
Extra-solar planets
The HARPS GTO Legacy
Current census of the low-mass planet population
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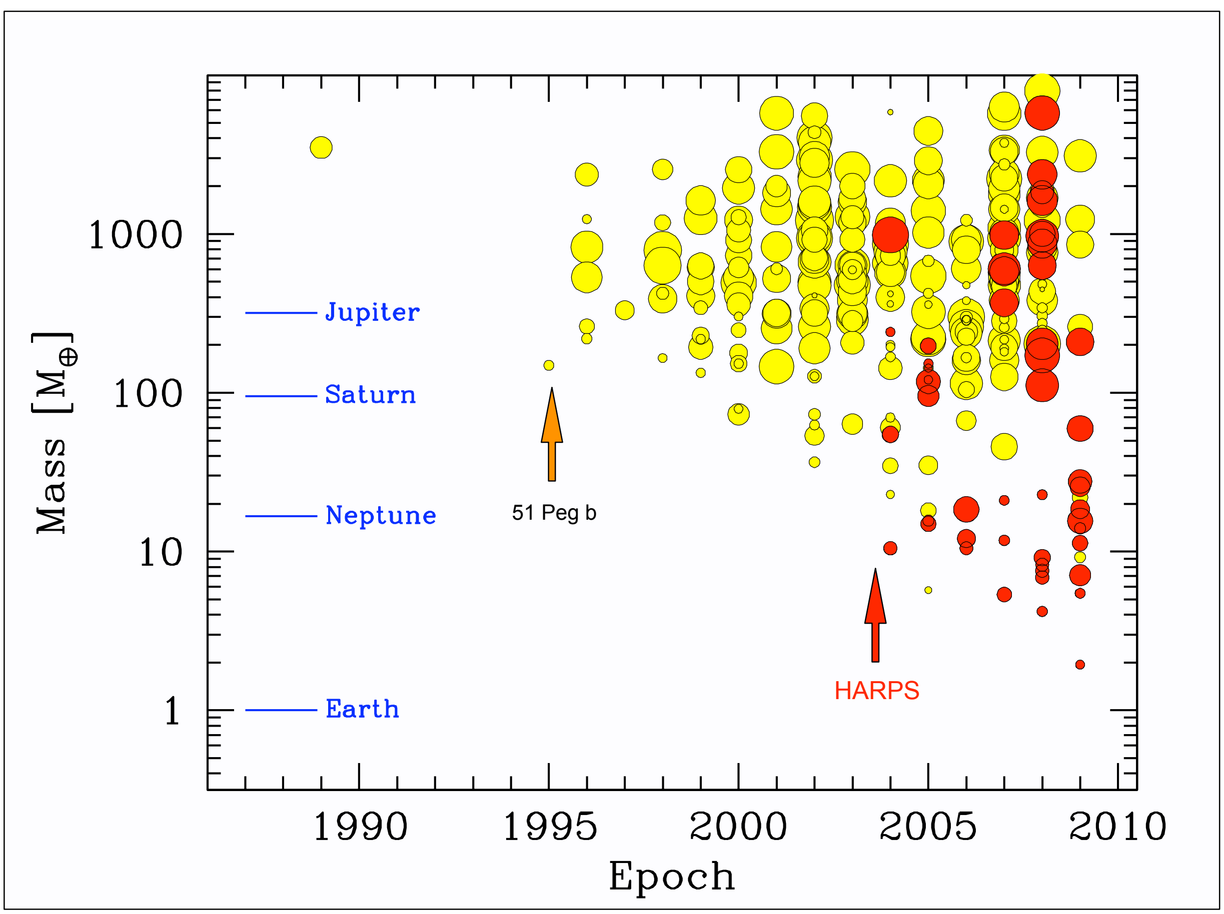
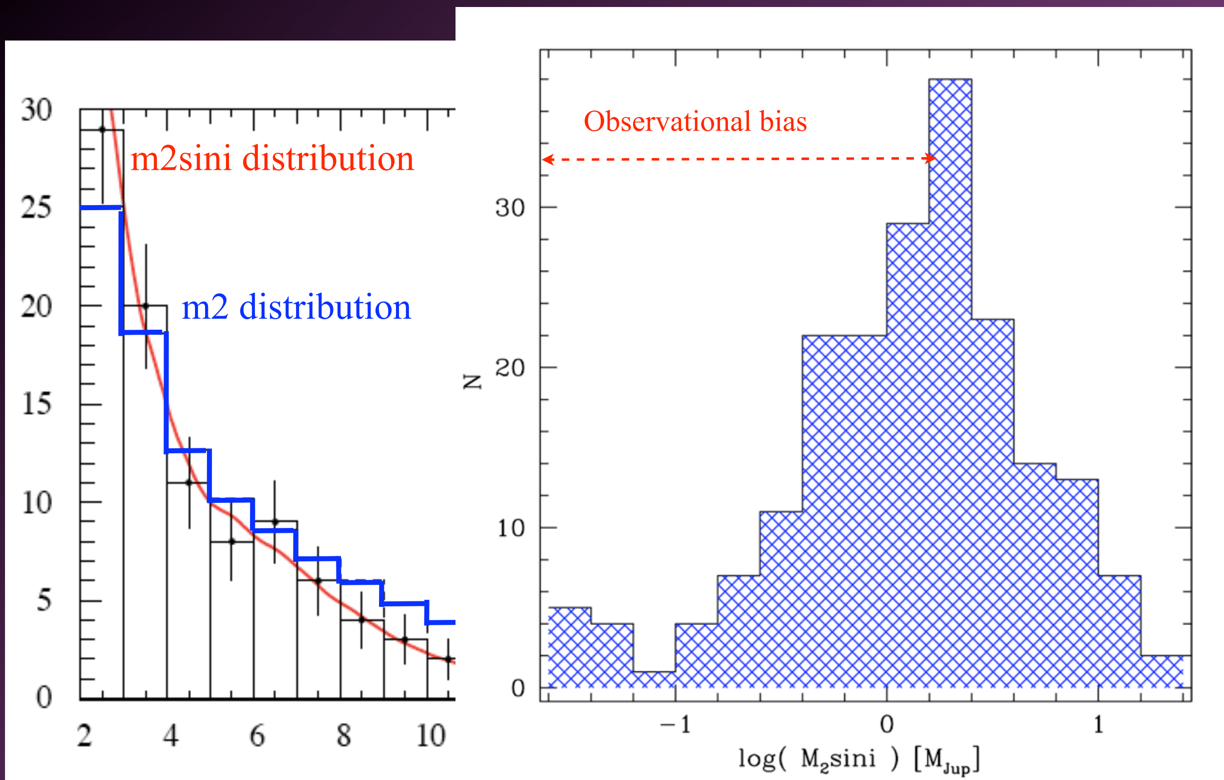

1000
100
10
1
Mass [M⊕]
Jupiter
Saturn
Neptune
Earth
51 Peg b
HARPS
1990
1995
2000
2005
2010
Epoch

