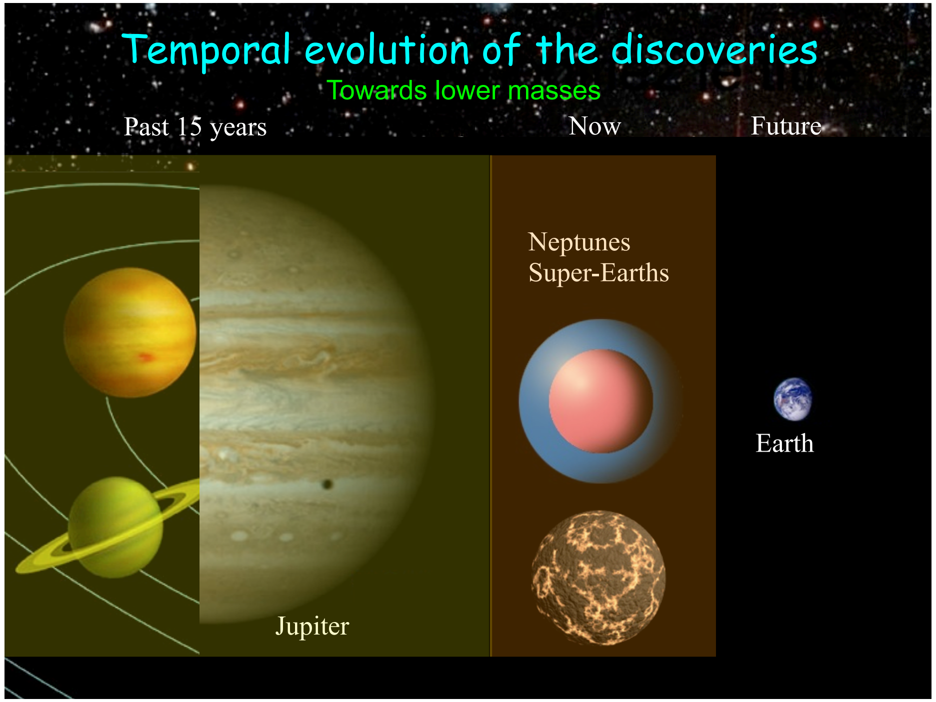


Available exoplanet sample

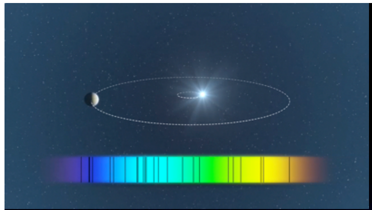
The extra-solar planet encyclopedia (Jean Schneider, Paris)

All Catalogs
update : **24 July 2012**

All Candidates detected	**777 planets**
Candidates detected by radial velocity *update : 24 July 2012*	570 planetary systems 715 planets 96 multiple planet systems
Transiting planets *update : 24 July 2012* (Next talk, F Bouchy)	205 planetary systems 239 planets 30 multiple planet systems
Candidates detected by microlensing *update : 02 June 2012*	15 planetary systems 16 planets 1 multiple planet systems
Candidates detected by imaging *update : 05 April 2012*	27 planetary systems 31 planets 2 multiple planet systems
Candidates detected by timing *update : 24 July 2012*	12 planetary systems 15 planets 2 multiple planet systems

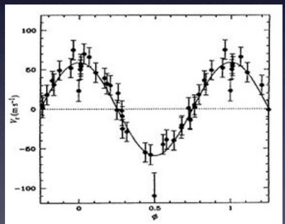
outline

- History and general context
  - The pioneer role of ESO
- RV's: Statistical properties from super-Earths to giant planets.
  - ESO-based Coralie and HARPS surveys
  - planetary orbital parameters (gaseous giants vs low-mass planets)
  - multi-planet systems
  - properties of parent stars (metallicity, M-dwarf survey)
- Transit follow-up of short-period RV planets
  - physical planet properties
  - system geometries
- The future: RV detection of Earth-type planets in the HZ of stars
  - limitations
  - instrumental progress for RV's and limitations
  - follow-up from space



Planet detectability with radial velocities

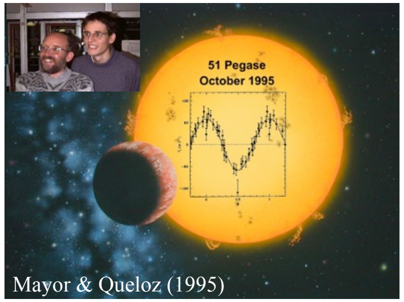
$$k_1 = \frac{28.4\ \mathrm{m\,s^{-1}}}{\sqrt{1-e^2}} \frac{m_2 \sin i}{M_{\mathrm{Jup}}} \left(\frac{m_1 + m_2}{M_{\mathrm{Sun}}}\right)^{-2/3} \left(\frac{P}{1\ \mathrm{yr}}\right)^{-1/3}$$



51 Peg b
0.5 Jupiter @ 0.05 AU : 56 m s^{-1}

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	: 0.09 m s^{-1}

The "beginning": ESO is already there



A Radial Velocity Search for Extra-Solar Planets Using an Iodine Gas Absorption Cell at the CAT + CES

1994

M. KÜRSTER[1], A.P. HATZES[2], W.D. COCHRAN[2], C.E. PULLIAM[2], K. DENNERL[1] and S. DÖBEREINER[1]

[1]Max-Planck-Institut für Extraterrestrische Physik, Garching, Germany
[2]McDonald Observatory, The University of Texas at Austin, Austin, U.S.A.

Table 1: *Comparison of Radial Velocity Programmes*

Telescope	Technique	Resolving power	Δλ [Å]	σ [m s^{-1}]	Reference
Mt. John 1.0-m	Digital CC	100,000	45	55	Murdoch et al. 1993
McDonald 2.7-m	Telluric O_2	200,000	12	15–20	Cochran & Hatzes 1990
Steward 0.9-m	Fabry-Perot	74,000	300	8–14	McMillan et al. 1993, MS
CFHT 3.6-m	HF cell	40,000	133	13	Campbell et al. 1988
Lick 0.6-m CAT	I_2cell	40,000	200	20	Marcy & Butler 1993
McDonald 2.1-m	I_2cell	48,000	24	20–25	Hatzes & Cochran 1993
McDonald 2.7-m	I_2cell	200,000	9	10–15	Cochran & Hatzes 1994
ESO 1.4-m CAT	I_2cell	100,000	48	4–7	This work

1997

The ESO Precise RV Survey for Extra-solar Planets: Results from the First Five Years

Abstract. Results are presented from the first five years of the high precision RV survey carried out with the 1.4m CAT+CES spectrograph at ESO La Silla. This RV survey of 37 solar-type stars was begun in Nov. 1992. Using an iodine gas absorption cell for self-calibration we currently achieve a long-term precision of 20 m/s in a 30-min exposure of a 5.5 mag star. This value is the typical 'working' precision in survey work, i.e. an average over all observing conditions.

=> Improved later: Eps Eri (1999), Iota Hor (2000)

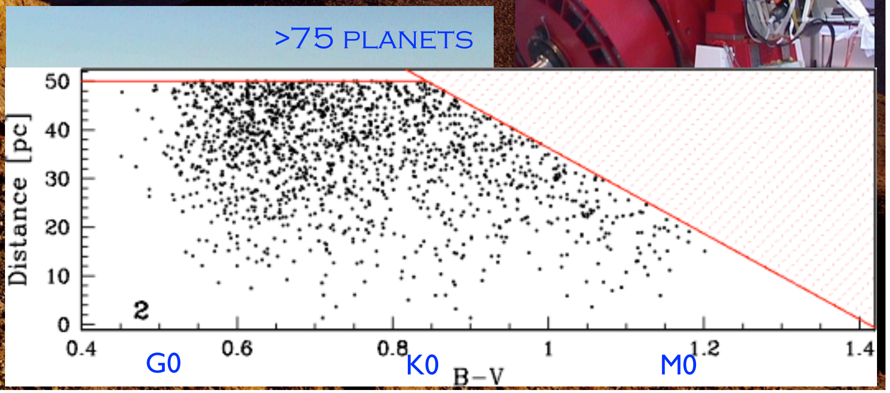
Euler+Coralie – La Silla (1998-...)

