The Atmospheres of Neptune “Analogs”, Super-Earths and Earth-like Exoplanets:

What We Know and Future Prospects

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UCSB/Las Cumbres Observatory Global Telescope (LCOGT)

EVOPLANETS15 Discussion Session

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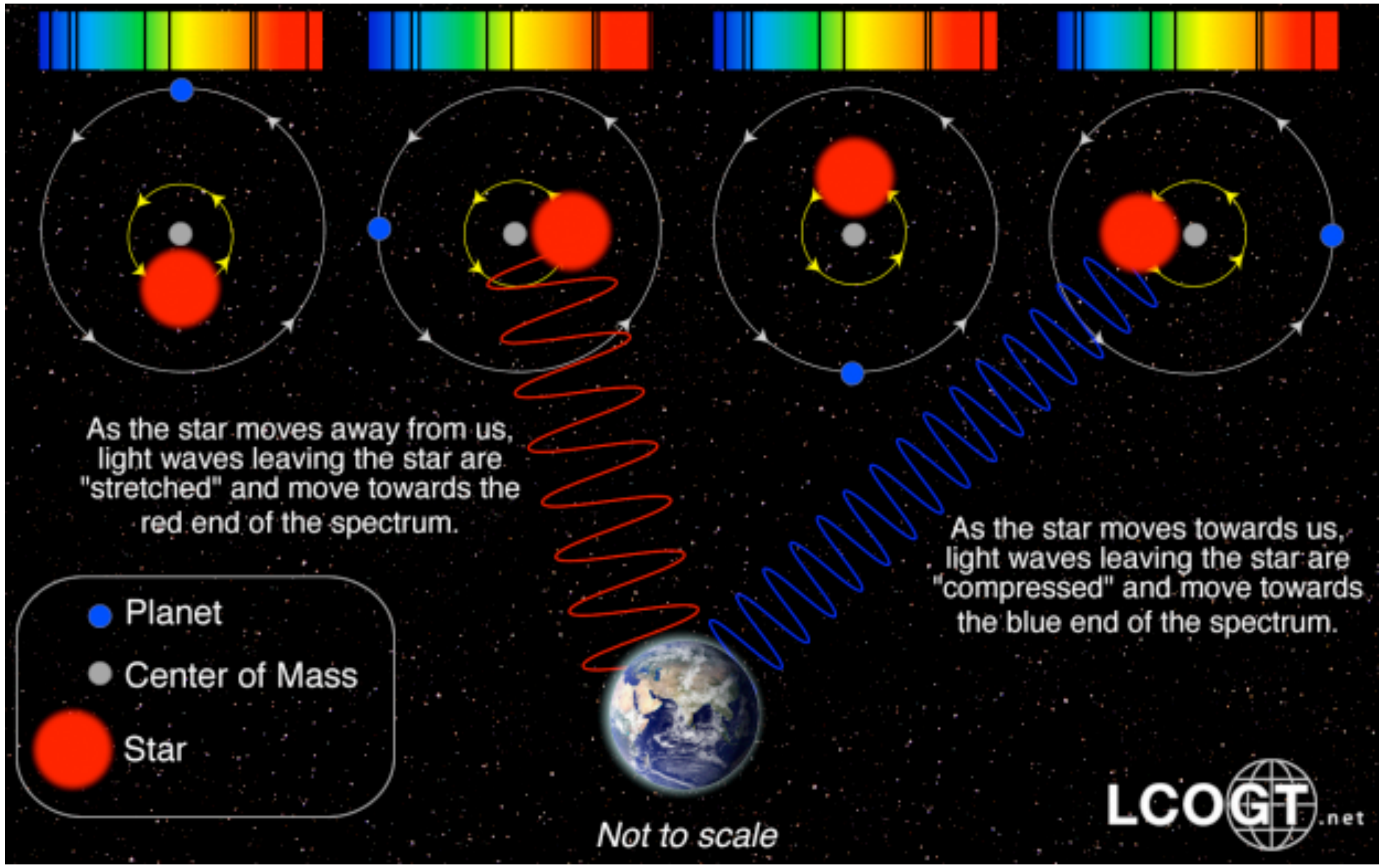
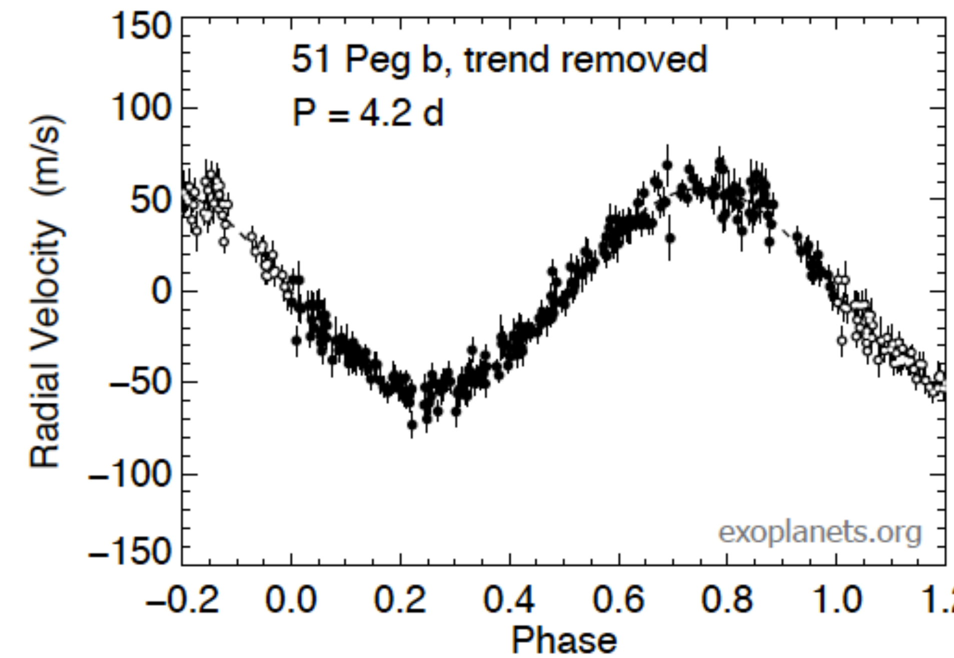
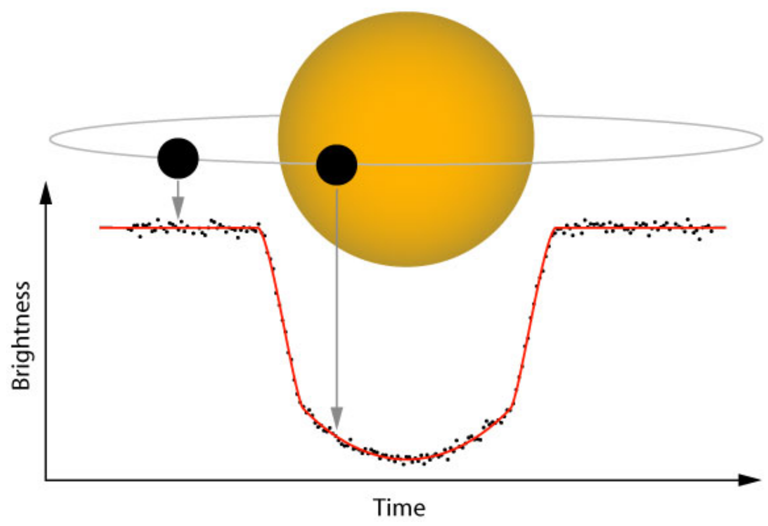
Measuring Exoplanet Masses: Radial Velocity

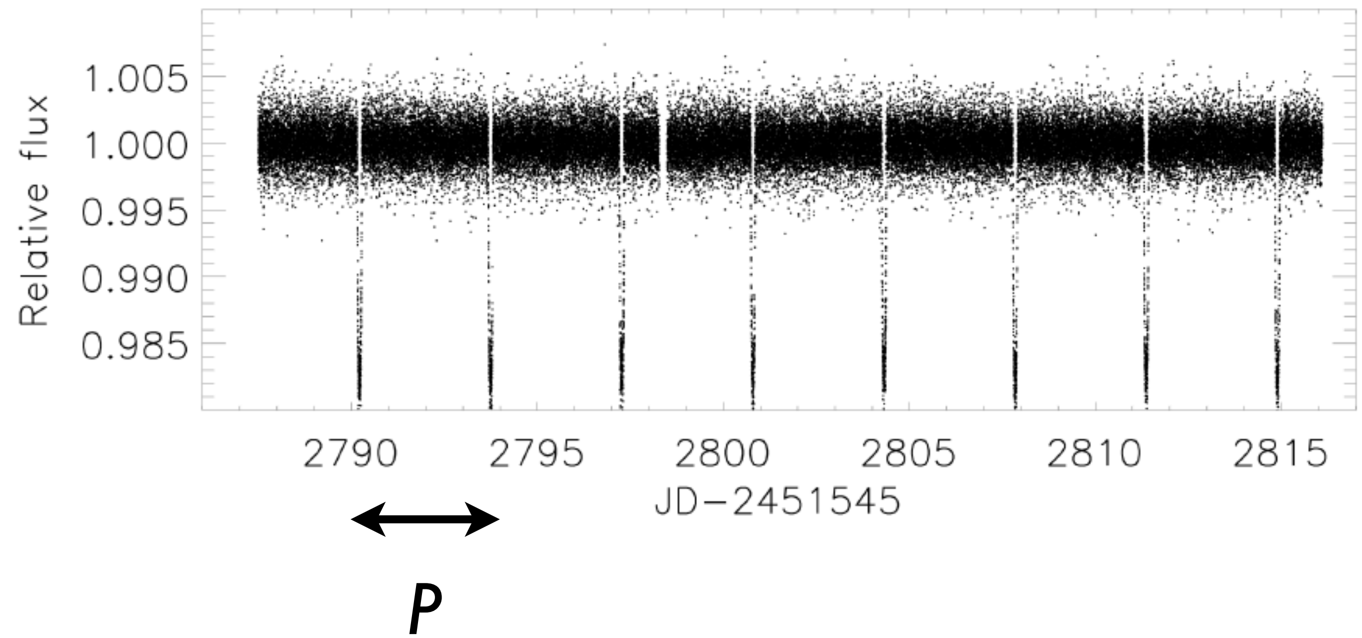


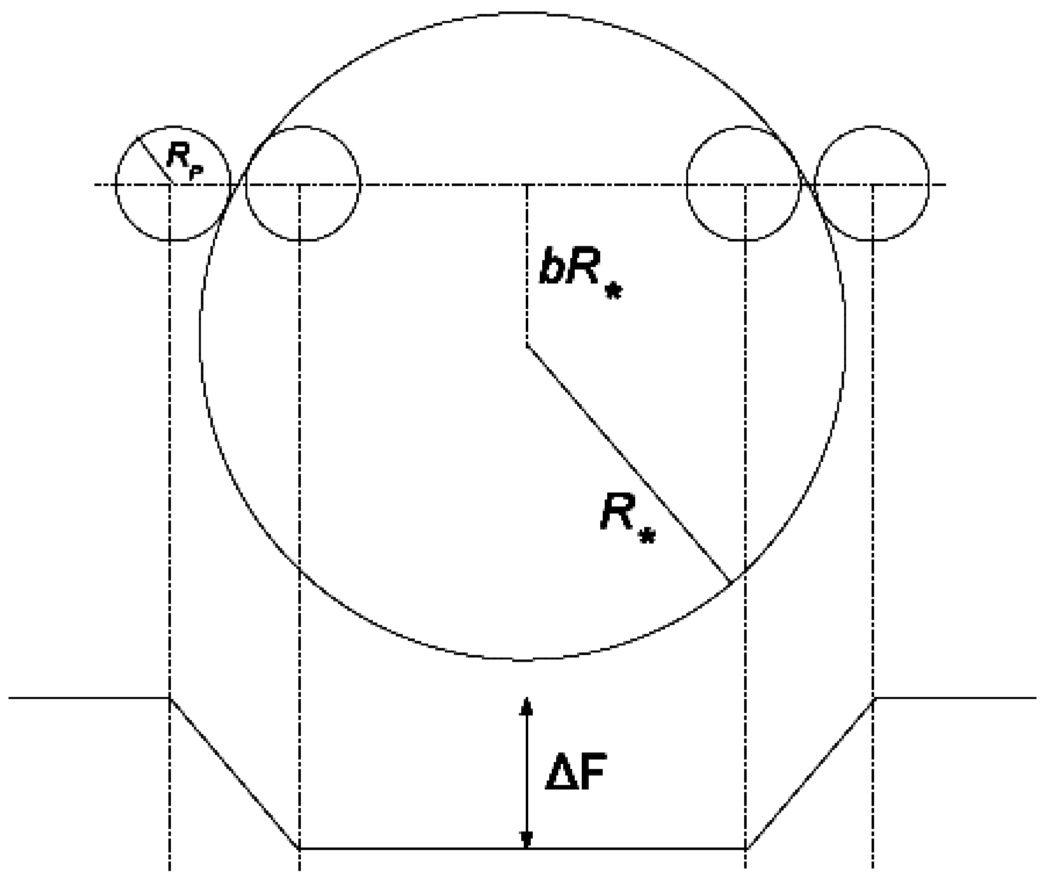


Radial velocity curve provides the ***orbital elements*** and ***minimum mass (*** $M_P \sin i$ ***)*** of the exoplanet (from the stellar velocity component along the line of sight).

Measuring Exoplanet Sizes: Transits







$$\Delta F = (R_P/R_S)^2$$

R_P = planetary radius

R_S = stellar radius

The transit duration determines the **orbital inclination** and **the semi-major axis to stellar radius ratio**.

