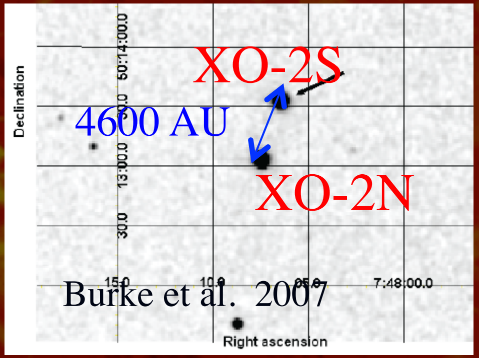
Interpretation of measurements of transiting exoplanets



Caitlin Griffith (University of Arizona)

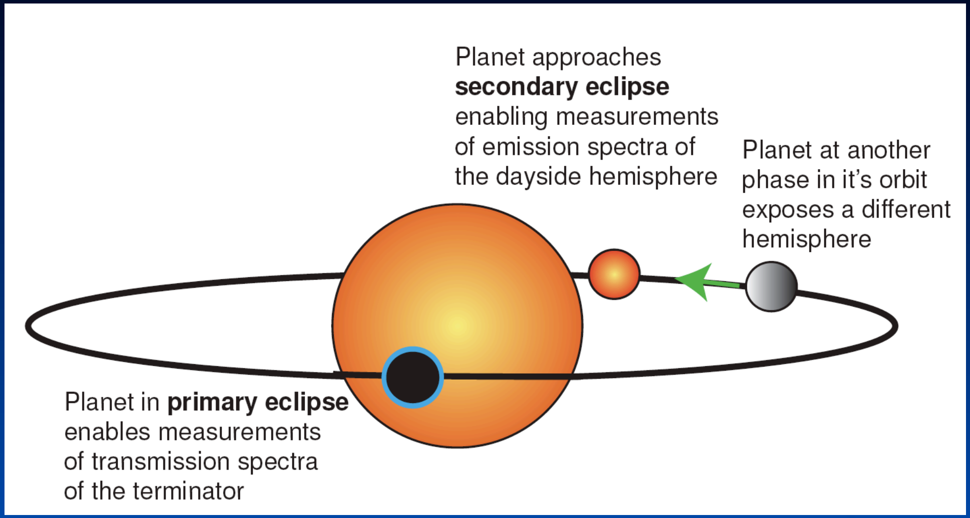
Collaborators: J. Turner, J. Teske, R. Zellem, G. Tinetti, M. Swain, P. Deroo, K. Cunha, S., R. Zellem, S. Schuler, V. Smith, J. Tennyson, R. Freedman. N. Lewis, H. Knutson

HD209458b
Mass: 0.69 M_J
Radius: 1.32 R_J
Parent Star: G0
V Magnitude: 7.65
$[Fe/H]_{Star}$: 0.04
Semi-major axis: 0.045 AU

XO-2b
Mass: 0.57 M_J
Radius: 0.97 R_J
Parent Stars (2): KOV
V Magnitude: 11.2
$[Fe/H]_{Star}$: 0.39*
Semi-major axis: 0.037 AU

* *Teske et al. 2013*

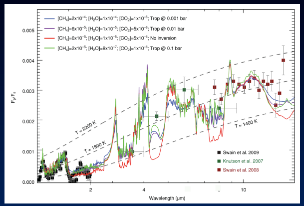
Degenerate Solution Sets



Secondary eclipse: derived composition depends on the temperature profile
Primary transit: derived composition depends on radius at specified pressure
Full phase measurements: derived ΔT has meaning if pressure level is known

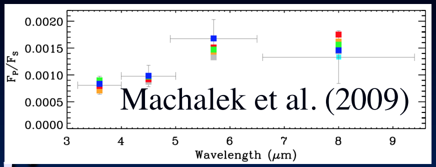
What is the nature of these degeneracies?
How sensitive are they?
How can we derive the composition & thermal profile?

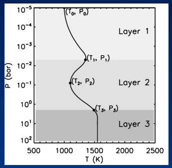
Analyze all measurements together.
And measure the radius



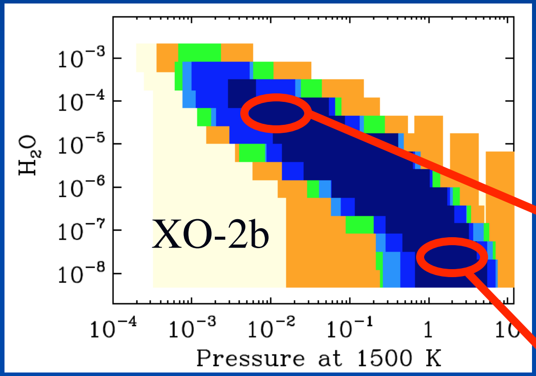
Secondary Eclipse:

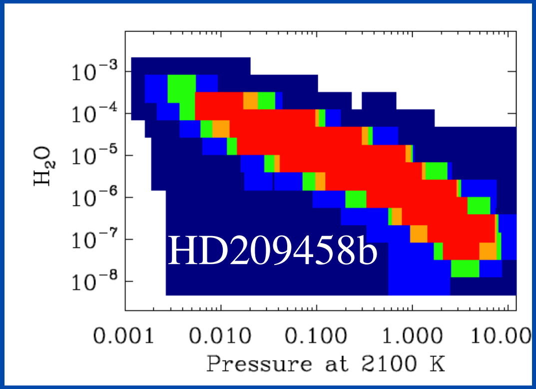
Solutions from 17 million RT calculations

