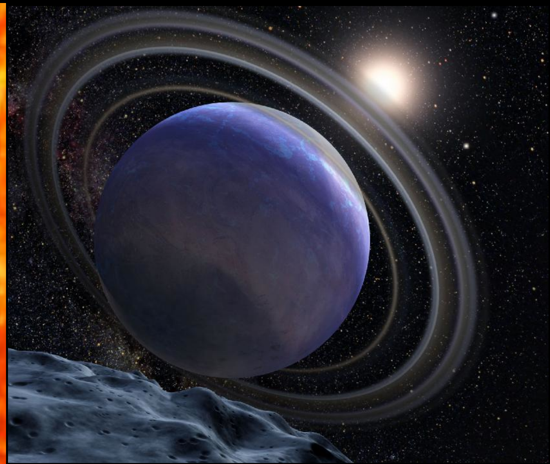
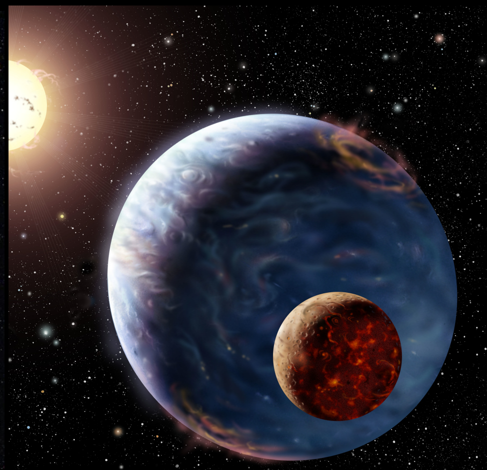
Exploring the Diversity of Hot Jupiter Atmospheres


Heather Knutson

UC Berkeley

Easier

Harder

Exoplanet Characterization 101:

What is the planet's bulk composition?

What is its temperature?

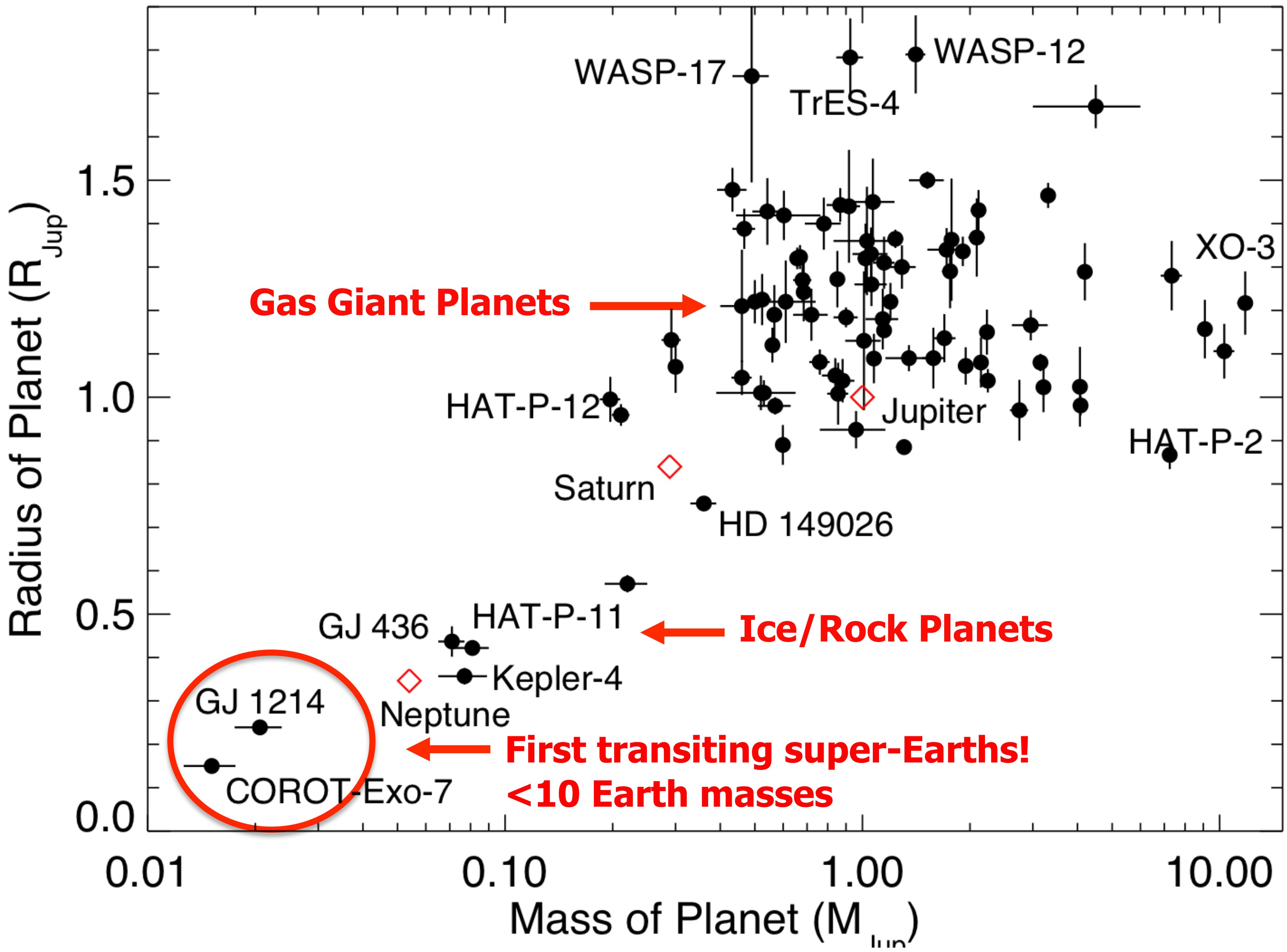
Its atmospheric composition?

What about atmospheric circulation?

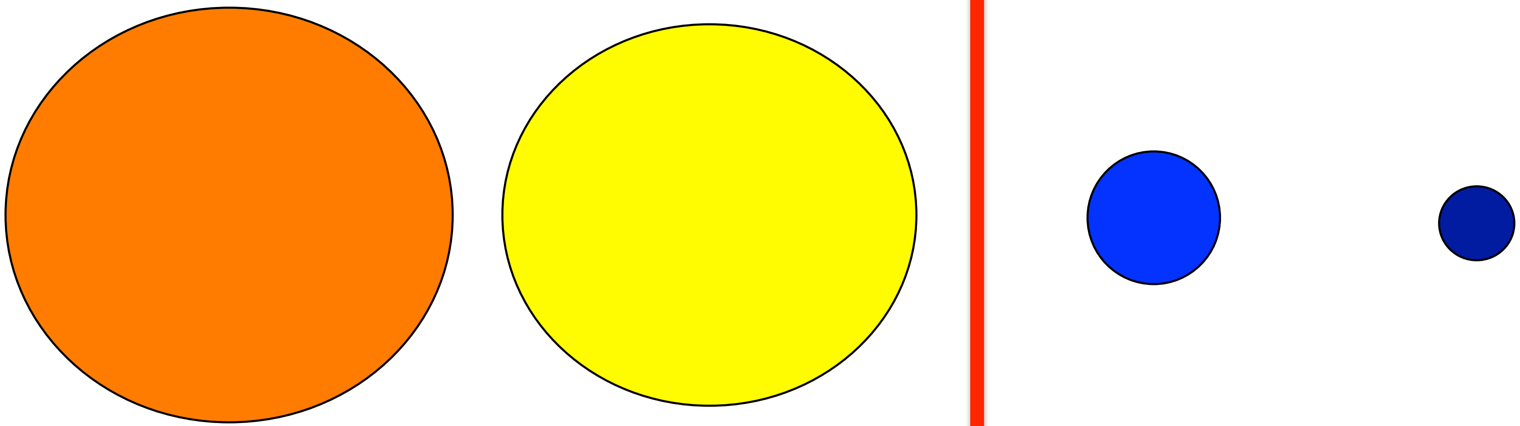
Hot Jupiters are **good test cases** for exoplanet characterization (big, hot, lots available). Current challenge is to explain diversity in observed properties.

Kepler & CoRoT (and Mearth!) are enabling the first studies of **smaller** and/or **cooler** transiting planets.

A Multitude of Transiting Planets



Four Exoplanets: A Comparison



Planets drawn to scale.

HD 209458b
Mass: 0.66 M_{Jup}
Radius: 1.32 R_{Jup}
T_{eqil}=1360 K

HD 189733b
Mass: 1.15 M_{Jup}
Radius: 1.15 R_{Jup}
T_{equil}=1130 K

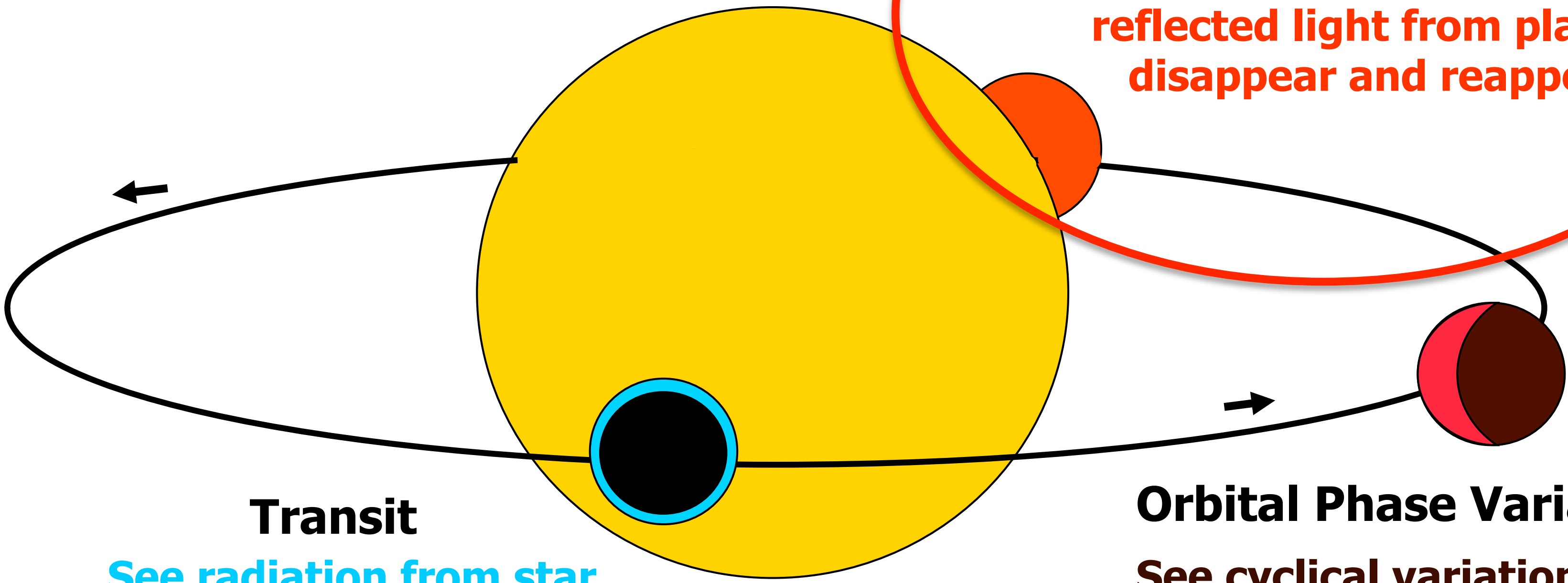
GJ 436b
Mass: 0.07 M_{Jup}
Radius: 0.44 R_{Jup}
T_{equil}=700 K

GJ 1214b
Mass: 0.02 M_{Jup}
Radius: 0.24 R_{Jup}
T_{equil}=560 K

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

These are four of the **brightest** transiting planet systems known today.
Also some of the **best-studied**.

Transiting Planets as a Tool for Studying Exoplanetary Atmospheres



Secondary Eclipse

See thermal radiation and reflected light from planet disappear and reappear

Transit

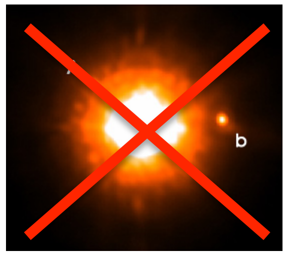
See radiation from star transmitted through the planet's atmosphere

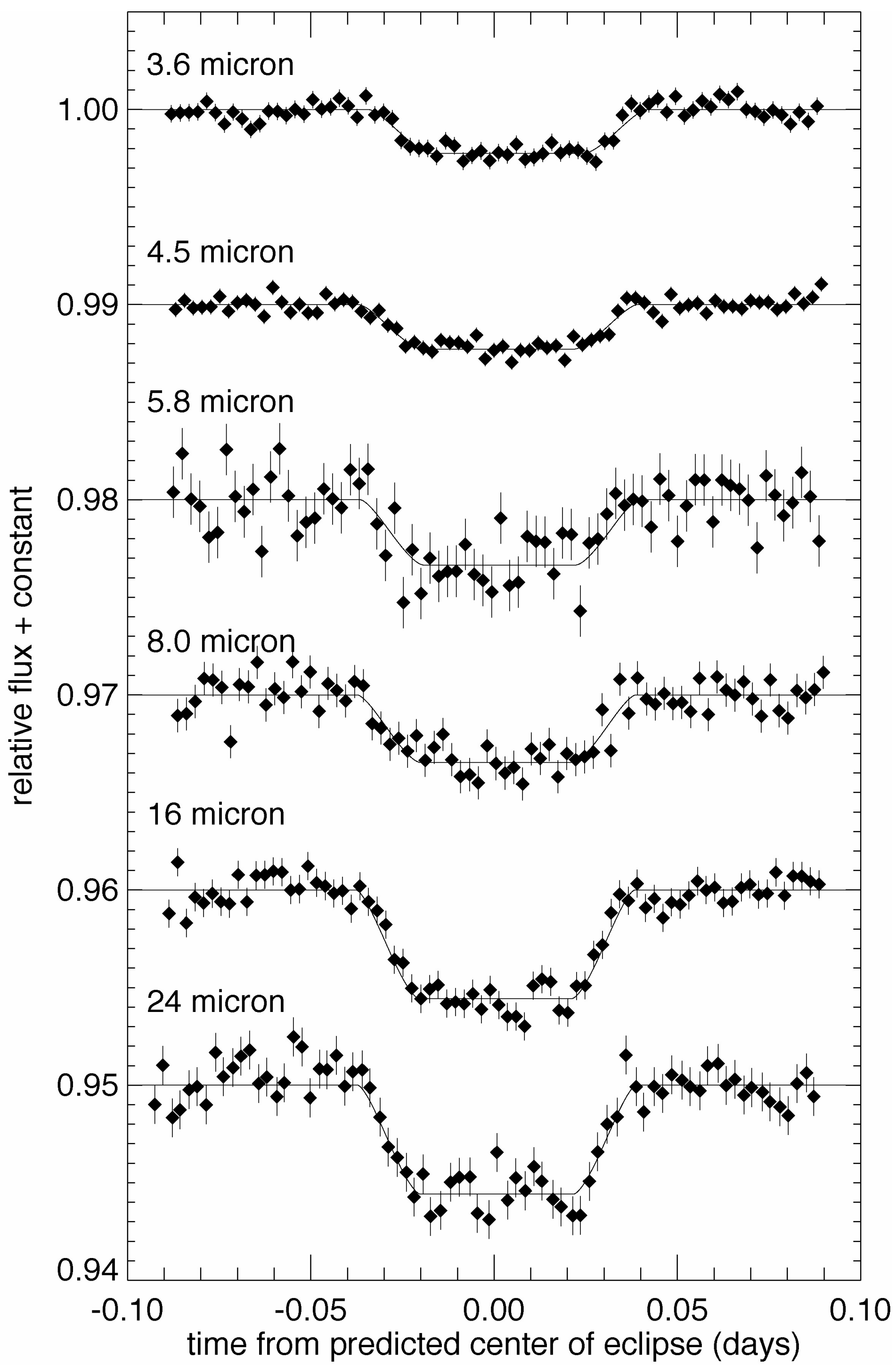
Orbital Phase Variations

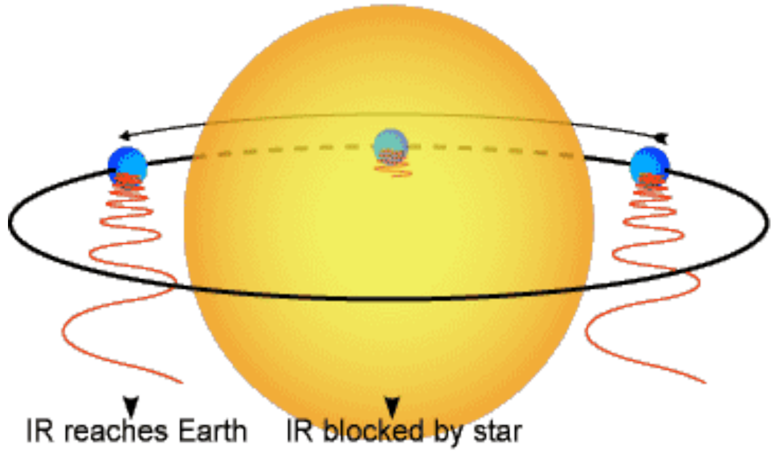
See cyclical variations in brightness of planet

Why eclipsing systems?

Can study planets 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.

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

The Atmospheric Composition of HD 189733b

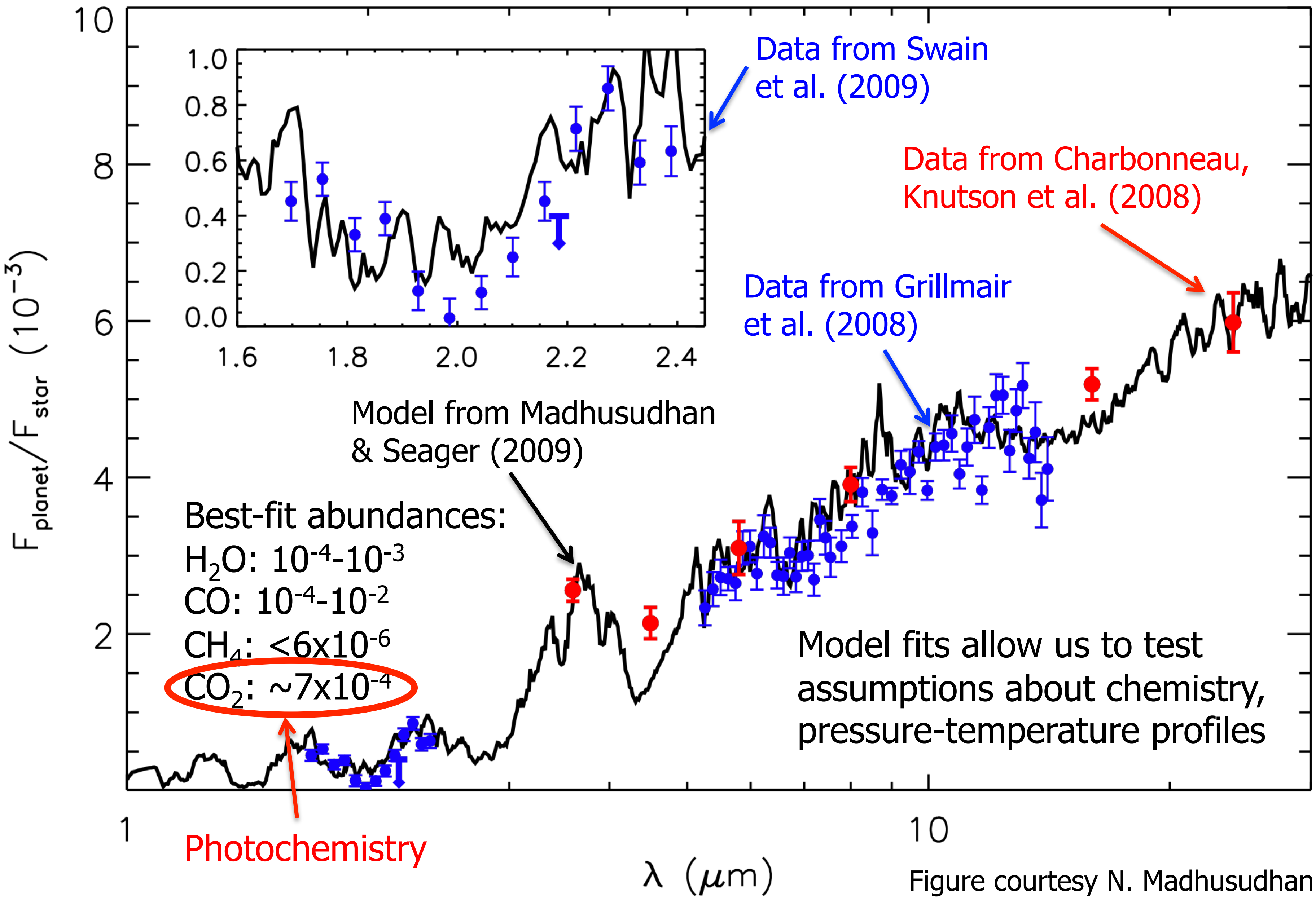
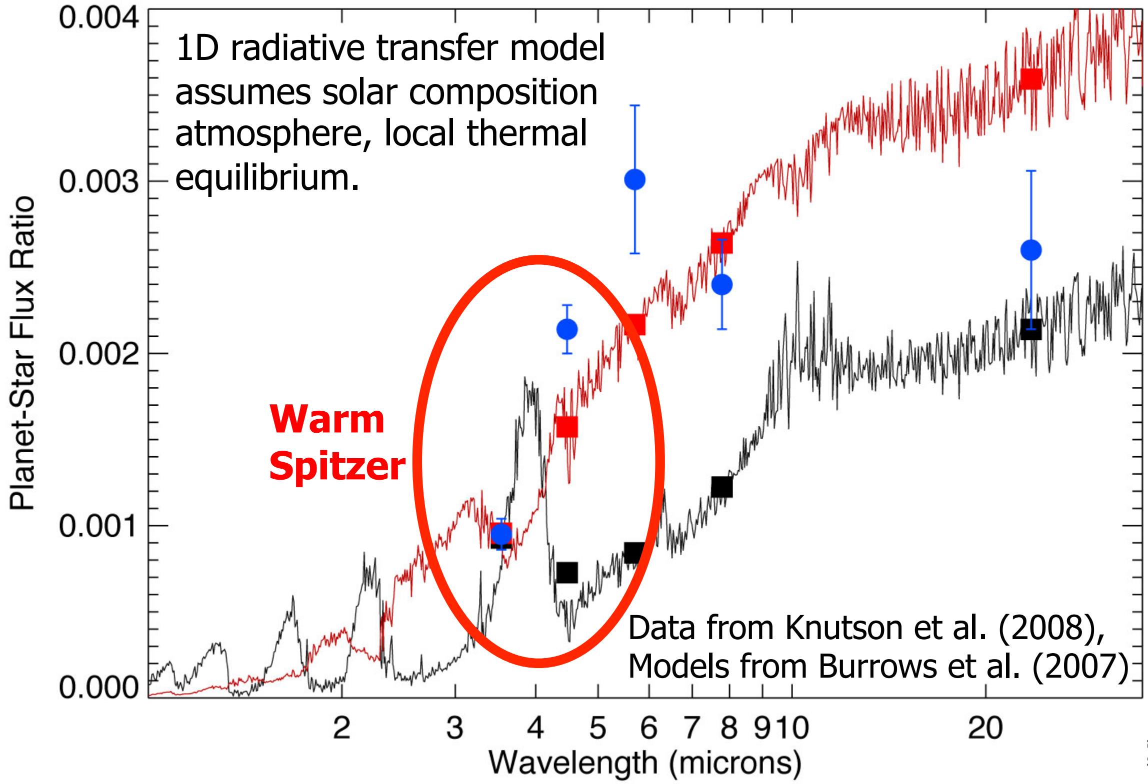
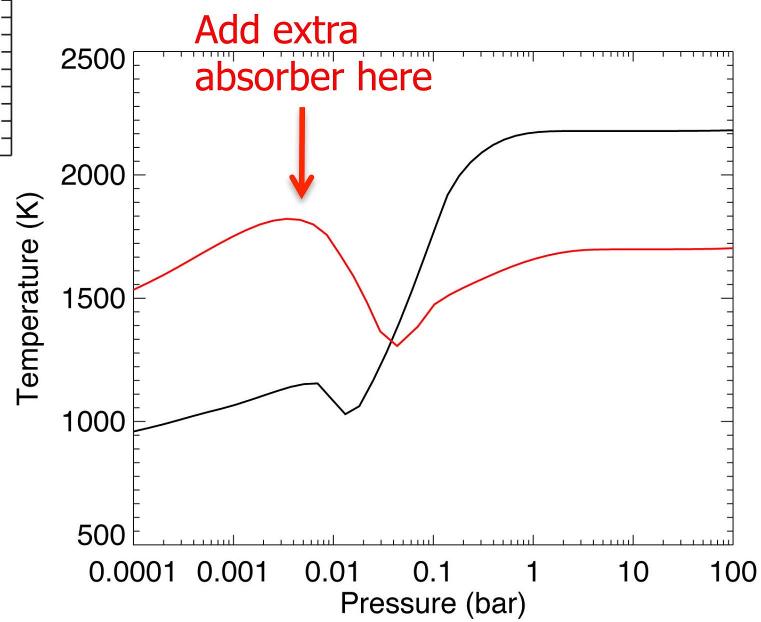


Figure courtesy N. Madhusudhan

Hot Jupiters Have A Range of Atmosphere Types.

