Twenty years of discoveries in Exoplanets:

From the first planet to future instrumentation

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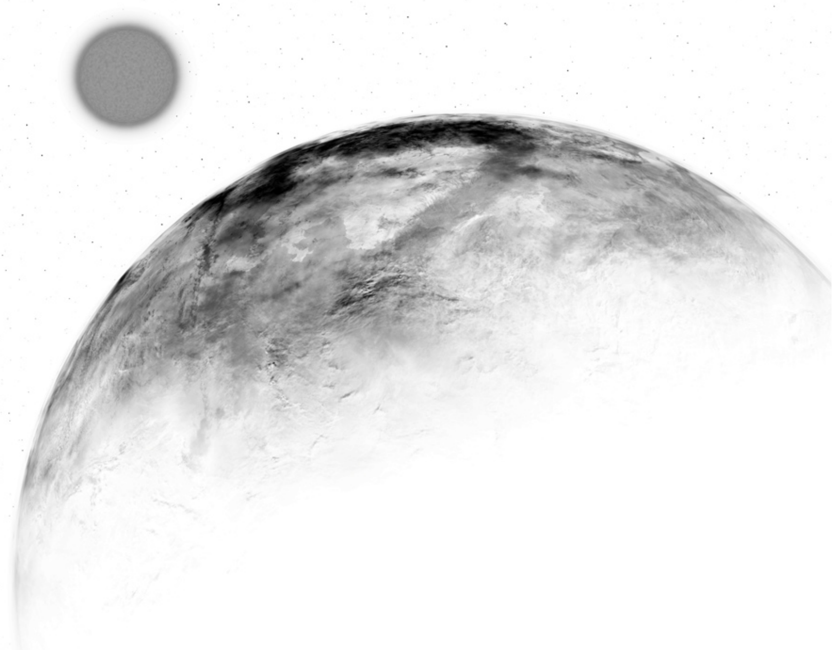
Exoplanet Focus Meeting @ ESO Santiago, 4th June 2015

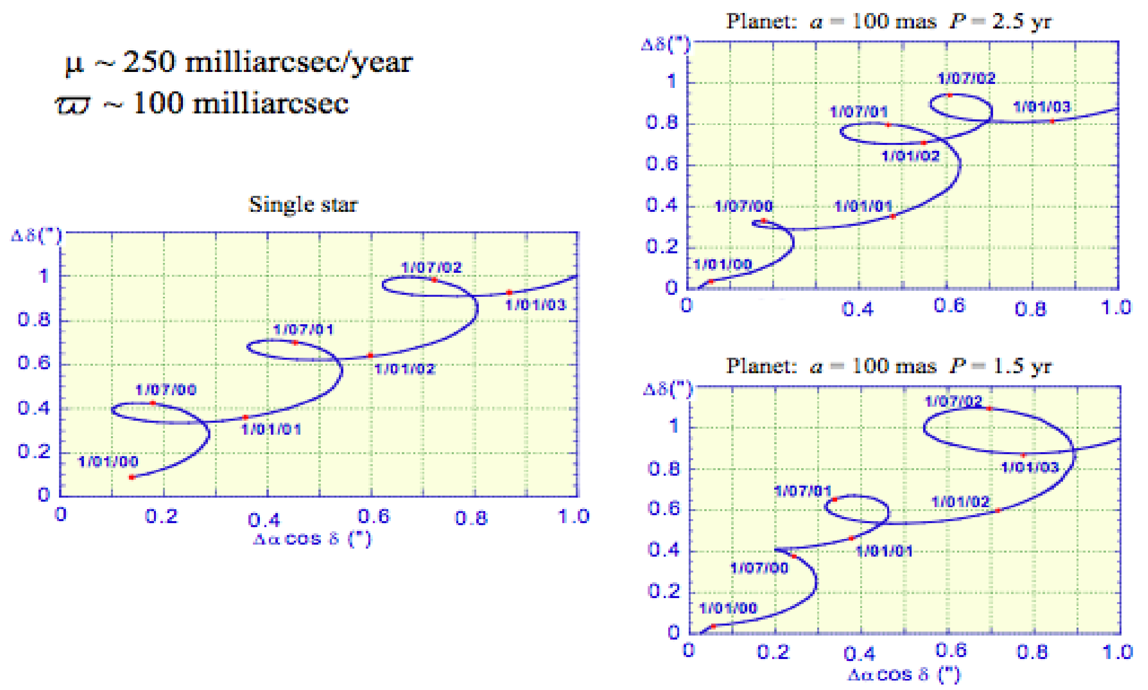
Outline

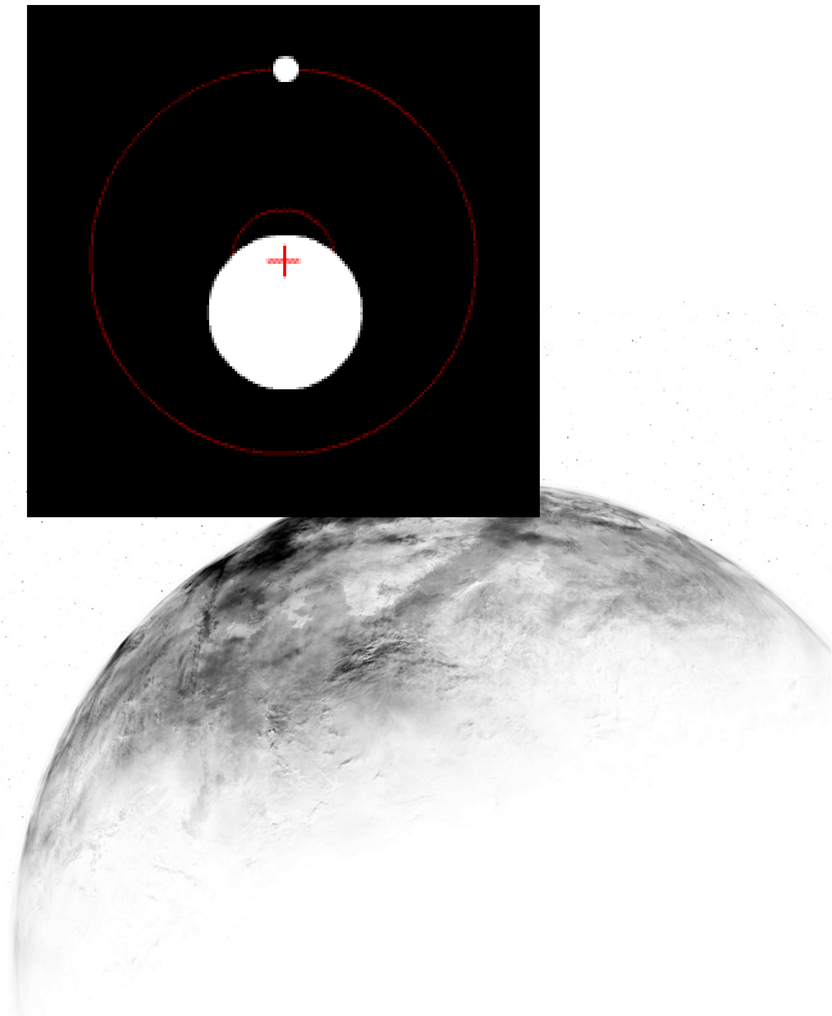
- The first detection attempts & the first planet;
- Detection Methods;
- The architecture of planetary systems;
- The road to another Earth & Future Instrumentation.



Searching for exoplanets by astrometry

Astrometry can be used to measure the wooble induced by an unseen planetary companion. Probably the most famous study was that of *Peter van de Kamp* on Barnard Star's “companion”, that was later refuted.





The pulsar planet

"Precise timing measurements of pulses from the recently discovered 6.2 ms pulsar PSR1257 + 12 are used to demonstrate that (...) **the pulsar is orbited by two or more planet-sized bodies**. The planets detected so far have masses of at least 2.8 and 3.4 earth masses. Their respective distances from the pulsar are 0.47 AU and 0.36 AU, and they move in almost circular orbits with periods of 98.2 and 66.6 days.."

\- **Wolszczan & Frail (1992)**

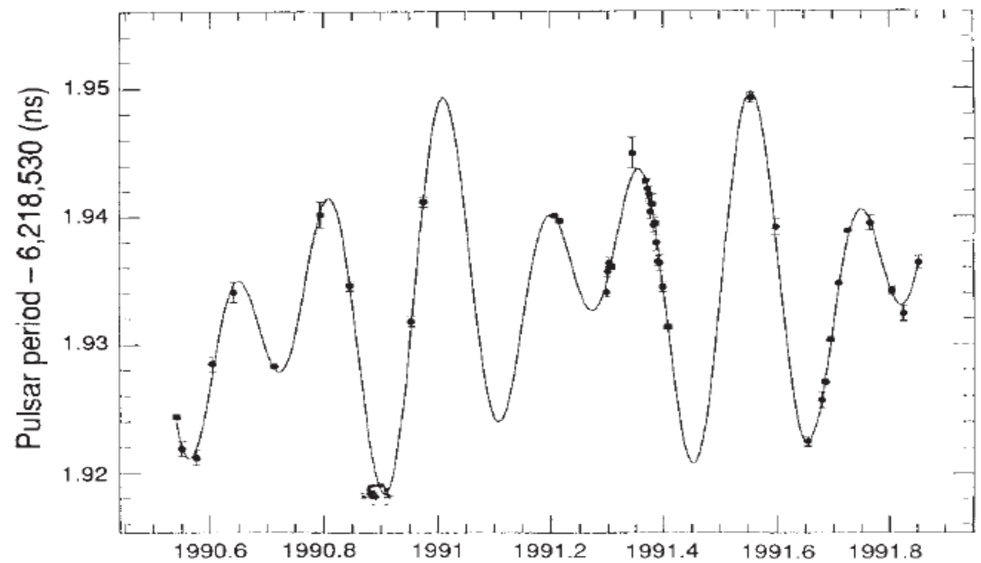
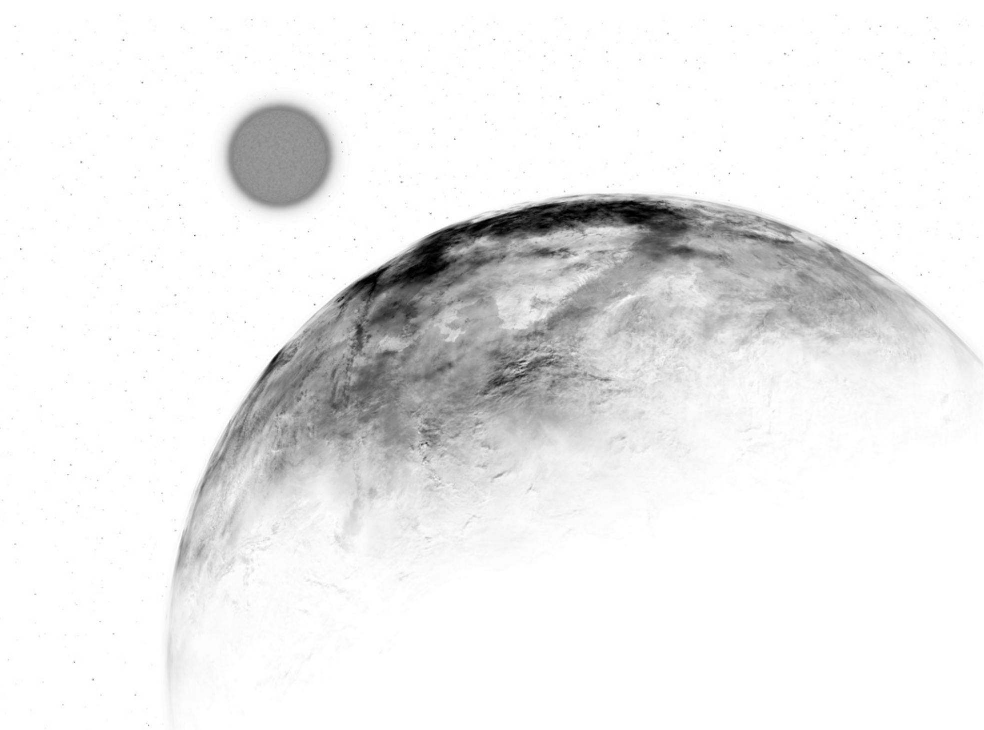
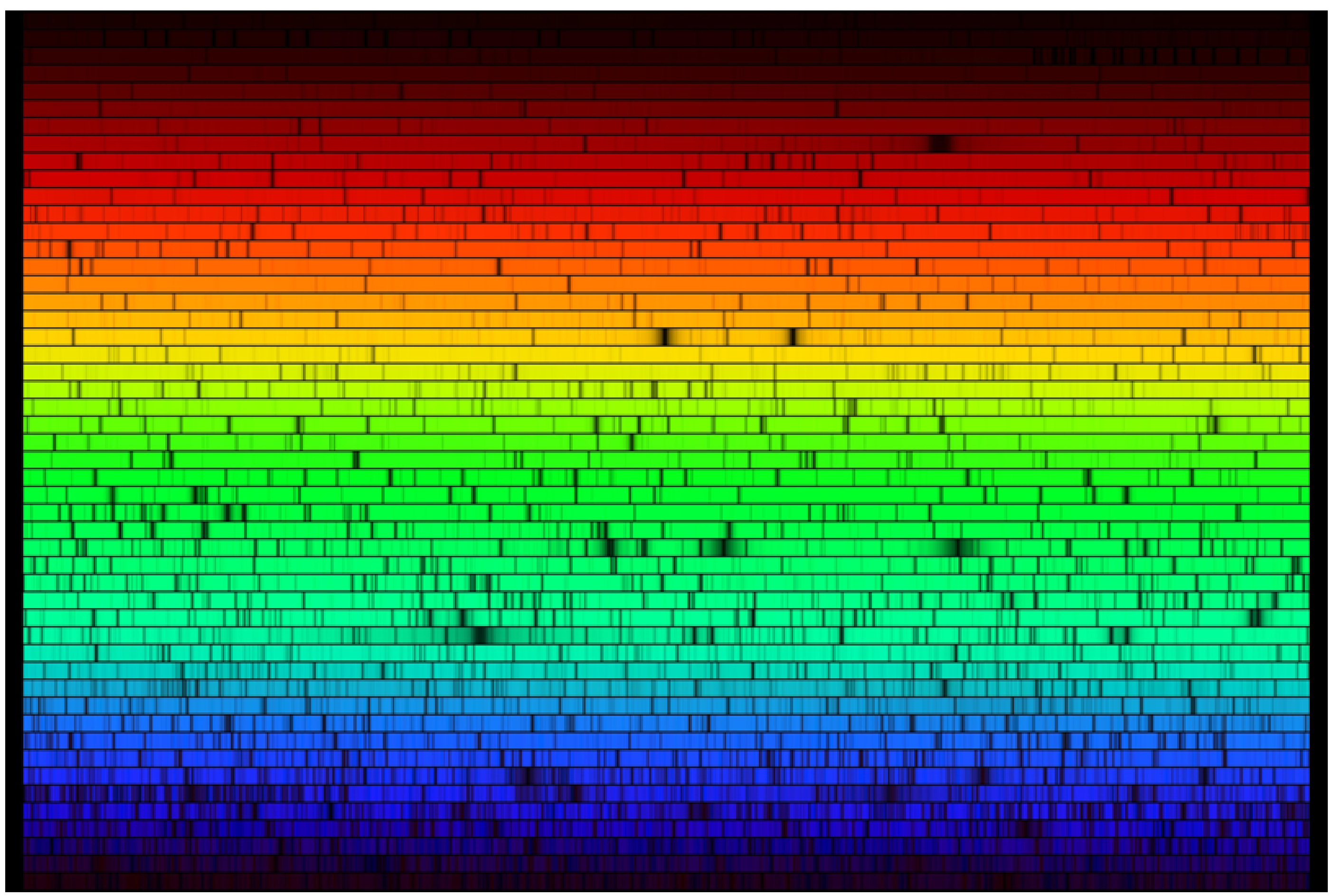


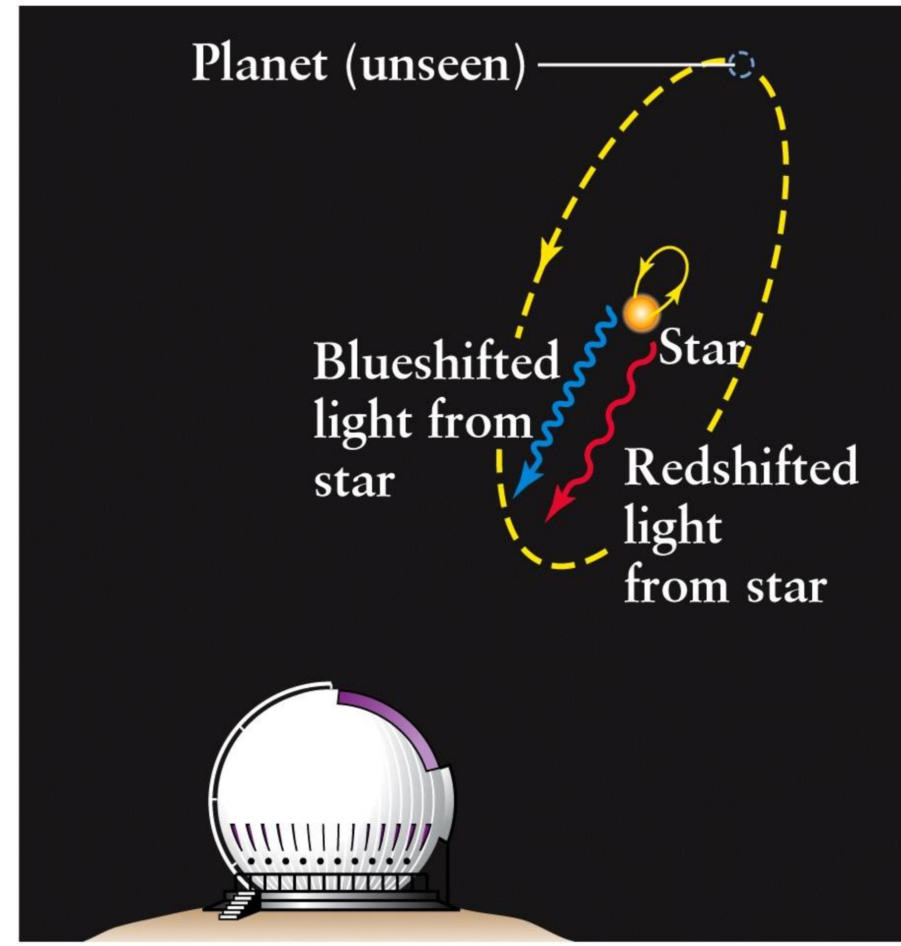
FIG. 3 Period variations of PSR1257 +12. Each period measurement is based on observations made on at least two consecutive days. The solid line denotes changes in period predicted by a two-planet model of the 1257 +12 system.



Radial Velocities

When a star moves along our line of sight, we can measure its ***radial velocity*** by **Doppler Effect**





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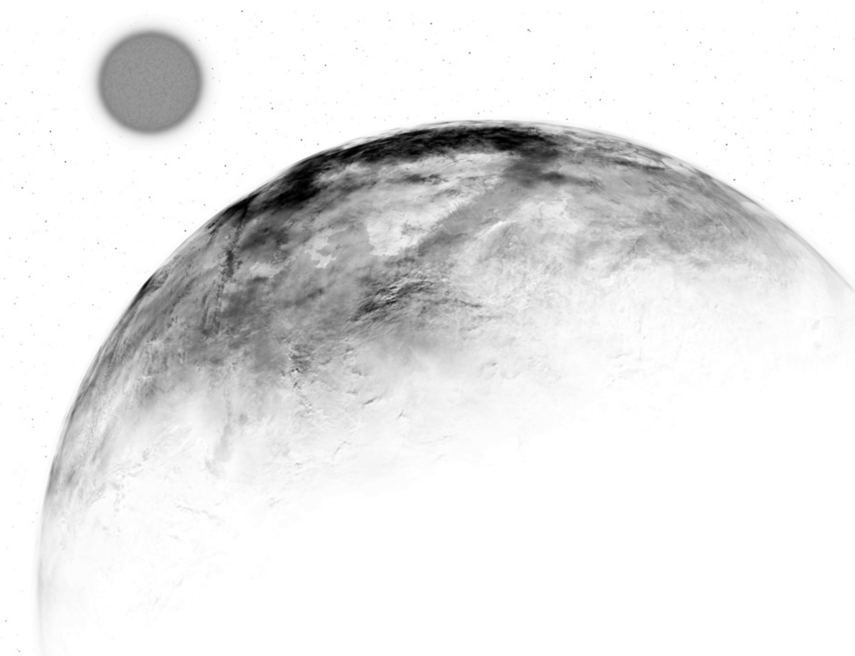
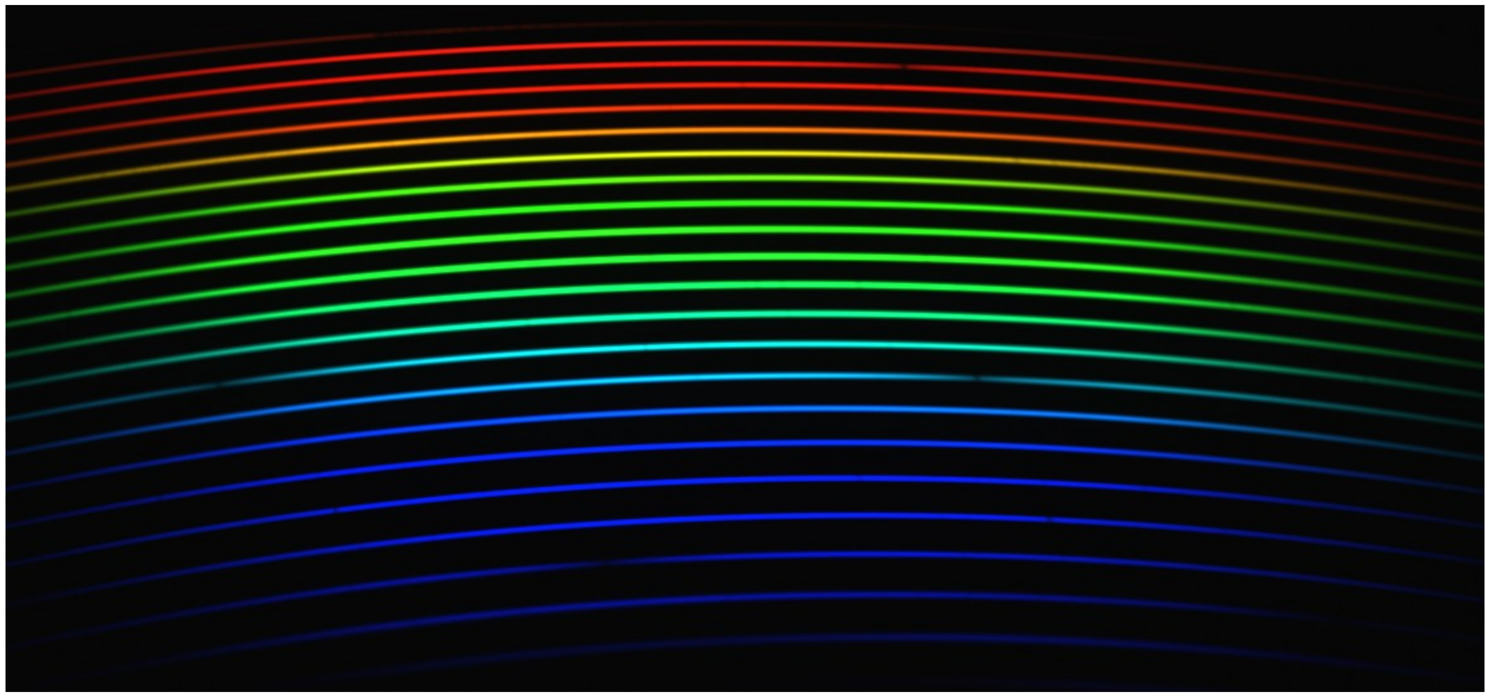
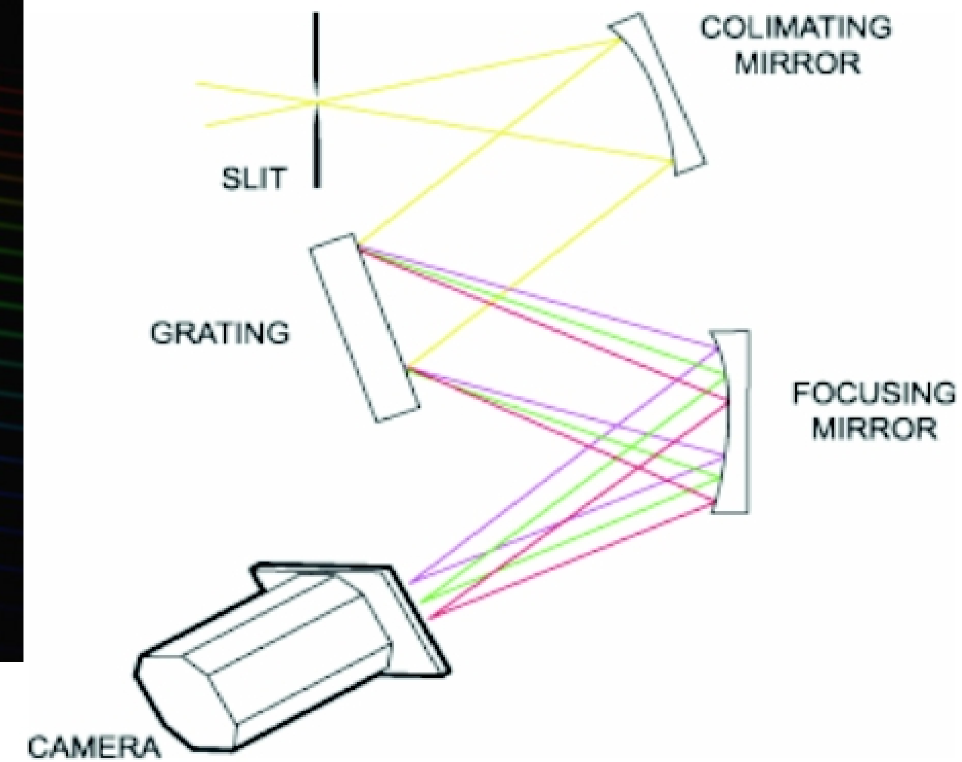


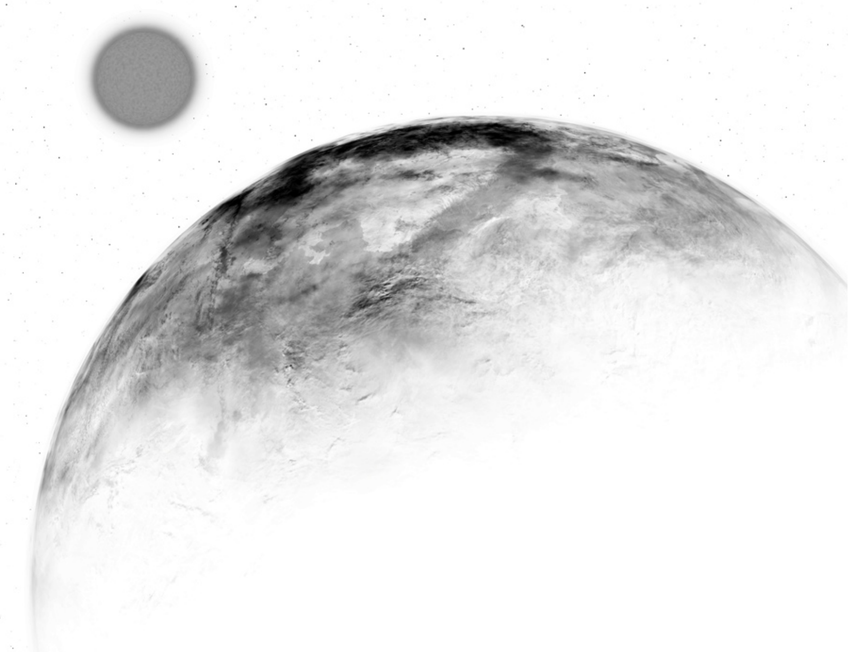
Radial Velocities





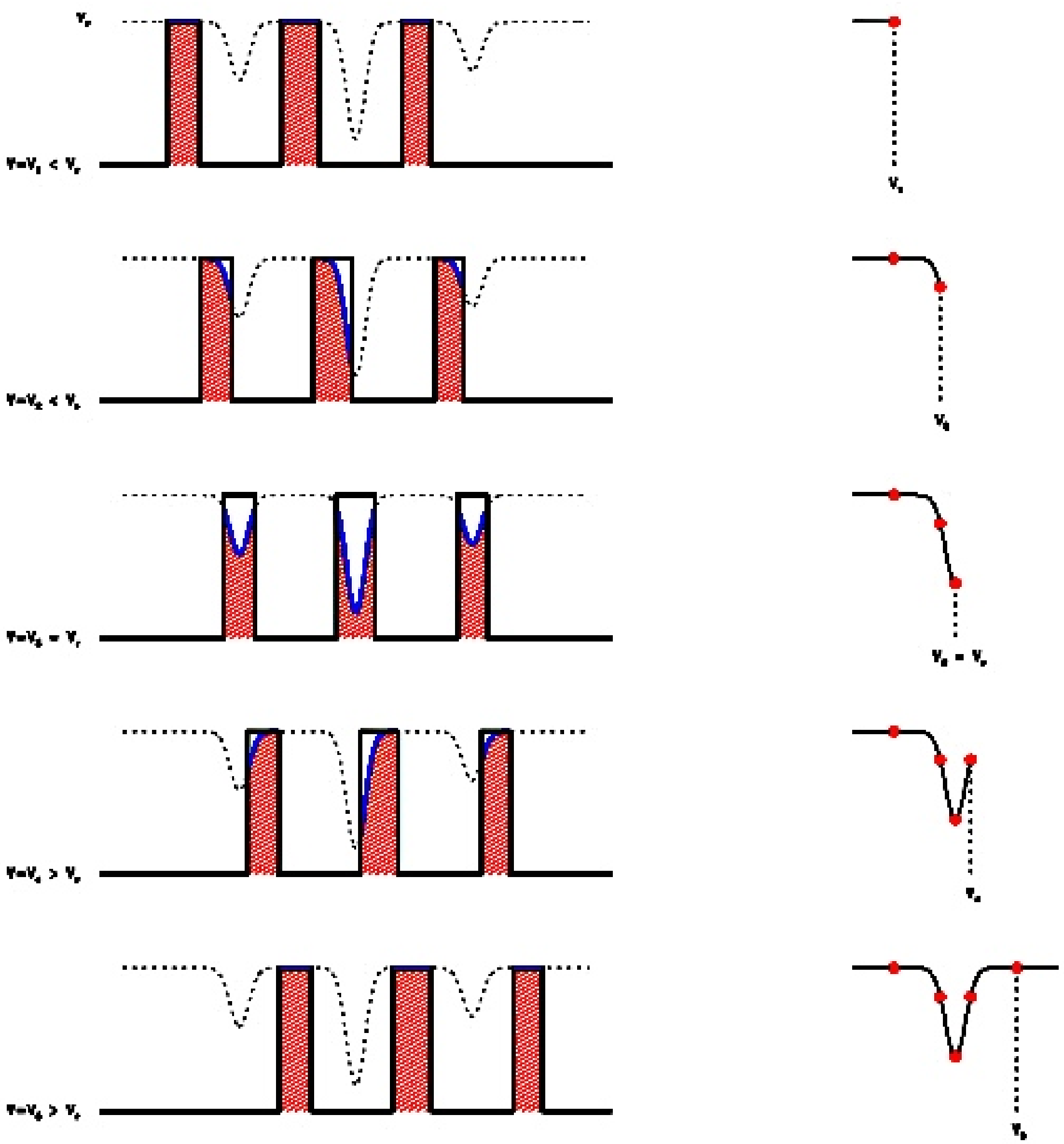
The advent of high-resolution cross-dispersed ***echelle spectrographs*** opened new venues.

