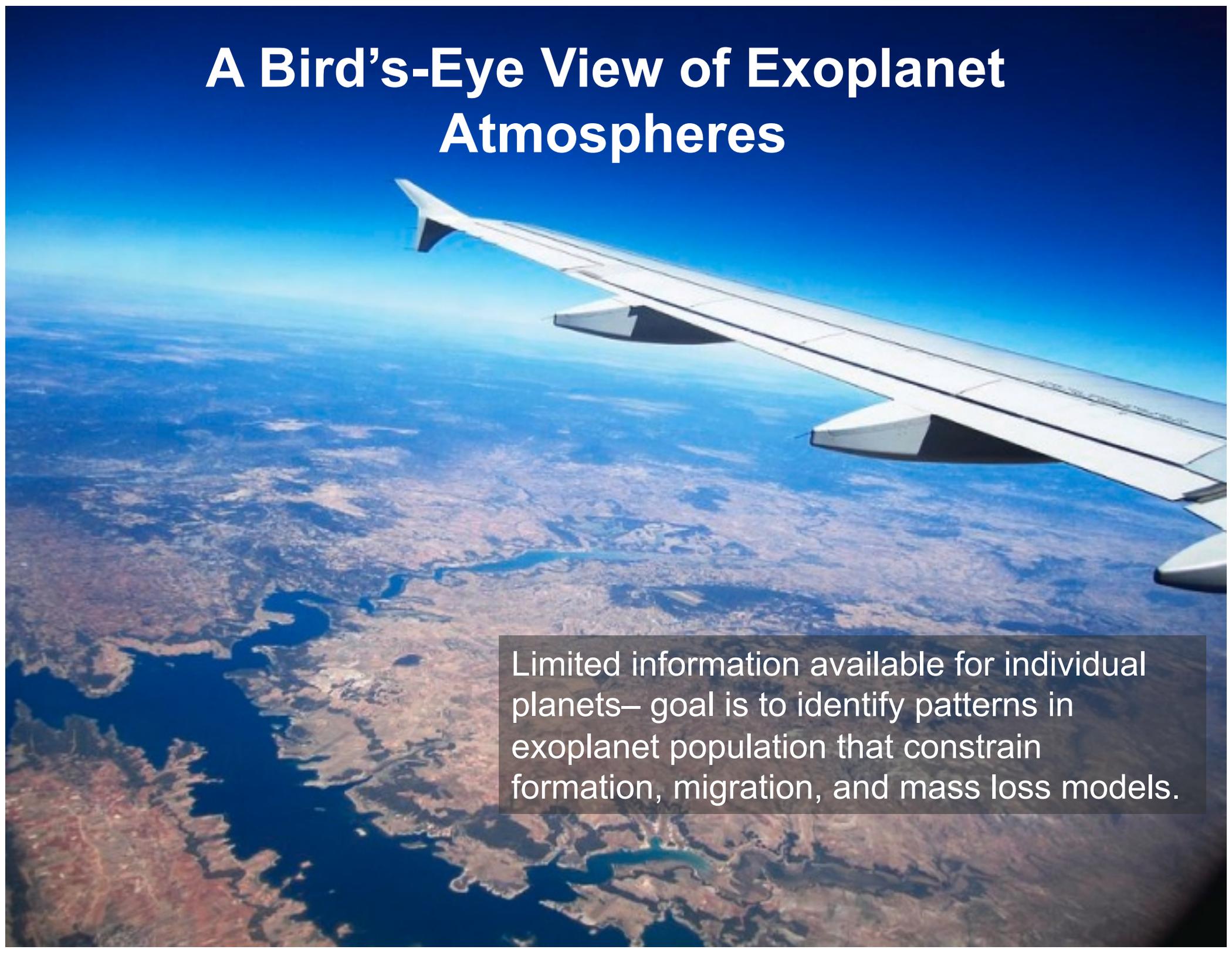


# Characterization of Transiting Planet Atmospheres

Heather Knutson

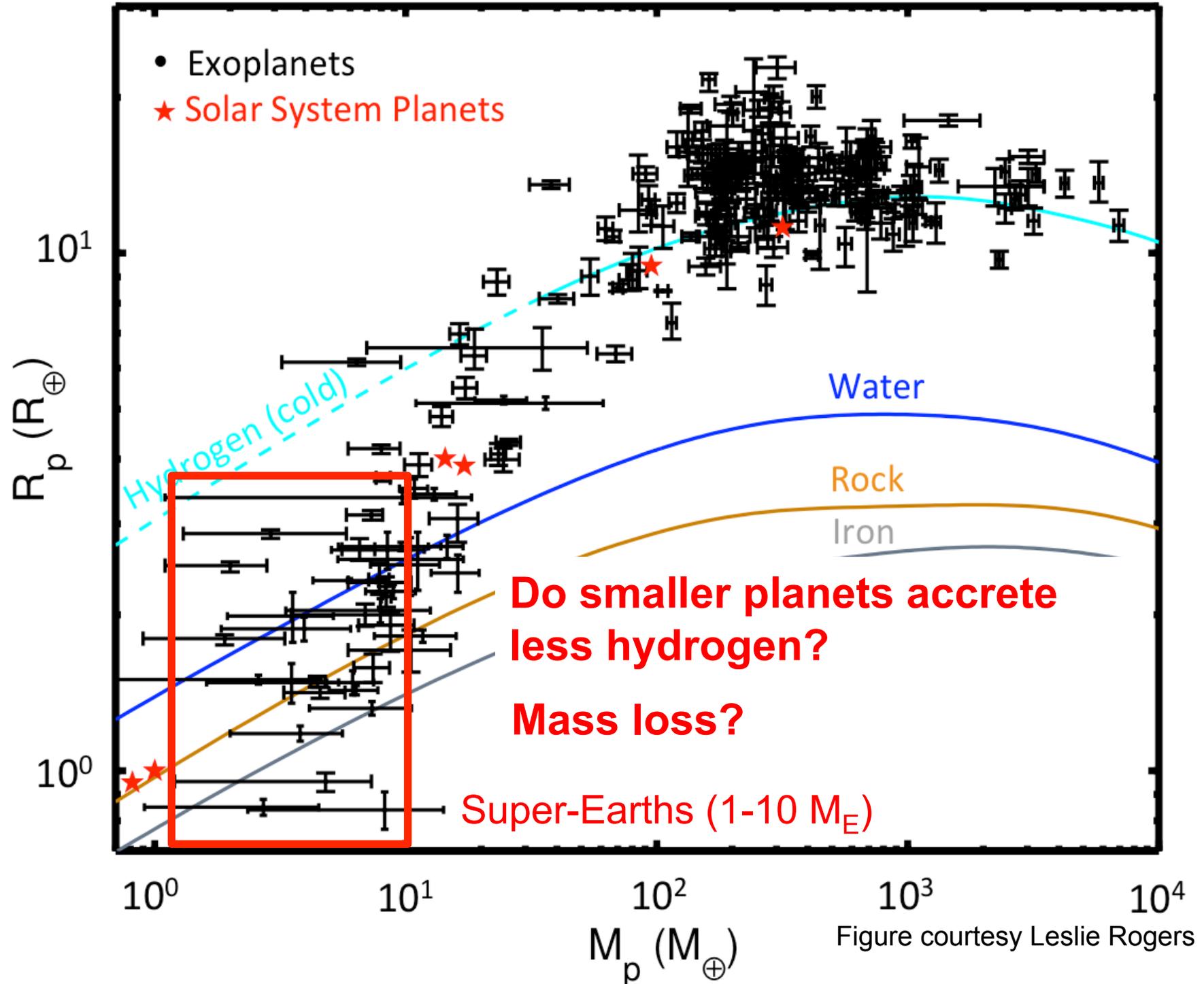
Division of Geological and Planetary  
Sciences, Caltech

# A Bird's-Eye View of Exoplanet Atmospheres

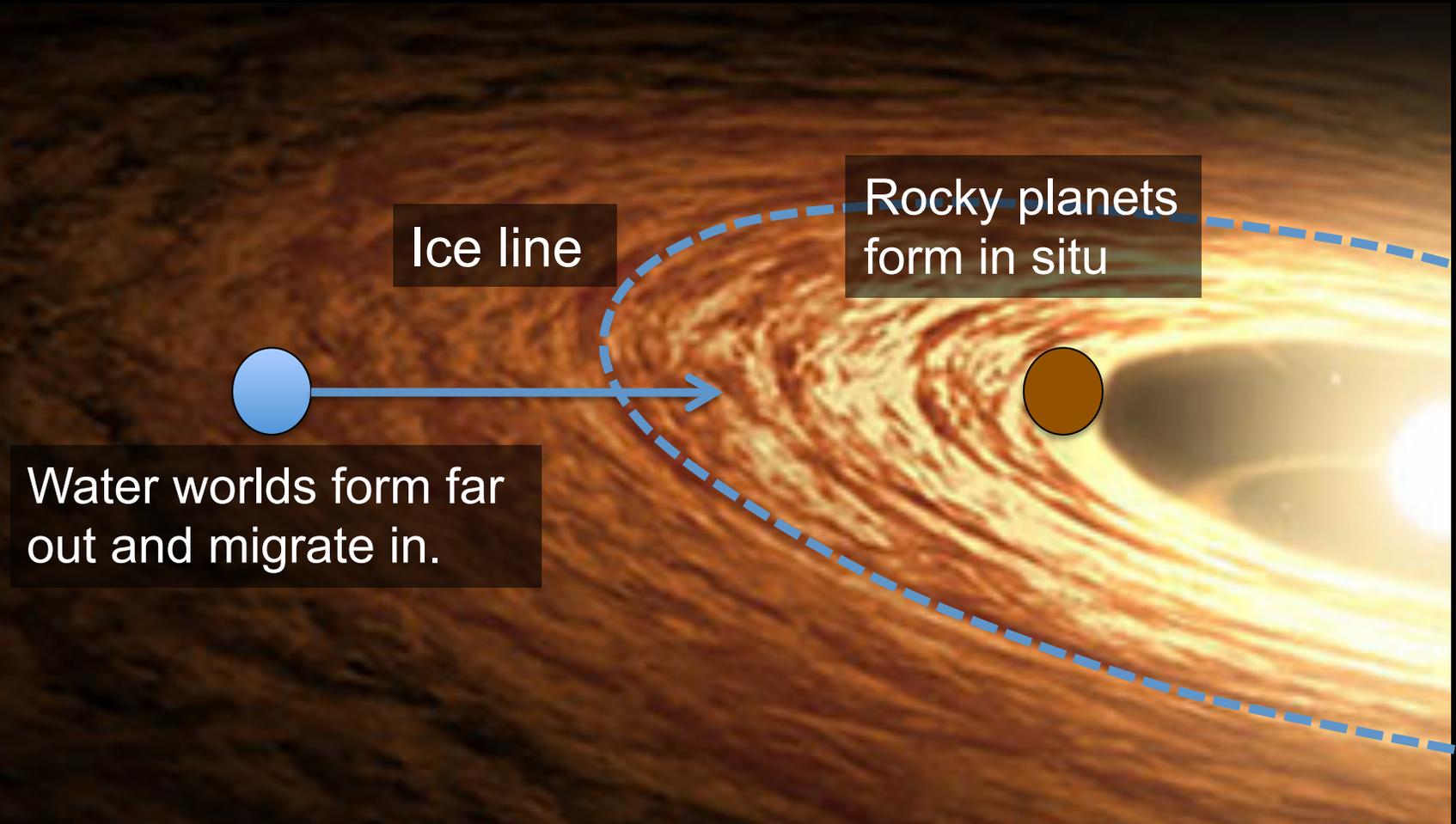
A photograph taken from an airplane window, showing the white wing of the aircraft extending from the top right towards the center. Below the wing, the Earth's surface is visible from a high altitude, showing a complex network of brown and tan landmasses, rivers, and large bodies of dark blue water. The sky above is a clear, bright blue, fading into a lighter blue near the horizon. The overall perspective is from a high angle, looking down at the planet.