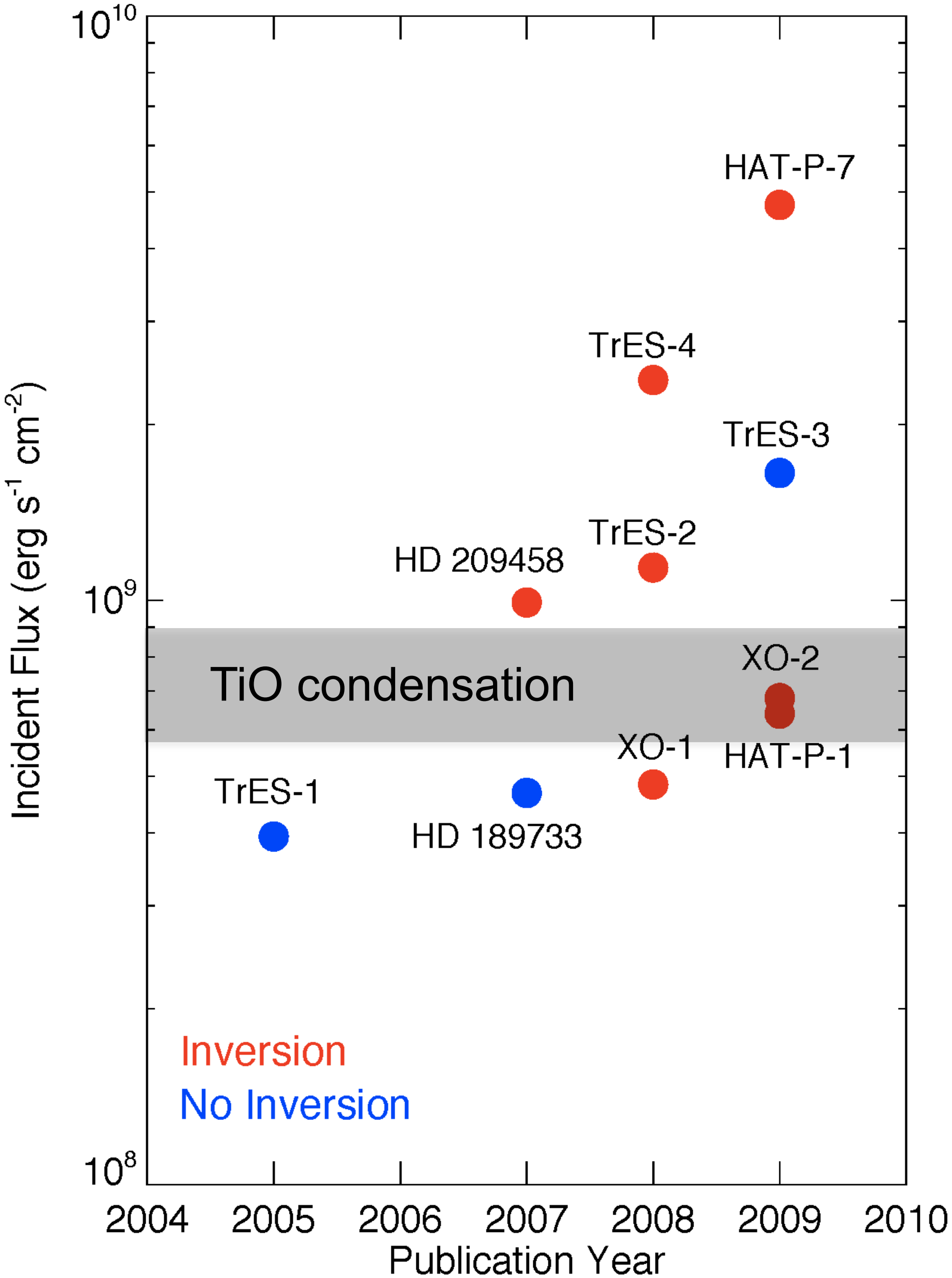


Best described by a model with a temperature inversion and water features in emission instead of absorption.



Why would two hot Jupiters with similar masses, radii, compositions, and temperatures have such different emission spectra?

See talk by Fortney, poster by de Kok.



What causes temperature inversions in hot Jupiter atmospheres?

Gas phase TiO?

Problem: inversions do not appear to correlate with temperature

Also difficult to maintain at altitude. Spiegel et al. (2009)

One alternative: sulfur compounds

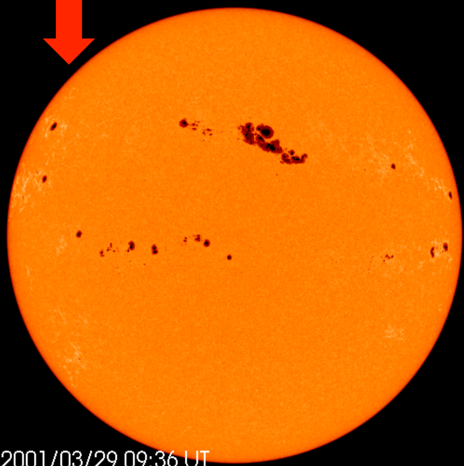
Nonequilibrium chemistry model, Zahnle et al. (2009)

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

Active vs. Quiet Stars

Image credit ESA/NASA, Frederic Pont

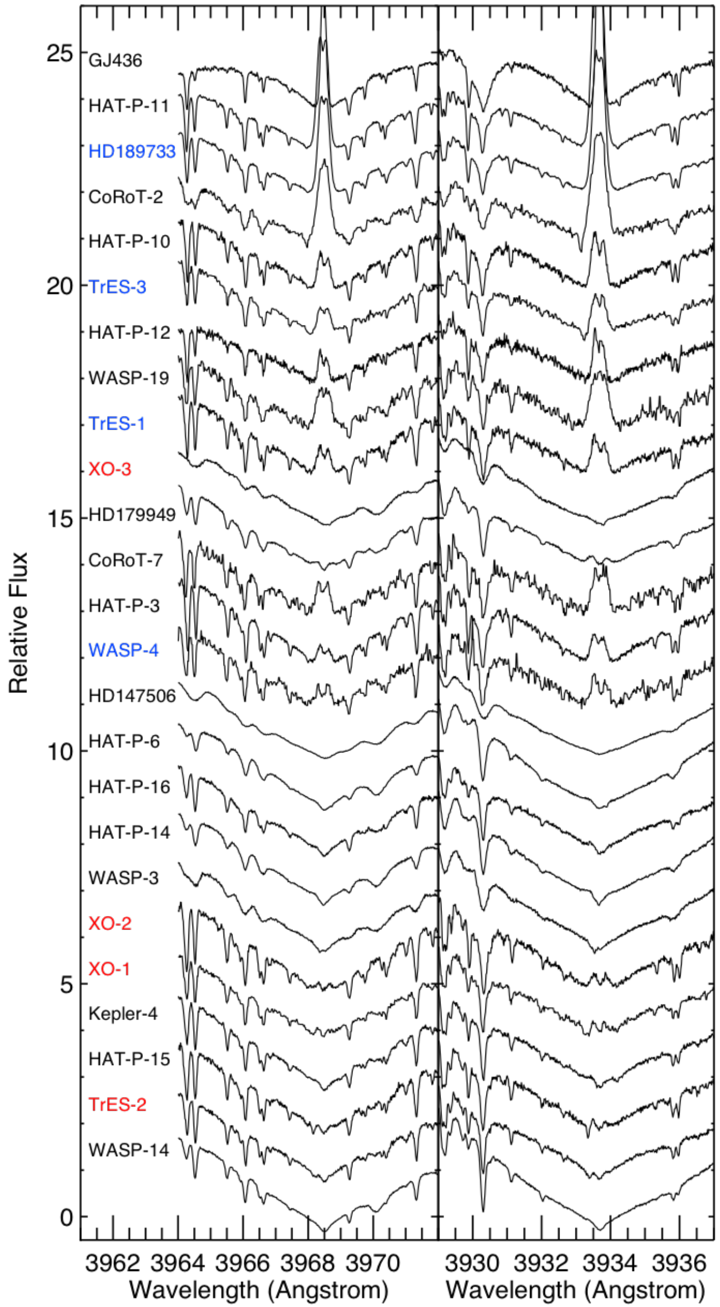
Active stars have enhanced magnetic fields, more spots, and increased UV/X-ray fluxes relative to quiet stars.

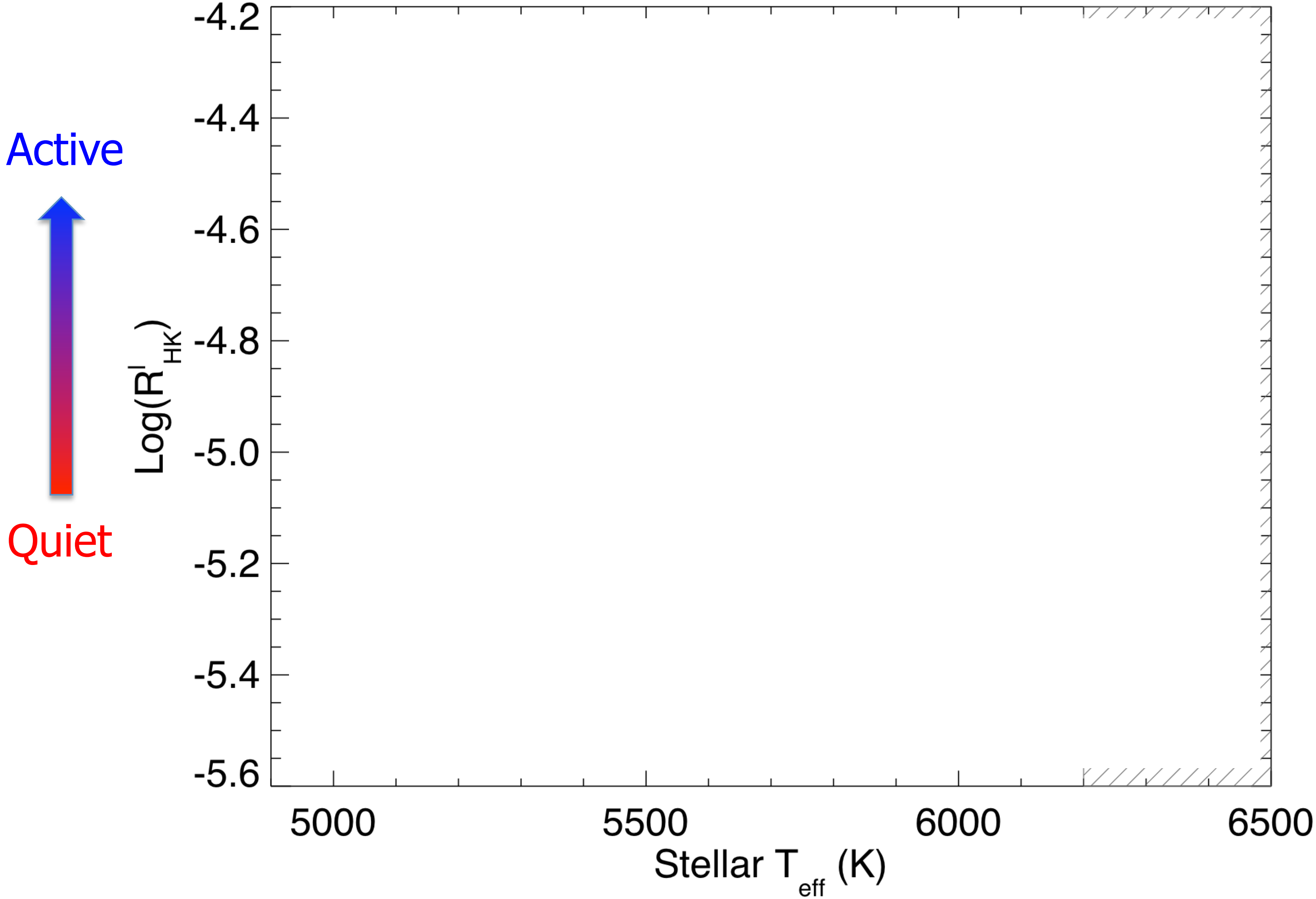


How do we measure activity?

Active

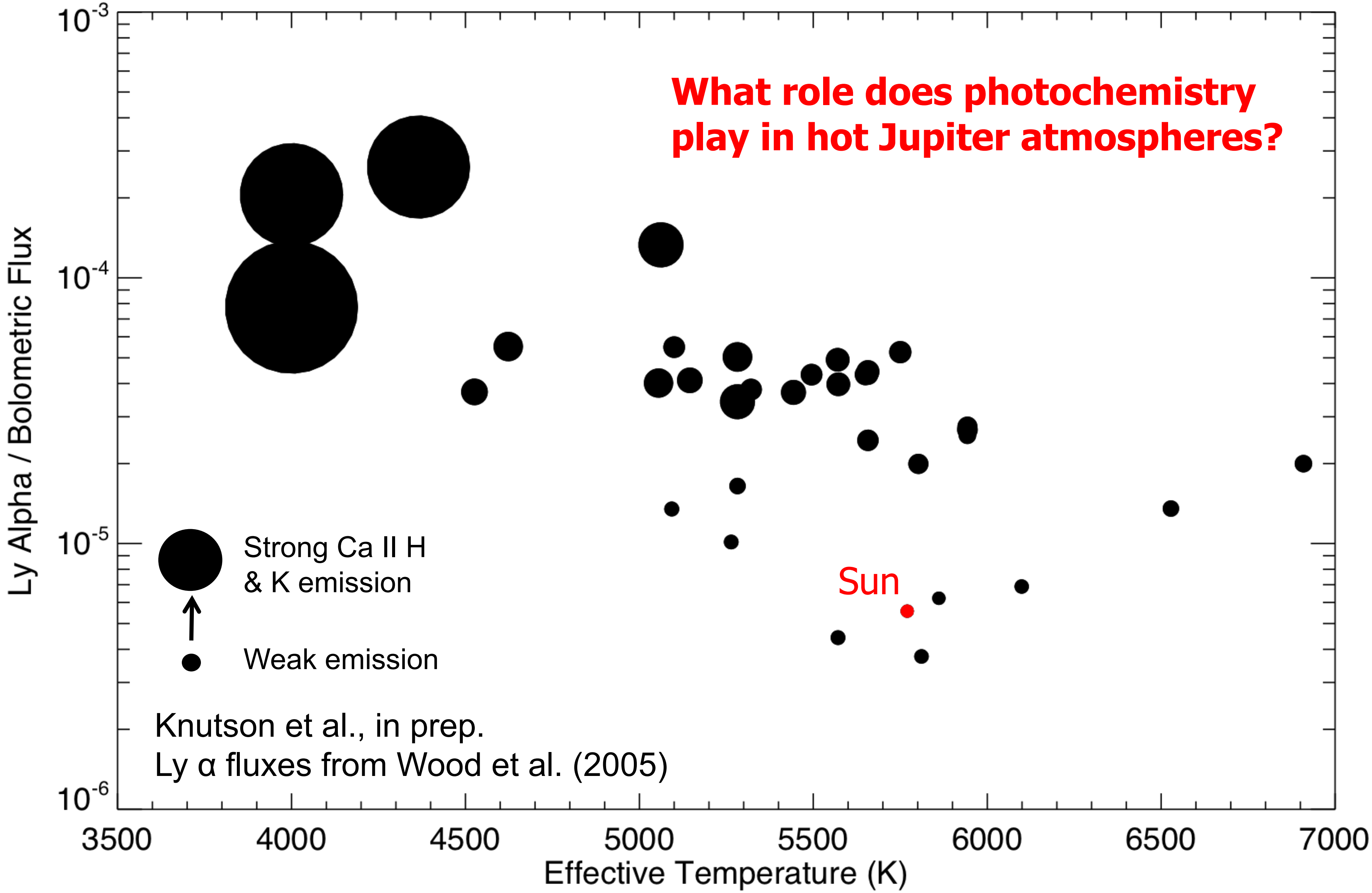
Quiet



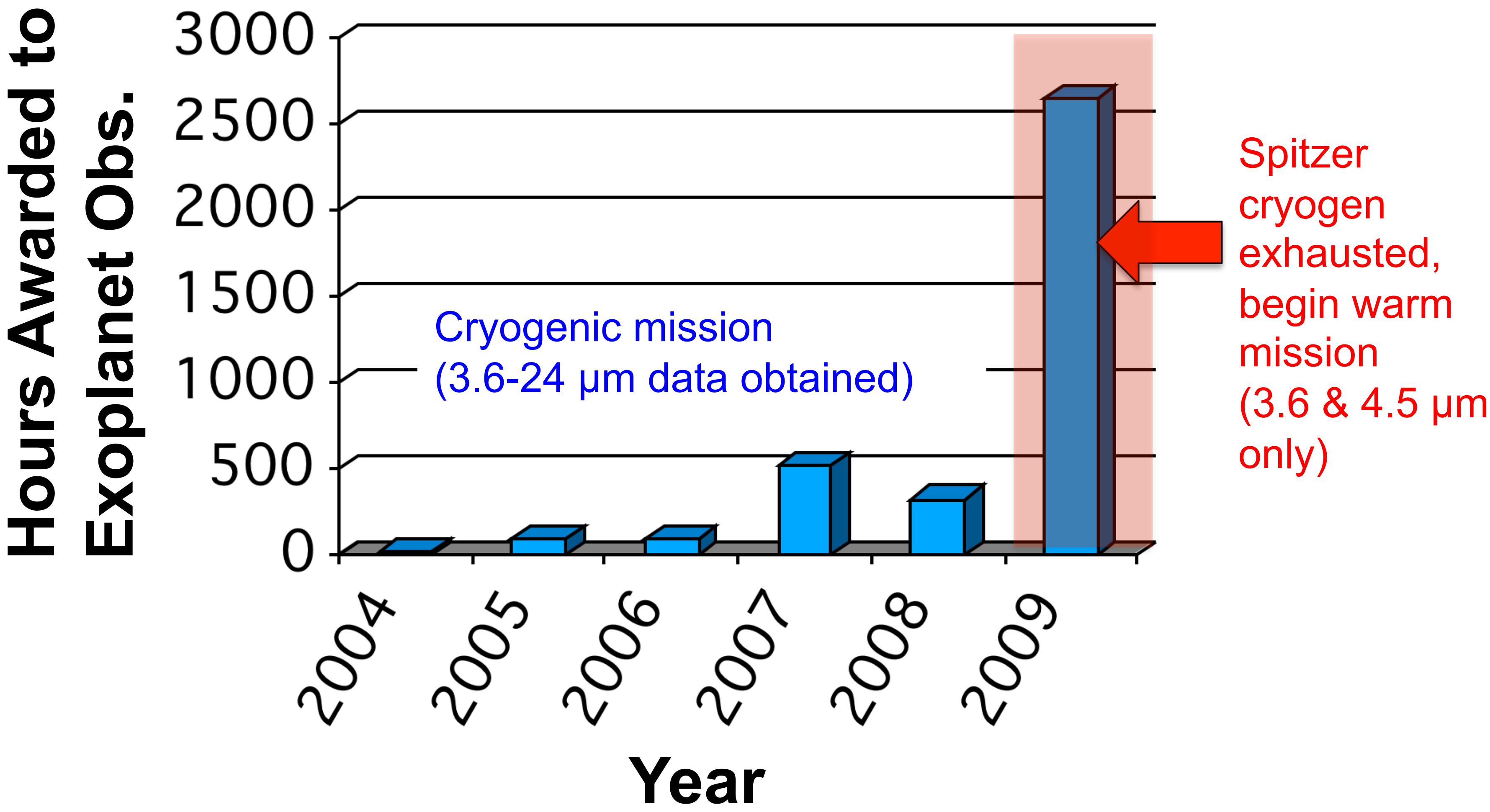


Active
Quiet
Log(R'_HK)
-4.2
-4.4
-4.6
-4.8
-5.0
-5.2
-5.4
-5.6
5000
5500
6000
6500
Stellar T_eff (K)

Lyman α Flux vs. Spectral Type

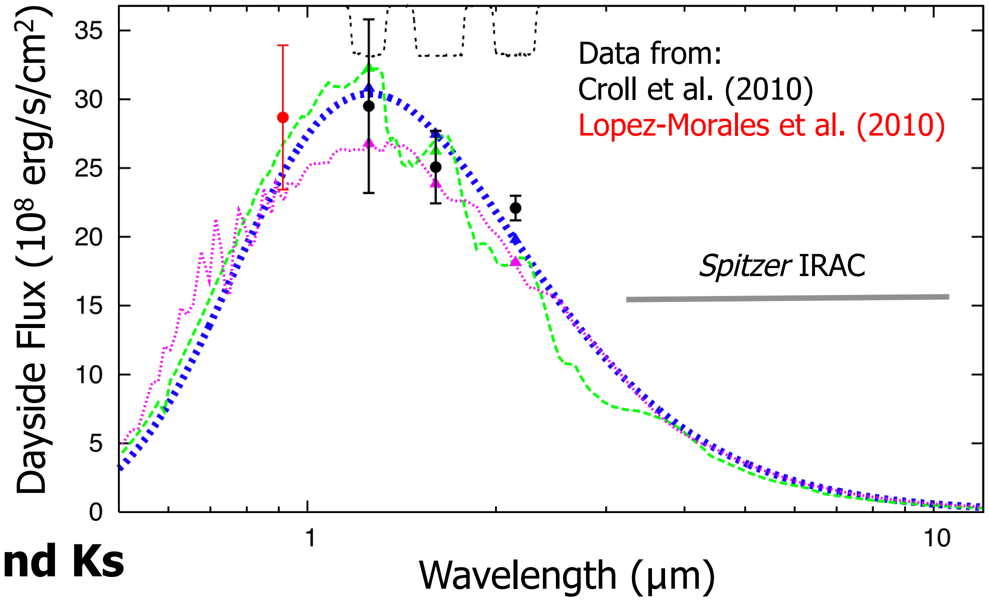


The Spitzer Space Telescope's Extended Warm Mission

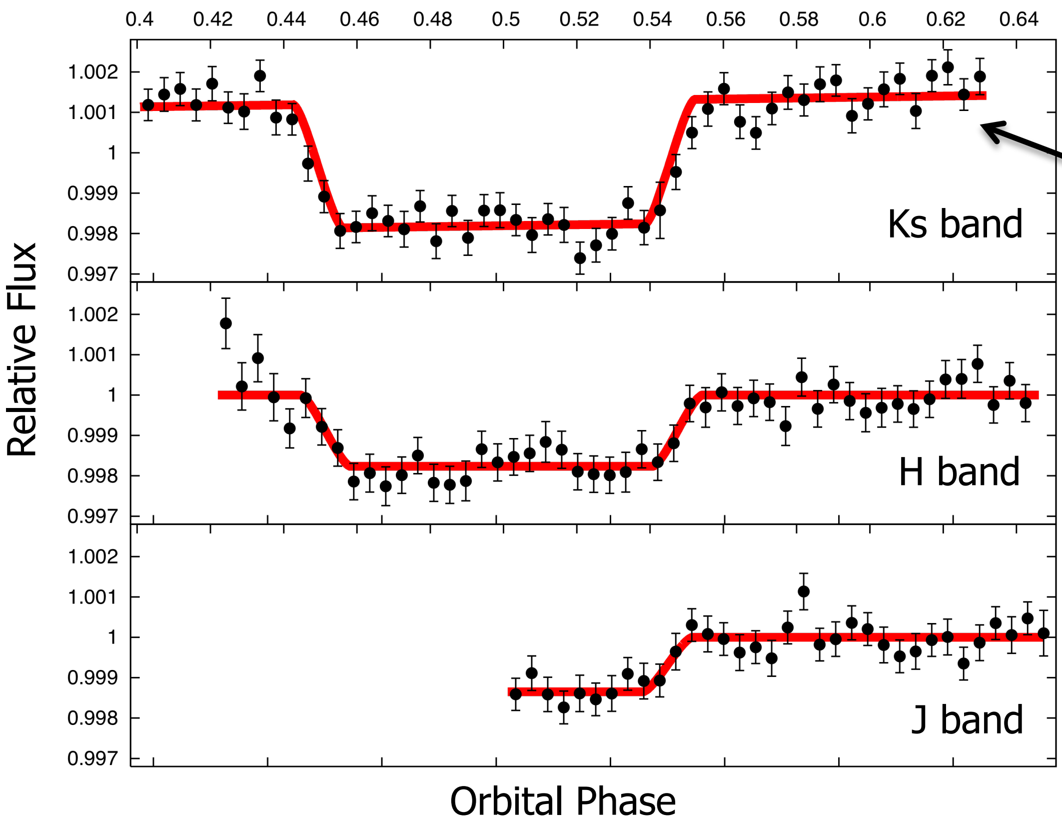


Talk by Harrington, posters by Anderson, Blecic, Campo, Cubillos, Hardy, Maxted, Nymeyer.

A New Era of Ground-Based IR Observations



WASP-12 secondary eclipse in J, H, and Ks

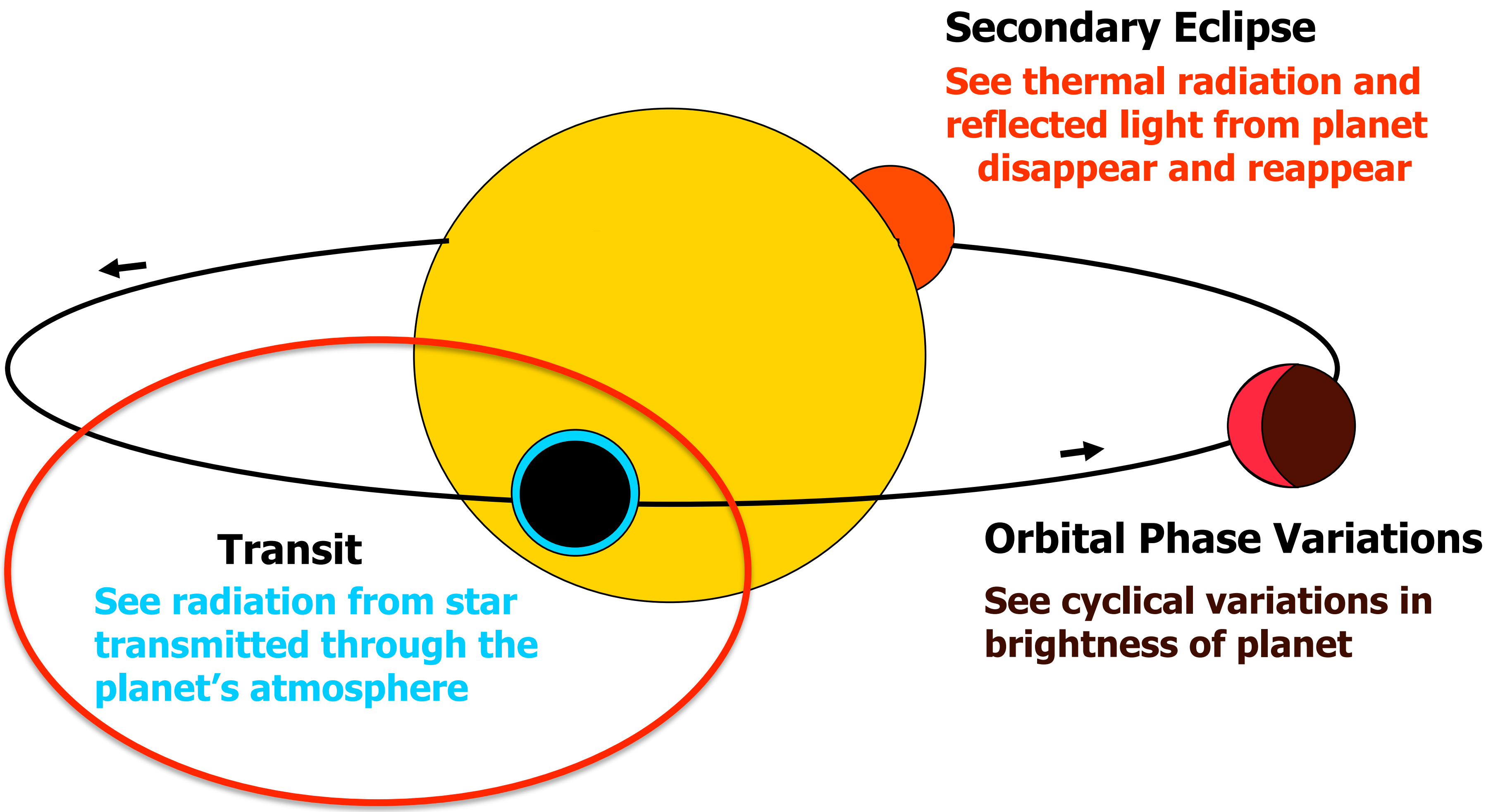


24 σ detection!

