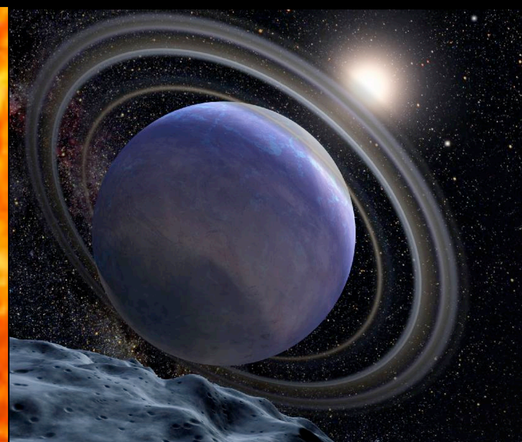
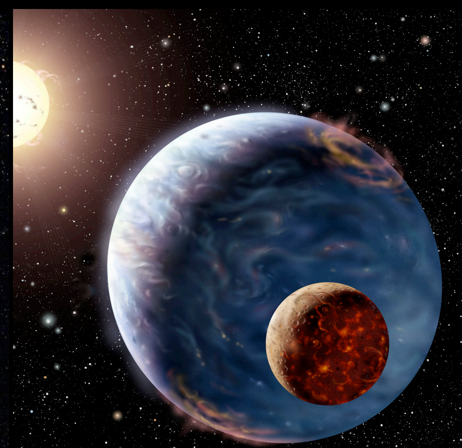
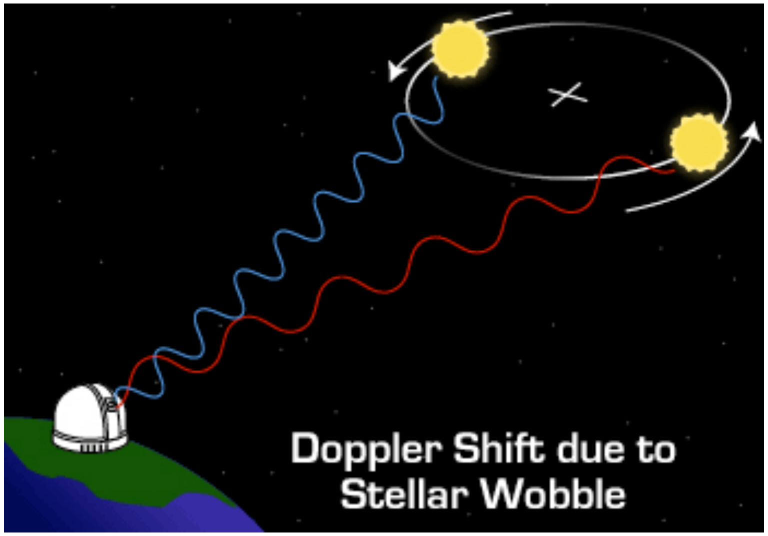
Properties of Exoplanetary Systems: A Spitzer Portrait Gallery

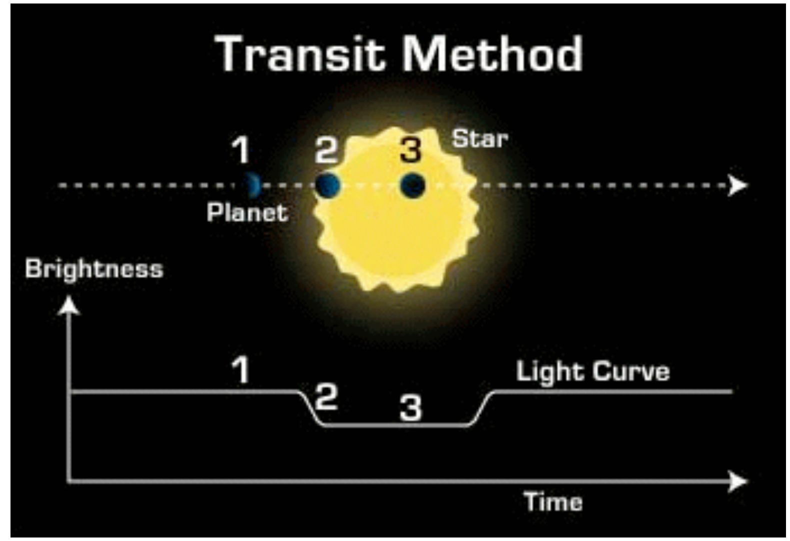





Heather Knutson

UC Berkeley

Two Commonly Used Methods for Finding & Characterizing Exoplanets





Doppler Method

Determine Planet Mass

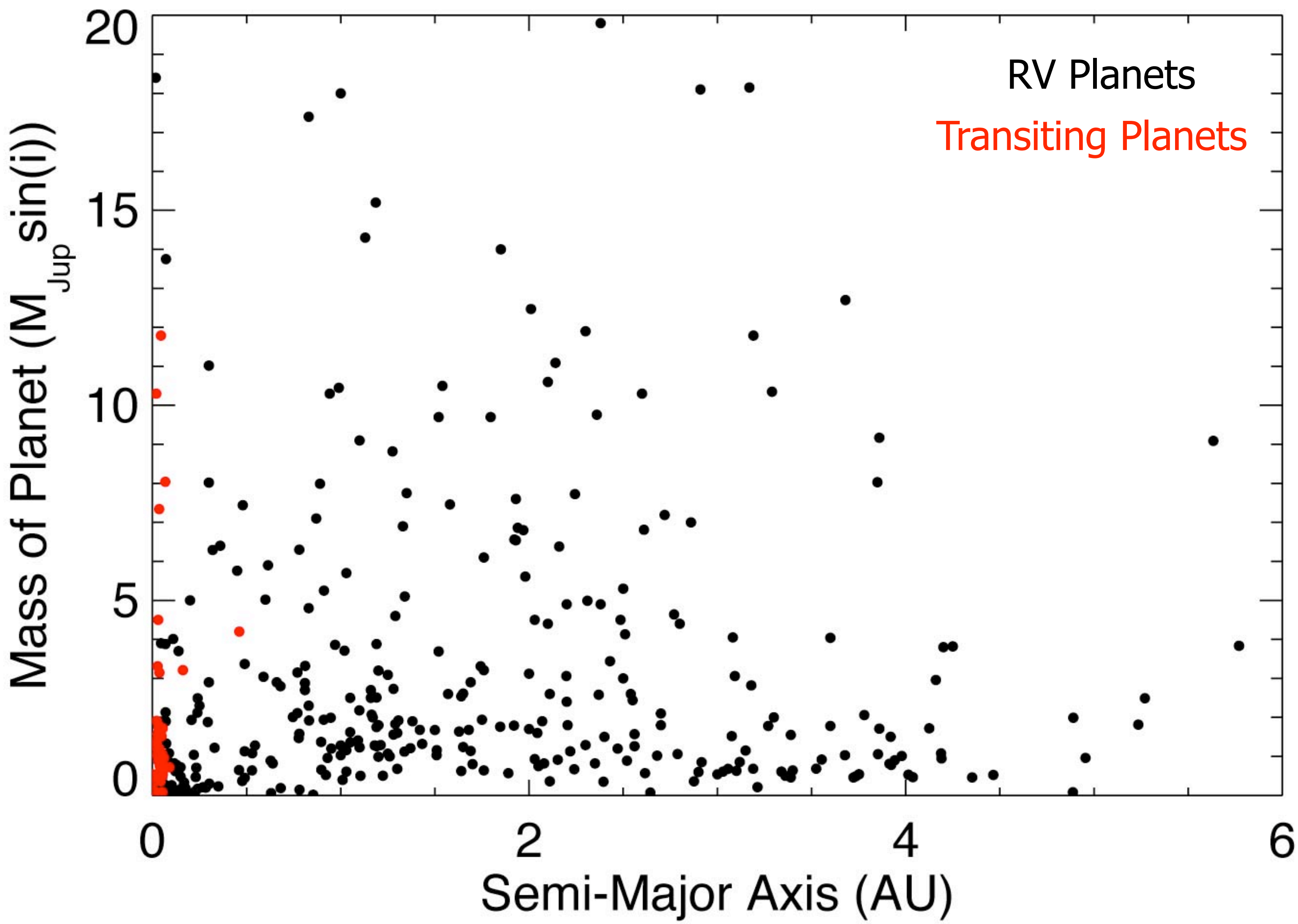
Transit Method

Determine Planet Diameter

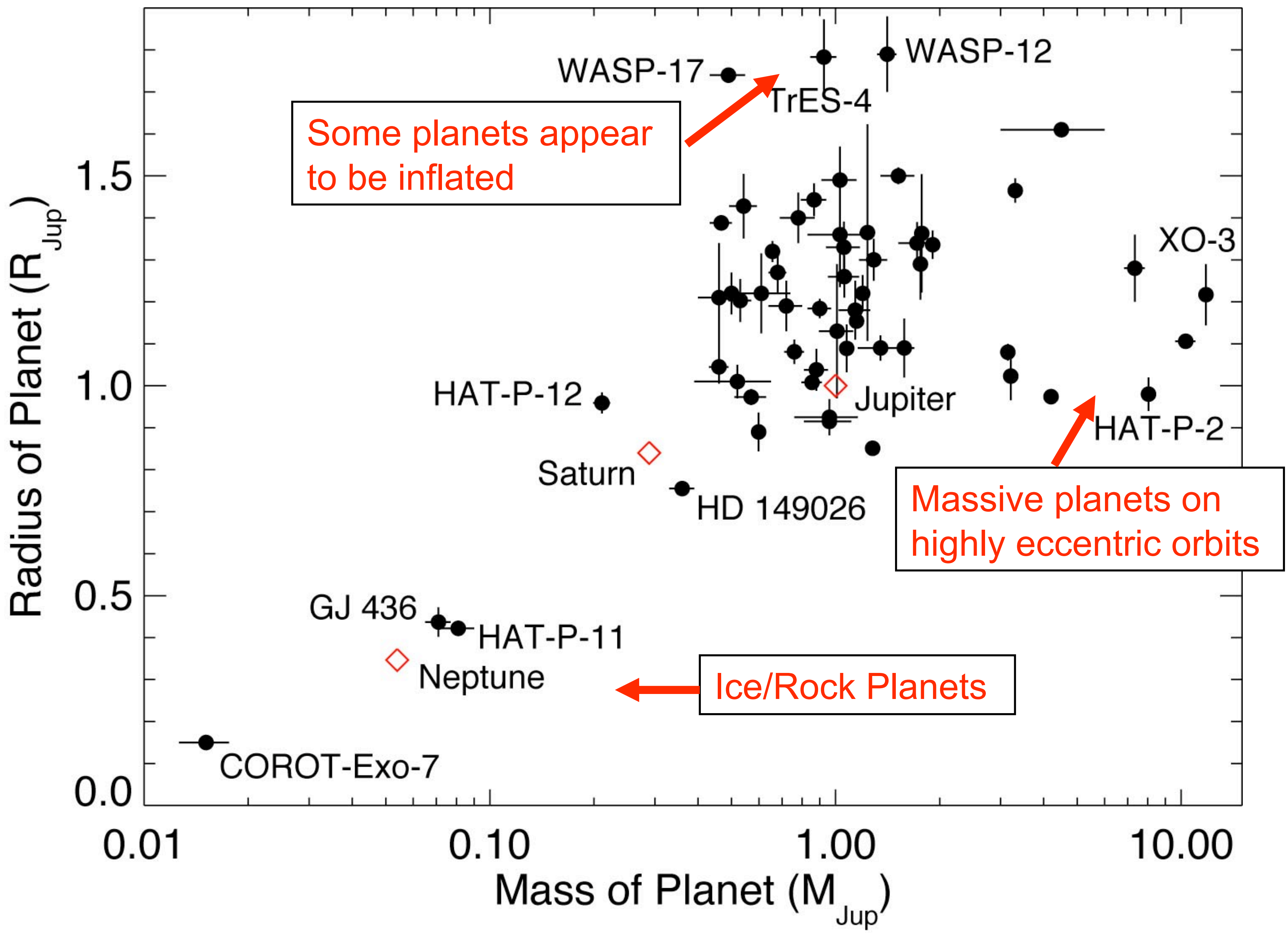
Calculate Planet Density and Infer Composition:

Gas giant (Jupiter), Ice giant (Neptune), or Rocky planet (Earth)

Ongoing Surveys Have Discovered 400+ Planets So Far…



...56 of Those Planets Are Transiting.