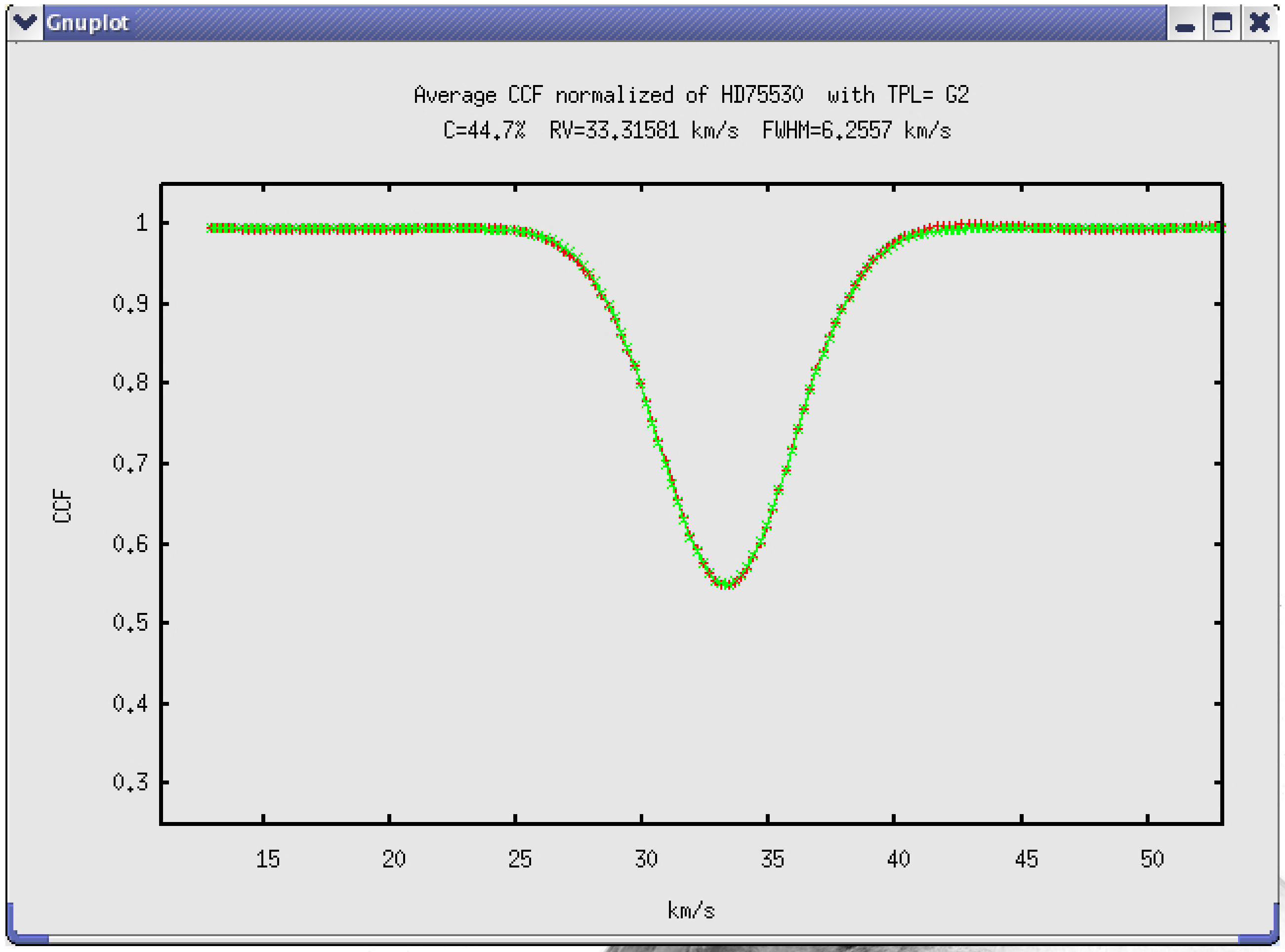
To reach m/s-level measurements one must be able to ***measure a line shift of the order of 1/1000 the pixel size***



Radial Velocities

Cross-correlation with a **template mask** creates an average stellar line, the **CCF**

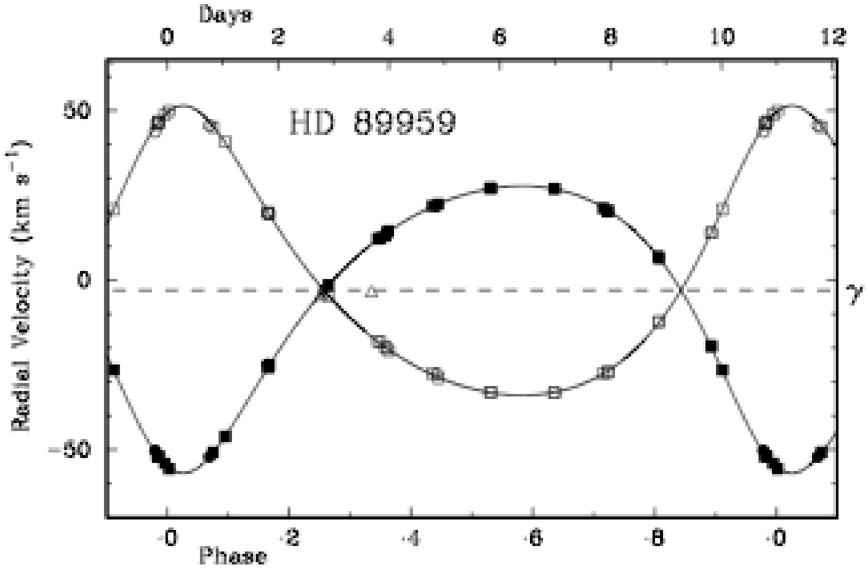




Cross-Correlation Function

Melo et al. 2001, PhD. Thesis

Radial Velocity Method



Griffin & Filiz (2010)

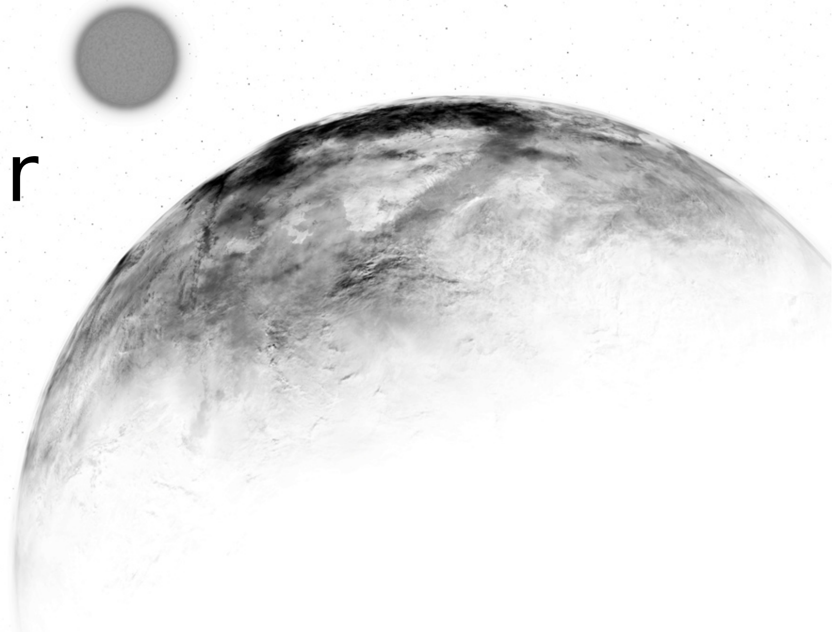
$$r = \frac{a(1-e^2)}{1+e\cos(\theta-\omega)}$$

$$V_{rad} = \dot{z} = \frac{2\pi a \sin i}{P\sqrt{1-e^2}}[\cos(\theta+\omega) + e\cos\omega] + \gamma$$

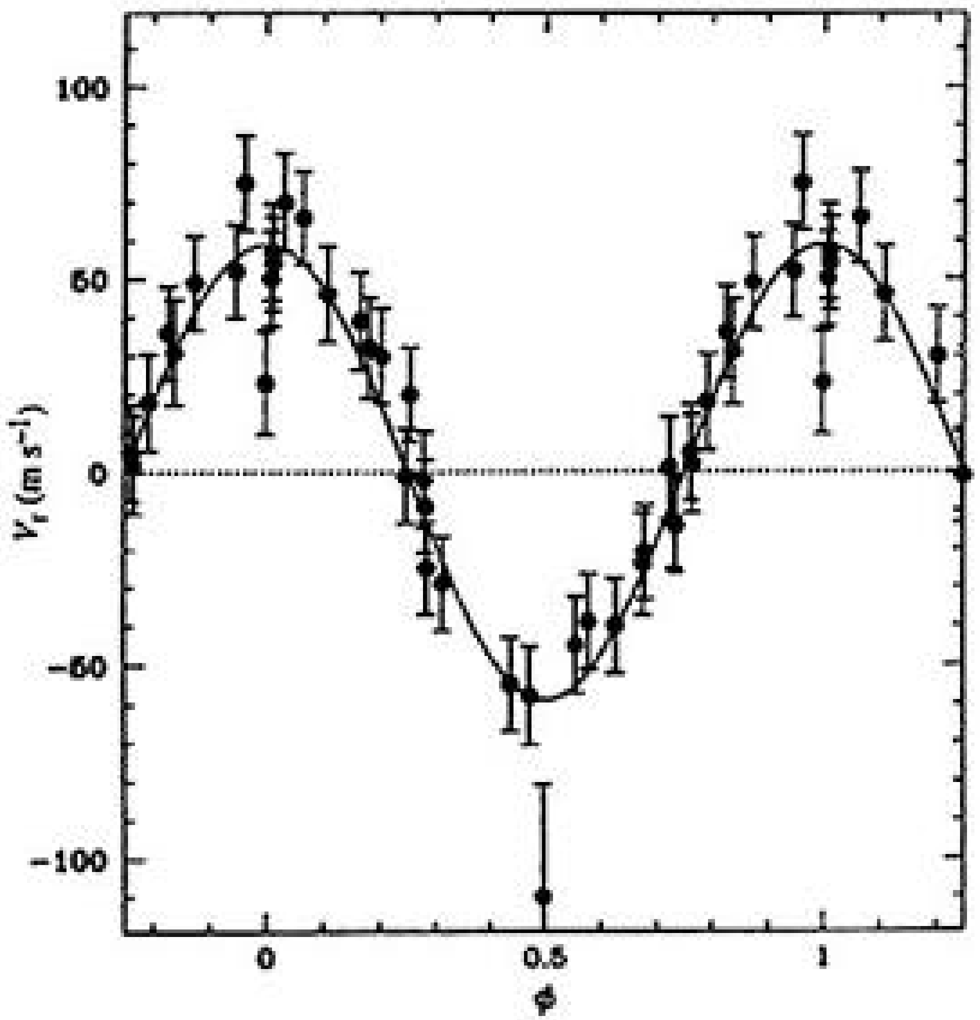
$$K_1 = \frac{28.4}{\sqrt{1-e^2}} \frac{m_2 \sin i}{M_{Jup}} \left(\frac{m_1}{M_\odot}\right)^{-2/3} \left(\frac{P}{1\mathrm{yr}}\right)^{-1/3} [m/s] .$$

Radial Velocities brought us a wealth of information on Galactic Dynamics and stellar binarity, among many others

Duquennoy & Mayor (1991)



The weird Extrasolar worlds



A Jupiter-mass companion to a solar-type star

Michel Mayor & Didier Queloz

Geneva Observatory, 51 Chemin des Maillettes, CH-1290 Sauverny, Switzerland

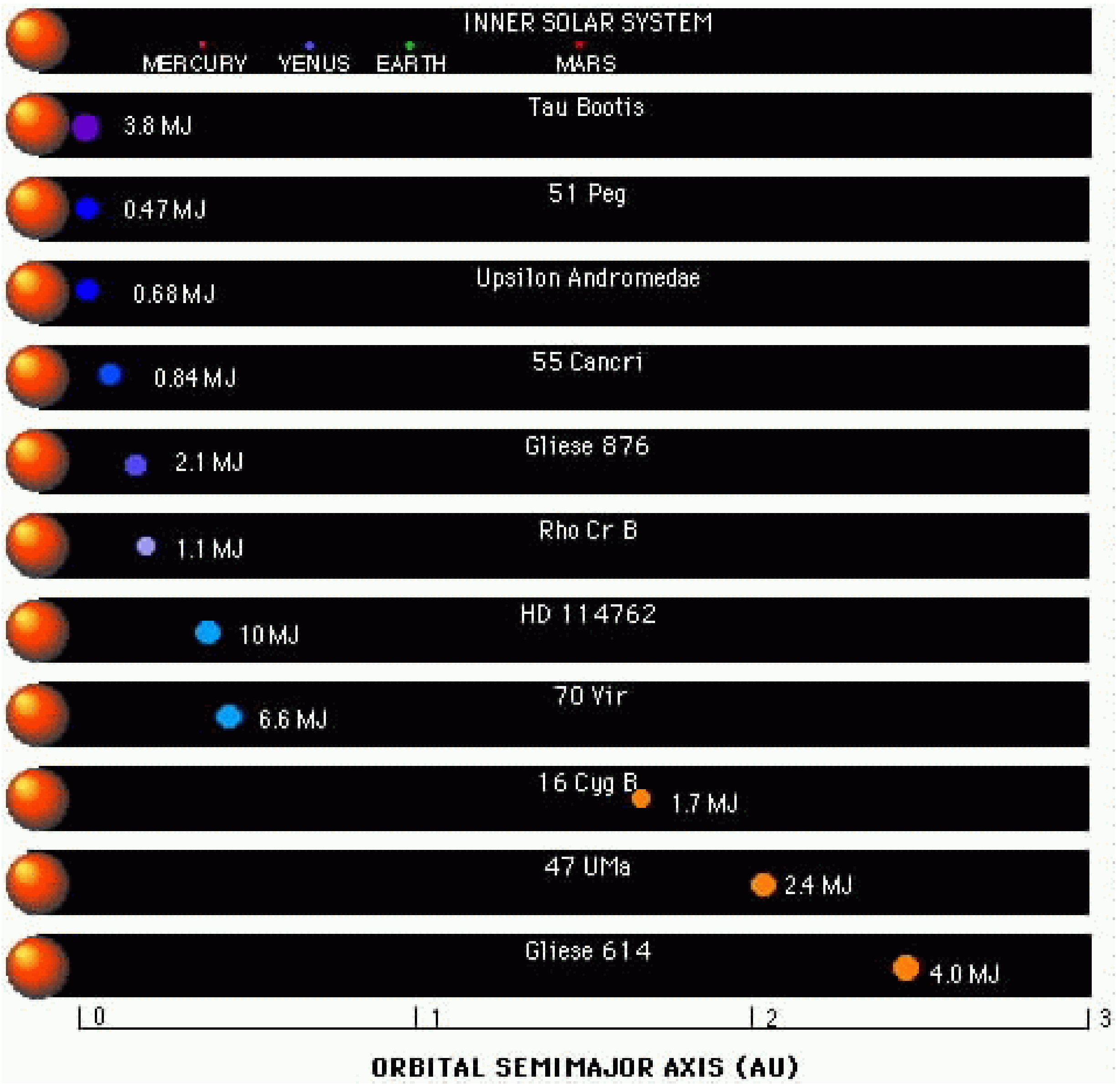
The presence of a Jupiter-mass companion to the star 51 Pegasi is inferred from observations of periodic variations in the star's radial velocity. The companion lies only about eight million kilometres from the star, which would be well inside the orbit of Mercury in our Solar System. This object might be a gas-giant planet that has migrated to this location through orbital evolution, or from the radiative stripping of a brown dwarf.

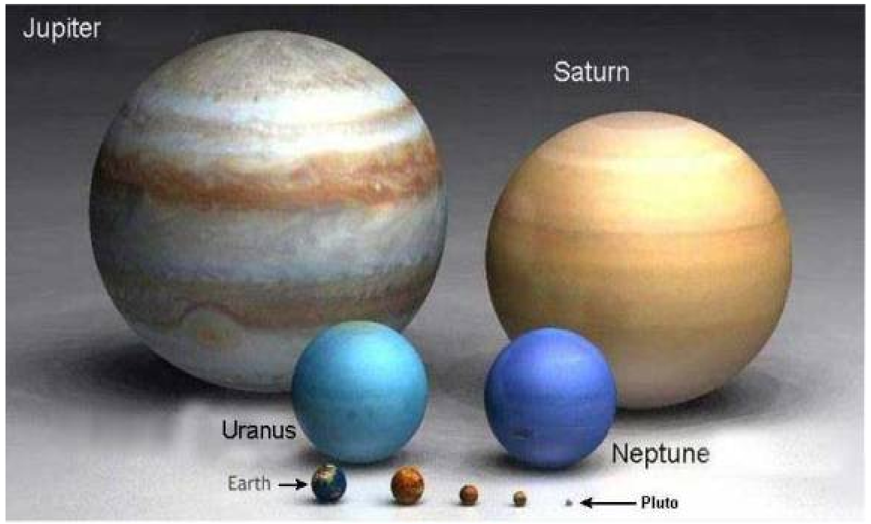
Mayor & Queloz (1995)

We can measure the ***mass*** of a planet, as well as its ***orbital period*** and ***distance***.

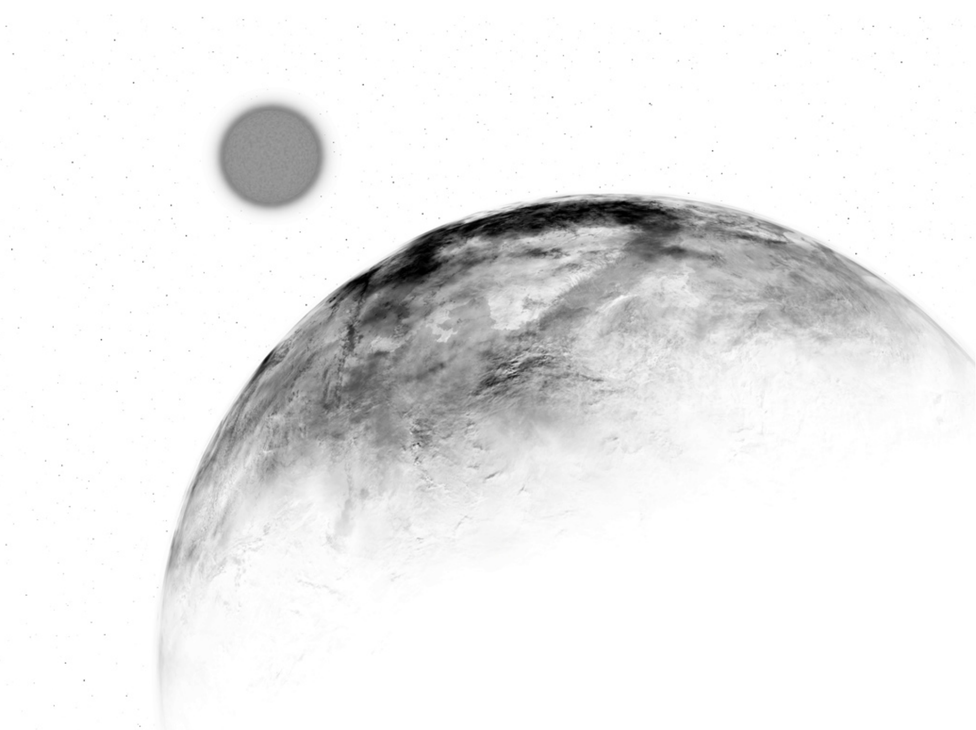
m_2	$K_1(P=3\,d)$	$K_1(P=1\,yr)$	$K_1(P=5\,yr)$	
M_{Jup}	140.8	28.4	16.6	*m/s*
M_{Nep}	7.60	1.53	0.90	*m/s*
$M_{\oplus}$	44.3	8.9	5.2	*cm/s*

Brave new worlds





The planets discovered were very unlike ours, and that was only the beginning...



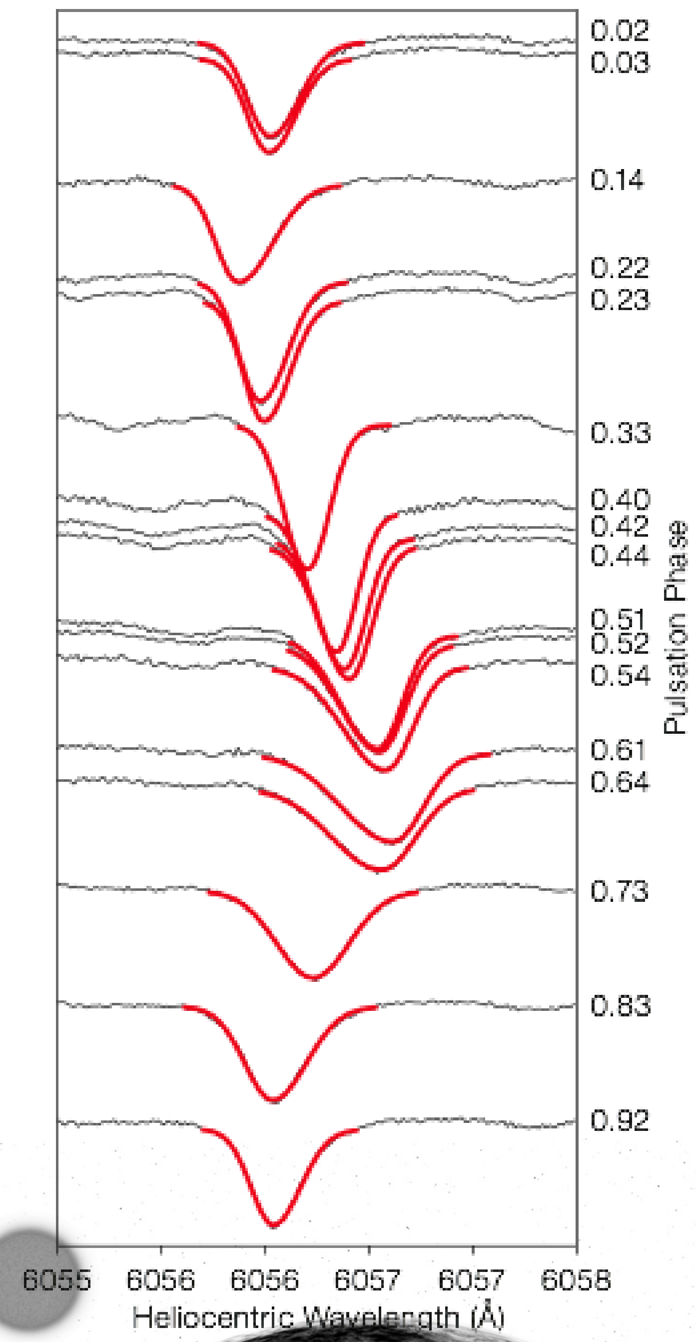
But... is it a planet?

Several authors argued that the signal was real, but of stellar origin, and not attributable to a planet.

A line-profile deformation could lead to a change in average radial velocity and could be misinterpreted as a planet.

Some others also argued that the planets could be brown dwarfs on inclined orbits, but this was dismissed using astrometric analysis and by statistical arguments.

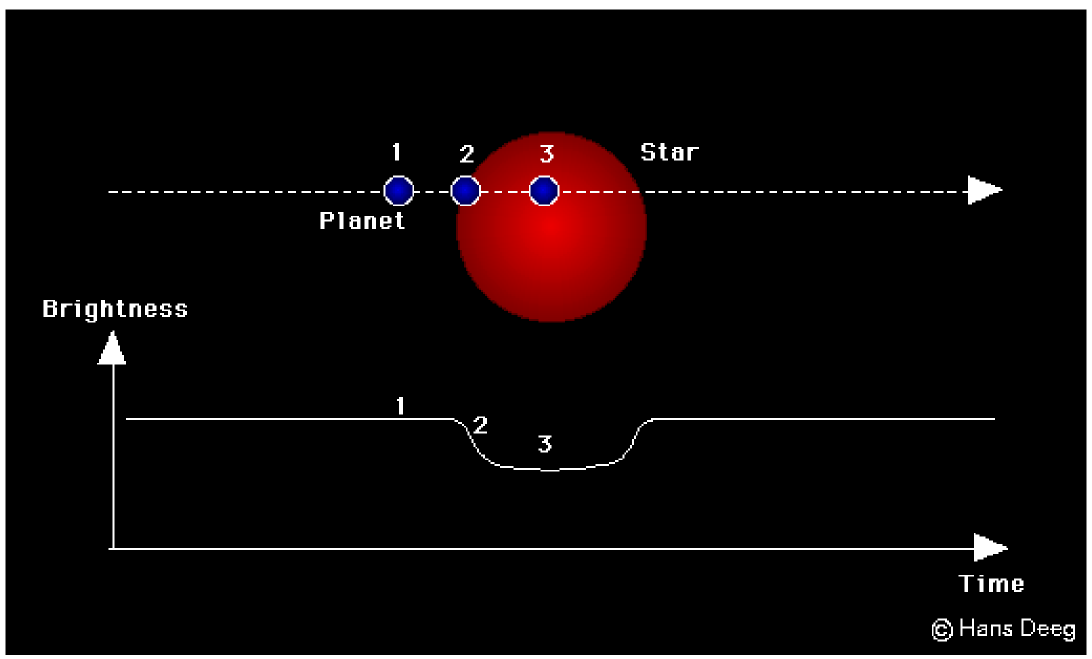
The average overestimation factor corresponds to the average ($sin\ i$)$^{-1}$ angle for a random distribution of angles, and is 1.27.

