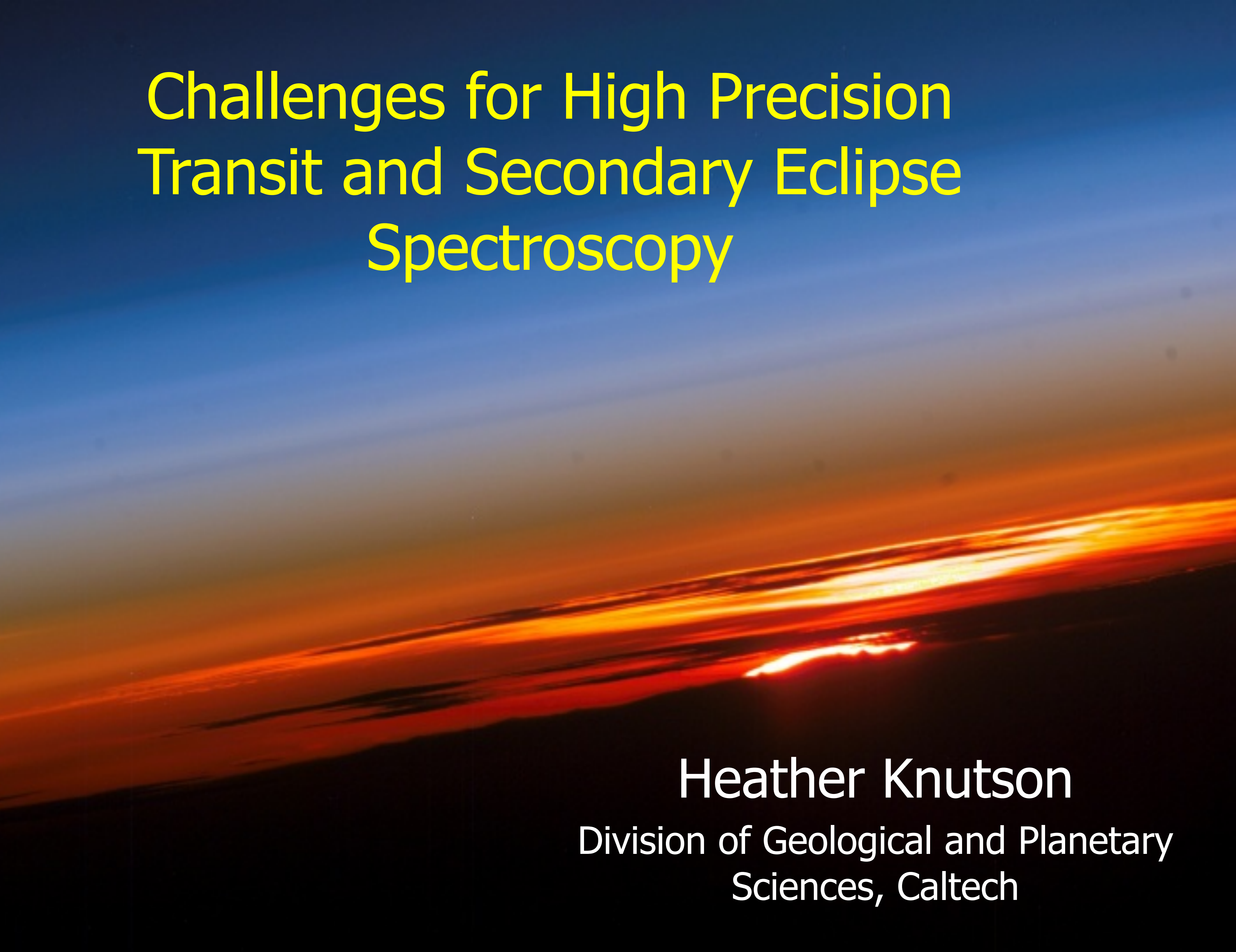
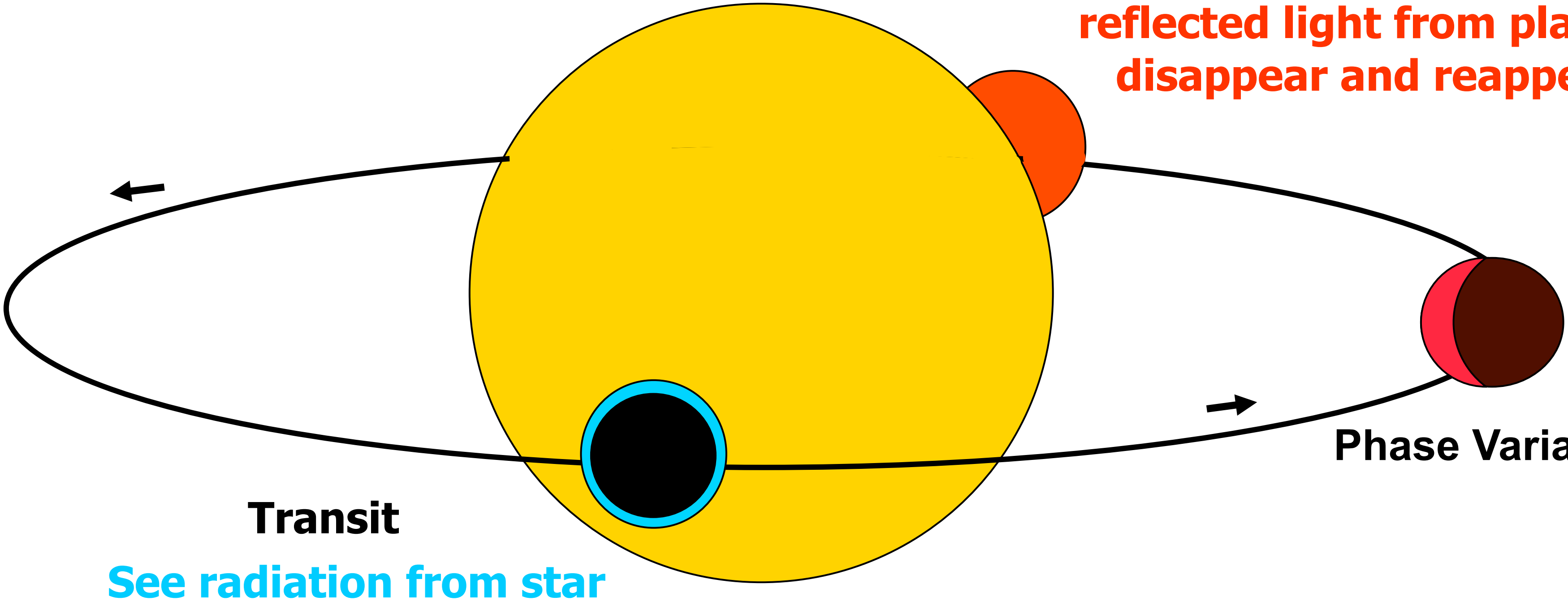


Challenges for High Precision Transit and Secondary Eclipse Spectroscopy

Heather Knutson
Division of Geological and Planetary Sciences, Caltech

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

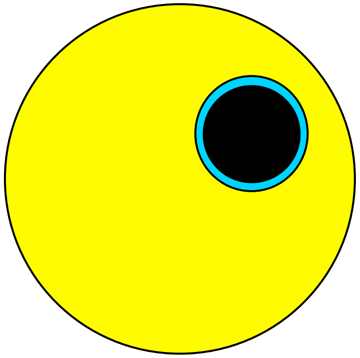
Phase Variation

Transit

See radiation from star transmitted through the planet's atmosphere

Important to consider noise properties in both **time domain** and **wavelength domain.** Noise can be instrumental (e.g., telescope pointing variations) or astrophysical (e.g., star spots).

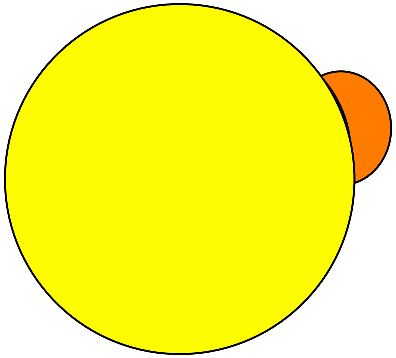
Order of Magnitude Estimates of Signal Size



Absorption During Transit (%):

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

mean molecular weight



Secondary Eclipse Depth (IR):

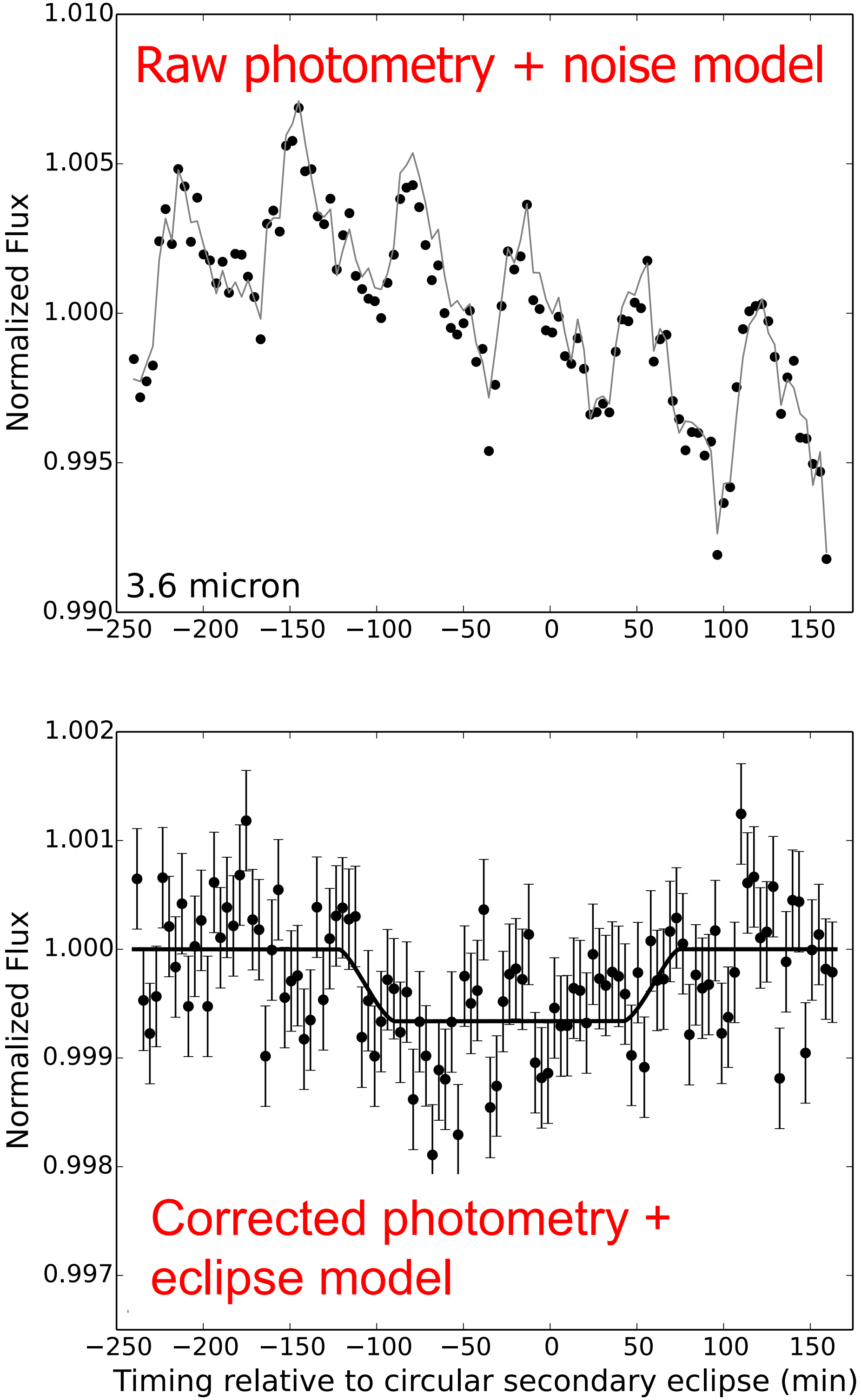
$$\left(\frac{R_p}{R_*}\right)^2\left(\frac{T_p}{T_*}\right)$$

Signals on the order of **100-1000 ppm for transiting hot Jupiters, 1-10 ppm for Earth-like planets** (assumes G-early M hosts).

Sources of Instrumental Noise I.

Time Domain

Are most sensitive to noise on **timescales comparable to events of interest** (transit ingress/egress – transit duration, ~10-100 minutes).