Easier

Harder

Exoplanet Characterization 101:

What is the planet's bulk composition?

What is its temperature?

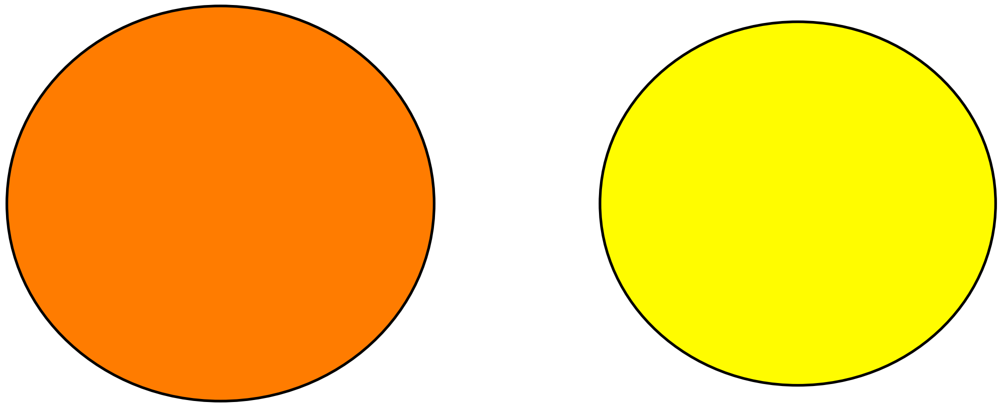
Its atmospheric composition?

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 will soon enable the first studies of **smaller** and/or **cooler** transiting planets.

Two Exoplanets: A Comparison



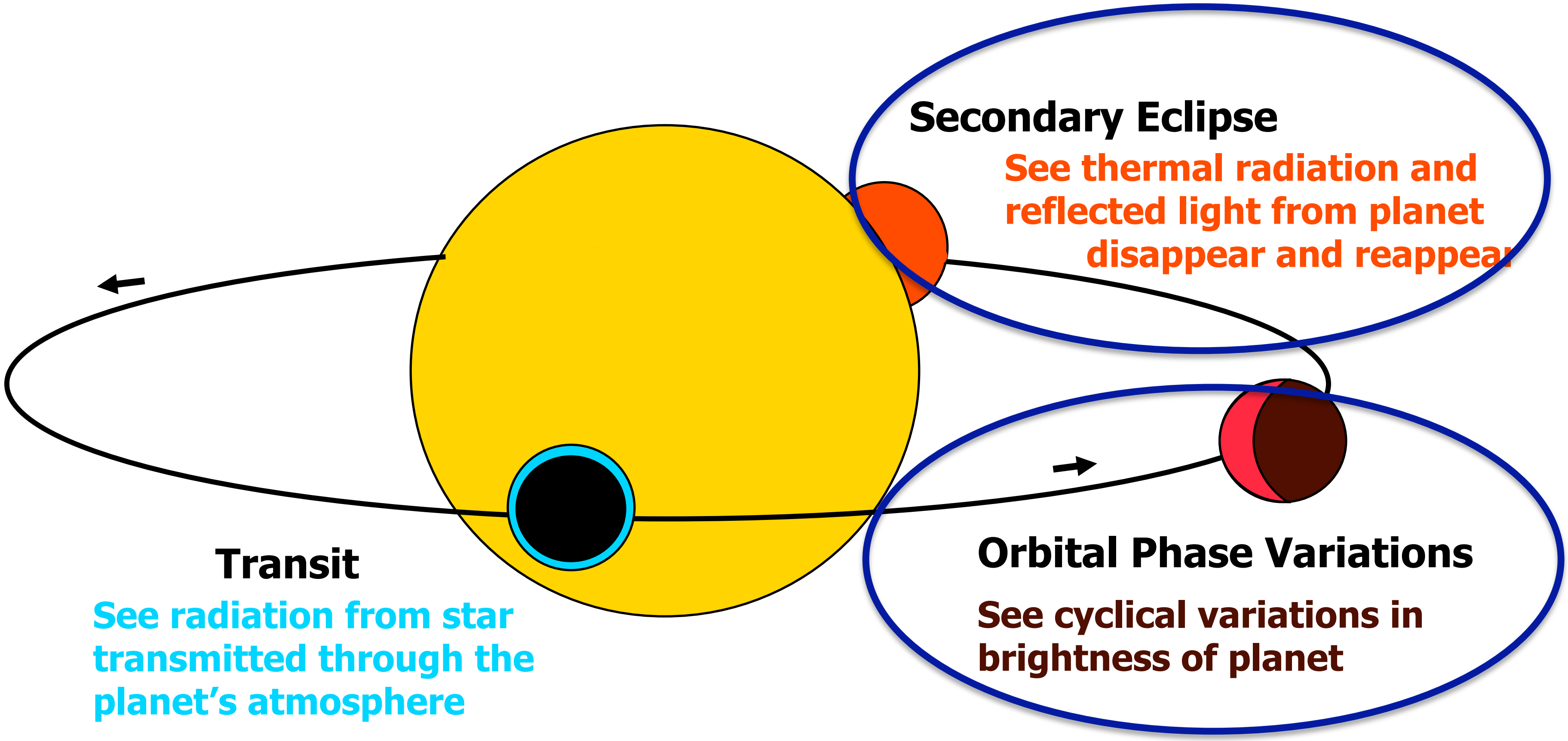
HD 209458b
G0V primary, m_k = 6.3
Mass: 0.66 M_{Jup}
Radius: 1.32 R_{Jup}
P=3.525 days
T_{eqil}=1450 K

HD 189733b
K0V primary, m_k = 5.5
Mass: 1.15 M_{Jup}
Radius: 1.15 R_{Jup}
P=2.218 days
T_{equil}=1200 K ←

Equilibrium temperature assumes planet absorbs all incident flux and re-radiates as a blackbody

These are the two **brightest** transiting planet systems known today.
Also by far the **best-studied**.

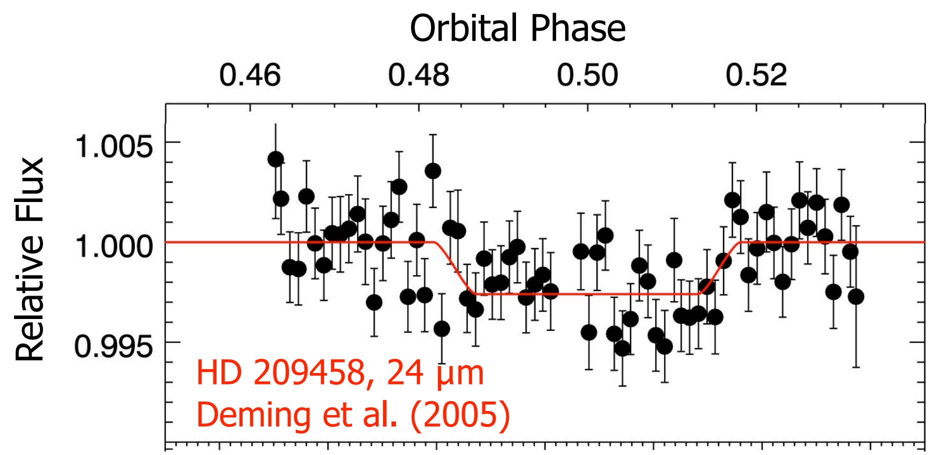
Transiting Planets as a Tool for Studying Exoplanet Atmospheres

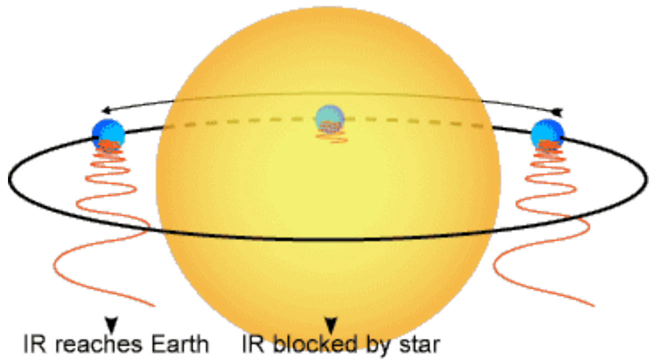


***Spitzer* has provided some of the best examples of these two phenomena in the infrared to date.**

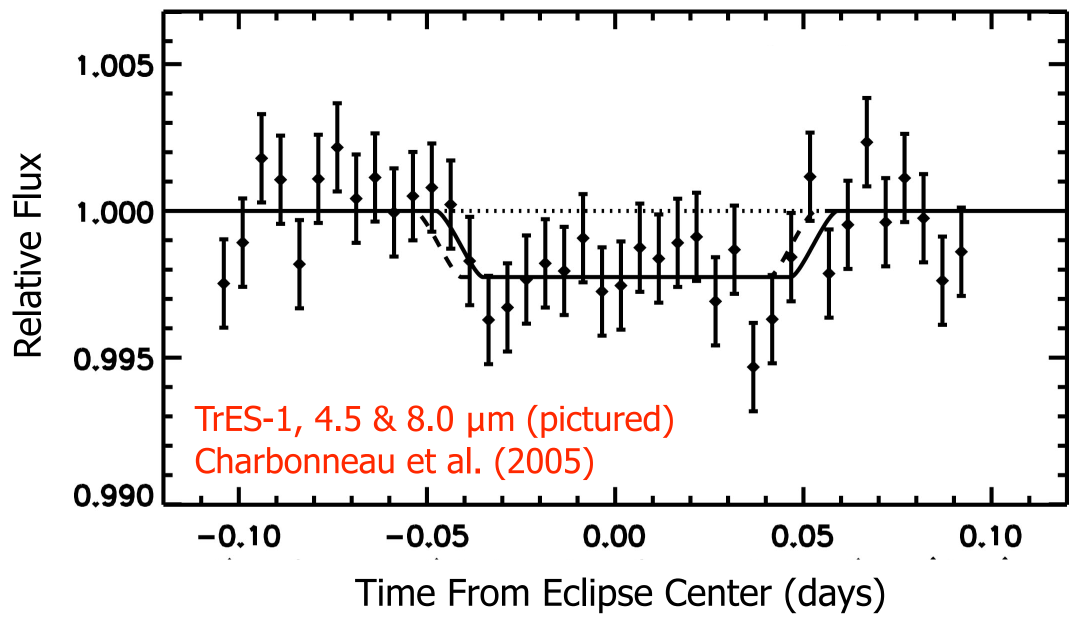
2005: First Detection of Light From An Extrasolar Planet

Can measure the planet's emitted flux without the need to spatially resolve the planet's light separate from that of the star.