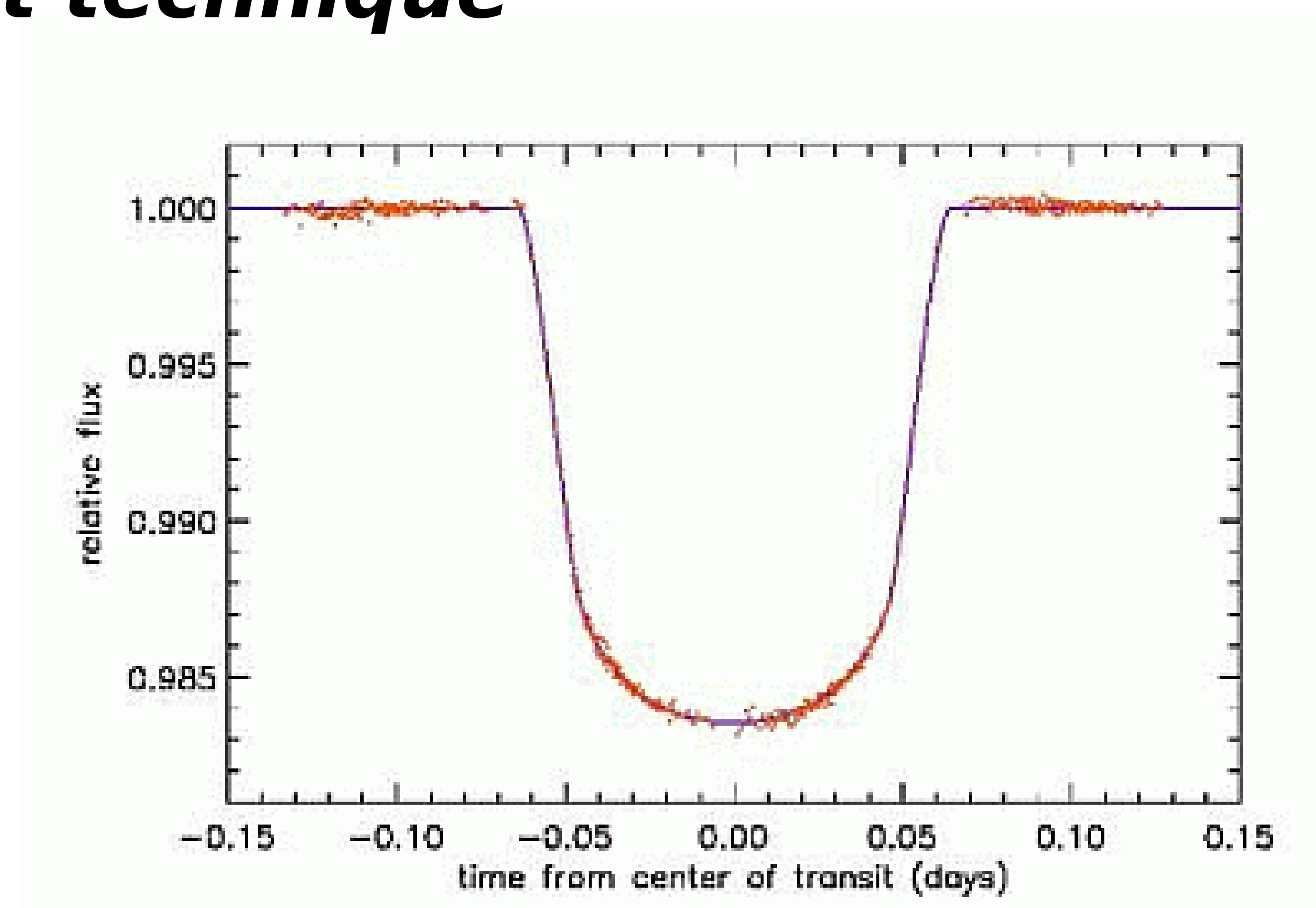


Nardetto et al. (2008)

The first transiting planet

The orbit of planet can put it in front of the star, blocking the light as received by us and giving rise to the ***transit technique***

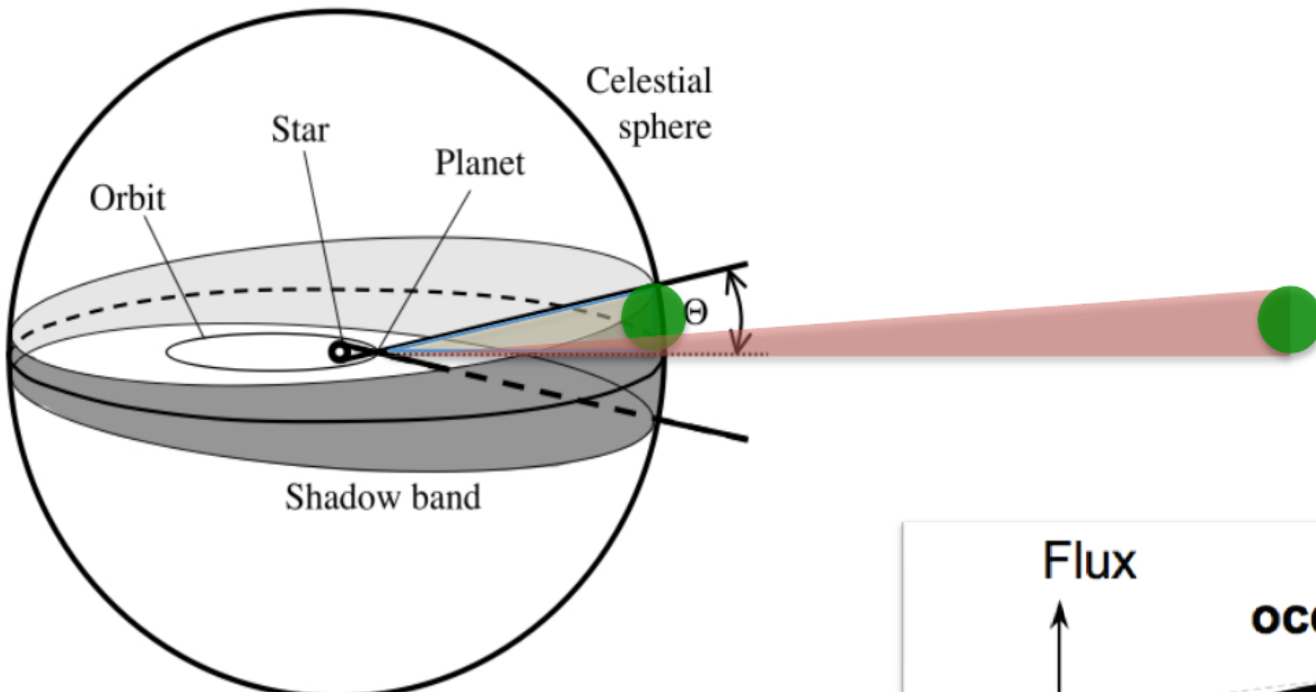


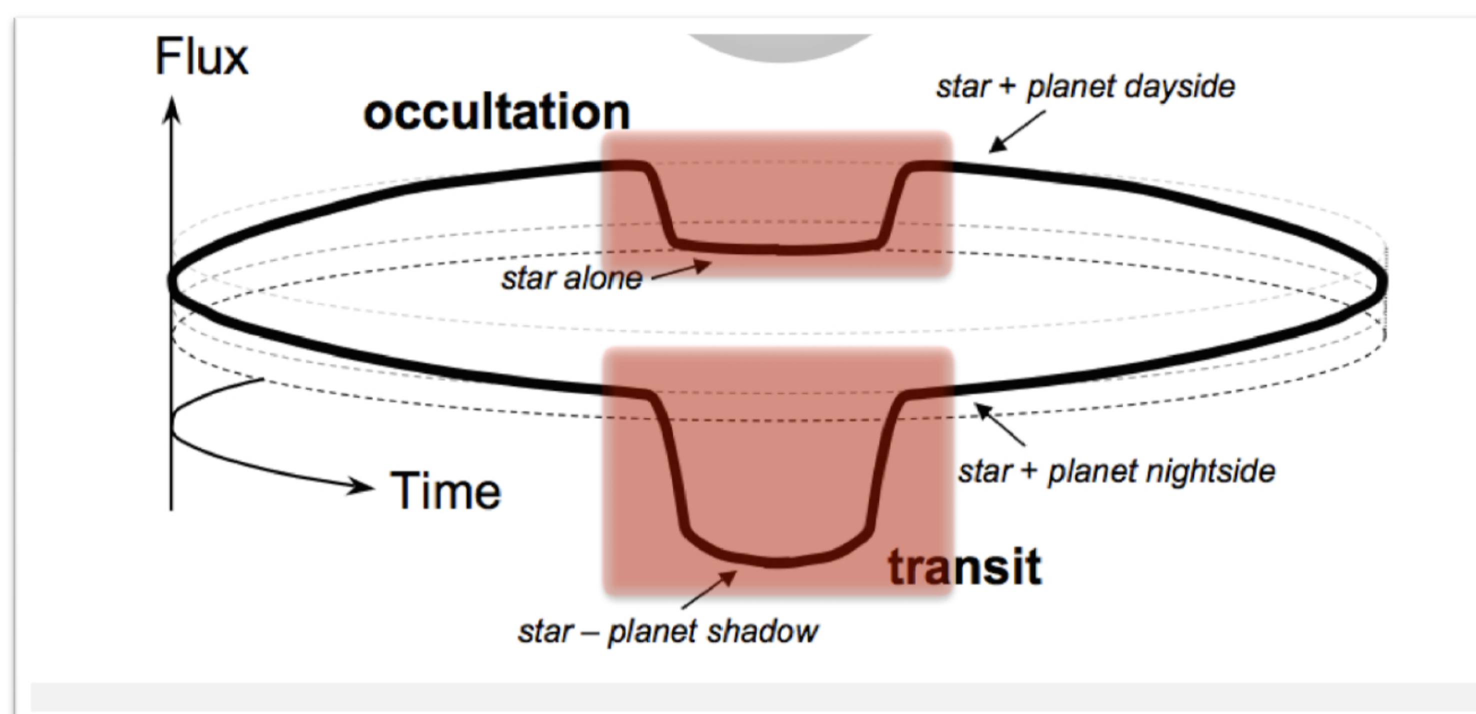


The first planet detected in transit was HD209458 by **Charbonneau et al. (2000)**

Transiting planets

Only a small fraction of planets transit or produce occultations.





From Winn (2010)

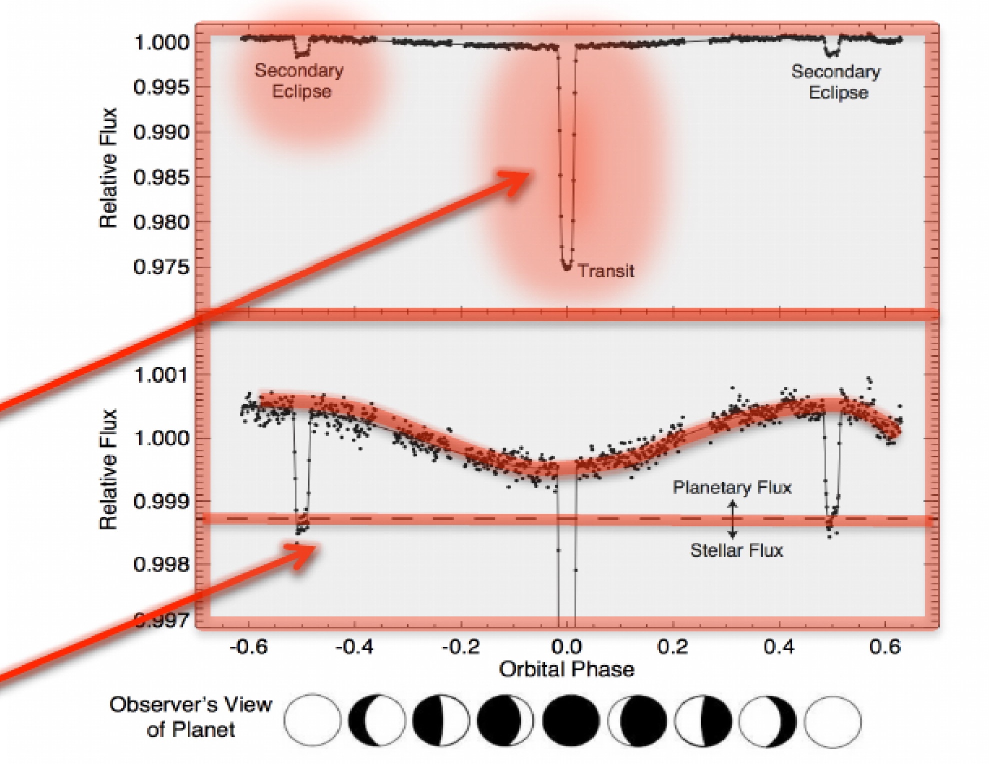
Transiting planets

$$f(t) \equiv F(t)/F_\star$$

$$F_p/F_\star = k^2 I_p/I_\star$$

$$f(t) = 1 + k^2 \frac{I_p(t)}{I_\star} - \begin{cases} k^2 \alpha_{\rm tra}(t) \\ 0 \\ k^2 \frac{I_p(t)}{I_\star} \alpha_{\rm occ}(t) \end{cases}$$

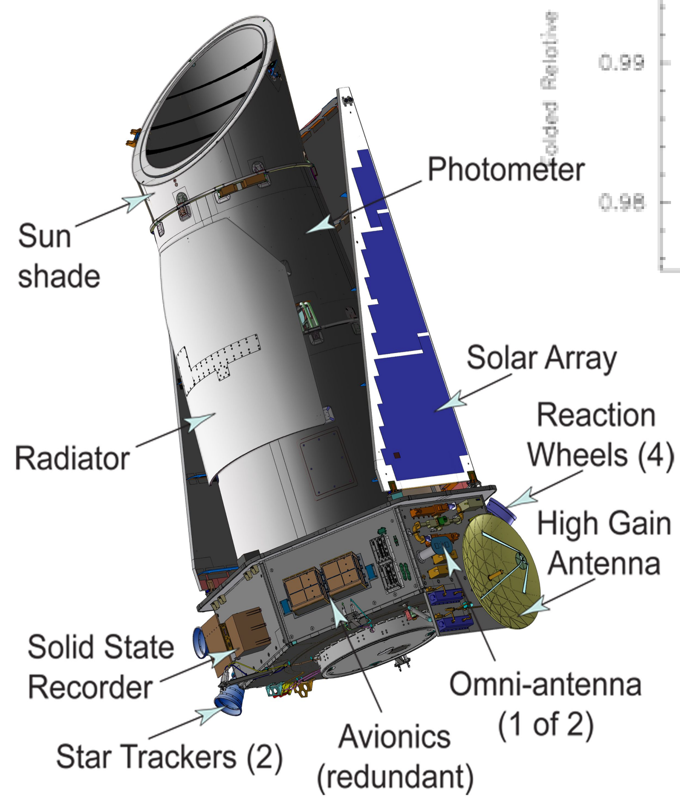
Madhusudhan 2014 et al.

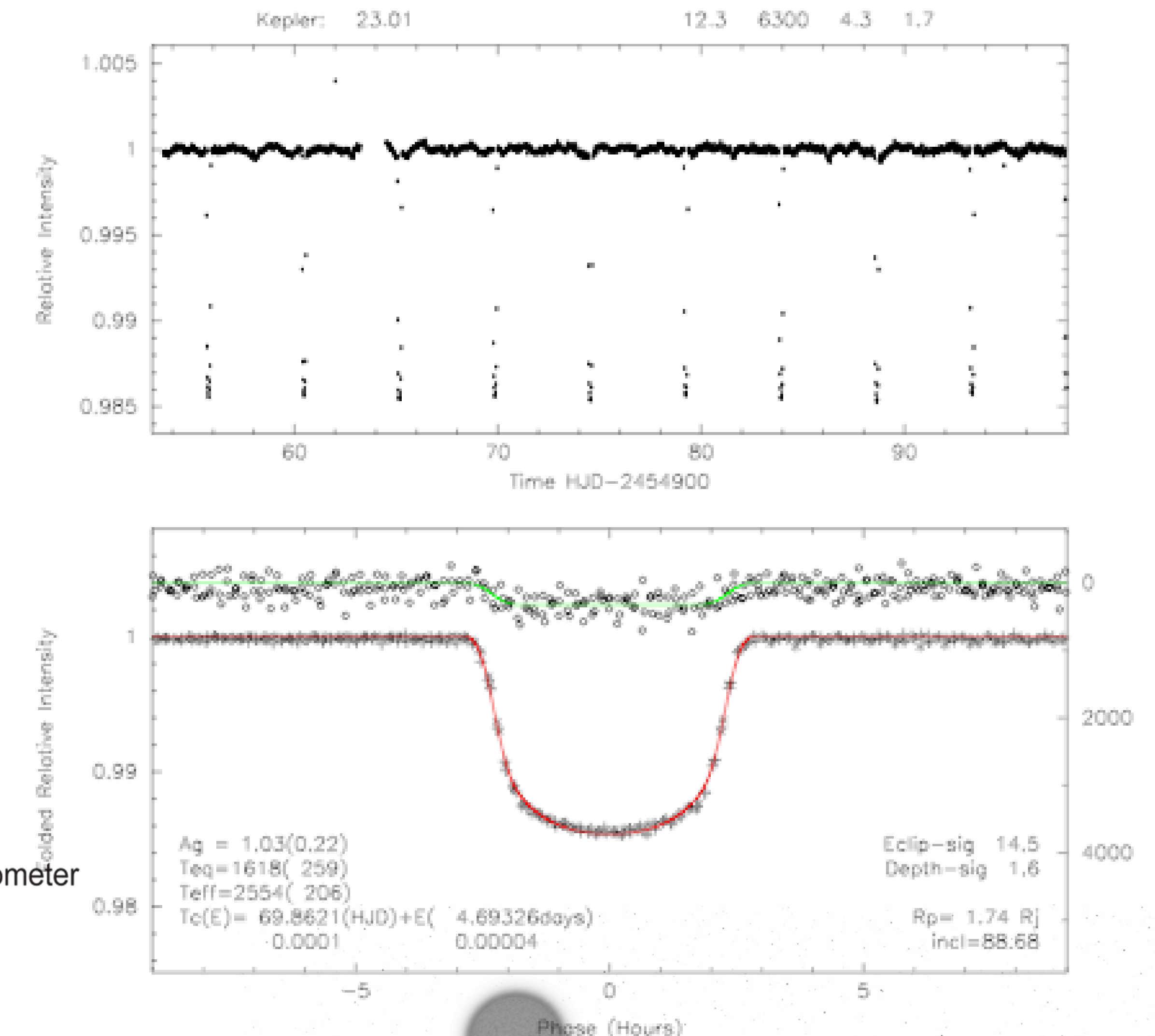


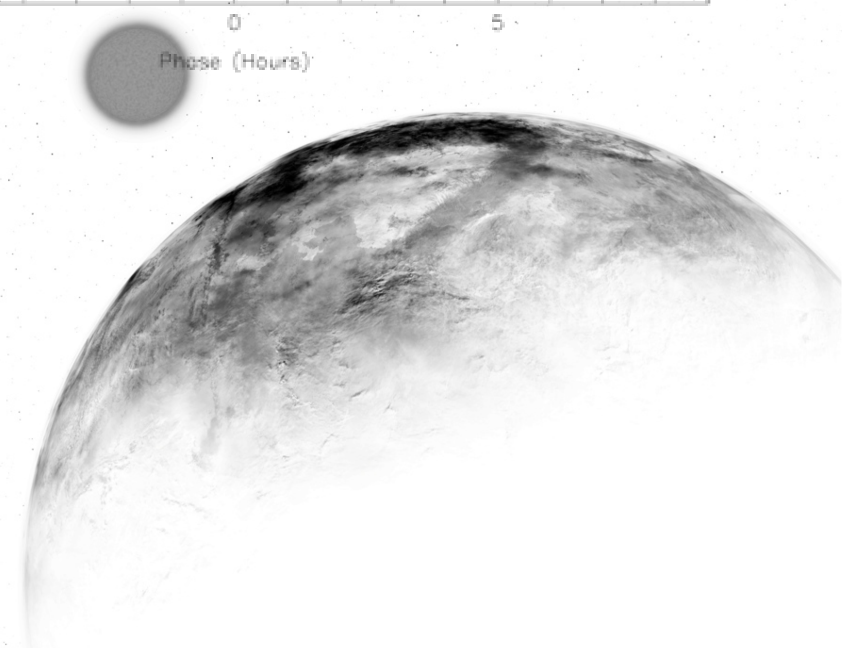
The detailed analysis of the lightcurve reveals the flux coming form the planet and its albedo, among other properties

See Jorge Martins's talk

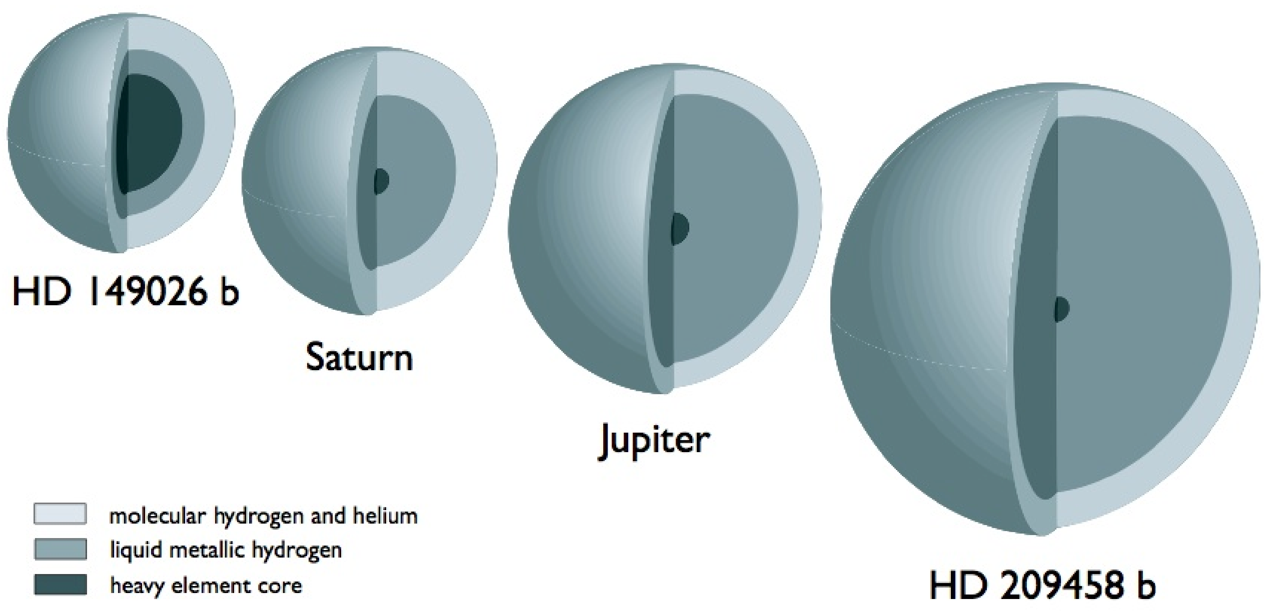
Transiting planets

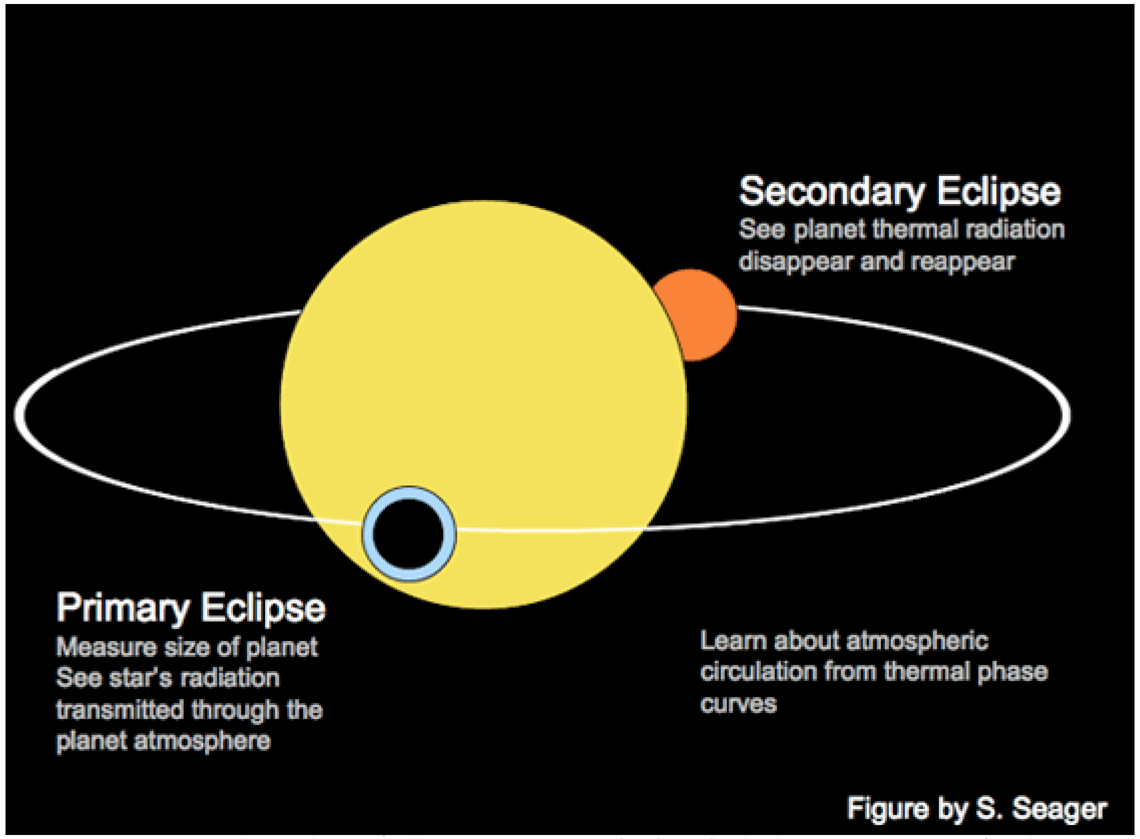


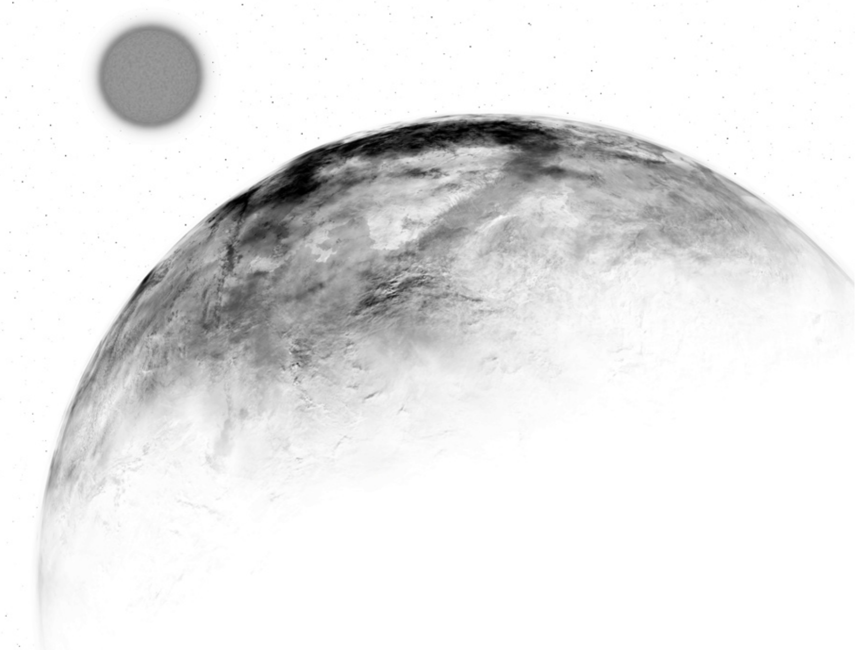




Transiting planets



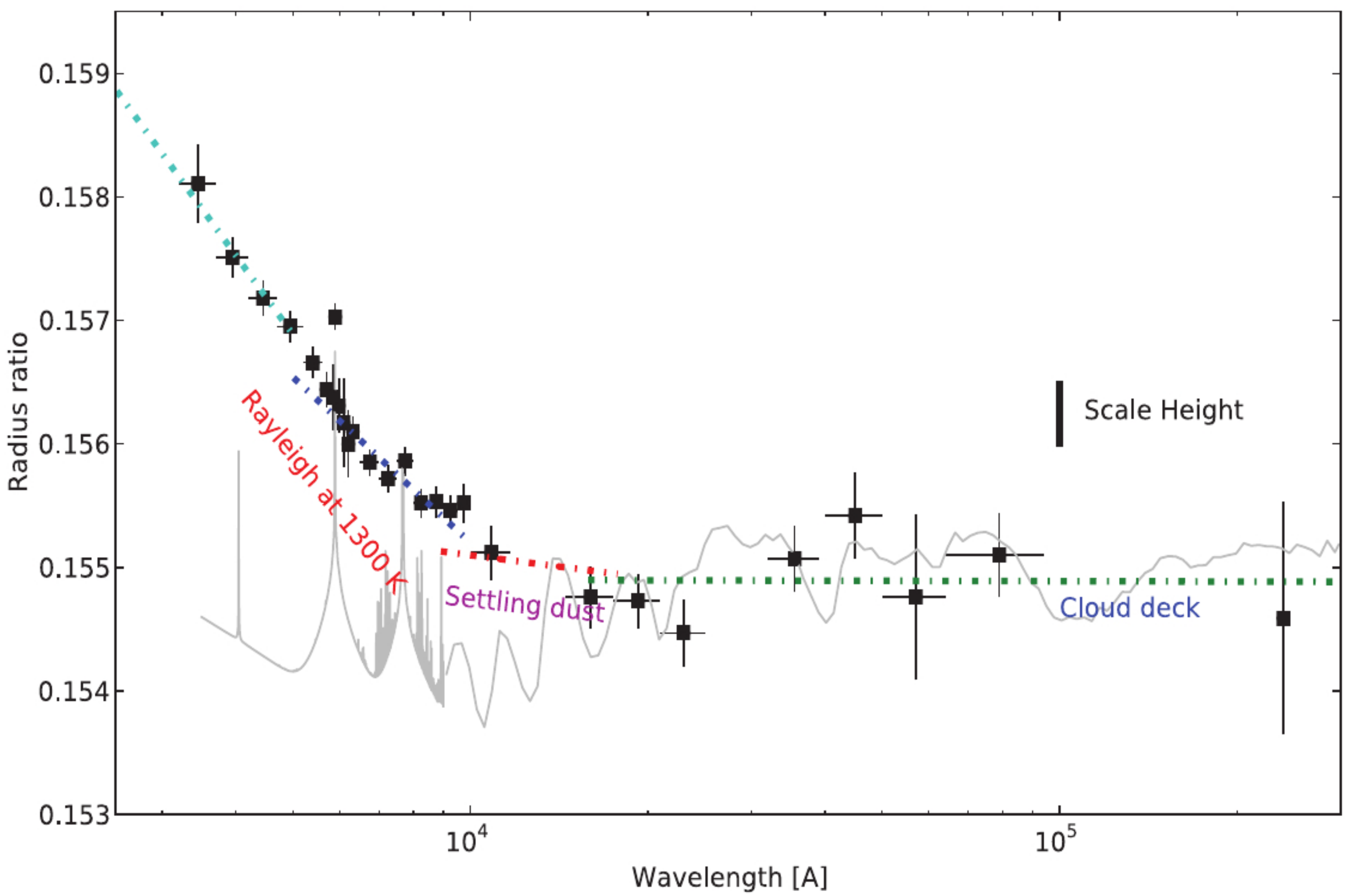


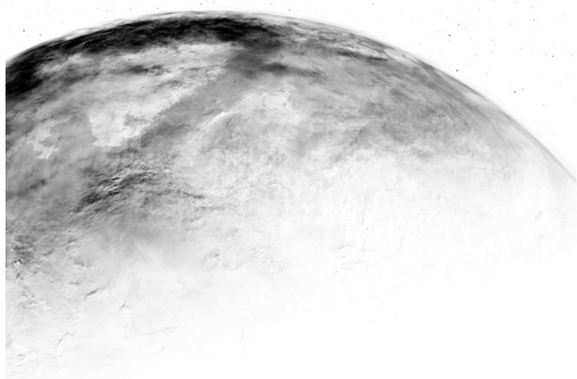


We can measure the radius of a planet and access its true mass. Using the two, we get the ***bulk density*** of the planet

The spectra?