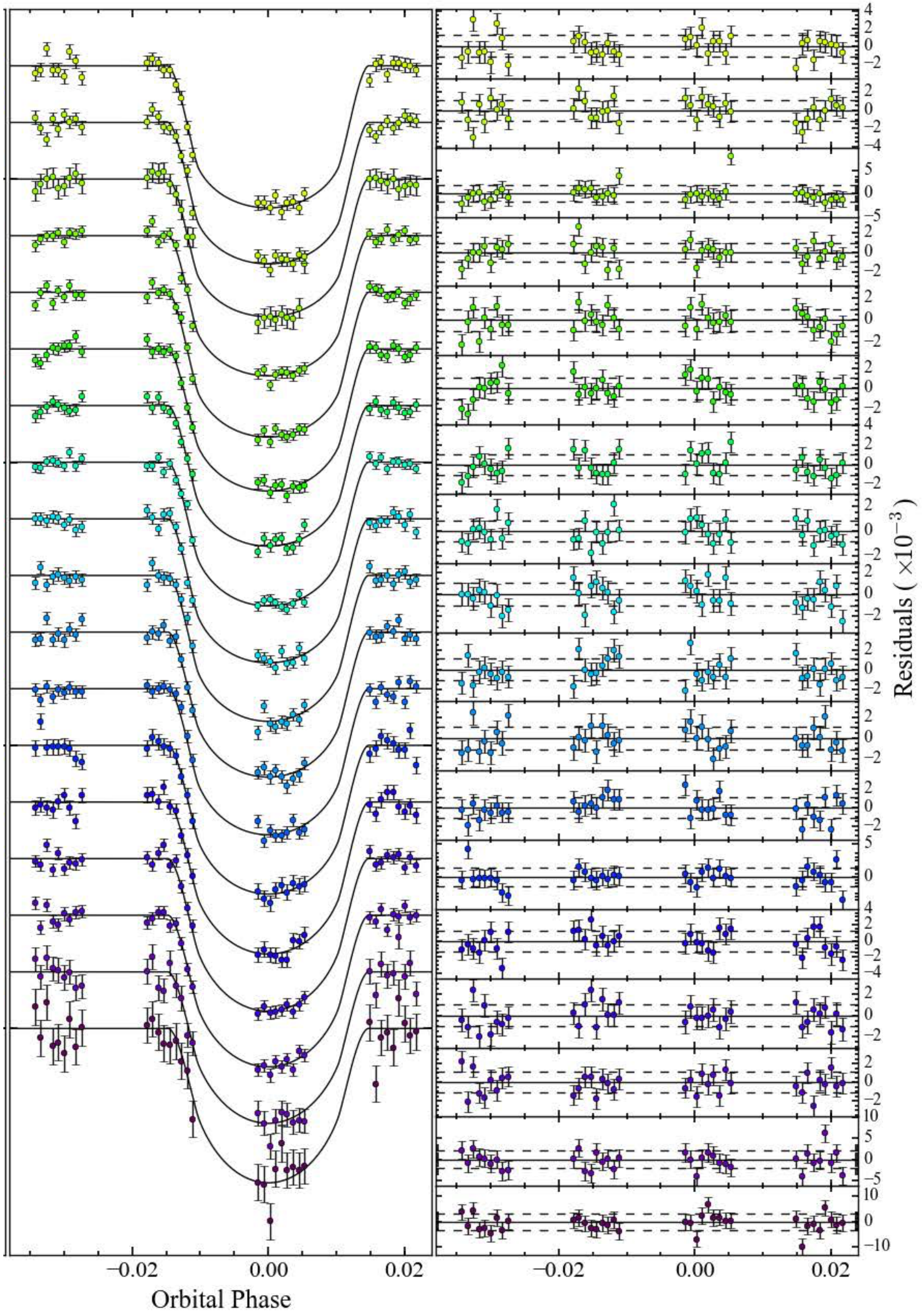


Spitzer secondary eclipse observations of HAT-P-13b (Buhler et al. 2016)

Sources of Instrumental Noise II.

Wavelength Domain

To zeroth order instrumental noise in spectroscopic time series data is usually constant across wavelengths, but **this assumption is not perfect.**



STIS transmission spectroscopy of WASP-39b (Fischer et al. 2016)

Most Common Sources of Time-Correlated Noise

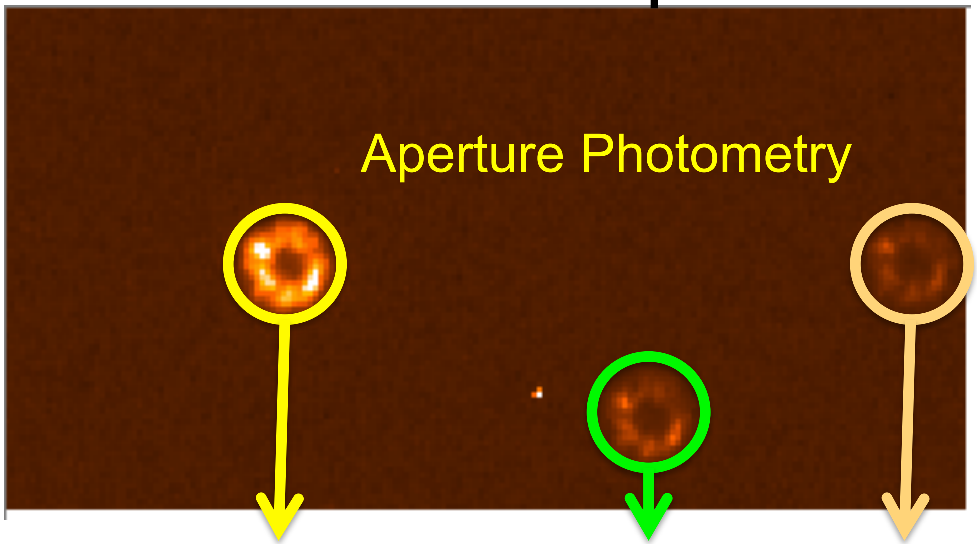
1. Pointing drift + intra- and inter-pixel sensitivity variations (e.g., Spitzer)

2. Changes in PSF from telescope breathing, seeing variations, etc.

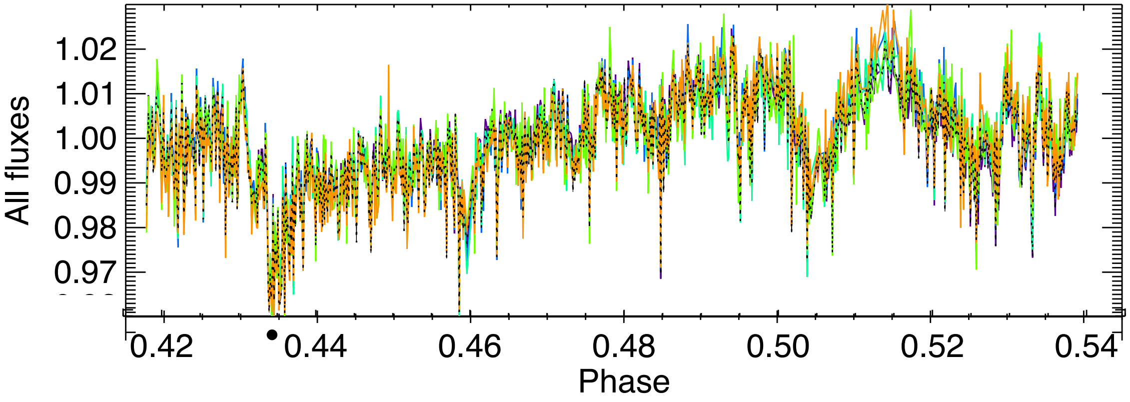
3. Varying sky background (important at ~10-100 ppm level even for bright stars!)

4. Nonlinearity in detector response at high fluxes

Part of a Typical Science Image from a Ground-Based Telescope

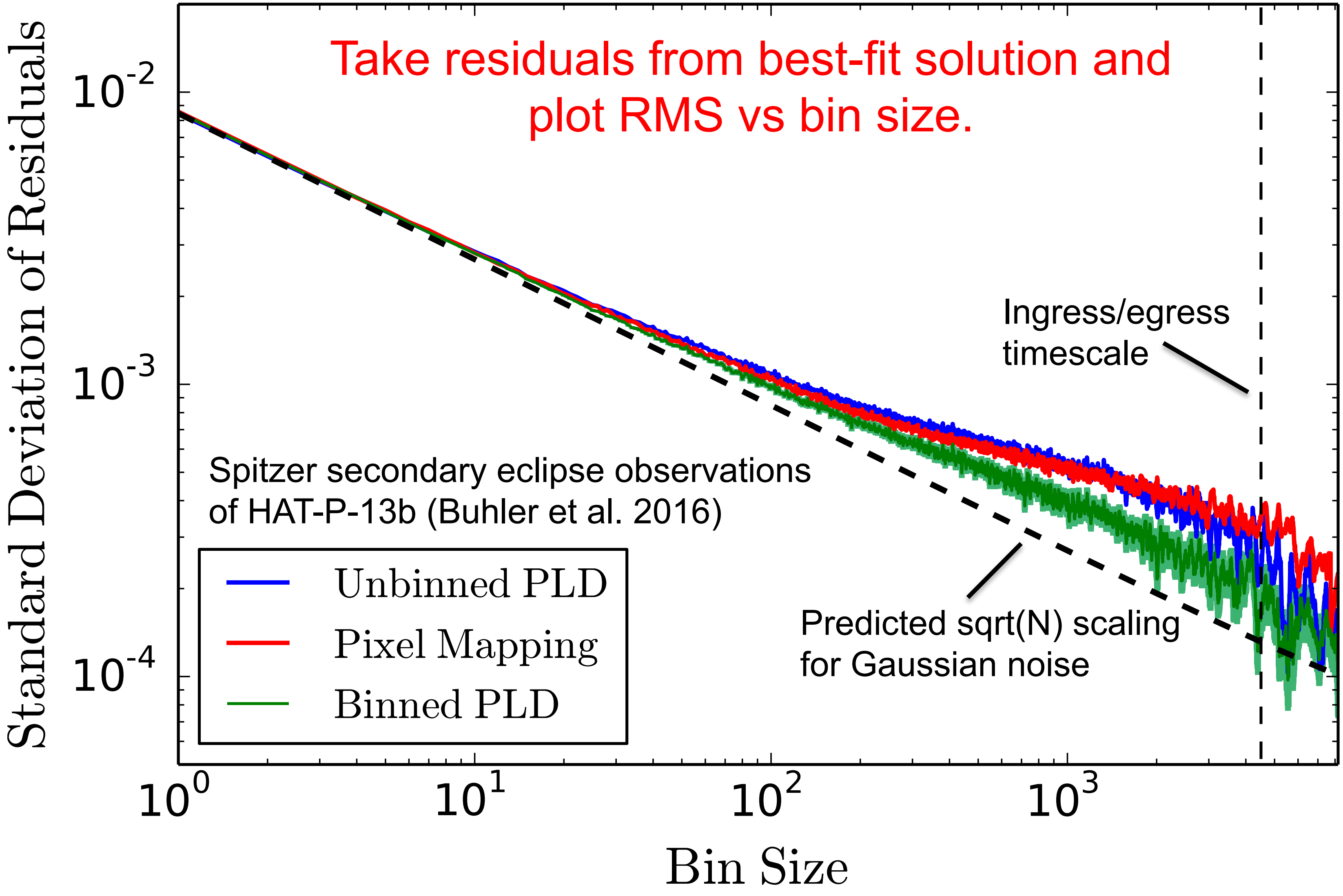


Raw Multi-Star Photometry



O’Rourke et al. (2014)

Evaluating Noise Properties:
Are Measurement Errors Independent & Gaussian?


Take residuals from best-fit solution and plot RMS vs bin size.

Spitzer secondary eclipse observations of HAT-P-13b (Buhler et al. 2016)

Ingress/egress timescale

Predicted sqrt(N) scaling for Gaussian noise

In an ideal world, we would be able to find a model that perfectly removed the instrumental + astrophysical noise sources, leaving us with **residuals dominated by Gaussian, uncorrelated noise.**

Model Fitting & Parameter Estimation:
Methods for Dealing With Time-Correlated Noise

Simple but imperfect solutions:

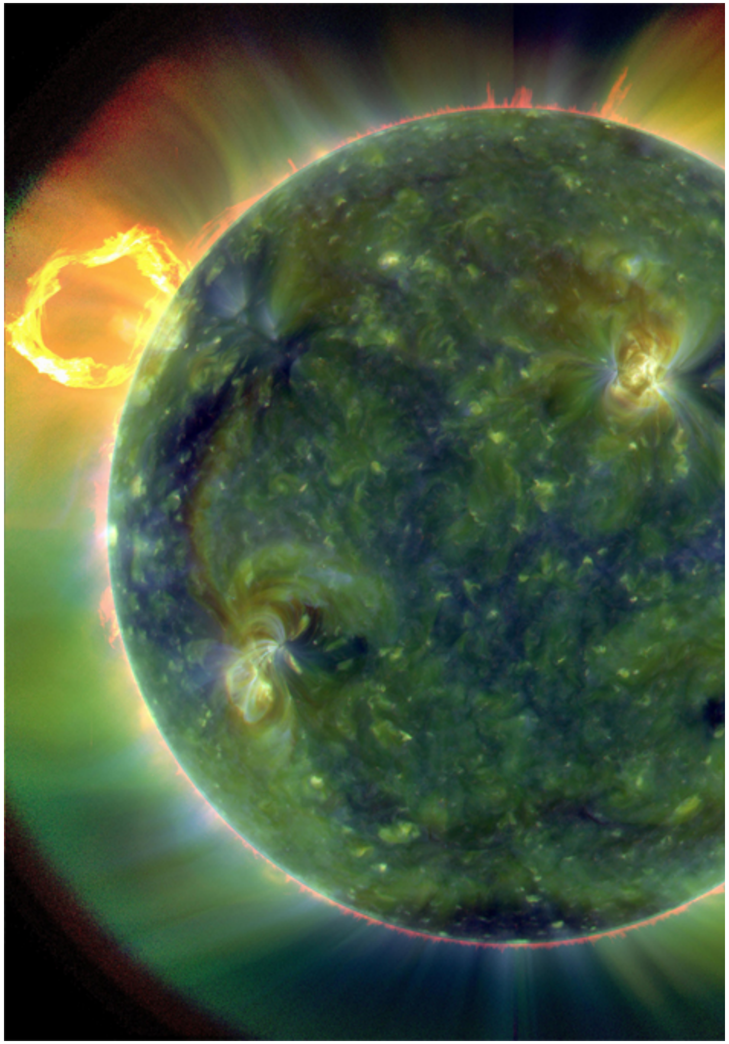
1. Rescale measurement errors by factor equal to excess RMS at relevant timescale (Pont et al. 2006, Winn et al. 2007)
2. Residual permutation (doesn't seem to work well in practice; see Carter et al. 2009)

Better but more complicated solutions:

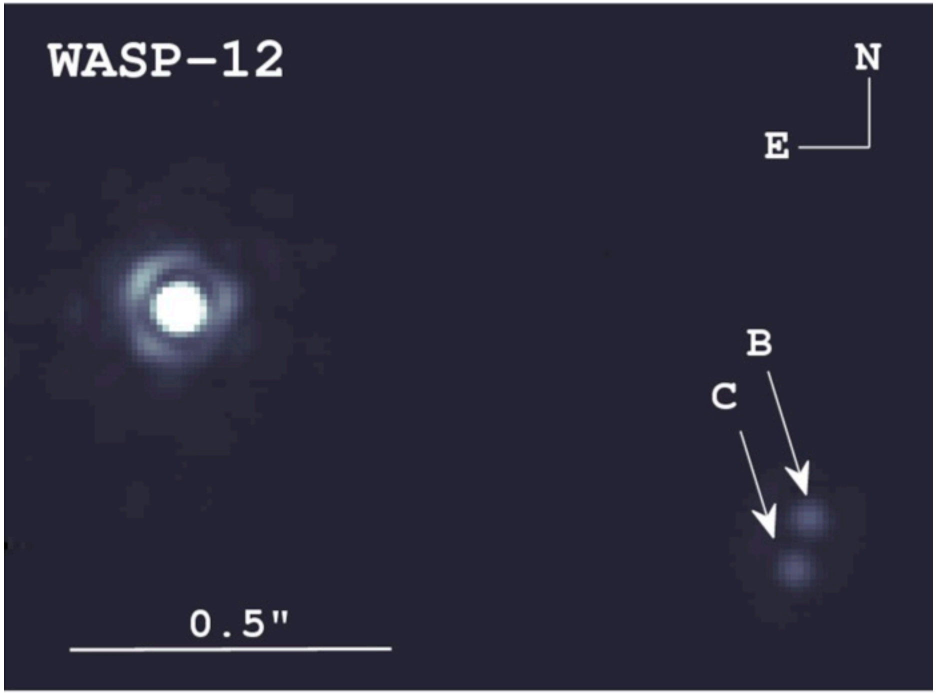
1. Explicitly allow for time-correlated noise in fit via correlation matrix. One way to do this is with Gaussian processes (GEORGE package in Python by D. Foreman-Mackey; see Montet et al. 2016 for an example with Spitzer lightcurves).
2. Transform to a space where individual data points are not correlated (aka wavelet transform, Carter et al. 2009). Also see Morello et al. (2014, 2015) for a variant on this approach using a wavelet transform + Independent Component Analysis.