1.2-m Euler Swiss telescope
Simultaneous thorium technique

M. Mayor, S. Udry, D. Queloz, F. Pepe, D. Ségransan, C. Lovis, D. Naef, N.C. Santos, M. Gillon, P. Figueira, M. Marmier, A. Triaud, J. Hagelberg, X. Dumusque, M. Lendl, J. Sahlmann, +....

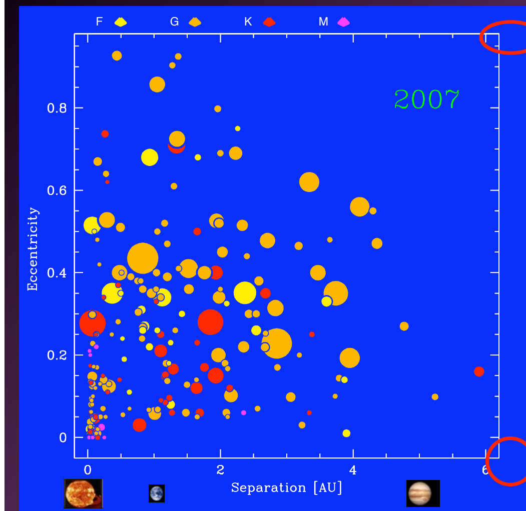
Precision: ~5 m/s
-> Photon-noise limited (-> 5-10 m/s)

Volume-limited sample: 1650 F8-M0 dwarfs
(Queloz et al. 2000, Udry et al. 2000)



Extra-solar planets: radial-velocity detections

1995-2012: >700 RV planets => diversity

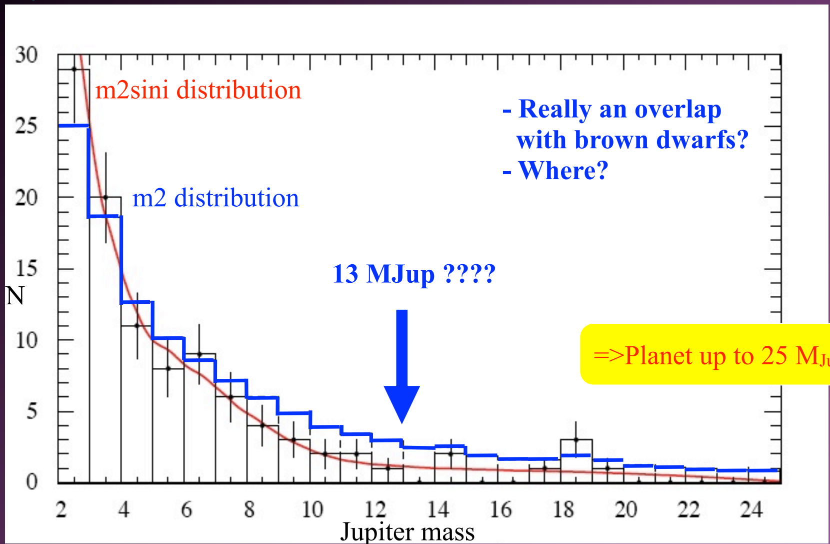


Statistical properties

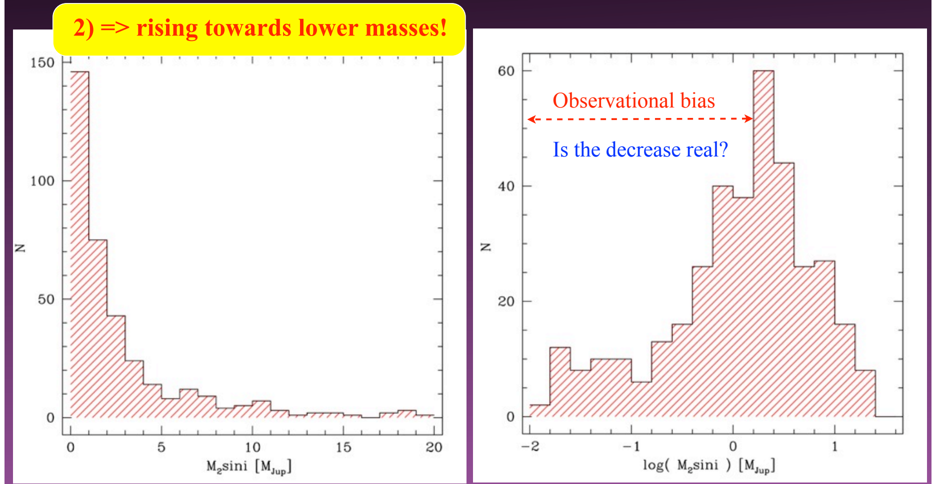
- Percentage
  - ~10% of observed stars host giants
  - ~0.5-1% of Hot Jupiters
- Mass distribution
  - 1.5 M_{Earth} < M_{pl} < 20 M_{Jup}
- Period
  - 0.74 d < P < ...
- Eccentricity-period distribution
  - 0 < e < 0.93
- Multi-planet systems
- Proprerties of host stars
  - metallicity, mass, binaries

Planetary mass distribution

Segransan et al. 2009



Planetary mass distribution



Planet detectability with radial velocities

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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}
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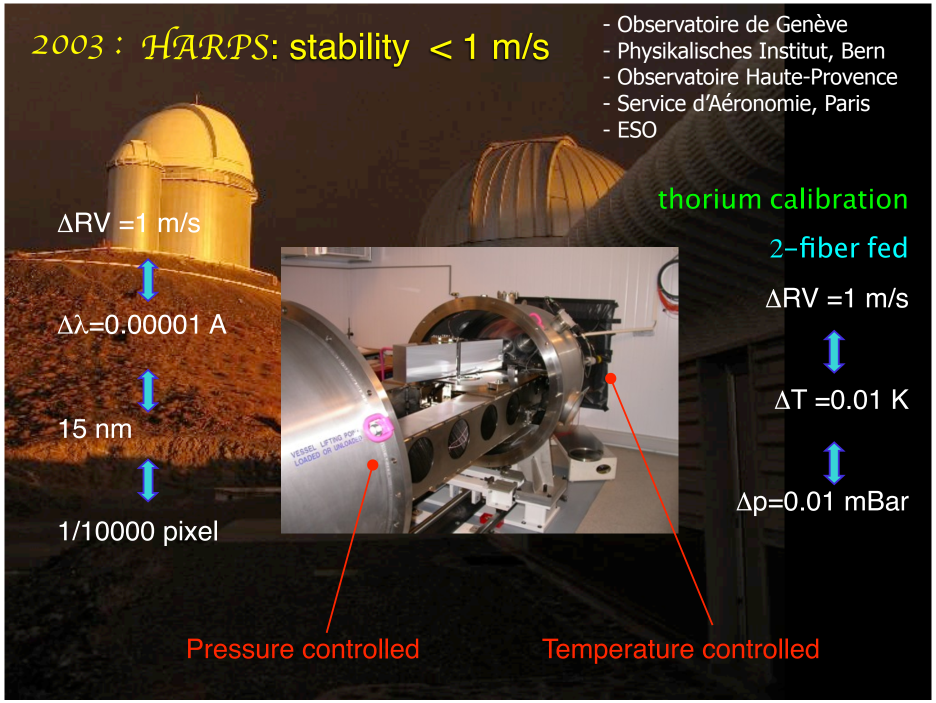
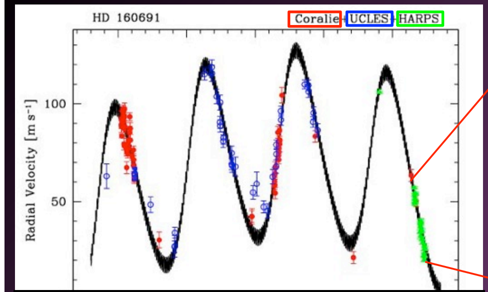
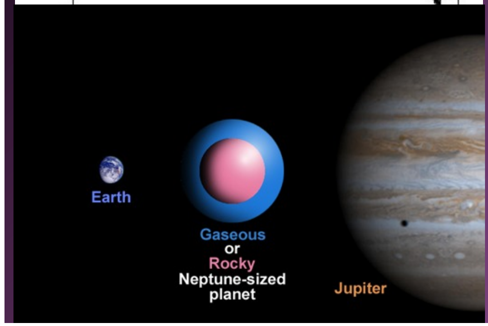
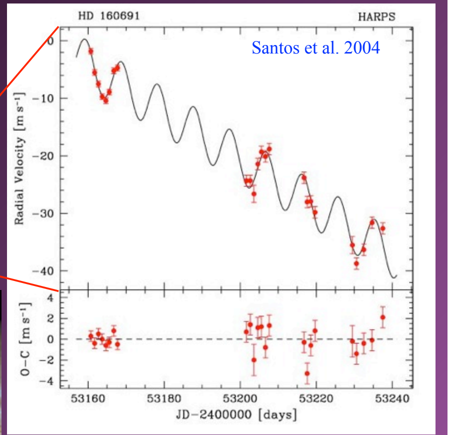
Earth	@ 1 AU	: 0.09 m s^{-1}



