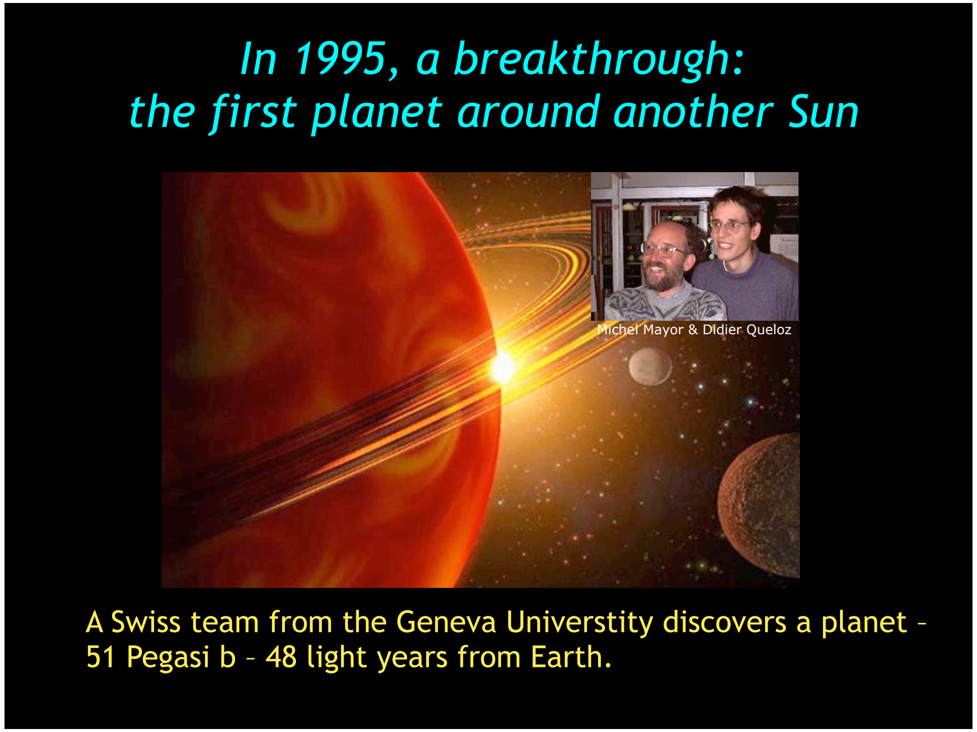
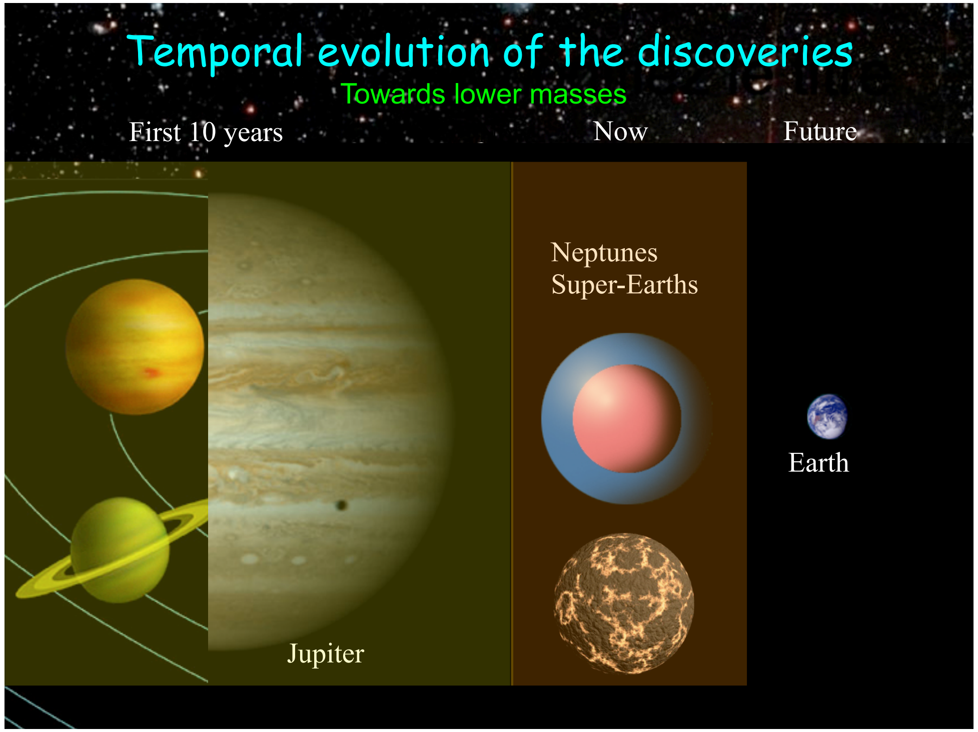

Exoplanet population properties
from the
radial-velocity and transit surveys
Stéphane Udry
Geneva University/Geneva Observatory
Switzerland

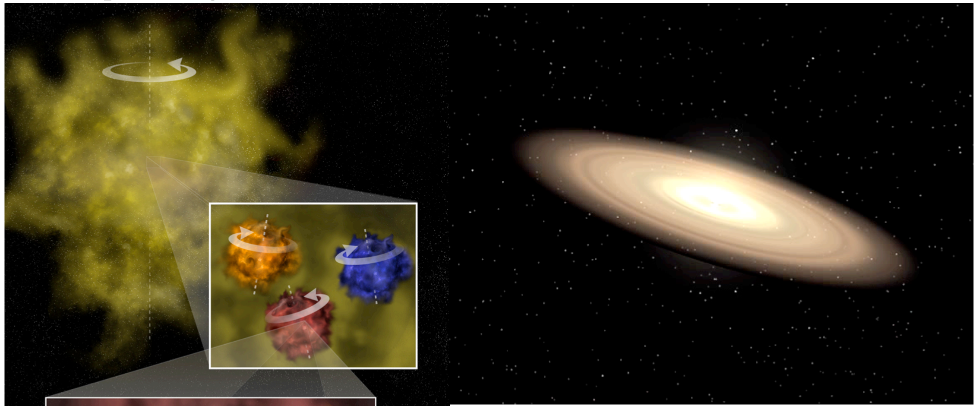

In 1995, a breakthrough:
the first planet around another Sun
Michel Mayor & Didier Queloz
A Swiss team from the Geneva Universtity discovers a planet – 51 Pegasi b – 48 light years from Earth.

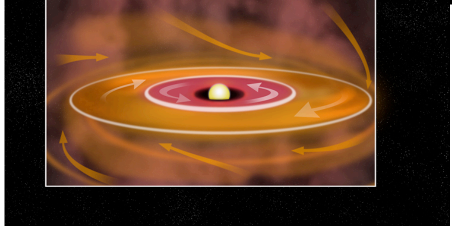

Temporal evolution of the discoveries
Towards lower masses
First 10 years
Now
Future
Neptunes
Super-Earths
Earth
Jupiter


outline
• General context
• RV's: Statistical properties from super-Earths to giant planets.
– Geneva: the Coralie and HARPS surveys
– planetary orbital parameters (gaseous giants vs low-mass planets)
– multi-planet systems
– properties of parent stars (metallicity, M-dwarf survey)
• Insights from transits (ground-based, CoRoT, Kepler)
– physical planet properties
– system geometries
– summary of important Kepler findings
• The detection of Earth-type planets in the HZ of stars
– Status: M-dwarfs, solar-type stars
– instrumental progress for RV's and limitations
– other techniques (space)

Stellar and planetary formation

Collapse of a gas cloud

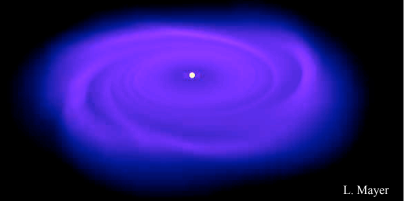




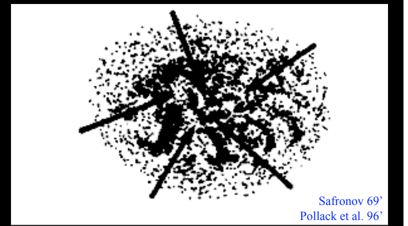
Discs : natural by-product of stellar formation
=> nursery of planets

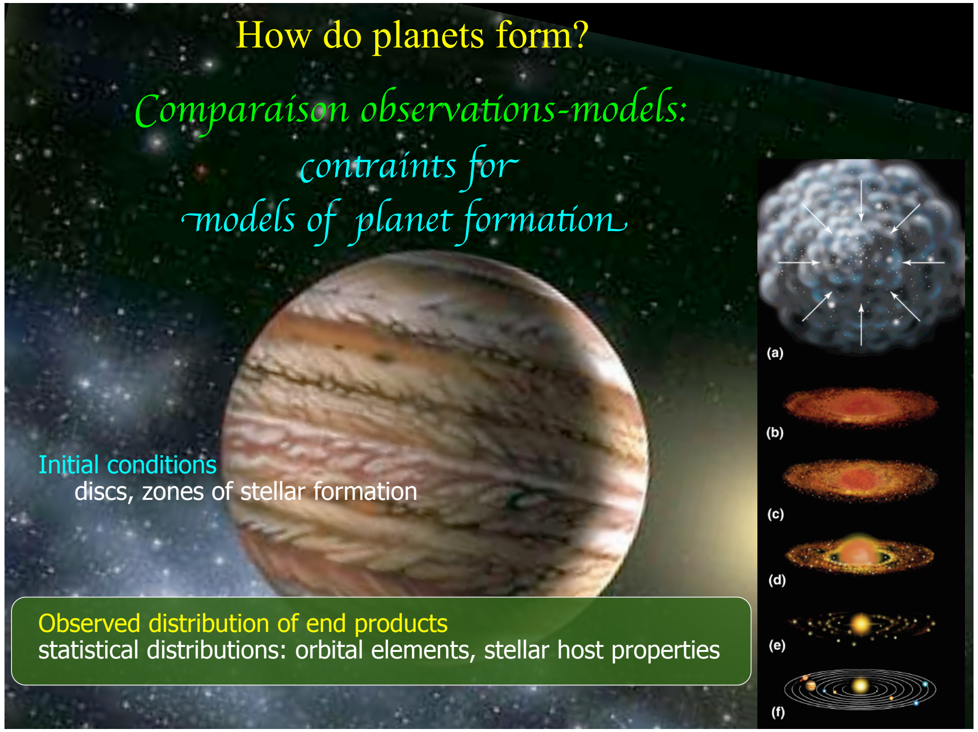
Planets buid up from the gas and dust particles in the protoplanetary discs

Gravitational instability



Core accretion





Available exoplanet sample

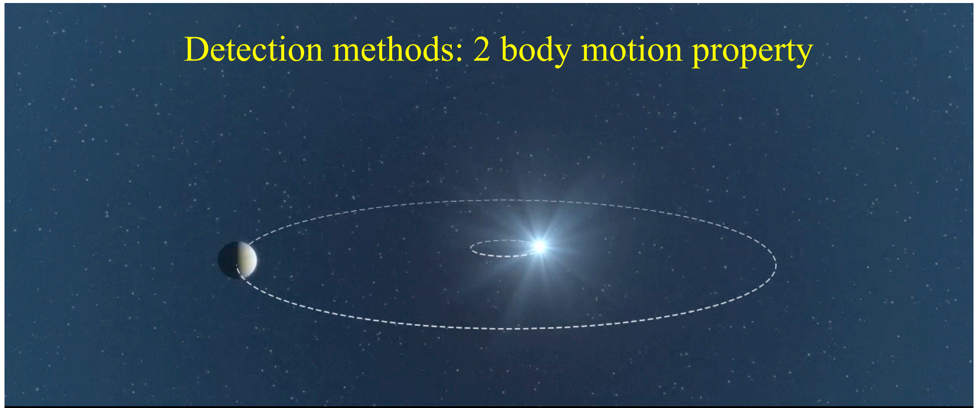
The extra-solar planet encyclopedia (Jean Schneider, Paris)

All Catalogs
update : **05 June 2012**

All Candidates detected — **775 planets**

- Candidates detected by radial velocity or astrometry
  update : 05 June 2012
  567 planetary systems
  712 planets
  96 multiple planet systems
  - Transiting planets
    update : 05 June 2012
    201 planetary systems
    235 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 : 22 May 2012
  12 planetary systems
  16 planets
  3 multiple planet systems

