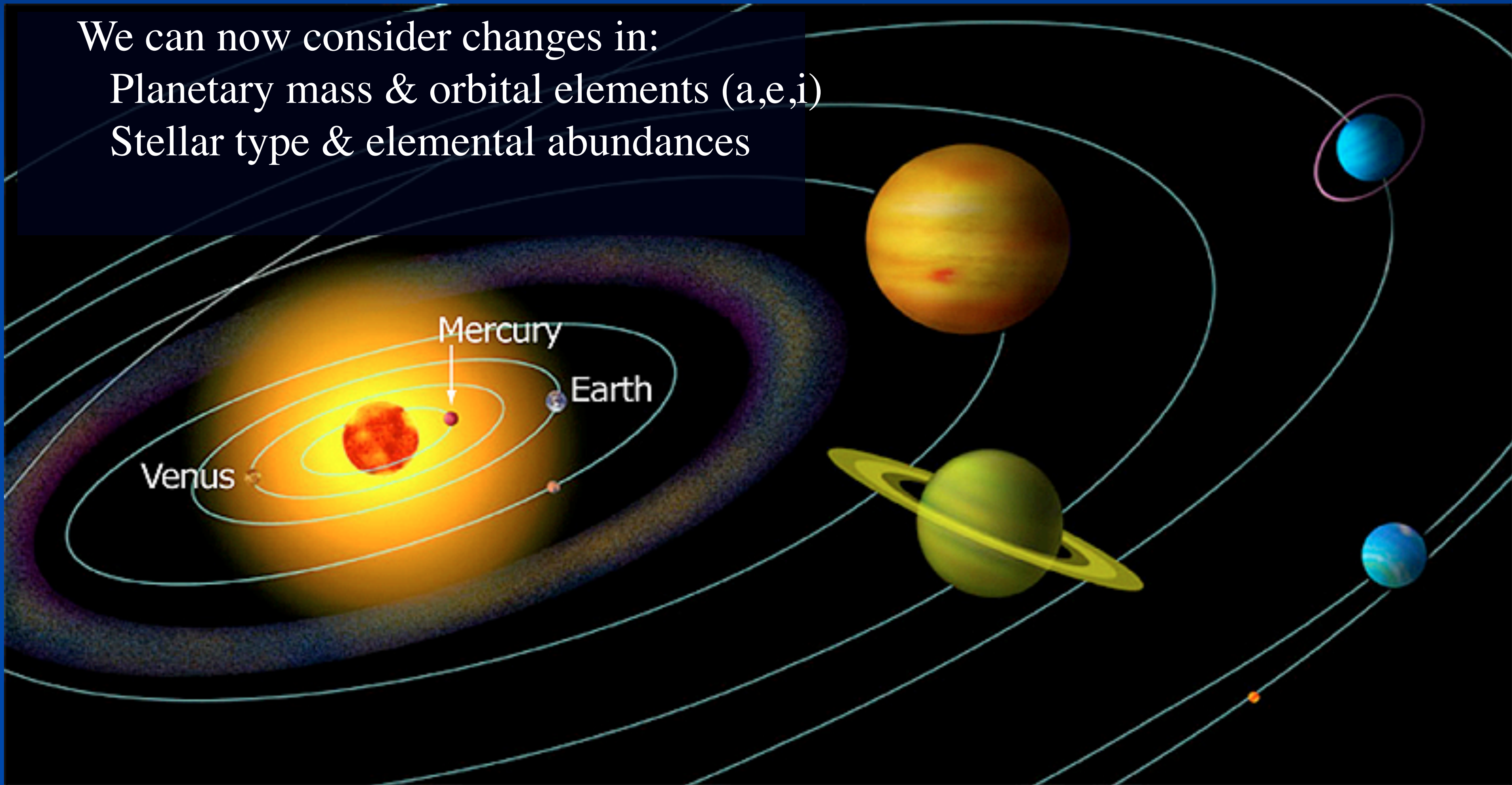
Optical & IR Spectroscopy of Transiting Exoplanets (review)

Caitlin Griffith (University of Arizona)

We can now consider changes in:
- Planetary mass & orbital elements (a,e,i)
- Stellar type & elemental abundances

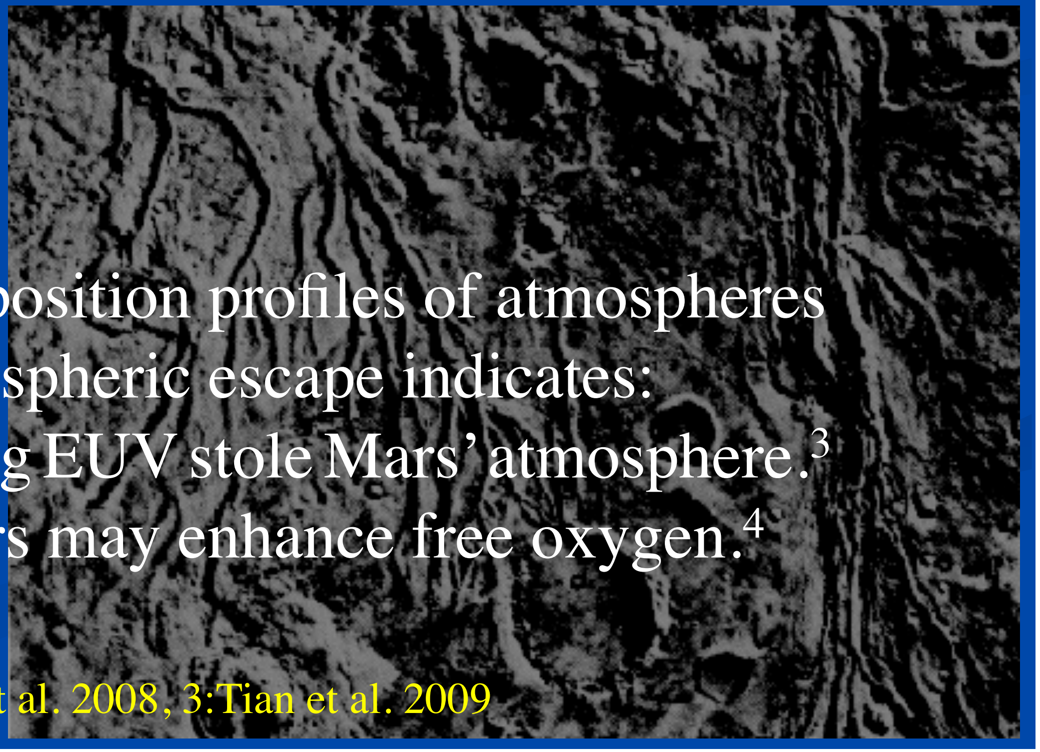


Stellar Effects on Planets

Magnetosphere & Ionosphere

Recent work on Titan's atmosphere indicates:

1) Haze is formed near ionosphere[1]
2) Haze consists in part of amino acids[2]



Planetary Insolation:

Temperature & Composition profiles of atmospheres

Recent work on atmospheric escape indicates:

1) The Sun's strong EUV stole Mars' atmosphere.[3]
2) XUV of M stars may enhance free oxygen.[4]

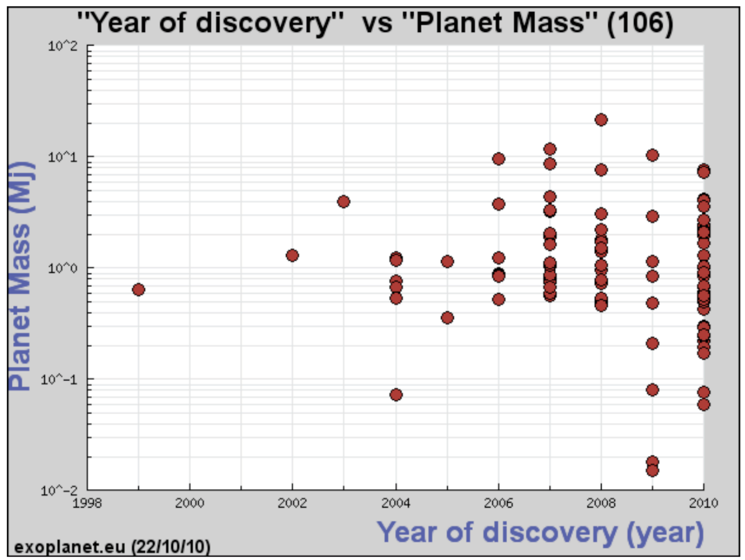
1: Lavvas et al. 2008, 2: Horst et al. 2010; 3:Tian et al. 2008, 3:Tian et al. 2009

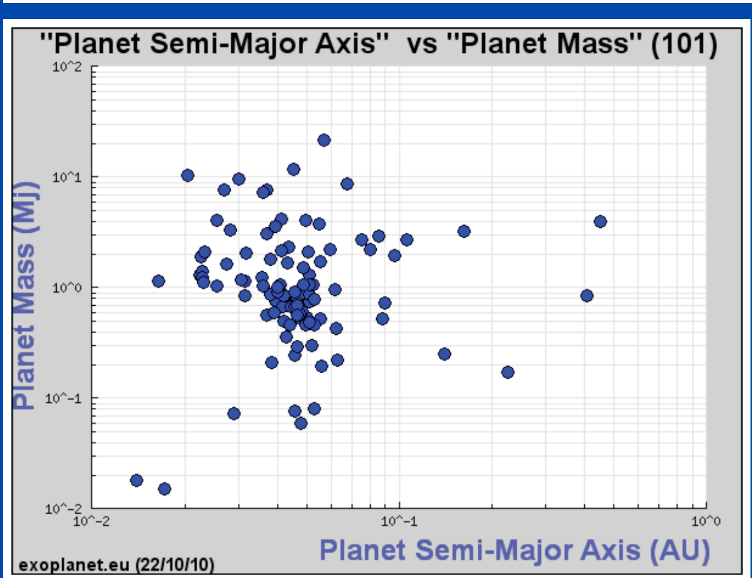
Two Approaches

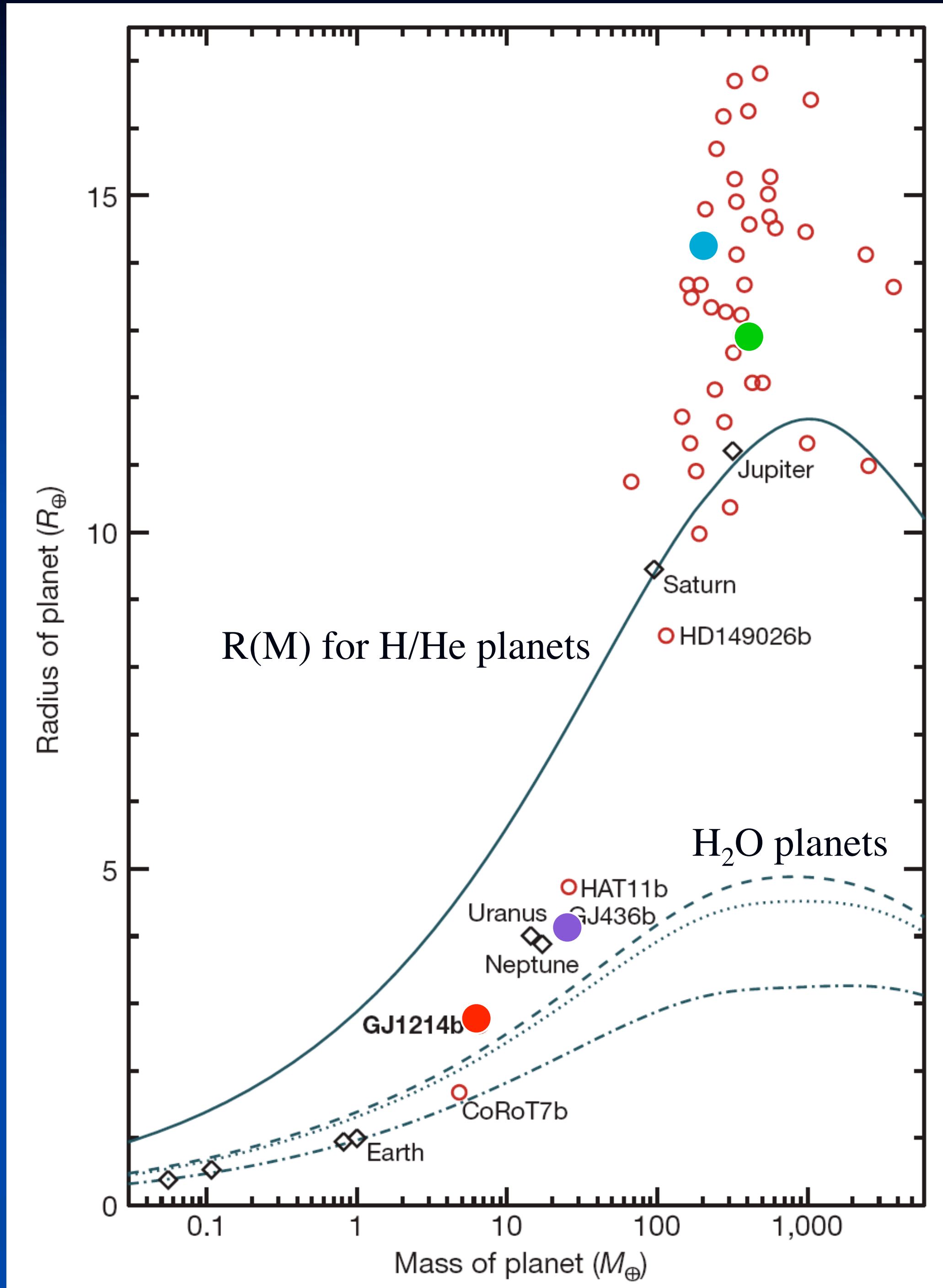
Models → Data

Models ← Data

106 Transiting Planets







Charbonneau et al. 2009

Taken from Jean Schneider's site: exoplanet.eu

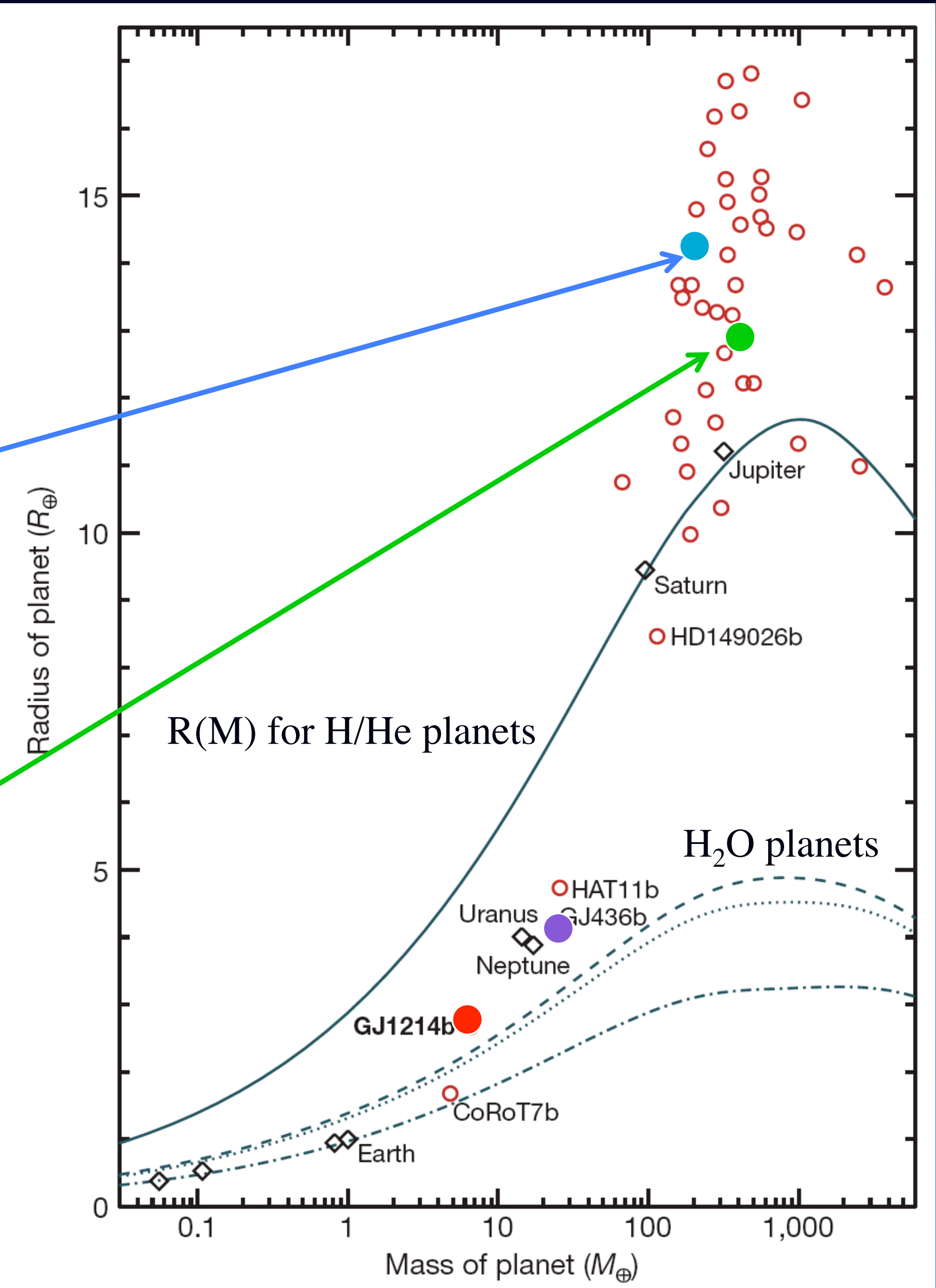
Detection of an exoplanetary atmosphere

HD209458b

Parent Star: G0
V Magnitude: 7.65
$[Fe/H]_{Star}$: 0.04
Mass: 0.69 M_J
Radius: 1.32 R_J
Semi-major axis: 0.045 AU

HD189733b

Parent Star: K1
V Magnitude: 7.67
$[Fe/H]_{Star}$: -0.03
Planet's Mass: 1.13 M_J
Radius: 1.38 R_J
Teq ~ 1200 K
Semi-major axis: 0.03 AU



Charbonneau et al. 2009

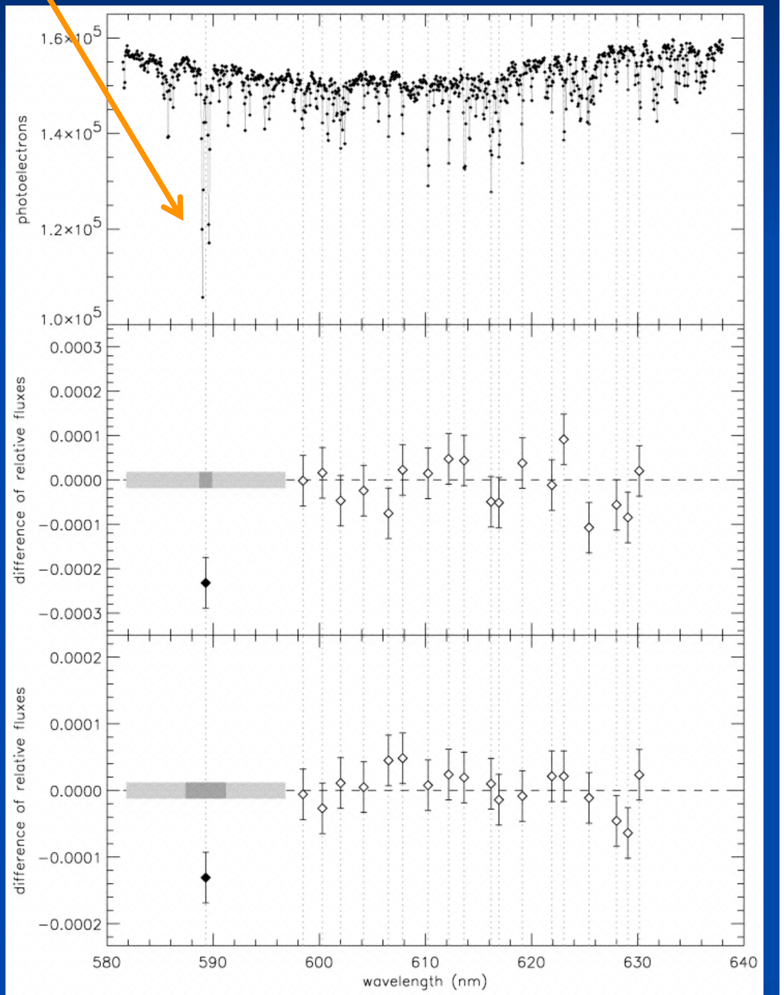
Some of the First Measurements of Exoplanetary Atmospheres