Precision at work -> zoom toward smaller-mass planets







$p = 9.5$ d
$m_{pl} = 10.5\ M_{Earth}$

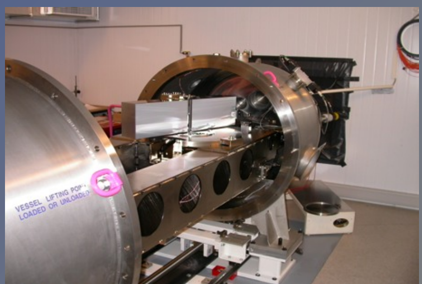
Scientific objectives of HARPS GTO

100 garanteed nights/year over 5 years

- A systematic monitoring of ~ 2000 star (G, K, M)
  - improve the available statistics for solar-type stars (orbital elements)
  - survey of low-mass stars
- Enlarge the planetary and orbital parameter space (higher precision)
  - smaller mass planets
  - longer periods
- Better constrain multi-planet systems
- Check chemical abundance effect:
  - metallicity: planet-search around halo deficient stars
- Radial-velocity follow-up of COROT transit candidates

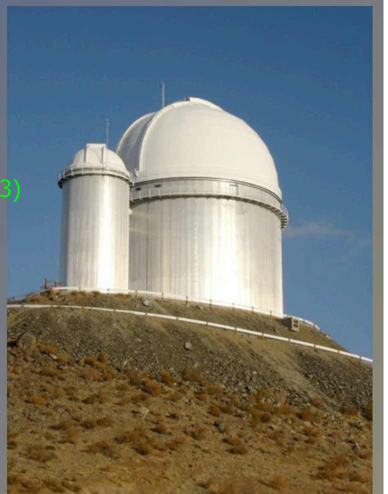
The HARPS search for low-mass planets

- Sample of ~400 slowly-rotating, nearby FGK dwarfs from the CORALIE planet-search survey + known planets
- HARPS log(R'_{HK})<-4.8 => ~376 good targets
  Non evolved (Sousa et al. 2009)
- Observations ongoing since 2004
- Focus on low-amplitude RV variations
  => about 50% of HARPS GTO time (250 nights)
  => continuing with ESO LP over 4 years (-->2013)

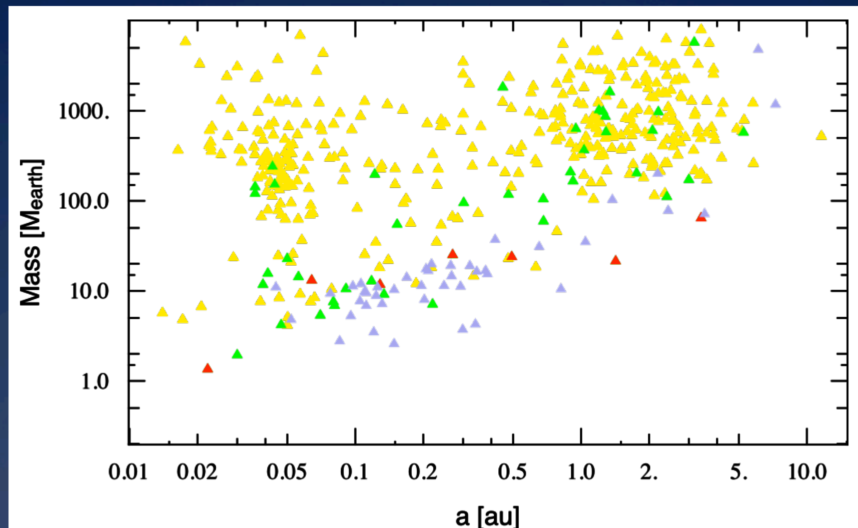


HARPS

ESO-3.6m @ La Silla

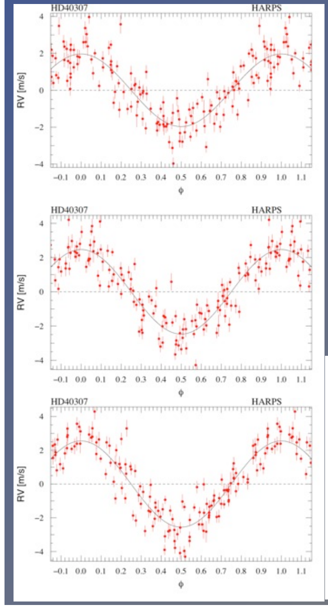


HARPS planets (~150 planets)



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 $M_\oplus$

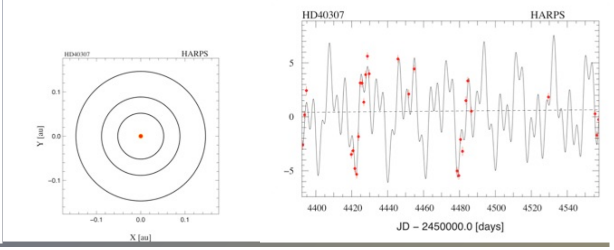
P_2 = 9.62 days
e_2 = 0.03
m_2 sini = 6.9 $M_\oplus$

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



HD10180 : 7-planet system

P_1 = 1.18 day
e_1 = 0
m_1 sini = 1.5 $M_\oplus$

P_2 = 5.76 days
e_2 = 0.07
m_2 sini = 13.2 $M_\oplus$

P_3 = 16.4 days
e_3 = 0.16
m_3 sini = 11.8 $M_\oplus$

P_4 = 49.7 days
e_4 = 0.06
m_4 sini = 24.8 $M_\oplus$

P_5 = 122.7 days
e_5 = 0.13
m_5 sini = 23.4 $M_\oplus$

P_6 = 595 days
e_6 = 0.0
m_6 sini = 22 $M_\oplus$

P_7 = 2150 days
e_7 = 0.15
m_7 sini = 67 $M_\oplus$

Lovis, Segransan, Udry, Mayor et al. 2010

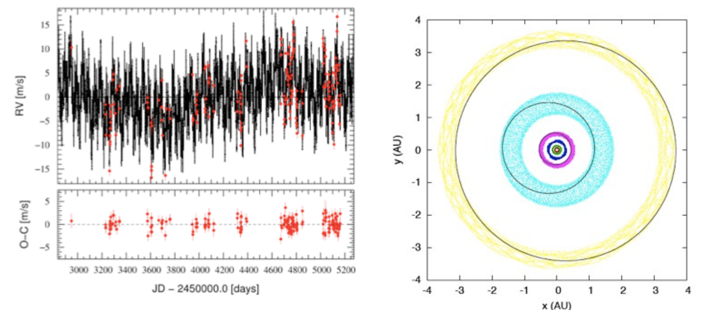
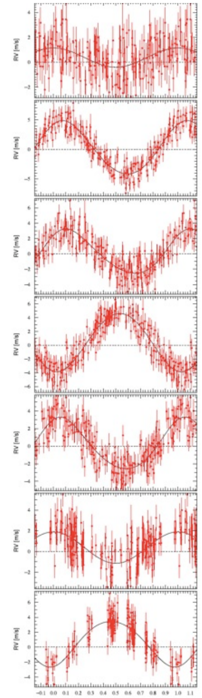