Planetary mass distribution



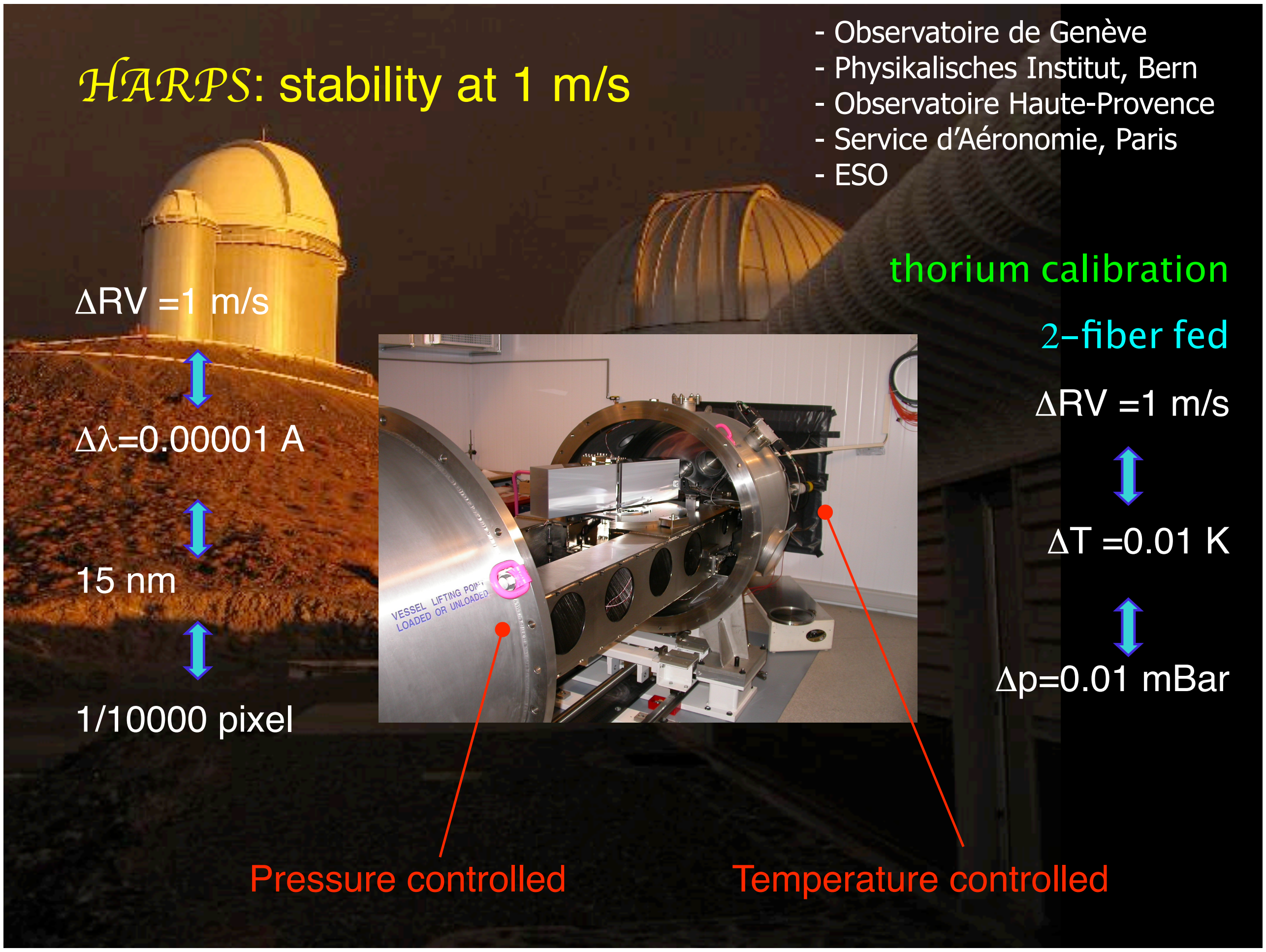
Planet Detectability with radial velocities

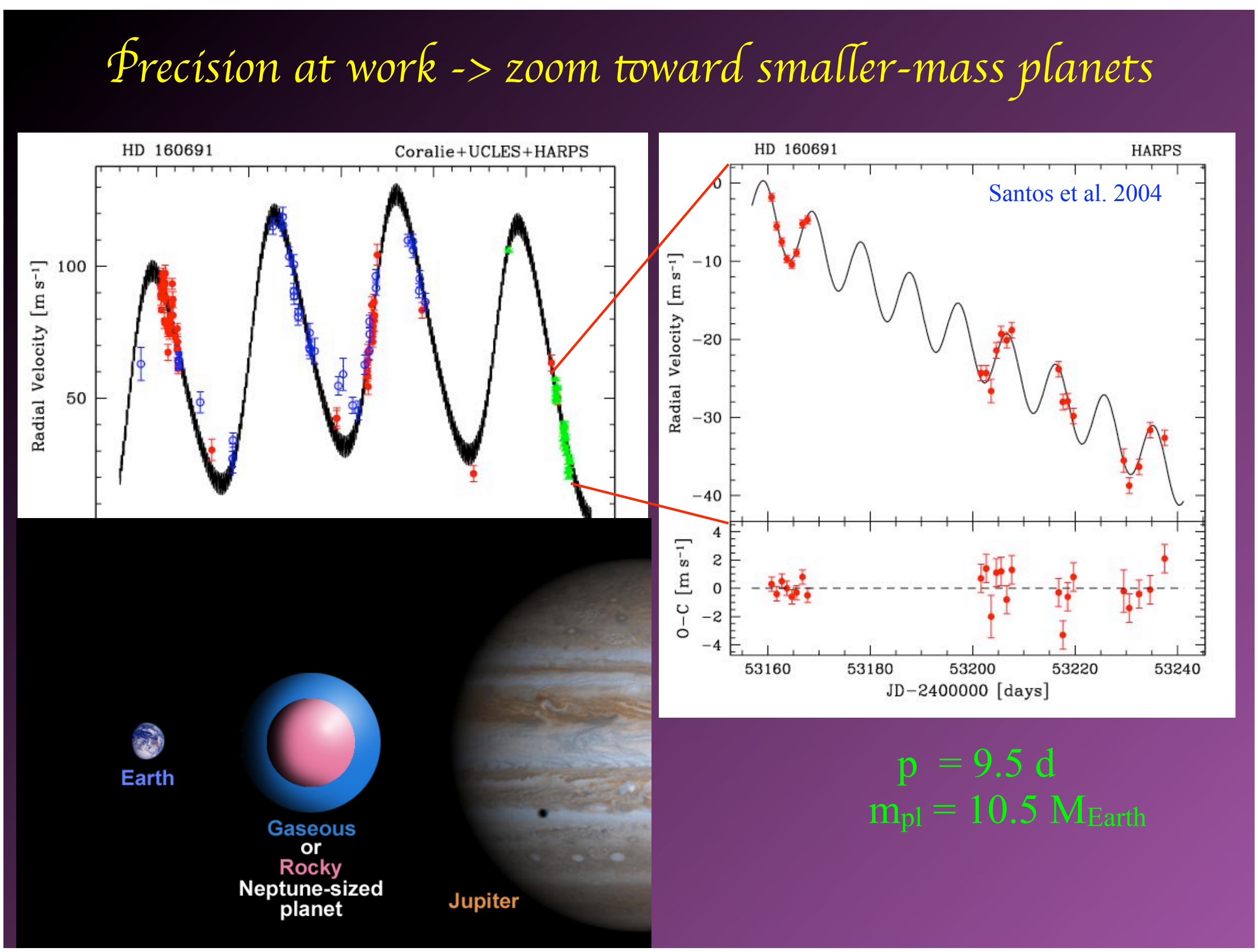
$$k_1 = \frac{28.4\ \mathrm{m\ s^{-1}}}{\sqrt{1-e^2}} \frac{m_2 \sin i}{M_{\mathrm{Jup}}} \left(\frac{m_1 + m_2}{M_{\mathrm{Sun}}} \right)^{-2/3} \left(\frac{P}{1\ \mathrm{yr}} \right)^{-1/3}$$

Jupiter	@ 1 AU	: 28.4 m s^{-1}
Jupiter	@ 5 AU	: 12.7 m s^{-1}
Neptune	@ 0.1 AU	: 4.8 m s^{-1}
Neptune	@ 1 AU	: 1.5 m s^{-1}
Super-Earth (5 $M_{\oplus}$)	@ 0.1 AU	: 1.4 m s^{-1}
Super-Earth (5 $M_{\oplus}$)	@ 1 AU	: 0.45 m s^{-1}
Earth	@ 1 AU	: 9 cm s^{-1}

A few m/s precision OK
for giant planets
e.g. Jupiters out to > 5 AU

Need to go below 1 m/s
for close super-Earths!