Limited information available for individual planets— goal is to identify patterns in exoplanet population that constrain formation, migration, and mass loss models.

# A Mass-Radius Diagram for Exoplanets

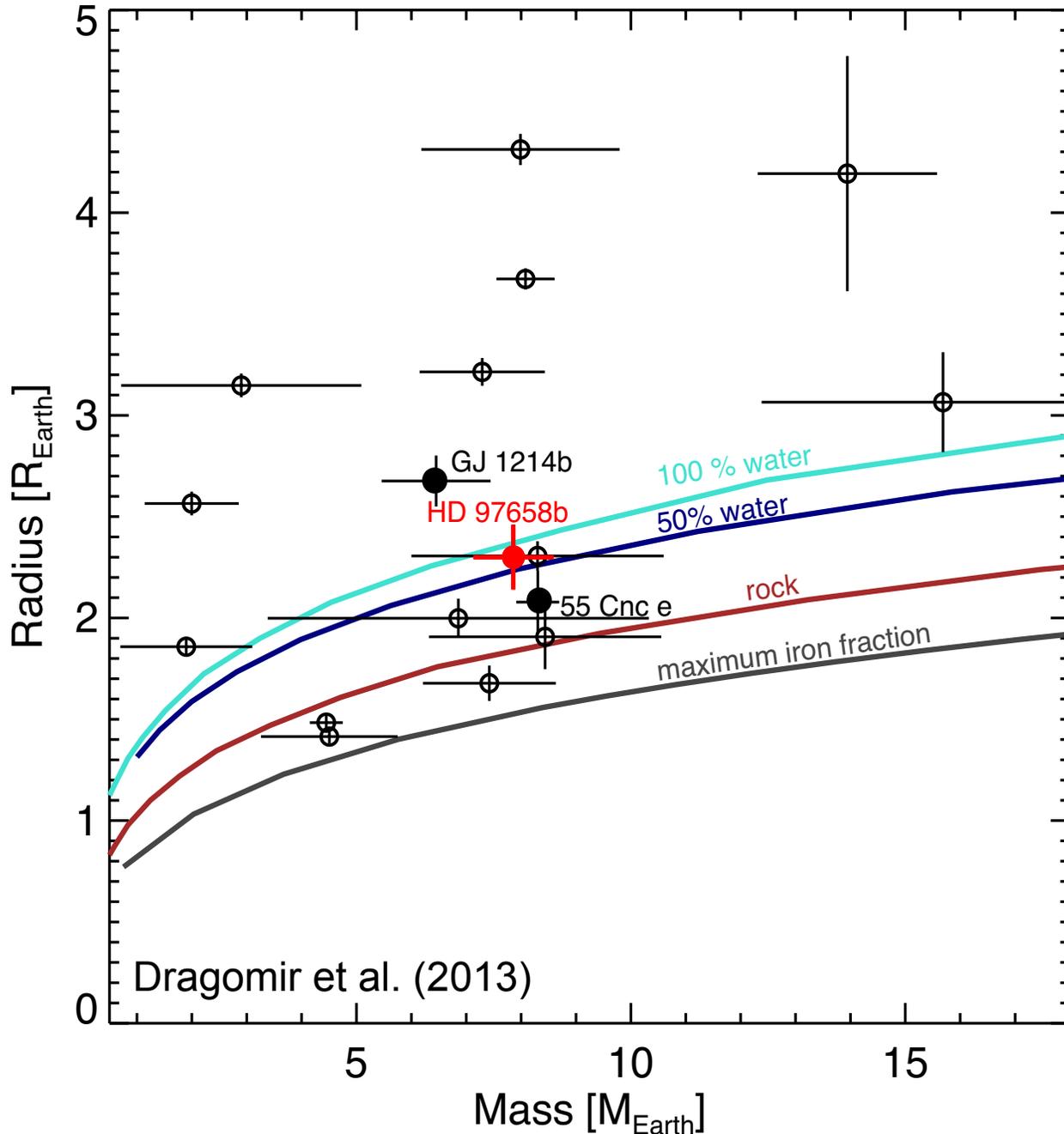


# Composition as a Clue to Origin of Close-in Super-Earths

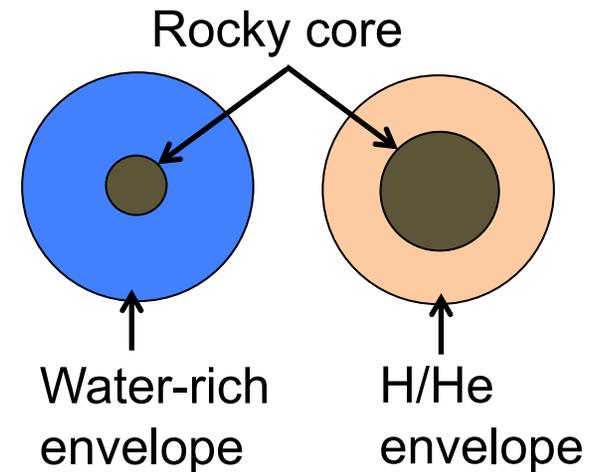


Premise: small planets grow by accreting solids, so bulk composition reflects that of the solids in the disk at the formation location.

# Determining Super-Earth Compositions

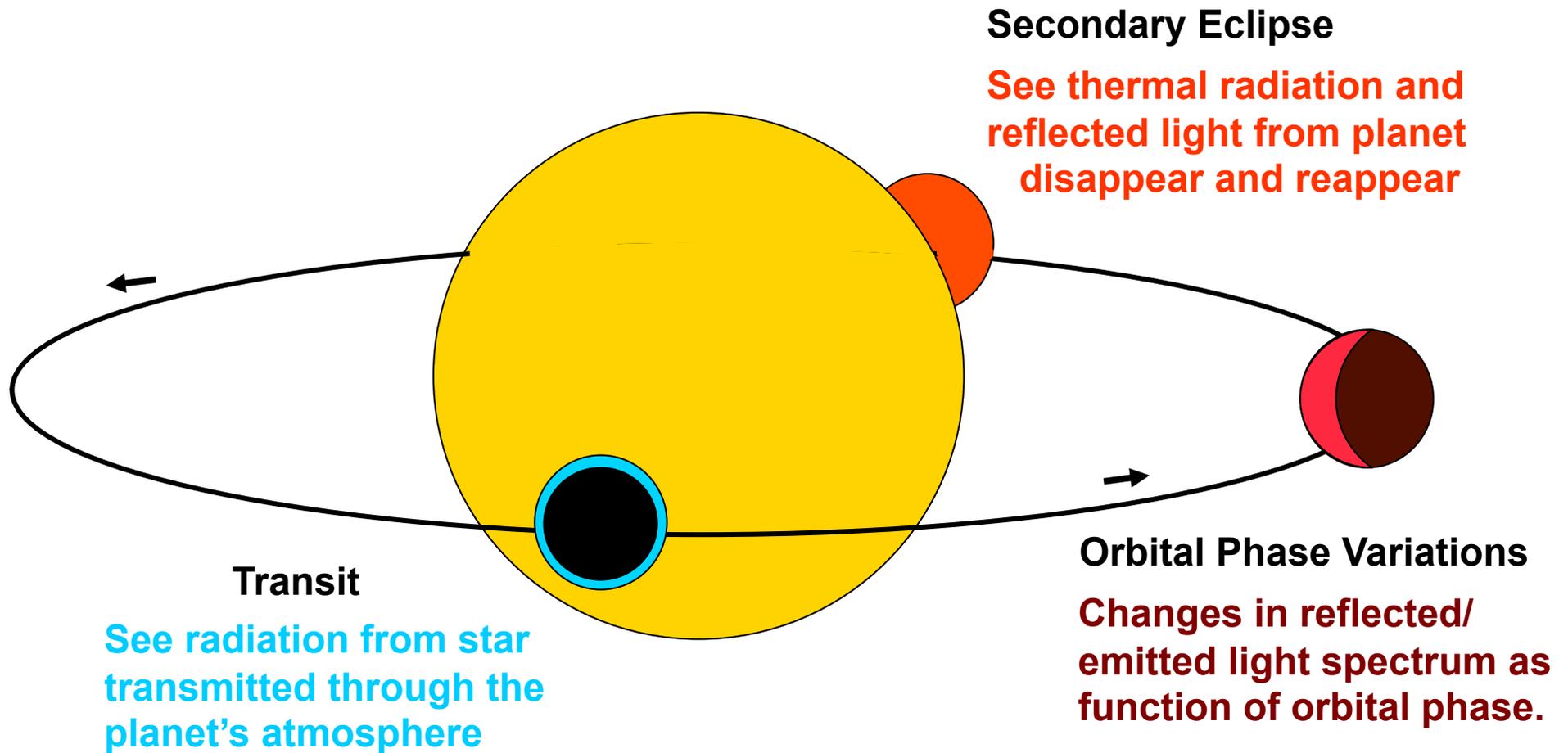


Caveat: the presence of thick atmospheres makes it difficult to **uniquely constrain** bulk compositions from mass and radius alone.

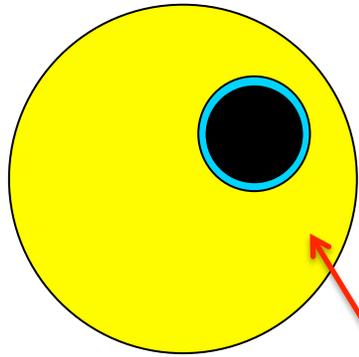


**Water world** (migrated from beyond ice line) **or rocky with a H/He envelope** (in situ formation)?

# Observations of Eclipsing Systems Allow Us to Characterize Exoplanet Atmospheres



# Scaling Laws for Transiting Planets

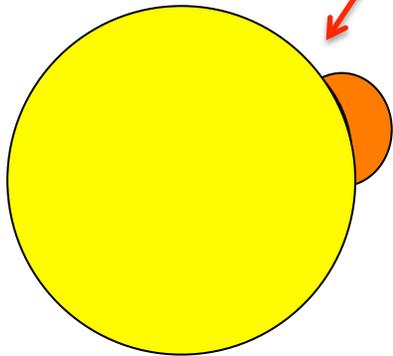


Absorption During Transit (%):

$$\frac{10R_p}{R_*^2} \left( \frac{kT_p}{\mu g} \right)$$

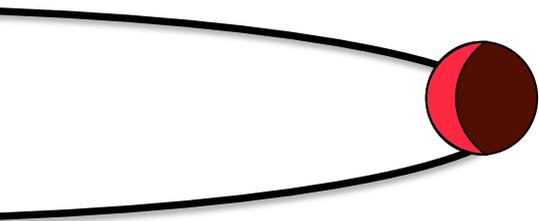
mean molecular weight

M stars preferred!