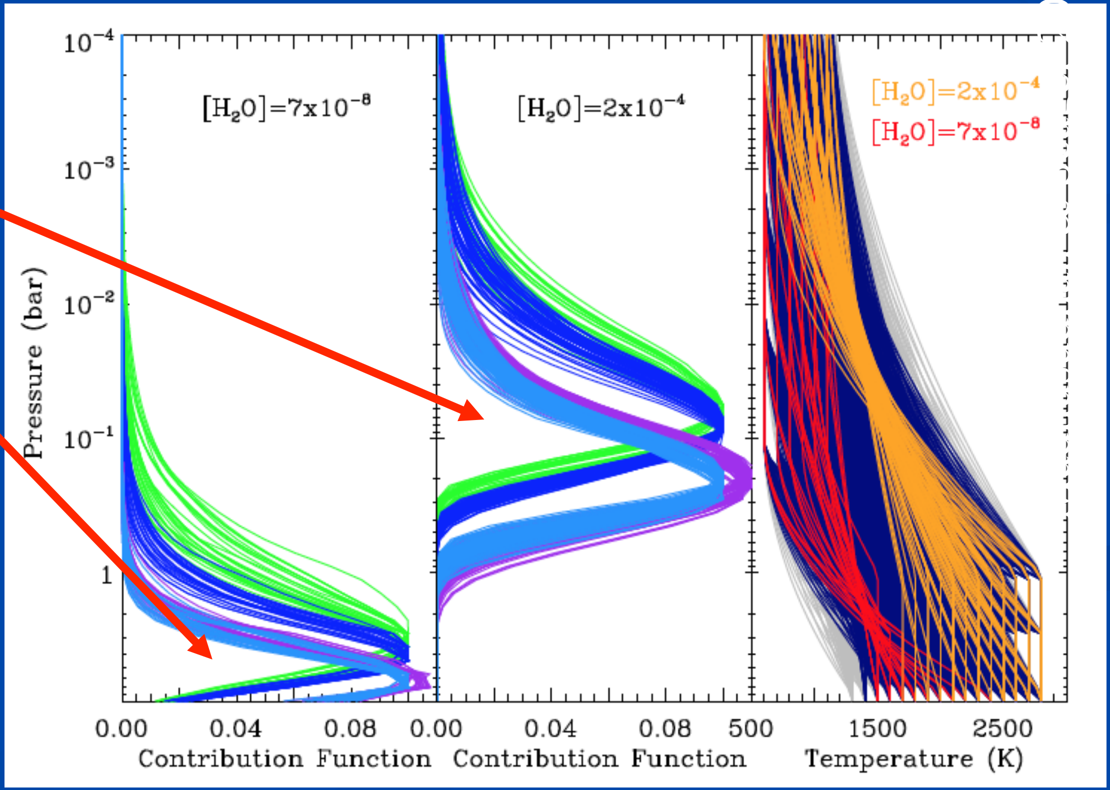




Temperature : 4-5 parameters (Madhusudhan & Seager 2009)
Composition: 4 parameters – mixing ratios of H_2O, CH_4, CO and CO_2

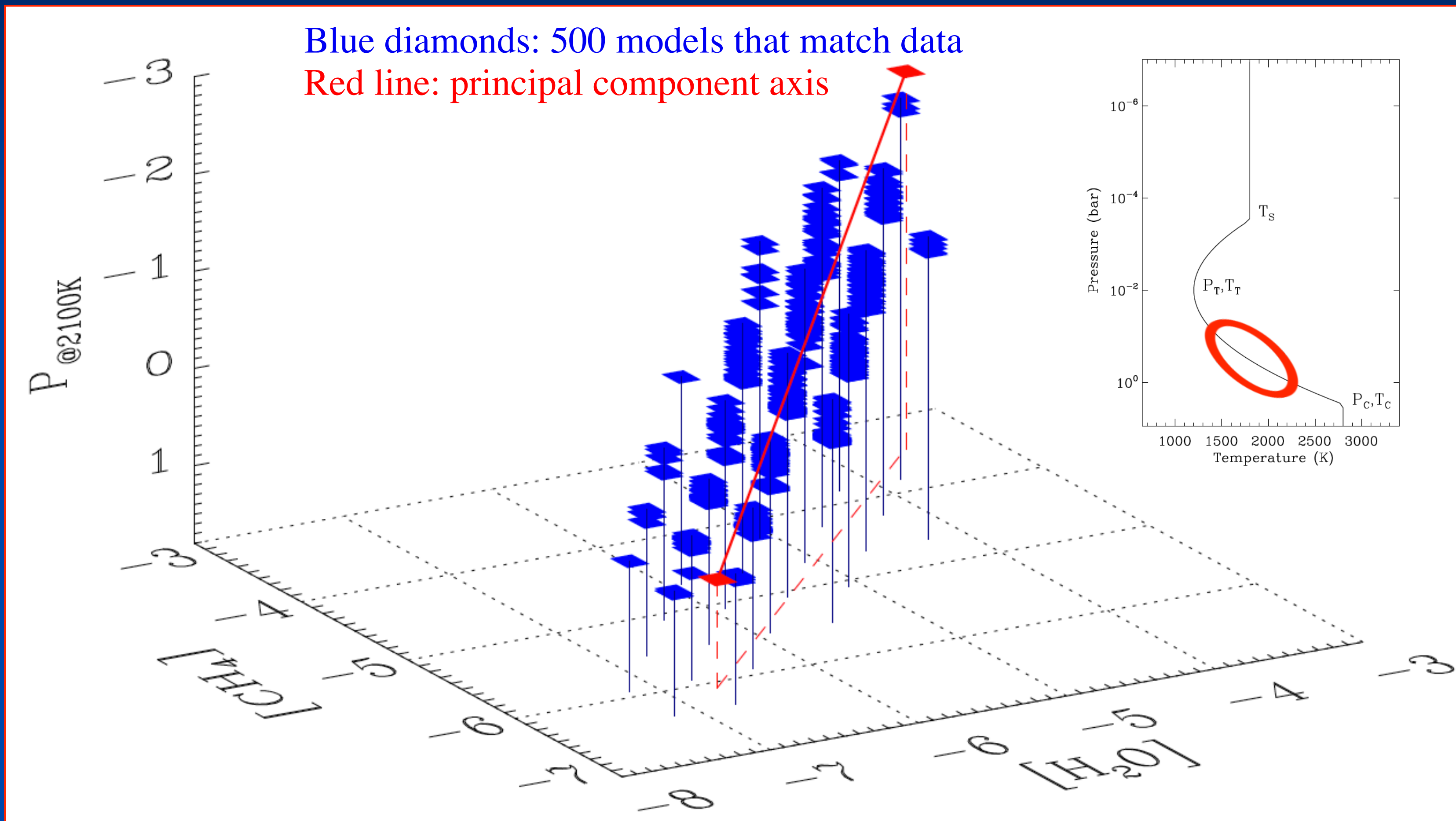






Principal Component Analysis

Correlations between the n=9 parameters that match the data

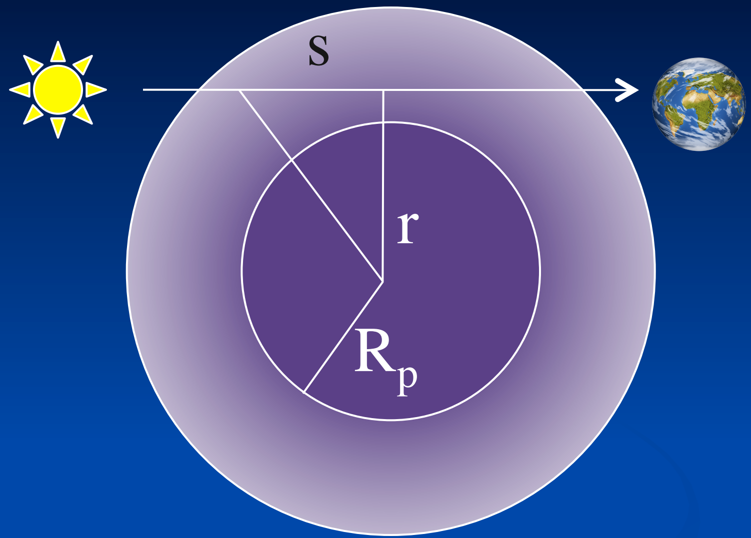


Diagonalize the covariance matrix, $C_{n,n}$ i.e. $C_{i,j}=cov(p_i,p_j)$ & $C_{i,i}=var(p_i,p_i)$
Principal component: eigenvector defined by the maximum eigenvalue