Fig. 5. Radial velocity time series with the 7-Keplerian model overplo



Combined Coralie+HARPS stellar sample

CORALIE volume-limited sample:

- distance < 50 pc
- log R'$_{HK}$ < -4.75 (F,G); -4.70 (K)
- no binaries
- measurement precision ~5-10 m/s (depending on star magnitude)

822 FGK stars (1998 to present)

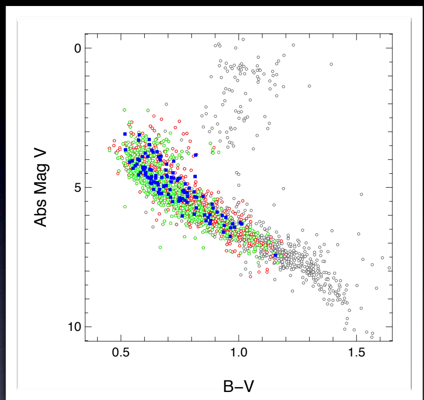
Focus on gaseous giant planets, long periods

HARPS subsample:

- measurement precision ~0.5 m/s (photon noise + instrument)

376 FGK stars (2003 to present)

Focus on super-Earths and Neptune-mass planets



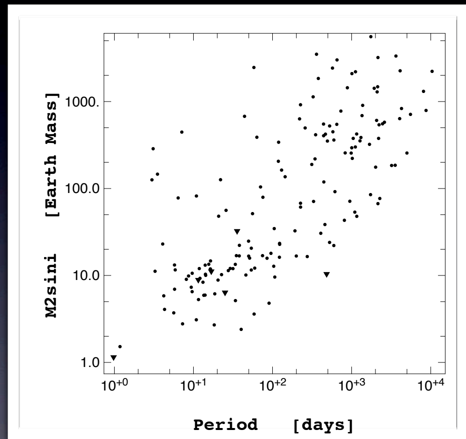
The HARPS search for southern extra-solar planets

XXXIV. Occurrence, mass distribution and orbital properties of super-Earths and Neptune-mass planets*

M. Mayor[1], M. Marmier[1], C. Lovis[1], S. Udry[1], D. Ségransan[1], F. Pepe[1], W. Benz[2], J.-L. Bertaux[3], F. Bouchy[4], X. Dumusque[1], G. LoCurto[5], C. Mordasini[6], D. Queloz[1], and N.C. Santos[7,8]

Mayor et al. 2011

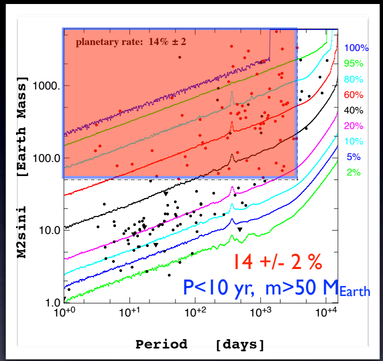
The Msini - log P plane



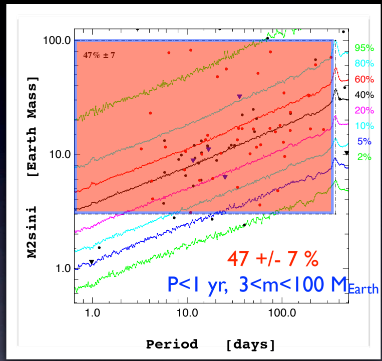
155 planets in 102 planetary systems

Occurrence frequency estimate

2) Detection probability of the survey



HARPS + Coralie



HARPS only

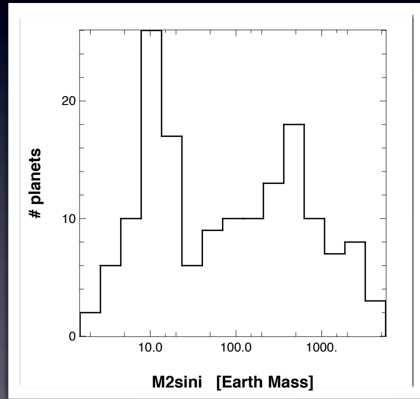
3) Occurrence rate

$$f = N_{pl} / N'_{star}$$

N'_{star} = # of star for which the planet is detectable

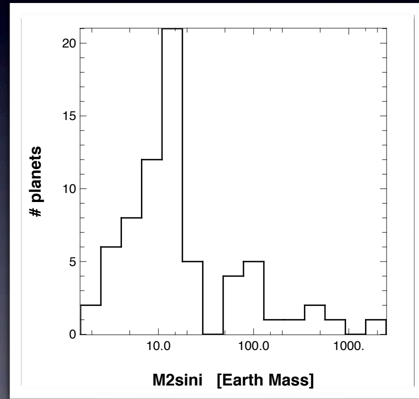
Mass distribution

Detections in the global sample



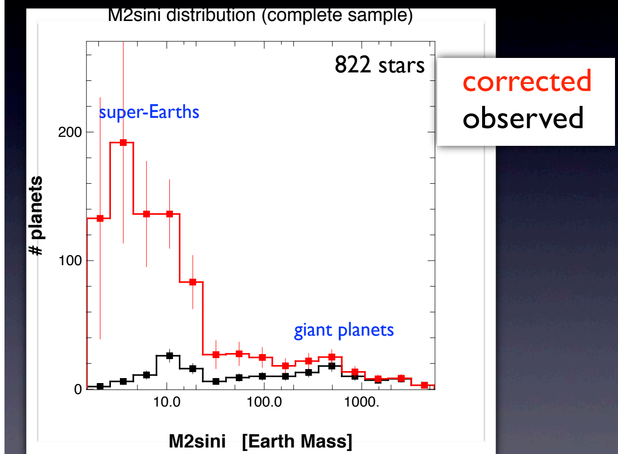
Predominant occurrence of planets with $m_{pl} \sin(i) < 30$ Earth masses

