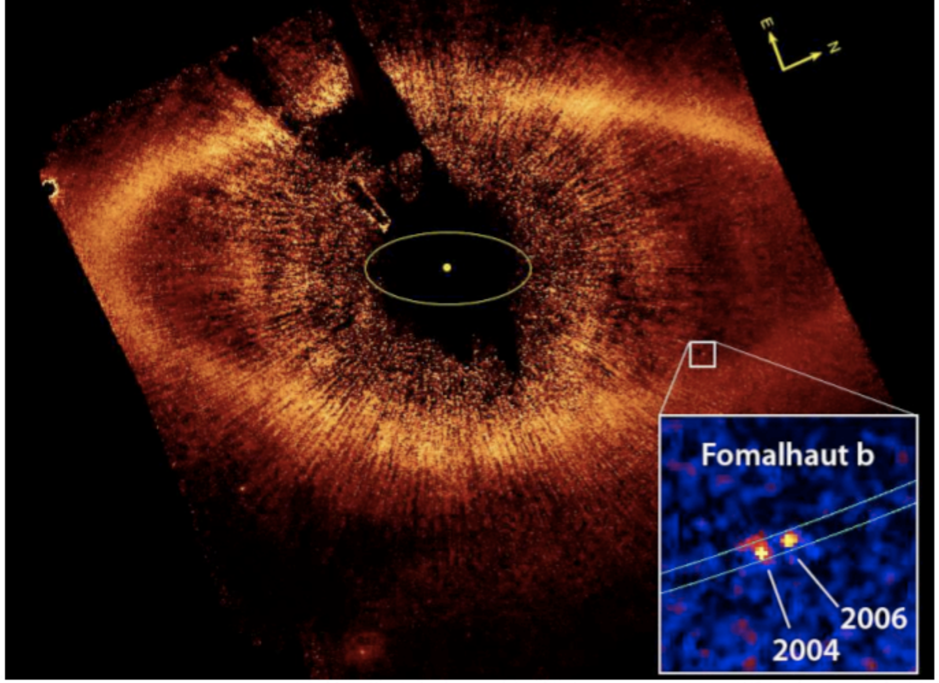
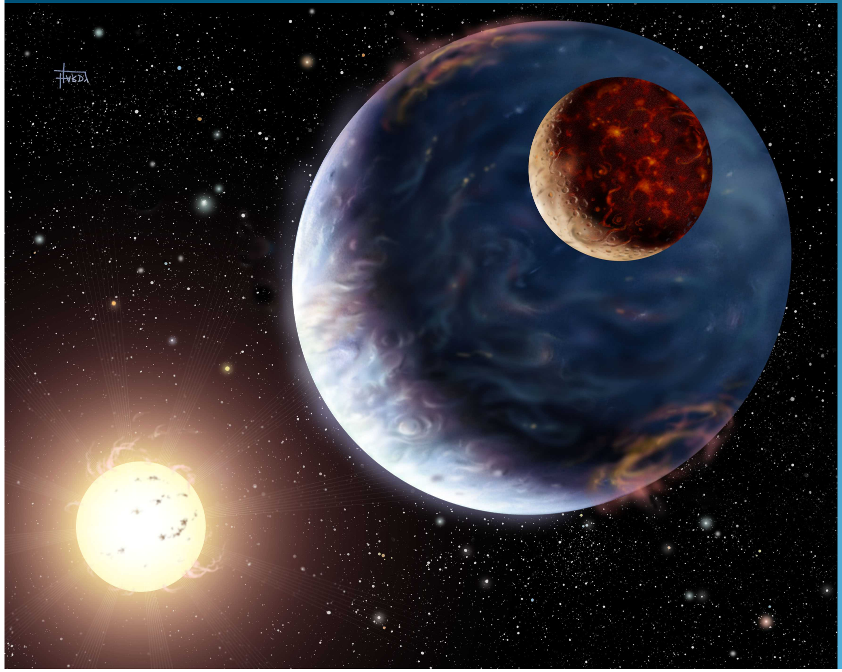
Exoplanet Discovery and Characterisation





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ESO 20100303

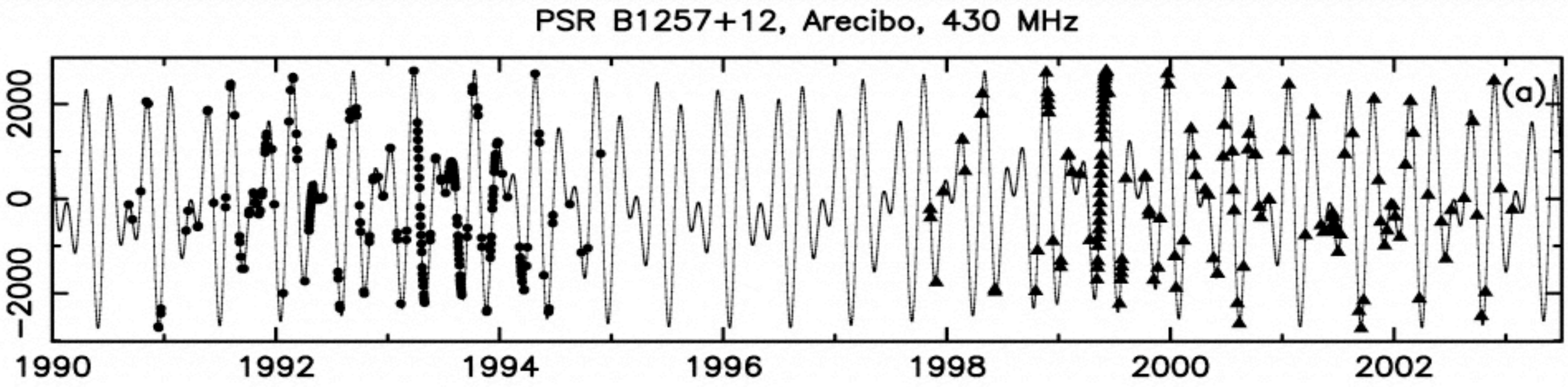
Overview

- Historical perspective and the first confirmed detections
- Search techniques:
    - Radial Velocity (RV) wobbles
    - Direct Imaging
    - Microlensing
    - Transits
    - Astrometry
    - Radio (auroral emission, LOFAR)

- Physical parameter characterisation:
    - Populations – observed and predicted
    - mass-radius plane and composition
    - orbital eccentricity, tides etc
    - ESP atmospheres

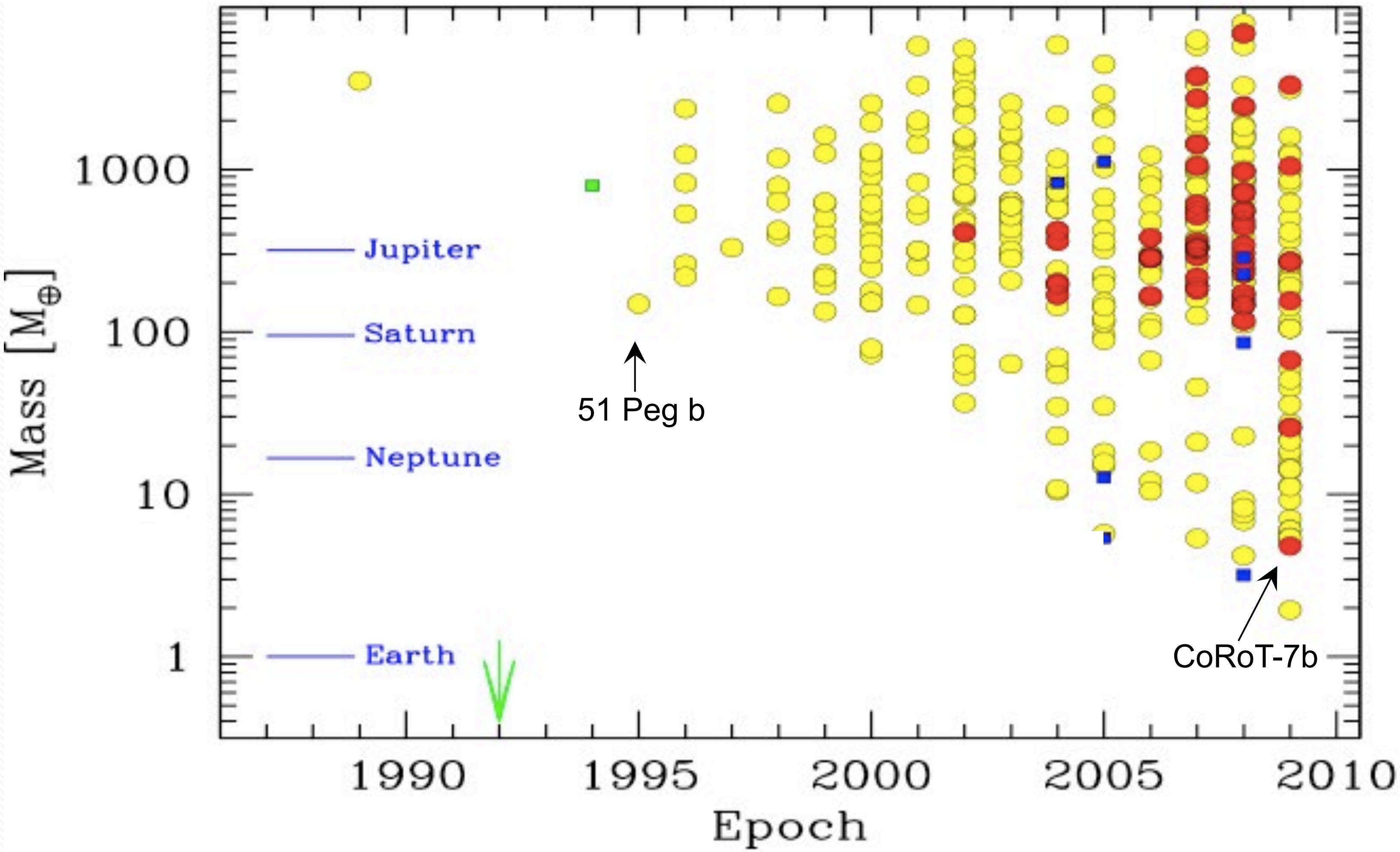
Historical "Discovery"

- A number of claims throughout the 20th Century of planetary companions (eg Barnard's star), none of which were confirmed.
- First genuine planets came from an unexpected source – pulsar timing (Wolszczan & Frail 1992)

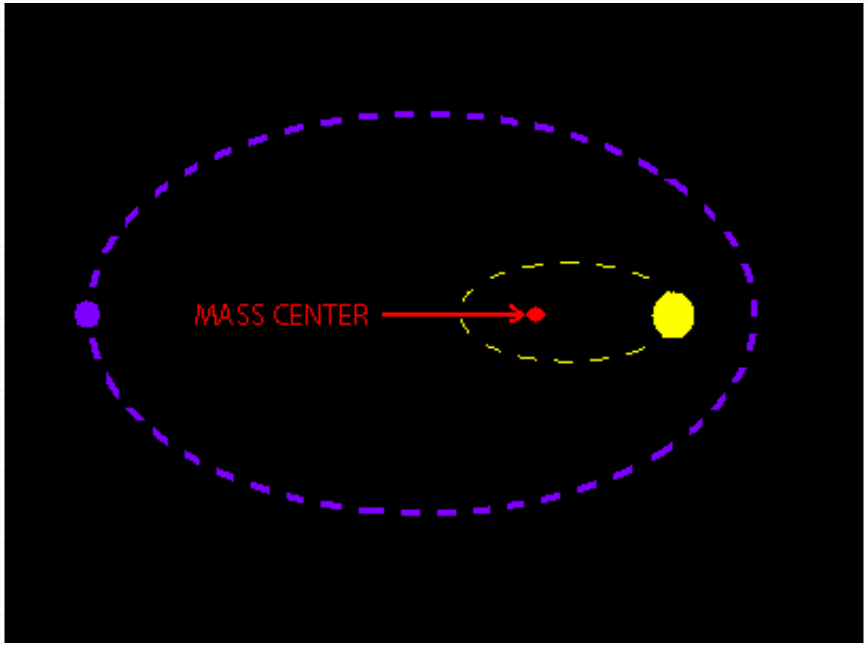


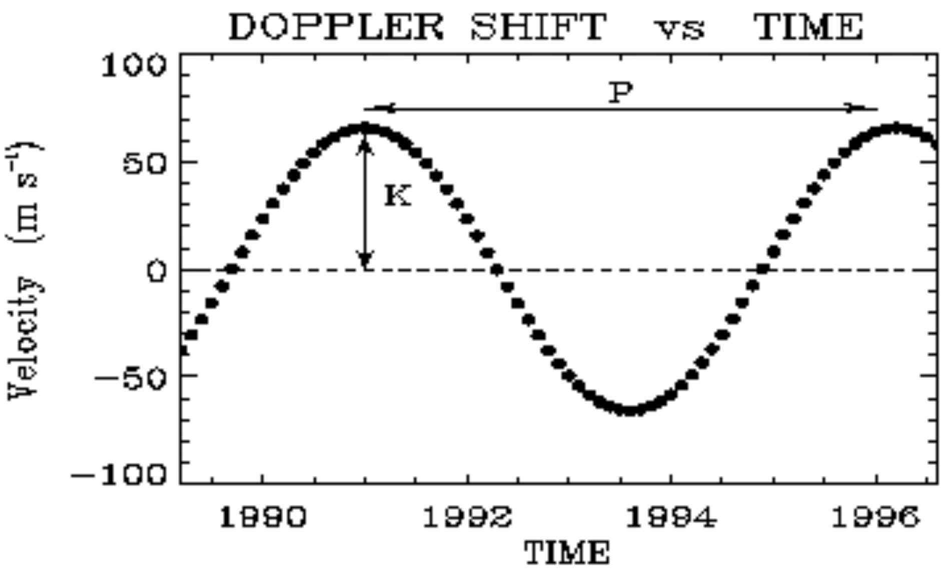
- First planets around main sequence star, 51 Peg, in 1995 – first hot Jupiters (Mayor & Queloz 1995)

The Pace of Discovery



Radial Velocity Detection





Keplers Laws: $$r^3 = \frac{GM_*}{4\pi^2} P^2$$

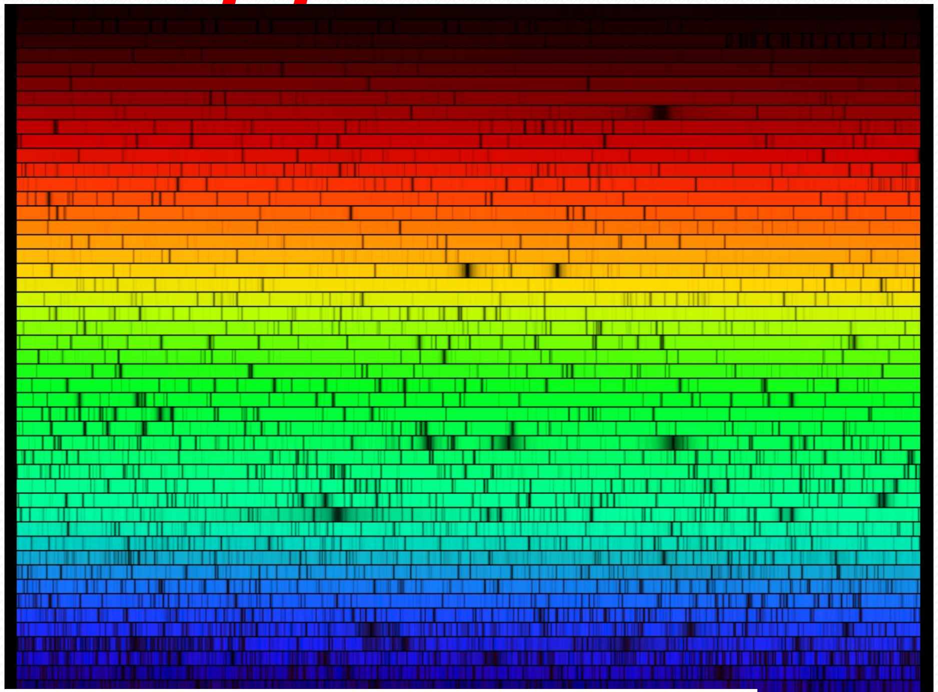
Velocity of Planet: $$V_{PL} = \sqrt{GM_* / r}$$