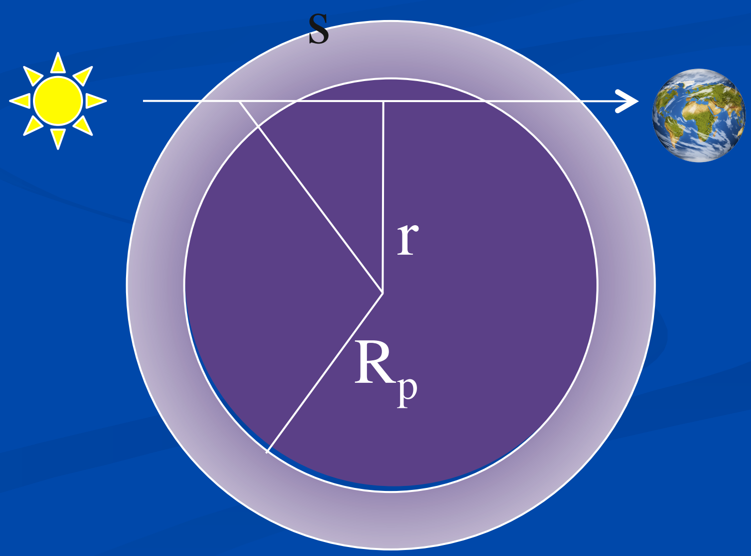
Primary Eclipse

The nature of the degeneracies in the solution set

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



Small Rp ->more gas inferred



Large Rp ->less gas inferred

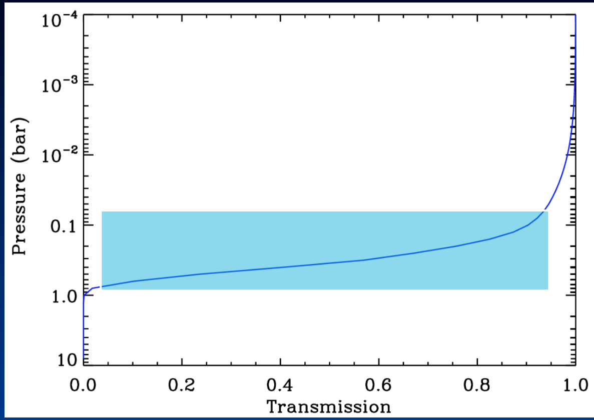
Temperature vs Composition

Higher T -> higher opacity
-> higher scale height
-> less gas inferred

Rp = radius at specified pressure where the atmosphere is optically thick
T(R) = transmission through the limb a distance R from the planet's center

How sensitive?

Results of a few tested analytical calculations



Pressure ranged probed per wavelength: ~ 55 factor of pressure

Sensitivity of optical depth to radius uncertainty: $\frac{\kappa_L}{\kappa_S} = e^{(-\Delta R/H)}$

-> Depends on the atmospheric scale height and absorption regime

Consider a $1M_J$, $1R_J$, T_{eq}=1000 K, H=150 km planet.

A planet size increase of 1%: k_L/k_S = exp(-4.6) = 0.01

Effect on derived mixing ratio:

Weak line limit: $[H_2O]_L/[H_2O]_S$ = 0.01

Strong line limit: $[H_2O]_L/[H_2O]_S$ = 0.0001 ←

Mixing ratio uncertain to a factor of 10,000

Sensitivity of optical depth to temperature $Tr(R) = \exp(-N(R)\ (2\pi RH)^{1/2}\ \kappa_e)$

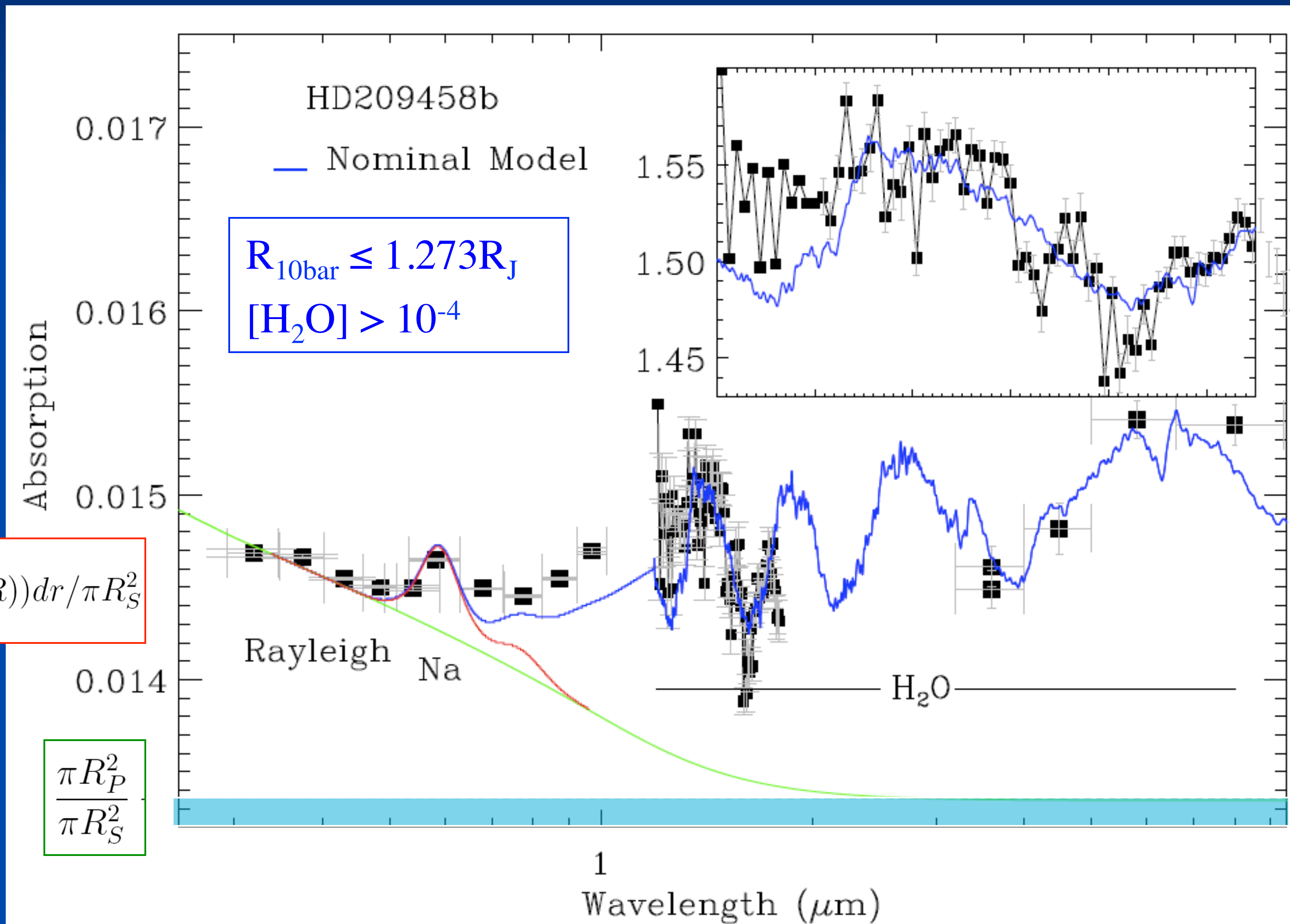
-> Depends on the planet's temperature & spectral opacity