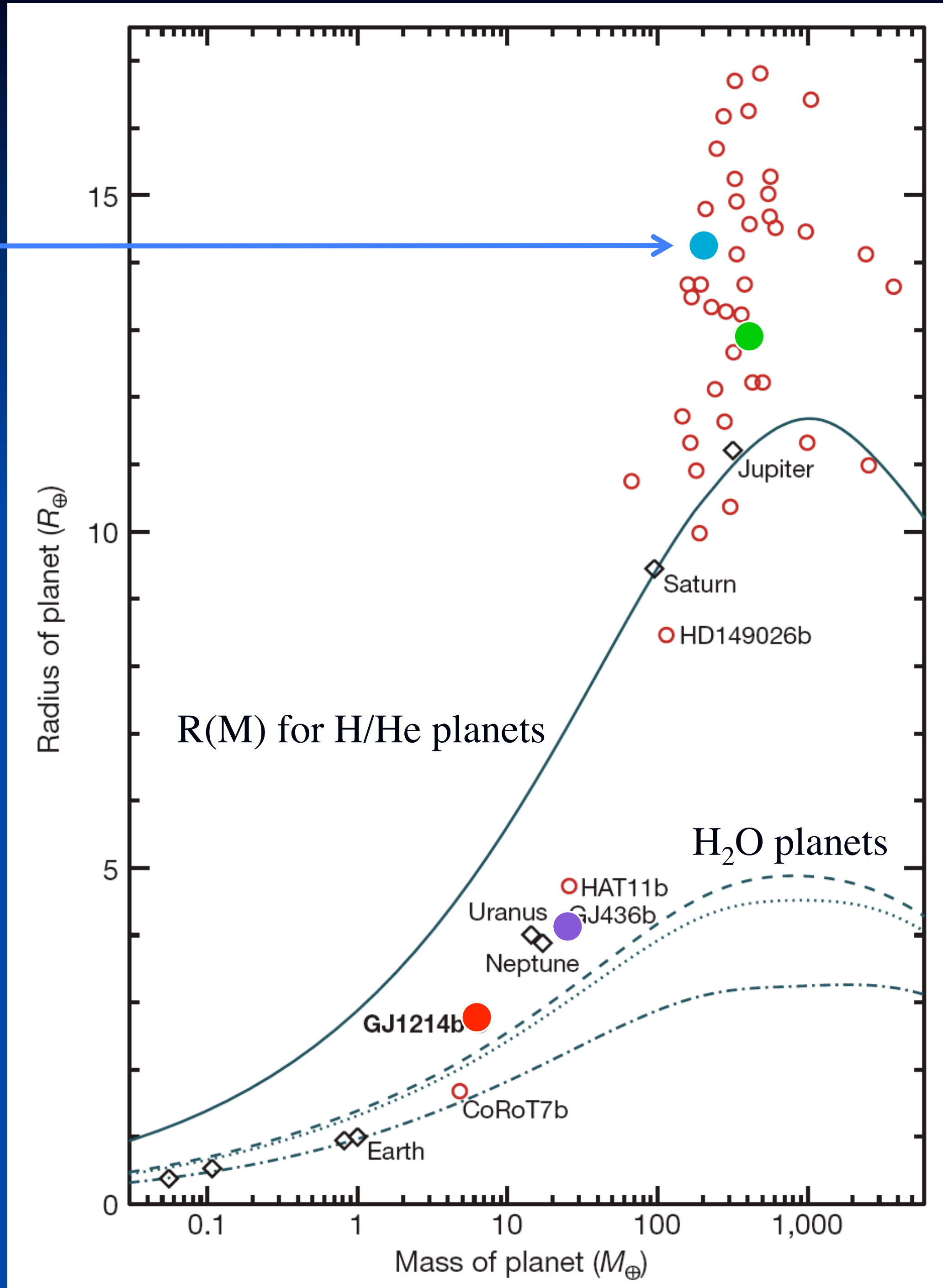
Planetary Atomic Absorption
&
Planetary Emission

Detection of an exoplanetary atmosphere

Na HD209458b

Charbonneau et al. 2002



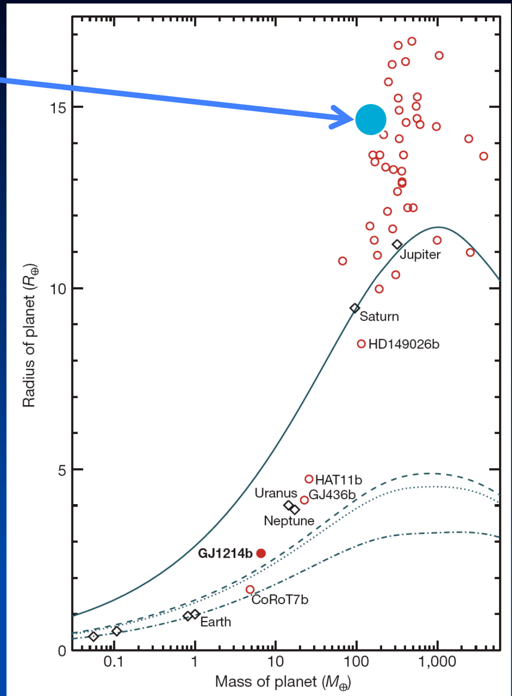


Charbonneau et al. 2009

Absorption due to planet's Na

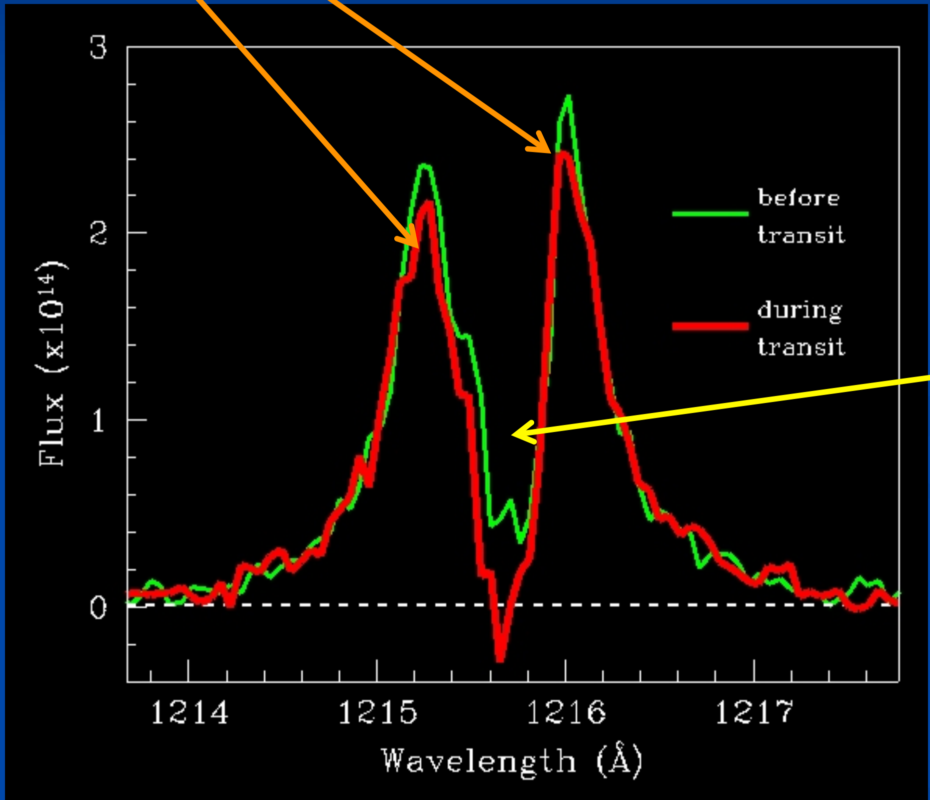
Escape of Hydrogen?

HD209458b



Ly α

Absorption of star's Ly α



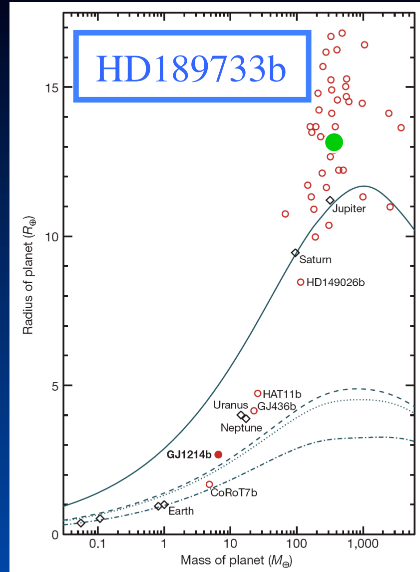
Contamination from geocoronal emission

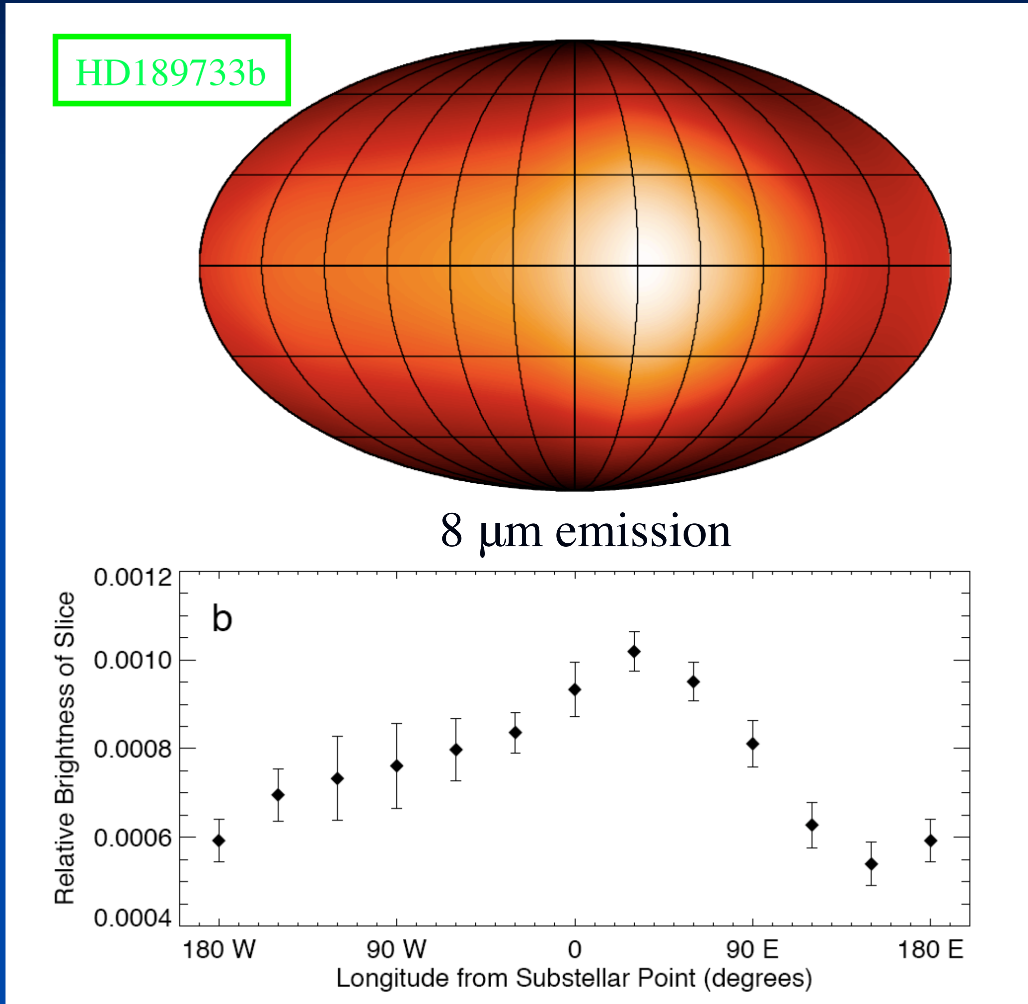
Vidal-Madjar et al., *Nature*, 2003
Ballester, Sing, Herbert, *Nature*, 2007
Ben-Jaffel, ApJL, 2008

Absorption from H beyond the Roche limit (Vidal-Madjar)

Extinction by hot thermospheric hydrogen (Koskinen et al. 2010)

Exoplanet's Emission

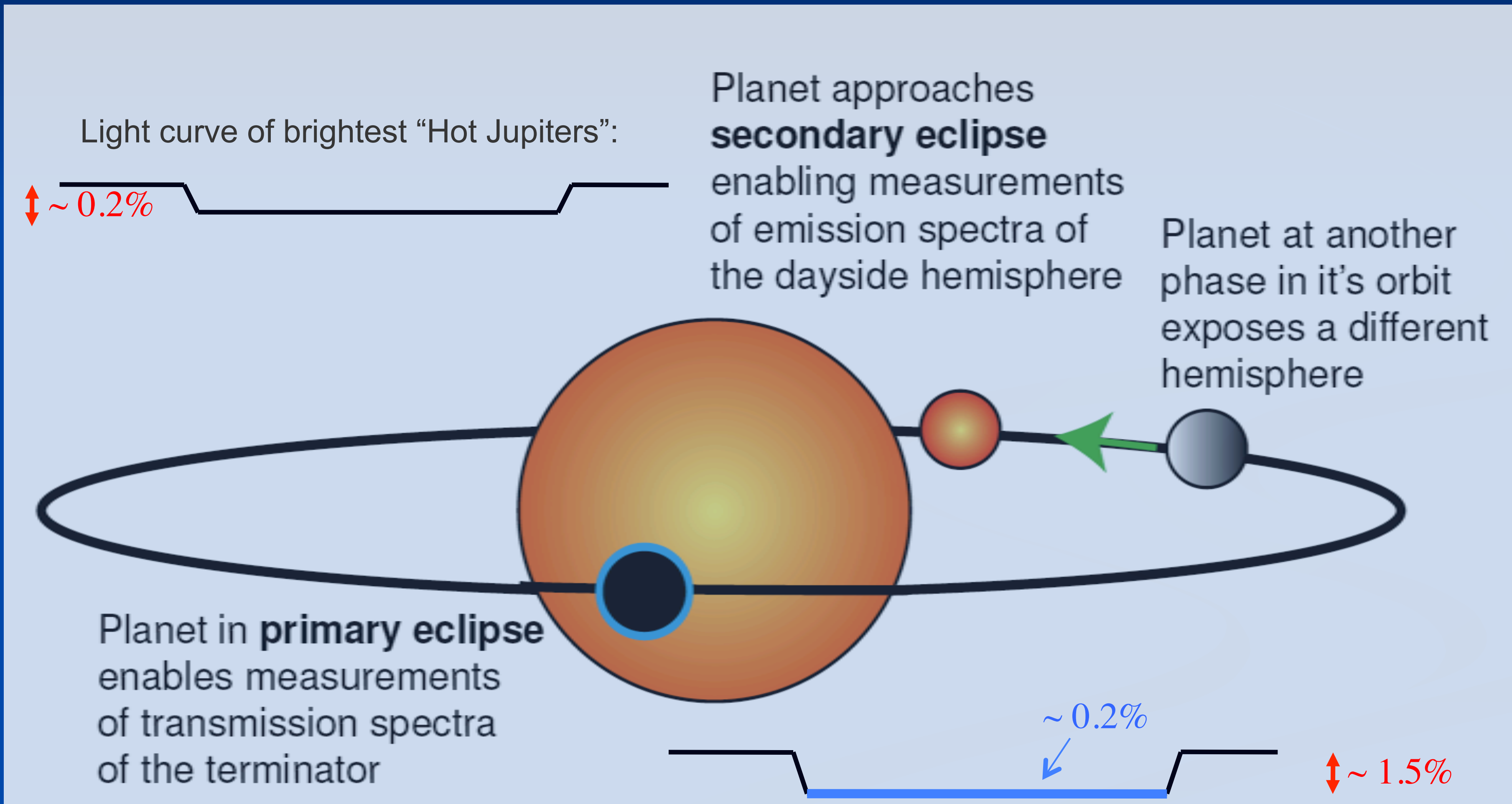




Knutson et al. 2007

Emission photometry: Charbonneau et al. 2005, Demming et al. 2005 (HD209458b)

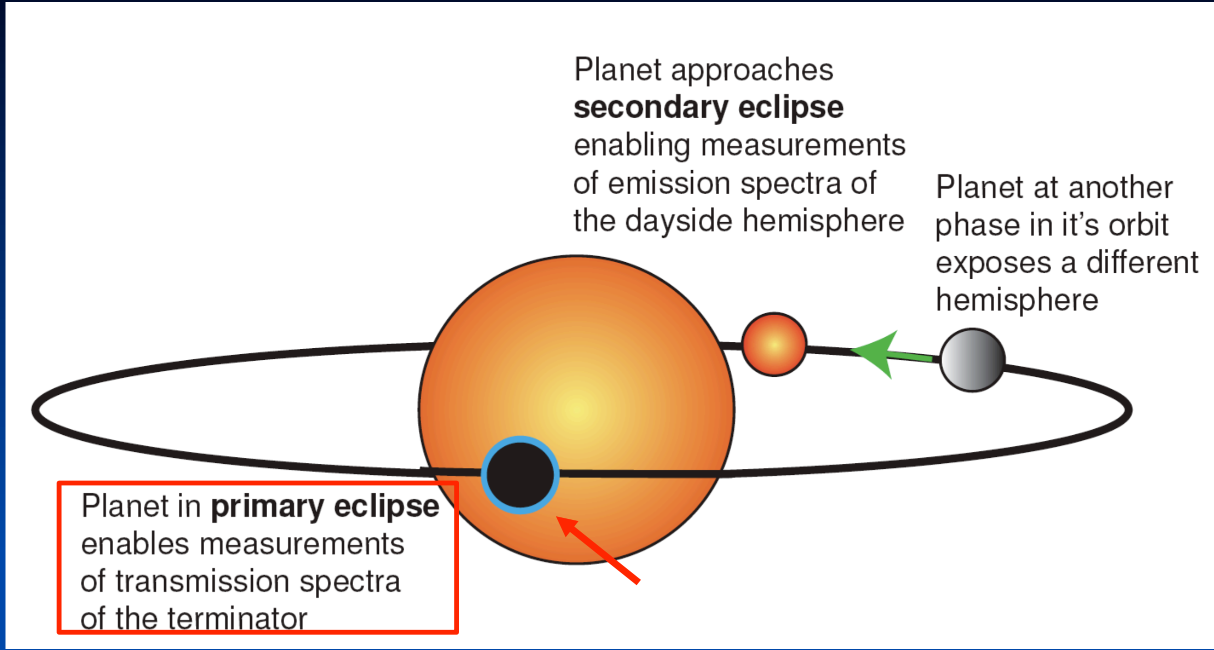
Primary vs Secondary Transits:



Secondary Transit provides information on Temperature & Composition Profiles

Primary Eclipse

Composition &
Atmospheric scale height



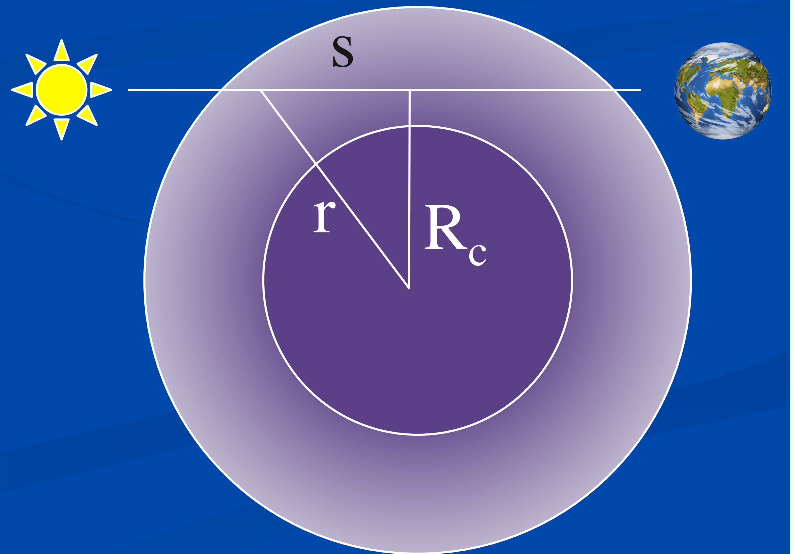
Depth of the observed light curve:

$$A = \frac{\pi R_P^2}{\pi R_S^2} + \int_{R_P}^{\infty} 2\pi r(1 - T(R))dr/\pi R_S^2$$

Integrate the column density along the tangent line:

$$\int_{-\infty}^{\infty} N(r)ds \approx N(R_c)\,(2\pi R_c H)^{1/2}, \quad where\ H = \frac{R_g T}{mg}$$

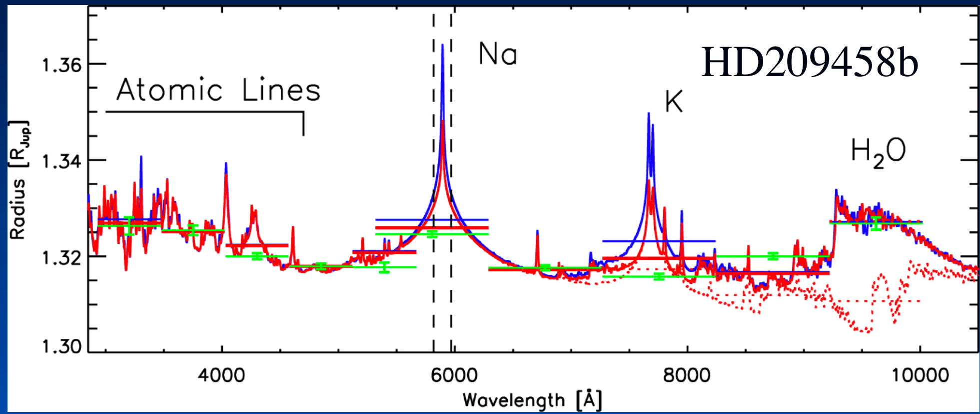
$N(R_c)$ is the density at the tangent line's closest distance to the planet's center, R_c



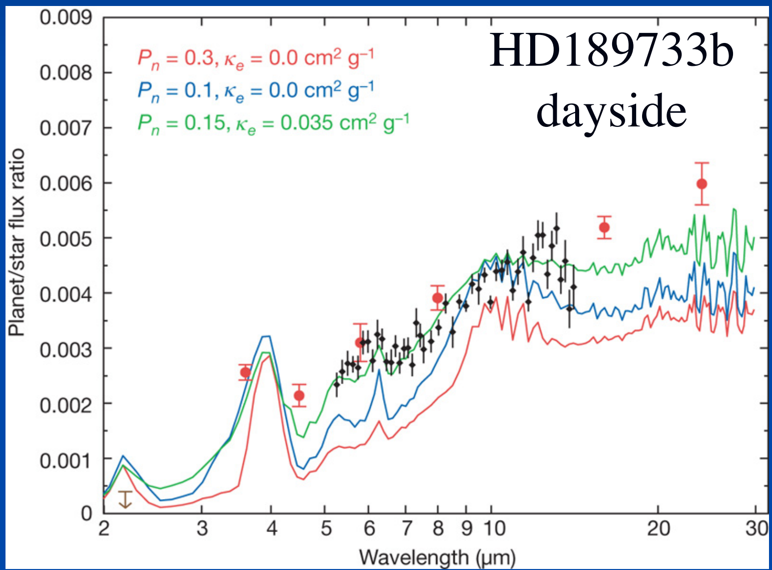
Degeneracy of $R_{10\ bar}$ & composition

Detection of Molecules in Extrasolar Planets

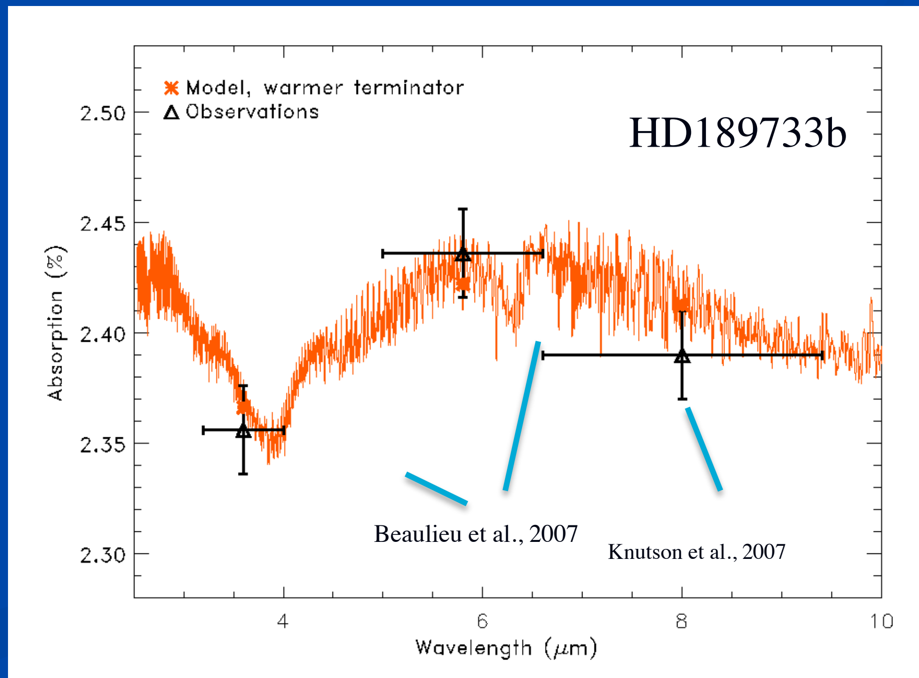
Molecular Composition: H_2O



Barman et al., 2007



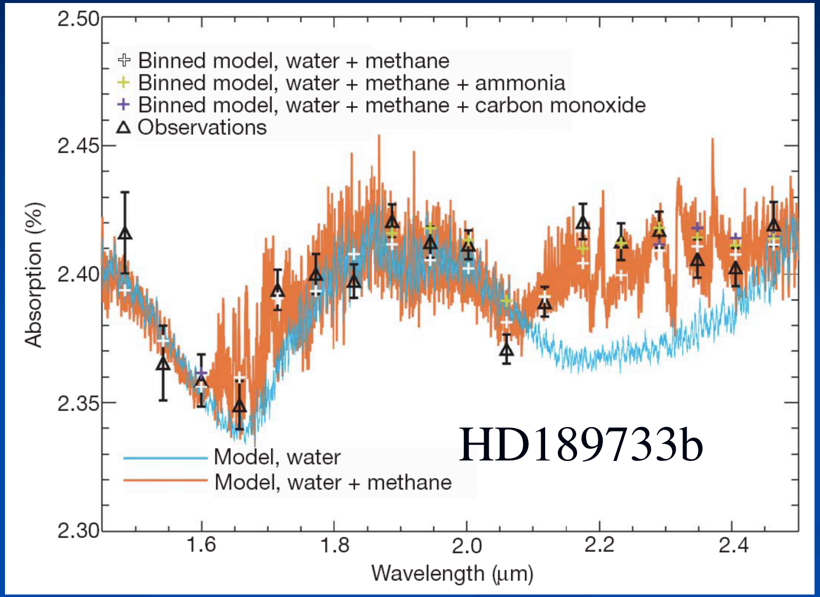
Grillmair. 2008



Tinetti *et al.*, Nature, 2007

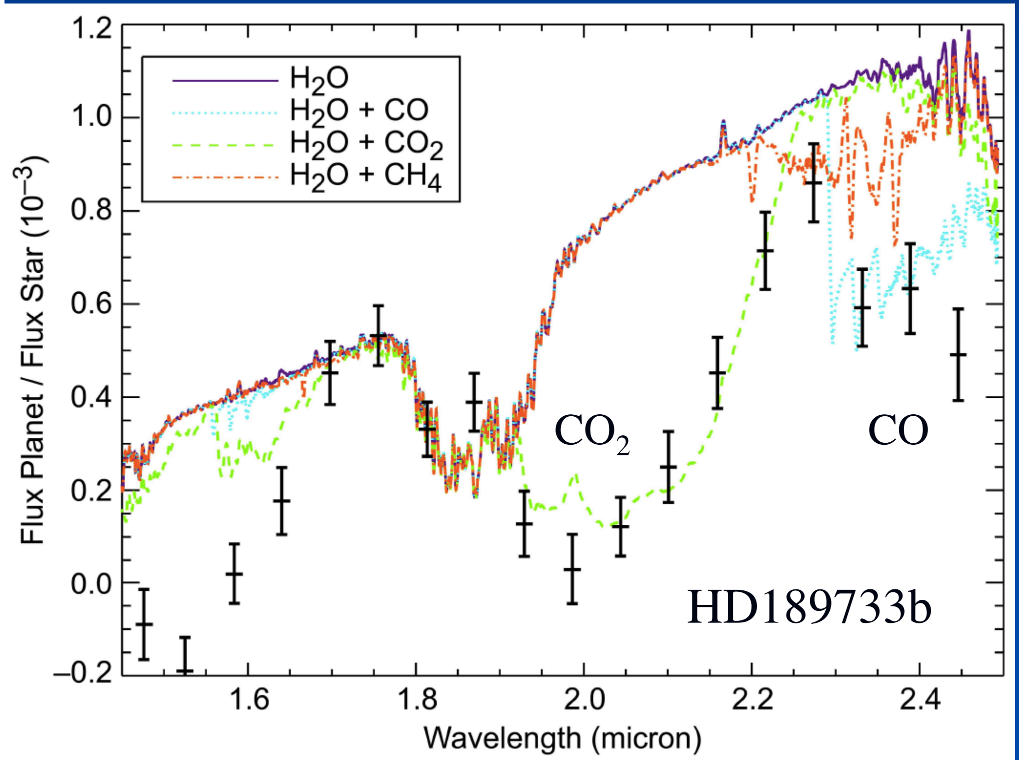
Molecules: CH_4, CO_2 & CO

CH_4



Swain, Vasisht, Tinetti, *Nature*, 2008

CO & CO_2



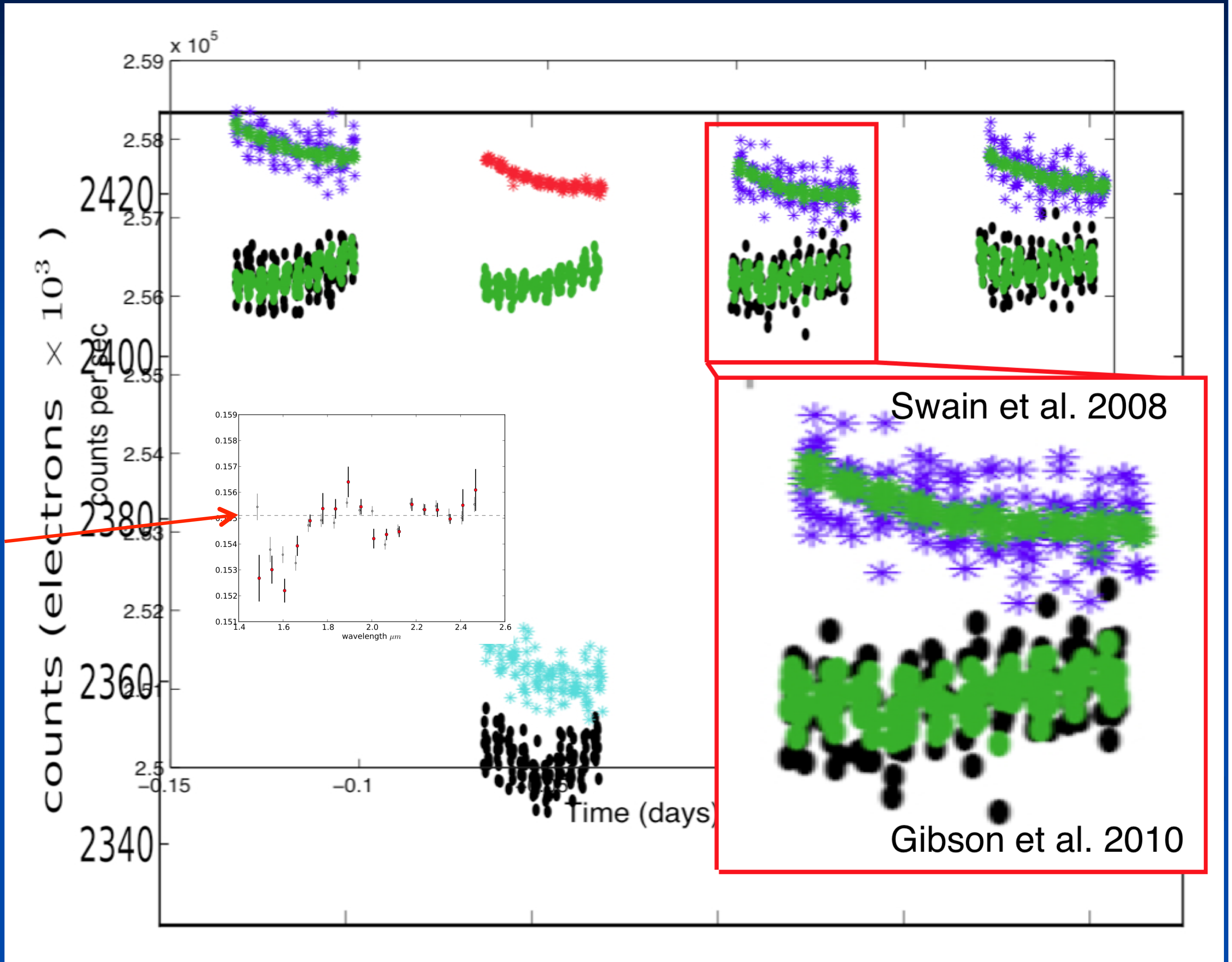
Swain et al, *Ap J.* 2009

All measurements are space-based

Swain et al. 2008 and Gibson et al. 2010 compared
- controversy becomes confirmation -

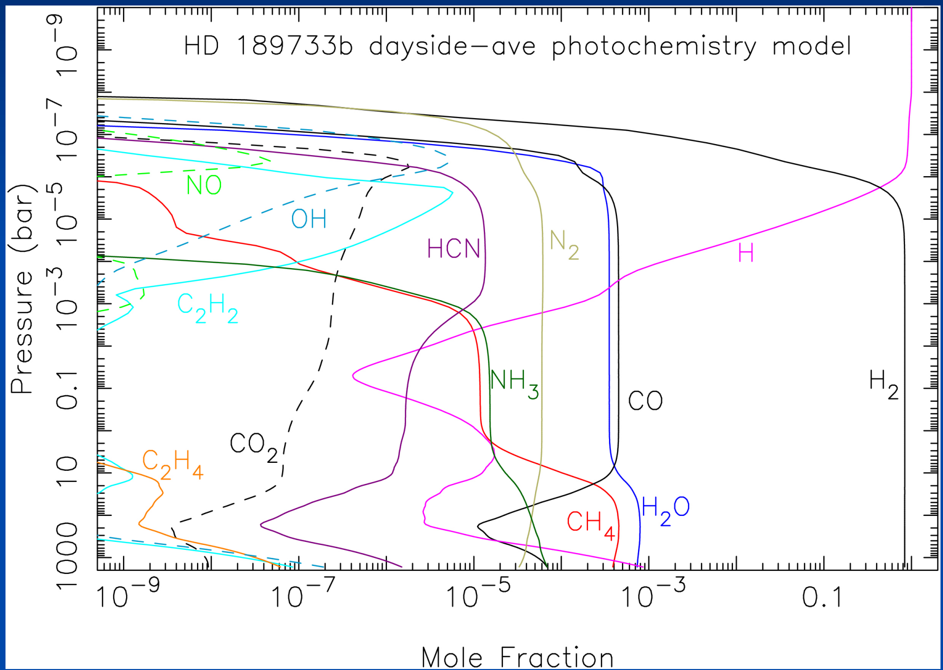
HST/NICMOS
HD189733b 1.4-2.5 um

- Figures taken directly from both papers
- Single channel photometry compared
    - Blue (Swain)
    - Black (Gibson)
- Instrument model for both shown in green
- **Key difference is the SNR of instrument model**
- **Noisy instrument model = noisy Gibson result (red)**
- The Gibson result with larger errors is due to a poorly determined instrument model.
- If you can make the comparison by eye in these kinds of plots, the difference is very big.

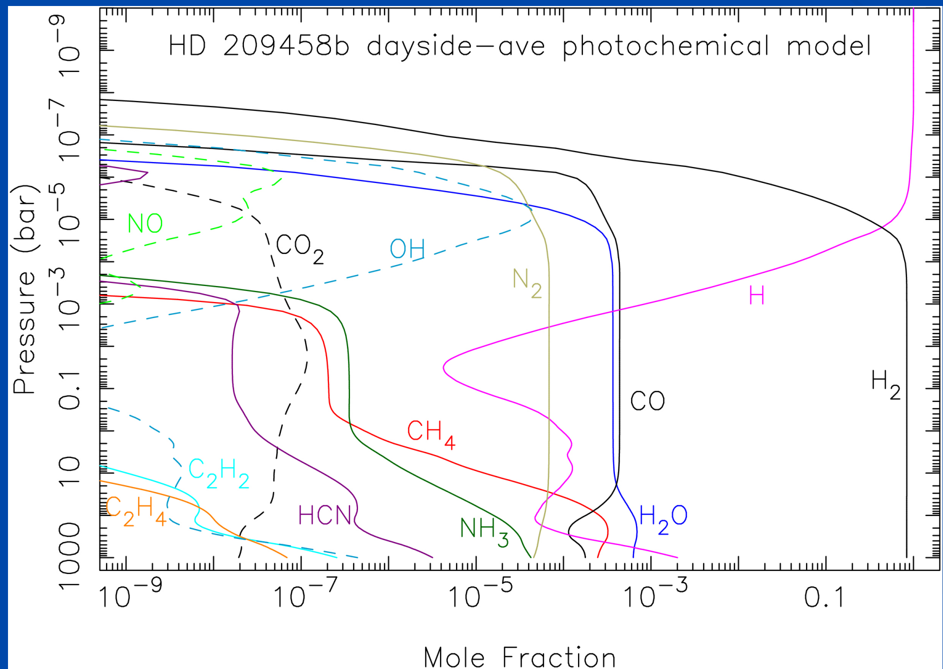


The XO-1 extracted spectrum does not agree, because Gibson omitted the decorrelation parameters (ΔX, ΔY, & θ) which trace the small motions of the spectrum across the detector, the main source of systematic errors.

Are the detected molecules expected?