Momentum Conservation: $$M_{PL} V_{PL} = M_* V_*$$

Observations: $$K = V_* \sin i$$

Collecting observables gives: $$\frac{M_* K}{V_{PL}} = M_{PL} \sin i$$

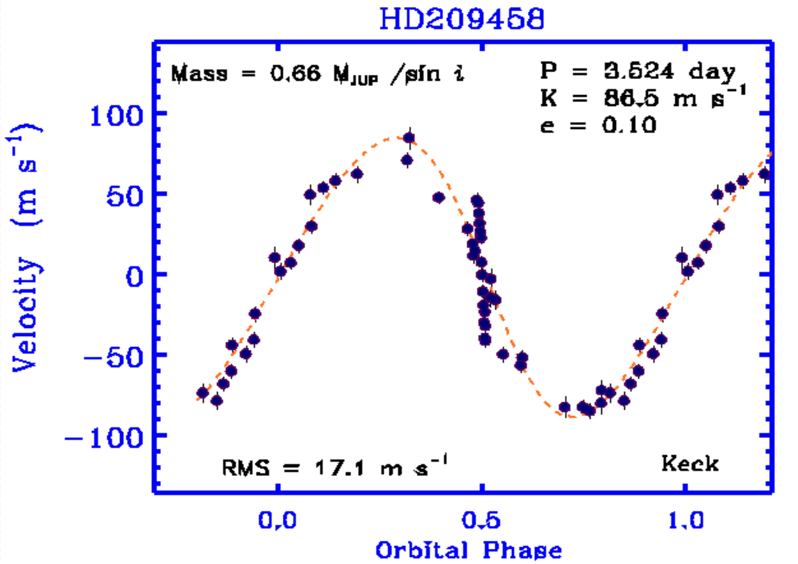
Doppler motion: Real Data

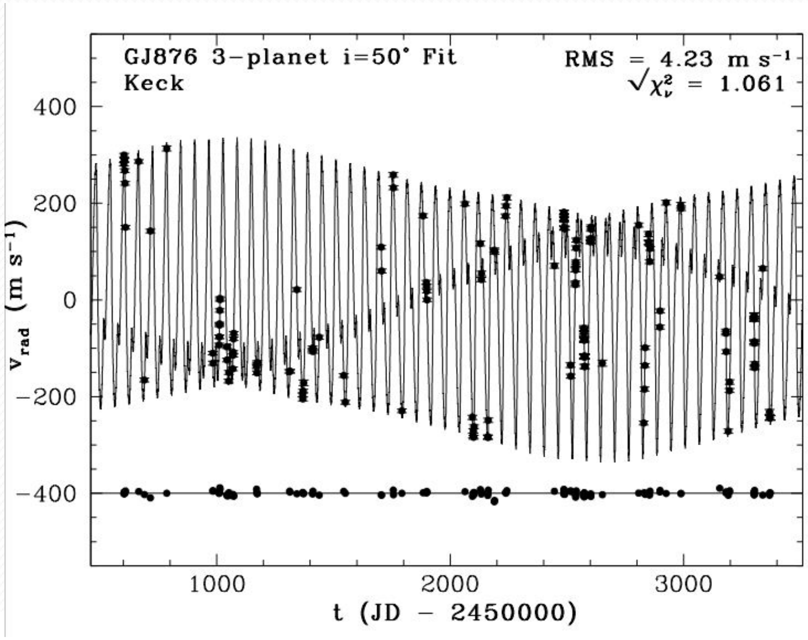


Can only get required accuracy with narrowed lined stars ie late F, G, K, M stars.

Radial velocity curves (note velocity semi-amplitudes):

1) HD209458 – single planet
2) GJ876 – 3 companion model





RV Surveys

- Important to remember that measurement is $M_{PL}\sin i$
- RV observations on their own only establish Periods and Orbits with certainty but almost nothing about the planet itself.
- RV surveys have been the most successful route to planet statistics
- Detection of low mass planets problematic because of small signal and stellar activity/noise (reflex motion for the star in an earth analog system ~9 cm/s…)

Direct Imaging

- Planets are visible due to scattered starlight or because they are self luminous. The planetary cross-section is small so that scattered starlight is faint compared to host star (table in delta mags):

	0.1AU	1AU	5.2AU
Earth	20.4	25.4	29.0
Jupiter	15.5	20.6	24.1

Ratio more favourable at IR wavelengths where planets can be self-luminous (depending on temperature). Need to block light from host star (coronagraph).

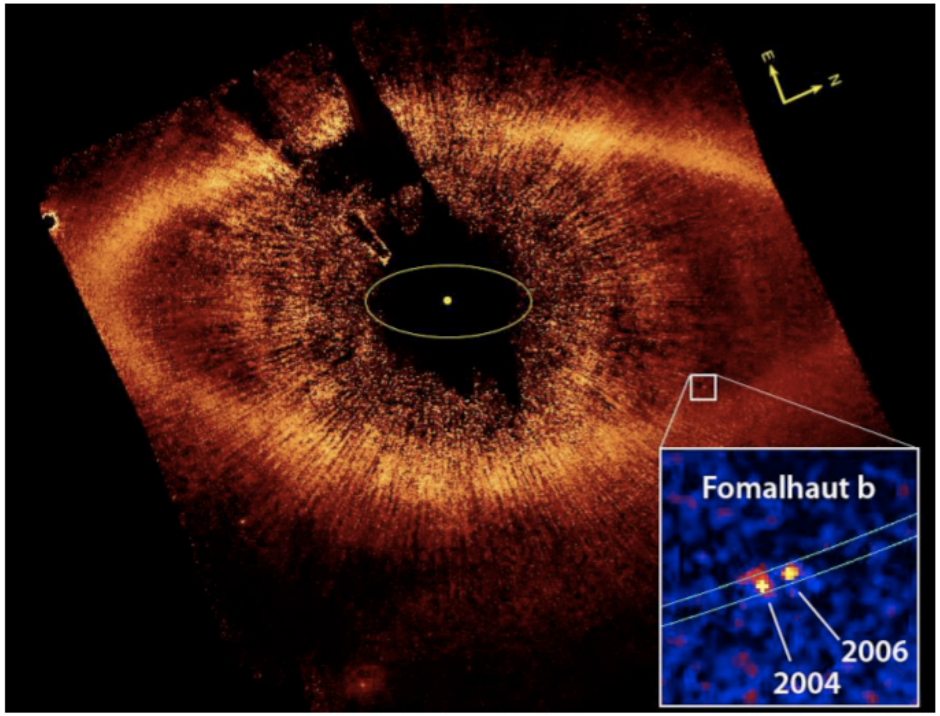
- Resolution: as viewed from 10pc the Earth would be 0.1 arcsec and Jupiter 0.5 arcsec from the Sun. At 100 pc the separations are 10 and 50 milli-arcsec respectively. Telescope resolution (in milli-arcsec) dependant on aperture and wavelength:

	500nm	2.2µ	10µ
10m Keck	12.2	54	400
42m ELT	2.9	12.8	58

Optical – resolution ok, contrast bad, IR – resolution worse, contrast better

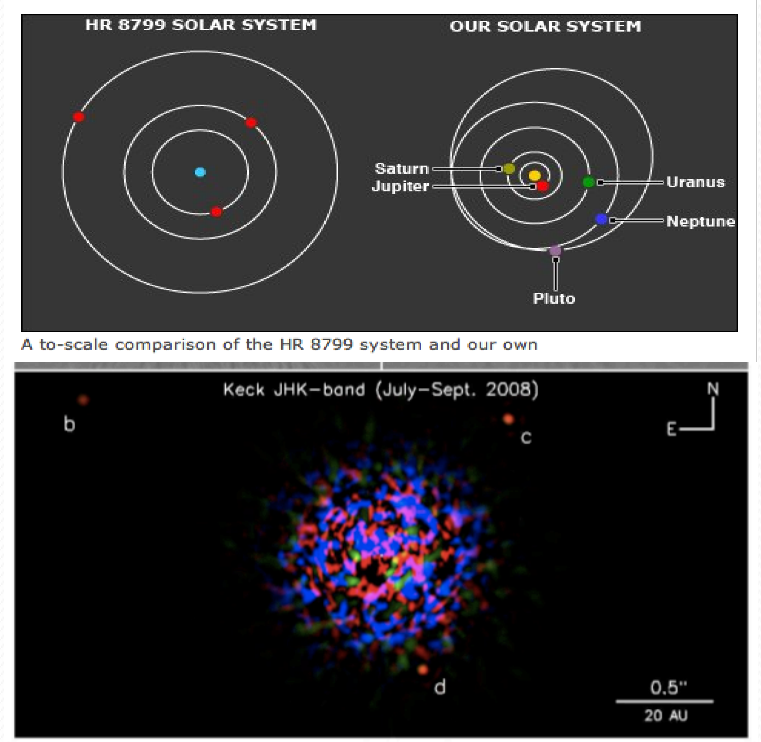
Detections

Brown dwarf + ESP
Chauvin et al 2004



Fomalhaut – Kalas et al 2008

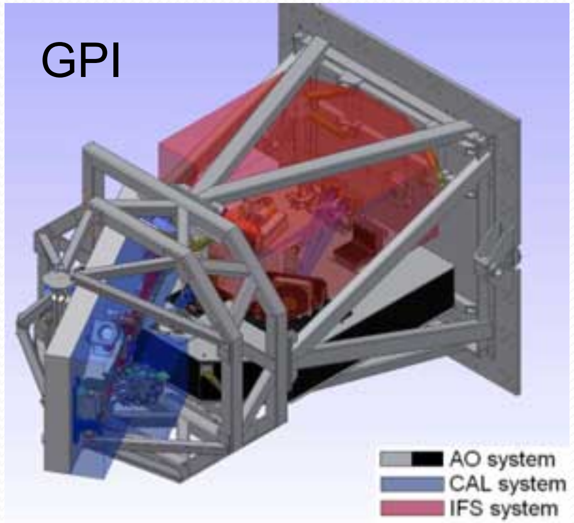
Massive planets at large
distances from their stars



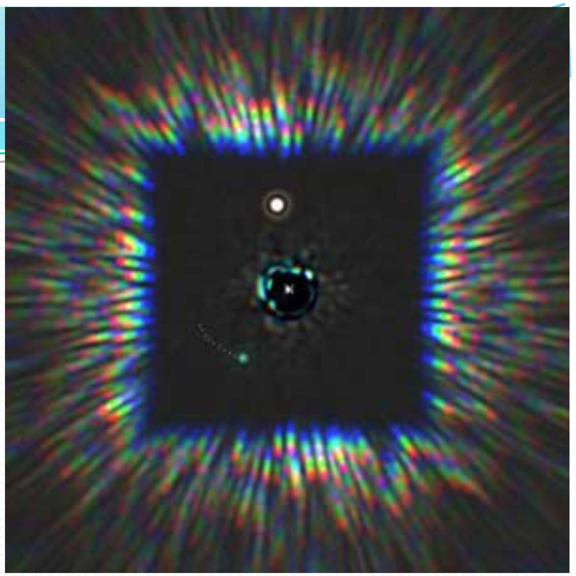
A to-scale comparison of the HR 8799 system and our own

HR8799 – 3 planets, Marois et al 2008

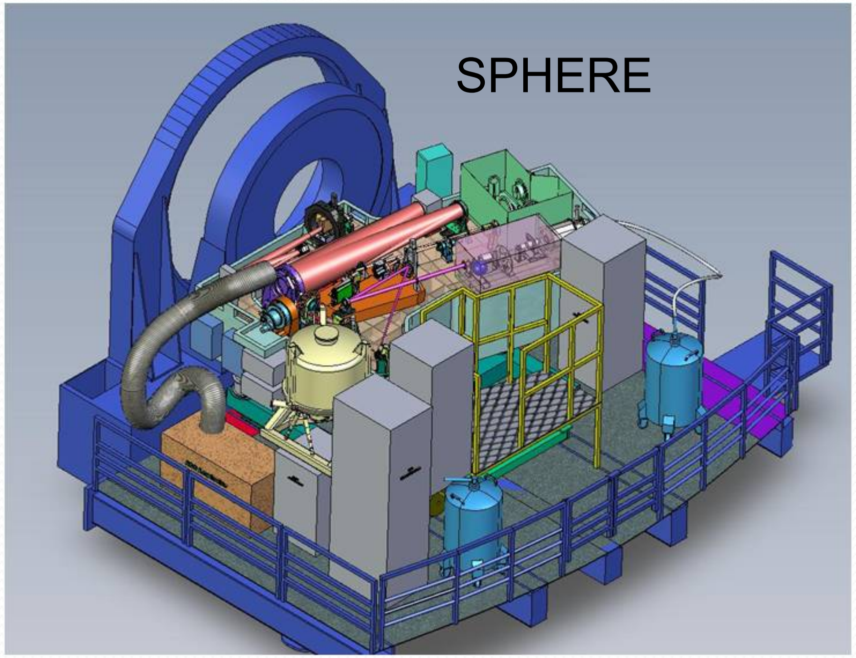
Direct Ground based imaging

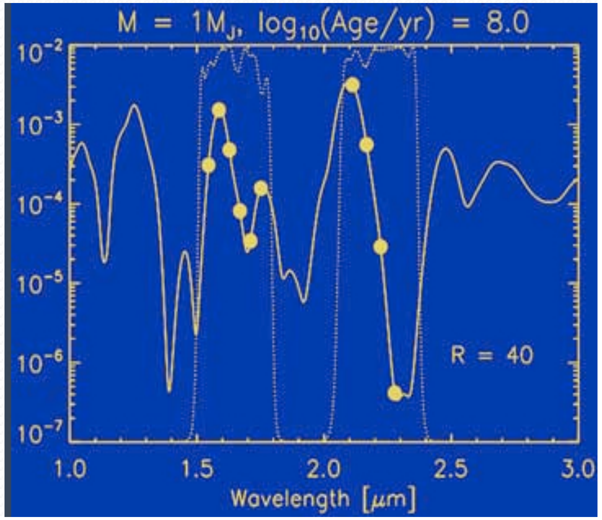


- *Coronagraphic devices*
- *Large, young, planets at 5AU*



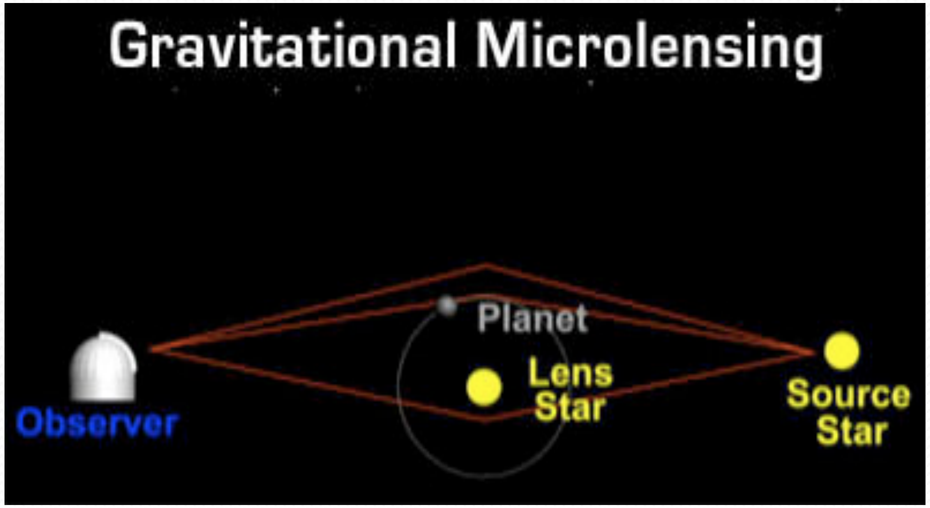
Drivers: high contrast 14-16 mags, high angular resolution 0.1-3 arcsec, sensitivity down to V=10, companions to H~24, spectral resolution R~30





Microlensing

- Microlensing occurs when the gravitational field of star acts like a lens magnifying the light of a distant background star. Alignment has to be almost exact for this to occur. If the lensing star has a planet this too (if there is alignment) can act as a lens.