Astrophysical Noise Sources:
Is My Measurement Biased?

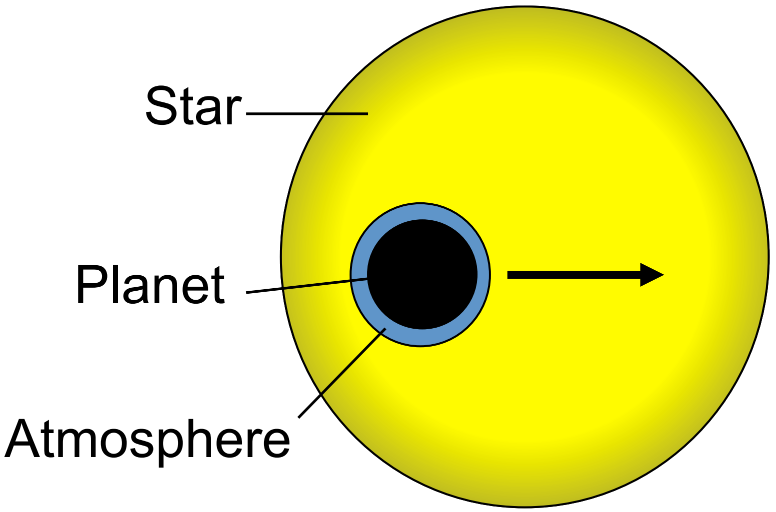
Things that can affect transit shape:
Limb-darkening, star spots



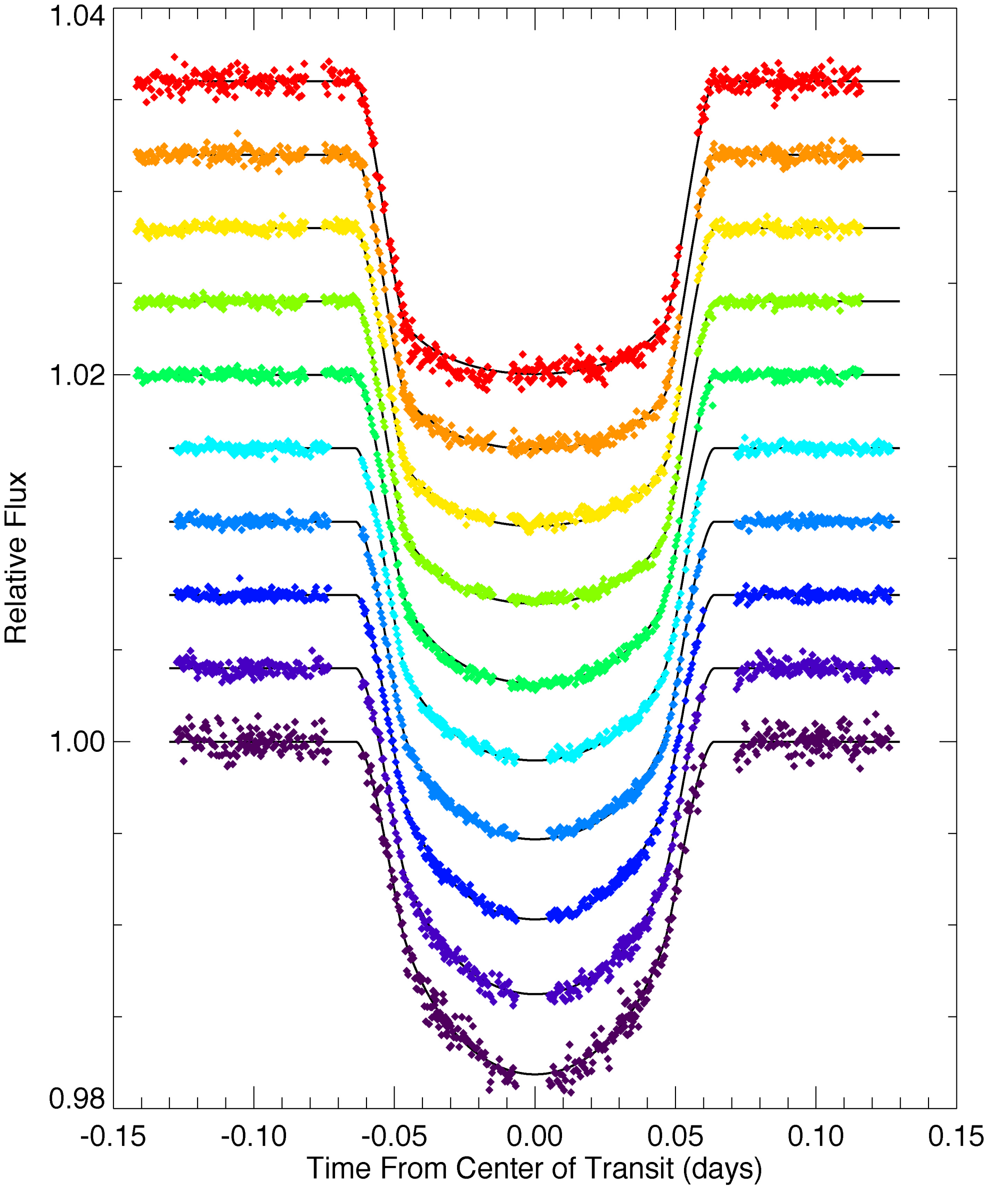
Things that can affect transit depth:
Star spots, contamination from 2nd star



Importance of Stellar Limb-Darkening Models for 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)

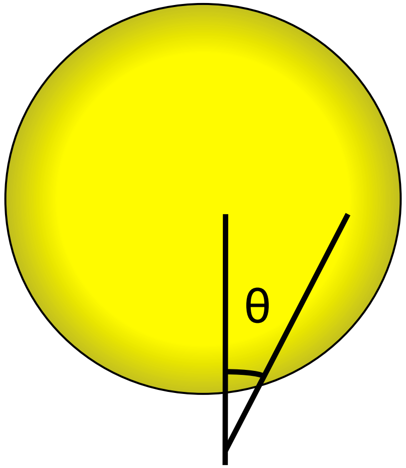
Sources of Stellar Limb-Darkening Models

Claret (2000), Sing (2012), Kipping (2016)

1. **Empirical:** Three-parameter limb-darkening law (Espinoza & Jordan 2016, Kipping 2016)

2. **1D Stellar Atmosphere Models**: Four-parameter nonlinear coefficients. Kurucz/ATLAS models good for FGK stars ([http://kurucz.harvard.edu)](http://kurucz.harvard.edu). PHOENIX models (Husser et al. 2013); better for M stars (include TiO), higher resolution in mid-IR.

3. **3D Models:** Hayek et al. (2012), Magic et al. (2015). Unlike 1D models, appear to be an excellent match to HST transit light curves



Models give I(λ,μ) where μ=cos(θ)

Calculating LD Coefficients from a Model (Sing 2012):

1. Calculate photon-weighted average I(μ) over desired bandpass.

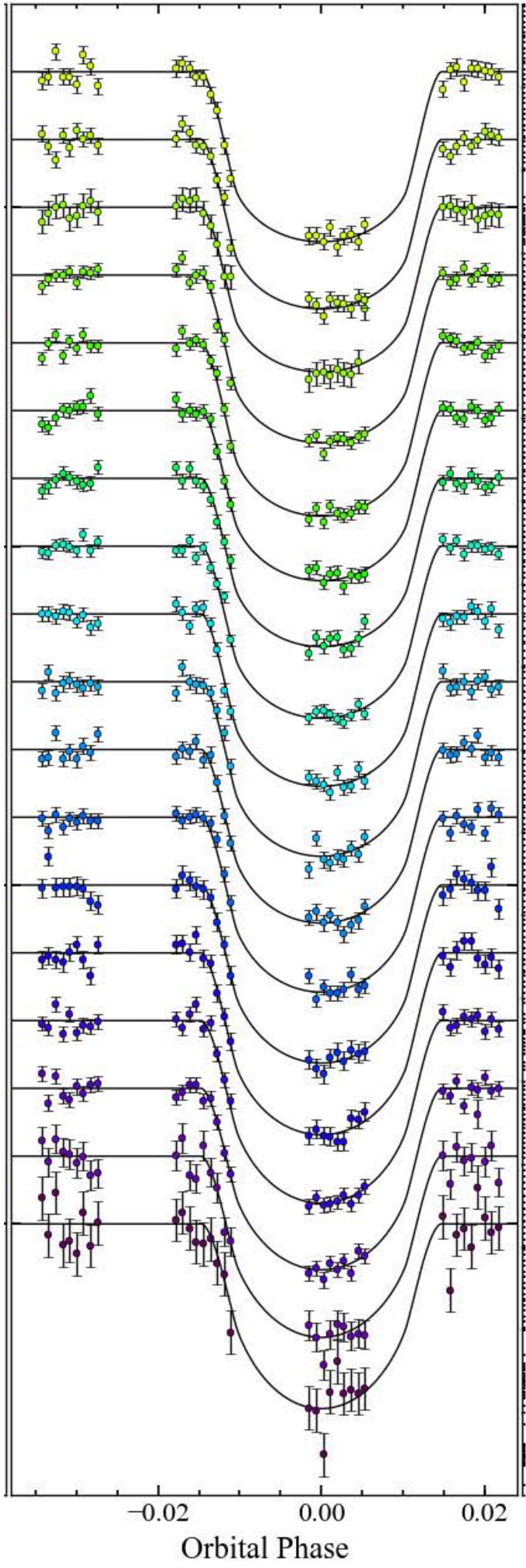
2. Fit I(μ) with desired limb-darkening model to obtain coefficients.

Caveats and Cautions

Fitting: Limb-darkening coefficients can be degenerate with instrumental noise model for non-uniformly sampled light curves (e.g., HST). Blind fits can also sample unphysical limb-darkening profiles (see Kipping 2016 for advice on priors).

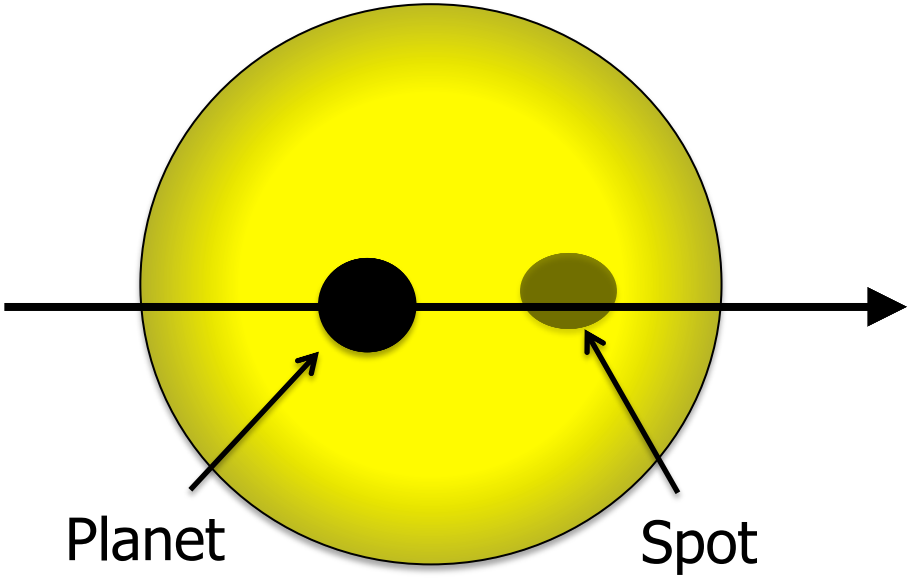
Models: Stellar models don't always match observed limb-darkening, particularly for M dwarfs. Must also account for uncertainty in our knowledge of stellar parameters.