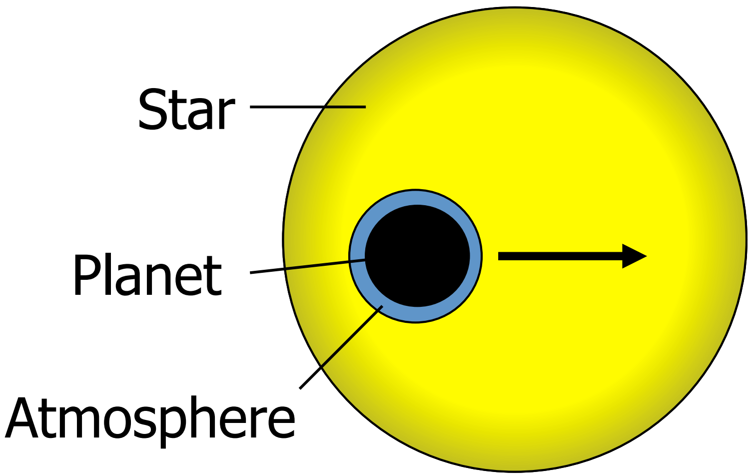
- Observations sample peak of energy distribution for hottest planets.
- Can be combined with *Spitzer* observations (Campo et al. 2010) to constrain models.

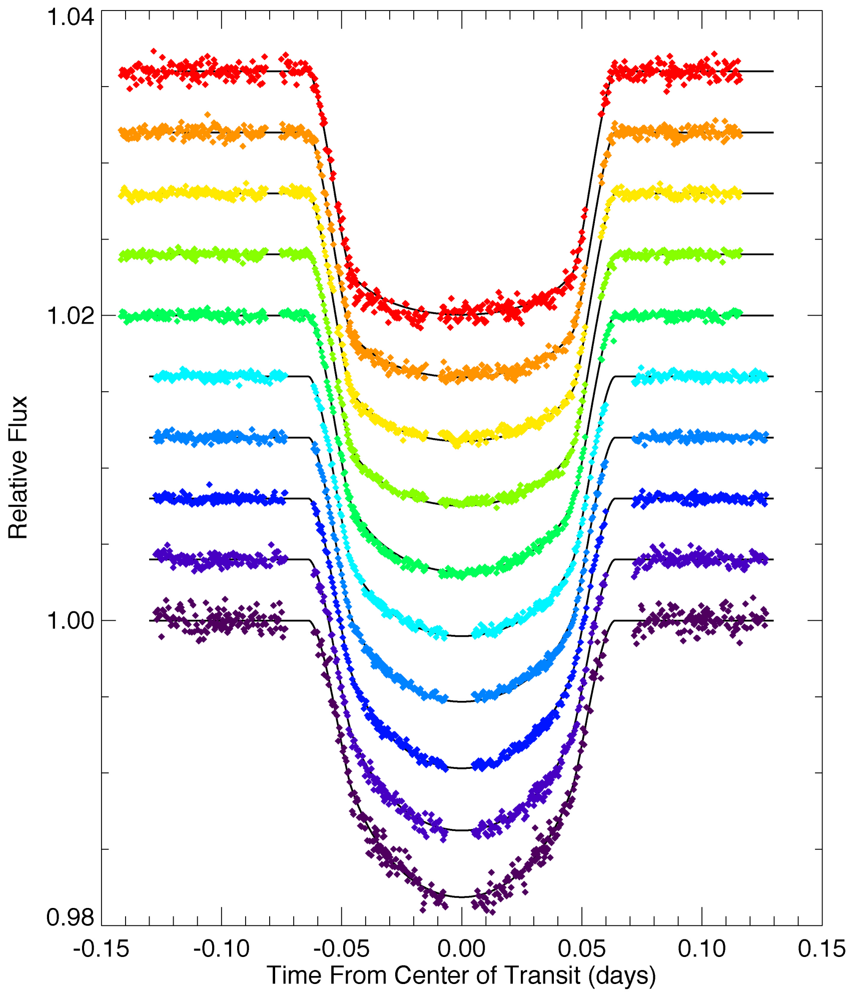
Croll et al. (2010).
See posters by de Mooij, Rogers.

Transiting Planets as a Tool for Studying Exoplanetary Atmospheres



Characterizing Atmospheres With Transmission Spectroscopy



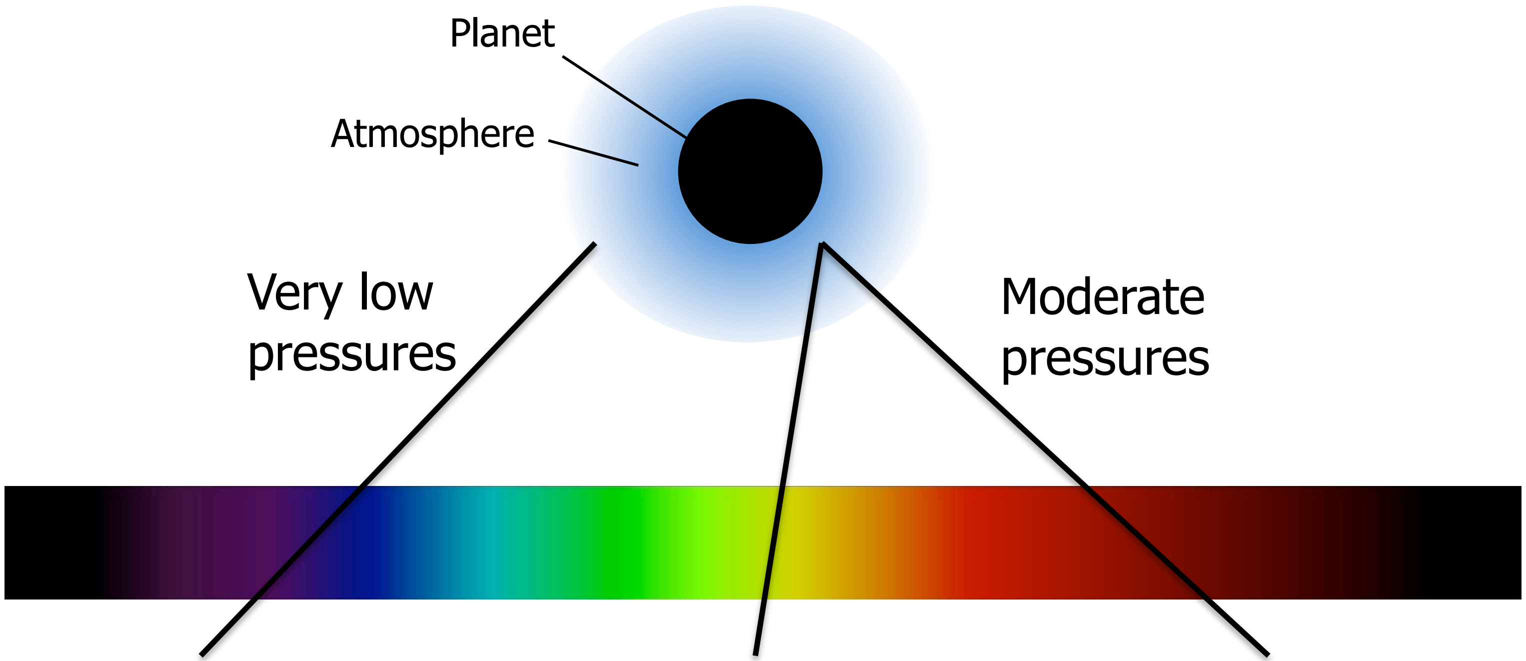


HST STIS transits of HD 209458b from 290-1030 nm (Knutson et al. 2007a)

A little history:

- Best observations to date from STIS, ACS (optical) and NICMOS (IR) instruments on the Hubble Space Telescope
- Disaster! Failure of STIS in 2004, ACS in 2006/2007, and NICMOS in 2008
- Recent repairs and installation of WFC3 in May 2009 enable new, large observing programs

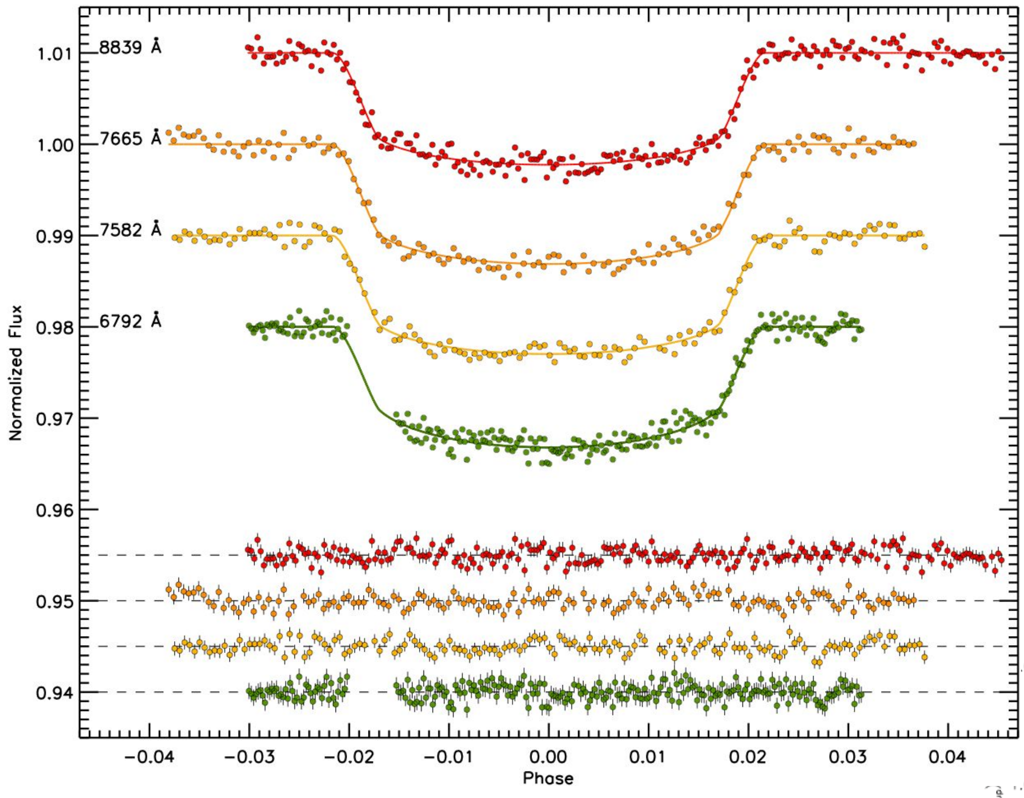
Hot Jupiters from the UV to the IR



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?

See talks by Sing, Lecavelier des Etangs and posters by Fossati, Gibson, and Jaemin.

Transmission Spectroscopy: Not Just for Space Telescopes

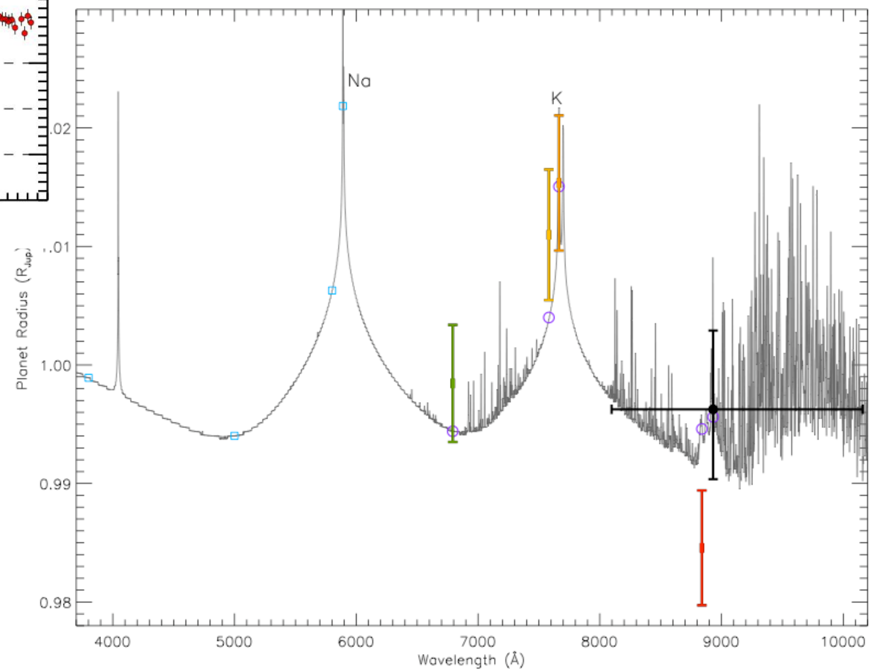


Tunable filter on the Gran Telescopio Canarias

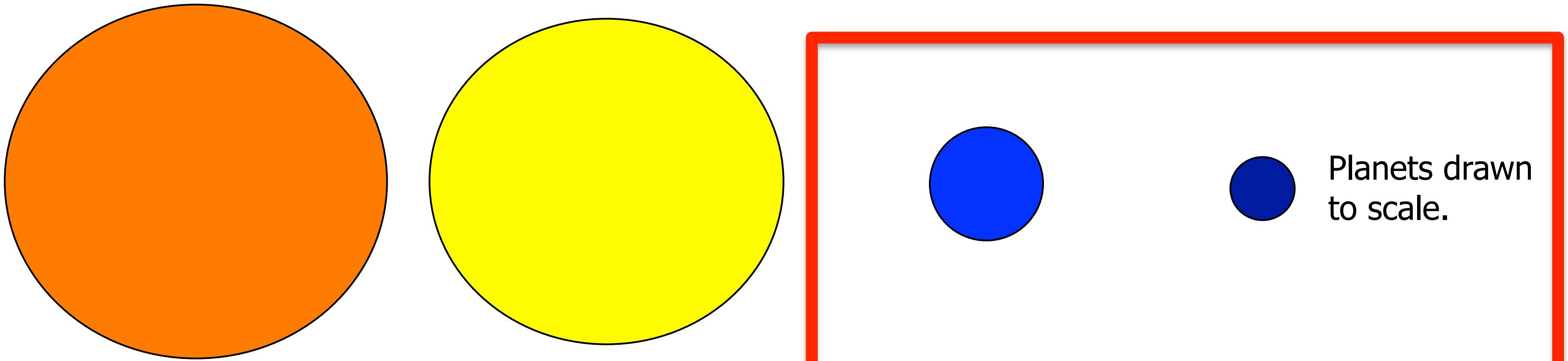
First detection of potassium absorption
XO-3b, Sing et al. (2010)

HD 80606b, Colón et al. (2010)

See talks by Sing and Snellen, posters by Colón, Jensen, Redfield, and Wood.



Smaller and Cooler: A Look at Two Lower-Mass Planets



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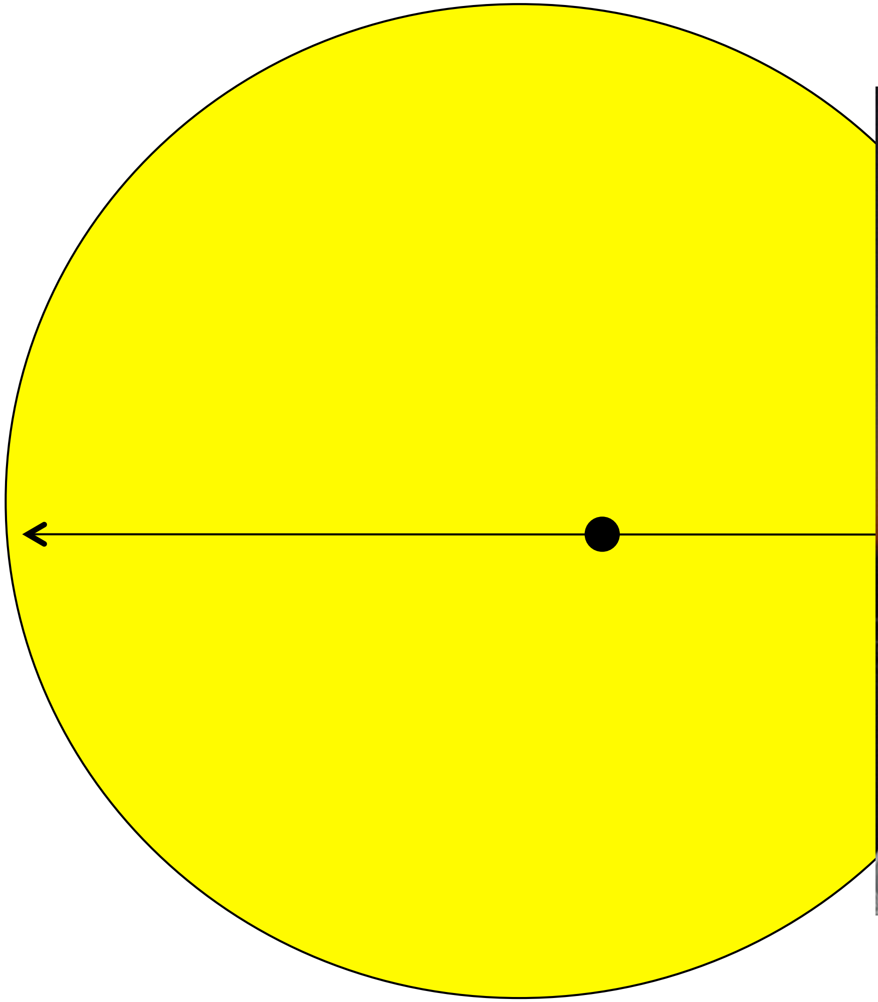
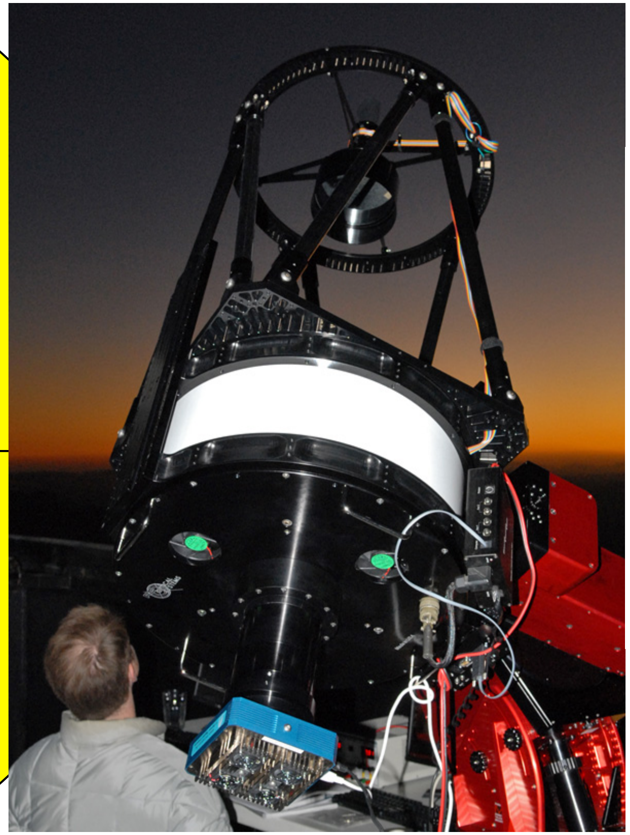
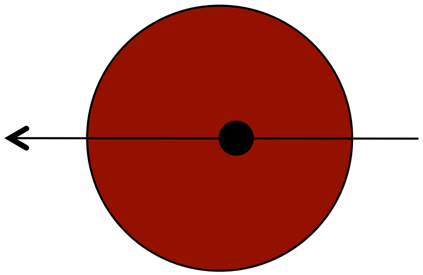
The M Dwarf Opportunity





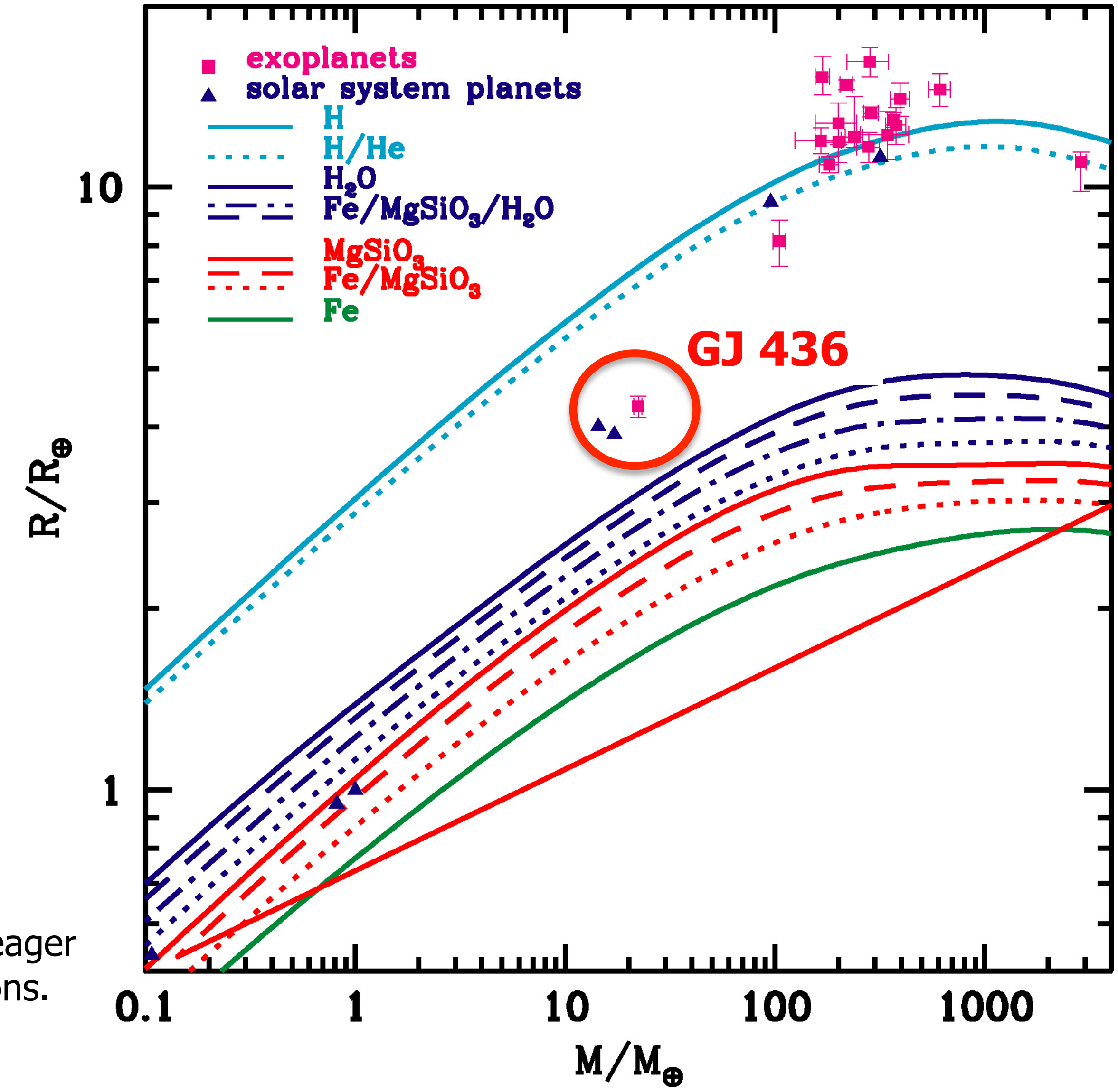
The Mearth project is surveying the closest ~2000 M dwarfs for transiting planets (Nutzman & Charbonneau 2008, Irwin et al. 2008)



An earth-sized planet transiting a M5 star (0.27 R_{sun}, 3400 K) creates a 0.1% eclipse.

GJ 436b:
A Cooler, Neptune-Sized Transiting Planet

Unlike hot Jupiters, GJ 436b has a lower temperature and metal-rich interior. How might this affect its atmospheric composition?



Prediction: more CH_4, less CO

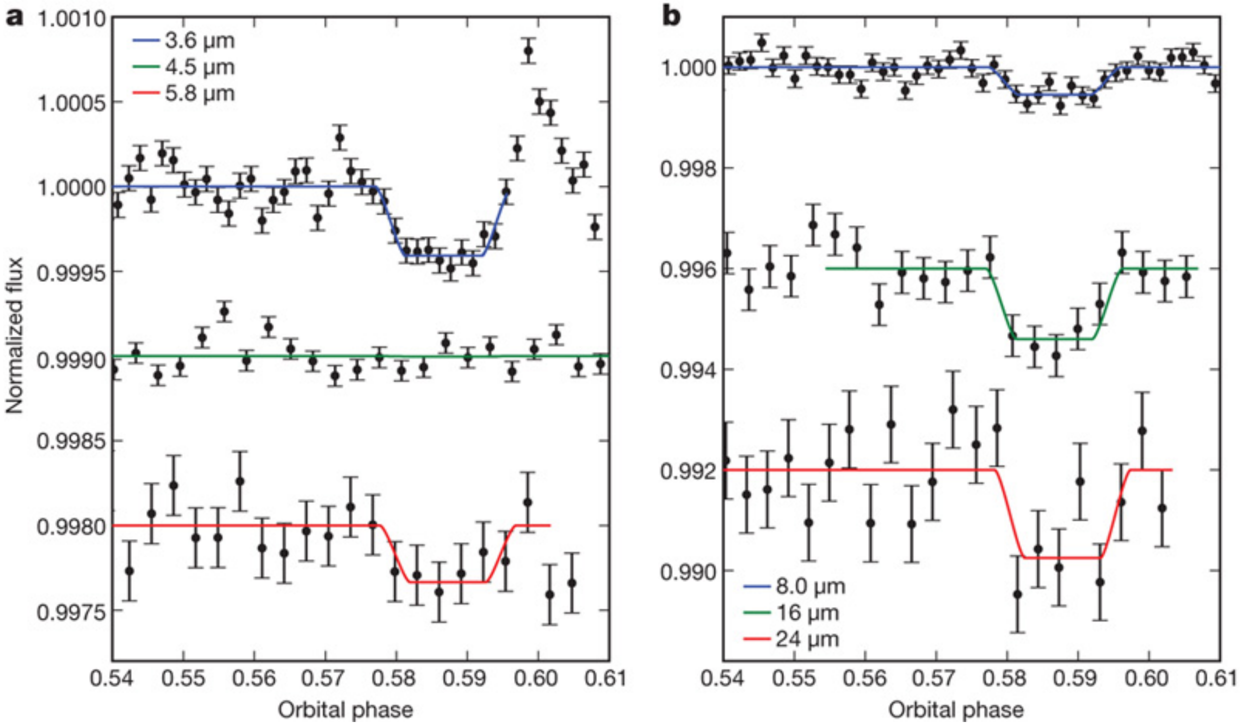
CH_4 is 100x CO in brown dwarf GJ 570D, 800 K

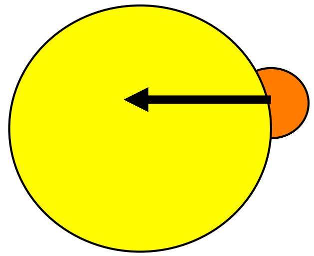
Saumon et al. (2006),
Stevenson et al. (2010)

Planet mass-radius relations from Seager et al. (2007) for different compositions.