A temperature uncertainty of 300 K: Mixing ratio uncertain to a factor of 4

Derived in Griffith 2013

Transmission Spectra

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



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

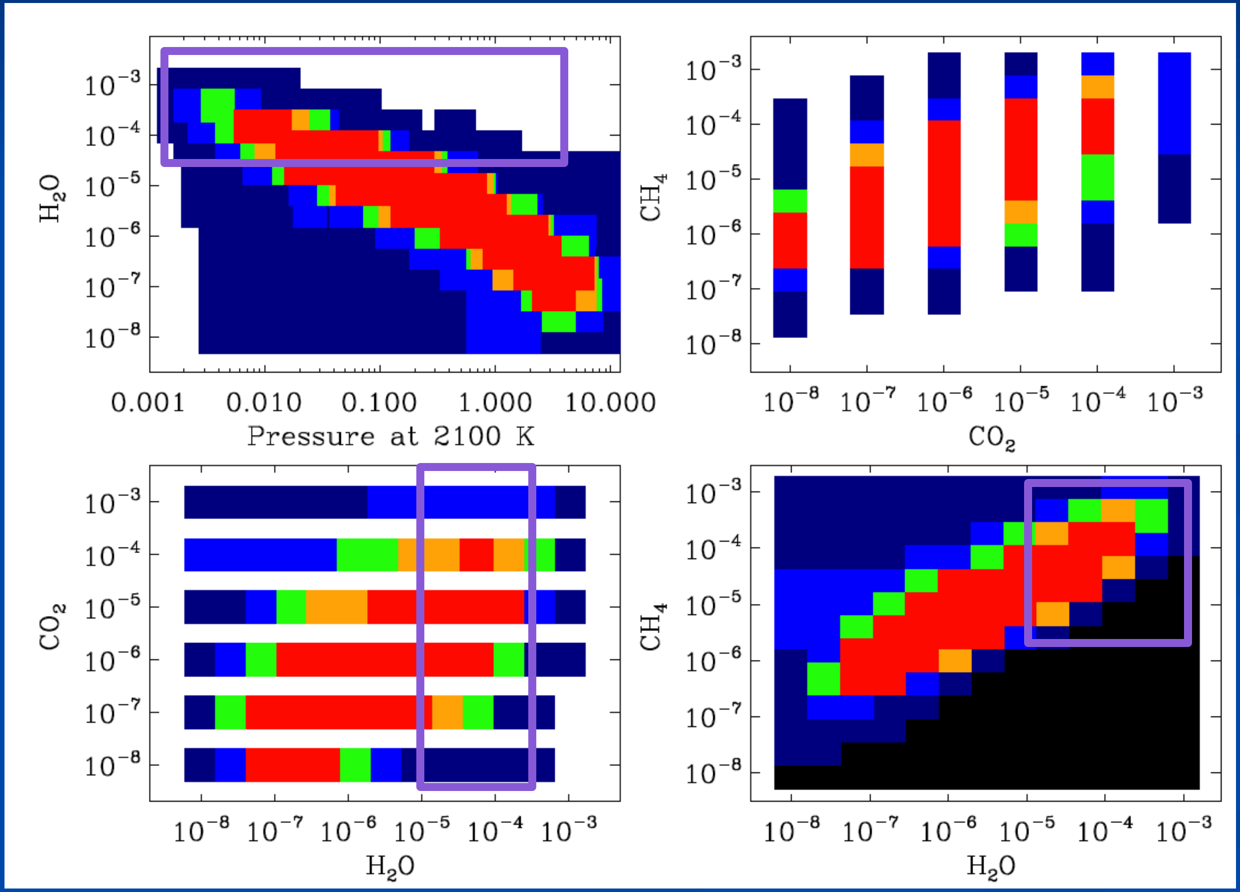
$$\frac{\pi R_P^2}{\pi R_S^2}$$

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

Griffith et al. 2013, In prep.