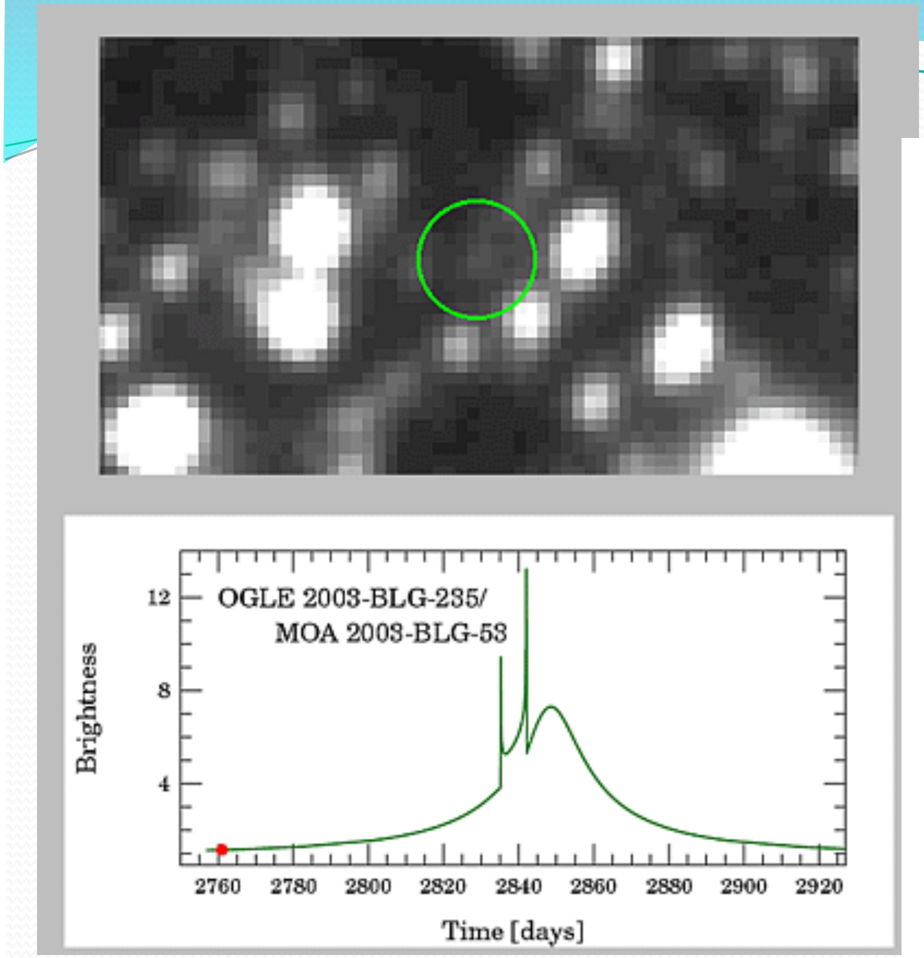
Magnification can be extremely high!

example	Duration (d)	Brightening (mags)
Hot Jupiter	5	4
"Jupiter"	3	3
"Earth"	0.167 (4hr)	1

Assuming d=5kpc

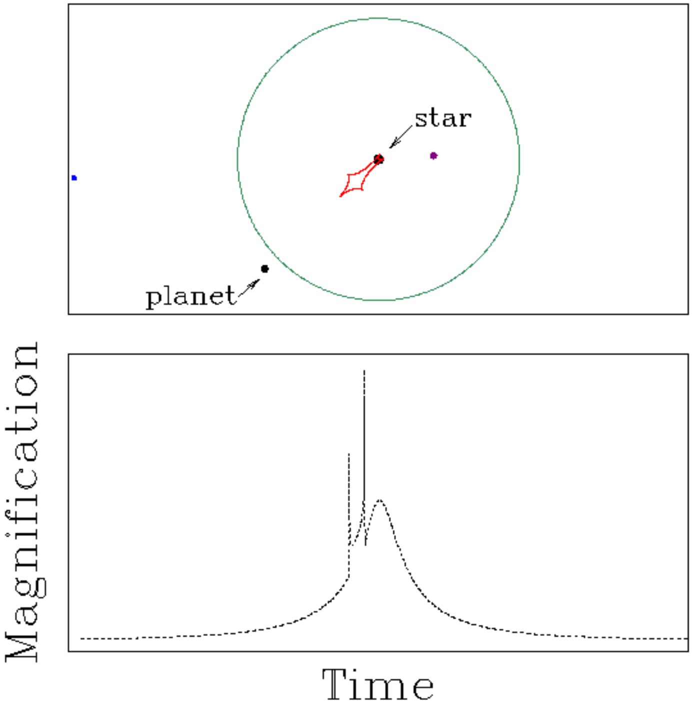
Duration $$t_E = \sqrt{4GM_{PL}dV/c^2}$$

The PLANET collaboration



Light Curve

OGLE 2003-BLG-235 2M$_J$ at ~3AU from an M or K dwarf host
Bond et al 2004, Bennett et al 2006



High Res. image

Microlensing pro's and con's

- Microlensing events are rare, planetary microlensing even rarer and rapid. Need to observe a lot of stars.
- Lensing stars/planets are distant and microlensing event will not re-occur.
- Currently the only way to reach masses of 1 M_E or even below.
- Can be used to sample planetary frequency around populations of stars that are otherwise difficult to observe (most of the lensing stars are K or M dwarfs).

Transit Surveys

When combined with RV measurements, transit observations are very powerful enabling an understanding of the planets physical parameters

Transit light curve => accurate estimate of fractional radius

RV Measurement => mass function estimate

(note dependence on stellar parameters above)

Together give the bulk density of the planet which can be directly compared to theoretical models

Bright transiting planets also prime targets for atmospheric analysis etc

Transit Detection

Mostly geometry - get: radius of planet/star, inclination of orbit.

$$r_{Jup} \approx 0.1\, R_{Sun}$$

Depth:

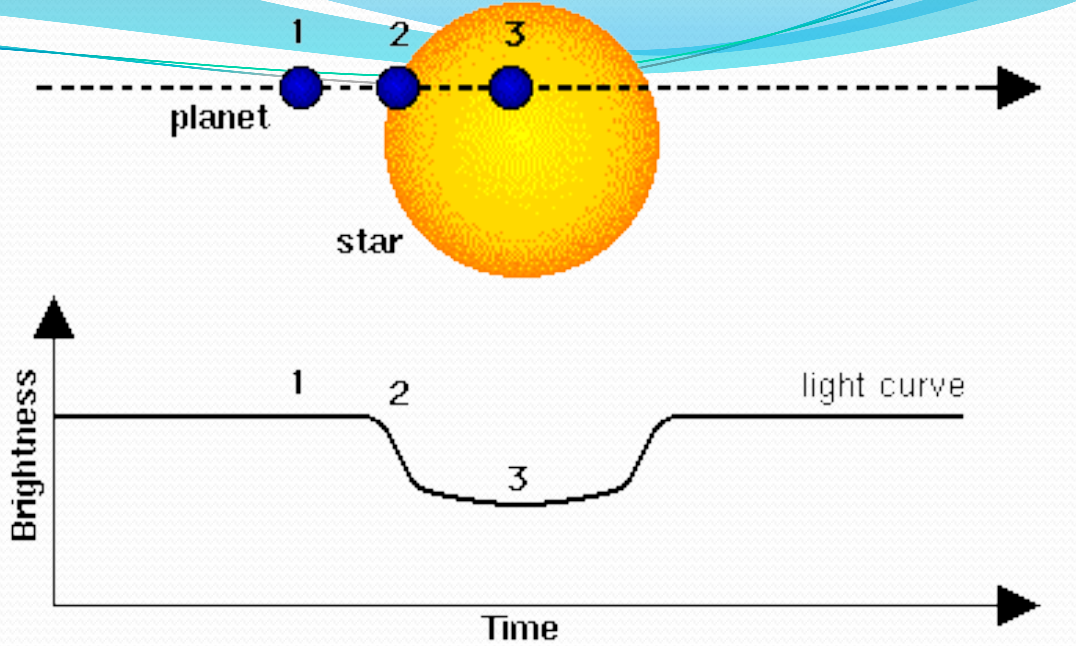
$$\frac{\Delta f}{f} \approx 1\% \left(\frac{r_p}{r_{Jup}}\right)^2 \left(\frac{R_*}{R_{Sun}}\right)^{-2}$$

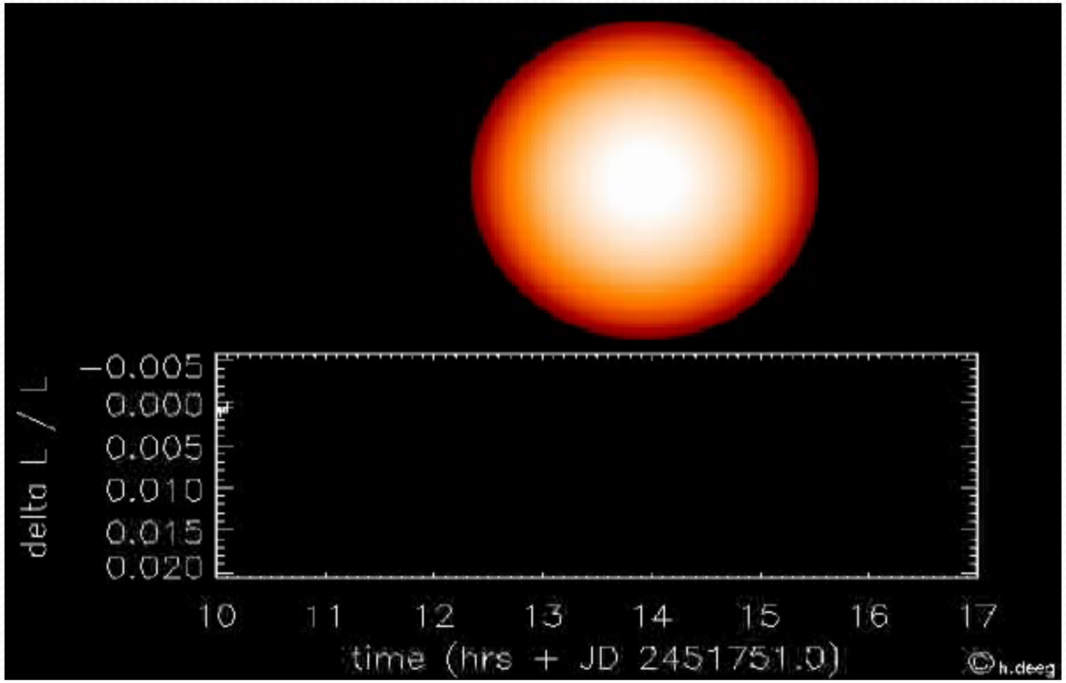
Duration:

$$\Delta t \approx 3h \left(\frac{M_*}{M_{Sun}}\right)^{2/3} \left(\frac{P}{4d}\right)^{1/3}$$

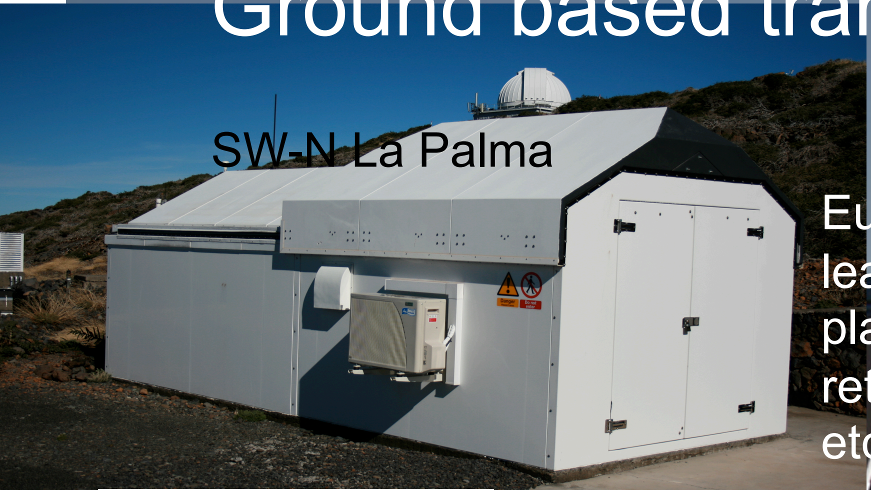
Probability:

$$P_t \approx 10\% \left(\frac{R_*}{R_{Sun}}\right) \left(\frac{M_*}{M_{Sun}}\right)^{-1/3} \left(\frac{P}{4d}\right)^{-2/3}$$

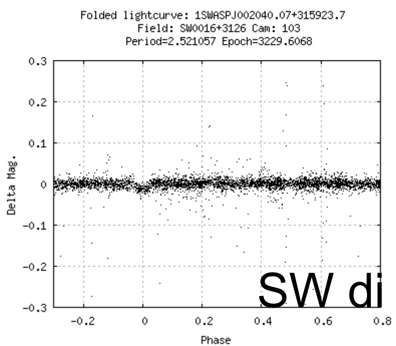




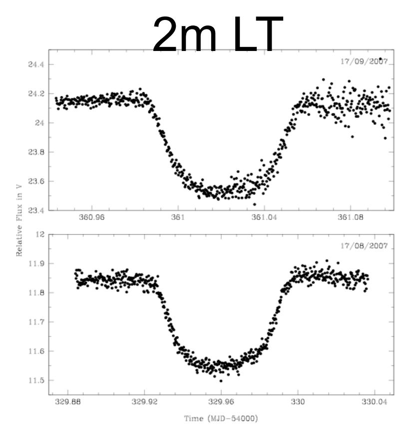
Ground based transits: SuperWASP

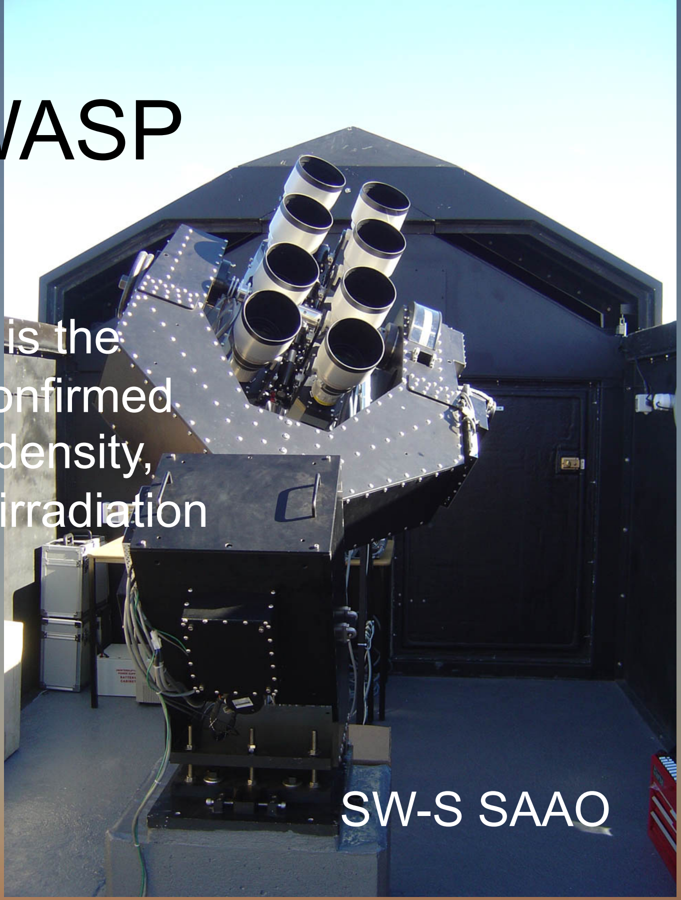

SW-N La Palma

European WASP project is the leading survey with 34 confirmed planets. Largest, lowest density, retrograde orbit, highest irradiation etc



SW discovery


2m LT


SW-S SAAO

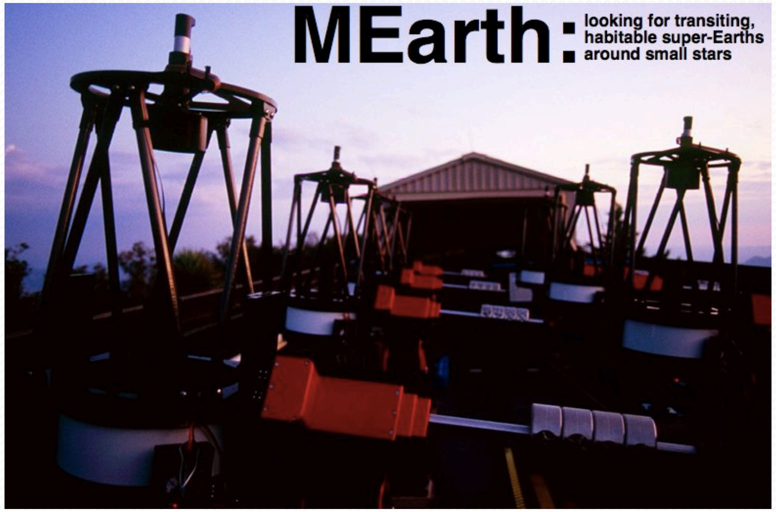
Of the known transiting systems all but one at short periods (most with P< few days). Exception HD80606, P~110d (discovered spectroscopically)

Smaller Planets via Smaller Stars

- Transit observations give the fractional radius R_{PL}/R_* relatively easy route to small planets is to observe small stars – several M dwarf surveys ongoing.