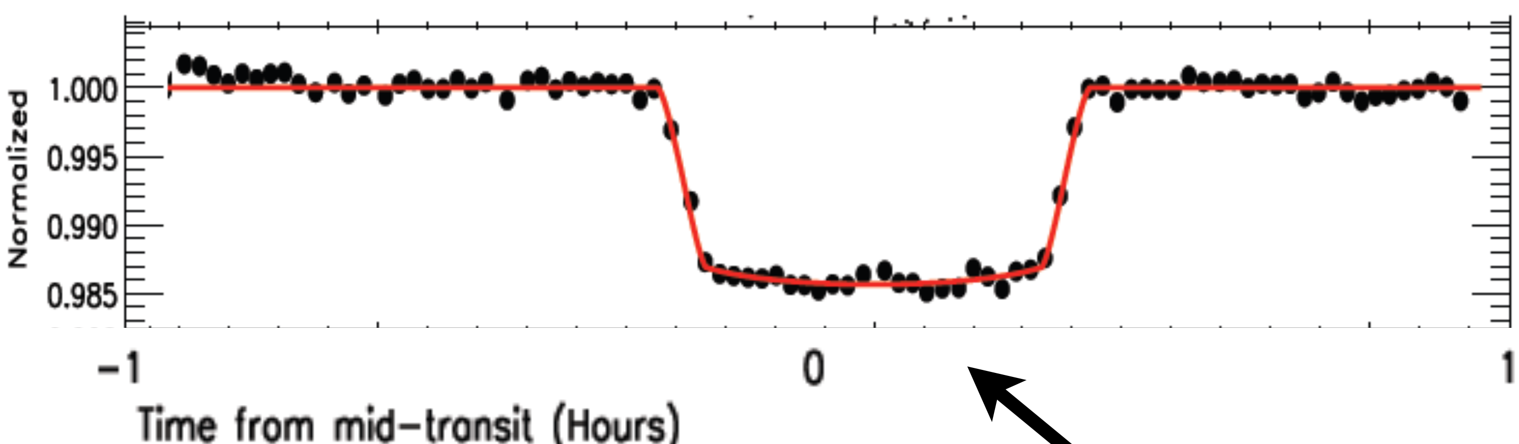
How to Find the Small Exoplanets That Are Best for Follow-up Observations

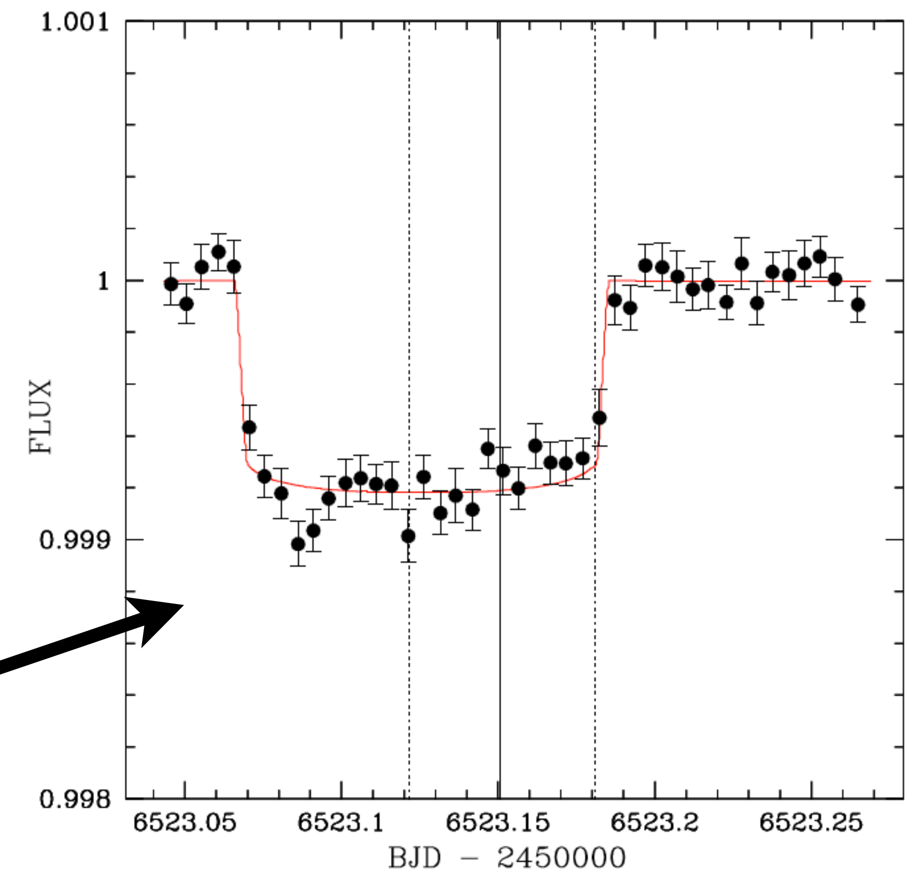
Searching for planets transiting small stars (M dwarfs)

Example: GJ 1214b, a 2.7 R_{Earth} planet orbiting a M5 dwarf.
Exhibits ~1.5 % transits.

Searching for planets transiting bright (nearby) stars

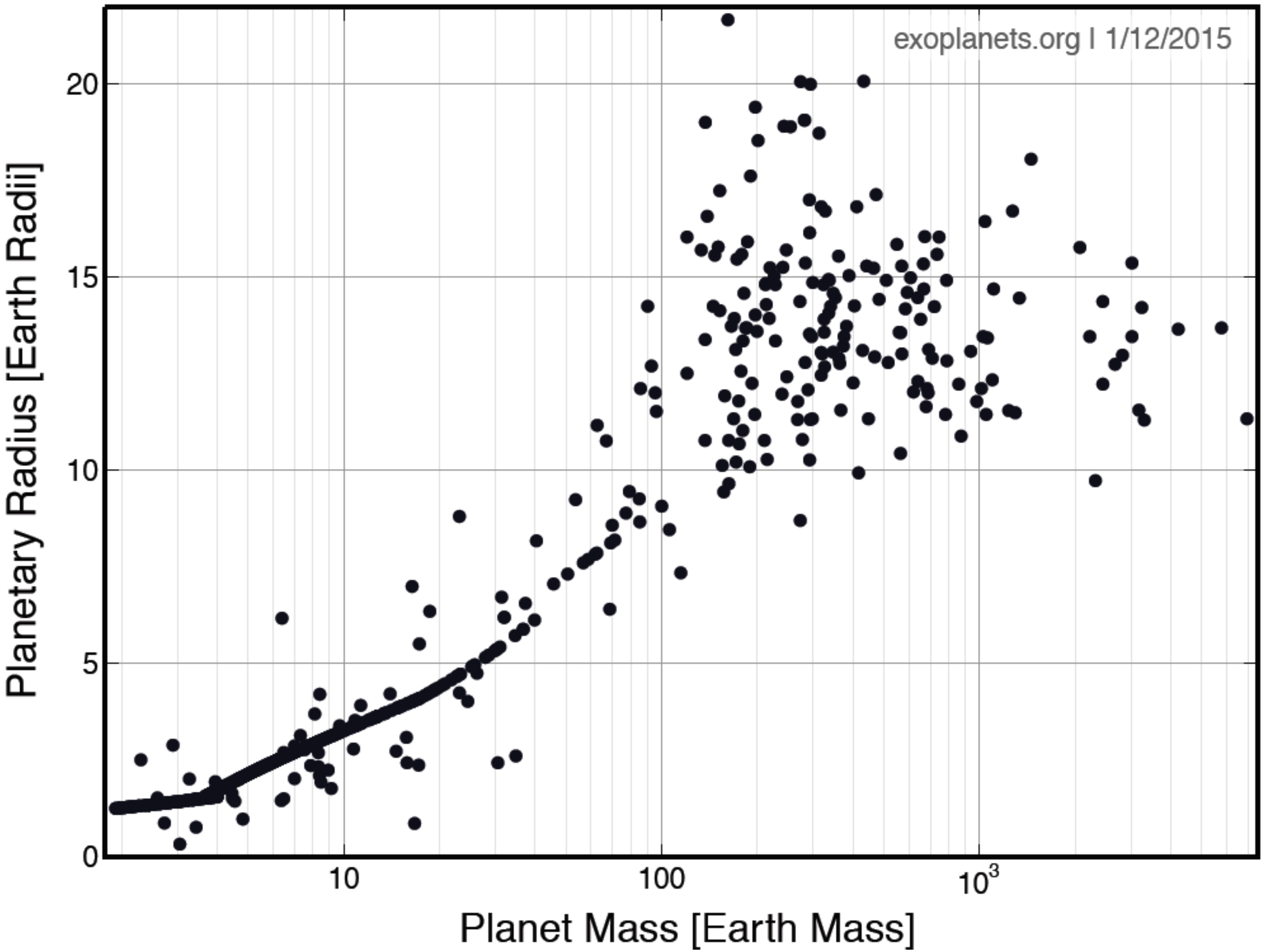
Example: HD 97658b, a 2.3 R_{Earth} planet orbiting a K1 dwarf.
Exhibits ~0.1% transits.