Secondary Eclipse Depth (IR):

$$\left( \frac{R_p}{R_*} \right)^2 \left( \frac{T_p}{T_*} \right)$$

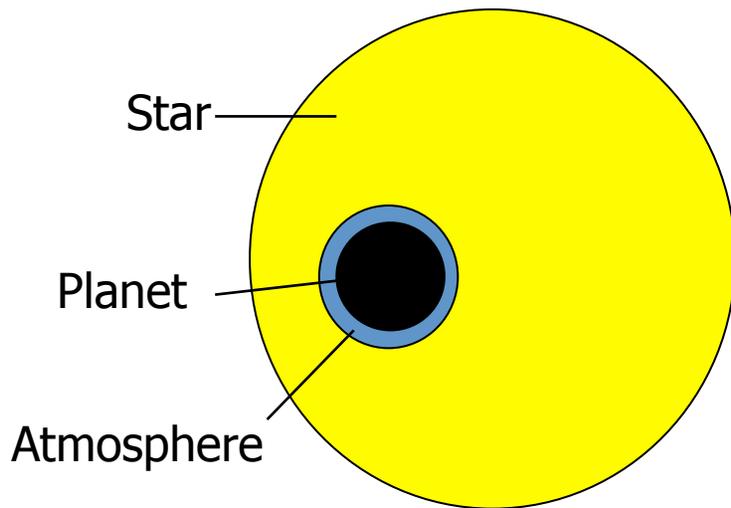
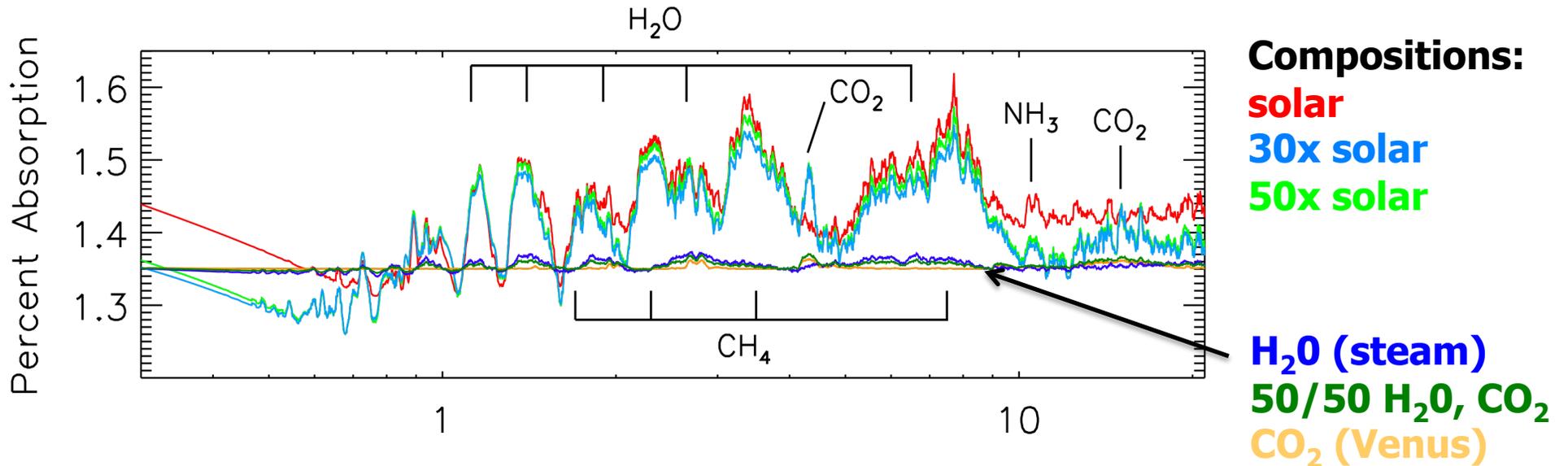


Orbital Phase Variations:

Always less than secondary eclipse depth.

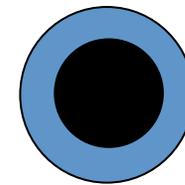
Three ways to decrease signal: smaller planet, lower temperature, heavier atmosphere.

# Transmission Spectroscopy Measures Mean Molecular Weight of Atmosphere



Scale Height

$$H = \frac{kT}{g\mu}$$



Large scale height



Small scale height

# Characterizing the Warm Transiting Neptune GJ 436b

**GJ 436A:**

0.5  $M_{\text{Sun}}$ , 3600 K

**GJ 436b**

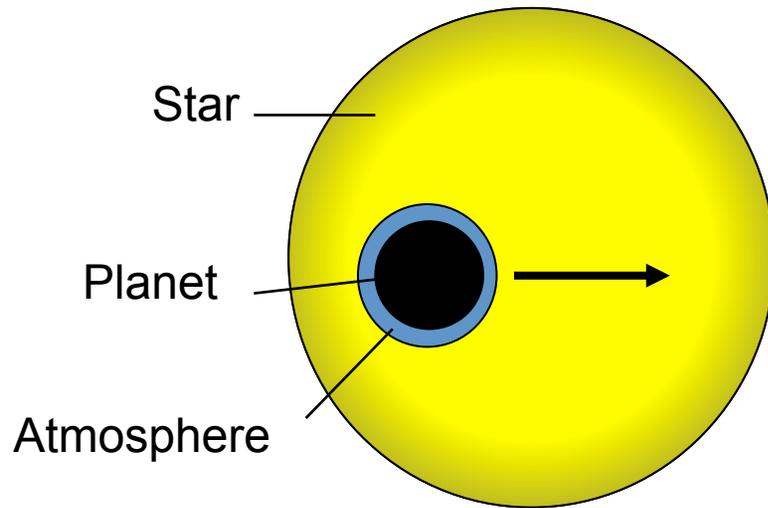
23  $M_{\text{earth}}$ , 2.6 day orbital period  
~800 K



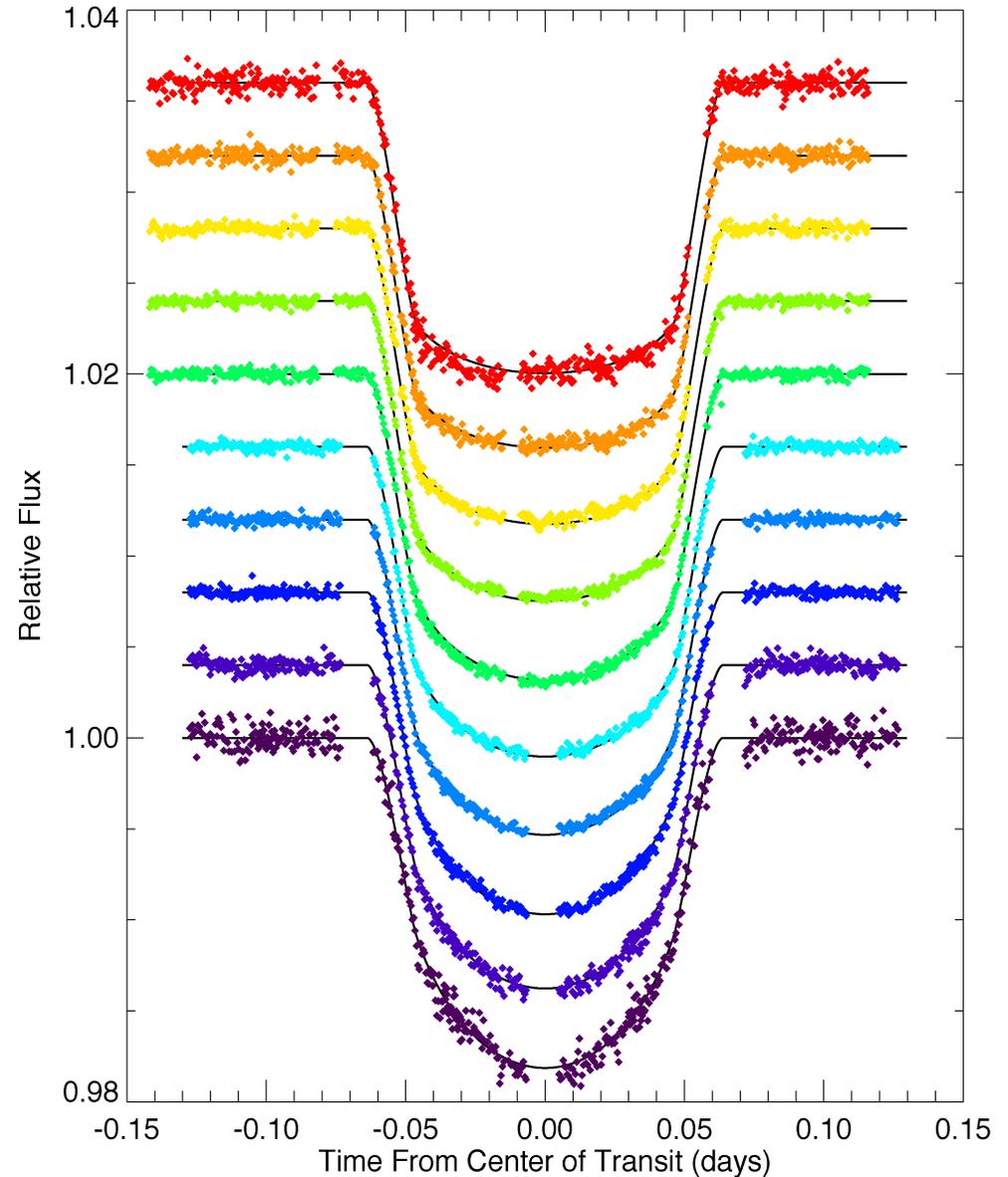
Estimated **H/He mass fraction** between 3-22%, comparable to Neptune (Nettelmann et al. 2010).

GJ 436 system  
to scale.

