

Extrasolar planetary systems

- Examples of data from different detection methods
- Characteristics of observed planetary systems
- Mysteries posed by exoplanet observations....

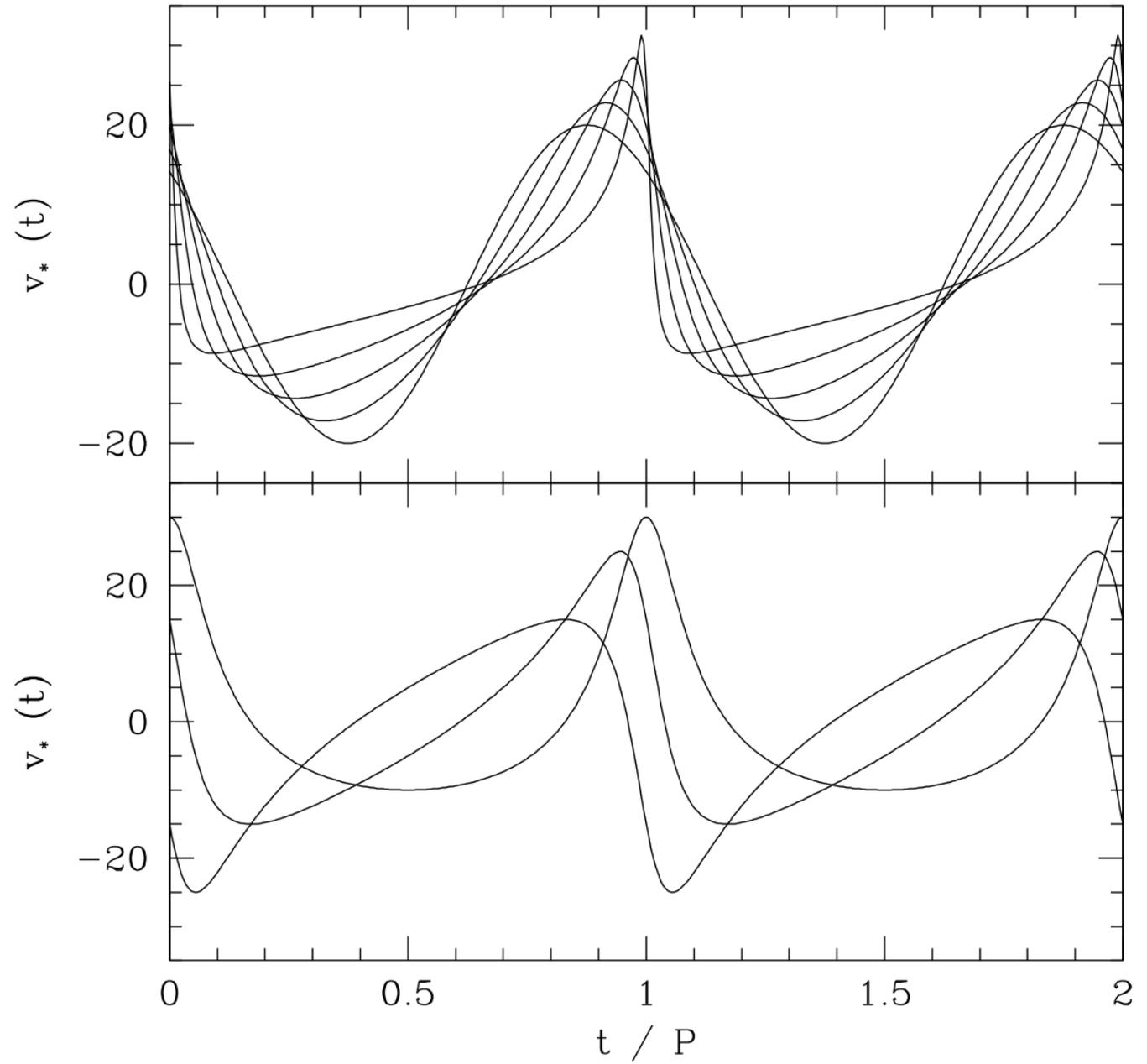
Radial velocity

Recall observables

- Period
- **Minimum** mass ($M_p \sin i$)
- Eccentricity (from shape of RV curve)
- Orientation of ellipse (not very interesting)

Change e

Change orientation



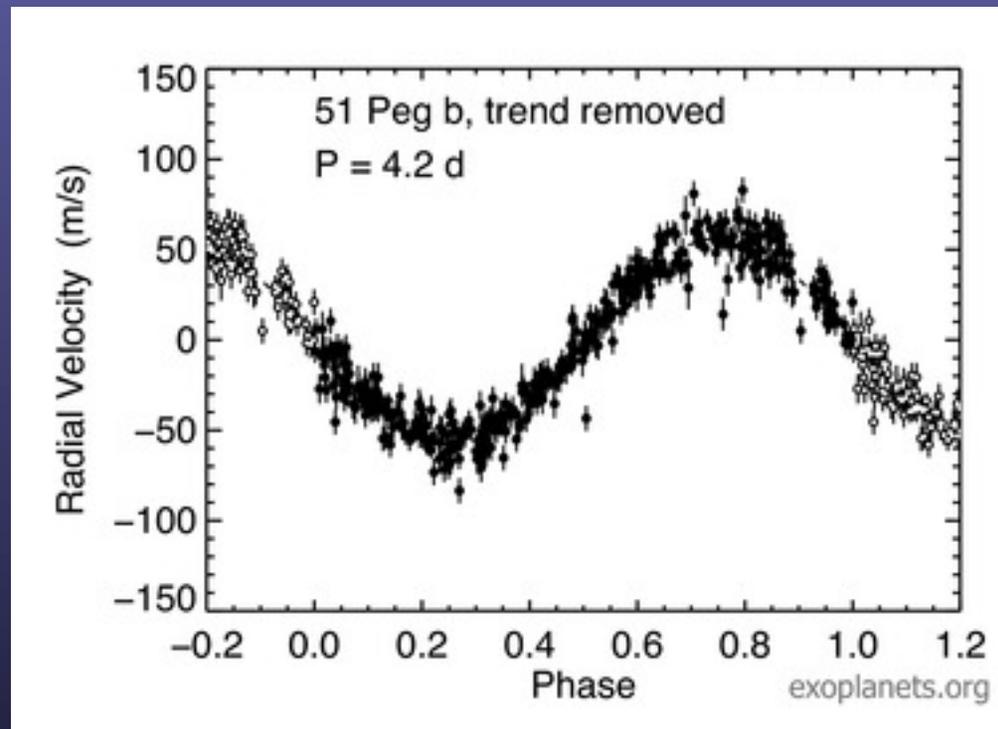
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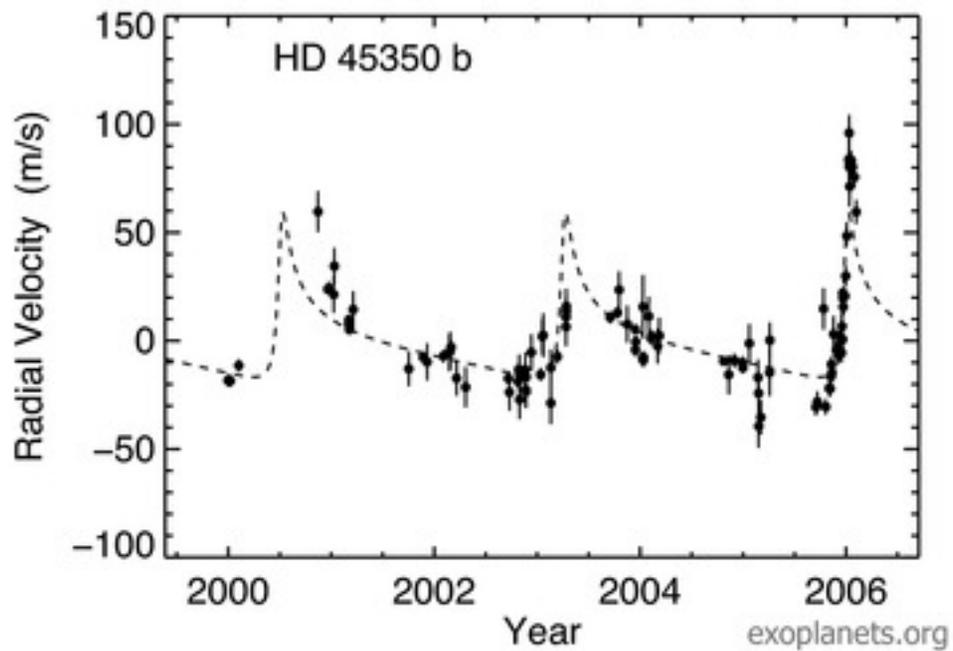
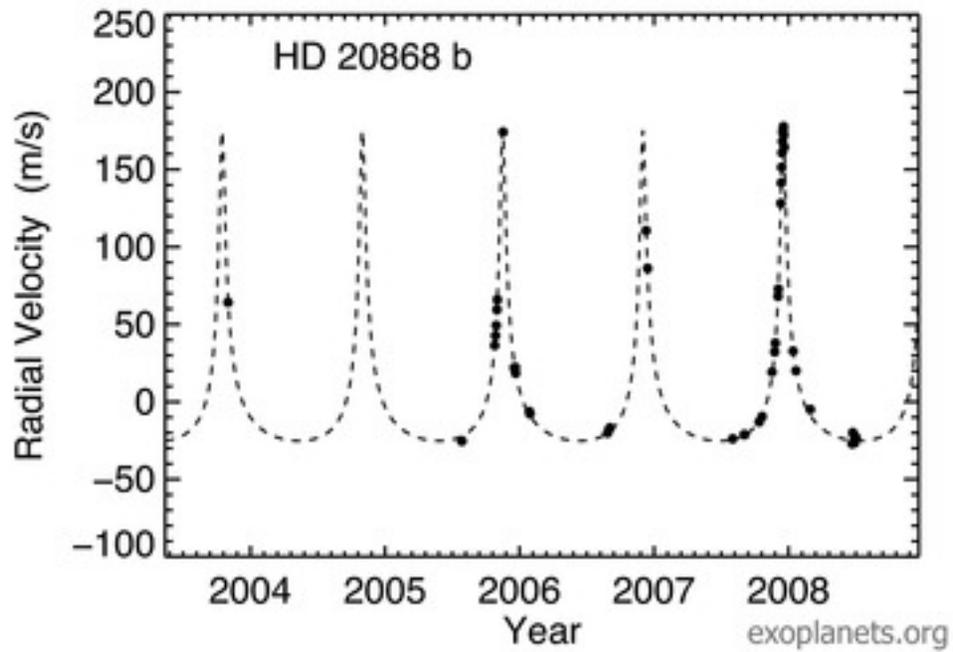
...it depends!