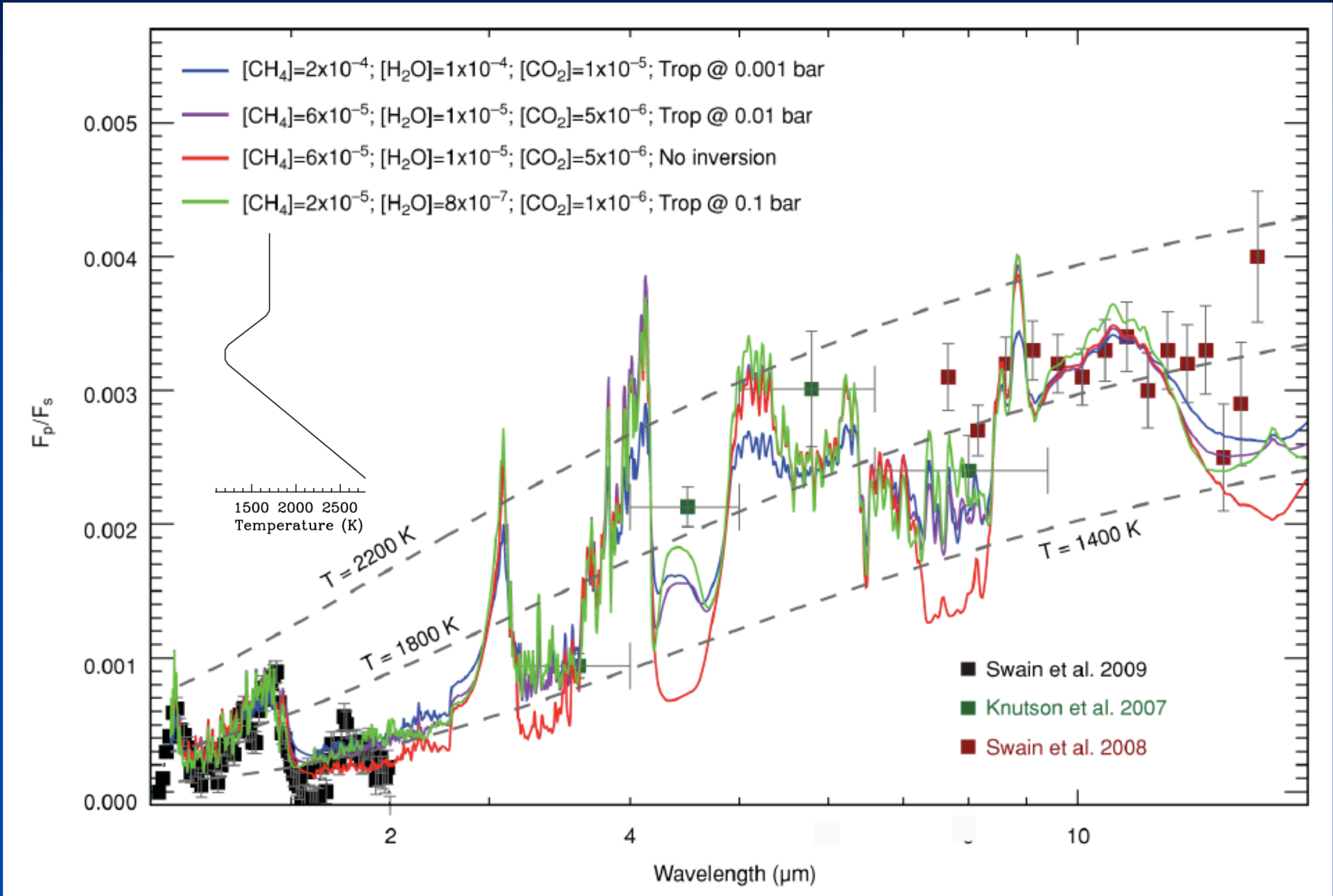
Calculations from Julie Moses



But do we derive similar abundance profiles?

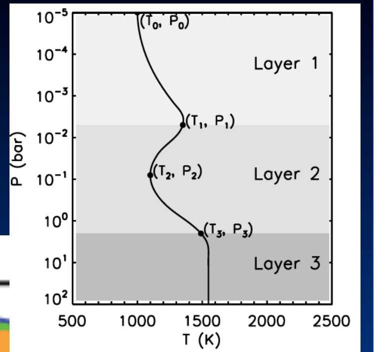
Many methane atmospheres

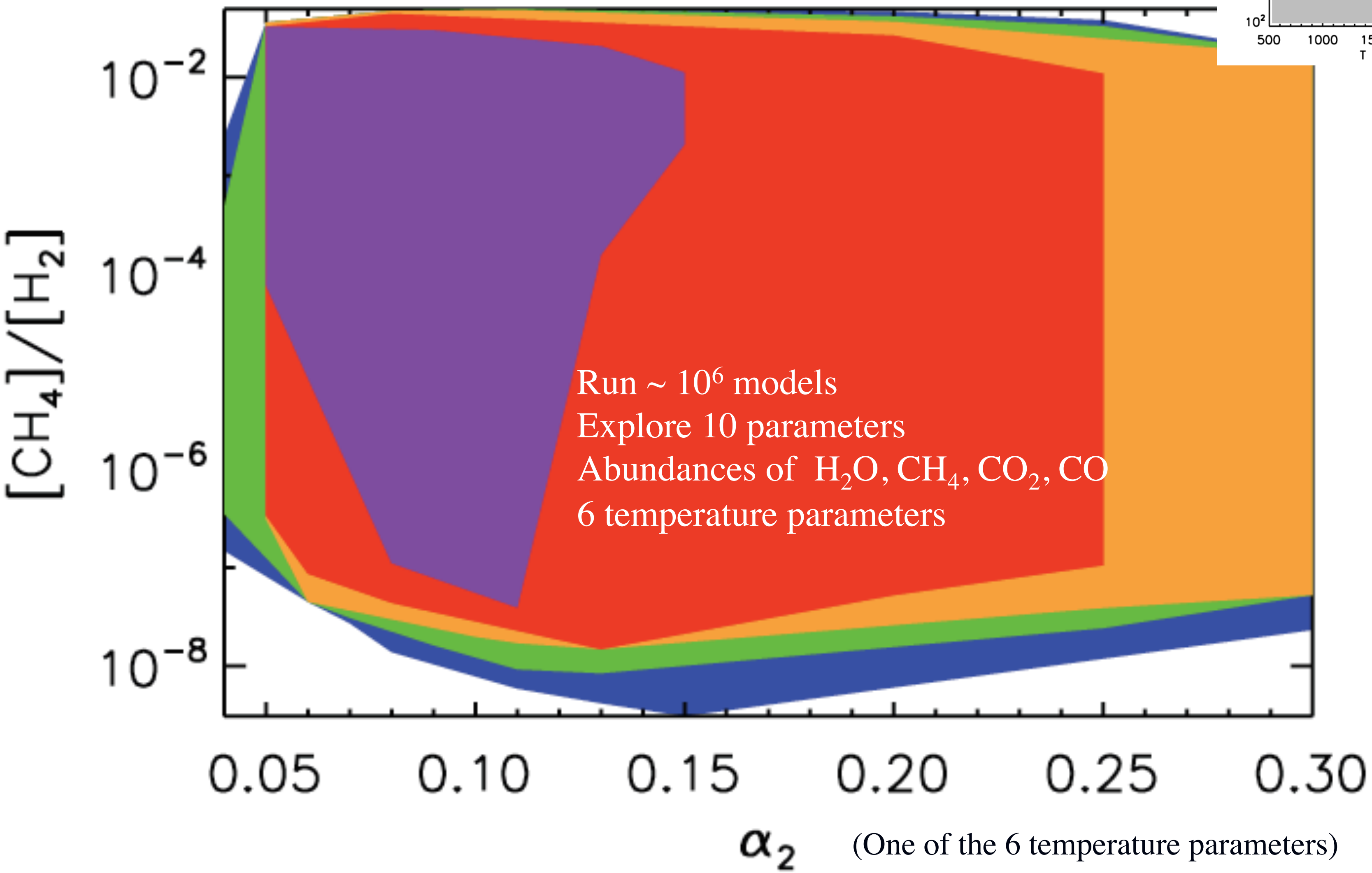
Composition & Temperature Profiles



Swain et al. 2009

Degenerate Solutions





(One of the 6 temperature parameters)

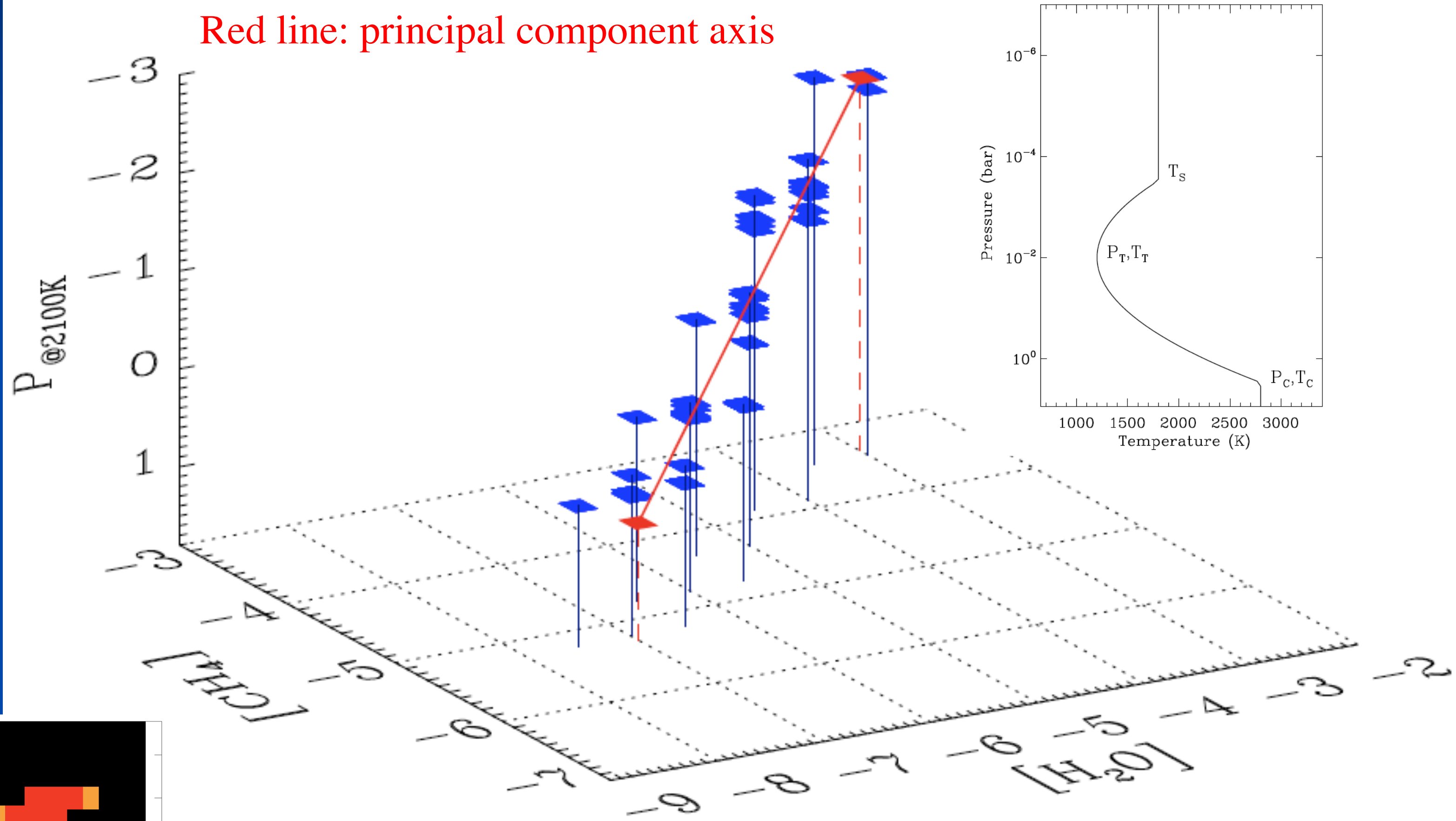
Madhusudhan & Seager 2009

Principal Component Analysis

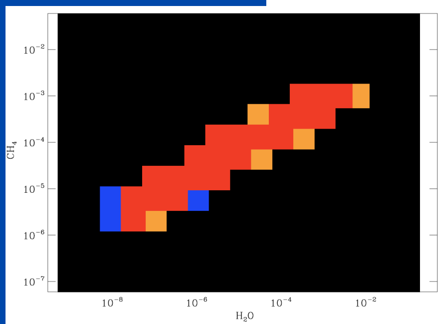
Correlations between the n=8 parameters that match the data

Blue diamonds: 500 models that match data

Red line: principal component axis



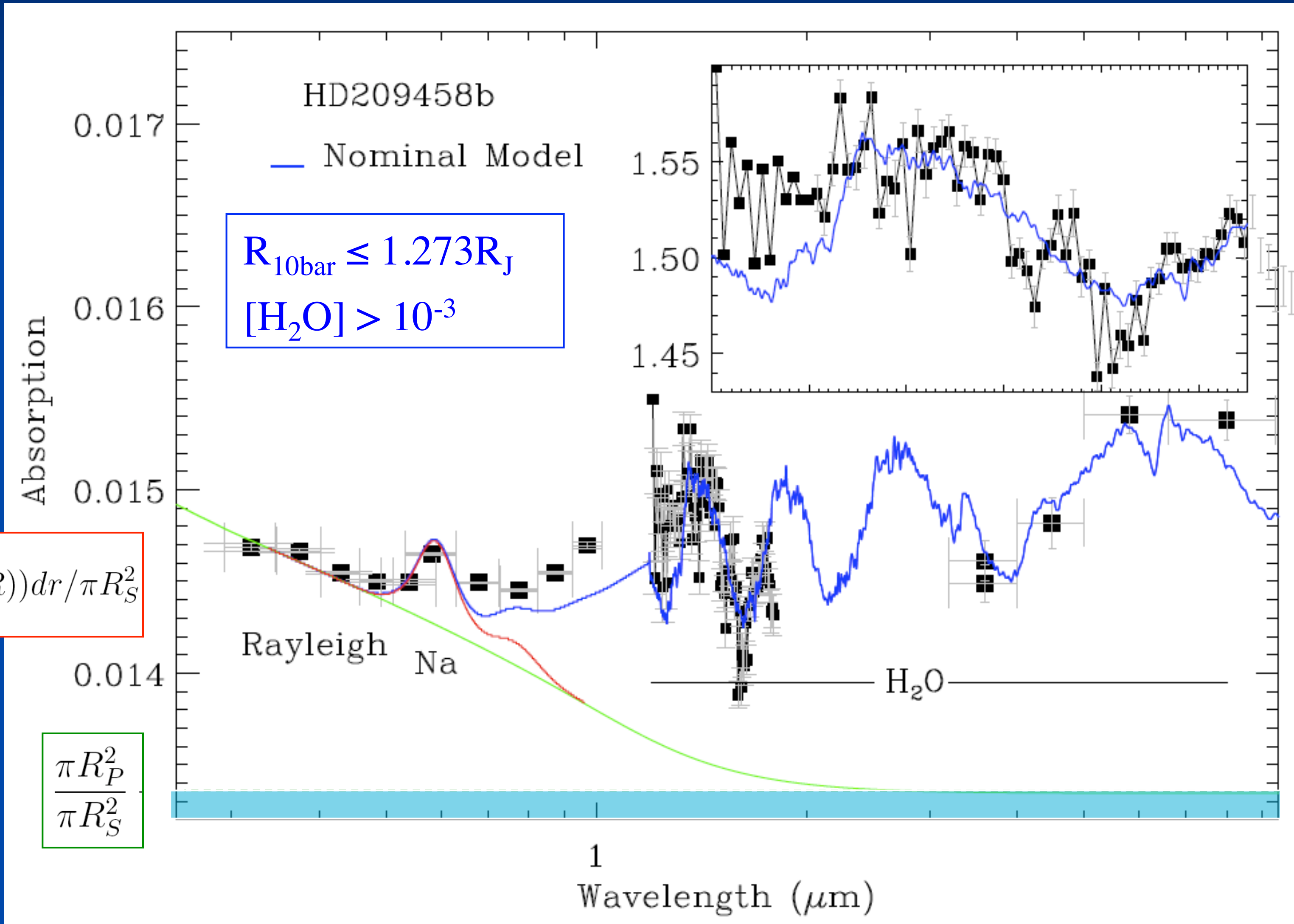
Griffith et al. 2010, In prep.



Eigenvalues of covariance matrix, $C_{n,n}$ i.e. $C_{i,j}$=cov(p_i,p_j) & $C_{i,i}$=var(p_i,p_i)

Transmission Spectra

System	$(R_{planet}/R_{star})^2$	Atmosphere
HD209458b	0.0132	0.001-0.002
GJ1214b	0.0135	0.003 (H_2)
Earth	8.4x10^{-5}	10^{-6}



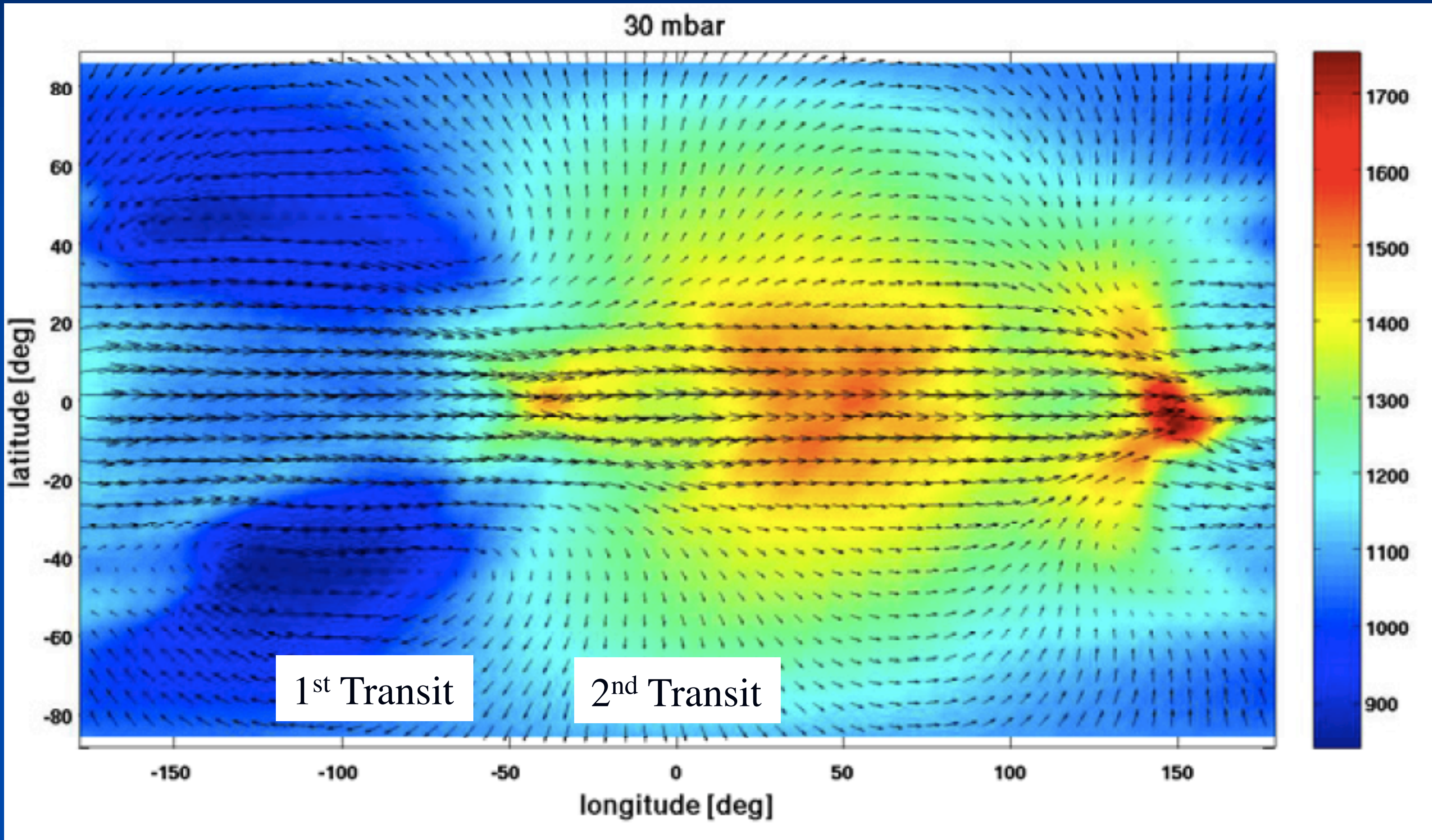
$$\int_{R_P}^{\infty} 2\pi r(1 - T(R))dr/\pi R_S^2$$

