Introduction to Transit (and Secondary Eclipse) Spectroscopy

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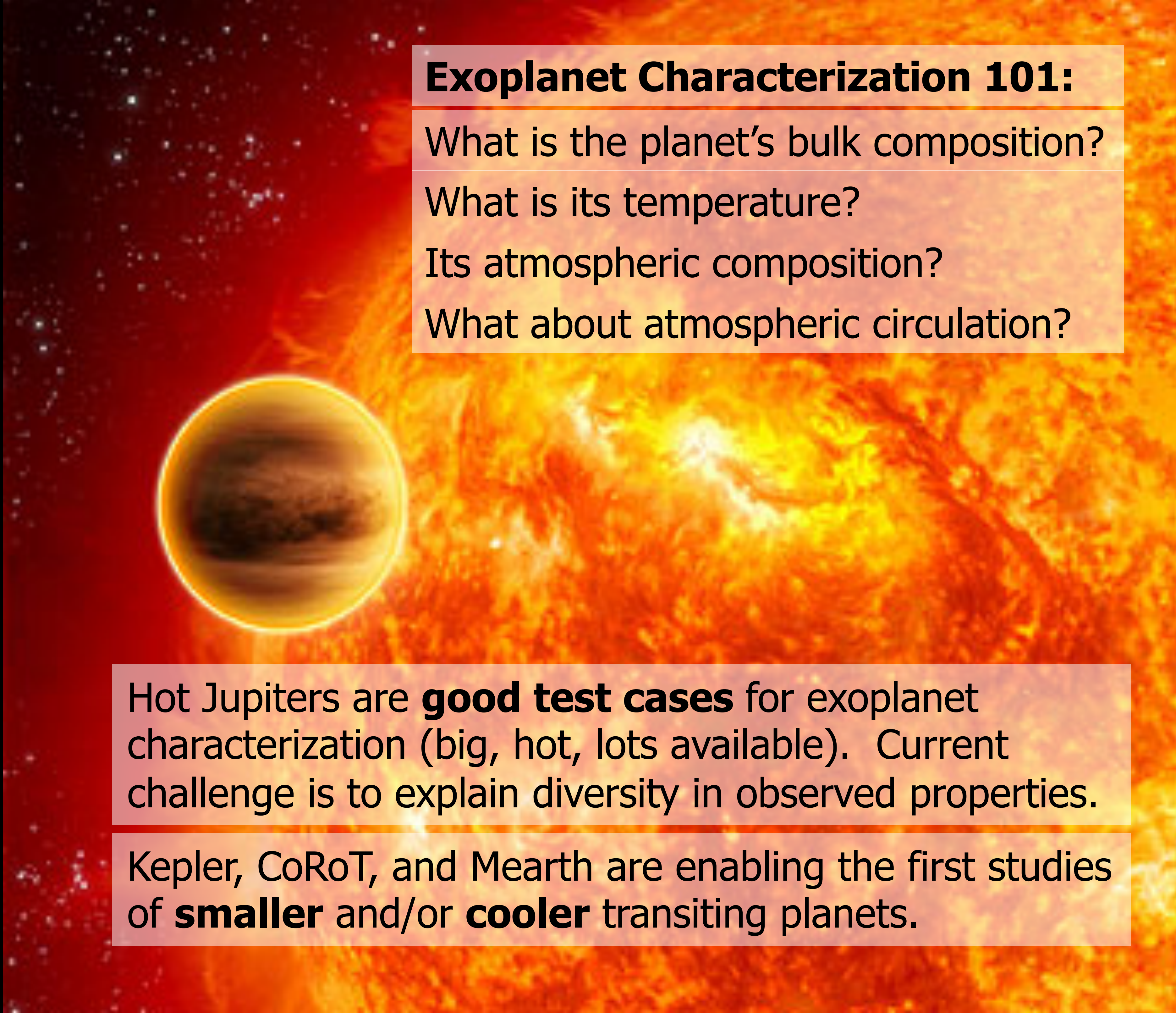
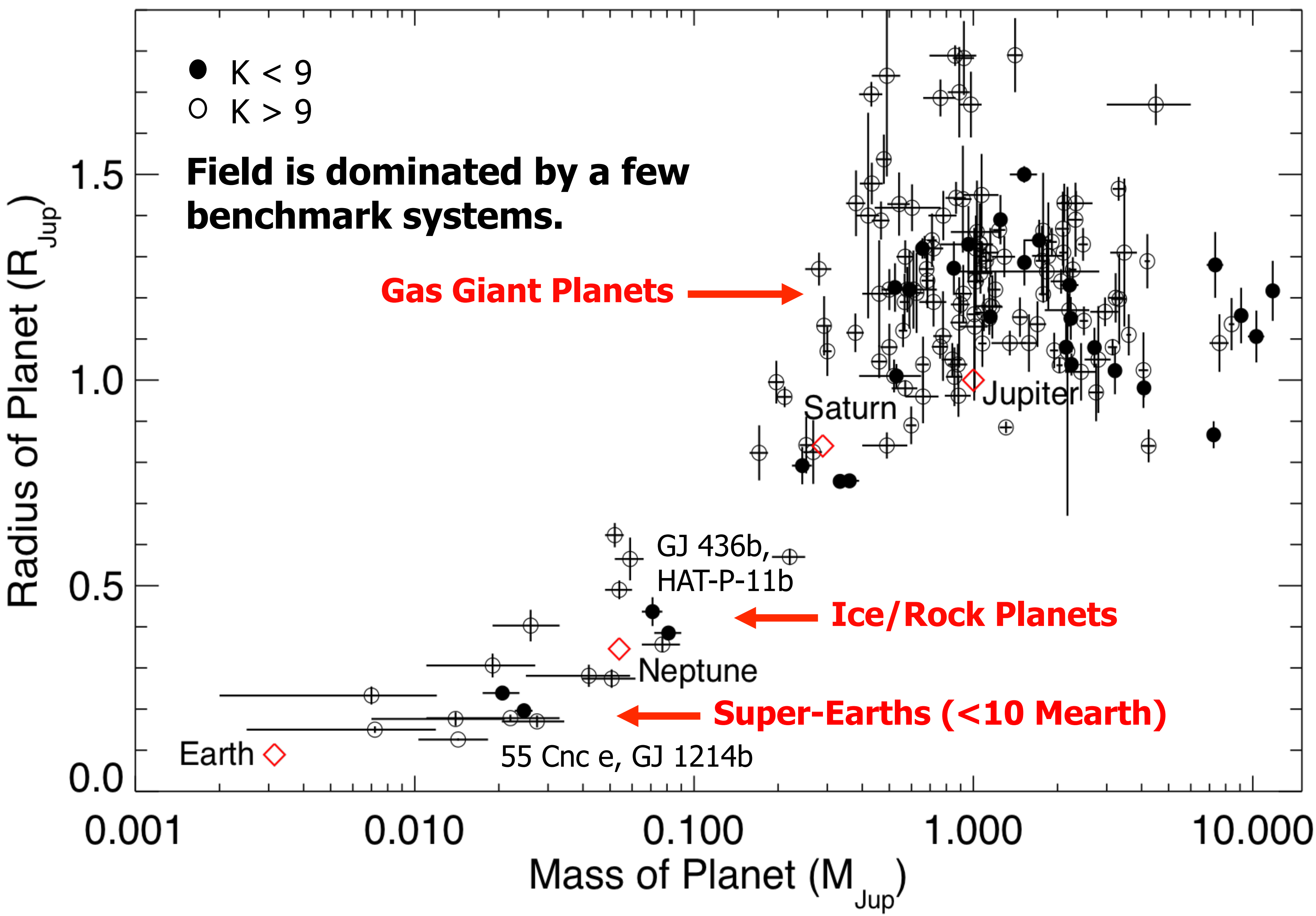

Exoplanet Characterization 101:
What is the planet's bulk composition?
What is its temperature?
Its atmospheric composition?
What about atmospheric circulation?
Hot Jupiters are **good test cases** for exoplanet characterization (big, hot, lots available). Current challenge is to explain diversity in observed properties.
Kepler, CoRoT, and Mearth are enabling the first studies of **smaller** and/or **cooler** transiting planets.

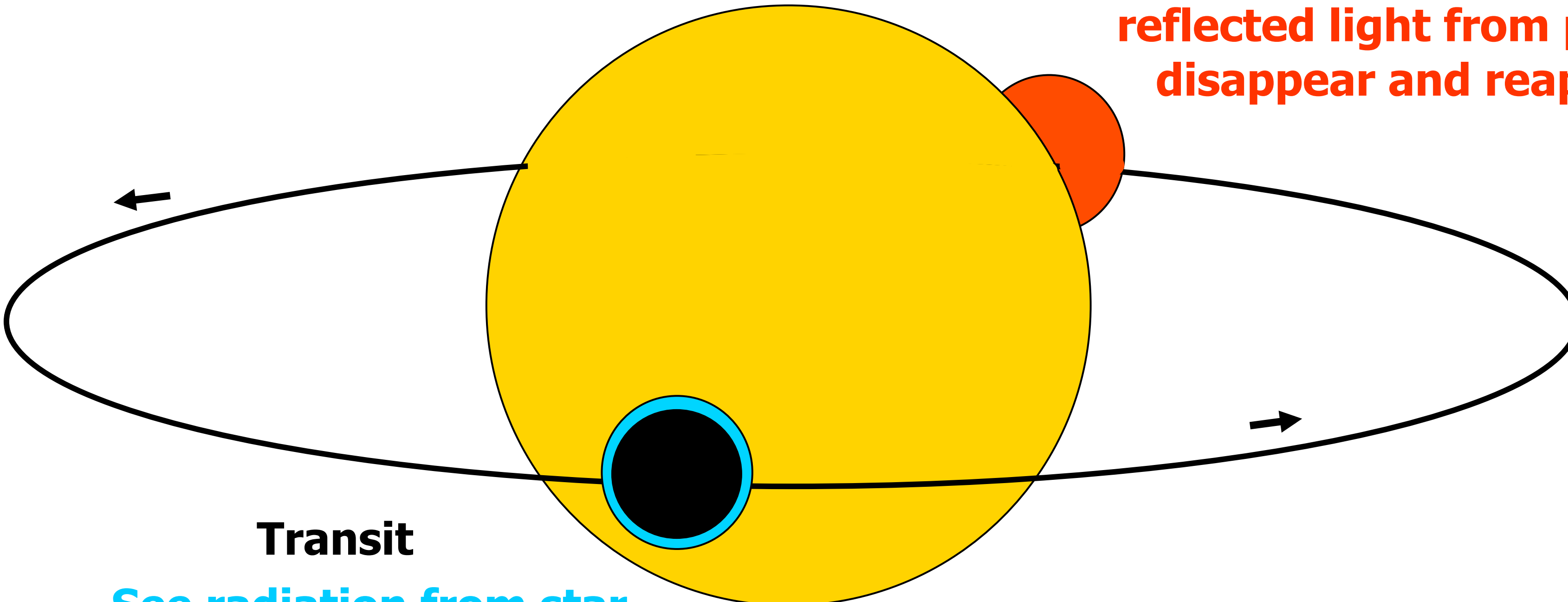
Bright Stars Make the Best Targets for Atmosphere Studies



What Do Different Types of Events Tell Us About the Planet's Atmosphere?

Secondary Eclipse

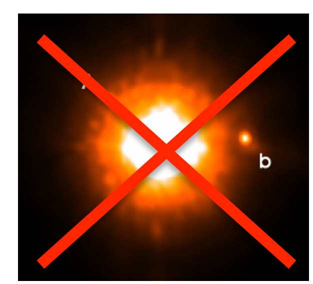
See thermal radiation and reflected light from planet disappear and reappear



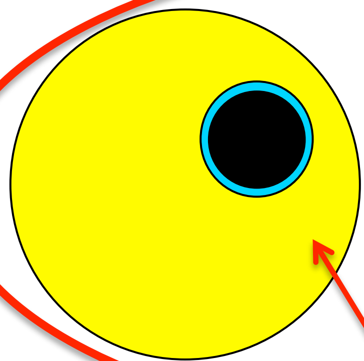
Transit

See radiation from star transmitted through the planet's atmosphere

Why eclipsing systems?
Can characterize planets without the need to spatially resolve the planet's light separate from that of the star.



Scaling Laws for Transiting Planets

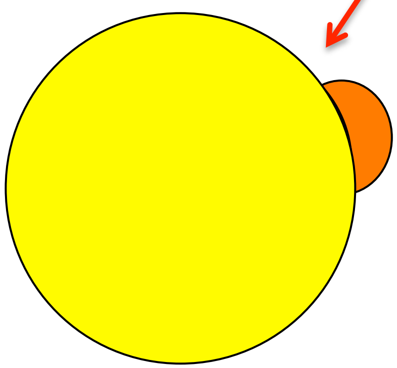


Absorption During Transit (%):

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

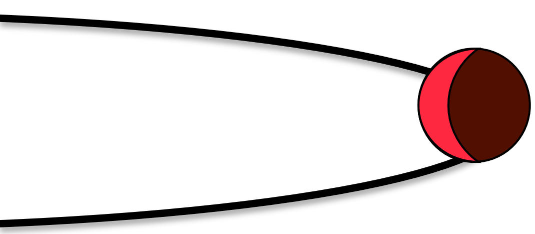
mean molecular weight

M stars preferred!