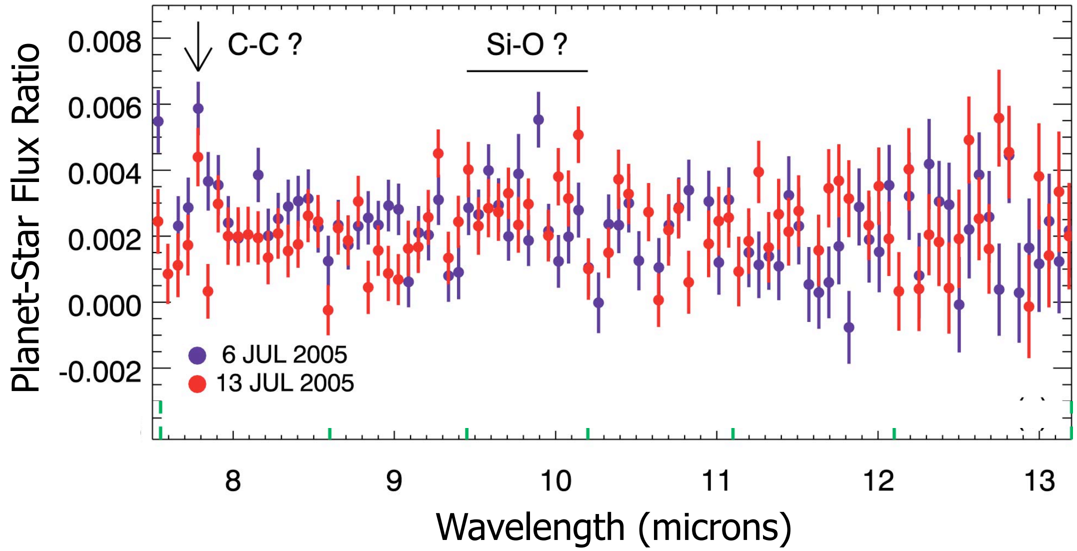
Observe the decrease in light as the planet disappears behind the star and then reappears.



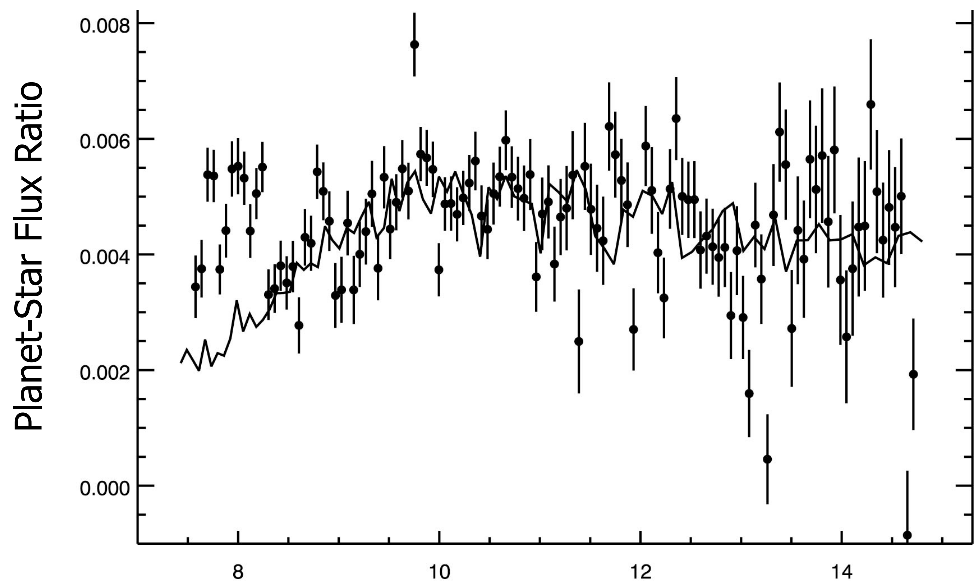
2007: First Spectrum for an Extrasolar Planet

IRS observations of two planets during secondary eclipse:

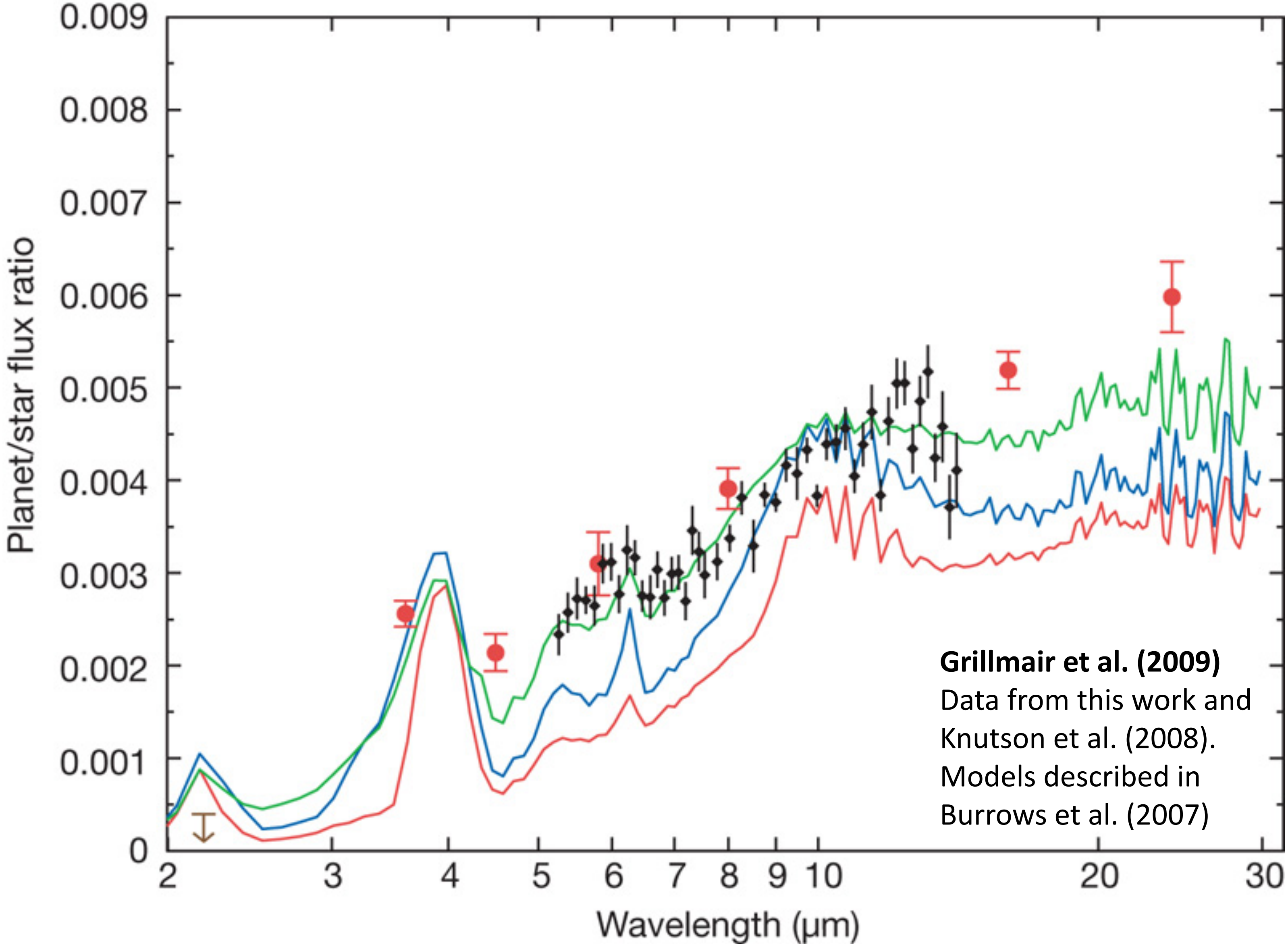
HD 209458b
Richardson et al. (2007)



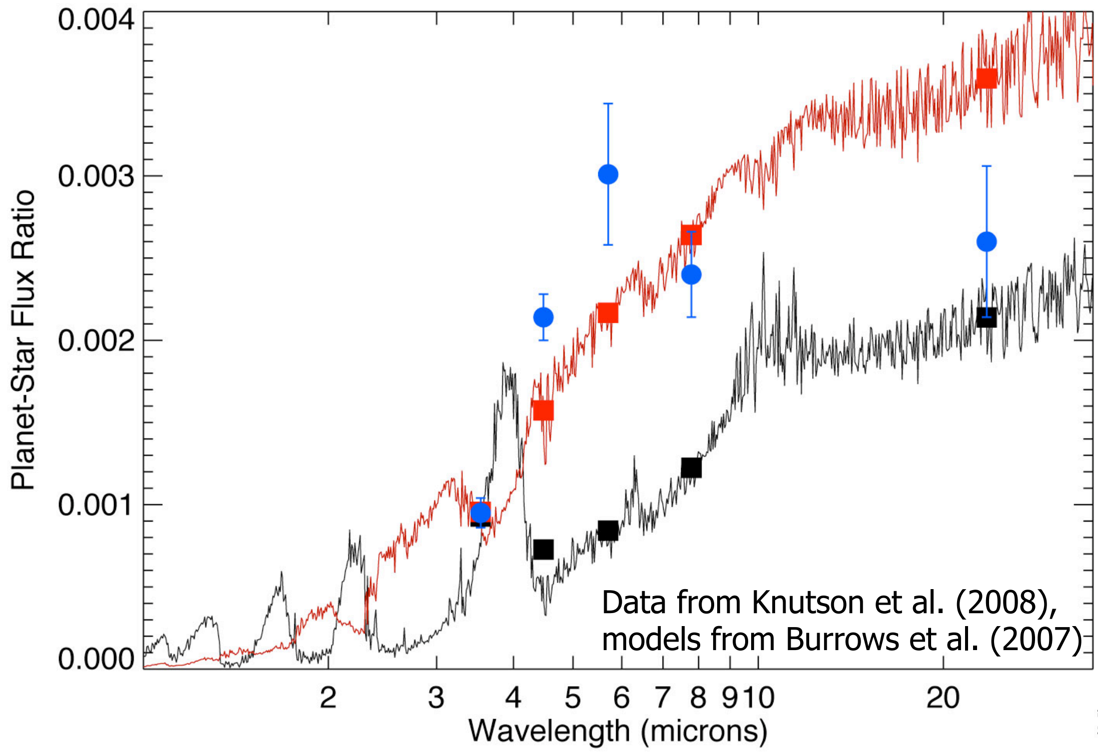
HD 189733b
Grillmair et al. (2007)