- when the eccentric planet is close to the star, velocity perturbation is **larger**
- BUT, “most of the time”, the eccentric planet is far away, and perturbation is **smaller**

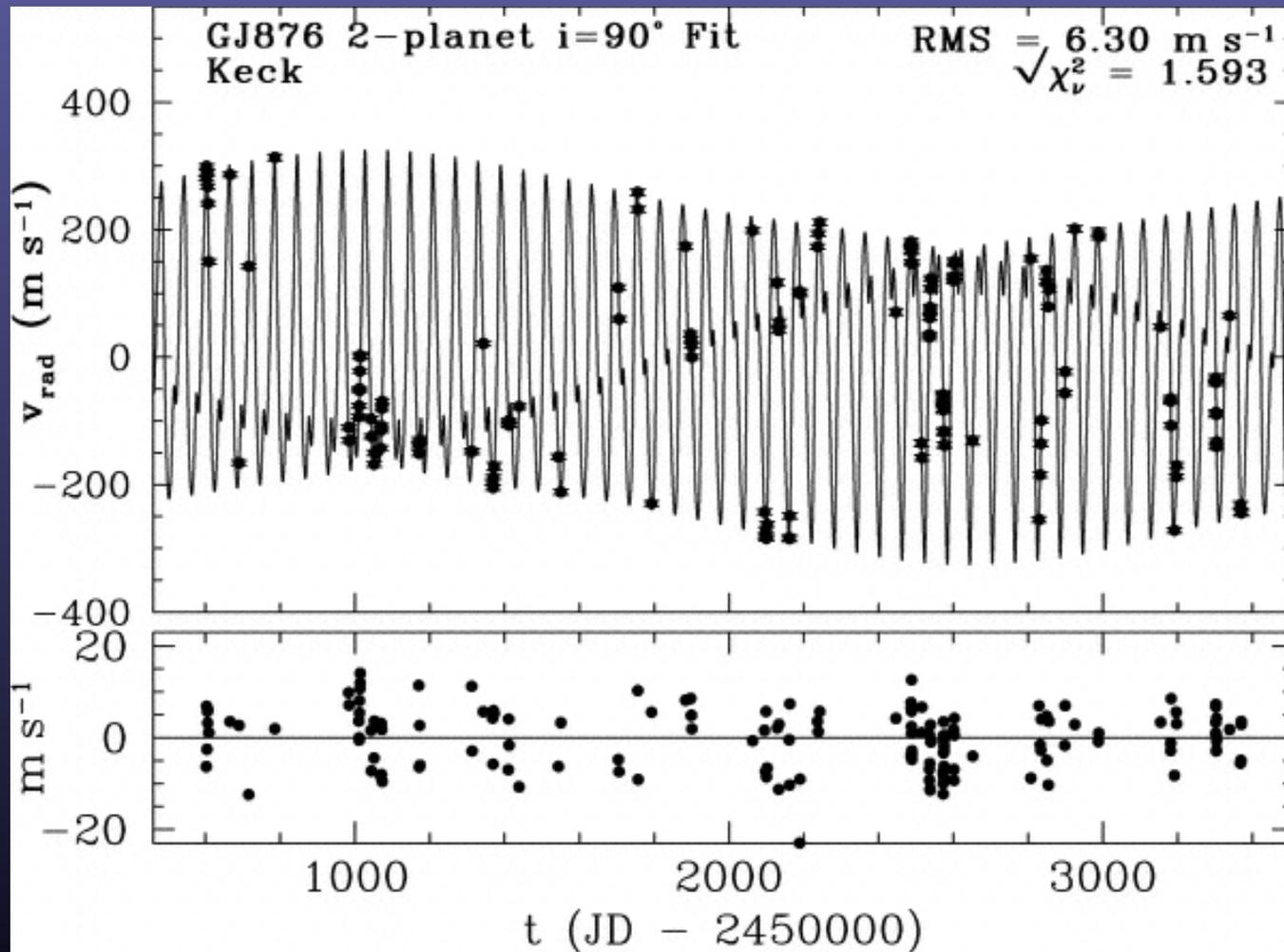
51 Peg – typical (and first!) hot Jupiter... gas giant in close-in, circular orbit



