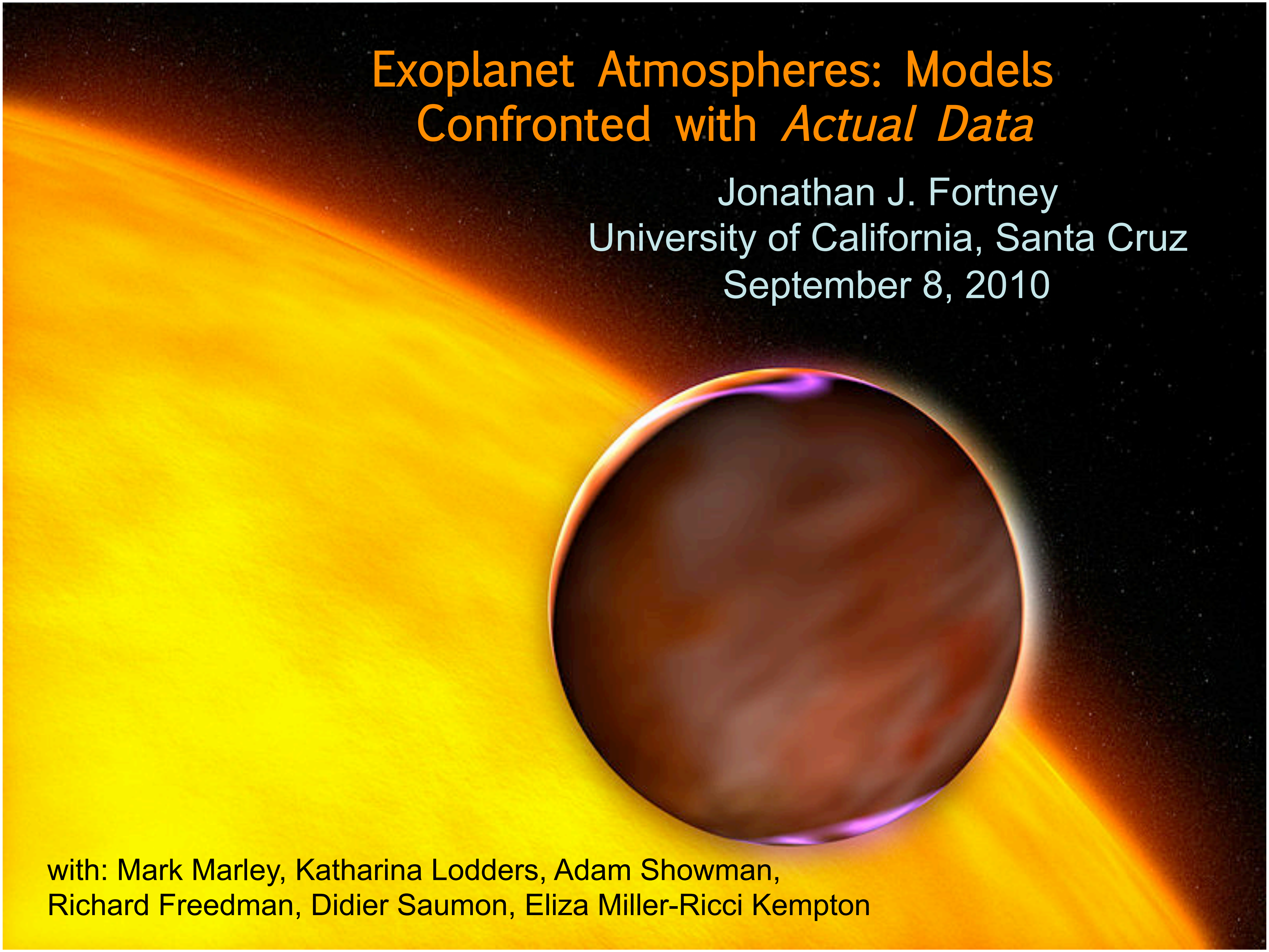
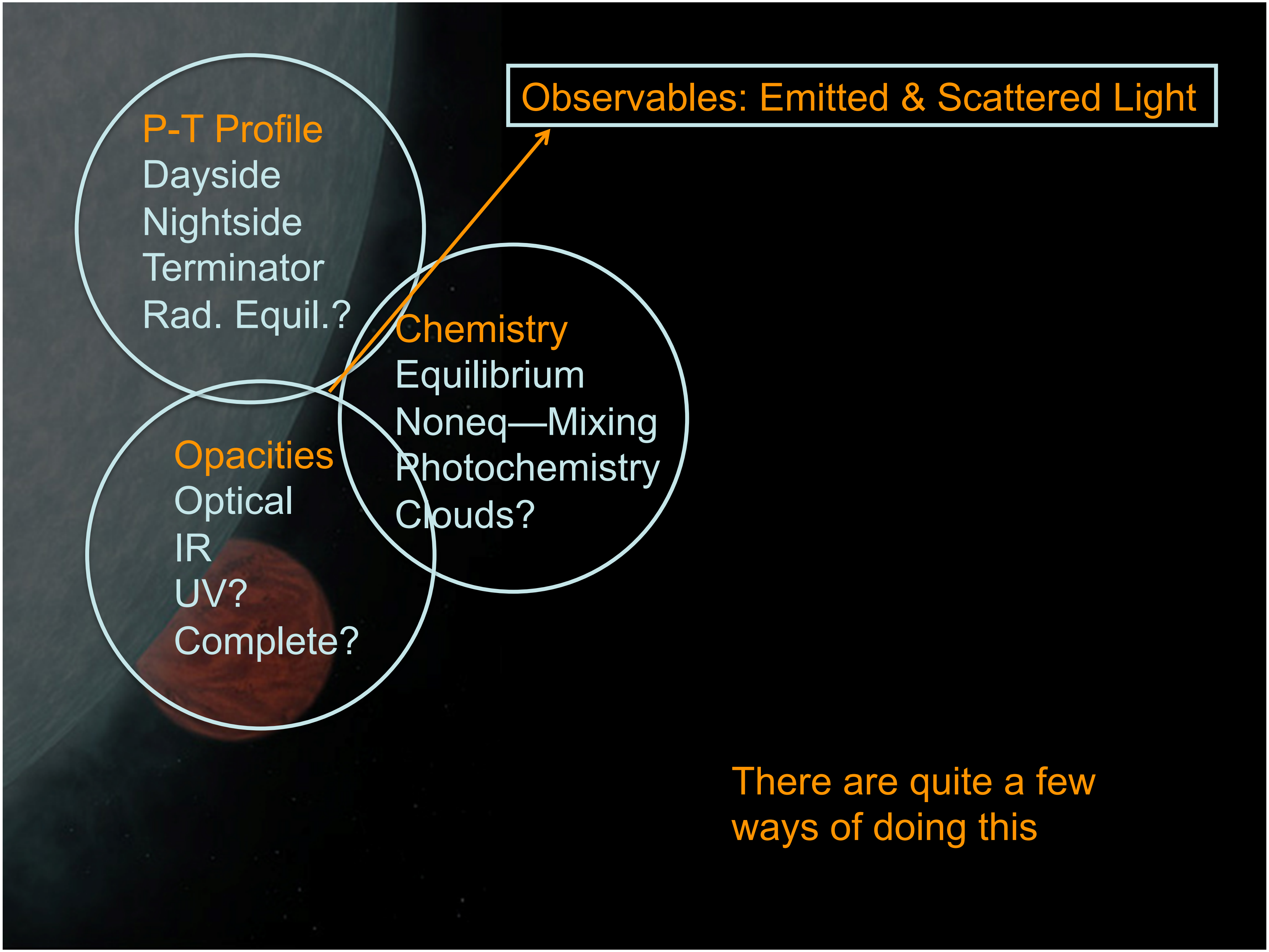


Exoplanet Atmospheres: Models
Confronted with *Actual Data*
Jonathan J. Fortney
University of California, Santa Cruz
September 8, 2010
with: Mark Marley, Katharina Lodders, Adam Showman,
Richard Freedman, Didier Saumon, Eliza Miller-Ricci Kempton

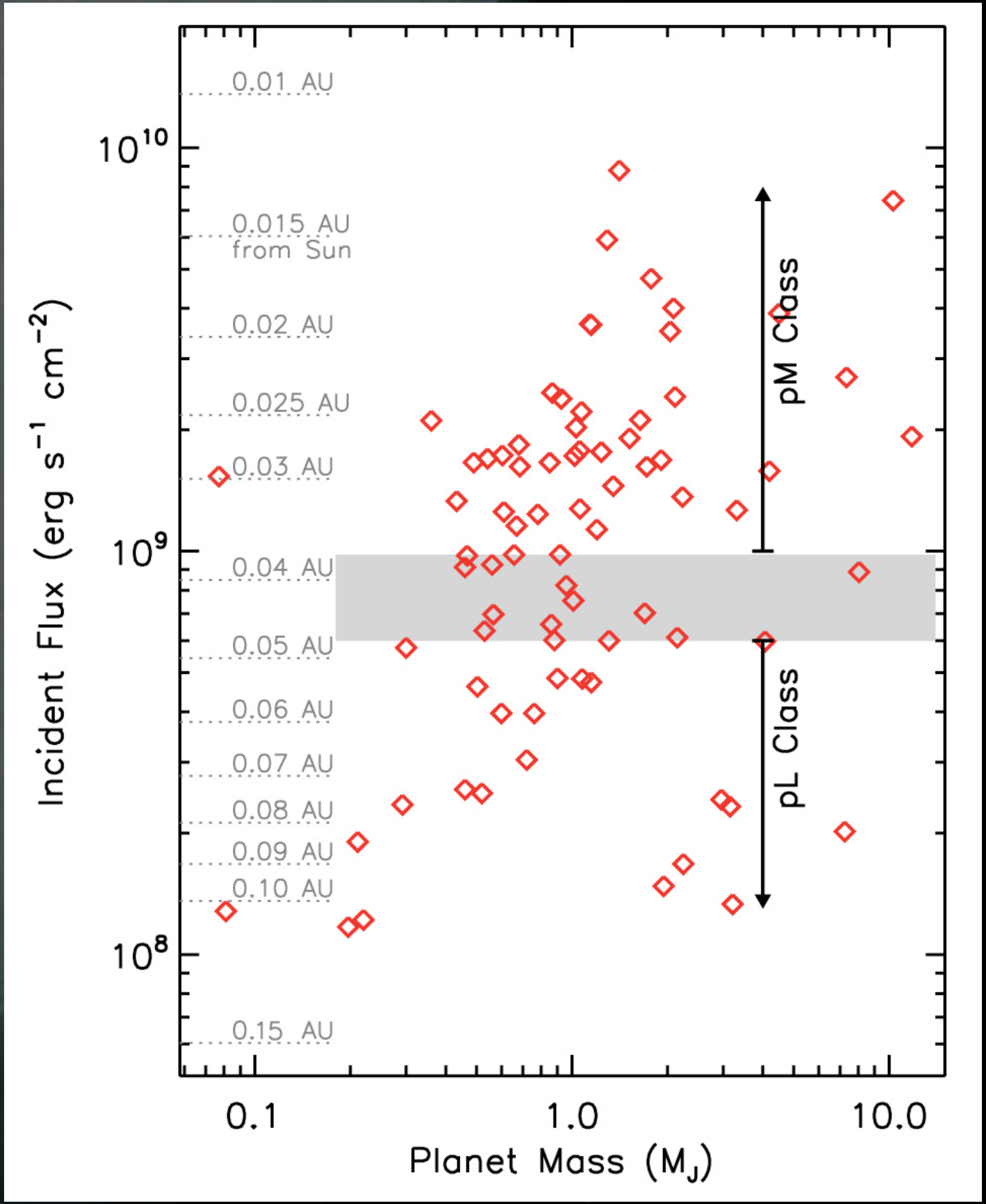
Modeling Atmospheres: What are the Goals?

- Formation: Do the atmospheres of exoplanets have abundance patterns similar to those in our solar system?
    - Jupiter: ~3X solar, Saturn: ~10X solar (in C and P)
    - Uranus & Neptune ~50X solar in methane
    - Hot planets give us unprecedented access to H_2O, CO, CO_2, NH_3

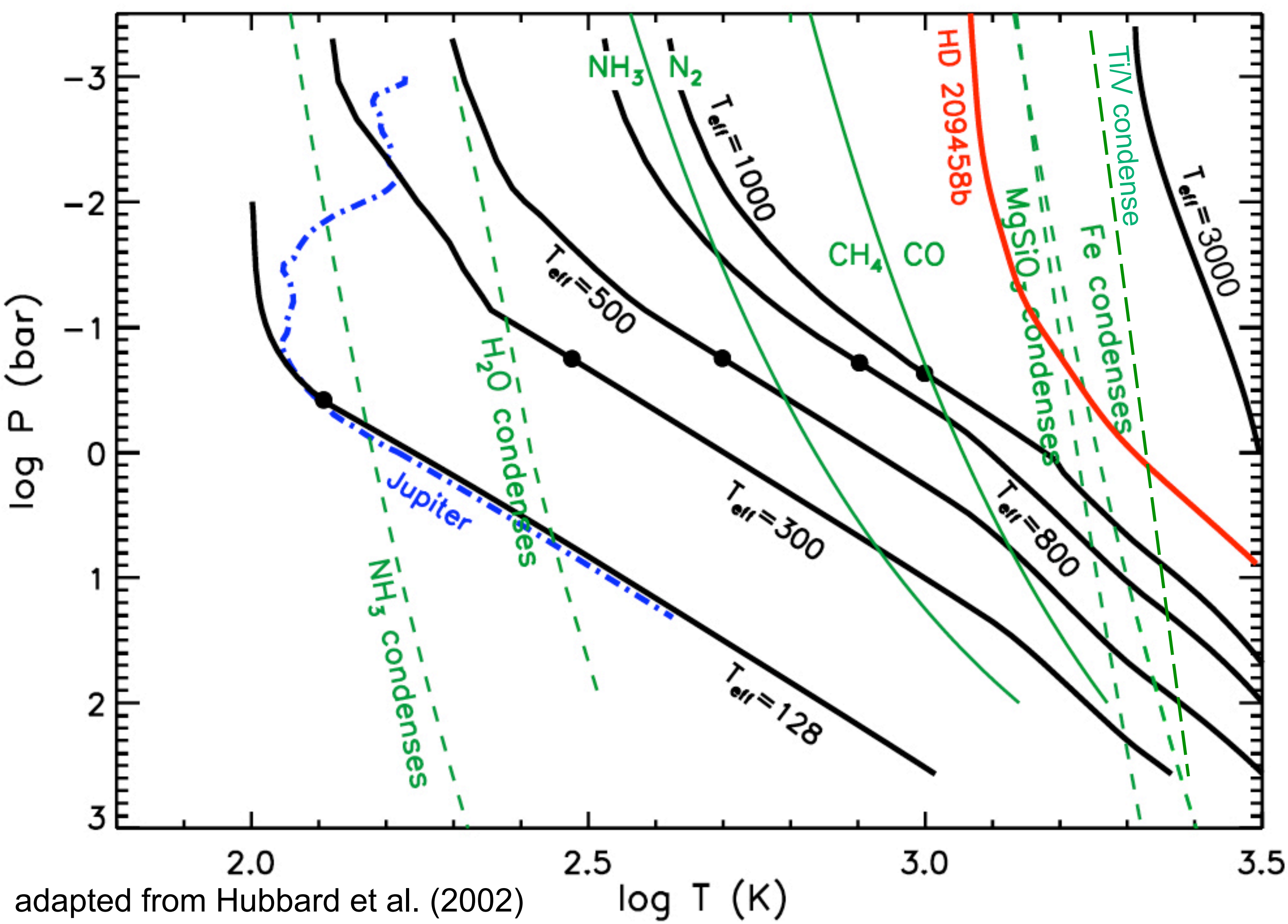
- Atmospheric physics and chemistry: Can we link common processes?
    - Formation of temperature inversions
    - Day/night temperature contrast


Observables: Emitted & Scattered Light
P-T Profile
Dayside
Nightside
Terminator
Rad. Equil.?
Chemistry
Equilibrium
Noneq—Mixing
Photochemistry
Clouds?
Opacities
Optical
IR
UV?
Complete?
There are quite a few ways of doing this

What is a "hot Jupiter"?



Diversity!