Secondary Eclipse Depth (IR):

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

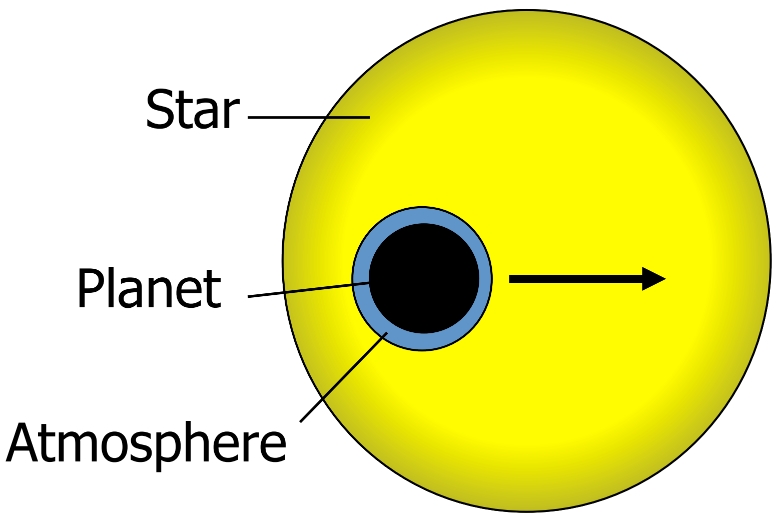


Orbital Phase Variations:

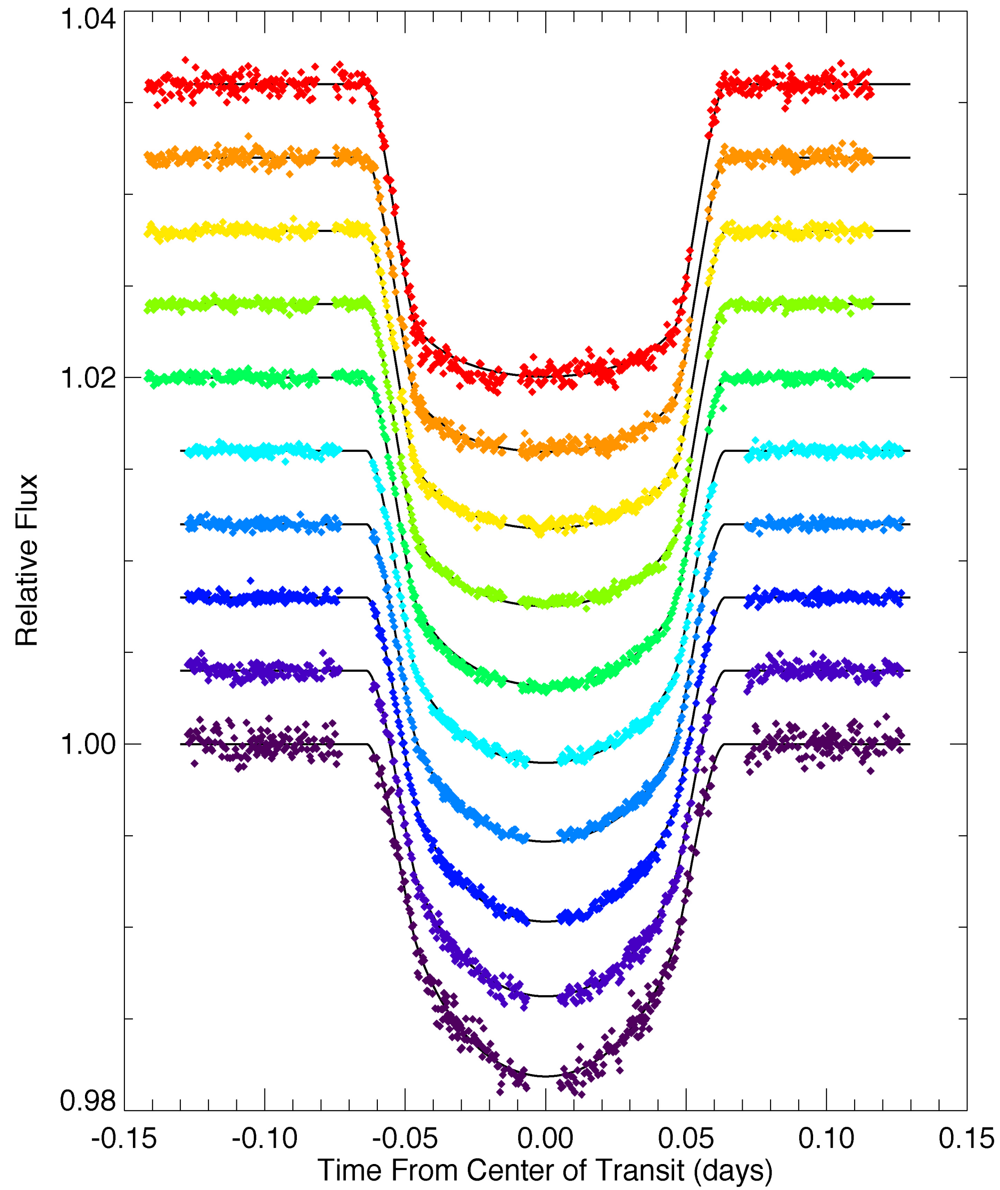
Always less than secondary eclipse depth.

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

Characterizing Atmospheres With Transmission Spectroscopy



A good understanding of **limb-darkening** is crucial for determining the planet's wavelength-dependent radius.



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

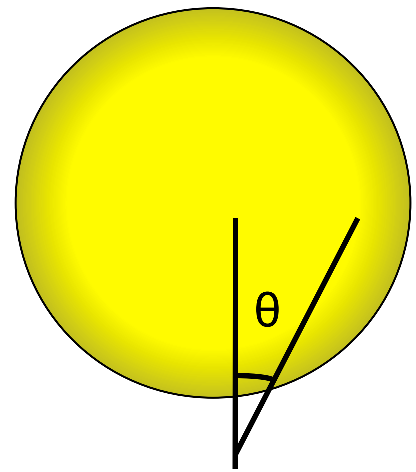
Sources of Stellar Limb-Darkening Models

Claret (2000), Mandel & Agol (2002), Sing (2012)

1. **Empirical**
   - Quadratic coefficients

2. **1D Stellar Atmosphere Models**
   - Four-parameter nonlinear coefficients
   - Kurucz/ATLAS models; good for FGK stars. Available at: http://kurucz.harvard.edu
   - PHOENIX models; better for M stars (include TiO), higher resolution in mid-IR. Available at: ftp://ftp.hs.uni-hamburg.de/pub/outgoing/phoenix/NextGen

3. **3D Models (Hayek et al. 2012)**
   - HD 189733, HD 209458



Models give I(λ,μ) where μ=cos(θ)

Calculating LD Coefficients from a Model:

1. Calculate photon-weighted average I(μ) over desired bandpass (e.g., Sing 2012)

2. Fit I(μ) with desired limb-darkening model to obtain coefficients.

Caveats and Cautions

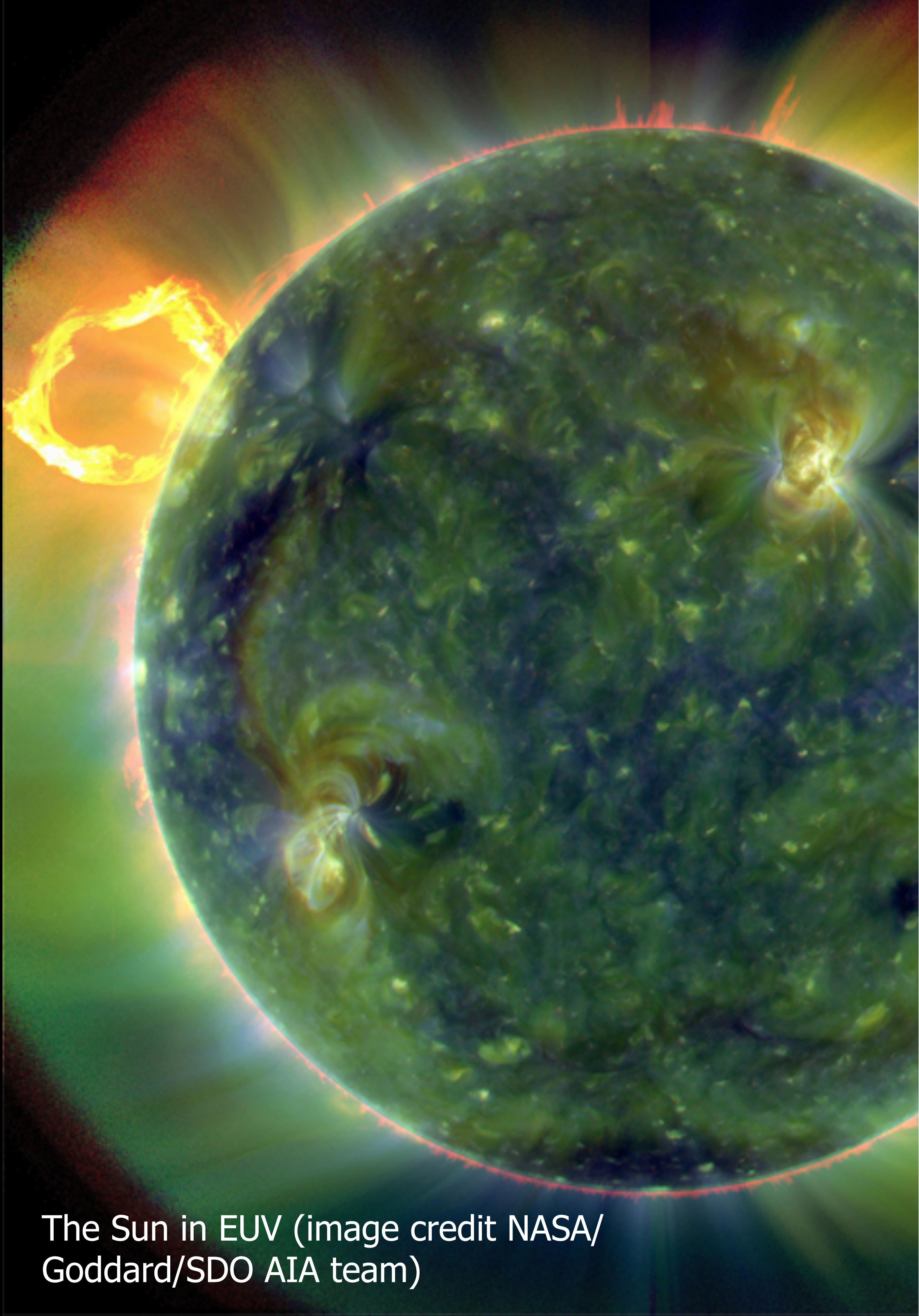
• Generally, the broader the band, the more reliable the prediction

• Limb-brightening in line cores

• Uncertainties are greater at shorter wavelengths

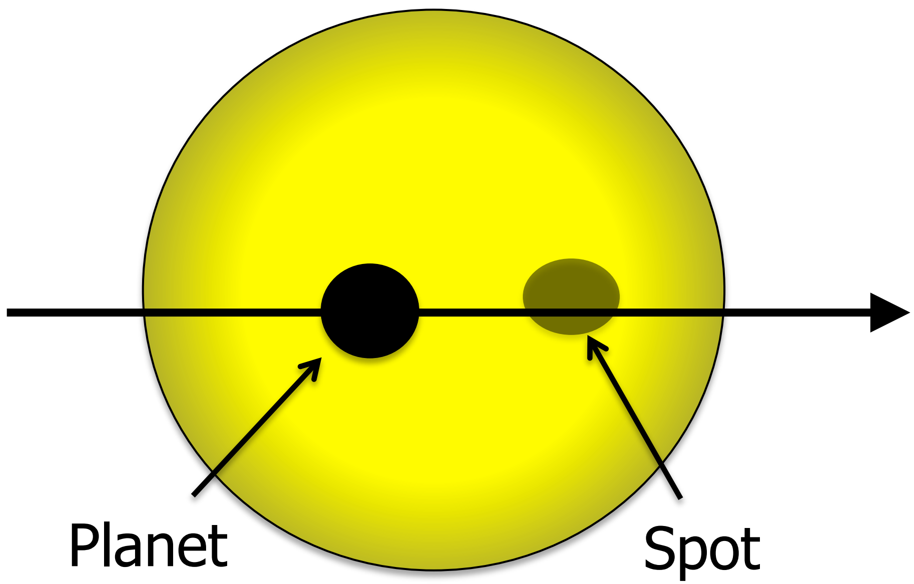
• Late M stars also more problematic (models not as reliable, well-tested)

David Sing's website is a great resource for limb-darkening coefficients: http://www.astro.ex.ac.uk/people/sing/David_Sing/Limb_Darkening.html

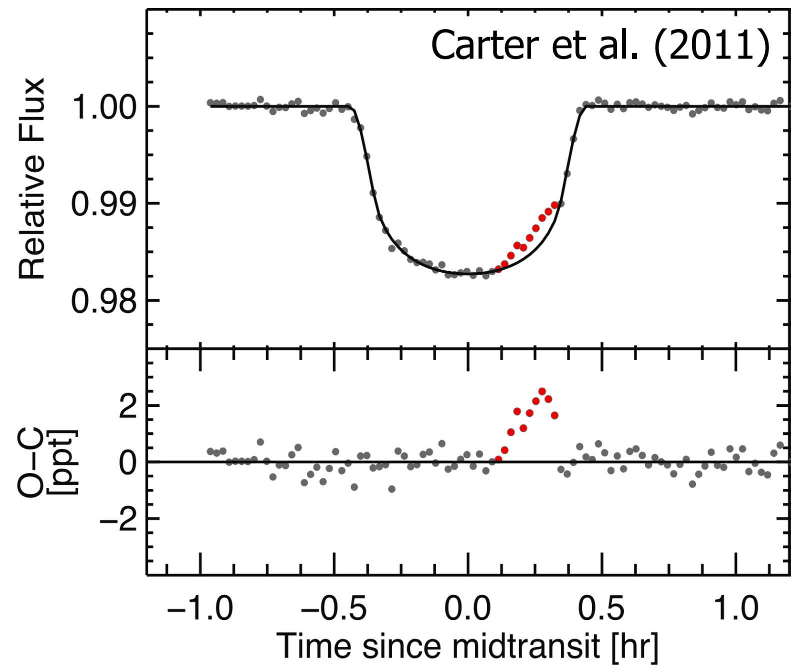


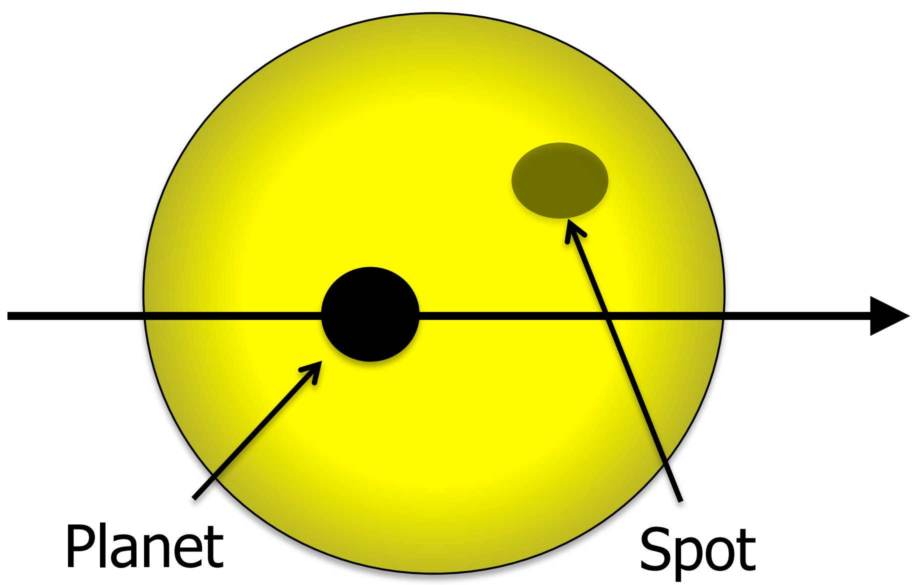
The Sun in EUV (image credit NASA/Goddard/SDO AIA team)