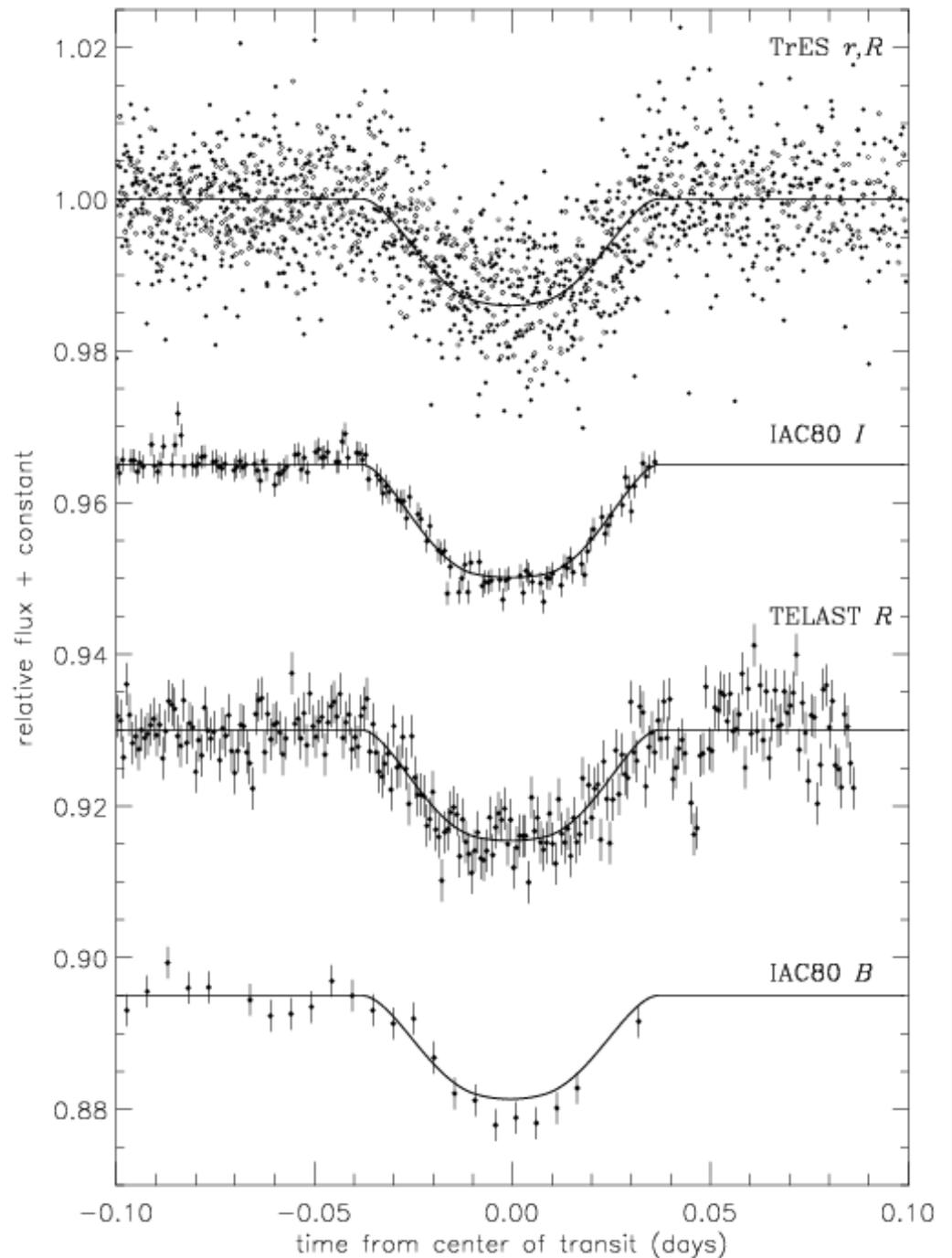
Examples with eccentric orbits

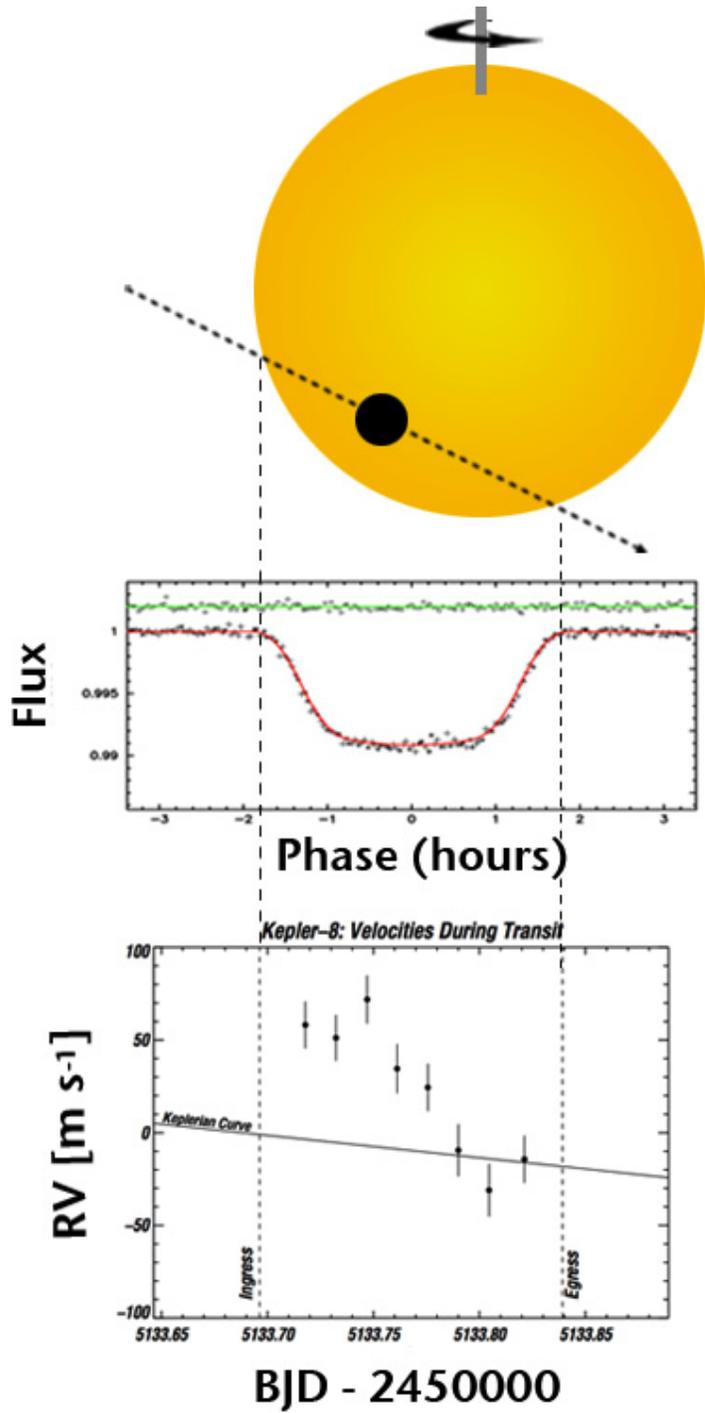


Example showing combined signal of two planets around the same star – in this case with very different periods so fairly easy to separate...

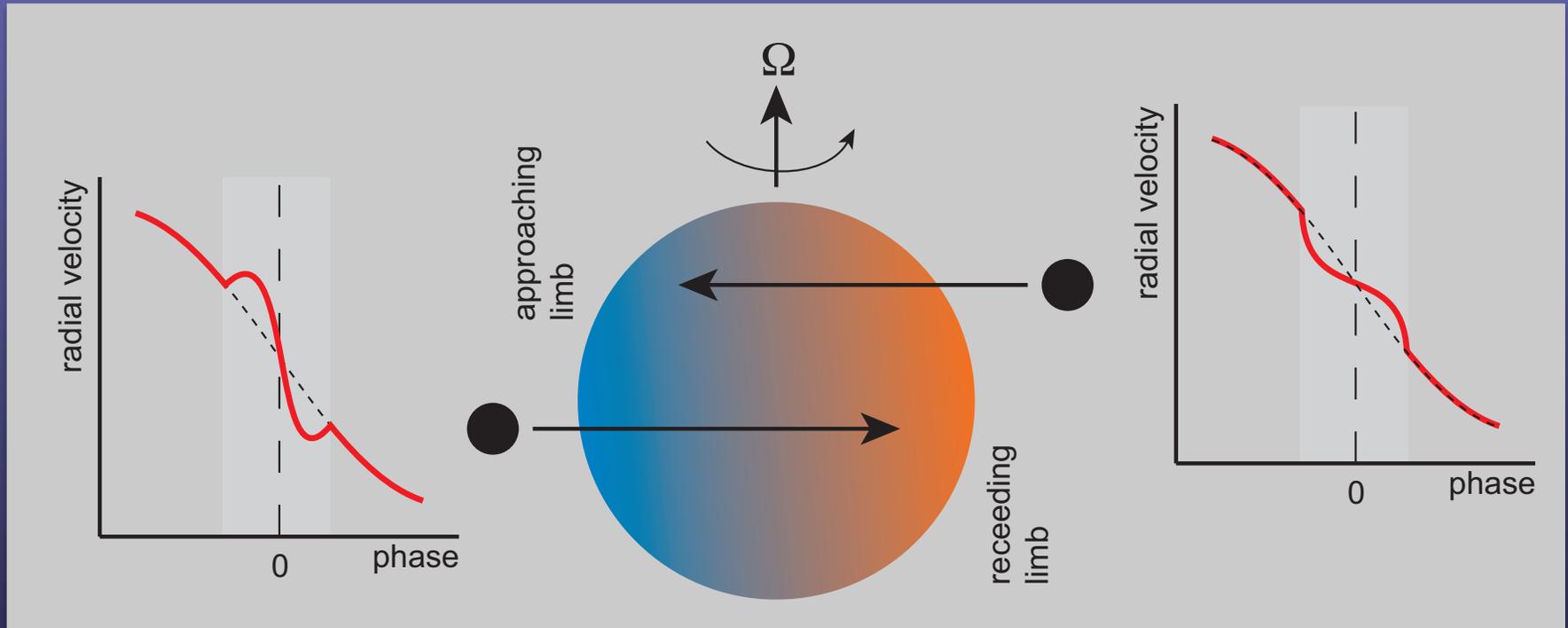


Transits: example of ground-based data quality... can detect $\sim 1\%$ dips needed to find hot Jupiters but significant atmospheric fluctuations very evident!



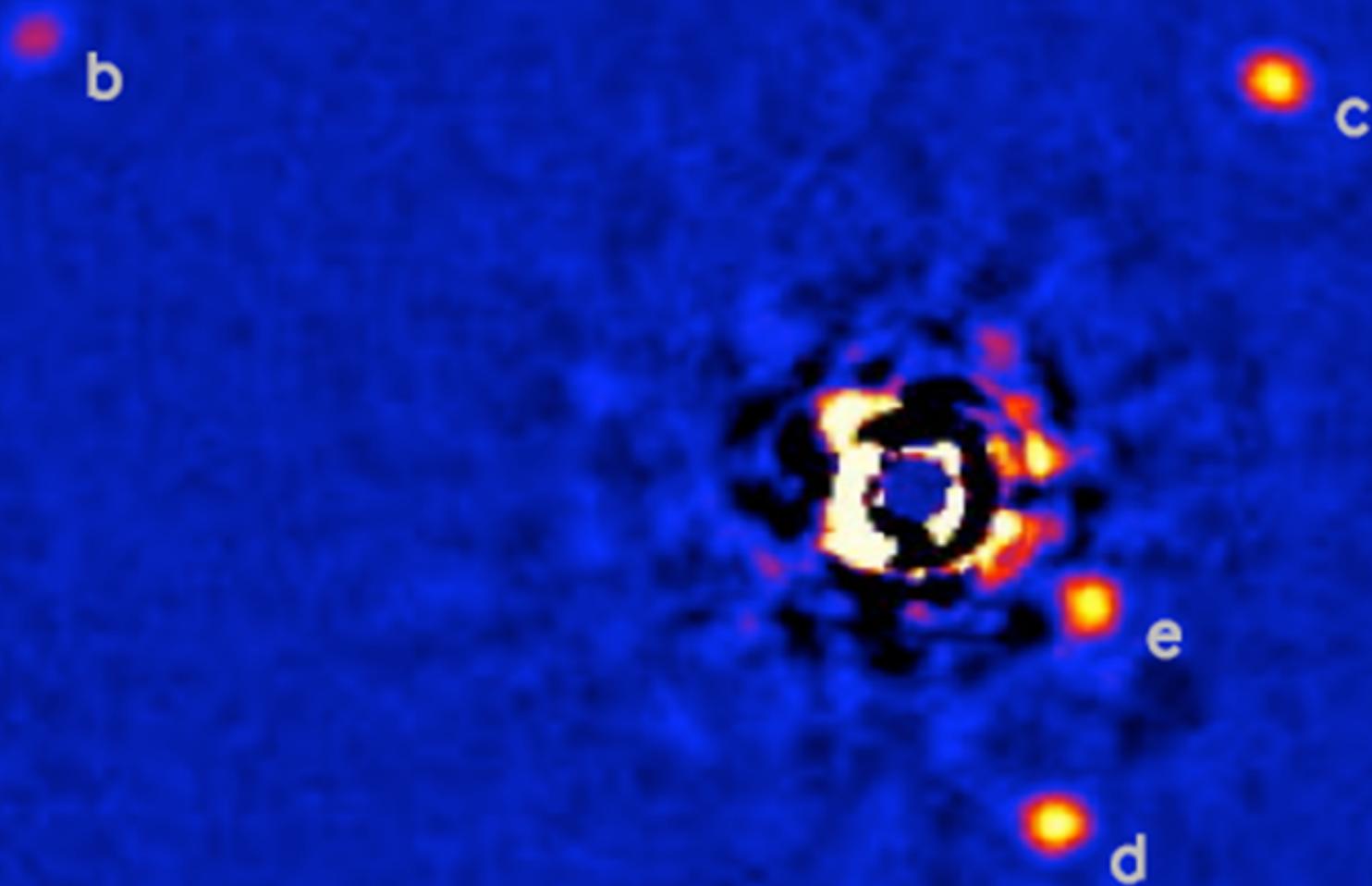


Kepler example data:
here the radial velocity
has also been measured
during the transit