A Dayside Emission Spectrum for GJ 436b

Stevenson et al. (2010)

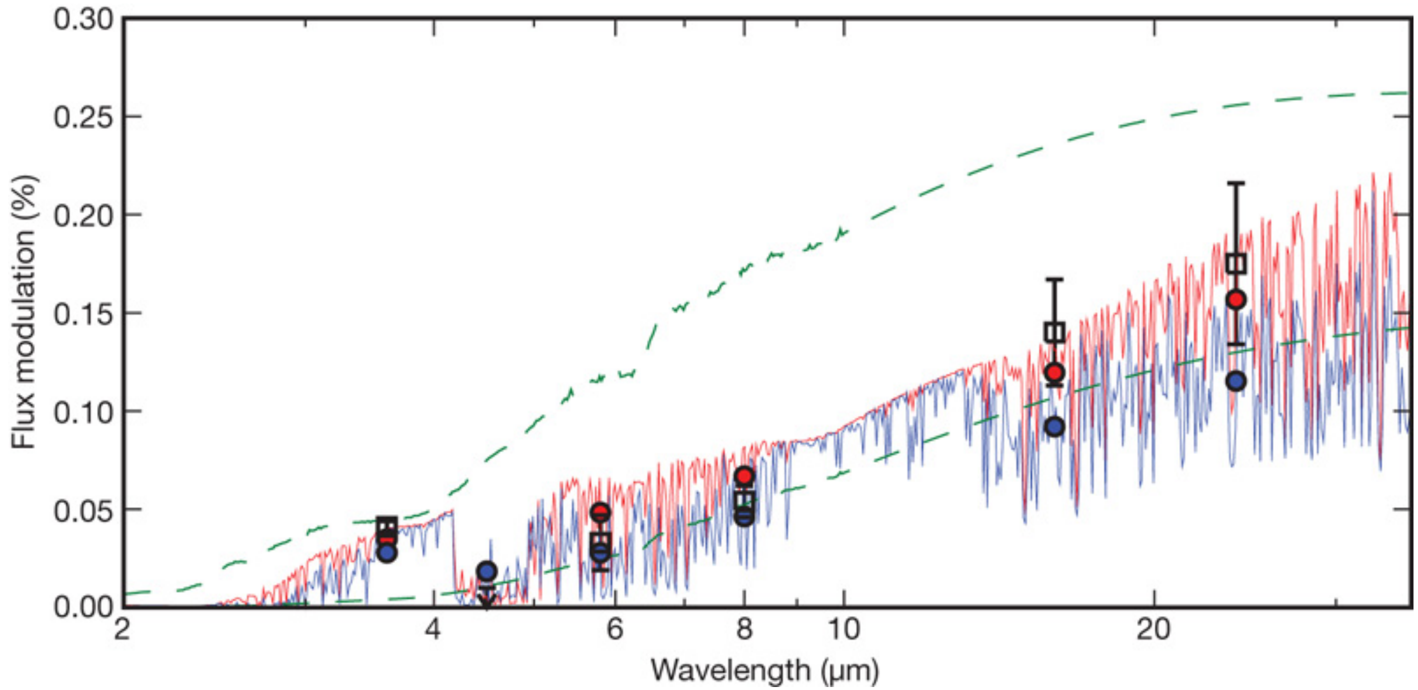




CH_4 / CO Ratio:

Predicted: 100

Measured: <0.001



A (Contradictory) Transmission Spectrum for GJ 436b

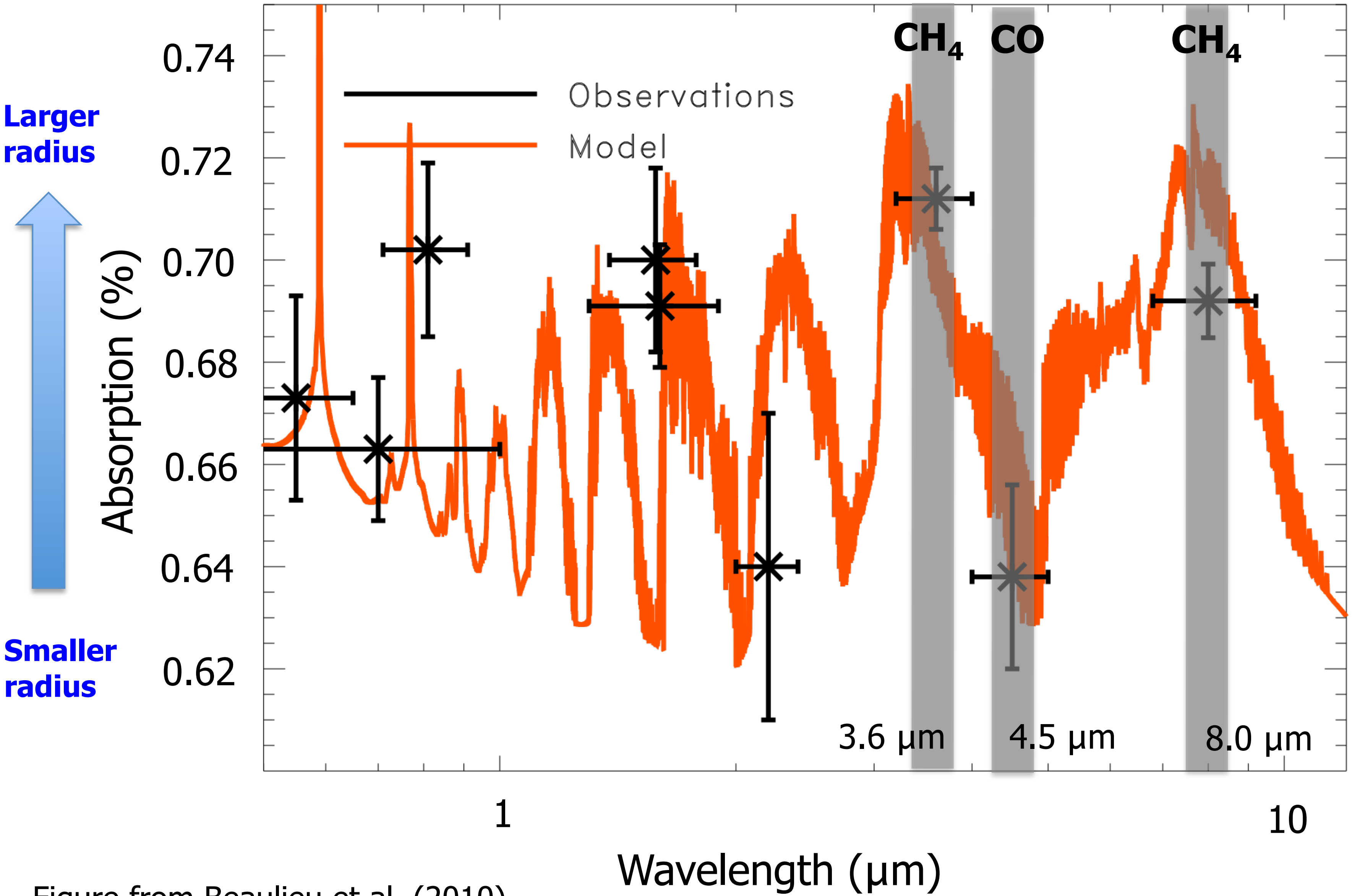


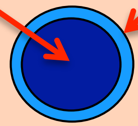
Figure from Beaulieu et al. (2010)

Characterizing the Transiting Super-Earth GJ 1214b

Interior:

Average density
1900 kg m^{-3}

Can’t be pure rock, might be water with a steam atmosphere or could have some H/He



Atmosphere:

Could be water vapor or H-dominated (depends on interior composition).

GJ 1214b
Mass: 6.55 M_{Earth}
Radius: 2.68 R_{Earth}
T_{equil}=390-560 K
(albedo 0-0.75)

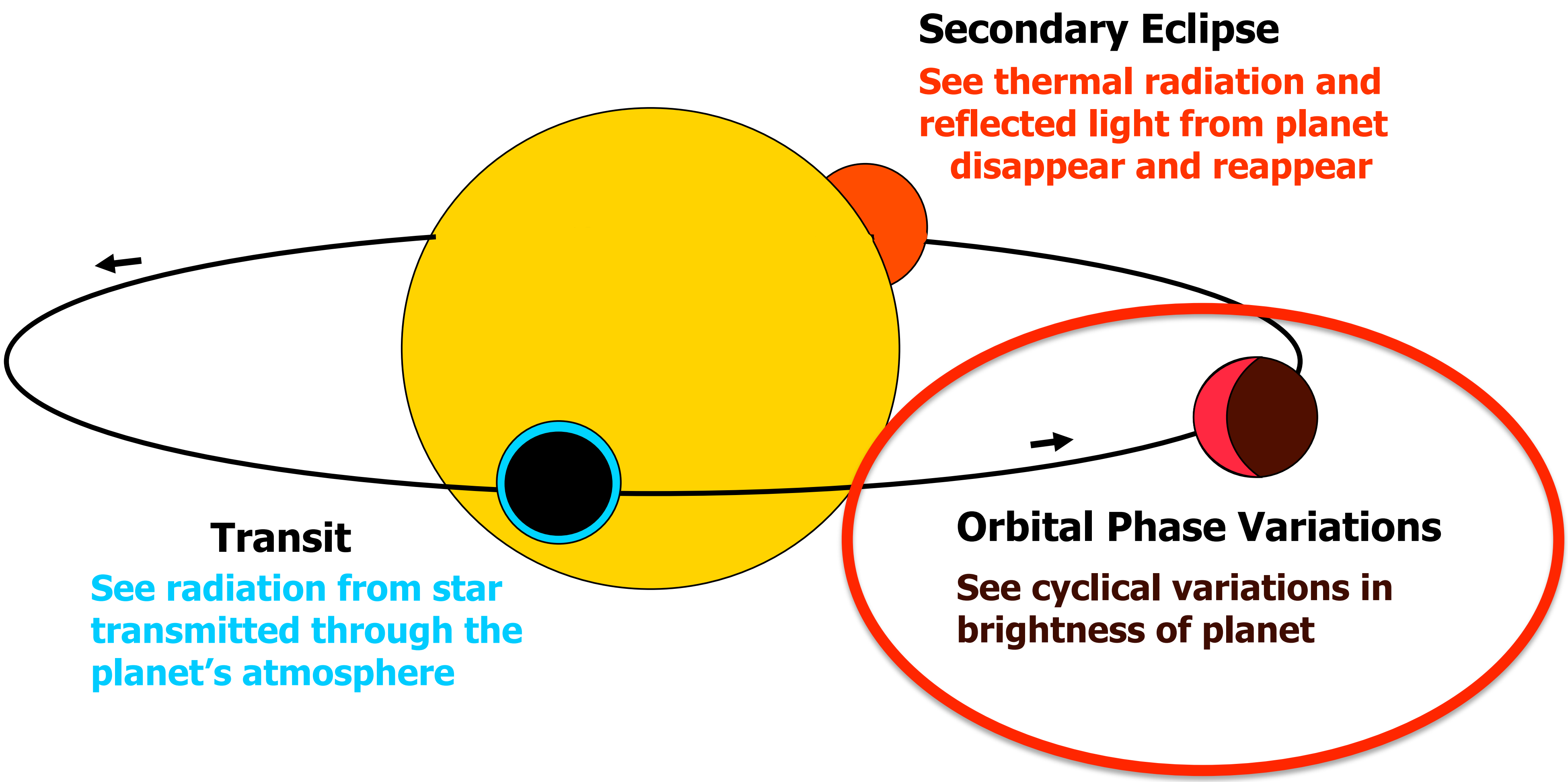
1.4% transit depth

See talk by Eliza Kempton.

GJ 1214A
Mass: 0.16 M_{Sun}
Radius: 0.21 R_{Sun}
T_{eff}=3000 K

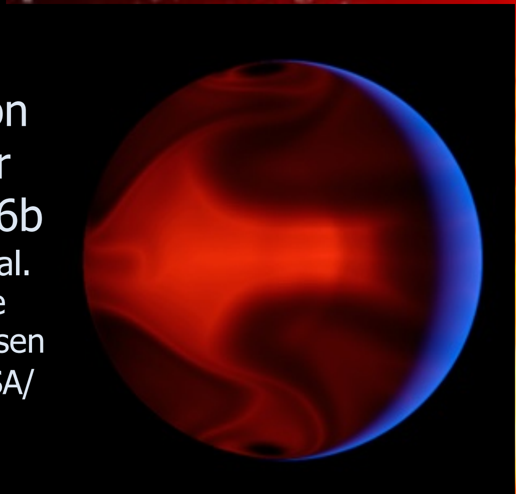
GJ 1214 system to scale.

Transiting Planets as a Tool for Studying Exoplanetary Atmospheres



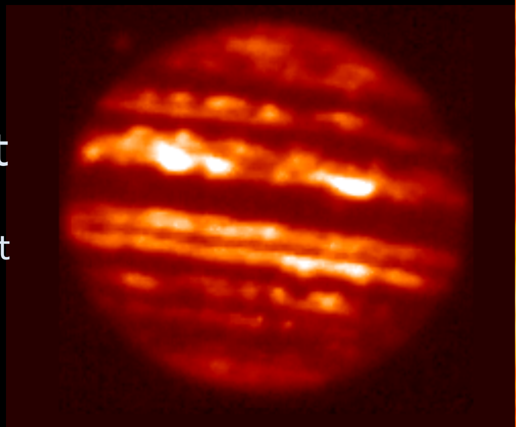
Circulation model for HD 80606b

Laughlin et al. 2009, image credit D. Kasen (UCSC)/NASA/JPL-Caltech



Jupiter at 4.8 µm.

Image credit Glen Orton



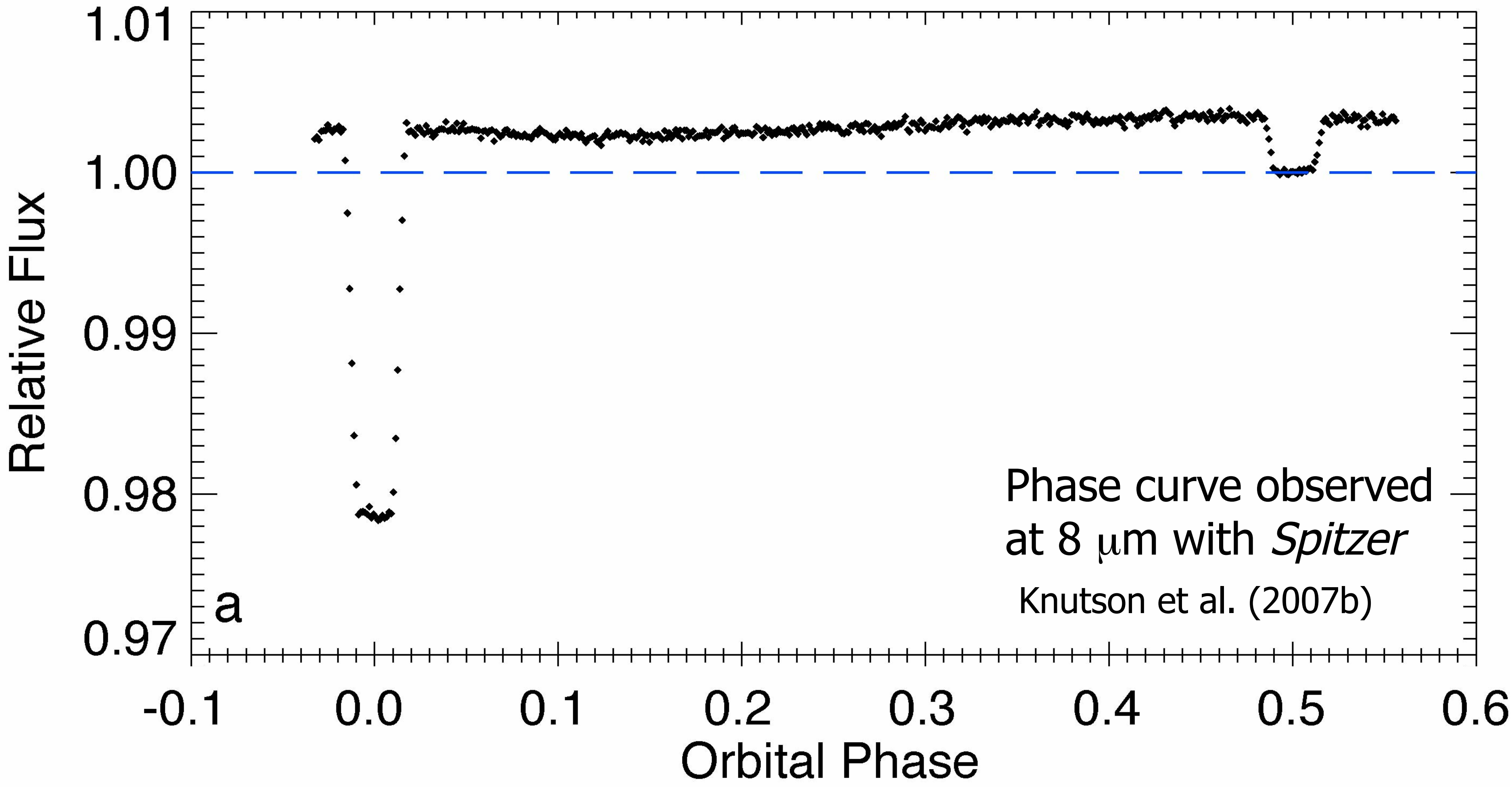
What does the atmospheric circulation look like?

Close-in exoplanets should be **tidally locked**, may have large thermal and/or chemical gradients between the two hemispheres.

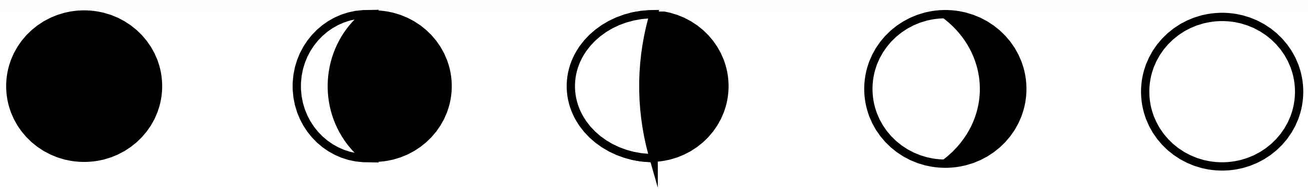
Planet's slow rotation means that the circulation should be **global in scale** (few broad jets, large vortices).

Image credit: ESA/C. Carreau

As the World Turns:
HD 189733b Over Half an Orbit

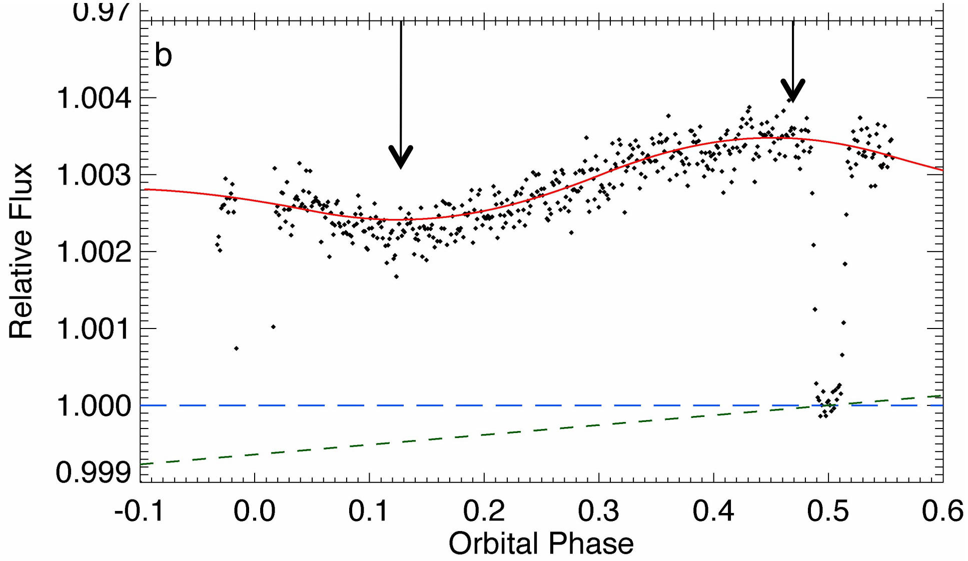


Observer's View of Planet



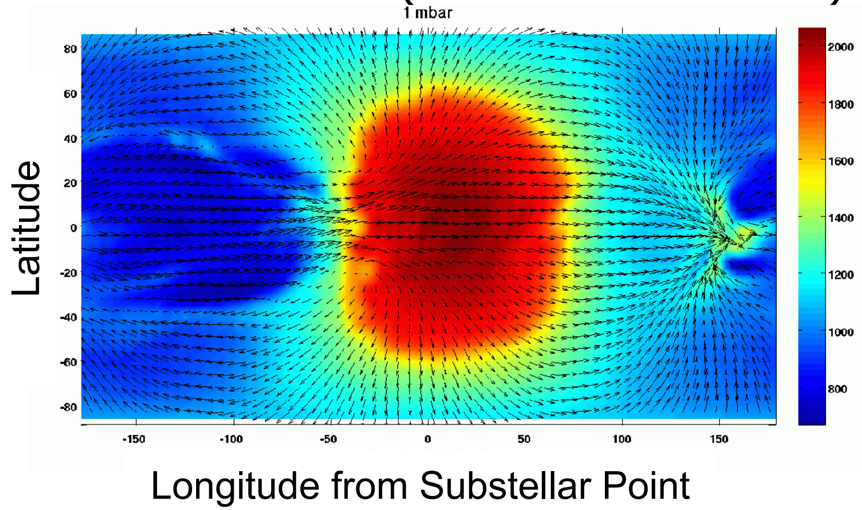
Mapping Exoplanet Atmospheres: HD 189733b's Hot Night Side

See talks by Showman, Dobbs-Dixon, Cowan, posters by Arias

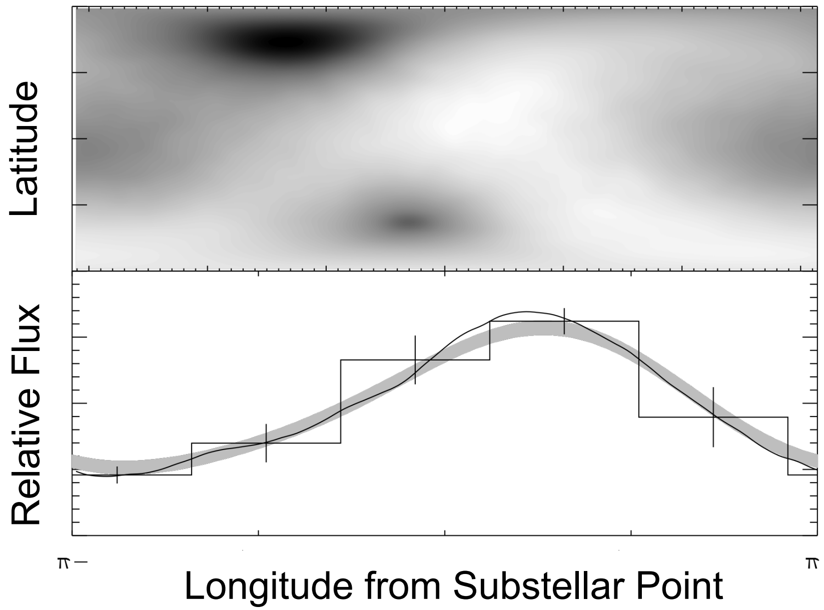


1. Spitzer 8 μm phase curve
(Knutson et al. 2007b)

3. Circulation Model (Showman et al. 2009)



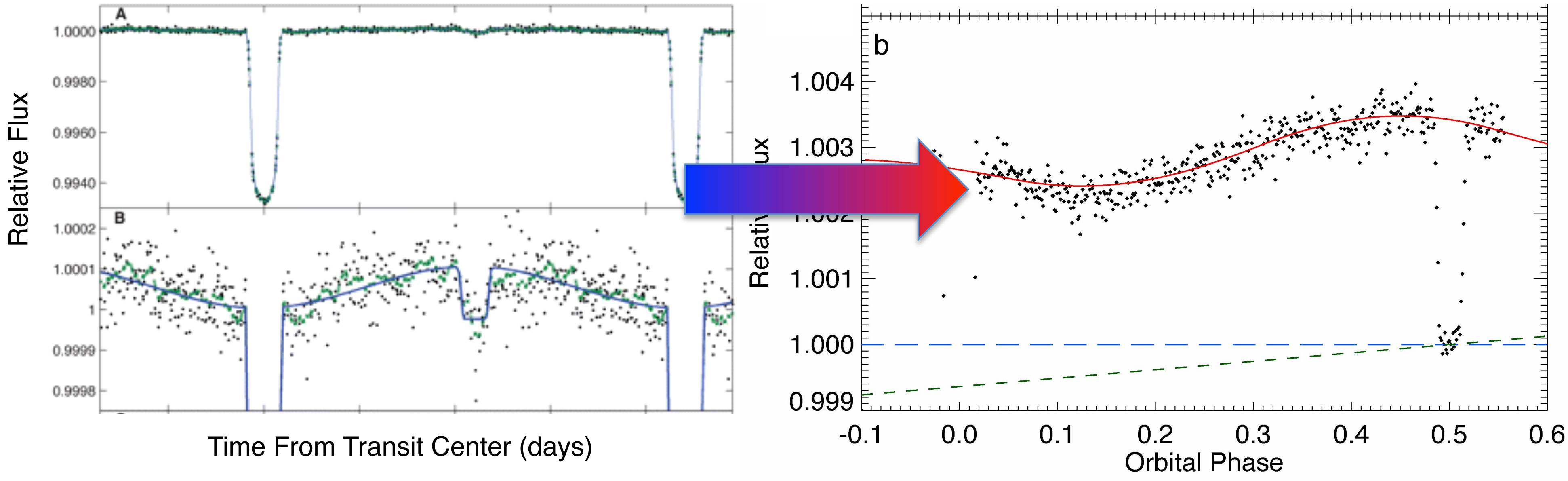
2. Longitudinal Temperature Profile (Cowan et al. 2008)



Do All Hot Jupiters Have Similar Circulation Patterns?