Stellar Activity is Bad for Transits

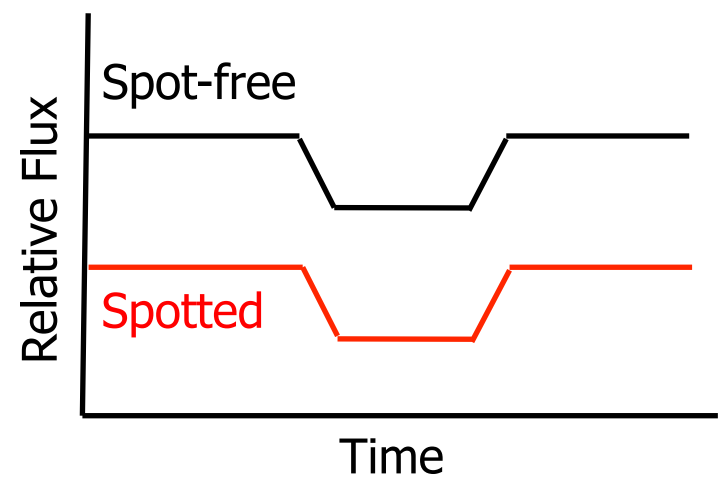


Scenario 1: Occulted Spot

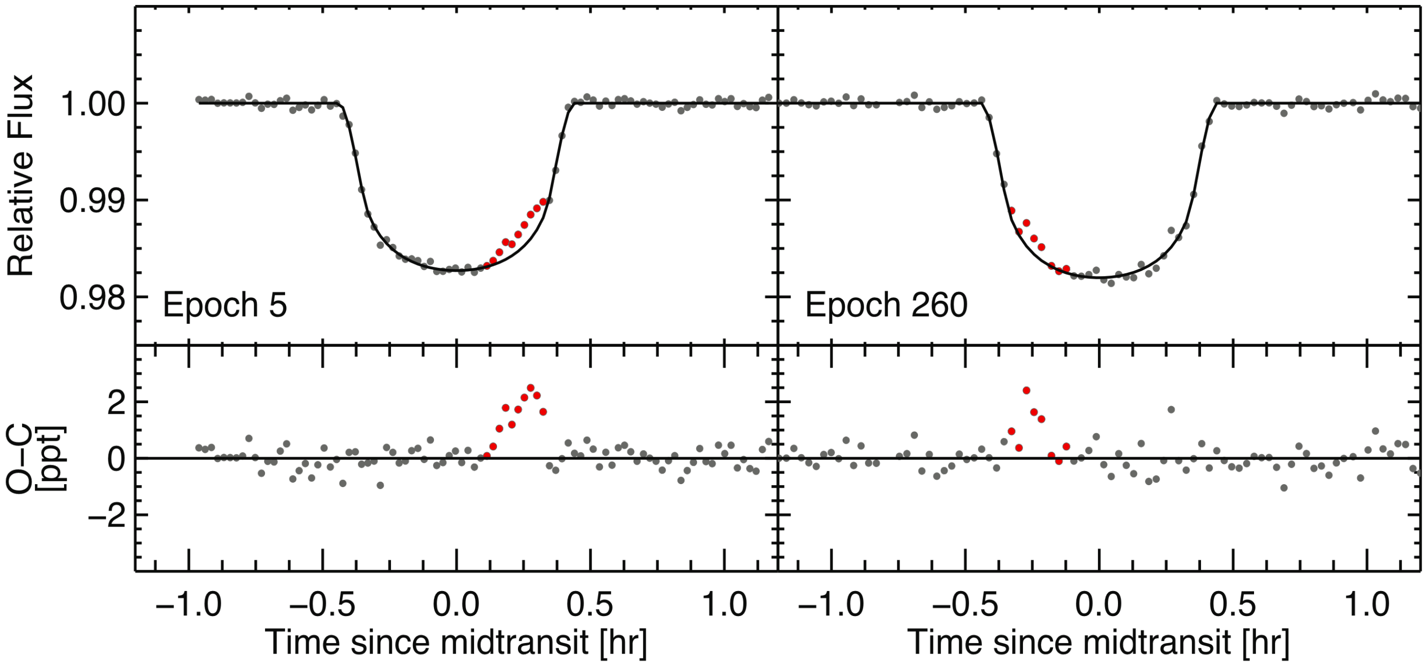




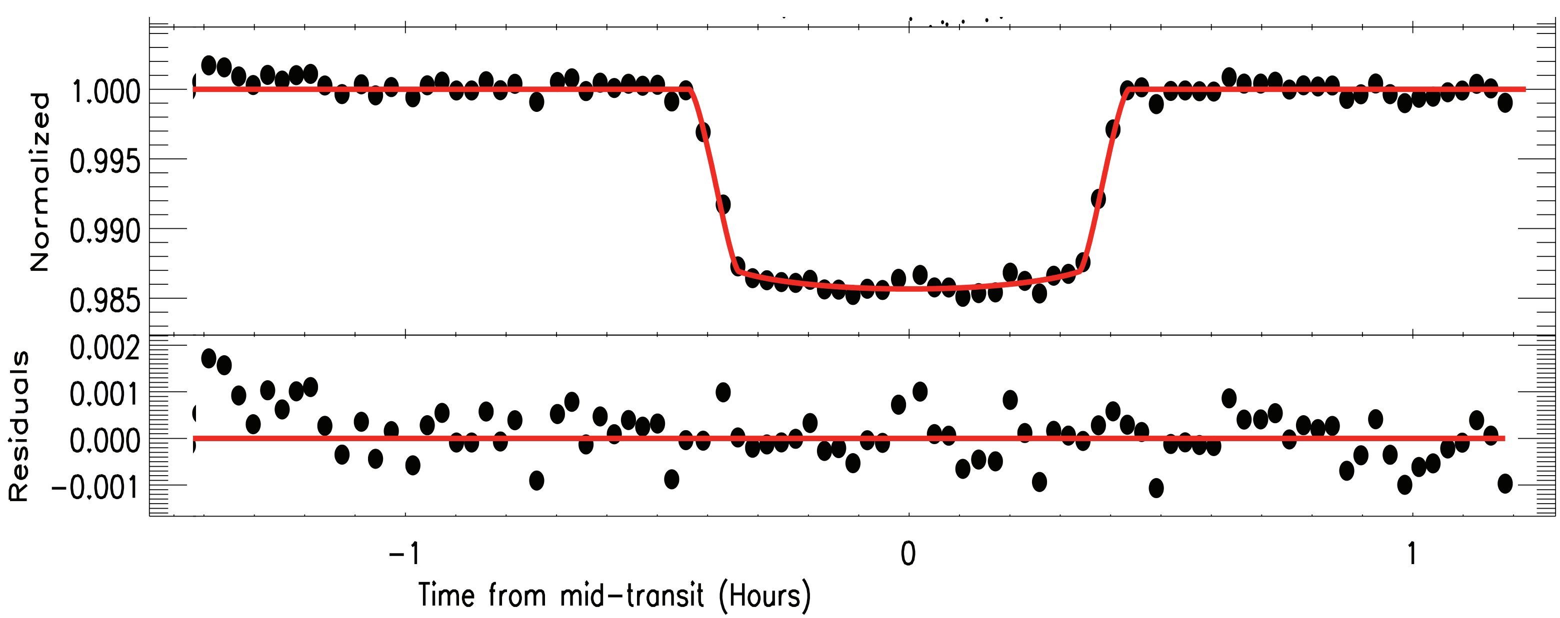
Scenario 2: Non-Occulted Spot



Will Stellar Activity Affect All Transiting Planets Orbiting M Stars?



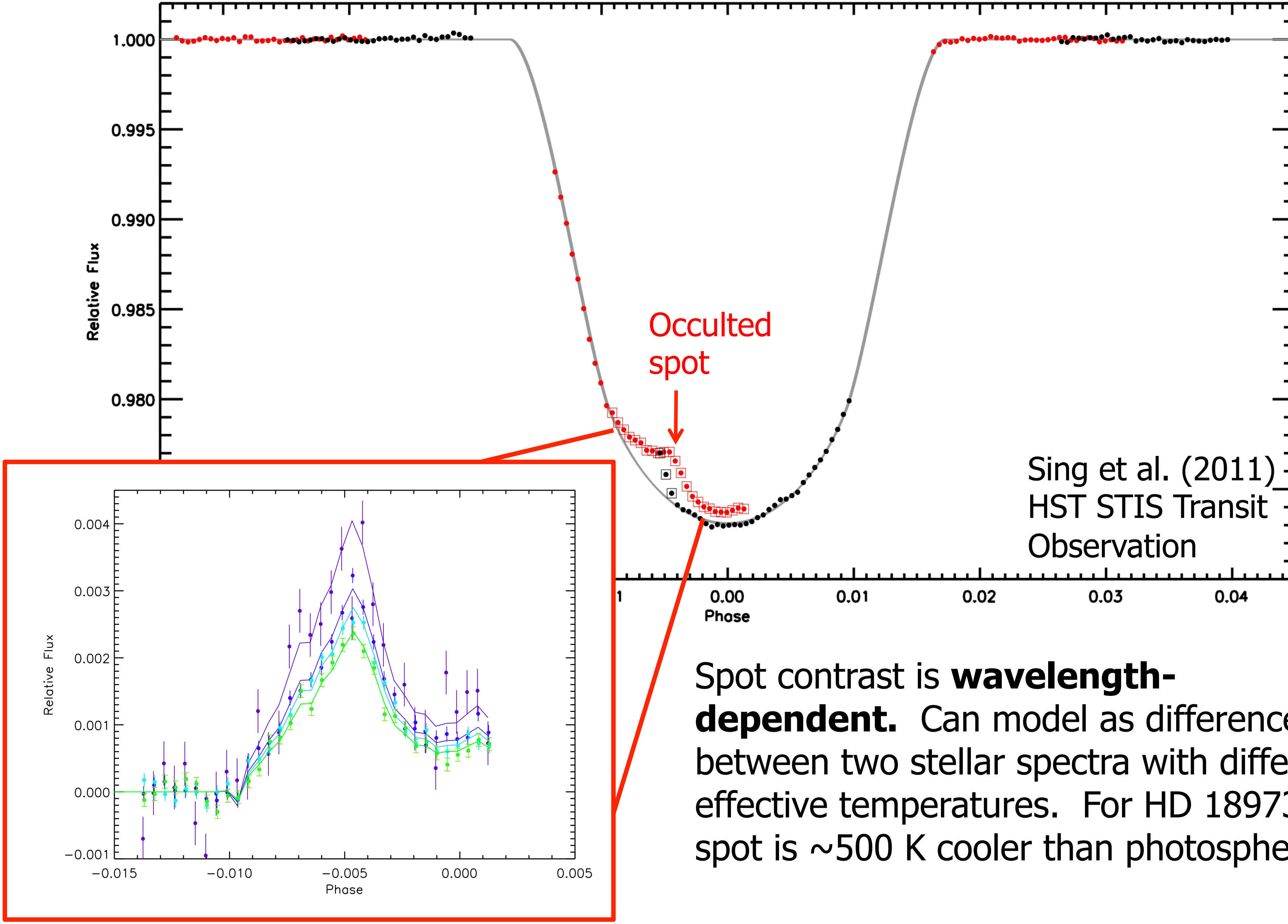
R′ band transits of GJ 1214b, 6.5 m Magellan Clay telescope (Carter et al. 2011)



Spitzer 4.5 μm transit of GJ 1214b (Desert et al. 2011)

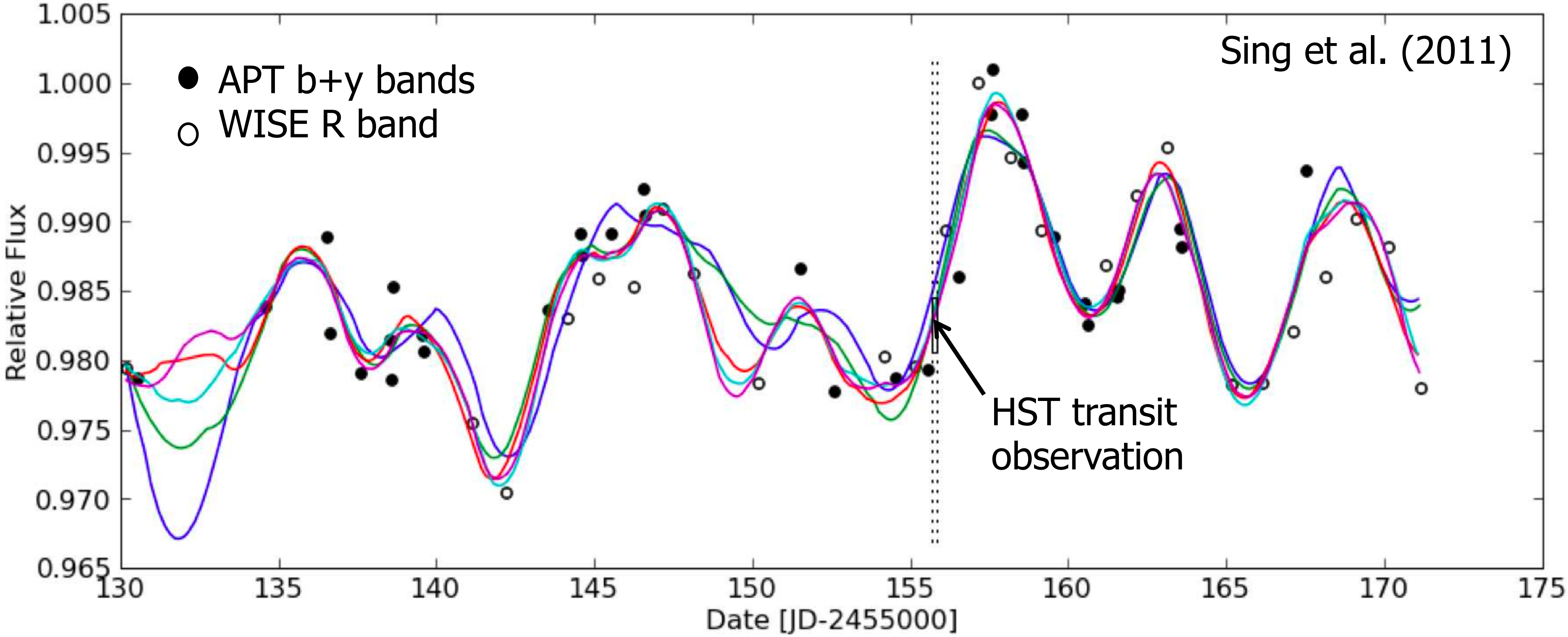
Effect of spots + LD is minimized at longer wavelengths.