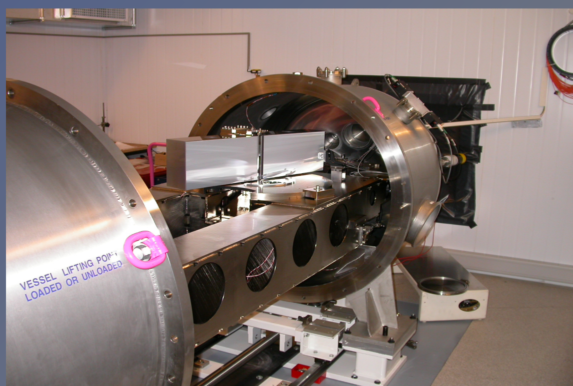

HARPS: stability at 1 m/s
- Observatoire de Genève
- Physikalisches Institut, Bern
- Observatoire Haute-Provence
- Service d'Aéronomie, Paris
- ESO
ΔRV =1 m/s
Δλ=0.00001 A
15 nm
1/10000 pixel
thorium calibration
2-fiber fed
ΔRV =1 m/s
ΔT =0.01 K
Δp=0.01 mBar
VESSEL LIFTING POINT LOADED OR UNLOADED
Pressure controlled
Temperature controlled


Precision at work -> zoom toward smaller-mass planets
HD 160691
Coralie+UCLES+HARPS
Radial Velocity [m s⁻¹]
100
50
HD 160691
HARPS
Santos et al. 2004
Radial Velocity [m s⁻¹]
0
−10
−20
−30
−40
O−C [m s⁻¹]
4
2
0
−2
−4
53160
53180
53200
53220
53240
JD−2400000 [days]
Earth
Gaseous
or
Rocky
Neptune-sized
planet
Jupiter
p = 9.5 d
m_pl = 10.5 M_Earth

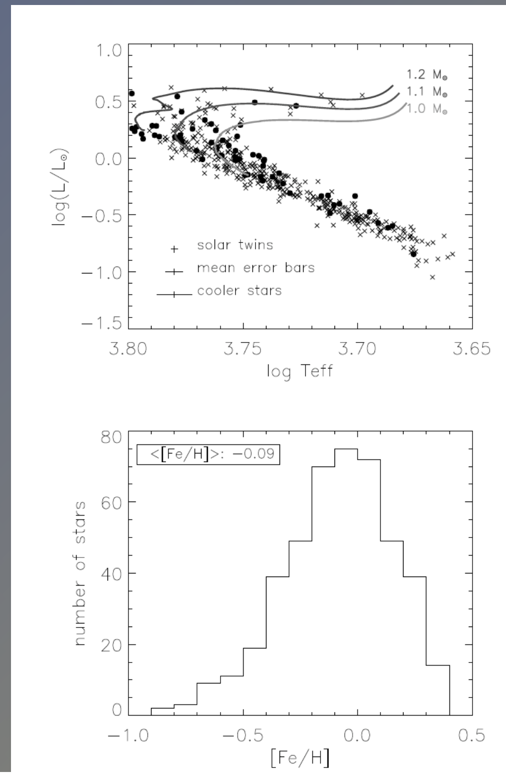
The HARPS search for low-mass planets

- Sample of ~400 slowly-rotating, nearby FGK dwarfs from the CORALIE planet-search survey + known planets
- HARPS log(R'_HK)<-4.8 => ~280 good targets
  Non evolved (Sousa et al. 2009)
- Observations ongoing since 2004
- Focus on low-amplitude RV variations

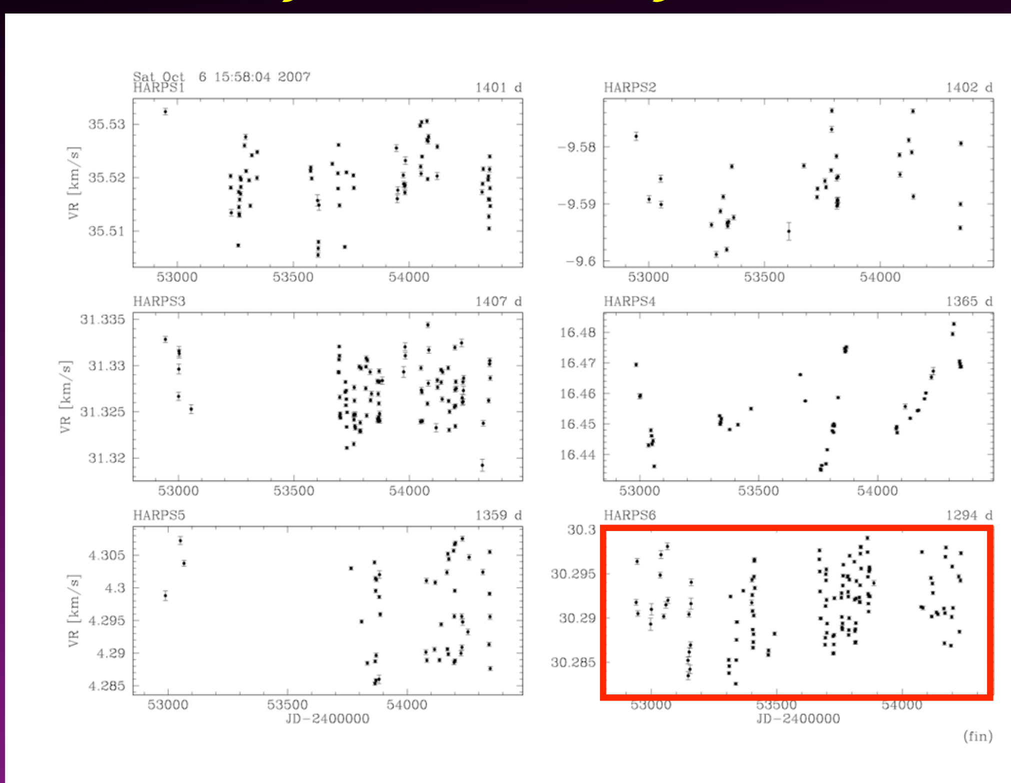
  => about 50% of HARPS GTO time



HARPS



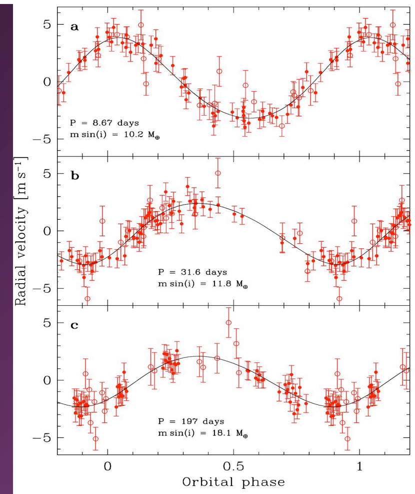
Harps: a blossom of candidates (I)

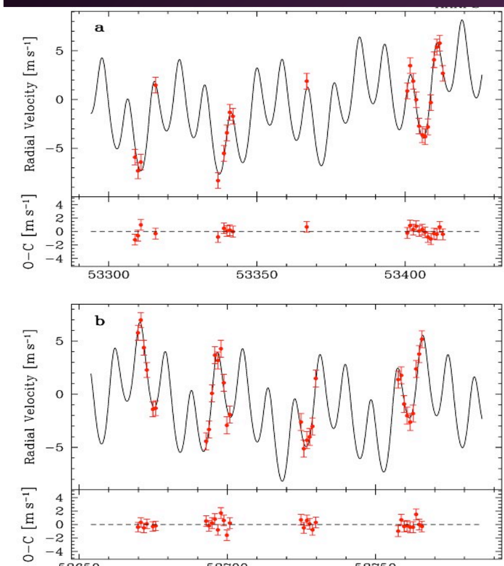


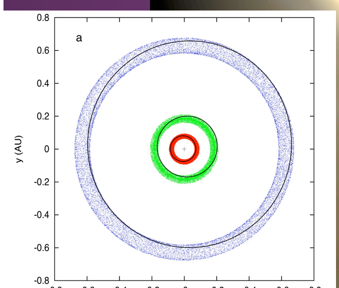
HD 69830: A trio of Neptunes

P1 = 8.67 days a = 0.078 AU M sini = 10.2 M_{Earth}
P2 = 31.6 days a = 0.186 AU M sini = 11.8 M_{Earth}
P3 = 197 days a = 0.63 AU M sini = 18.1 M_{Earth}

HARPS@3.6-m telescope, ESO La Silla

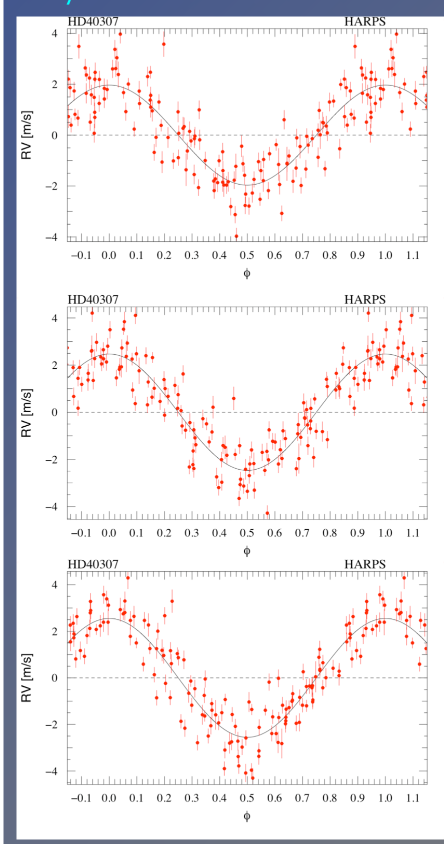






An emerging population of Hot Neptunes and Super-Earths

Mayor et al. A&A 2009



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

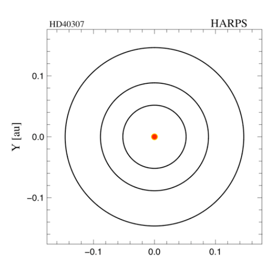
P_2 = 9.62 days
e_2 = 0.03
m_2 sini = 6.9 $M_\oplus$