Visible Light Phase Curve
HAT-P-7 / Kepler

IR Phase Curve
HD 189733b / Spitzer



Large gradients:

~~u And b* (Harrington et al. 2006)~~
Crossfield et al. (2010)

HD 179949* (Cowan et al. 2007)

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

Welsh et al. (2010)

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

Intermediate gradients:

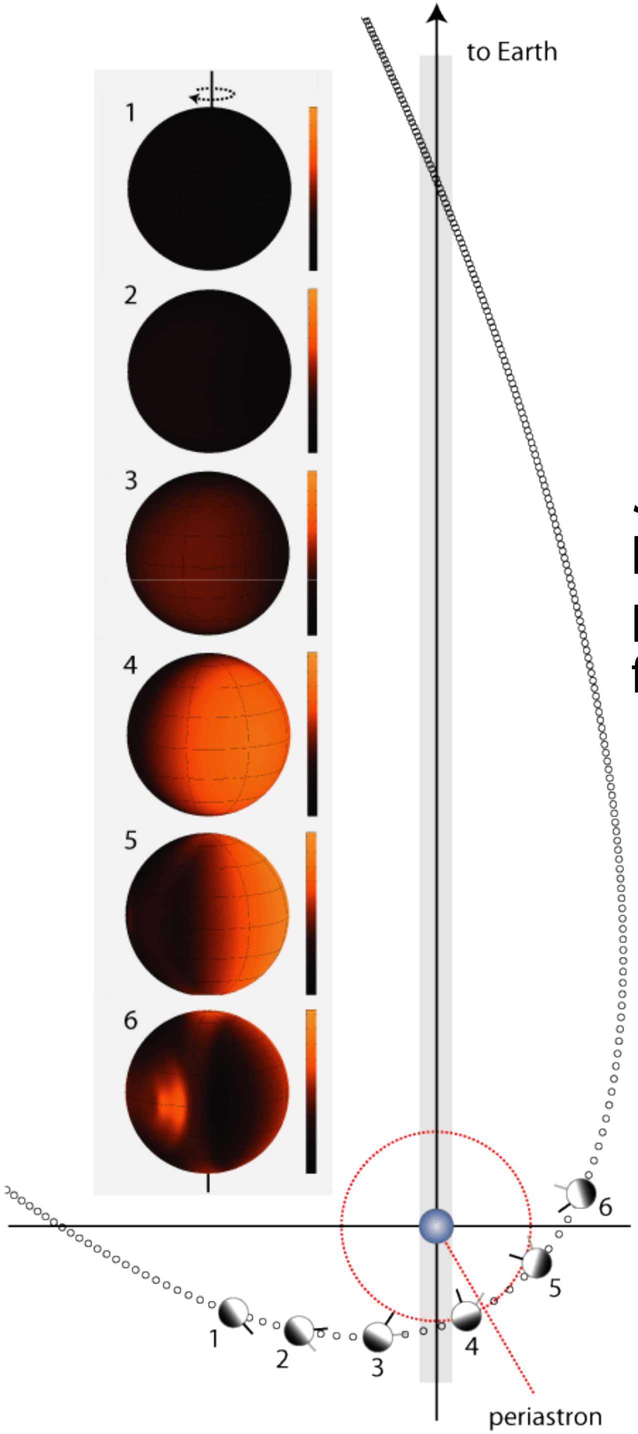
HD 149026 (Knutson et al. 2009c)

Small gradients:

HD 189733b (Knutson et al. 2007, 2009a)

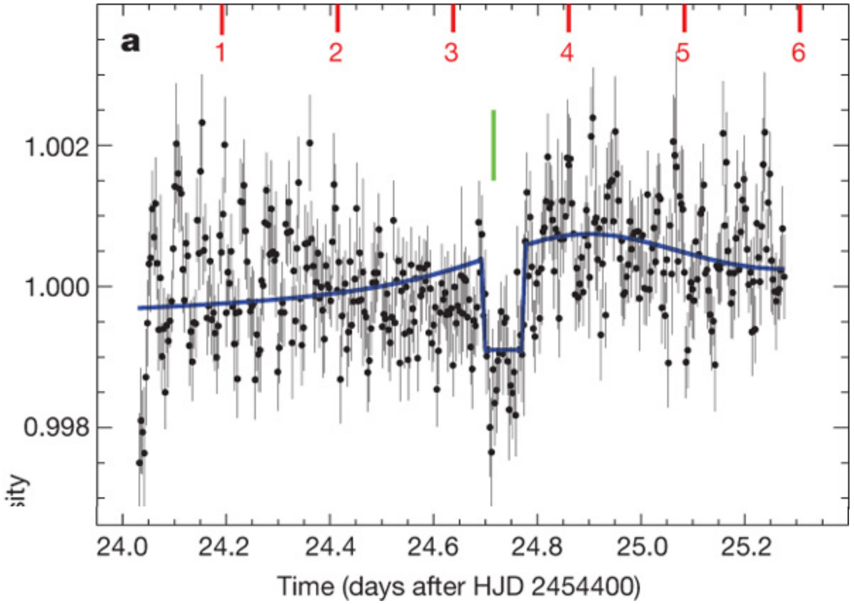
HD 209458 (Cowan et al. 2007, Knutson et al.2010, in prep.)

See poster by Maxted for WASP-18.



Circulation on Eccentric Planets

Spitzer detected heating during periastron passage for HD 80606b...

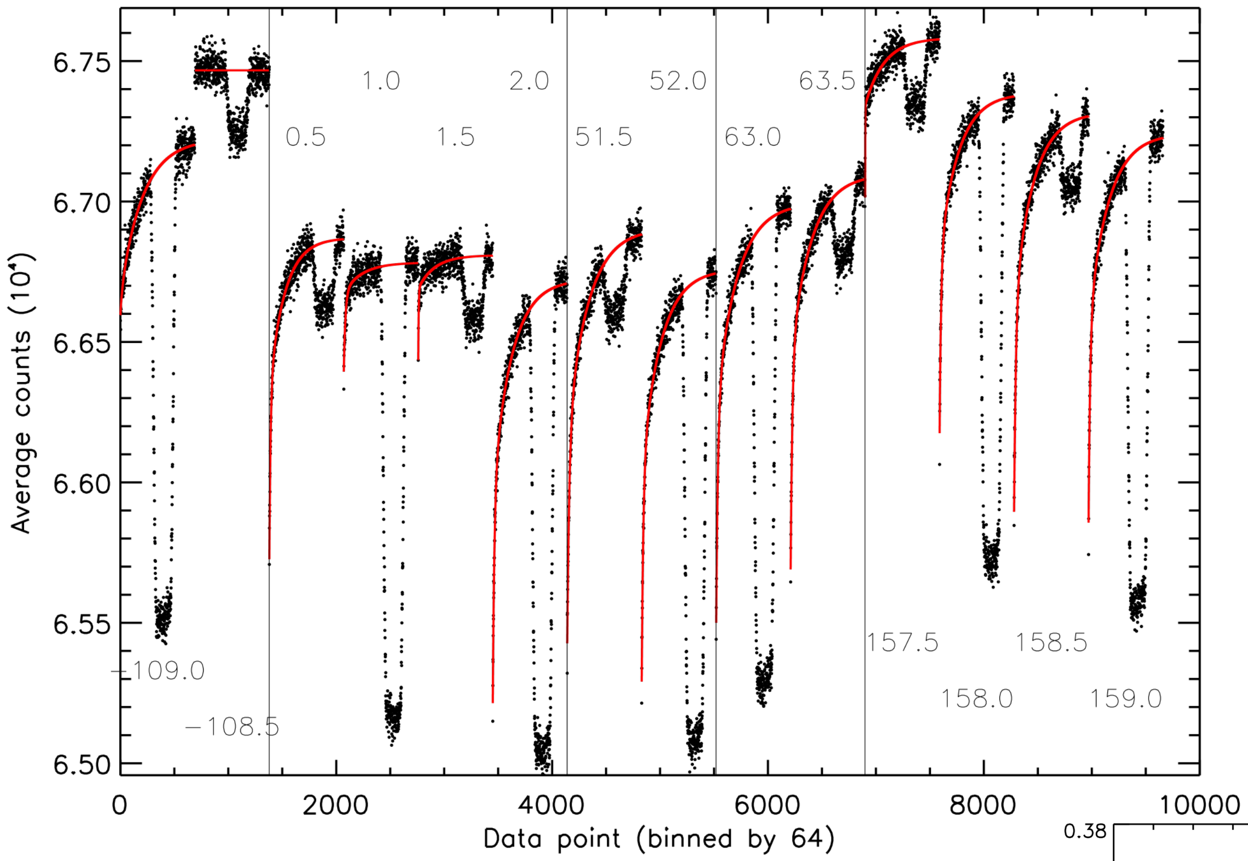


Laughlin et al. (2009)

But do eccentric planets have stable weather patterns?

See poster by Kataria.

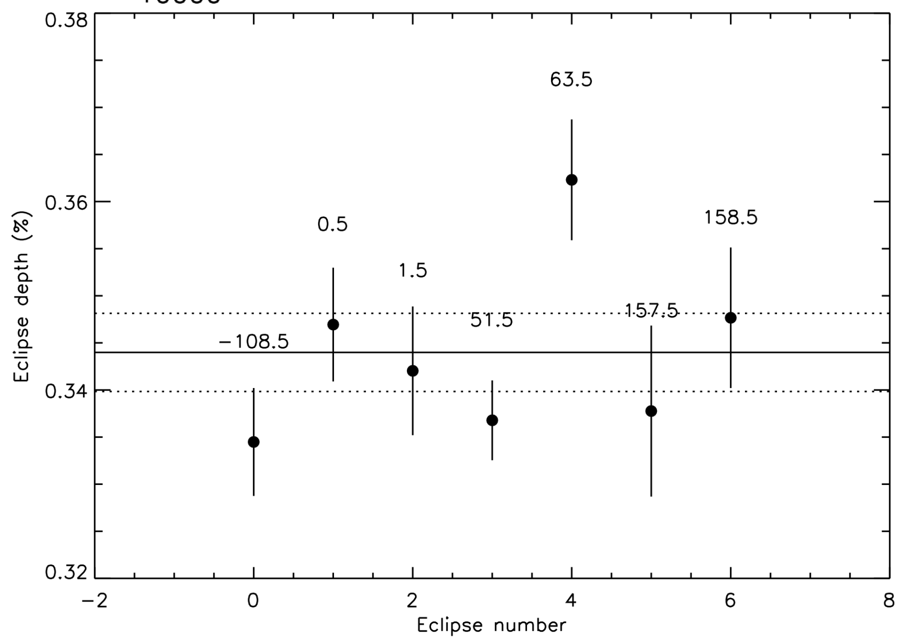
Are Hot Jupiters Variable?

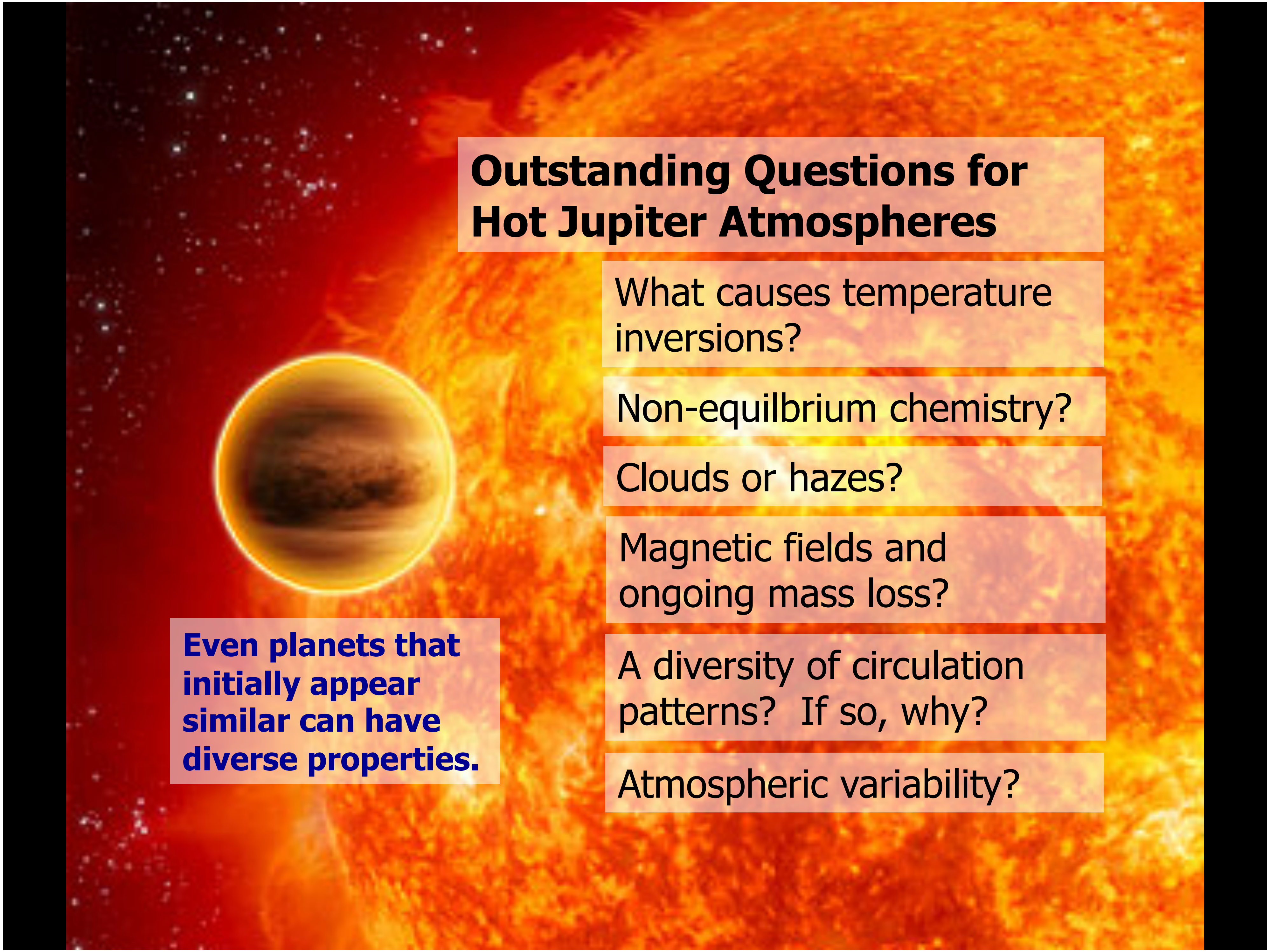


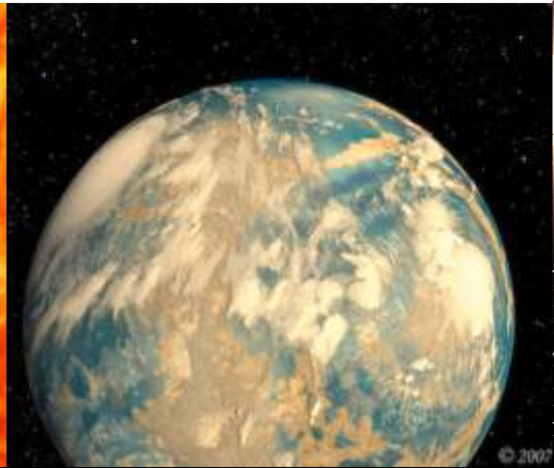
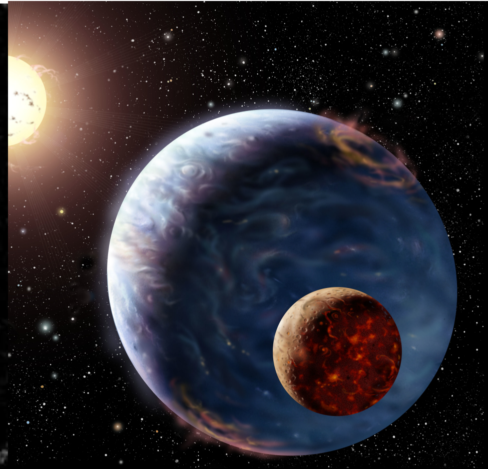
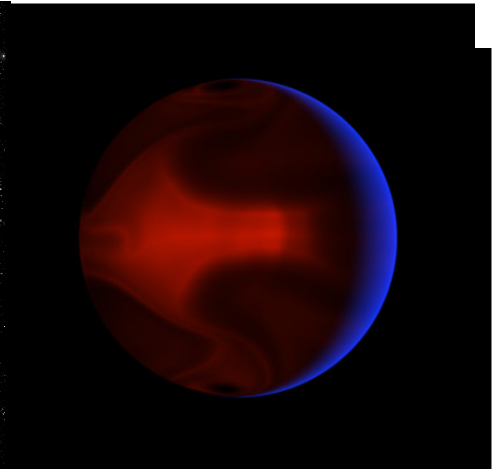
Fourteen transits and secondary eclipses of HD 189733b observed by *Spitzer*

Agol et al. (2010)

Dayside flux varies by <2.6% (1σ)

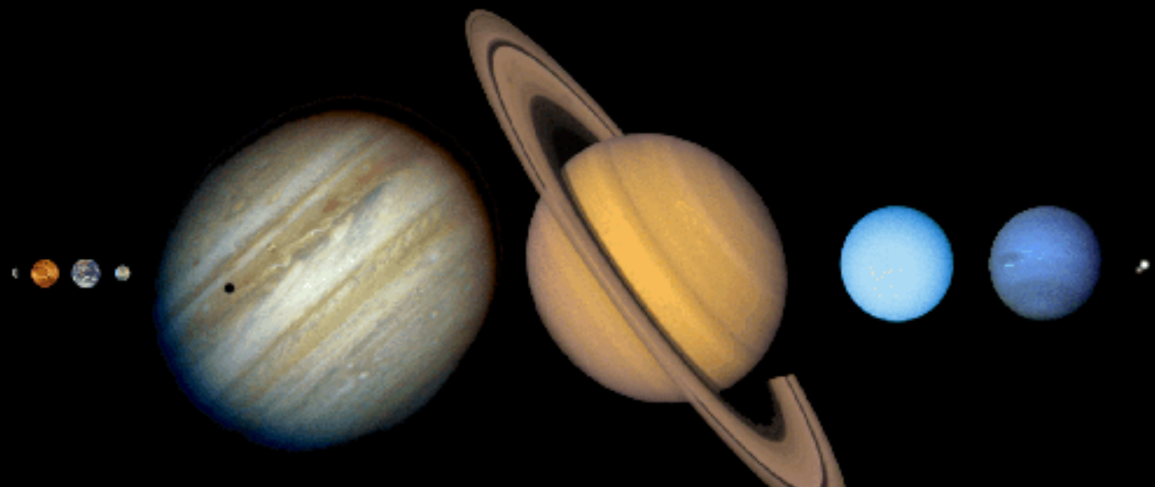


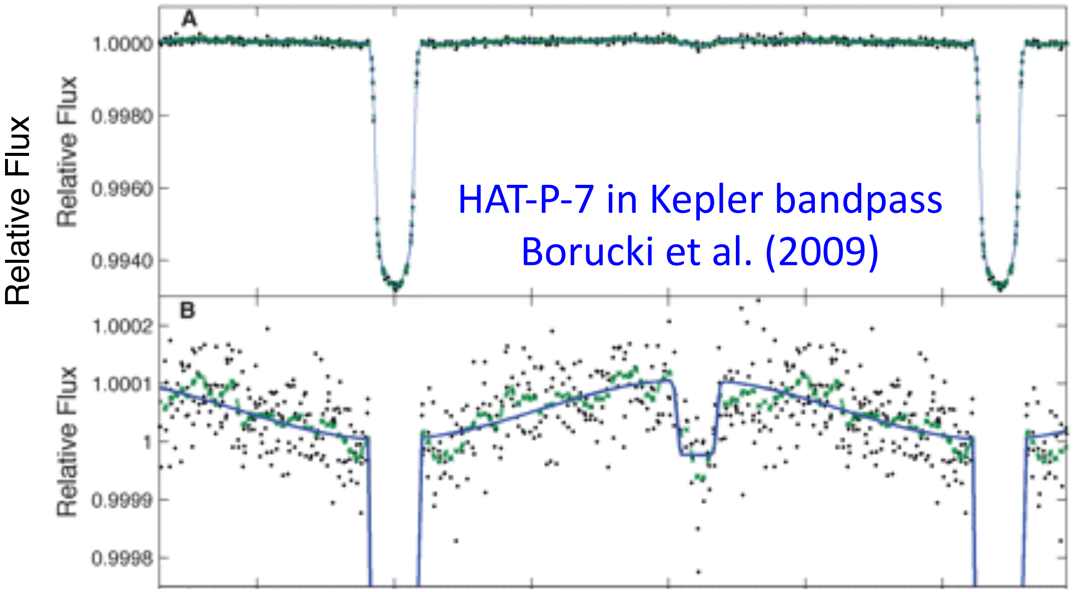

Outstanding Questions for Hot Jupiter Atmospheres
What causes temperature inversions?
Non-equilbrium chemistry?
Clouds or hazes?
Magnetic fields and ongoing mass loss?
A diversity of circulation patterns? If so, why?
Atmospheric variability?
Even planets that initially appear similar can have diverse properties.

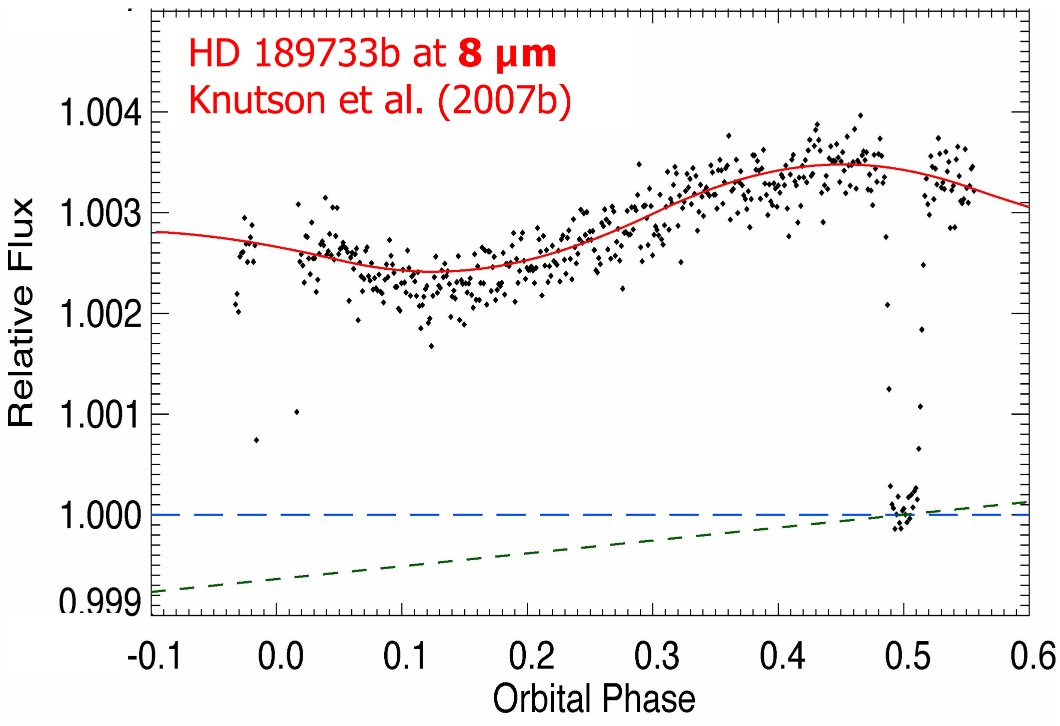





The future of exoplanet atmosphere studies:

1. Studies of hot Jupiters are transitioning from an exploration phase to a survey phase with the goal of explaining the observed diversity in their properties.
2. These same techniques will soon be applied to a much wider range of planet types, including eccentric planets, cool(er) Jupiters, hot Neptunes, and superhot Super-Earths.







