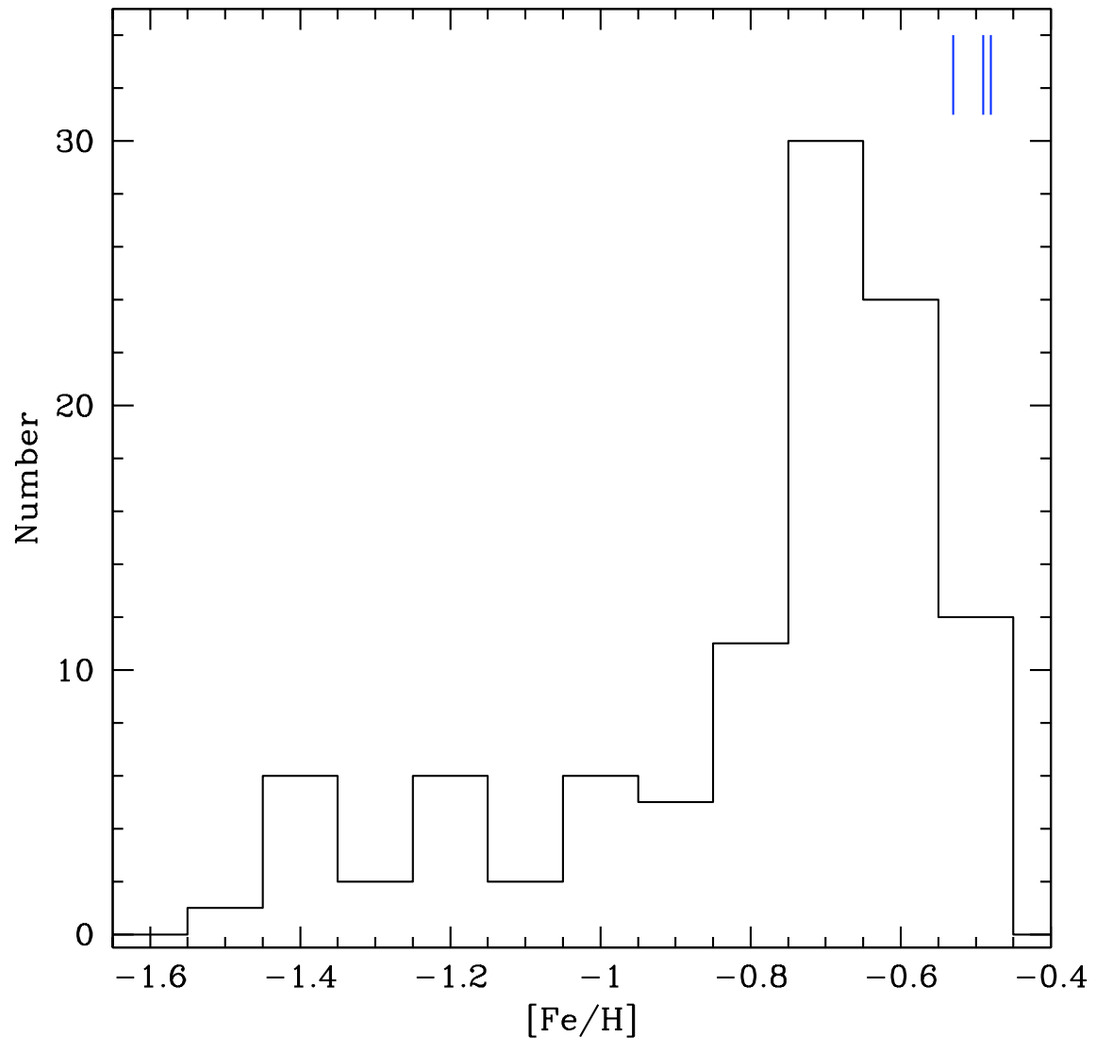
Goal:

Study giant planet frequency in metal-poor domain

Results:

- 3 new giant planets in long period (P>1.5 yr) orbits (HD171028b, HD181720b, HD190984b)
- One more published candidate (HD107094)
- Lower frequency rate than solar-metallicity stars
- But: long period giant planets are not rare around moderately metal-poor stars
- Still: all planets in metal-rich tail of the sample