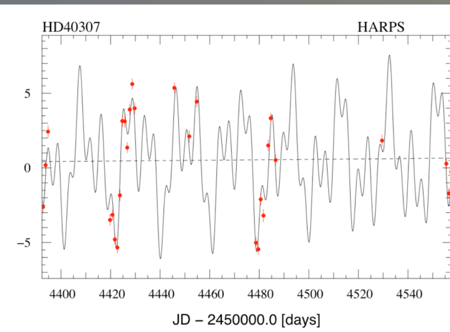
P_3 = 20.5 days
e_3 = 0.04
m_3 sini = 9.7 $M_\oplus$

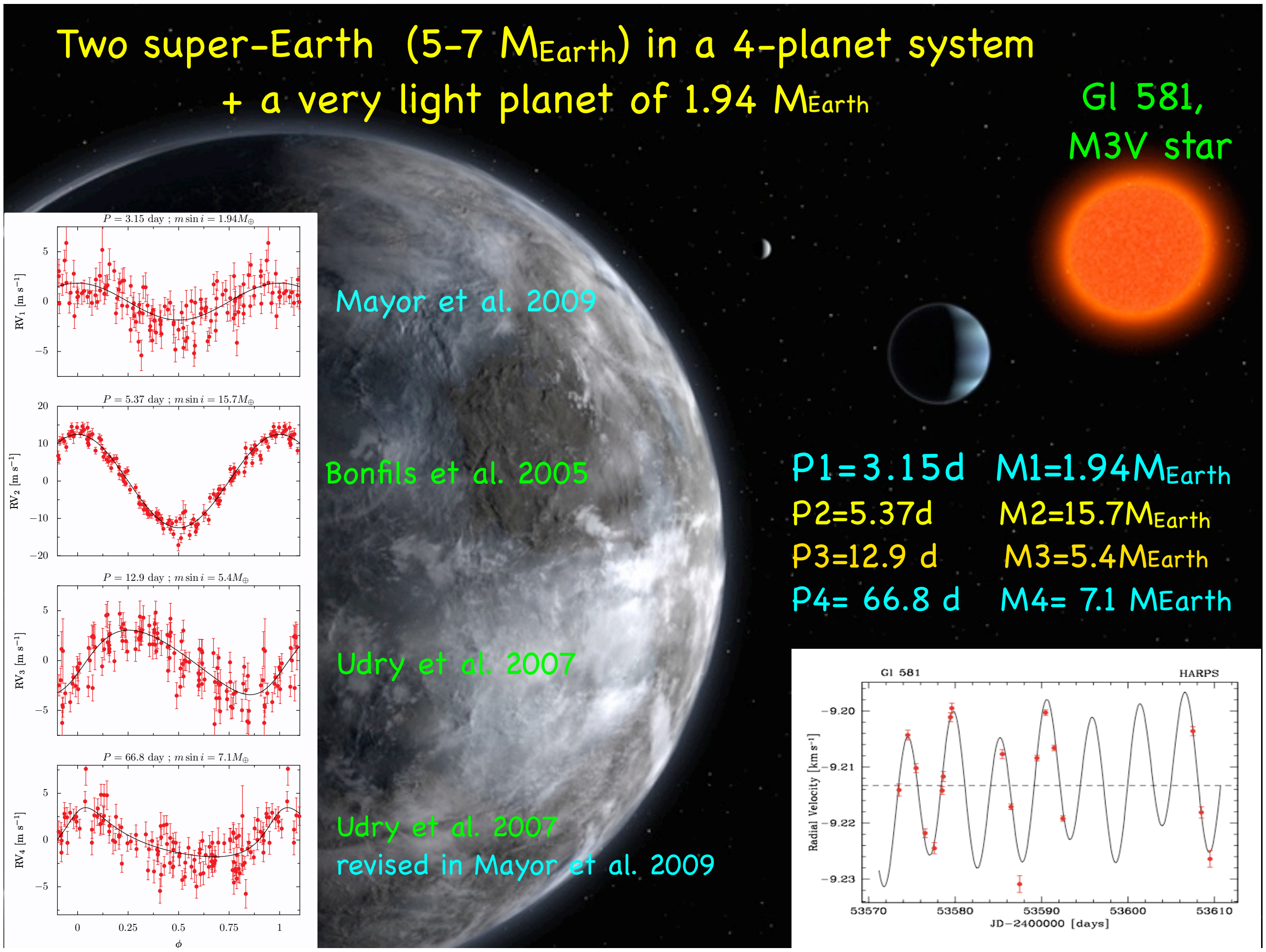
HD 40307
K2 V
Dist 12.8 pc
[Fe/H] = -0.31