The Power of Combined Kepler/CoRoT + Spitzer Observations

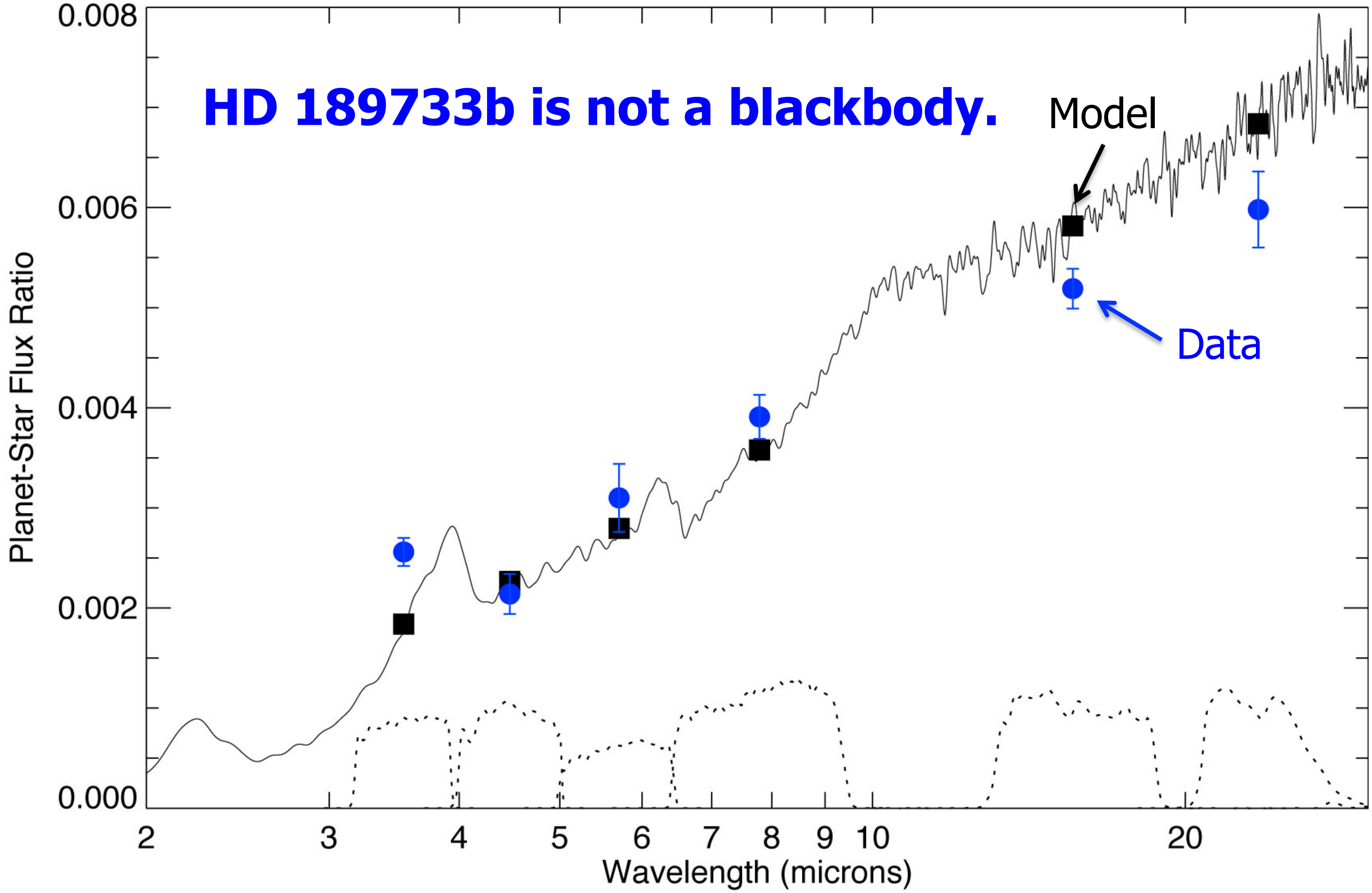
Reflected

+

Thermal*

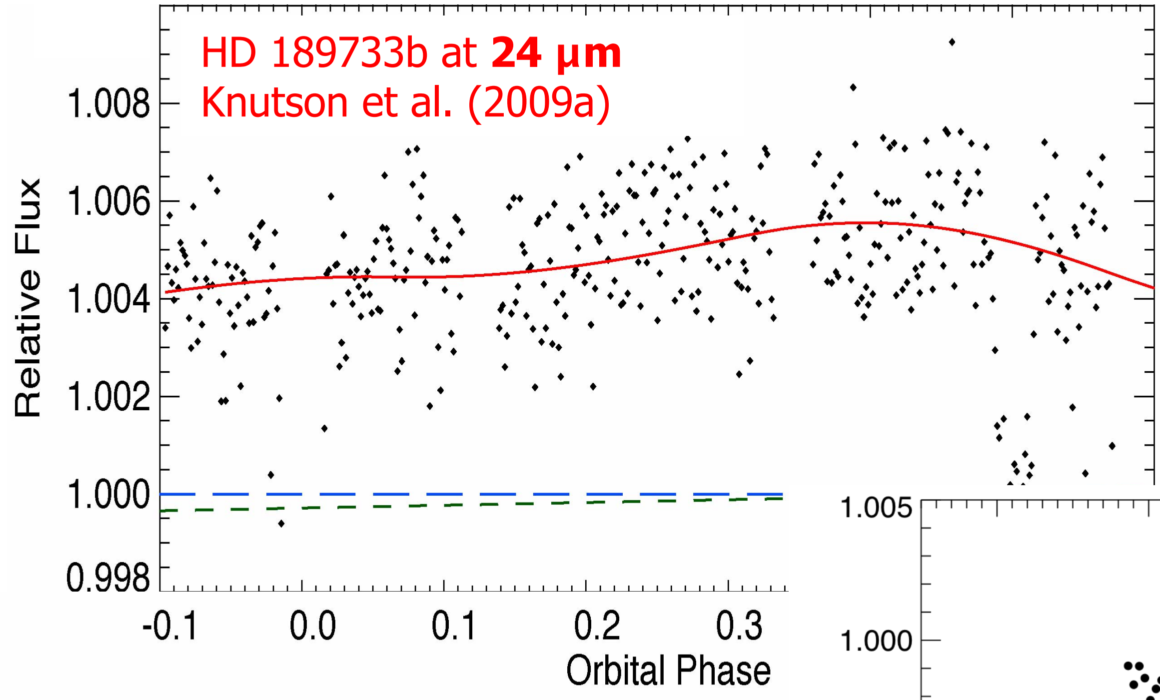
= Albedo

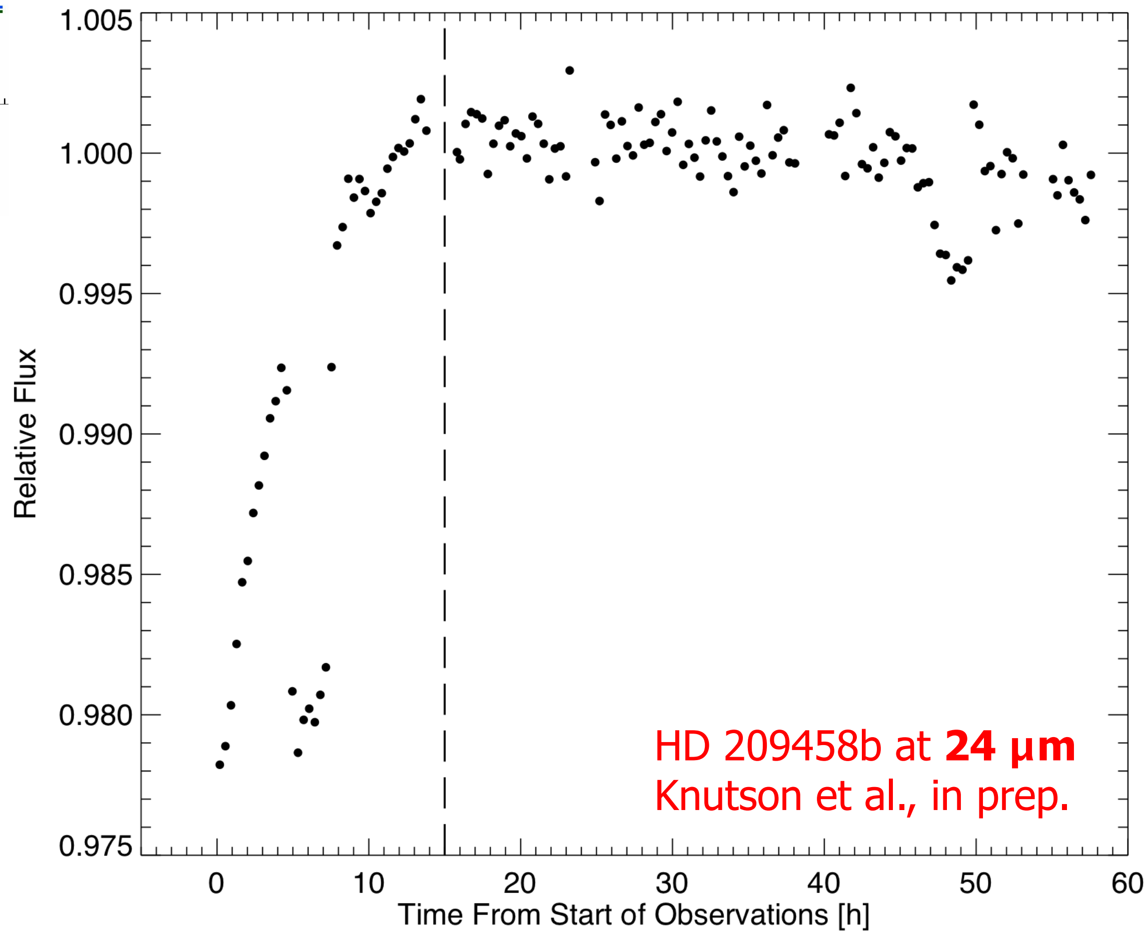
*Will only have IR secondary eclipse data (including some JHK from ground-based obs.) for a majority of systems.



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

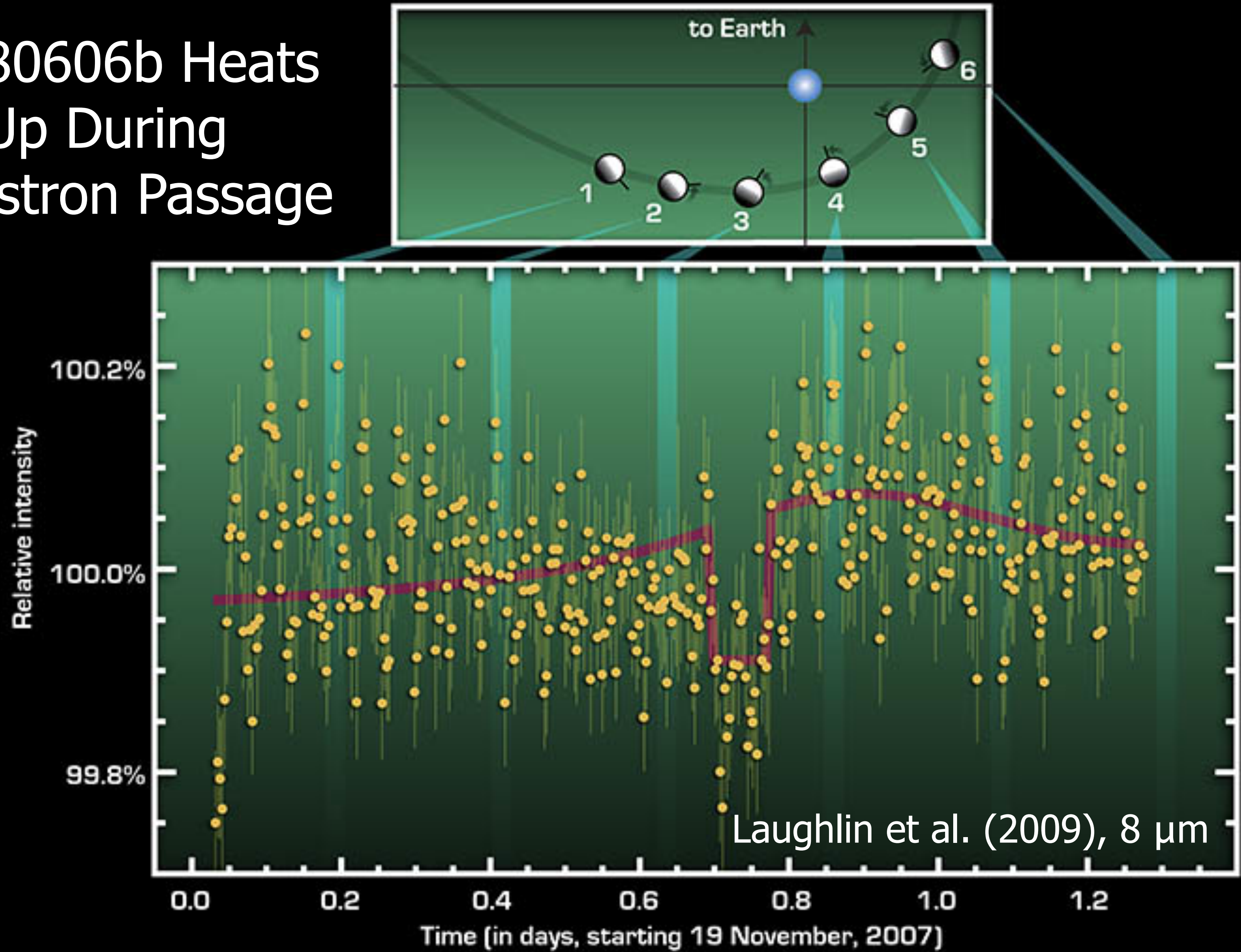
NEW: A 24 µm Phase Curve for HD 209458b





Both HD 189733b and HD 209458b have warm night sides.

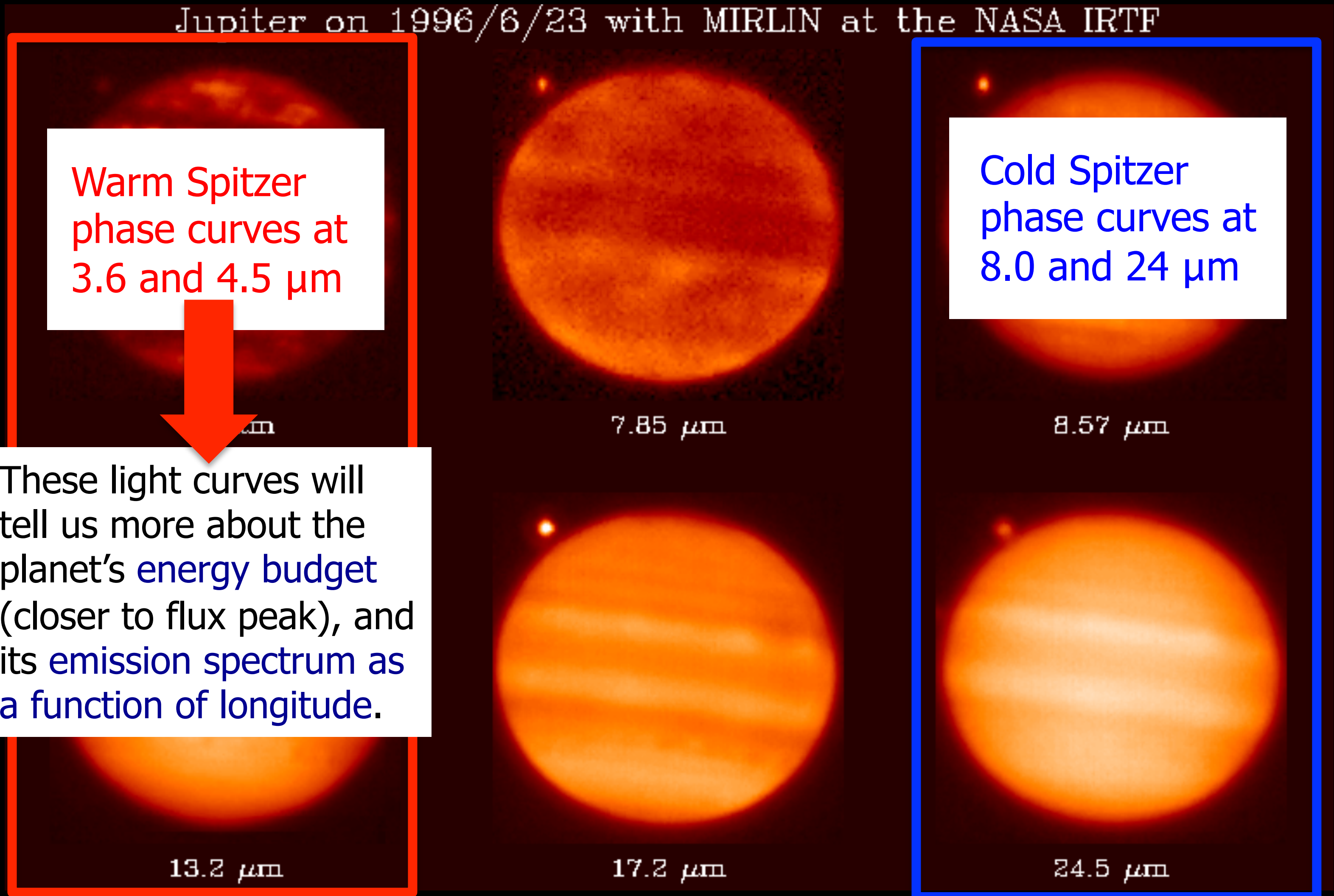
HD 80606b Heats Up During Periastron Passage



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

The need for multi-wavelength observations:

Planets are not blackbodies (and we shouldn't treat them that way).



Warm Spitzer phase curves at 3.6 and 4.5 μm

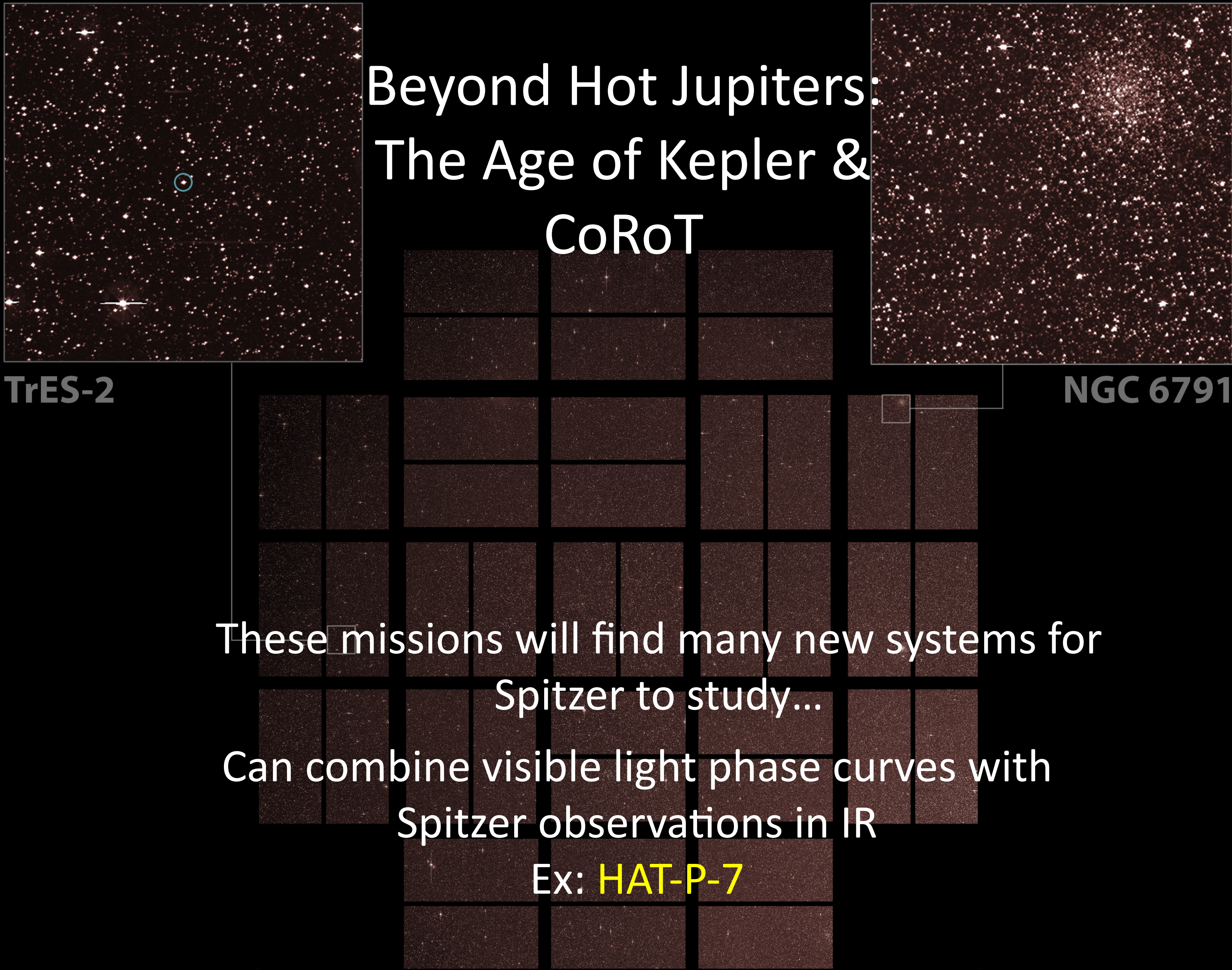
Cold Spitzer phase curves at 8.0 and 24 μm

These light curves will tell us more about the planet's energy budget (closer to flux peak), and its emission spectrum as a function of longitude.

Image credit G. Orton

Will have full-orbit, multi-wavelength phase curves for five planets spanning 3.6-24 μm (up to four bands per planet, 1138 hours, PI H. Knutson) by end of 2011.

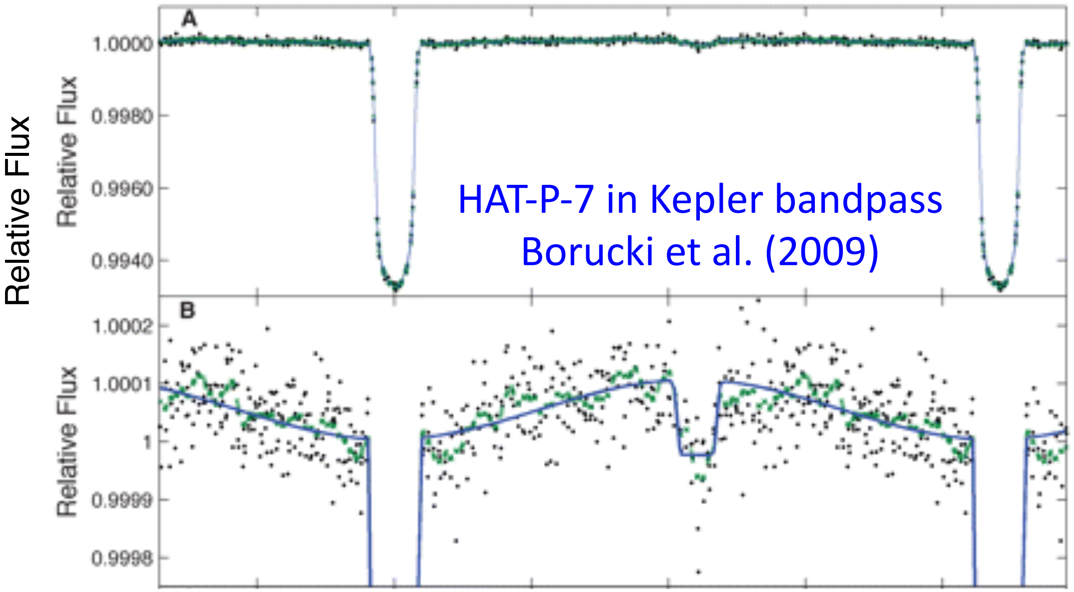
Beyond Hot Jupiters: The Age of Kepler & CoRoT

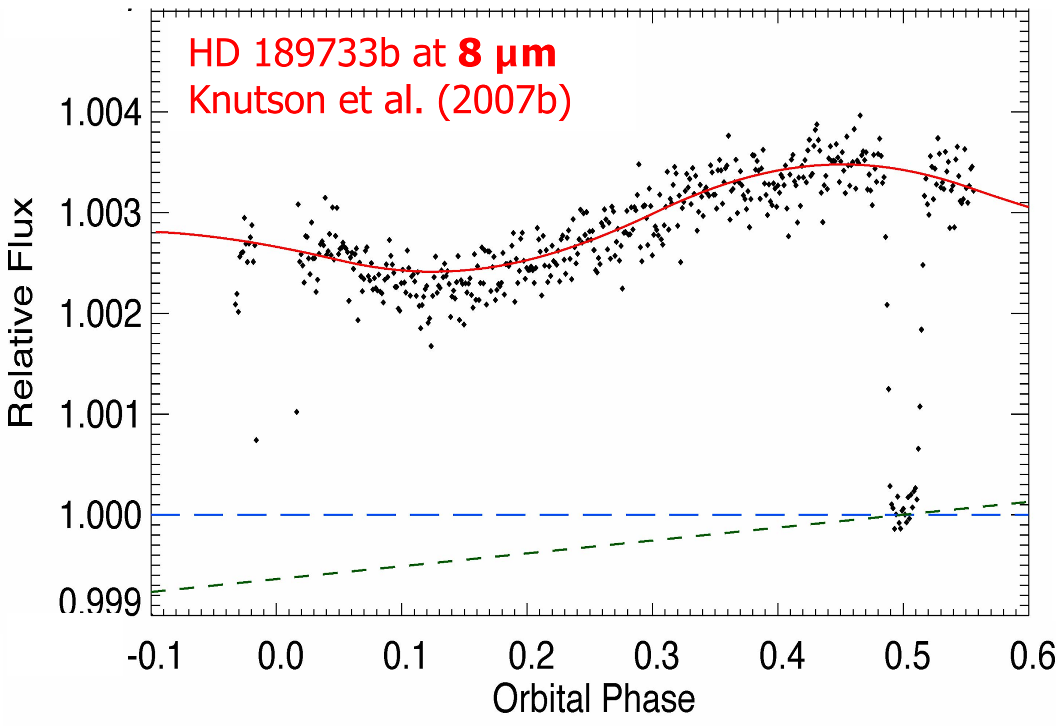


These missions will find many new systems for Spitzer to study…

Can combine visible light phase curves with Spitzer observations in IR

Ex: HAT-P-7





The Power of Combined Kepler/CoRoT + Spitzer Observations

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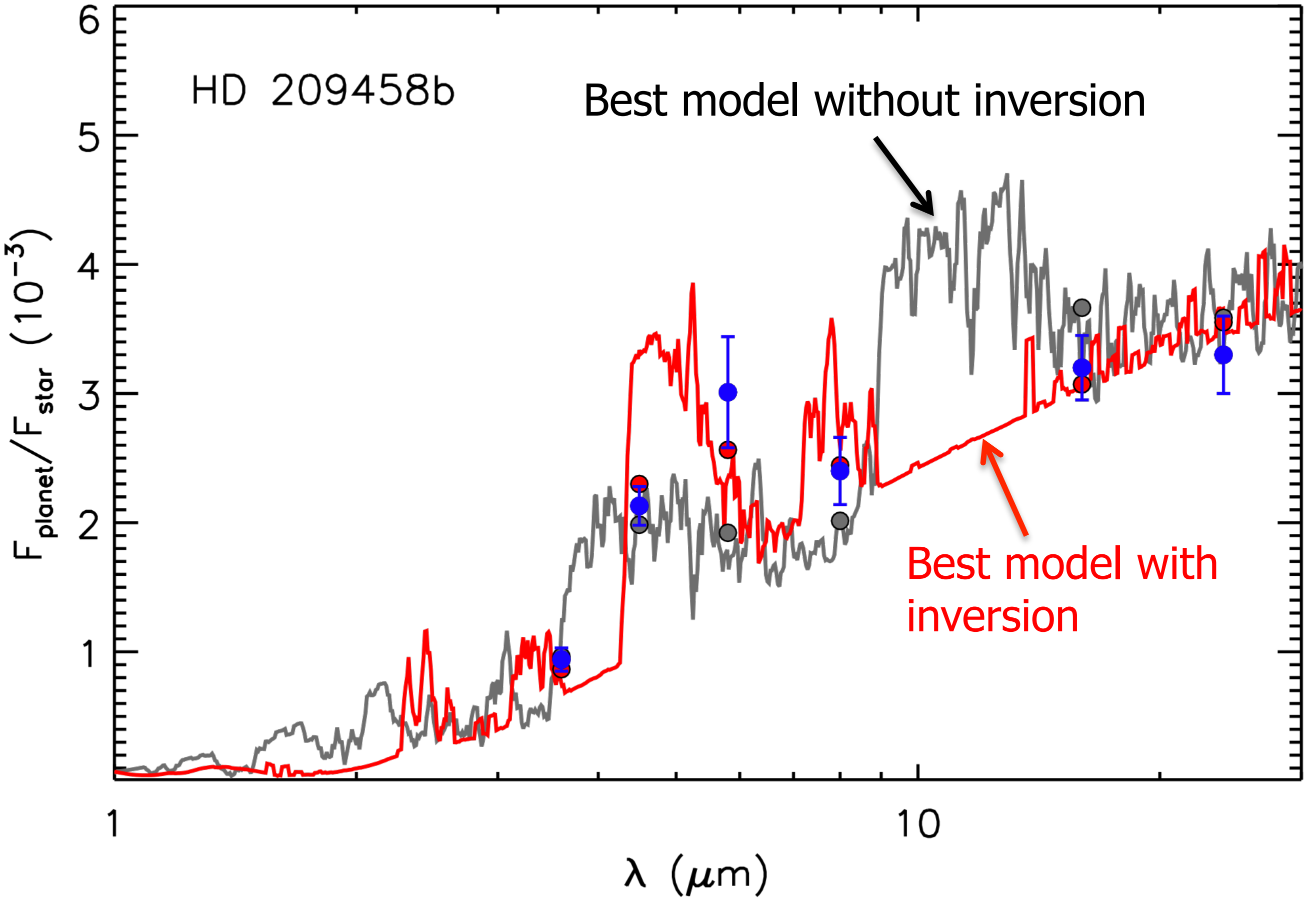
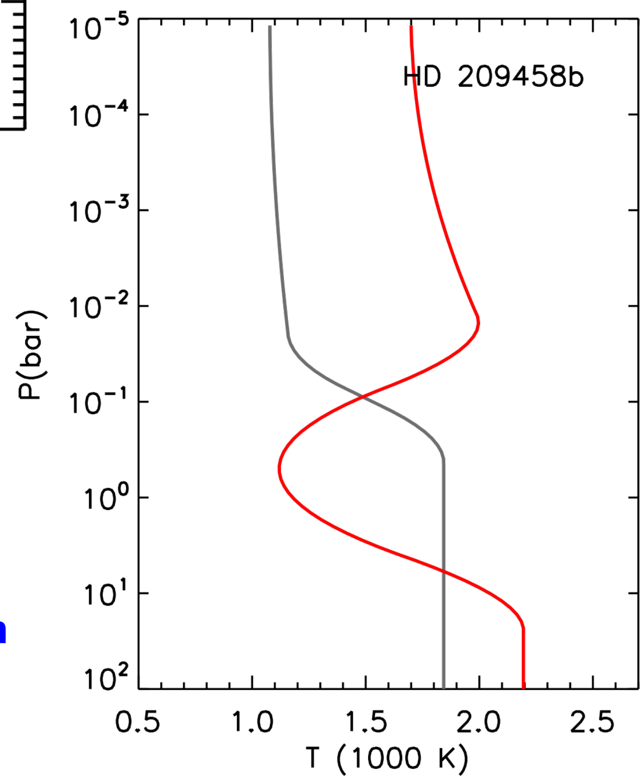


Is an inversion the only explanation?