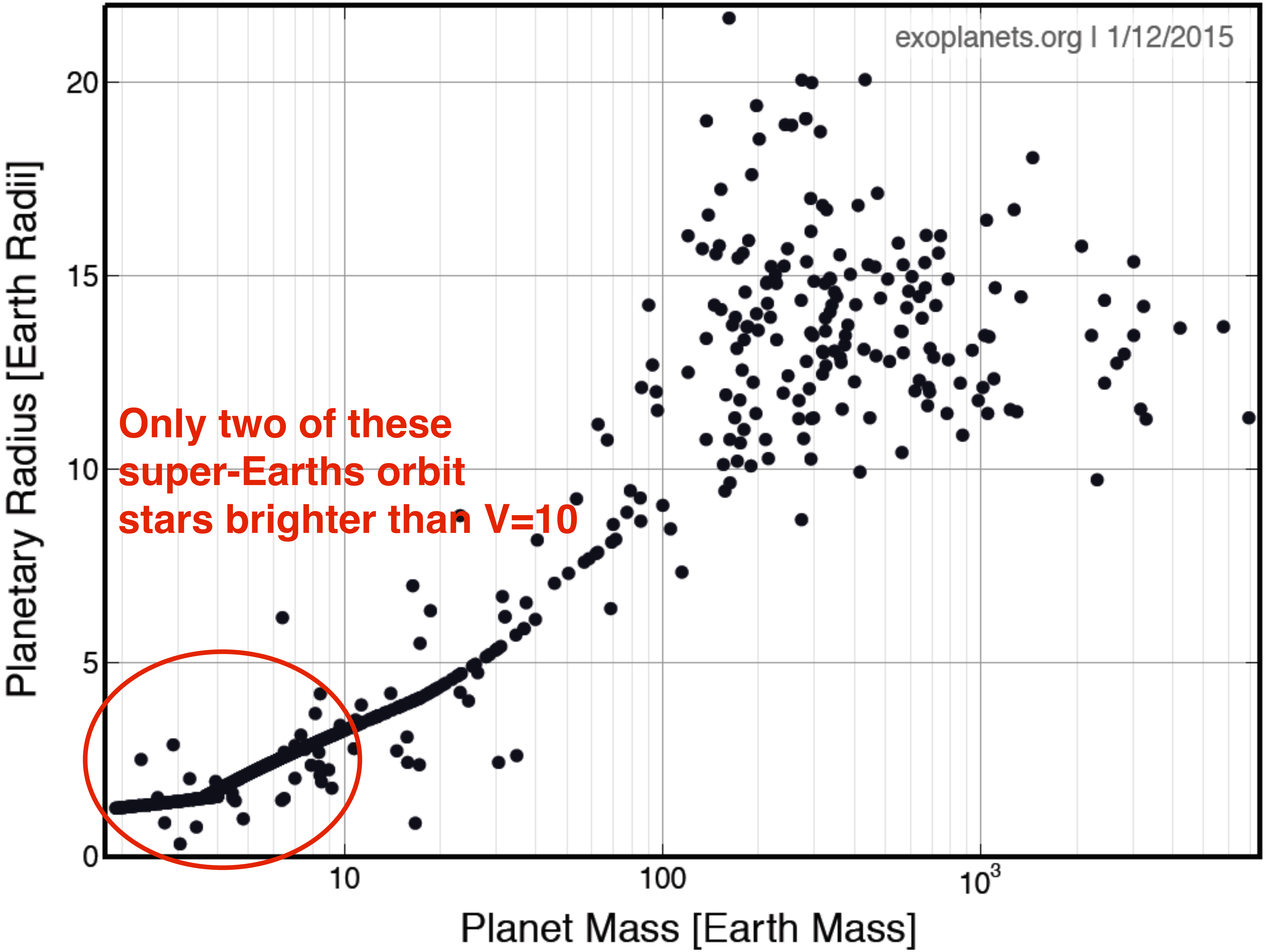


Spitzer

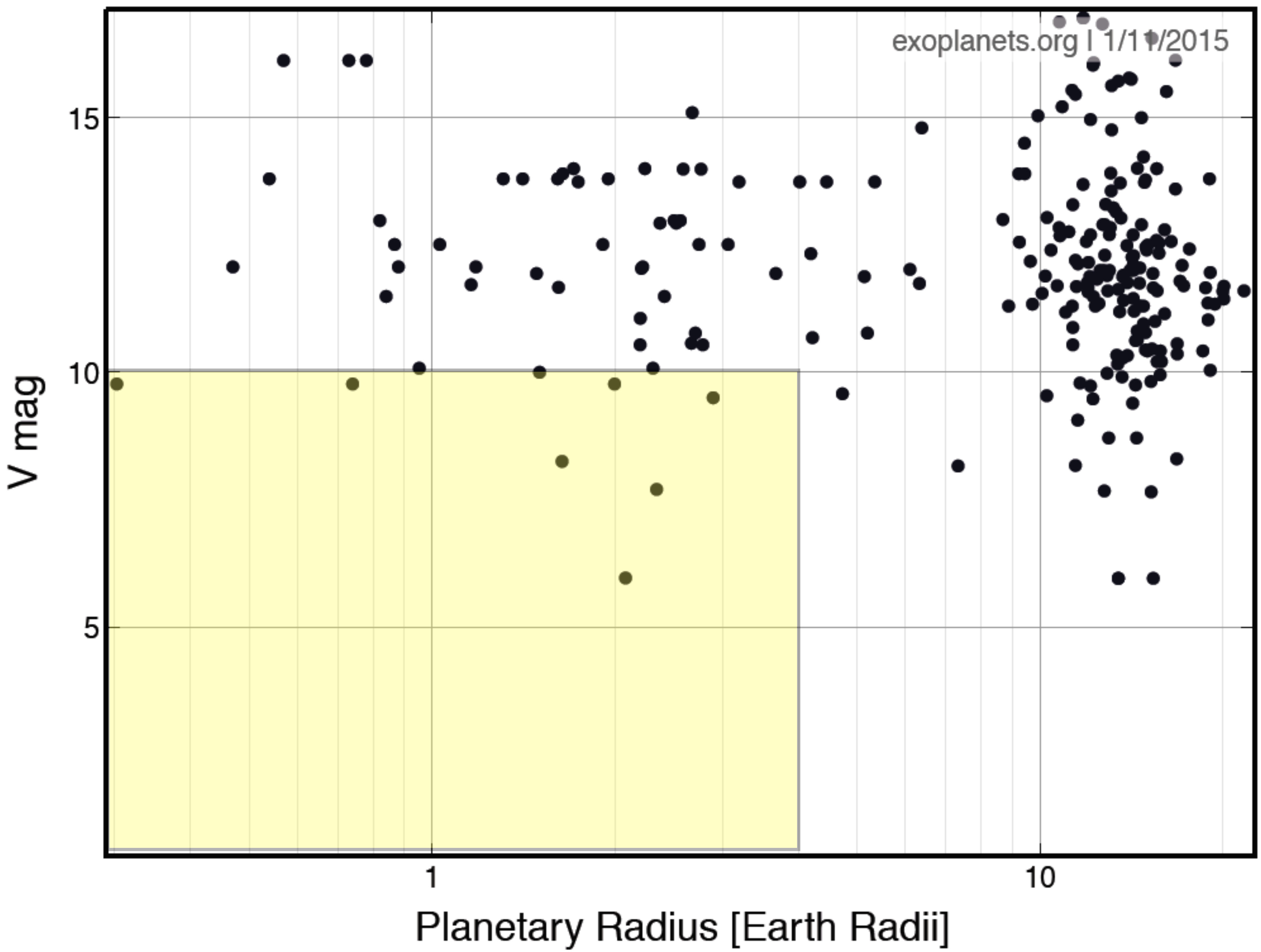
Known transiting exoplanets



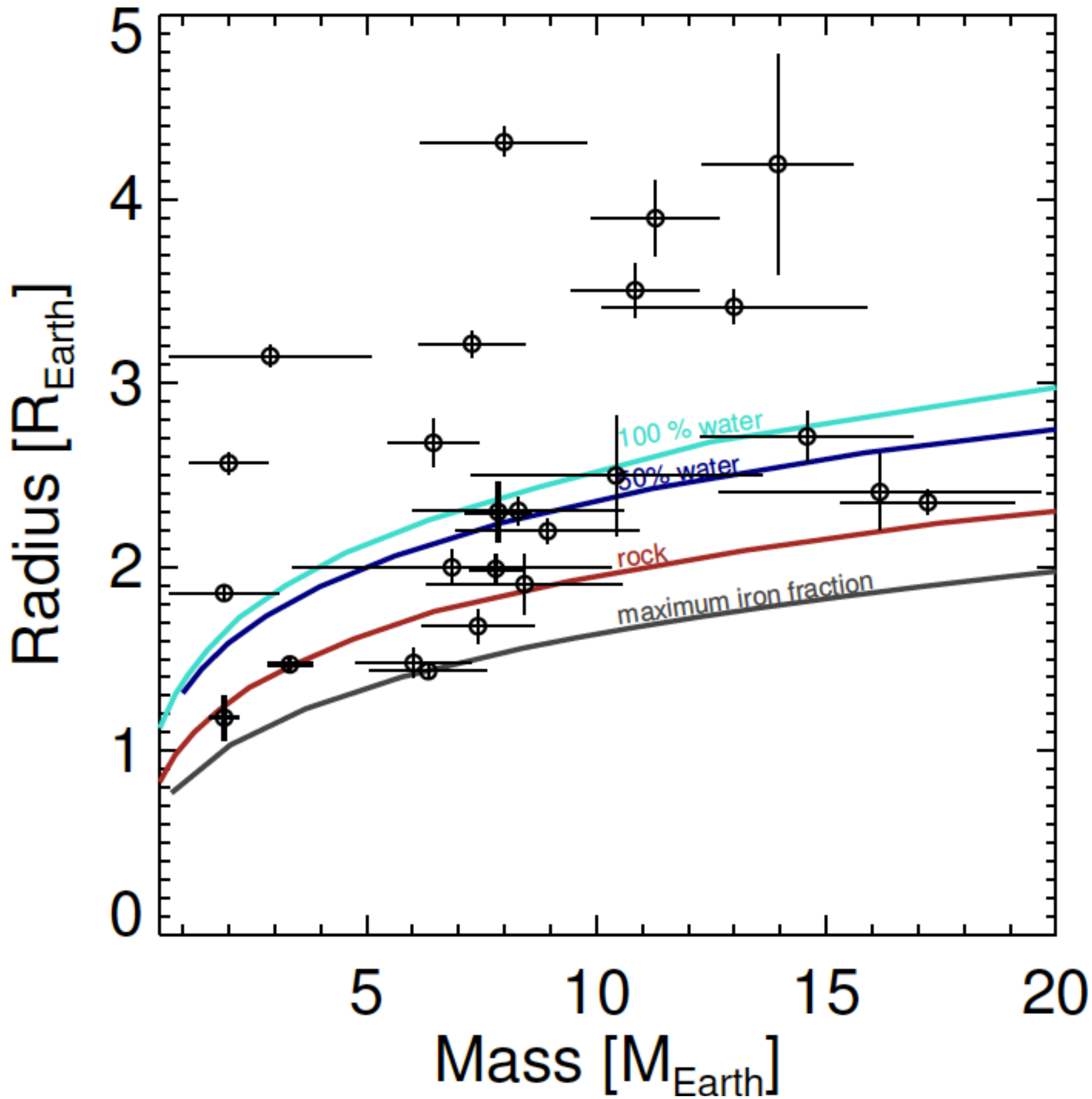
Known transiting exoplanets



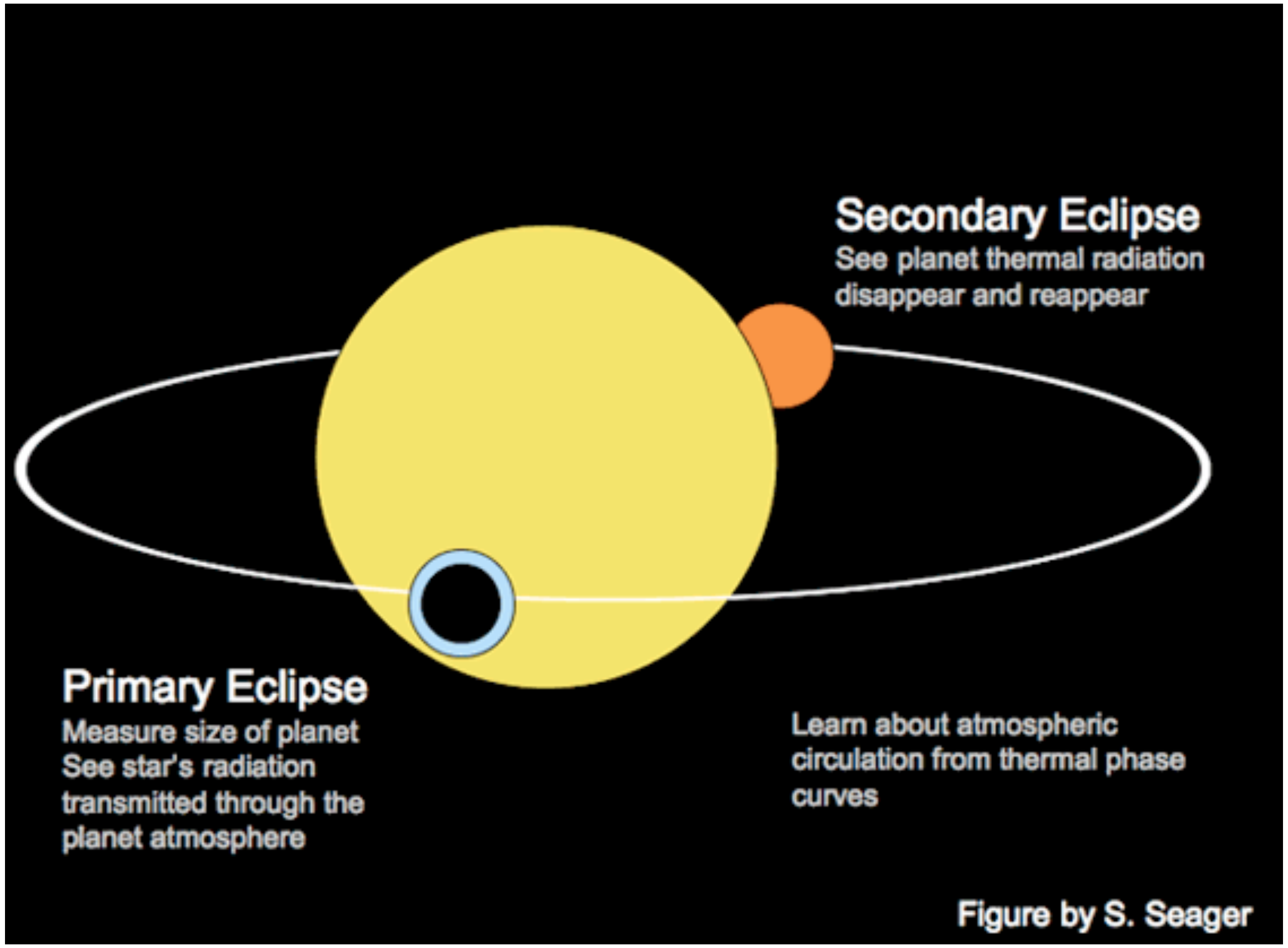
Known transiting exoplanets

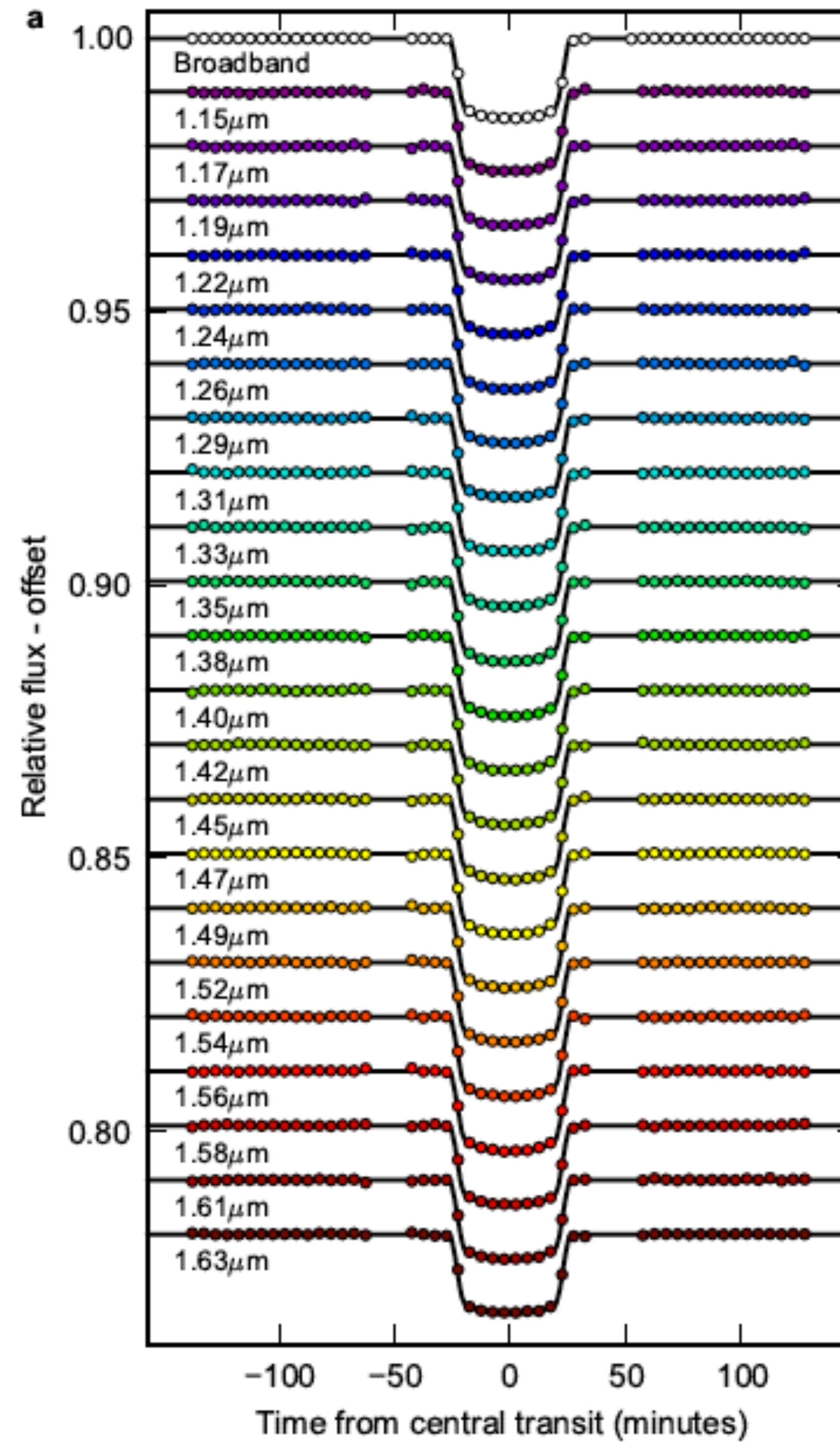


Density ≠ Composition



Transmission spectroscopy





For small planets, we have to go to space (currently Hubble Space Telescope, Spitzer Space Telescope).

Transmission spectroscopy

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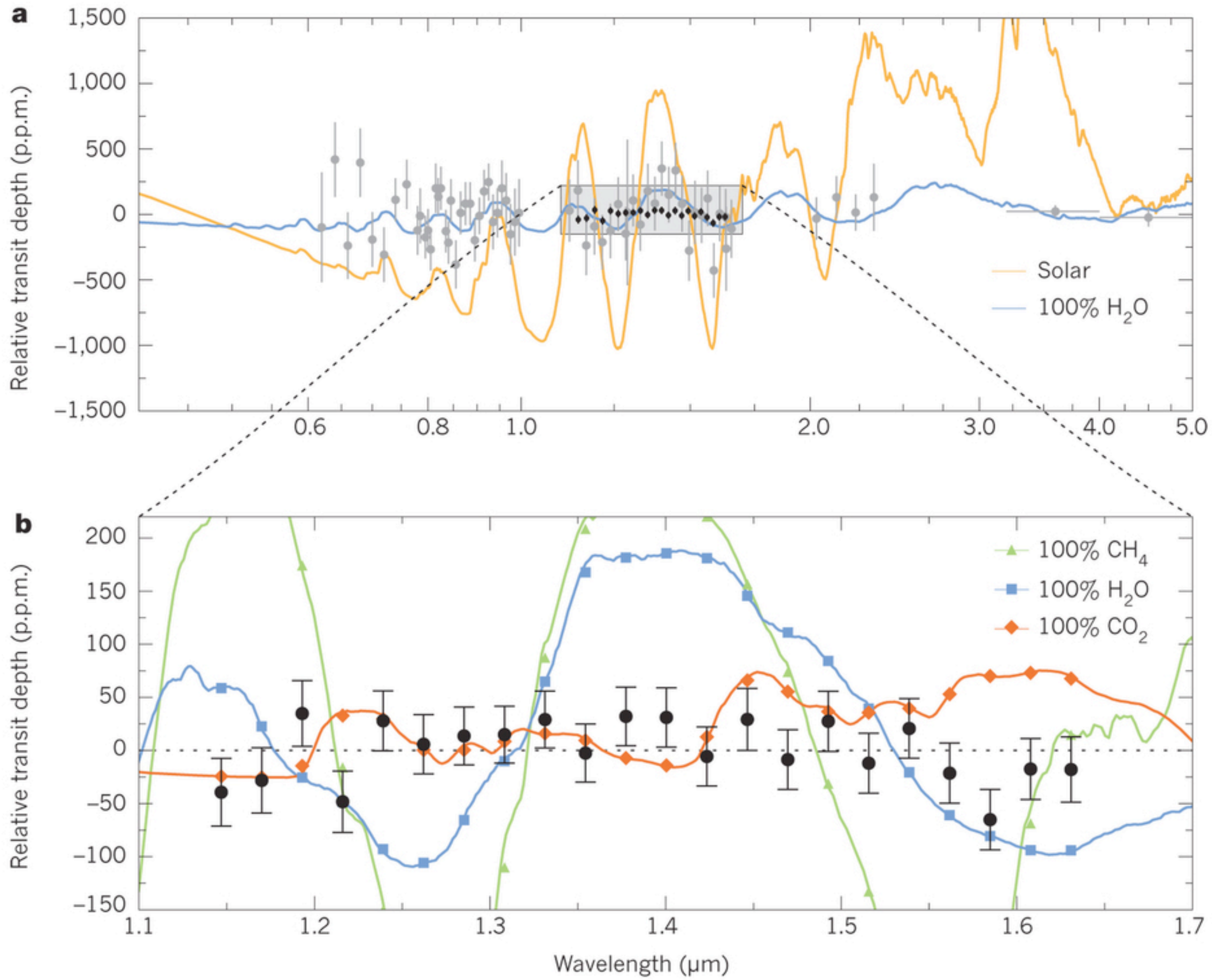