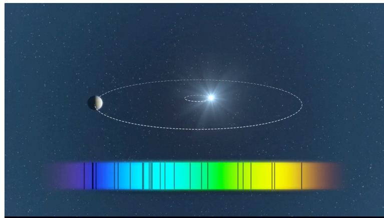
Detection methods: 2 body motion property



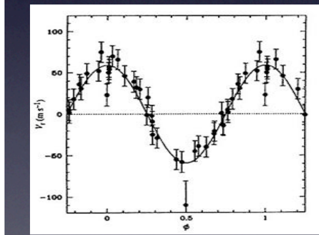
RV technique | Astrometry | Transit

+ Photometric variation: phase function

Planet detectability with radial velocities



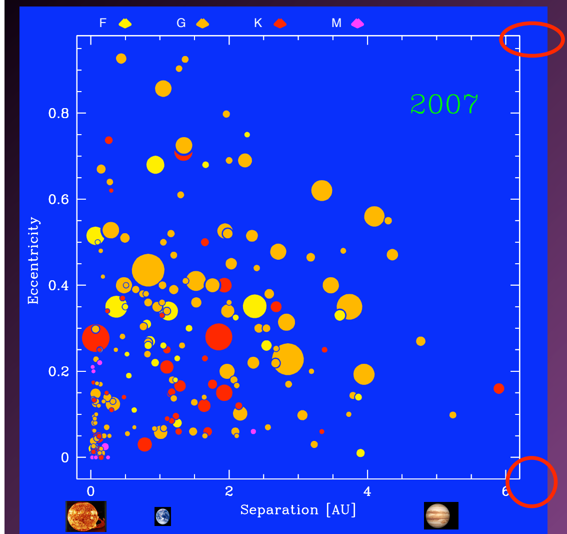
$$k_1 = \frac{28.4\ \mathrm{m\ s^{-1}}}{\sqrt{1-e^2}}\ \frac{m_2 \sin i}{M_{\mathrm{Jup}}} \left(\frac{m_1 + m_2}{M_{\mathrm{Sun}}}\right)^{-2/3} \left(\frac{P}{1\ \mathrm{yr}}\right)^{-1/3}$$



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	: 0.09 m s^{-1}

Extra-solar planets: radial-velocity detections

1995-2012: >700 RV planets (+ transit candidates)



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

WARNINGS

1) There are biases !!!!
   - Generally avoid "unsuitable" stars for RV searches (activity, rotation, age, ...)
   - Magnitude-limited samples, Metallicity-biased samples

2) Uniformity of precision and coverage?

3) Heterogeneity of targets (dwarfs, giants, binaries, etc.)

BUT

1) Surveys with "non solar" targets are progressing

2) There are large good samples
   - LicK+Keck+AAT 1330 FGKM stars
   - CORALIE volume-limited sample: 1650 F-K dwarfs

The Geneva 1.2-m Euler telescope + CORALIE spectrograph at La Silla Observatory (ESO/Chile)

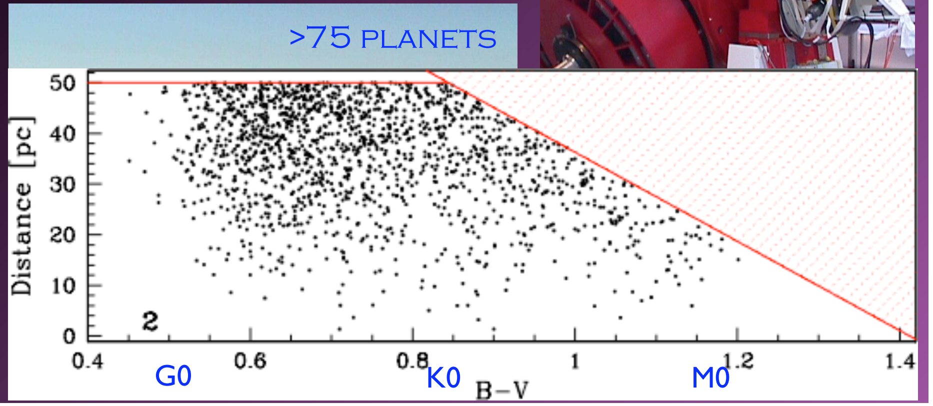
Euler+Coralie – La Silla (1998-...)

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, +....

1.2-m Euler Swiss telescope
Simultaneous thorium technique

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

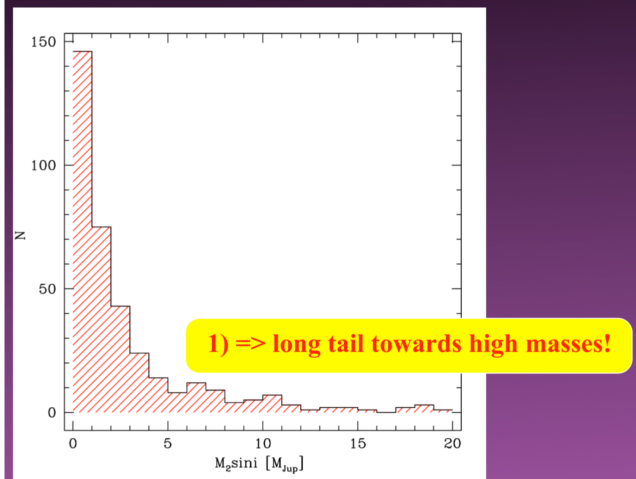
Volume-limited sample: 1650 F8-M0 dwarfs
(Queloz et al. 2000, Udry et al. 2000)



Planetary mass distribution

End of 2011: > 700 planets

Linear scale



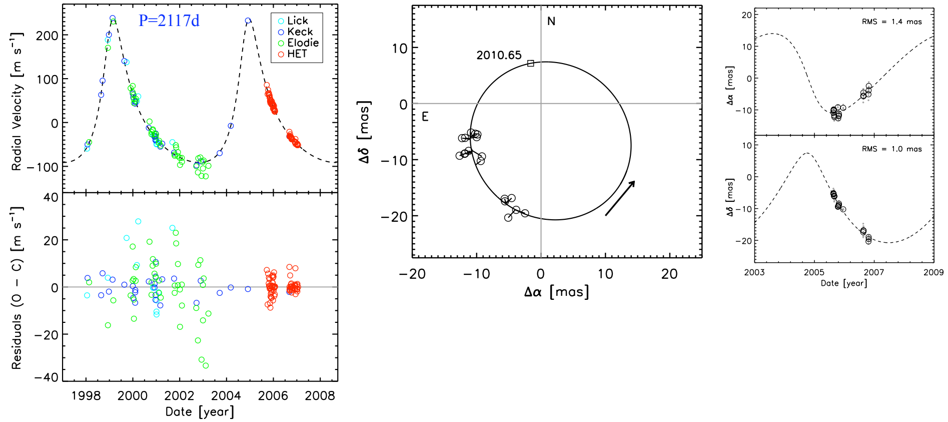
Massive planets: true mass from astrometry

HD 33636 b (Bean et al. 2007)

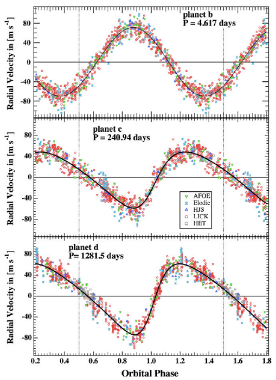
Radial velocities
$m2\sin i = 9.3 M_{Jup}$

HST Fine Guidance Sensor
$m2 = 142 \pm 11\ M_{Jup}$

→ late M star companion



Massive planets: "true" mass from astrometry



Ups And (McArthur et al. 2010)

HST Fine Guidance Sensor

$P_b = 4.6$ d

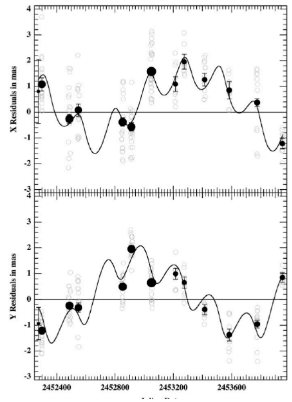
$P_c = 240$ d

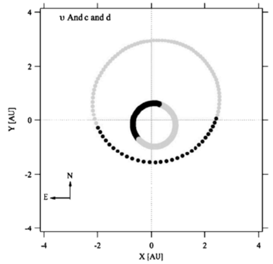
$P_d = 1281$ d

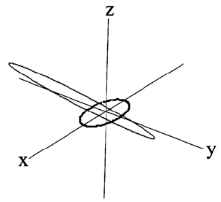
$m_b \sin i = 0.7\ M_{Jup}$

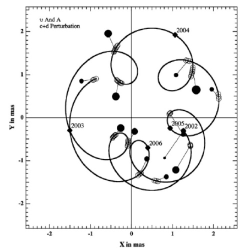
$i_c = 8^o$ $m_c = 12\ M_{Jup}$

$i_d = 24^o$ $m_d = 10\ M_{Jup}$



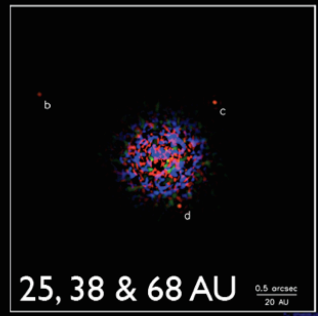






HR8799 b, c, d : 7, 10 & 10 M_{Jup}

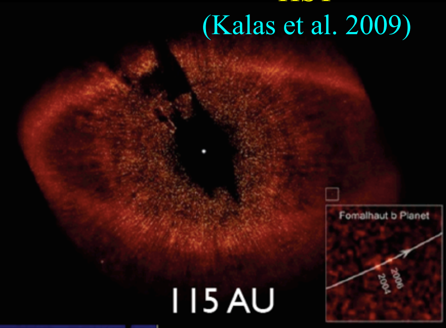
(Marois et al. 2009)



Formalhaut b : 3 M_{Jup}

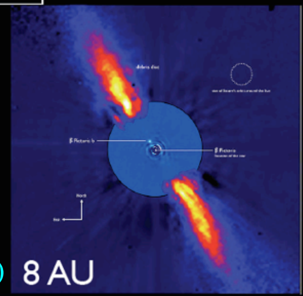
HST

(Kalas et al. 2009)



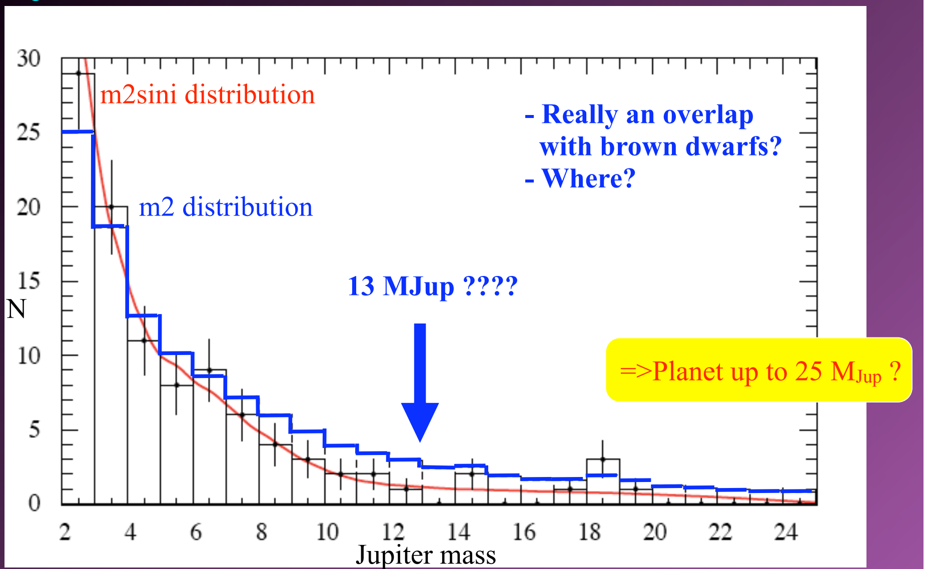
Beta Pic b : 8 M_{Jup}

(Lagrange et al. 2009, 2010)



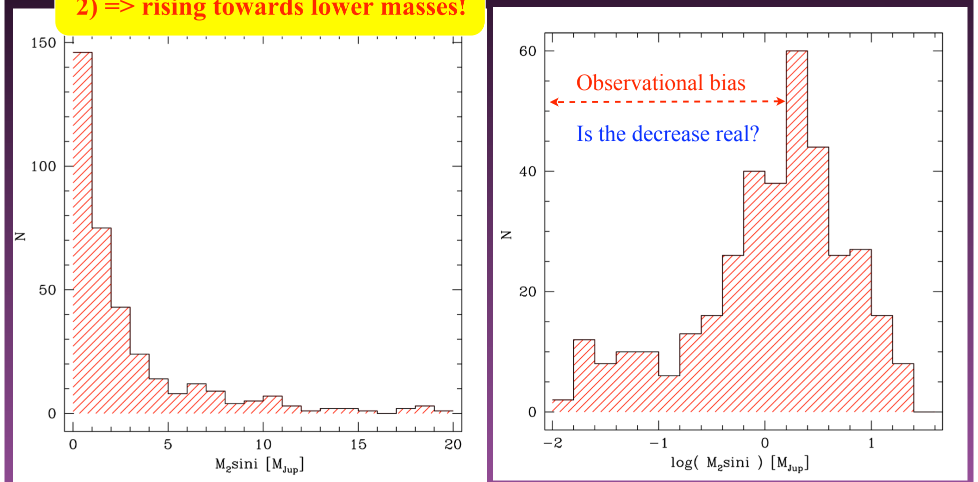
Planetary mass distribution

Segransan et al. 2009



Planetary mass distribution

2) => rising towards lower masses!