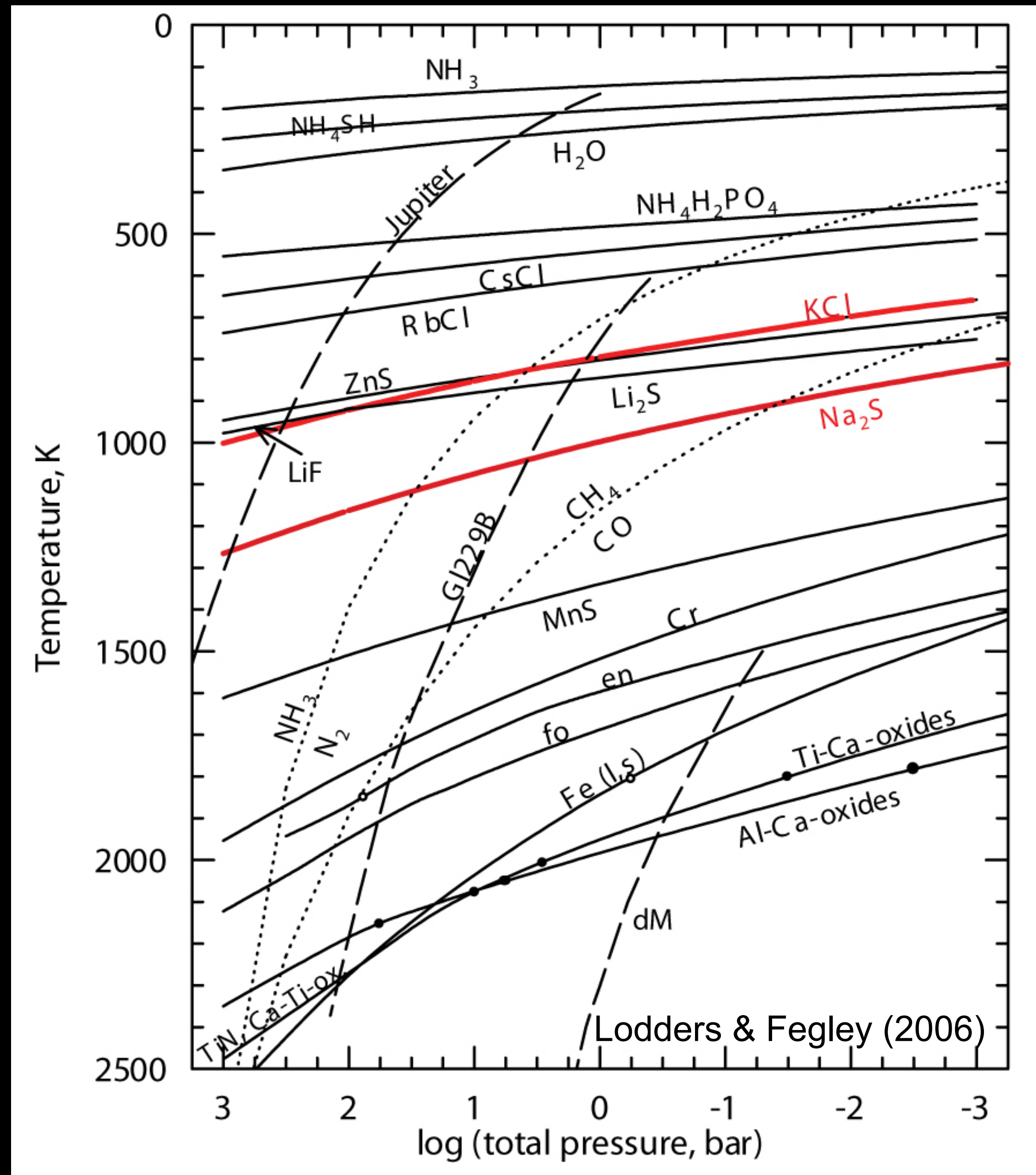


adapted from Hubbard et al. (2002)

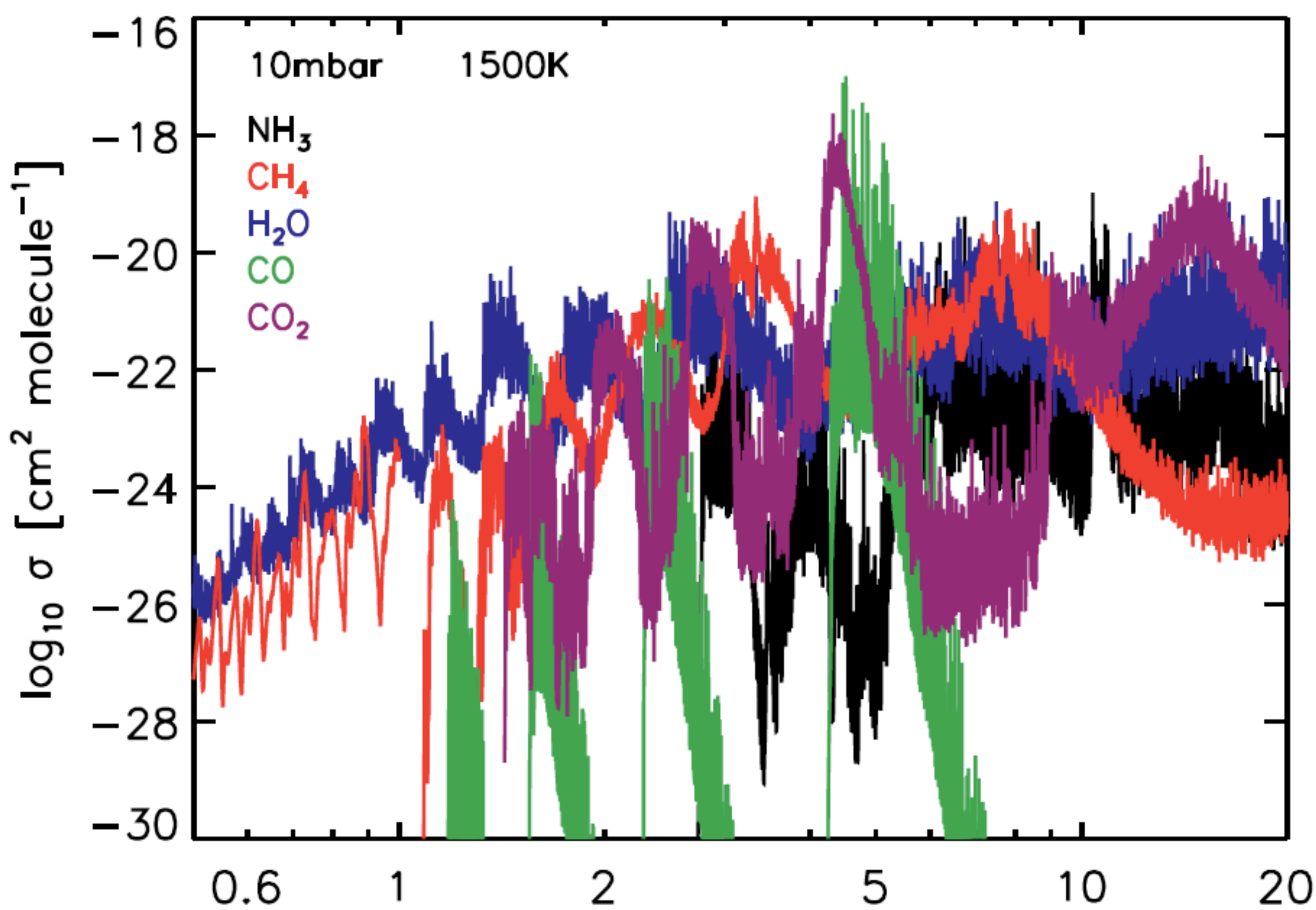
Pressure-Temperature (*P*-*T*) profiles from Jupiter to a 3000K M dwarf star

Equilibrium chemical abundances over a wide range of P and T

The important species:
(probably)
H_2O
CO
CO_2
CH_4
N_2
Na
K
TiO
Fe+silicate clouds

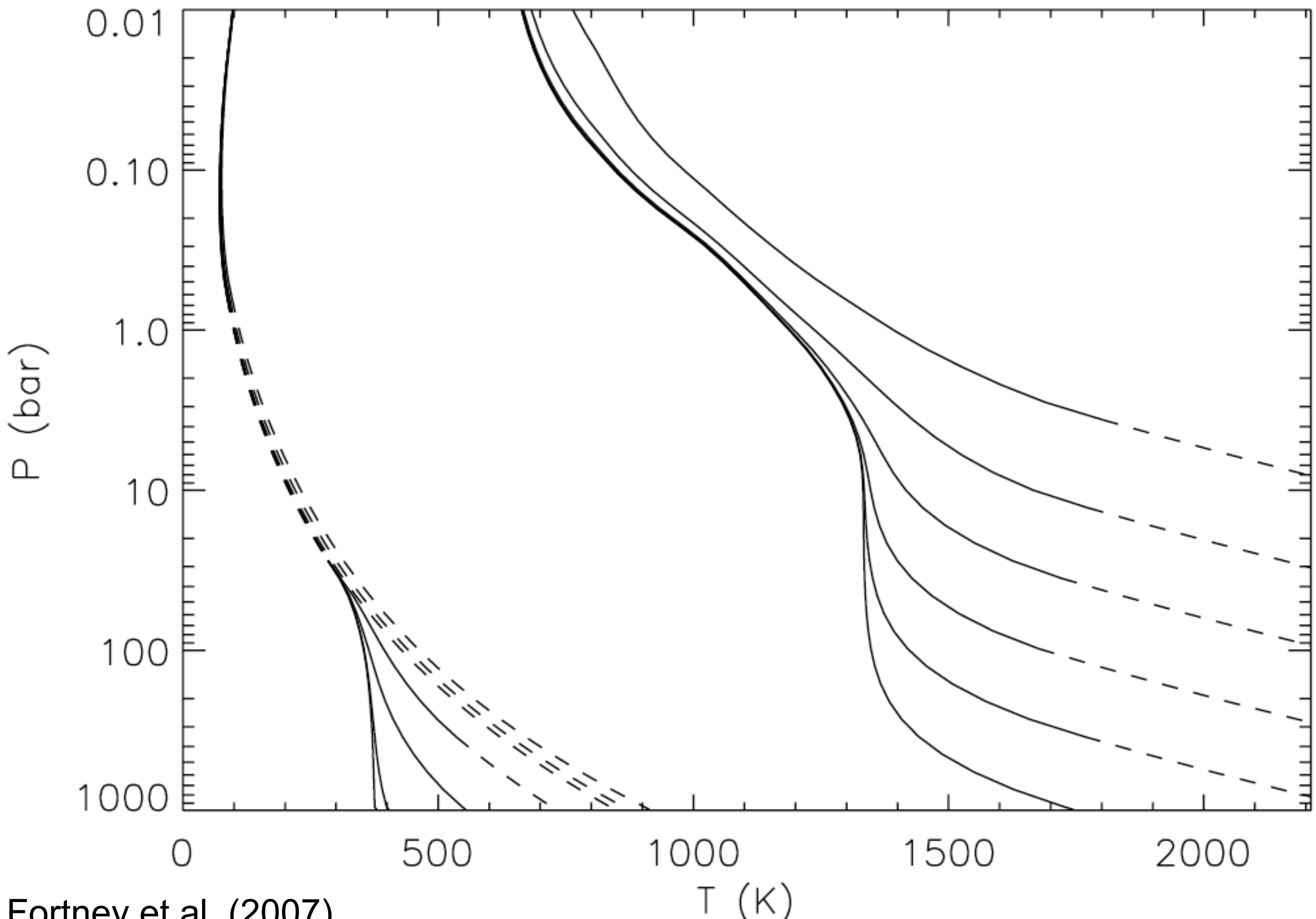


Absorption cross-sections per molecule



Shabram, Fortney, et al. (2010)

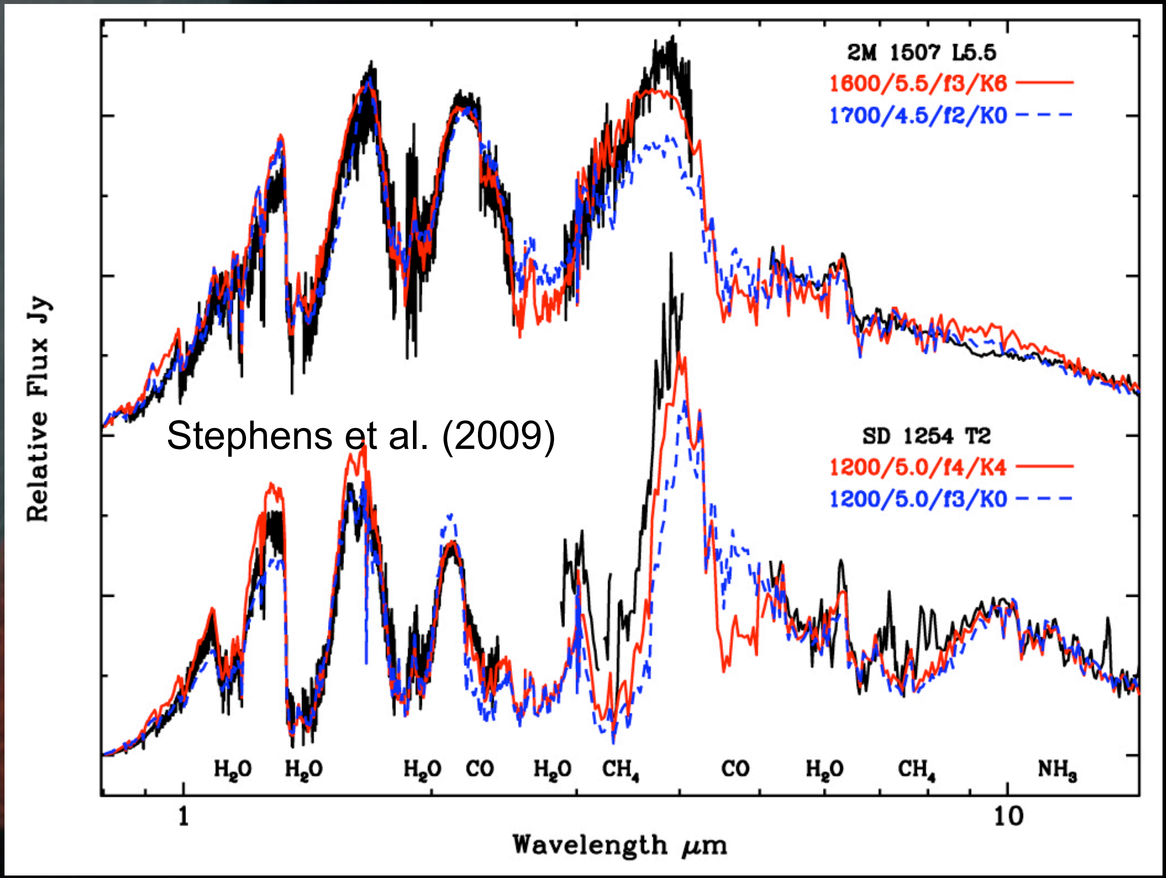
Hot Jupiters: Fully Radiative Atmospheres



Fortney et al. (2007)

Nice analytical work: Hansen (2008) and Guillot (2010)

There is some reason to expect that we might know what we're doing…



…but then there is the uneven irradiation (in space and time), the photochemistry, the (likely) non-solar abundances… so, we'll see.

Many Different Ways of Doing This…

P-T in radiative equilibrium, equil. chemistry

Fortney + Marley et al. (2005, 2006, 2008)
Sudarsky et al. (2003)
Burrows et al. (2005, 2006)
Barman et al. (2005, 2007)
Seager et al. (2005)

P-T from 3D models

Fortney & Showman (2006-2010)
Burrows + Rauscher et al. (2010)

P-T in rad equil, plus knobs

Burrows + Spiegel et al. (2008-2010)

Non-Equil Chemistry

Vertical Mixing: Cooper & Showman & Fotney (2006)
Madhu & Seager (2010)
Photochem: Stay tuned: Kempton, Moses, Zahnle

P-T and chemistry free to roam

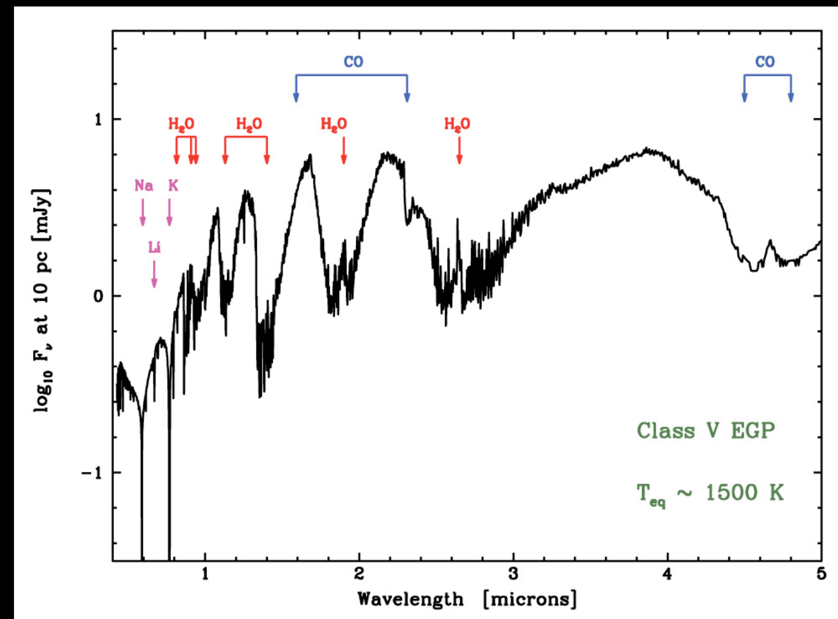
Madhu & Seager (2009, 2010)
Tinetti & Griffith (2007-2010)

Hot Jupiters: The Expectations

- Low Bond Albedos

- Dark in the optical due to Na, K, maybe TiO
- Maybe some are reflective, *if* silicate clouds are important

- Infrared: H_2O, CO opacity carve the spectrum



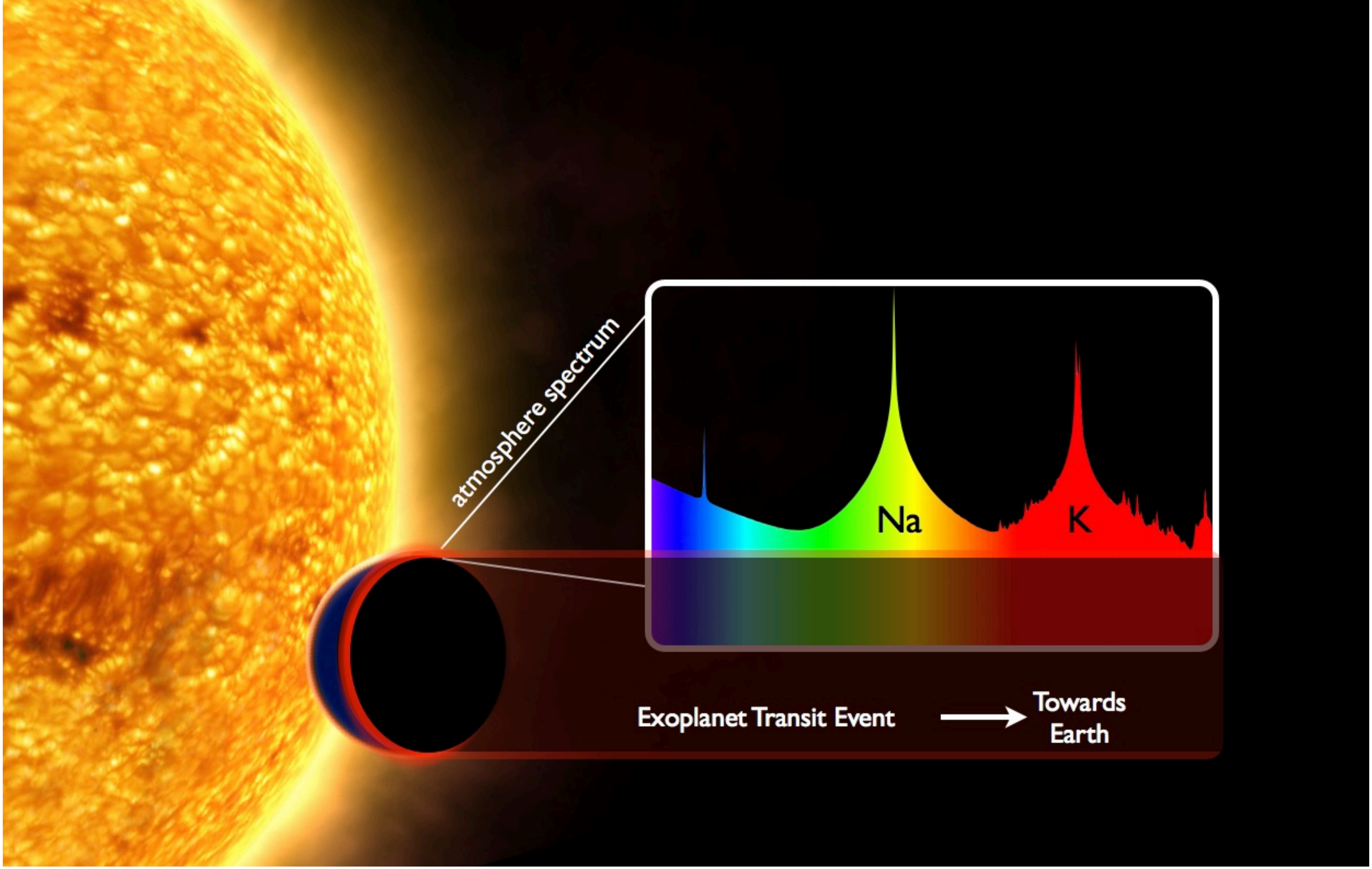
Sudarsky et al. (2003)