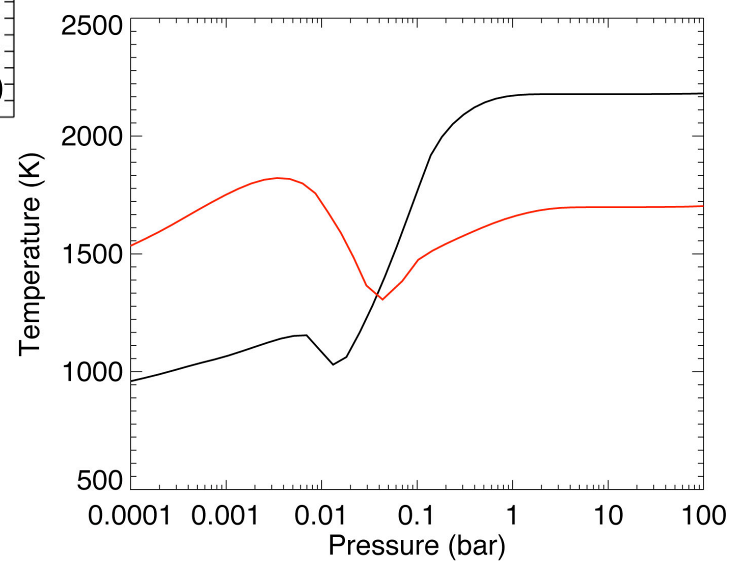
State-of-the-Art Spitzer Observations of HD 189733b



HD 209458b: Evidence for Two Classes of Hot Jupiter Atmospheres

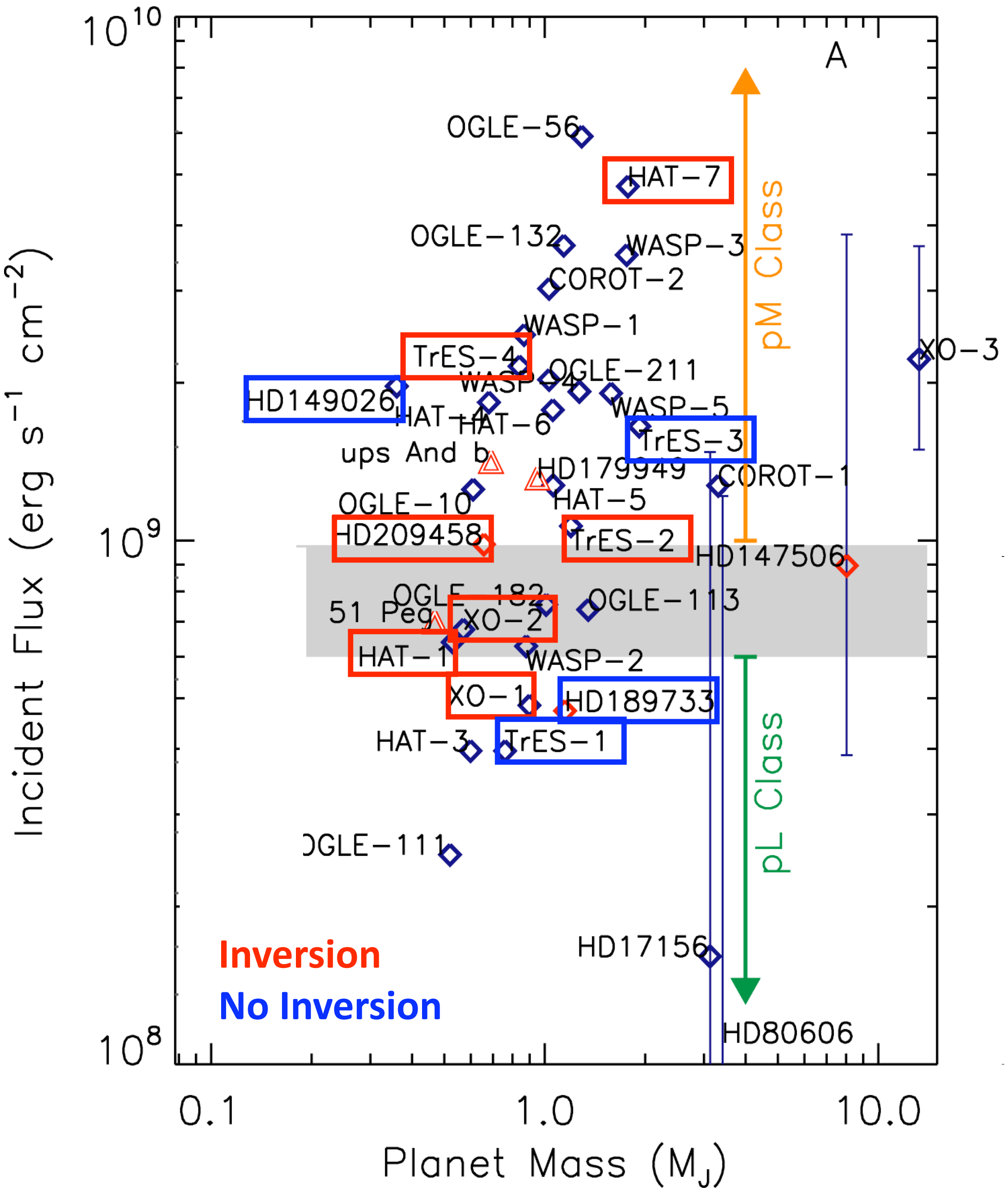


Requires a model with a temperature inversion and water features in emission instead of absorption.



Why would two hot Jupiters with similar masses, radii, compositions, and temperatures have such different pressure-temperature profiles?

Can gas-phase TiO explain temperature inversions?



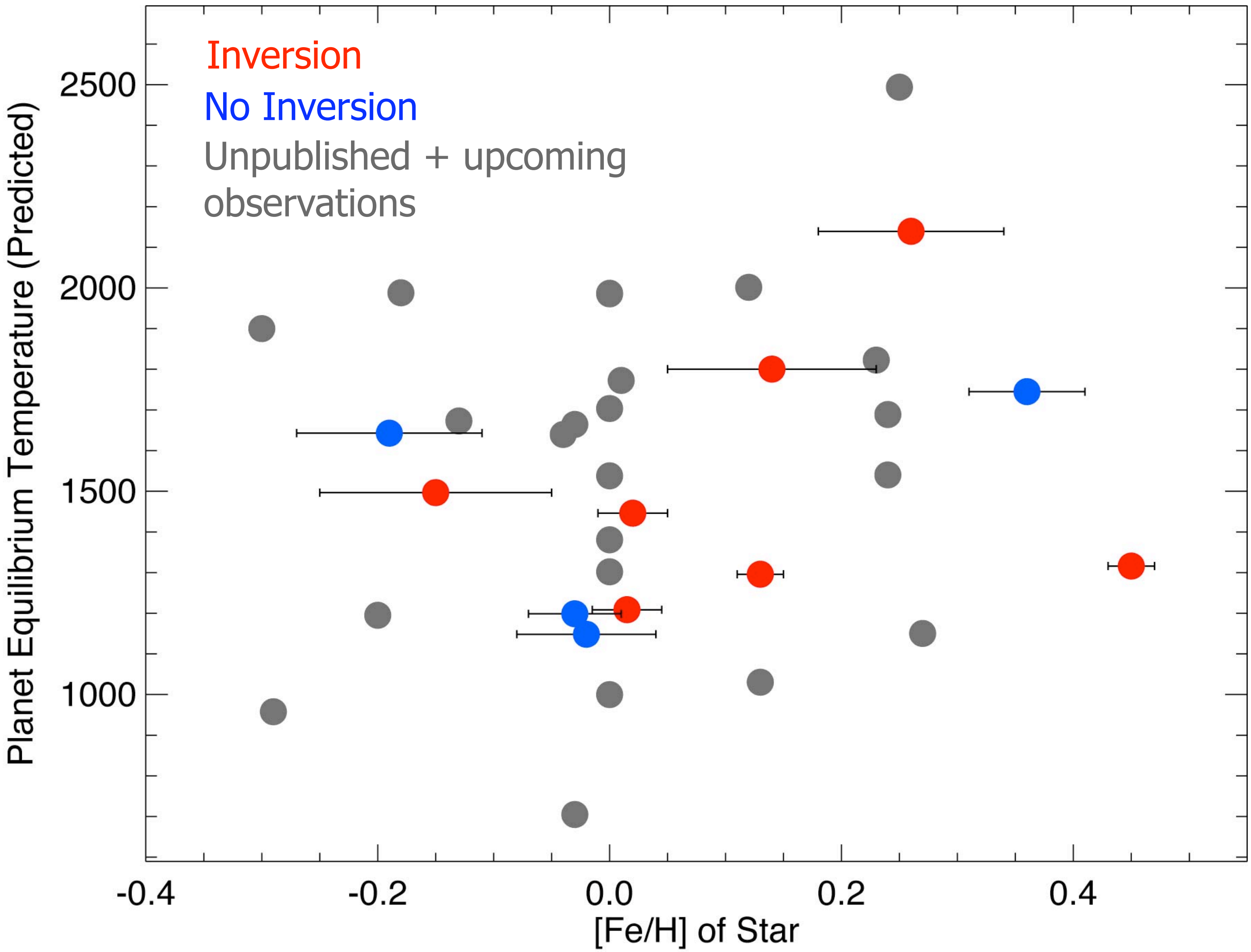
Problem: inversions do not appear to correlate with temperature

One alternative:
sulfur photochemistry
(Zahnle et al. 2009)

As described in Hubeny et al. (2003), Burrows et al. (2007, 2008), and Fortney et al. (2008)

Figure from Fortney et al. (2008)

Do Temperature Inversions Correlate With Any Other Properties of These Systems?