Most results have been obtained with space telescopes, such as Hubble and Spitzer, which are unaffected by telluric absorption and do not have the Earth atmosphere to contribute to red noise, and provide thus a more stable noise background.

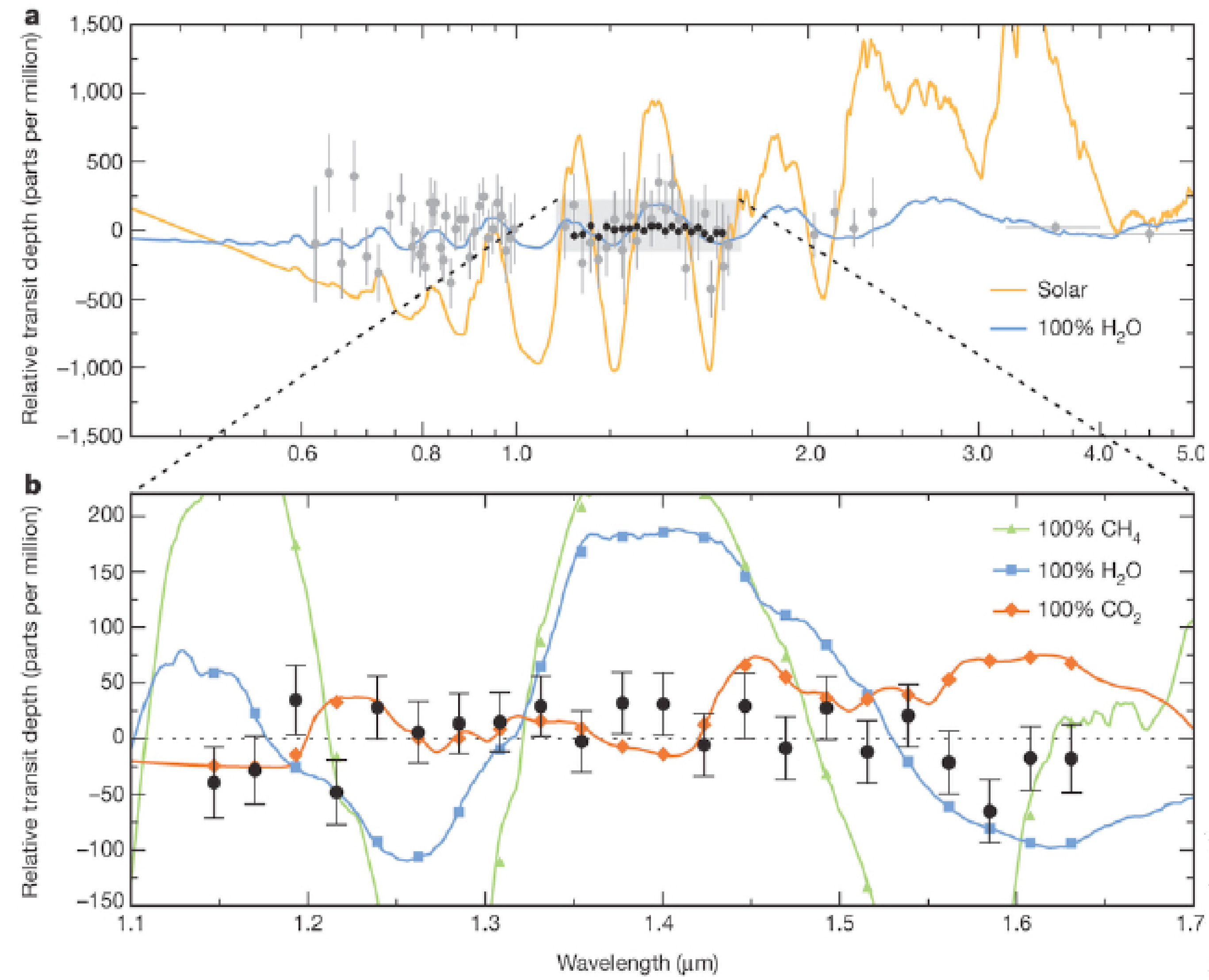




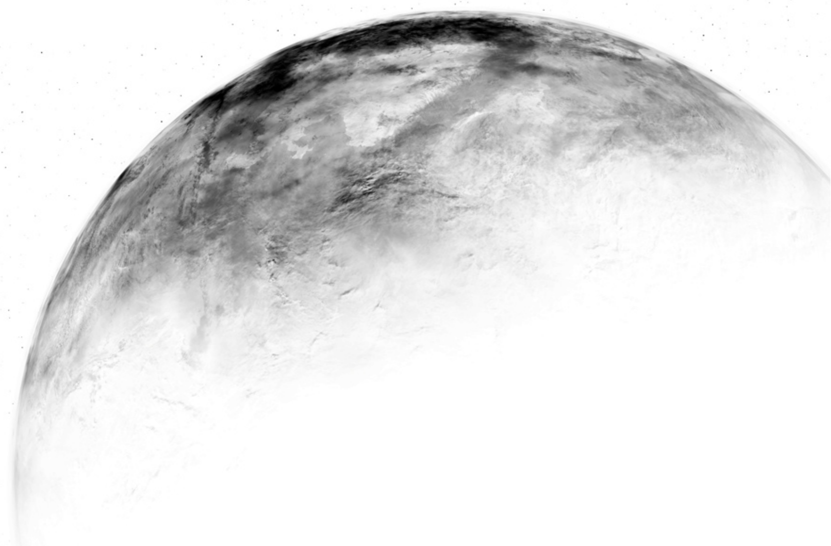
See Elyar Sedaghati's talk

Transmission Spectroscopy

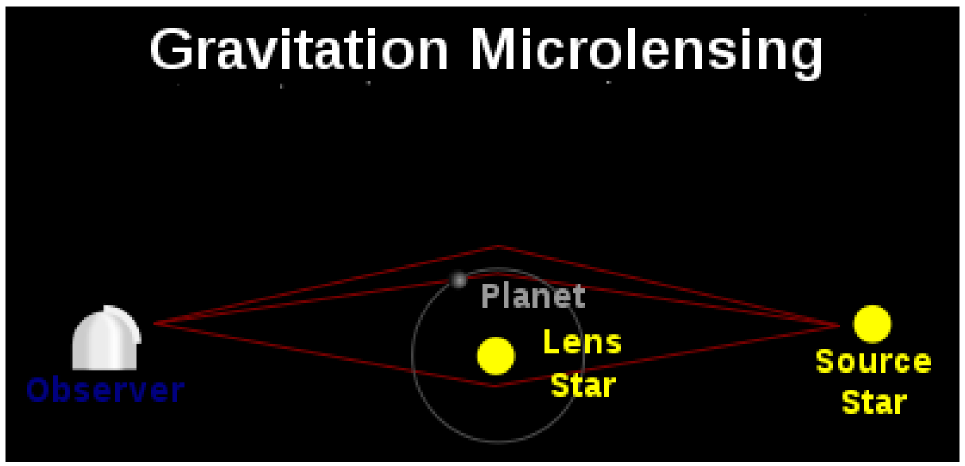
Kreidberg et al. 2014

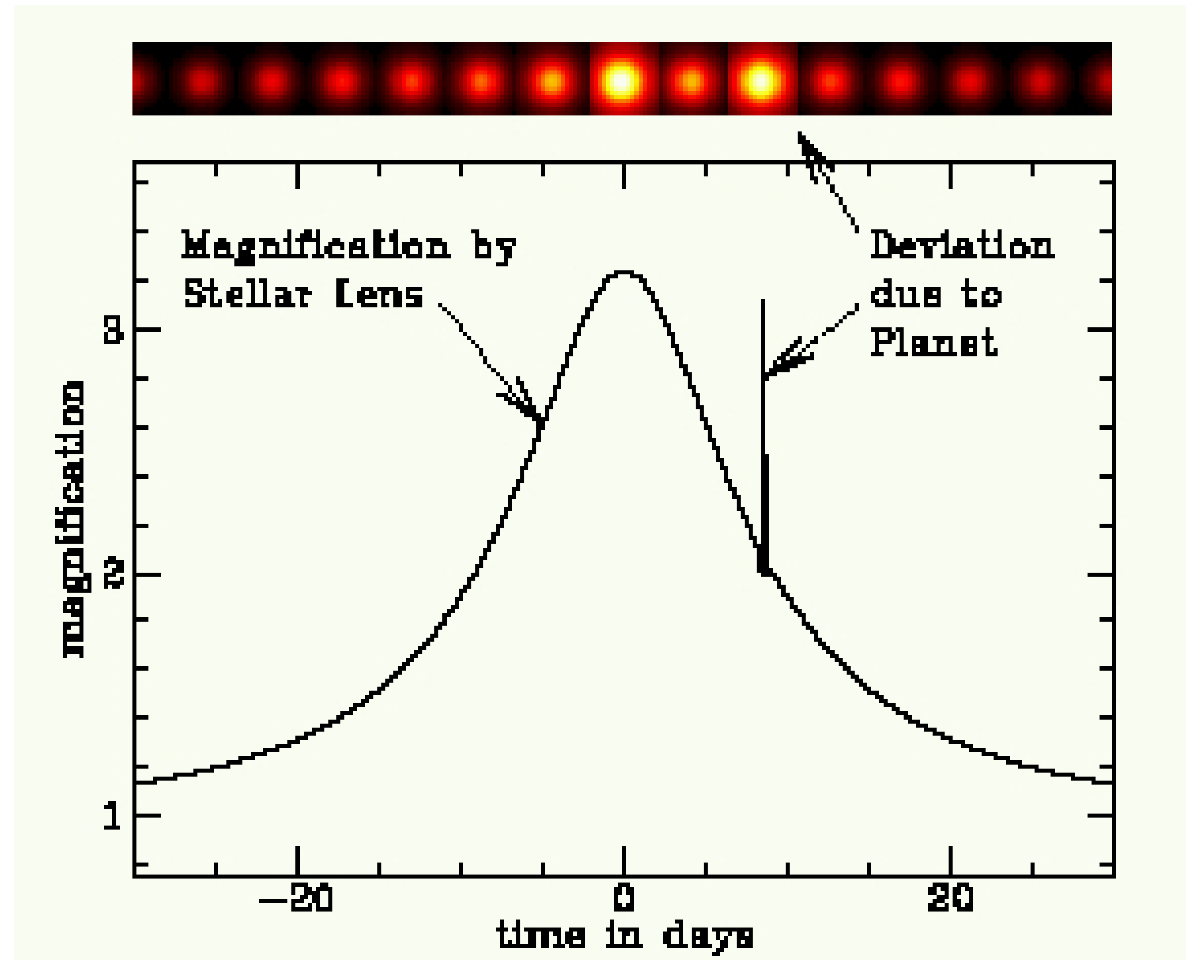


GJ1214 b was observed in transmission spectroscopy, revealing a surprisingly flat spectra. The observation was only possible because GJ1214 is an M-dwarf!

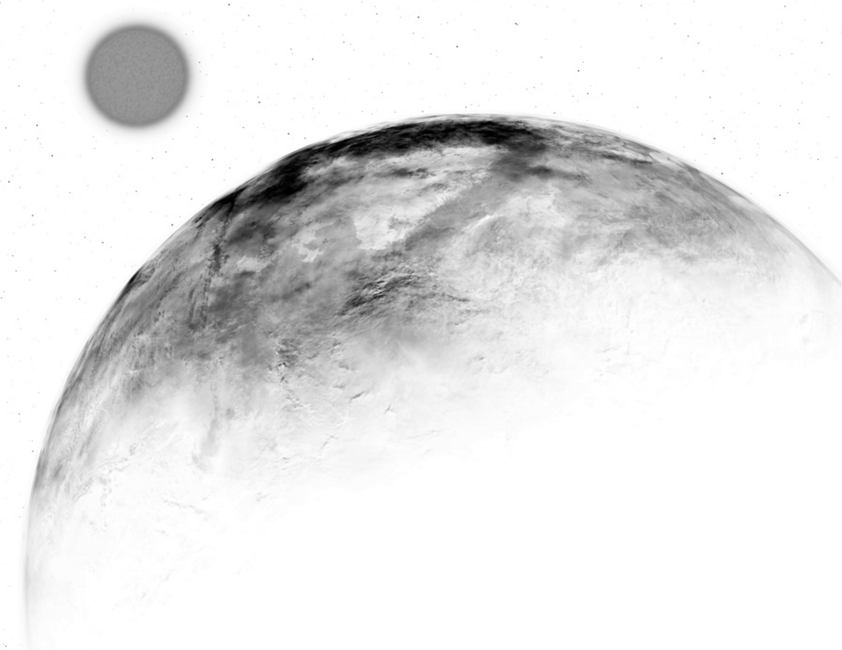


Gravitational Microlensing





As a planet intersects the line coming from a star, its gravitational field can magnify the light, giving rise to *gravitational microlensing effects*



Gravitational Microlensing

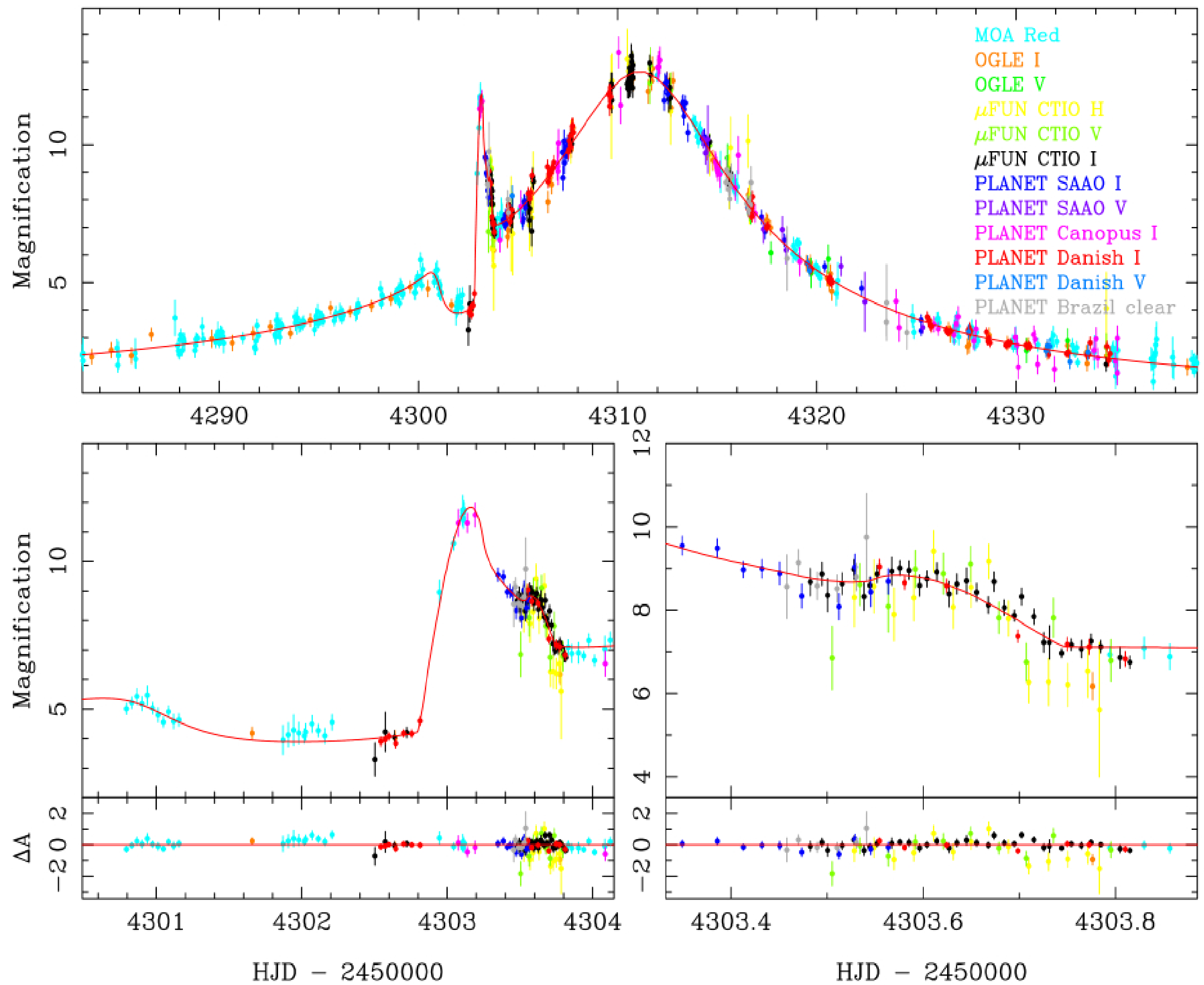
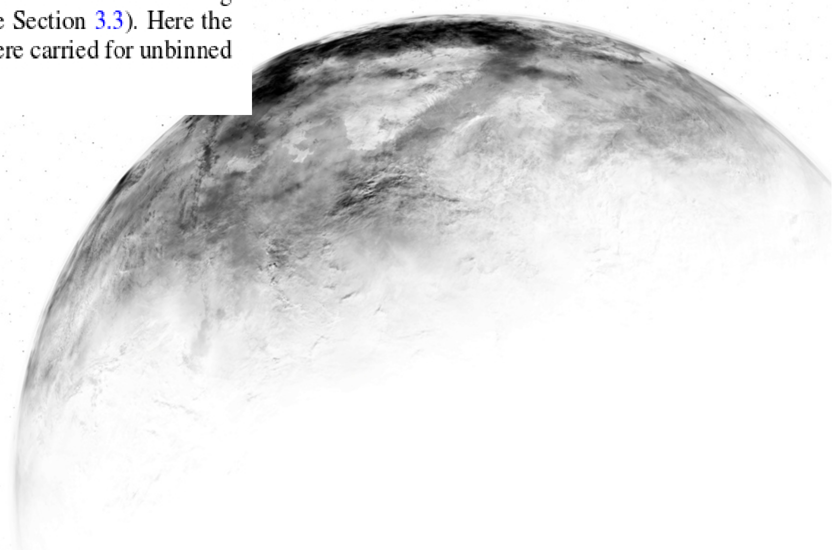


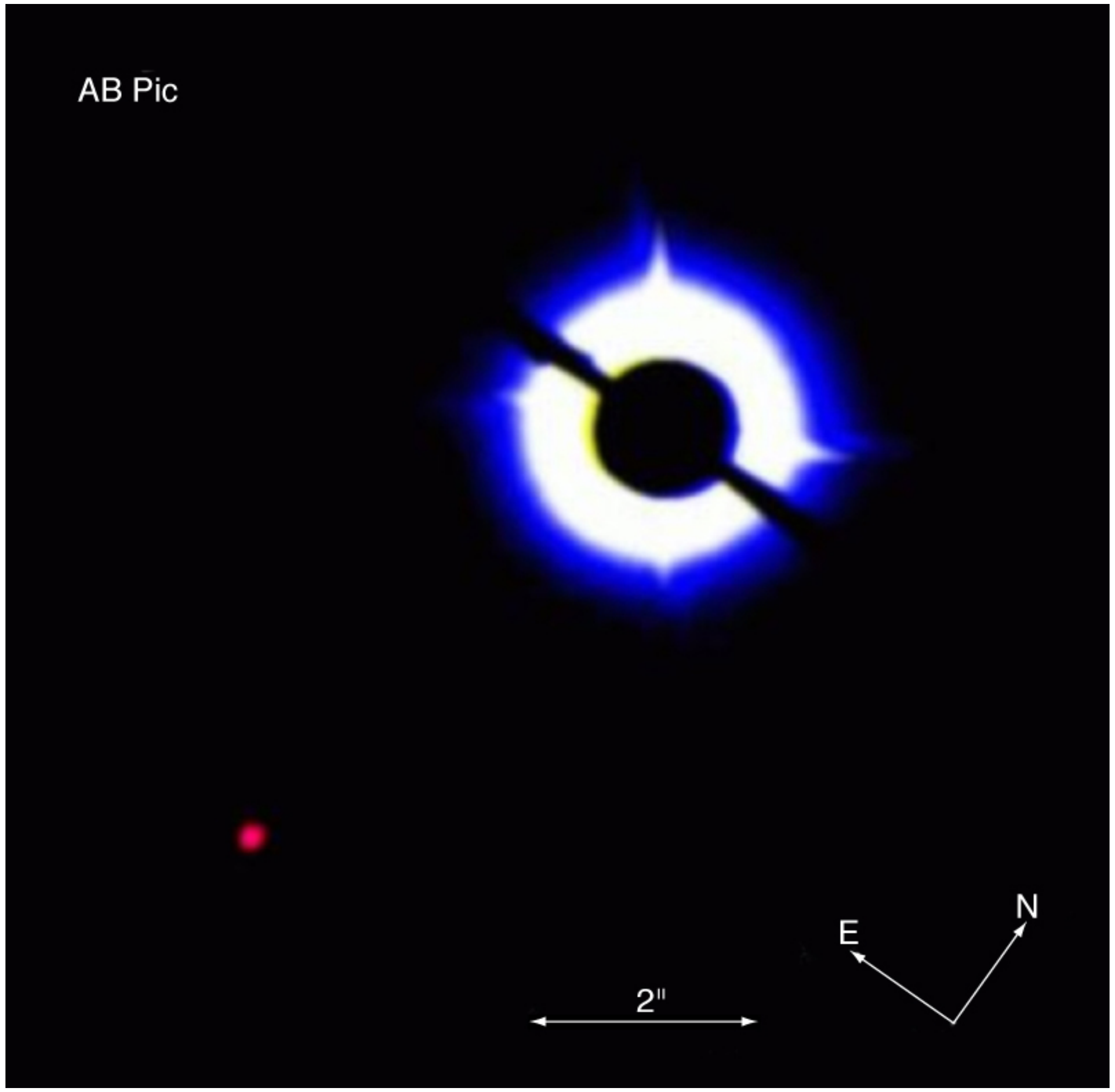
Figure 1. Light curve of OGLE-2007-BLG-368 over the whole event (top panel), around the planetary deviation (lower-left panel) and the second caustic crossing (lower-right panel) with the residual from the best fit model. The red lines indicate the best fit xallarap model with the Kepler constraint (see Section 3.3). Here the light curves of μFUN CTIO I, H and PLANET Brazil are binned by 0.01, 0.01, and 0.02 days, respectively, for clarity. Note that the fittings were carried for unbinned light curves.