It's the most plausible one.



Madhusudhan & Seager (2010), in prep.
Compare best-fit inverted and non-inverted models where P-T profiles and chemistry are allowed to vary.

With inversion:	Without inversion:
$H_2O = 10^{-7}$	$H_2O = 3x10^{-4}$
$CO = 7x10^{-3}$	$CO = 10^{-5}$
$CH_4 = 3x10^{-6}$	$CH_4 = 7x10^{-5}$
$CO_2 = 10^{-9}$	$CO_2 = 7x10^{-9}$

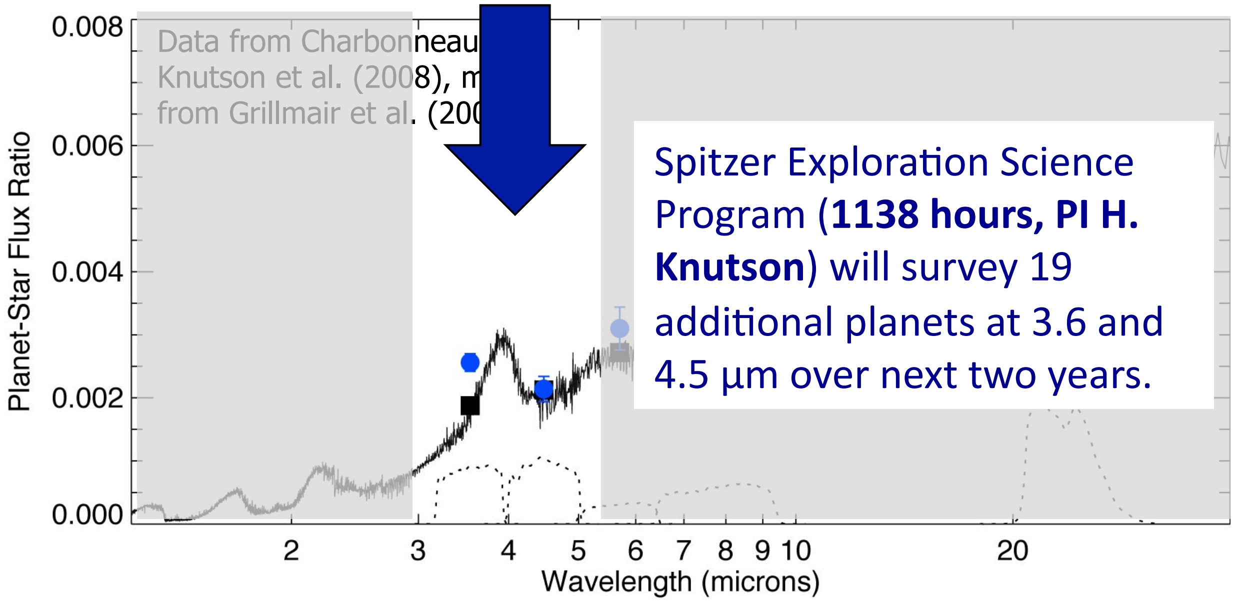
CO should be much more abundant than methane at 1400 K

Two Classes of Hot Jupiter Atmospheres

Observations in the 3.6 and 4.5 μm channels can be used to determine whether or not a given planet has an inversion.

HD 189733b is well-described by a model with water and CO bands in absorption.

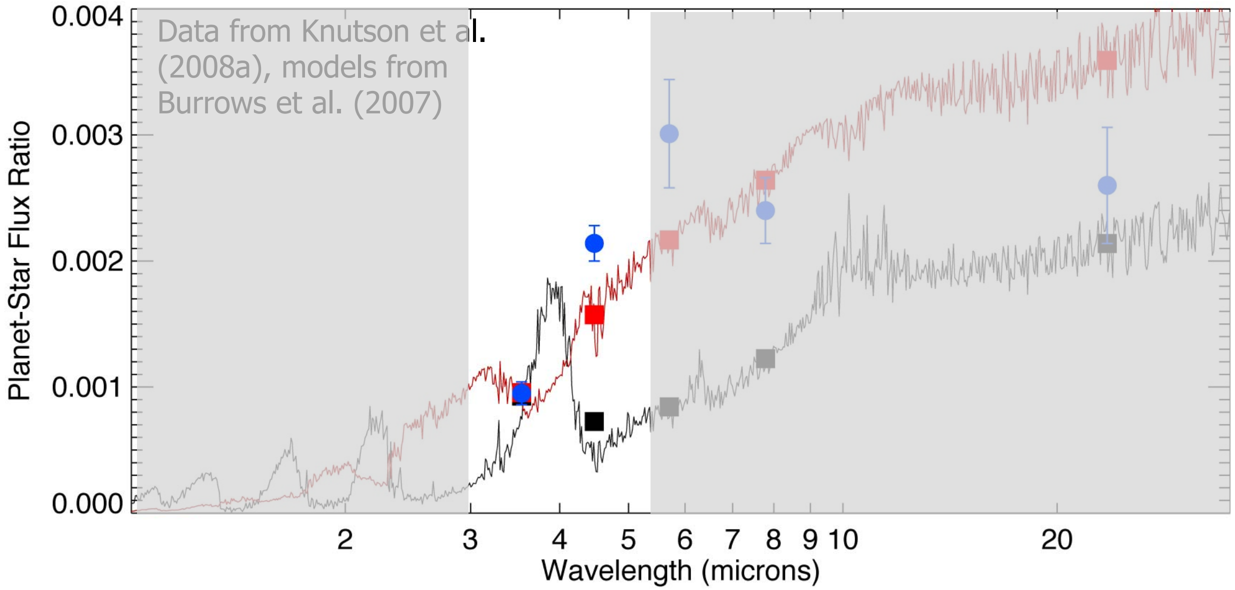
No stratosphere.



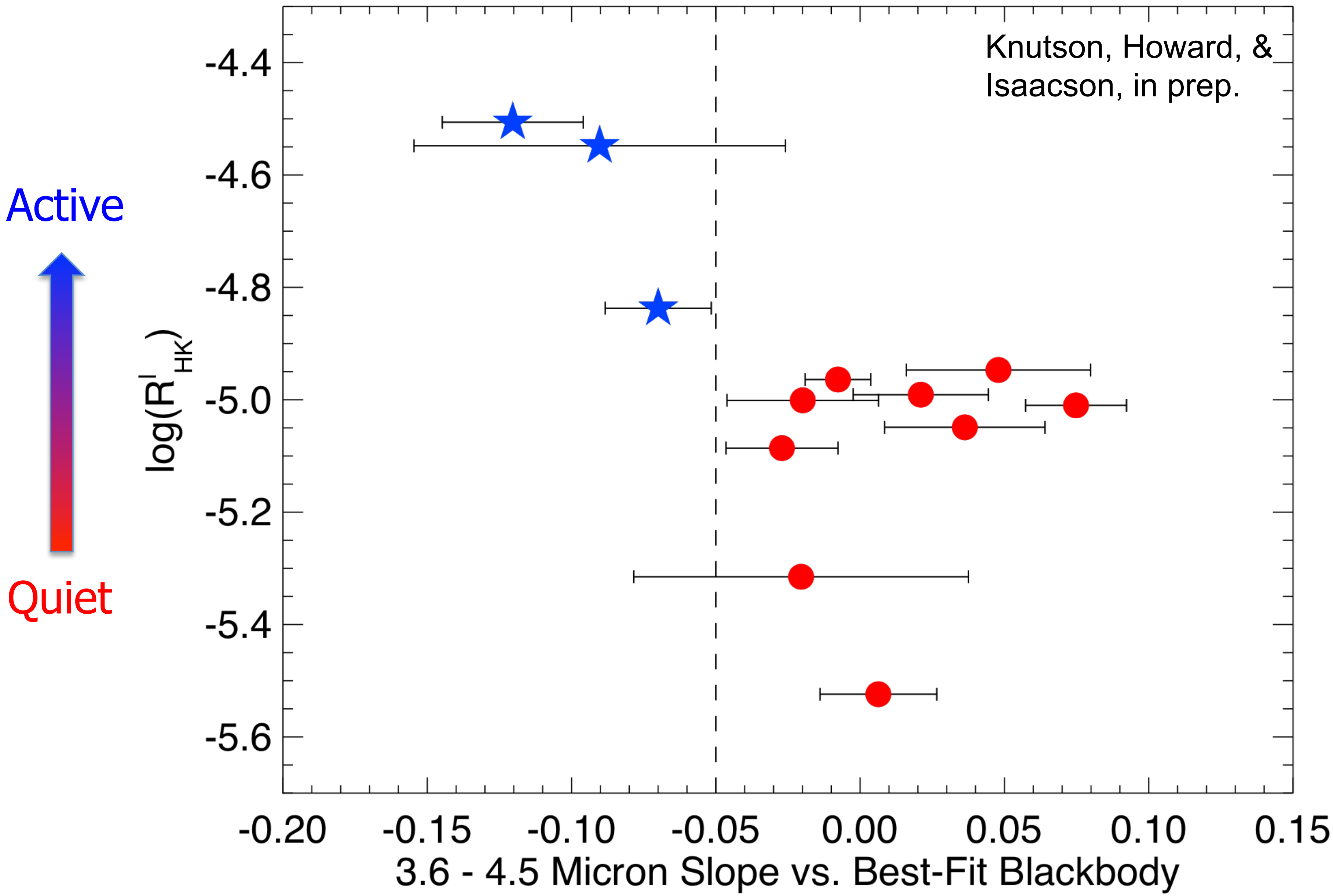
Spitzer Exploration Science Program (**1138 hours, PI H. Knutson**) will survey 19 additional planets at 3.6 and 4.5 μm over next two years.

HD 209458b is NOT well-matched by this model, has water and CO *emission* features.

Stratosphere.

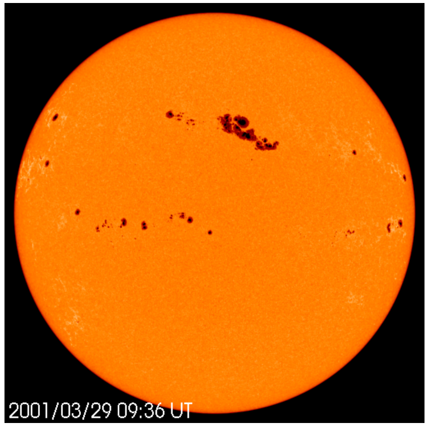


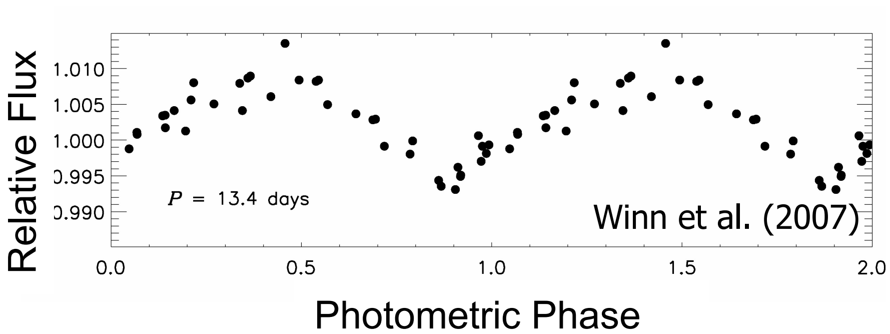
A Model-Independent Metric for Classifying Hot Jupiter Atmospheres



Complications: Star Spots and Detector Effects

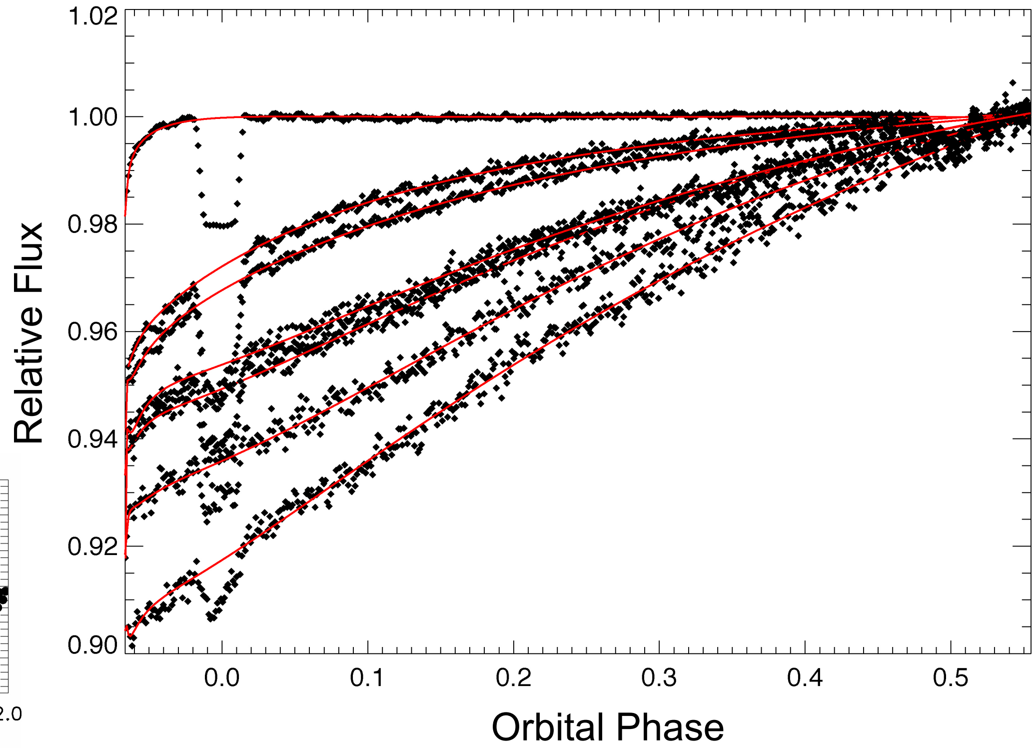
The brightness of the star can vary as spots rotate in and out of view.





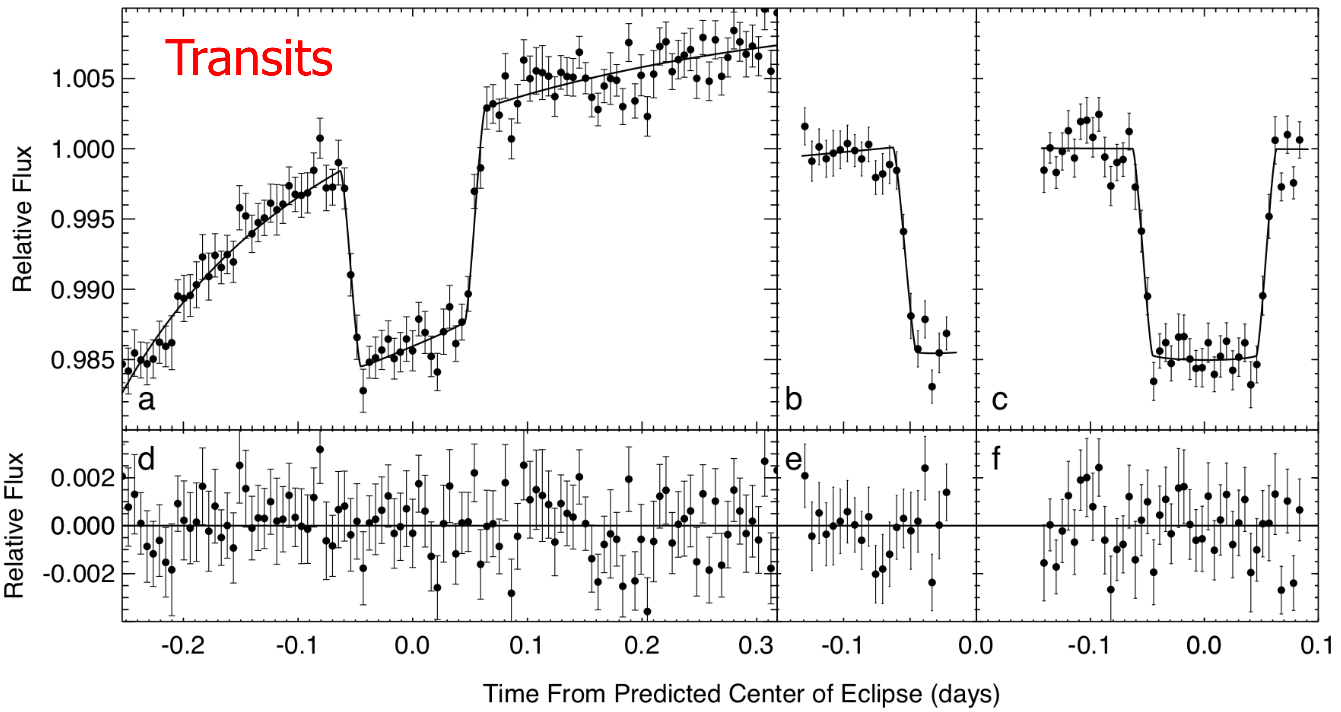
Use simultaneous ground-based optical (b+y) data to characterize behavior of spots during Spitzer observations.

We must also correct for time-dependent detector effects.

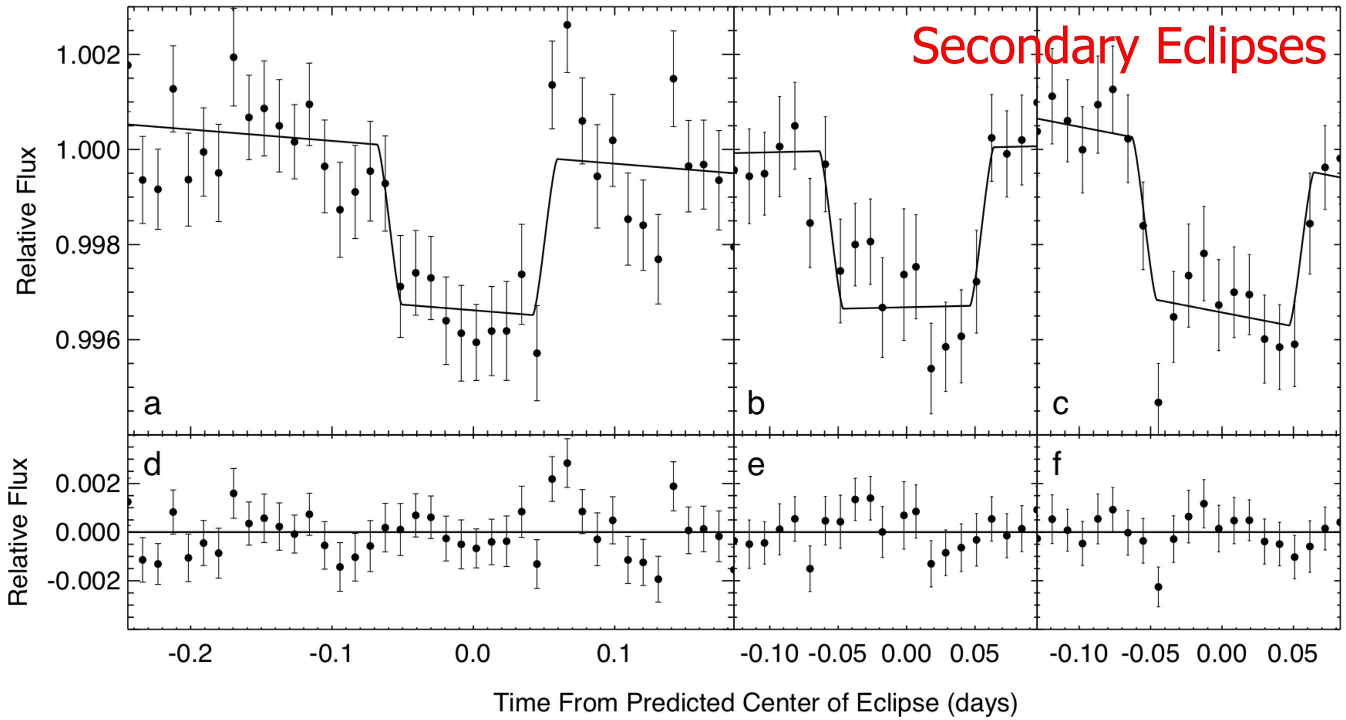


Describe behavior of ramp as a function of illumination level and correct individual pixels accordingly.

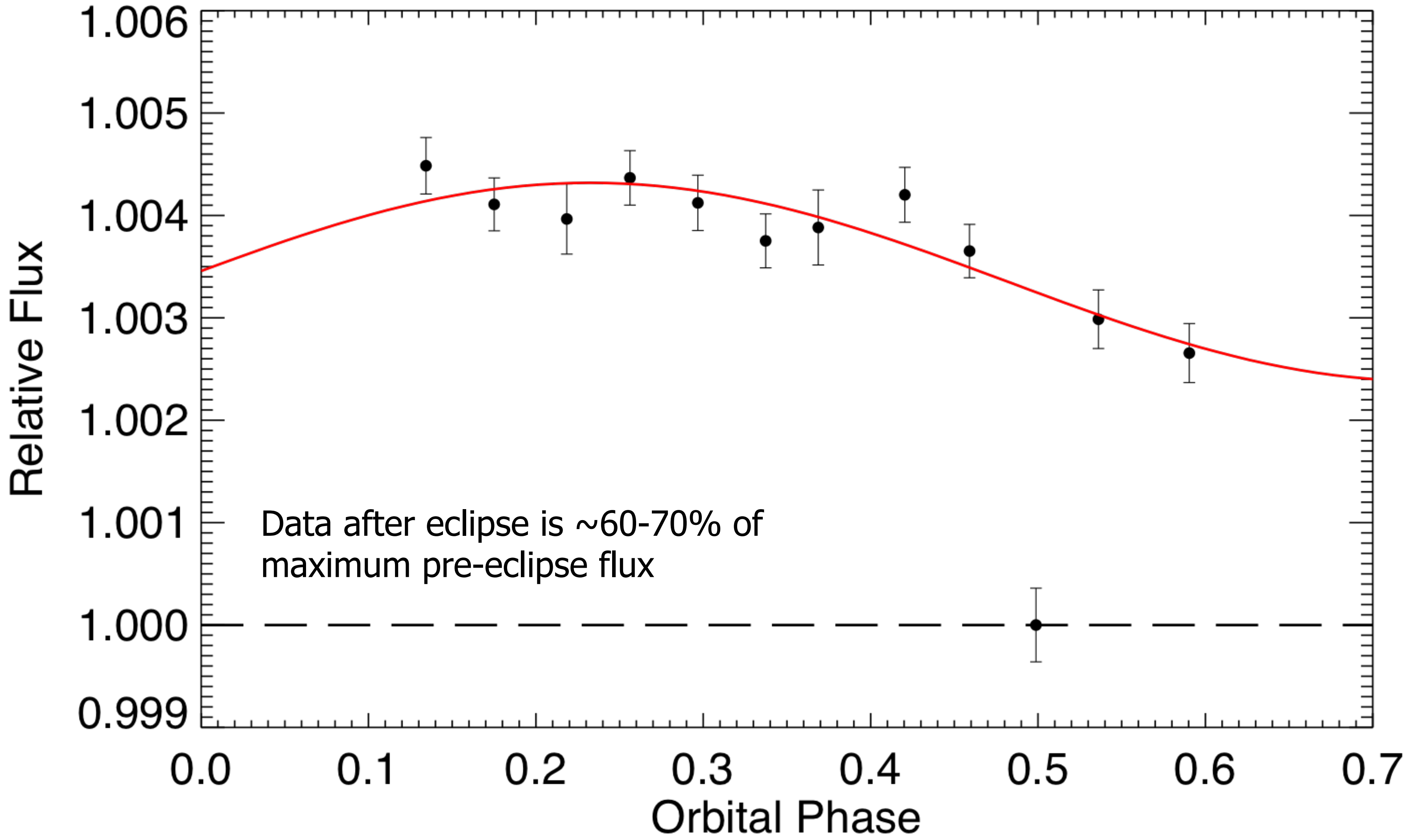
A Survey of Archival HD 209458b Observations



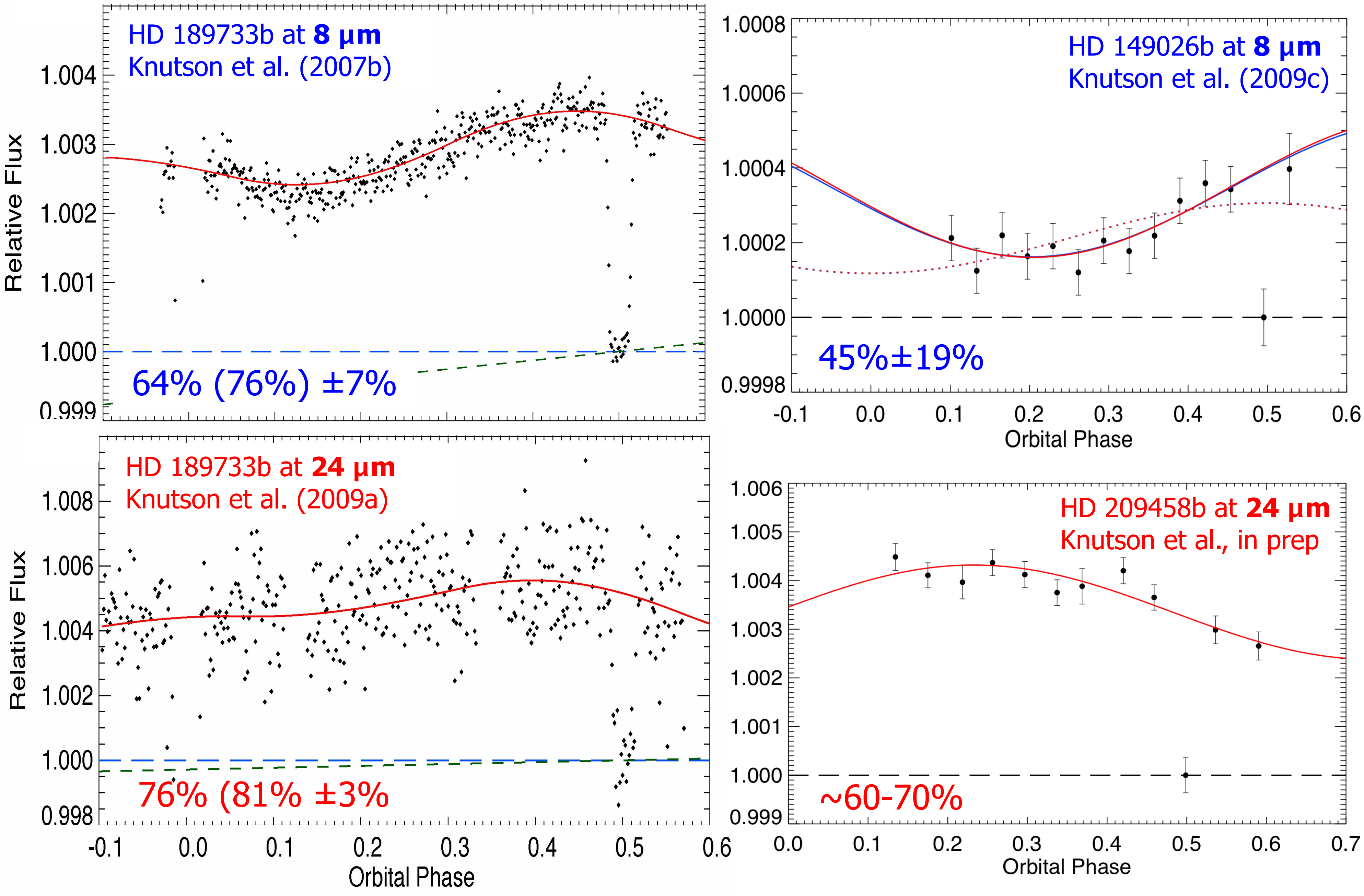
Conclusion: MIPS array is usually (but not always) preflashed by preceding observations.