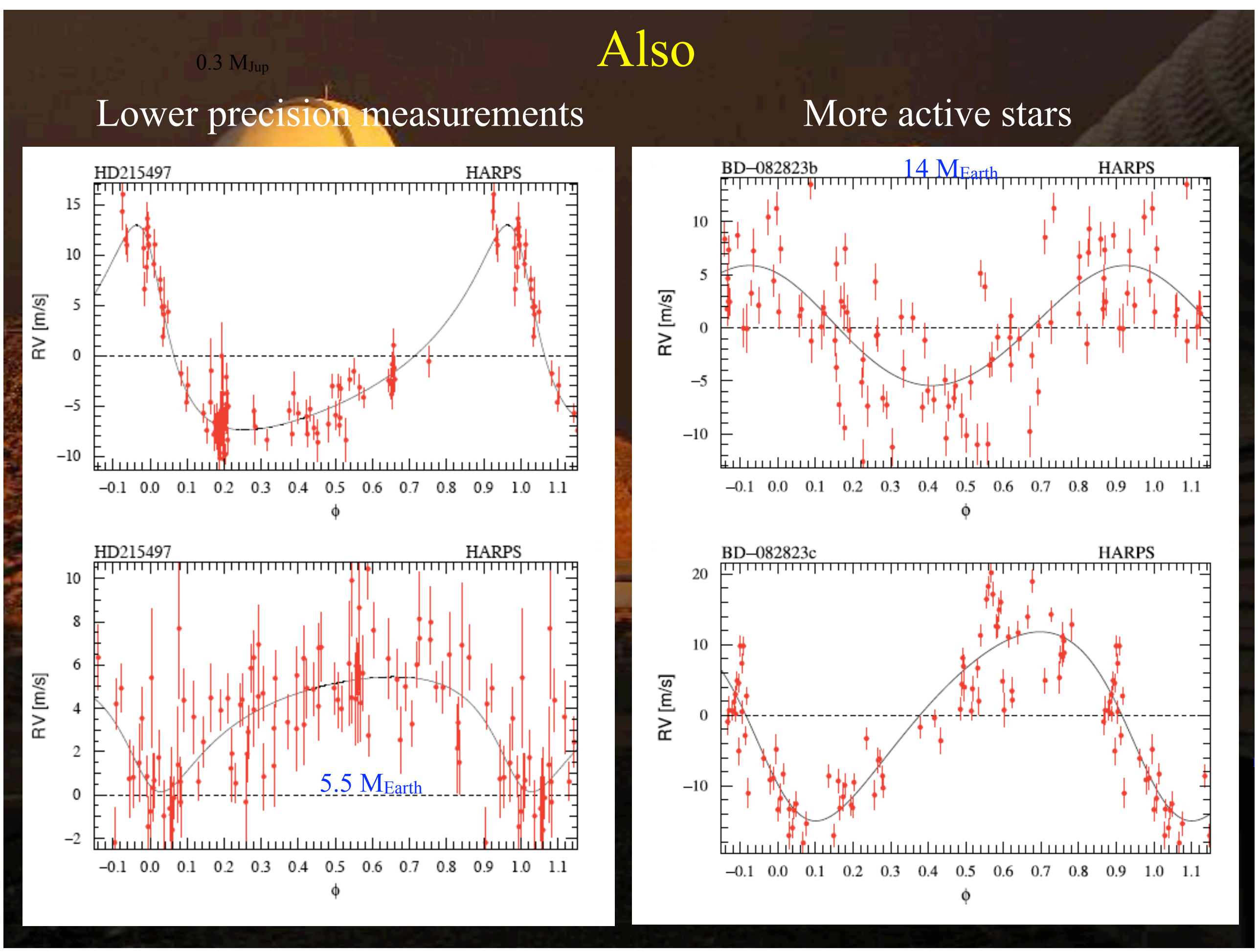
O-C = 0.85 m/s
135 observations

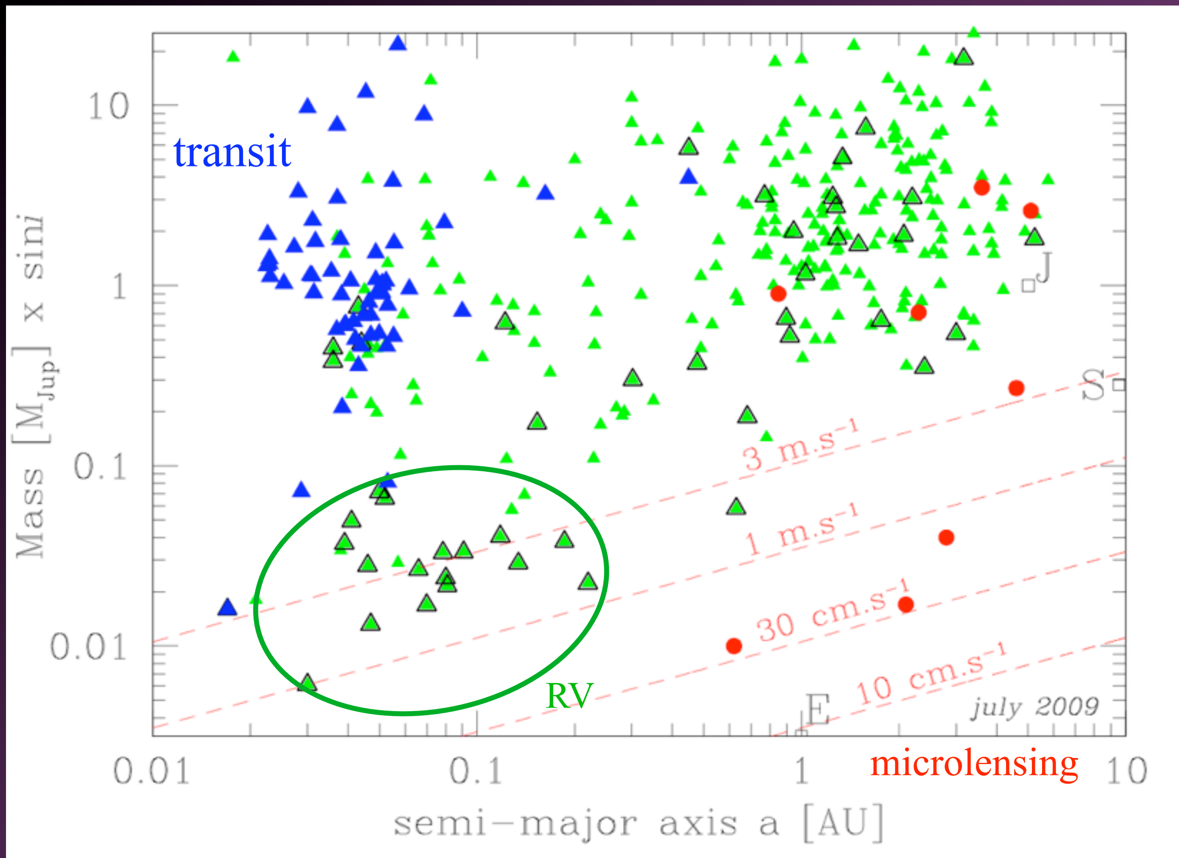
+ drift = 0.5 m/s/y



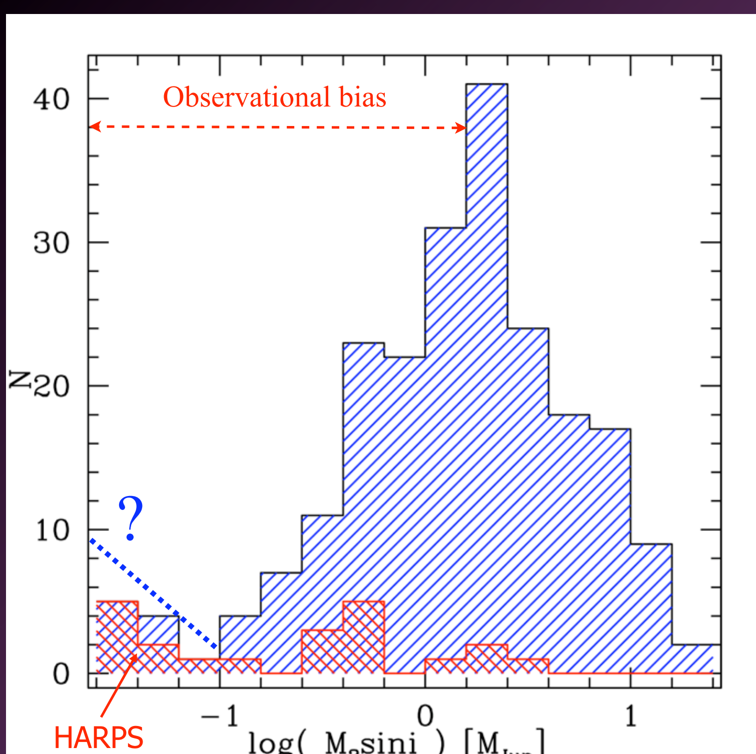



Two super-Earth (5-7 MEarth) in a 4-planet system
+ a very light planet of 1.94 MEarth
Gl 581,
M3V star
Mayor et al. 2009
Bonfils et al. 2005
Udry et al. 2007
Udry et al. 2007
revised in Mayor et al. 2009
P1=3.15d M1=1.94MEarth
P2=5.37d M2=15.7MEarth
P3=12.9 d M3=5.4MEarth
P4= 66.8 d M4= 7.1 MEarth
Gl 581
HARPS
Radial Velocity [km s−1]
JD−2400000 [days]


Also
0.3 MJup
Lower precision measurements
More active stars
HD215497
HARPS
RV [m/s]
φ
5.5 MEarth
BD−082823b
14 MEarth
BD−082823c



Harps: exploration of small-mass domain



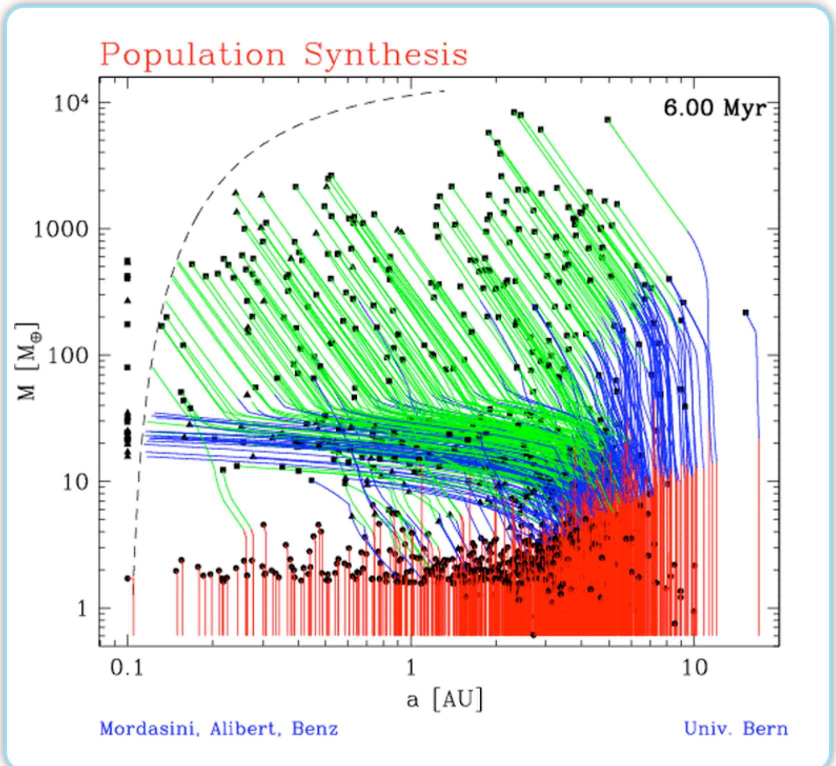
1. New mass domain

2. "Rise" towards the
   the very small masses?