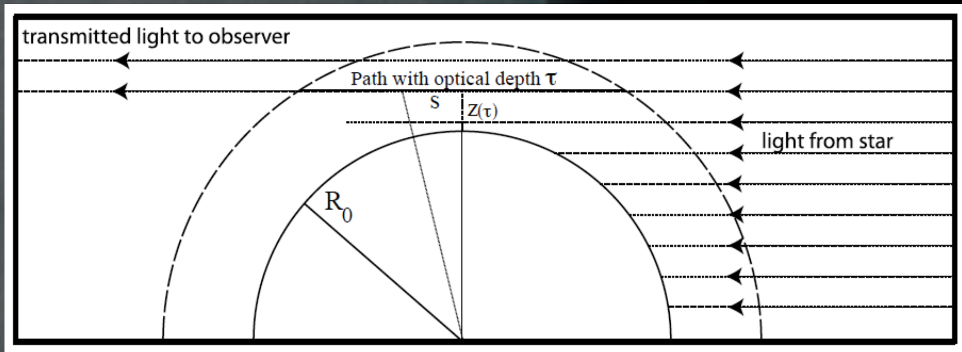
Hot Jupiters: The Reality

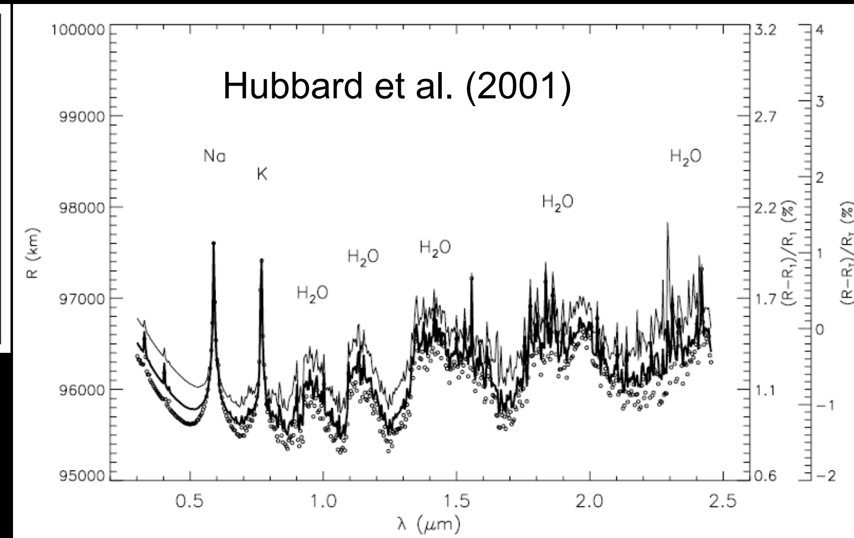
- Some Evidence for Low Bond Albedos
- Dark in the optical due to Na, K, maybe TiO
- Maybe some are reflective, *if* silicate clouds are important

- Infrared: Observations are consistent with H_2O, CO opacity carving the spectrum

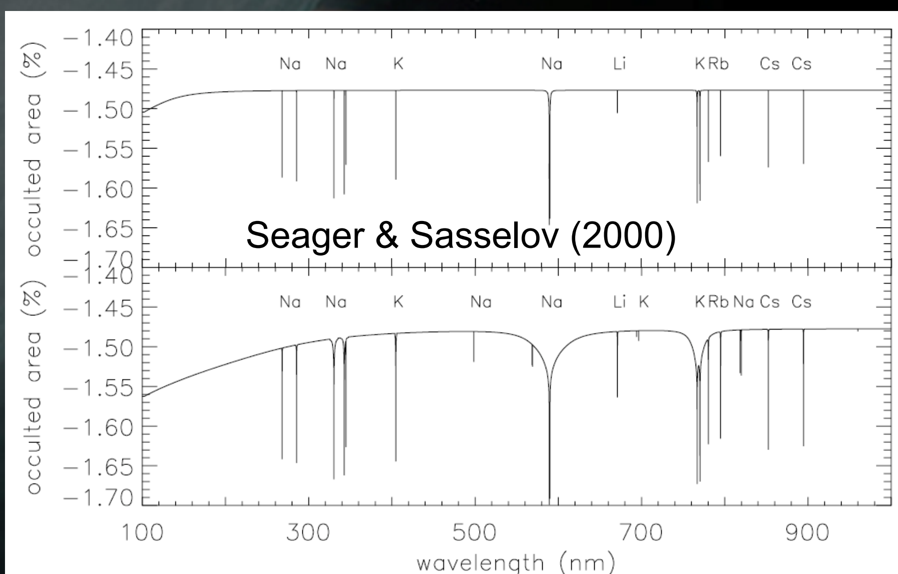
Transmission Spectra: Conditions at the Terminator

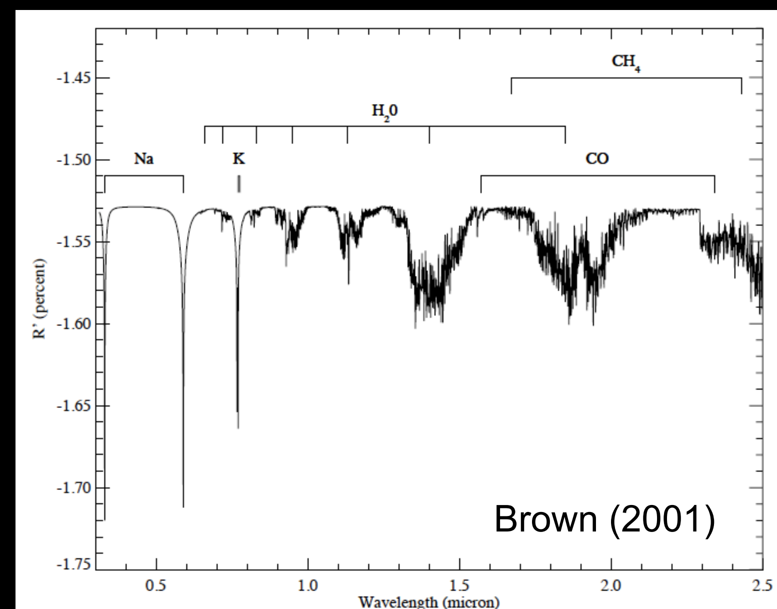




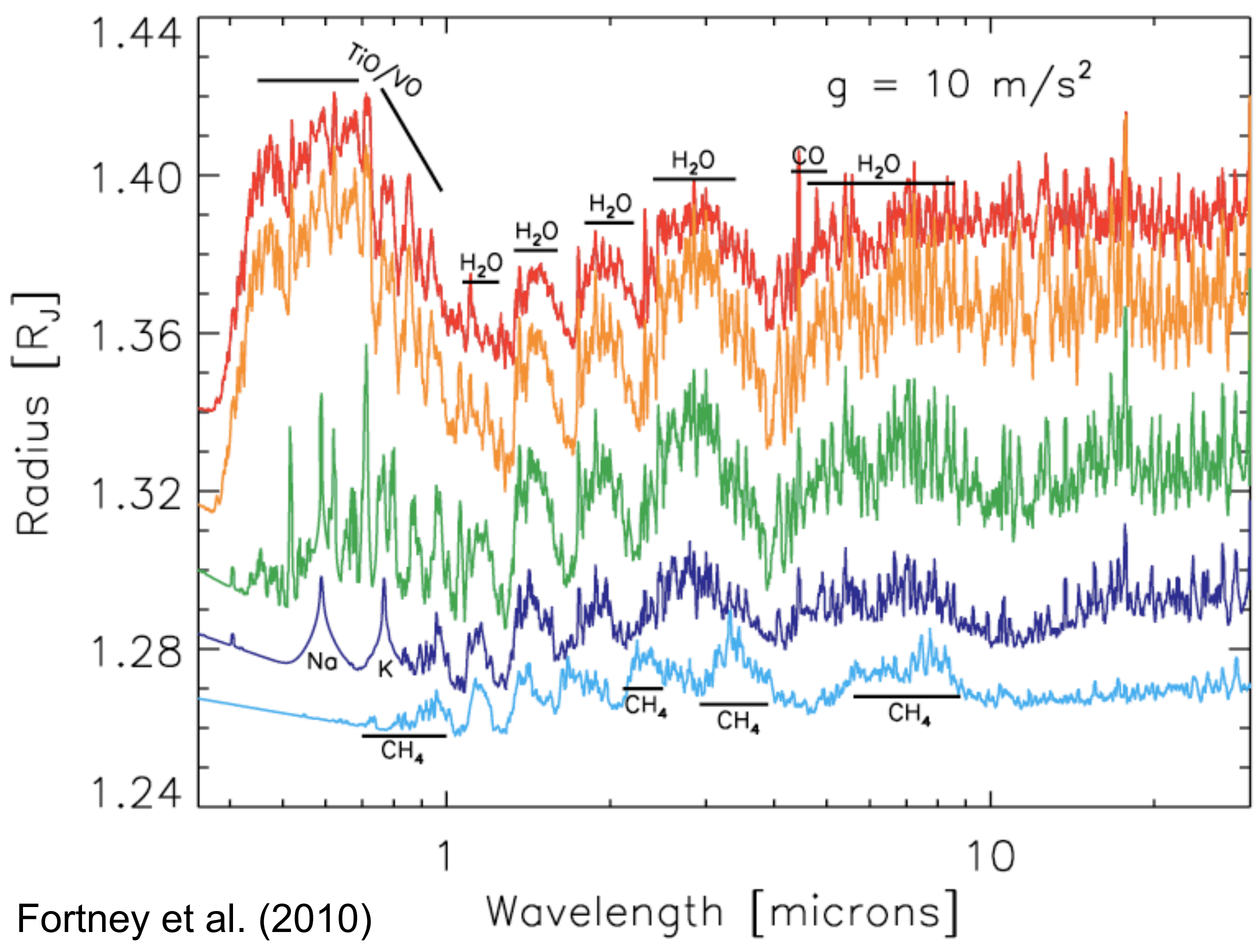


Model Transmission Spectra, 2000-01

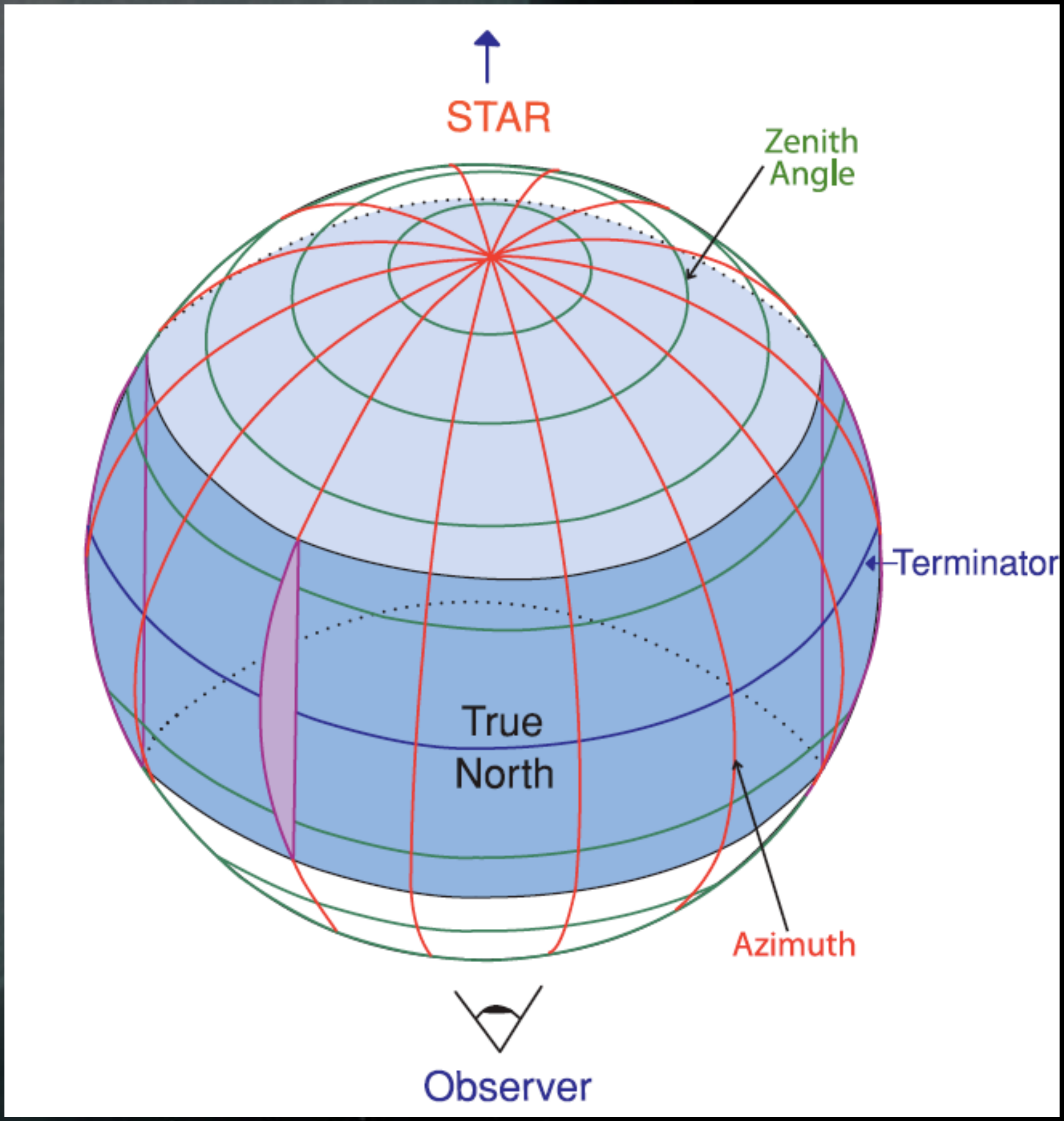




Na, K, H_2O, CO, TiO, VO



Fortney et al. (2010)

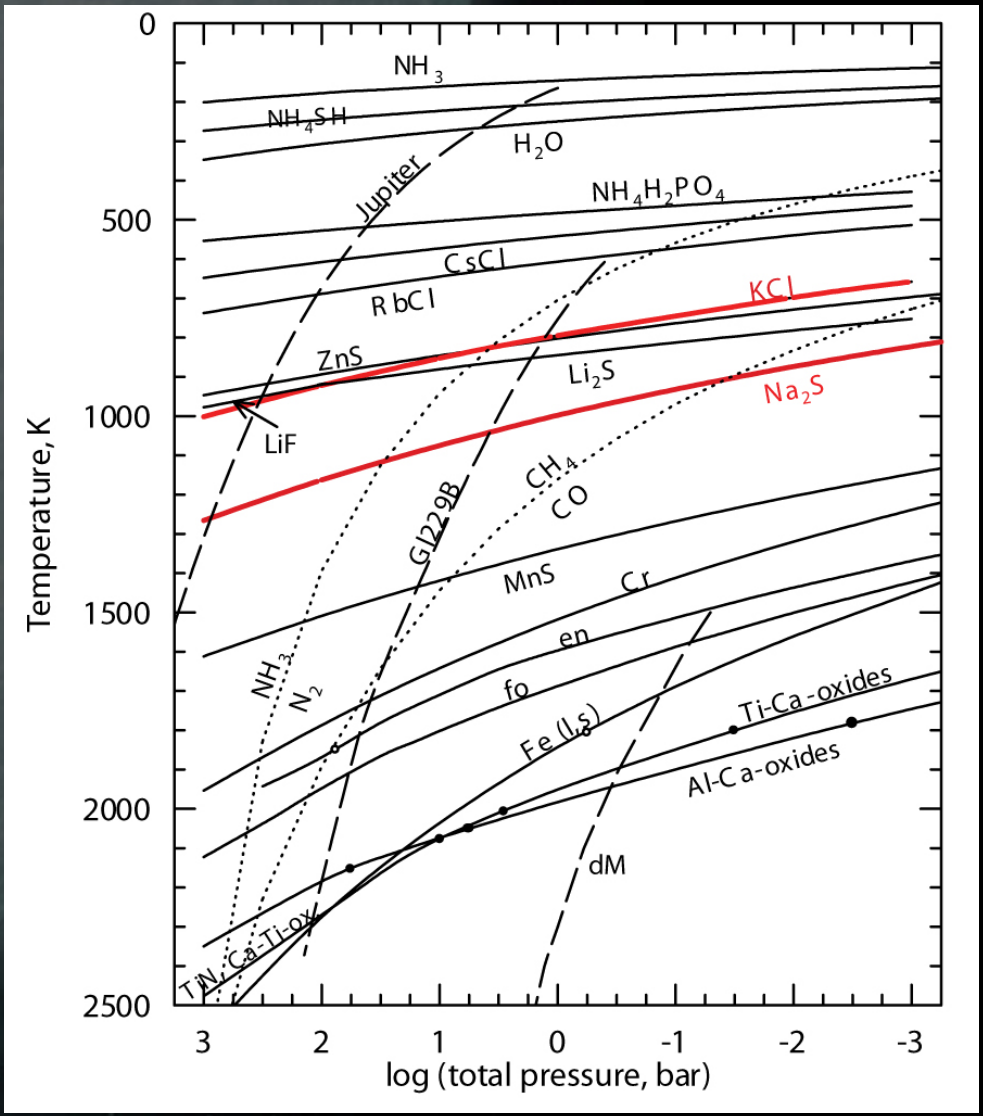


Fortney et al. (2010): Transmission spectra of the Showman et al. (2009) 3D GCM models of HD 209458b and HD 189733b