Planet detectability with radial velocities

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

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HARPS: stability < 1 m/s

- Observatoire de Genève
- Physikalisches Institut, Bern
- Observatoire Haute-Provence
- Service d'Aéronomie, Paris
- ESO

ΔRV =1 m/s

↕

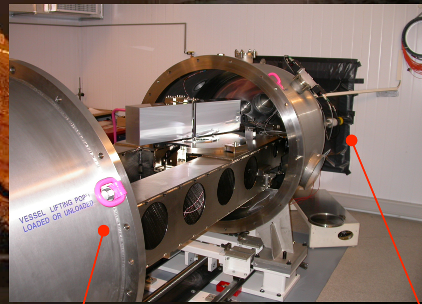
Δλ=0.00001 A

↕

15 nm

↕

1/10000 pixel



thorium calibration

2–fiber fed

ΔRV =1 m/s

↕

ΔT =0.01 K

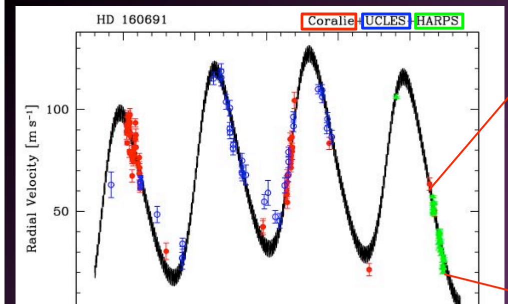
↕

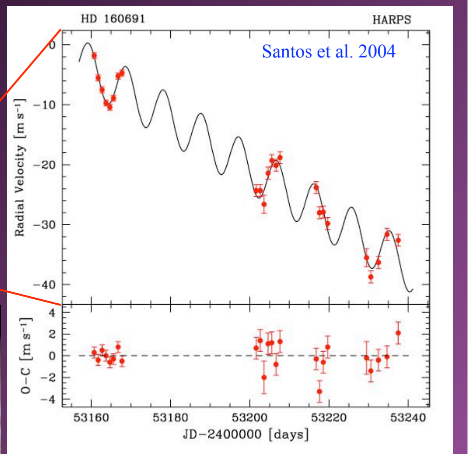
Δp=0.01 mBar

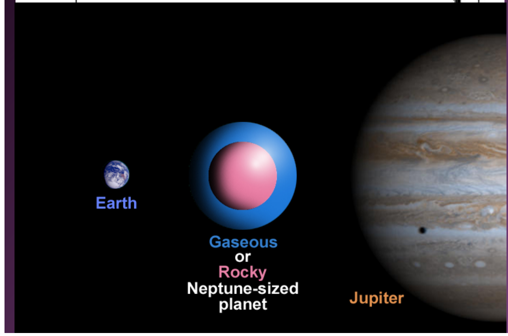
Pressure controlled

Temperature controlled

Precision at work -> zoom toward smaller-mass planets







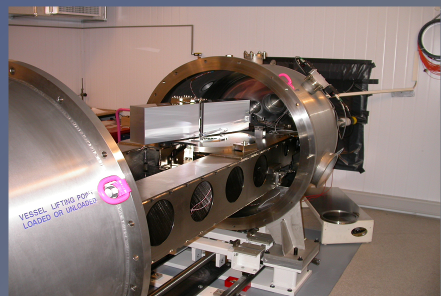
$p = 9.5$ d

$m_{pl} = 10.5\ M_{Earth}$

The HARPS search for low-mass planets

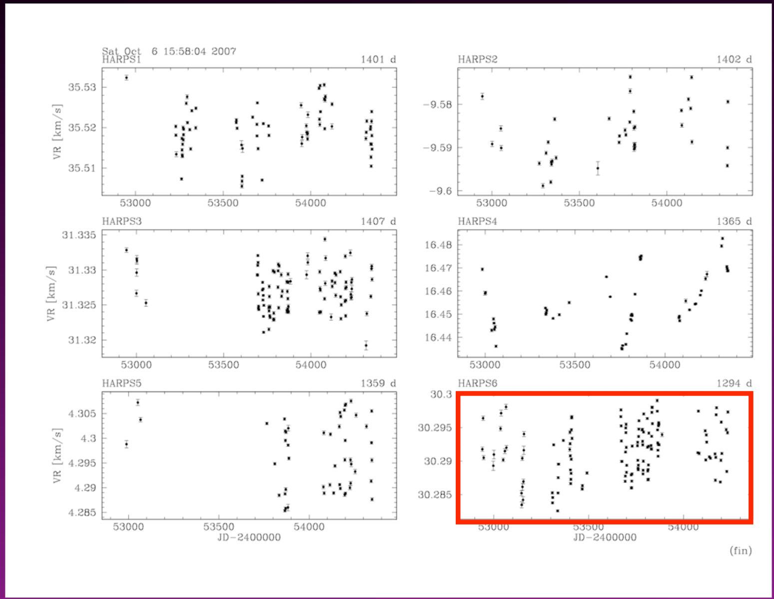
- Sample of ~400 slowly-rotating, nearby FGK dwarfs from the CORALIE planet-search survey + known planets
- HARPS $\log(R'_{HK})<-4.8$ => ~376 good targets
  Non evolved (Sousa et al. 2009)
- Observations ongoing since 2004
- Focus on low-amplitude RV variations
  => about 50% of HARPS GTO time (250 nights)
  => continuing with 280 nights over 4 years (-->2013)

ESO-3.6m @ La Silla



HARPS

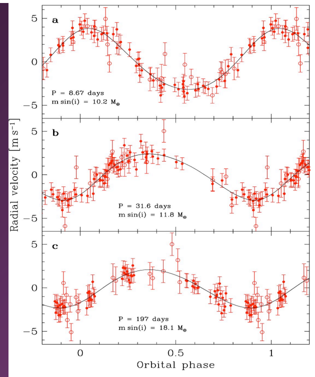
Harps: a blossom of candidates (I)

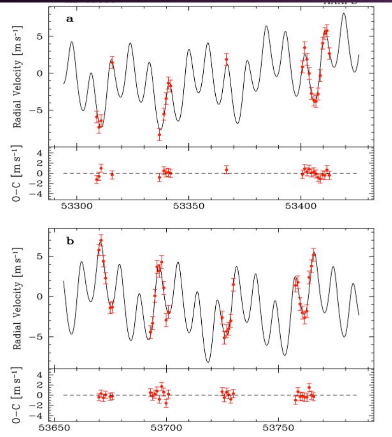


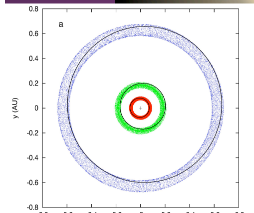
HD 69830: A trio of Neptunes

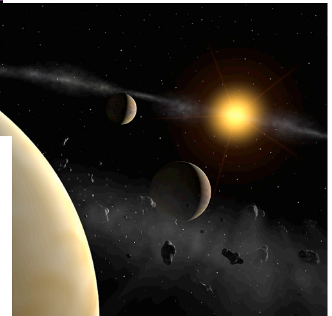
P1 = 8.67 days	a = 0.078 AU	M sini = 10.2 M_{Earth}
P2 = 31.6 days	a = 0.186 AU	M sini = 11.8 M_{Earth}
P3 = 197 days	a = 0.63 AU	M sini = 18.1 M_{Earth}

HARPS@3.6-m telescope, ESO La Silla





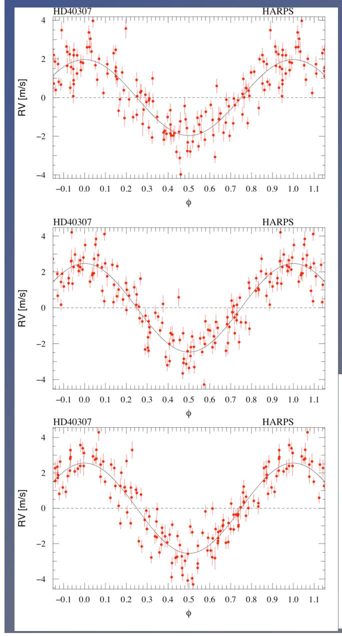




Lovis et al., Nature 2006

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 $M_\oplus$

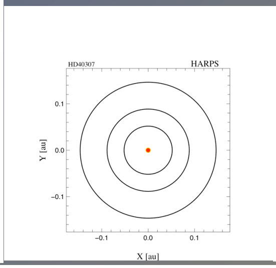
P_2 = 9.62 days
e_2 = 0.03
m_2 sini = 6.9 $M_\oplus$

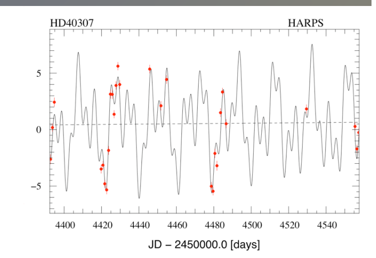
P_3 = 20.5 days
e_3 = 0.04
m_3 sini = 9.7 $M_\oplus$

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

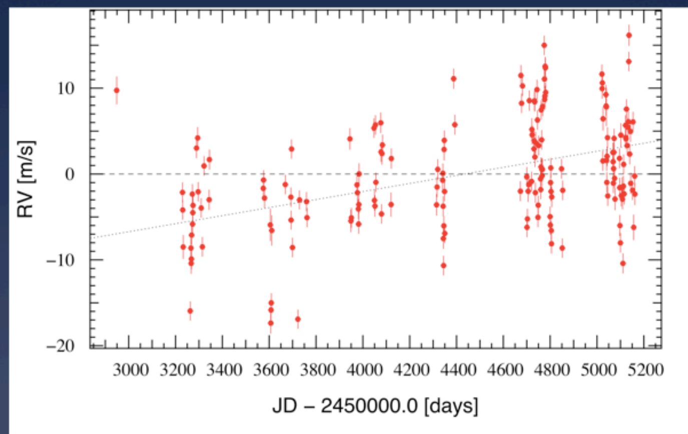
O-C = 0.85 m/s
135 observations

+ drift = 0.5 m/s/y





HD10180



175 HARPS precise radial velocities

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 $M_\oplus$

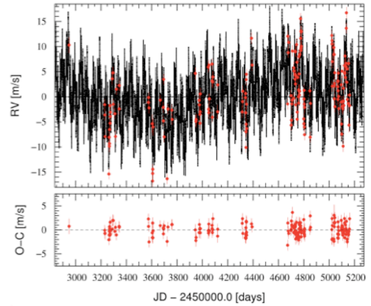
P_4 = 49.7 days
e_4 = 0.06
m_4 sini = 24.8 $M_\oplus$

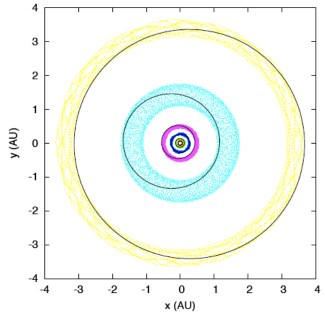
P_5 = 122.7 days
e_5 = 0.13
m_5 sini = 23.4 $M_\oplus$