# Characterizing Atmospheres With Transmission Spectroscopy

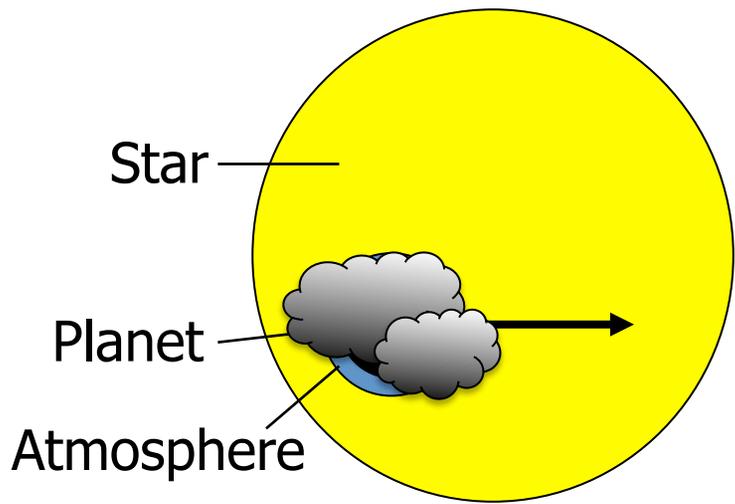
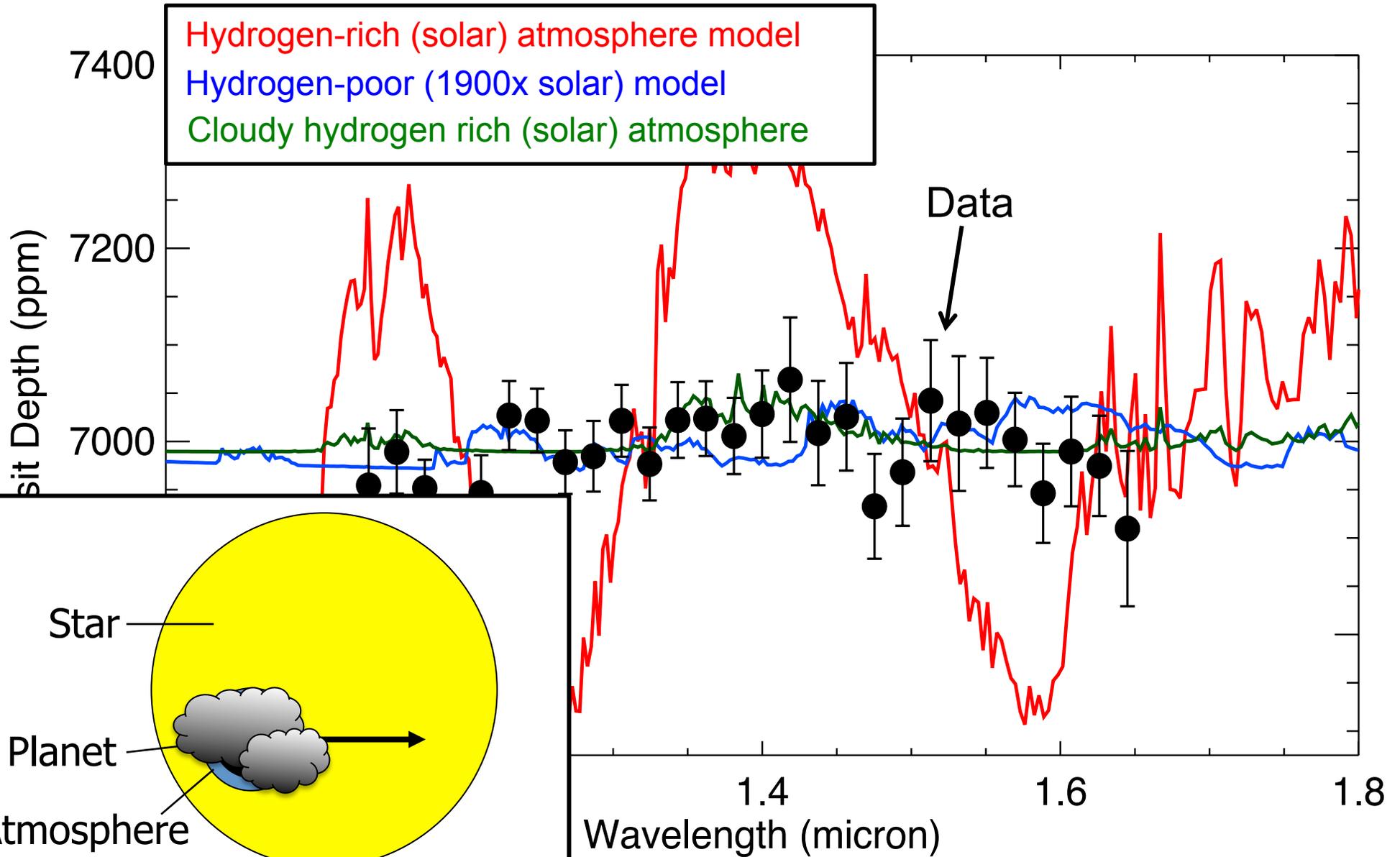


A good understanding of **limb-darkening** is needed in order to determine the planet's wavelength-dependent radius.



HST STIS transits of HD 209458b from 290-1030 nm (Knutson et al. 2007a)

# A Hubble Space Telescope Transmission Spectrum for Warm Neptune GJ 436b



**Super-Earth GJ 1214b also has similar clouds (Kreidberg et al. 2014)**

Knutson et al. (2014)

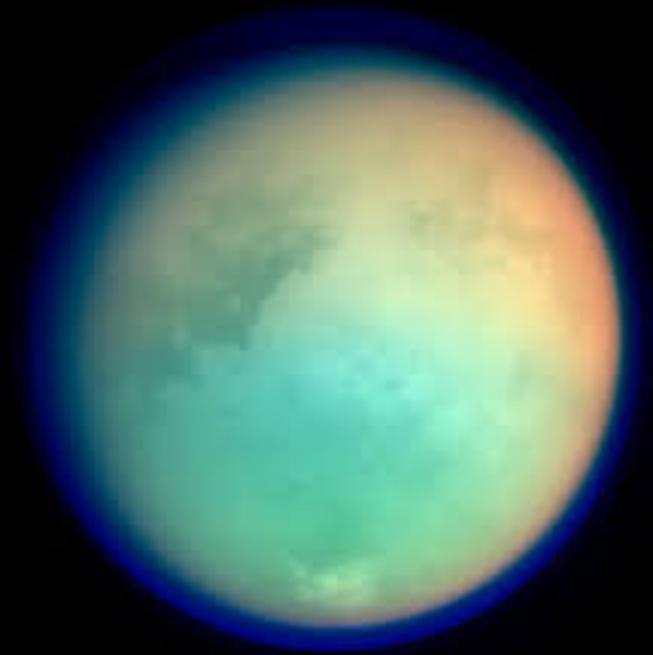
# What Might Form Clouds on GJ 436b and GJ 1214b?

Condensate clouds like the Earth?



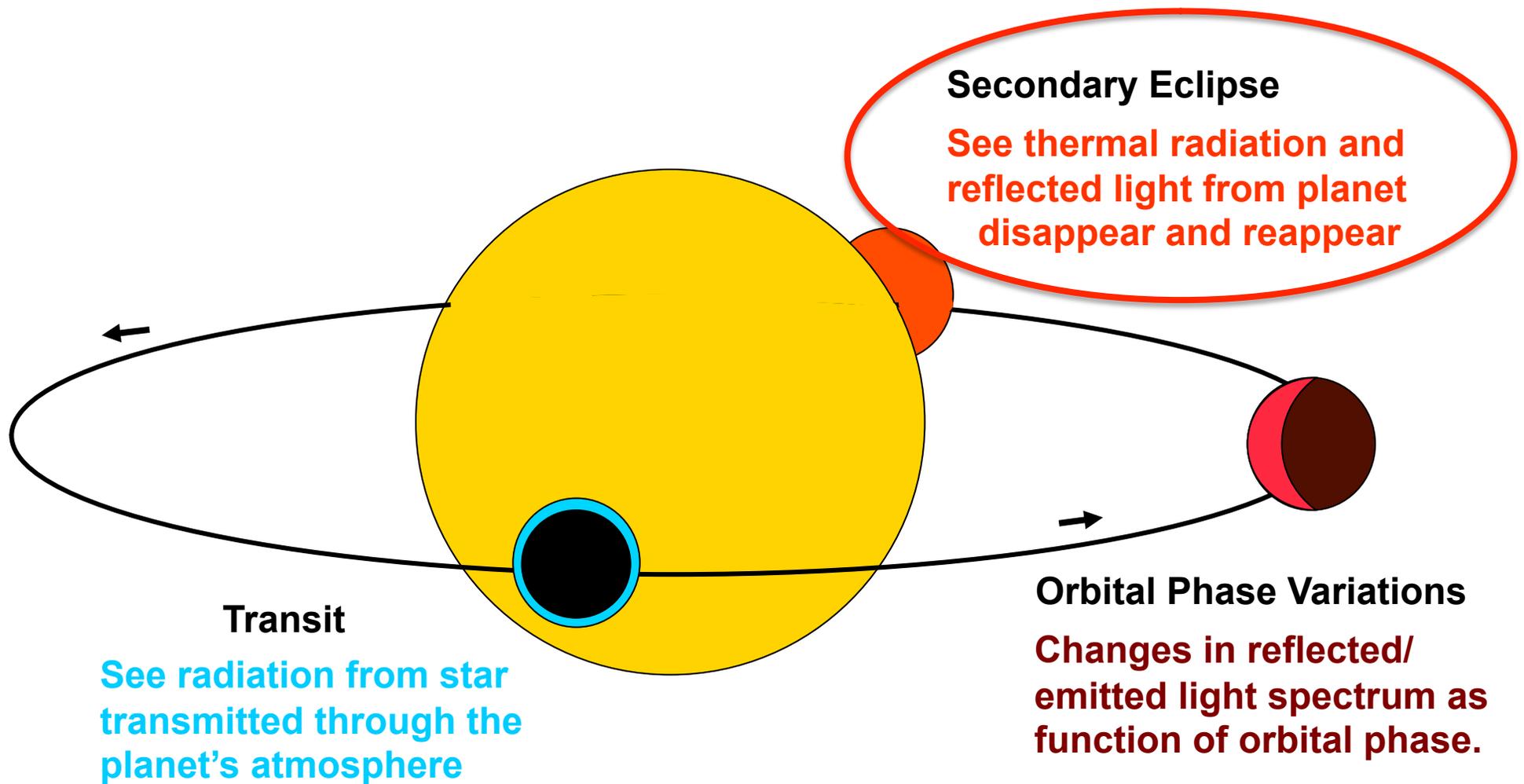
Zinc sulfide or potassium chloride (Morley et al. 2013)

Photochemical hazes like Titan?