10 bar radius:
$R_P \leq 1.273\ R_J$

$$\frac{\pi R_P^2}{\pi R_S^2}$$

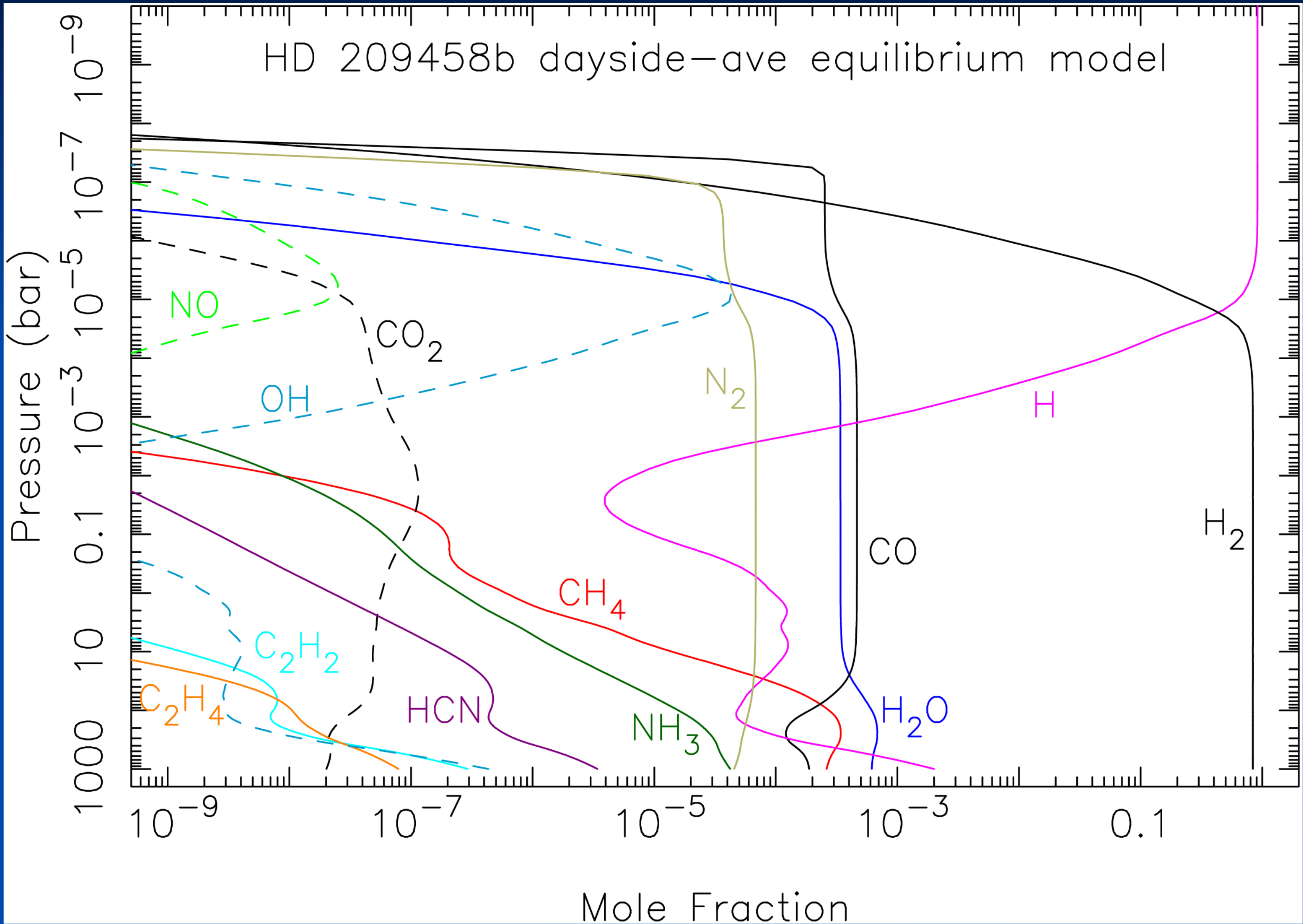
Griffith et al. 2010, In prep.

1st & 2nd transits probe different hemispheres



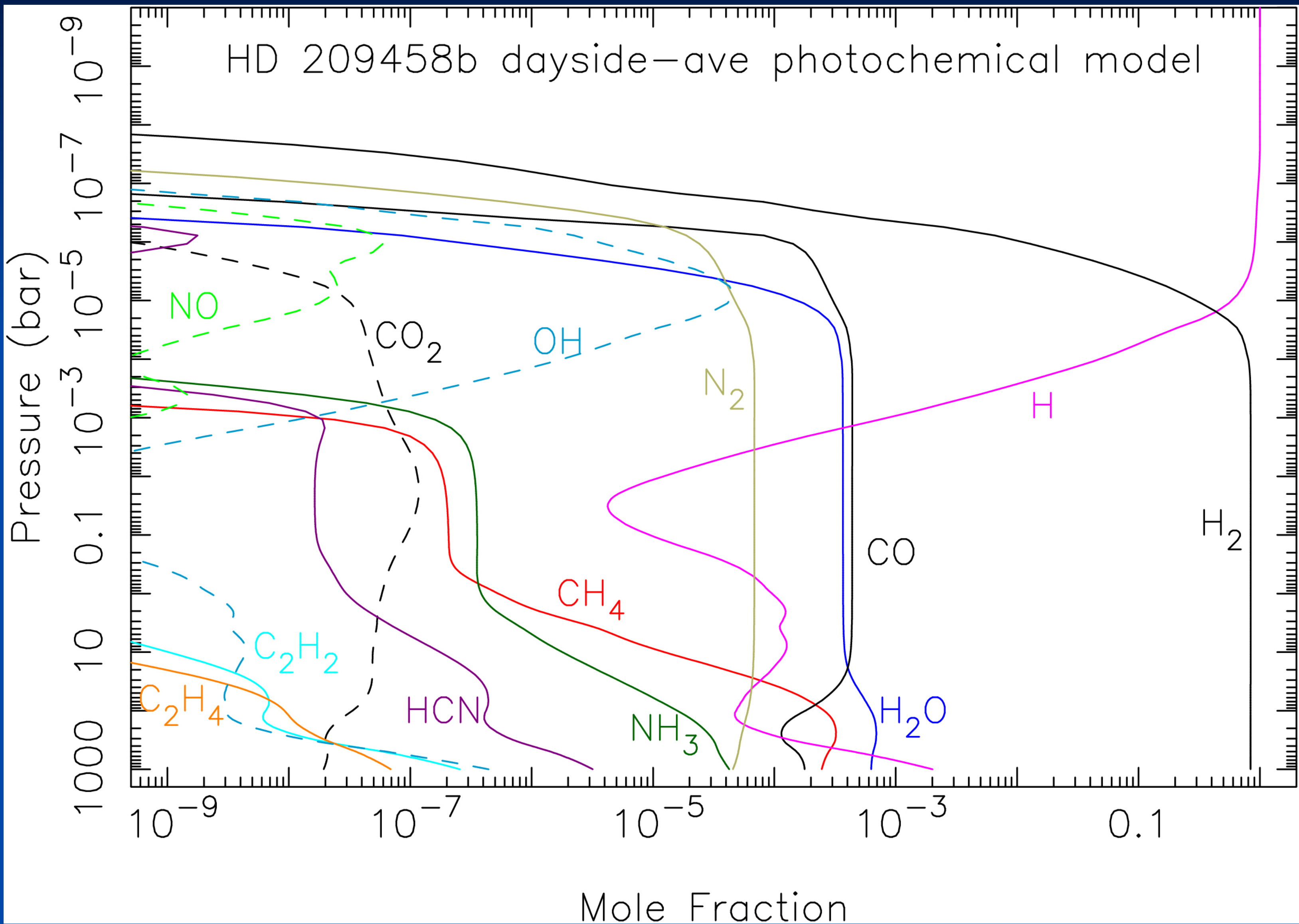
From Showman et al. 2009

Thermochemical Equilibrium



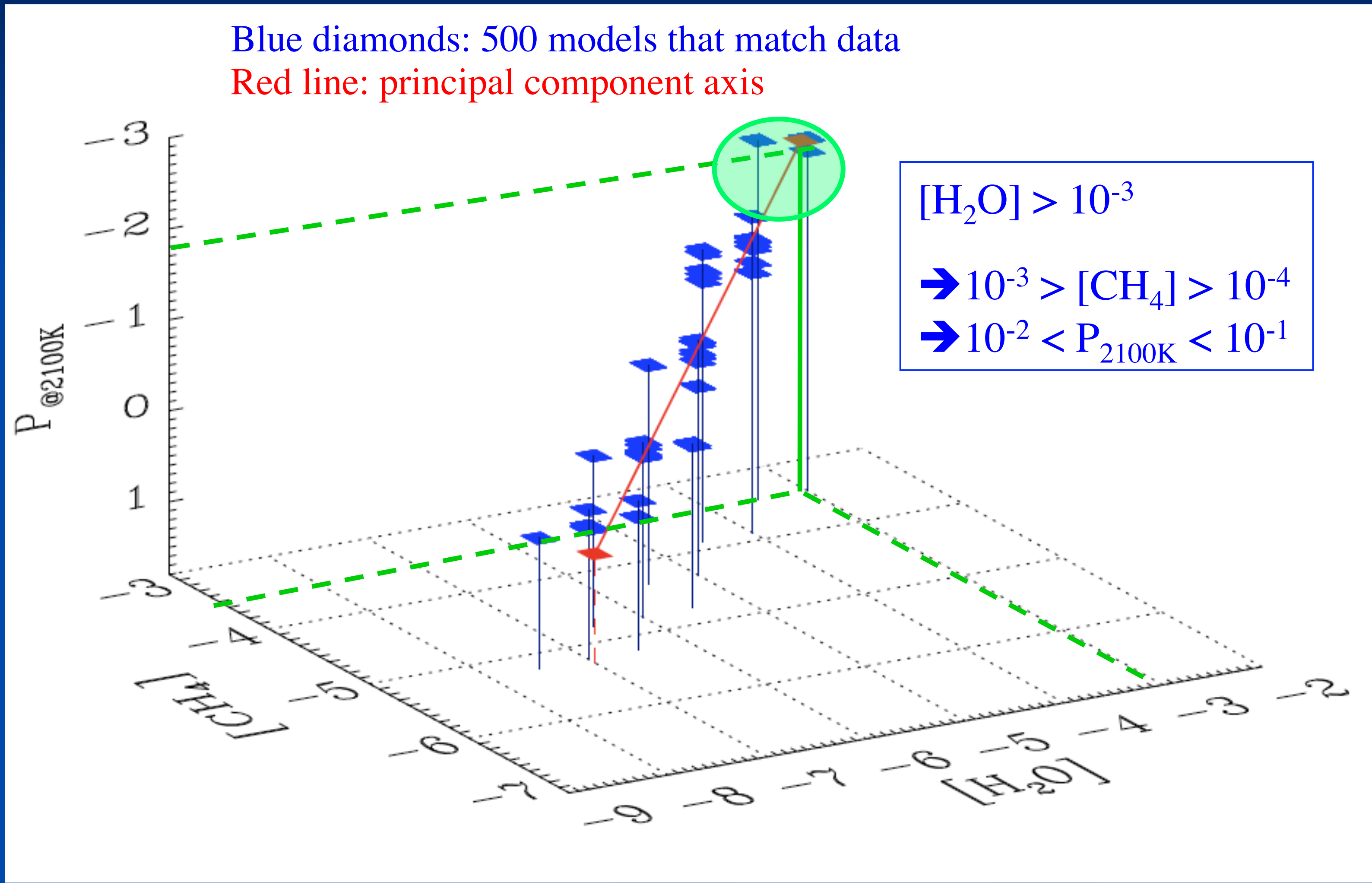
From Julie Moses

With Photochemistry



From Julie Moses

Greedy H_2O unites observations



Griffith et al. 2010, In prep.

Indications

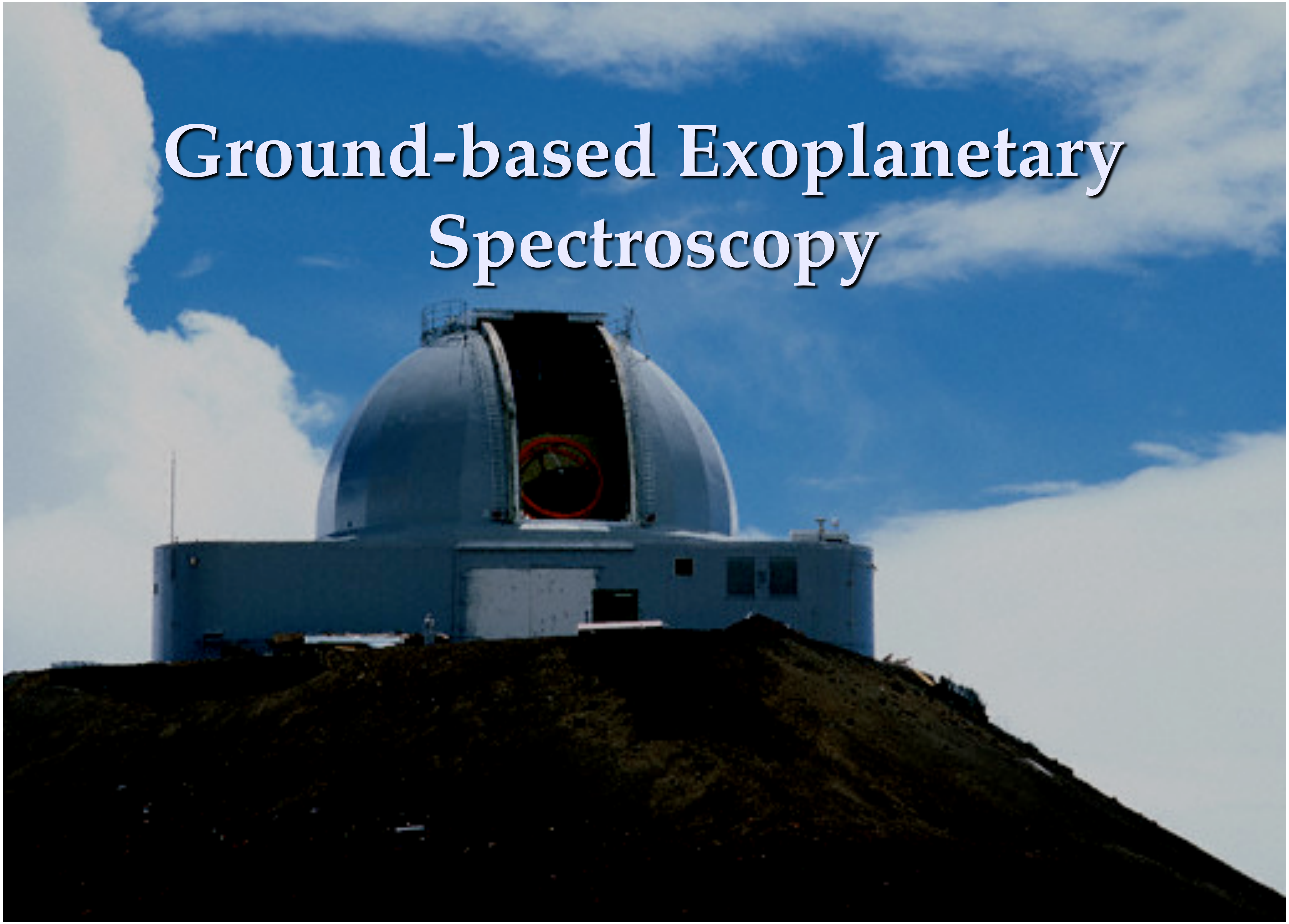
We find that:

- HD209458b's 0.4 um spectrum constrains the planet's radius, simply because Rayleigh scattering dominates.

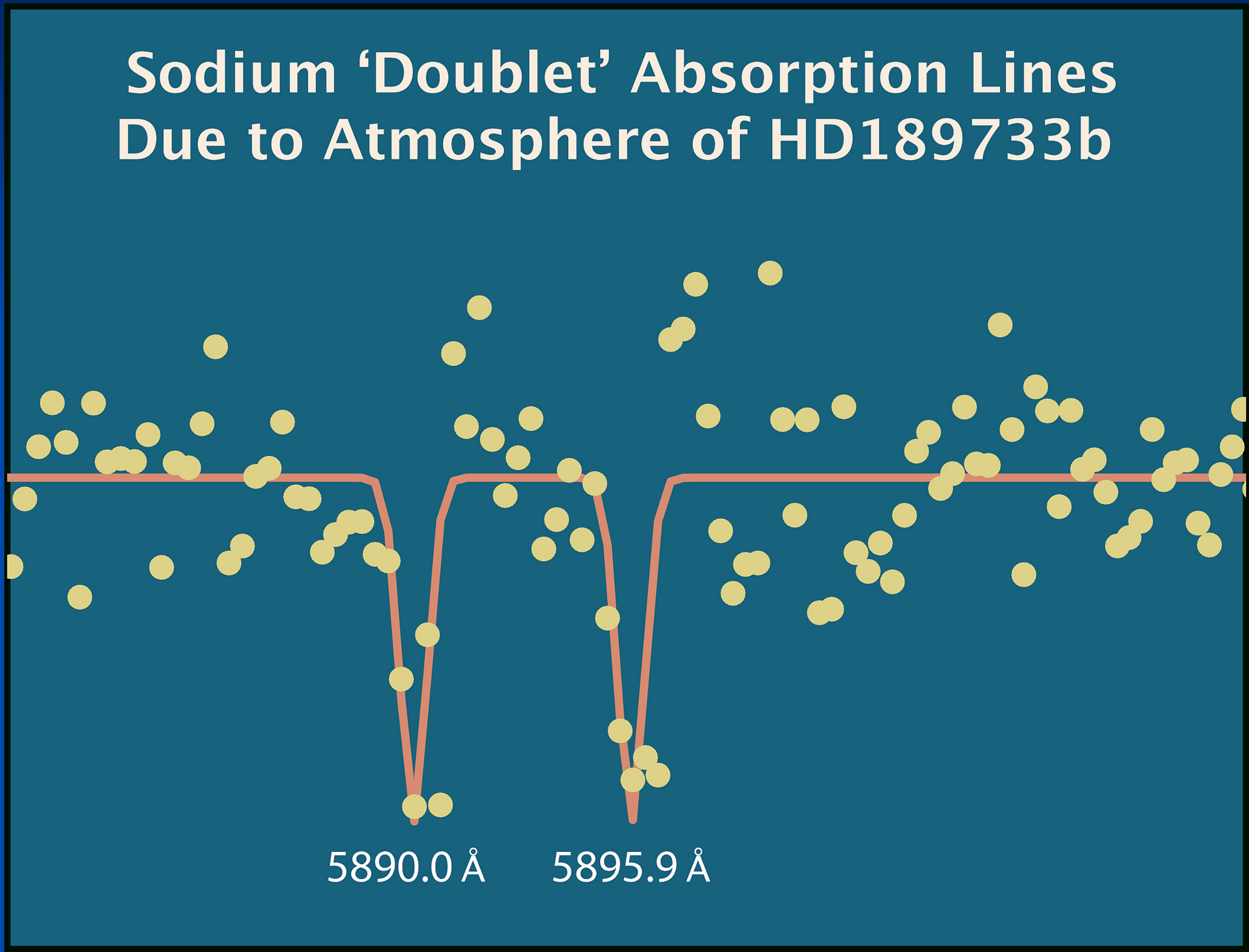
- Transmission & emission spectra can be analyzed jointly to constrain the composition and thermal structure because H_2O largely dictates the spectrum, and its abundance is expected to be constant.