- Examples are WTS (UKIRT), MEarth – both are targeting nearby M dwarfs (which are still faint at optical wavelengths).

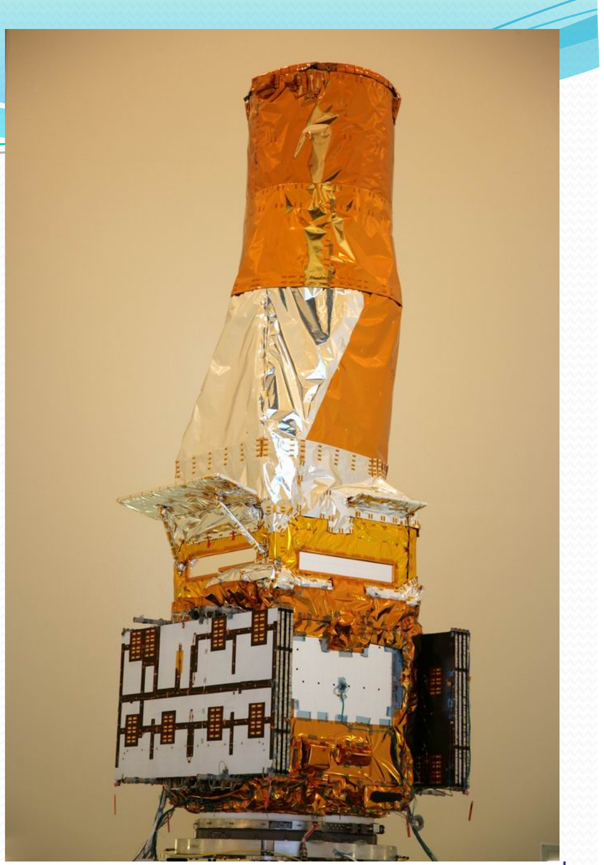
MEarth-1 announced December 2009, Charbonneau et al 2009
2.7Re, 6.6Me

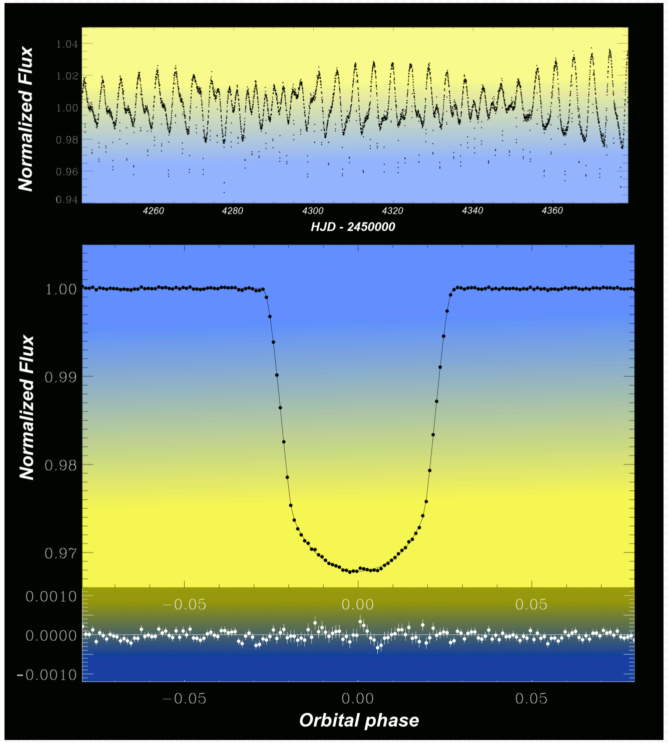


- Space based surveys….

Convection Rotation and planetary Transits - CoRoT

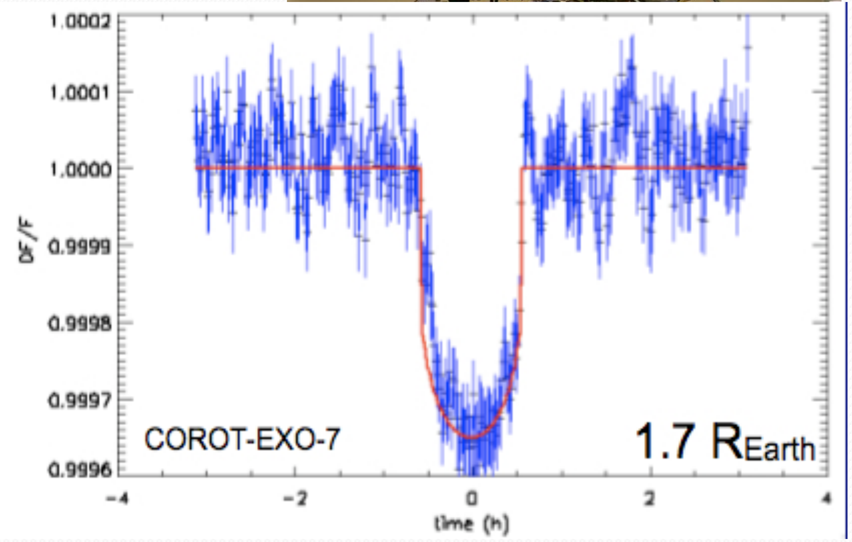
Currently has 7 planets and several more coming. CoRoT-7b announced Feb 2009 probably terrestrial.





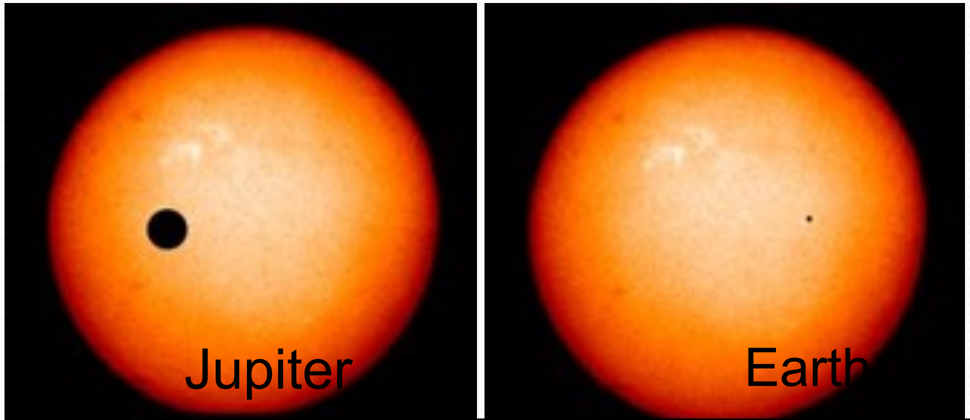
CoRoT-2b – planet orbiting an active star (note modulation due to star spots and stellar rotation)

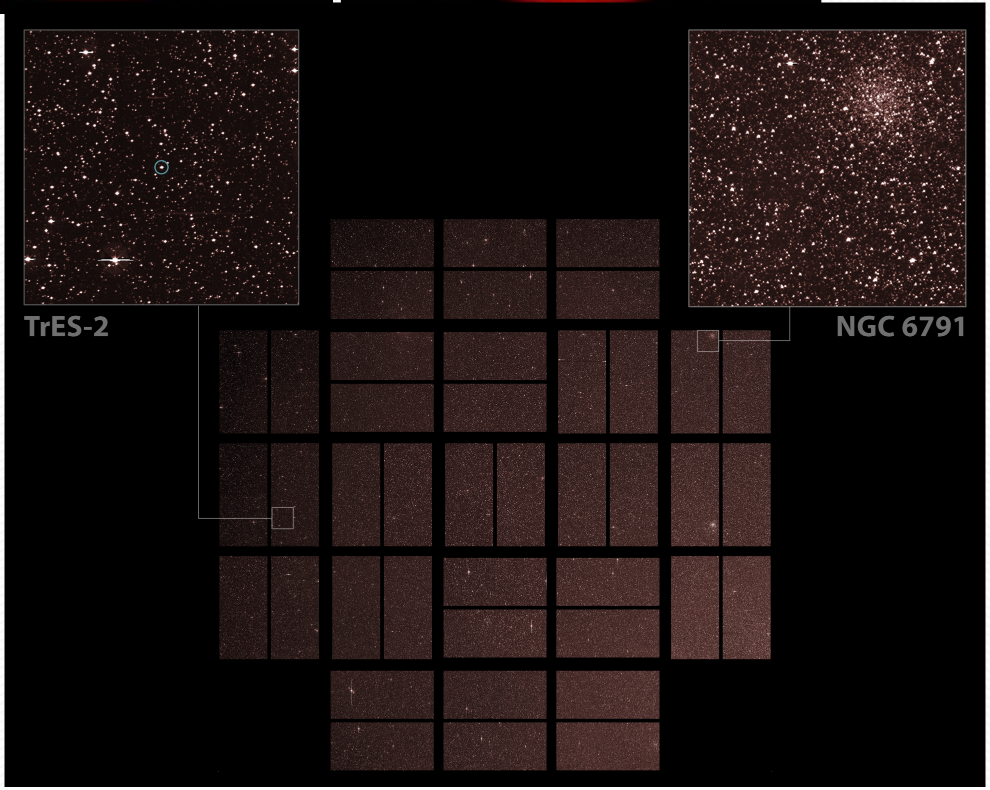
$M_{PL} \sim 6\text{-}10\ M_E$
Likely a rocky planet.



KEPLER (launched 2009)

The *size* of the problem:



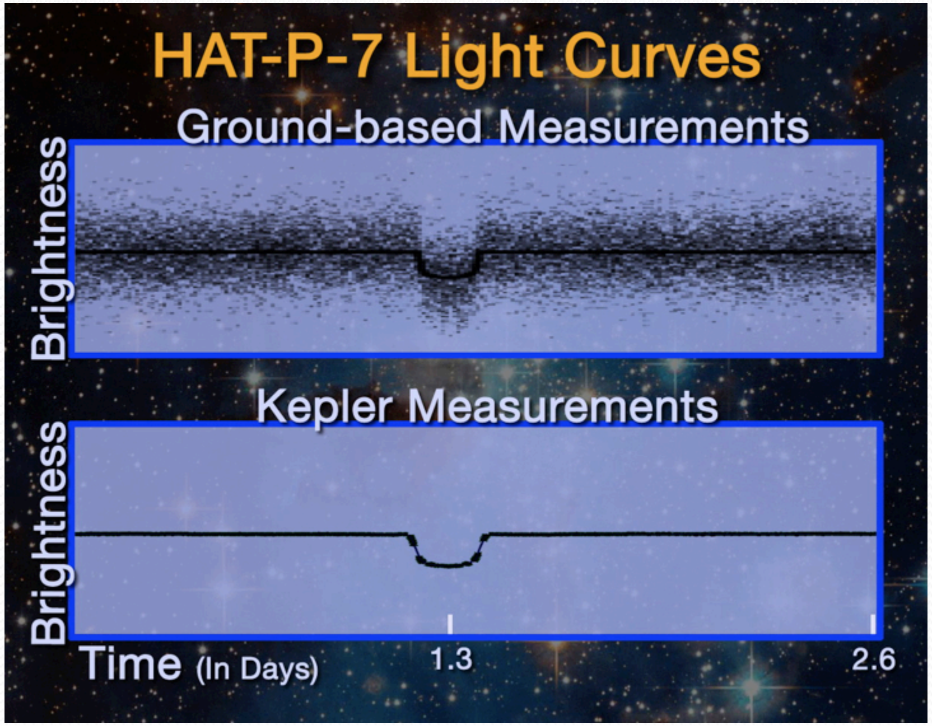


0.95m schmidt telescope

FOV ~ 105 square deg.