Solutions from 17 million RT calculations

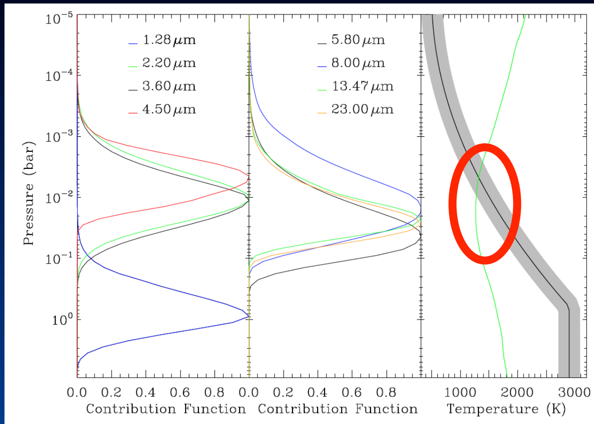
HD209458b



Red: best fit / Red – Orange fit within errors

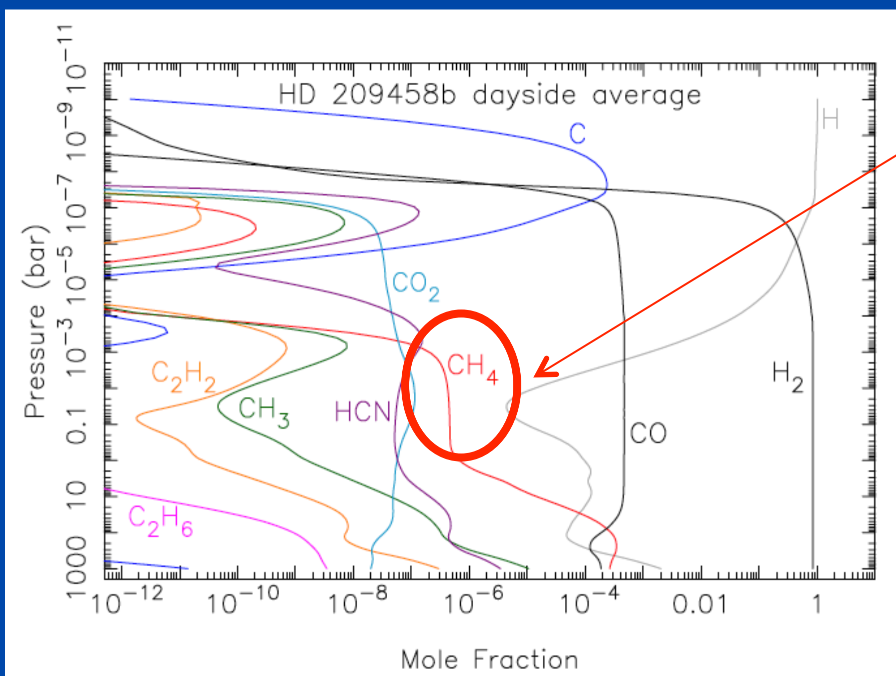
Implications

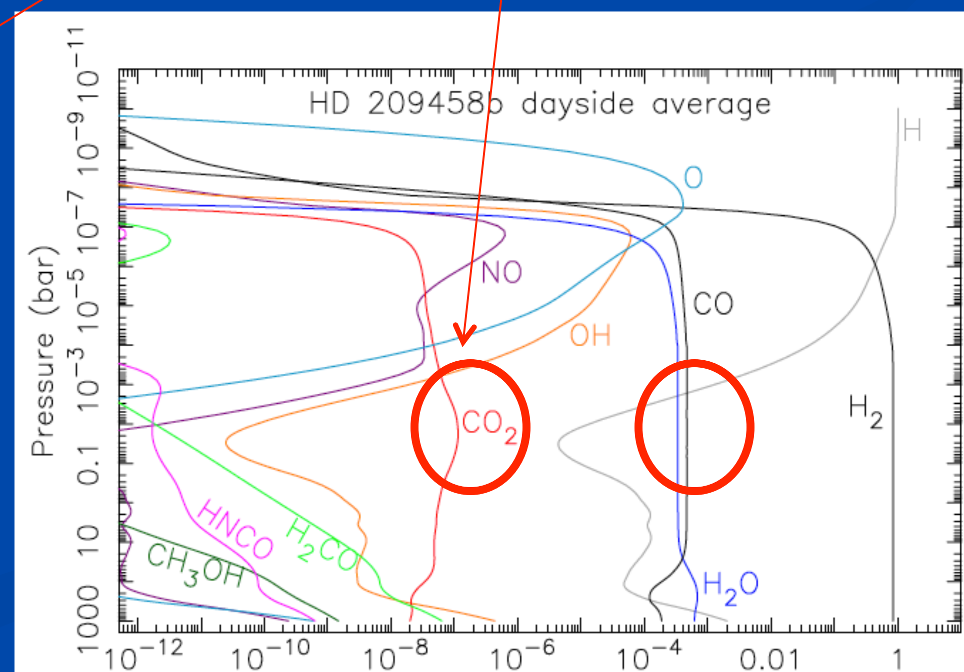
Solar abundance star & planet



Pressure region probed

$10^{-4} < [H_2O] < 5x10^{-4}$
$10^{-5} < [CH_4] < 3x10^{-4}$
$10^{-7} < [CO_2] < 1x10^{-4}$
$10^{-2} < P_{2100K} < 10^{-1}$





Moses et al. 2011, Schuler et al. 2011

Study of current data with radius measurements

Test assumptions in the analyses & data interpretation

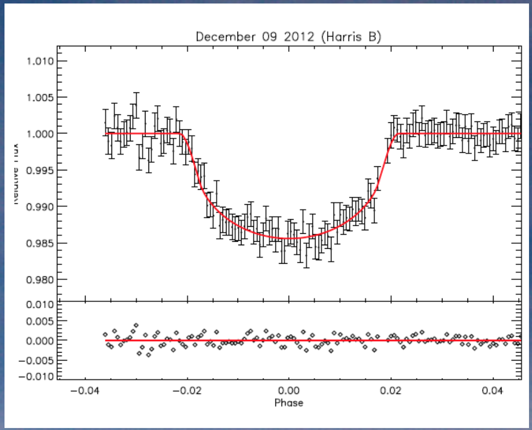
Exoplanets with both primary and secondary transit observations* and easily observable in Northern Hemisphere.

Exoplanet	M	e	Primary	T_{eq}
CoRoT-1b	1.03	0.025	G0V/6298	1898
CoRoT-2b	3.31	0.028	G7V/5575	1393
GJ 1214b	0.02	0.014	M/3026	520
GJ436b	0.07	0.029	M2.5/3684	650
HAT-P-6b	1.06	0.052	F6/6570	1530
HD209458b	0.71	0.048	G0V/6075	1316
TrES-1	0.76	0.039	K0V/5230	1060
TrES-2	1.25	0.036	G0V/5850	1472
TrES-3	1.91	0.023	G/5720	1657
TrES-4	0.92	0.051	F/ 6200	1782
WASP-1b	0.86	0.038	F7V/6200	1644
WASP-12b	1.4	0.023	G0/6300	2320
WASP-2b	0.85	0.031	K1V/5150	1171
WASP-24b	1.03	0.036	F8-9/6075	1514
WASP-3b	2.06	0.031	F7V/6400	1826
XO-1b	0.9	0.049	G1V/5750	1168
XO-2b	0.62	0.037	K0V/5340	1203
XO-4b	1.72	0.056	F5V/5700	1328
HAT-P-1b	0.52	0.067	GOV/5975	1182
WASP-14b	7.34	0.036	F5V/6475	1719