New "category" of planets

small-mass normalisation
=> x 8 (?)

Formation tracks



M_{star}=1 $M_{\odot}$
Nominal model

Type I migration
(Analytical rate reduced by f_I)

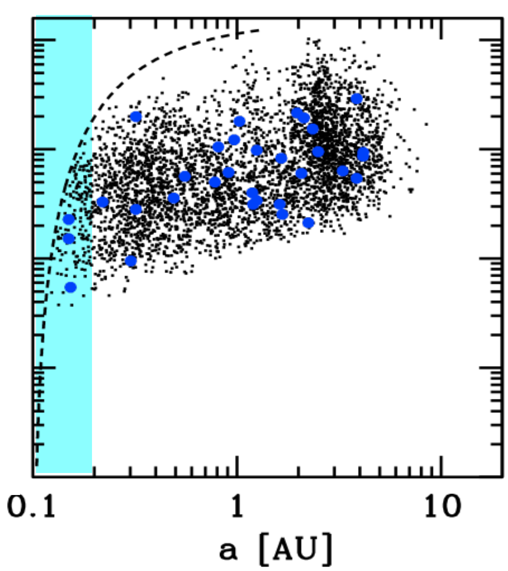
Type II migration
(Disk dominated: M_p<$M_{disk,loc}$)

Type II migration
(Planet dominated: M_p>$M_{disk,loc}$ & disk limited gas accretion)

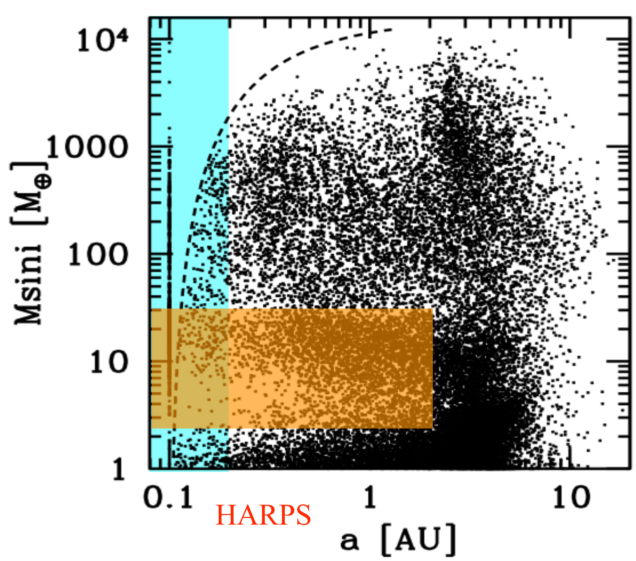
see also
Ida & Lin models

Monte-Carlo Simulations of planet formation via core accretion

10 m/s



all



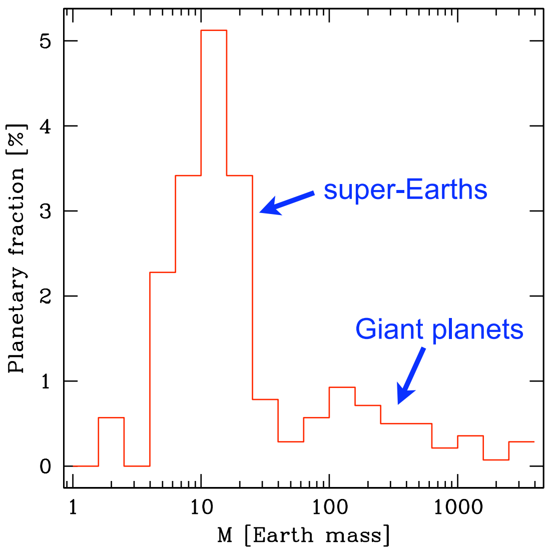
Prediction: Many very small mass, solid planets

- Mordasini, Benz, Alibert (2004-2008)
- Ida & Lin (2004-2008)

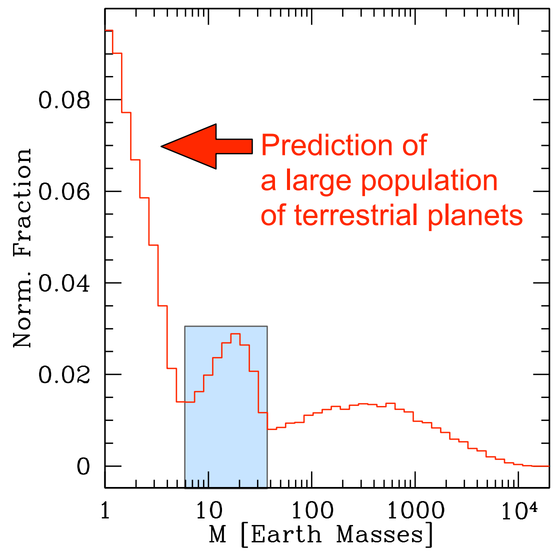
Some properties of close-in low-mass planets

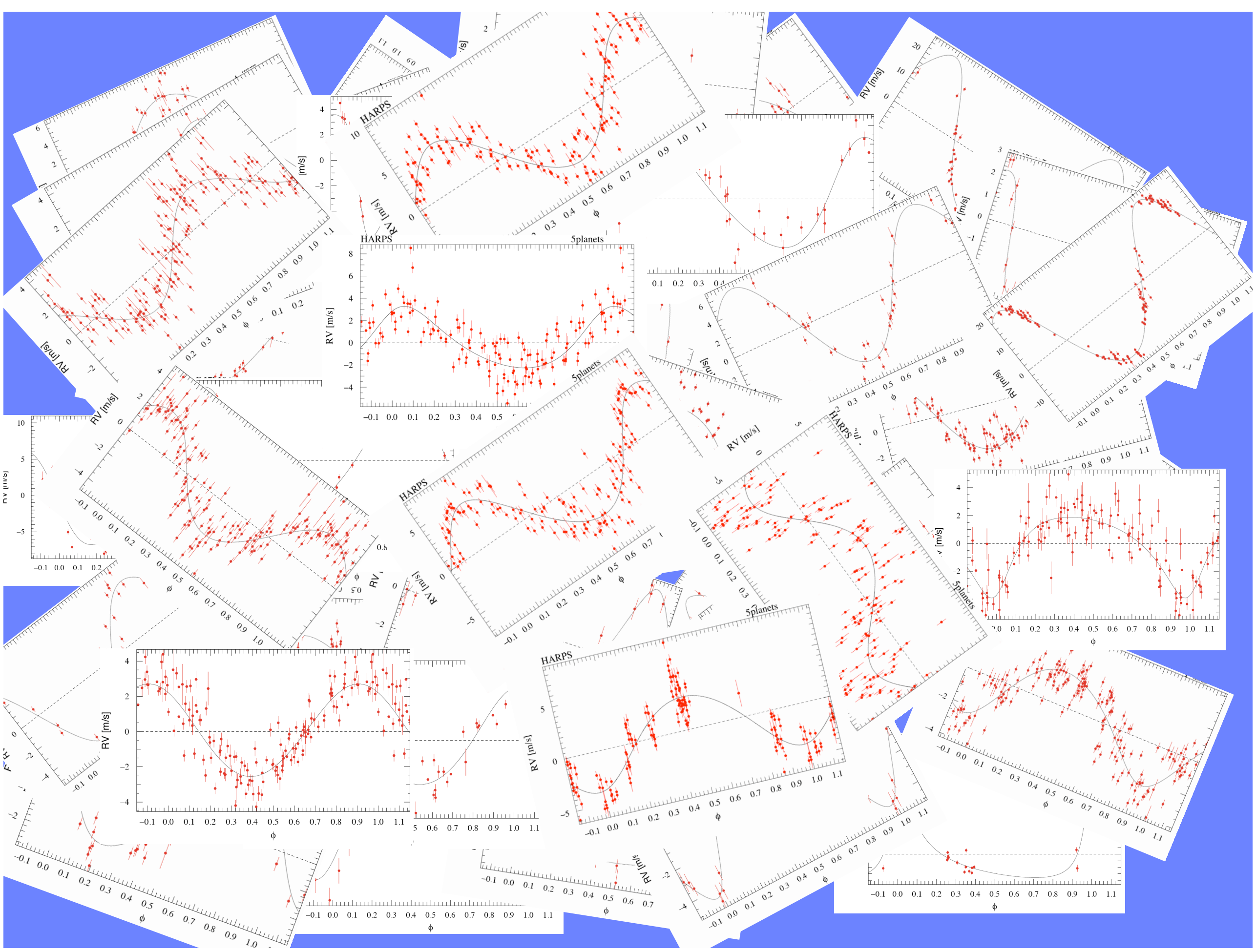
1) Mass distribution

Observations
(normalized distribution)