An effort to better understand the terminator region

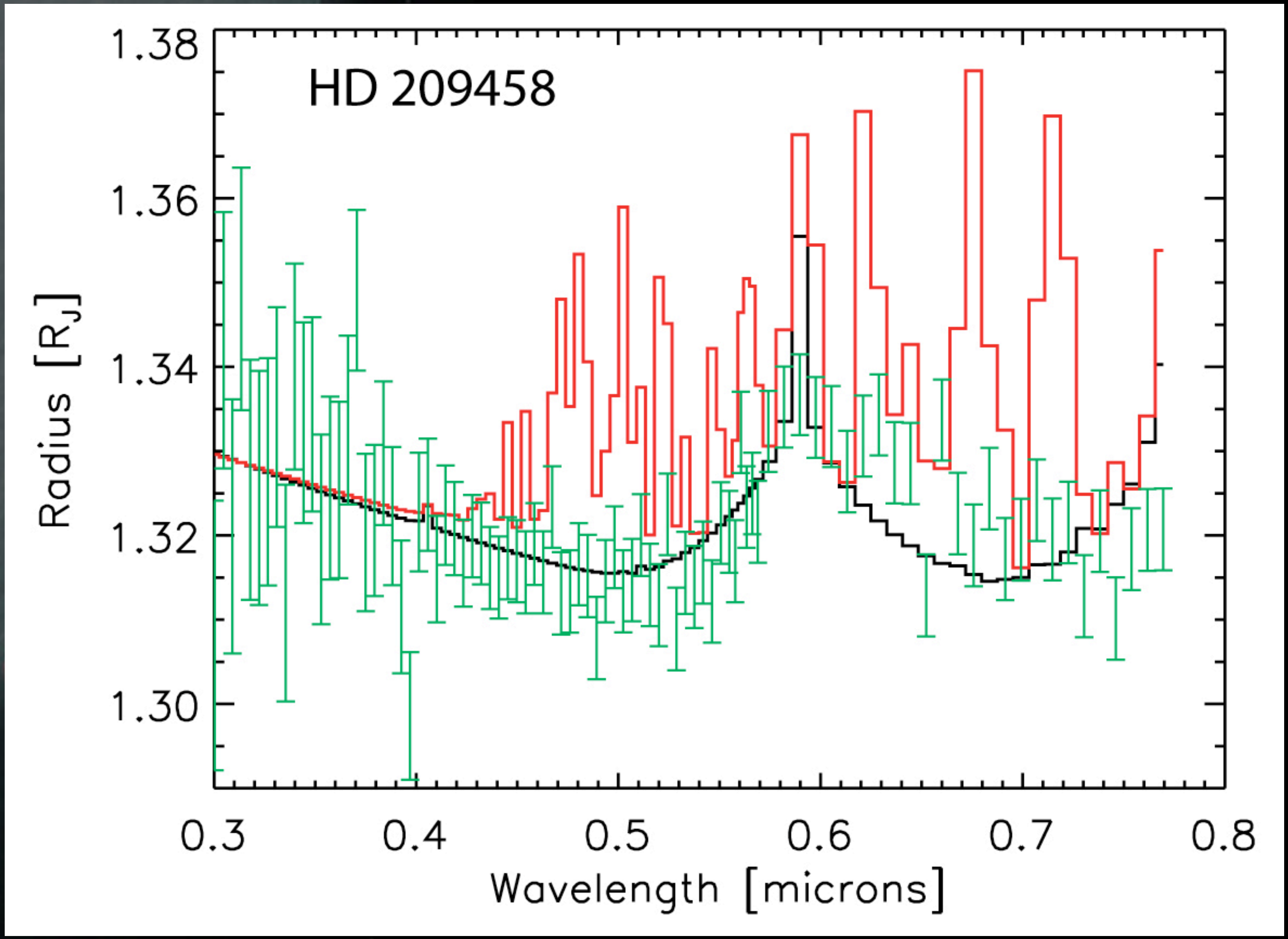
See also Burrows et al. (2010), Dobbs-Dixon et al. (in prep).

Lodders & Fegley (2006)



Alkalis should be present down to ~1000 K

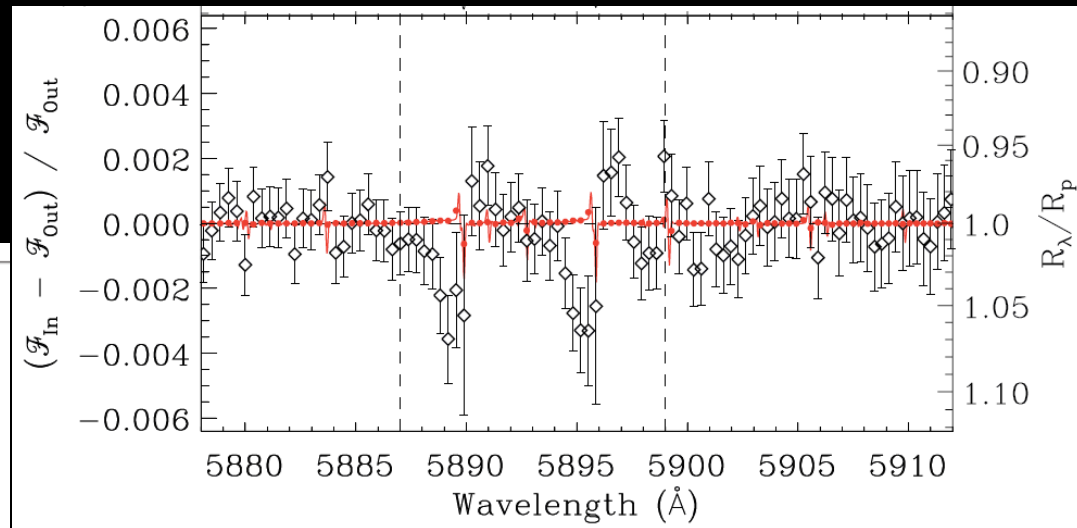
HD 209458b: Transmission Models Compared to Data



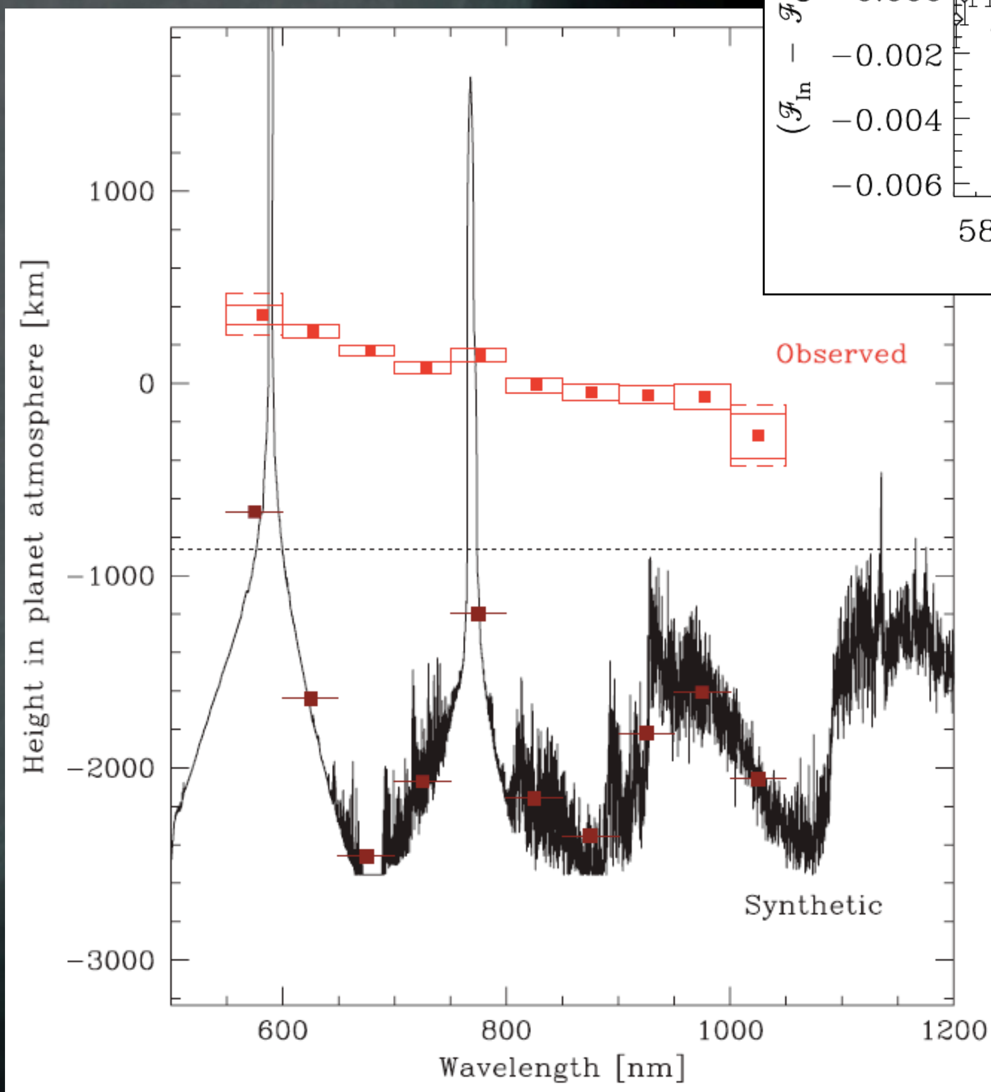
Fortney et al. (2010)

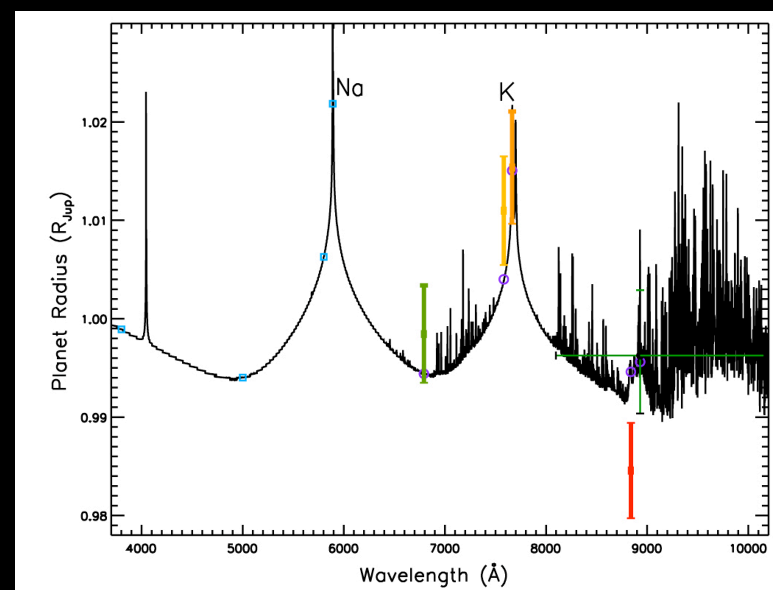
data from Sing et al. (2008)

More Na, and K



Redfield et al. (2008)





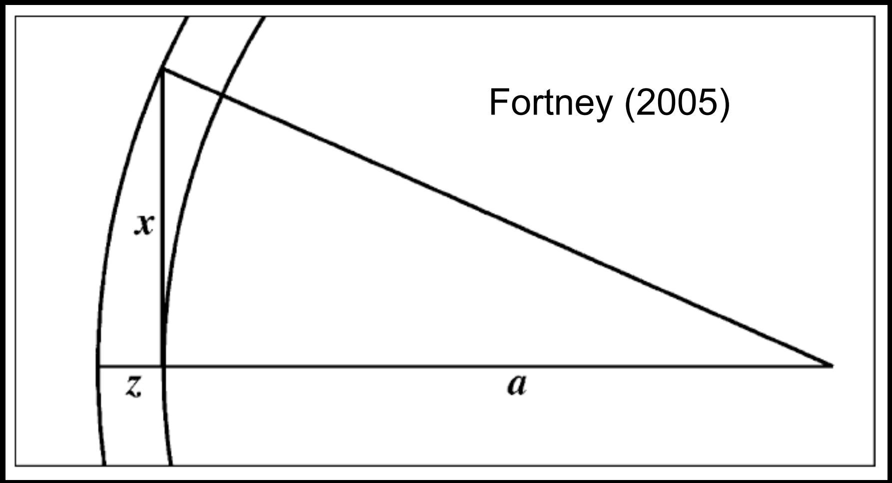
Sing et al. (2010)

Pont et al. (2008)

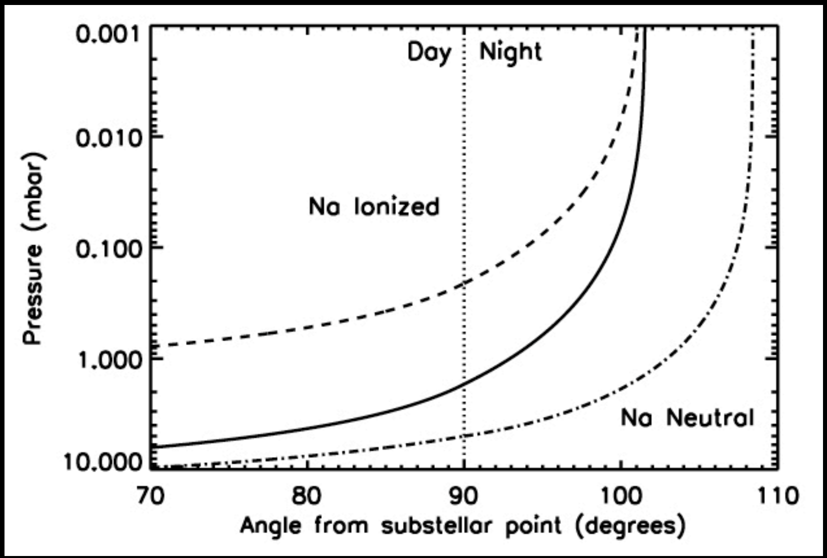
Alkalis in Transmission

Na: some evidence for weakening, relative to models. Alkali metals are easy to photo-ionize. Also, minor clouds species can obscure absorption features

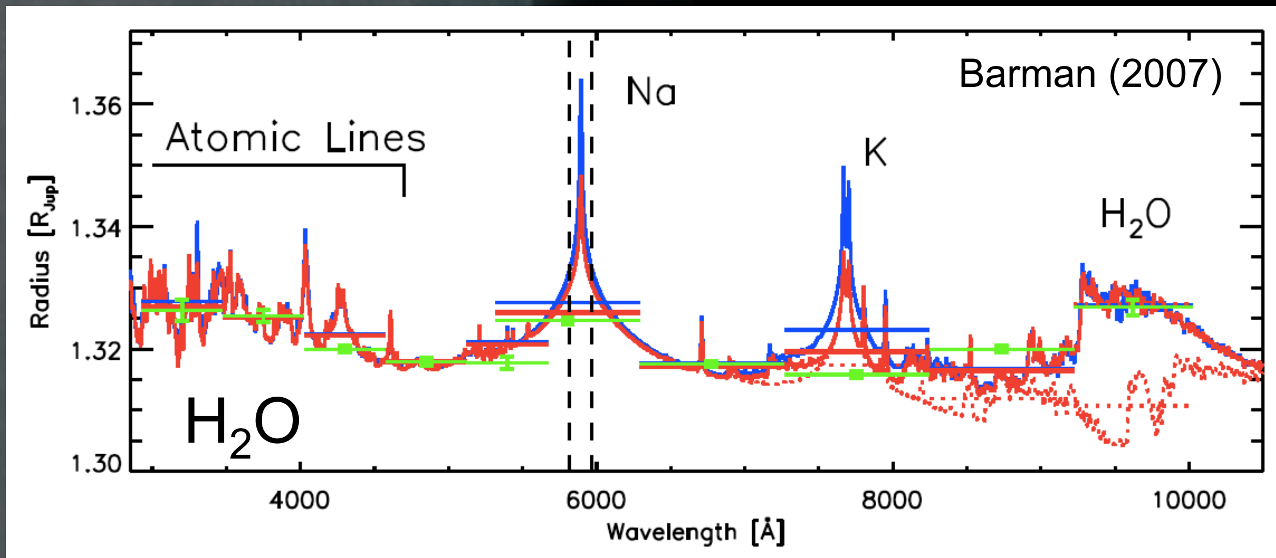
K: too early to tell



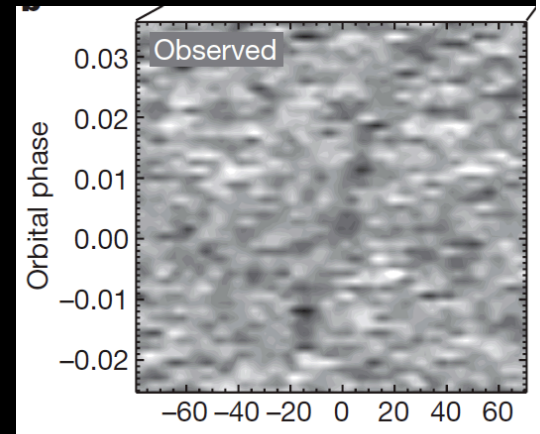
$$\frac{\tau_{\mathrm{H}}}{\tau_{\mathrm{V}}} = \sqrt{\frac{2\pi a}{H}}$$



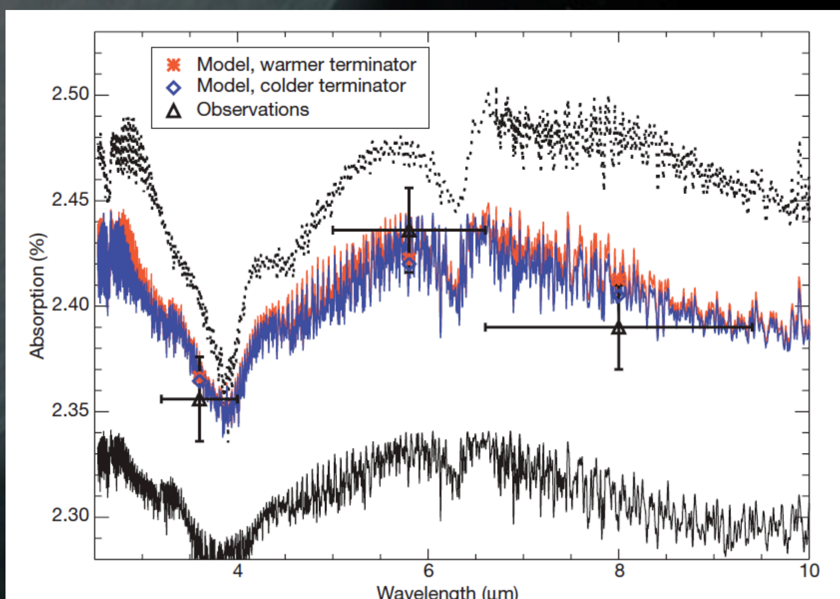
Fortney et al (2003)

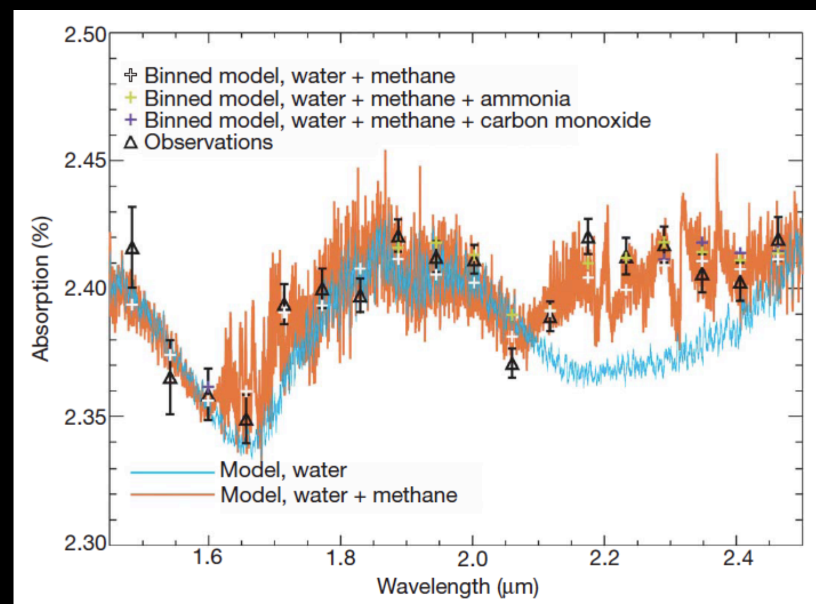


CO, with blueshift!