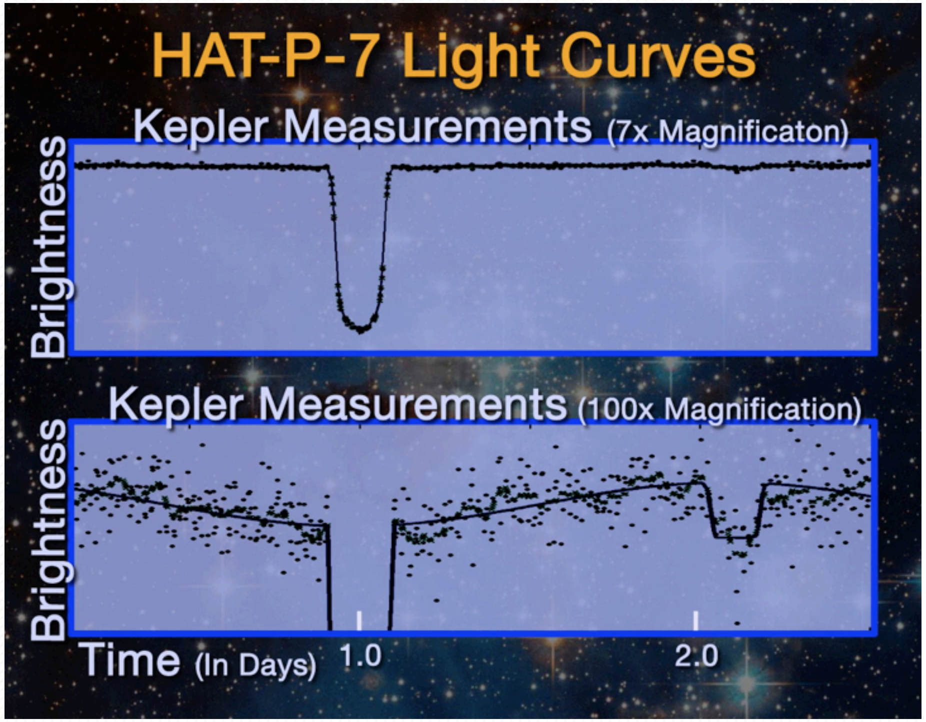
100000 MS stars, with
V=10 - >14 mag

Kepler Early "Results"

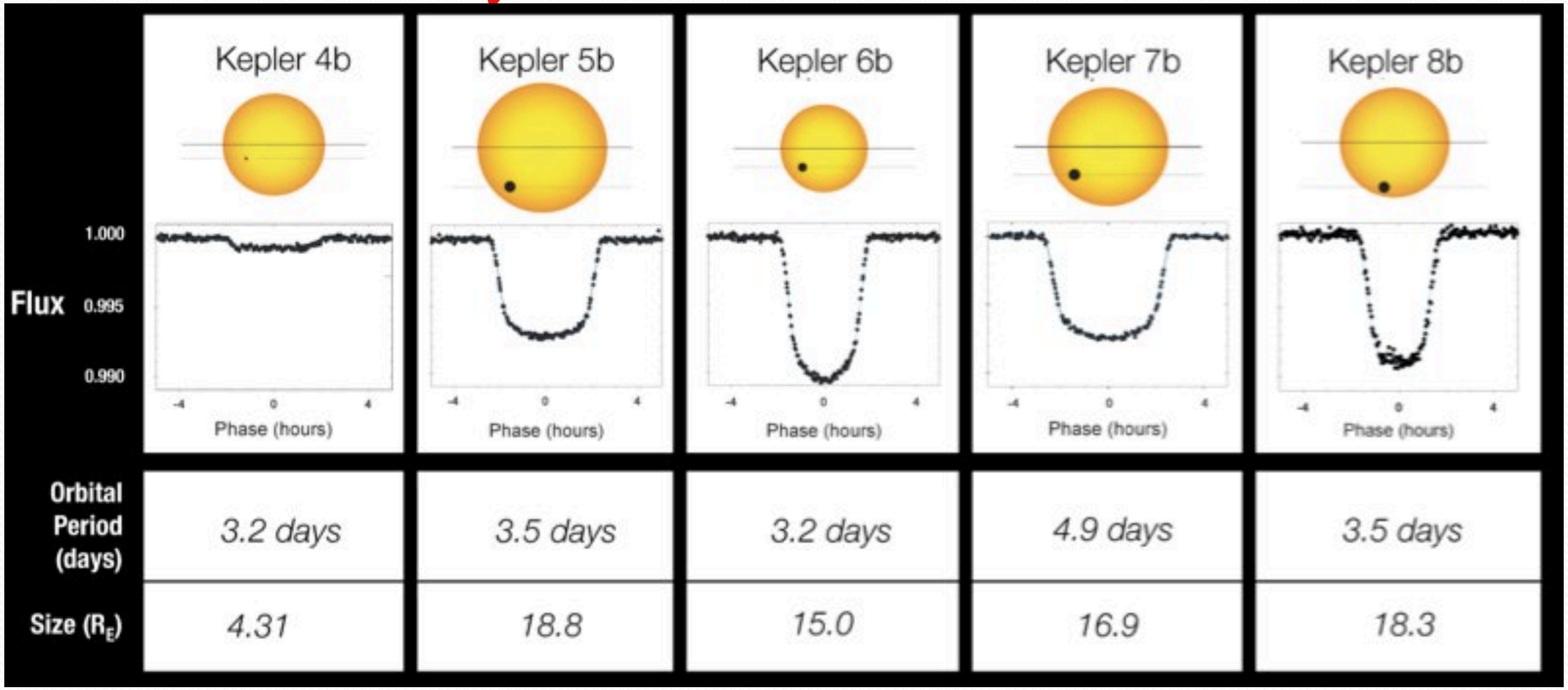


Early light curves demonstrate that the Kepler camera has the sensitivity to detect transits from Earth sized planets.

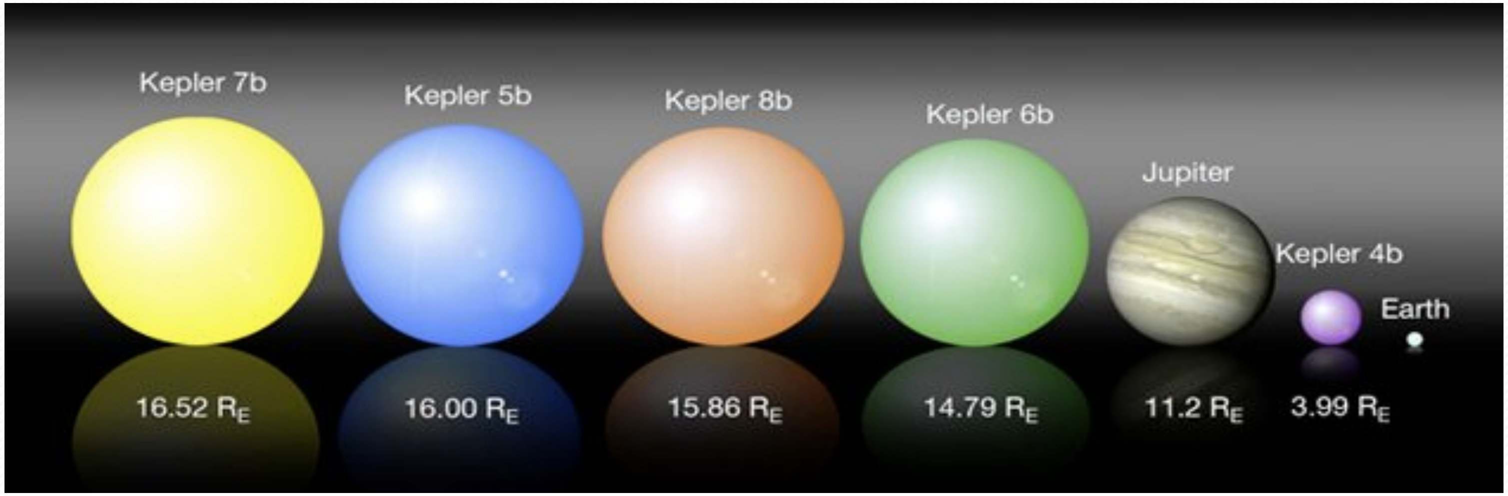
RV confirmation of small planets around faint Kepler targets will be extremely challenging.



First Kepler Planets *4 Jan 2010*



	Kepler 4b	Kepler 5b	Kepler 6b	Kepler 7b	Kepler 8b
Orbital Period (days)	3.2 days	3.5 days	3.2 days	4.9 days	3.5 days
Size (R_E)	4.31	18.8	15.0	16.9	18.3



Kepler Legacy (!)

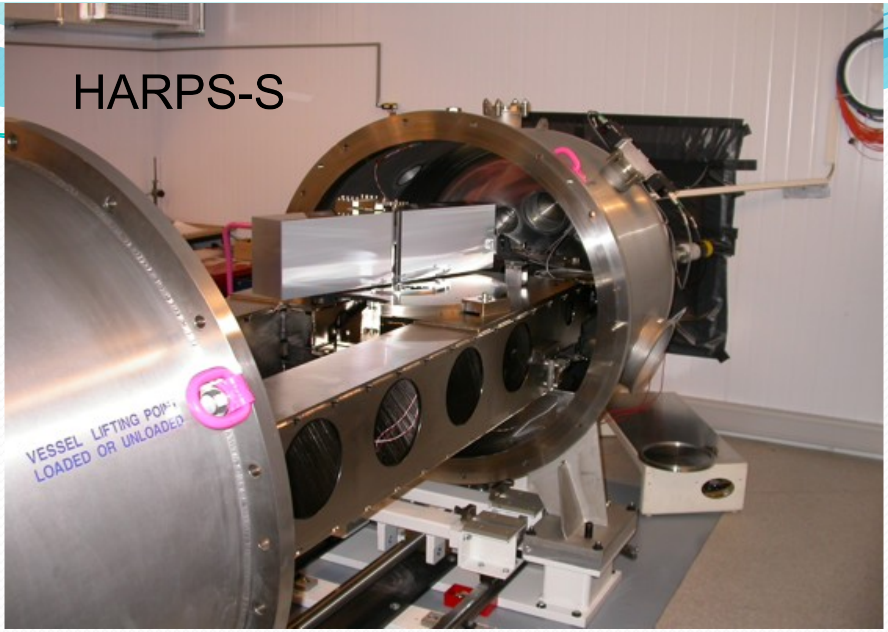
Time will tell but:
35 hot jupiters bright enough for RV confirmation (14th mag) - HARPS-N WHT.

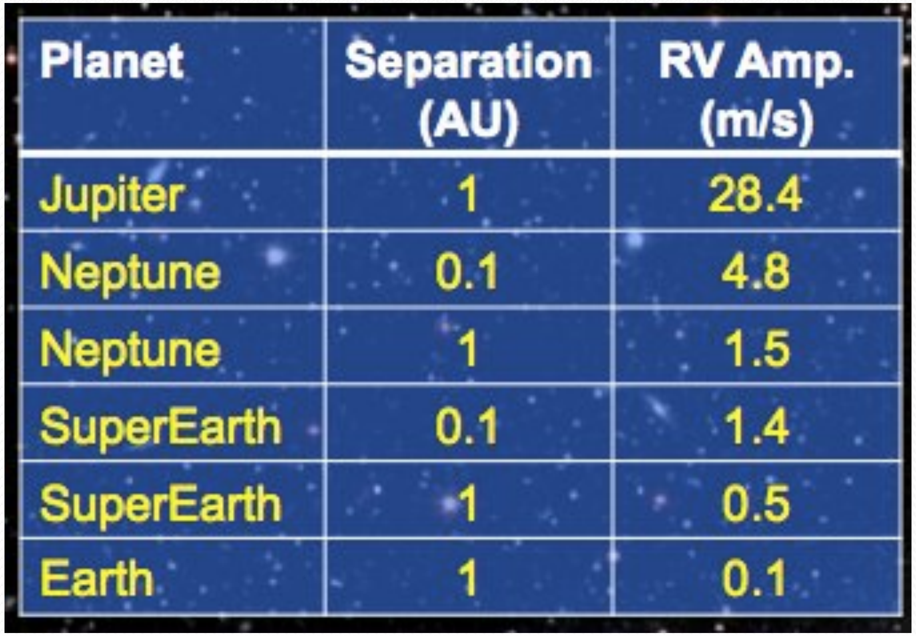
Superearths? Yes - hopefully many

Terrestrial planets? Probably…
Earth analogs? (confirmation will be extremely difficult - see later)

Kepler will give statistics

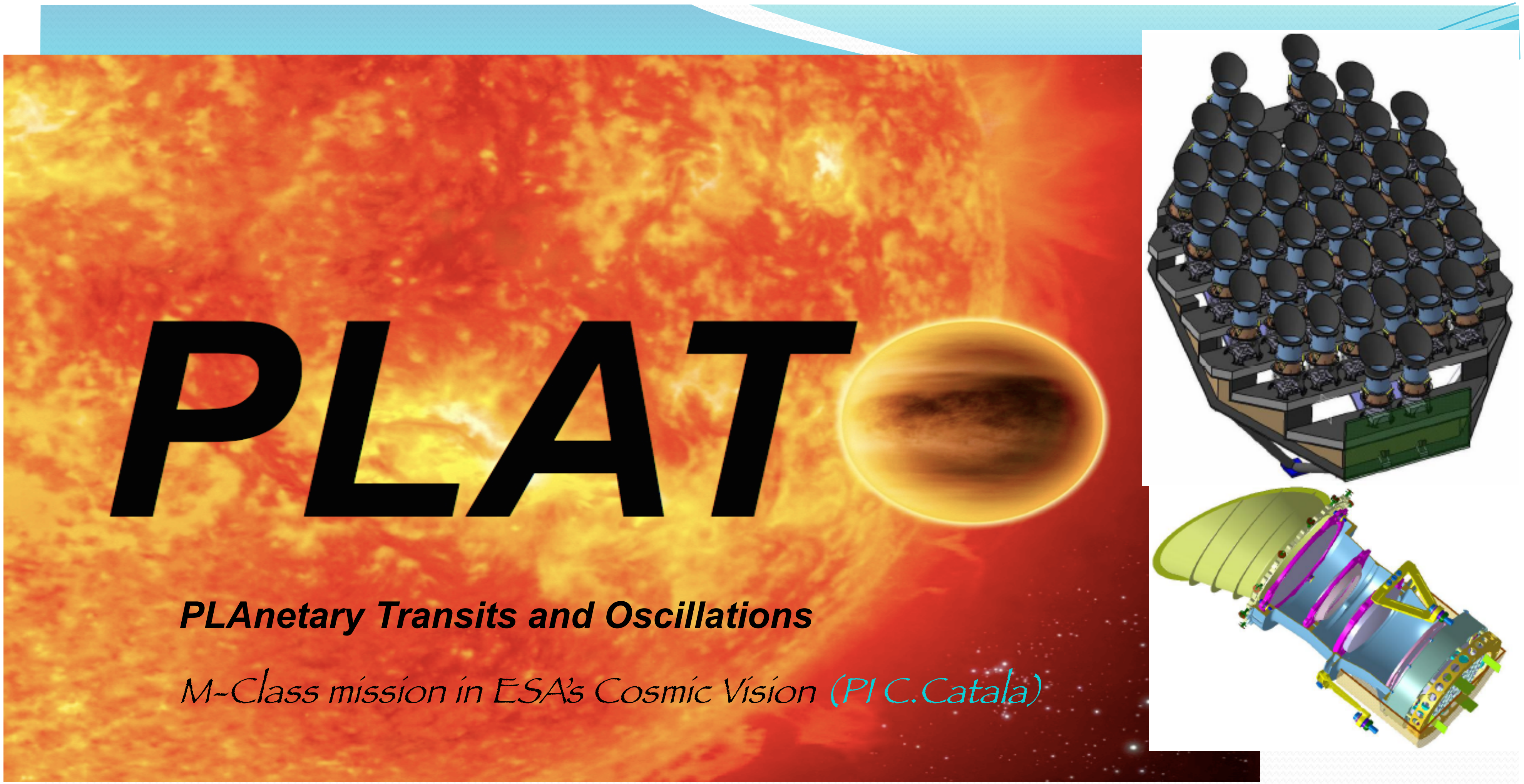
Best hope for small planets until PLATO





Planet	Separation (AU)	RV Amp. (m/s)
Jupiter	1	28.4
Neptune	0.1	4.8
Neptune	1	1.5
SuperEarth	0.1	1.4
SuperEarth	1	0.5
Earth	1	0.1

RV reflex motion



PLAnetary Transits and Oscillations

M-Class mission in ESA's Cosmic Vision (PI C.Catala)

Mainly concentrating on bright stars to maximize follow up potential and minimize blending/confusion issues

AIMS: *Identify bright host stars with HZ planets to search for bio-markers, atmospheres, understand planetary system evolution*