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

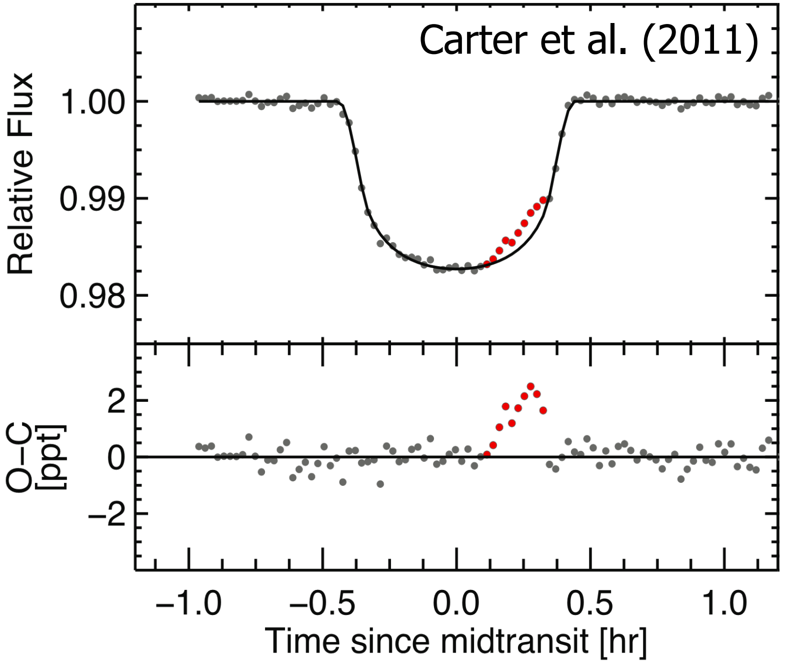


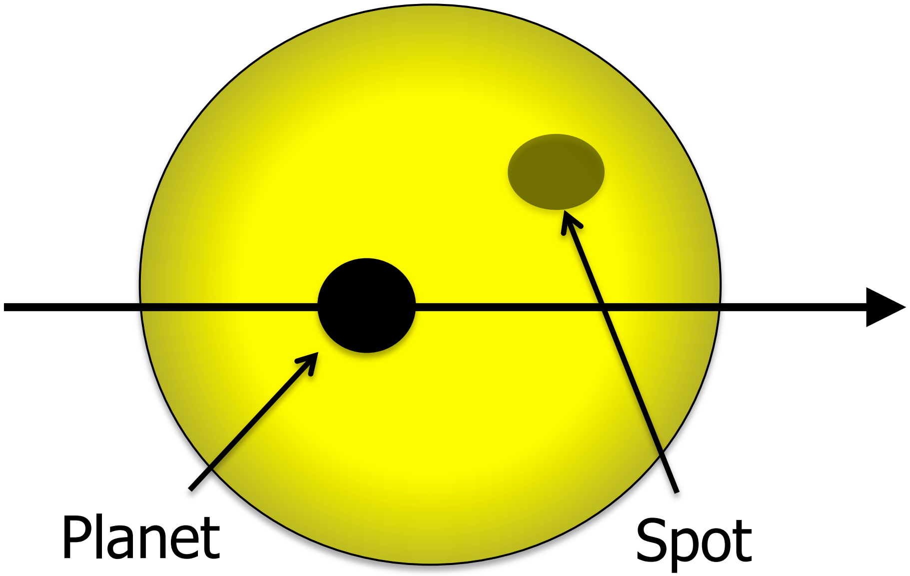
STIS transmission spectroscopy of WASP-39b (Fischer et al. 2016)

Stellar Activity is Bad for Transits

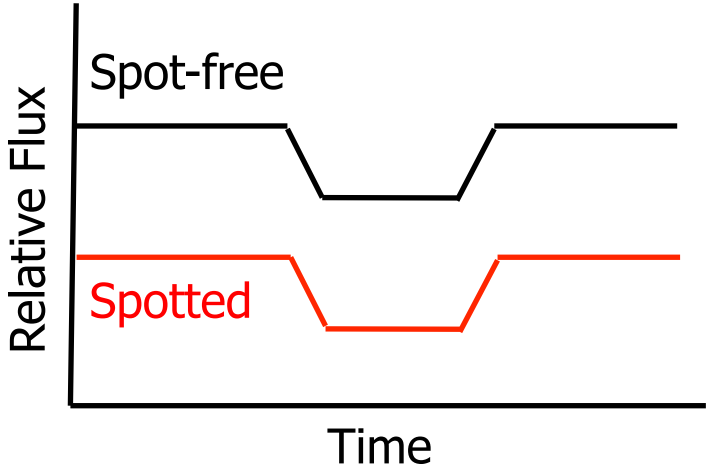


Scenario 1: Occulted Spot

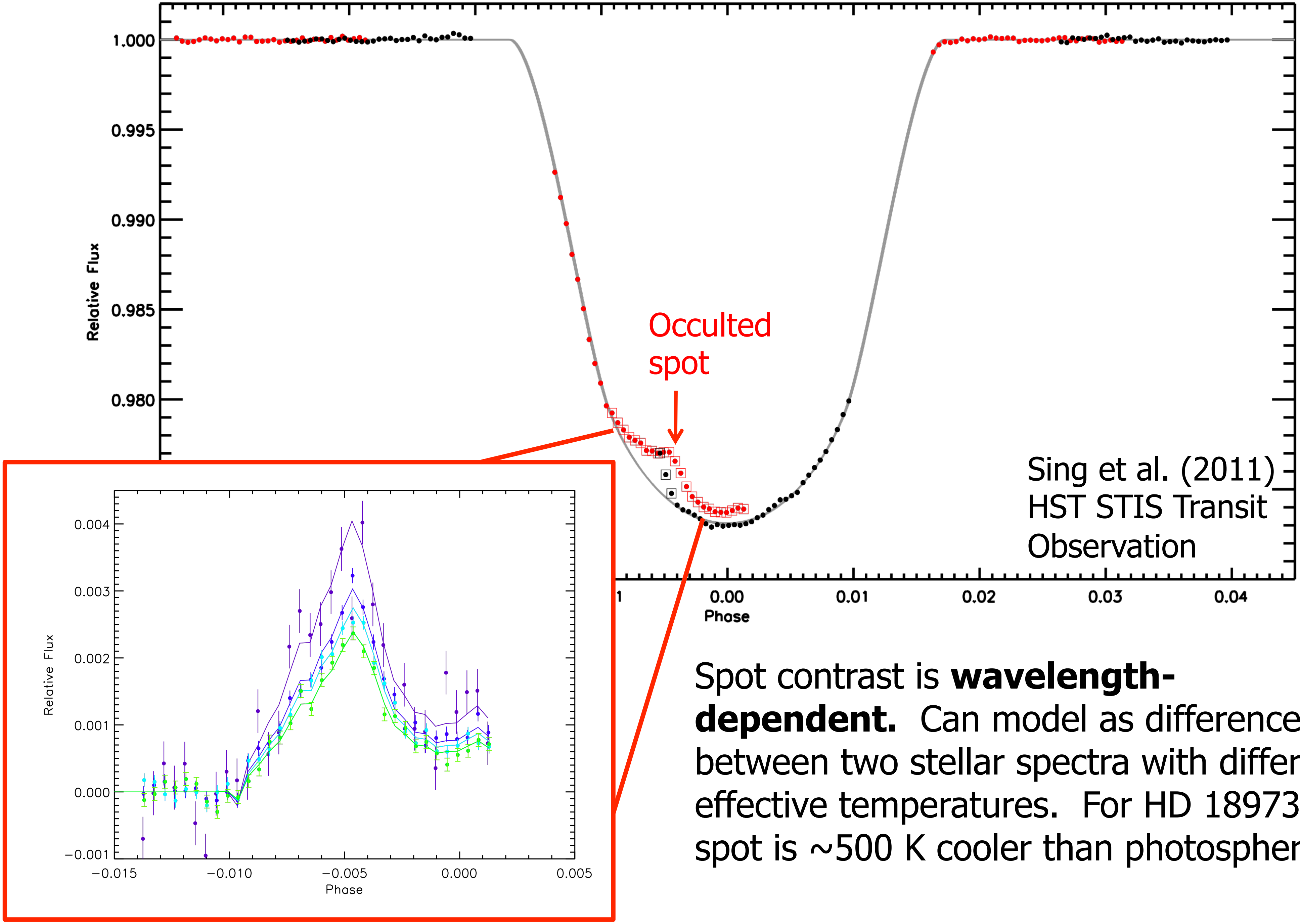




Scenario 2: Non-Occulted Spot



HD 189733: What to do when spots are unavoidable.

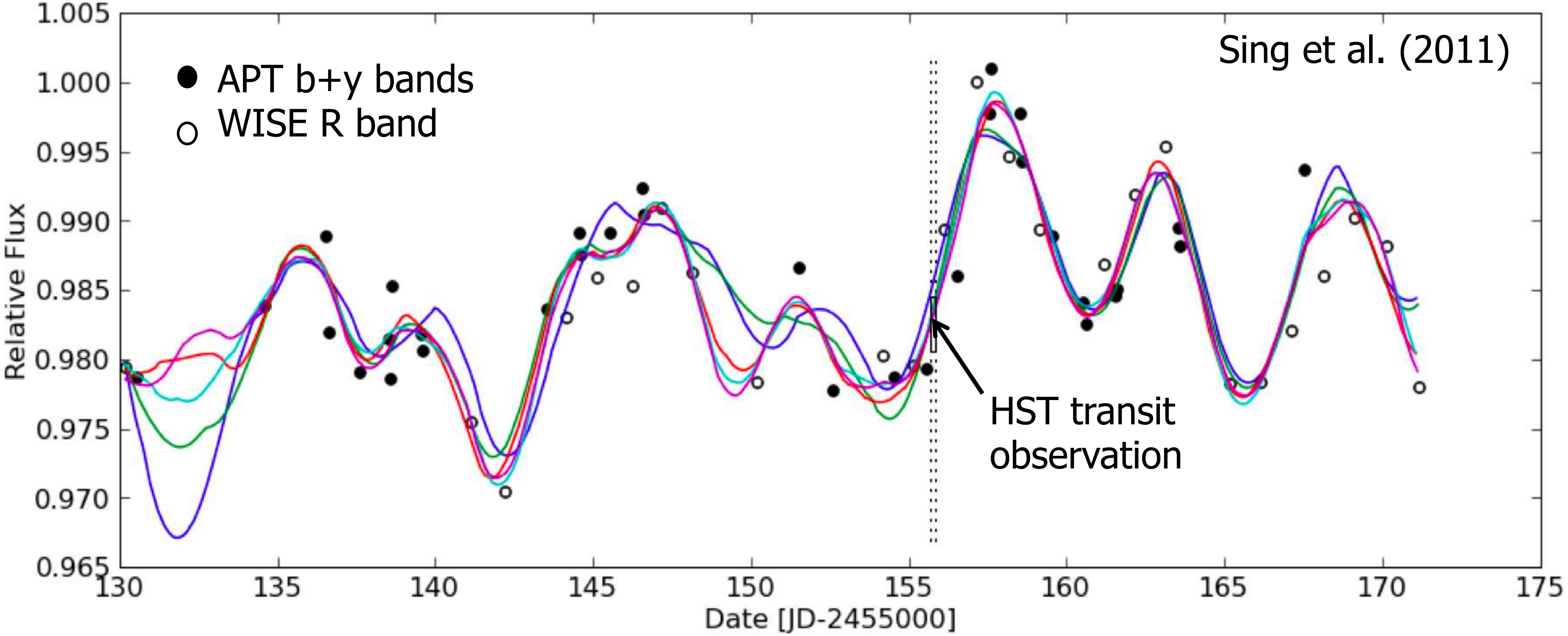


Occulted spot

Sing et al. (2011) HST STIS Transit Observation

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.

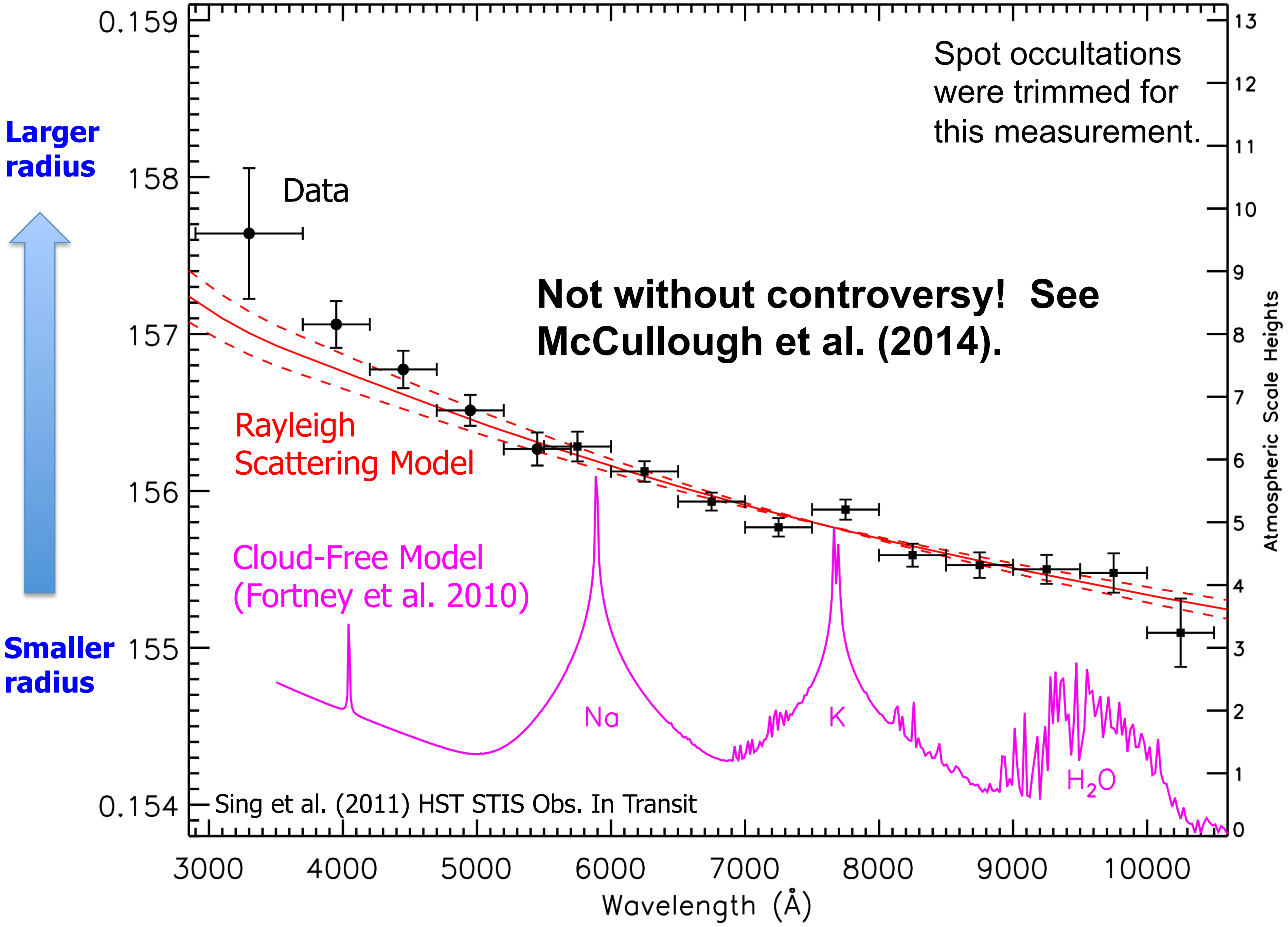
Correcting for Unocculted Spots With Ground-Based Monitoring Data