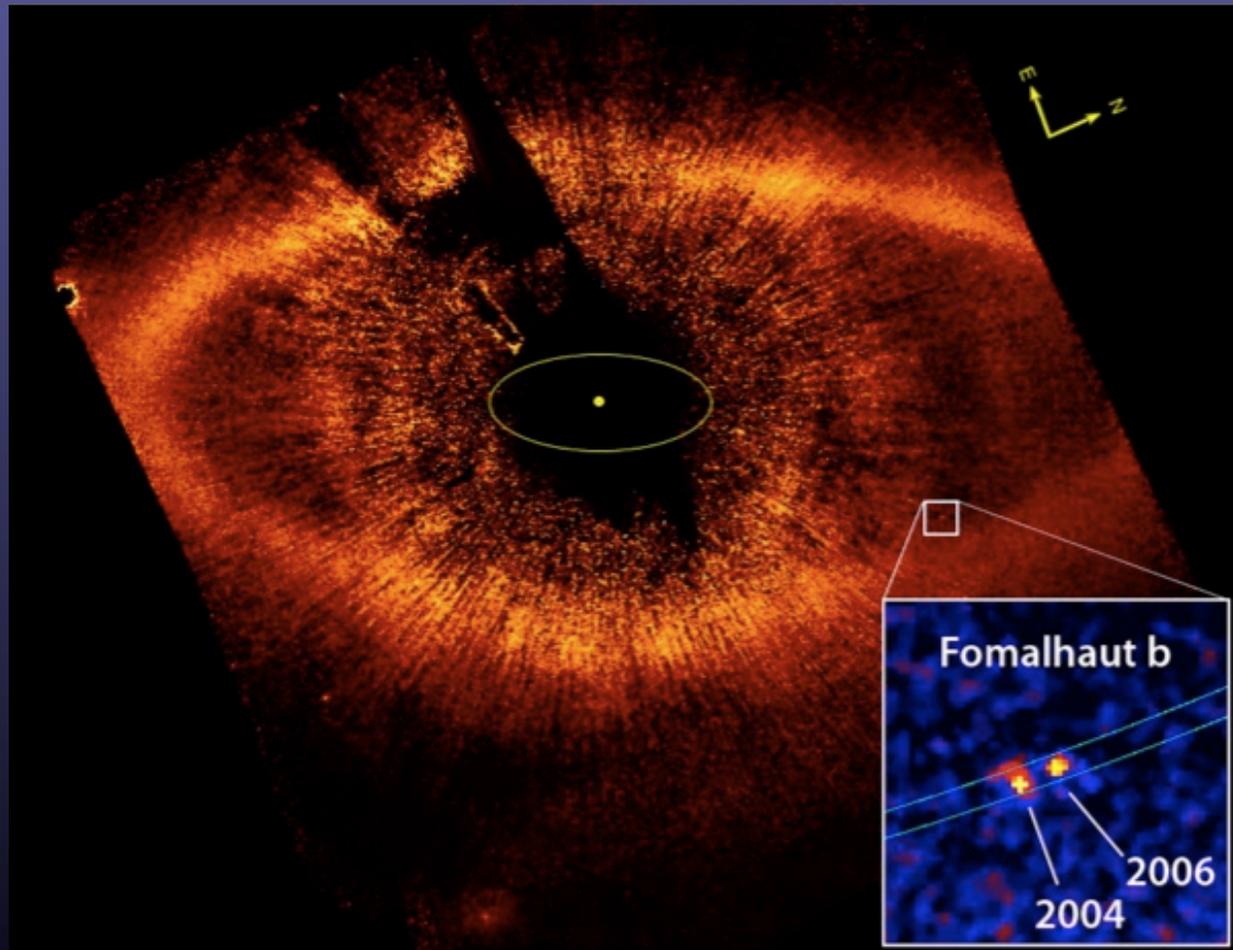
Measurement of the RV signal during the transit allows us to infer the *inclination* of the orbit with respect to the stellar equator – e.g. is the planet co-rotating with the stellar spin, counter-rotating, or polar orbiting?

Direct imaging – example of HR 8799, four very massive planets (5-10 M_{Jup}) at 15-70 AU scales from their host star

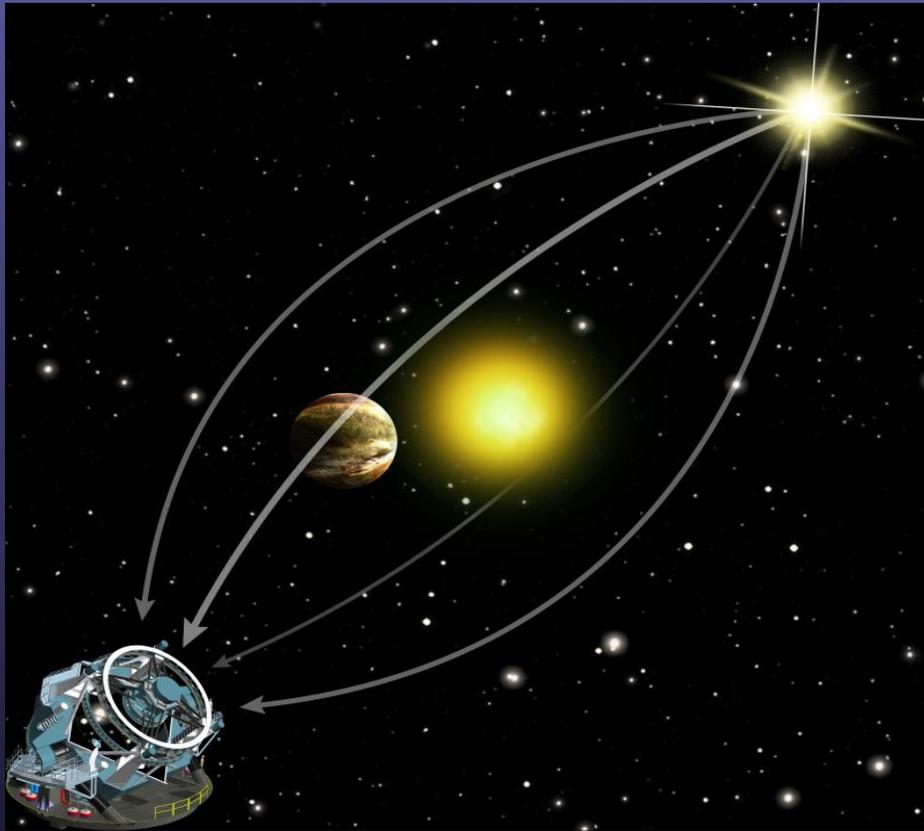


November 1, 2009 L'–band

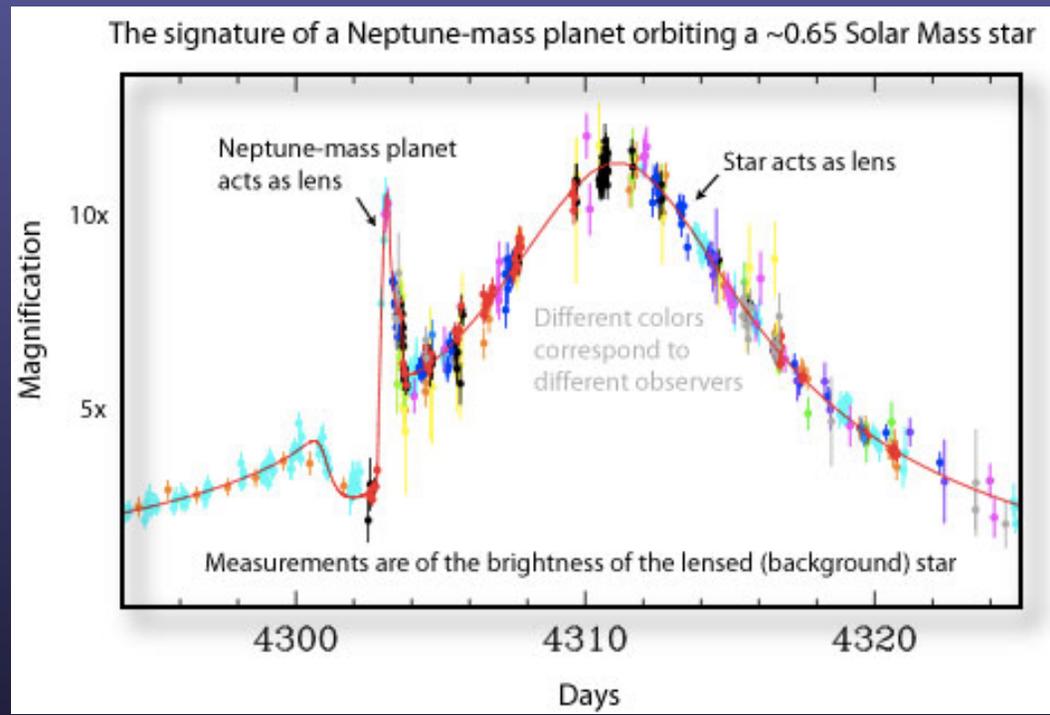
Direct imaging – example of Fomalhaut... very puzzling as planet is detected in optical (HST) *but not in the near-IR*. Is it a low mass planet with rings (lots of scattered light, little planetary emission?). Or something else?