Some Challenges for 1D Atmosphere Models

1. Are we getting the chemistry right?

HD 209458b:
Best-fit mixing ratios for common IR absorbers

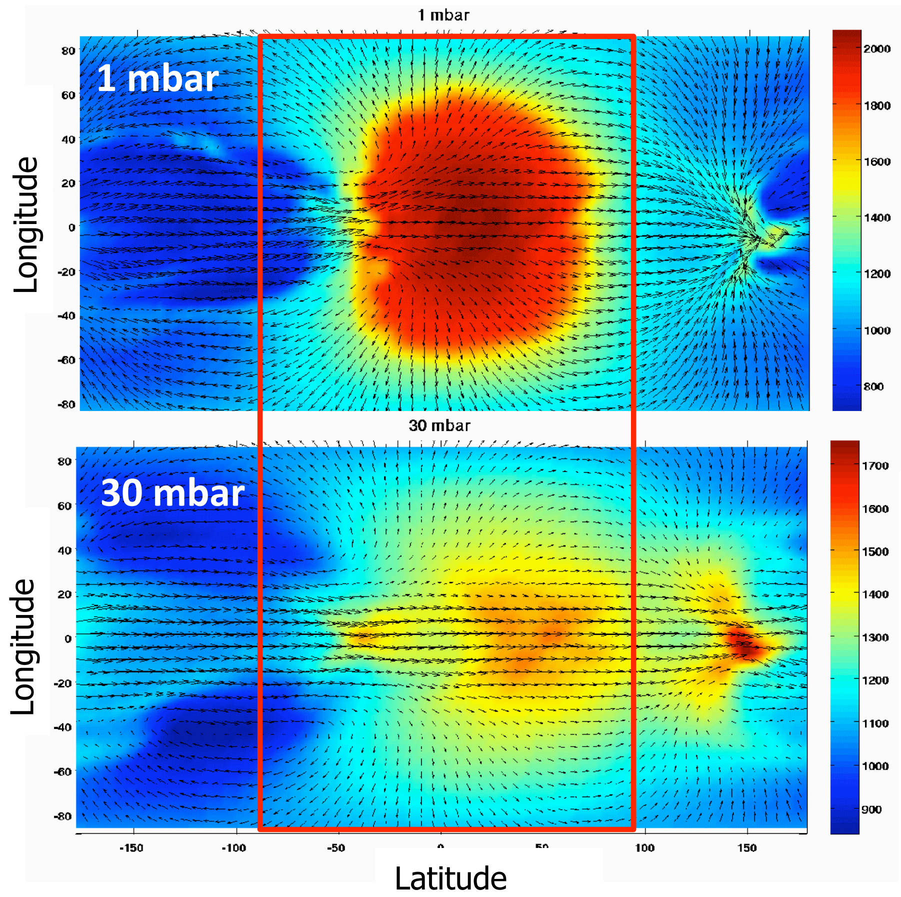
H_2O: $< 10^{-8} - 10^{-5}$
CH_4: $4 \times 10^{-8} - 0.03$
CO: $> 4 \times 10^{-4}$
CO_2: $4 \times 10^{-9} - 7 \times 10^{-8}$

Madhusudhan & Seager (2009)

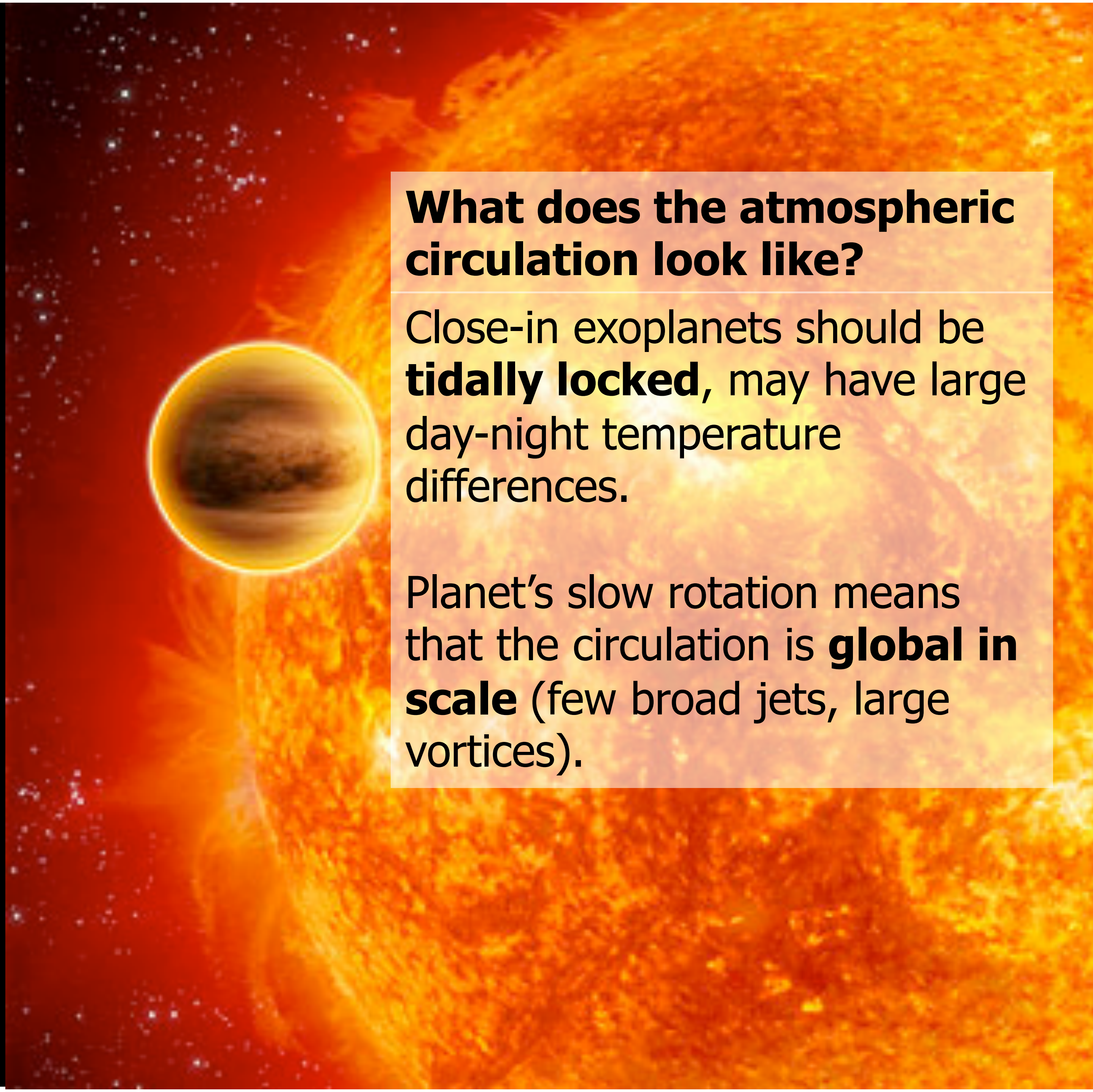
2. What about the P-T profiles?

Circulation, clouds, and additional high-altitude absorbers can all alter the shape of the default P-T profile.

3. Where/how is energy transported to the night side?



Circulation model for HD 209458b from Showman et al. (2008)



What does the atmospheric circulation look like?

Close-in exoplanets should be **tidally locked**, may have large day-night temperature differences.

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

Mapping the Day-Night Circulation With Phase Curves

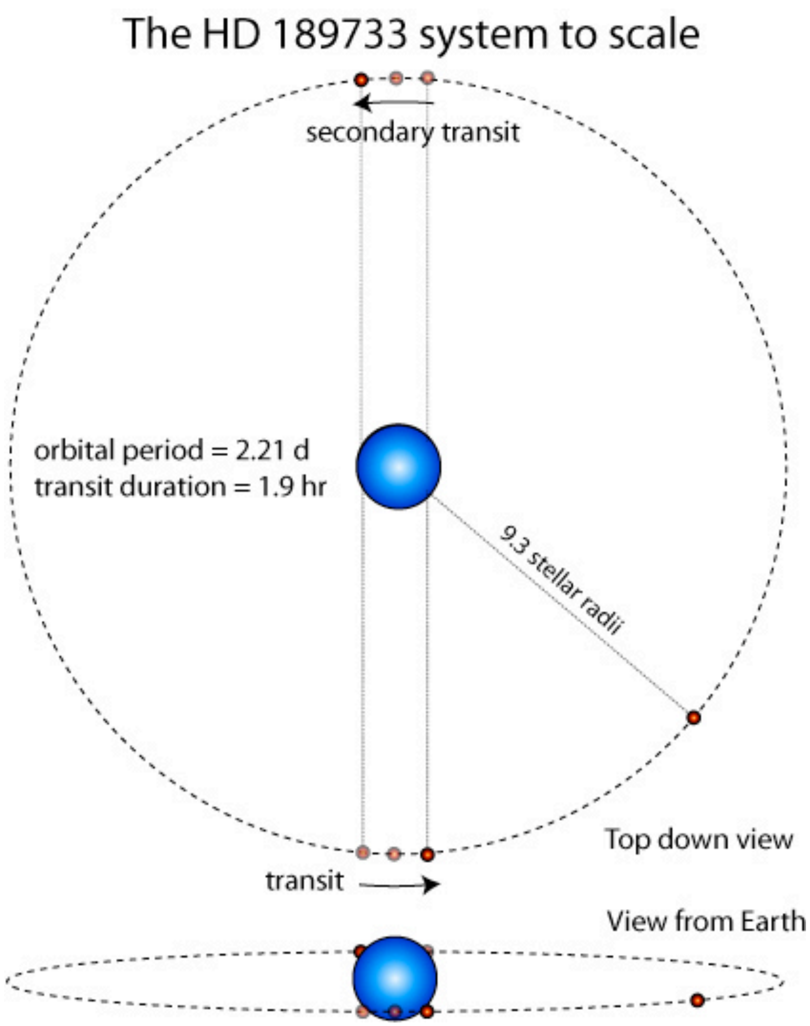
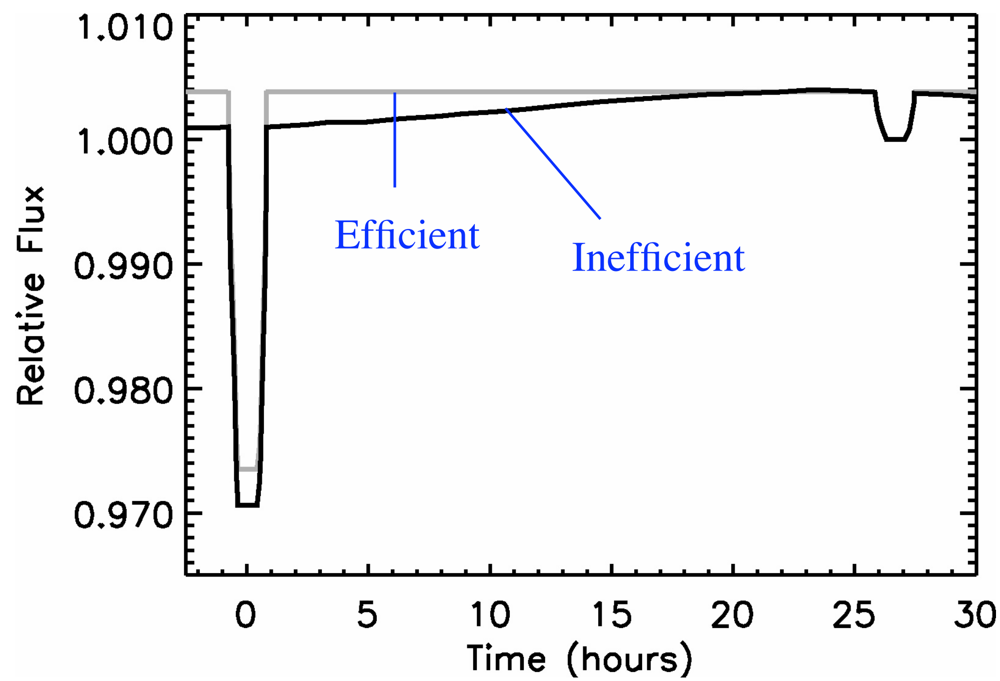
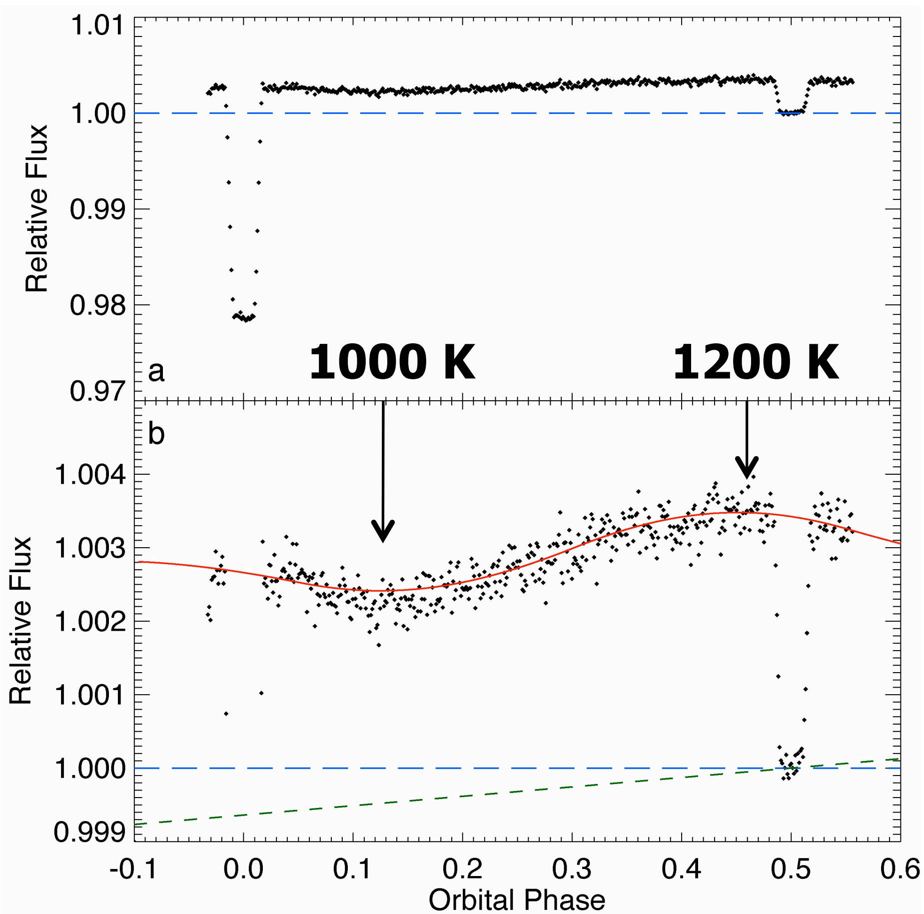