Models
(Mordasini et al. 2009)





Statistics of occurrence low-mass planets

- Sample of ~400 slowly-rotating, nearby FGK dwarfs
- HARPS log(R'_HK)<-4.8 => ~280 good targets
  non evolved
- Stars with too small # of observations: 117 stars

=> 163 stars for which we can say something

Nothing	Rather no planet	Hint of planet	Planets
55/163	14/163	31/163	63/163
34%	8%	19%	39%

> Between 39% (conservative) and 58% (optimistic) of solar-type stars in the HARPS high-precision survey host planets with masses below 50 M_{Earth}

Systems with Neptunes and super-Earths

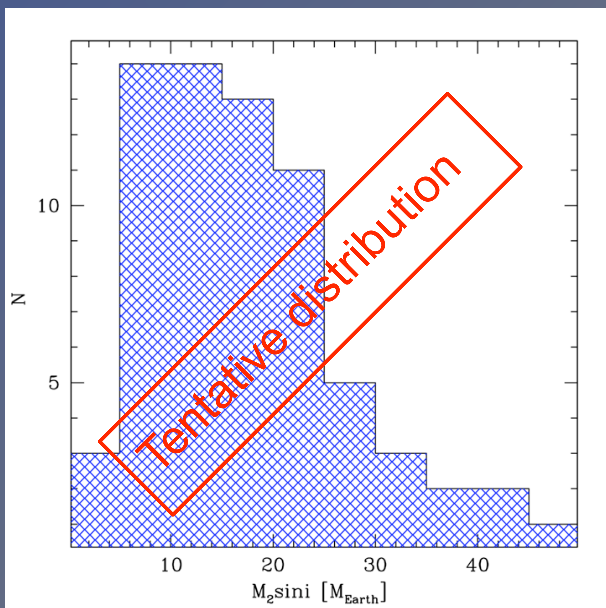
An emerging new population

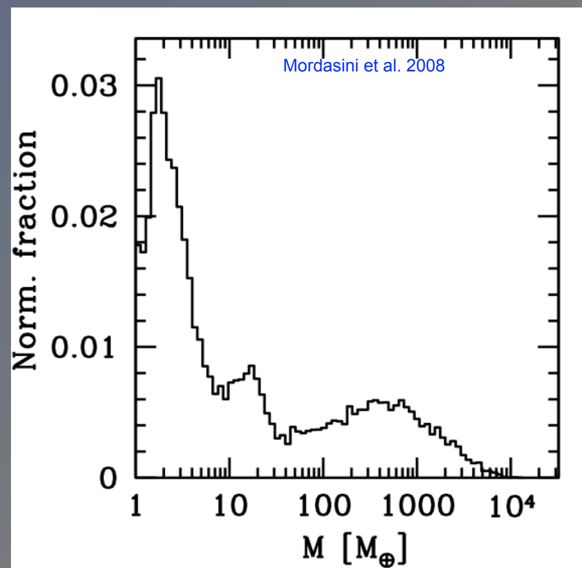
Properties?
comparison with giant panets?

Some properties of close-in low-mass planets

1) Mass distribution

- Mass distribution grows towards lower masses, as predicted by core accretion (Mordasini et al. 2008)
- Detection bias below ~10 $M_\oplus$

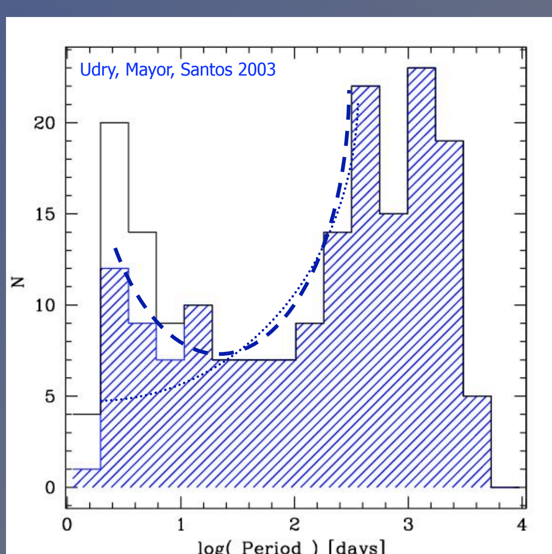


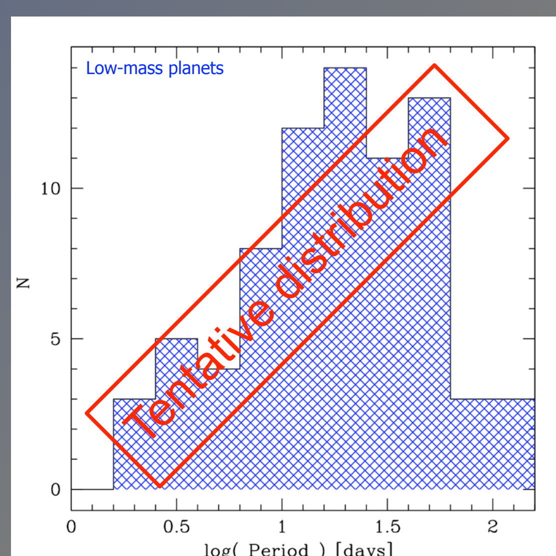


Some properties of close-in low-mass planets

2) Period distribution

- For small-mass planets, no peak at ~3 days. Rise to >10 days? -> migration stops earlier than for gas giants ? No stopping mechanism? Type I ?





Planetary multiplicity for systems with at least one Neptune or Super-Earth (in VR surveys only)

- M stars
  - GJ 436 N + ??
  - GJ 876 R + 2 G
  - GJ 581 3R
  - GJ 674 N
  - GJ 176 R
- G and K stars
  - 55 Cnc N + 4 G
  - Mu Ara N + 3 G
  - GJ 777A N + G
  - HD 69830 3N
  - HD 4308 N
  - HD 219828 N + G
  - HD 40307 3R
  - HD 181433 R + 2 G
  - HD 47186 N + G
  - HD7924 R

R Super-Earth
N Neptune-type
G Gaseous giant planet

~50% of multi-planet systems

7 / 10 !!!
Multi-planet systems

Trend confirmed by unpublished candidates
(including curved drift)

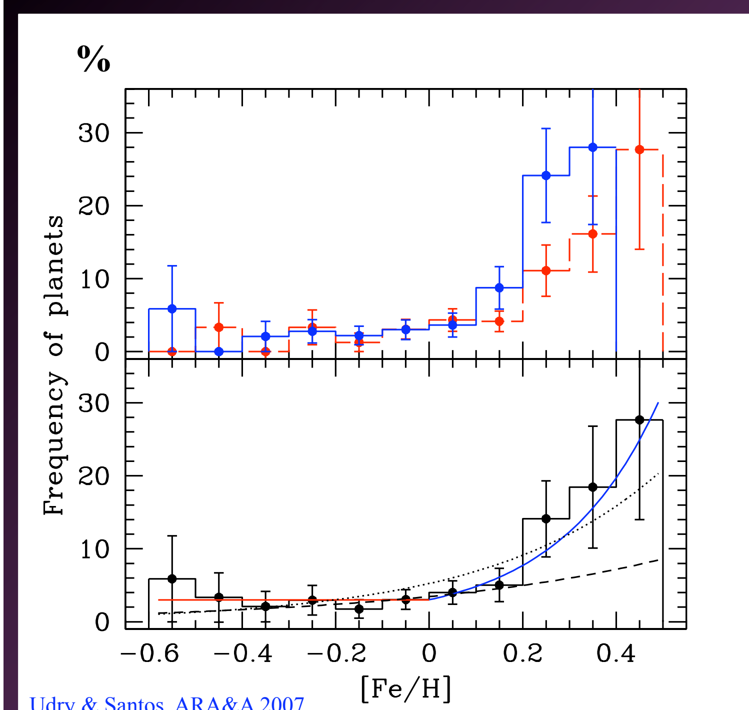
(HARPS)

Metallicity corrélation of planet-host stars

Giant gaseous planets

Stars with planets are more metal rich?