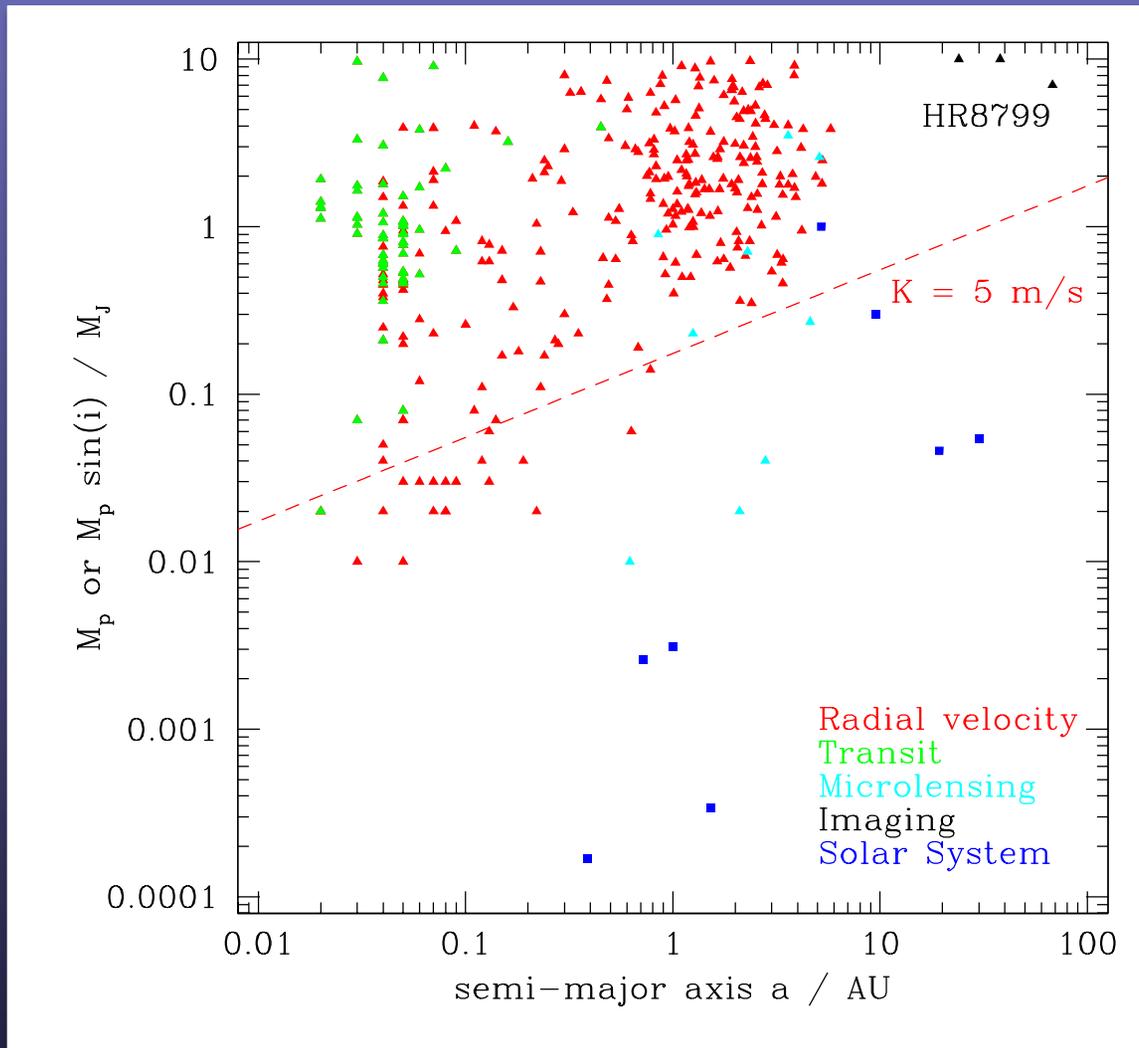


Microlensing – have not discussed this method in detail but it can also be used to find low mass planets...

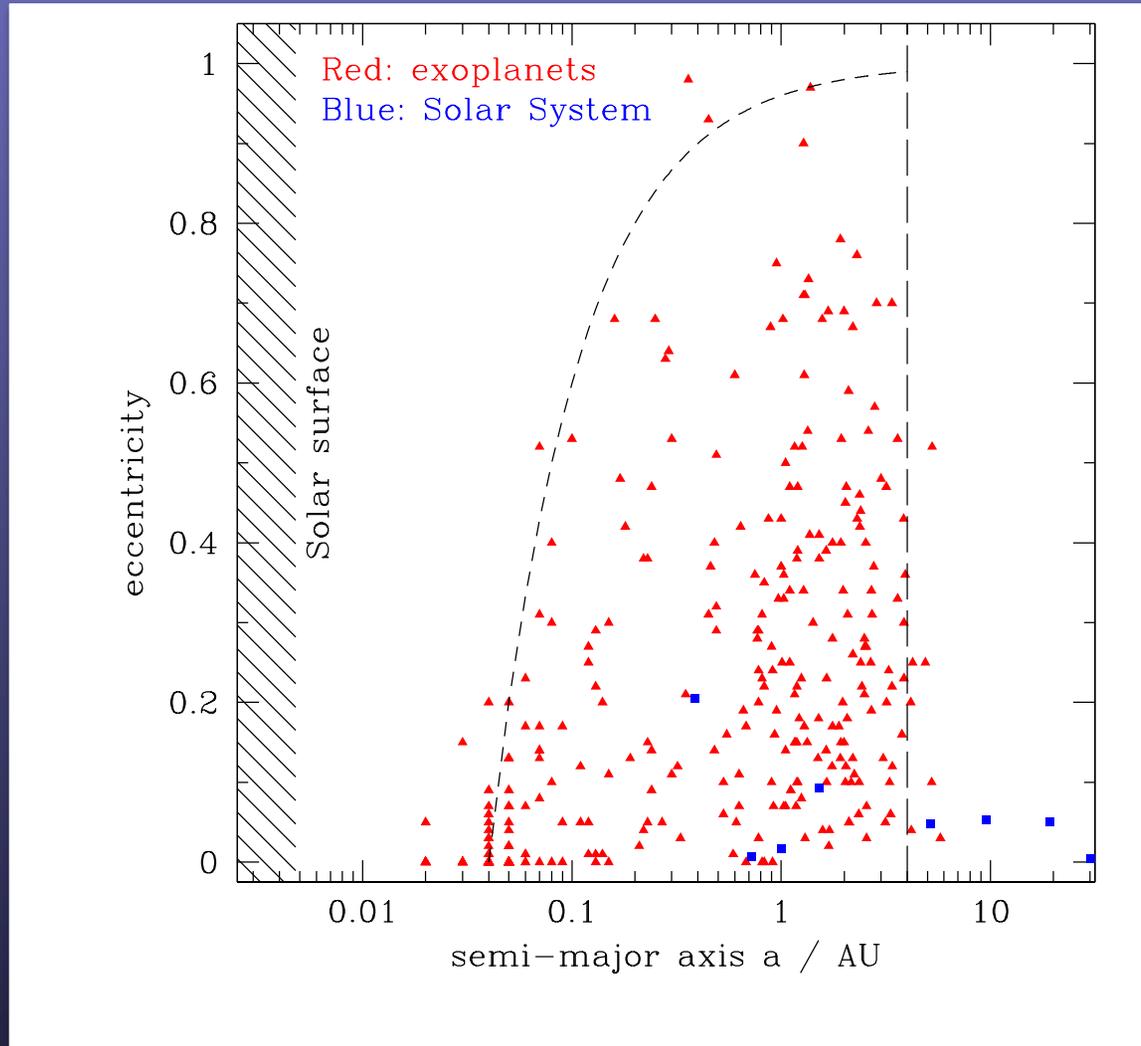


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Properties of RV (and some transit) planets in the plane of planet orbital radius vs $M_p \sin i$