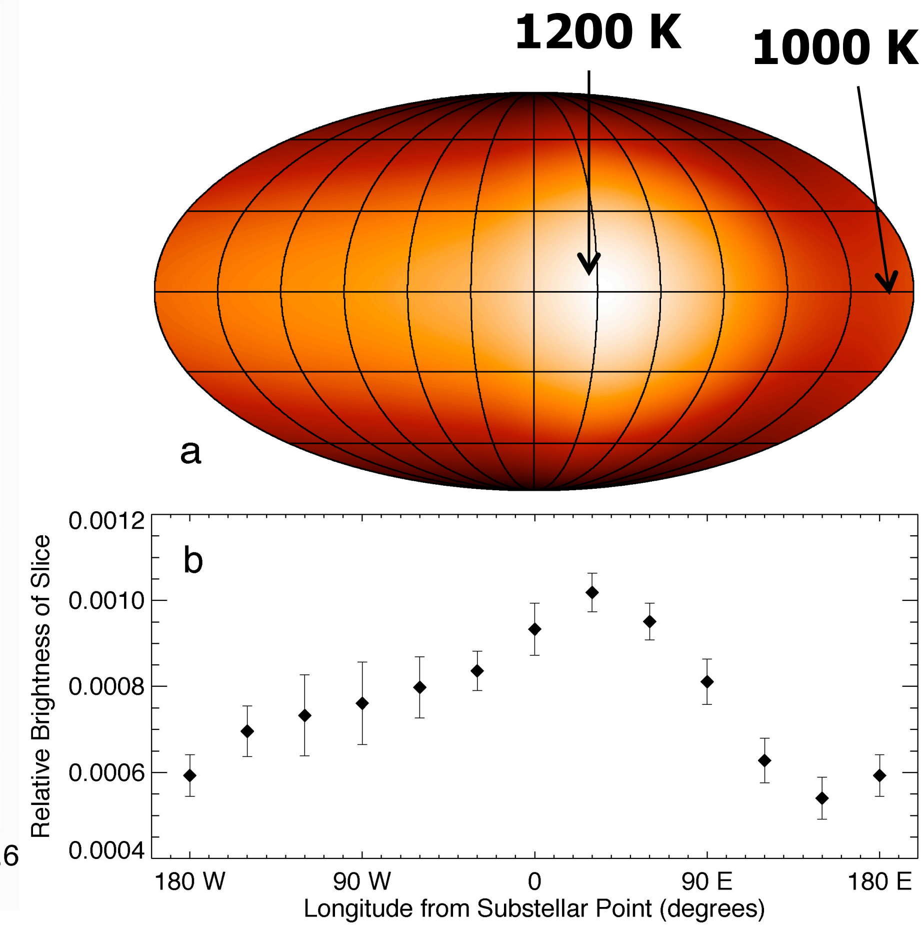
Image courtesy G. Laughlin

Size of observed variation depends on efficiency of day/ night circulation



First Longitudinal Temperature Profile for an Exoplanet: HD 189733b's Warm Night Side



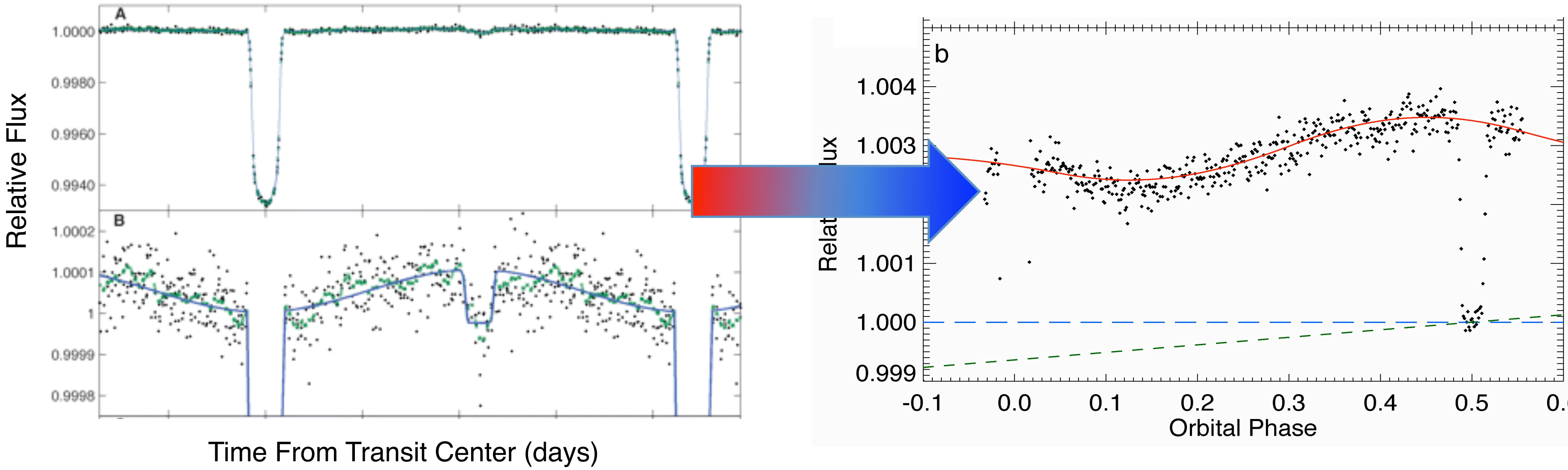


Spitzer 8 μm observations of HD 189733b (Knutson et al. 2007b, *Nature* 447, 183).

Evidence for a Diversity of Day-Night Circulation Patterns

Large day-night brightness gradient
HAT-P-7 / Kepler

Small day-night brightness gradient
HD 189733b / Spitzer



Large gradients:

υ And b* (Harrington et al. 2007)

HD 179949* (Cowan et al. 2008)

HAT-P-7 (Borucki et al. 2009)

* non-transiting planet, brightness/ temperature gradient degenerate with unknown orbital inclination and planet radius

Intermediate gradients:

HD 149026 (Knutson et al. 2009)

Small gradients:

HD 189733b (Knutson et al. 2007)

HD 209458 (Knutson et al., in prep.)