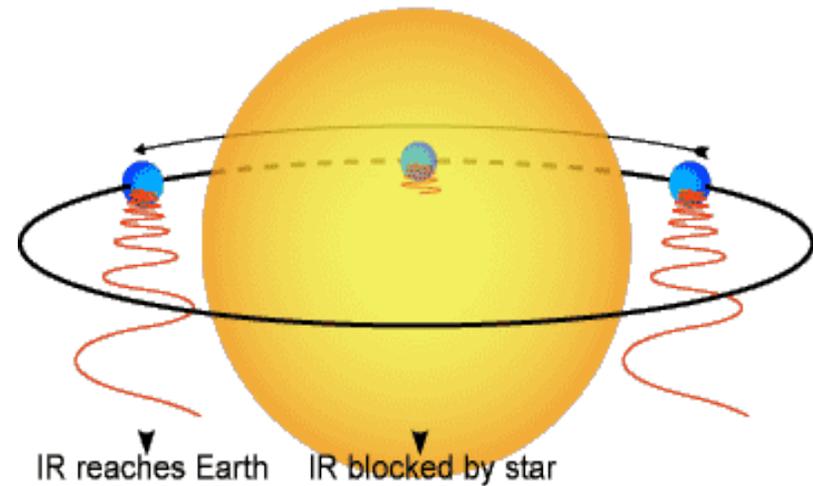
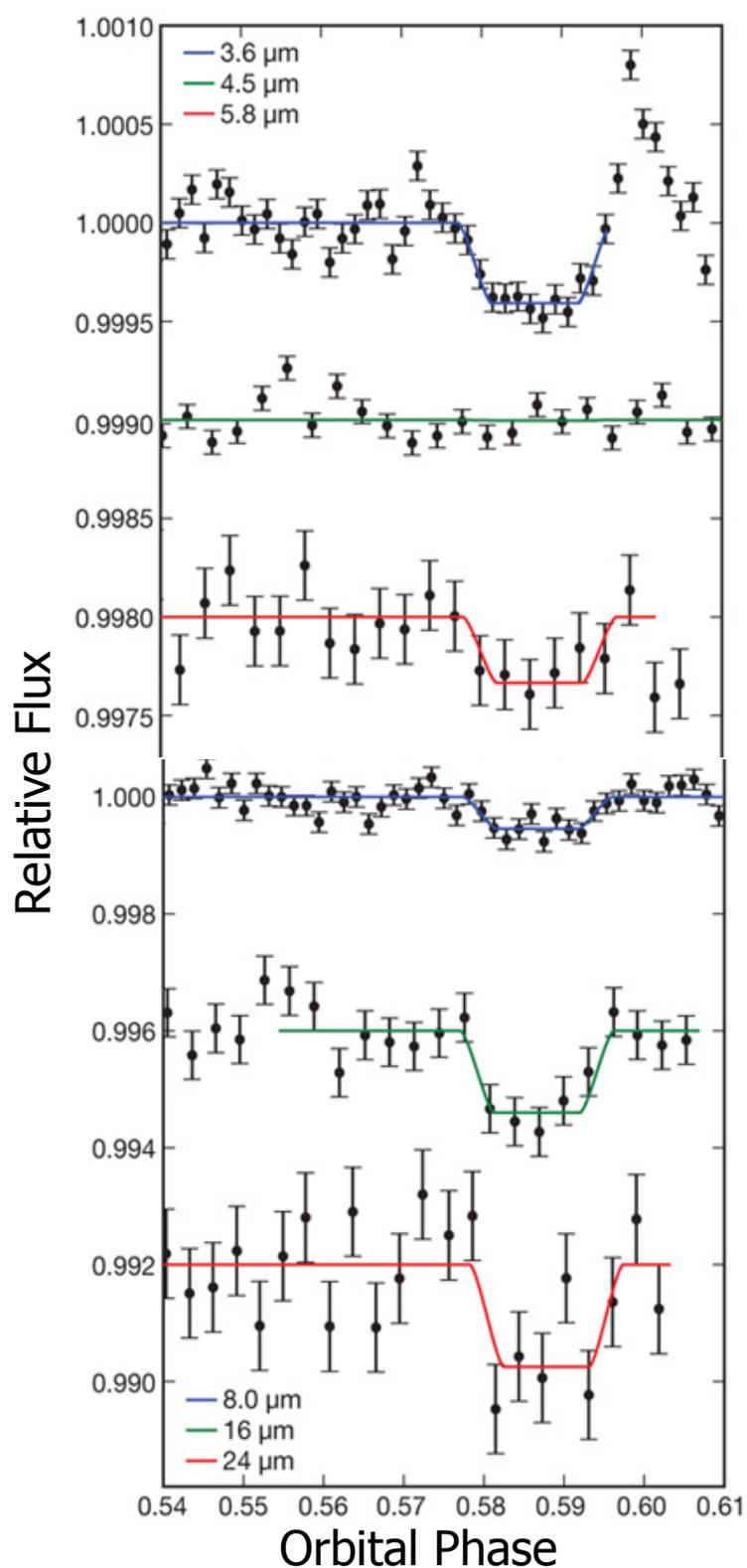
Photochemistry converts methane to "soot" (long hydrocarbon chains)

# Observations of Eclipsing Systems Allow Us to Characterize Exoplanet Atmospheres



# Constraints on GJ 436b's Dayside Emission Spectrum from *Spitzer*

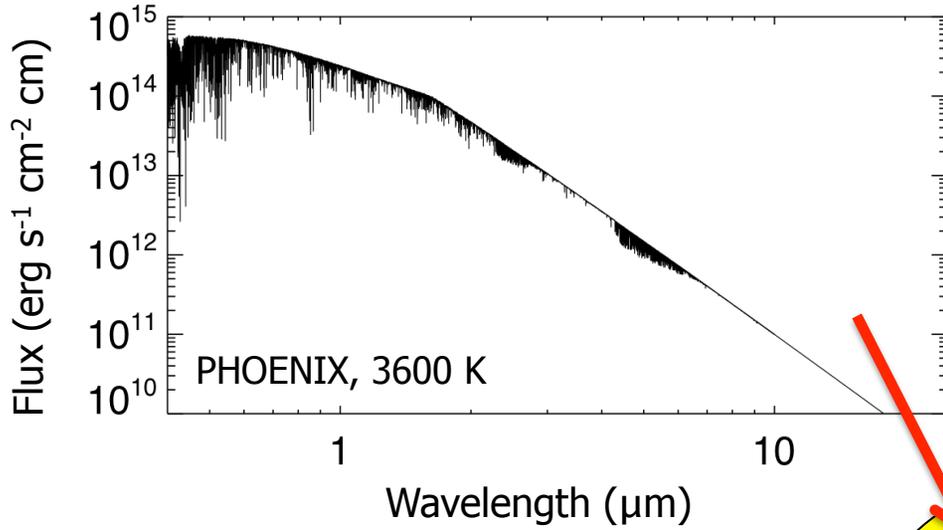
Stevenson et al. (2010, 2012)



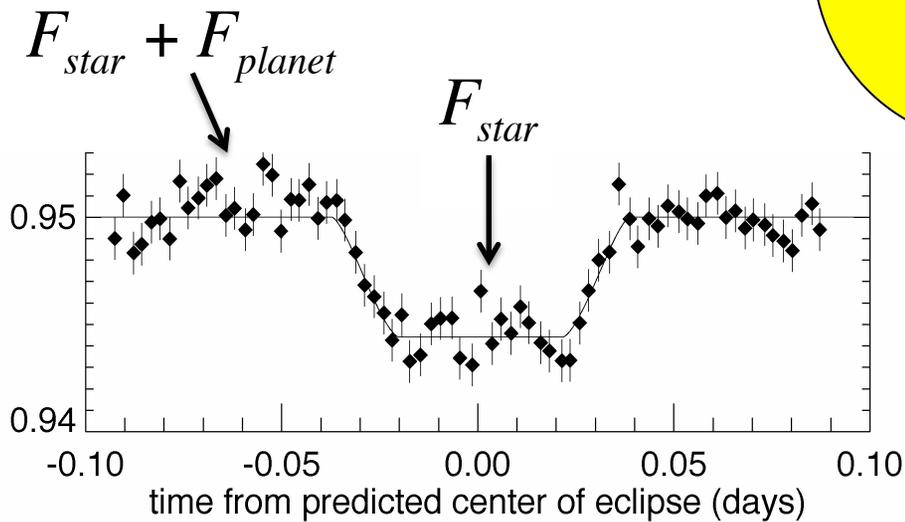
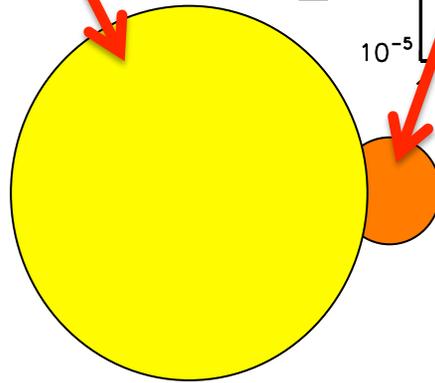
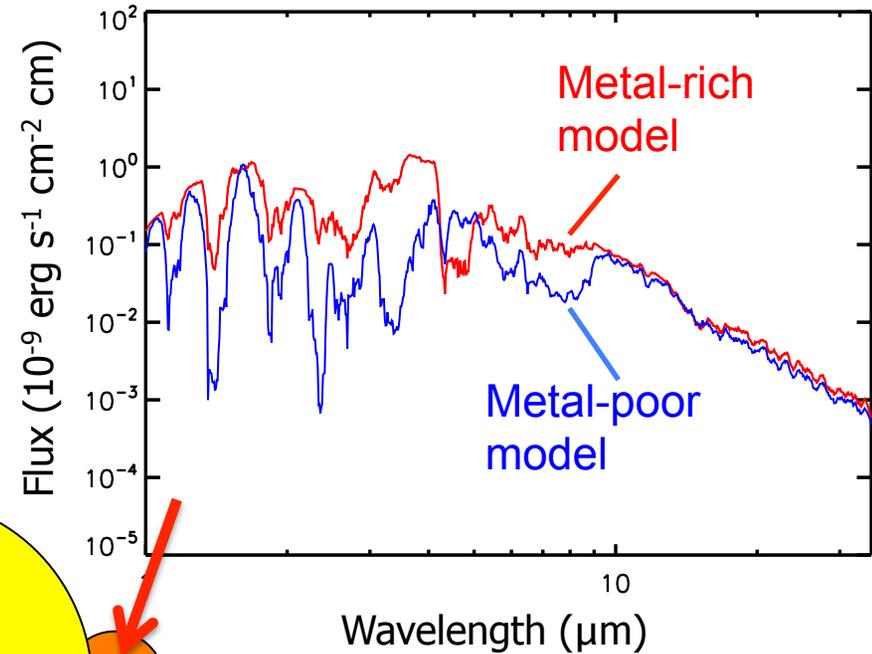
Observe the decrease in light as the planet disappears behind the star and then reappears.