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





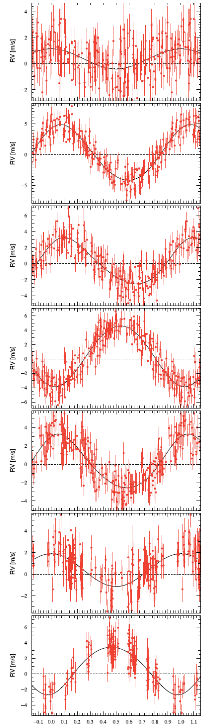
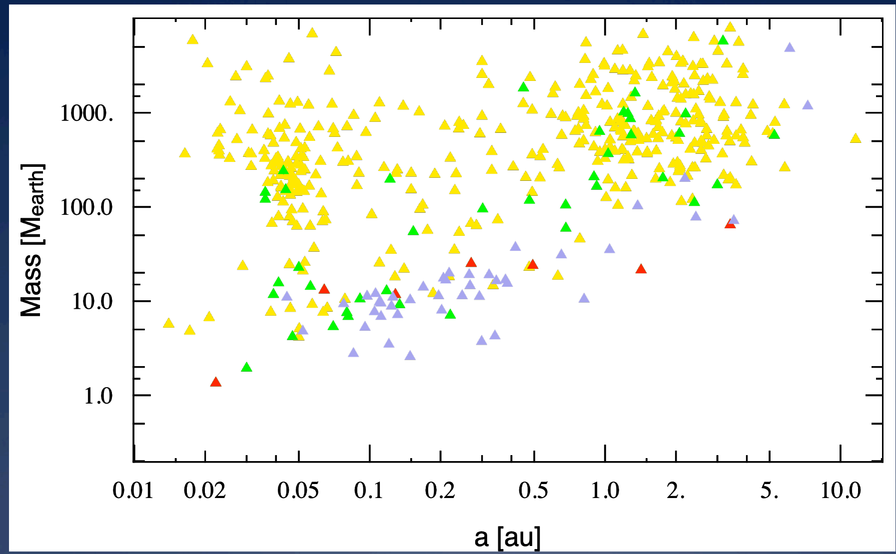


Fig. 5. Radial velocity time series with the 7-Keplerian model overplo

HARPS planets



Combined Coralie+HARPS stellar sample

CORALIE volume-limited sample:

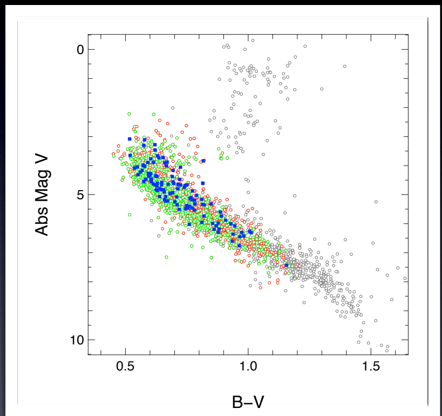
- distance < 50 pc
- log R'_{HK} < -4.75 (F,G); -4.70 (K)
- no binaries
- measurement precision ~5-10 m/s
  (depending on star magnitude)

822 FGK stars (1998 to present)
Focus on gaseous giant planets, long periods

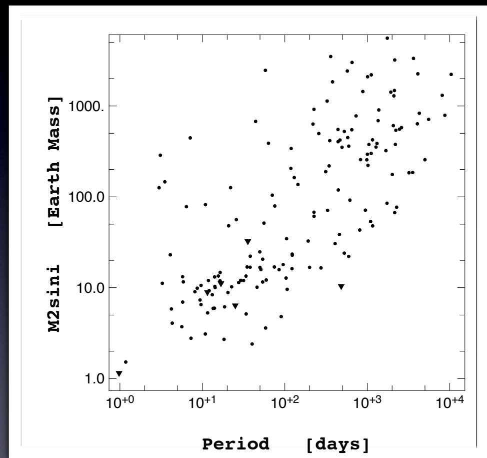
HARPS subsample:

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

376 FGK stars (2003 to present)
Focus on super-Earths and Neptune-mass planets



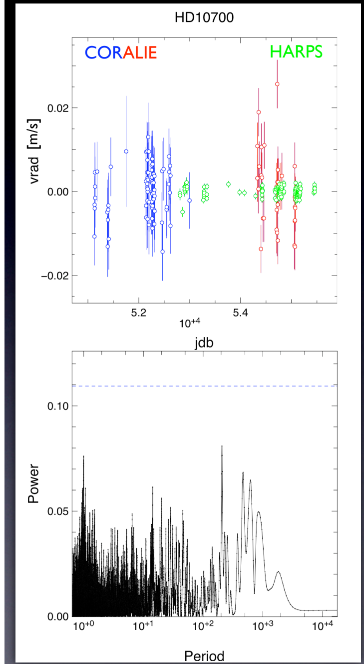
The Msini - log P plane

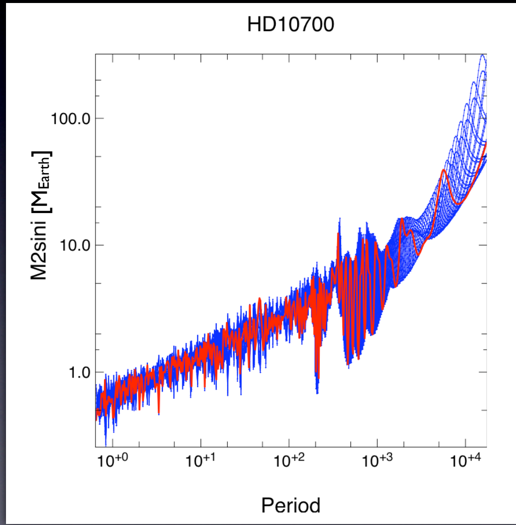


155 planets in 102 planetary systems

Occurrence frequency estimate

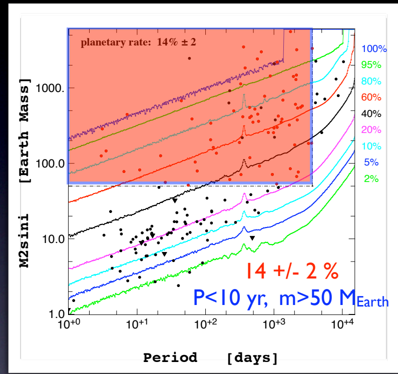
1) Detection limits for each star



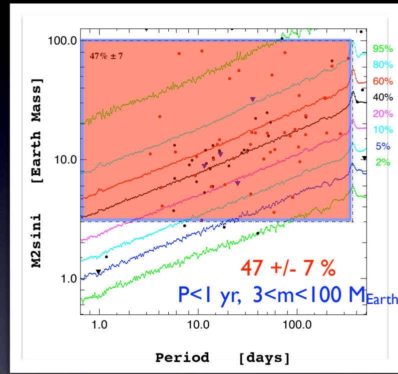


Occurrence frequency estimate

2) Detection probability of the survey



HARPS + Coralie



HARPS only

3) Occurrence rate

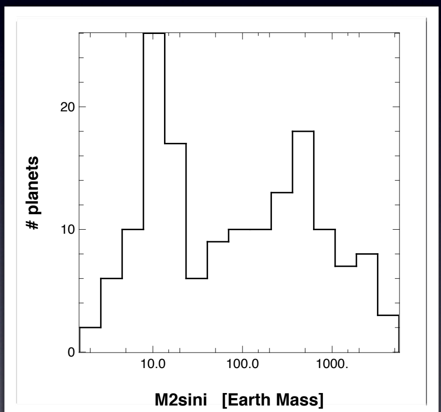
$$f = N_{pl} / N'_{star}$$

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

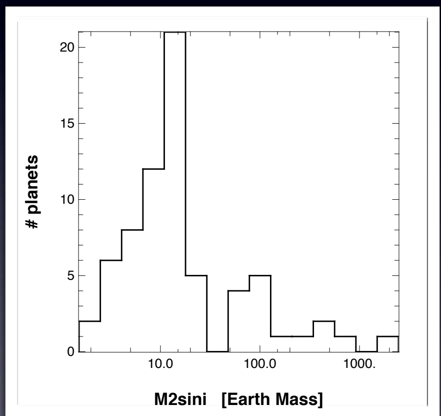
Mass distribution

Predominant occurrence of planets with m2sin < 30 Earth-masses

Detections in the global sample

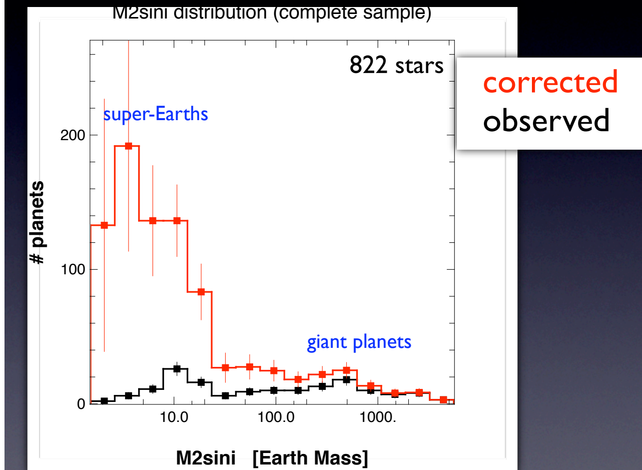


...and for P < 100 days

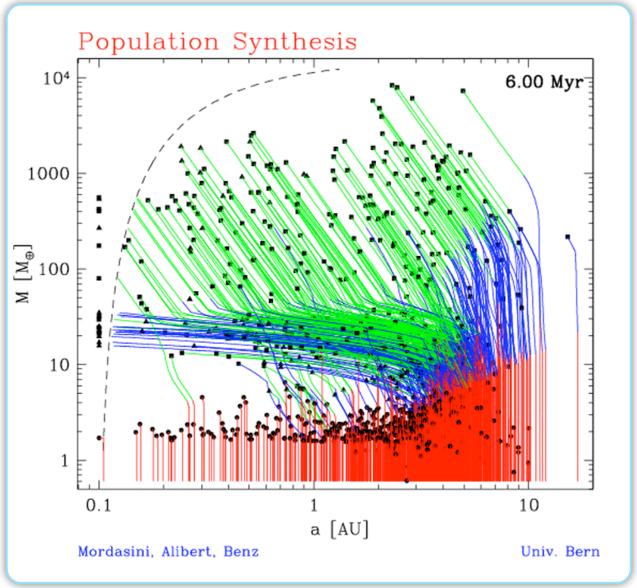


Mass distribution

with incompleteness correction



Formation tracks



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

Type I migration
(Analytical rate reduced by f_I)

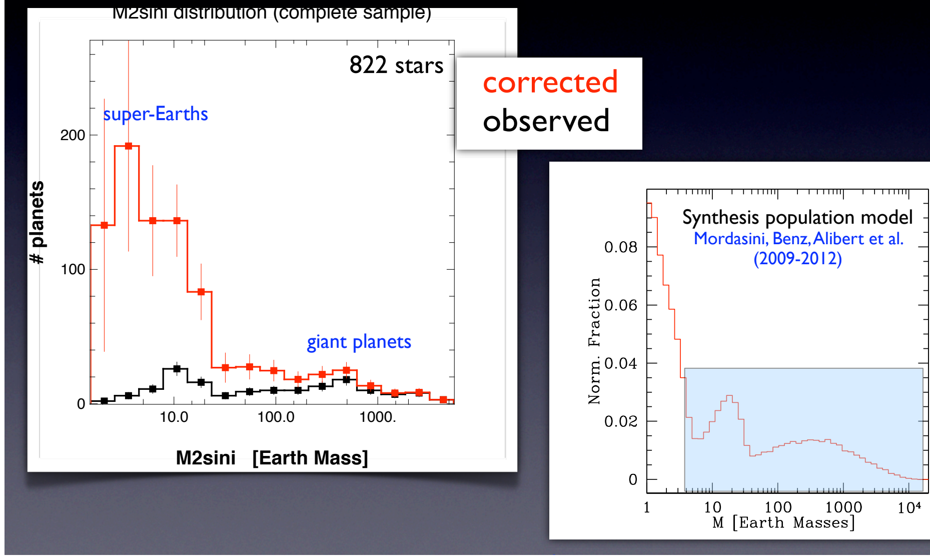
Type II migration
(Disk dominated: M_p<$M_{disk,loc}$)