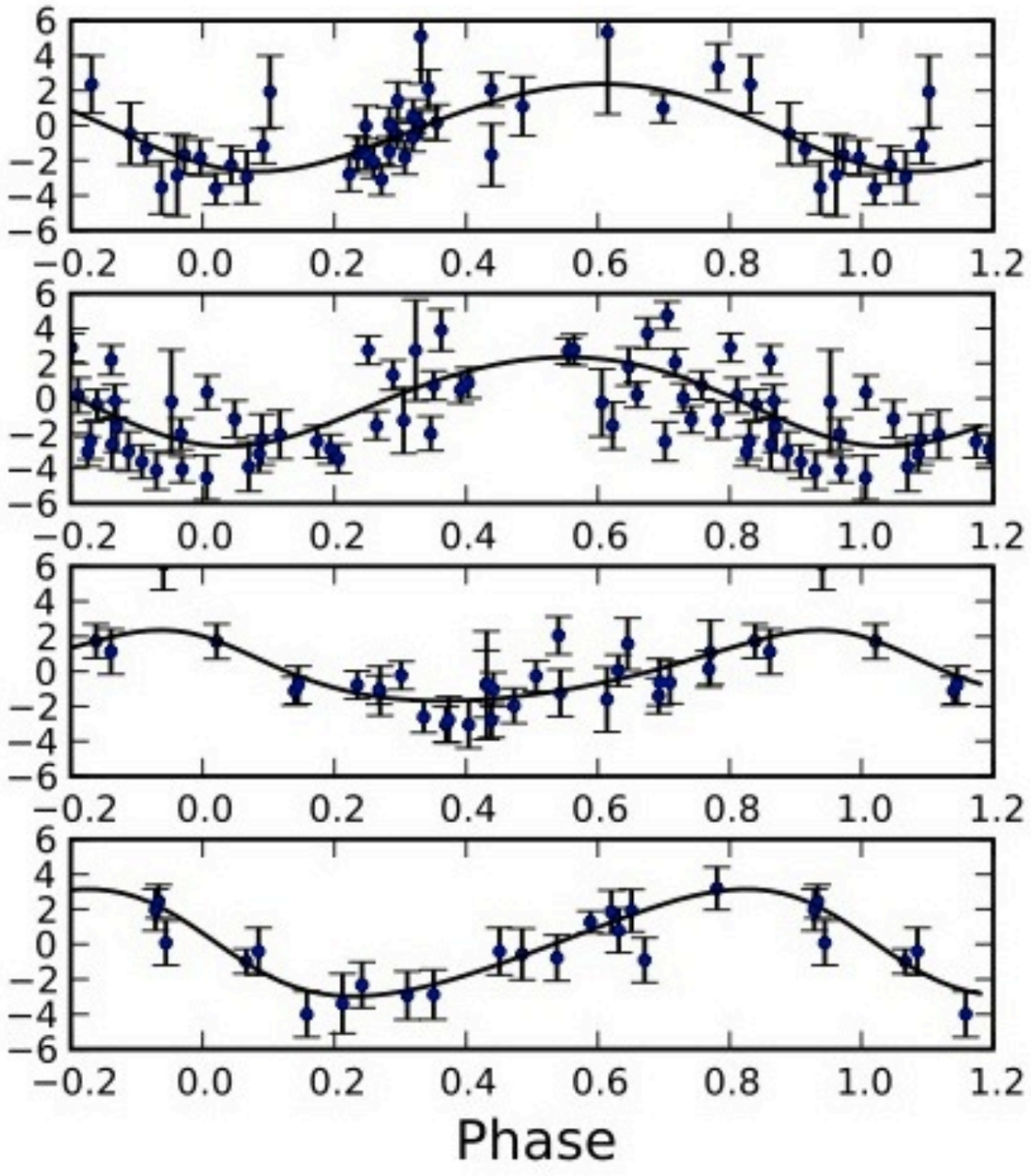
Santos et al. (2011); Mortier et al. (2012)



The HARPS Search for Southern Extra-Solar Planets
The metal-deficient sample

Future (now):

- Extend study to incidence of Neptunes/ Super-Earths around moderately metal-poor stars
- Large program with HARPS now running
- ~100 stars at very high precision
- Complementary study with HARPS-N
- Several very low mass candidates start to appear
- Further test planet formation models



Northern Hemisphere possible programmes

- A good statistics of Neptune mass planets orbiting metal deficient stars. (northern counterpart of Santos'one) .... request a significant nb of nights.
- Improve the lower limit for host star metallicity for the formation of gaseous giant planets.(id)
- Detection of very low mass planets orbiting solar-type stars (northern counterpart of Pepe's one). ... request a significant nb of nights and a control of the RV precision on weeks-months-years.
- RV follow-up of gaseous giant planet transits detected by WASP (or similar surveys)

Northern Hemisphere possible programmes ... but with some difficulties

- Detection of planets orbiting evolved stars.
  Already several existing programmes .
- Rossiter-McLaughlin effect : need a spectrograph with a good efficiency on a not too small telescope. (maybe some possibilities taking into account the delta-longitude with Mt Abu)
- Search for low mass planets hosted by stars already known to have gaseous giant planets.