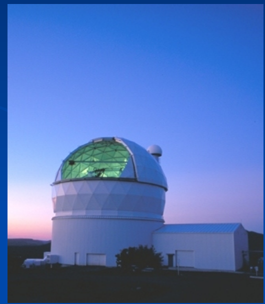
- Suggest supersolar abundance of H_2O

- We need more data…


Ground-based Exoplanetary
Spectroscopy

Detection of Na from Ground-based Facilities



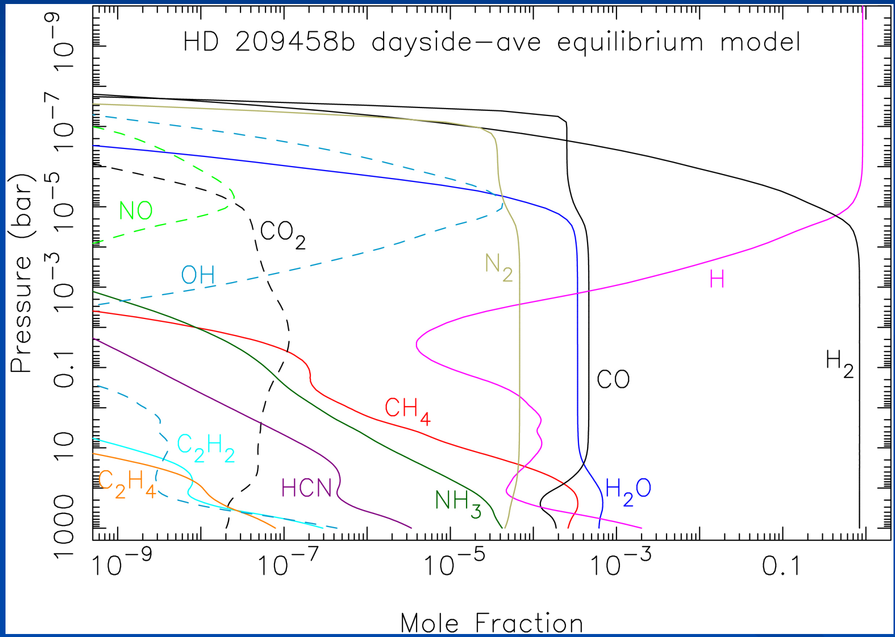


HRS/HET

Redfield *et al.*, 2008; Snellen et al., 2008; Sing et al., 2010

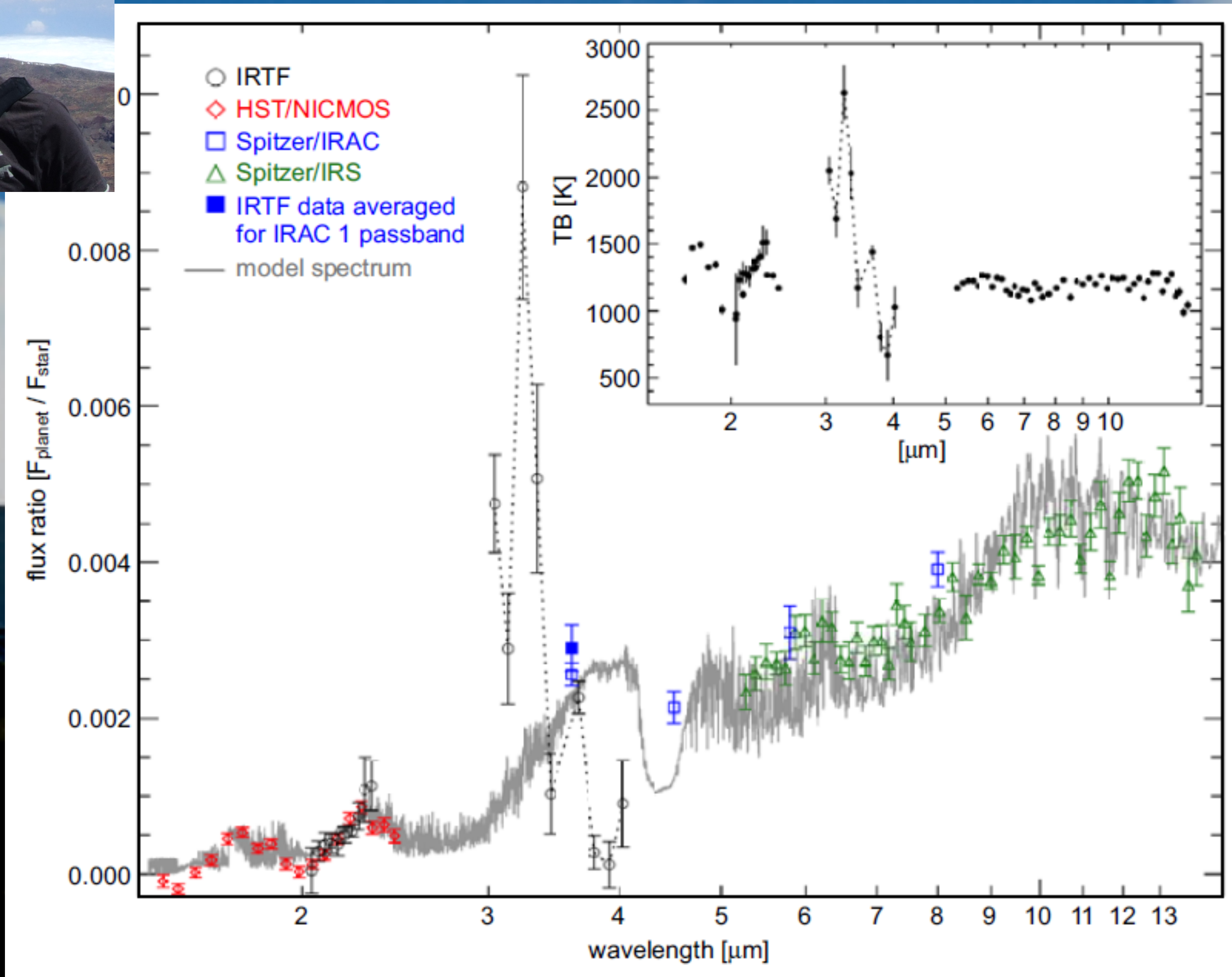
Detection of CO in HD209458b

Supersolar abundance:
[CO] = 1-3x10^{-3}



Snellen et al., 2010

Detection of 3.3 um feature on HD189733b



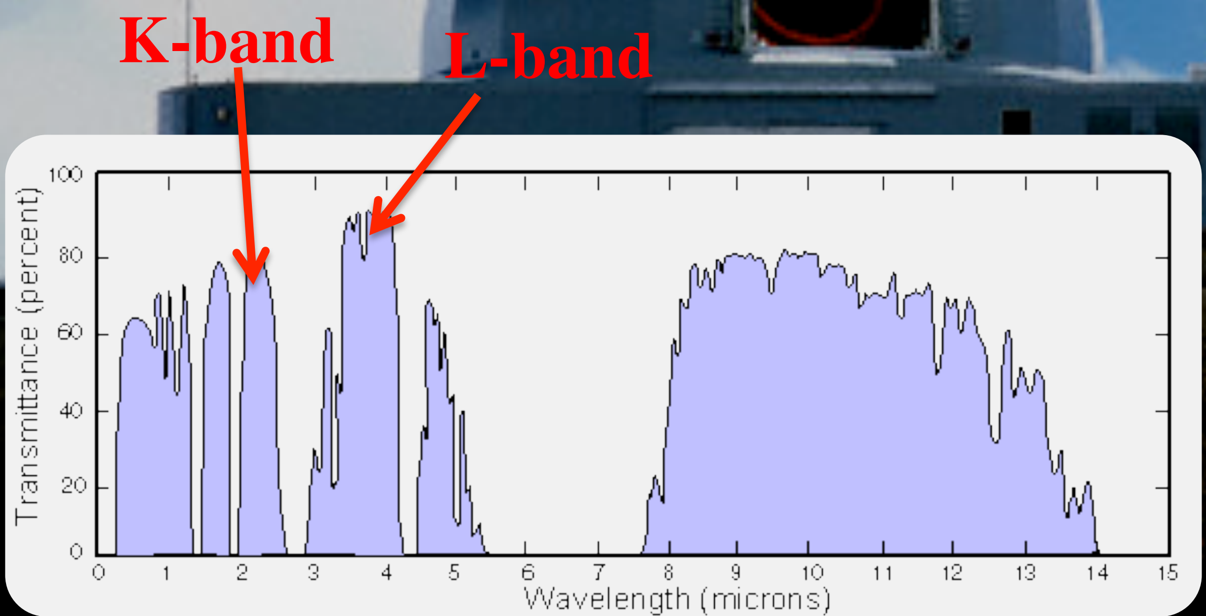
Swain et al. 2010

NASA Infrared Telescope Facility (IRTF)

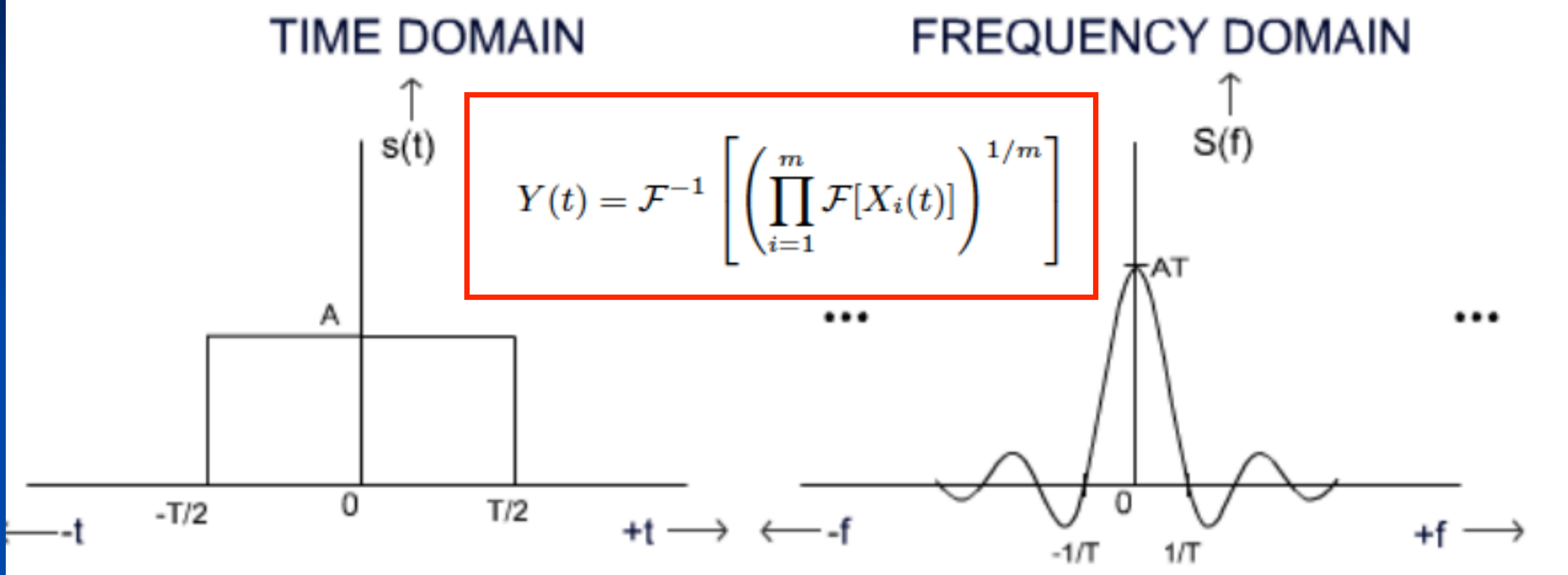
- 3.0 m primary mirror
- Mauna Kea
- optimized for NIR

SpeX instrument:

- Cross dispersion grism
- 1.9 – 4.2 microns
- Medium resolution R ~ 2000



Spectral Analysis



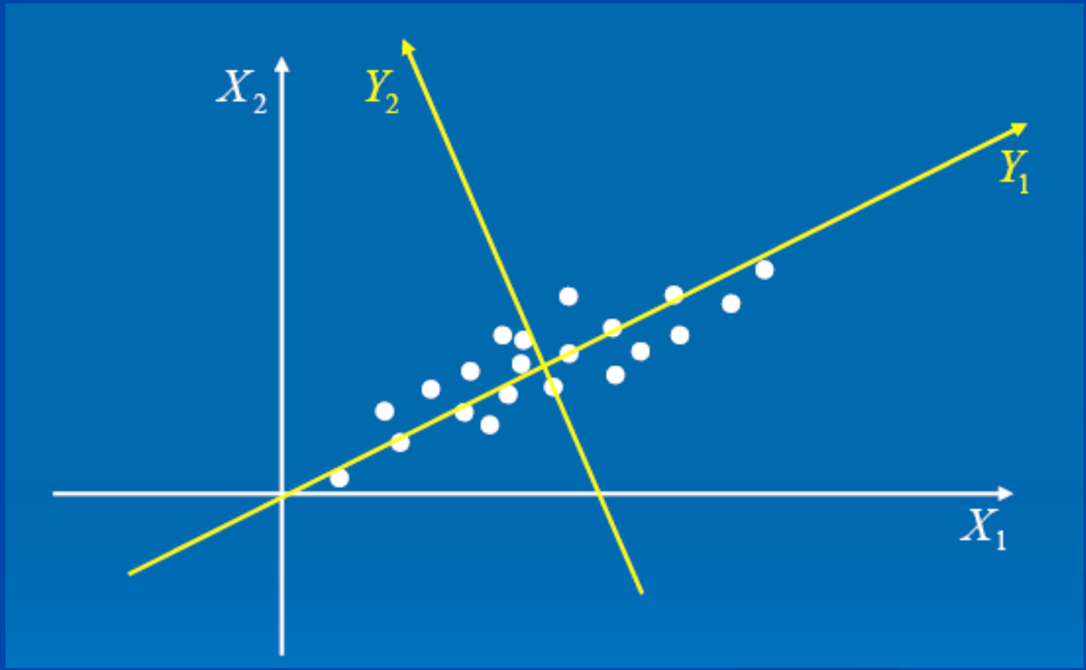
$$Y(t) = \mathcal{F}^{-1}\left[\left(\prod_{i=1}^{m} \mathcal{F}[X_i(t)]\right)^{1/m}\right]$$

$$s(t) = \begin{cases} A & |t| < T/2 \\ A/2 & |t| = T/2 \\ 0 & |t| > T/2 \end{cases} \longleftrightarrow S(f) = AT\,\frac{\sin(\pi T f)}{\pi T f}$$

Use different calibration techniques to extract systematic errors
Use different methods to extract the light curve signal

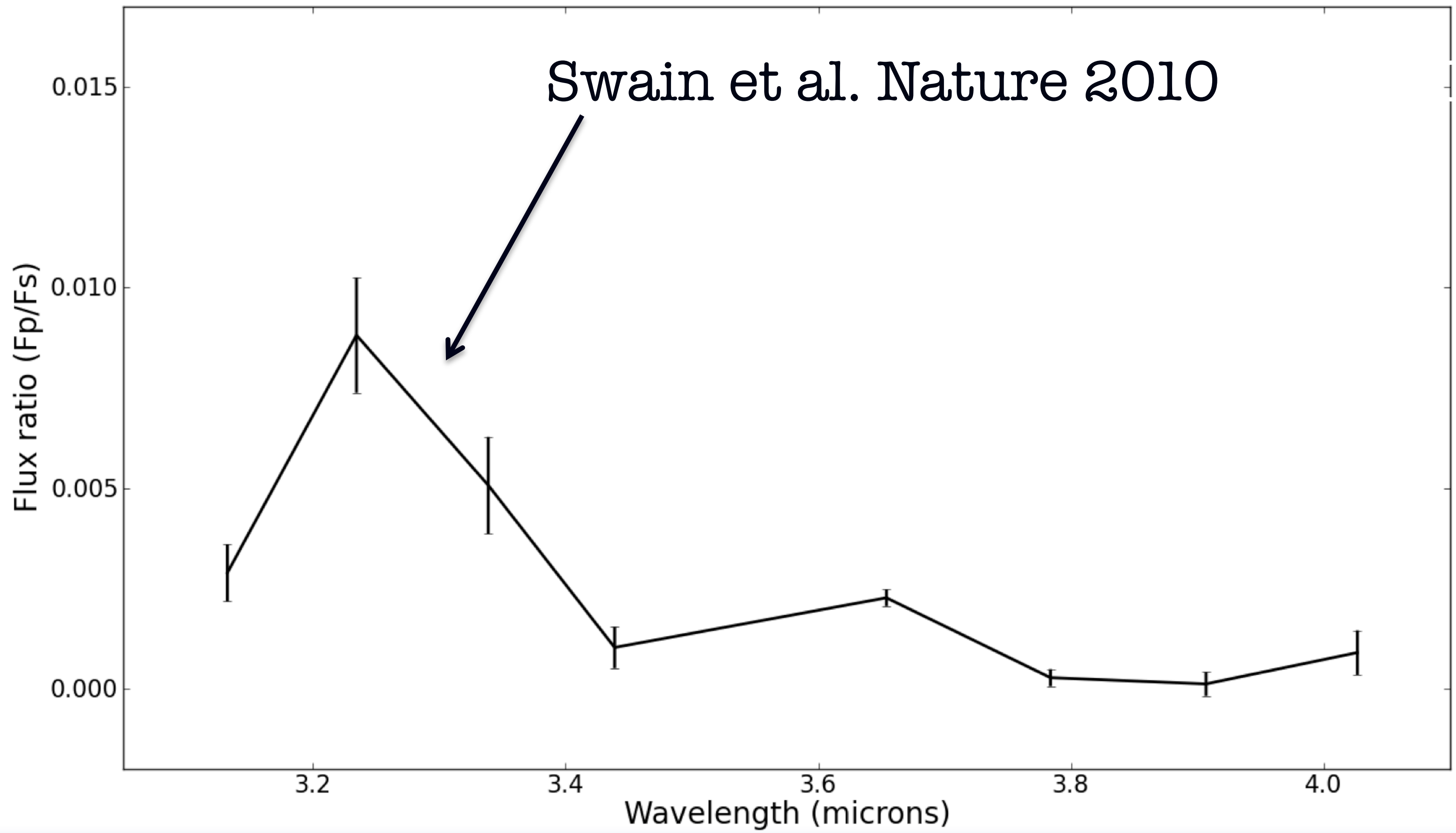
Principal Component Analysis

- PCA finds a new horthonormal base, which better represents the dataset
- Y_1 first principal component, Y_2 the second