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

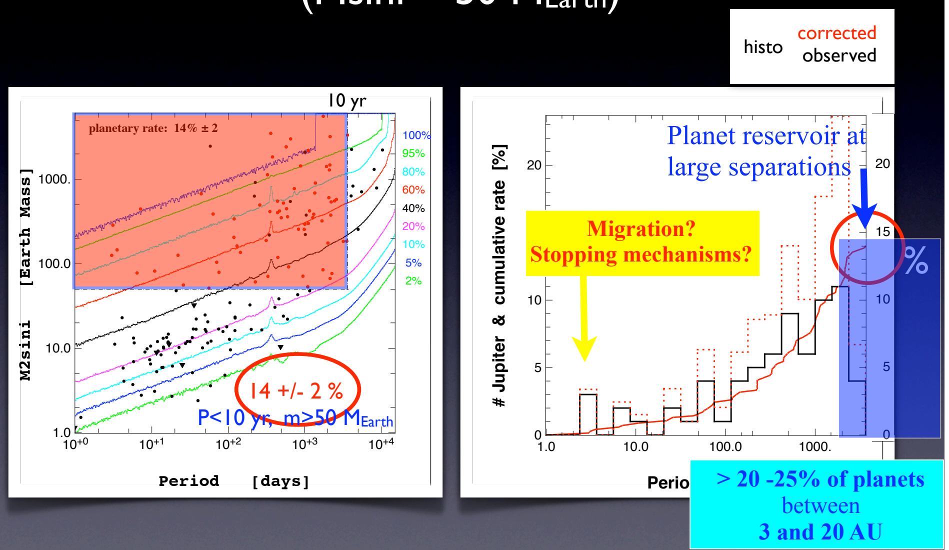
Also
Ida & Lin (2004-2010) models

Mass distribution

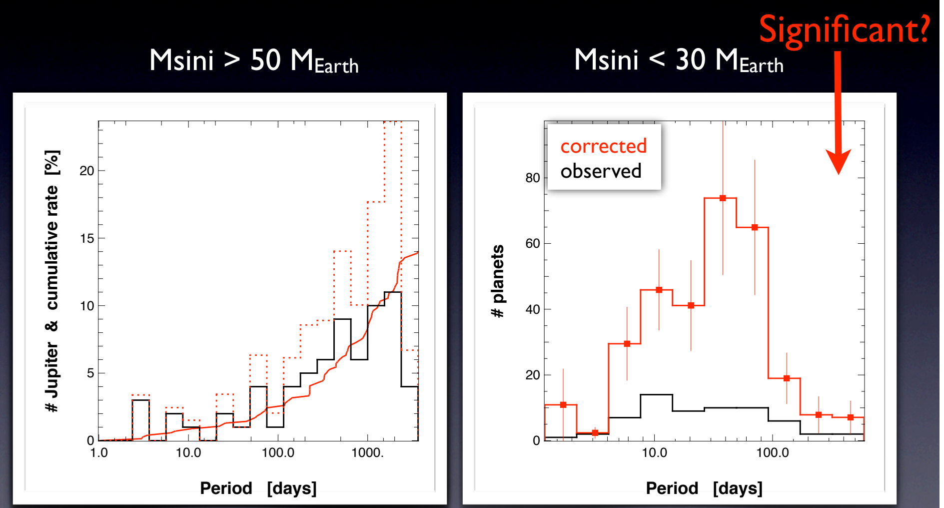
with incompleteness correction



Gaseous giant planets (Msini > 50 M_{Earth})



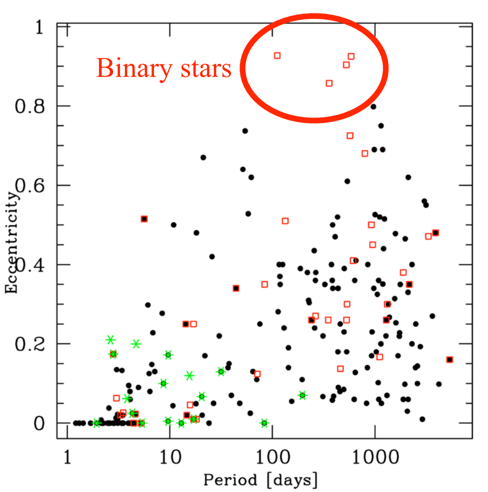
Period distribution for Msini < 30 Earth-masses



Exoplanet eccentricities

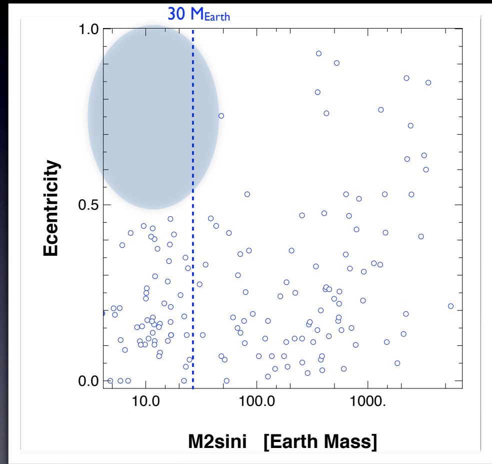
- High observed eccentricities
  - <e> = 0.28 > any planet of the SS

Origin?
Formation - evolution?



- Possible explanations
  - Planet-planet interactions
  - Planet-planetesimal interaction
  - Influence of stellar or planet companion (Kozai effect)
  - Planet-disk interaction (M_{pl}>10 M_{Jup})
  - Dynamical interactions in a cluster
  - Multi-planet migration
  - Others

Eccentricities as a function of Msini



Lack of
eccentric low-mass planets

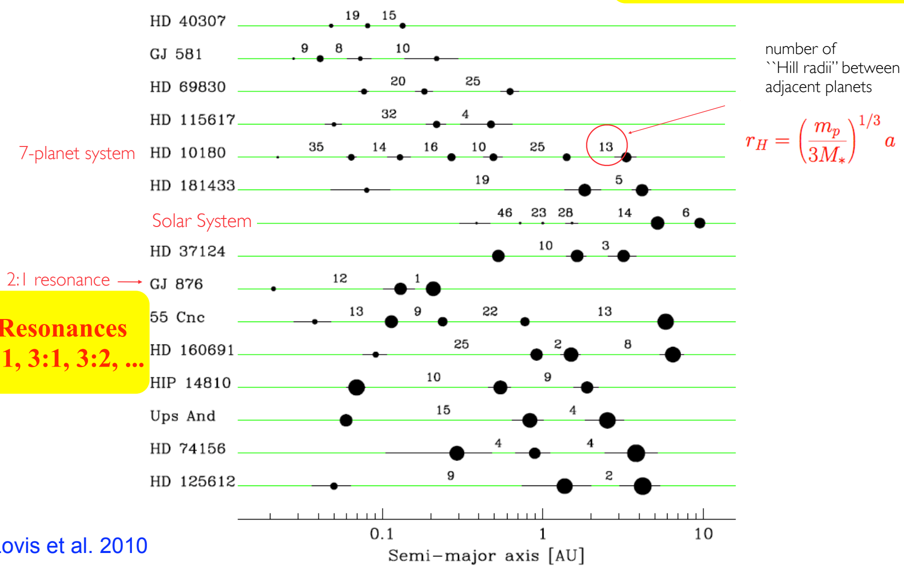
Formation?
Stability?

Especially taking into account that
1. "e" is often overestimated
2. small-mass planets in systems

Radial-velocity Systems with n>2 planets

multi-planet systems: many are almost optimally ``packed''

Also a constraint for planet formation models!



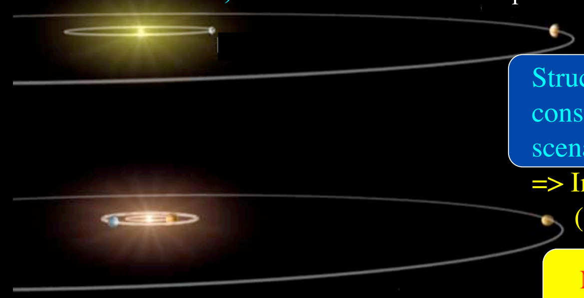
Resonances 2:1, 3:1, 3:2, ...

Lovis et al. 2010

Multi-planetary systems (RV surveys)

- Present statistics
  RV: 145 planets in multi-planet systems:
  ~ 20-25 % of known exoplanets
  (+ transit candidates)

- Most of them with 2 planets
- HD10180: 7 planets
- 55 Cnc : 5 planets
- Mu Ara, Gl876 : 4 planets
- Ups And, HD69830, HD40307: 3 planets



Structure helps us to understand/ constrain planet-formation scenarios

=> Importance of dynamics
(stability, Inner structure,...)

Need for good modeling of evolution processes!

- longest-running programmes
  --> largest fraction of multi-planet systems
  Planets mainly form in multi-planet systems

Need for multi-planet formation models!

Multiplicity

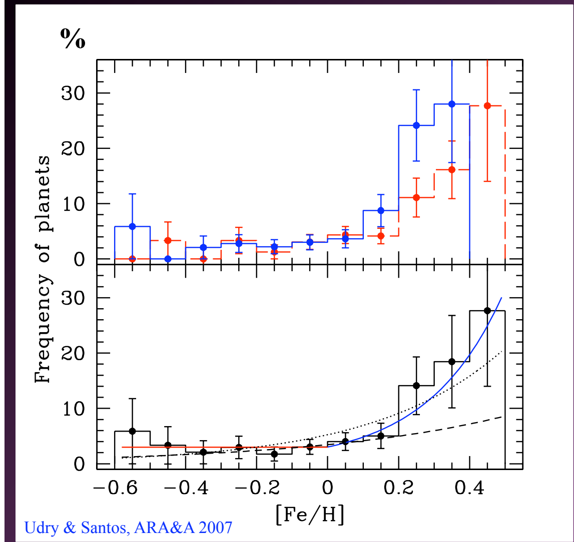
> 70 % of planetary systems with m2sini< 30 M Earth include more than one planet

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

Fischer & Valenti 2002-2005

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

Average: 2 regimes
flat + power law

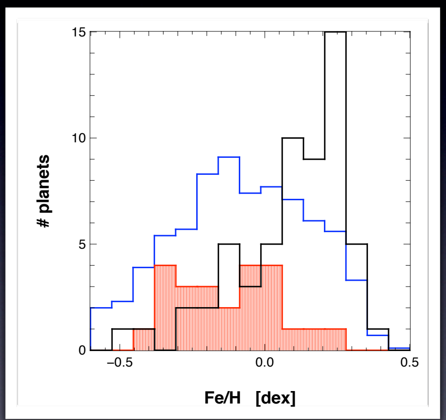
Constant probability at low metallicities ?

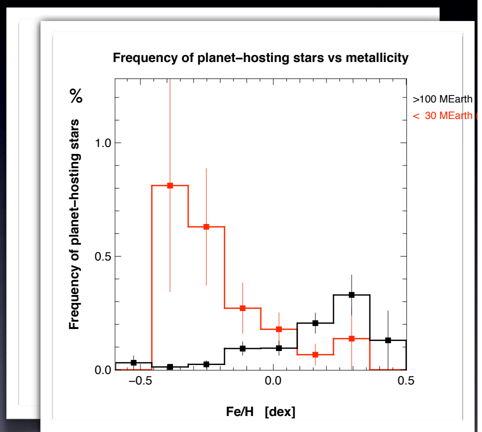
Host star metallicities

Blue : Entire sample

Black : Msini > 100 MEarth

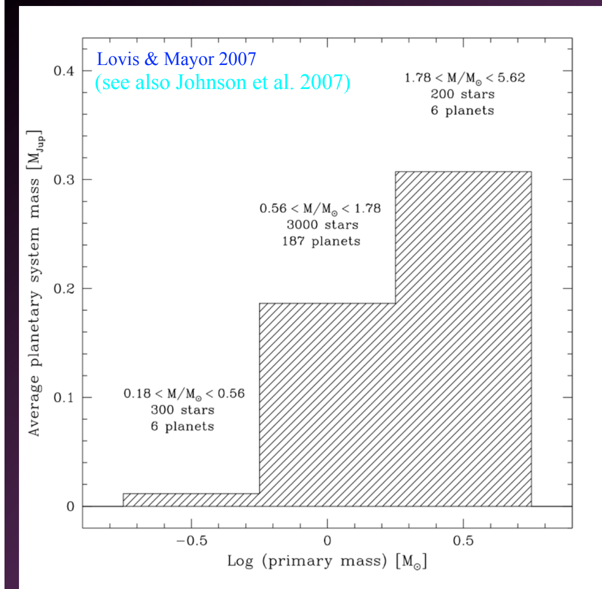
Red : Msini < 30 MEarth





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

Properties of planet-host stars: ii) primary mass



Equal bin in log(M_{star})