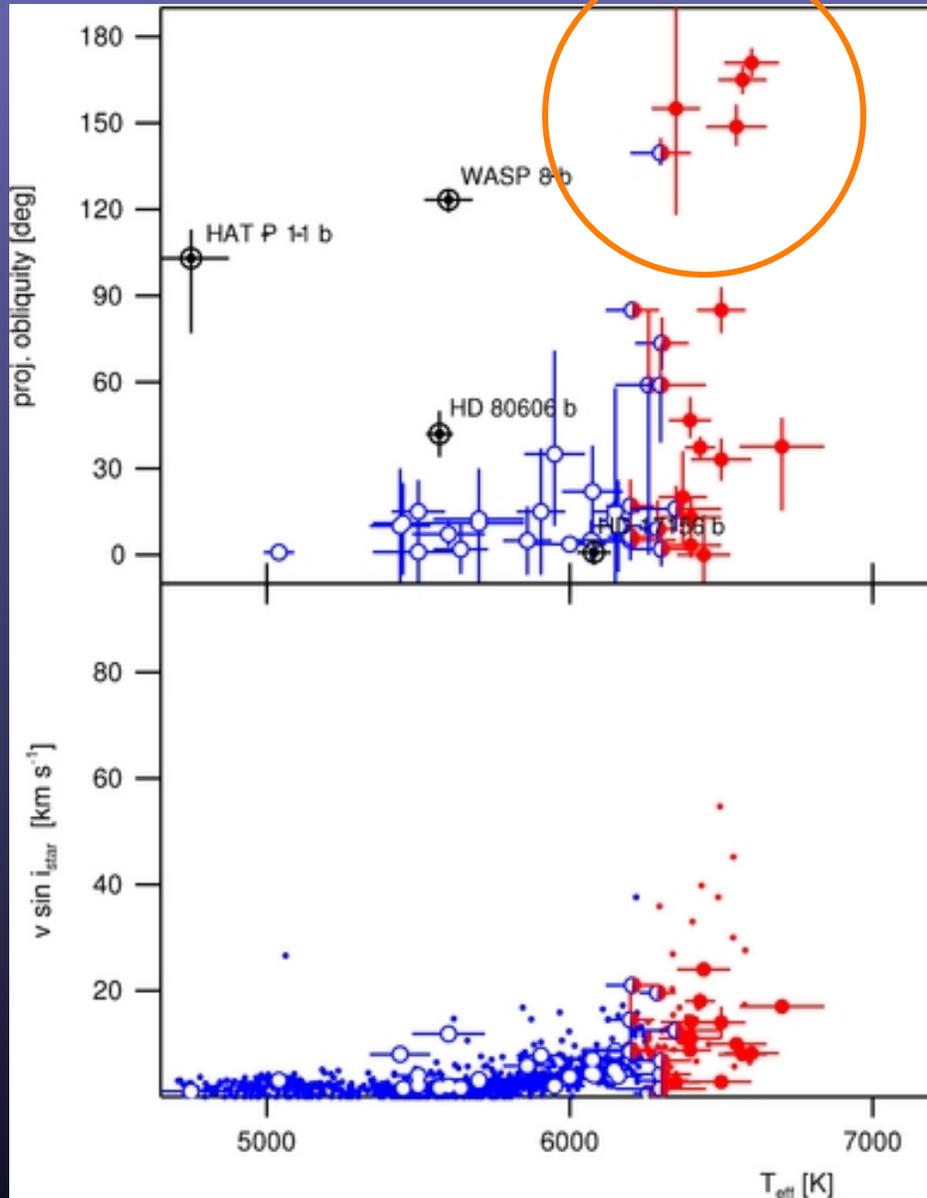


Properties of RV detected massive planets in the plane of planet orbital radius vs orbital eccentricity

Two immediately obvious differences with Solar System:

- gas giants in *very* short period orbits – “hot Jupiters”, $a < 0.1$ AU... there are no planets at all in Solar System anything like this close in
- planets further out often (not always) have quite eccentric orbits, and some are highly eccentric (only comets have such high e in the Solar System)

From RV measurements during transit... these are hot Jupiters whose orbits are “backwards” with respect to the spin of their stars!



Some hot Jupiters have substantially **inclined** orbits...

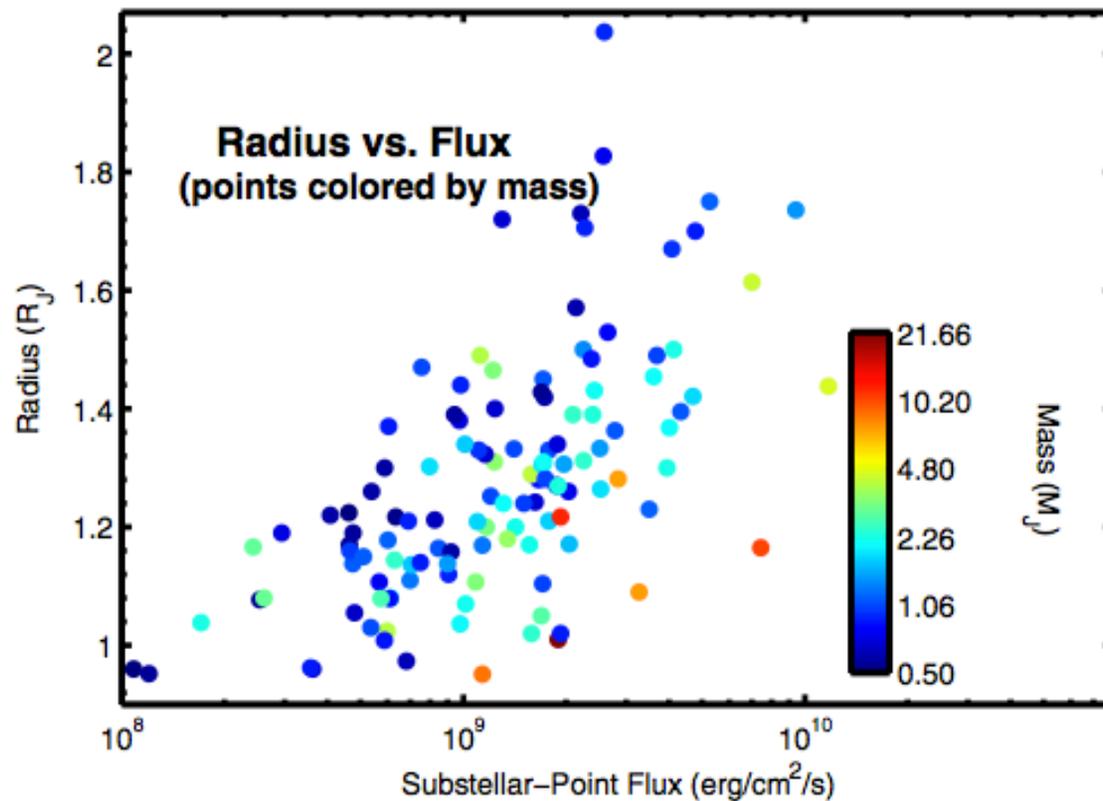


Figure 1. Radius vs. incident flux. For each transiting planet in the radius range from 0.9 to 2.07 R_J found on <http://exoplanet.eu> (circa 2013 February), we plot the planet's radius against the incident stellar flux at the substellar point; points are colored according to planet mass. The planets with the largest radii tend to be highly irradiated and low mass.

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Might think not – close in planets are strongly heated by star, and amount of inflation correlates with the strength of stellar irradiation