Future Steps: More Systems, Multiple Wavelengths

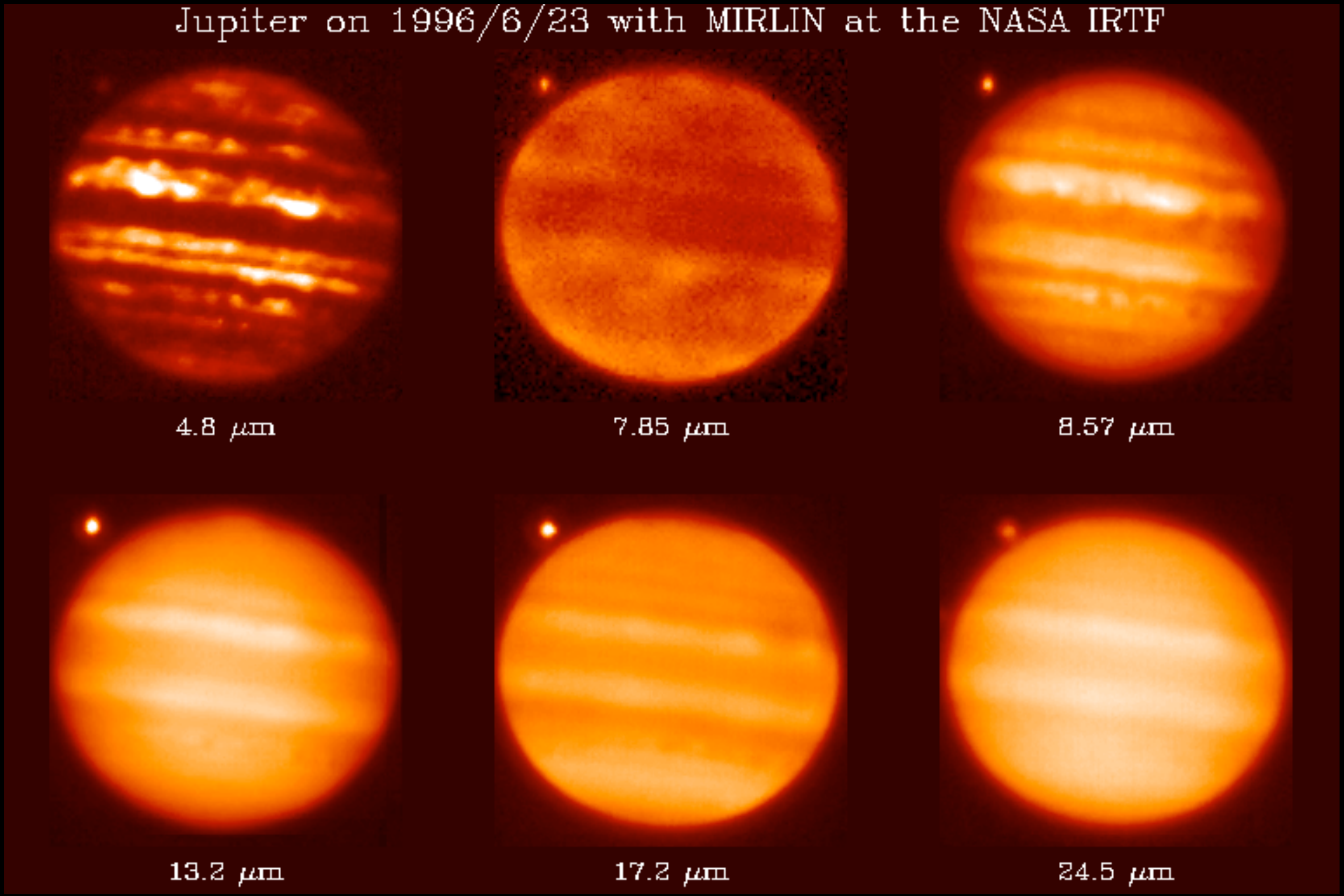
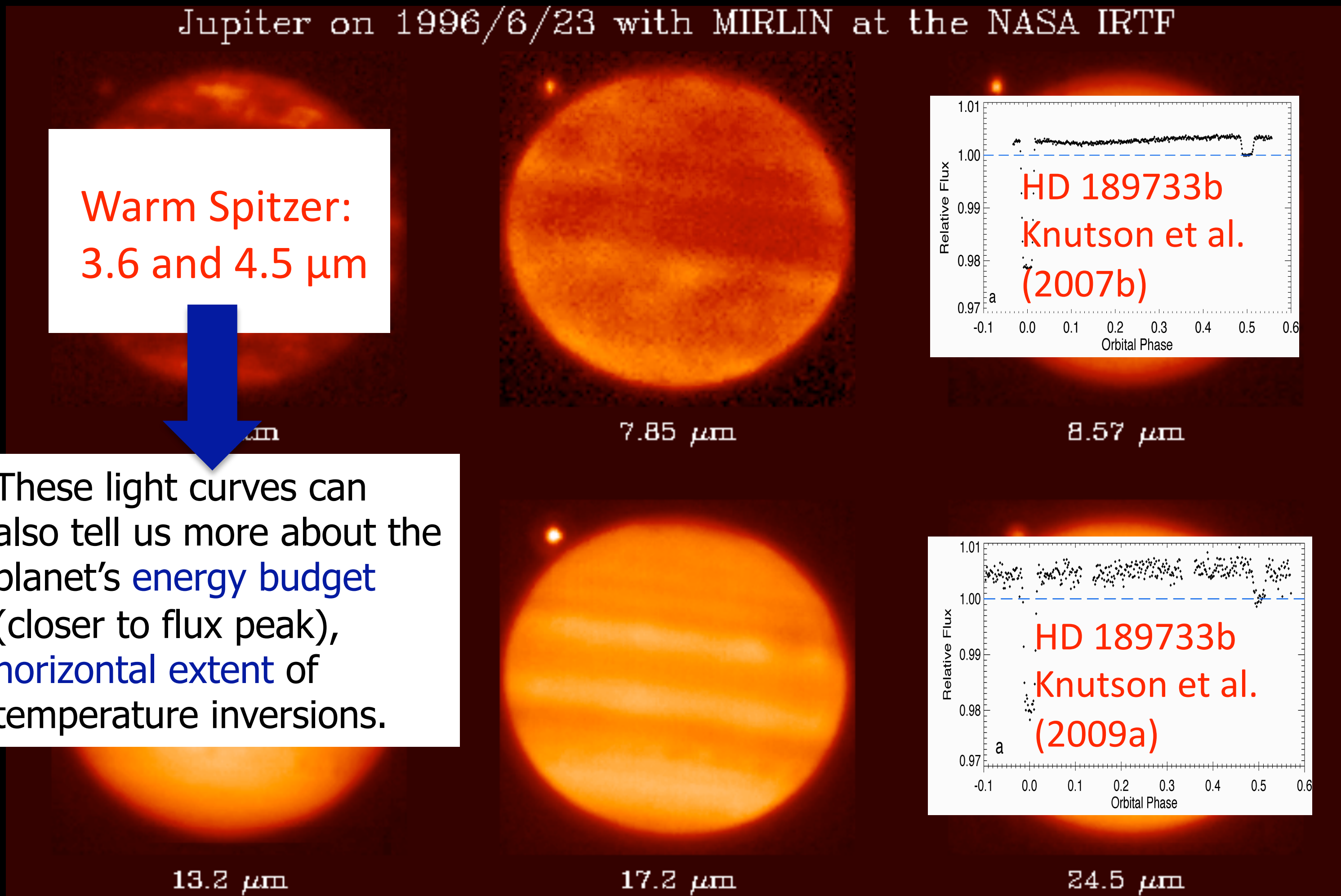


Image credit G. Orton

Will have full-orbit phase curves for five planets spanning 3.6-24 μm (up to four bands per planet, 1138 hours, PI H. Knutson) by end of two-year warm mission.

Future Steps: More Systems, Multiple Wavelengths



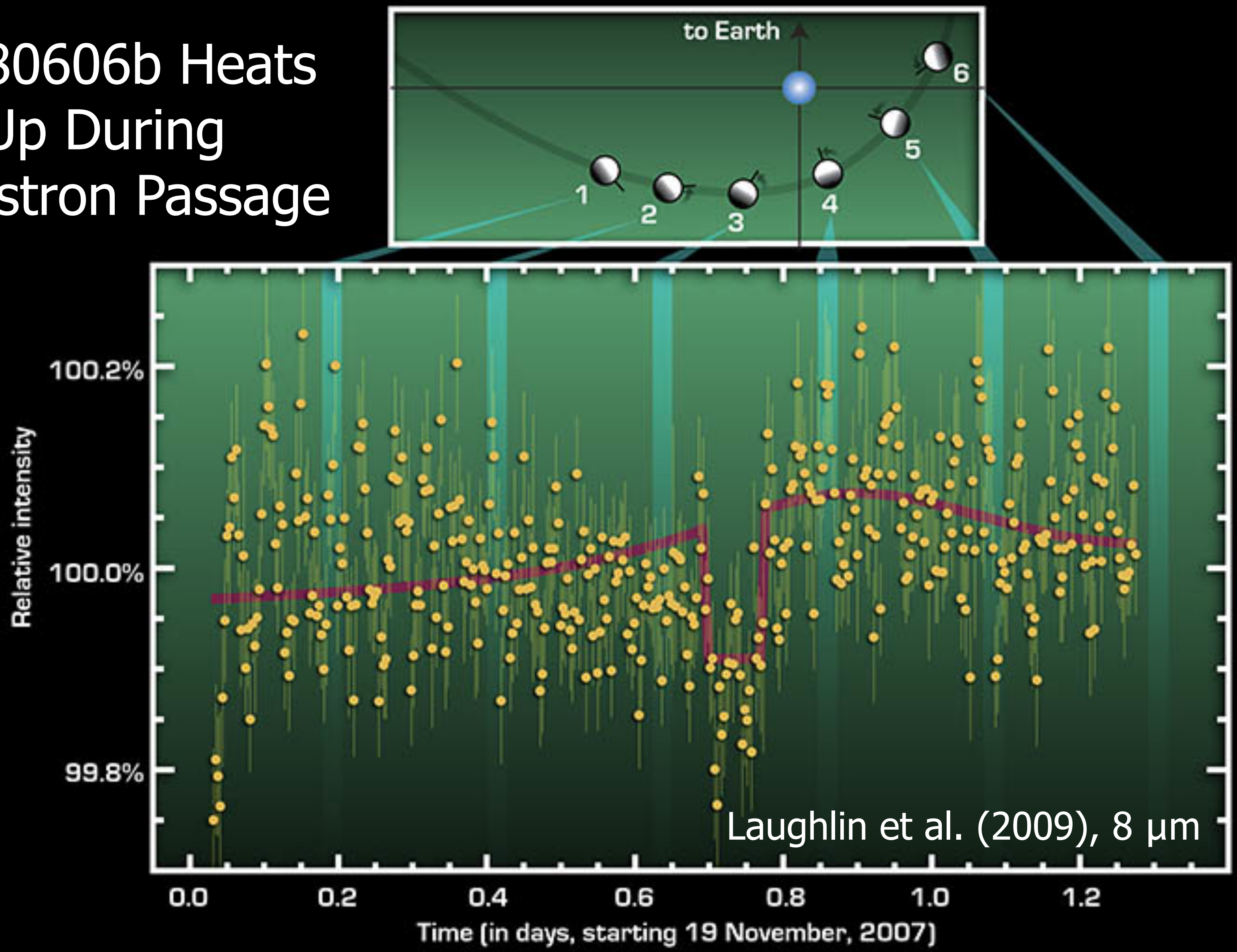
Warm Spitzer:
3.6 and 4.5 μm

These light curves can also tell us more about the planet's energy budget (closer to flux peak), horizontal extent of temperature inversions.

Image credit G. Orton

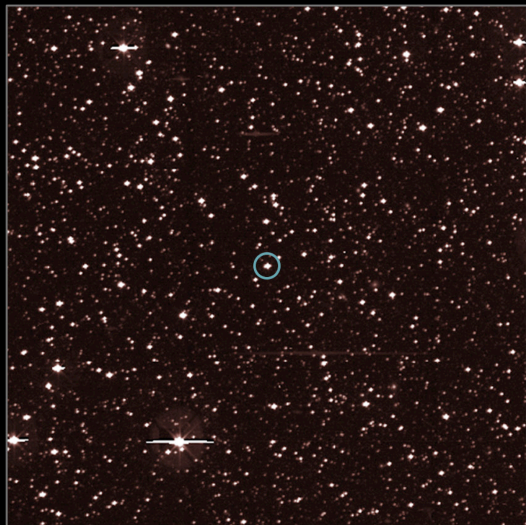
Will have full-orbit phase curves for five planets spanning 3.6-24 μm (up to four bands per planet, 1138 hours, PI H. Knutson) by end of two-year warm mission.

HD 80606b Heats Up During Periastron Passage

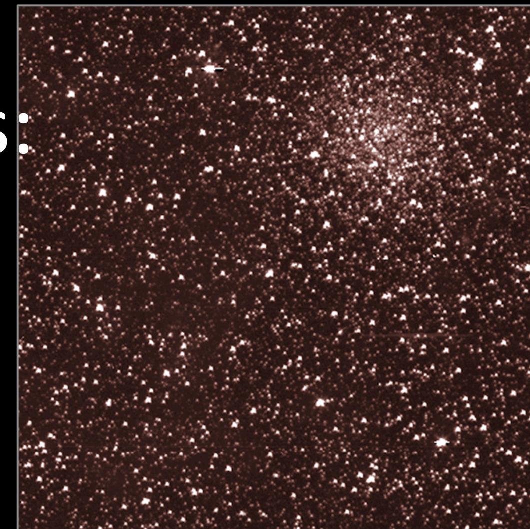


Spitzer will obtain phase curves for several more eccentric planets (HAT-P-2, HD 17156, XO-3) during the warm mission.