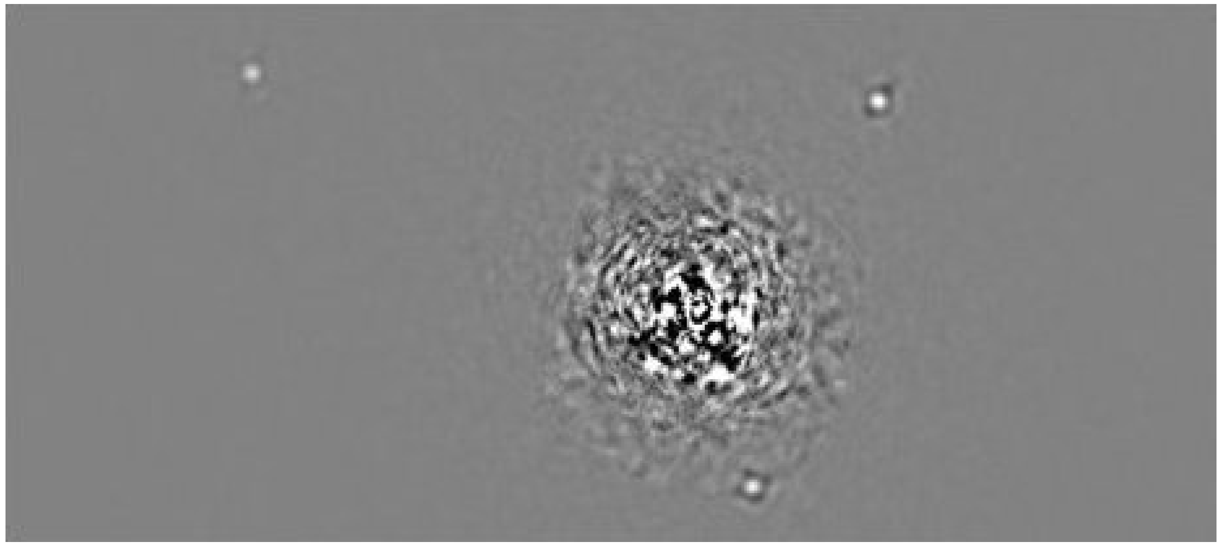
Gravitational microlensing is more sensitive at 1-10AU, showing cold neptunes are 3-4 times more common than jupiters

Sumi et al. 2010



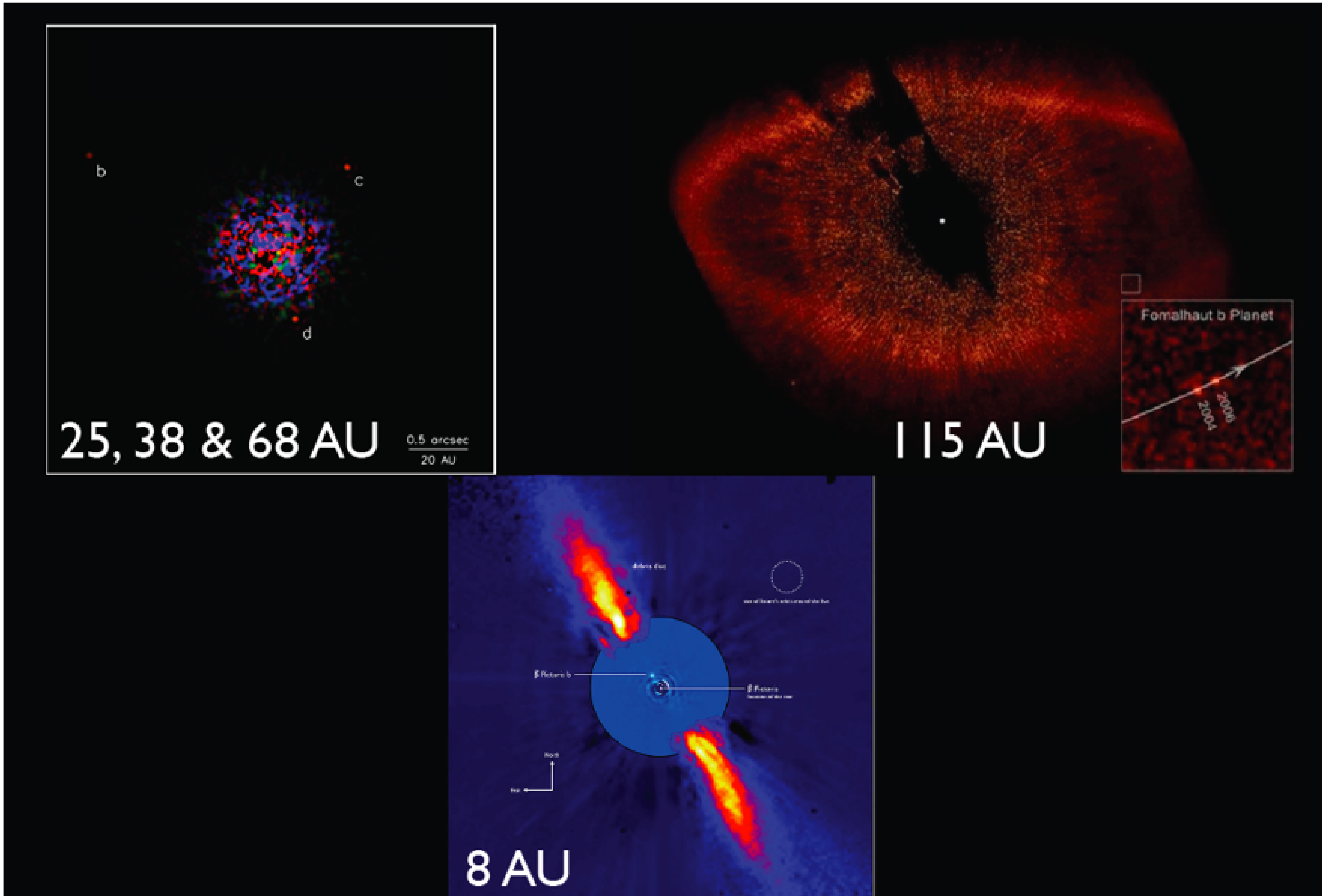
Direct Imaging





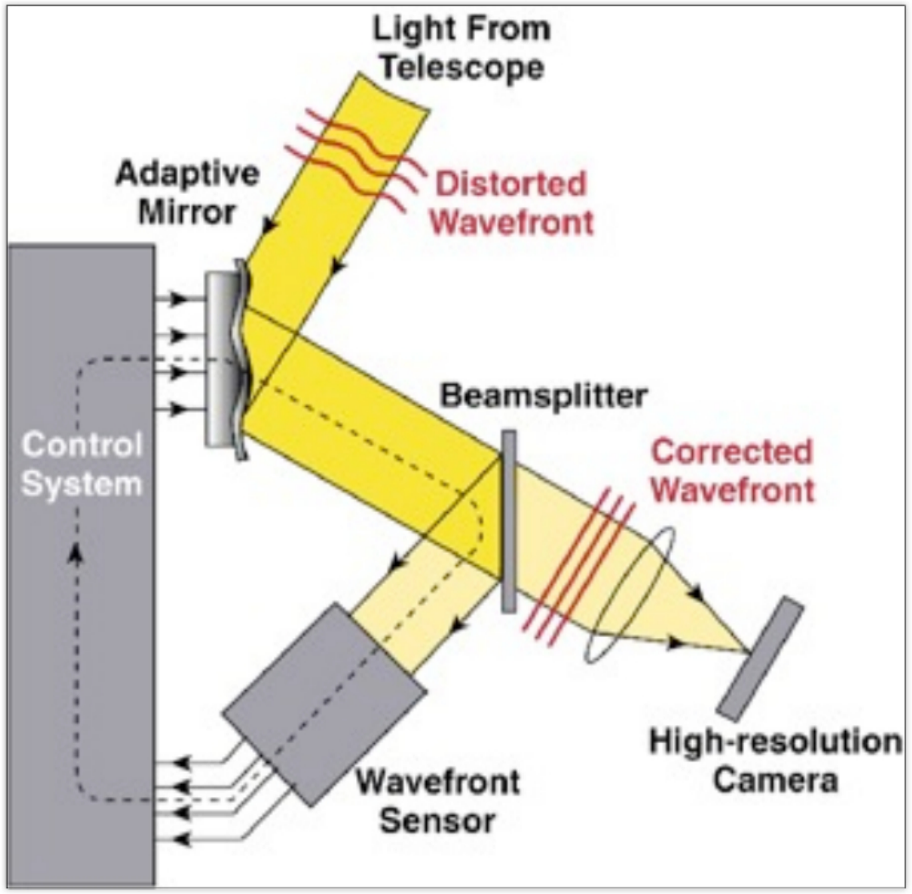
β Pic has a companion at 8-15 AU
HD8799 has at least 3 planets orbiting it

Direct Imaging



Kalas et al. (2008), Marois et al. (2008)

Direct Imaging



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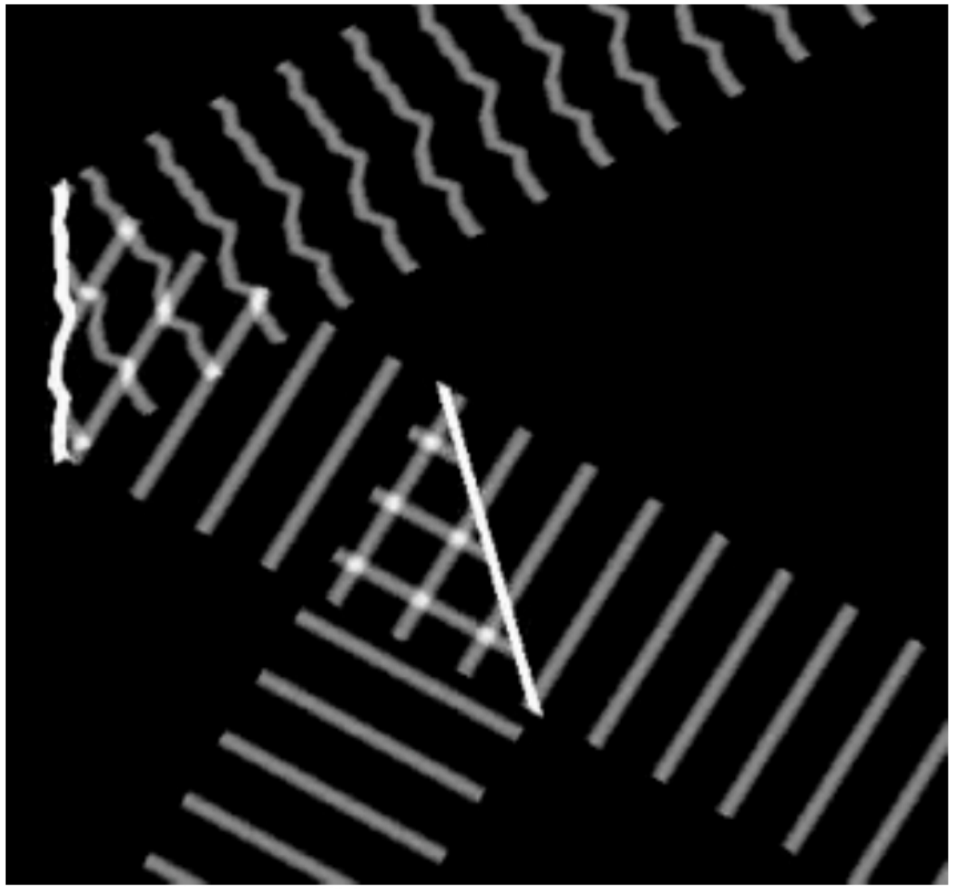


© Lacombe 2001

The usage of choronographs and adaptive optics to correct atmospheric turbulence permitted the direct imaging of extrasolar planets

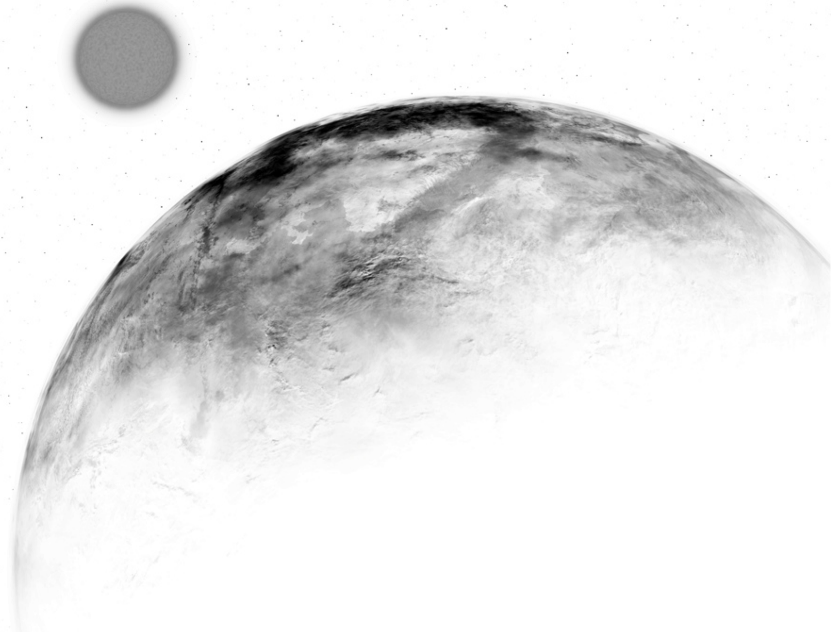
While the seeing is usually of 0.5-1'', the diffraction limit of a D=1.3m telescope is already at the 0.1'' level!

Direct Imaging

The main advantage of the direct imaging – other than being a direct measurement – is that probes orbital distances larger than 5 AU.

Unfortunately, its main disadvantage is that does not provide a direct mass measurement of the planet, and its mass has to be inferred from models that have a large uncertainty associated.

And... Radial velocity campaigns have now 20 years old and the two techniques are starting to reach the same parameter space (e.g. Moutou et al. 2014)



Astrometry

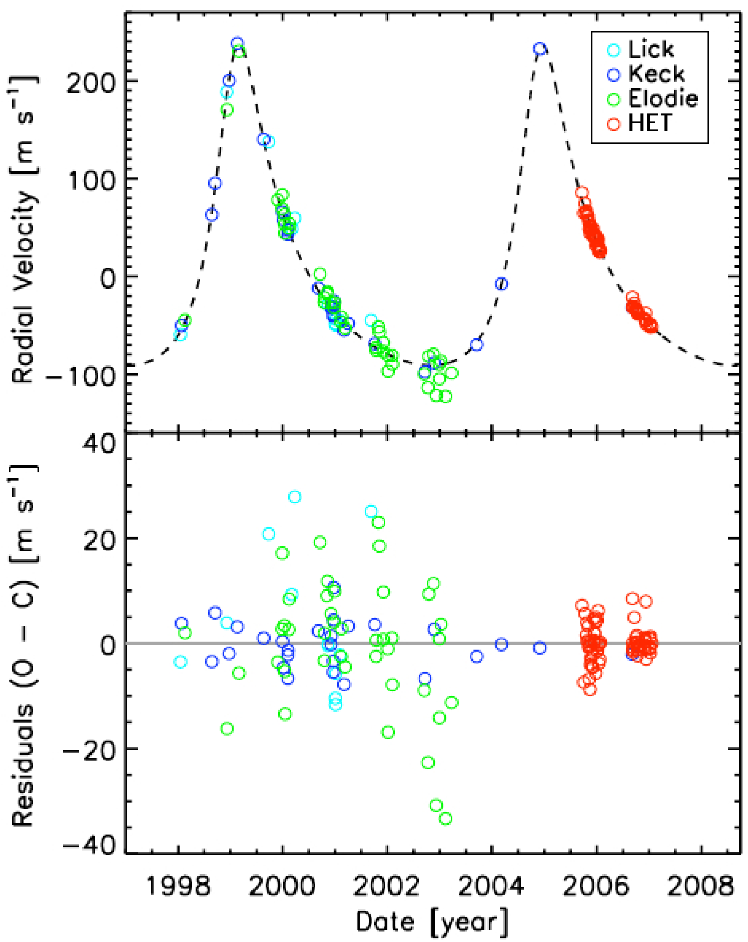
HD 33636 b (Bean et al. 2007)

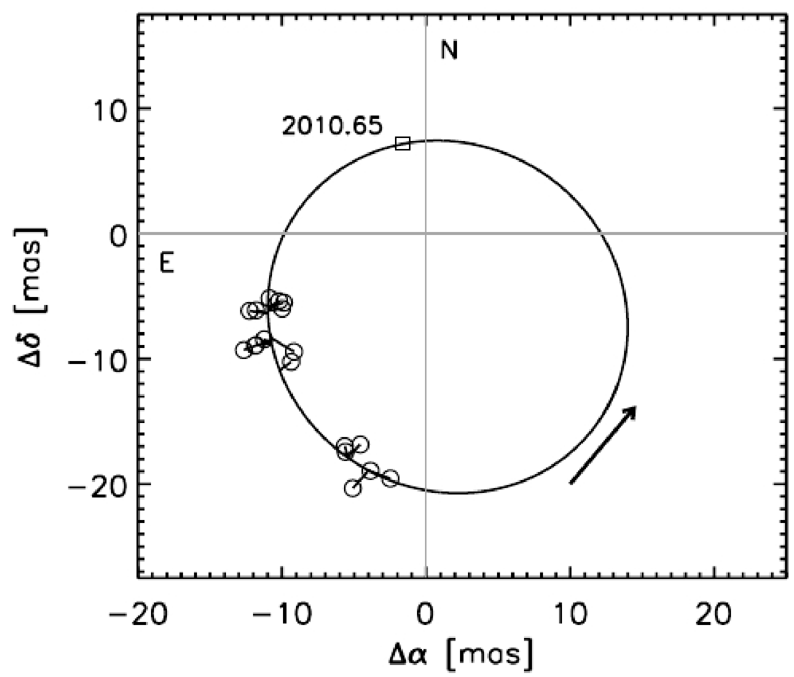
Radial velocities
m2sini = 9.3M$_{Jup}$

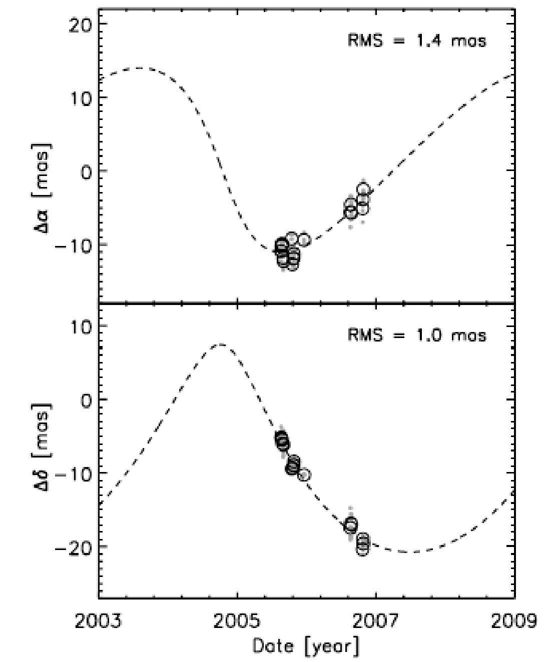
P=2117d

HST Fine Guidance Sensor
m2 = 142 +/- 11 M$_{Jup}$

late M star companion



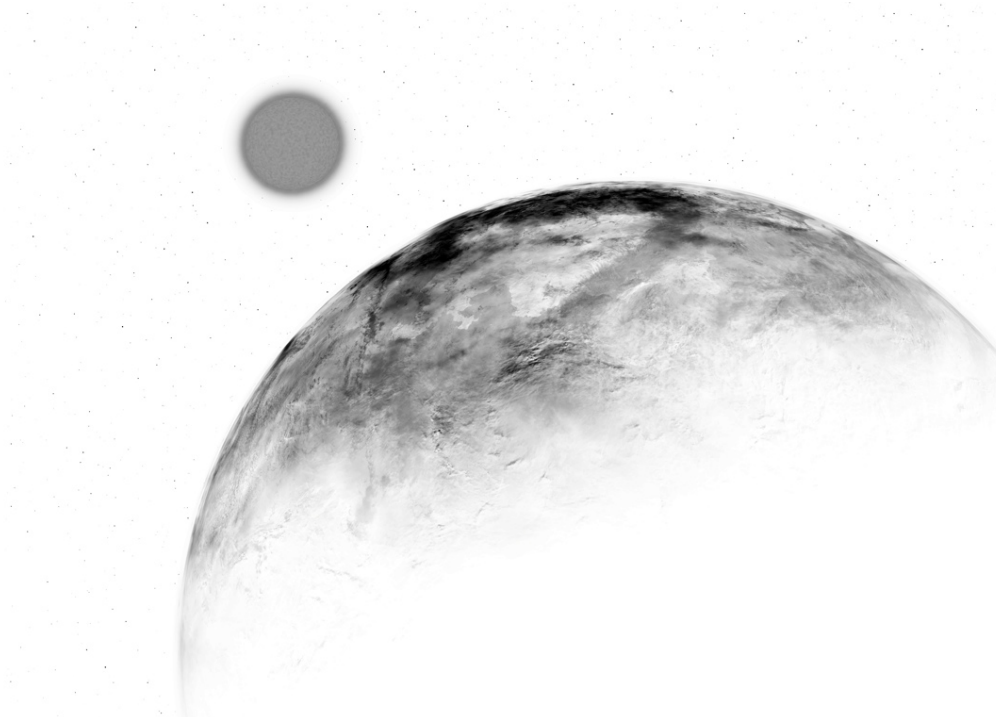




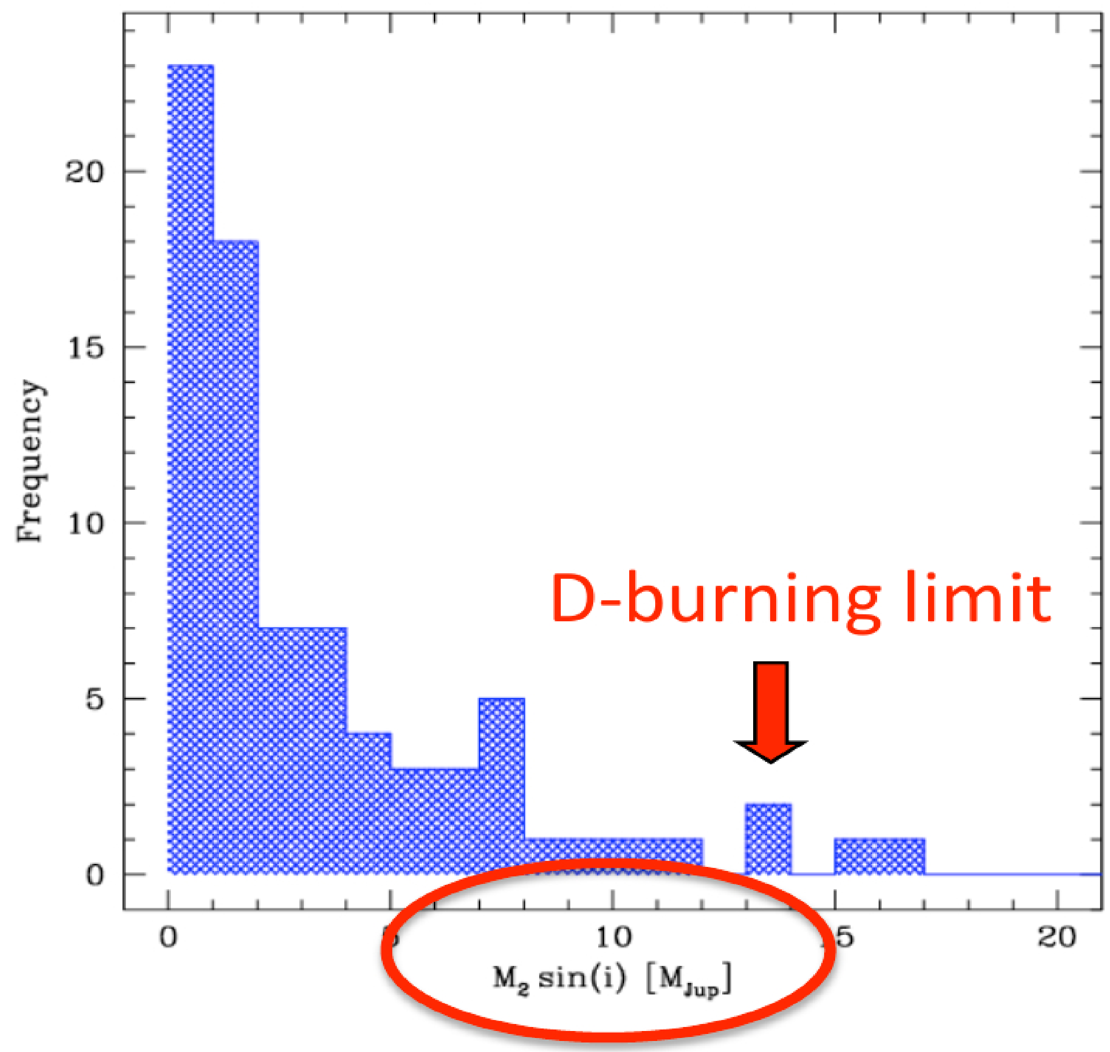
We are only now starting, the GAIA satellite will allow the precise astrometric and distance measurement of 10^6 stars!

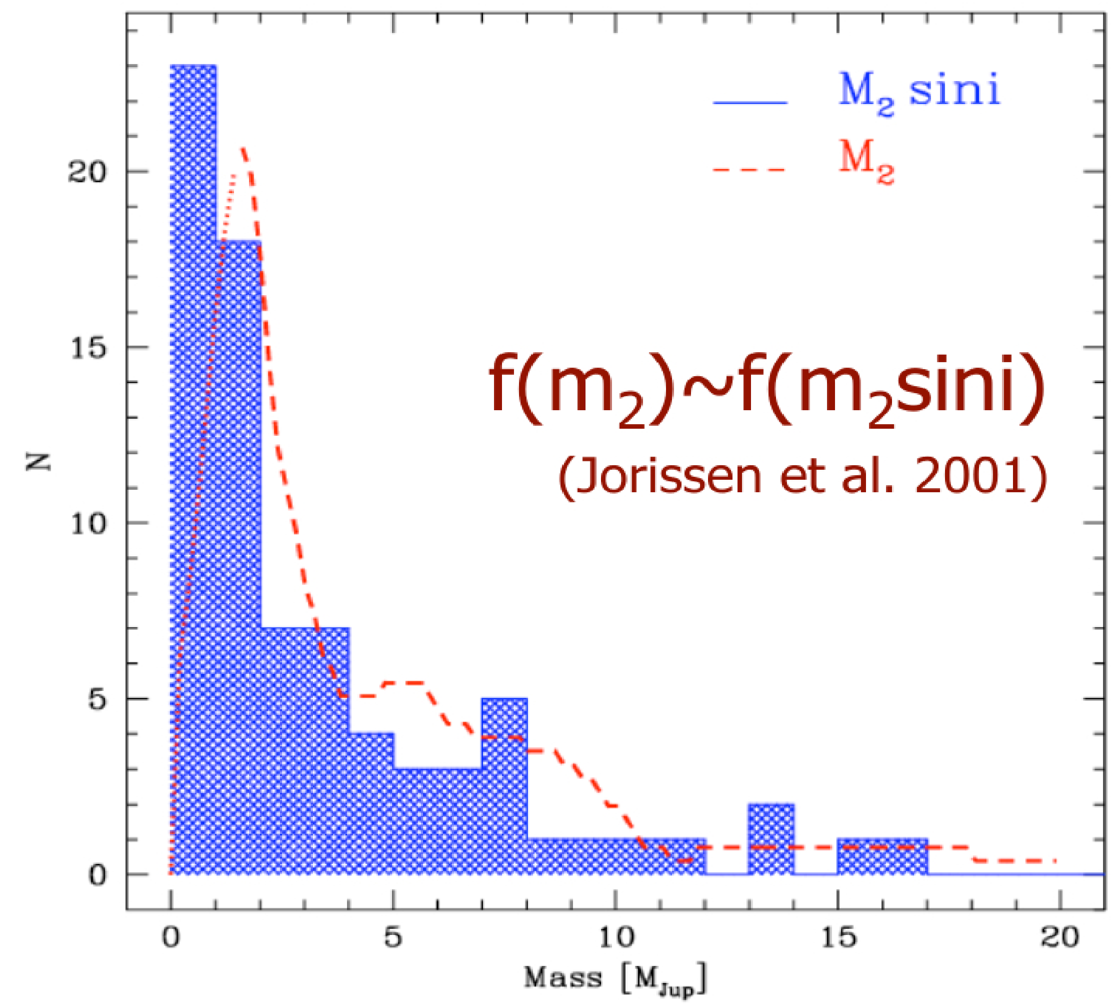
The Burning Questions

- Are Hot-Jupiters common?
- Is the formation of our system an unlikely event?
- How many stars have exoplanets?



The Mass distribution





There was an overabundance of low-mass planets since the beginning, in spite of the increased sensitivity to high-mass objects

The bounty

M. Mayor et al.: The HARPS search for southern extra-solar planets

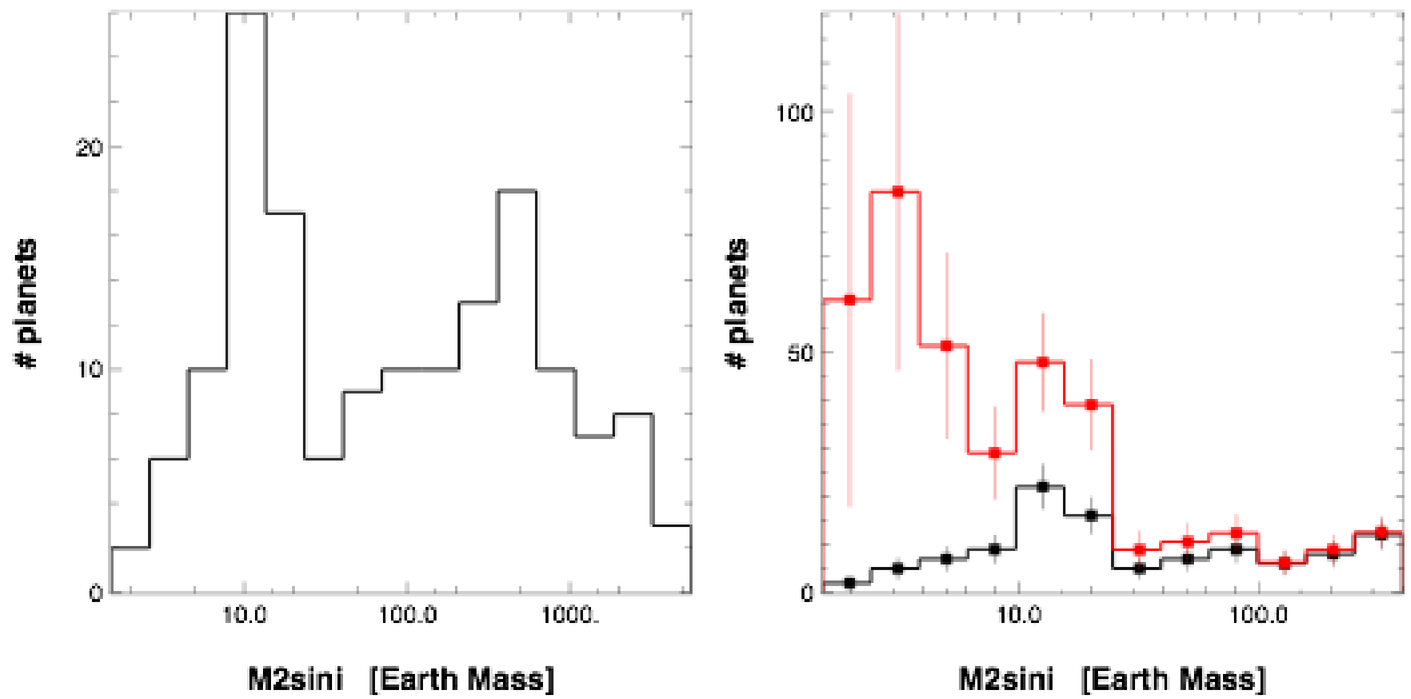


Fig. 10. Observed mass histogram for the planets in the combined sample. Before any bias correction, we can already notice the importance of the sub-population of low-mass planets. We also remark a gap in the histogram between planets with masses above and below ~30 $M_{\oplus}$.