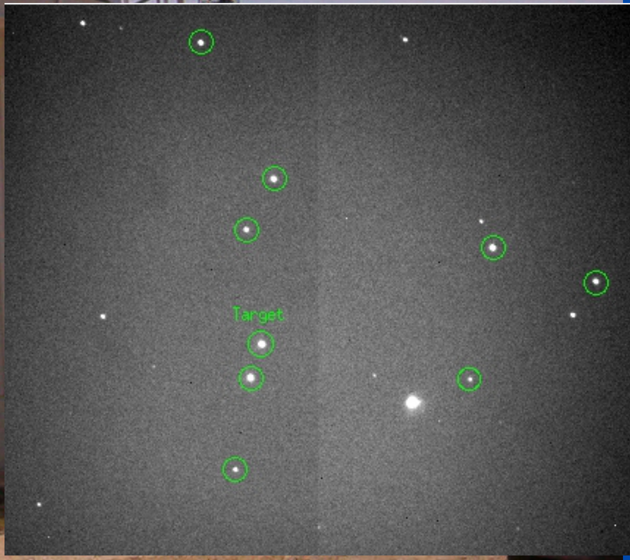
* Excepting GJ1214b

Photometry & Spectroscopy at 0.35 & 0.45 um

Steward 1.6 m Kepler Telescope

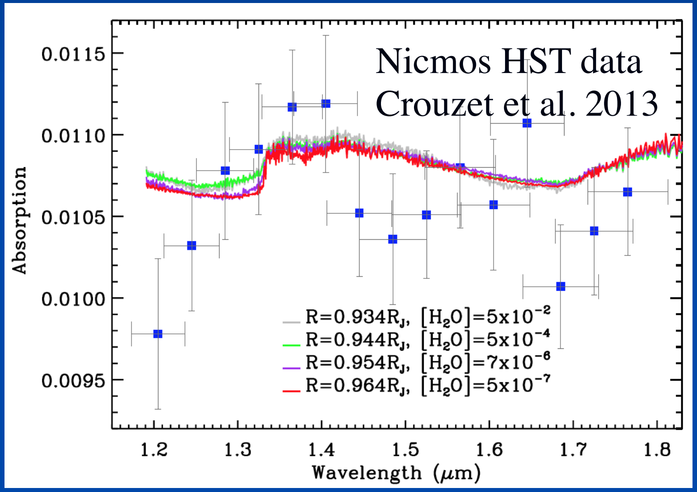


Program: A team of undergraduates (led by Jake Turner & Kyle Peterson) measure planetary radii and stability of system



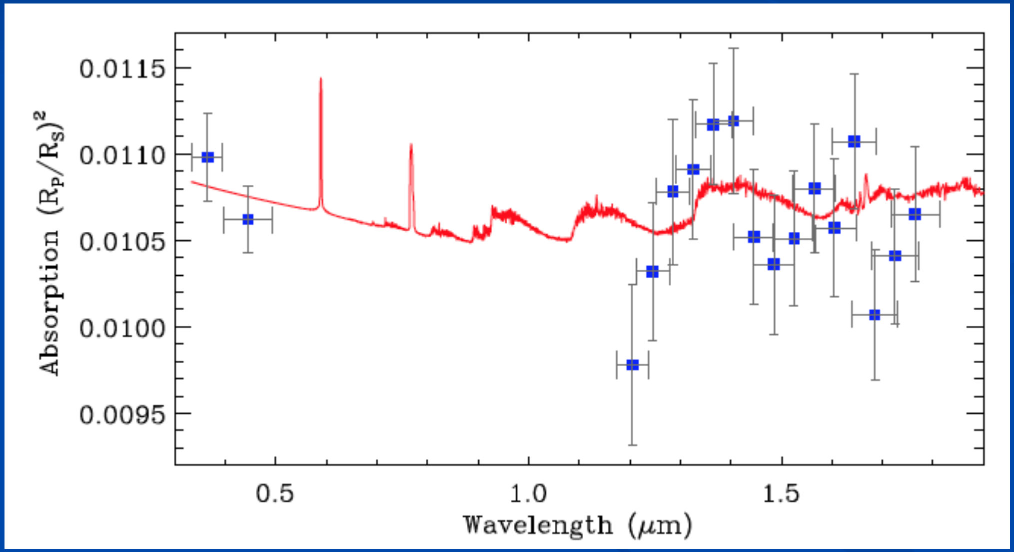
Instrument:
4096 x 4096 CCD
9.7 x 9.7 arcmin FOV