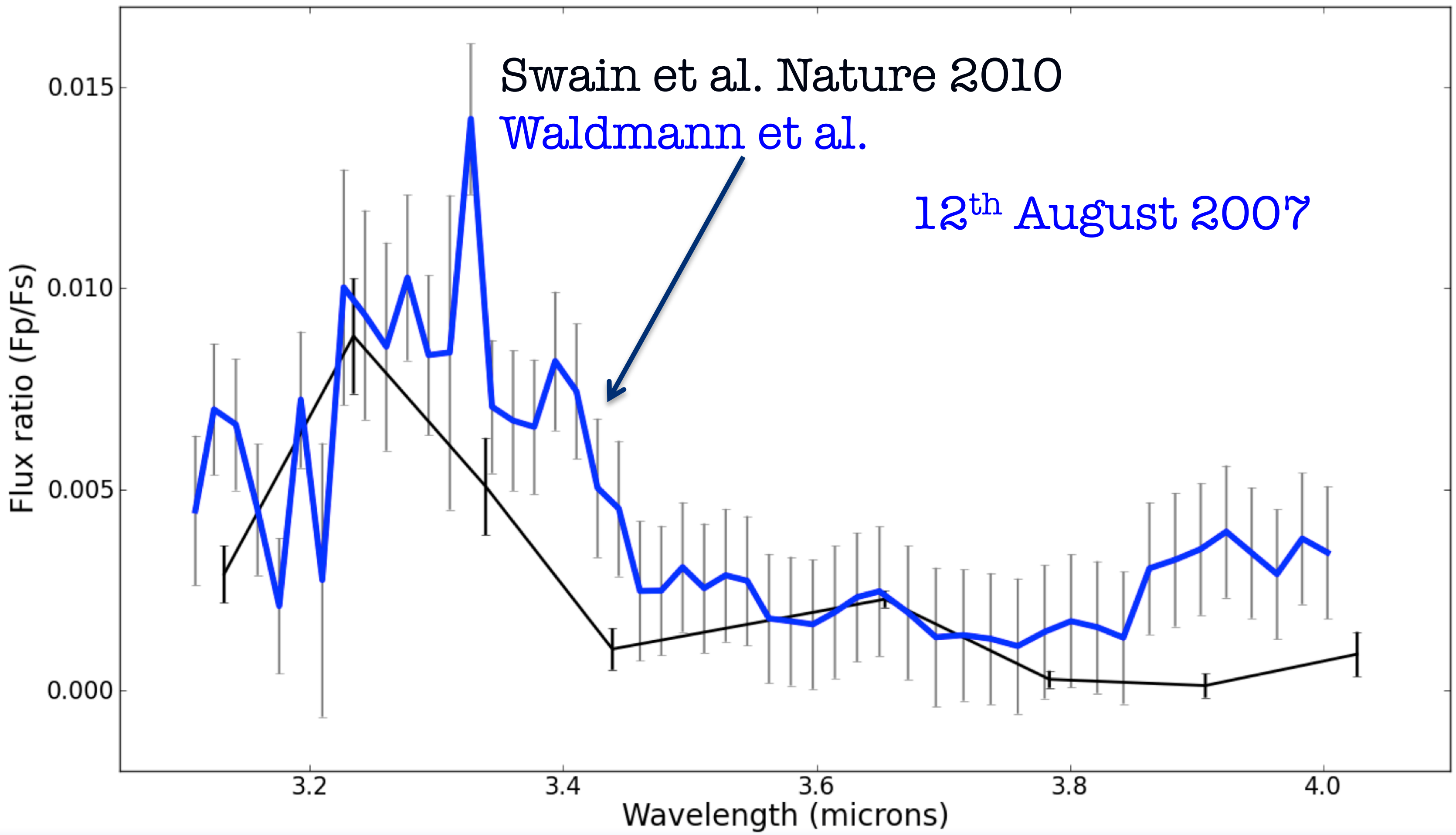
$$cov(X,Y) = \frac{\sum_{i=1}^{n}(X_i - \bar{X})(Y_i - \bar{Y})}{(n-1)}$$

HD 189733b – L band ground based spectroscopy



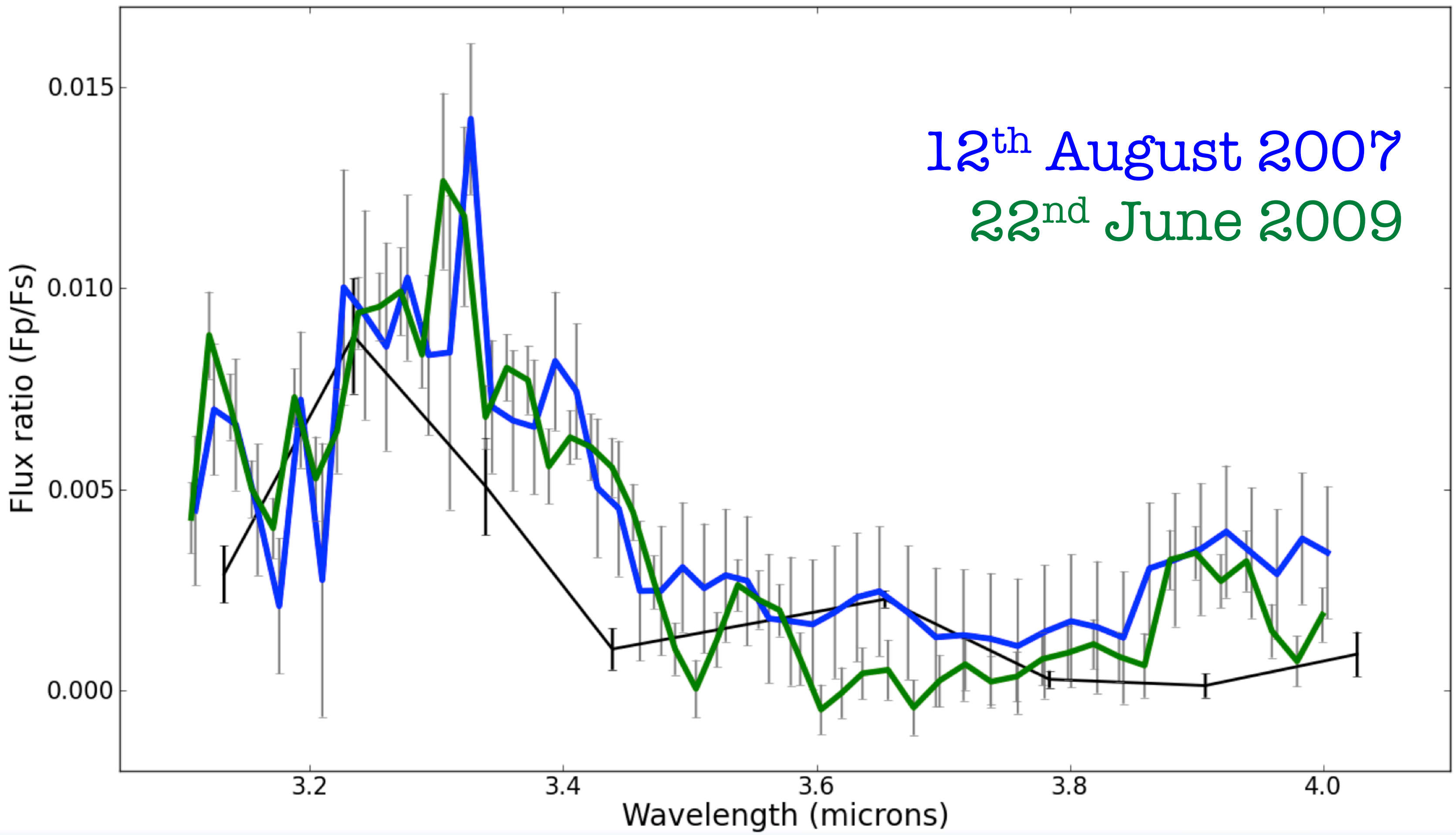
Swain et al. Nature 2010

HD 189733b – L band ground based spectroscopy



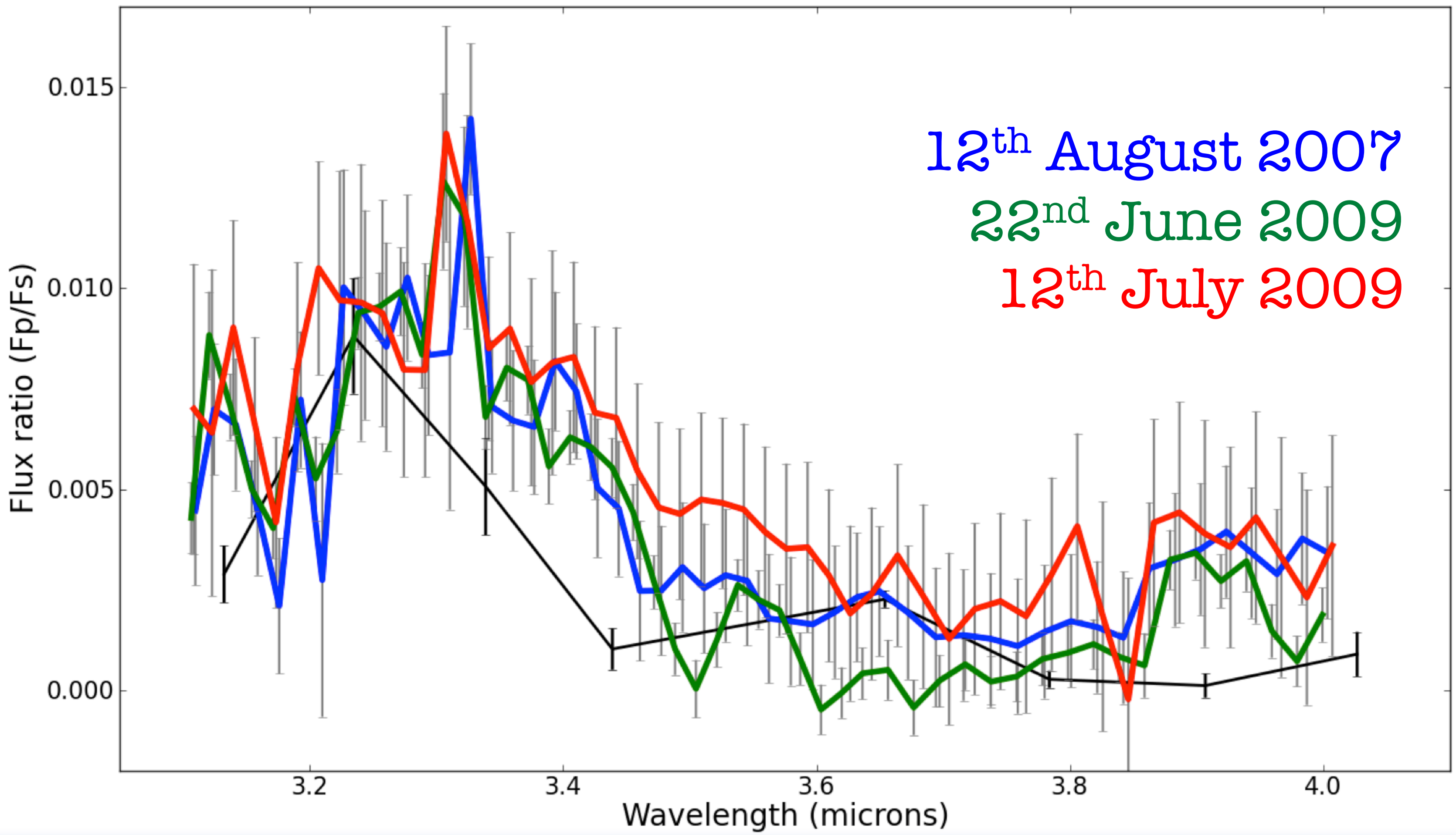
Swain et al. Nature 2010, Deroo et al., Waldmann et al. in prep.

HD 189733b – L band ground based spectroscopy



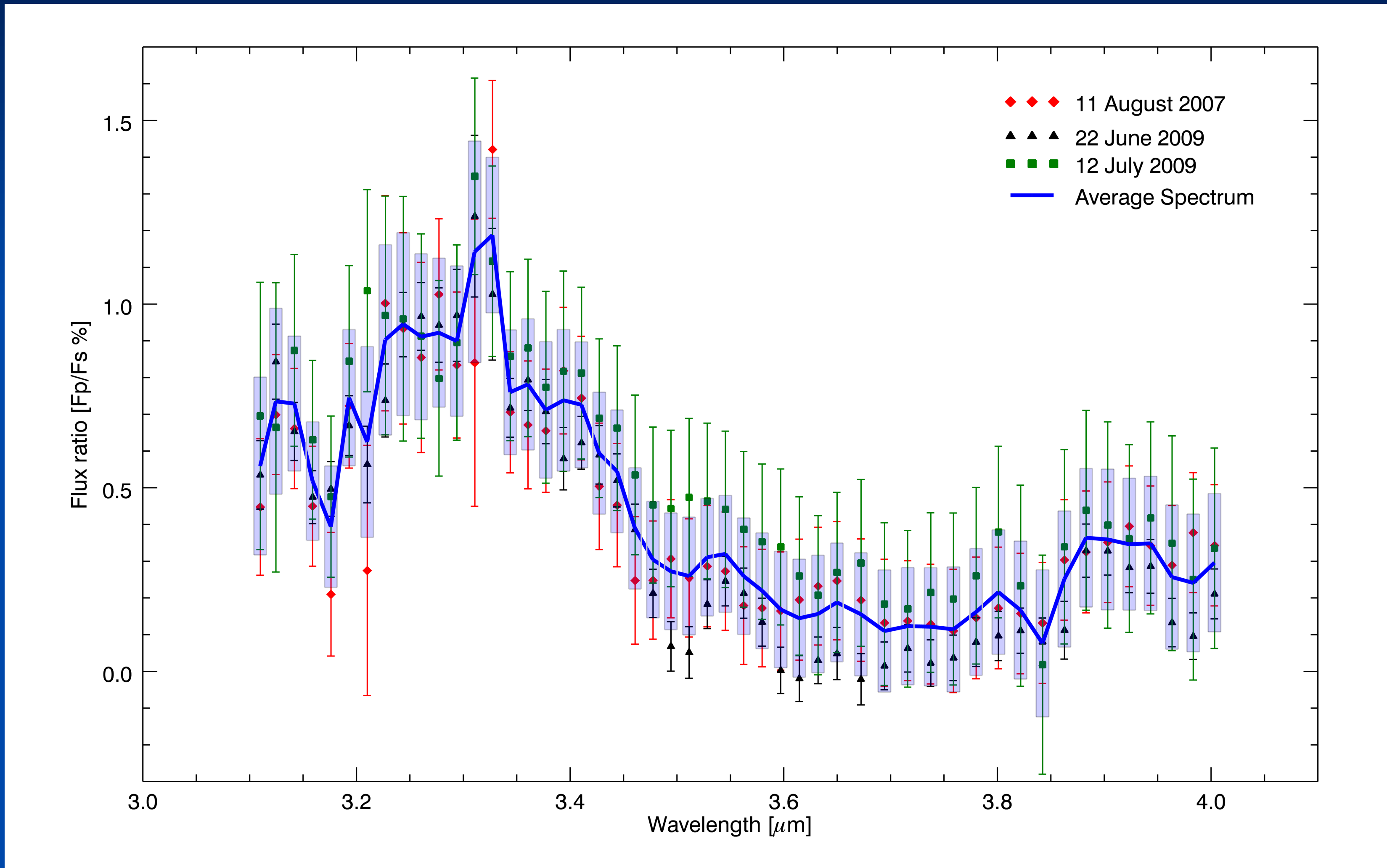
Swain et al. Nature 2010, Deroo et al., Waldmann et al. in prep.

HD 189733b – L band ground based spectroscopy



Swain et al. Nature 2010, Deroo et al., Waldmann et al. in prep.

HD 189733b – L band ground based spectroscopy



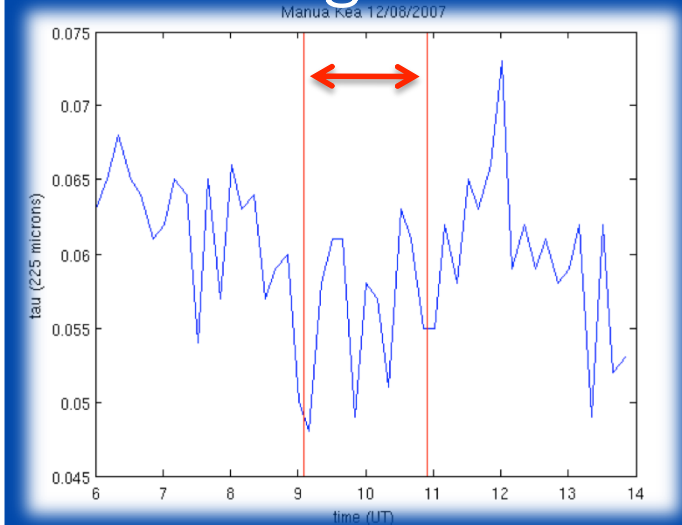
Swain et al. Nature 2010, Deroo et al., Waldmann et al. in prep.

It cannot be atmospheric water…

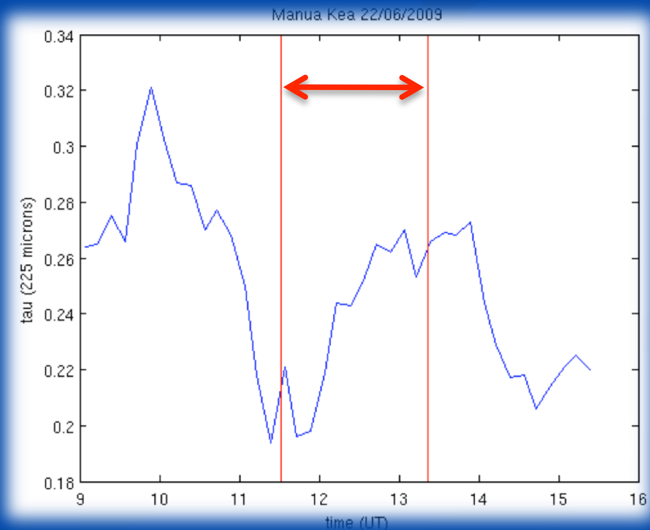
- Mandel *et al*. suggested that the spectra are due to telluric water

- Using the **225µm tau readings** obtained at the Caltech Submilimeter Observatory (CSO) on Manua Kea, we find **no correlation** between the spectra obtained and atmospheric effects