- M dwarfs
- solar stars
- higher masses ([sub]giants)

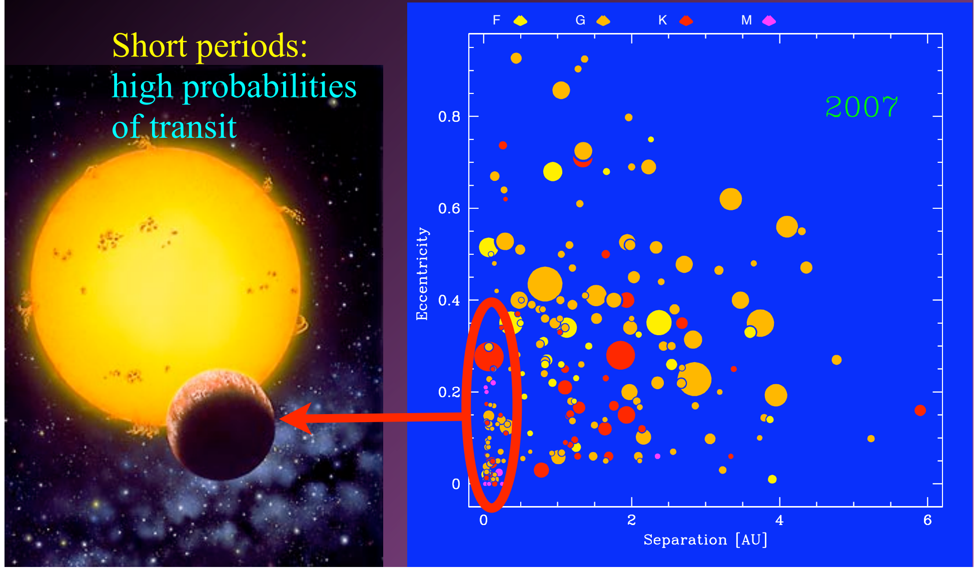
Planetary system mass
planet masses/star number

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

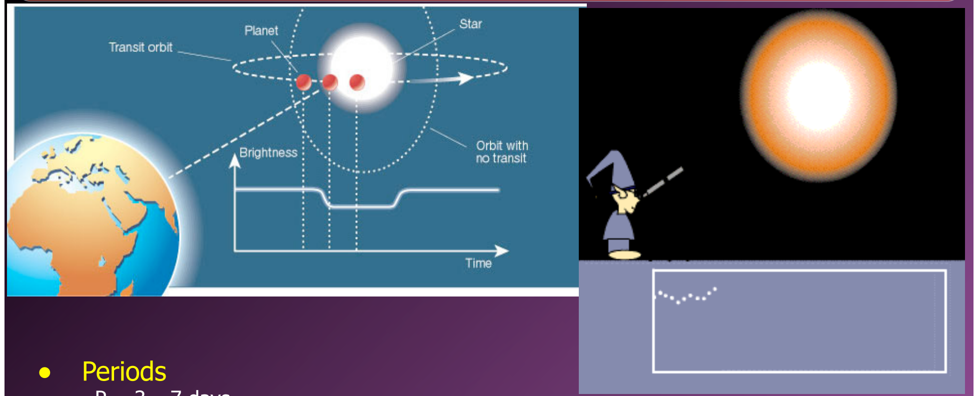
RV bias
underestimate the last bin

Constraints from transit detections

2000-2010: ~100 transiting planets



The power of shadows: photometric transit method

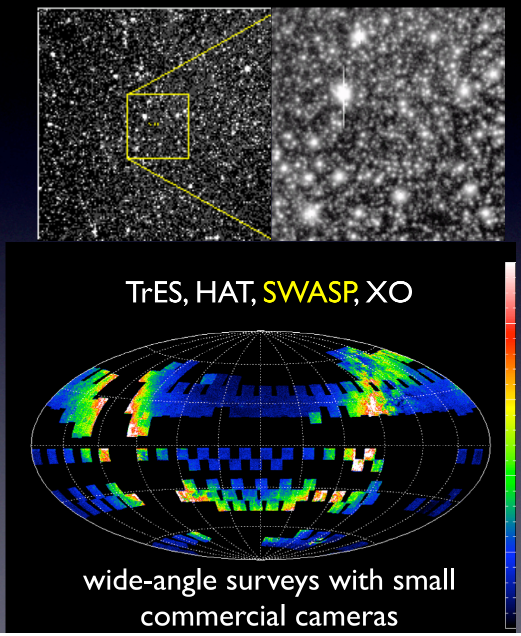


- Periods
  P = 3 – 7 days
- Probability
  $p_t = R_{star} / a = 0.1$
- Depth
  $\delta I / I = (R_{pl} / R_*) = 0.01$

R_{pl}, M_{pl} (VR), ρ

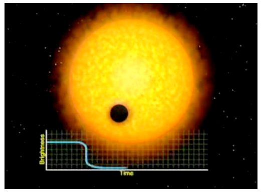
Contraints for models of planetary inner structure

Photometric surveys :V= 8-14 mag

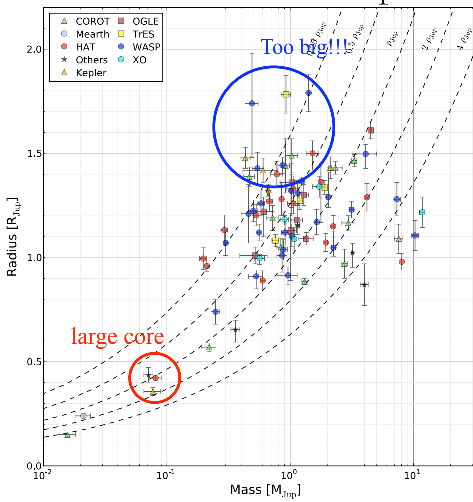


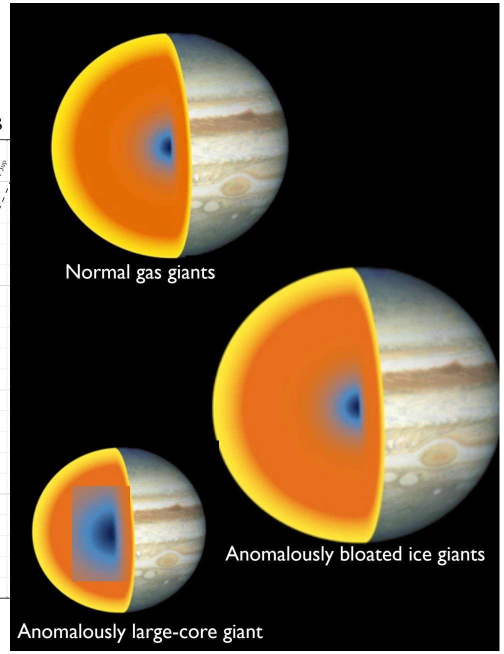
SWASP

Mass-radius-density relation for planets



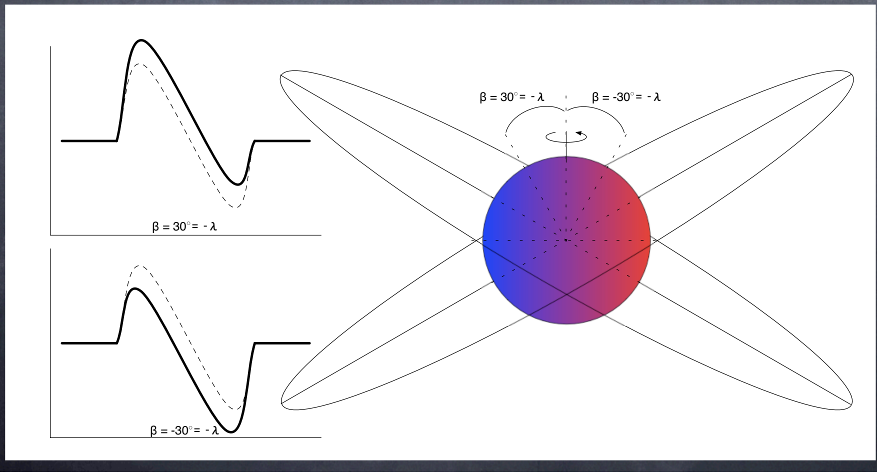
Gaseous planets



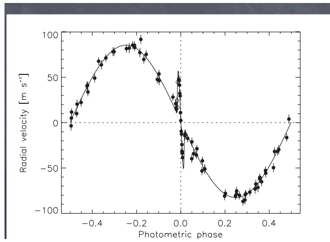


Rossiter-McLaughlin effect

Known since the early 20th century for eclipsing binaries, we can observe a transit spectroscopically. As the planet moves across the stellar disc, it covers part of it that move at different relative velocities to us showing an anomaly in the radial velocity curve.



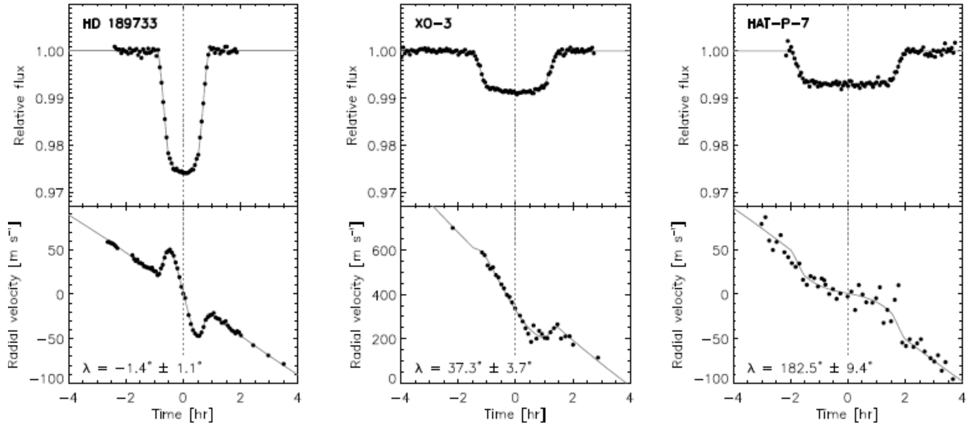
Examples of Rossiter effects



prograde

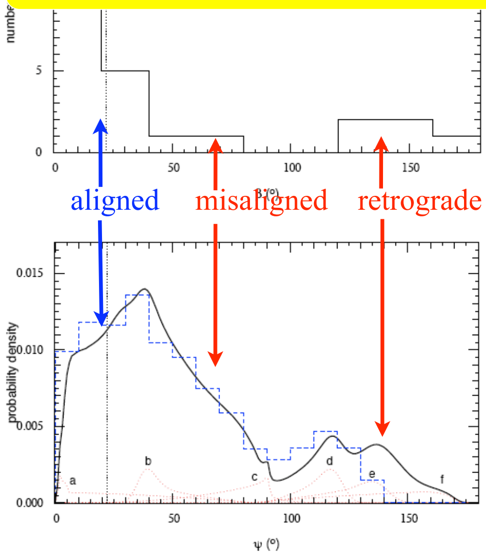
misaligned

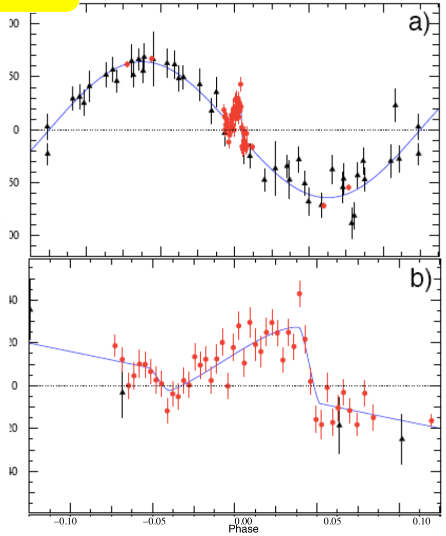
retrograde



Formation-evolution mechanisms?
Alternative models:
- migration by 3-body dynamics (Kozai?)
- evolution of 3 interacting planets?