A 24 μm Phase Curve for HD 209458b



Phase Curve Comparisons



Why Does the Day-Night Circulation Vary Between Planets?

Need a diverse, well-characterized sample for comparison.
Spitzer GO programs 40280, 50056, 60021 (PI H. Knutson)

Dayside stratosphere

HD 209458b
Mass: 0.66 M_{Jup}
Radius: 1.32 R_{Jup}
T_{eqil}=1400 K

Extremely hot

HAT-P-7
Mass: 1.78 M_{Jup}
Radius: 1.36 R_{Jup}
T_{eqil}=2100 K

Benchmark

HD 189733b
Mass: 1.15 M_{Jup}
Radius: 1.15 R_{Jup}
T_{equil}=1100 K

Metal rich

HD 149026b
Mass: 0.36 M_{Jup}
Radius: 0.76 R_{Jup}
T_{equil}=1700 K

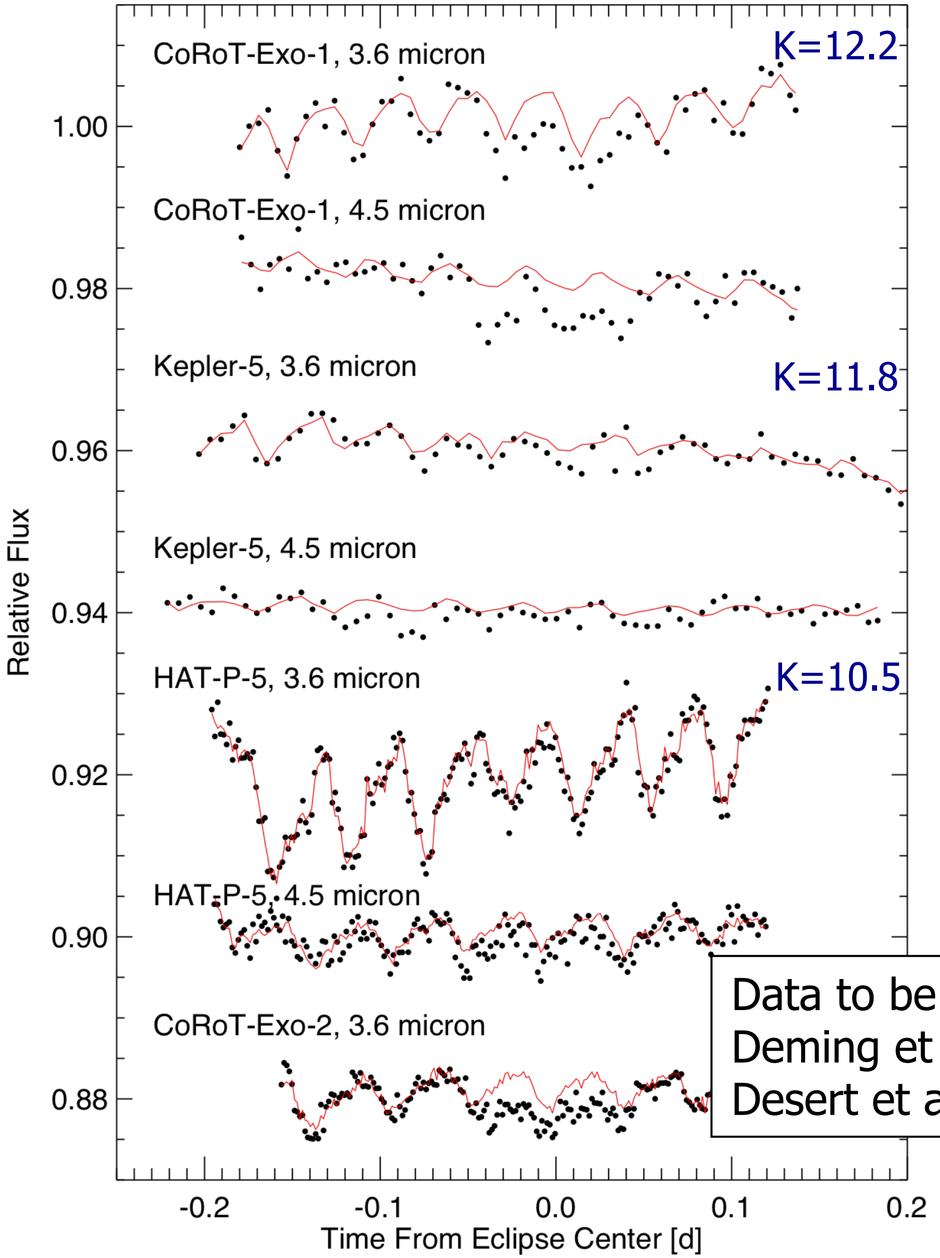
Massive and eccentric

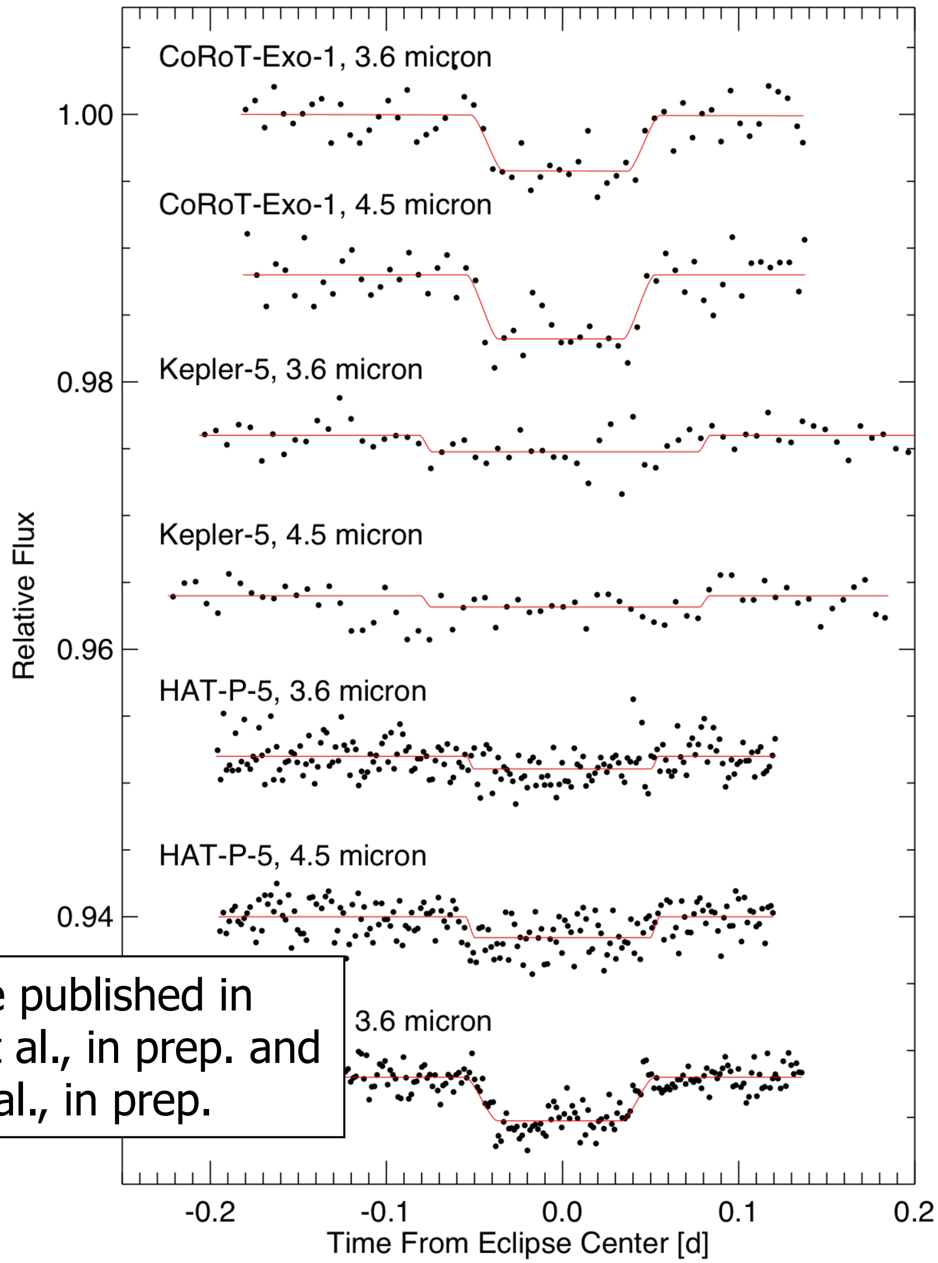
HAT-P-2
Mass: 8.04 M_{Jup}
Radius: 0.98 R_{Jup}
T_{eqil}=1200-2000 K

Small, cool, and eccentric

GJ 436b
Mass: 0.07 M_{Jup}
Radius: 0.44 R_{Jup}
T_{equil}=600-700 K

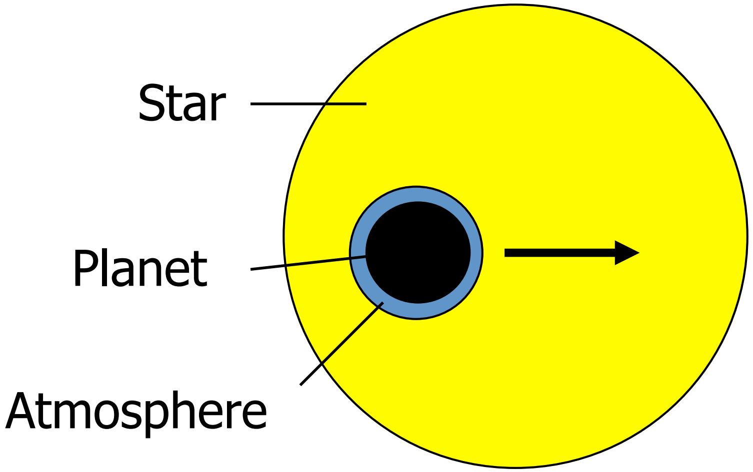
First Warm Mission Data: Four Planets

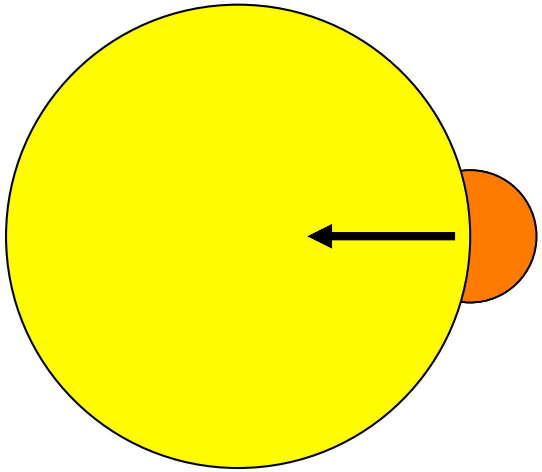




Data to be published in Deming et al., in prep. and Desert et al., in prep.

Does Chemistry Vary With Longitude/Altitude on HD 189733b?





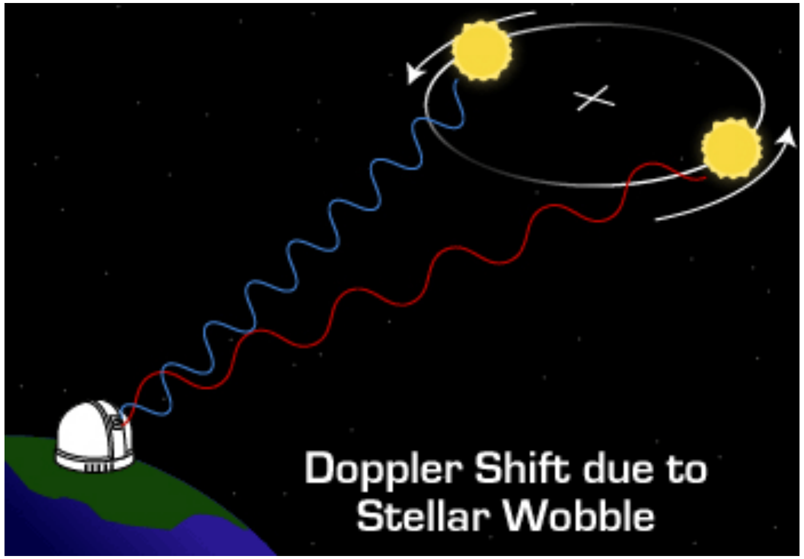
Transmission spectra probe the day-night terminator.

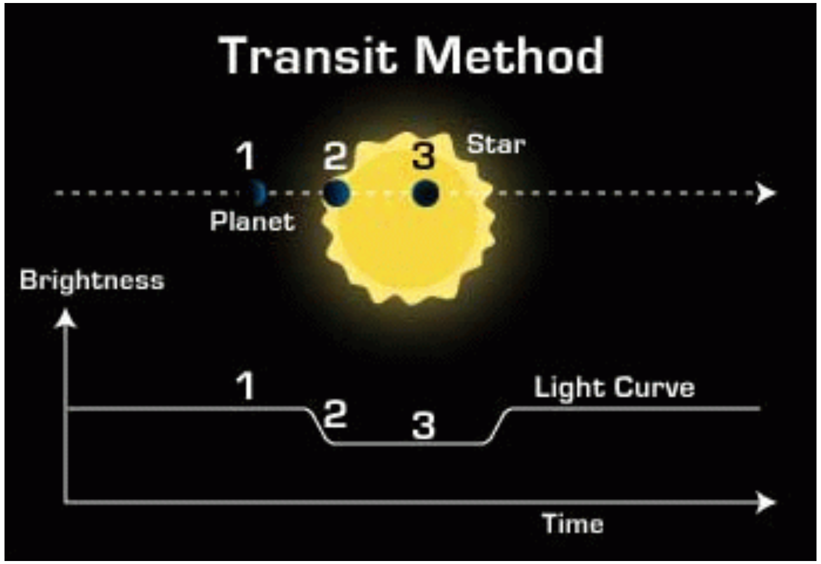
Secondary eclipses tell us about the dayside emission spectrum.

Best-fit abundances:	Best-fit abundances:
H_2O: 5×10^{-4}-0.1	H_2O: 10^{-4}-10^{-3}
CO: unknown	CO: 10^{-4}-10^{-2}
CH_4: 10^{-5}-0.3	CH_4: $<6\times10^{-6}$
CO_2: unknown	CO_2: $\sim7\times10^{-4}$

Madhusudhan & Seager (2009)

Two Commonly Used Methods for Finding & Characterizing Exoplanets





Doppler Method

Determine Planet Mass

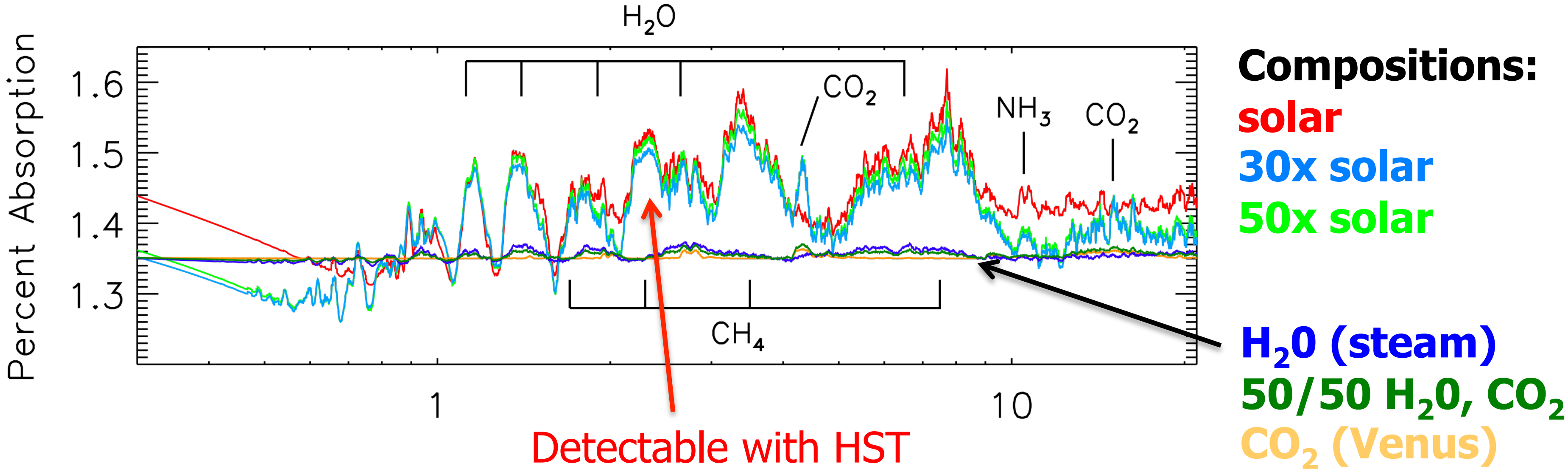
Transit Method

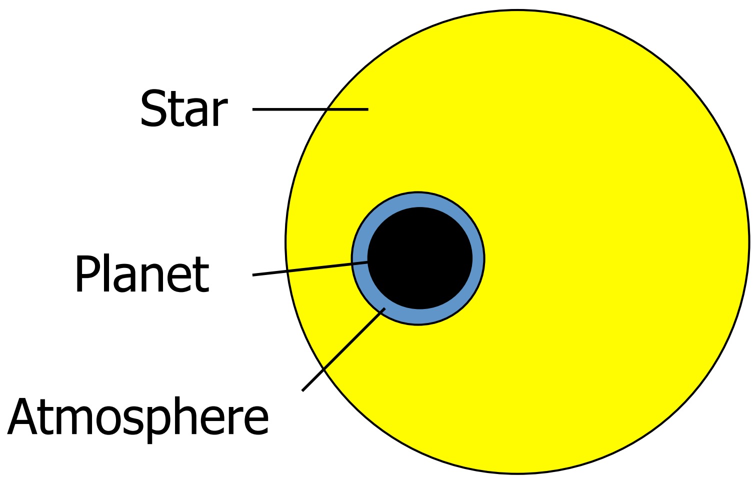
Determine Planet Diameter

Calculate Planet Density and Infer Composition:

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

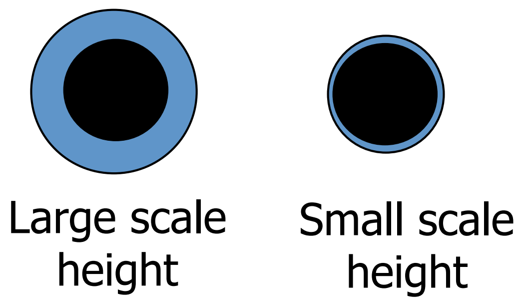
Determining the Composition of GJ 1214b's Atmosphere





Scale Height

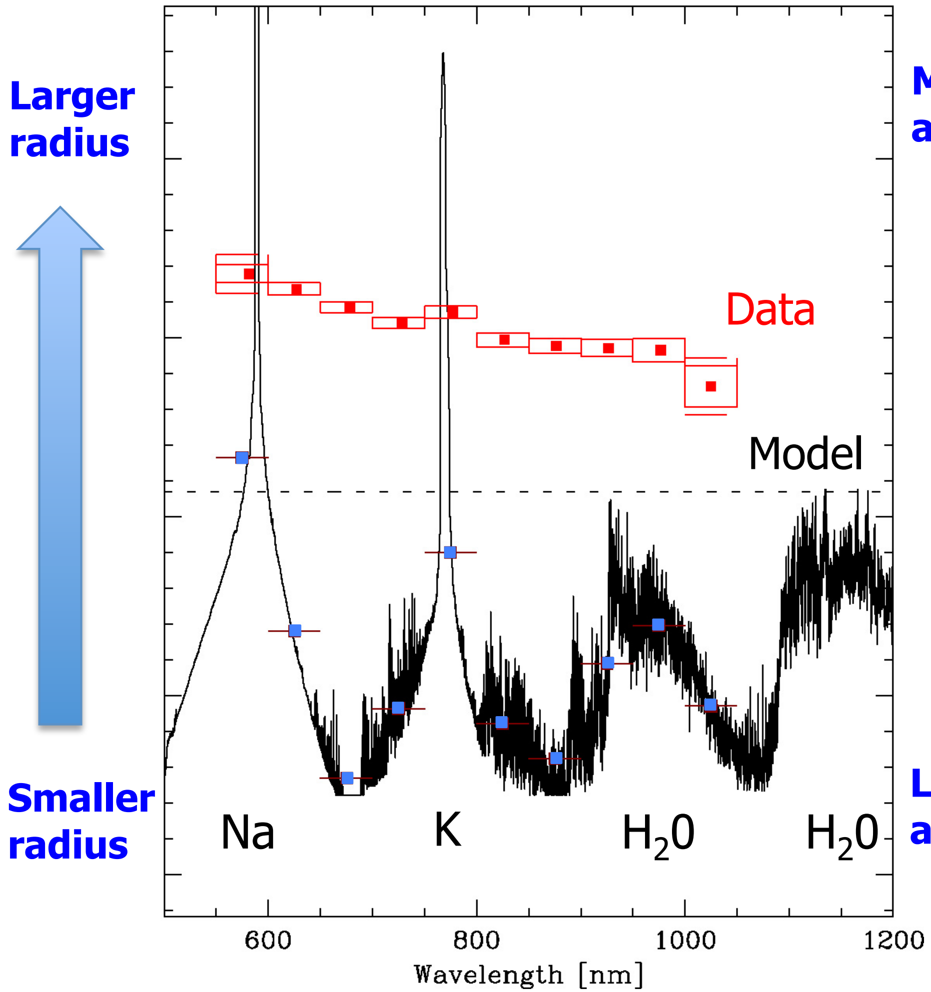
$$H = \frac{kT}{g\mu}$$



Miller-Ricci & Fortney (2010)

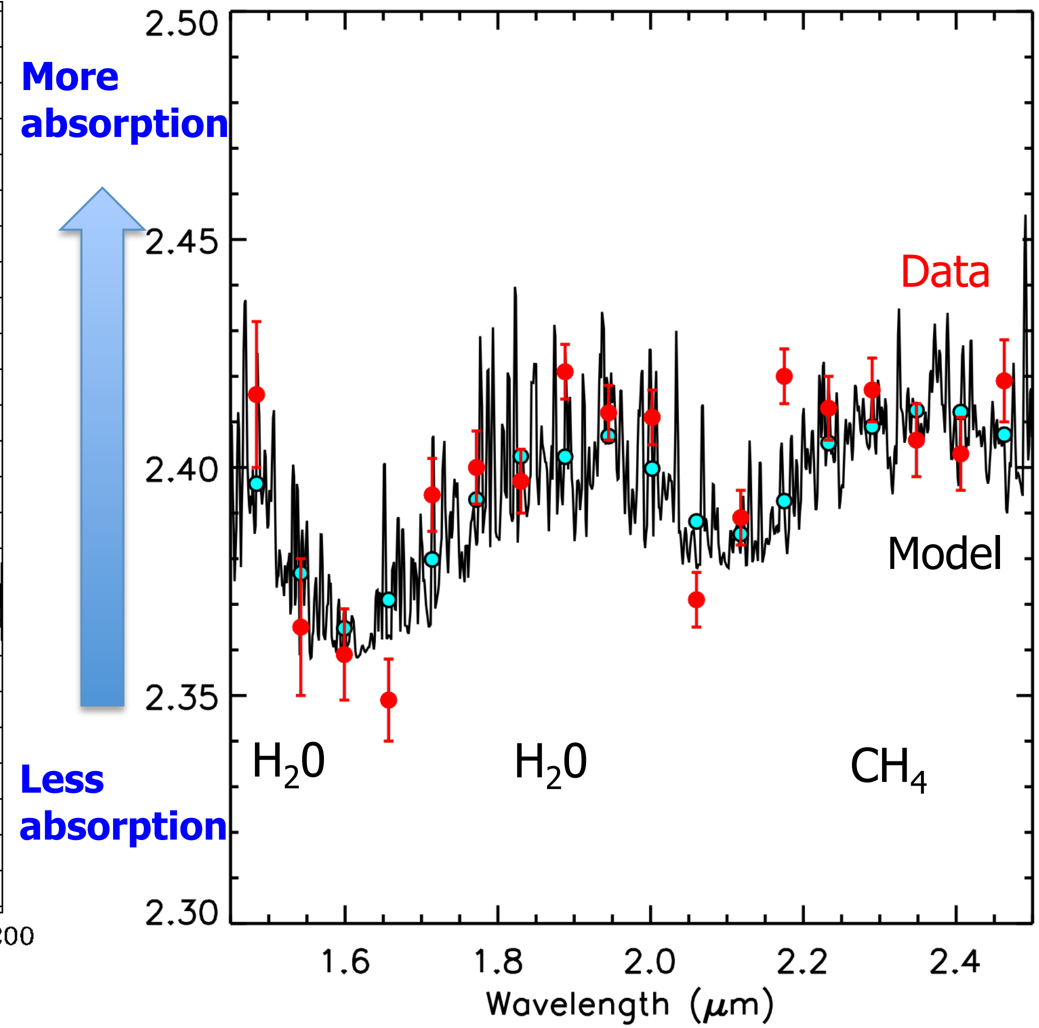
Water and Haze on HD 189733b

Featureless visible light spectrum indicates hazes…



Pont, Knutson et al. (2007) Hubble Space Telescope ACS observations of HD 189733.

… which disappear in infrared, revealing water and methane absorption features.



Swain et al. (2008) Hubble NICMOS observations, model from Madhusudhan & Seager (2009)