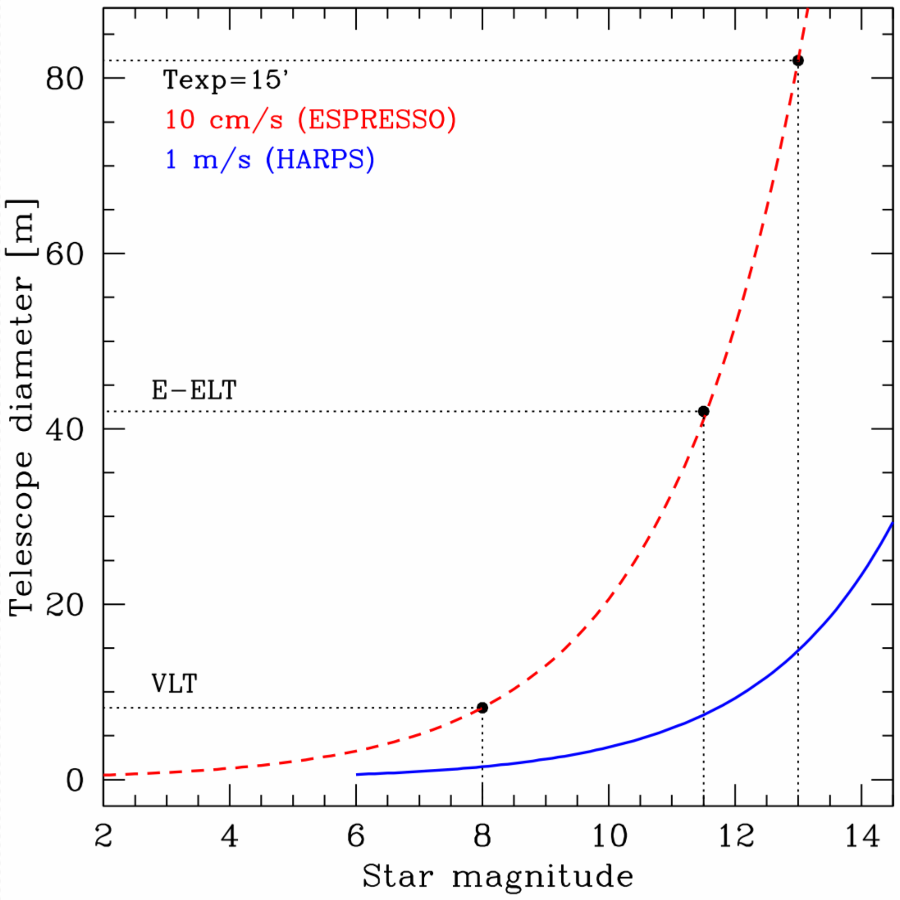
PLATO BRIGHT stars

Stars are noisy – spots, pulsations, prominences, granulation etc distort the RV signal, need plenty of observations to minimize these effects

For rocky planets will be:

1) able to severely constrain internal composition

2) Atmospheric composition



Transit detection pro's and con's

- Probability of transit decreases rapidly with increasing period – need to observe a lot of stars –

$$P_t \propto Period^{-2/3}$$

- For smallest planets stellar activity/noise an issue.
- Best way to get accurate information about the planet itself, limiting factor will be our knowledge of stellar masses/ages.
- The brightest planets can be characterised in other ways – temperatures, atmospheric structure and composition (Swain et al 2010, Tinetti et al 2008 etc).
- (Transit give high resolution 1d map of stellar disk (limb darkening, spots etc))

Astrometric detection

Astrometric techniques aim to measure the transverse component of the photocentric displacement. 'Astrometric Signature' given by:

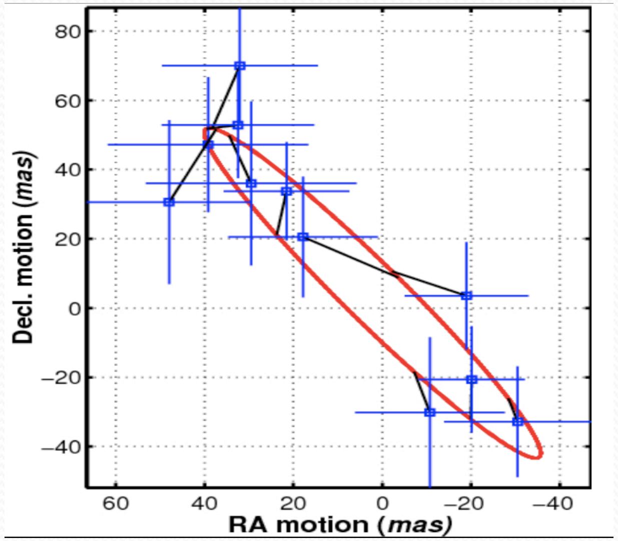
$$a = \frac{M_{PL}}{M_*} \frac{\alpha_{PL}}{d}$$

α_{PL} Semi-major axis (AU), *d distance* (pc)

Note – signature scales linearly with semi-major axis (ie better for long period objects), compliments RV technique/transits which have bigger signals at short periods.

Astrometric limit given by the non-uniformity of illumination over the stellar disk eg in the case of the sun - a spot covering 1% of disk would cause the apparent centre of the sun to shift by up to $0.005R_{Sun}$ (the wobble induced in the sun by the Earth is has a maximum amplitude $\sim 0.0003R_{Sun}$).

Astrometric First Detection?



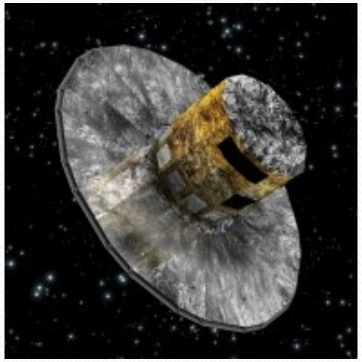
VB10 (Pravdo & Shaklin 2009). Host star is an extremely cool M dwarf

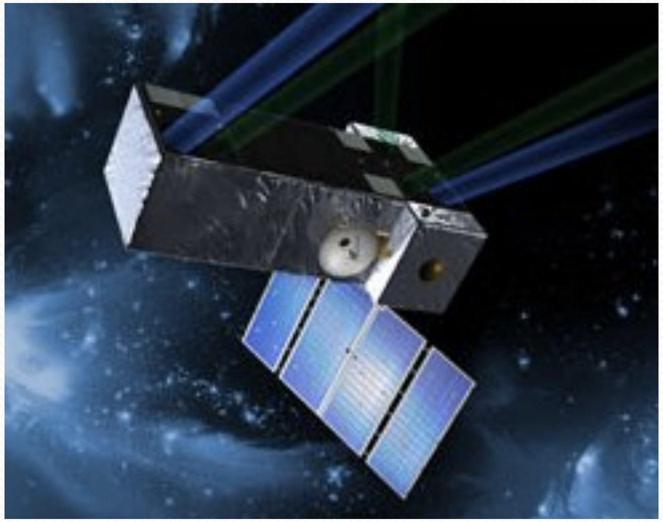
10yr of ground based measurements => 6 M_J companion in 0.74yr orbit

Not confirmed by recent results

Upcoming experiments

PRIMA/VLT (soon), ~30μas
GAIA (launch 2011/2), ~10μas





Maybe Sim(-lite) (2020? but not yet funded), 4μas

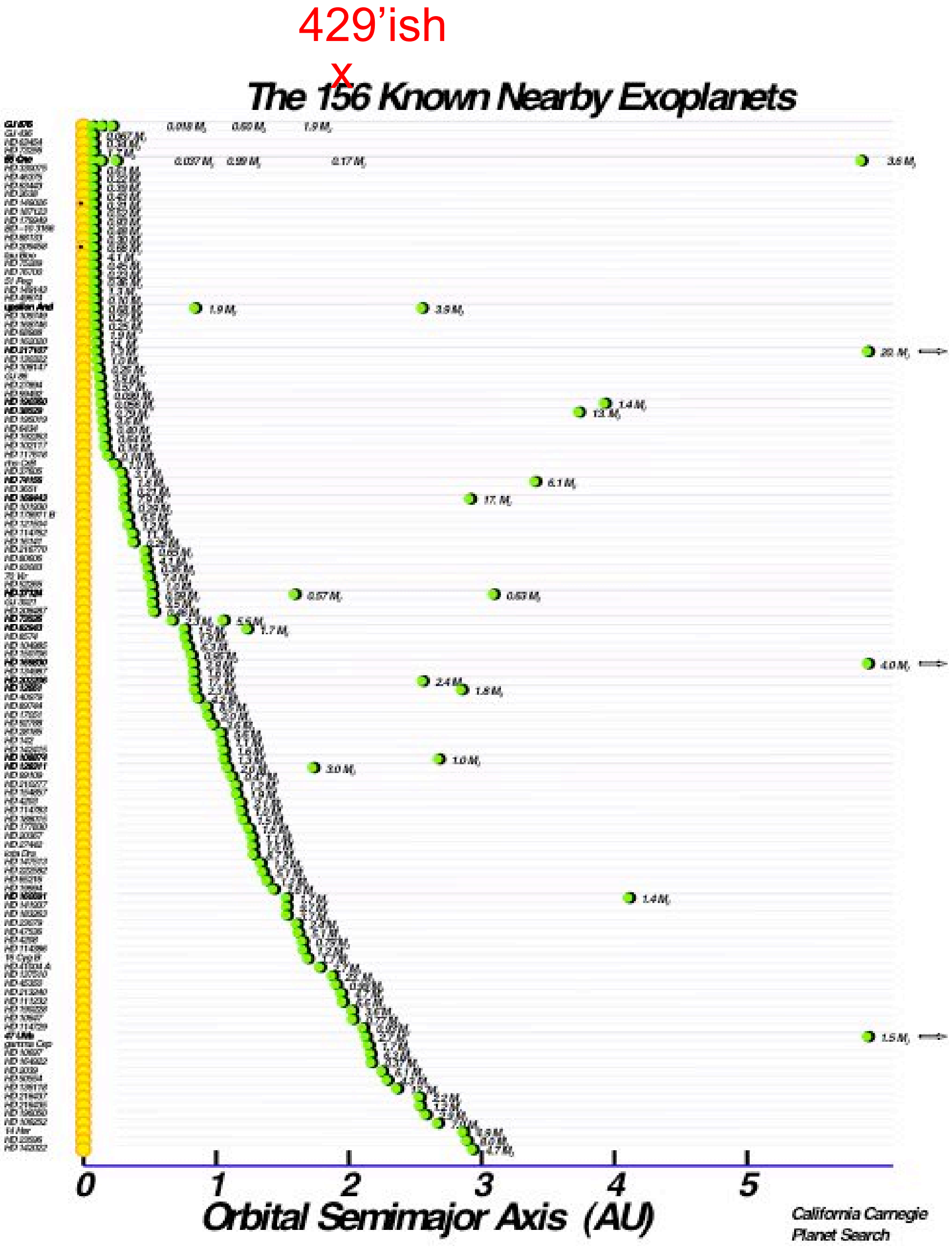
Astrometric signal + RV => orbital plane etc 10μas would enable the detection of

Jupiter's to 240pc, Uranus's to 44pc, Earth's to 1.5pc

Known exoplanets

Current census: 429 planets (Feb 2010)

- 399 planets in 339 systems, Oct 1995 – Feb 2010 from RV searches. 36 multiple systems.
- 9 planets in 6 systems from timing. 2 multiple systems.
- 69 Transiting planets (some of these discovered in RV surveys). 3 multiple systems.
- 10 from microlensing surveys. 1 multiple system.
- 1 by astrometry?
- 11 planets in 9 systems by direct imaging. 1 multiple system.