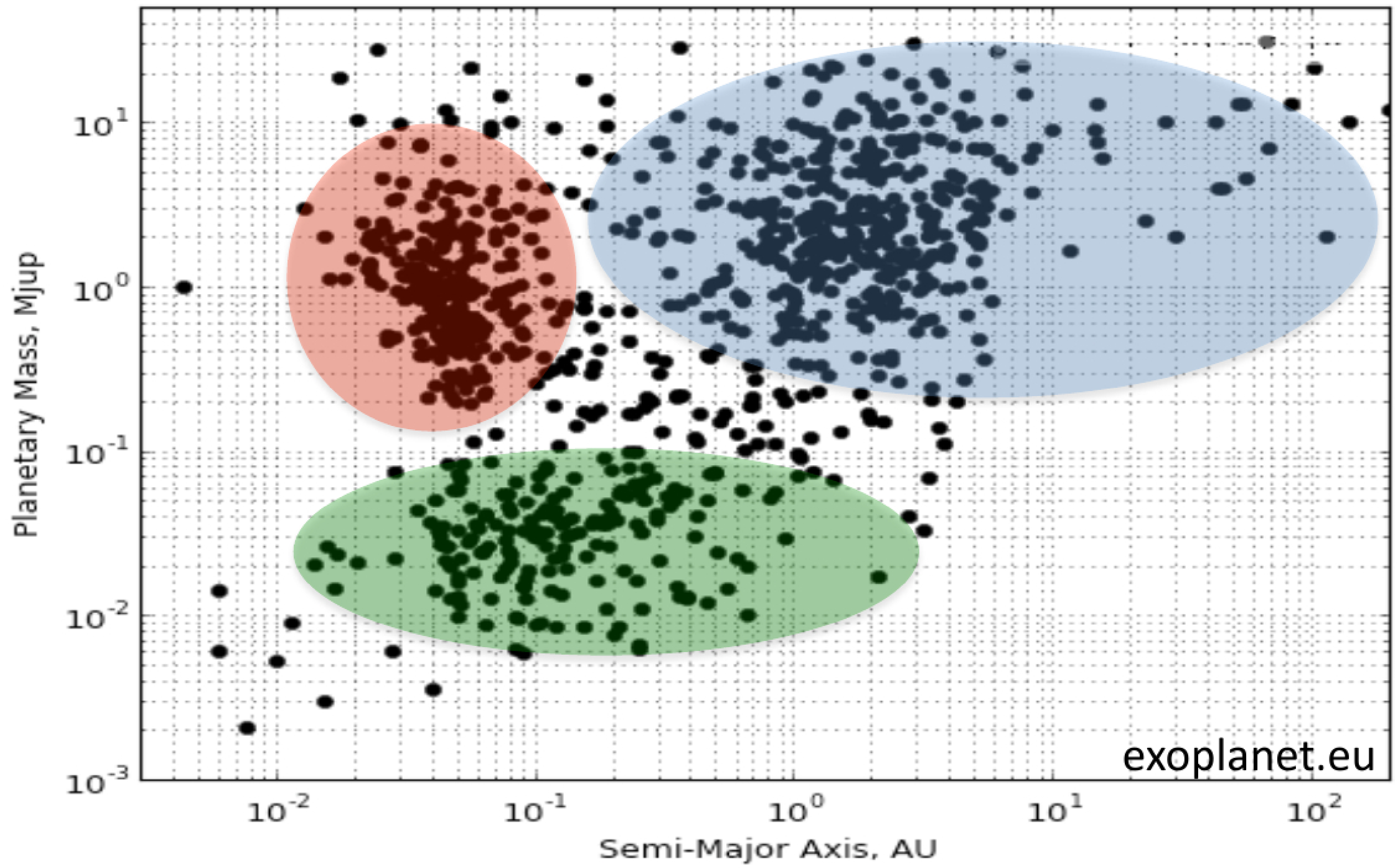
Fig. 12. Histograms of planetary masses, comparing the observed histogram (black line) and the equivalent histogram after correction for the detection bias (red line).

Planets are abundant, and low-mass planets are ***everywhere***

> 50% of FGK start have a planet with a P<100 days

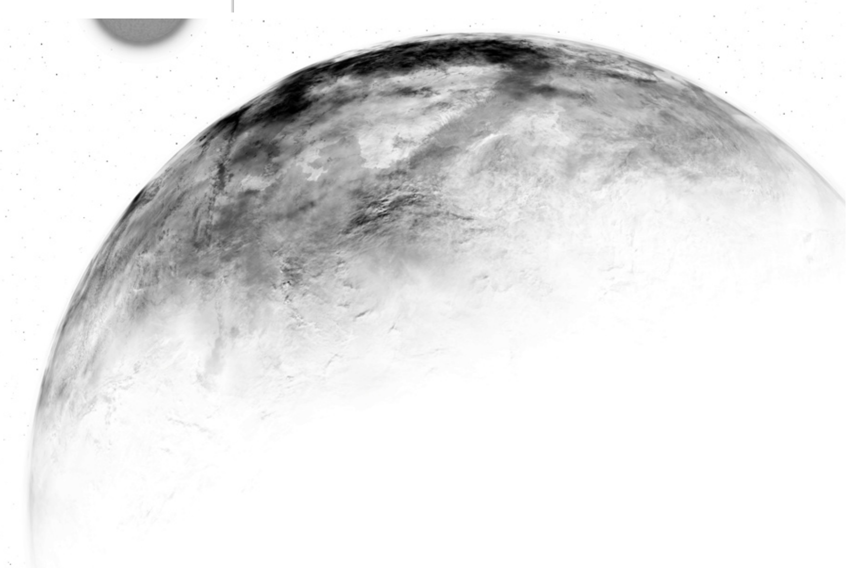
Mayor et al. (2011)

The bounty



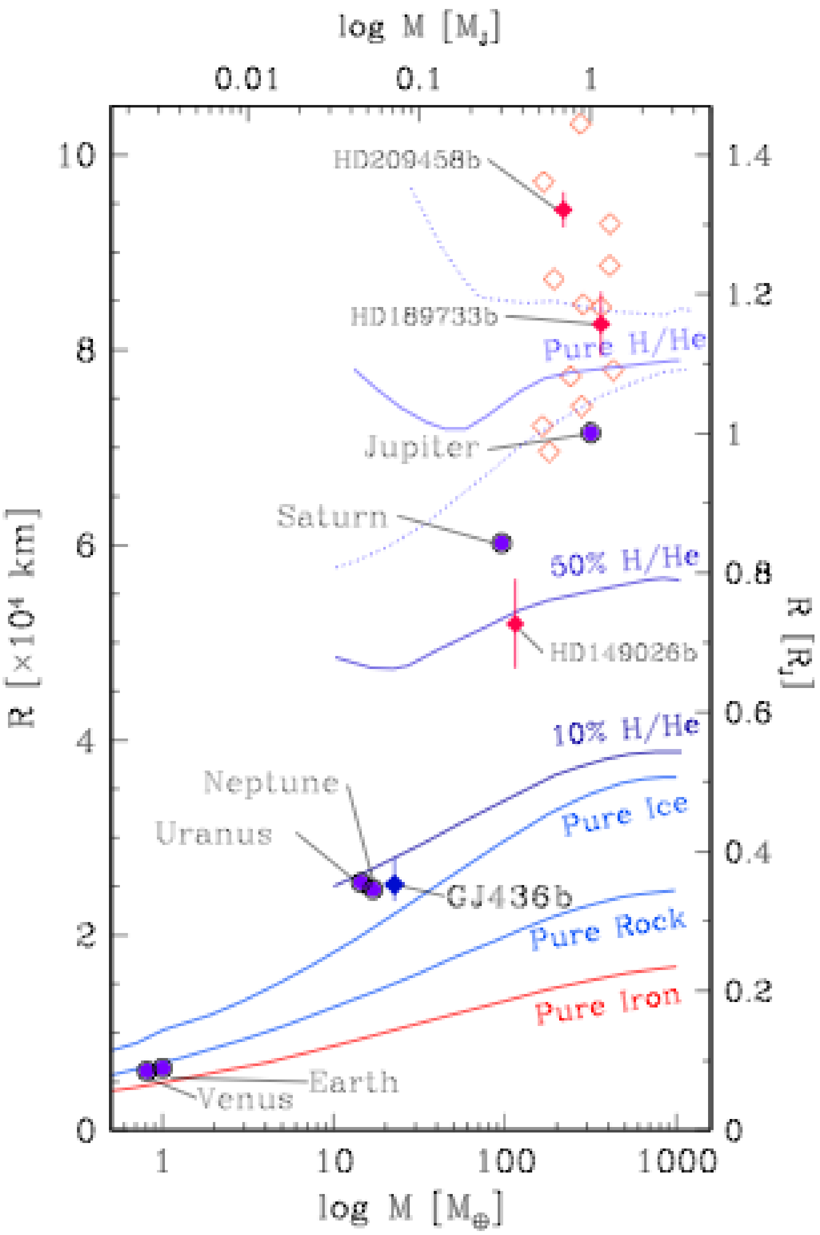
Hot Jupiters
Gas and ice giants
Super Earths and mini Neptunes

Planets cluster into three classes in a Mass – Semi-Major Axis plot

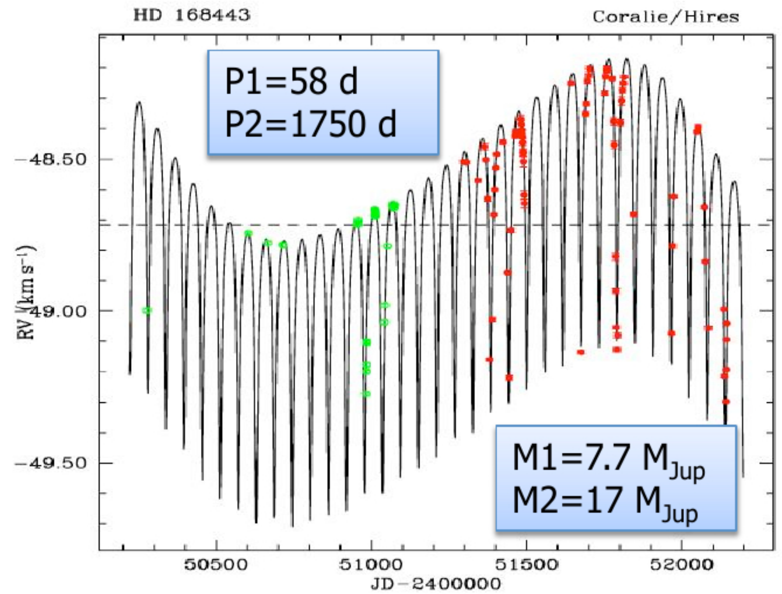


Food for thought

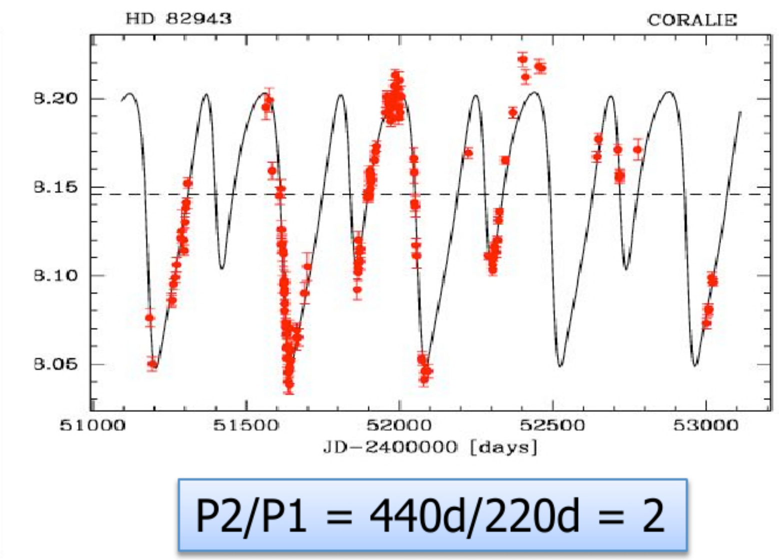
Planet structure models and **dynamic modelling** saw a huge boost during the last years.



Hierarchized



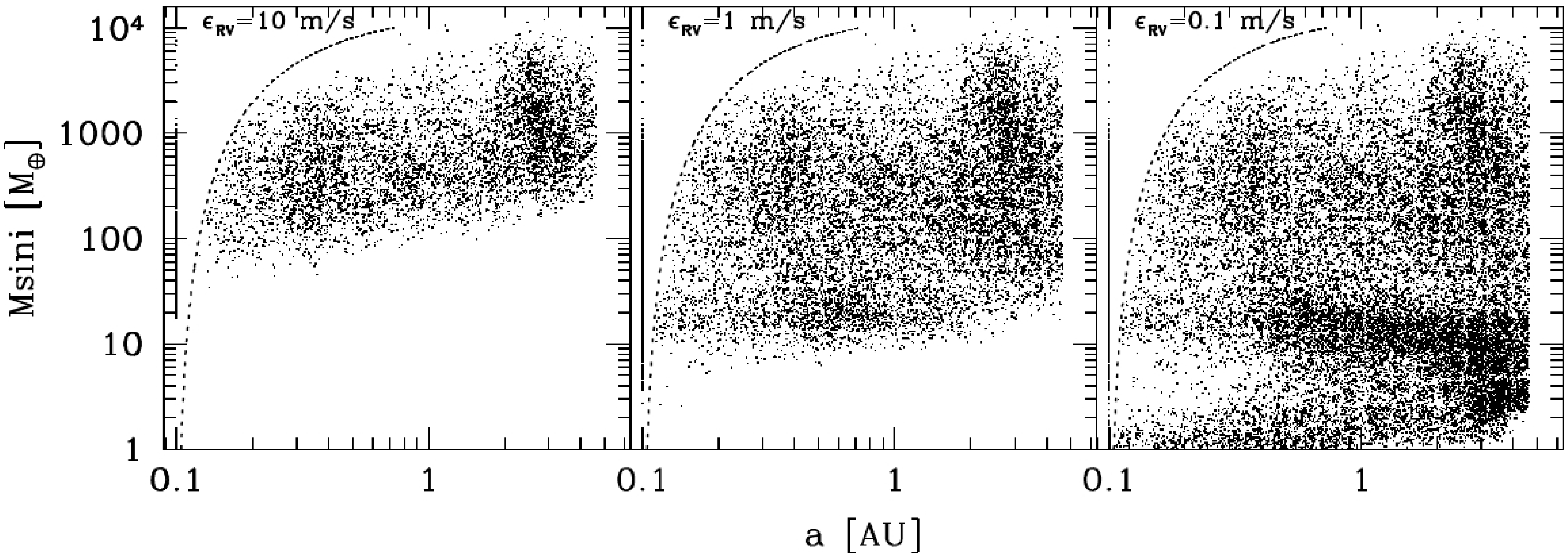
Resonant



Fortney, 2007
Correia et al. 2009

How can you form these planets?

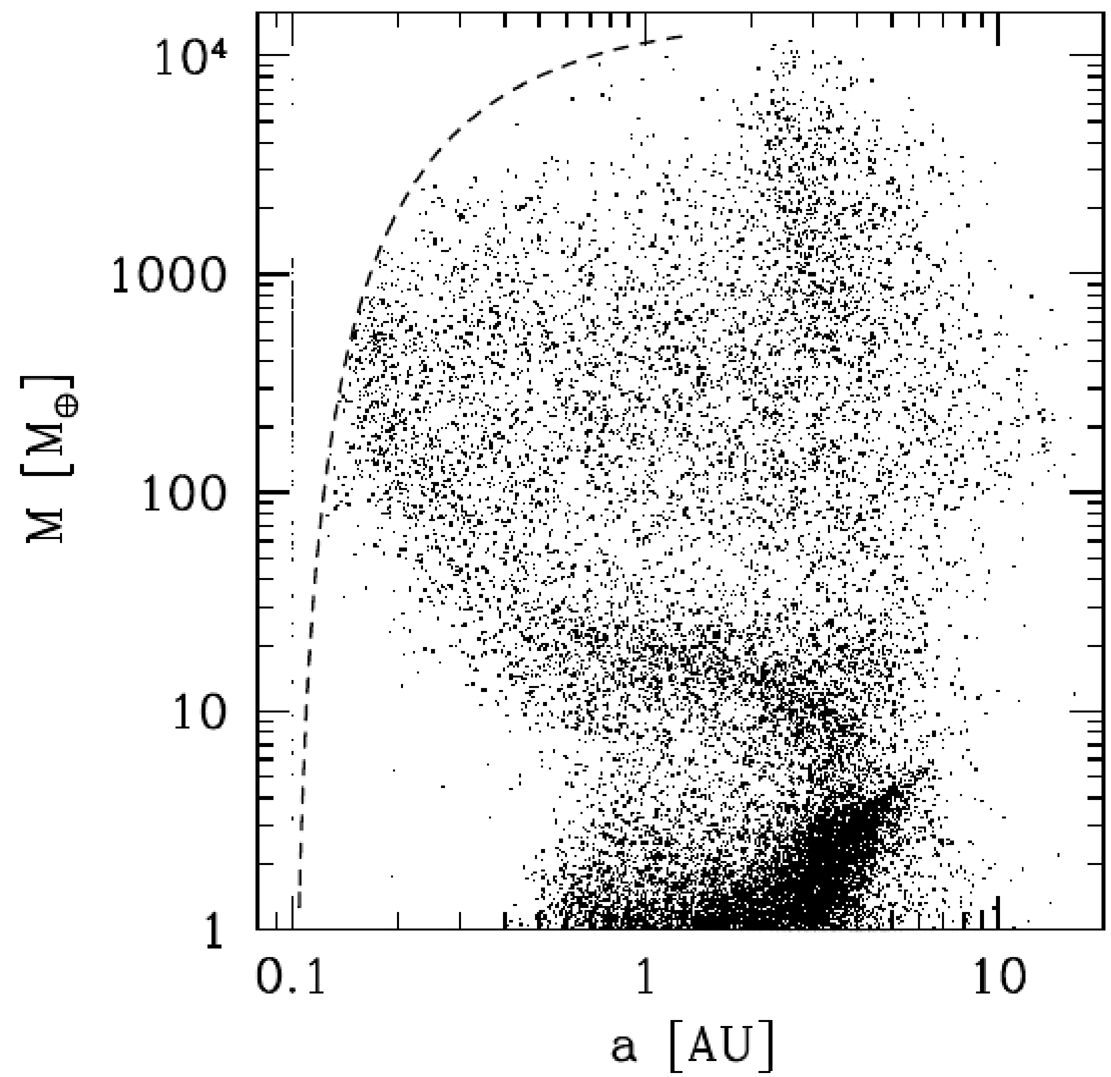
Core accretion predicts a vast number of exoplanets, that match the observations and are a common outcome of stellar formation

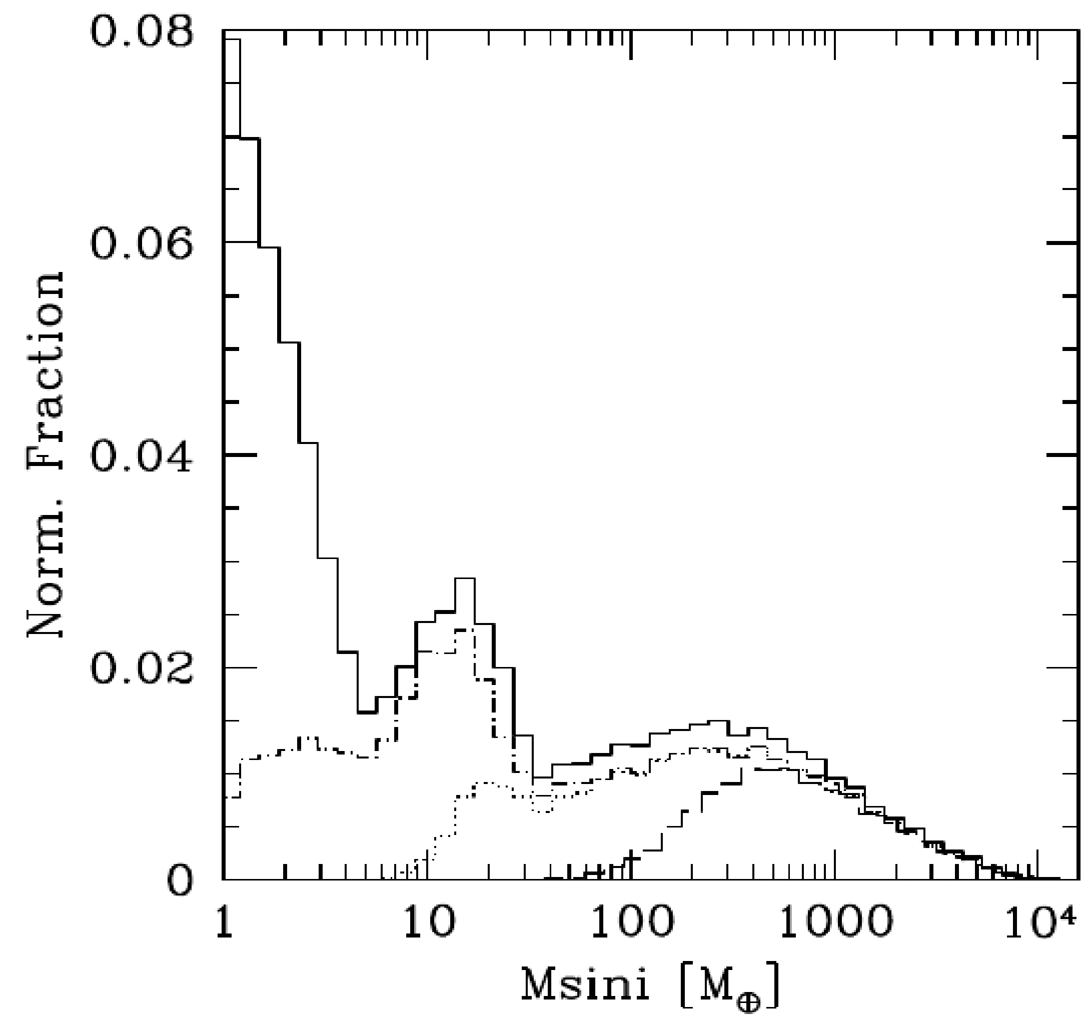


As we increase RV detection precision, we should find more and more planets.

The great victory of C.A.

It also predicts the clustering of planets around three mass classes: **Earth-like**, **Neptune-like**, and **Jupiter-like**.



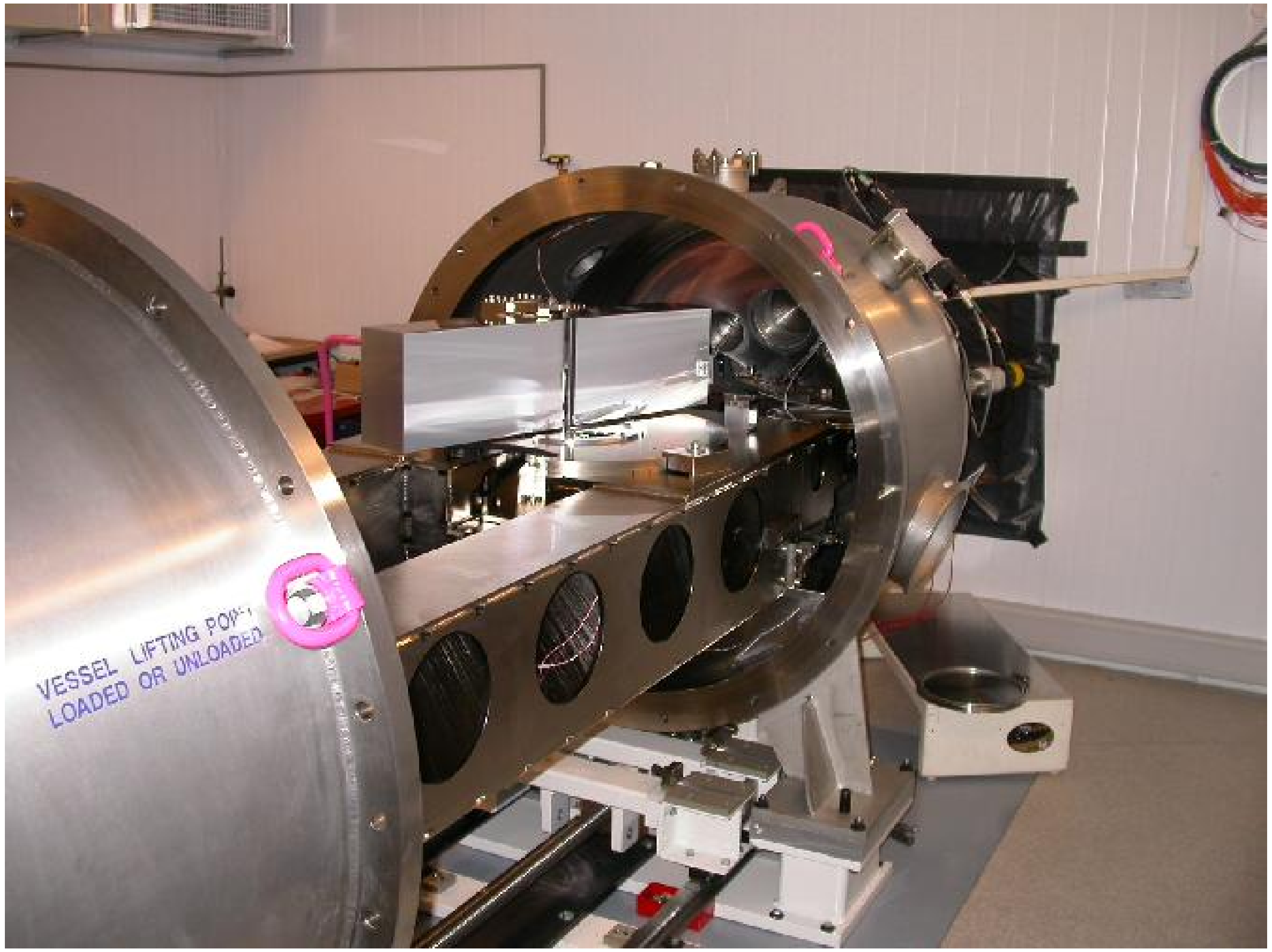


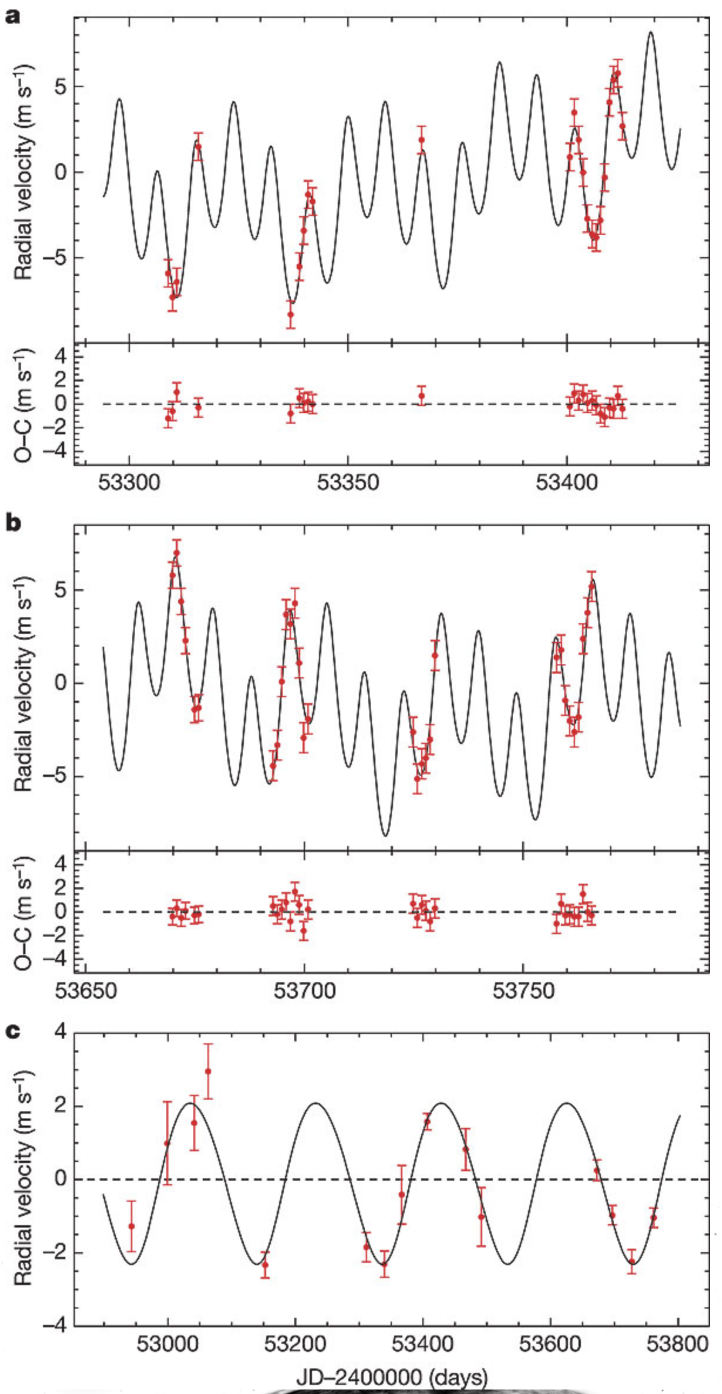
Mordasini et al. (2009b)