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



Larger radius

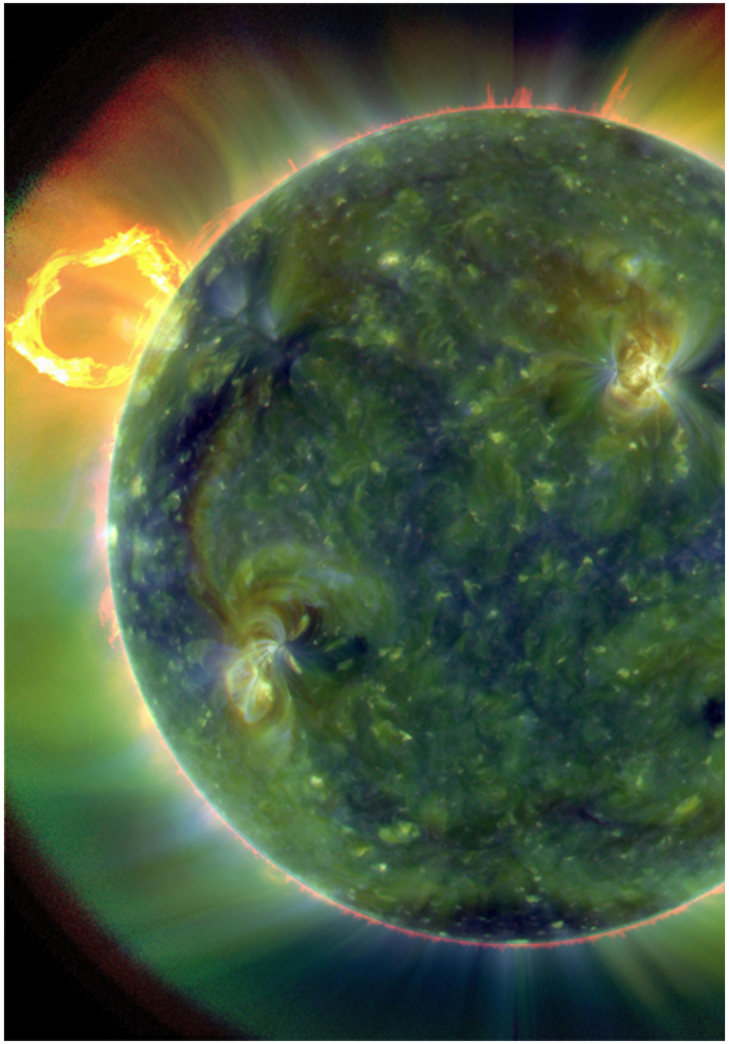
Smaller radius

Spot occultations were trimmed for this measurement.

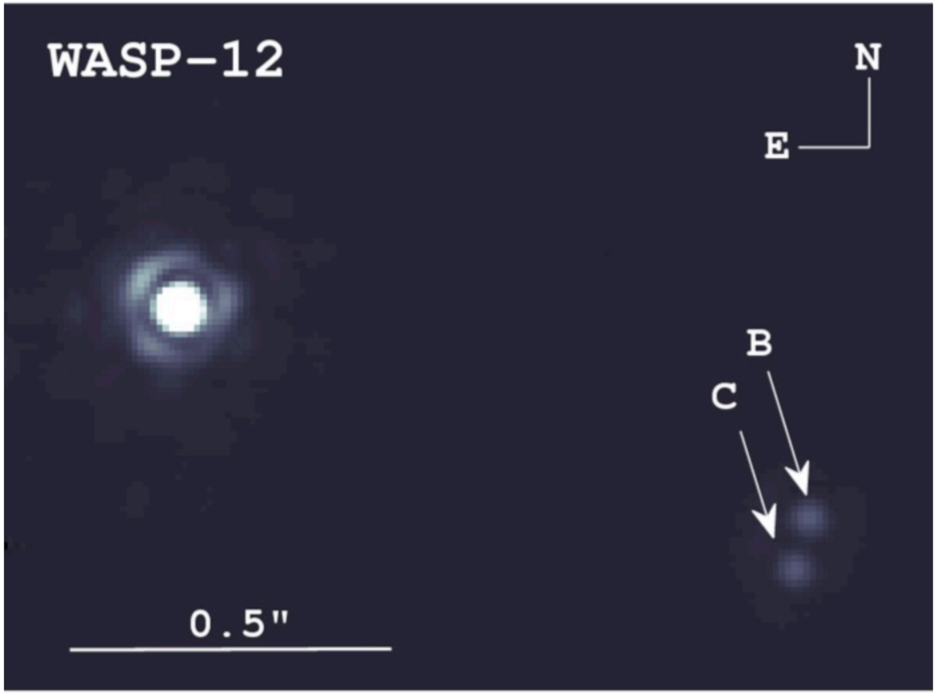
Not without controversy! See McCullough et al. (2014).

Astrophysical Noise Sources:
Is My Measurement Biased?

Things that can affect transit shape:
Limb-darkening, star spots

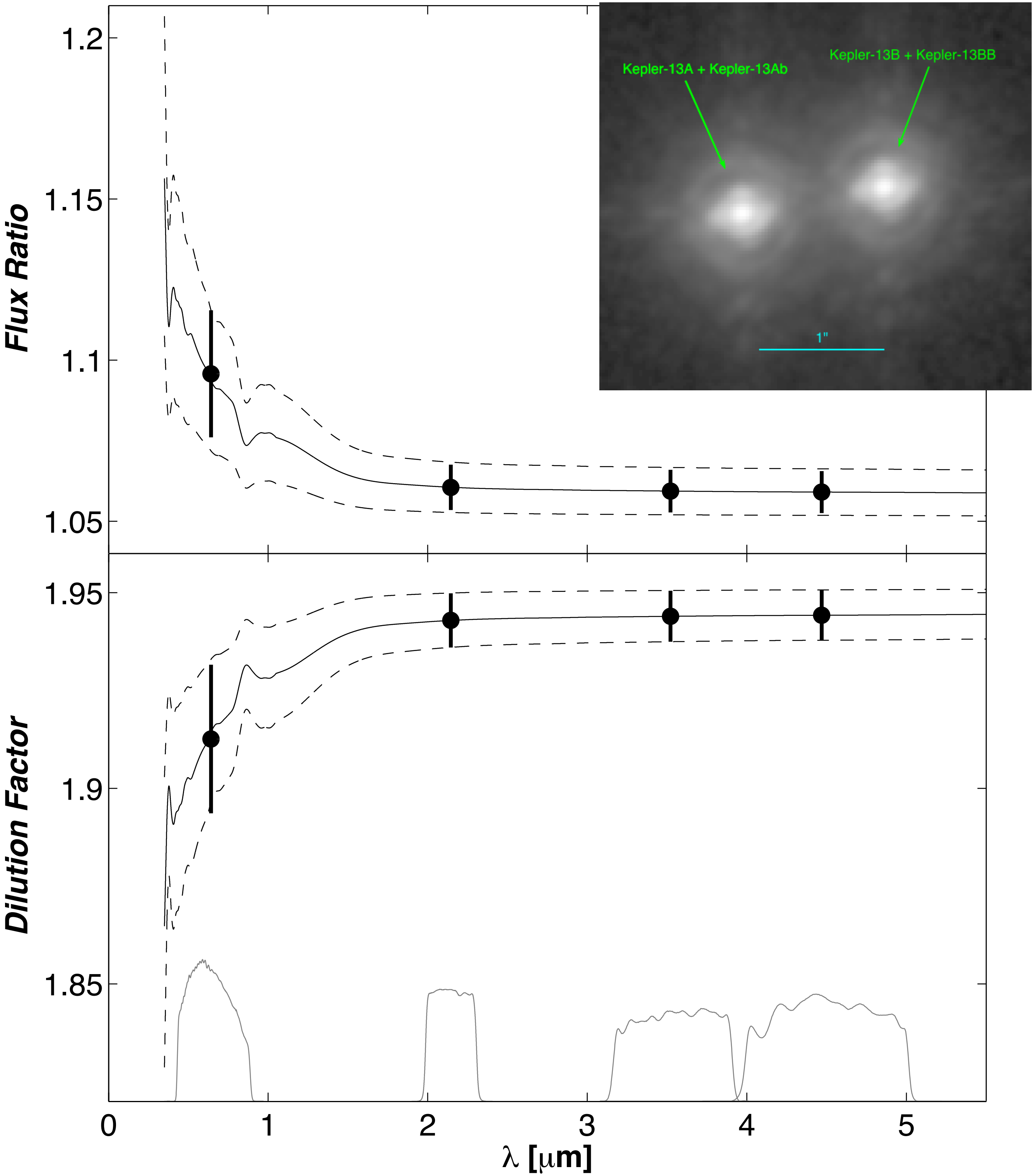


Things that can affect transit depth:
Star spots, contamination from 2nd star

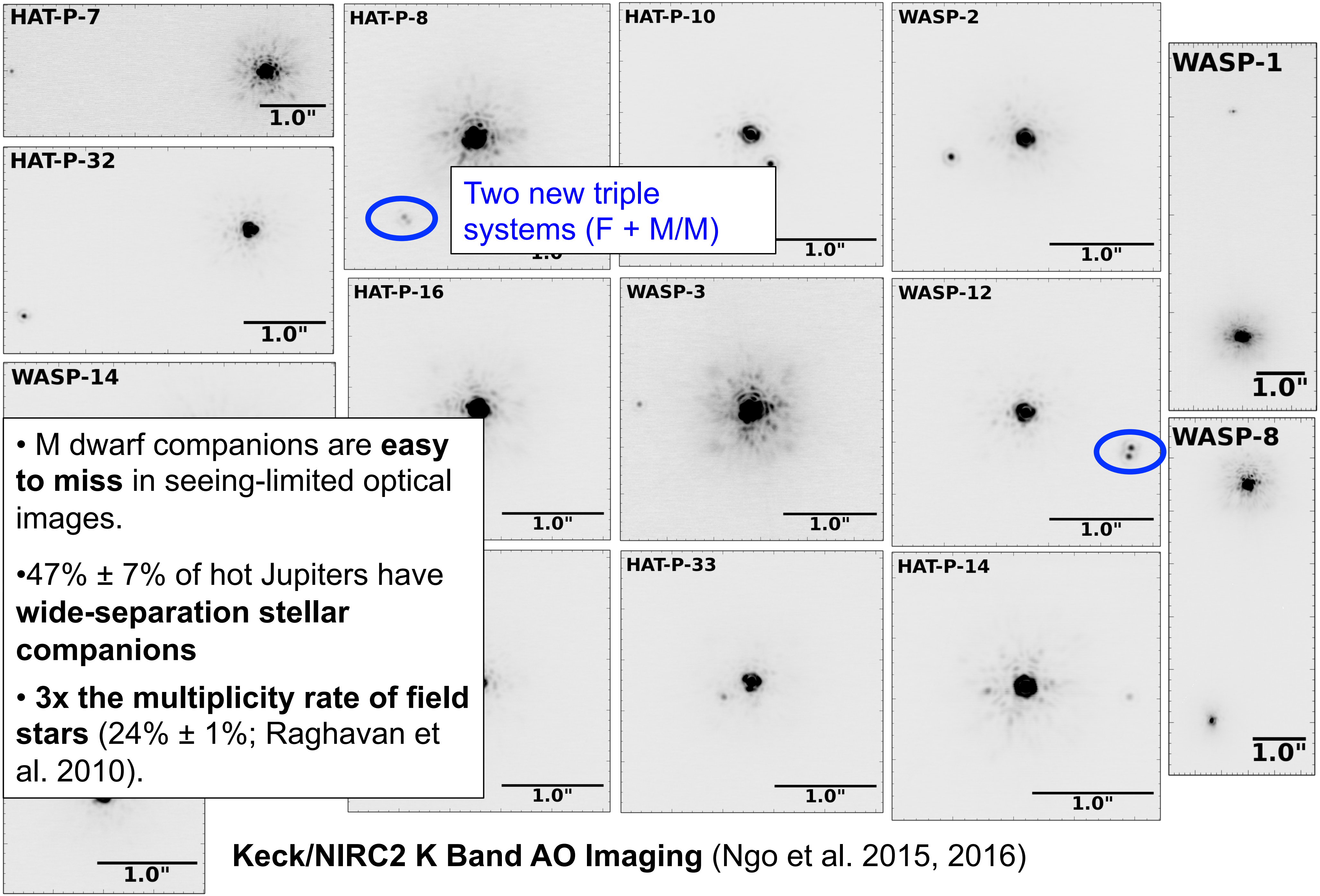


Contamination from Binary Companions: The Case of Kepler-13Ab

Transit and secondary eclipse depths reduced by a factor of two due to blended light from A star companion in binary system (Shporer et al. 2014).



Contamination from Binary Companions:
More Common Than You Might Think!



Two new triple systems (F + M/M)

- M dwarf companions are **easy to miss** in seeing-limited optical images.
- 47% ± 7% of hot Jupiters have **wide-separation stellar companions**
- **3x the multiplicity rate of field stars** (24% ± 1%; Raghavan et al. 2010).