Snellen et al. (2010)



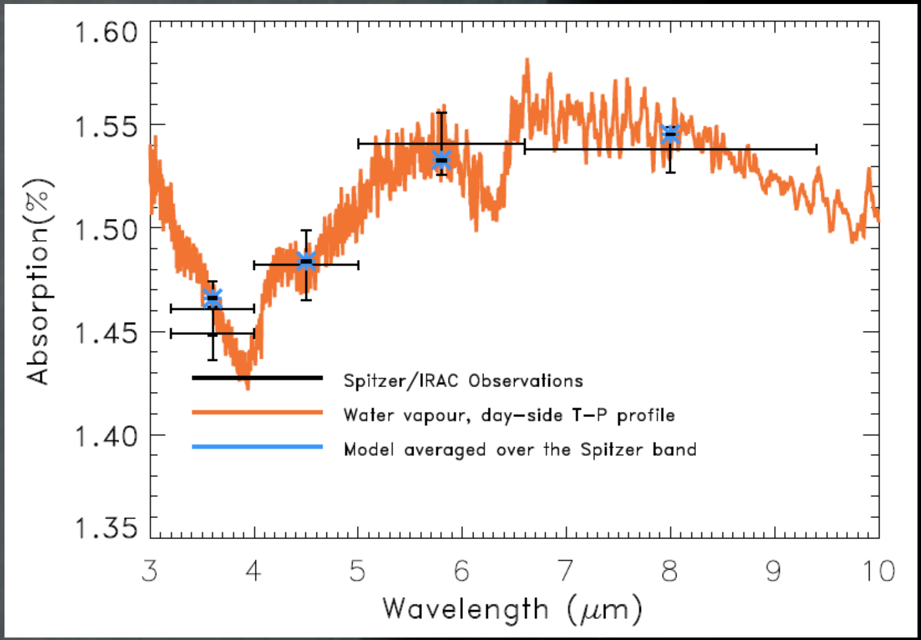


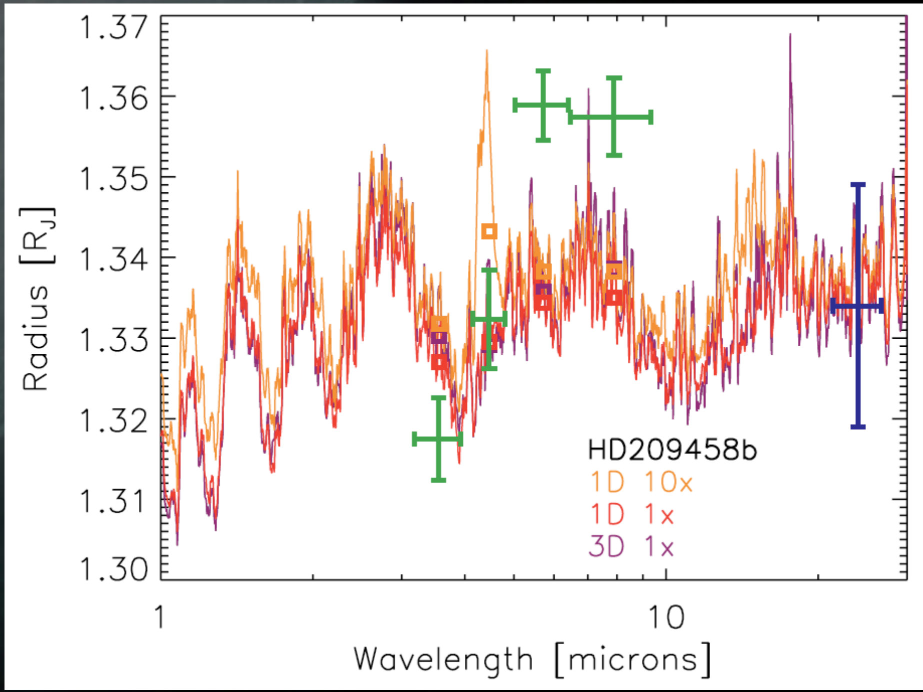
Tinetti et al. (2008)

H_2O

CH_4

Swain et al. (2008)





Let's Pause for a Minute

Beaulieu et al. (2009):
Water vapor in HD 209458b
Fit by Tinetti and collaborators

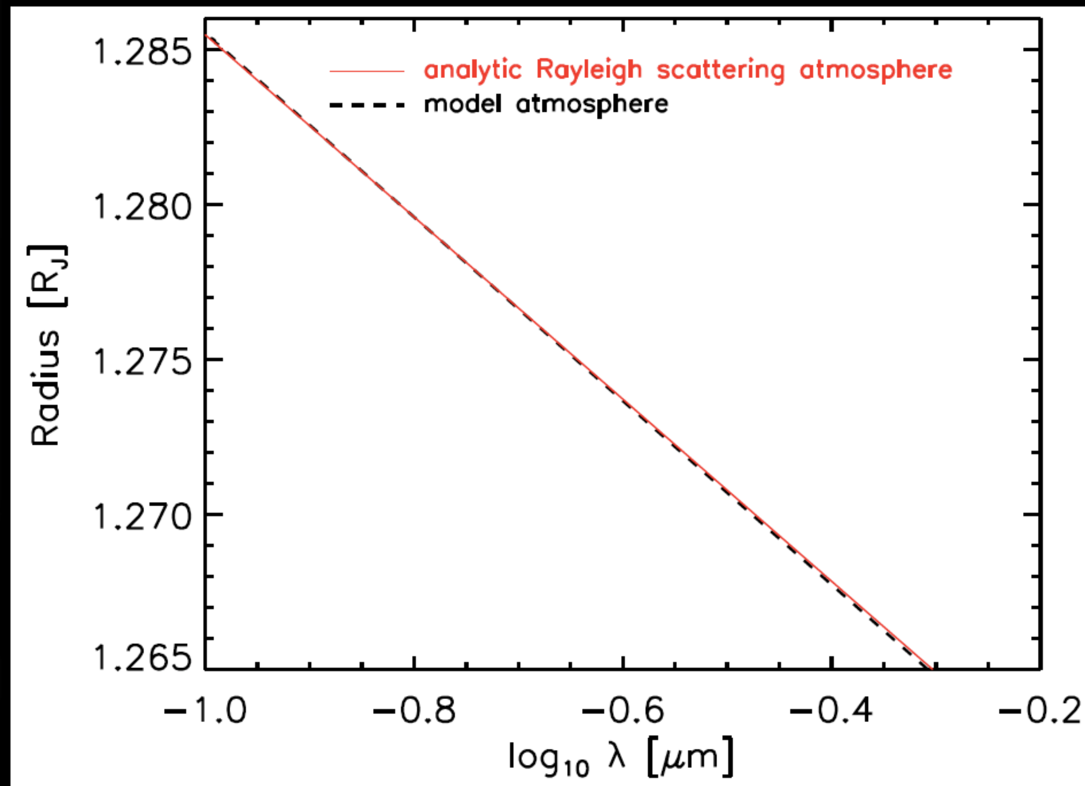
Fortney et al. (2010):
1D and 3D models HD 209458b
A poor match – why?

Analytic Transmission Spectra For Simple Atmospheres

Lecavelier des Etangs et al. (2008)

$$\sigma = \sigma_o(\lambda/\lambda_o)^\alpha$$

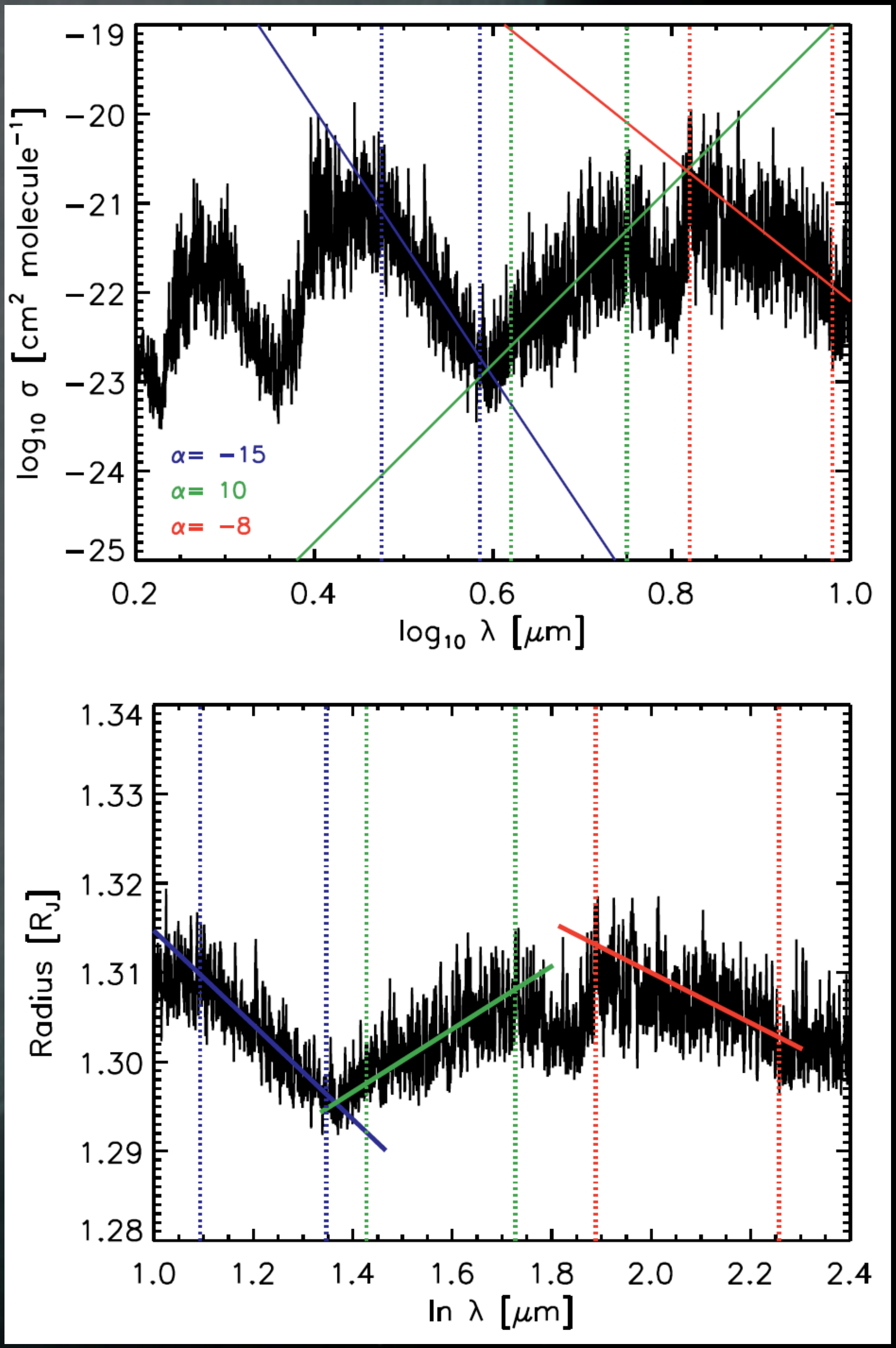
$$\frac{dR_p}{d\ln\lambda} = \alpha\frac{kT}{\mu g} = \alpha H$$



Shabram, Fortney, et al. (2010)

Transmission Spectra of Transiting Planet Atmospheres: Simulations of the Hot Neptune GJ 436b and Prospects for *JWST*

Megan Shabram[1], Jonathan J. Fortney[1], Thomas P. Greene[2], Richard S. Freedman[2,3]



Water Vapor Opacity Only

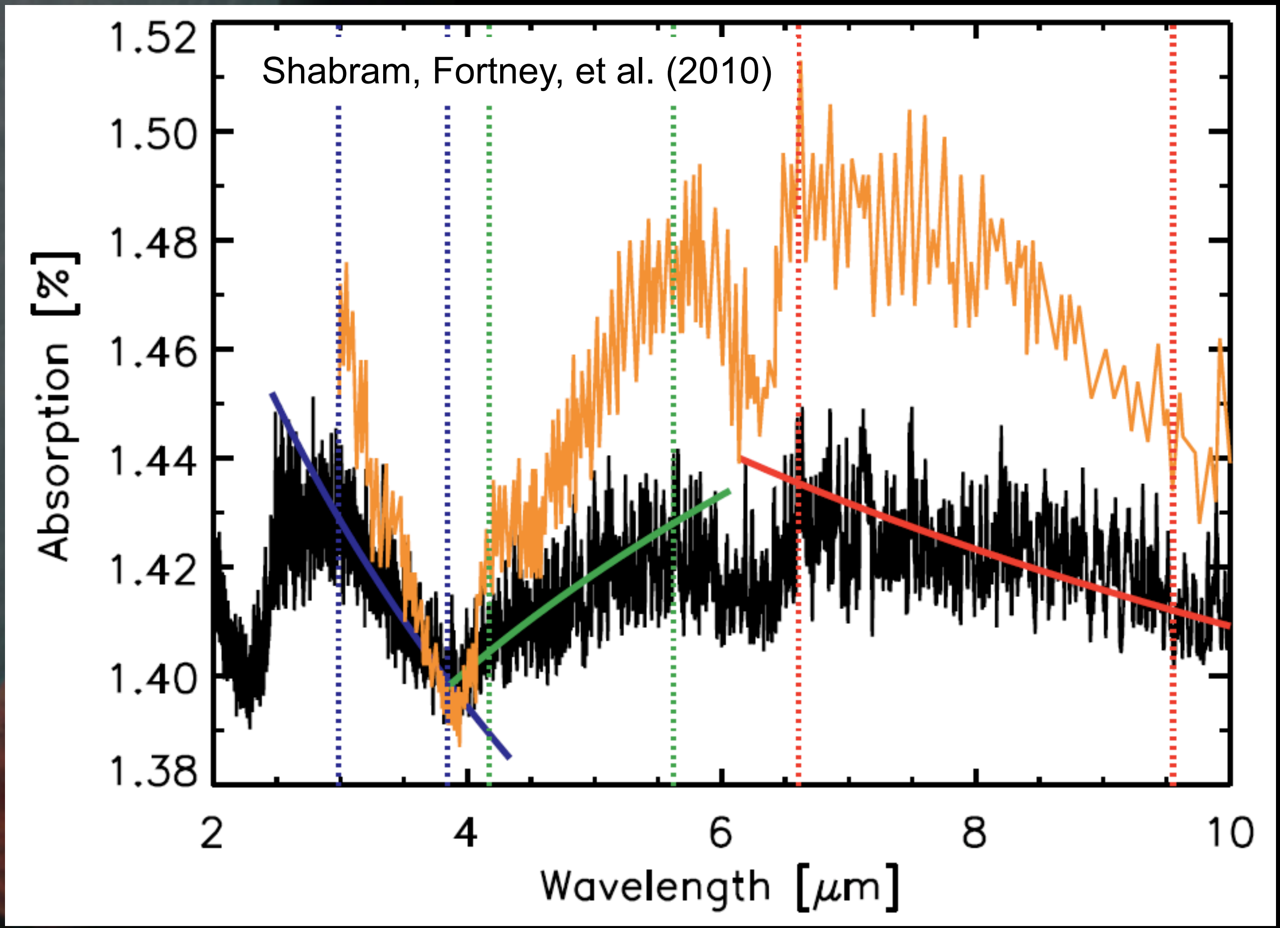
Fit for α in the mid-IR at 1500 K, 10 mbar