# Comparison to Models

## Stellar Atmosphere Model

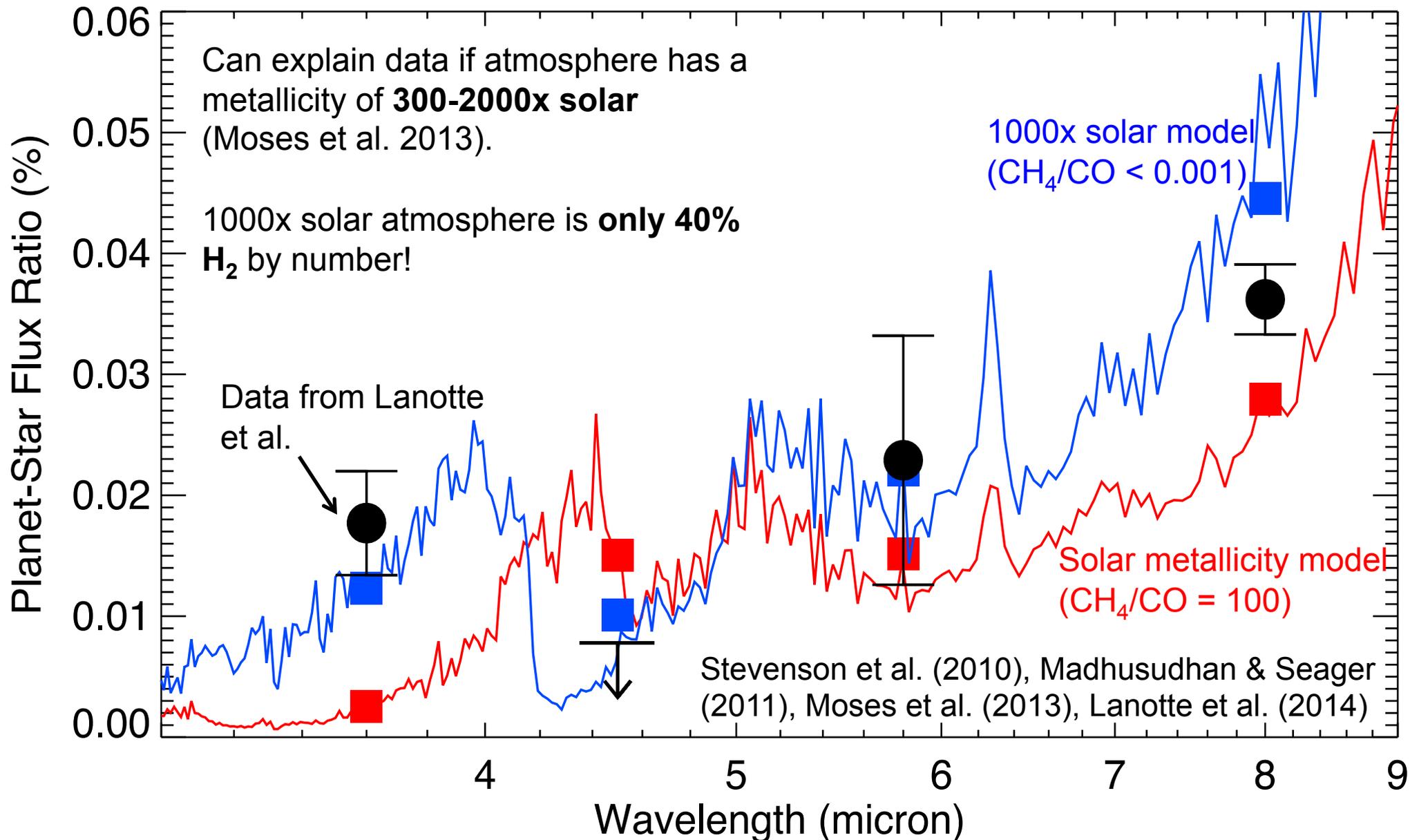


## Planet Atmosphere Models



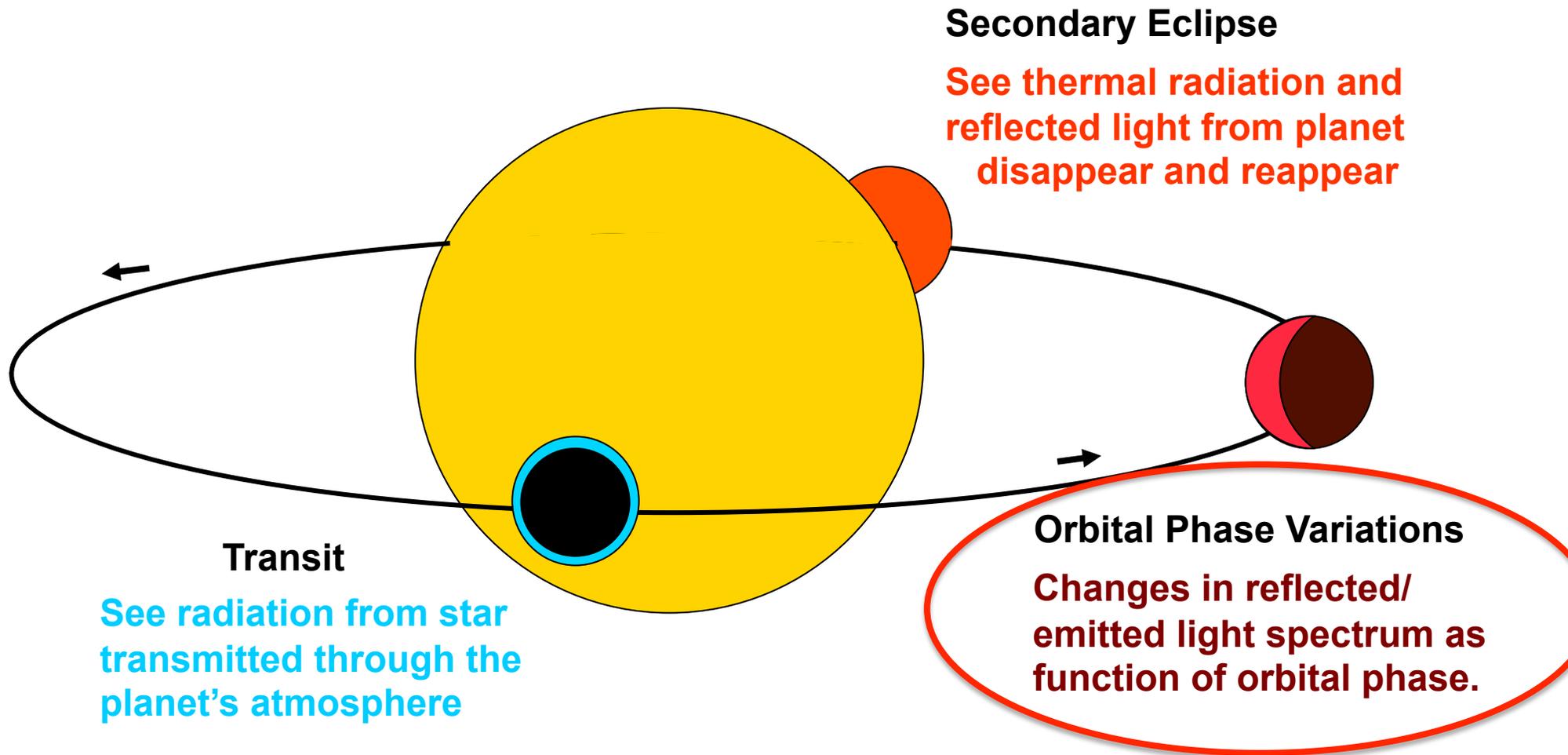
$$\text{depth}(\%) = \frac{F_{planet}}{F_{star} + F_{planet}} \approx \frac{F_{planet}}{F_{star}}$$

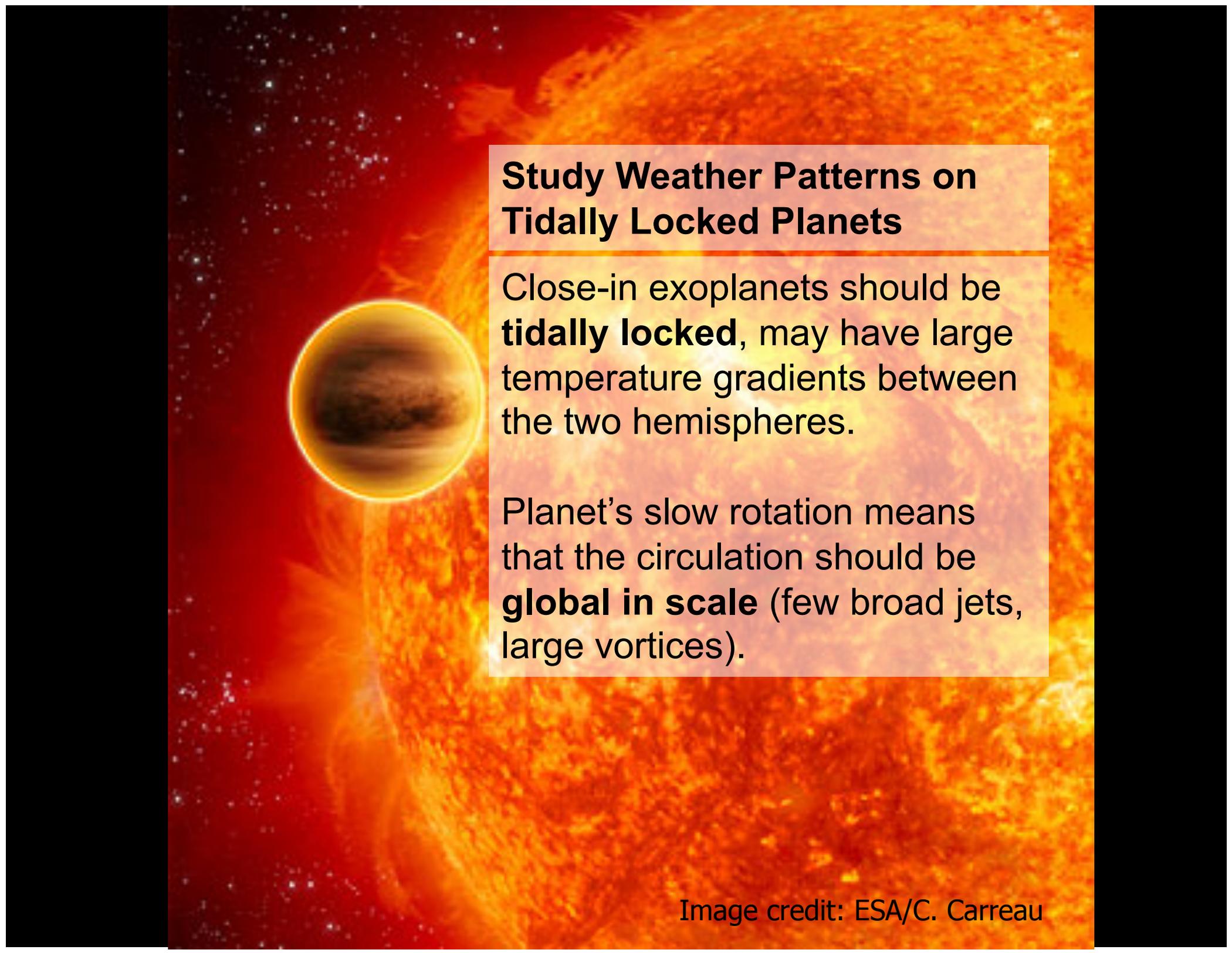
# GJ 436b: A Warm Neptune With a Metal-Rich Atmosphere