...and for P < 100 days



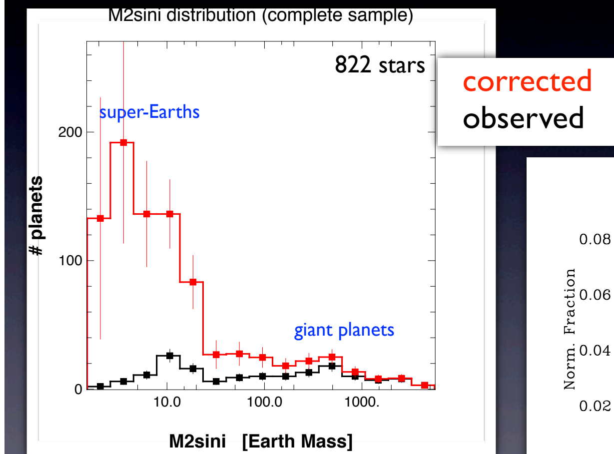
Mass distribution

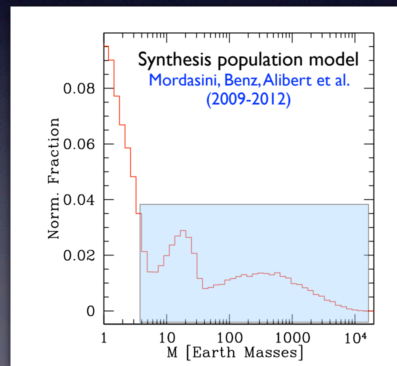
with incompleteness correction



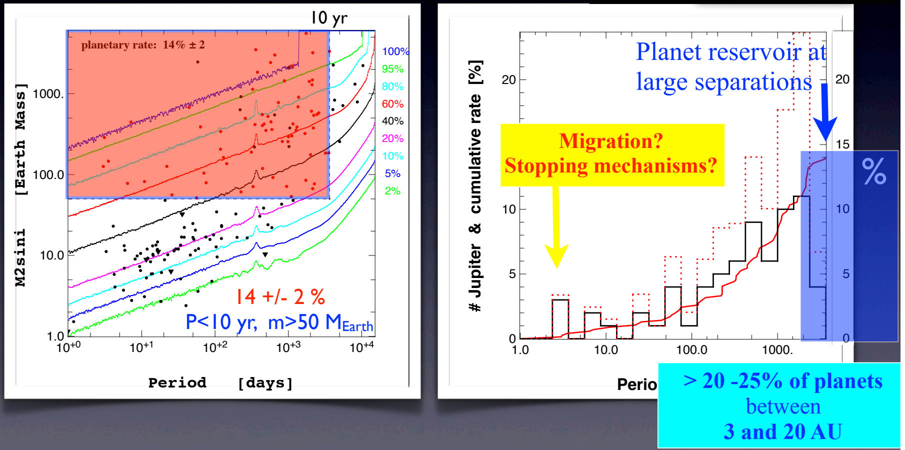
Mass distribution

with incompleteness correction

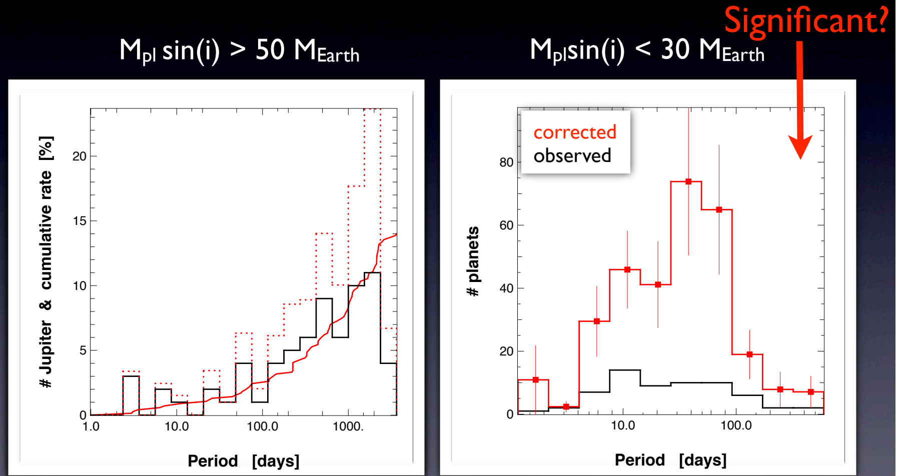




Period distribution: Gaseous giant (M_{pl} sin(i) > 50 M_{Earth})



Period distribution for M_{pl} sin(i) < 30 Earth-masses

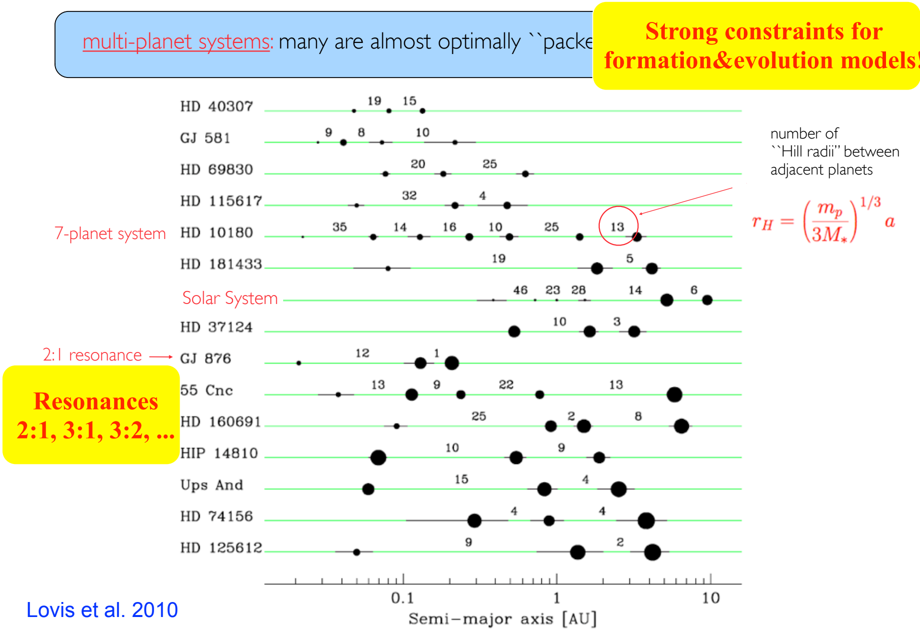


Multiplicity

20-25% of giants planets in multi-planet systems

> 70 % of planetary systems with m_{pl}sin(i)< 30 M_{Earth} include more than one planet

Radial-velocity Systems with n>2 planets

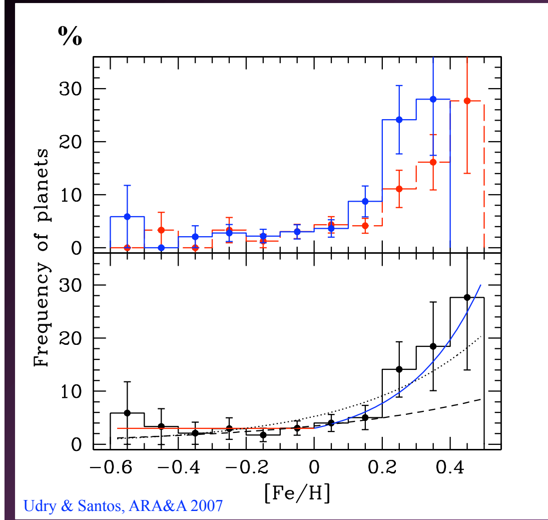


Lovis et al. 2010

Properties of planet-host stars: i) metallicity

Giant gaseous planets

Stars with planets are more metal rich?
(Gonzalez 1997, 1998, 1999)



Santos et al. 2001-2006
(Coralie, UVES, HARPS)

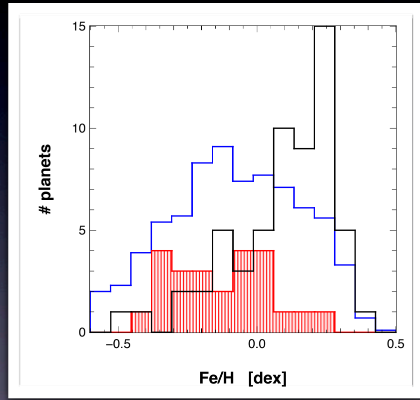
Fischer & Valenti 2002-2005

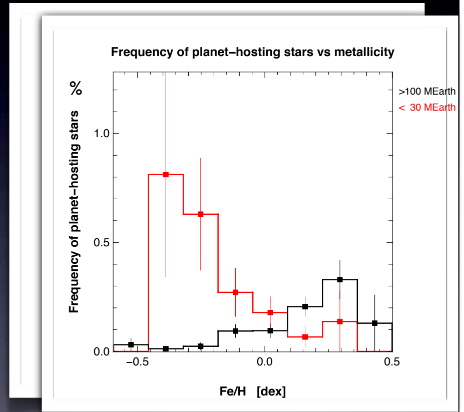
- Well-defined samples with and without planets
- Uniform analyses
- Large number of stars

Constant probability at low metallicities ?

Host star metallicities

Blue : Entire sample
Black : M_{pl} sin(i) > 100 MEarth
Red : M_{pl} sin(i) < 30 M_{Earth}





Small-mass planets: no clear dependency with metallicity
=> anticorrelation of planet occurrence probability (TBC)

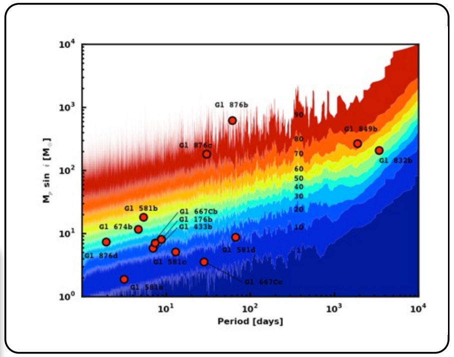
The HARPS Search for Southern Extra-Solar Planets
The M-dwarf sample

Bonfils et al. 2011, A&A in press (arXiv:1111.5019)

Sample:
~100 brightest M dwarfs < 11 pc

Results:

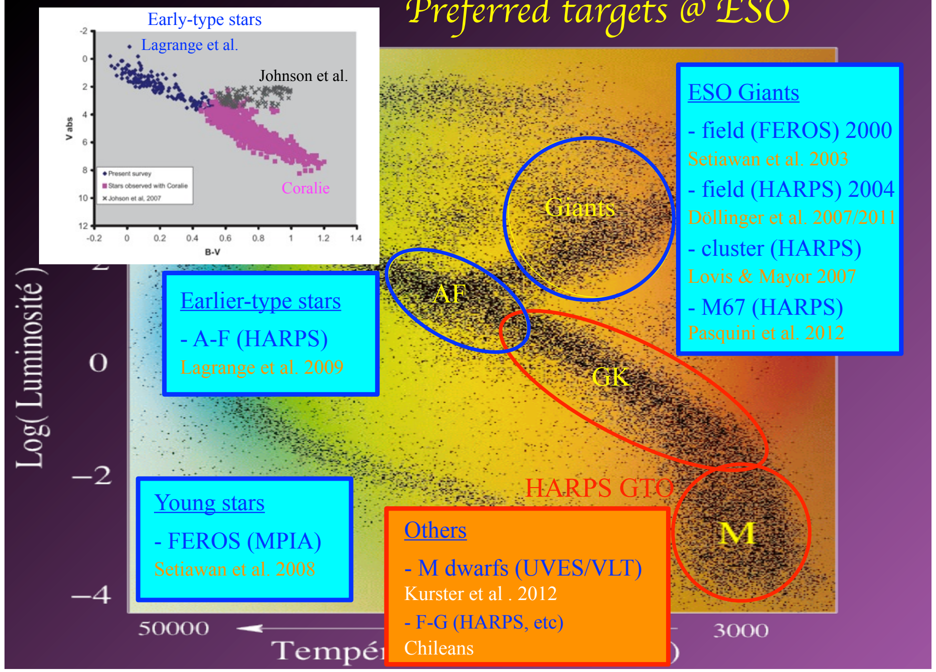
- 90% of M-dwarfs planets w/ $m \sin i$ < 20 Mearth
- lowest-mass planets (GJ 581e; $m \sin i$ = 1.9 Mearth)
- first prototypes of habitable planets (GJ 581 c&d)
- statistical results :
  - few Jupiter-mass planets
    $f < 1\%$ for $1 < P < 10$ day
    $f = 0.02^{+0.03}_{-0.01}$ for $10 < P < 100$ day
  - super-Earth are common (>30%)
    $f = 0.36^{+0.25}_{-0.10}$ for $1 < P < 10$ day
    $f = 0.52^{+0.50}_{-0.16}$ for $10 < P < 100$ day



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

(a direct measure)

Preferred targets @ ESO



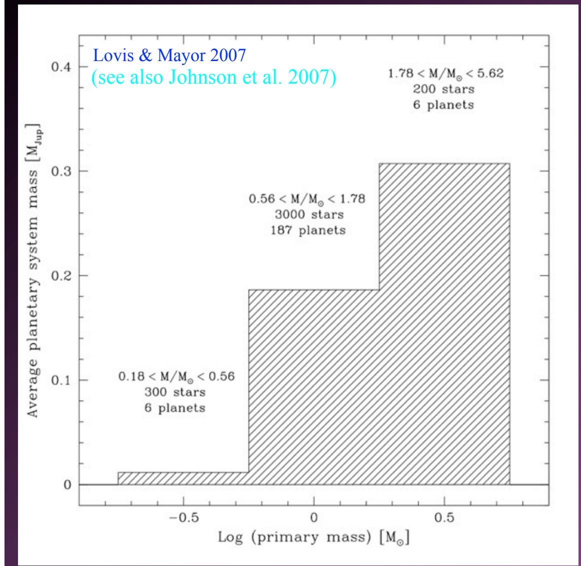
ESO Giants
- field (FEROS) 2000
Setiawan et al. 2003
- field (HARPS) 2004
Dollinger et al. 2007/2011
- cluster (HARPS)
Lovis & Mayor 2007
- M67 (HARPS)
Pasquini et al. 2012

Earlier-type stars
- A-F (HARPS)
Lagrange et al. 2009

Young stars
- FEROS (MPIA)
Setiawan et al. 2008

Others
- M dwarfs (UVES/VLT)
Kurster et al . 2012
- F-G (HARPS, etc)
Chileans

Properties of planet-host stars: ii) primary mass



Equal bin in log(M_{star})
- M dwarfs
- solar stars
- higher masses ([sub]giants)

Planetary system mass
planet masses/star number

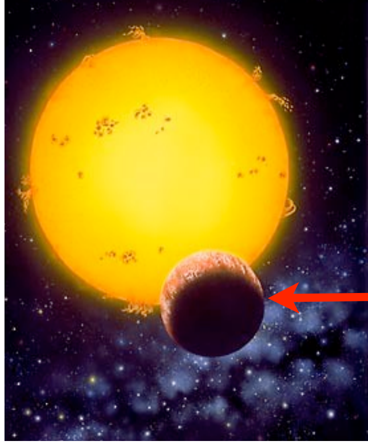
=> mass of planetary material scales with M_{star}