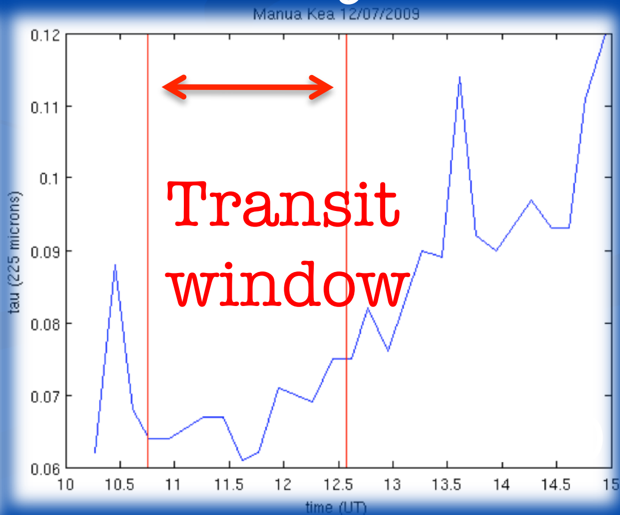
12th August 2007



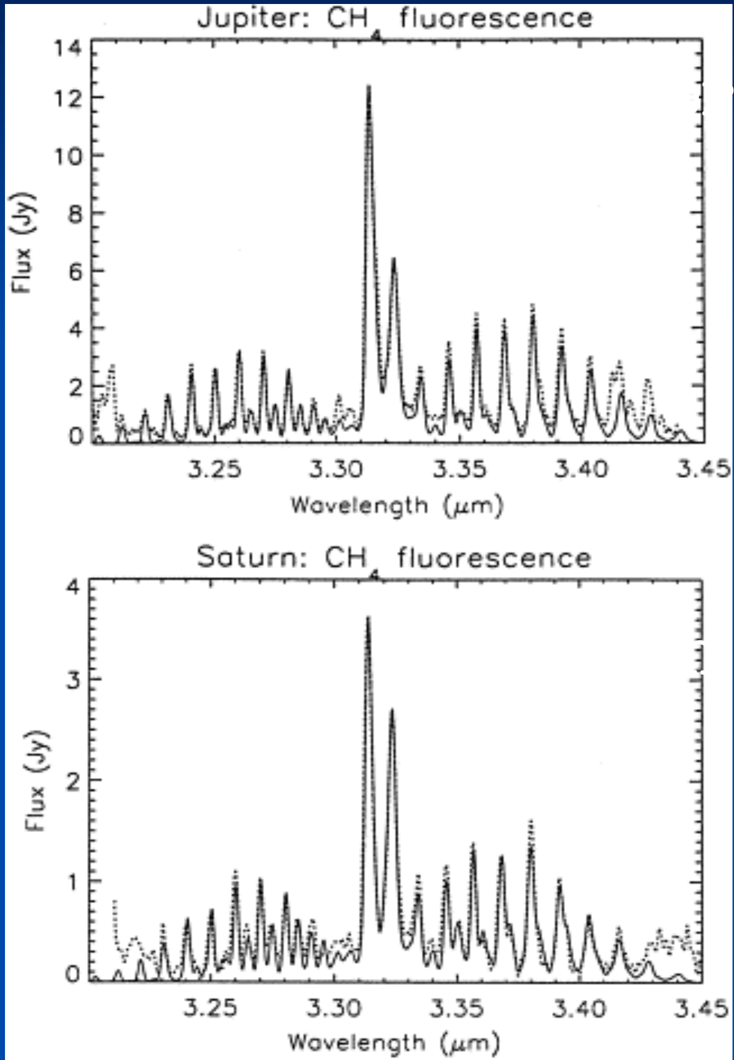
22th June 2009



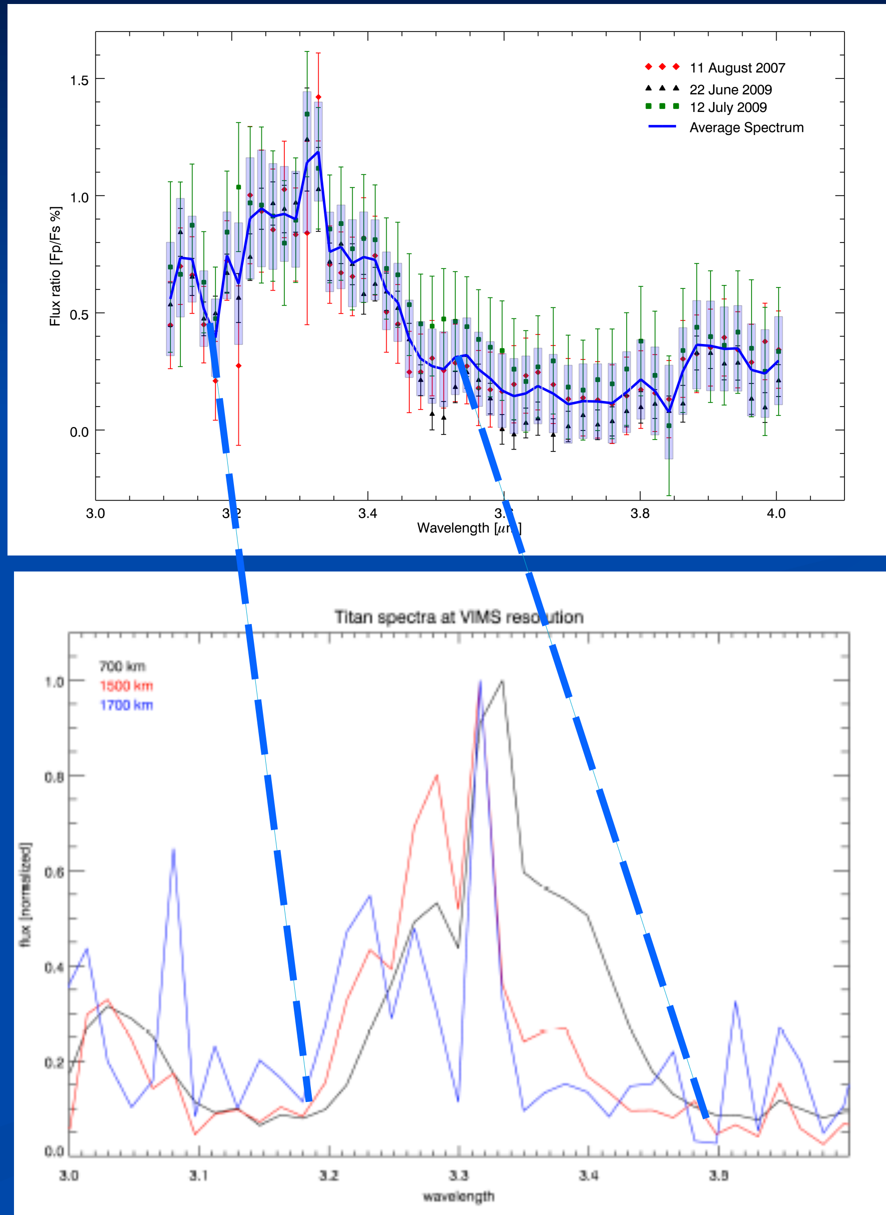
12th July 2009



Methane Emission



Drossart et al. 1999



Cassini VIMS

Status for HD209458b & HD189733b

Pretty Good

Confirmation of spectra on ground-based & space platforms

Confirmation of data analysis through different techniques

Detection of the most abundant C and O molecules

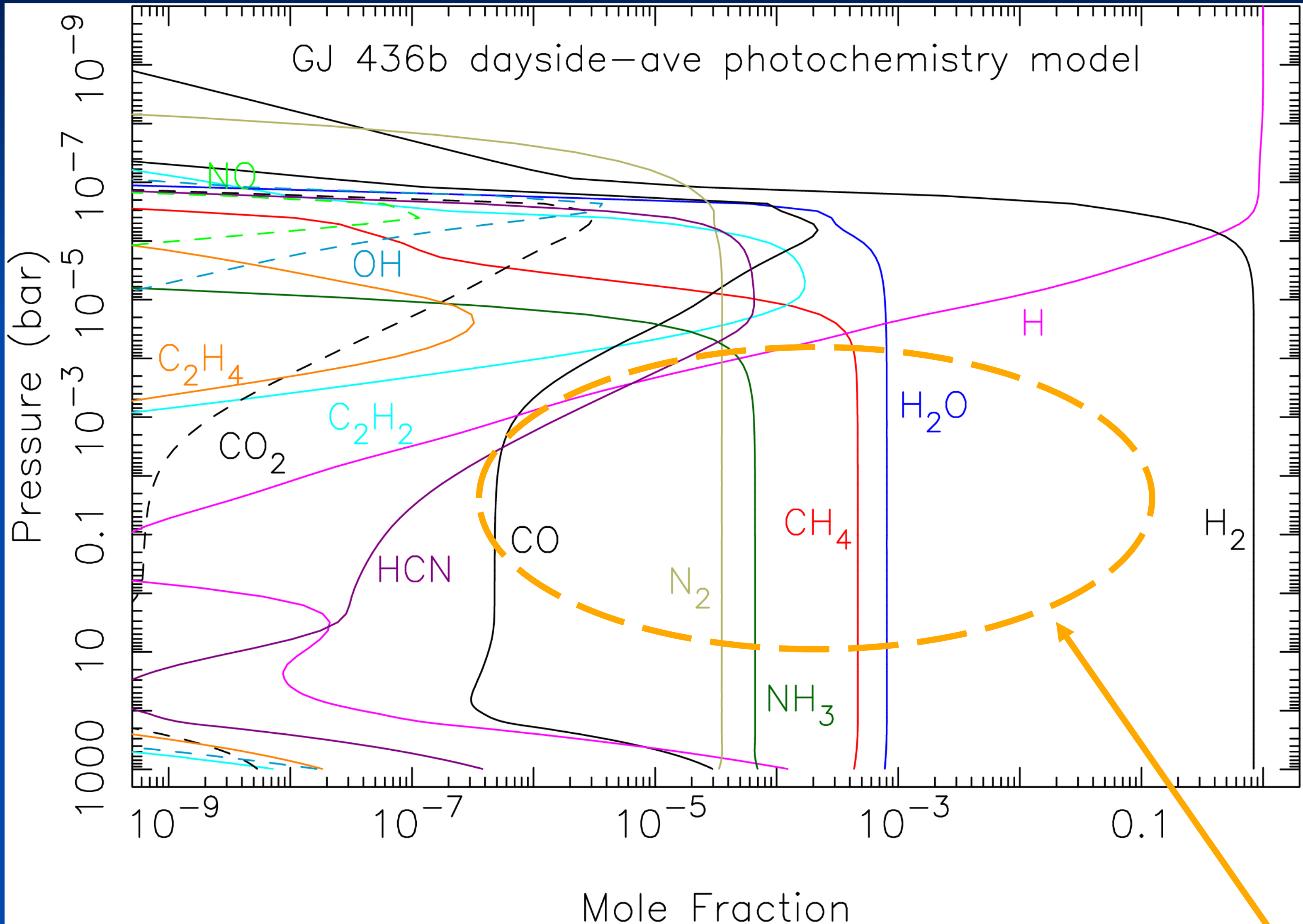
Beginning to constrain temperature & composition profiles

Measurements of temperature fields across planets

Evidence for hot upper atmospheres, possibly fluorescence

Evidence for atmospheric escape.

Little Guys: First GJ436b



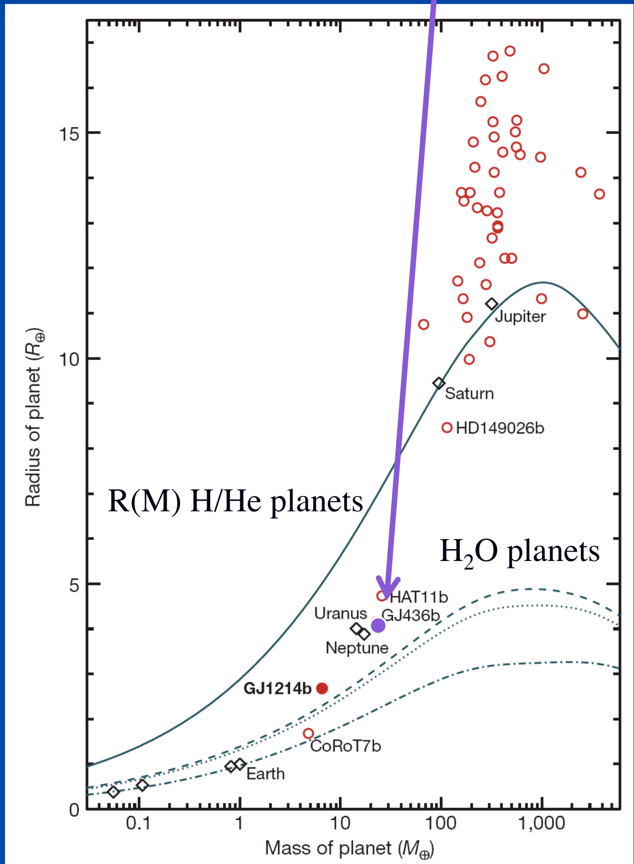
Calculations by Julie Moses

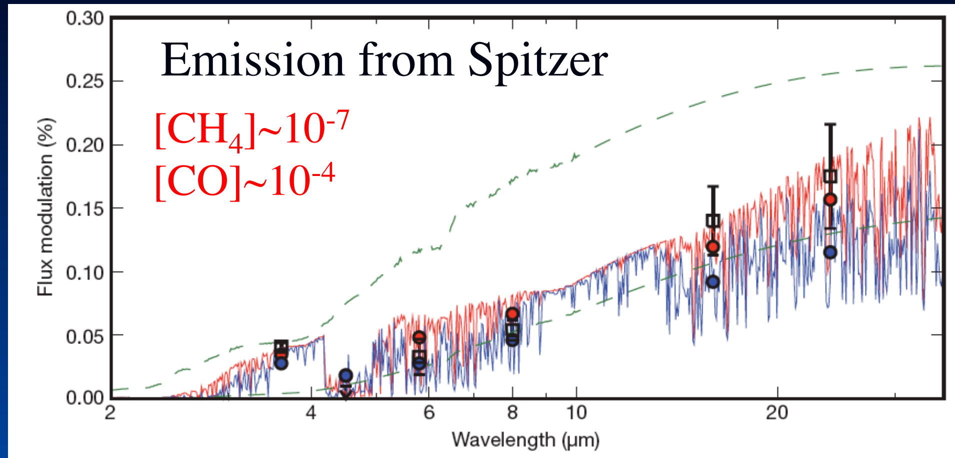
New chemistry regime: CH_4 & H_2O dominate

GJ436b:

Star: M2.5
Distance 10.2 pc
Mass: 0.07 M_J
Radius: 0.44 R_J
Semi-major axis: 0.03 AU
Teq ~ 700 K*

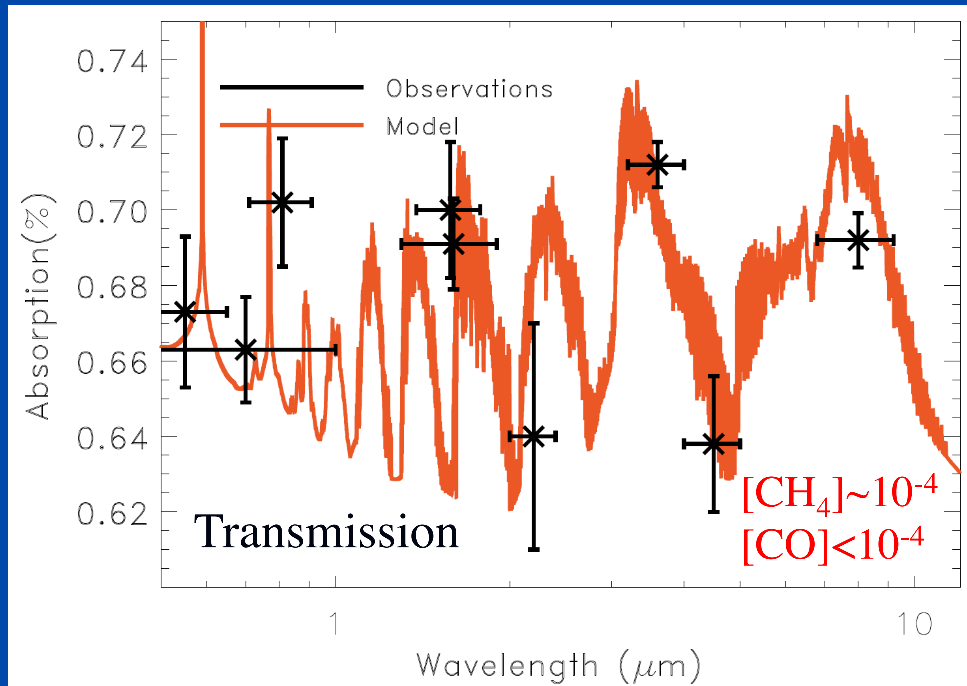
*Deming et al. 2007





Vertical mixing & photochemistry?

Stevenson et al., 2010; Madhusudhan & Seager 2010



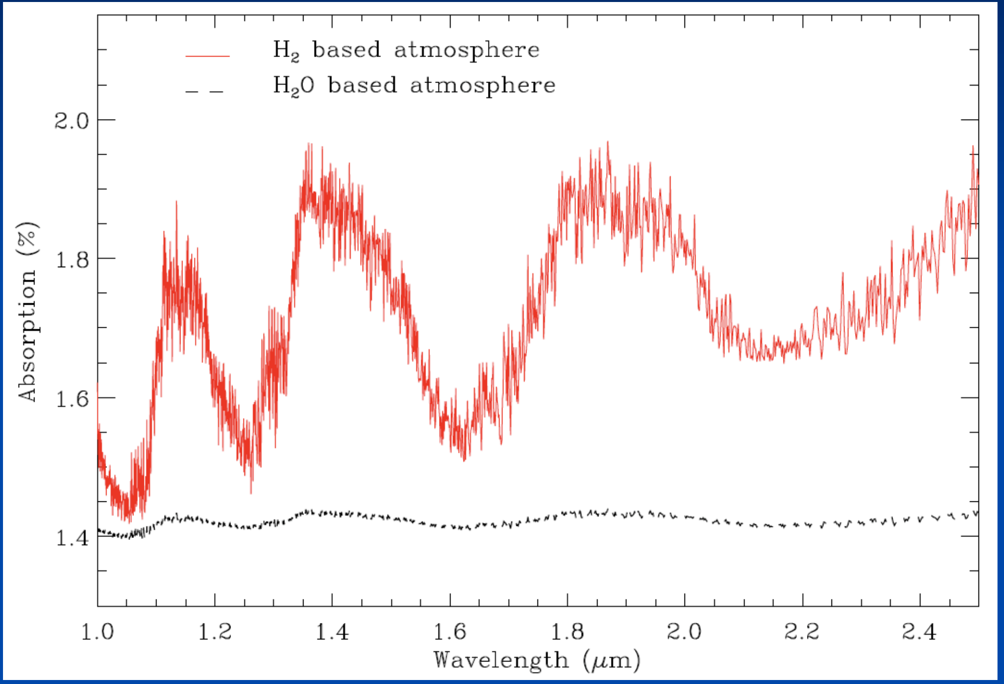
Chemical Equilibrium

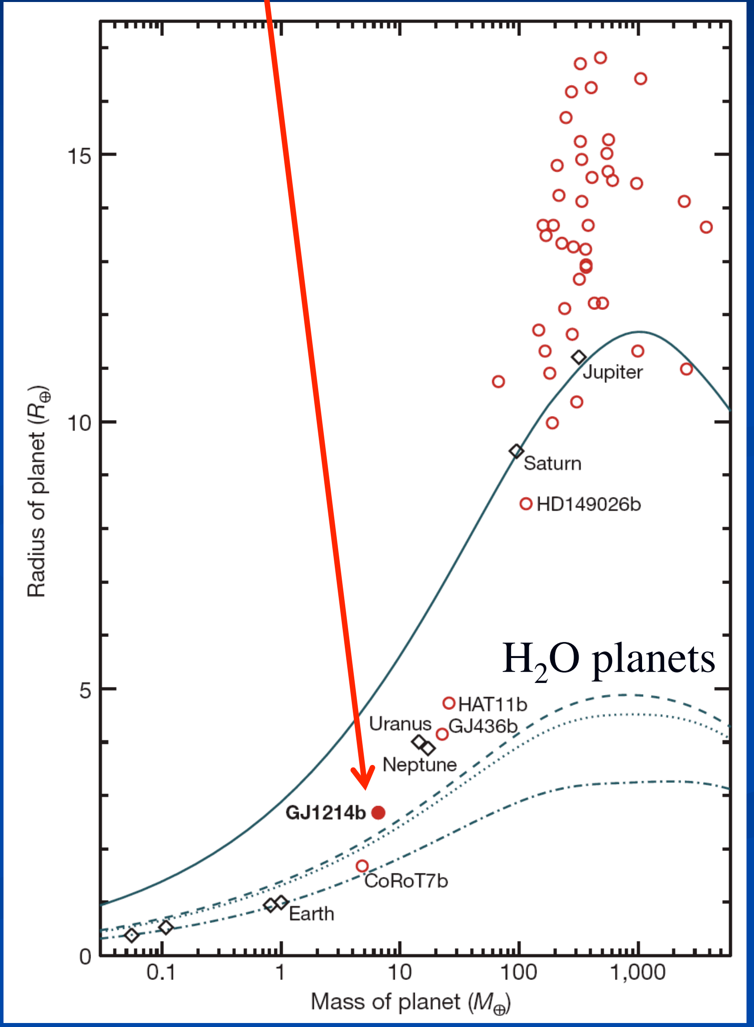
Beaulieu et al. 2010

Also flat 1.1-1.9 um transmission spectrum (Pont 2009)

GJ1214b:

Mass: 6.5 M_E
Radius: 2.7 R_E
Density: 1.87 g cm-3
Parent Star: M4.5
Semi-major axis: 0.014 AU
Teq < 500 K





System	$(R_{planet}/R_{star})^2$	Atmosphere
HD209458b	0.0132	0.001-0.002
GJ1214b	0.0135	0.003 (H_2)
Earth	$8.4x10^{-5}$	10^{-6}

Conclusions

- Evidence for atmospheric escape.
- Evidence for CO, CO_2, H_2O & CH_4
- Beginning to constraint T & composition profiles
- Need data at high spectral resolution & wavelength coverage.
- Need simultaneously observed Vis to IR
- Need information on hot CH4 lines
- Nonetheless, spectra are beginning to address interesting questions!