HD 189733: What to do when spots are unavoidable.



Spot contrast is **wavelength-dependent.** Can model as difference between two stellar spectra with different effective temperatures. For HD 189733, spot is ~500 K cooler than photosphere.

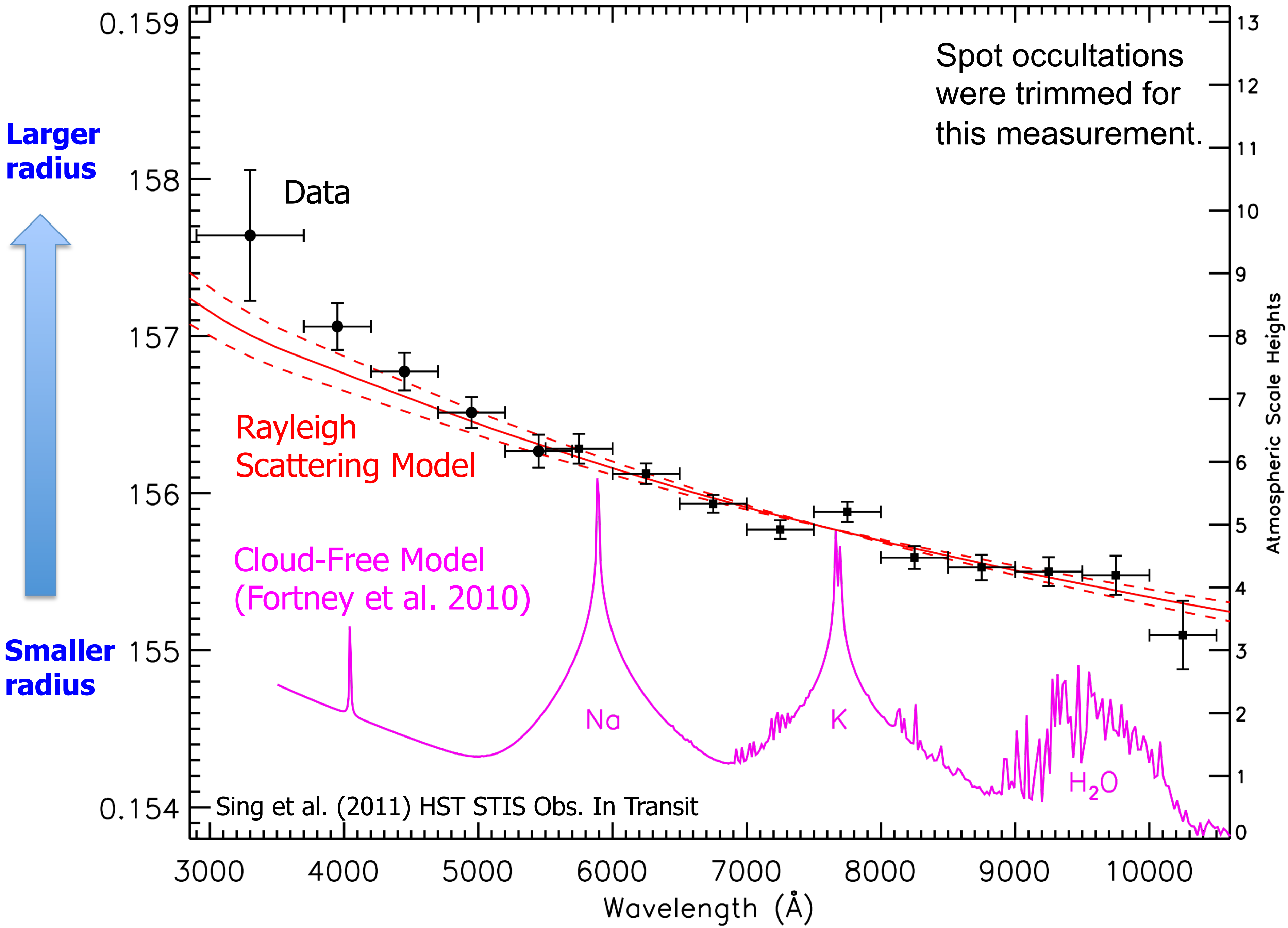
Correcting for Unocculted Spots With Ground-Based Monitoring Data



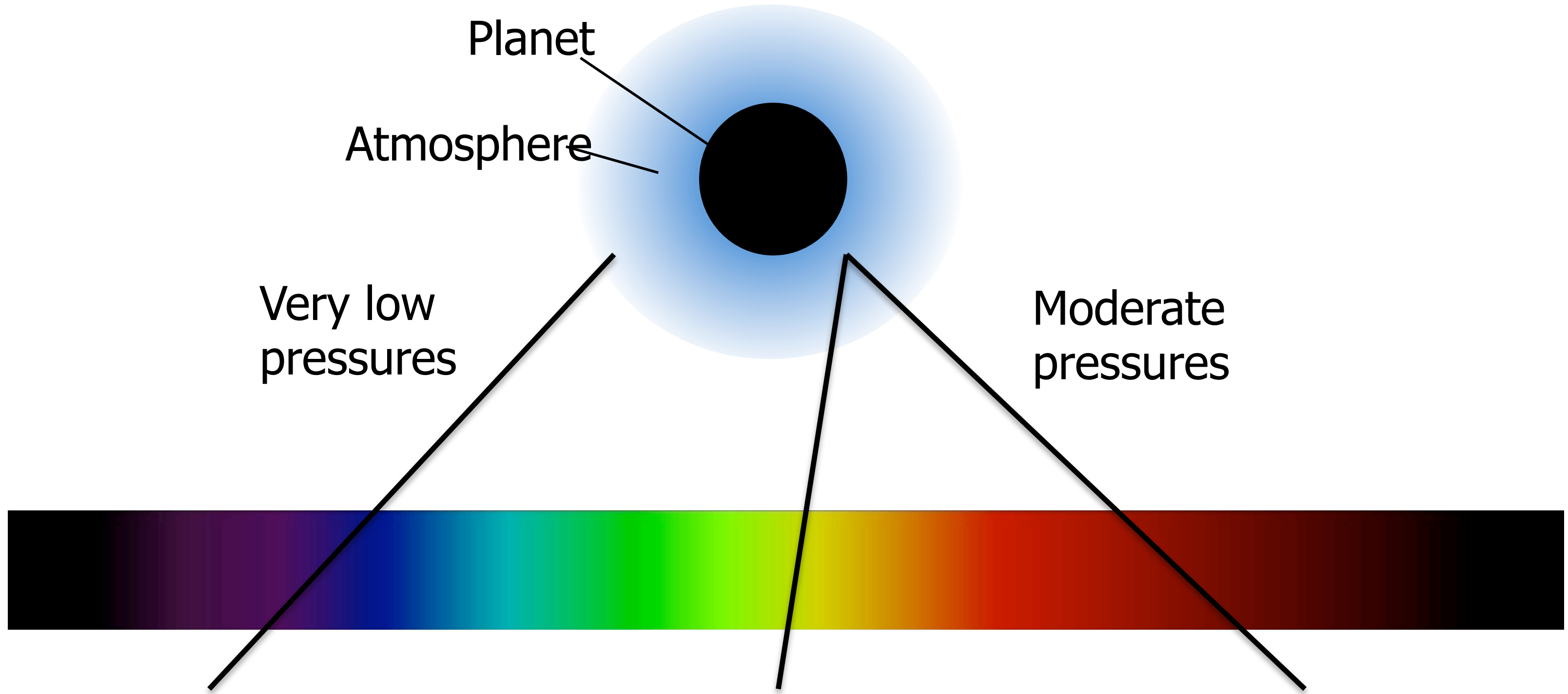
Three-Step Spot Correction
(Sing et al. 2011)

1. Determine spot temperature from occulted spots.
2. Determine decrease in flux dF due to spots at time of observations.
3. Use model spot spectra to convert dF to band of transit observations, add dF to transit light curve and fit for transit depth.

Result: A High-Altitude Haze

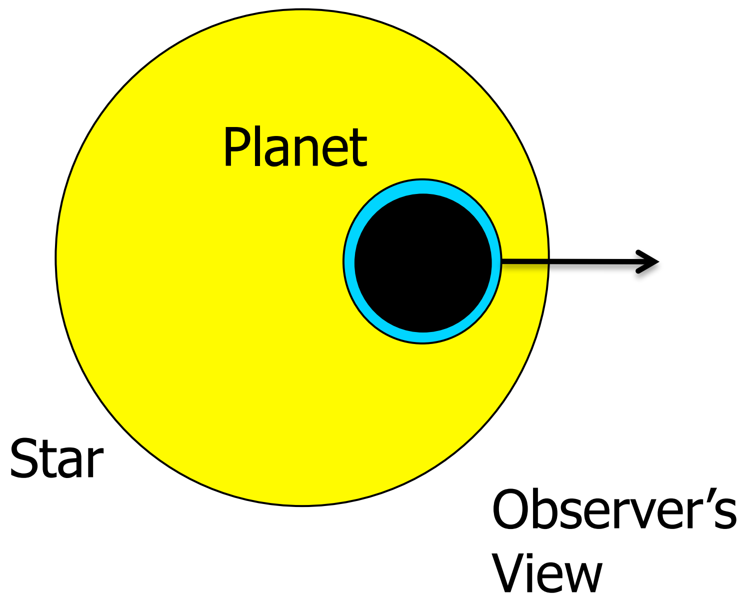


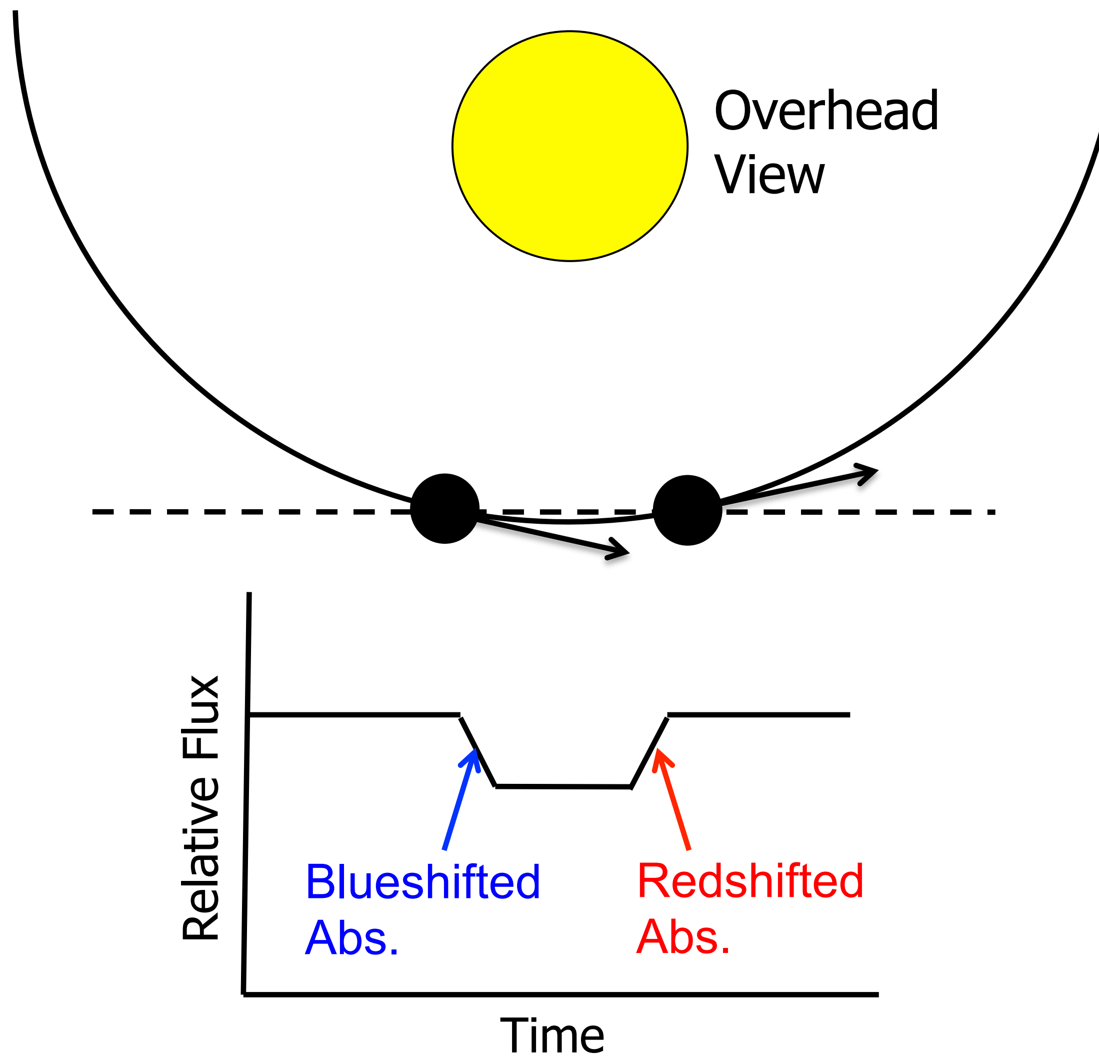
What Do We Learn From Transmission Spectroscopy?



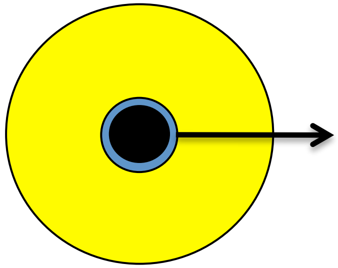
Wavelength	**UV**	**Visible**	**Infrared**
What do we measure?	Lyman alpha, ionized metals	Sodium, potassium, TiO(?)	Water, methane, CO, CO_2
What do we learn?	Atmospheric mass loss	Clouds/hazes or transparent? Other absorbers?	Is the chemistry in equilibrium?