Models courtesy M. Line & J. Fortney

# Observations of Eclipsing Systems Allow Us to Characterize Exoplanet Atmospheres



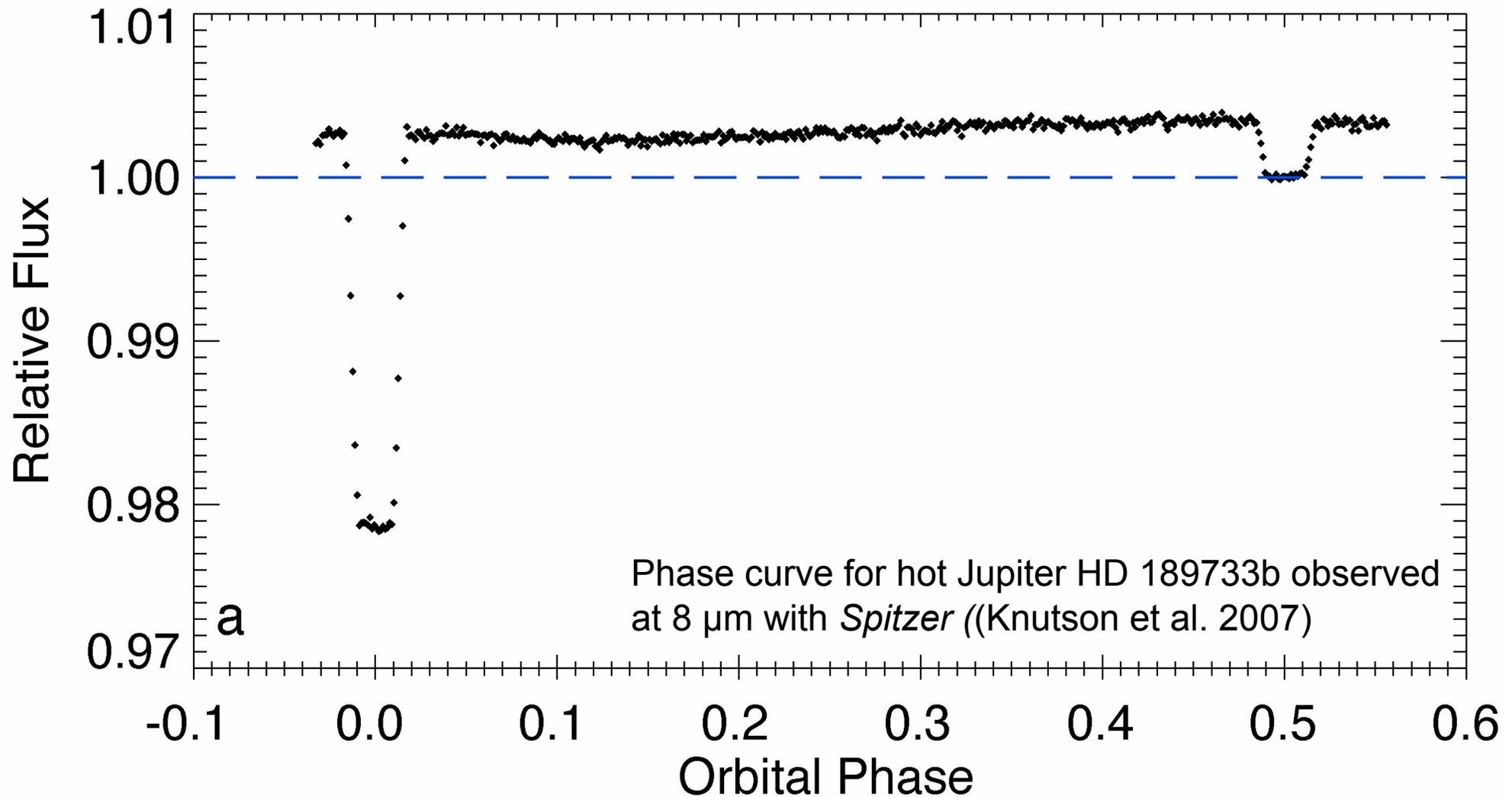
The background of the slide is a vibrant, fiery orange and red star, likely a red dwarf, with a smaller planet in the foreground. The planet is a pale yellowish-brown color with some darker, horizontal bands, suggesting a cloudy or atmospheric structure. The star's surface is highly textured with bright, irregular patterns, and the overall scene is set against a dark, star-filled space.

## Study Weather Patterns on Tidally Locked Planets

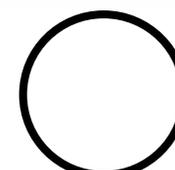
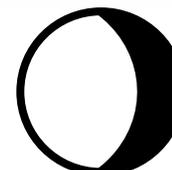
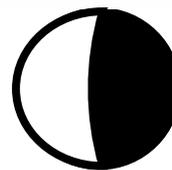
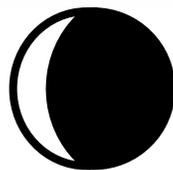
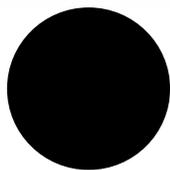
Close-in exoplanets should be **tidally locked**, may have large temperature gradients between the two hemispheres.

Planet's slow rotation means that the circulation should be **global in scale** (few broad jets, large vortices).

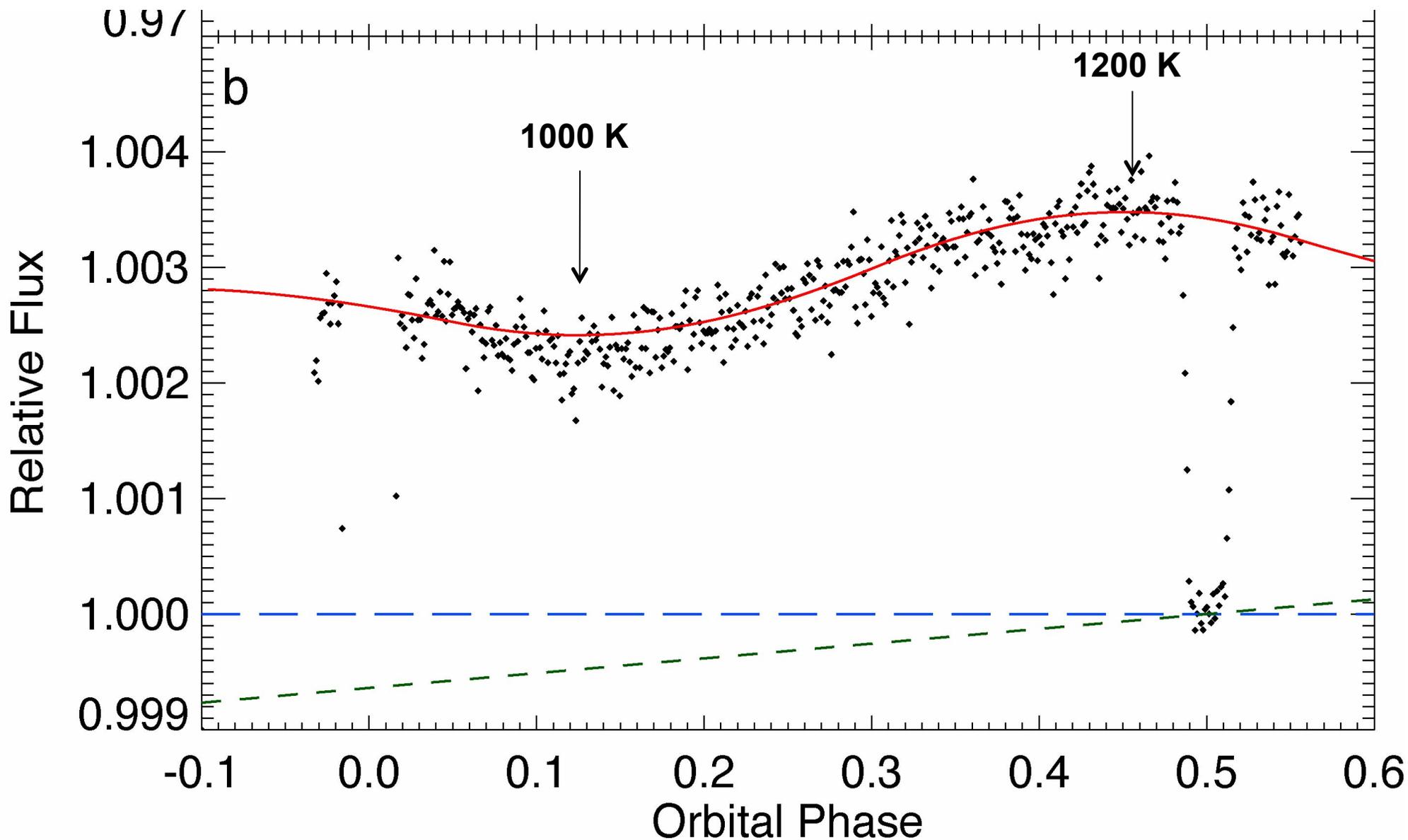
# Constraints on Atmospheric Circulation from Phase Curve Observations



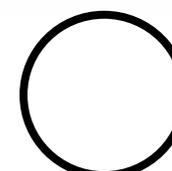
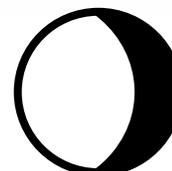
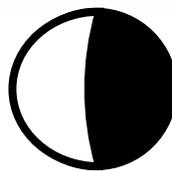
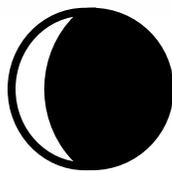
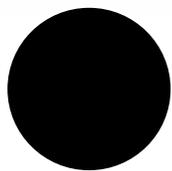
Observer's View of Planet