Example HST WFC3 transmission spectrum

A low scale-height water atmosphere suggests formation near or beyond the ice line

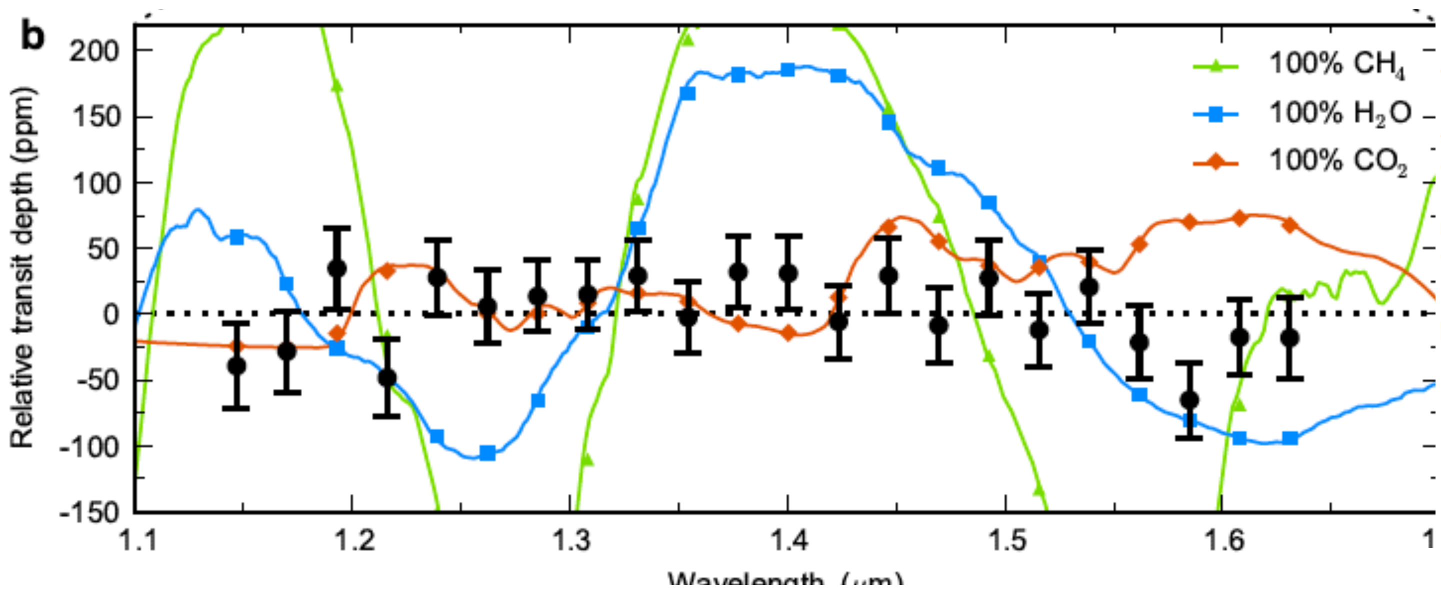
Probing the C/O ratio can constrain properties of the protoplanetary disk, and planet birthplace

For small planets, we have to go to space (currently Hubble Space Telescope, Spitzer Space Telescope).

Small exoplanets mostly show flat spectra in the IR...

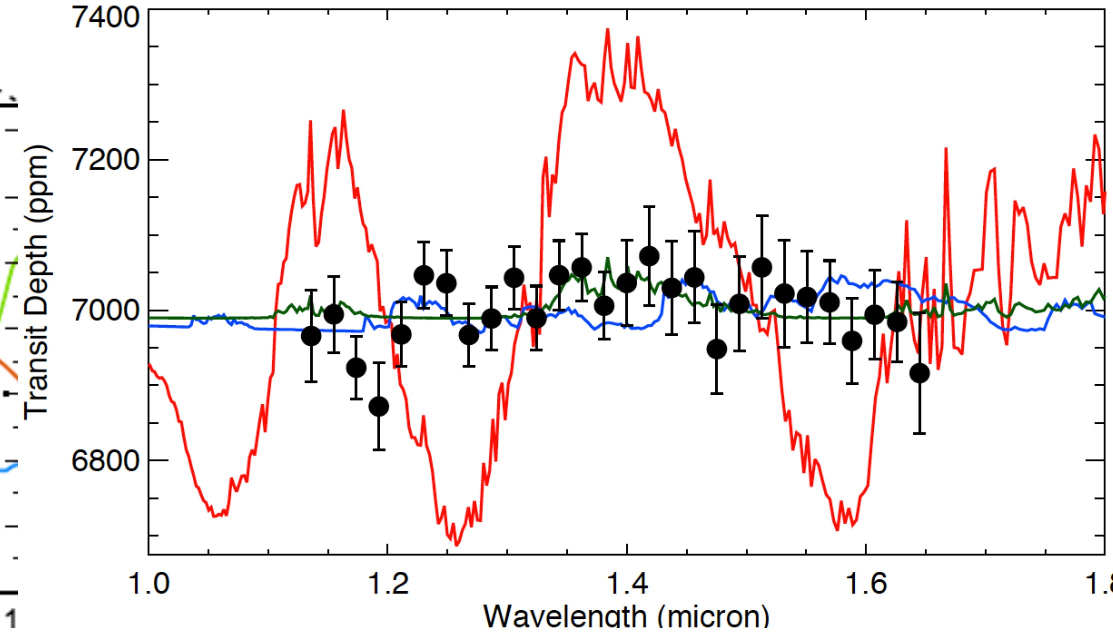
Kreidberg et al. (2014)

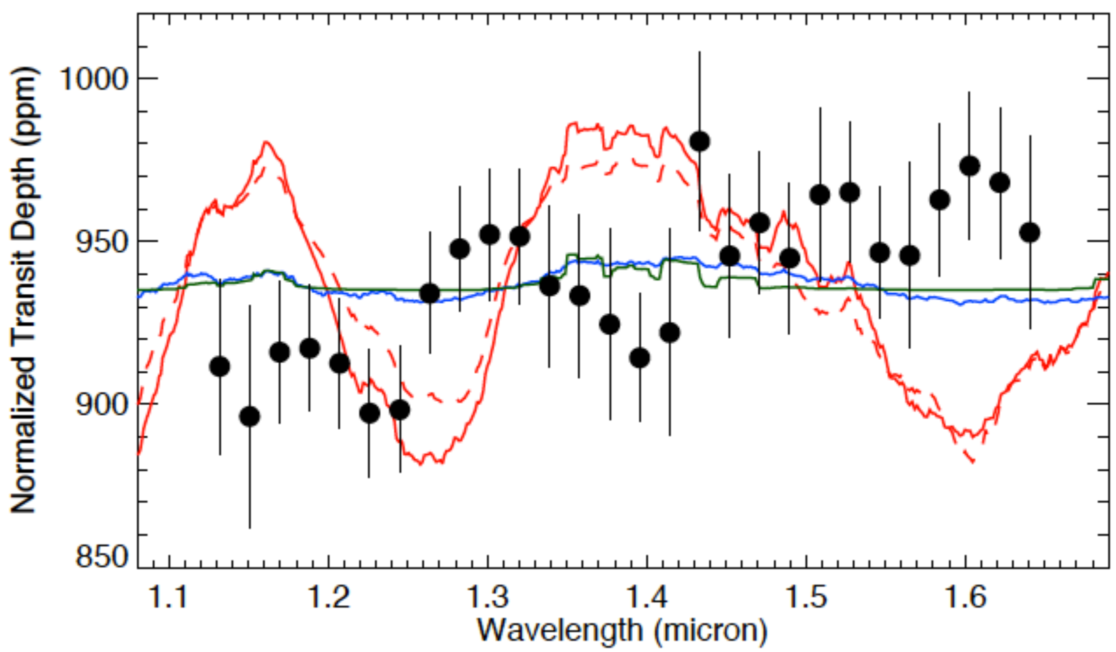
GJ 1214b ("cool" super-Earth)



Knutson et al. (2014)

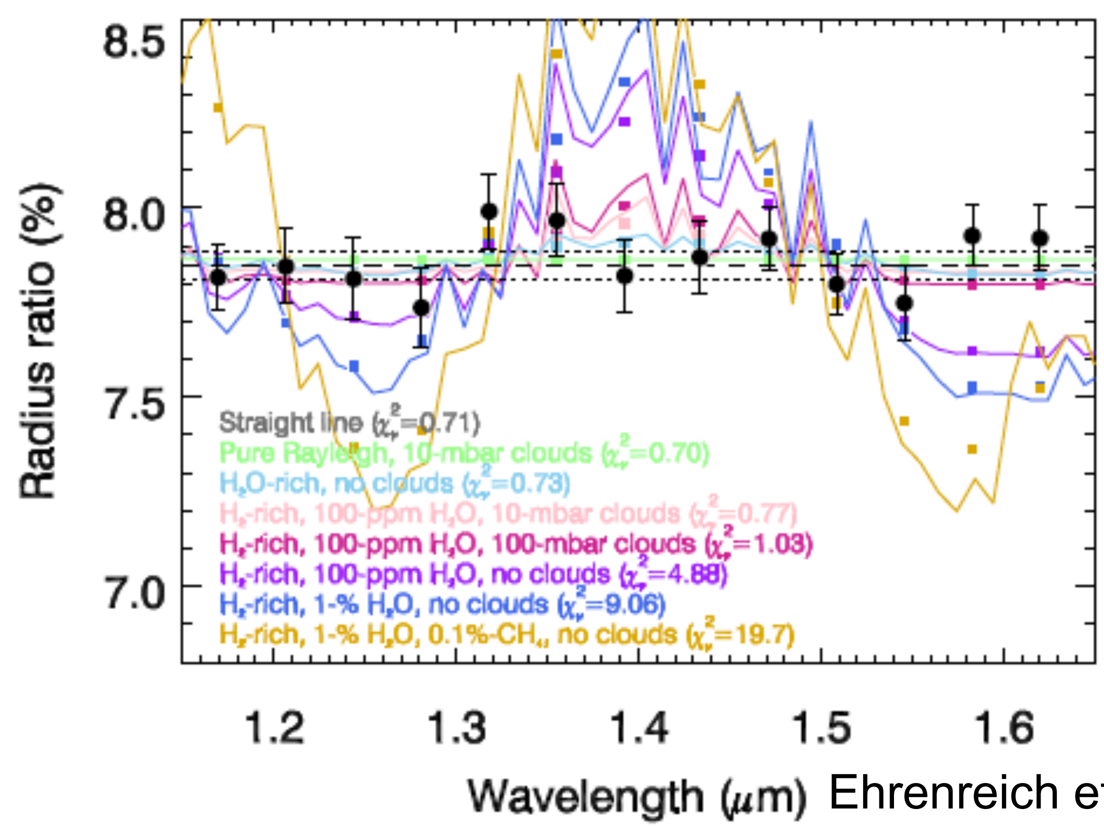
GJ 436b (warm Neptune-size)





Knutson et al. (2014)

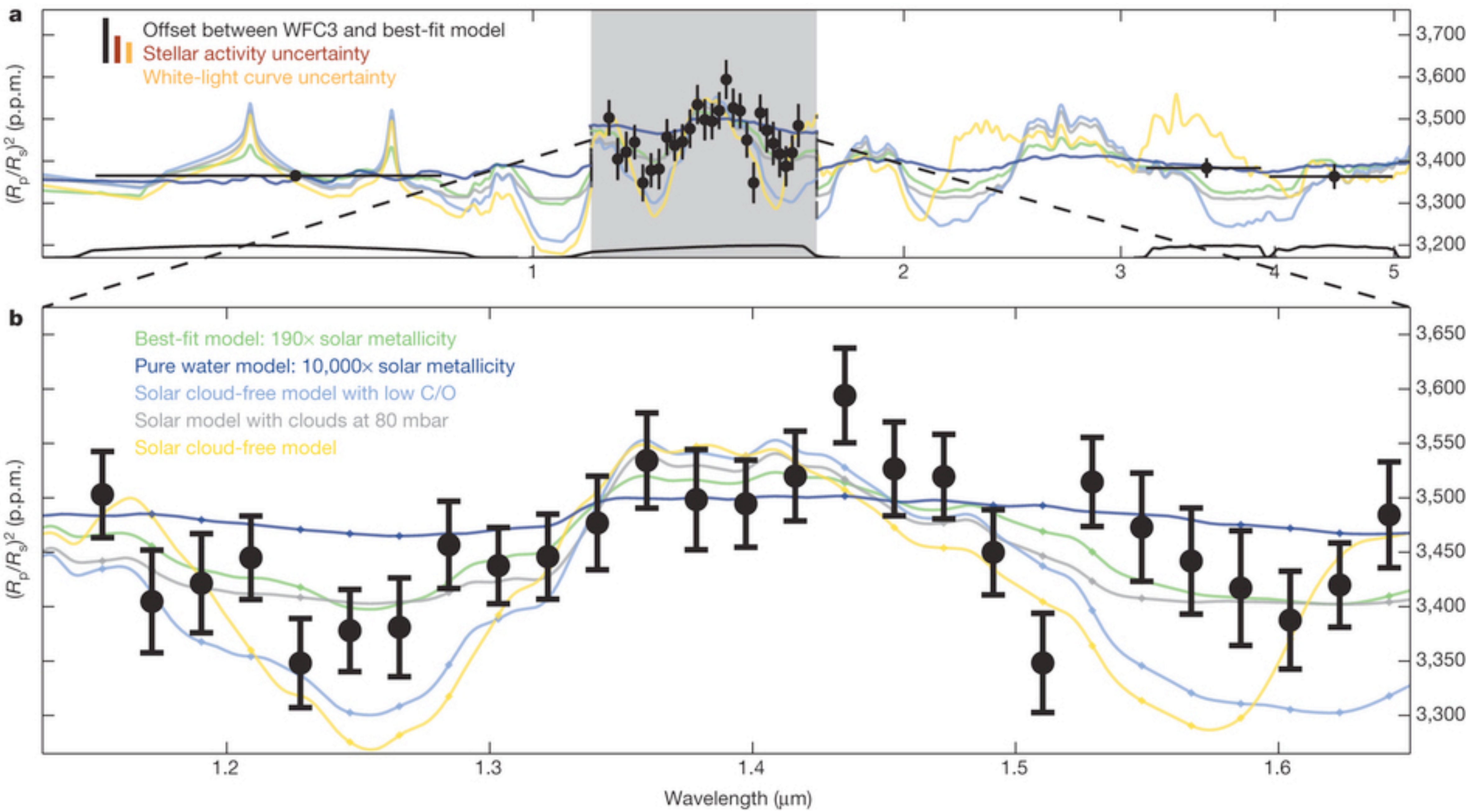
HD 97658b (warm super-Earth)



Ehrenreich et al. (2014)

GJ 3470b (warm Neptune-size)