A Less Conventional Transit Observation: Doppler Shifts with High Resolution IR Spectroscopy



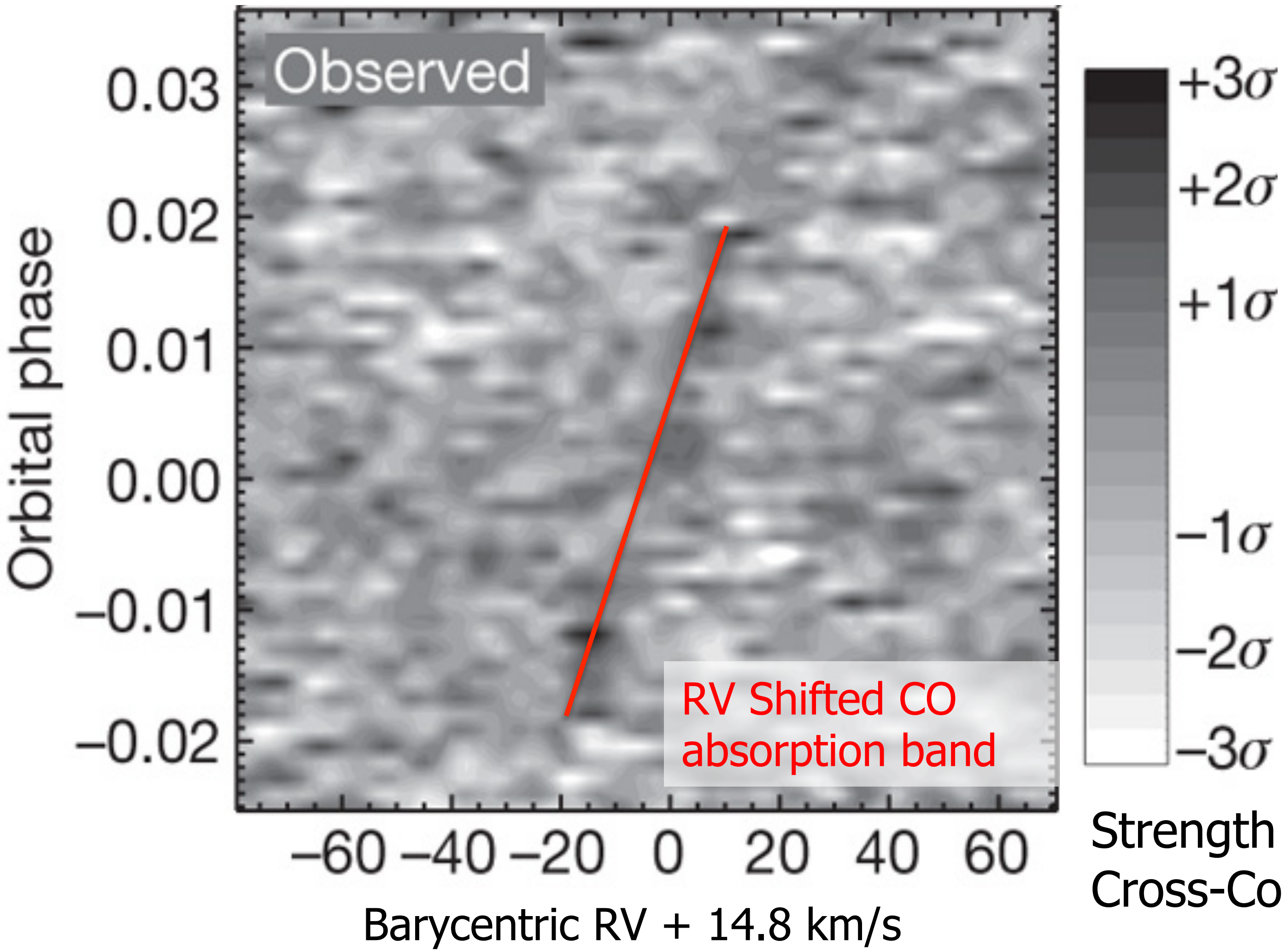


HD 209458b; Snellen et al. (2010)
GJ 1214b; Crossfield et al. (2011)



Detection of RV-Shifted Absorption from HD 209458b During Transit

VLT/CRIRES, Snellen et al. (2010)



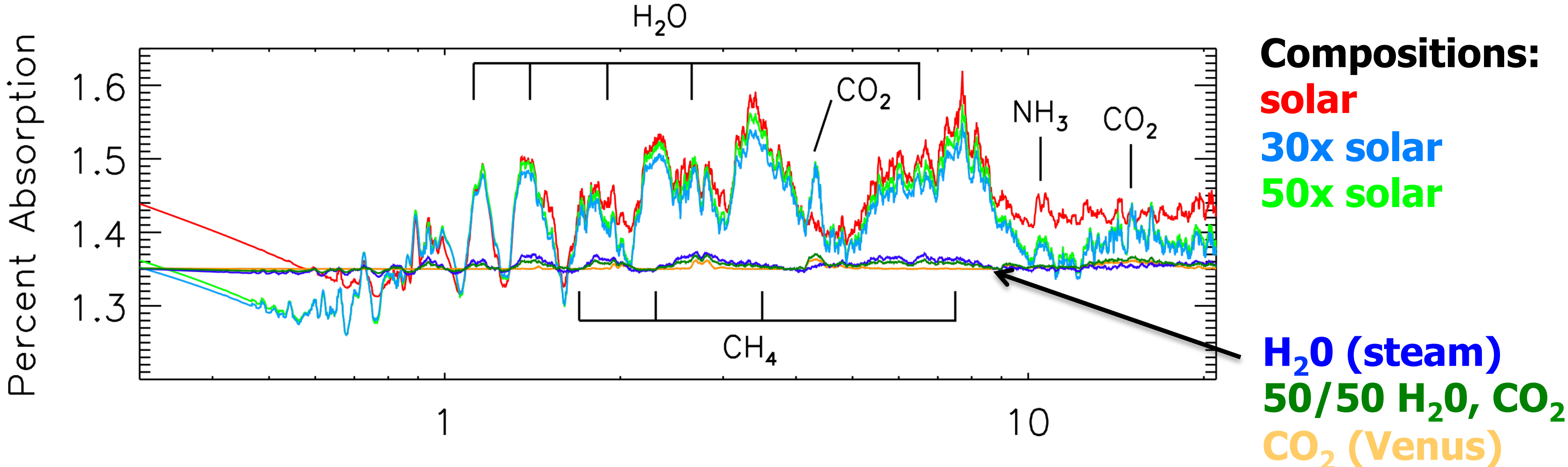
Strength of CO Cross-Correlation

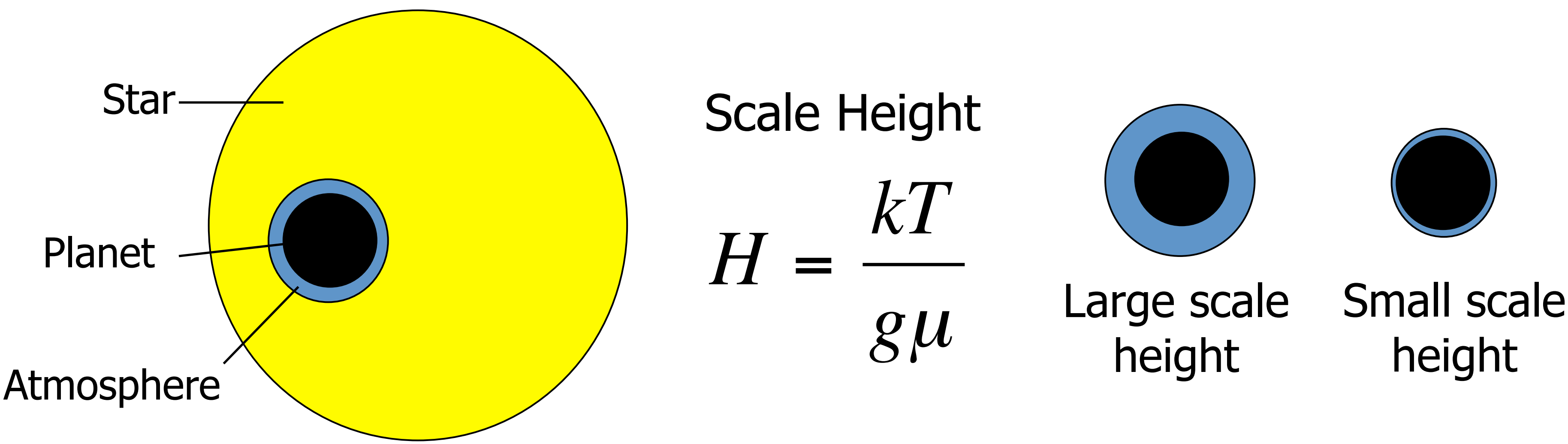
R = 100,000 K band spectrum

CO absorption detected at 5.6σ

Marginally significant (2σ) blueshift -> winds?

Transmission Spectroscopy of Super-Earth Atmospheres



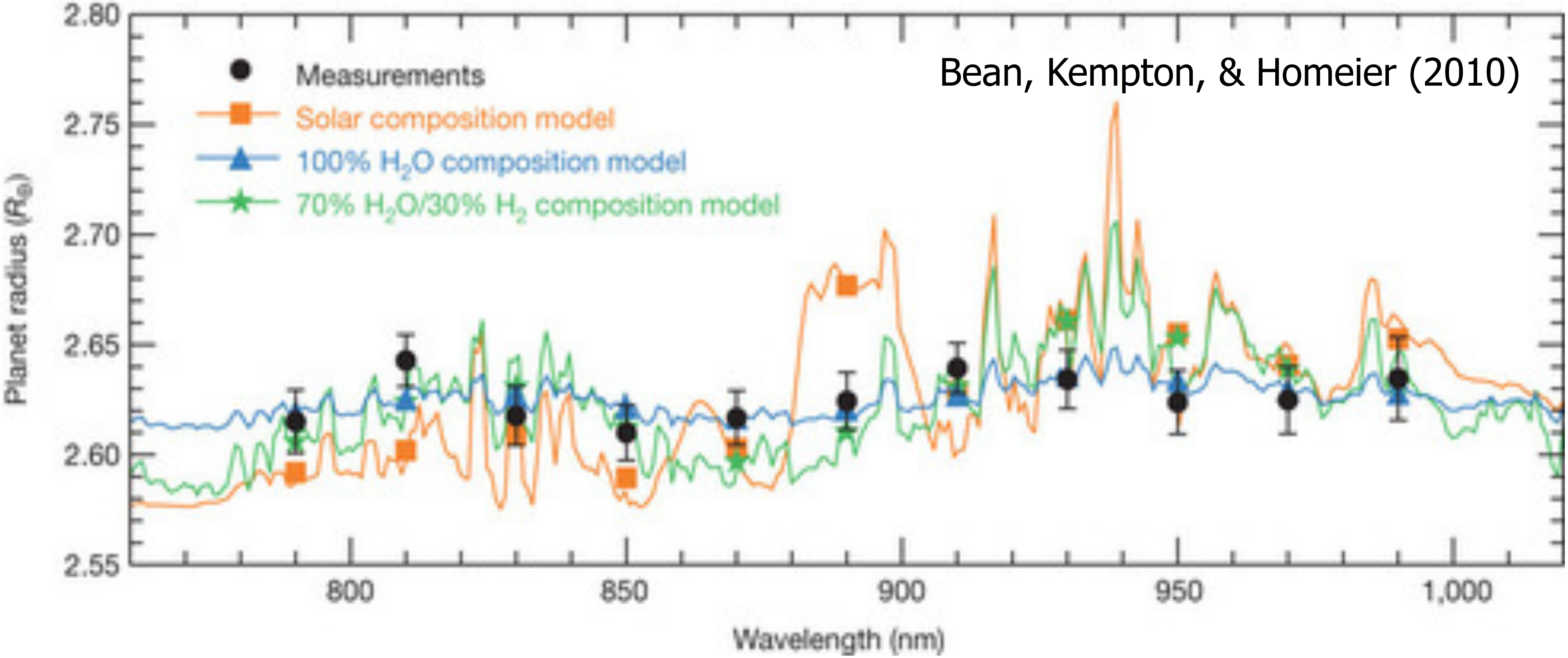


Scale Height

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

Miller-Ricci & Fortney (2010)