Retrograde candidates
(Triaud et al. 2010)

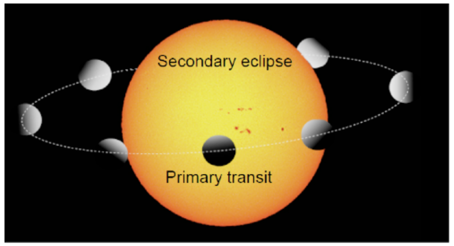




Atmospheres characterization of extrasolar planets

...Hot Jupiters are the best targets

Transiting planets



Opaque atmosphere

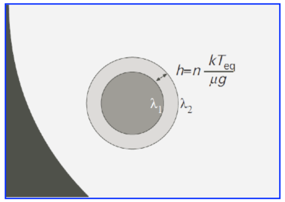
↓

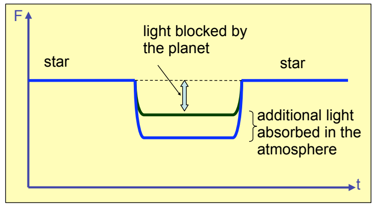
Planet is "larger"

↓

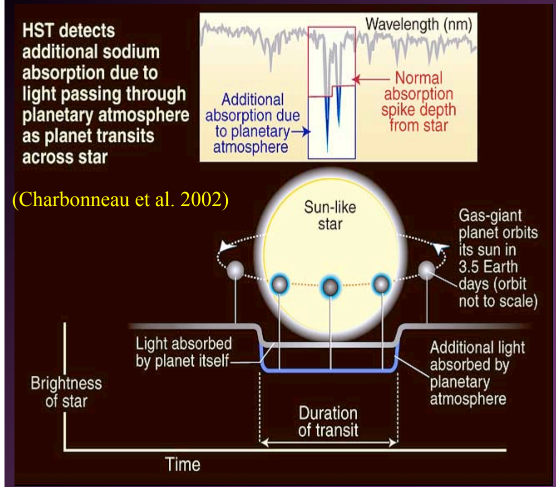
Transit is deeper

Primary eclipse: transmission in visible range





Transmission spectroscopy
Identification of atoms and molecules



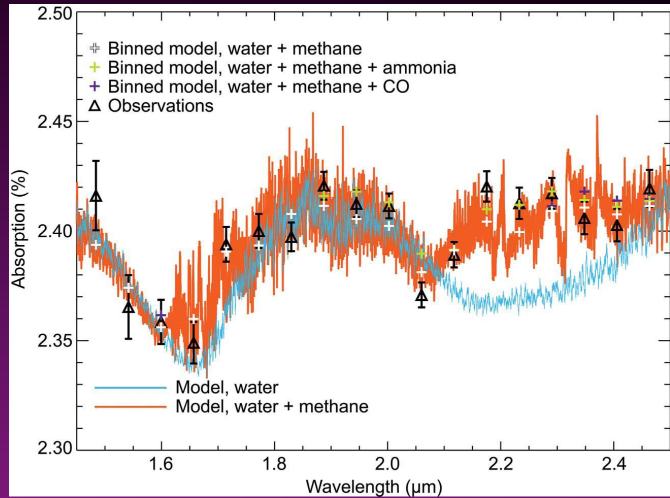
Solar composition + T>1000K

-> H_2, H_2O
(Grillmaire et al. 2008, Swain et al. 2008, 2009)

Also
- Na (Charbonneau et al. 2002)
- CO, CO2 (Swain et al. 2009ab, Madhusudhan & Seager 2009)
- CH_4 (Swain et al. 2008)

Rem: mainly for the 2 brightest stars with transit, HD209458 and HD189733

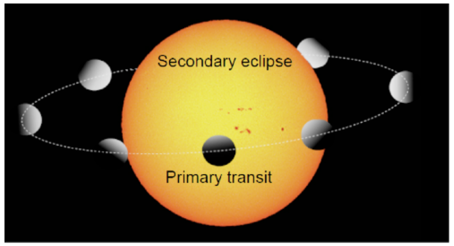
Transmission Spectra of Planet



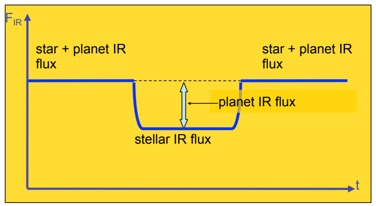
HST Nicmos finds H_2O and CH_4 in HD189733b
(Swain et al.2008)

Atmospheres characterization of extrasolar planets

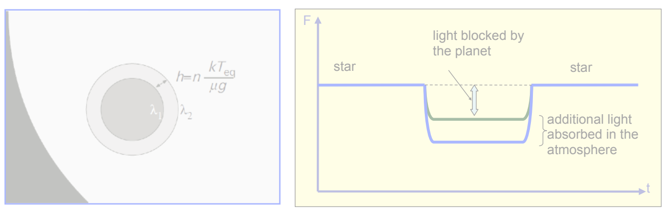
Transiting planets



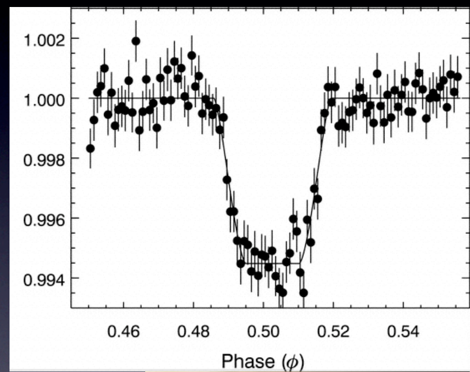
Secondary eclipse: IR emission

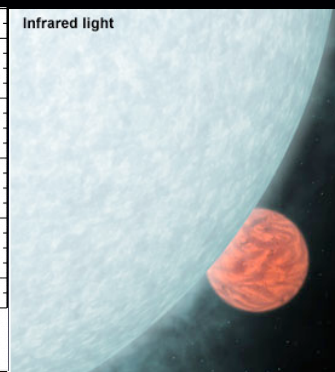


Primary eclipse: transmission in visible range

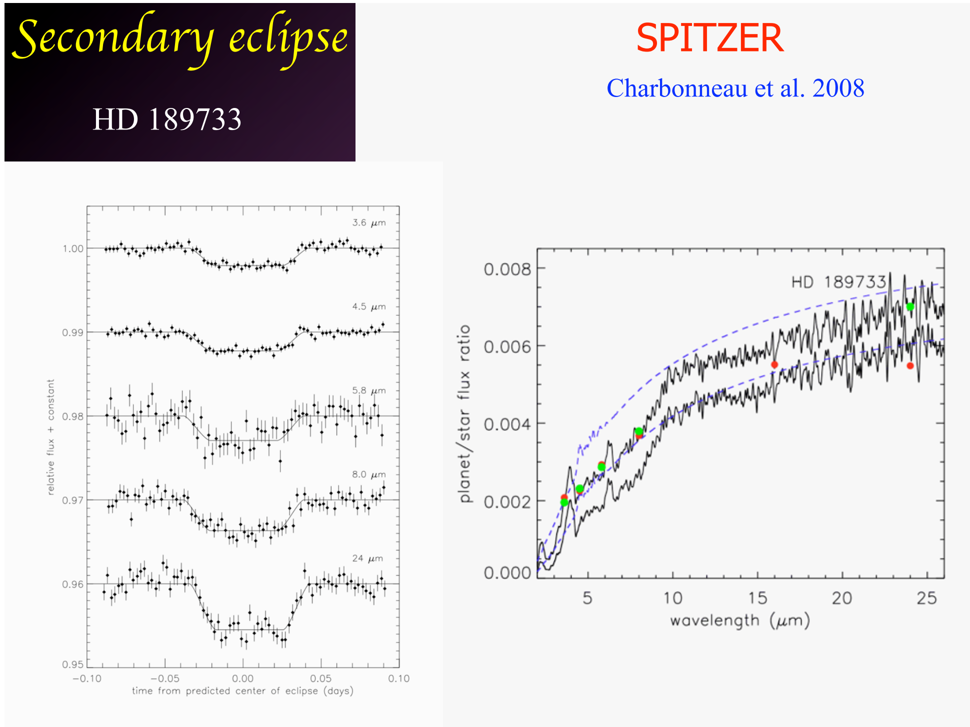


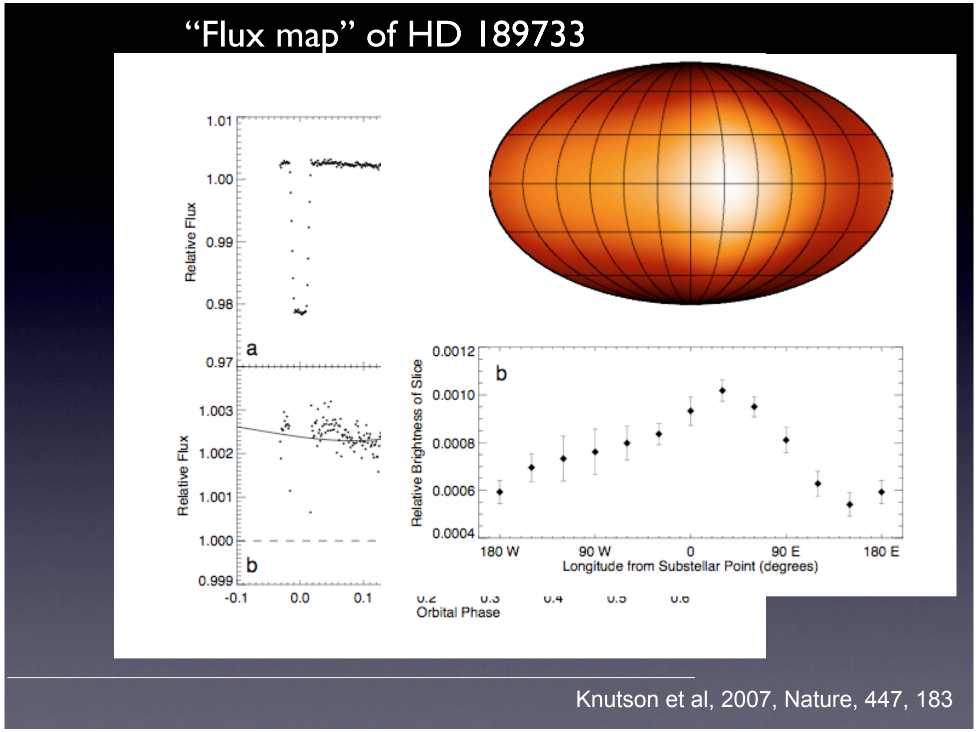
Detection of secondary eclipses HD189733

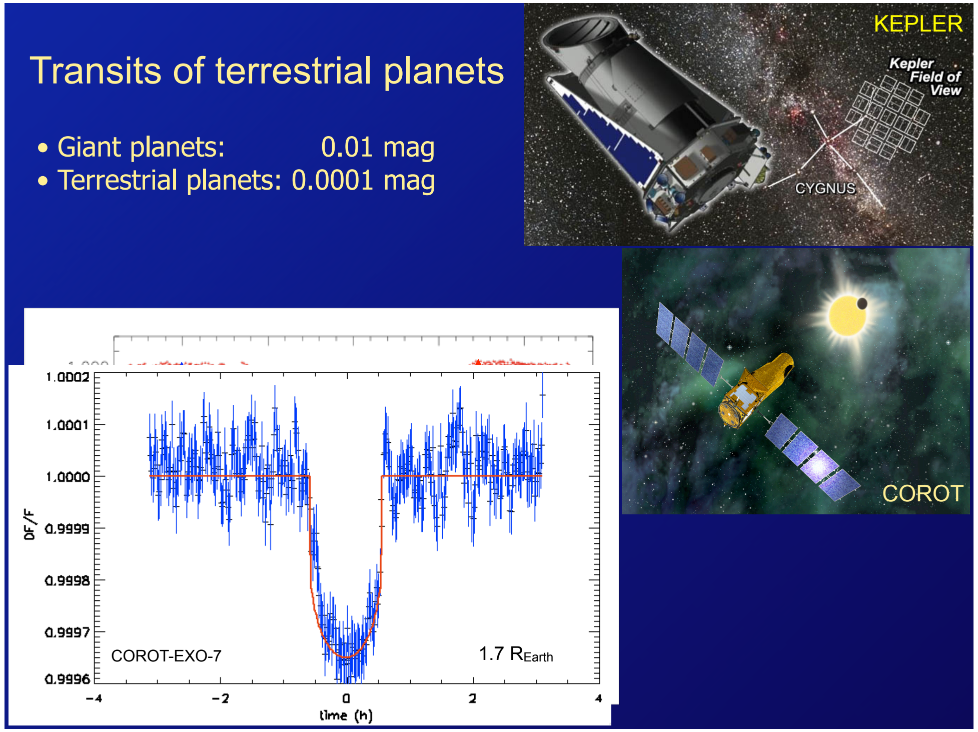




Deming et al. 2006 (Spitzer, 16 micron)