Keck/NIRC2 K Band AO Imaging (Ngo et al. 2015, 2016)

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.

Conclusions: A Primer for Precise Transit and Eclipse Spectroscopy

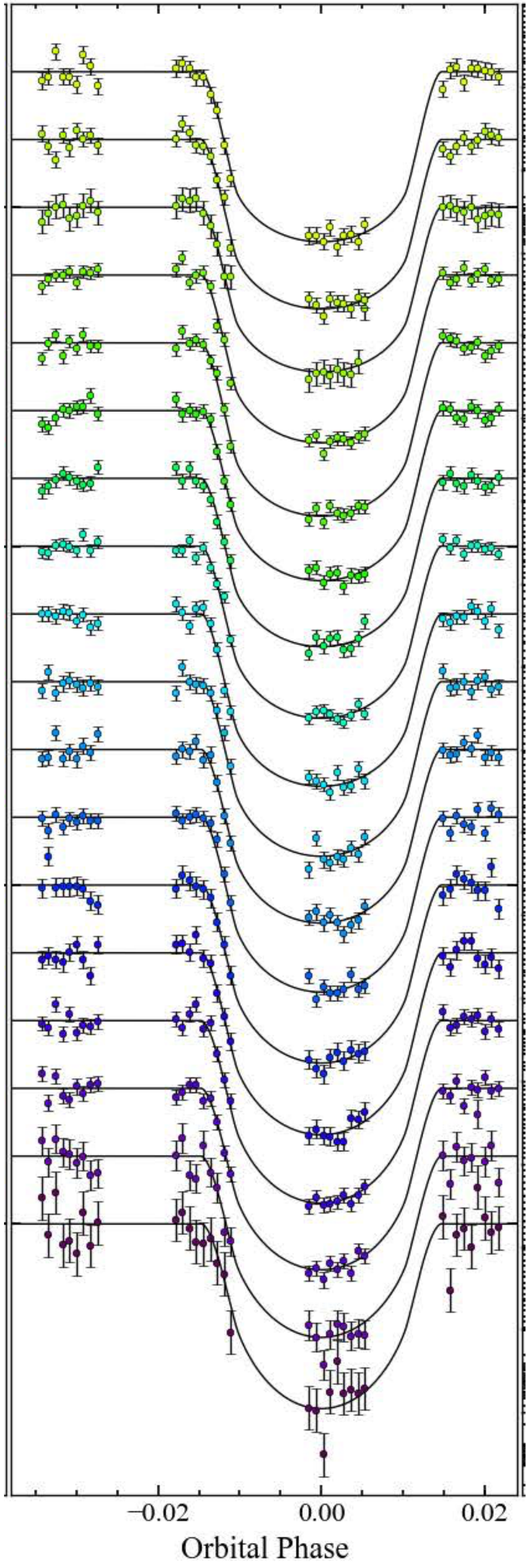
1. Can I identify & remove the sources of time-varying (non-transit) signals in my data?

2. Do my best-fit residuals appear to be Gaussian and uncorrelated? If not, need to adapt standard methods for estimating uncertainties in model parameters.

3. Is my measurement biased by astrophysical phenomena? E.g., spots, contamination from 2nd star.

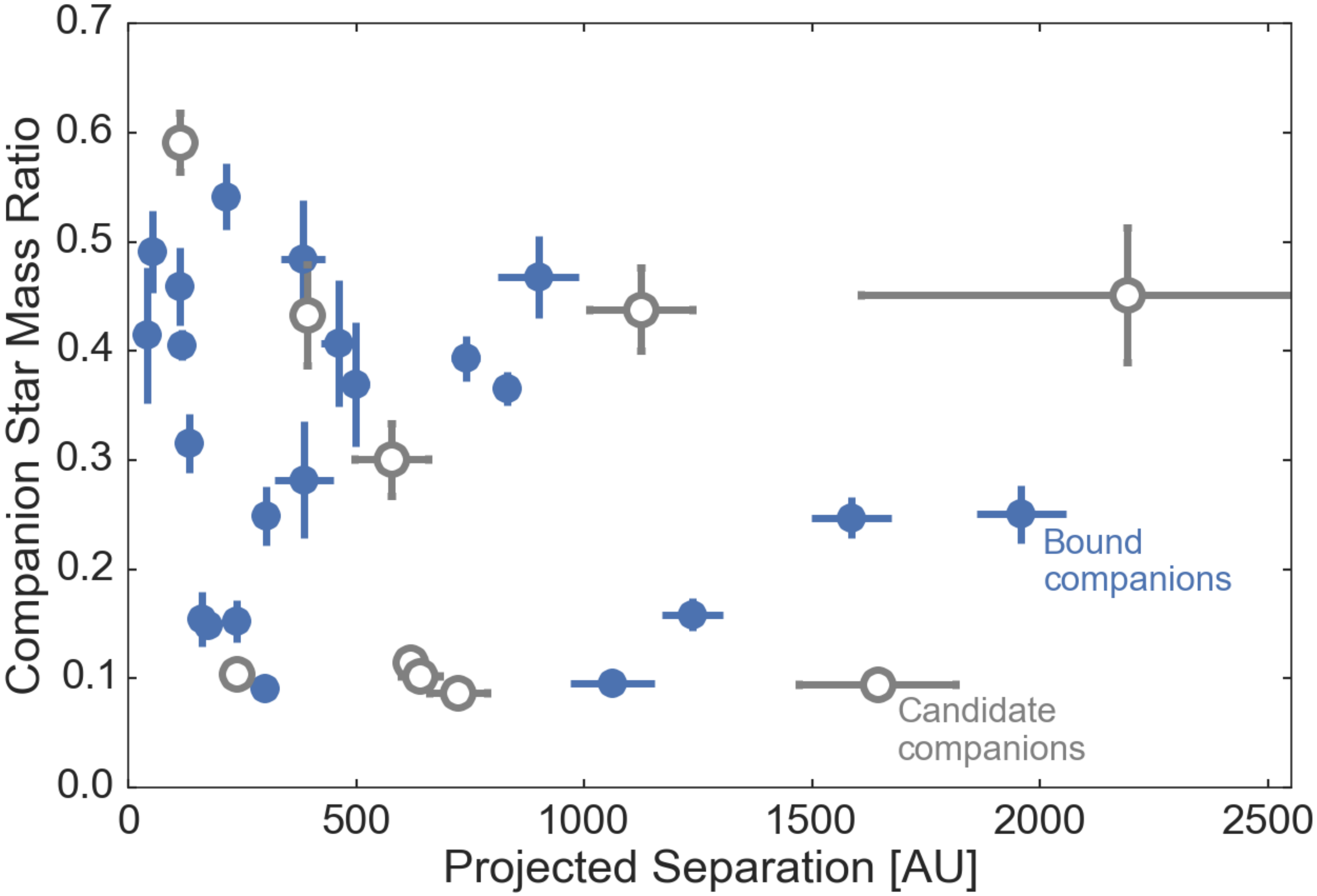
Always be skeptical– if your result seems strange/ surprising, they're probably wrong.

"Extraordinary claims require extraordinary evidence."



STIS transmission spectroscopy of WASP-39b (Fischer et al. 2016)

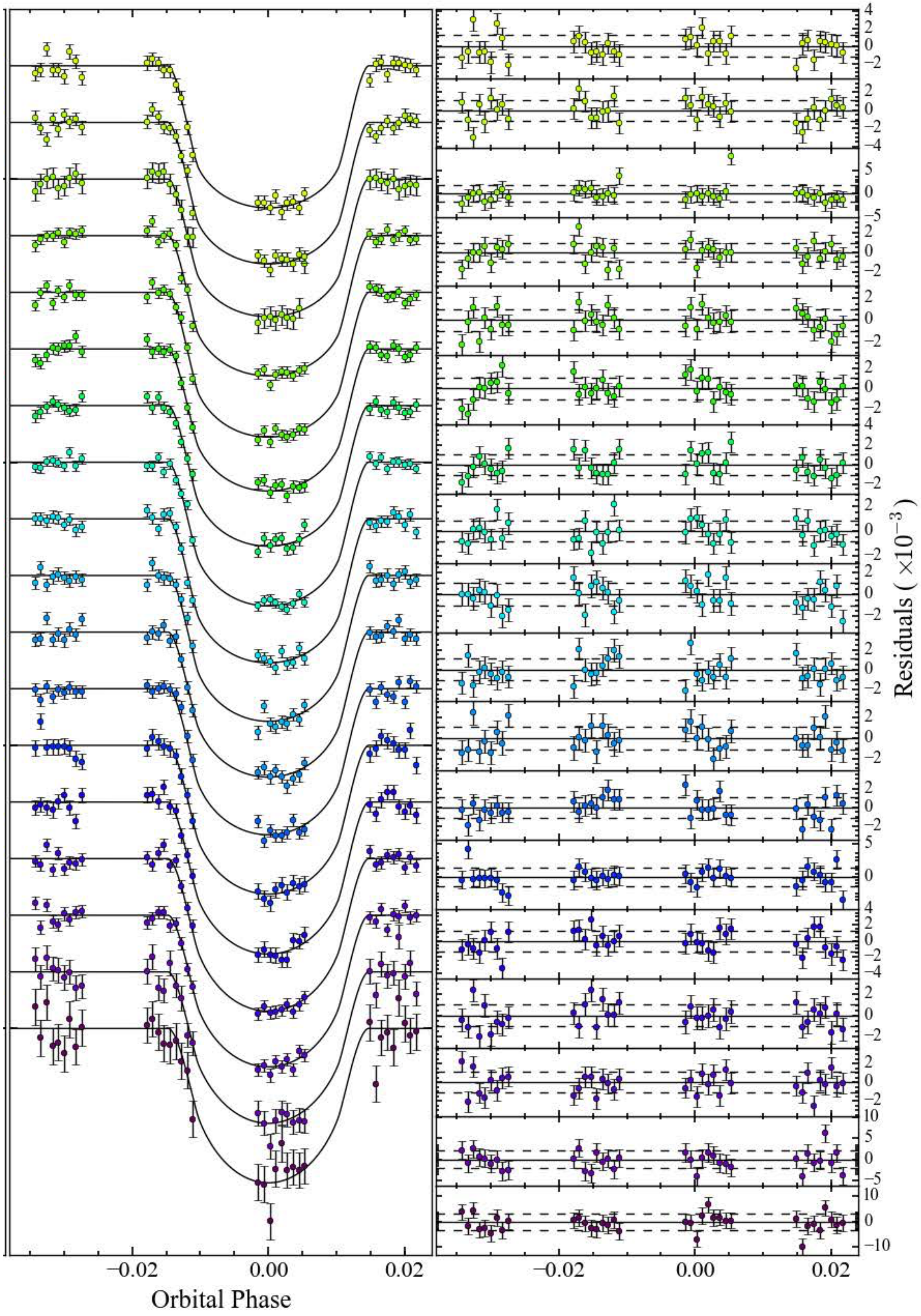
Stellar Companions in Hot Jupiter Systems



Ngo, Knutson et al. (2015, 2016)

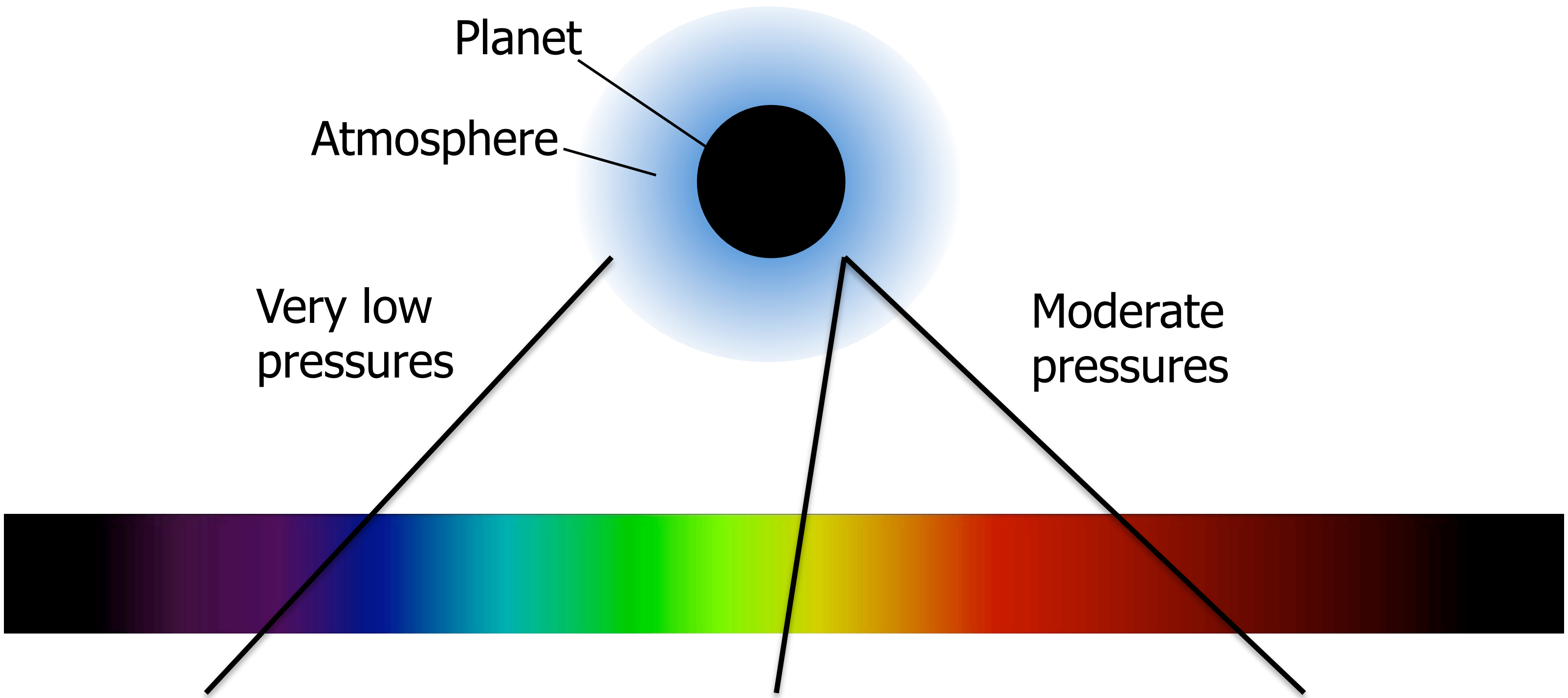
Sources of Instrumental Noise II.
Wavelength Domain