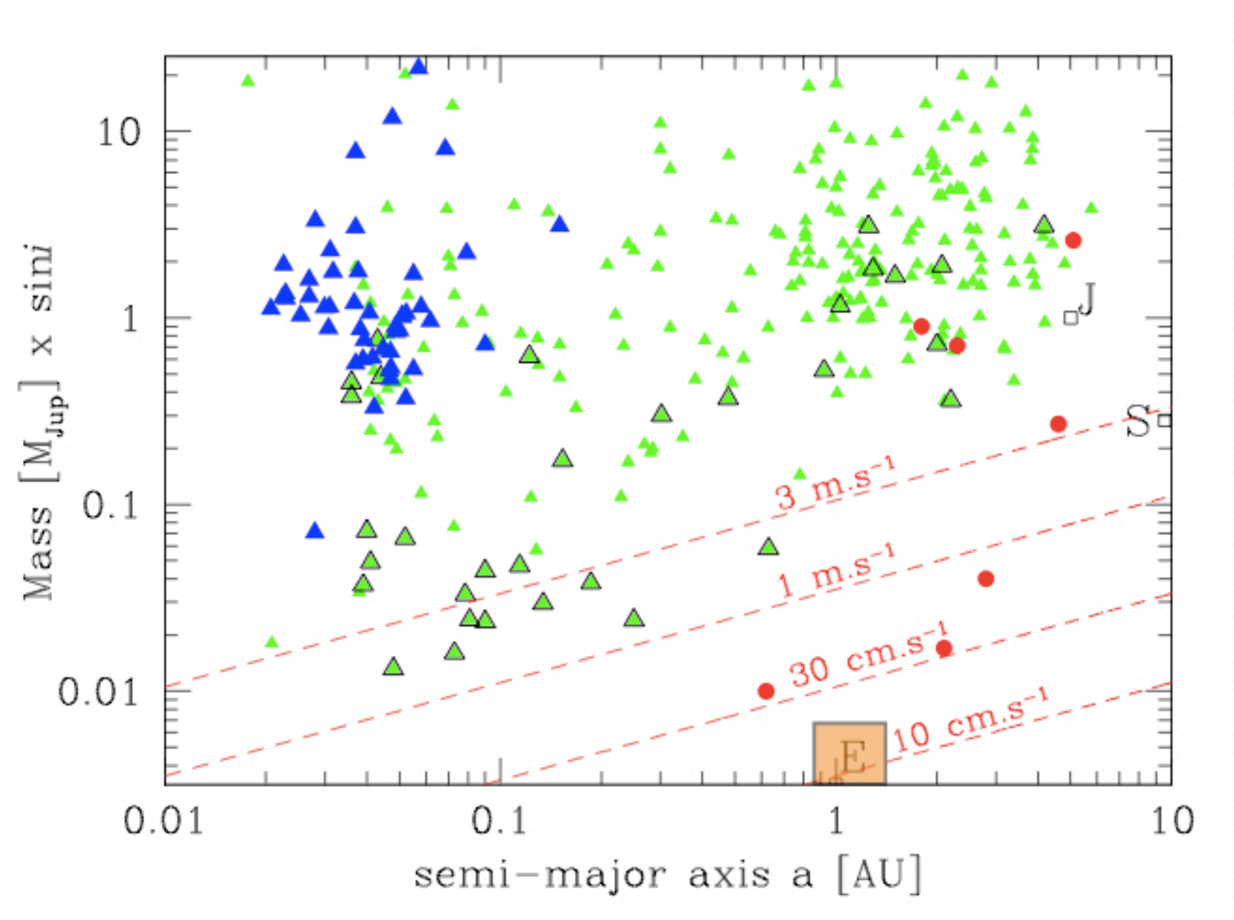


Detection Diagram

RV

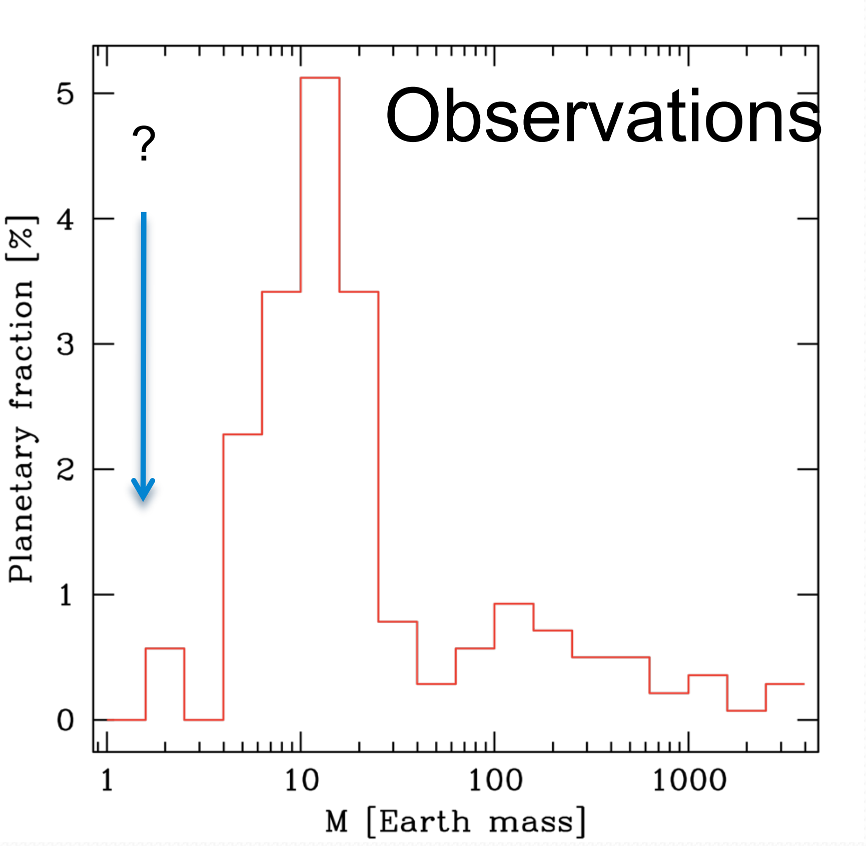
Transit

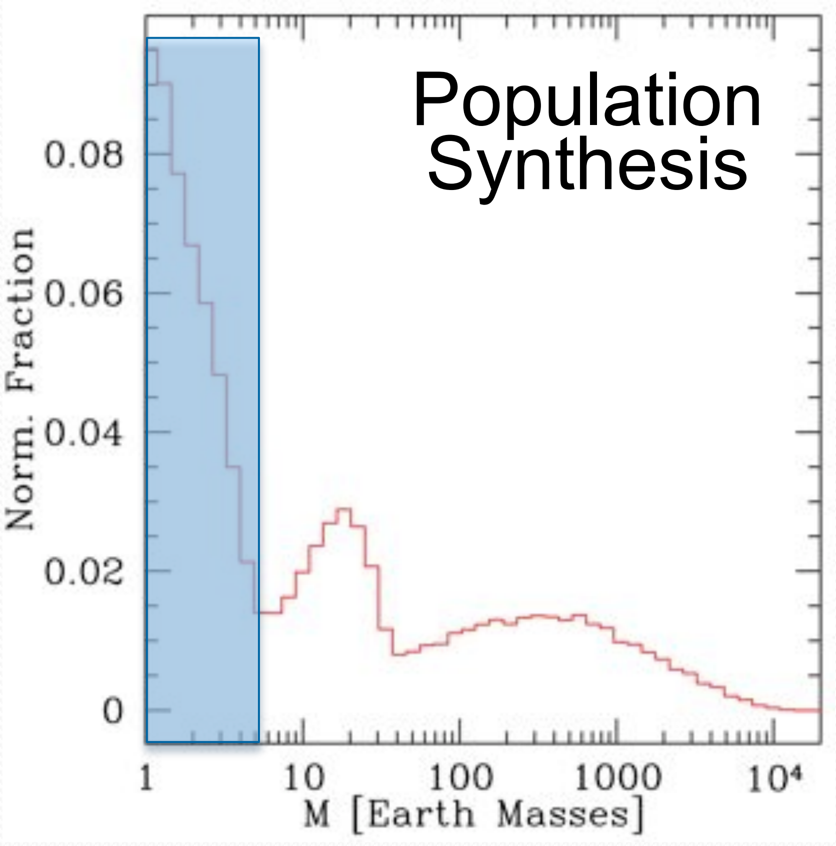
Microlensing



S.Udry

Planet population predictions

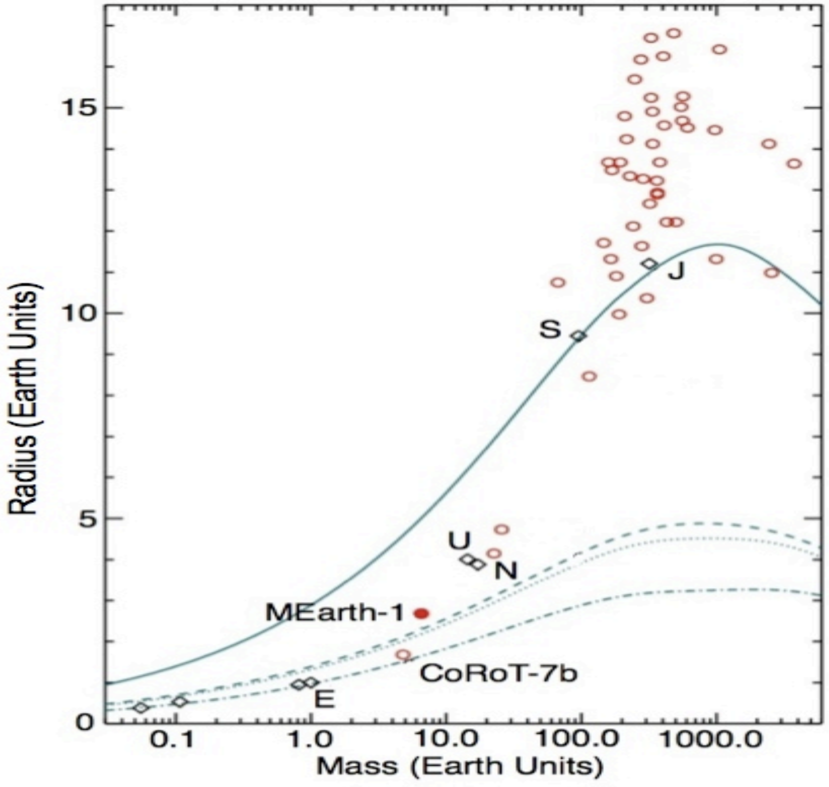




Small planets expected to be very common

ESP mass-radius relationship and composition

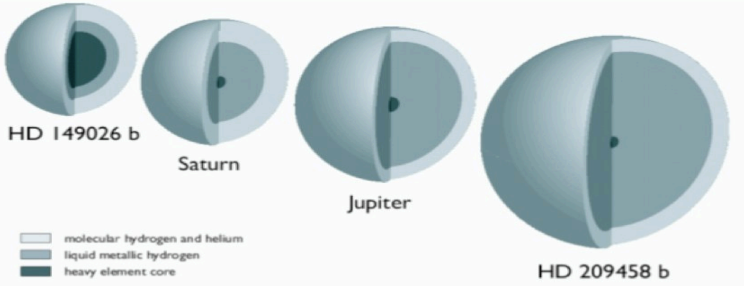
Transit surveys + RV give actual mass and radius of planet (relative to star). Can compare with theoretical models to examine bulk internal composition. For solid planets compositions range from iron through to ocean planets



Be aware – you don't need an *Ocean-planet* to have a *water-world*

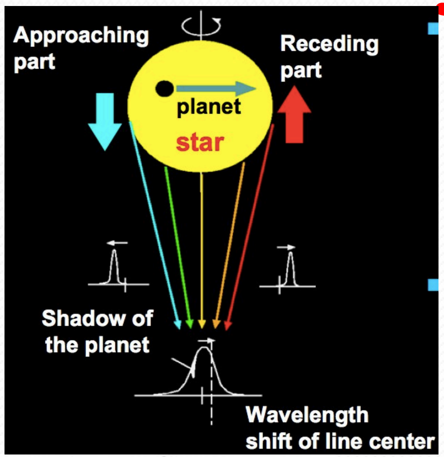
1.75Re
3Me

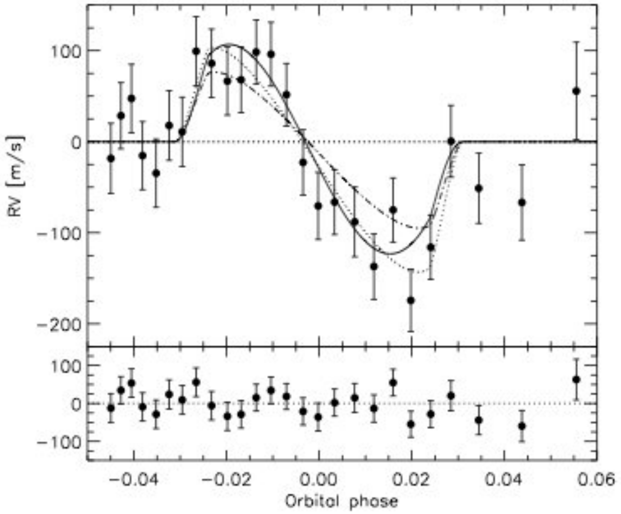
Much Diversity



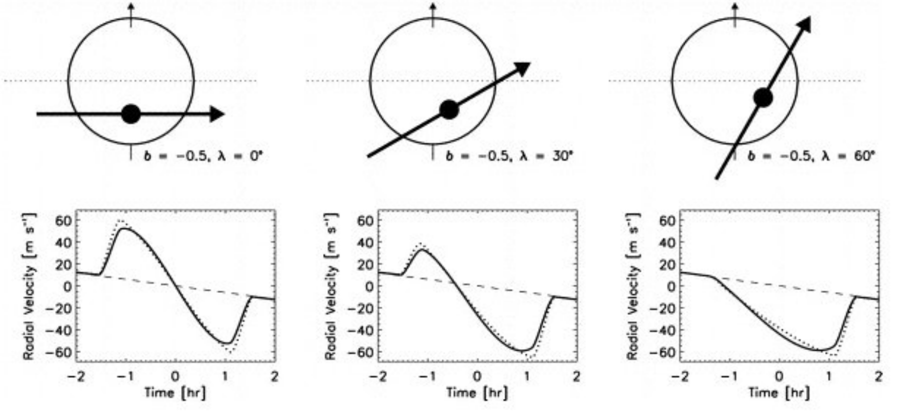
Spin - orbital alignment

Use Rossiter-McLaughlin effect (out of the binary star closet from 1924)

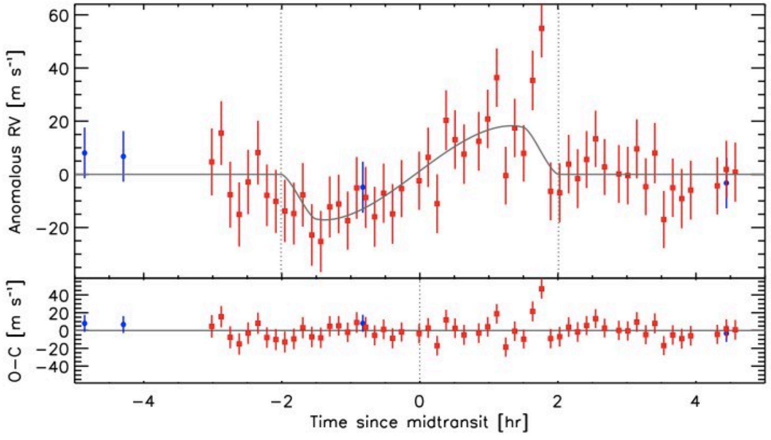




WASP-3 Simpson et al 2010



30% of large planets show misalignment.



HAT-P-7 Winn et al 2009

Orbital eccentricities and tidal effects

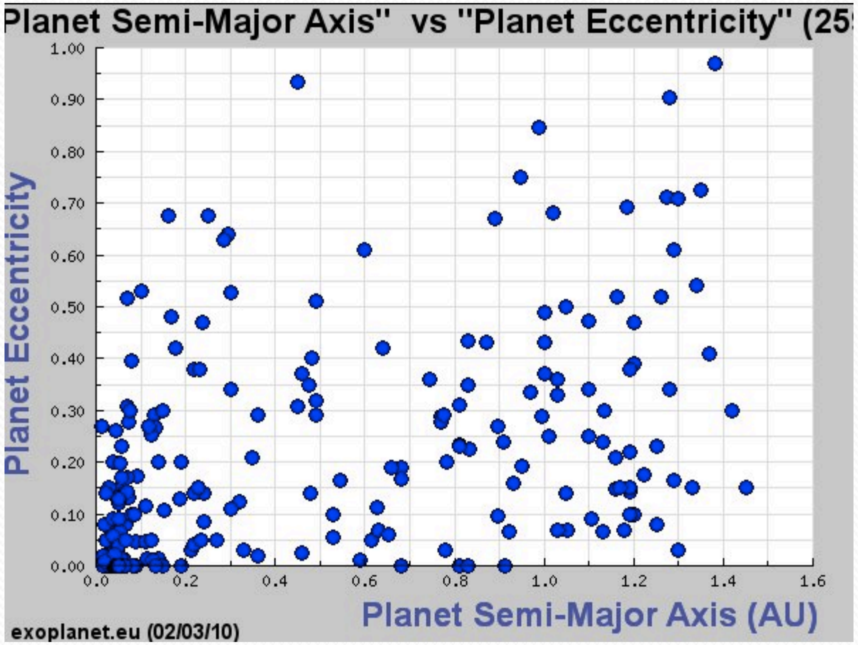
Eccentric Planetary orbits are extremely common

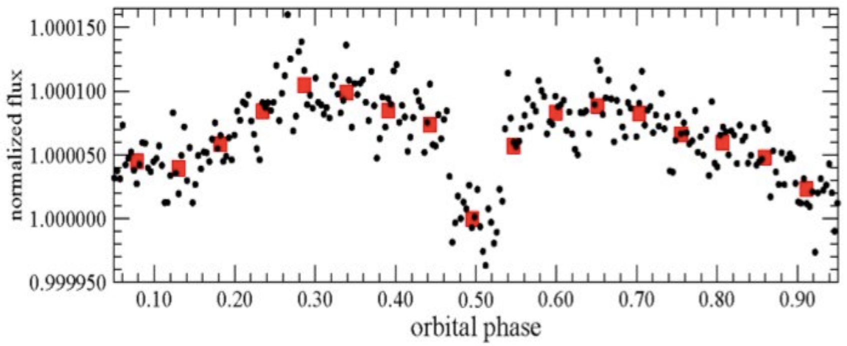
Planet-planet scattering (multi-body systems)

For planets in binary systems with one component's spin axis misaligned relative to orbital plane get Kovai effect which can push any planets into a highly eccentric orbit (oscillatory with i)

$$e_{\max} \approx \sqrt{1 - 5/3\cos^2 I_0}$$

Close in planets can raise tides on the stellar surface eventually will end in disruption of planet – WASP-18b (Hellier et al 2009)

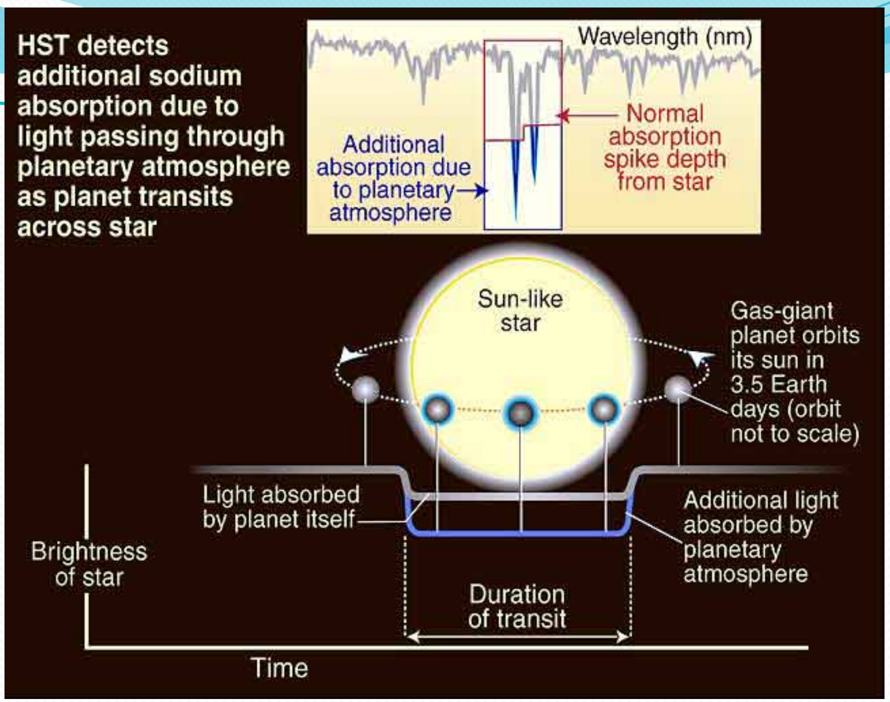




HAT-P-7 Walsh et al 2010

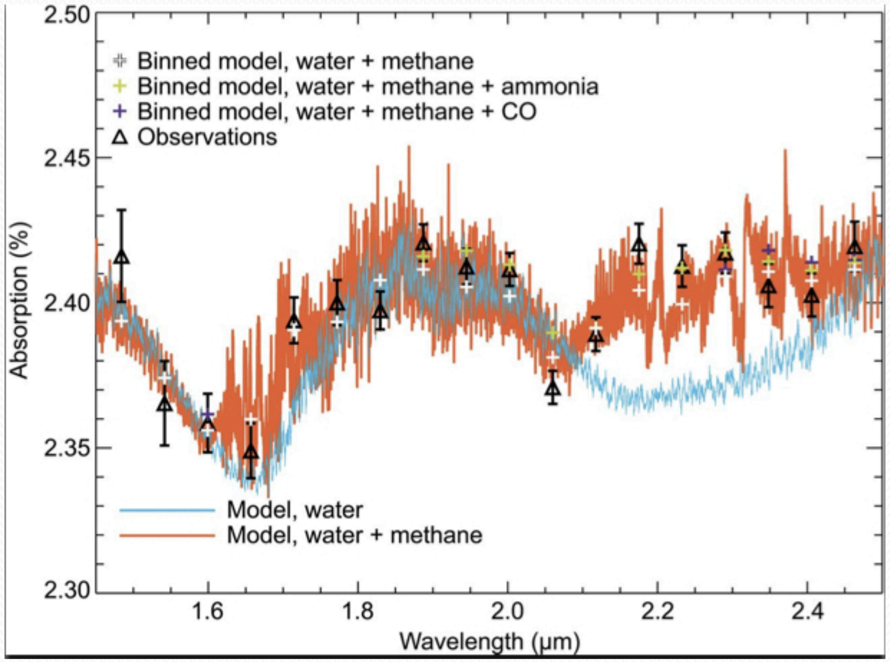
Exoplanet Atmospheres

- Information from Transit (radius), emission spectra (close to secondary eclipse), transmission spectra (transit), reflection