Enables the interpretation of current space-based data – here shown for XO-2b



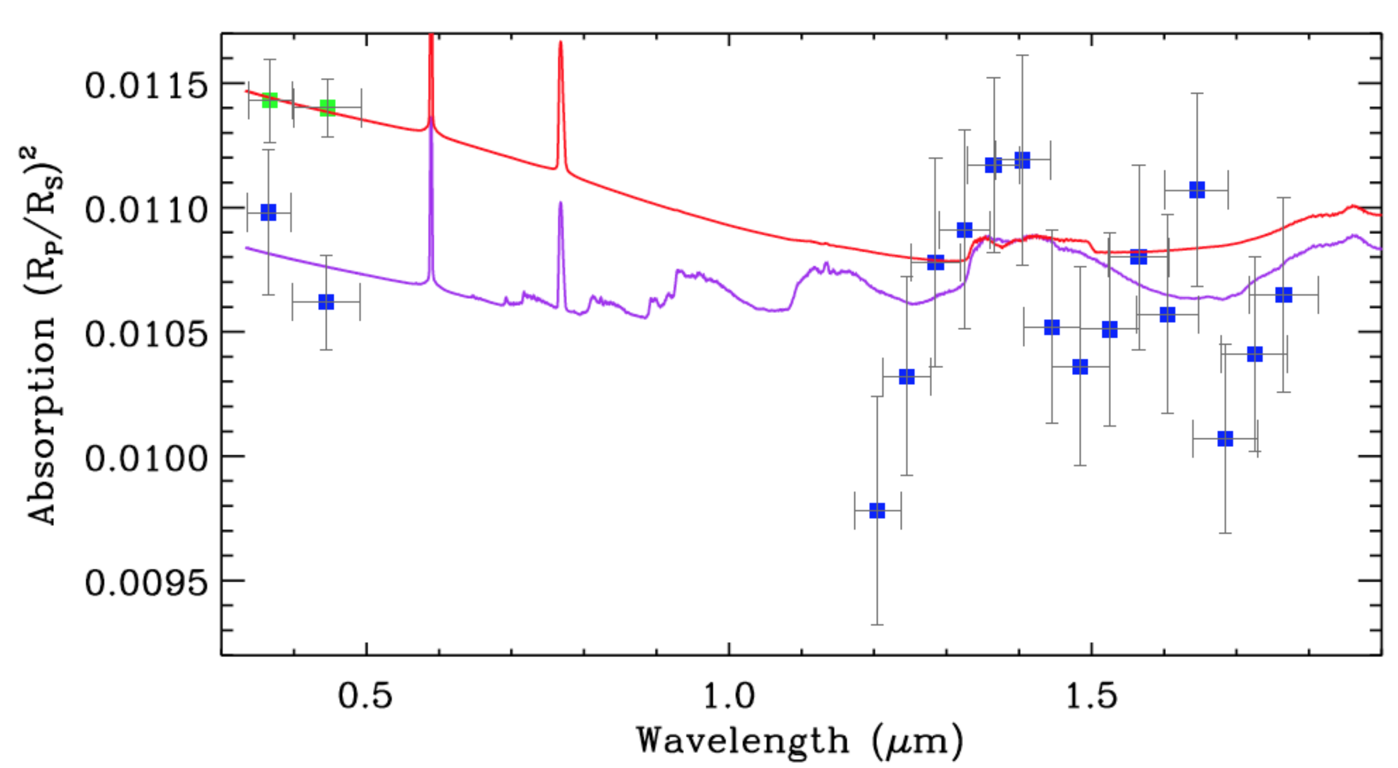
$[H_2O]$ ranges 5 orders of magnitude

->



$[H_2O]$ ranges 1 order of magnitude

But not quite…
Signs of temporal variability for XO-2b



Conclusions
(Prep for Echo)

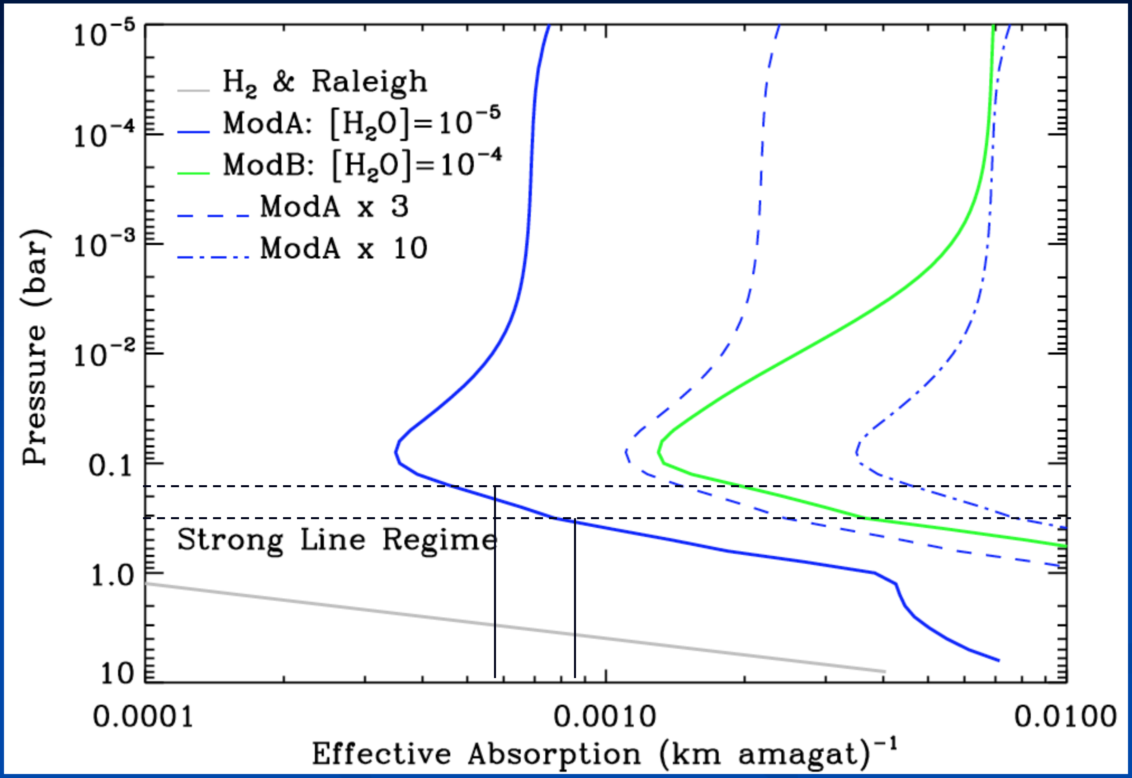
1) Radii determinations are essential and can be partially be started from ground.
2) Transmission & emission IR spectra complement retrieval efforts.
3) Full phase measurements are also needed toward this goal.*
4) Characterization of stellar properties (metallicity and activity) can be done now. +
5) Assumptions underlying the interpretations of IR data can be studied now.

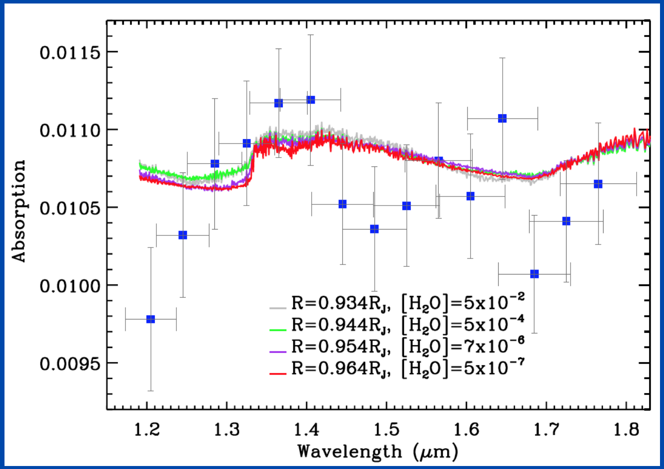
* *Student Rob Zellem and N. Lewis and H. Knutson are analyzing full phase data for HD209458b.*

+ *Student Johanna Teske and K. Cunha, S. Schuler, V. Smith are determining C, O, Fe and Ni of exoplanet hosts.*