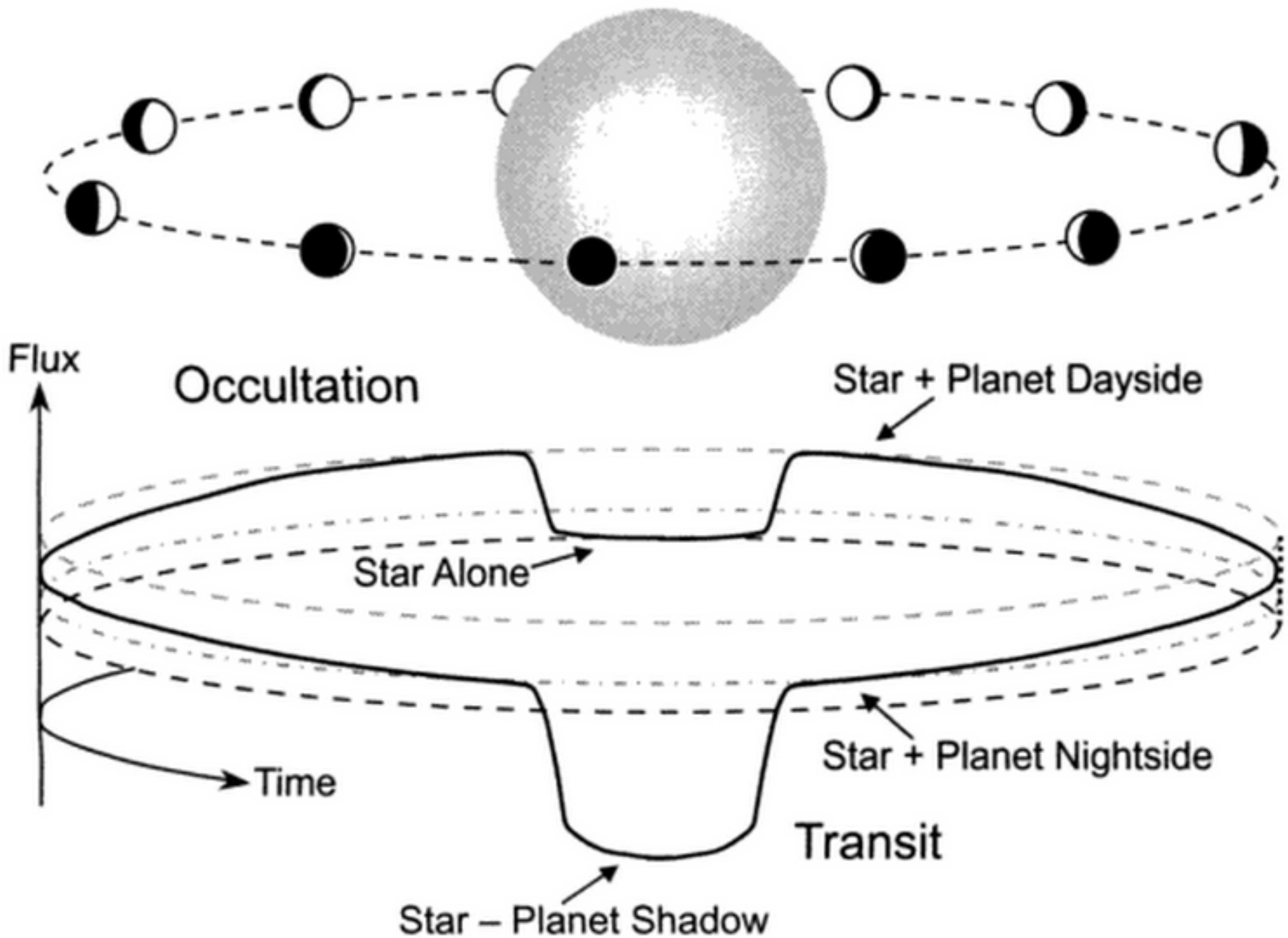
...Except for the Neptune-size HAT-P-11b



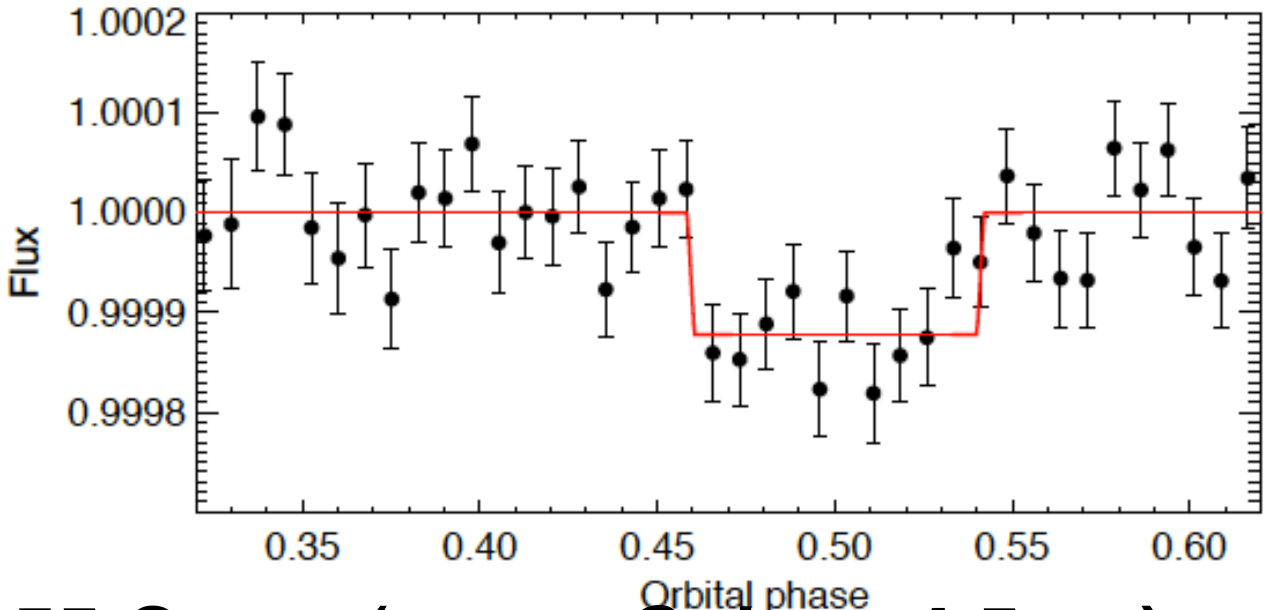
Fraine et al. (2014)

Warm (~900 K), slightly larger than Neptune

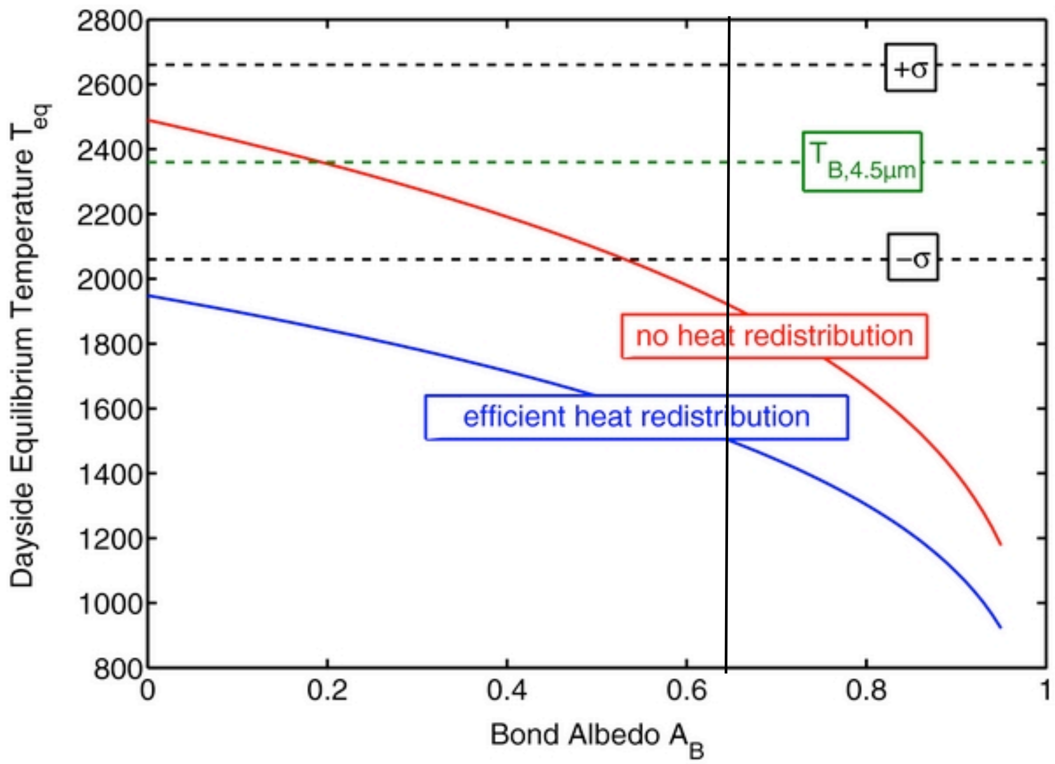
Emission Spectroscopy and Phase Variations



The secondary eclipses of 55 Cnc e and GJ436b



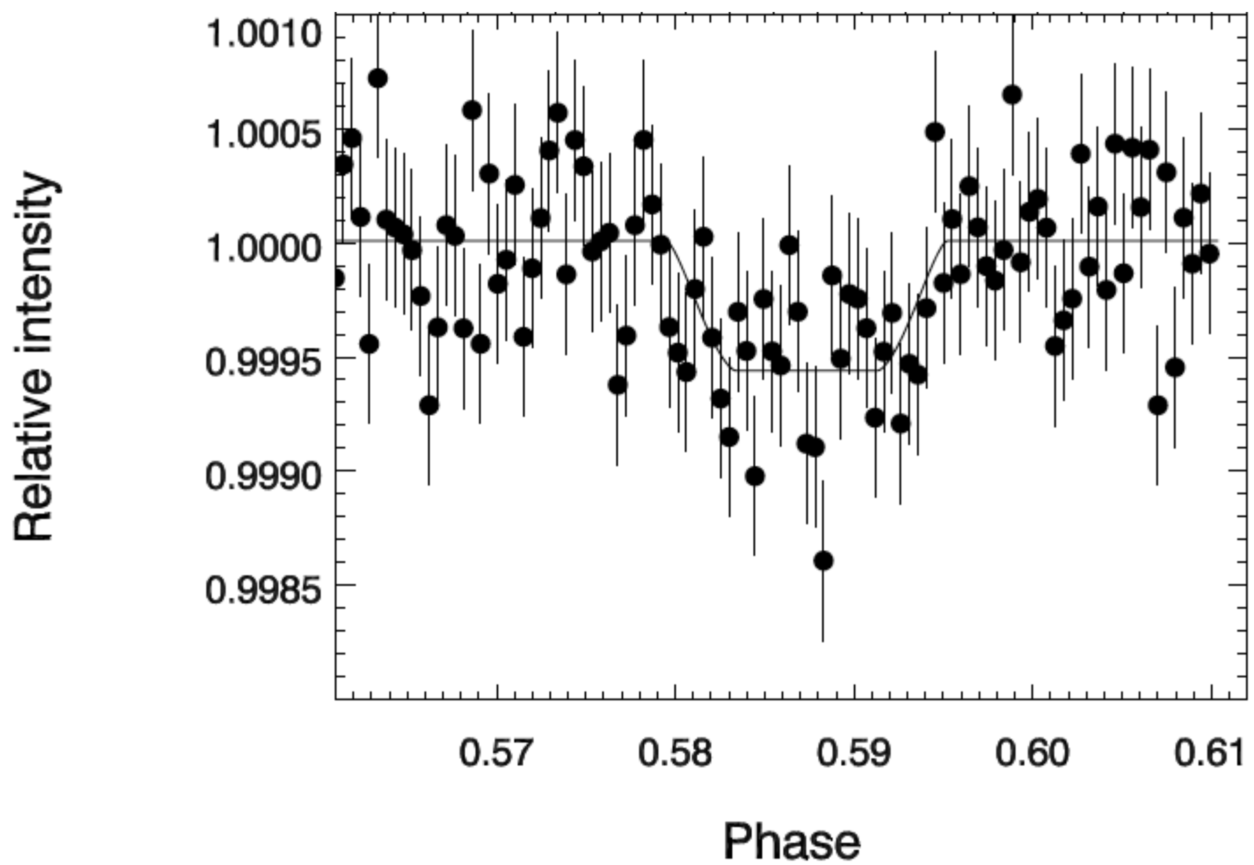
55 Cnc e (warm *Spitzer* 4.5μm)



Demory et al. 2012

Demory et al. (2012) determined a planetary effective temperature of **2360 ± 300 K.**

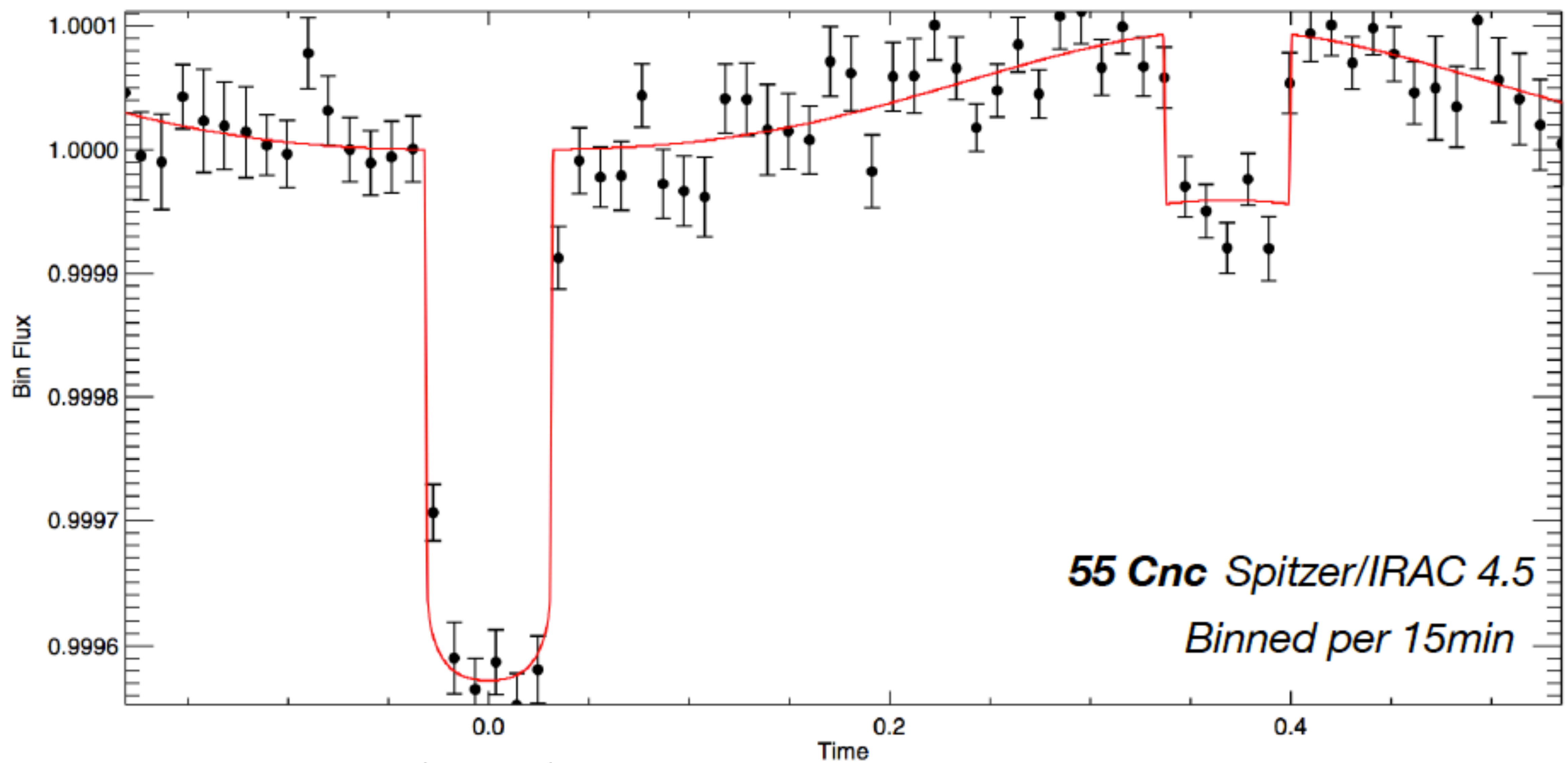
GJ 436b (*Spitzer* 8μm)