- Set up HD 209458b 1500 K isothermal model with water opacity only

- Calculation of planetary radii
- Compare to analytic relations

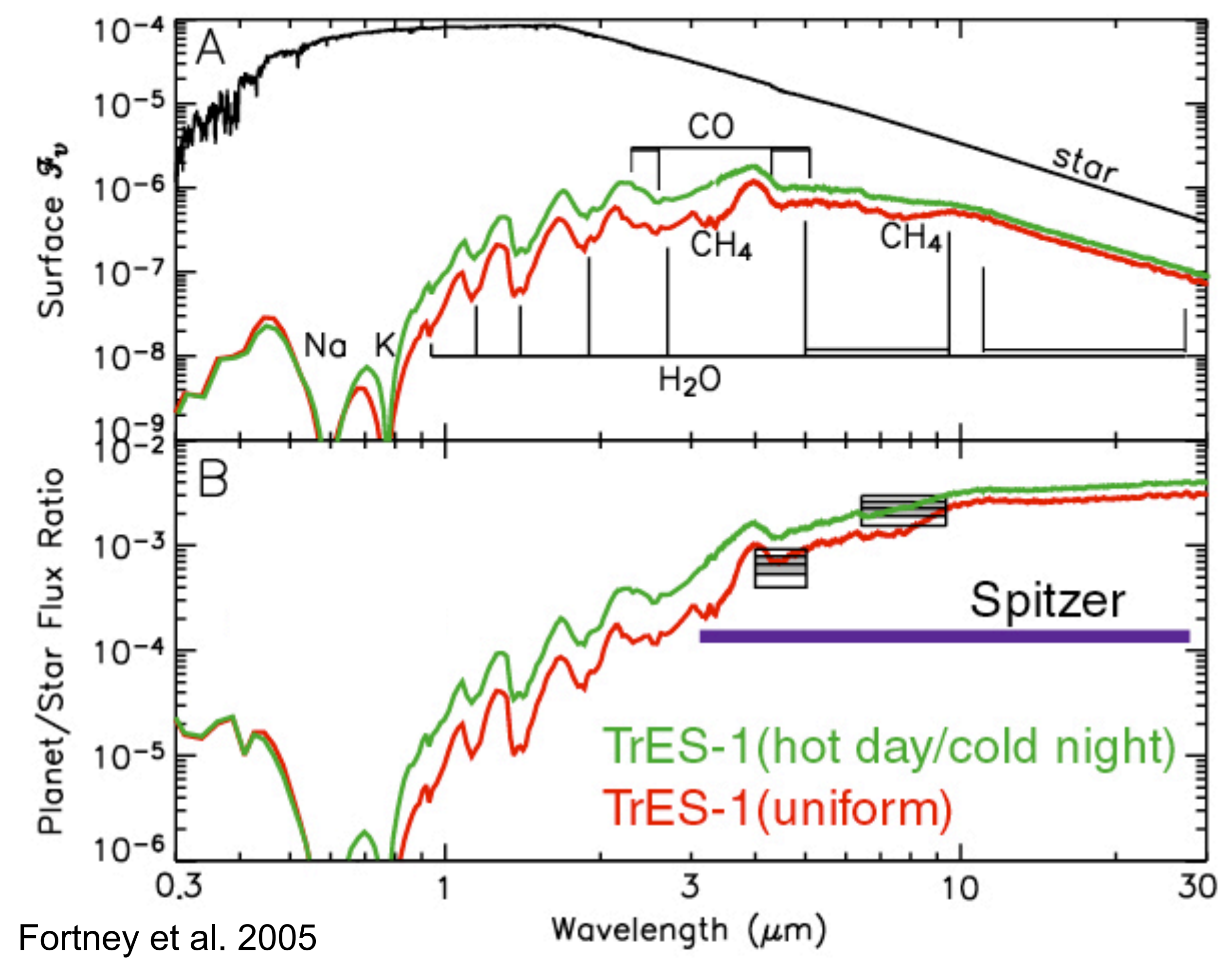
Shabram, Fortney, et al. (2010)

Comparison with Tinetti et al Model



Tinetti et al. model from Beaulieu et al. (2009): 1500 K, water vapor only

Tinetti et al. models dramatically overestimate the ***amplitude*** of transmission spectrum features.



Fortney et al. 2005

Secondary Eclipses

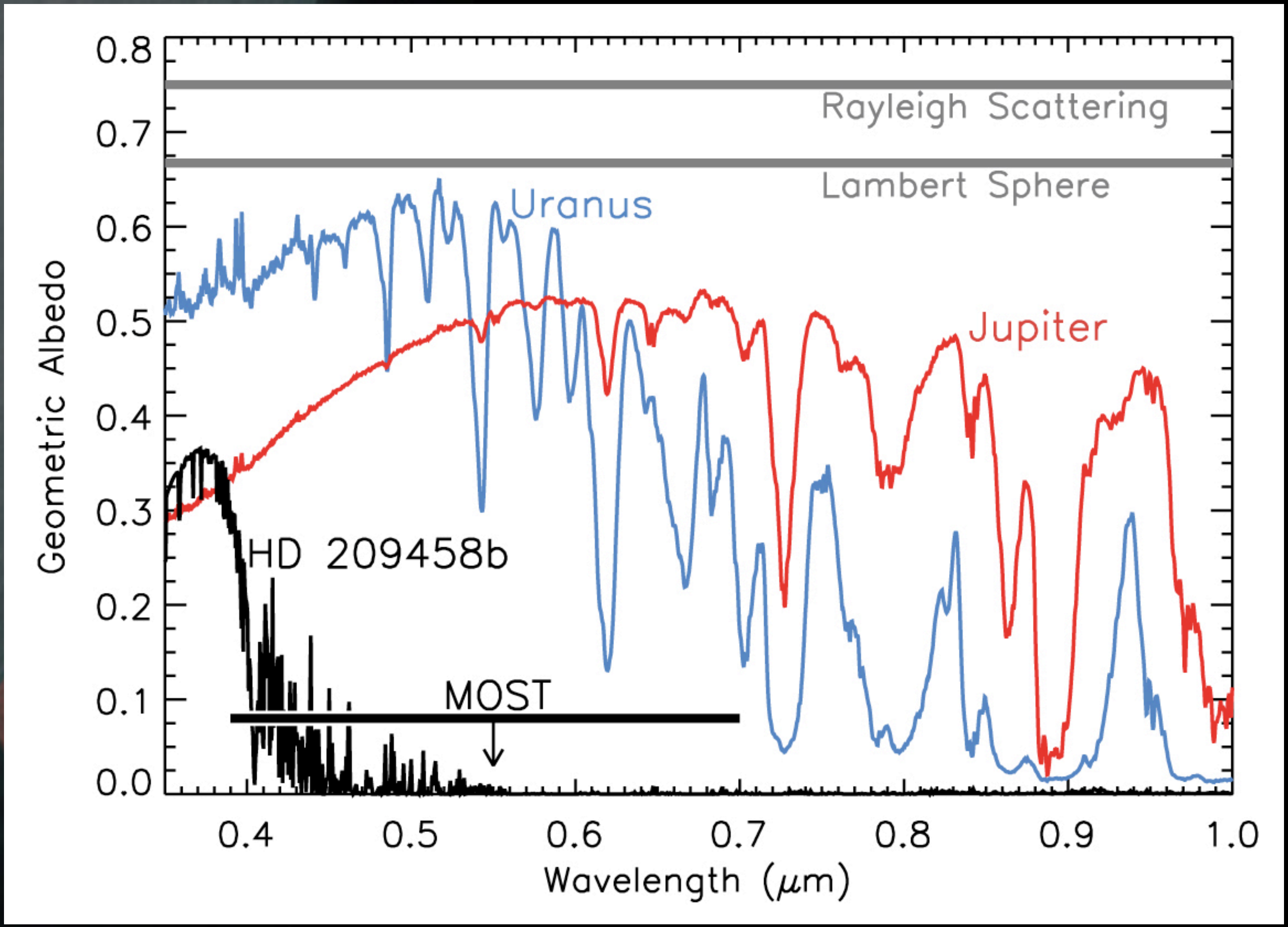
Wavelengths

Hot Jupiter planet/star flux ratios only become favorable in the infrared, which was great for *Spitzer*.

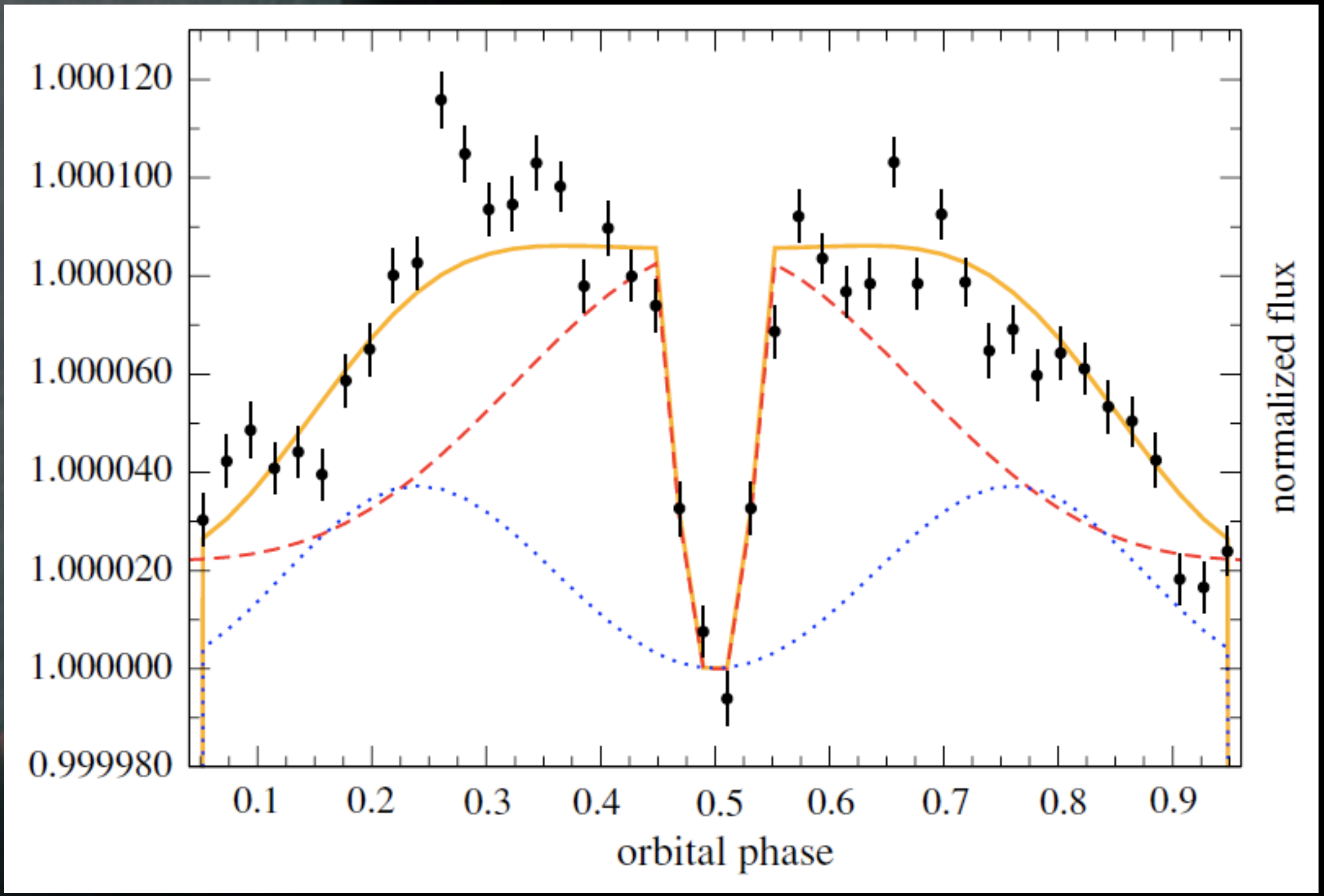
Planet/star flux ratios in the optical are generally extremely low

Recently detections in the near IR (JHK) bands have finally been achieved.

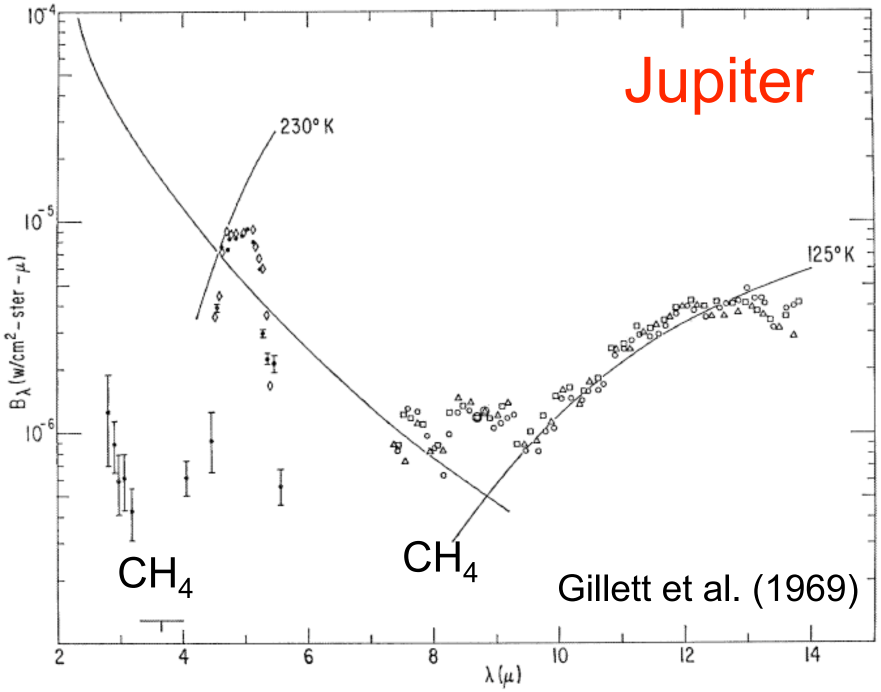
Low Geometric Albedos: Strong Optical Absorbers and No Clouds



HAT-P-7b lightcurve in the *Kepler* bandpass



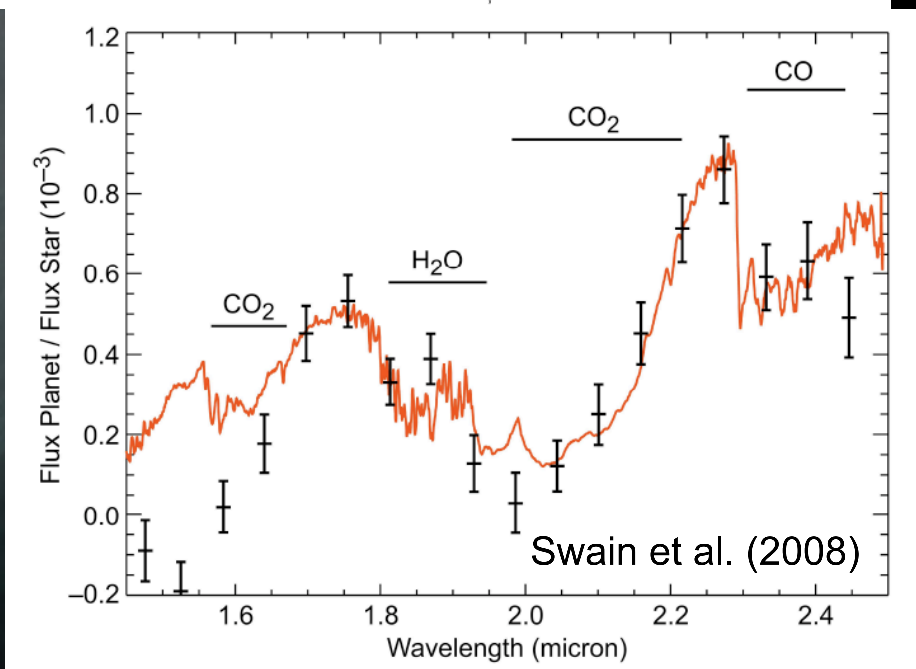
- A large day/night *flux* contrast with a small day/night *temperature* contrast
- *Kepler* and *CoRoT* bands are on the Wien side, not the R-J side

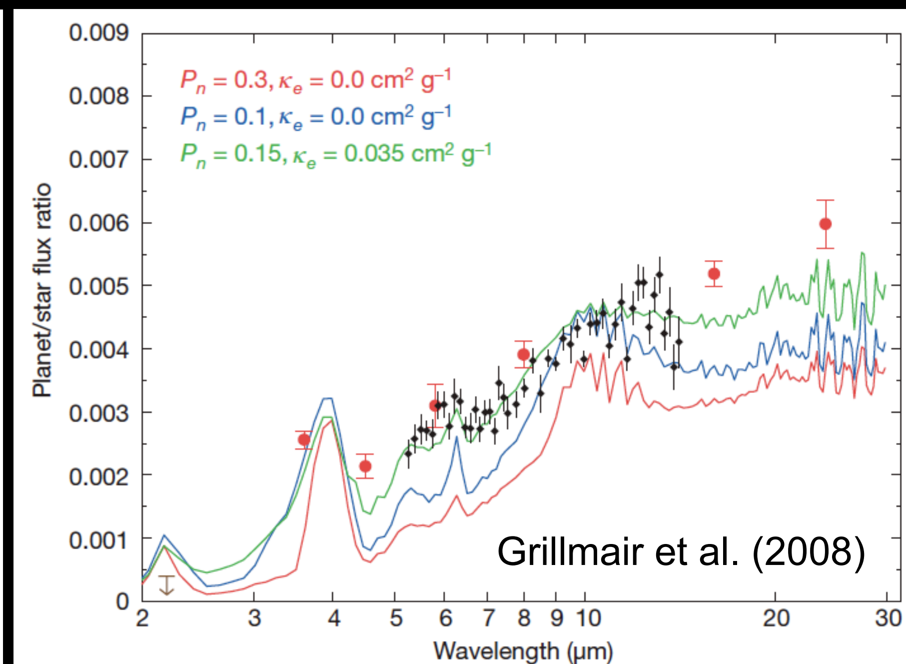


Spectroscopy of thermal infrared light emitted by the planets

- Jupiter, 1969
- HD 189733b, 2008

- For most transiting planets, spectra are difficult to obtain, so we can only measure the brightness in a few wide wavelength bands