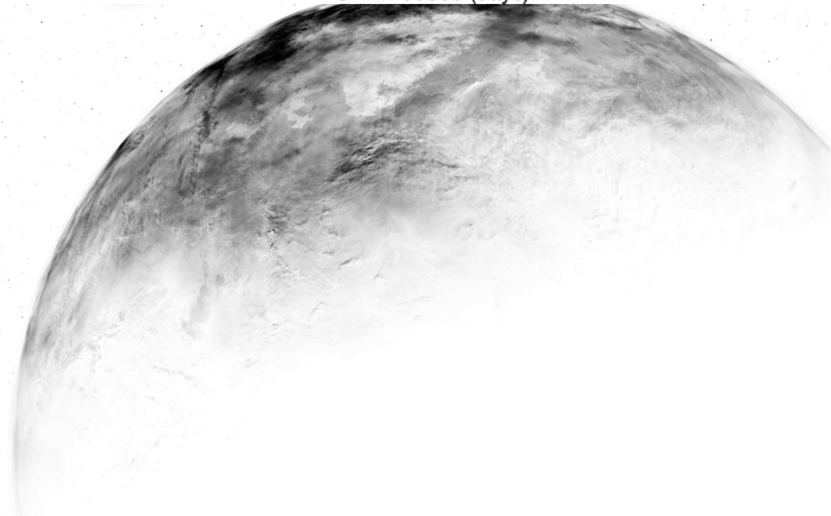
Radial Velocities

HARPS is the most precise spectrograph in the world

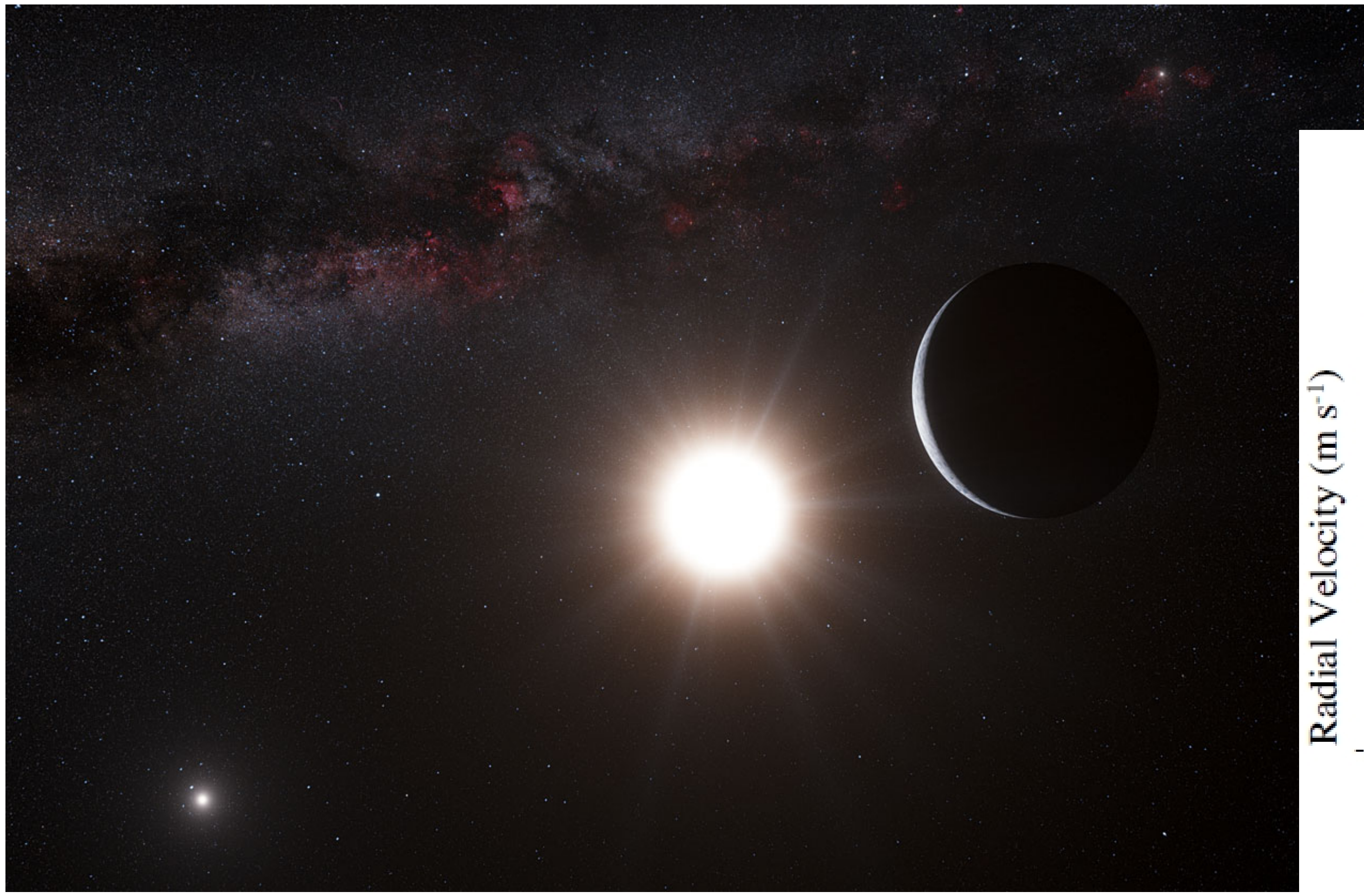
σ_{inst} < 50 cm/s

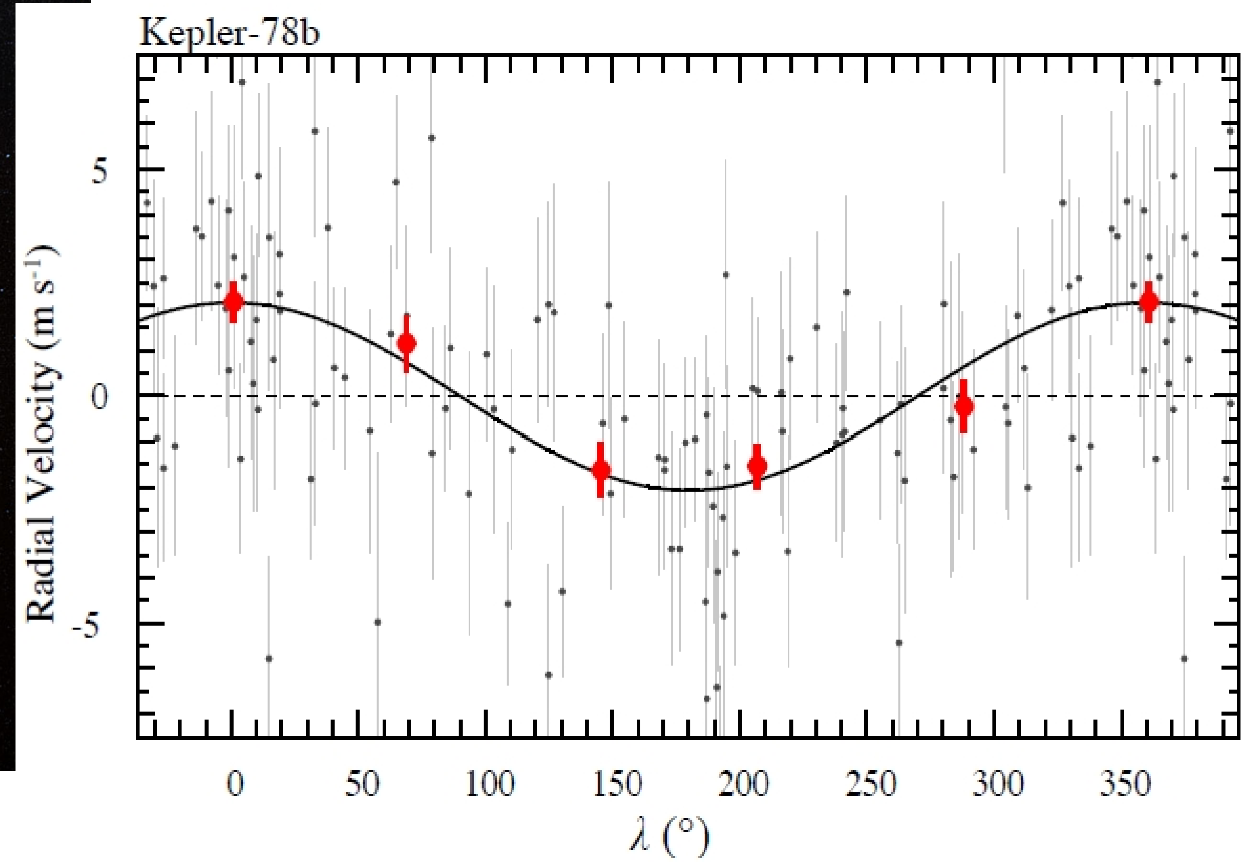




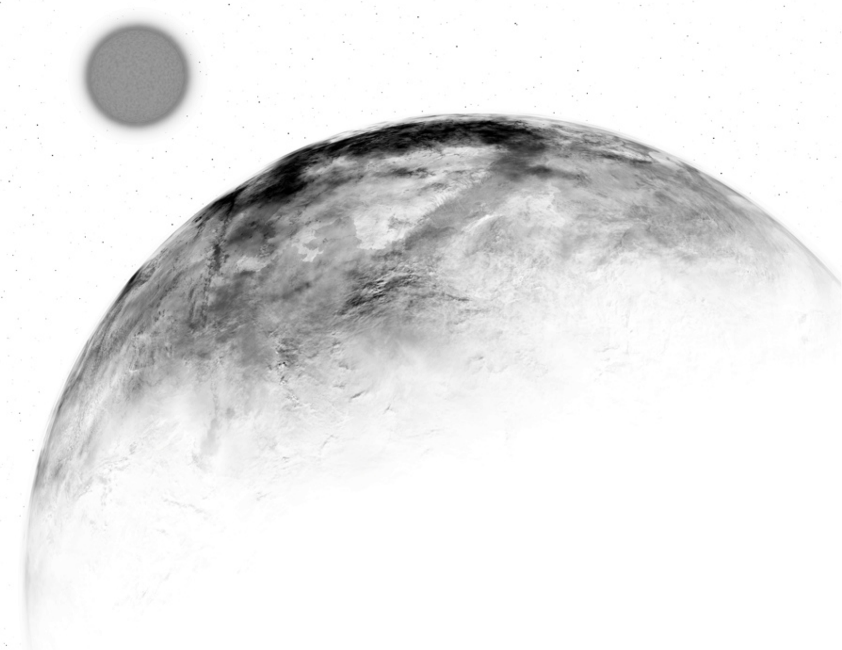


Radial Velocities





Two very interesting results were the detection of a ***planet with the mass of the Earth*** around ***Alpha Cen B*** and of a ***rocky planet*** with the same mass around ***Kepler-78***



Dumusque et al. (2012), Pepe et al. (2013)

Extrasolar planet systems

Lower-mass exoplanets, in the Earth-mass domain are frequently found in systems, but a huge diversity of systems exist

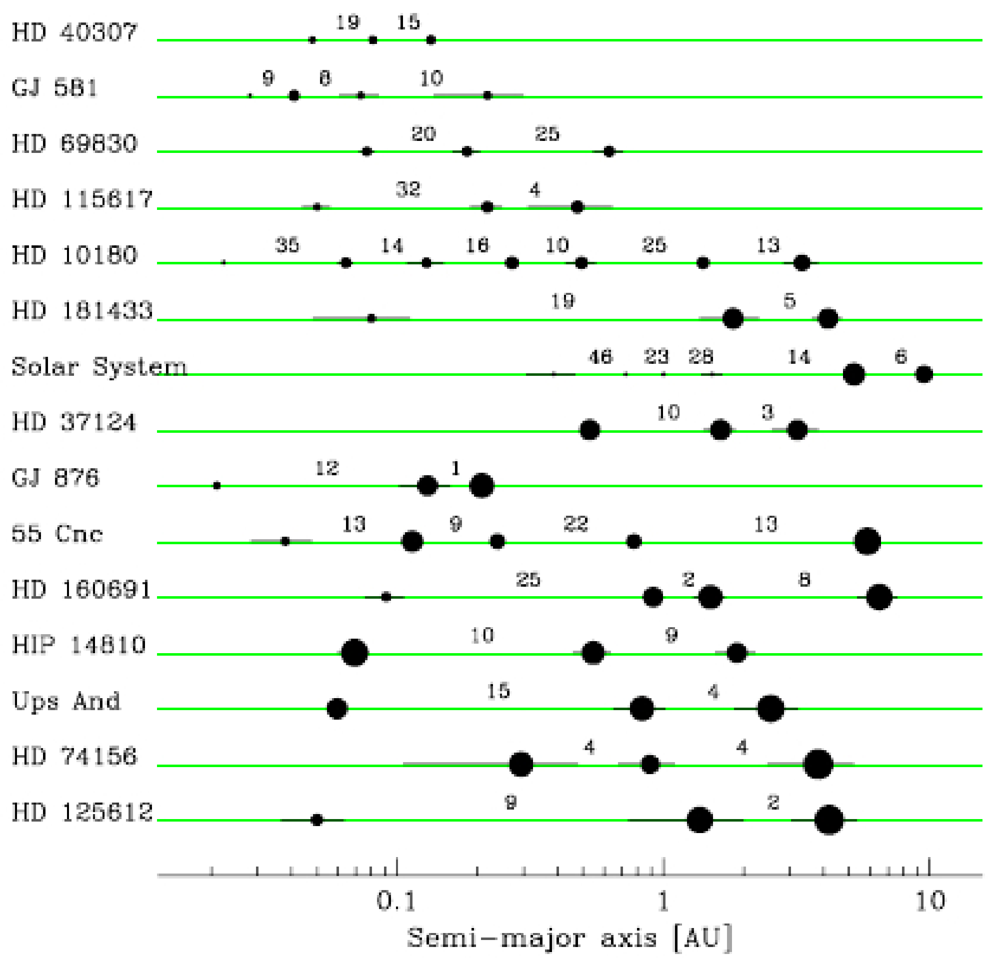
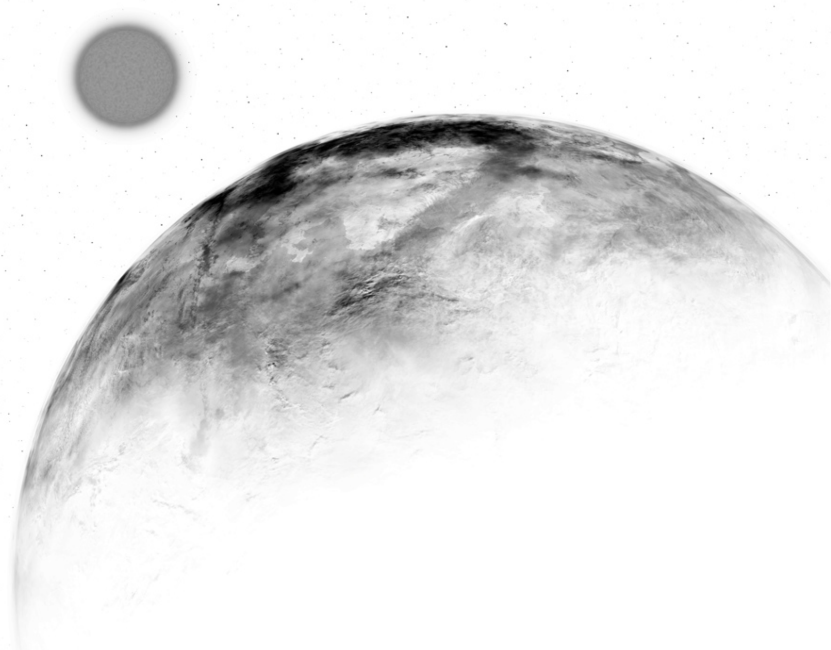


Fig. 13. The 15 planetary systems with at least three known planets as of May 2010. The numbers give the minimal distance between adjacent planets expressed in mutual Hill radii. Planet sizes are proportional to log ($m \sin i$).

Lovis et al (2011)



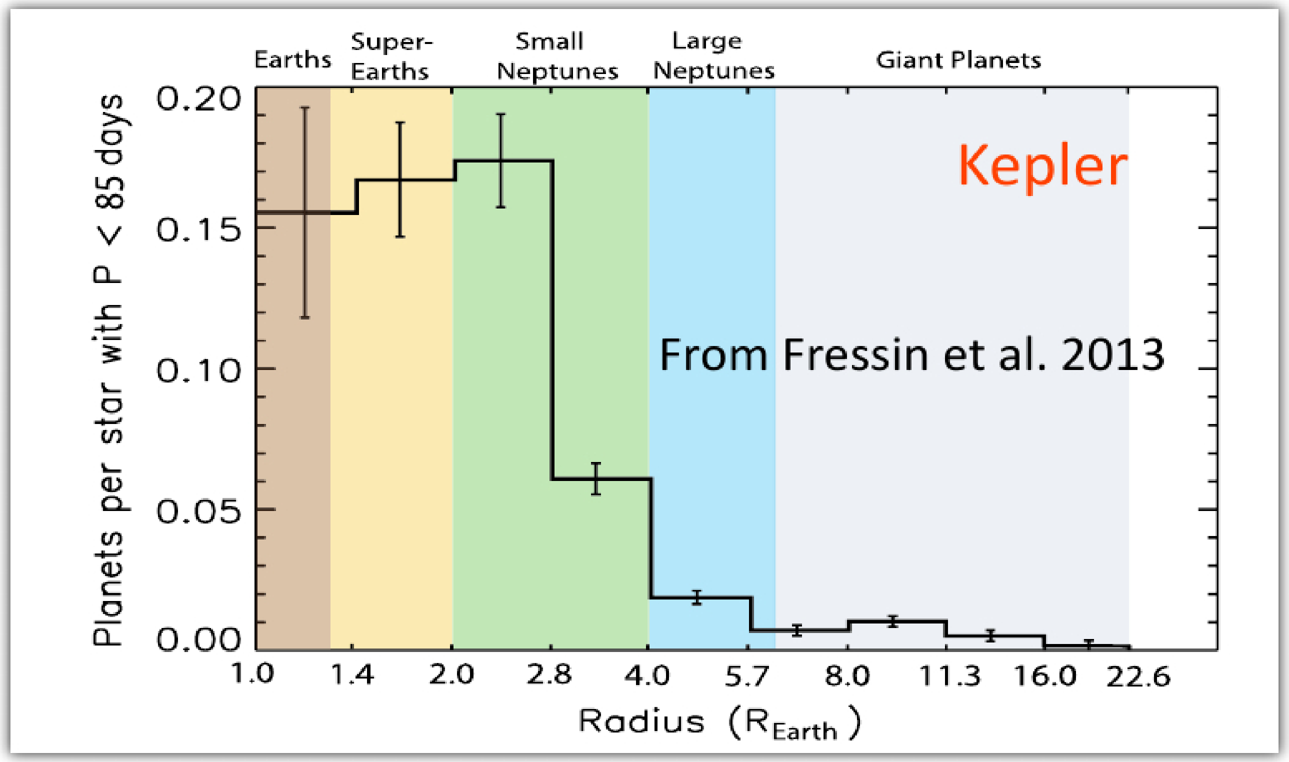
The road to here

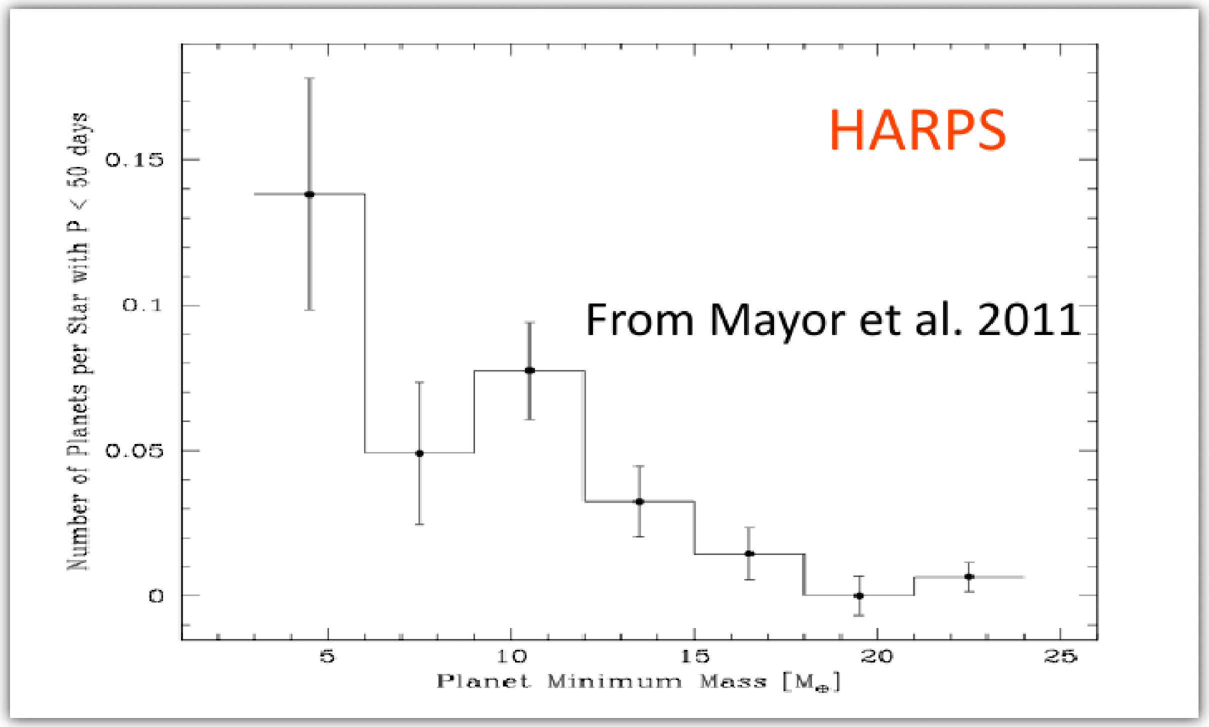
Most of the stars have planets, and the occurrence of planets from complete searches is at 30%

Unbiased, Normalized Mass and Radius Distributions

Occurrence rate for
P < 50 d, R = 1.25-6.0 $R_\oplus$:
f = 0.39 +/- 0.02 planet per star

Occurrence rate for
P < 50 d, Msini = 3-30 $M_\oplus$:
f = 0.33 +/- 0.05 planet per star



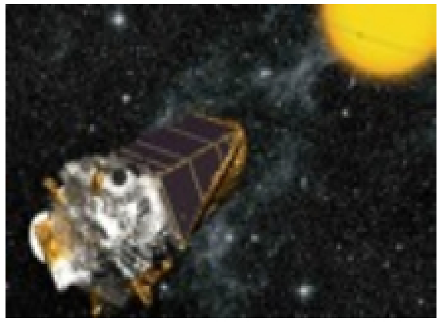


M dwarf studies

HARPS Search around M dwarfs
(~100 brightest M dwarfs < 11 pc)

(Bonfils et al. 2012, A&A)

M dwarfs with Kepler
(~4000 stars with T<4'000 K)



(Dressing & Charbonneau et al. 2013, ApJ)

- deficit of giant planets (wrt Sun-like stars)
  - 90% of M-dwarfs planets with masses < 20 $M_\oplus$

- P<10d	f < 1%
- 10d > P > 100d	f = 2 ± 2%

- Hot Neptunes and Super Earths are more frequent than hot Jupiters
  - super-Earth are common: >30% of the stars

- P < 10d	f = ~36 ± 20 %
- 10d > P > 100d	f = ~52 ± 20 %

Predominance of small-mass / small-size planets around small stars

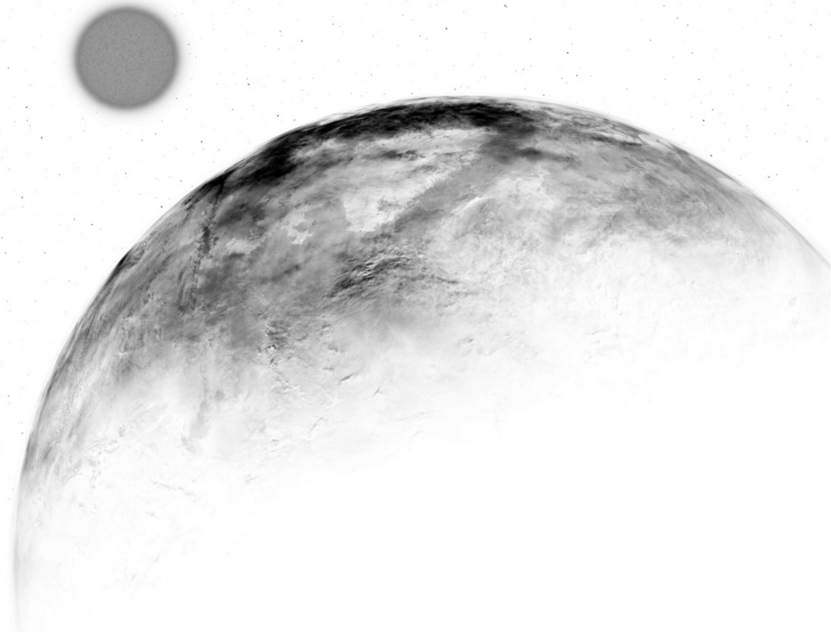
- Small-size planets are very common

- 0.5 - 4 $R_\oplus$	P < 50d	0.90 ± 0.04 planet/star
- 0.5 - 1.4 $R_\oplus$	P < 50d	0.51 ± 0.05 planet/star

Courtesy of Stephane Udry

The conclusions

- ***1% of the stars host Hot-Jupiters and 10% a gas giant, more frequent around metal-rich stars;***
- ***30% of the stars have a Neptune or earth-class mass planet (<30 Mearth) within a 100-days period orbit;***
- ***Most of the small/light planets occur in multiple systems of up to 7 planets;***

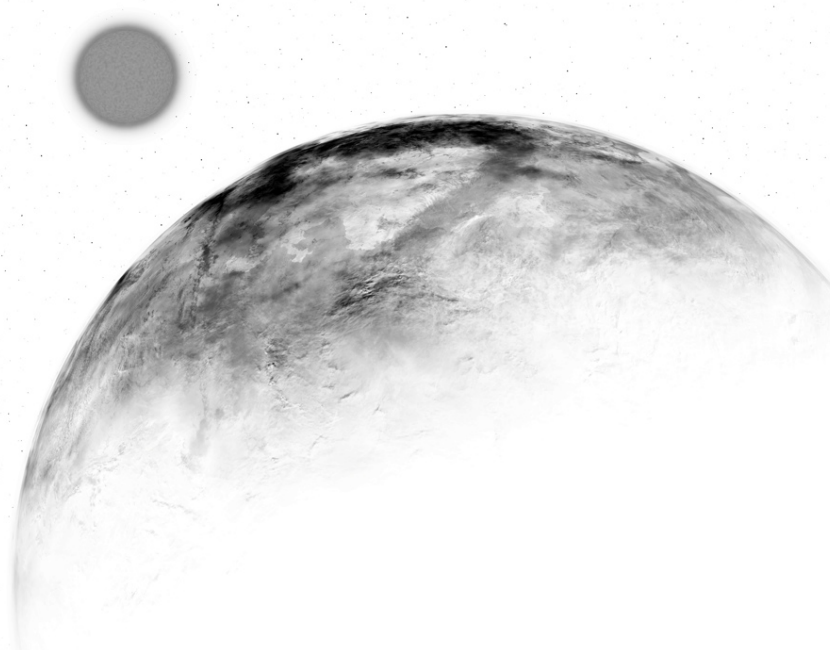


Radial Velocities

When ***several planets*** are present and with ***amplitudes at the level of instrumental precision***, it is very ***difficult to characterize their orbits***, due to the ***large number of parameters to fit***.

Most ***low-mass planets are found in systems***! This prompted an ever-increasing race for better precision.

m_2	$K_1(P=3\,d)$	$K_1(P=1\,yr)$	$K_1(P=5\,yr)$	
M_{Jup}	140.8	28.4	16.6	m/s
M_{Nep}	7.60	1.53	0.90	m/s
$M_{\oplus}$	44.3	8.9	5.2	cm/s



Radial Velocities

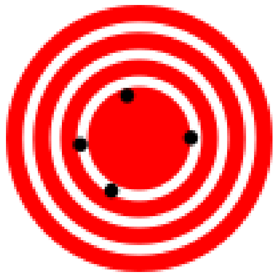
- Radial Velocities are velocities along the line of sight and can be calculated through the Doppler effect measured on spectral lines:

$$\frac{\Delta\lambda}{\lambda} = \frac{v}{c}$$

- It is fundamentally different from measuring directly a velocity on the plane of the sky;
- Precision on RV doesn't depend geometrically on distance to the source (except for noise contribution, always present).

Accuracy vs Precision

The ***accuracy*** of a measurement system is the degree of closeness of measurements of a quantity to its actual (true) value.



The ***precision*** of a measurement system, also called reproductibility or repeatability, is the degree to which repeated measurements under unchanged conditions lead to the same results.