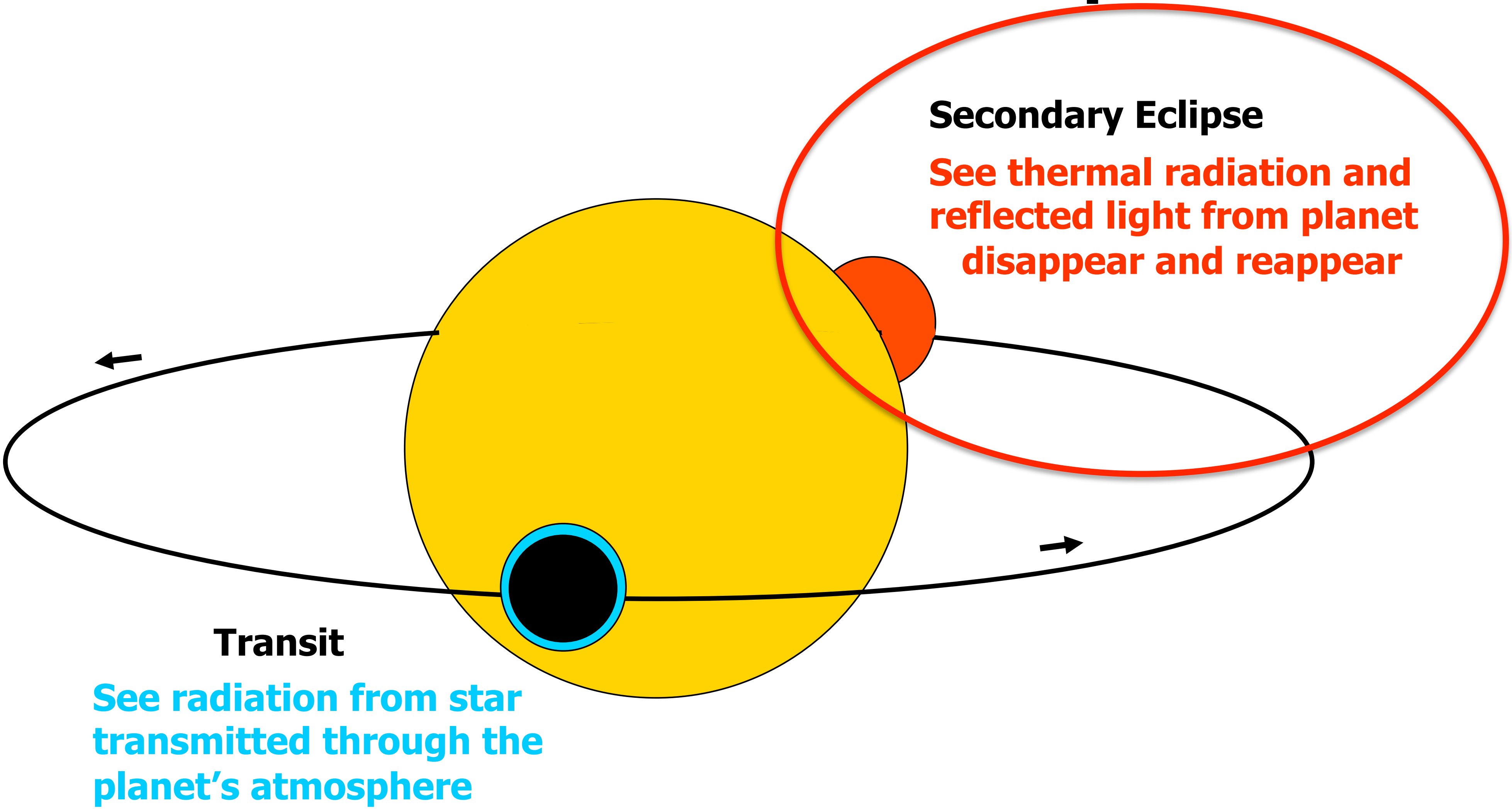
A Ground-Based Transmission Spectrum for GJ 1214b



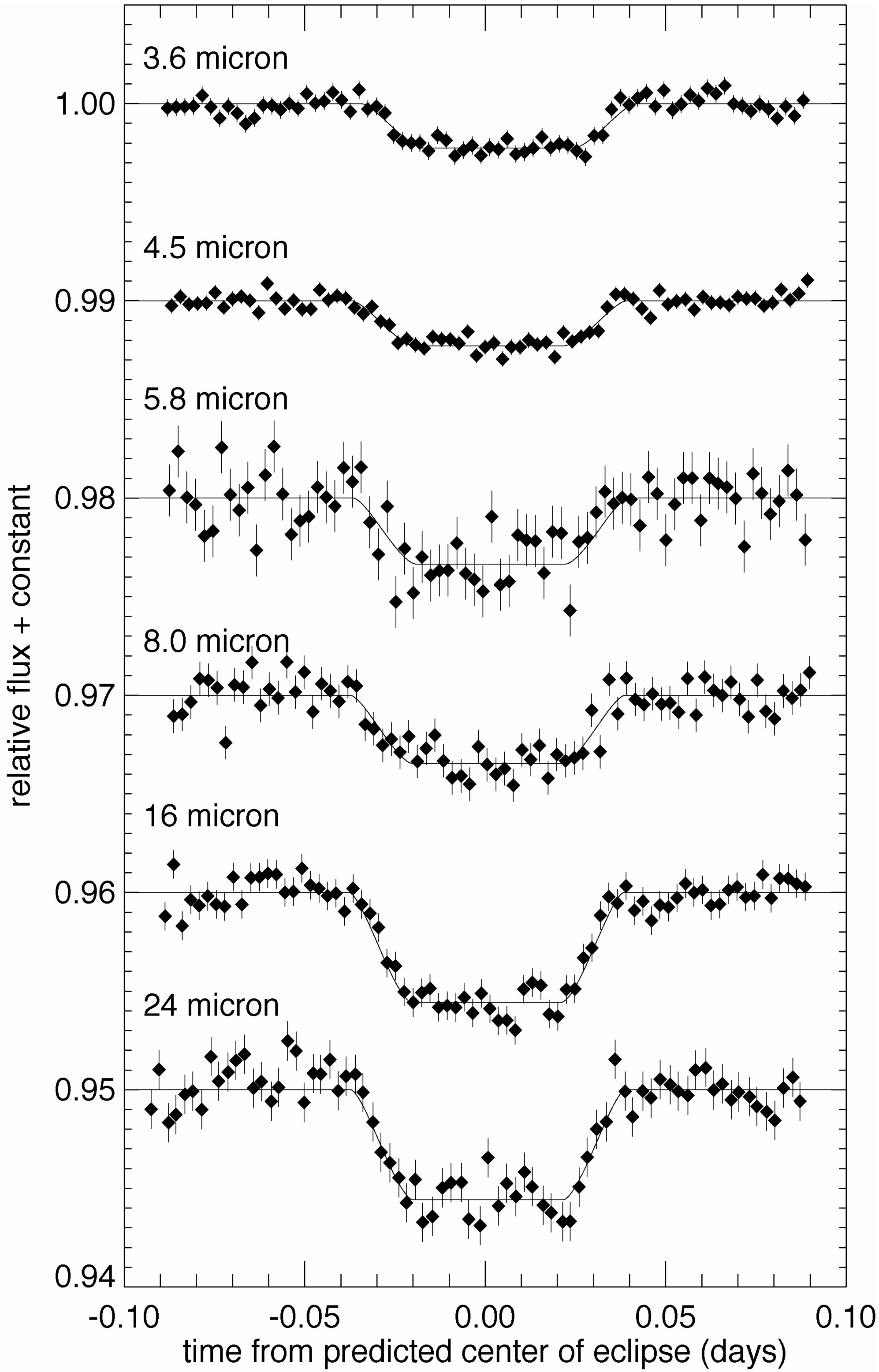
- Medium resolution spectra with FORS2/VLT, 12″ x 30″ slits
- Multi-object spectroscopy with six comparison stars within 6′
- Follow-up K band spectroscopy with Magellan/MMIRS, blue filter on FORS2 (Bean et al. 2011); CFHT (Croll et al.); HST (Berta et al.); Spitzer (Desert et al.)

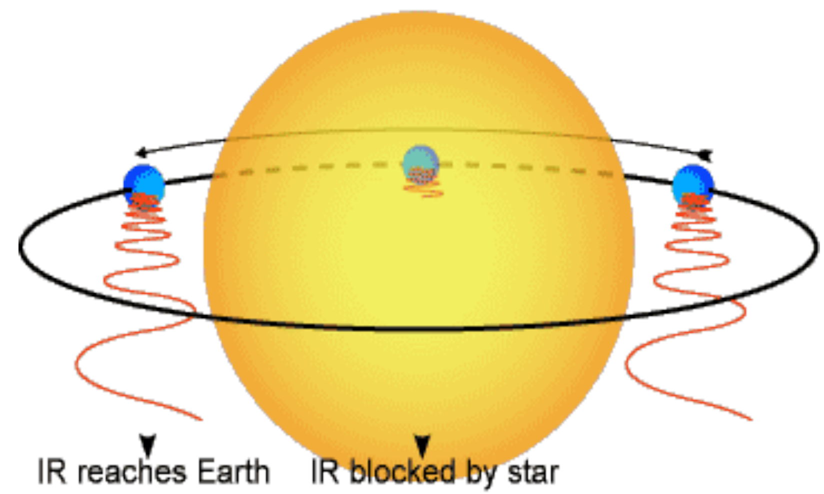
Planet must have water-dominated or cloudy atmosphere.

What Do Different Types of Events Tell Us About the Planet's Atmosphere?



Secondary Eclipse Spectroscopy



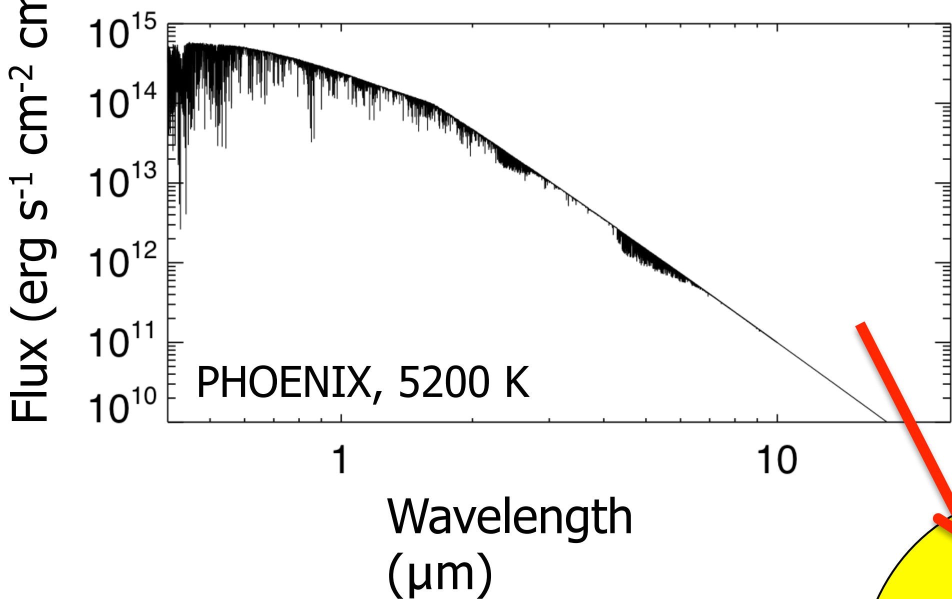


Observe the decrease in light as the planet disappears behind the star and then reappears.

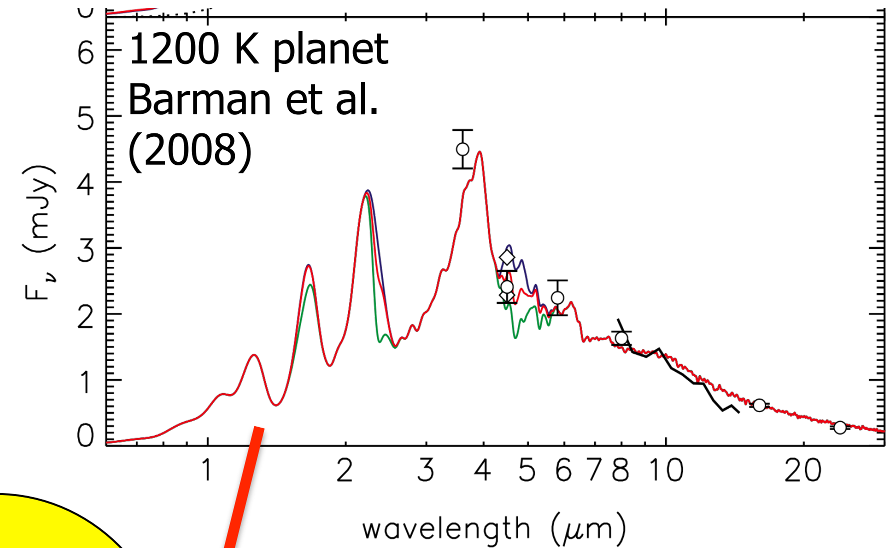
Spitzer observations of HD 189733b (Charbonneau, Knutson et al. 2008)