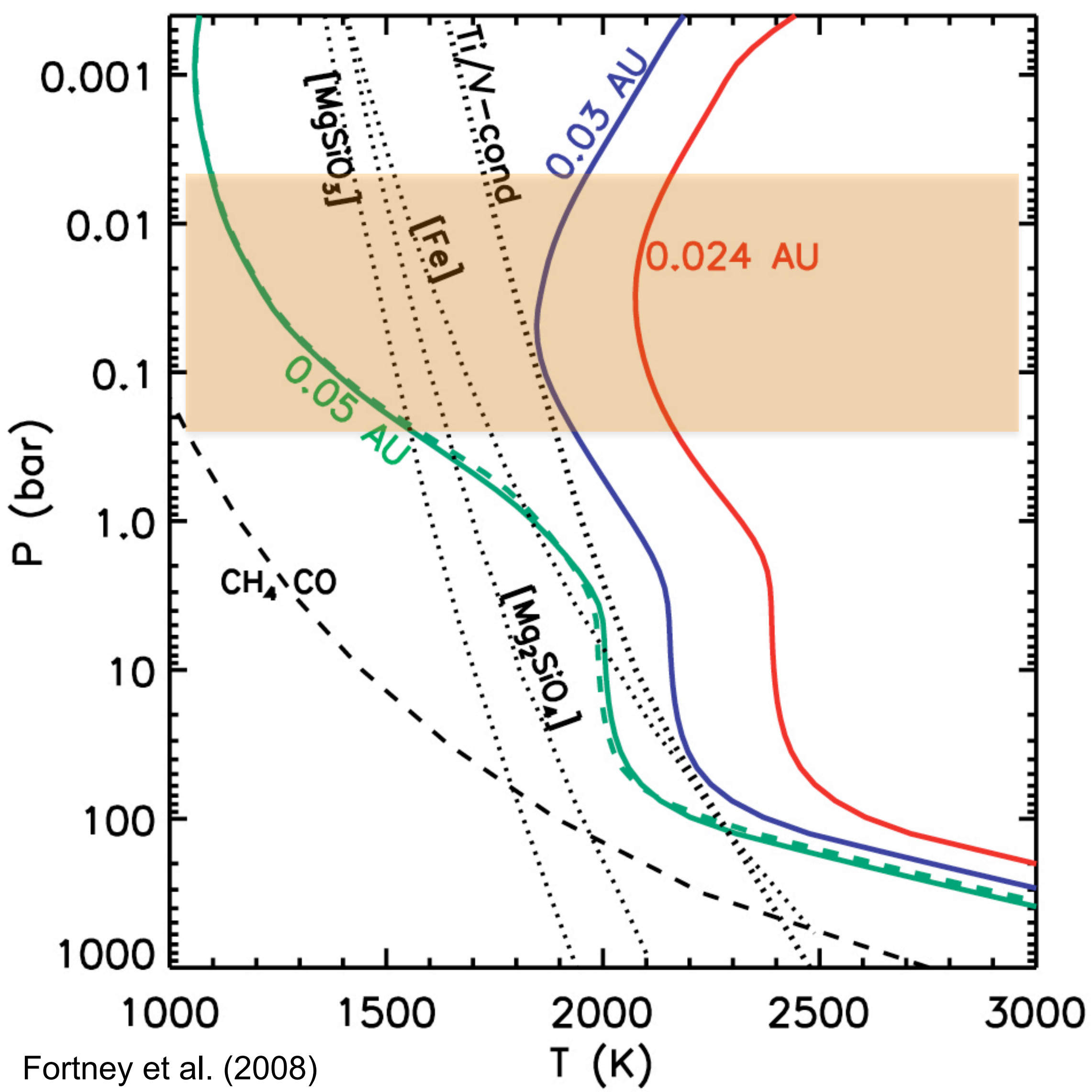


P-T Profiles as a function of irradiation level

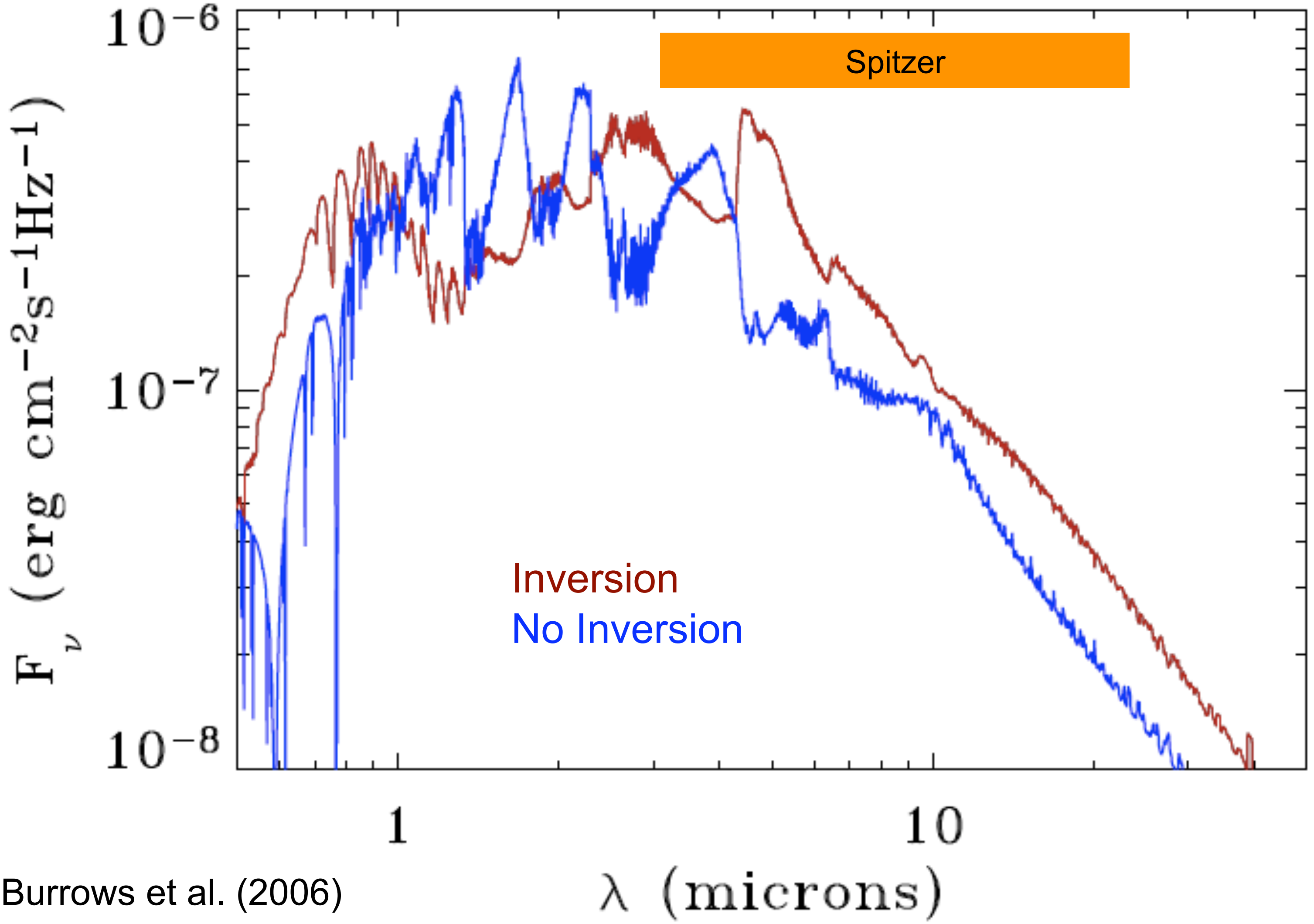
- 1D day-side models of planets within ~0.04 AU have atmospheres warmer than the condensation boundary of Ti/V, which are found as gaseous TiO and VO

- TiO/VO are strong absorbers of optical flux

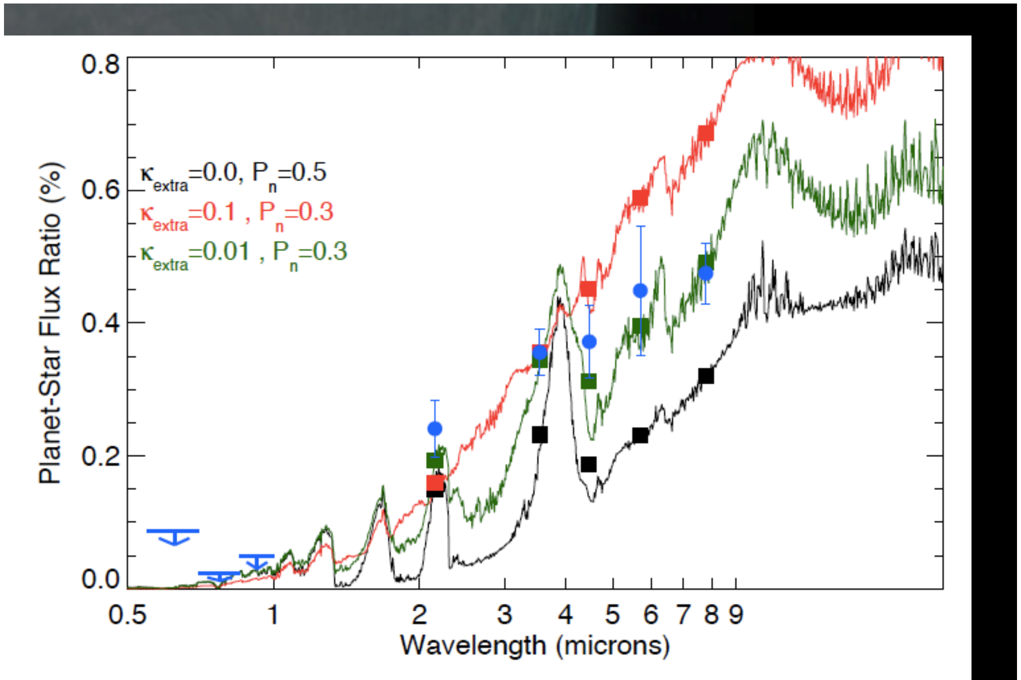
- Similar to M-type dwarfs (dM) we label the hottest planets pM. The cooler hot Jupiters are pL, similar to the L-type dwarfs (dL).



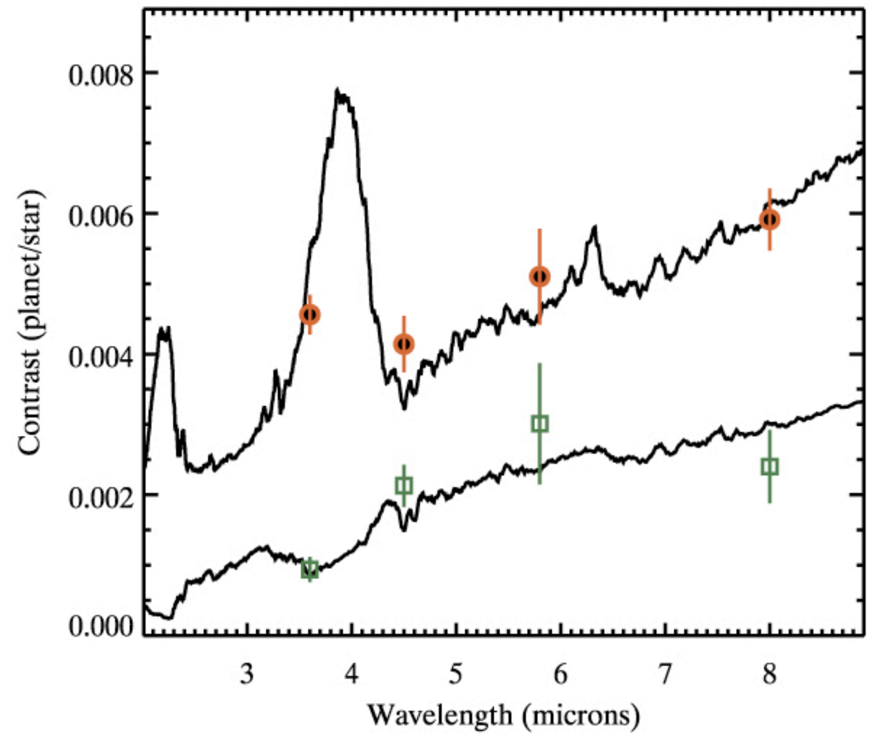
Fortney et al. (2008)



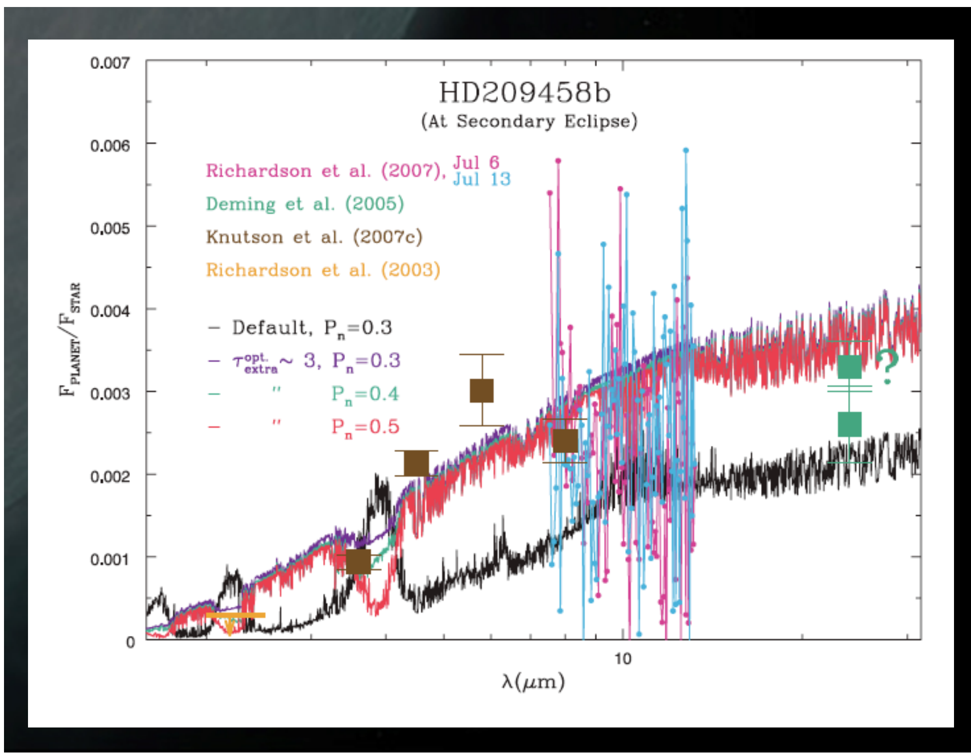
Burrows et al. (2006)



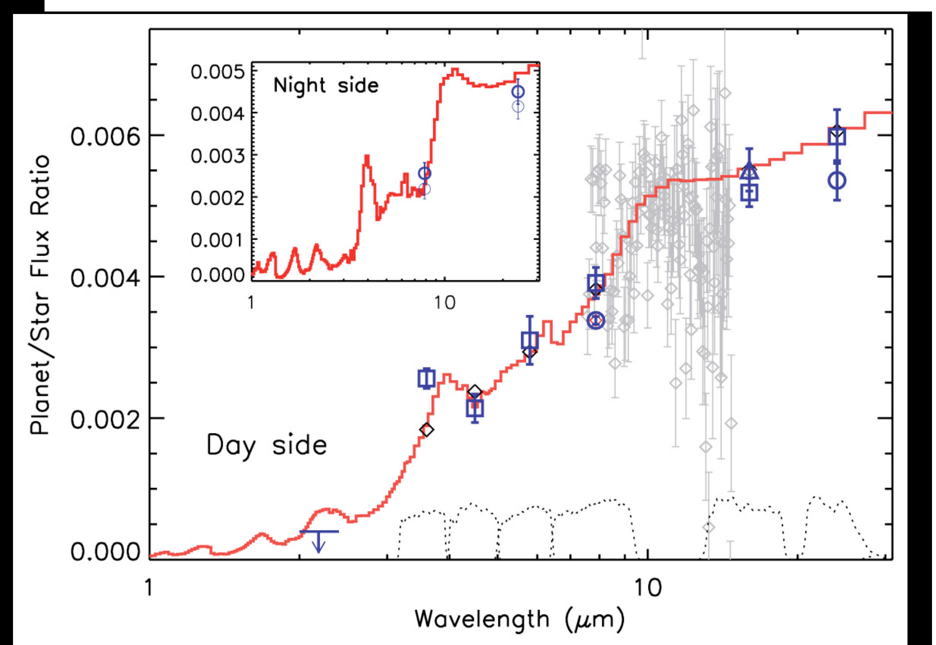
κextra=0.0, Pn=0.5
κextra=0.1 , Pn=0.3
κextra=0.01 , Pn=0.3
Planet-Star Flux Ratio (%)
0.8
0.6
0.4
0.2
0.0
0.5
1
2
3
4
5
6
7
8
9
Wavelength (microns)



Contrast (planet/star)
0.008
0.006
0.004
0.002
0.000
3
4
5
6
7
8
Wavelength (microns)

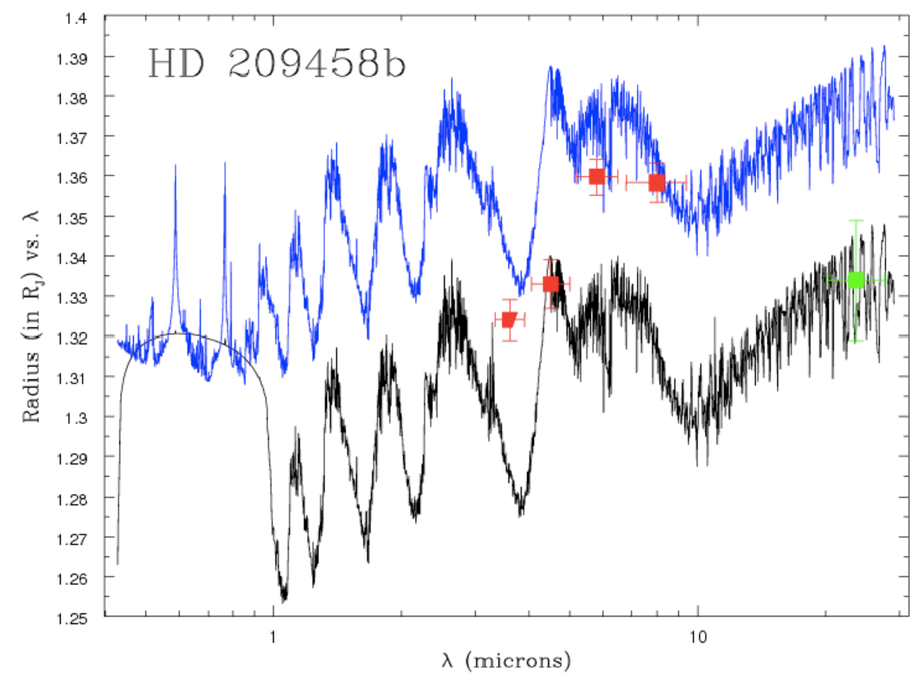


HD209458b
(At Secondary Eclipse)
Richardson et al. (2007), Jul 6
Jul 13
Deming et al. (2005)
Knutson et al. (2007c)
Richardson et al. (2003)
— Default, Pn=0.3
— τ opt. extra ~ 3, Pn=0.3
— " Pn=0.4
— " Pn=0.5
FPLANET/FSTAR
0.007
0.006
0.005
0.004
0.003
0.002
0.001
0
10
λ(μm)
?