To zeroth order instrumental noise in spectroscopic time series data is usually constant across wavelengths, but **this assumption is not perfect.**



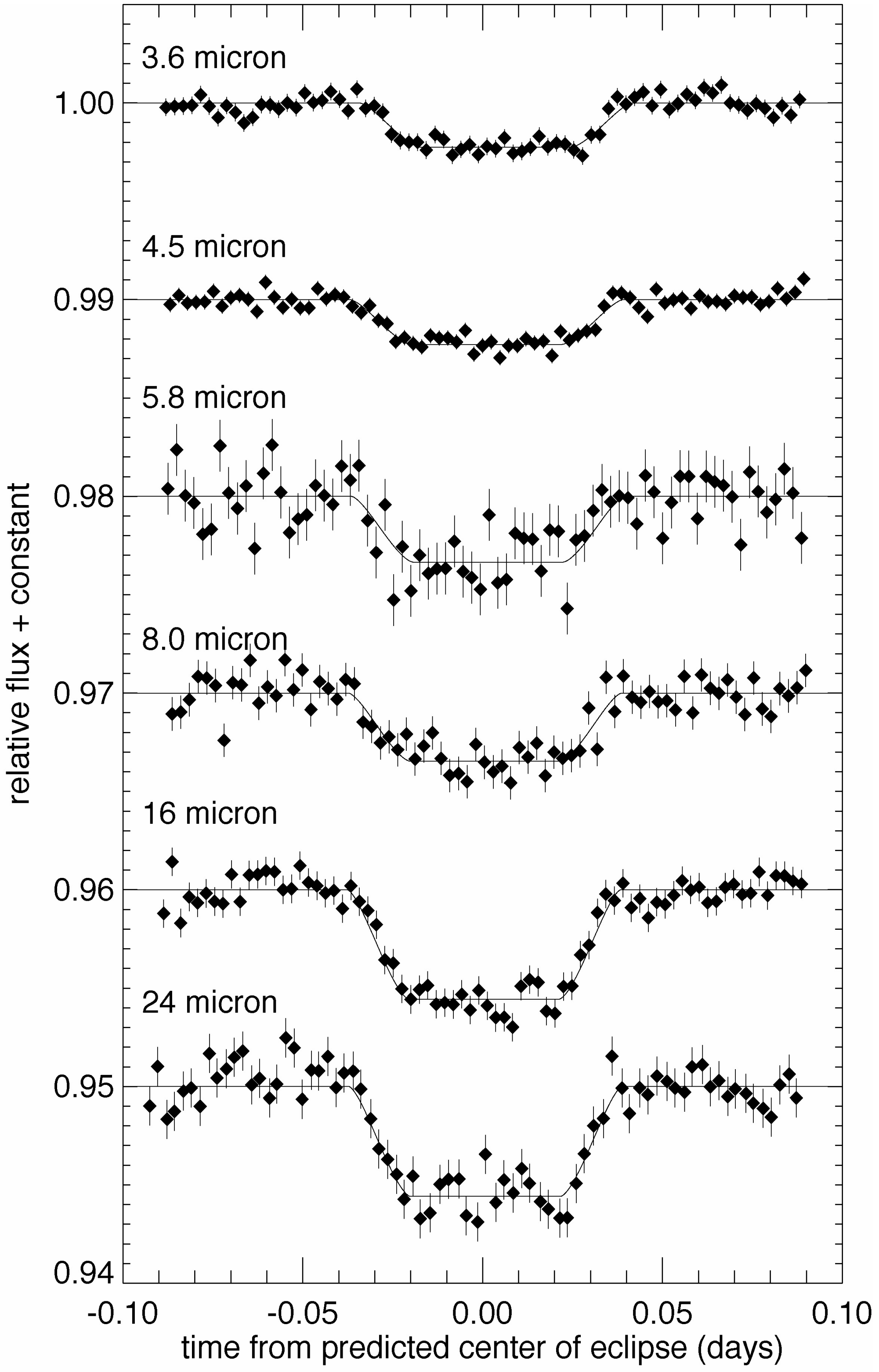
STIS transmission spectroscopy of WASP-39b (Fischer et al. 2016)

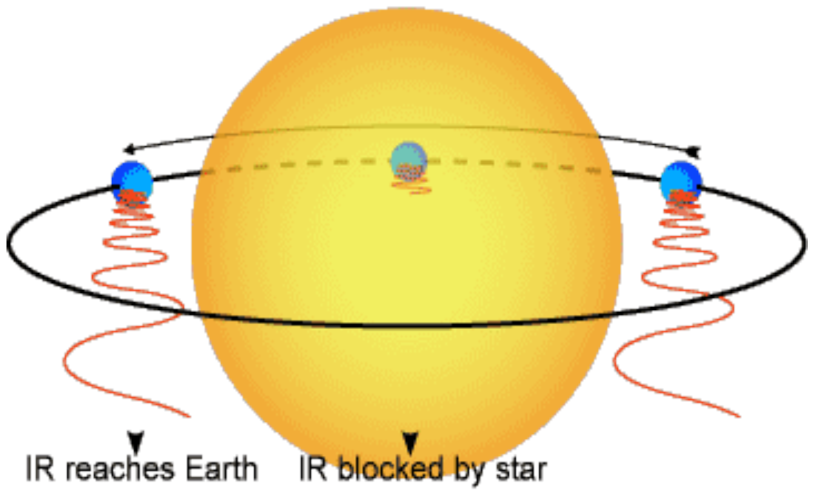
What Do We Learn From Transmission Spectroscopy?



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?

Secondary Eclipse Spectroscopy



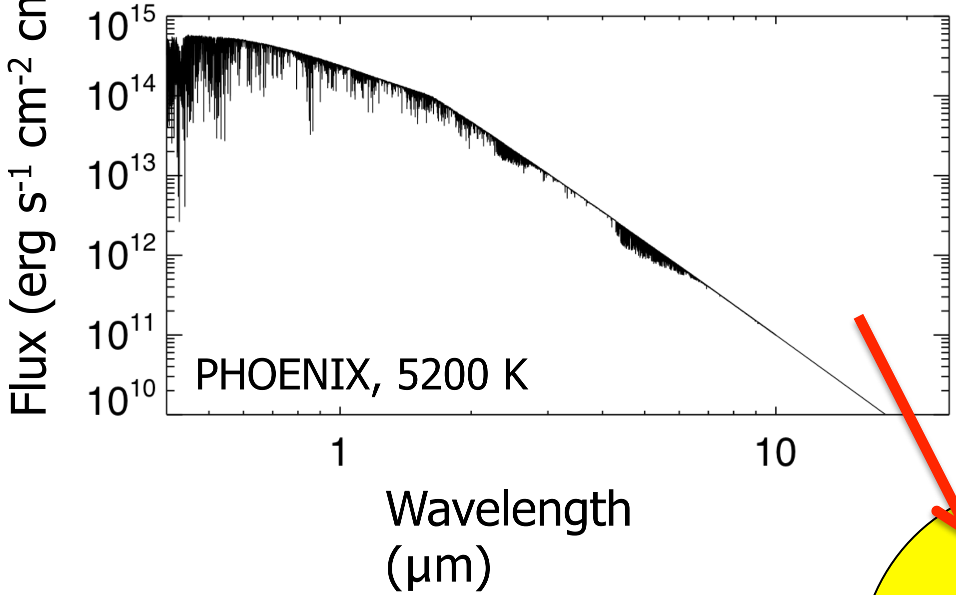


Observe the decrease in light as the planet disappears behind the star and then reappears.

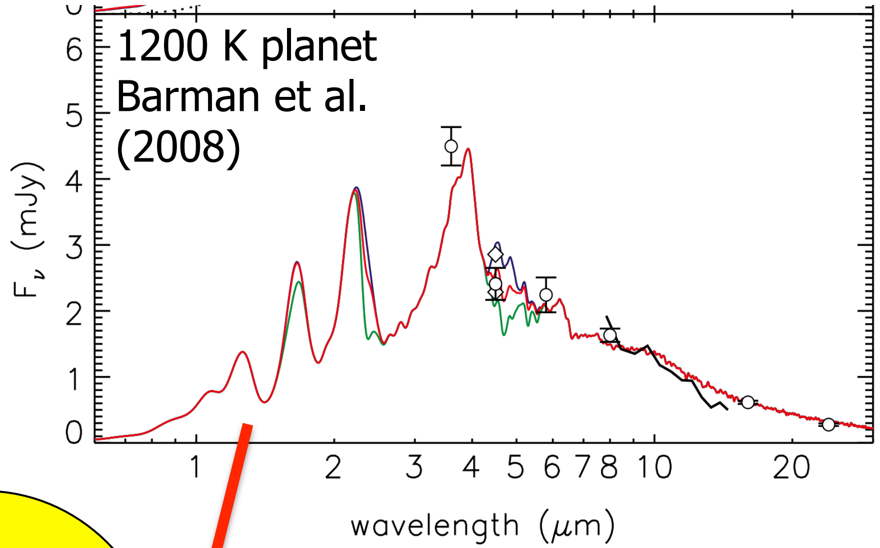
Spitzer observations of HD 189733b (Charbonneau, Knutson et al. 2008)

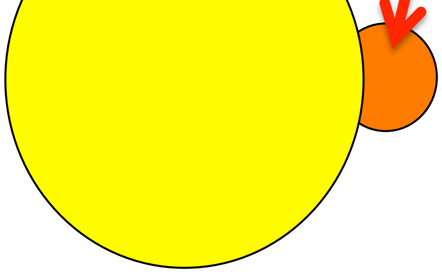
Comparison to Models

Stellar Atmosphere Model

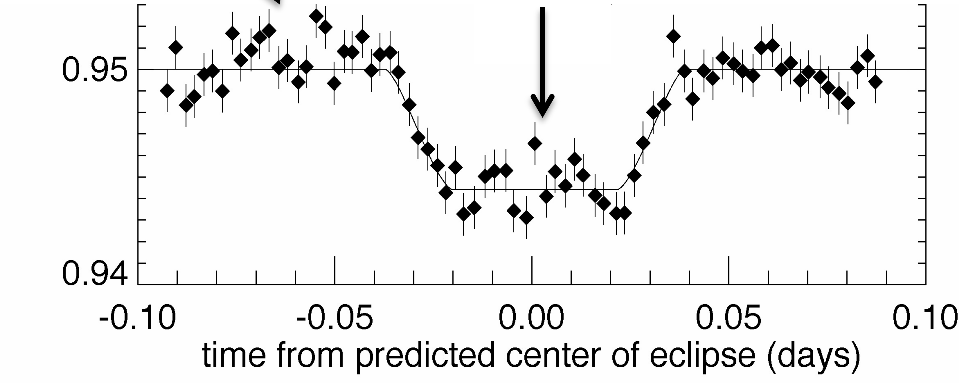


Planet Atmosphere Model



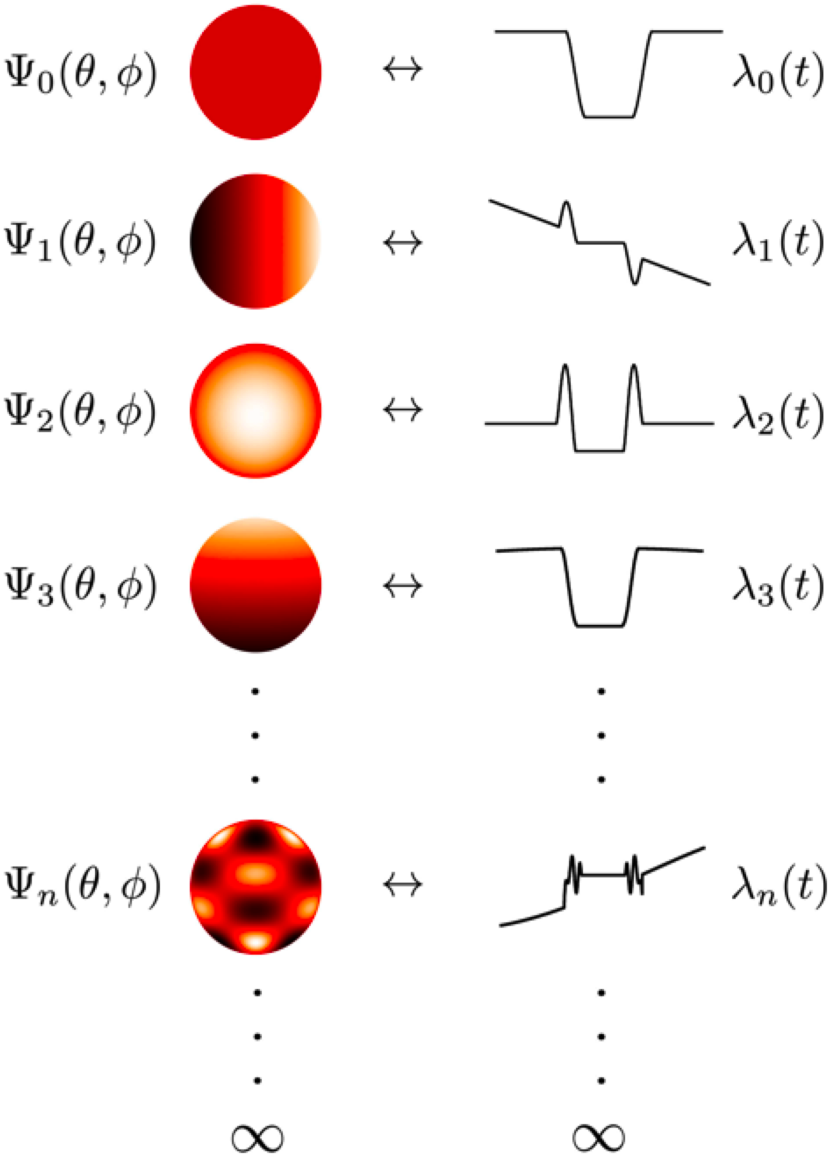


Model assumes solar composition atmosphere, chemistry in local thermal equilibrium.