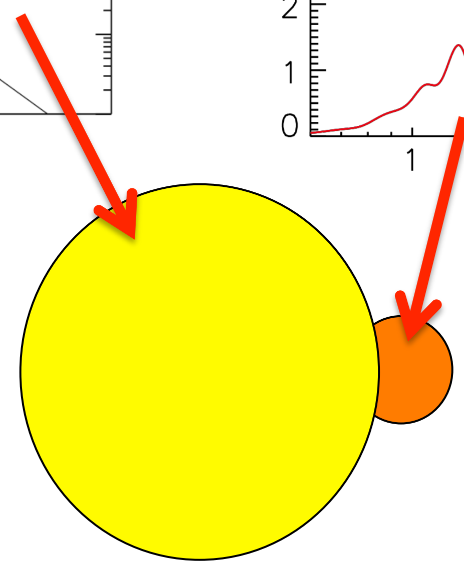
Comparison to Models

Stellar Atmosphere Model

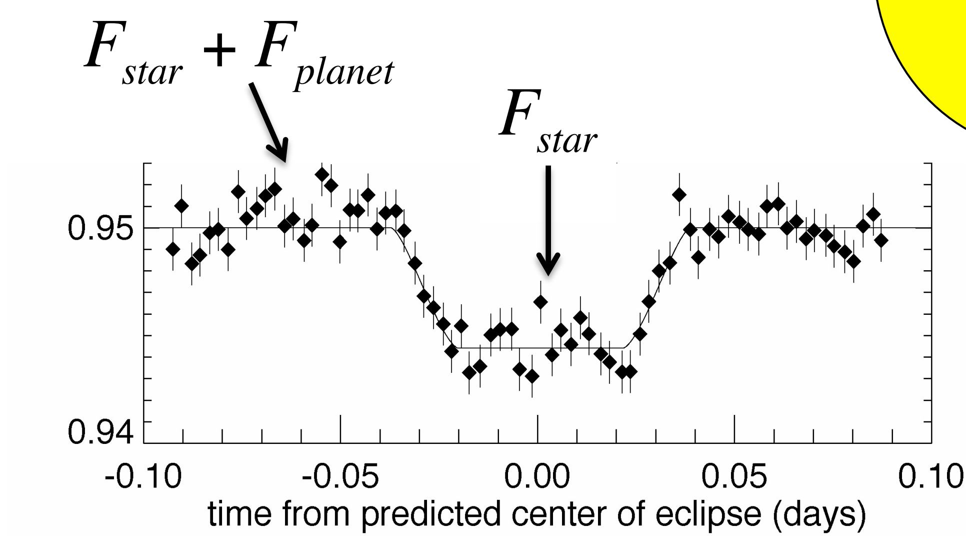


Planet Atmosphere Model

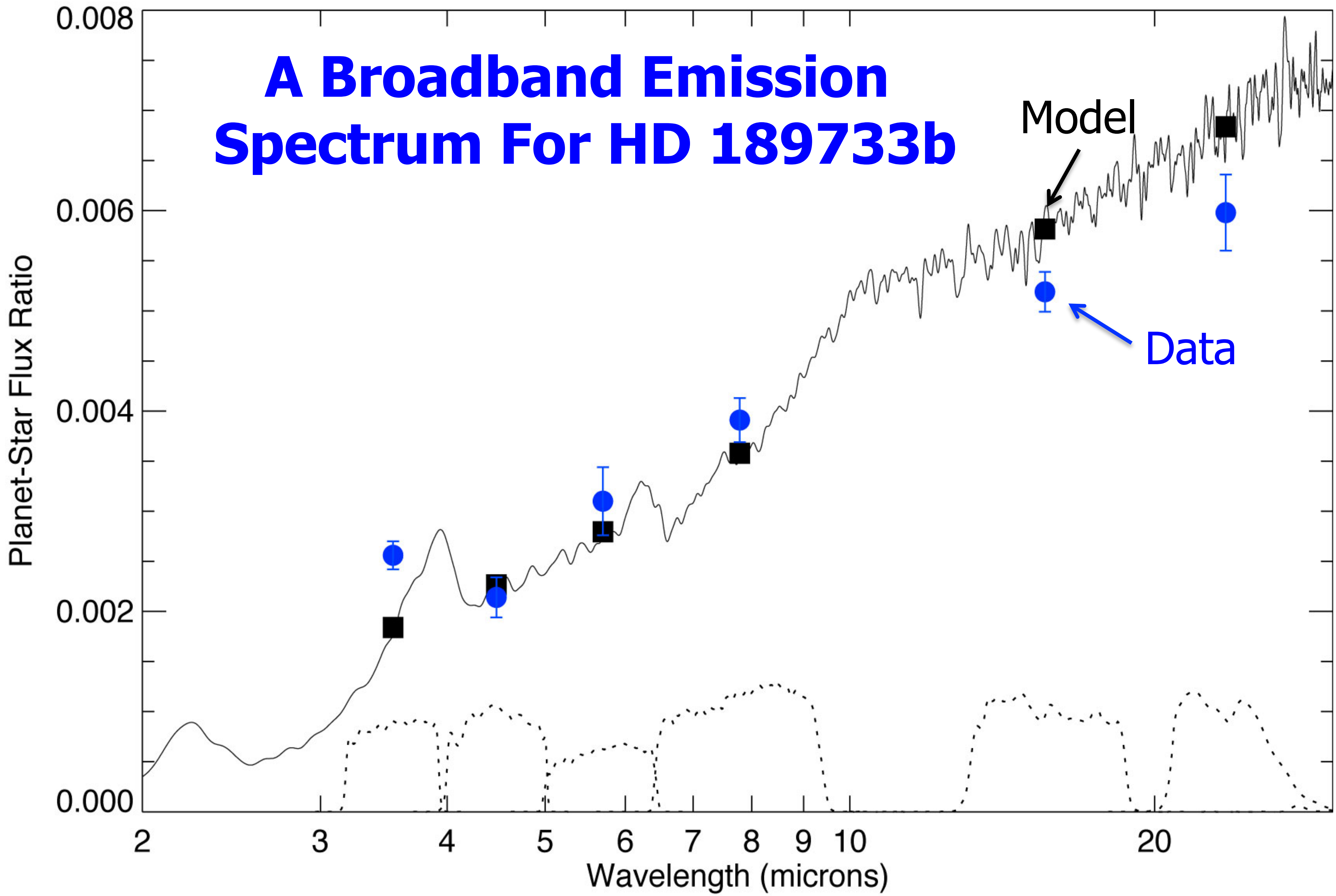




Model assumes solar composition atmosphere, chemistry in local thermal equilibrium.



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



Data from Charbonneau, Knutson et al. (2008)
Model from Barman (2008)

The Atmospheric Composition of HD 189733b

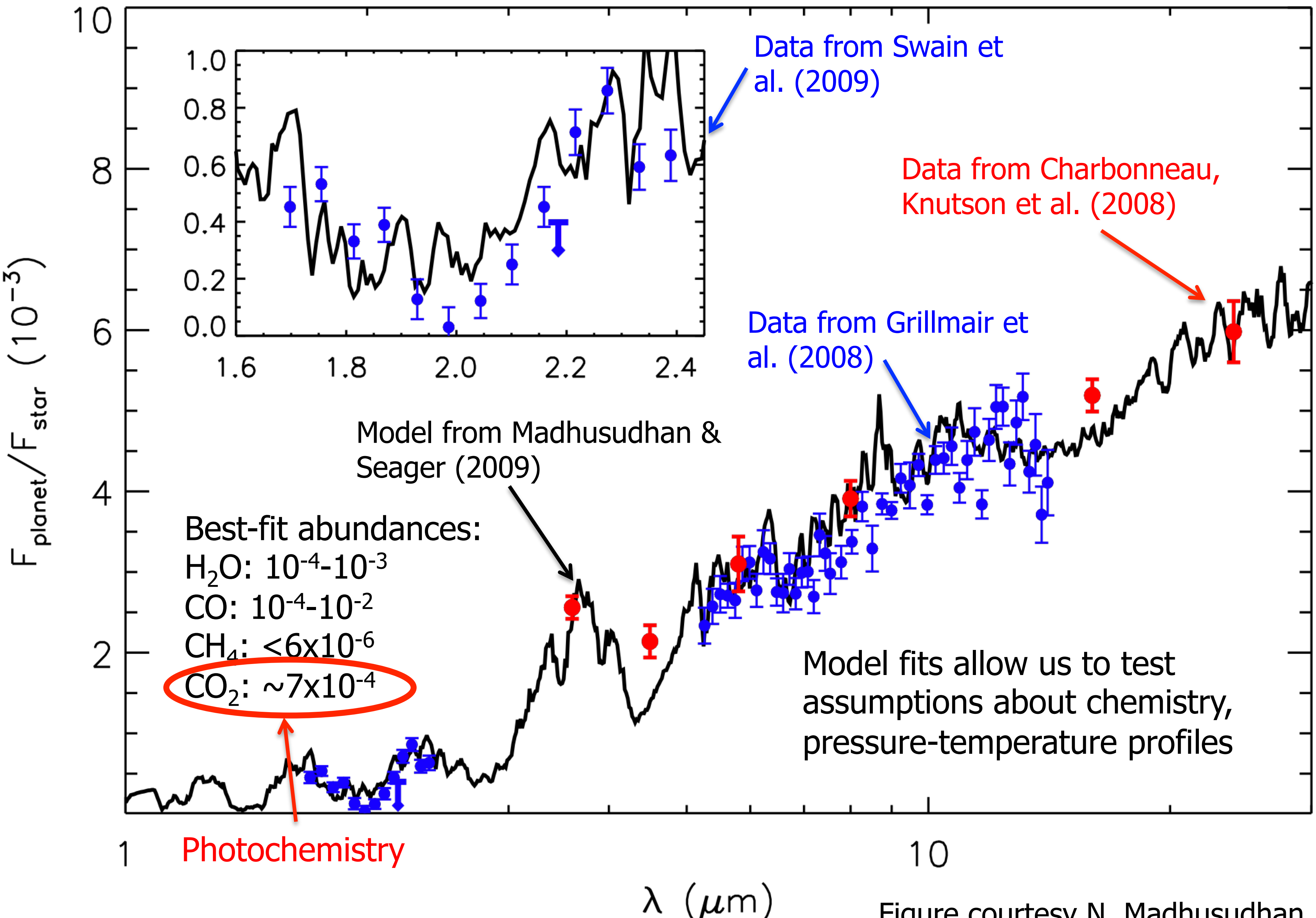
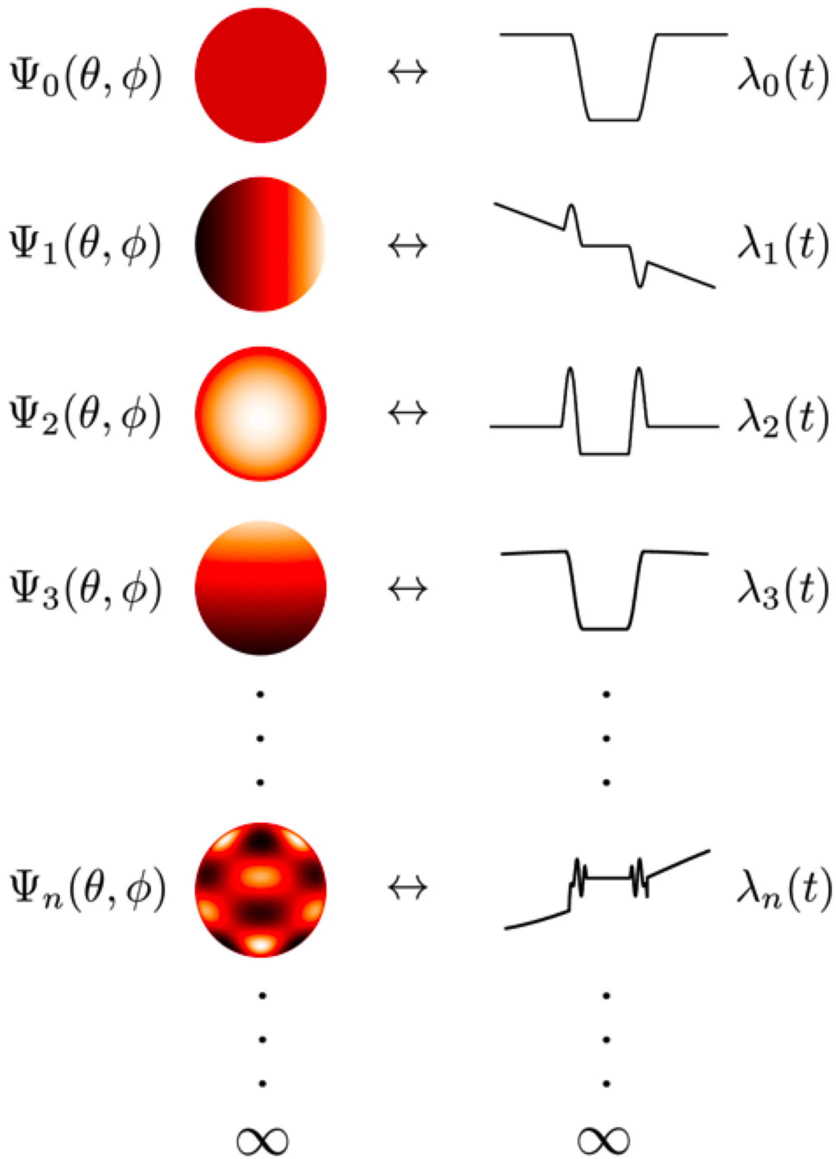
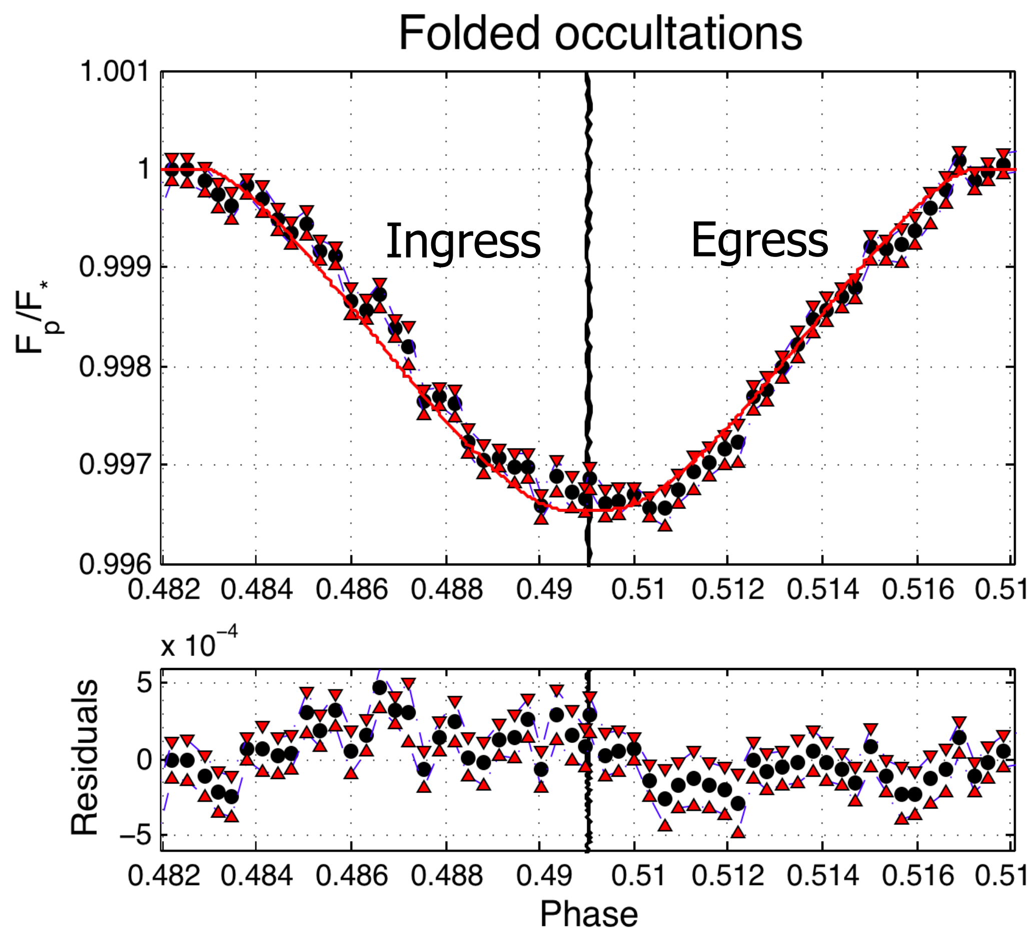


Figure courtesy N. Madhusudhan

What Happens When Your Planet is Not a Uniform Disk?