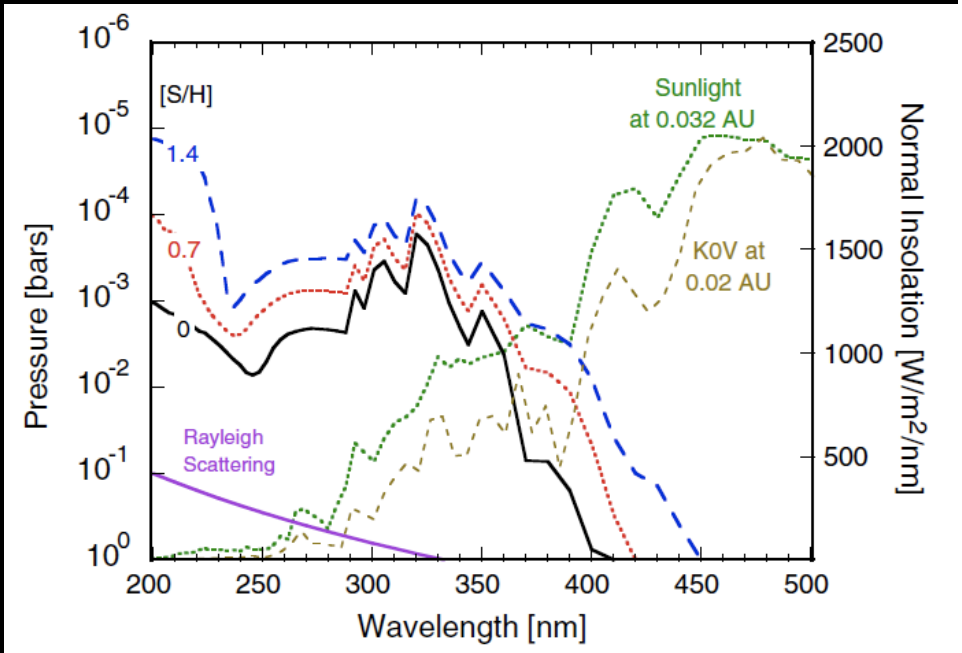


Night side
0.005
0.004
0.003
0.002
0.001
0.000
1
10
Day side
Planet/Star Flux Ratio
0.006
0.004
0.002
0.000
1
10
Wavelength (μm)

What causes the temperature inversions?



Burrows et al. (2008)



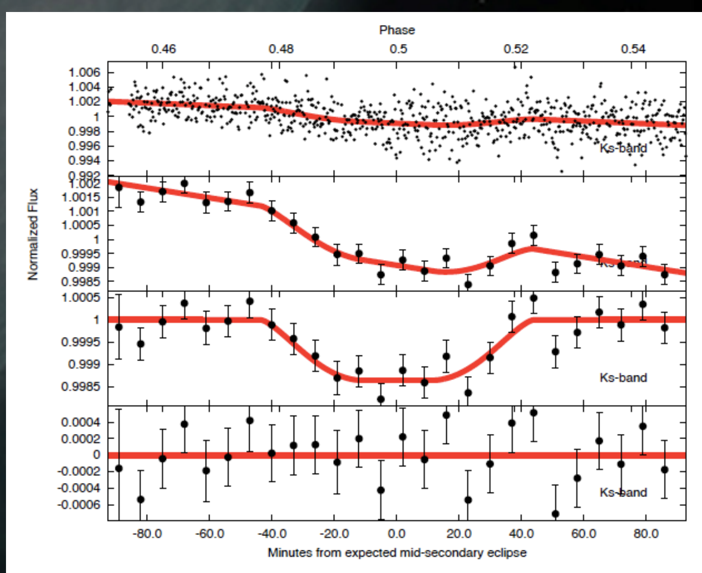
Zahnle et al. (2009)

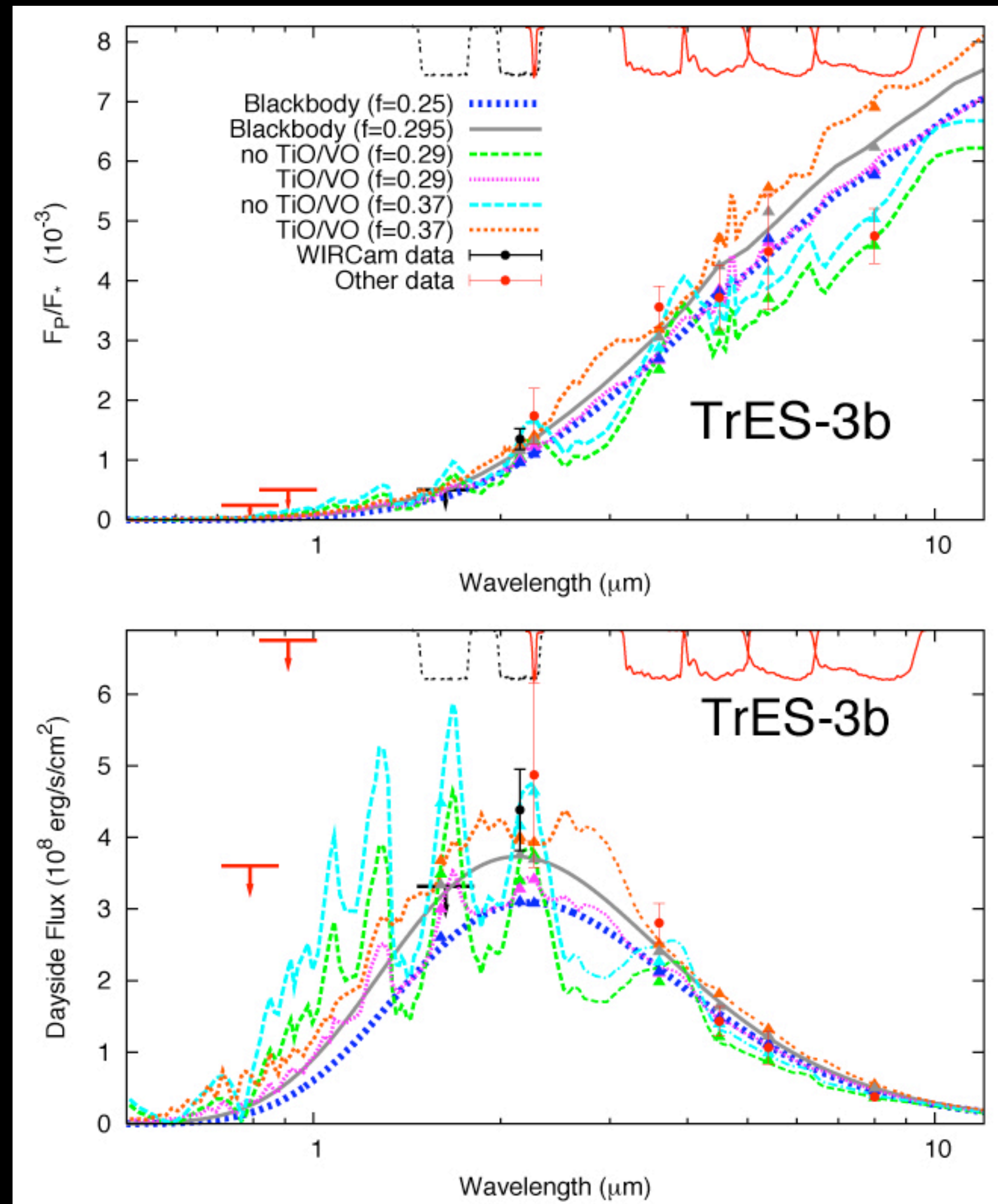
- If it is a radiative-transfer driven affect, it must be an incredibly strong and abundant optical or near UV absorber
- This is why TiO/VO are so attractive
- A purely dynamical effect?

Mid-IR actually gives us an incomplete view of these atmospheres

Near IR is where the bulk of the planet flux escapes

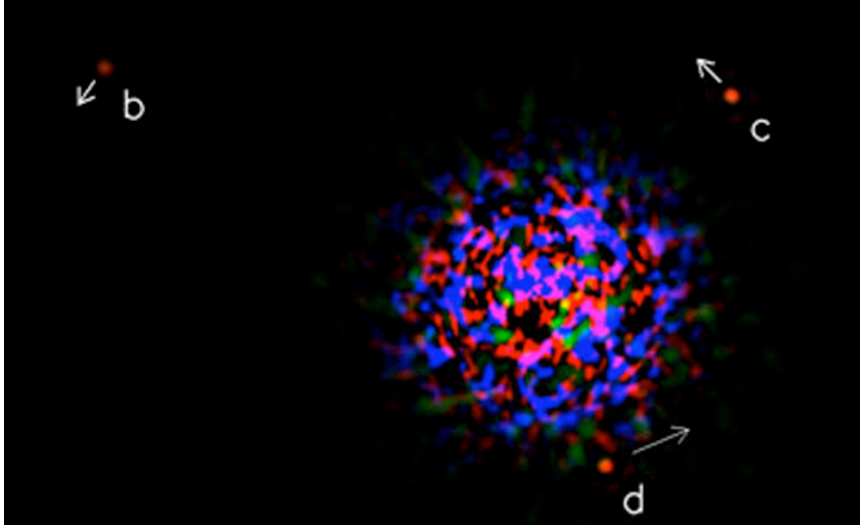
Many successes from the ground in the past 12 months

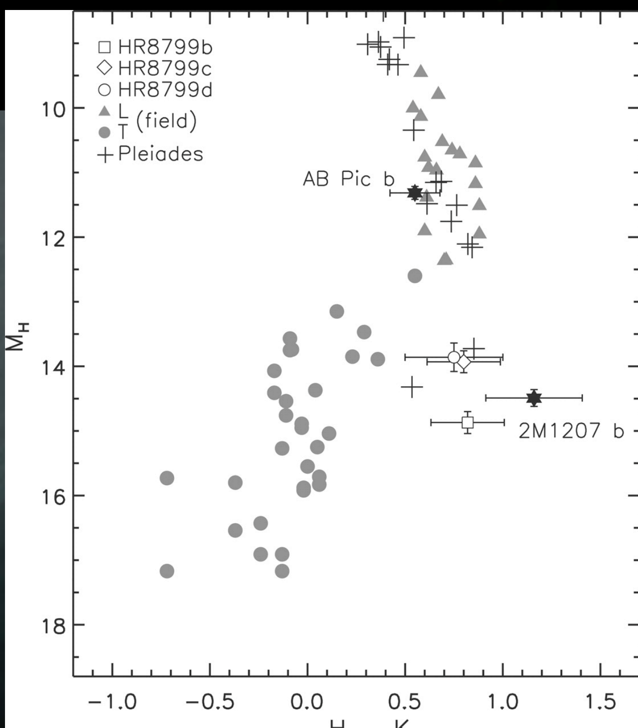


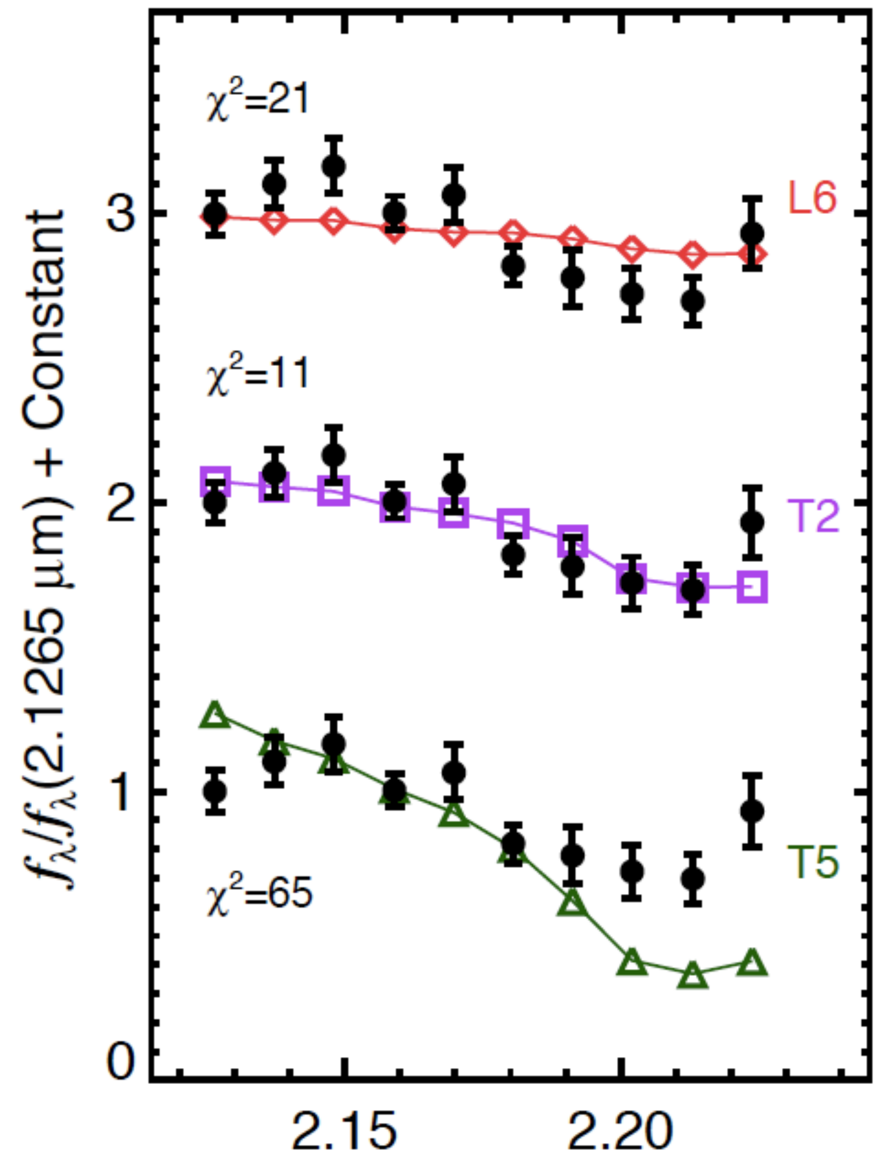


Croll et al., 2010

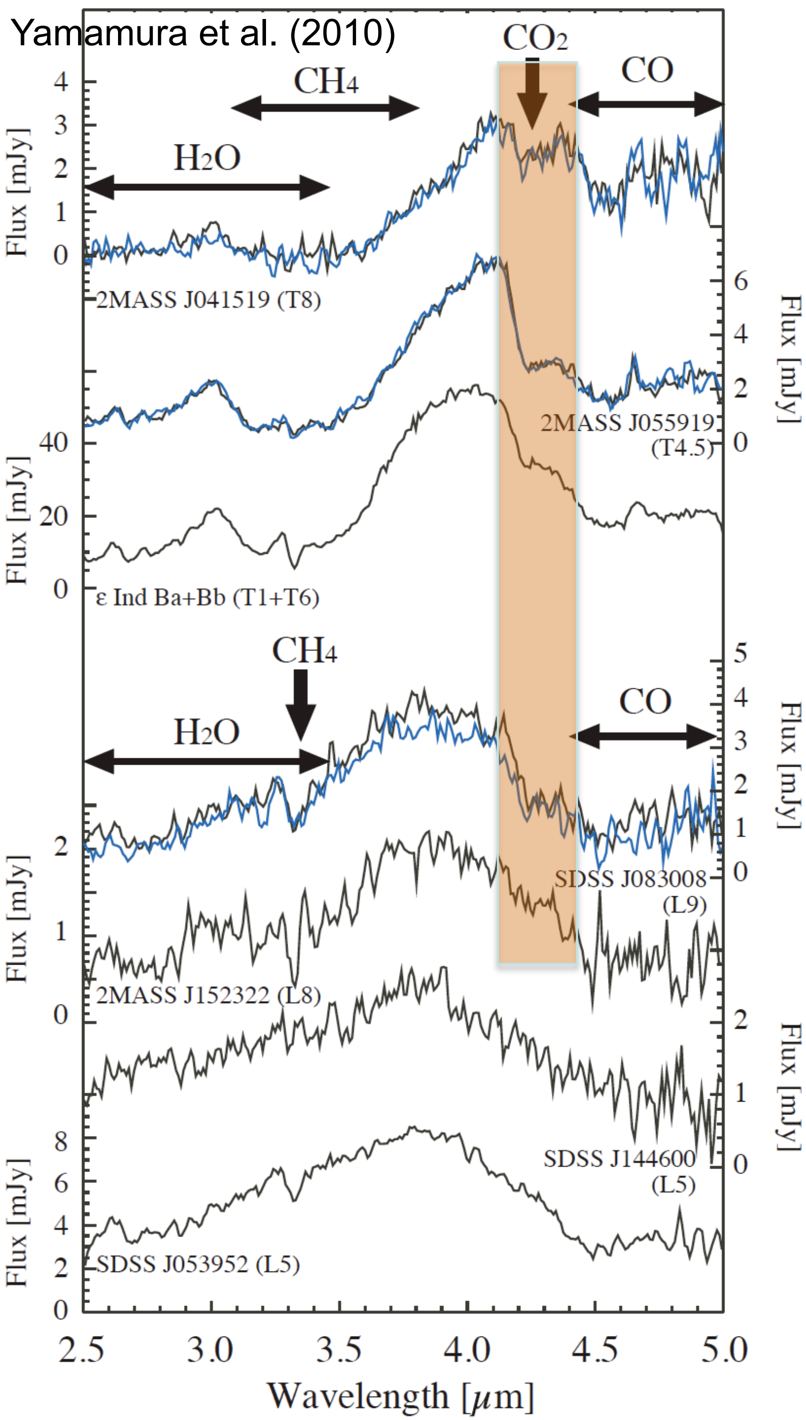
Spectra of Imaged Planets







Bowler et al. (2010)



As we move more from photometry to spectra for exoplanets we should expect fantastic surprises

For instance:

There are photometry on ~800 brown dwarfs and spectra for 200+, since 1995

CO_2 was just detected last month!

Japanese IKARA near-IR spectrograph found CO_2 in 5 of 7 brown dwarfs observed

A new molecule hiding in our one remaining blind spot!

Conclusions

Transmission Spectra: Observations are generally finding what was predicted: Na, K, H_2O(?), CH_4(?)

Do not yet put much weight on abundance determinations

Dayside Spectra: Most planets have temperature inversions. Not yet clear why

Do not yet put much weight on abundance determinations

JHK data will yield a more complete picture of dayside temperature structure

Most hot Jupiters are dark: Bond and geometric albedos of ~0.05-0.2

Day/night temperature contrasts are modest: see Knutson and Showman talks

Probing the the terminator and dayside of planets separately is an opportunity and a source of frustration