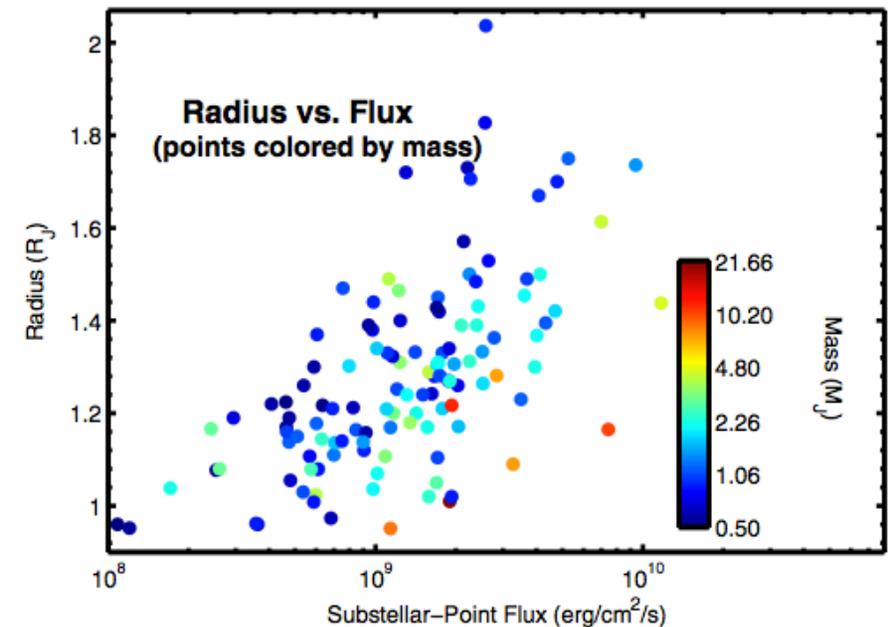


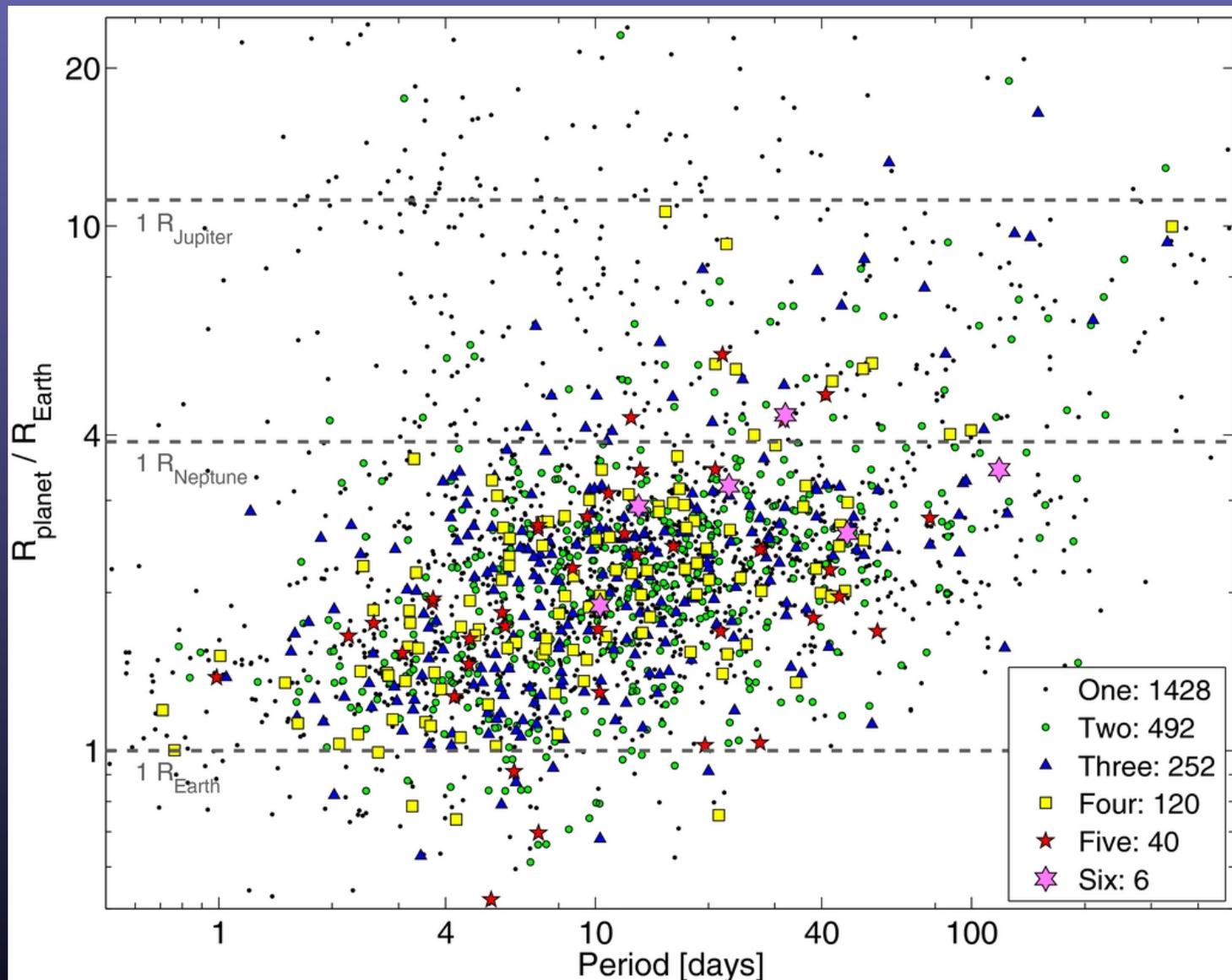
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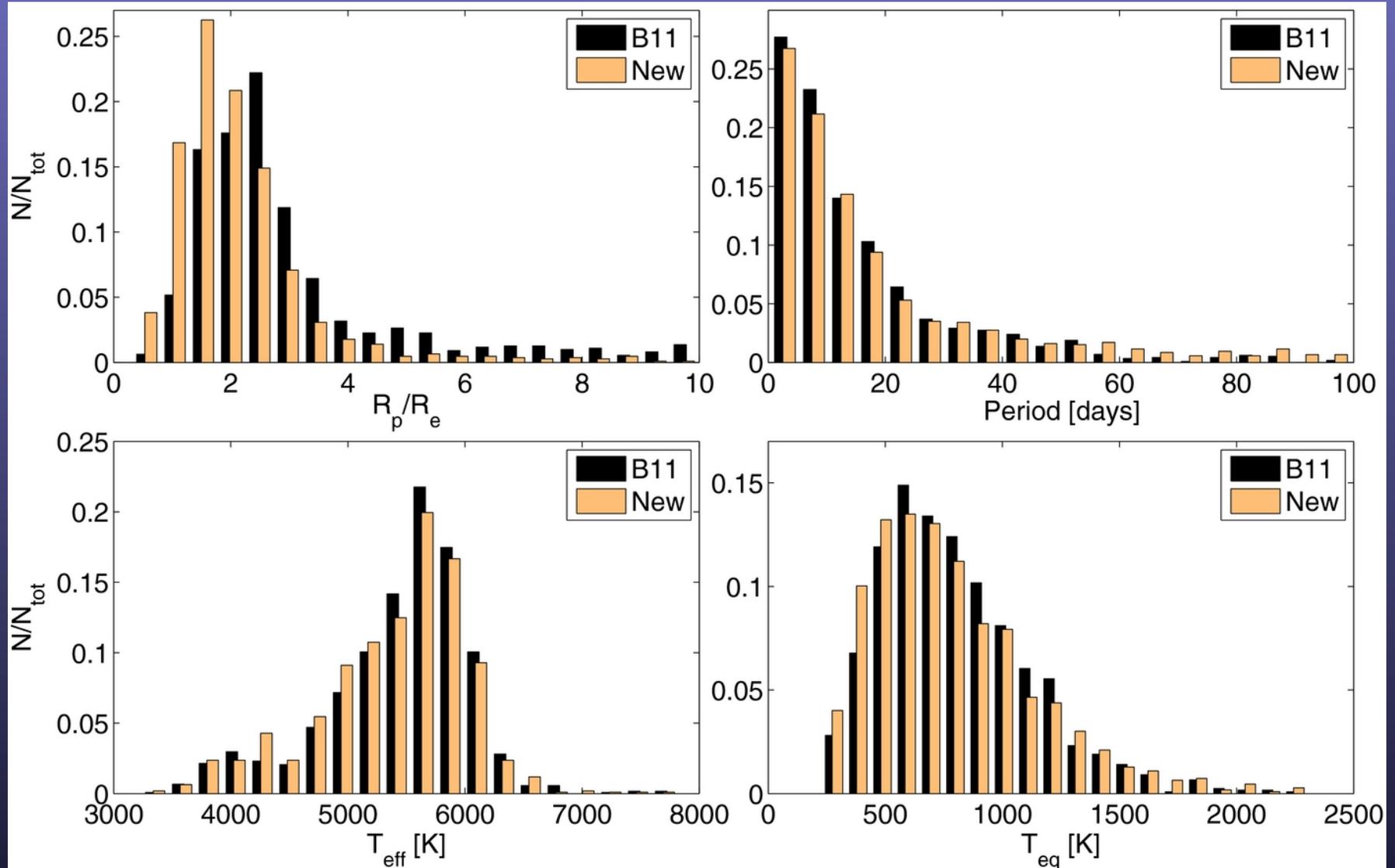
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BUT – starlight only directly heats the upper atmosphere, while radius depends on the conditions within the core... how do we get heat / energy from the surface and bury it deep within the interior?

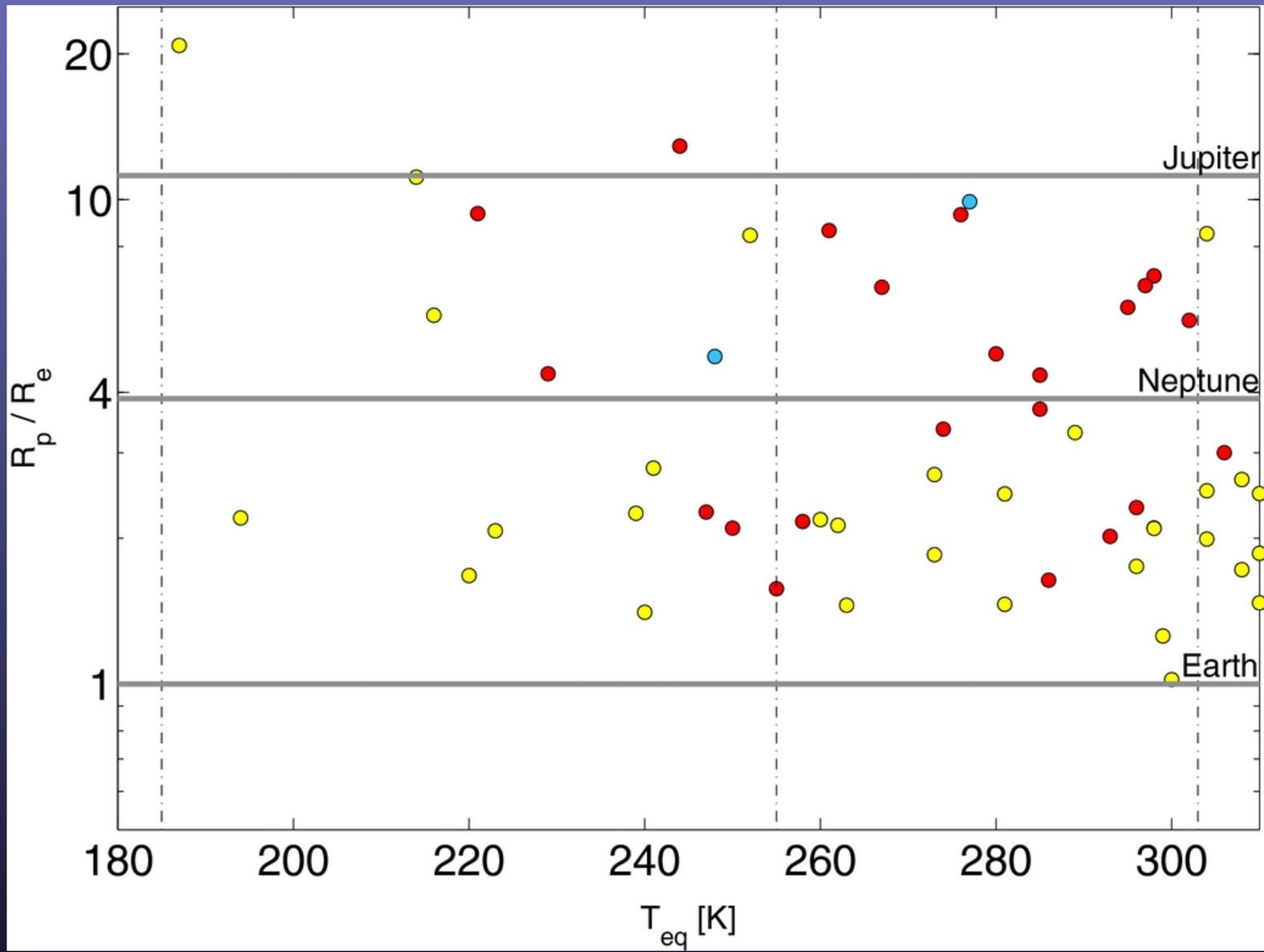
Kepler results (Batalha et al. 2013)