Deming et al. 2007

Deming et al. (2007) found a planetary effective temperature of **712 ± 36 K.**

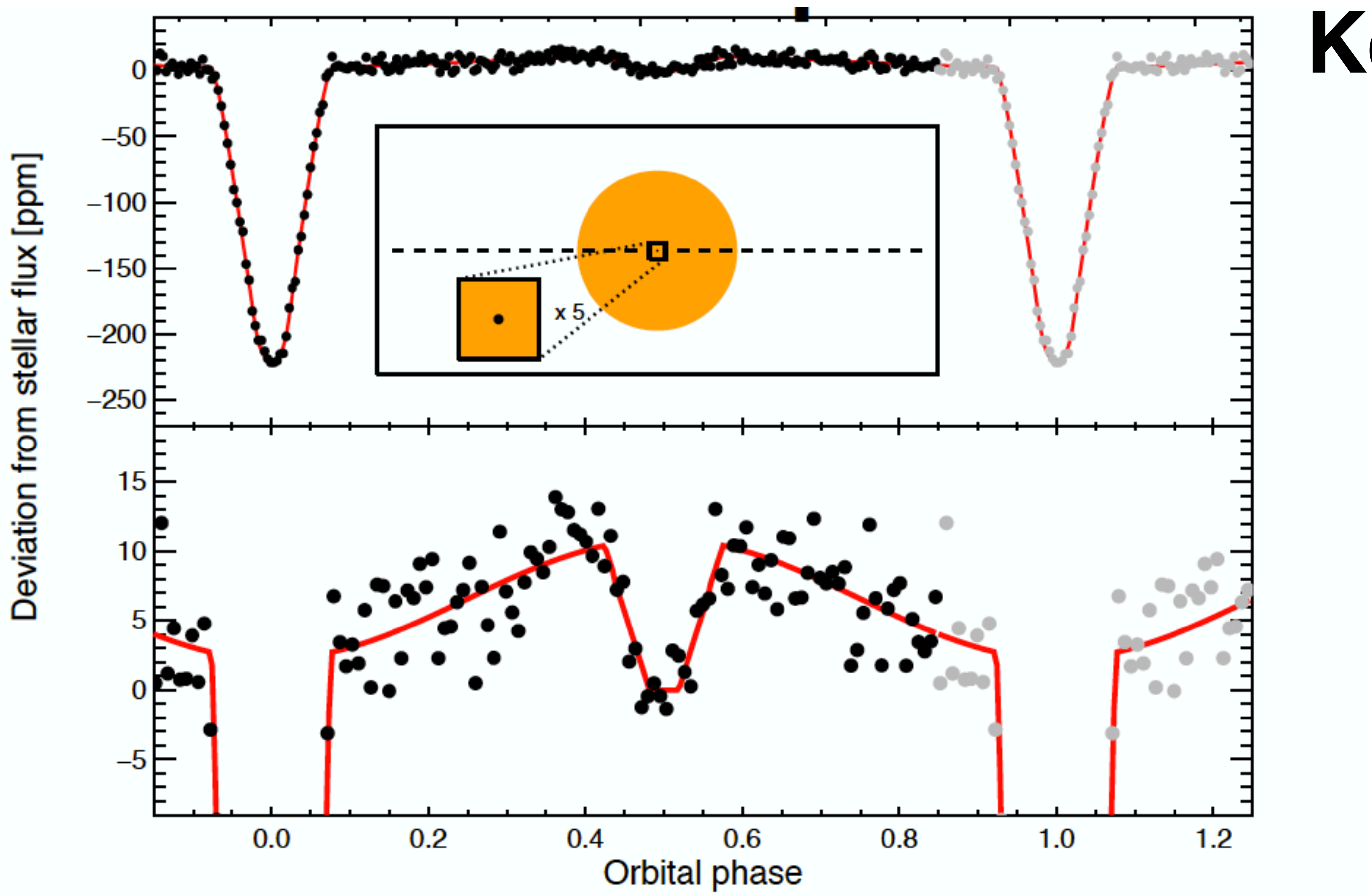
The thermal phase variations of 55 Cnc e



Demory et al. (in prep.)

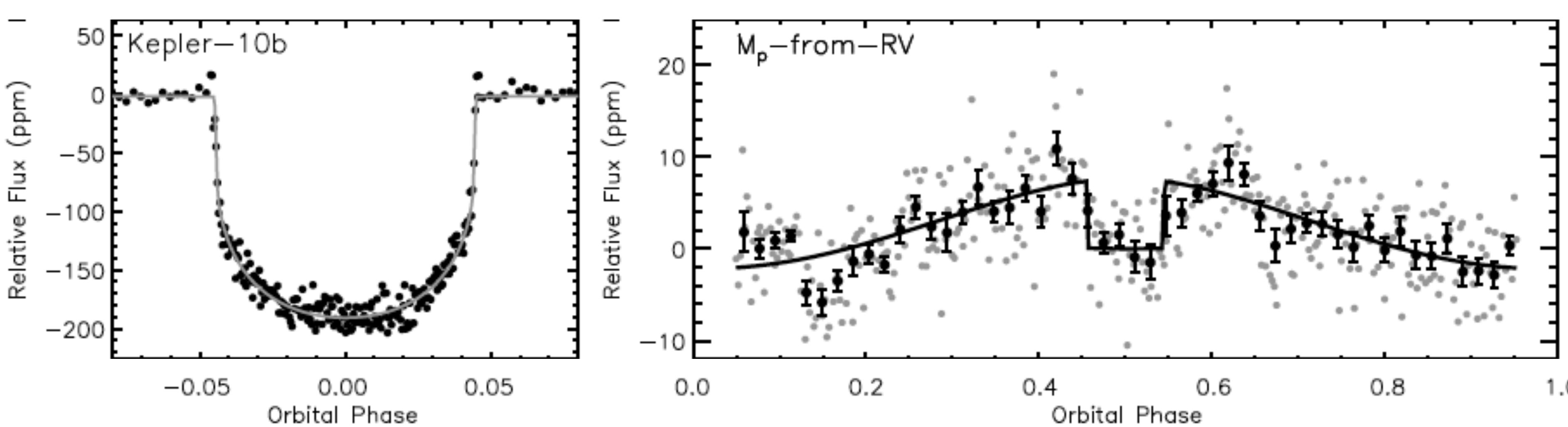
Phase variations of Kepler super-Earths

Kepler-78b



Sanchis-Ojeda et al. (2013)

Kepler-10b



Esteves et al. (2014)

What we need from theory

- 3D circulation models incorporating non-equilibrium chemistry and accurate opacities

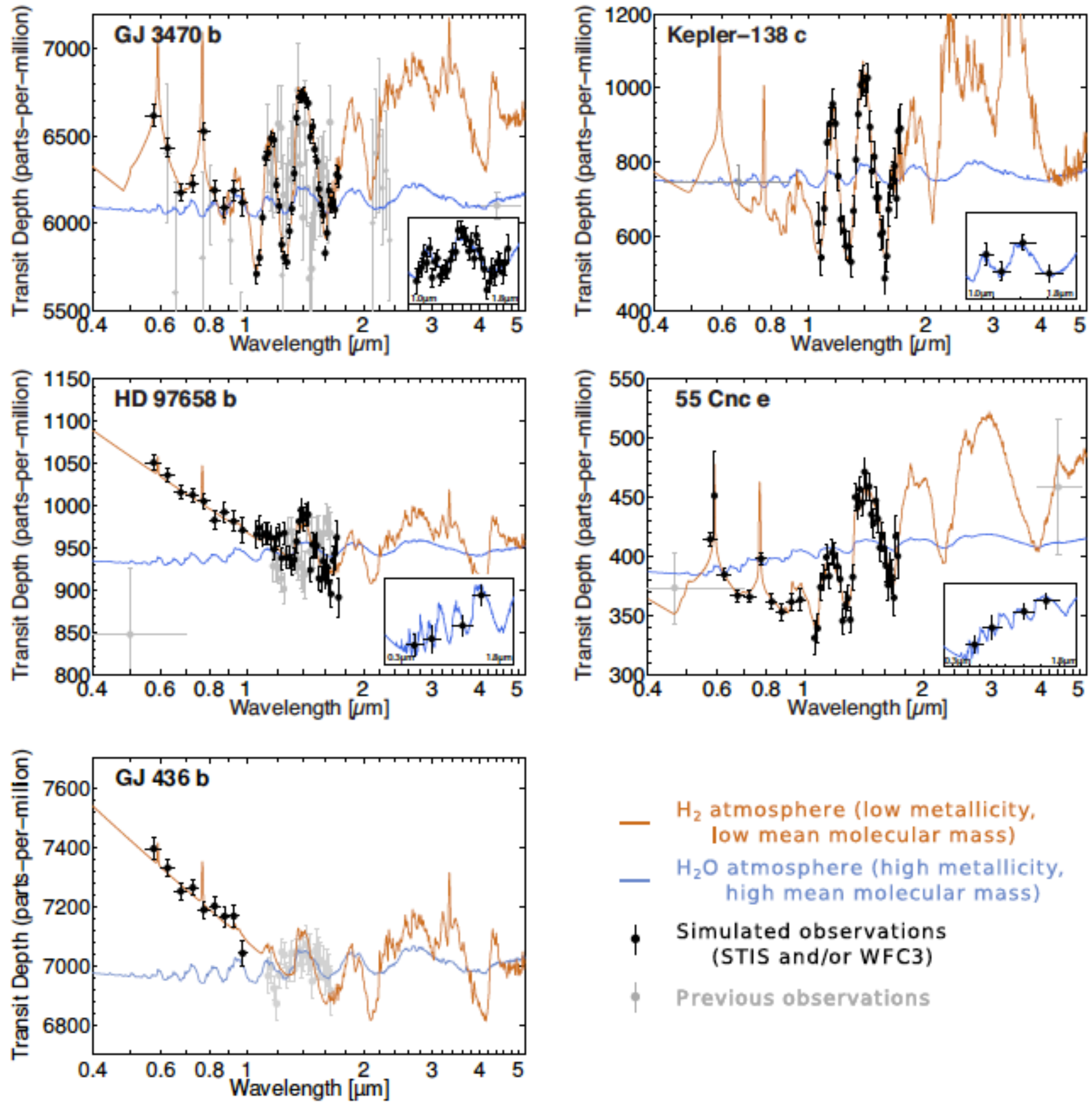
- Dependence of transmission spectra on abundances

- Condensate models to explain hazes and clouds

What next?

New data

- ongoing *HST STIS* and *WFC3* observations (PIs: B. Benneke and I. Crossfield)
- ongoing *Spitzer* observations at 3.6 μm (PI: D. Dragomir)
- ongoing *Spitzer* observations at 4.5 μm (PI: D. Dragomir)
- Possible CHARA observations to directly measure the stellar radius.

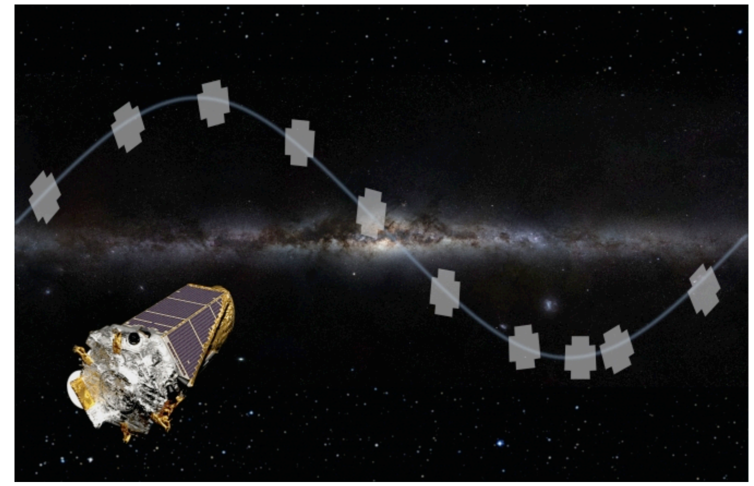


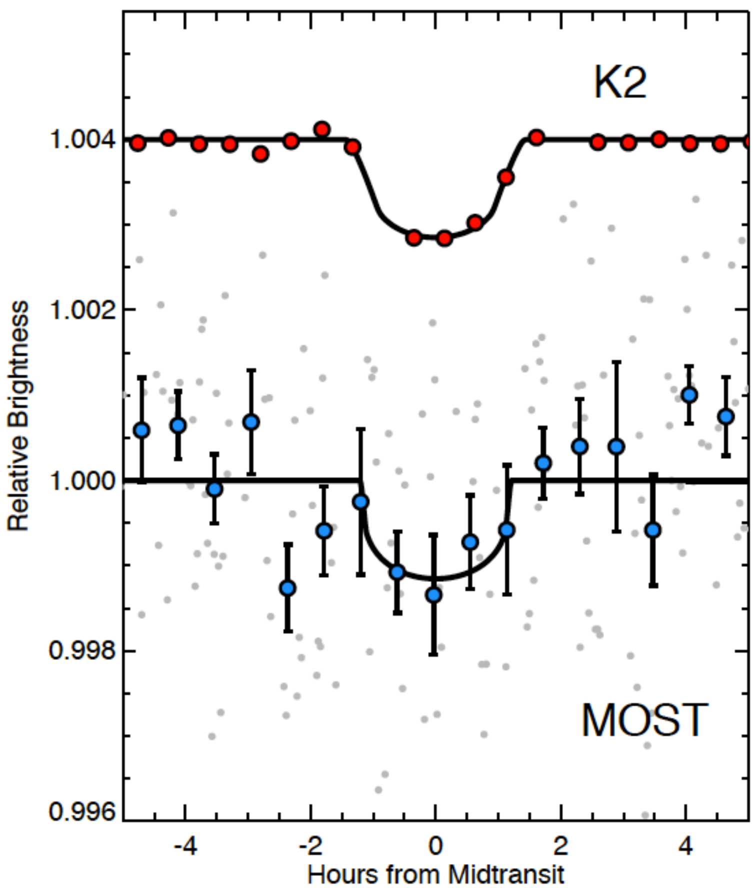
Scattering as a function of wavelength scale with particle size

What next?