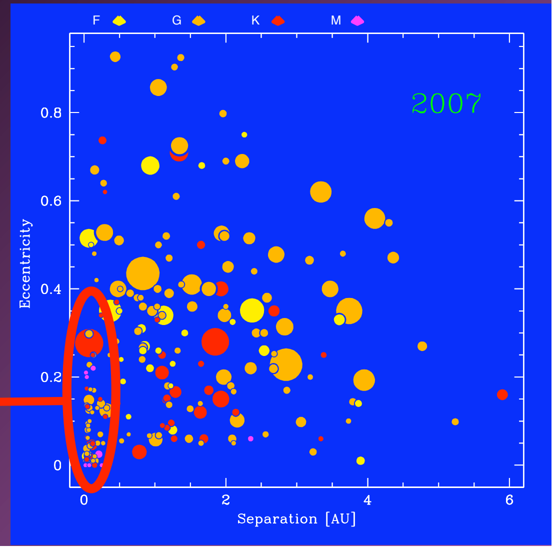
RV bias
underestimate the last bin

Constraints from transit detections

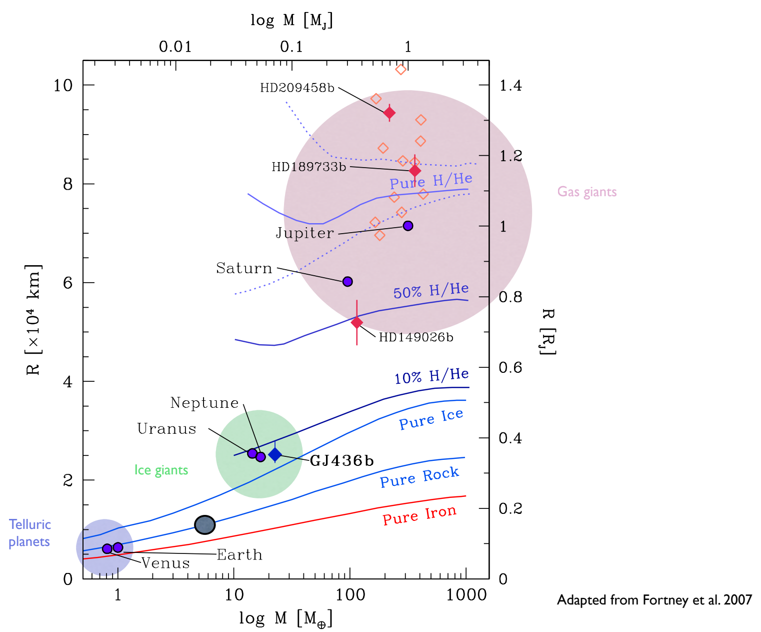
2000-2010: ~100 transiting planets

Short periods:
high probabilities
of transit



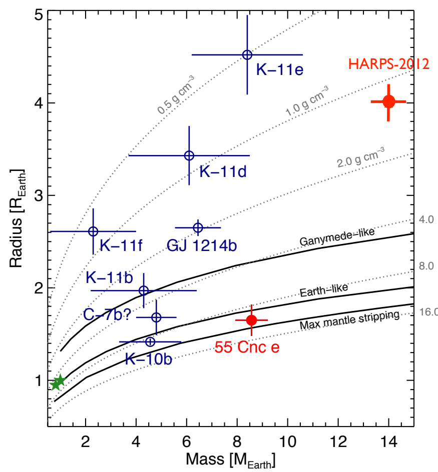


The mass-radius diagram for planets



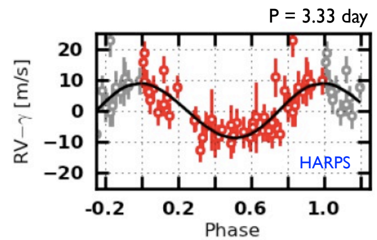
Adapted from Fortney et al. 2007

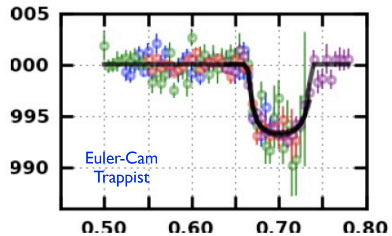
Observed mass-radius relationship



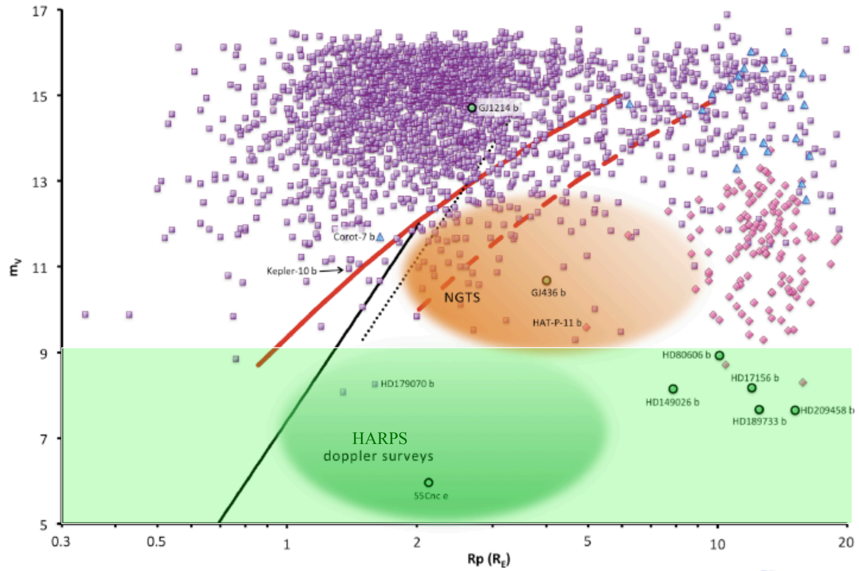
=> Diversity of composition

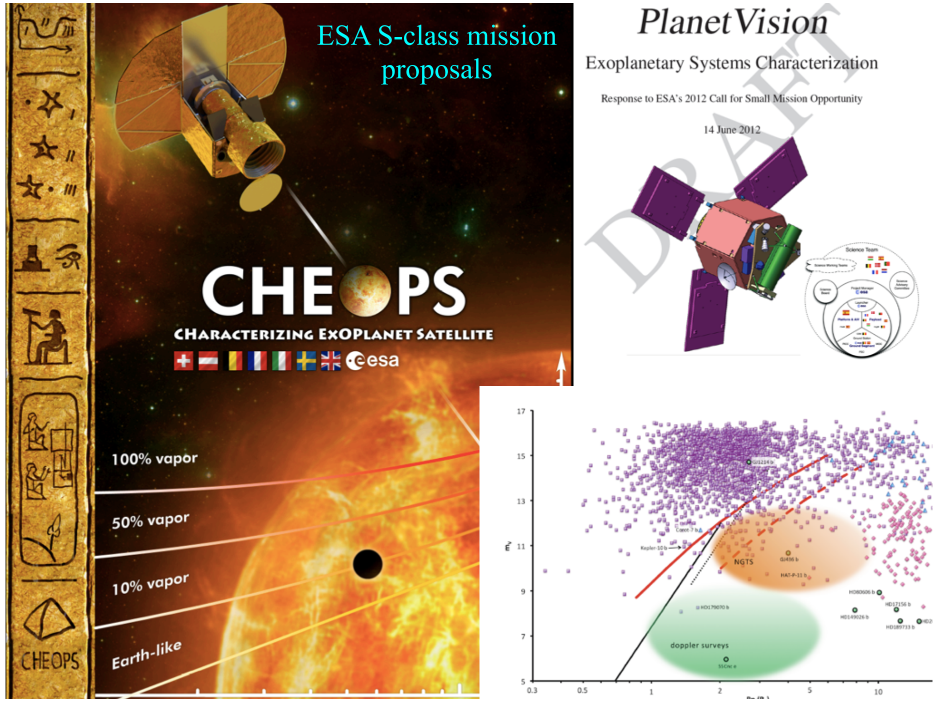
A new transiting Neptune: GJ 3470 b
(La Silla/ESO discovery)



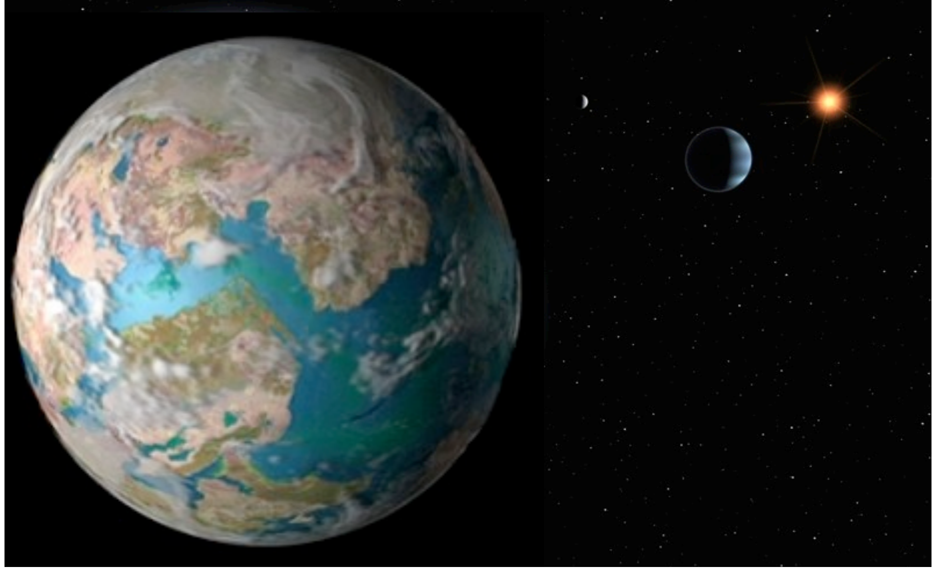


(Bonfils et al. 2012, A&A in press)



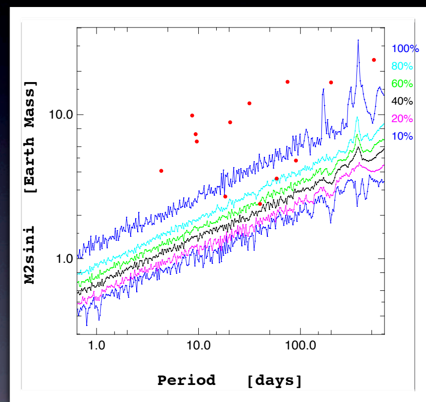


Detection of Earth twins in the HZ of stars ?