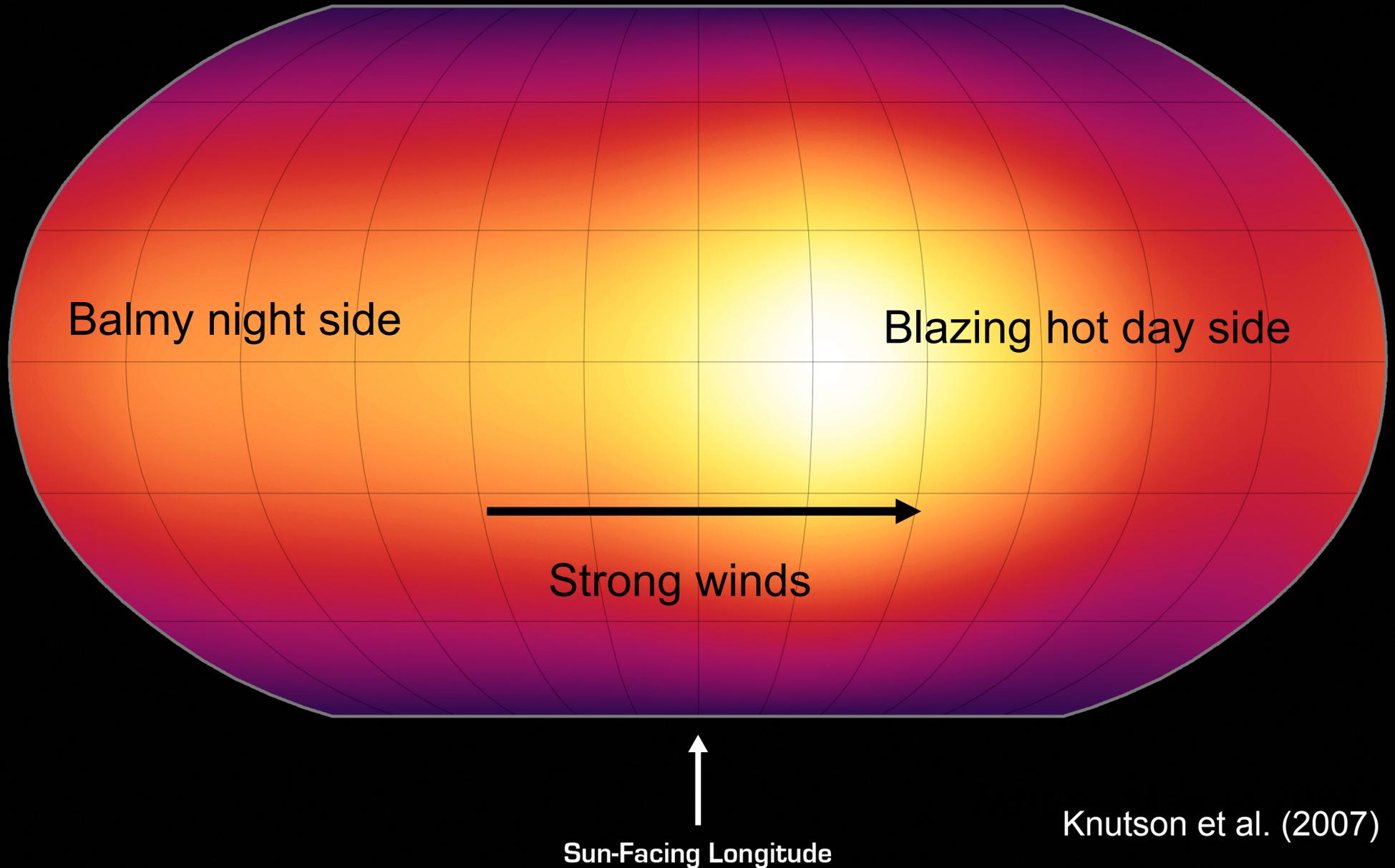
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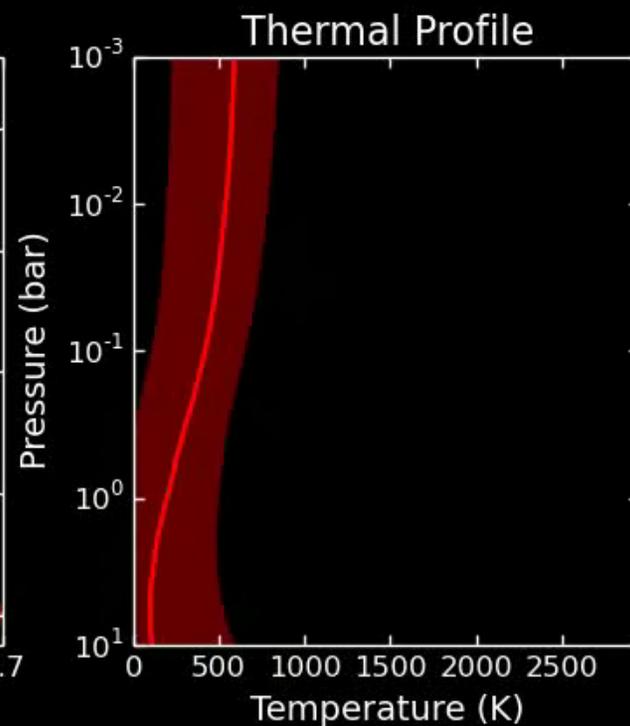
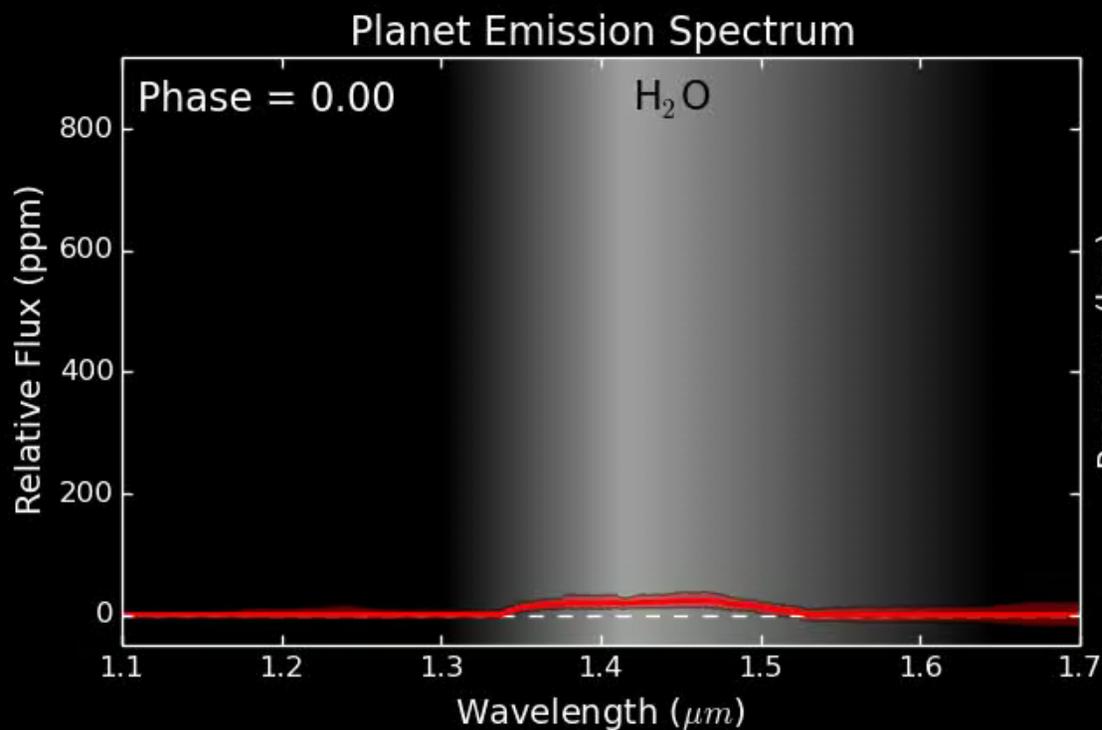
Observer's View  
of Planet



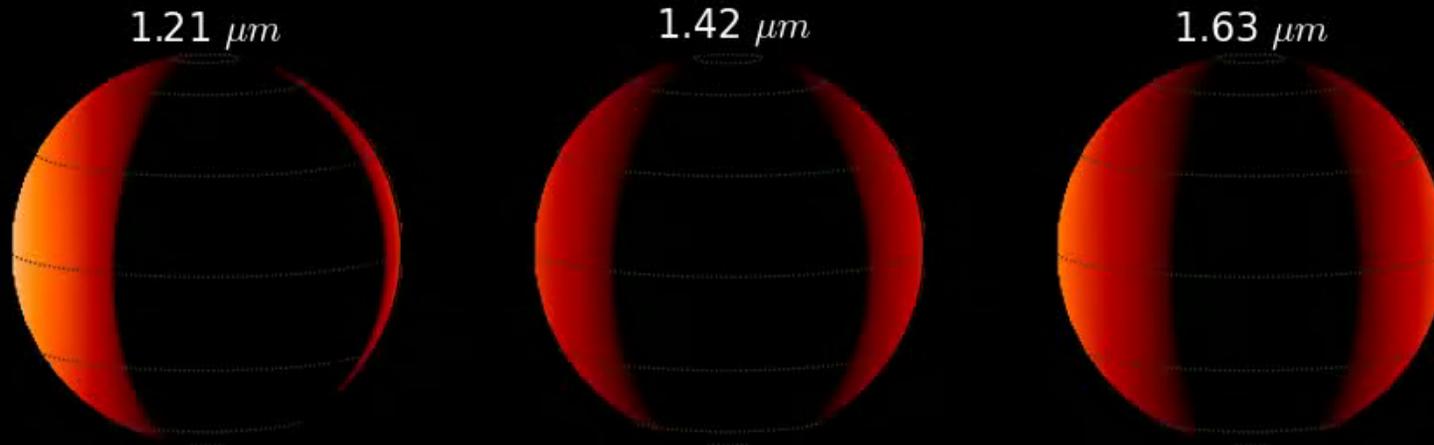
# Phase Curves Allow Us to Map Atmospheric Circulation Patterns for Tidally Locked Planets



# Multi-Wavelength Observations Map Thermal + Chemical Gradients in Atmosphere



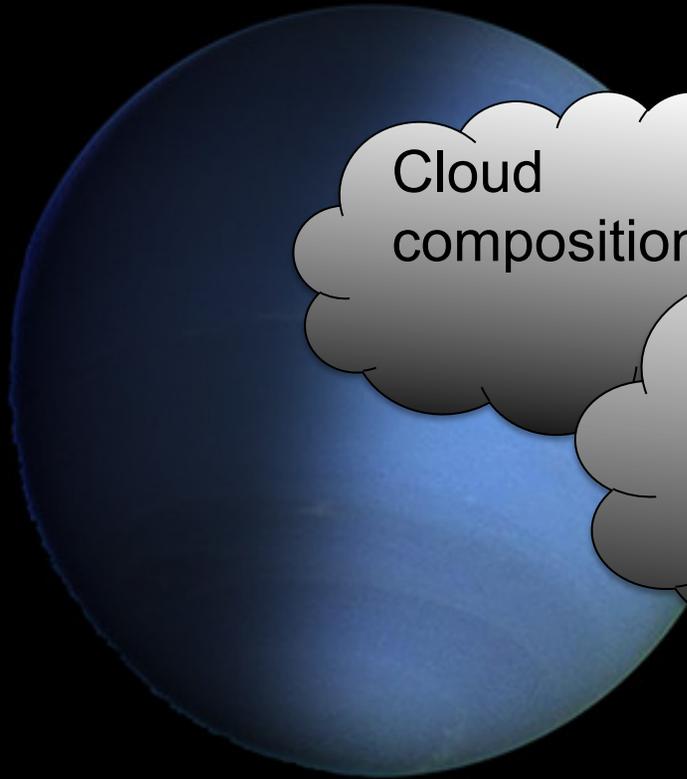
Brightness Temperature Maps



Stevenson et al. (2014)

# Conclusions: What Can We Learn from Atmosphere Studies?

Gas Giants



Cloud compositions?

Super-Earths



Can we pick cloud-free planets to study?

Habitable Zone Earths



Effect of tidal locking on planet climate?

Does atmospheric metallicity increase with decreasing mass?

Formation in situ or inward migration?

Planets drawn to scale.