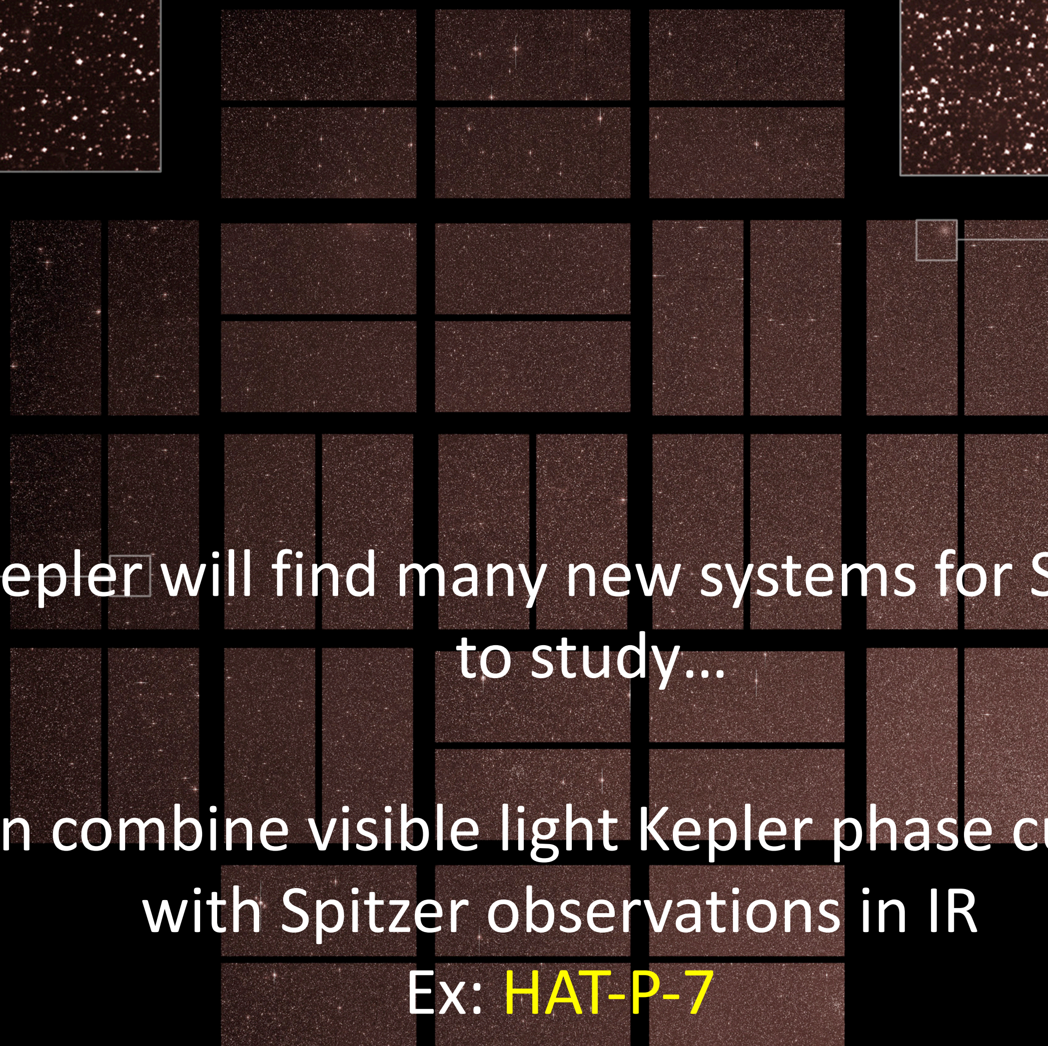
Beyond Hot Jupiters: The Age of Kepler



TrES-2



NGC 6791



Kepler will find many new systems for Spitzer to study…

Can combine visible light Kepler phase curves with Spitzer observations in IR

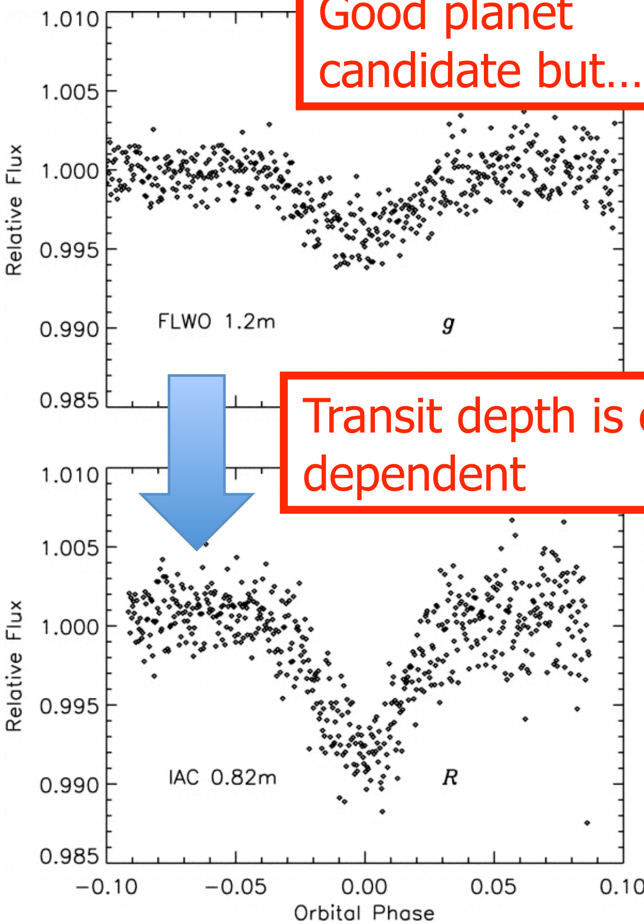
Ex: HAT-P-7

What Can Spitzer do with Kepler Targets?

1. Rejection of Astrophysical False Positives (40 candidates)

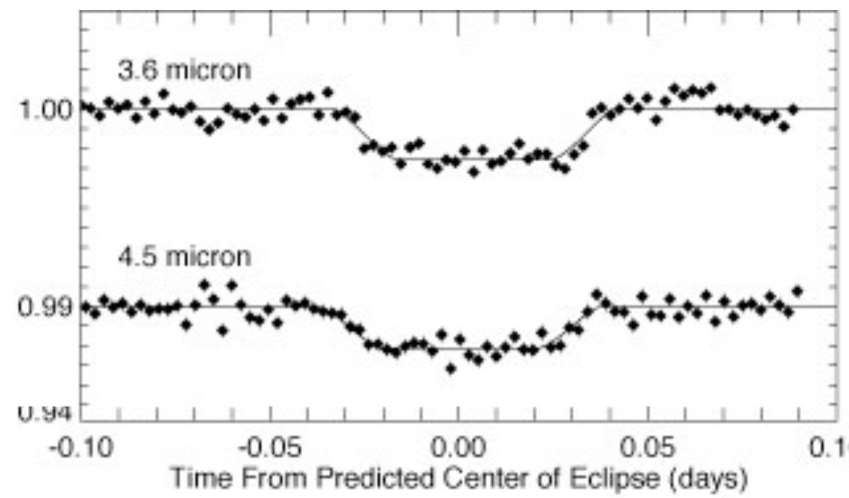
Good planet candidate but…

Transit depth is color dependent



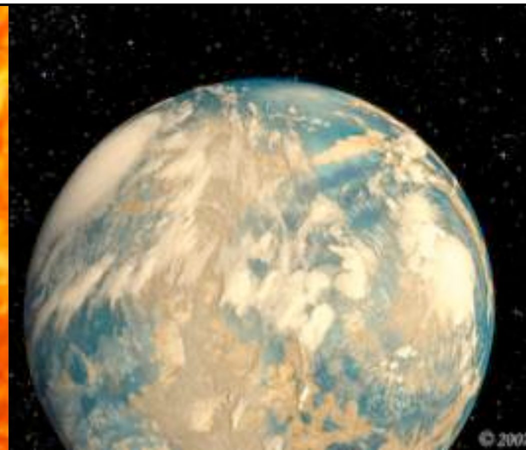
O'Donovan, Charbonneau, et al. 2006

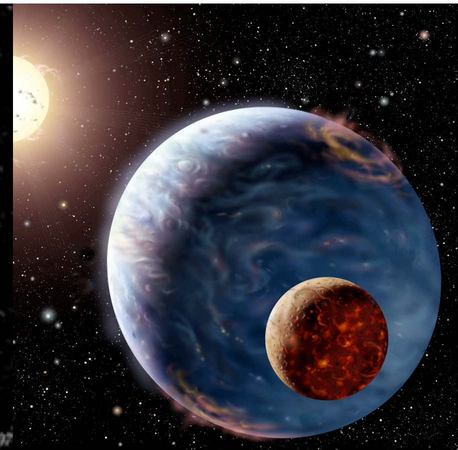
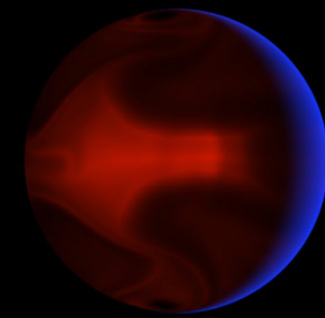
2. Secondary eclipse observations of select Kepler targets (20 planets)



Study previously inaccessible classes of exoplanets, namely cool Jupiters, hot Neptunes and superhot Super-Earths.

Exploration Science Program, 800 hours, PI D. Charbonneau

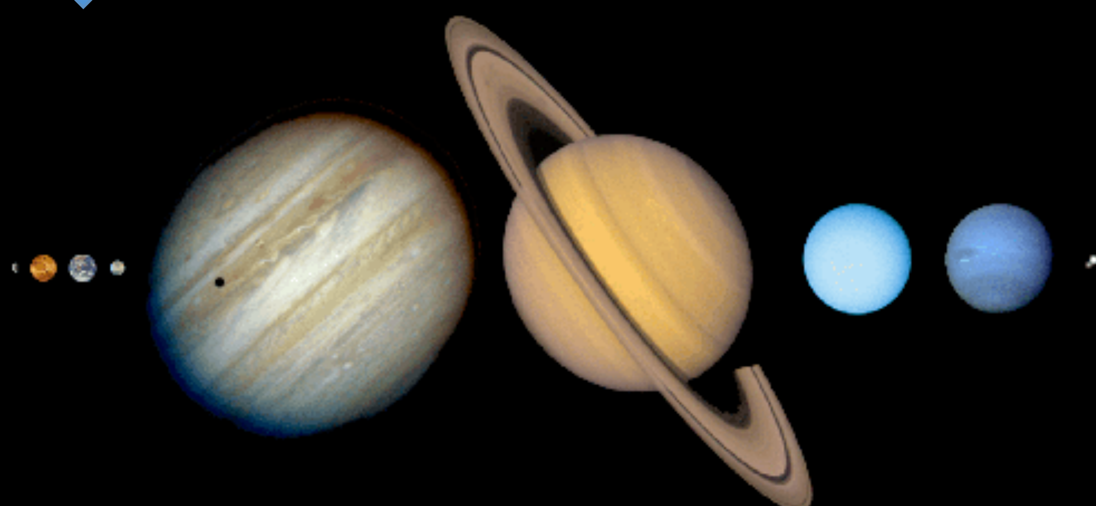



The next few years will see two major changes:

1.Studies of hot Jupiters will move from an exploration phase to a survey phase with the goal of explaining the observed diversity in their properties.

2.These same techniques will be applied to a much wider range of planet types, including eccentric planets, cool(er) Jupiters, hot Neptunes, and superhot Super-Earths.



Warm Spitzer will be at the forefront of both areas!

>2600 total hours of exoplanet observing time