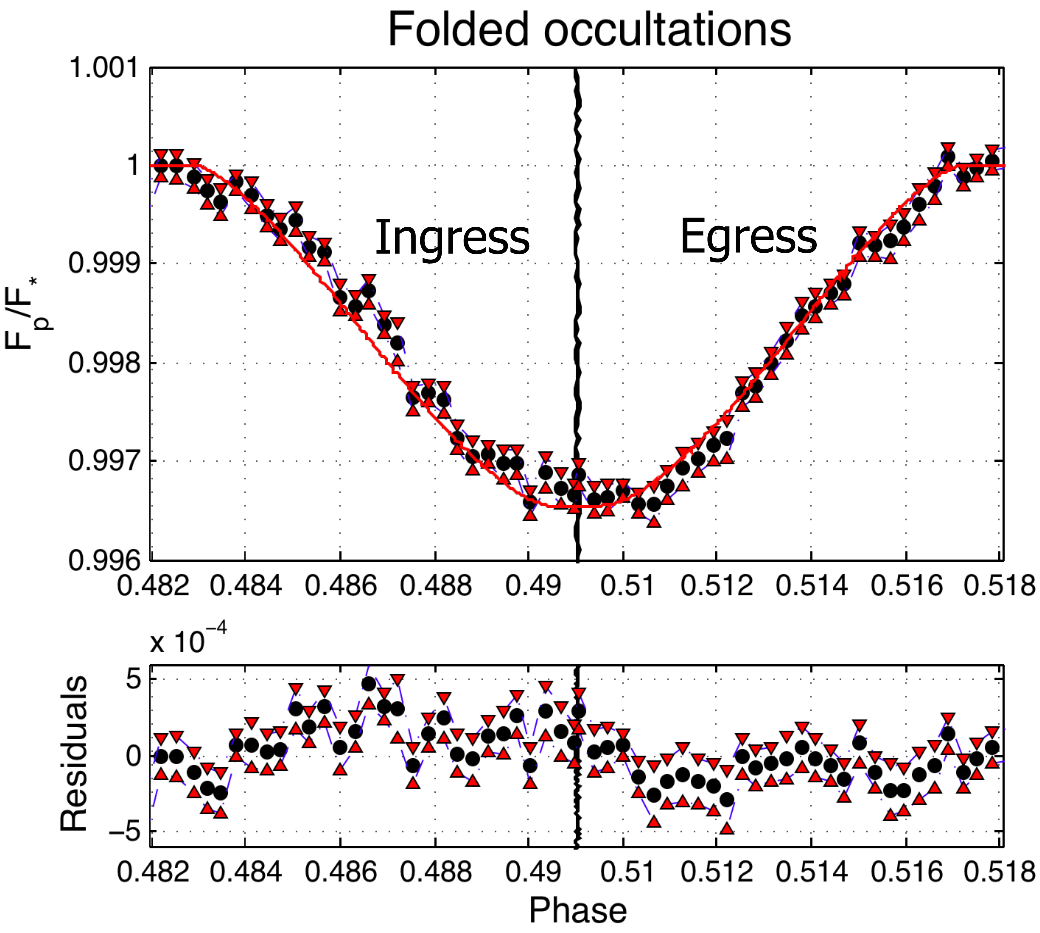


$$depth(\%) = \frac{F_{planet}}{F_{star} + F_{planet}} \approx \frac{F_{planet}}{F_{star}}$$

What Happens When Your Planet is Not a Uniform Disk?



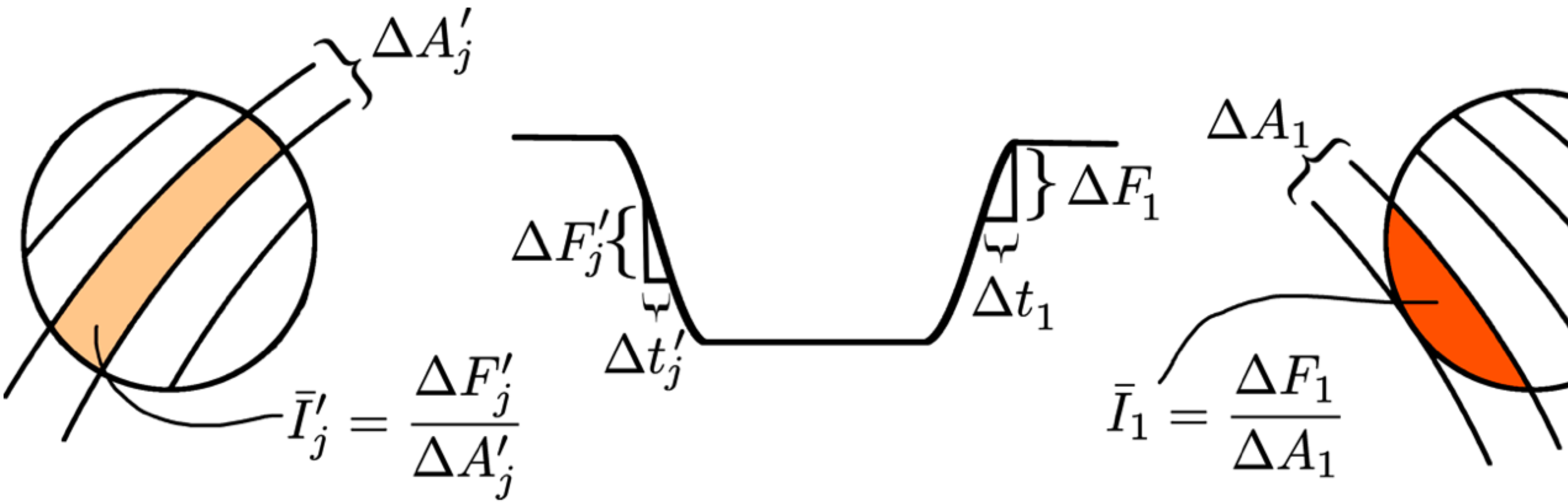
Majeau, Agol, & Cowan (2012)

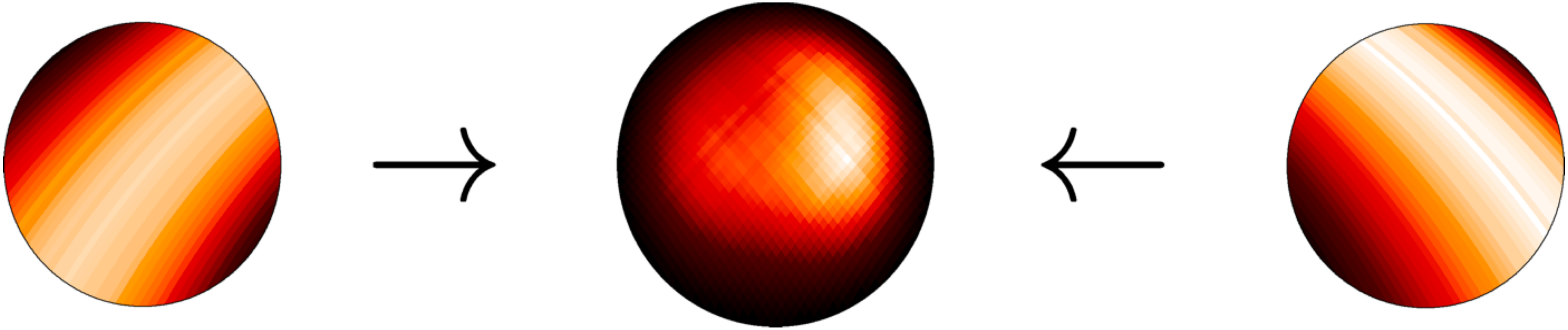


HD 189733b 8 μm secondary eclipse (Agol et al. 2010, de Wit et al. 2012).

Also see Williams et al. (2006).

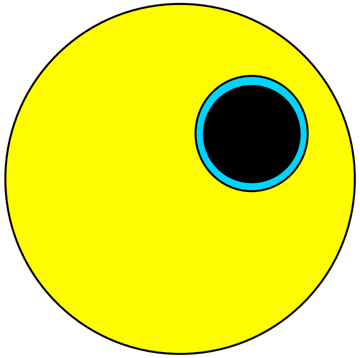
Secondary Eclipse Mapping





Majeau, Agol, & Cowan (2012)

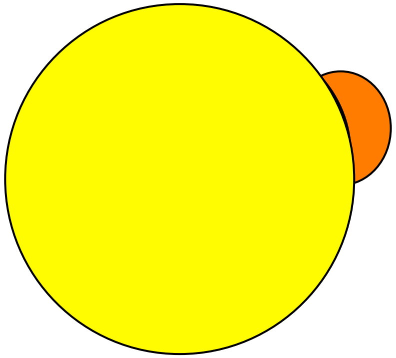
Wrapping it Up: An Observation Planning Cookbook for Transits + Eclipses



Absorption During Transit (%):

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

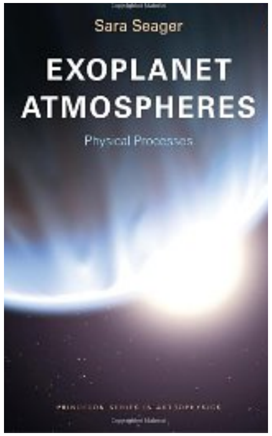
mean molecular weight

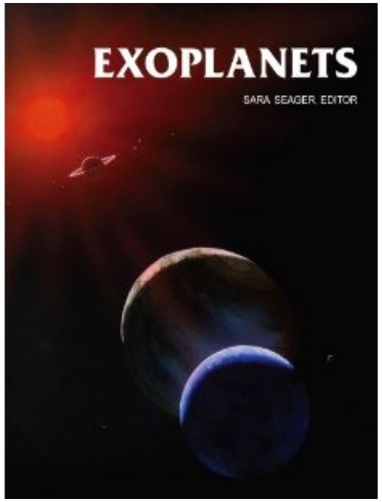


Secondary Eclipse Depth (IR):

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

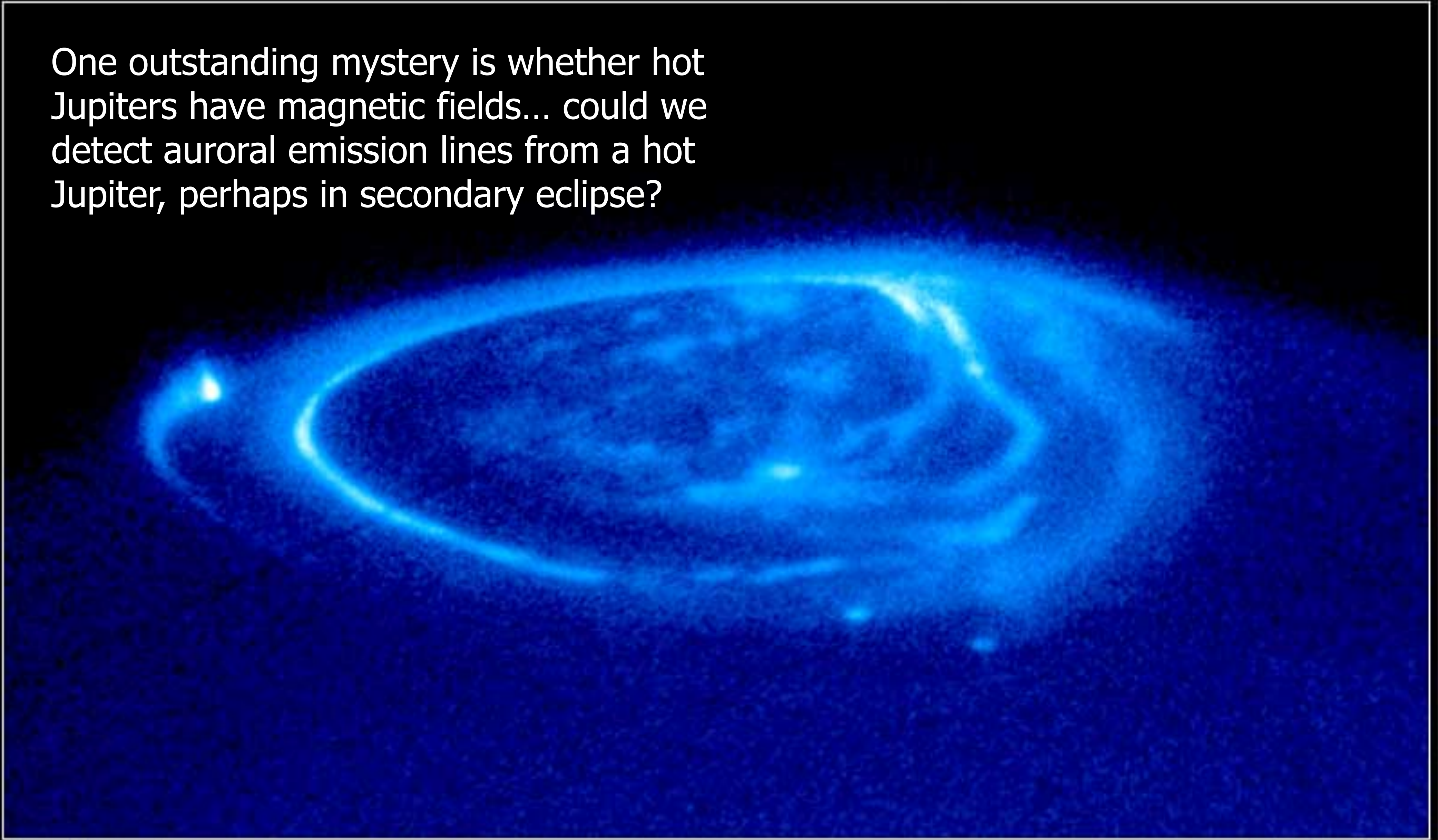
Good resources include:
Exoplanet Atmospheres by Sara Seager,
and *Exoplanets* (ed. Sara Seager)





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