1235 Feb 2011 ⟶ **Kepler candidates** (1781, Sept 2011) ⟶ 2326 Feb 2012

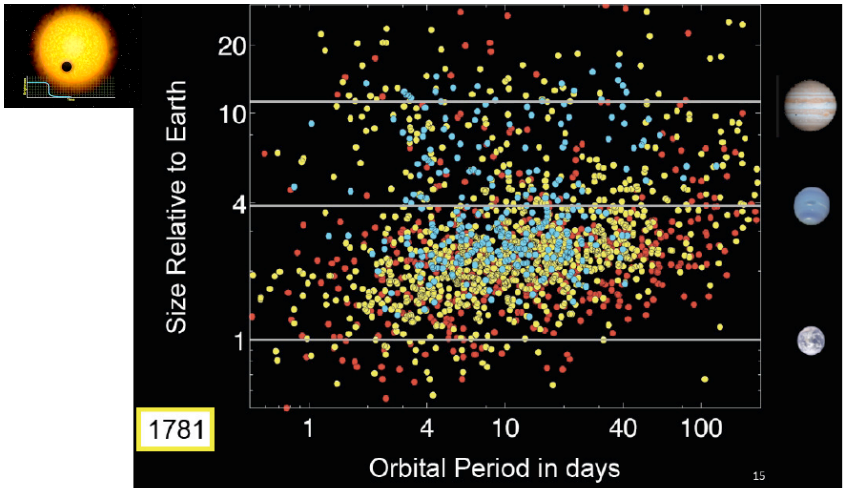
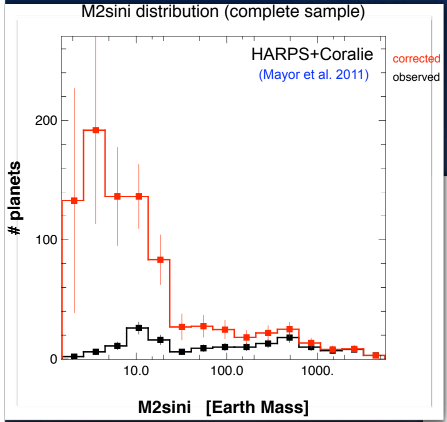


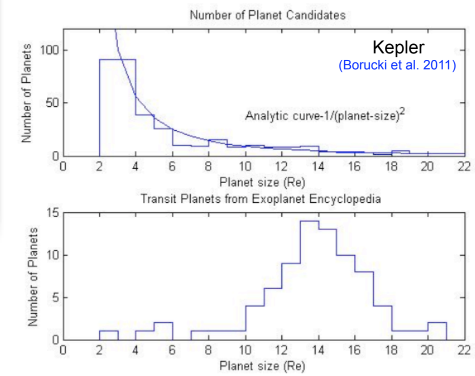
Fig. 2: The period-radius diagram for 1781 Kepler candidate planets as of September 2011.

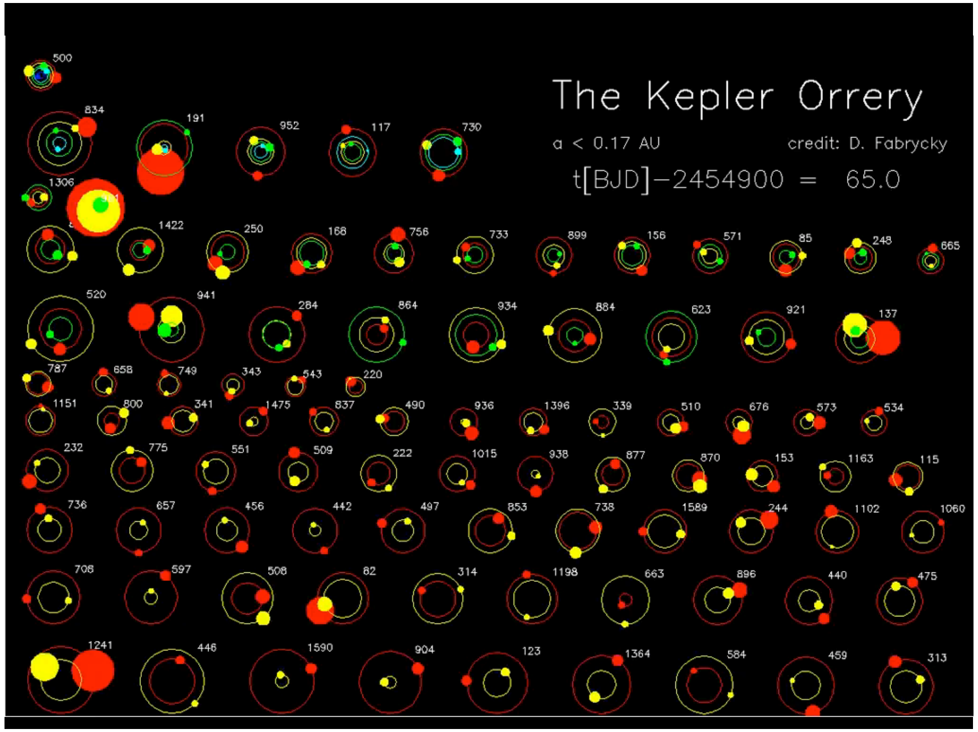
Faint stars => mass determination through RVs <u>very difficult</u>
=> TTV in some cases (multi-planet systems)

Mass distribution



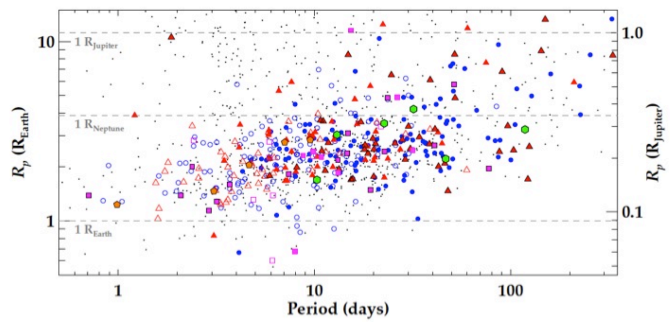
Size distribution





Multi-transiting KEPLER candidates

170 systems / Feb 2011 => 346 systems / Feb 2012



Numbers of multiplanets:

115 doubles, 45 triples, 8 quads,
1 & 1 of five and six

Borucki et al. 2011
Lissauer, Ragozzine, Fabrycky et al. 2011

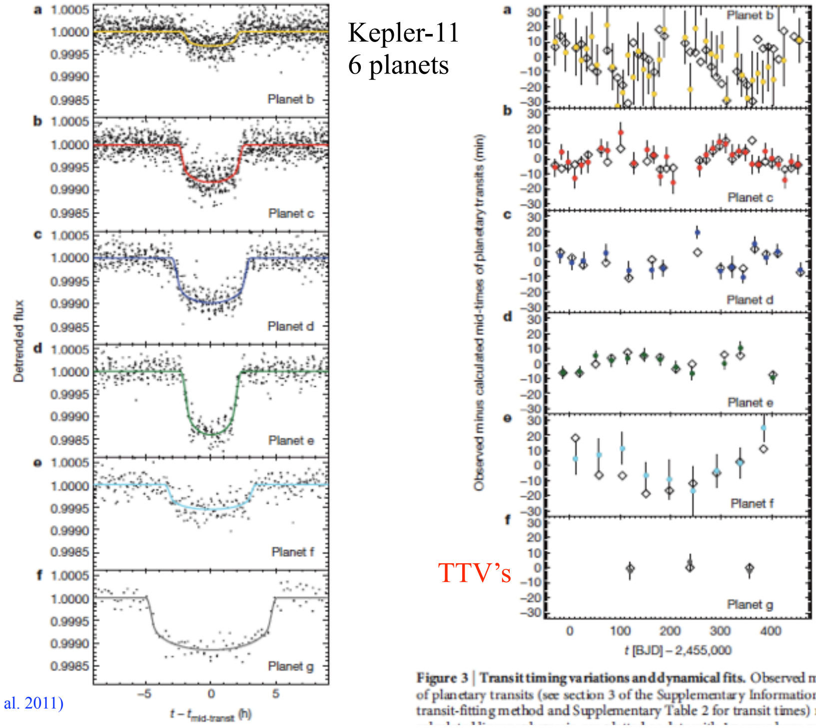
230 doubles
80 triples
27 quads
8 with 5 planets
1 with 6 planets

Kepler systems

Warning
No mass
Not all definitive

- Same features as RV systems
- Systems with TTV's
  - Kepler-9 (Holmann et al. 2010)
  - Kepler-11 (Lissauer et al. 2011)

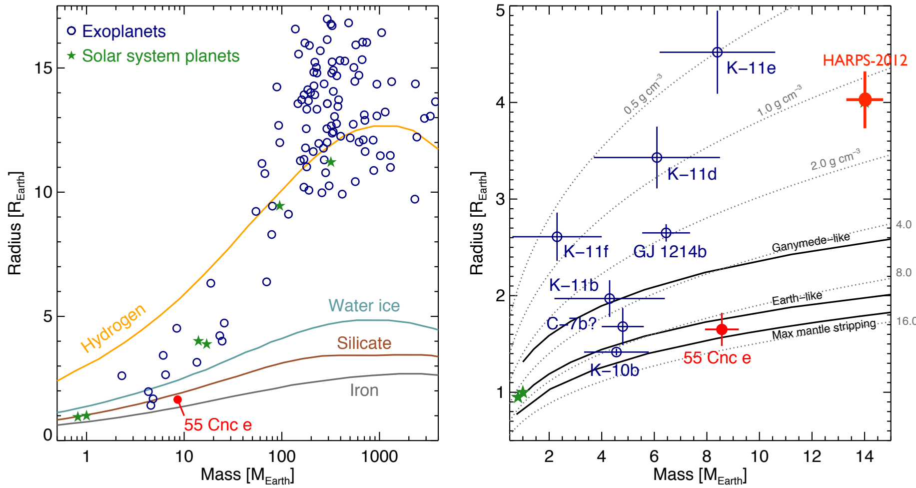
Very coplanar
Formation/evolution process?



(Lissauer et al. 2011)

Figure 3 | Transit timing variations and dynamical fits. Observed mid-times of planetary transits (see section 3 of the Supplementary Information for transit-fitting method and Supplementary Table 2 for transit times) minus a

Observed mass-radius relationship



=> Diversity of composition

Summary of constraints/questions for theoretical approaches

- Mass distribution
  - Long tail towards high masses => Maximum mass of planets = ~25 M_{Jup}
  - Bimodal distribution => higher occurrence frequency for low-mass planets
- Period distribution
  - Increasing distribution (in logP) => reservoir at large sep => Dmax for formation?
  - Giant planets: peak at 3 days, "Solid" planets: no pile-up => migration?
- Multi-planet systems
  - All kinds: only small masses or giants, mixed
  - Systems seem to be packed => planet spacing?
- Eccentricity distribution
  - Large range of observed values => origin? Importance of dynamics!
- Primary star properties
  - Metallicity - frequency correlation for gaseous giants, not for small-mass planets
  - Mass of planetary material scales with primary mass
- Constraints from transits
  - Variety in M-R relation (size, density) => variety of internal composition
  - System geometry (large fraction of misaligned systems) => formation processes?
  - Multi-transiting systems => formation? Importance of dynamics?
  - The path to the characterization of habitability

Related RV collaborations

Geneva
Students
External

HARPS: (solar-type) S. Udry, M. Mayor, F. Pepe, D. Queloz, C. Lovis, D. Ségransan, D. Naef, X. Dumusque, F. Bouchy, W. Benz, C. Mordasini, N.C. Santos, G. Locurto, J.-L. Bertaux

Coralie: S. Udry, D. Queloz, F. Pepe, M. Mayor, C. Lovis, D. Ségransan, A. Triaud, M. Marmier, J. Sahlmann, M. Lendl, J. Haguelberg, X. Dumusque, N.C. Santos, P. Figueira

HARPS (M dwarf) X. Bonfils, X. Delfosse, T Forveille, C. Perrier, S. Udry, M. Mayor, F. Pepe, D. Queloz, C. Lovis, D. Ségransan, M. Gillon, N.C. Santos, V. Neves

Dynamical analysis

Paris (F) J. Laskar
Aveiro (P) A. Correia
Monash (AUS) R. Mardling