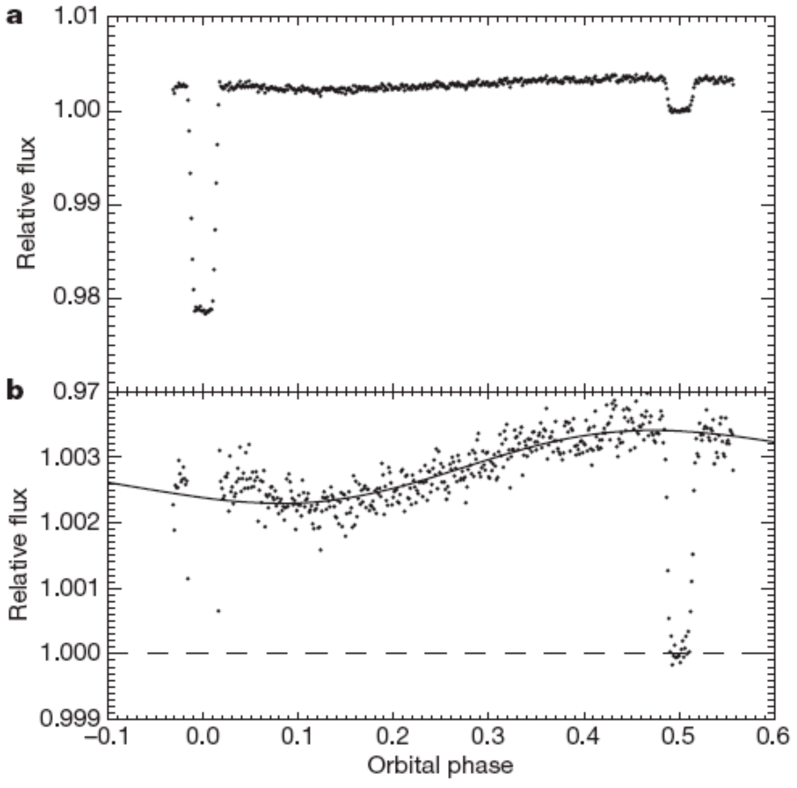
- Line emission observations better established (originally done with HST Charbonneau et al 2002), repeated from the ground.

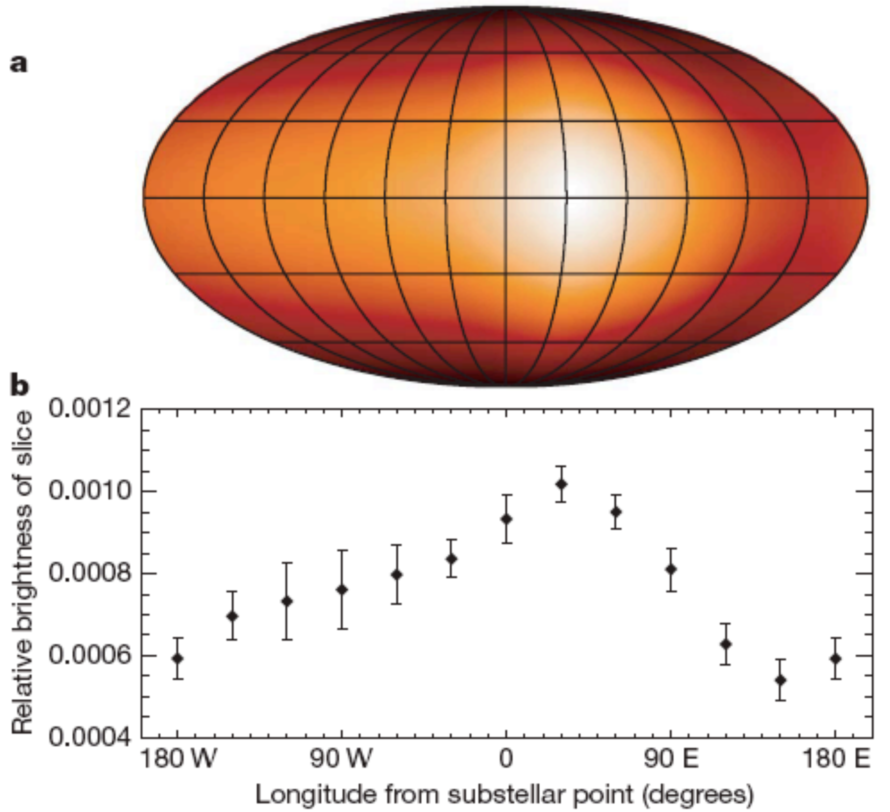
- SED results still controversial? Recent ground based confirmation (Swain et al 2010) maybe.



Tinetti et al 2008

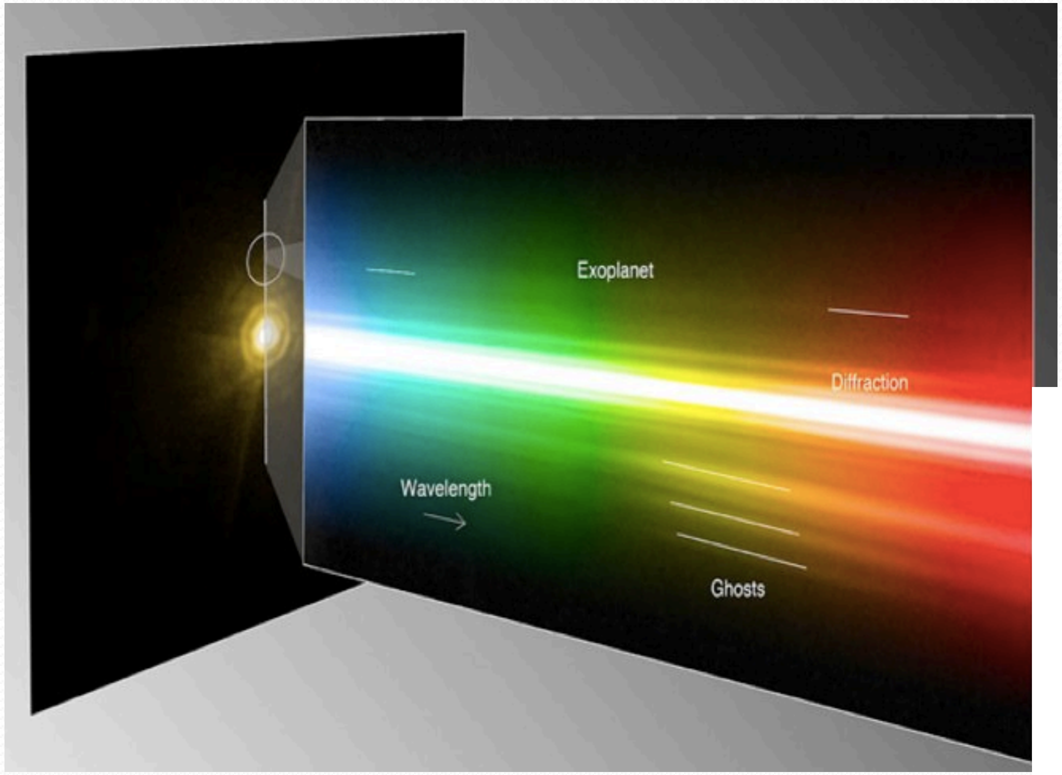
Secondary eclipses and thermal phase variations

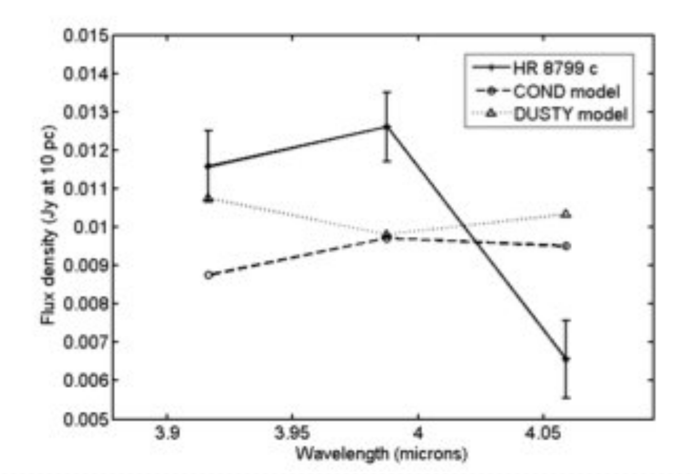




Spitzer 8μm light curve, Knutson et al 2007

HR8799 – first direct spectrum

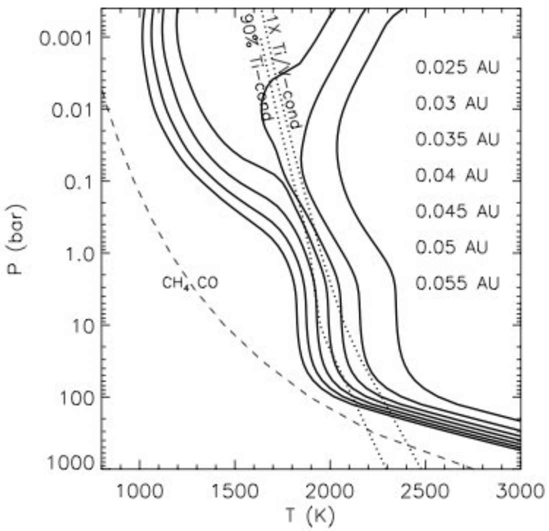




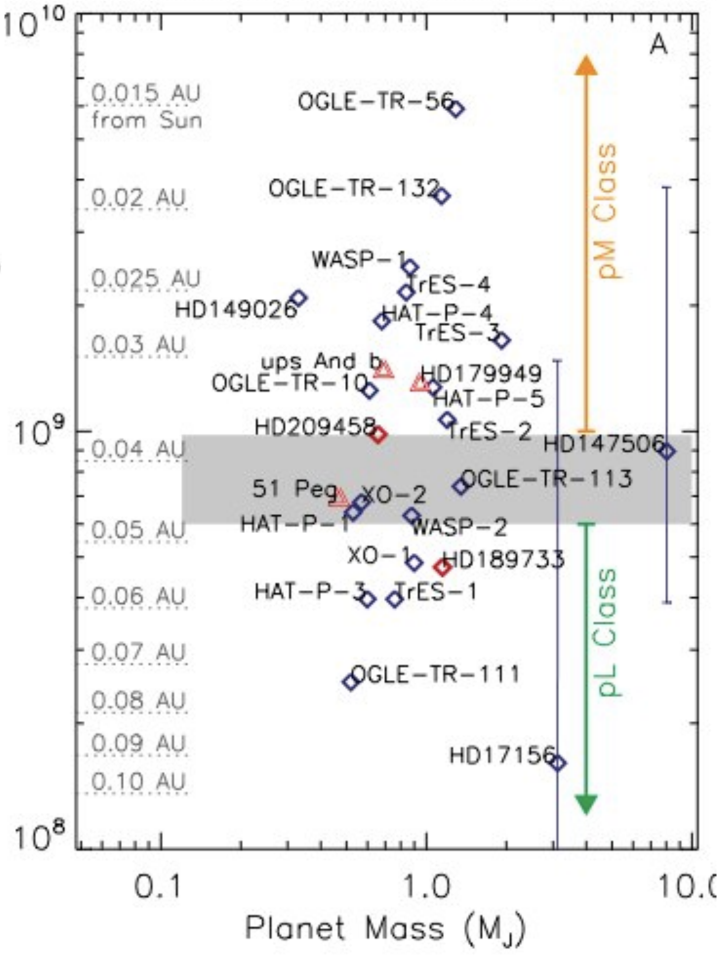
Jansen et al 2010

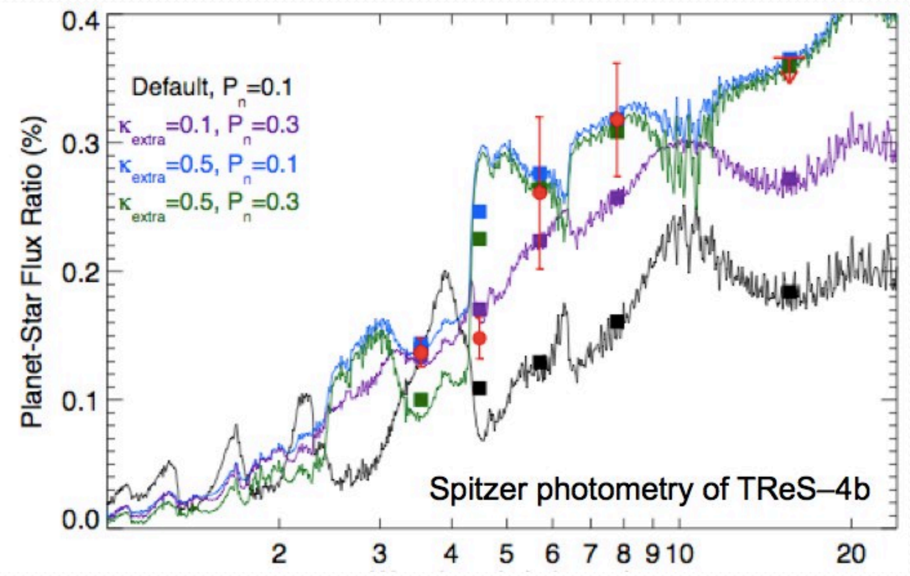
Structure in ESP atmospheres

Much theoretical work
eg Fortney et al 2008
find two classes of planet
dependant on incident
flux: pM hotter and have
TiO/VO gases, pL cooler



pM type have temperature
inversion in atmosphere
(hot stratosphere)





Summary…..

- No single discovery method can deliver everything we need!
- RV surveys (stats) with transits => accurate information on planets (relative to star – need to *understand* star).

- Models predict large population of rocky planets
- Results from CoRoT/Kepler may revolutionise our knowledge of the planet populations. PLATO will find nearby habitable zone rocky planets and charcterise host star.
- Starting to characterise/understand exoplanetary atmospheres (search for biomarkers) and bulk composition.

that's all folks!