We are interested in – *high* – precision.

- It is fundamentally different from measuring directly a velocity on the plane of the sky;
- Precision on RV doesn’t depend geometrically on distance to the source (except for noise contribution).

RV precision

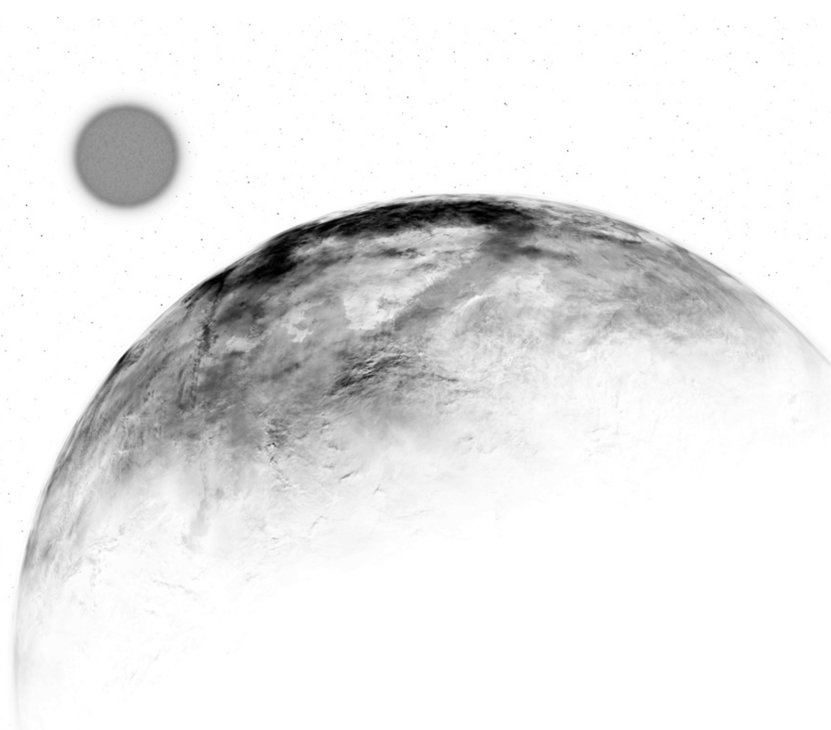
Hatzes & Cochran (1992) presented a (very) general formula that exhibited for a spectrum the properties we saw for single lines:

$$\sigma \propto \frac{1}{\sqrt{F}\,\sqrt{\Delta\lambda}\,R^{1.5}}$$

A different way of writing this is to apply BPQ (2001) to a Gaussian line. This delivers:

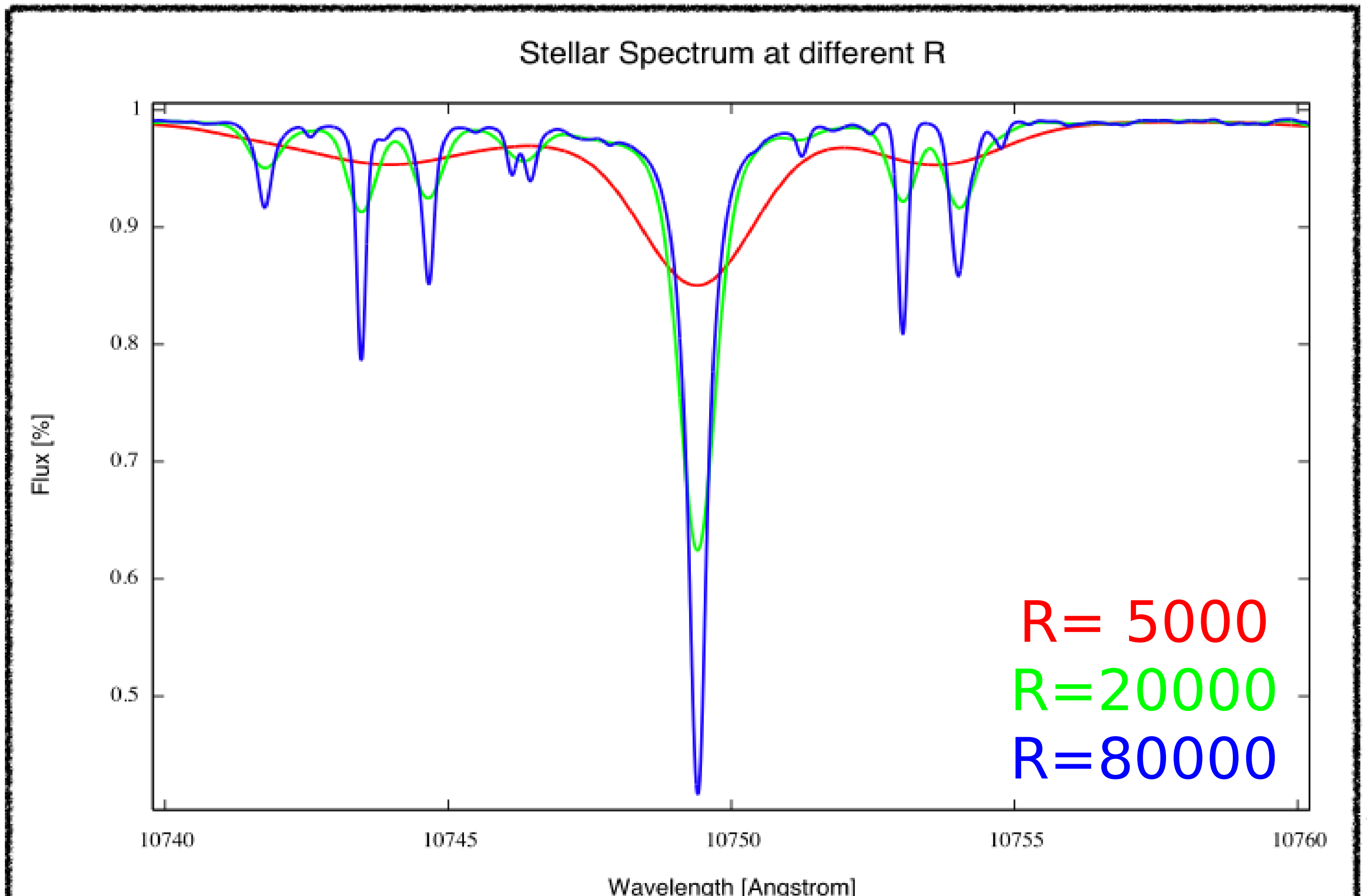
$$\sigma_{RV} = \frac{(\pi . \ln 2)^{-1/4}}{2} \frac{\sqrt{FWHM}}{SNR} \frac{\sqrt{PXLSC}}{C} F(C_{eff}) \; [m/s]$$

Where $F(C_{eff})$ is a polynomial function of the effective contrast $C_{eff} = \frac{C}{1+\sigma_D^2/A_0}$

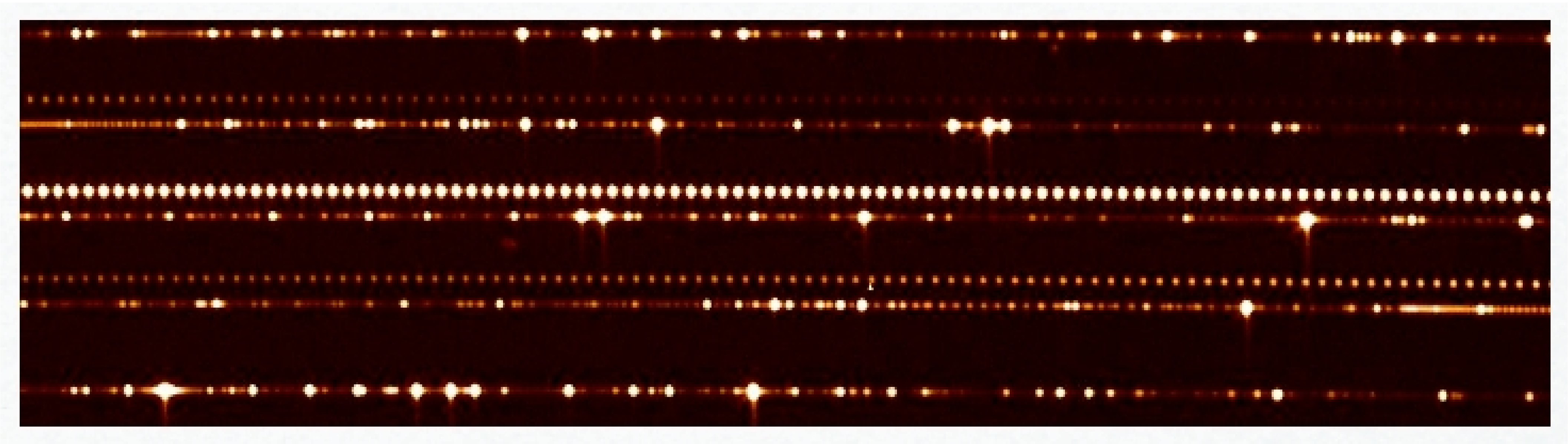


RV precision

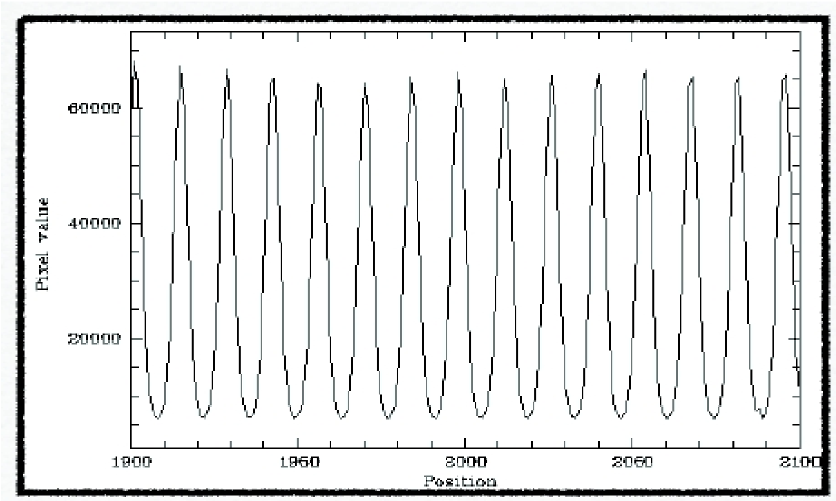
These has an important consequence: the larger the FWHM of a star or lower the resolution, the lower the RV precision. This is specially important for rapidly rotating stars (high *v.sini*)

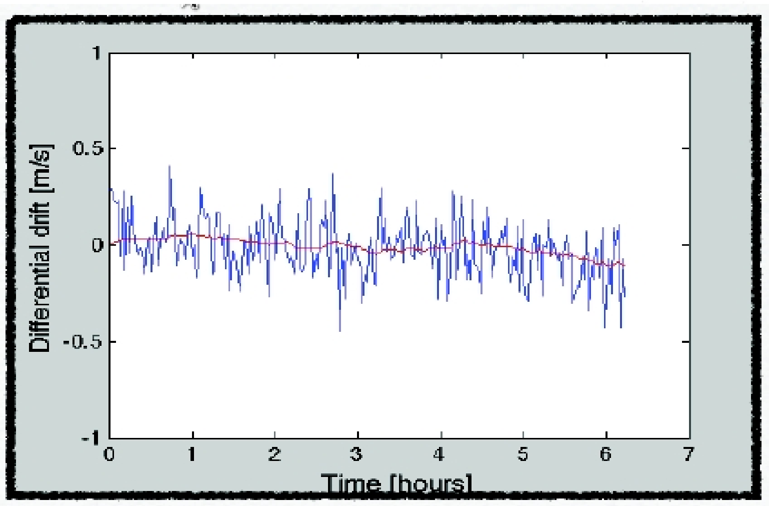


Improving the precision of RV

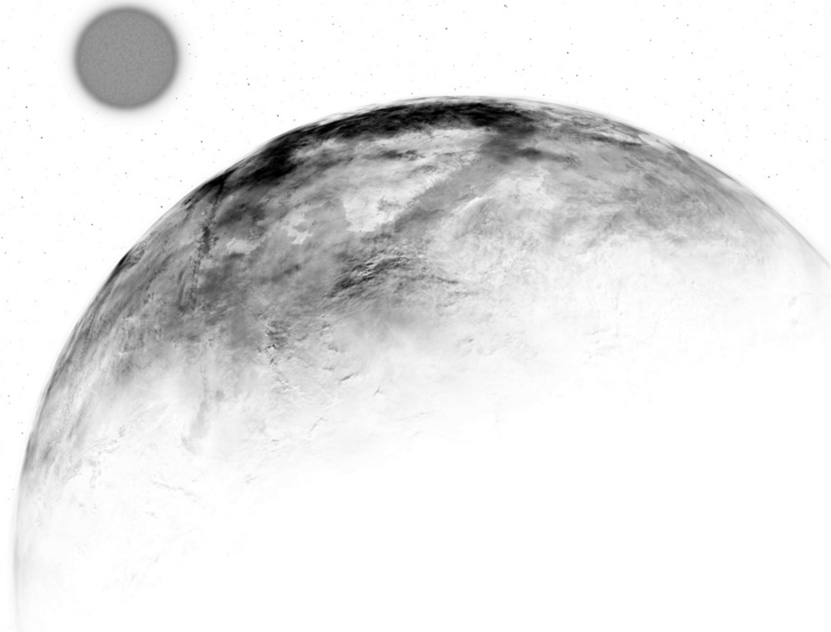


Recent experiments with **Fabry-Perot étalons and Laser frequency combs** show that a precision of below 40 cm/s obtained in the visible can be transferable to the nIR (e.g. *Halverson et al 2012*)

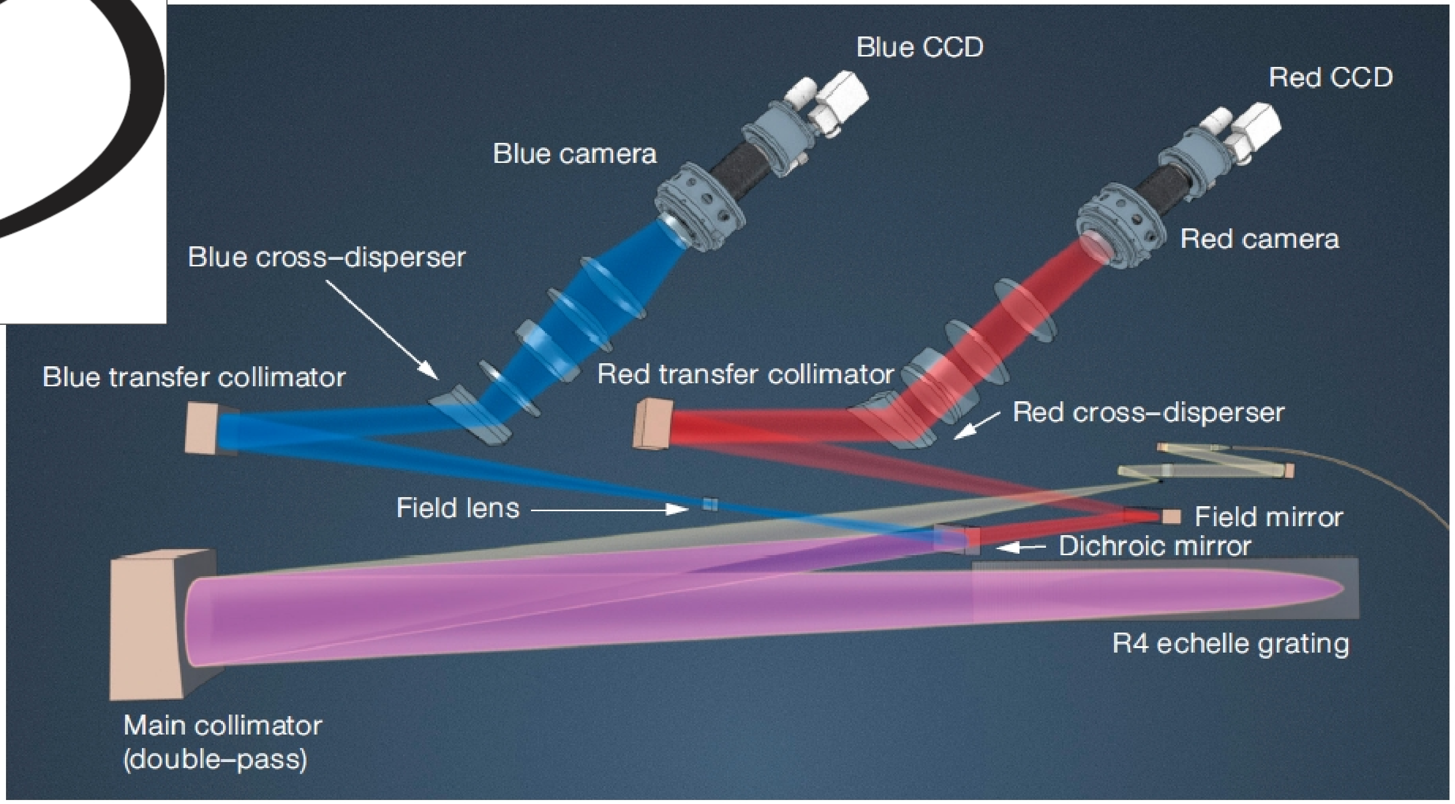




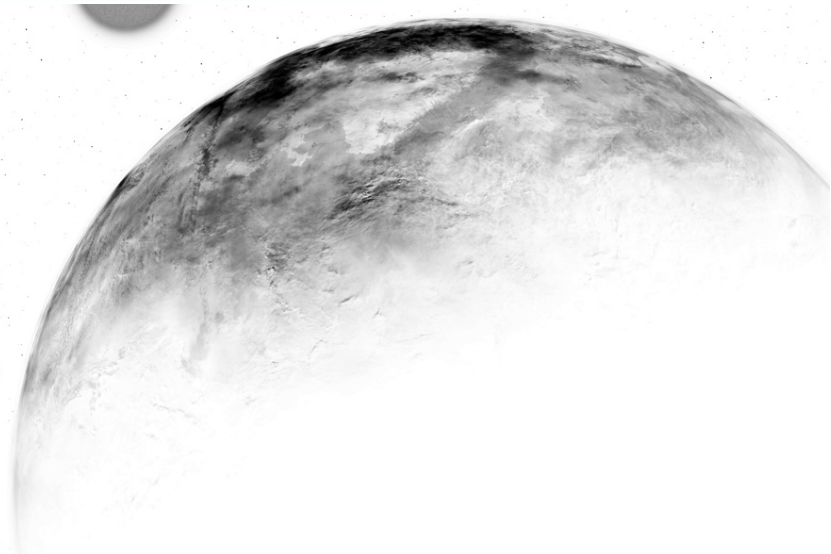
see Wildi et al. (2010)



ESPRESSO



ESPRESSO will reach a precision of ***10 cm/s***, making it possible to detect a ***one Earth-mass planet inside the habitable zone around a GK star***



The near Infra-Red

Why nIR RVs?

- Thr emission of the ***most abundant stars*** in the galaxy, M dwarves, peaks in the nIR;
- The reflex motion induced by a given planet on a ***M dwarf is ~3 times larger*** than on a GK star;
- The habitable zone is ***3 times closer.***

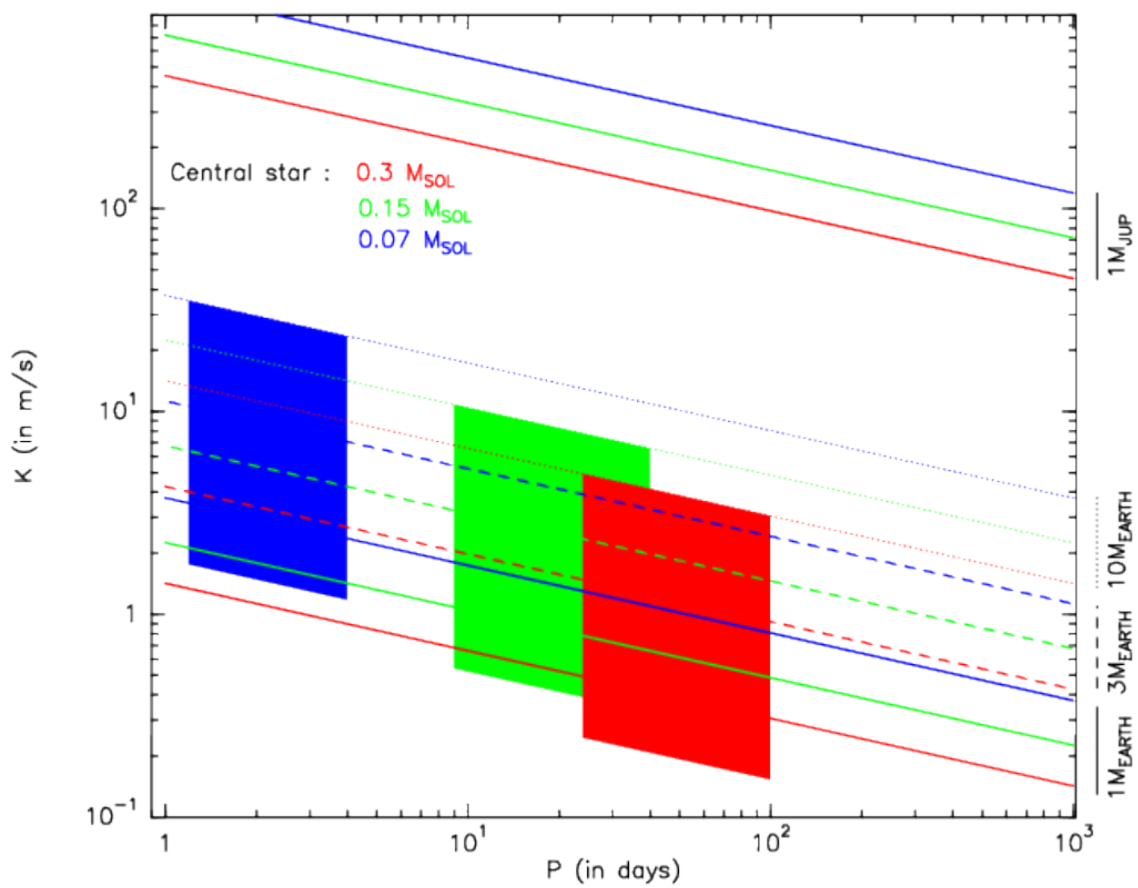
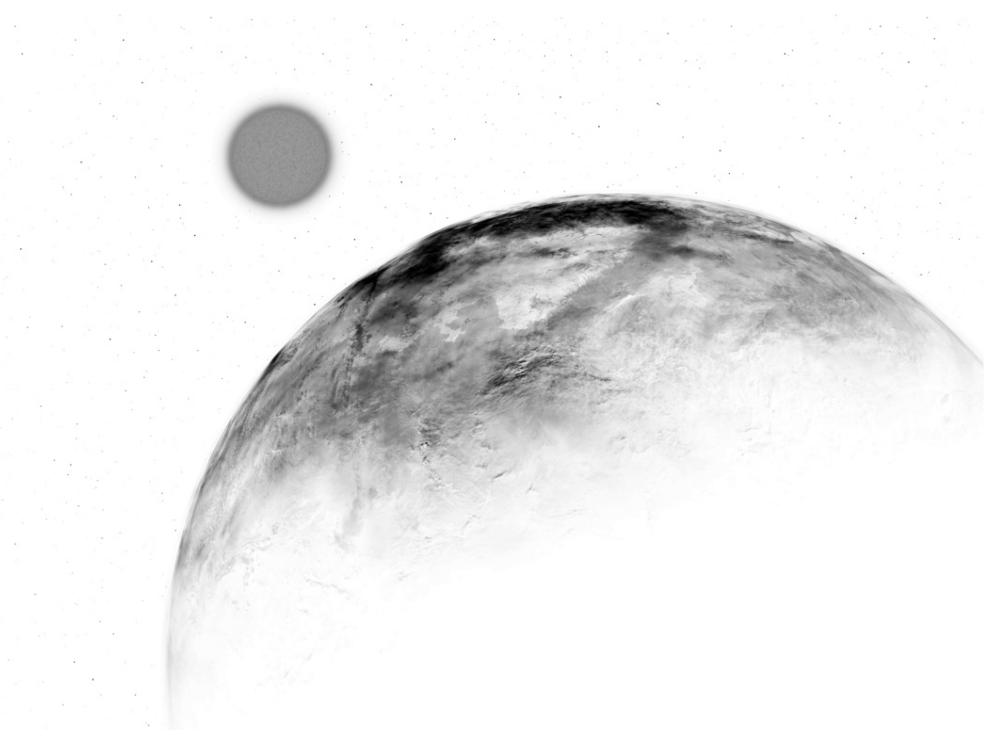


Fig 3.4: Radial velocity semi-amplitude K (in m/s) of the reflect motion induced by a planet on its host dwarf as a function of the planet orbital period P (in d), for planet masses of 1 $M_{\oplus}$ (full lines, bottom), 3 $M_{\oplus}$ (dashed lines), 10 $M_{\oplus}$ (dotted lines) and 1 $M_{♃}$ (full lines, top) and for host dwarf masses of 0.3 $M_{\odot}$ (red), 0.15 $M_{\odot}$ (green) and 0.07 $M_{\odot}$ (blue) - corresponding respectively to M4, M6 and early-L dwarfs. The red, green and blue parallelograms illustrate, for each dwarf mass, the RV impact of 0.5-10 $M_{\oplus}$ planets within the HZs, i.e. with orbital periods of 24-100 d, 9-40 d and 1-4 d for 0.3 $M_{\odot}$, 0.15 $M_{\odot}$ and 0.07 $M_{\odot}$ dwarfs respectively.



SPIRou

What will SPIRou be capable of?

- Detect and ***measure the frequency*** of ***Earth-mass planets*** around ***M dwarfs***
- ***Study*** how the ***magnetic fields*** impact on star/planet formation

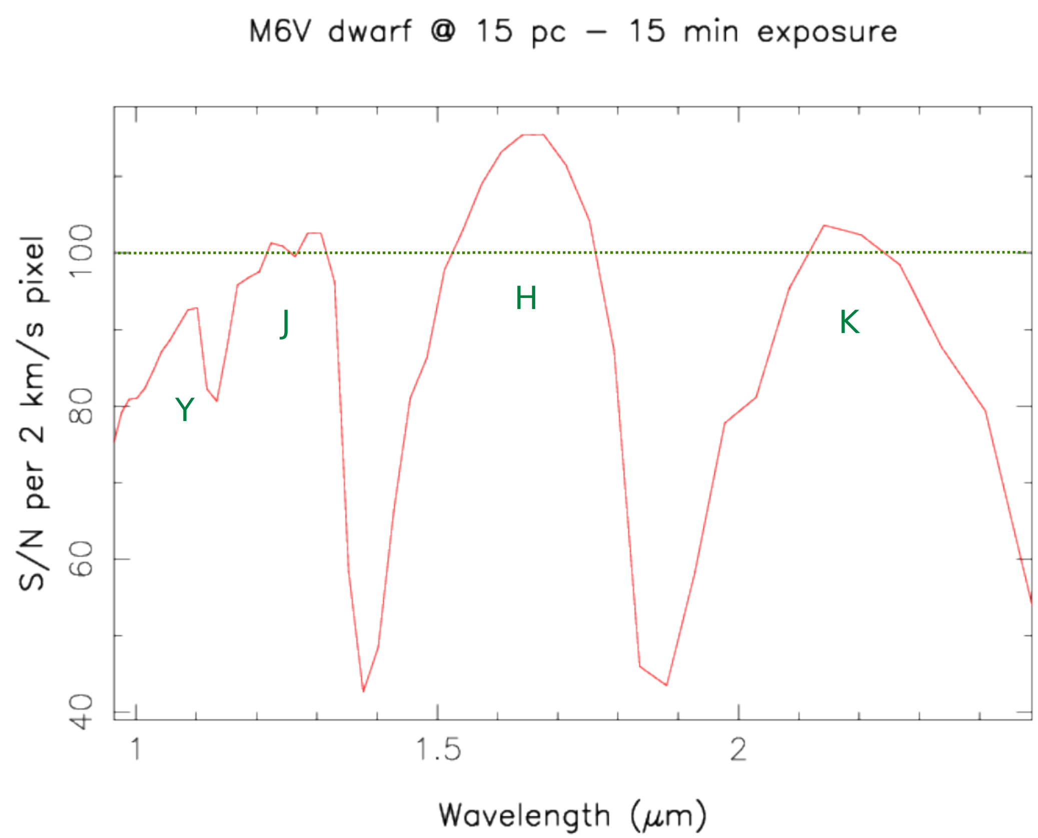


Fig 8.3: Estimated S/N (per 2 km/s pixel) as a function of wavelength for a 15 min exposure with SPIRou on a M6 dwarf located at 15 pc (J=10.4, K=9.5). The peak throughput of the instrument (telescope & detector included) is set to 15% and the photon distribution is taken from the NextGen models (Allard et al 1997, ARA&A 35, 137).