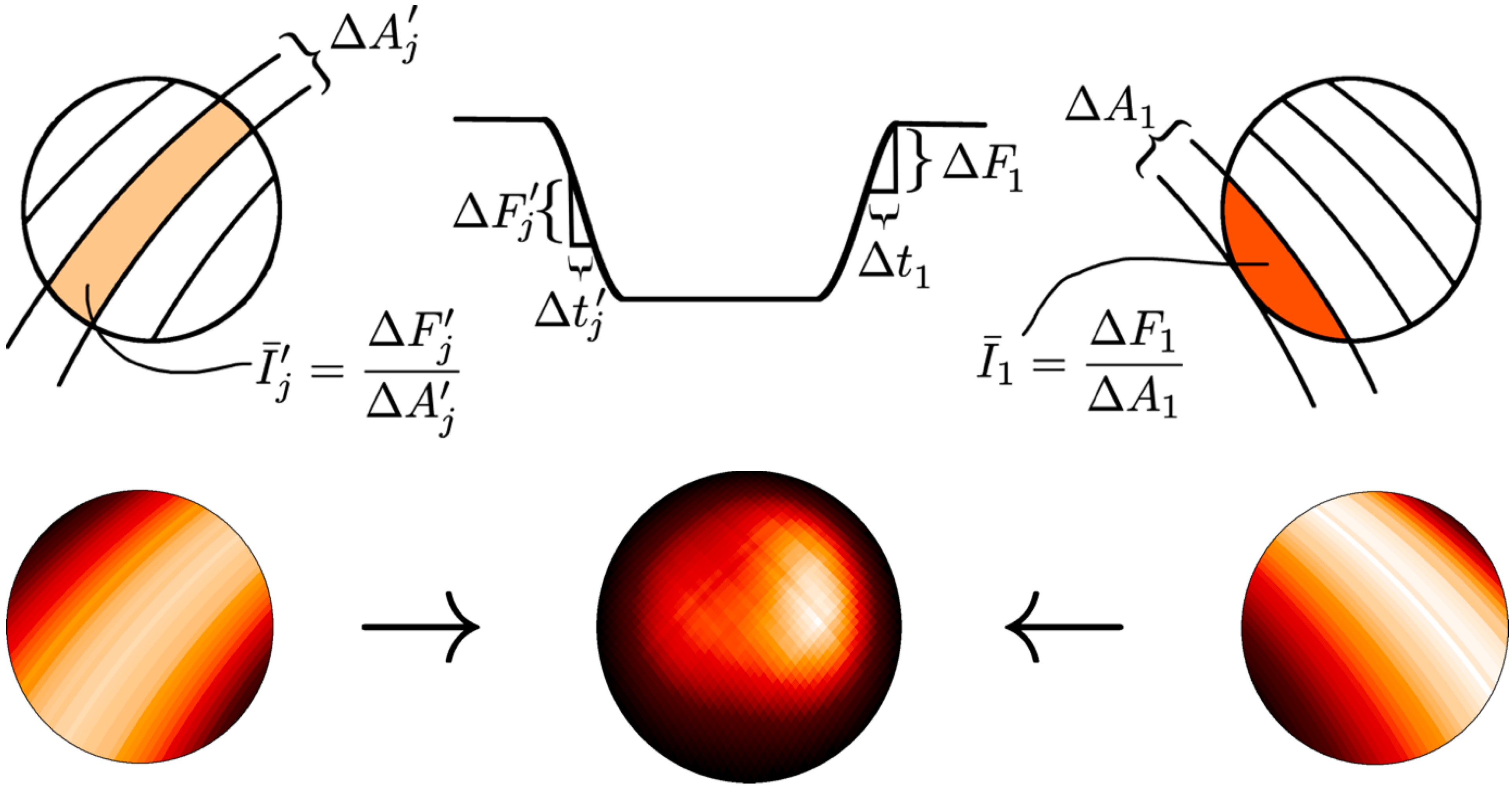
Majeau, Agol, & Cowan (2012)



HD 189733b 8 μm secondary eclipse (Agol et al. 2010, de Wit et al. 2012).

Also see Williams et al. (2006).

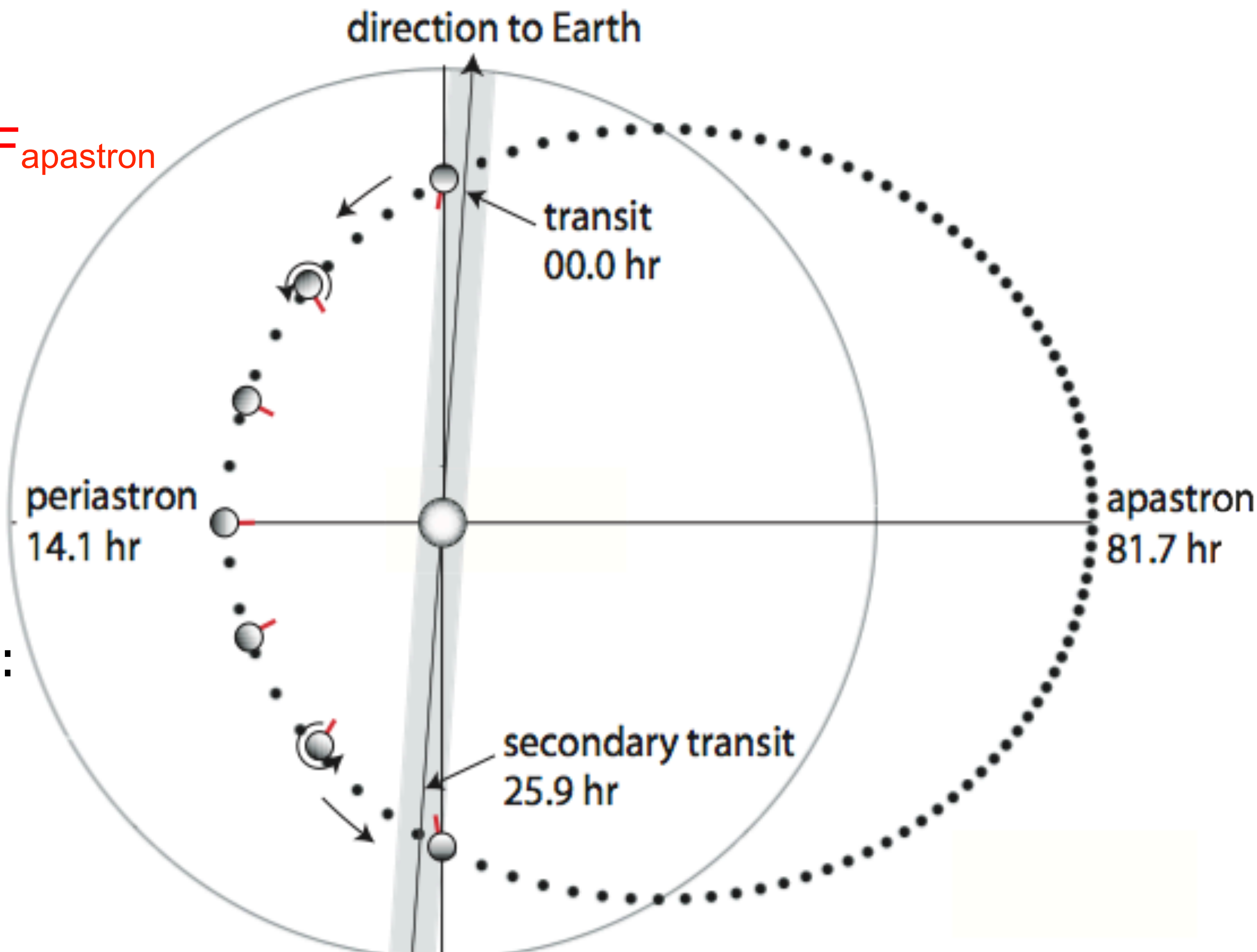
Secondary Eclipse Mapping



Majeau, Agol, & Cowan (2012)

Secondary Eclipses + Transits Constrain Orbital Eccentricity

HAT-P-2b
$F_{periastron} = 10 \times F_{apastron}$



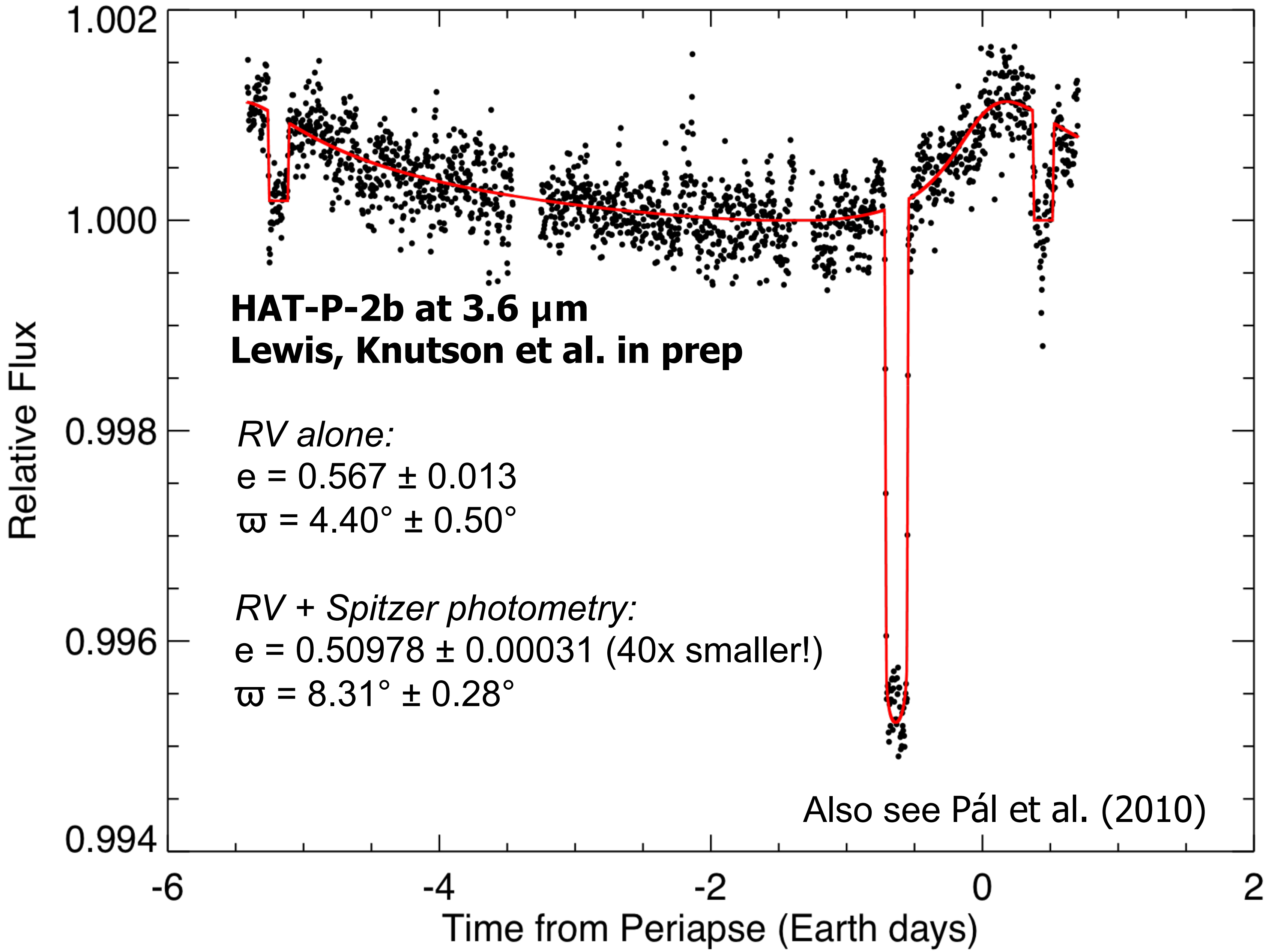
Pál et al. (2010):

$M = 9.09\ M_J$
$e = 0.5171$
$P_{orb} = 5.6$ days
P_{rot}✠ = 1.9 days

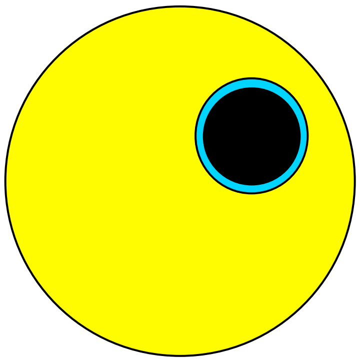
✠ Parameterization from Hut (1981)

figure credit G. Laughlin (oklo.org)

Secondary Eclipses + Transits Constrain Orbital Eccentricity



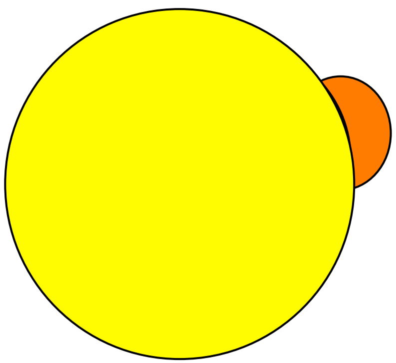
Wrapping it Up: An Observation Planning Cookbook for Transits + Eclipses



Absorption During Transit (%):

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

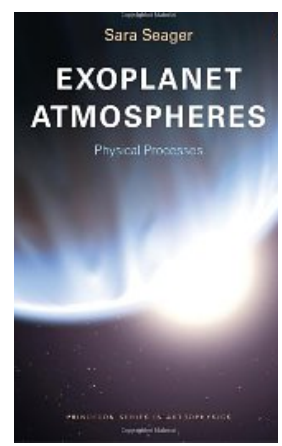
mean molecular weight

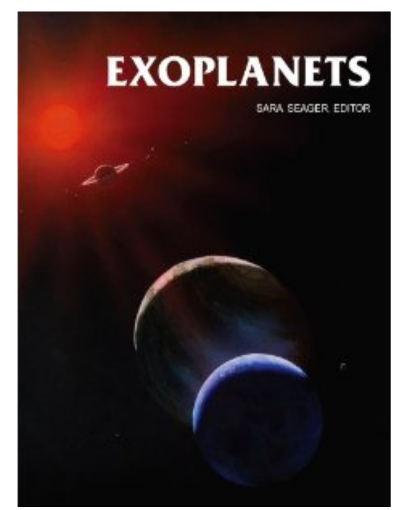


Secondary Eclipse Depth (IR):

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

Good resources include:
Exoplanet Atmospheres by Sara Seager, and *Exoplanets* (ed. Sara Seager)





Ground vs. Space

Pro: Stable, ultra-precise photometry + spectroscopy, higher IR sensitivity

Con: Small apertures generally limit targets to bright (V<12) stars, limited wavelengths available. Hard to do large surveys.

Pro: Better for faint stars, many bands available. Conducive to large surveys.

Con: Requires wide field of view, multiple comparison stars. Can be systematics-limited for bright stars.

Conclusion: Think Outside the Box

One outstanding mystery is whether hot Jupiters have magnetic fields… could we detect auroral emission lines from a hot Jupiter, perhaps in secondary eclipse?

Jupiter Aurora HST • STIS

NASA and J. Clarke (University of Michigan) • STScI-PRC00-38