Pushing down the limits

- Detection limits for the 10 stars with the largest number of HARPS measurements (N > 165)
- 15 planets hosted by these 10 stars
- Super-Earths are detectable up to a period of 1 year



HD 85512 b (Pepe et al. 2011)
P = 58.4 days, m_{pl} sin(i) = 3.6 M Earth
185 measurements

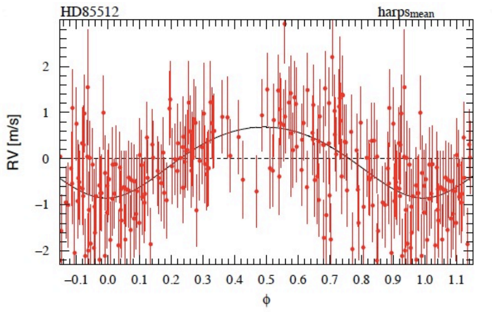
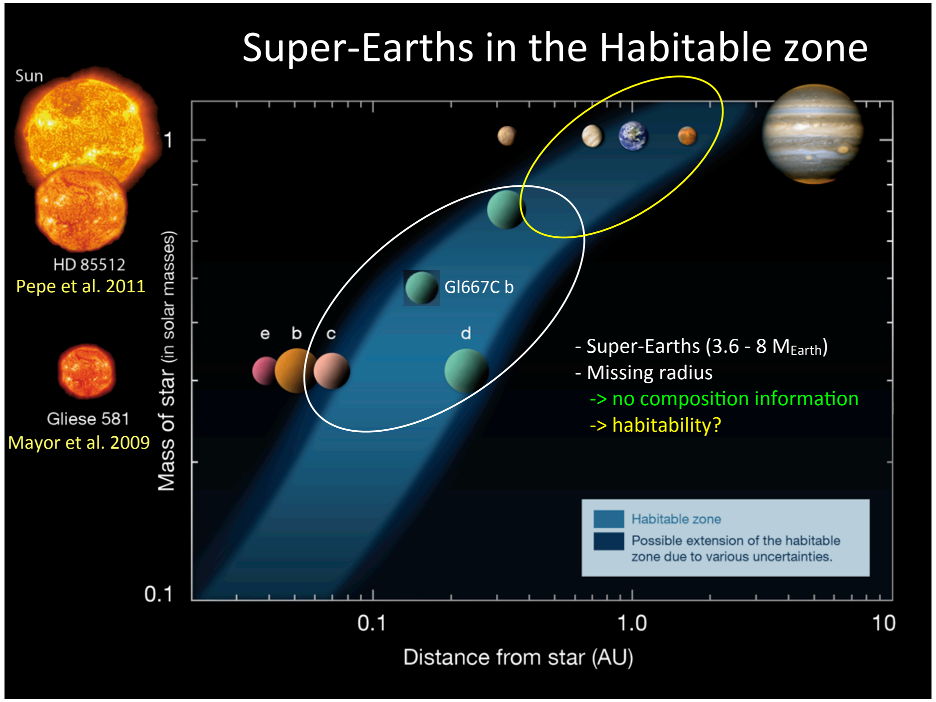
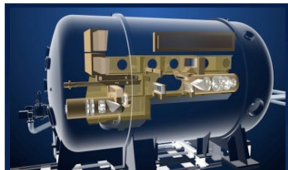


Fig. 13. Phase-folded RV data of HD 85512 and fitted Keplerian solution. The dispersion of the residuals is 0.75 m s^{-1} *rms*.



Future RV searches ... @ESO



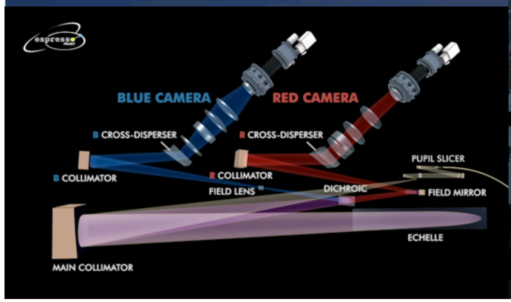
ESPRESSO@VLT

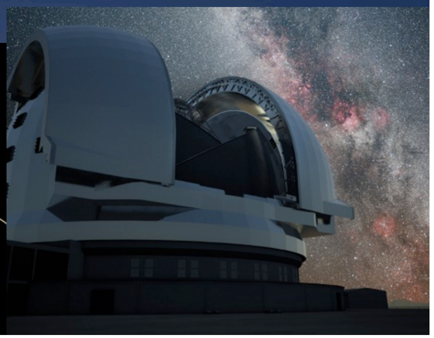
- Better precision on larger telescope
- Aim: 10 cm/s instrumental and photon noise
- Science: Search for Rocky planets in HZ, variability of fundamental constants, etc.
- Up to 4 UTs incoherently

HIRES@E-ELT

- Better precision on larger telescope
- Aim: cm/s-level instrumental and photon noise
- Science: Exoplanet characterization, cosmology, etc.

(COsmic Dynamics and EXo-earth experiment)





Lessons learned & points to take home

1) Leading role of ESO
   - as host: the Euler Swiss telescope (Coralie), FEROS
   - HARPS, presently the most precise instrument in the world
     => site of La Silla

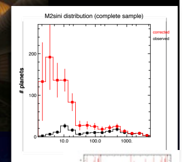
2) HARPS: Unprecedented statistical analysis of exoplanet properti[es]

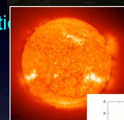
3) Better understanding of the star
   (stellar oscillation, activity, magnetic cycles, etc).

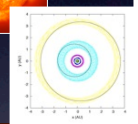
4) The more we observe, the more we know (HARPS is unique)
   => it is fundamental now to continue the observational effort
   => complete knowledge of our closest bright neighbors

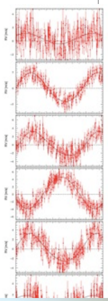
5) Transiting planets around bright stars are treasure trove for accessing planet internal structure, atmosphere composition, dynamics.
   => space facilities for low-mass planets

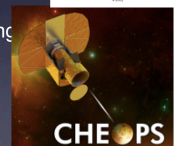
6) RV's are great (and cheap)
   - detections, orbital parameters, system geometry
   - complementarity to other techniques
     + transit (next talk by F. Bouchy)
     + astrometry (following talk by J. Sahlmann)
     + high-resolution spectroscopy

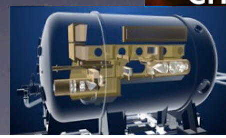


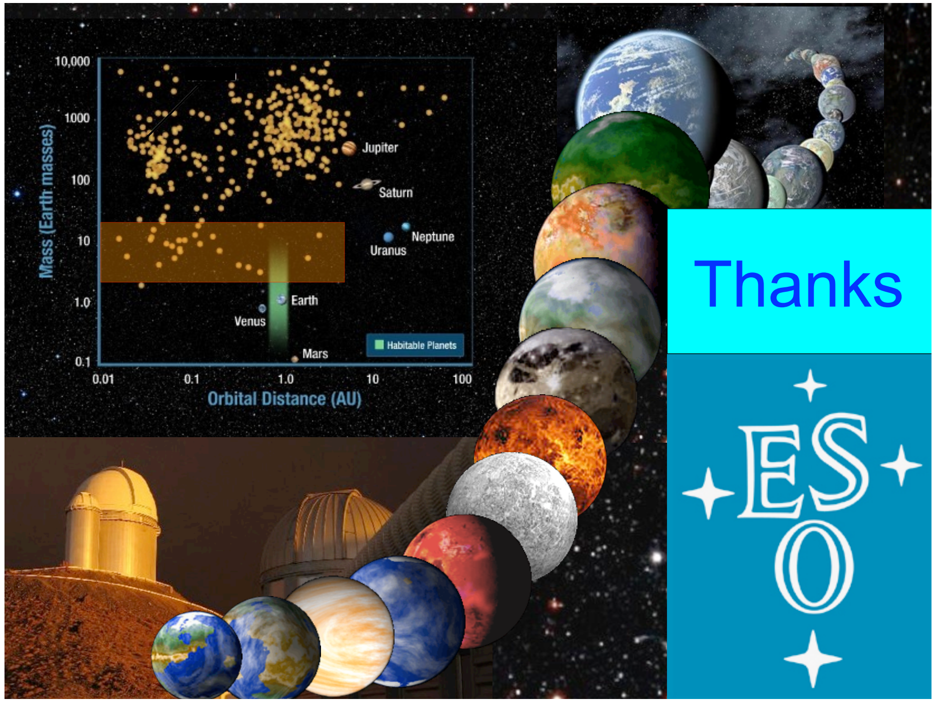












10,000
1000
100
10
1.0
0.1
Mass (Earth masses)
0.01
0.1
1.0
10
100
Orbital Distance (AU)
Jupiter
Saturn
Neptune
Uranus
Earth
Venus
Mars
Habitable Planets
Thanks
ESO