16 months of data, ~2300 candidates

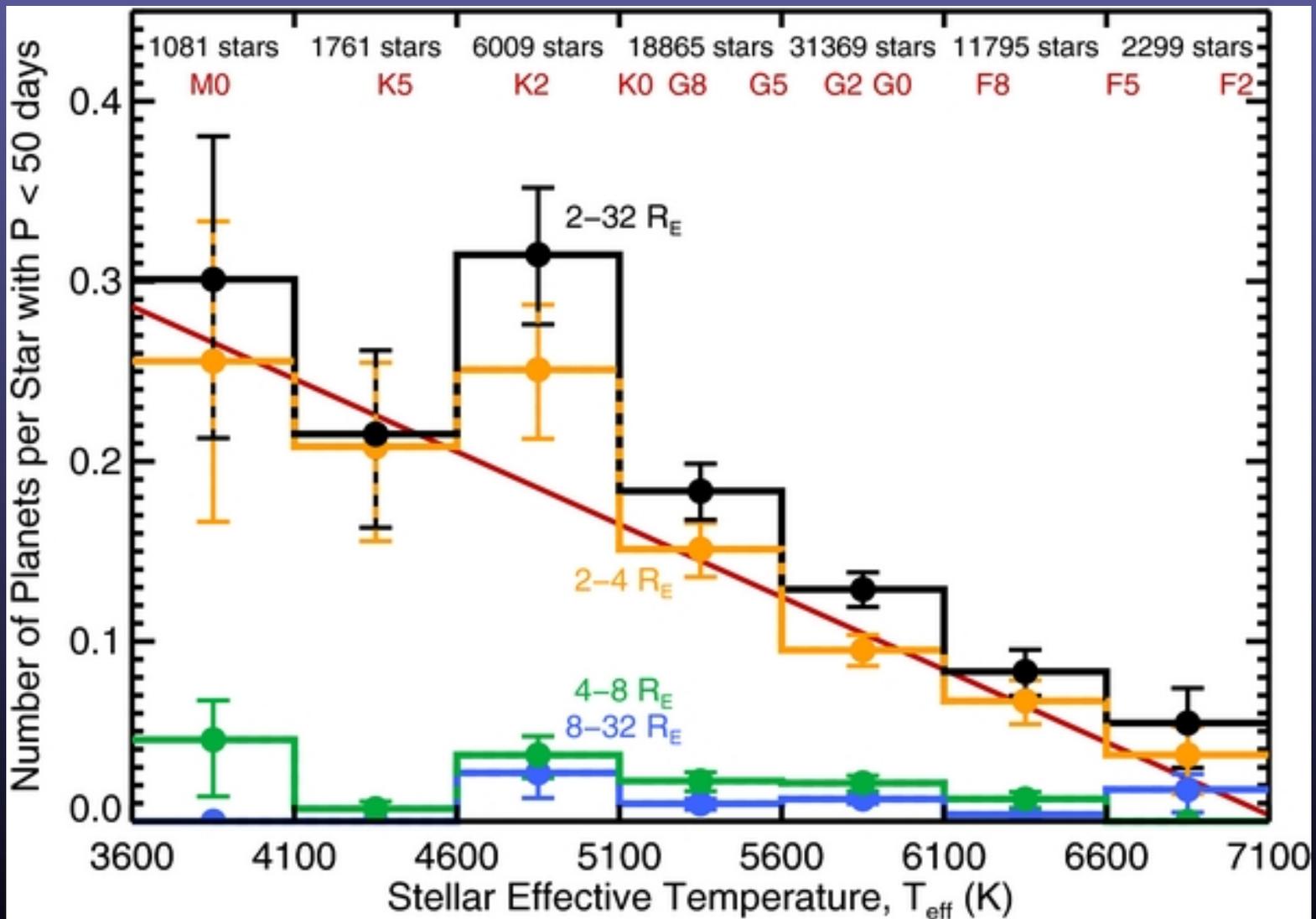


Many planets with radii intermediate between Solar System terrestrial and giant planets – what are these planets like?



Some candidates with equilibrium surface T compatible with being in the habitable zone

Amazingly high number of stars (especially slightly lower mass than the Sun) with close in planets within about 0.25 AU



High abundance (10-30%, depending on spectral type)
of detected planets within 0.25 AU

MOST of these have radii between Earth and Neptune –
no Solar System analogs

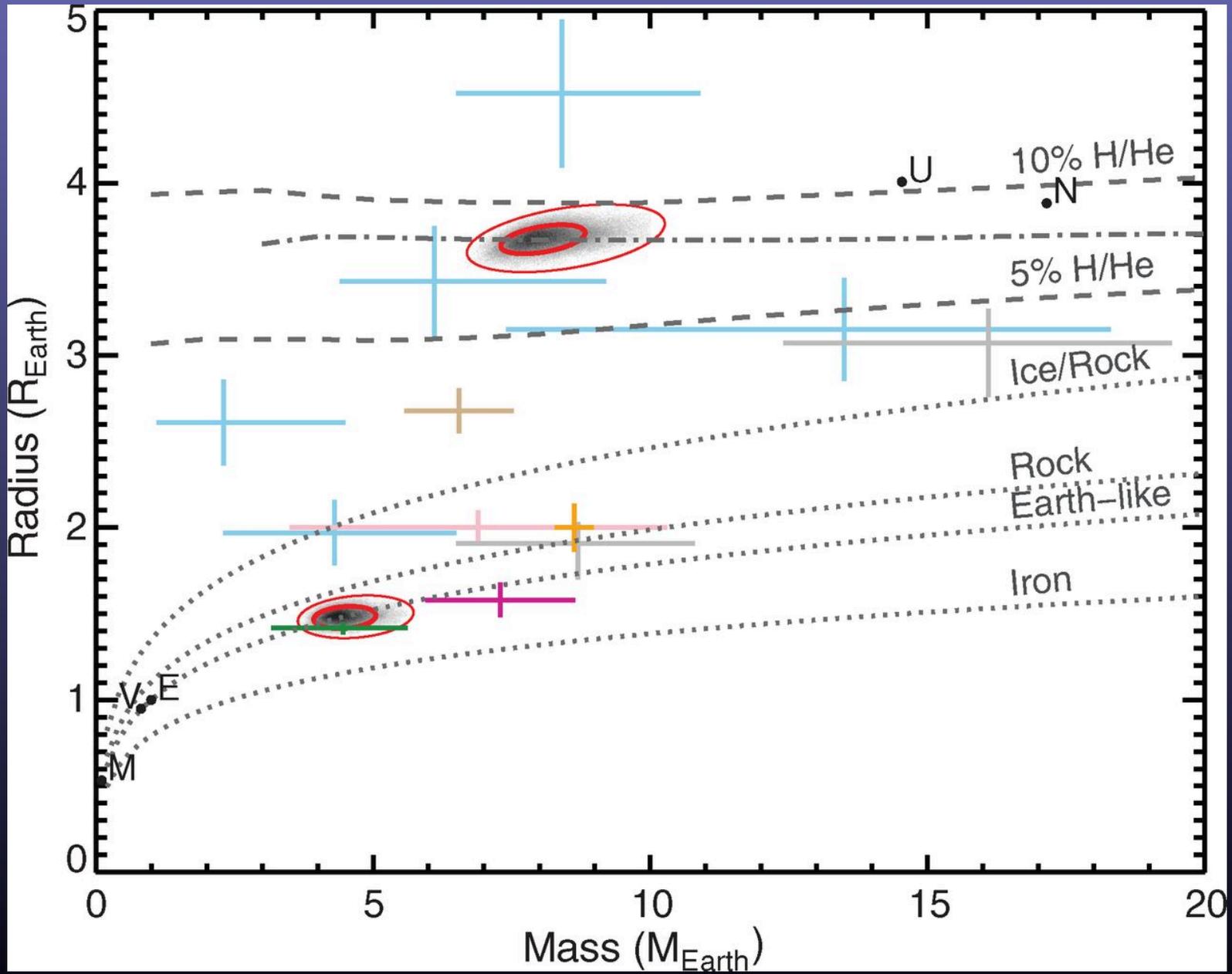
“Super-Earths” or “mini-Neptunes”

Kepler 36 (*Carter et al. 2012*)

<i>Planet b</i>	
Time of transit, T_b (BJD)	$2454960.9753^{+0.0055}_{-0.0058}$
Period, P_b (day)	$13.83989^{+0.0082}_{-0.0060}$
Orbital semimajor axis, a_b (AU)	0.1153 ± 0.0015
Mass, M_b (M_{\oplus})	$4.45^{+0.33}_{-0.27}$
Radius, R_b (R_{\oplus})	1.486 ± 0.035
Mean density, ρ_b (g cm^{-3})	$7.46^{+0.74}_{-0.59}$
Equilibrium temperature, $T_{\text{eq}, b}$ (K)	978 ± 11
<i>Planet c</i>	
Time of transit, T_c (BJD)	$2454955.9132^{+0.0011}_{-0.0010}$
Period, P_c (day)	$16.23855^{+0.0038}_{-0.0054}$
Orbital semimajor axis, a_c (AU)	0.1283 ± 0.0016
Mass, M_c (M_{\oplus})	$8.08^{+0.60}_{-0.46}$
Radius, R_c (R_{\oplus})	3.679 ± 0.054
Mean density, ρ_c (g cm^{-3})	$0.89^{+0.07}_{-0.05}$
Equilibrium temperature, $T_{\text{eq}, c}$ (K)	928 ± 10

Compositional diversity in multiple systems, even when the planets are very closely spaced...

Kepler 36 (Carter et al. 2012)



Kepler systems appear to be a new population of planetary system... how did they form?