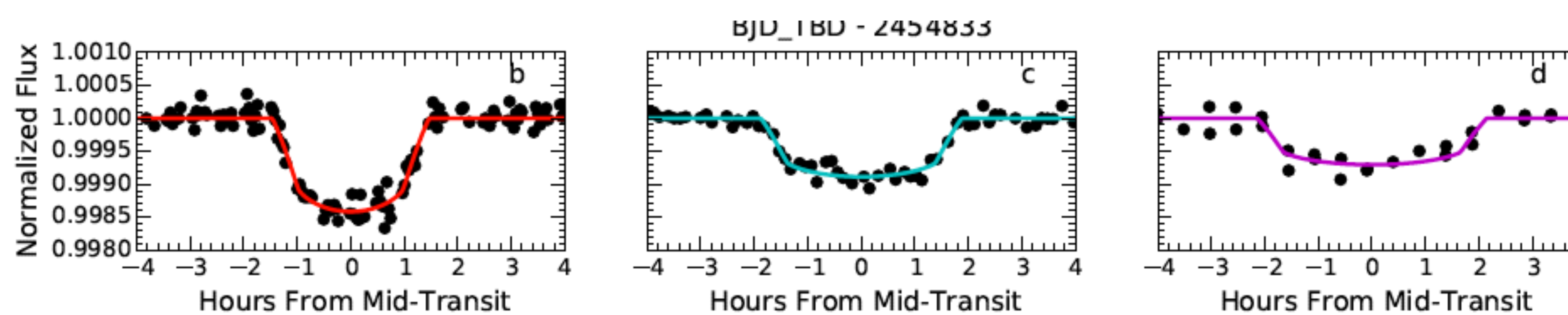
New planets (transiting bright/small stars)

Already trickling in from K2:

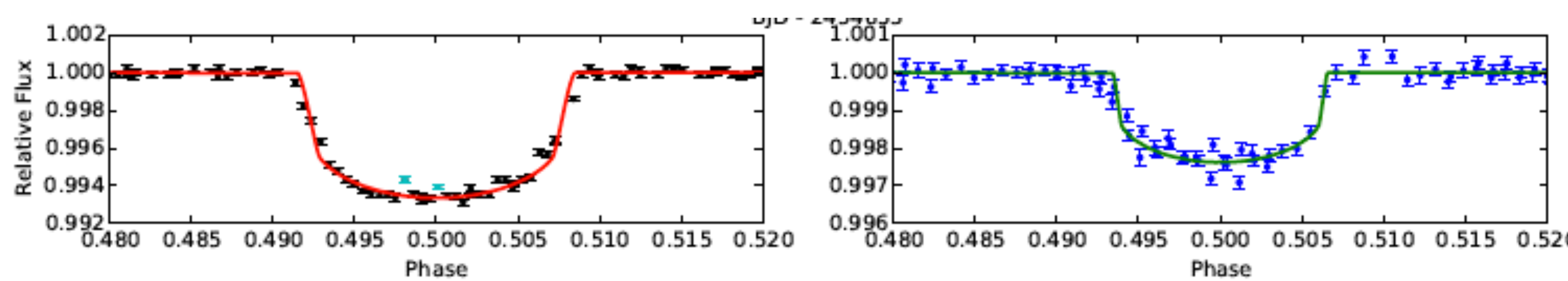




Vanderburg et al. 2015



Crossfield et al. 2015

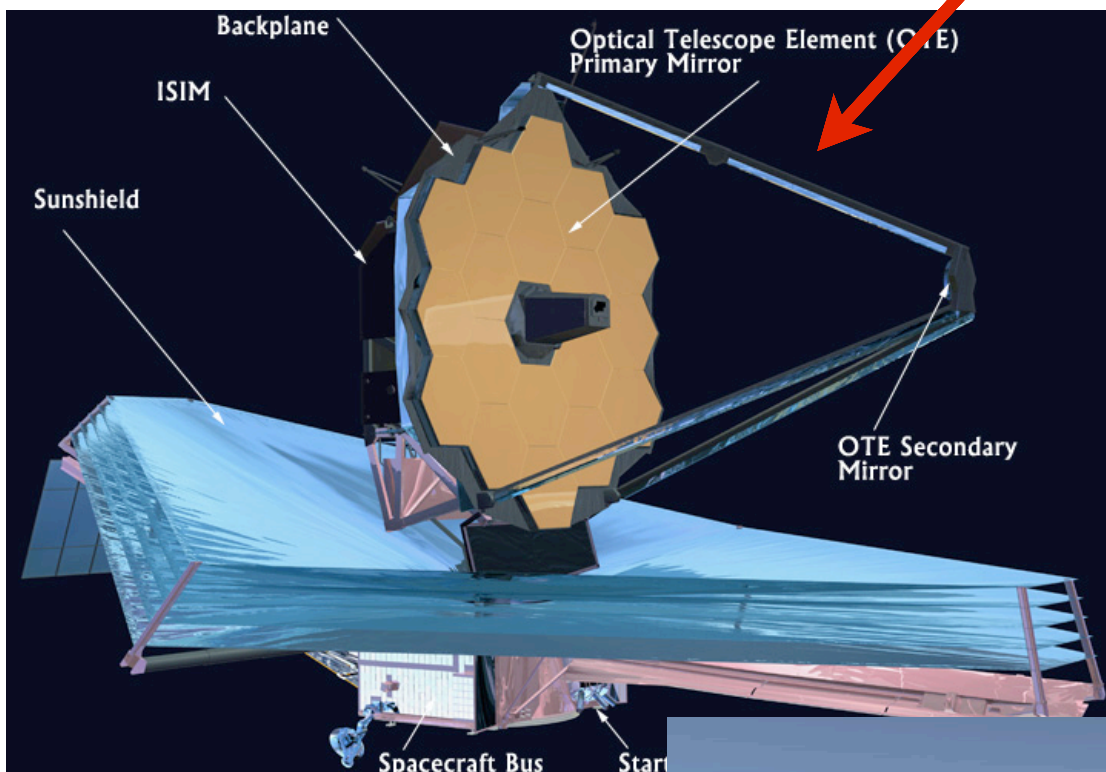


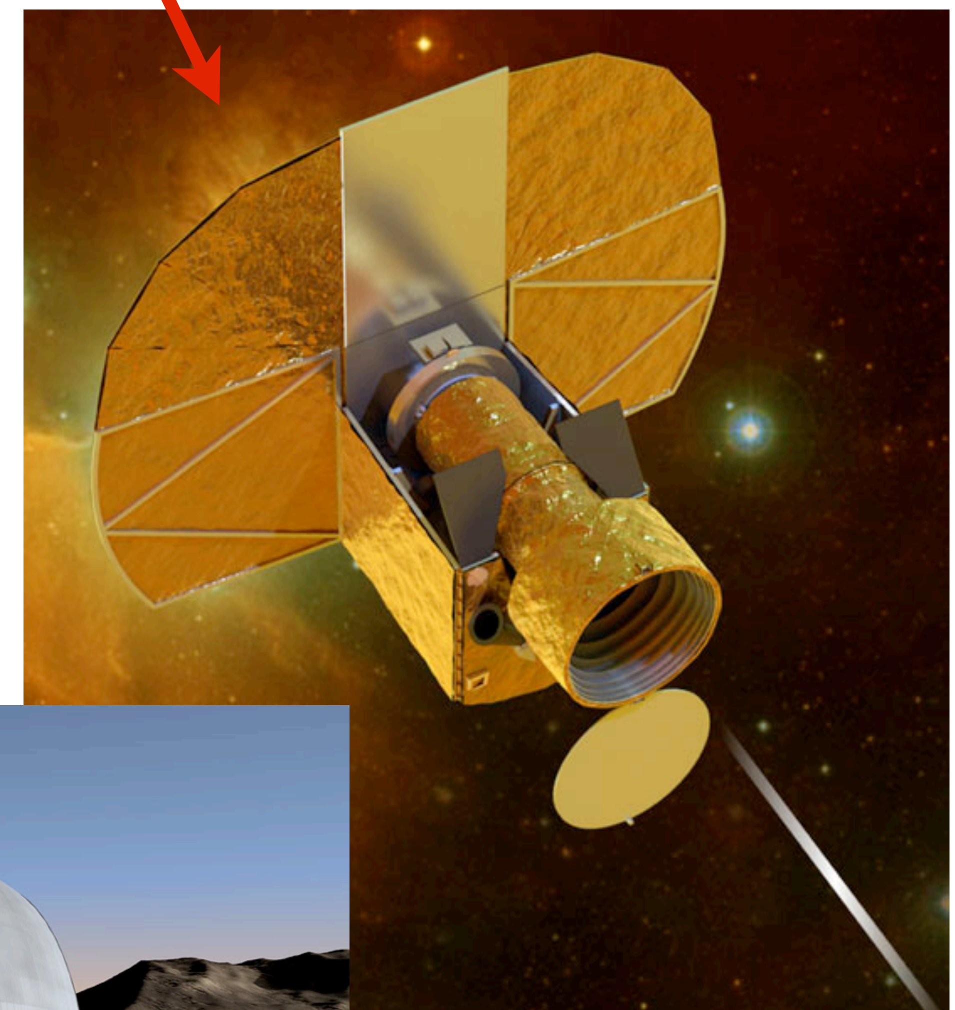
Armstrong et al. 2015

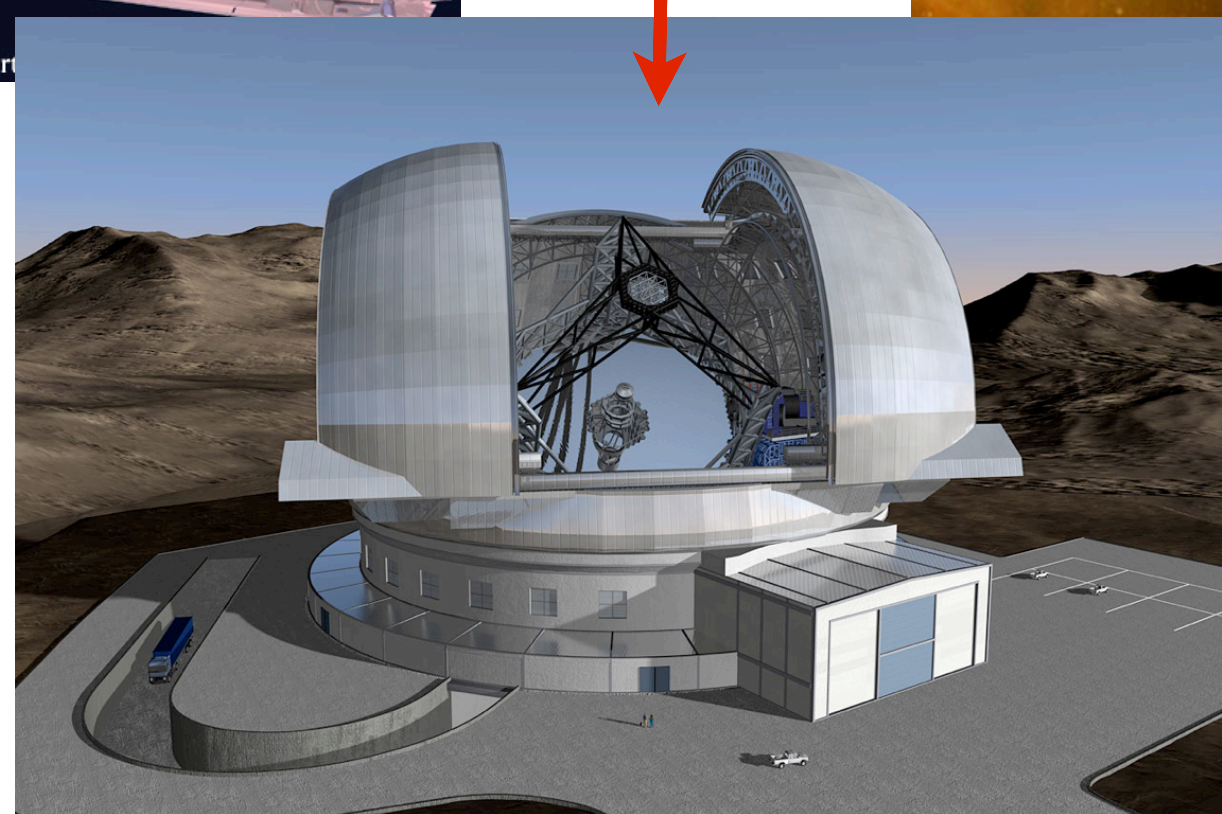
And many more to come from K2 and TESS

What next?

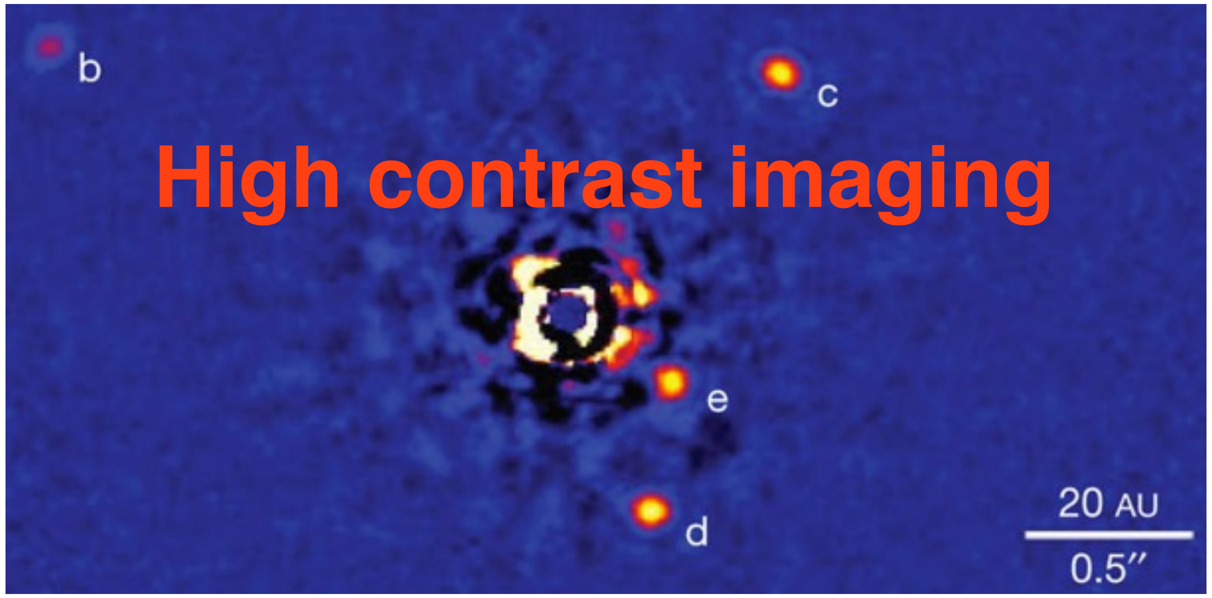
New observatories (JWST, E-ELT, CHEOPS, etc.)