(Gonzalez 1997, 1998, 1999)



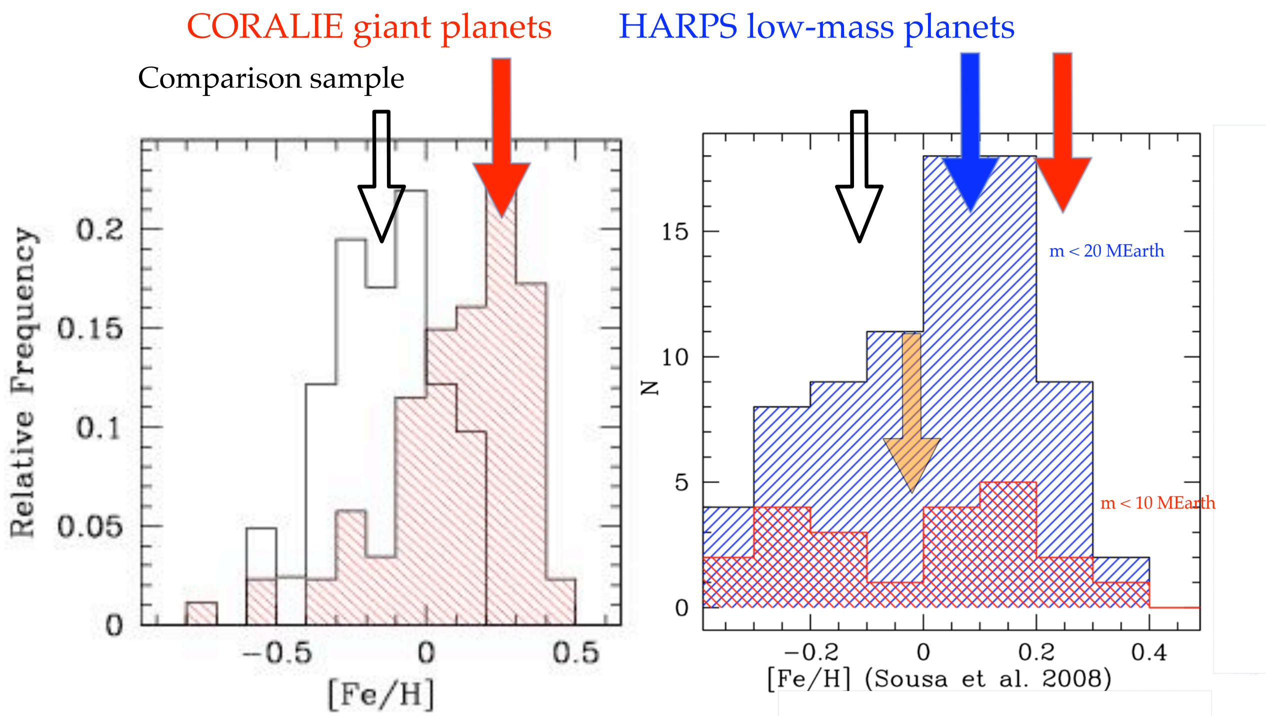
Santos et al. 2001-2006
Fischer & Valenti 2002-2005

- Well-defined samples with and without planets
- Uniform analyses
- Large number of stars

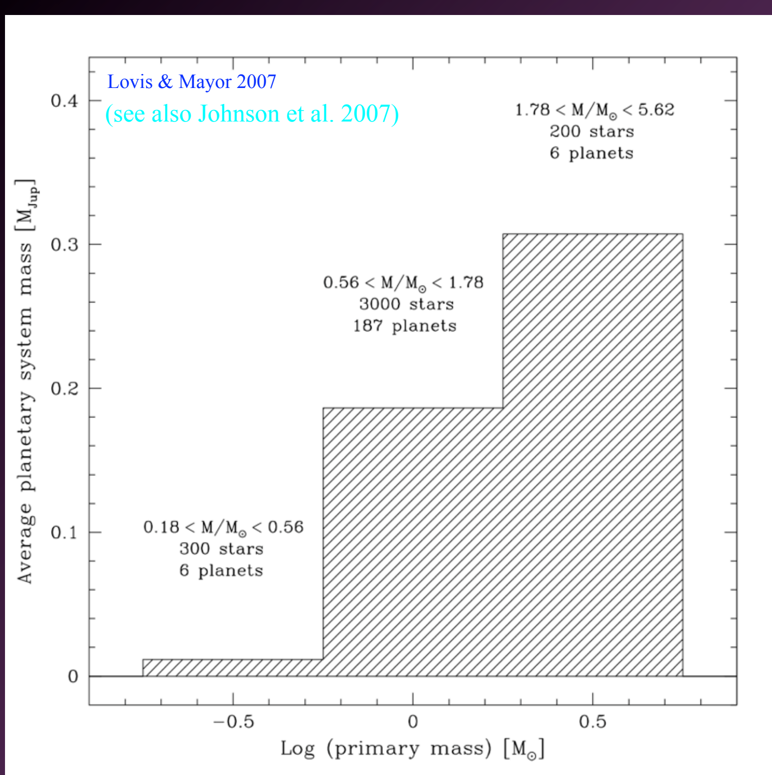
Average: 2 regimes
flat + power law

Constant probability at low metallicities ?

No metallicity correlation for low-mass planets ?



Primary-mass effect



Equal bin in log(M_{star})
- M dwarfs
- solar stars
- intermediate masses

Planetary system mass
planet masses/star number

=> mass of planetary material scales with M_{star}

RV bias
underestimate the last bin

Giant planets vs super-Earths

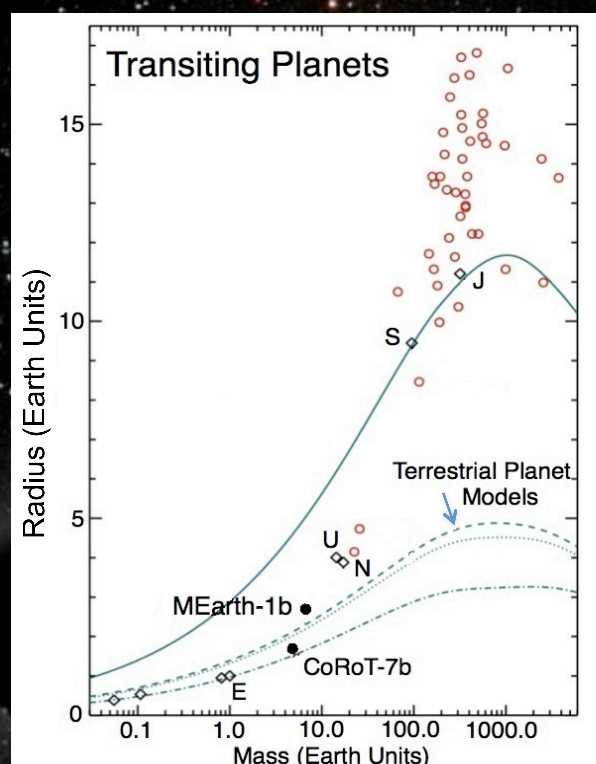
- Planetary mass distribution
  - continuous till high values (>20 M_{Jup})
  - bimodal, new low-mass planet population for small masses
  - small-mass population: rising towards low masses
- Period distribution
  - giants: accumulation at short period: migration effect
  - low-mass planets: no accumulation -> type I migration?
- Planet eccentricity
  - wide range of values observed, no significant differences between the 2 populations
- Planet multiplicity
  - seems to be the rule
- Host star metallicity
  - higher frequency of giants around metal-rich stars (not observed for giant stars?)
  - correlation not observed for low-mass planets
  - Low-mass planets: planet mass vs star metallicity weak correlation
- Primary mass
  - scaling between M1 and planetary material in the system
  - dependency of gaseous/solid ration on M1

Planetary parameter diversity

CoRoT, M-Dwarf surveys

- Transit → fractional radius (relative to host star) → inclination.
- RV → planetary mass
- 2 solid planets:
  - CoRoT-7b : Period ~ 0.85 d
  - MEarth-1b: Period ~ 1.50 d

=> Diversity




Detection of Earth twins in the HZ of solar-type stars ?