How else can we hope to observe small exoplanets?



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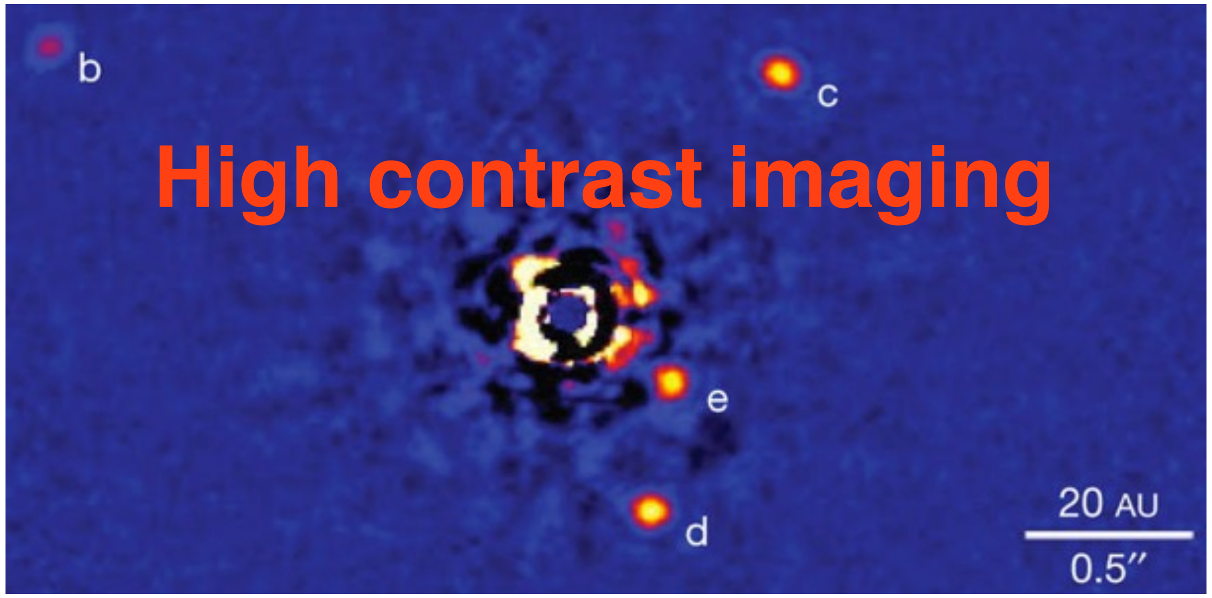

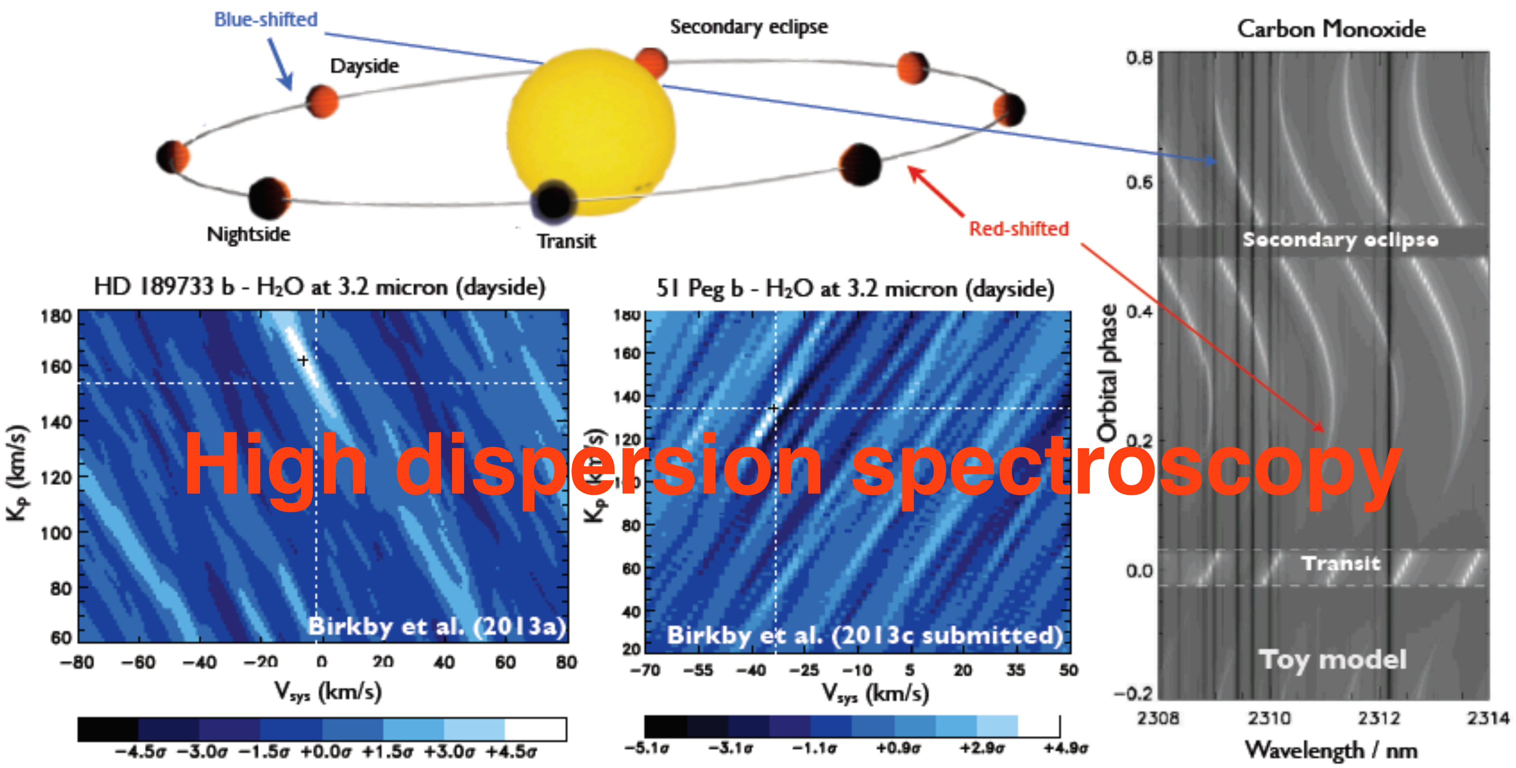

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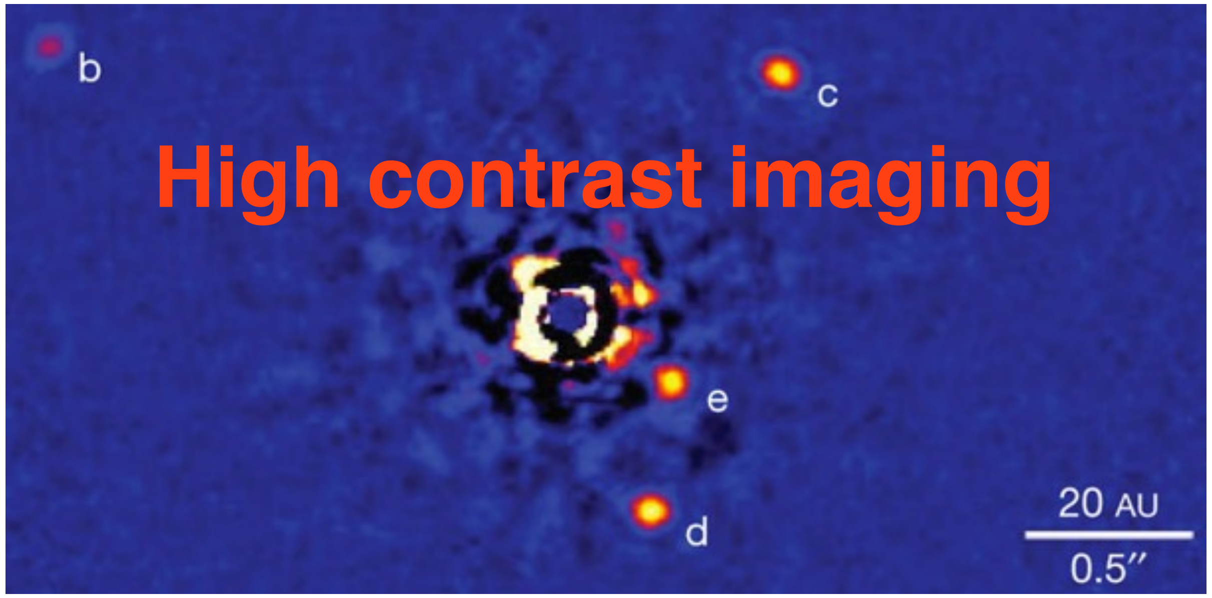

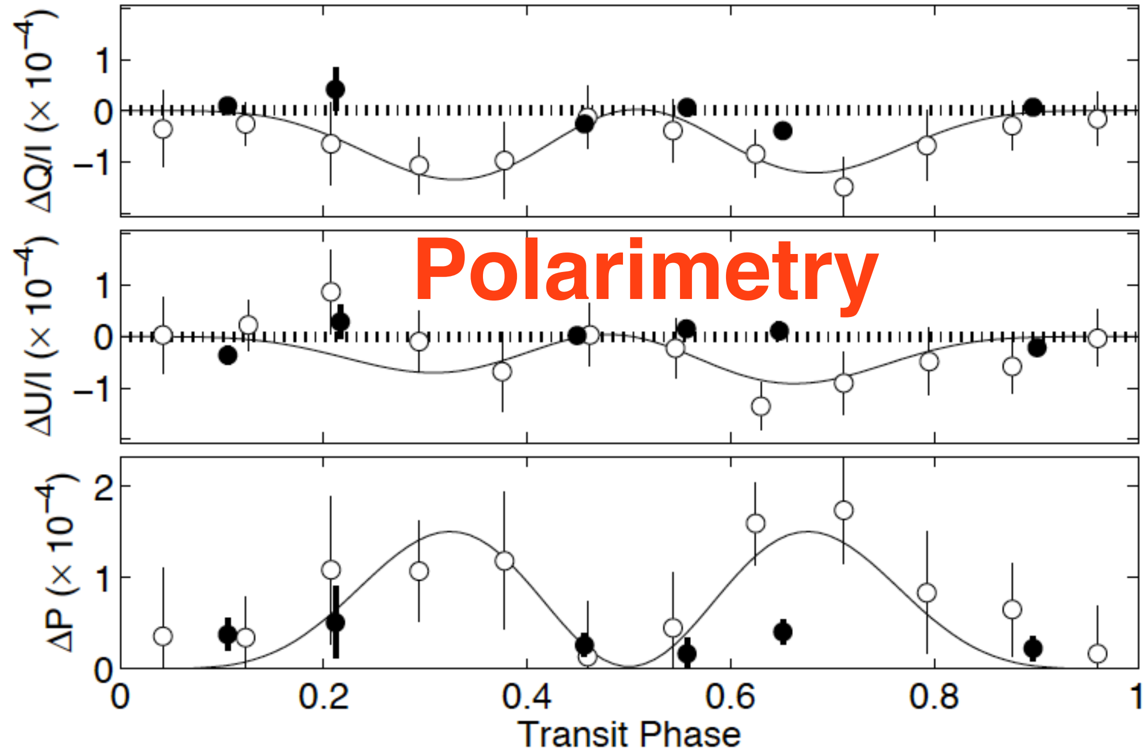

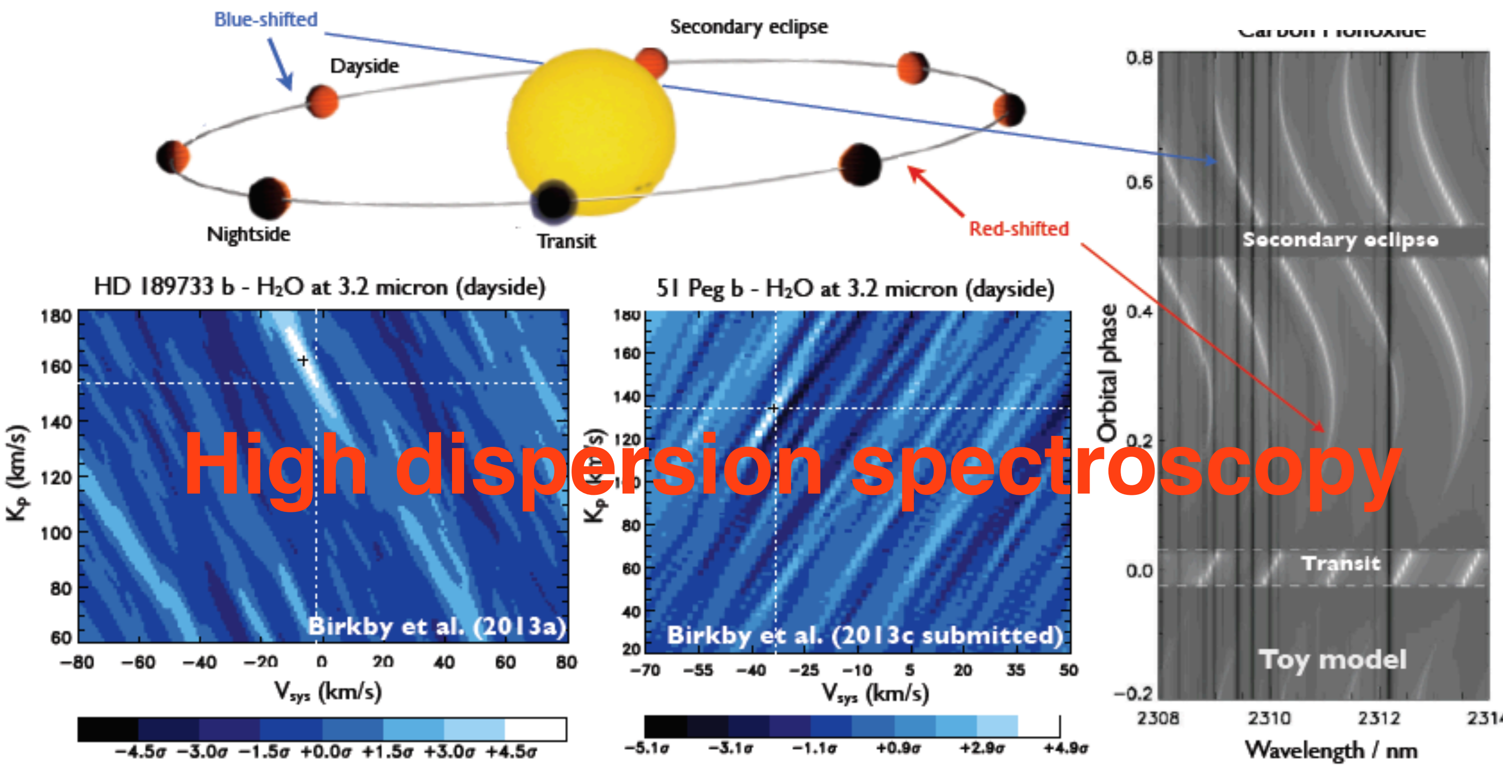

Summary

Super-Earth characterization is challenging.

Probing Earth-size planets even more so, as we will be looking at scale heights several times smaller.

Ways forward:
- observe more transits per system
- observe at shorter wavelengths
- population analysis