XO-2b Radius Dependence

Absorption characteristics at 1.56 um



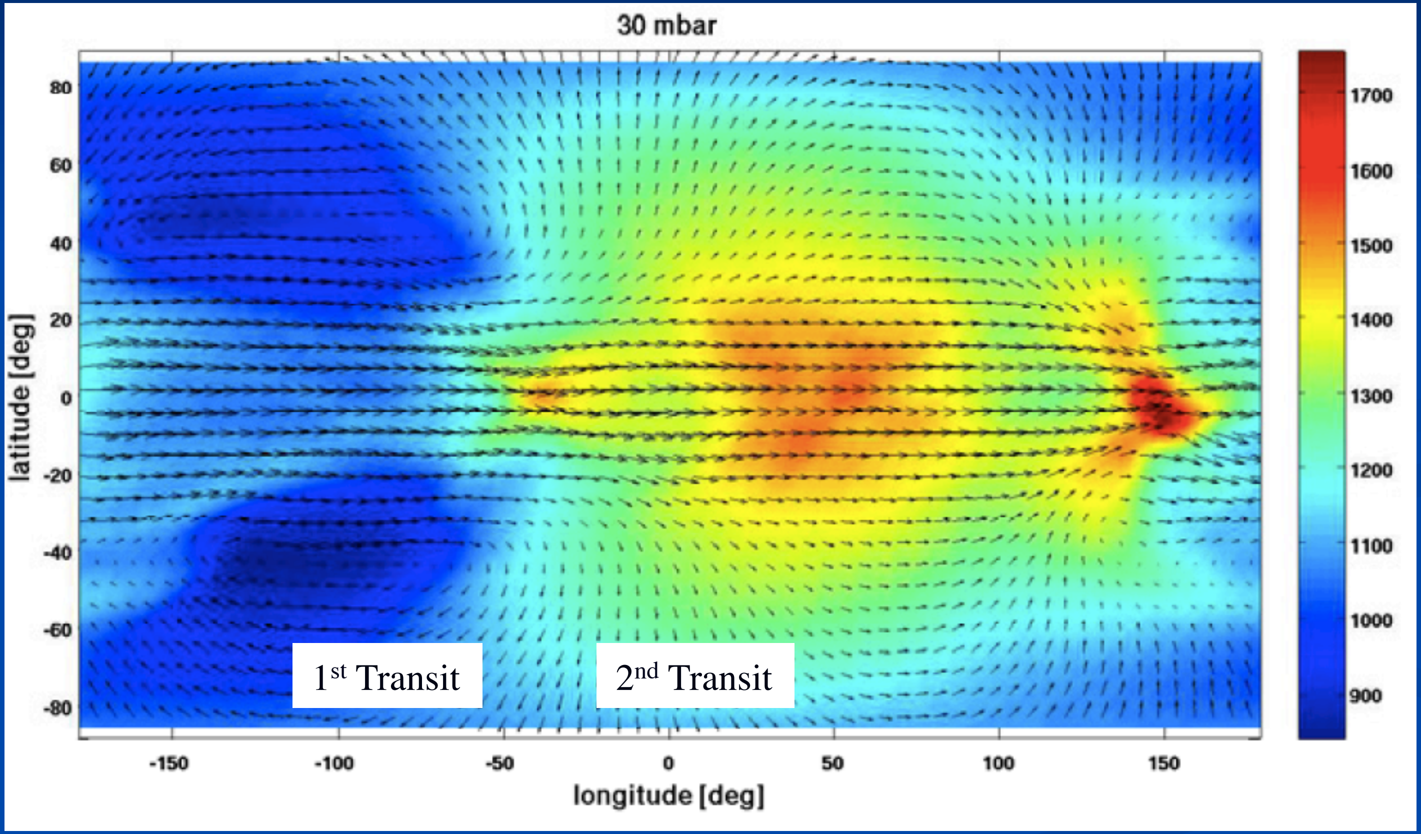


H_{XO2b} ~ 300 km. Therefore, for a 1% radius increase: $k_L/k_S = \exp(-2.2) = 0.11$

But the absorption is in the strong line regime. Thus: $[H_2O]_L/[H_2O]_S = 0.012$

However absorption increases in our favor: $[H_2O]_L/[H_2O]_S = 0.018 = 1/55$

1^{st} & 2^{nd} transits probe different hemispheres



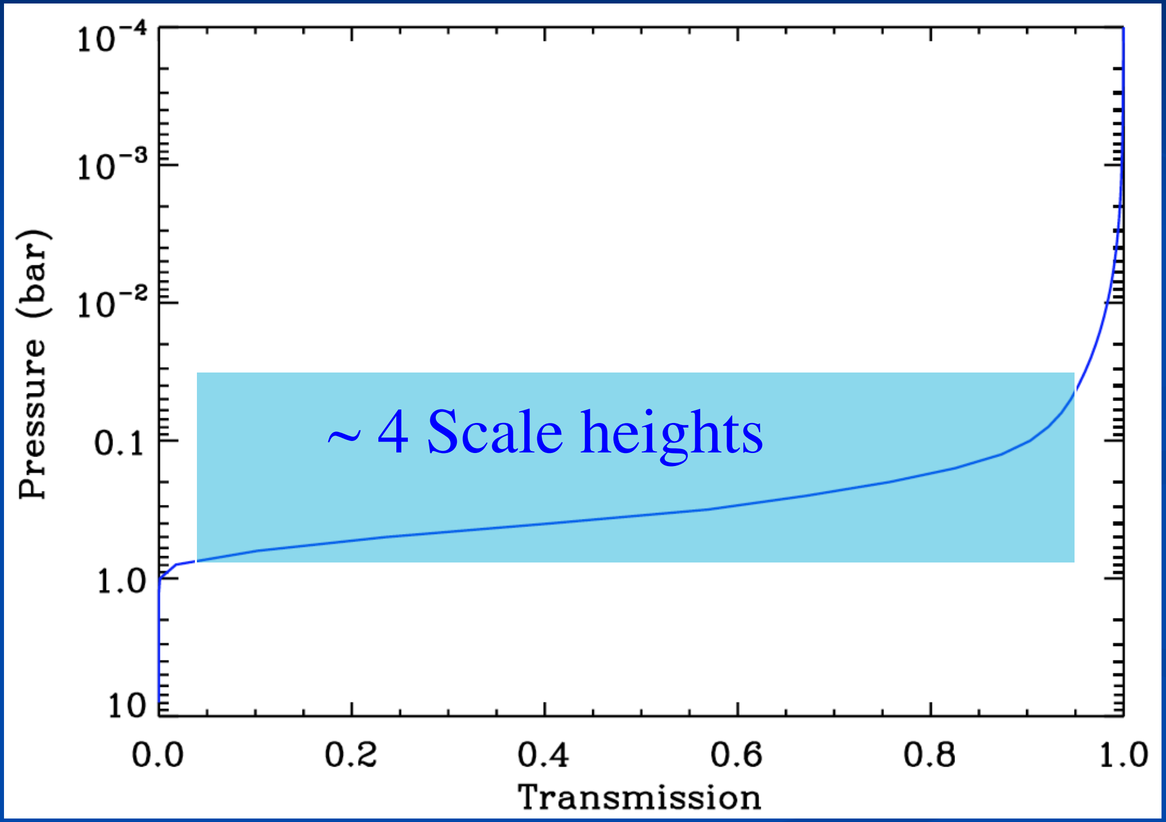
Showman et al. 2009

Similar H_2O, CH_4, CO_2 and CO abundances are predicted for 1st & 2nd transit at 1 - 0.001 bars
(Moses et al. 2011)

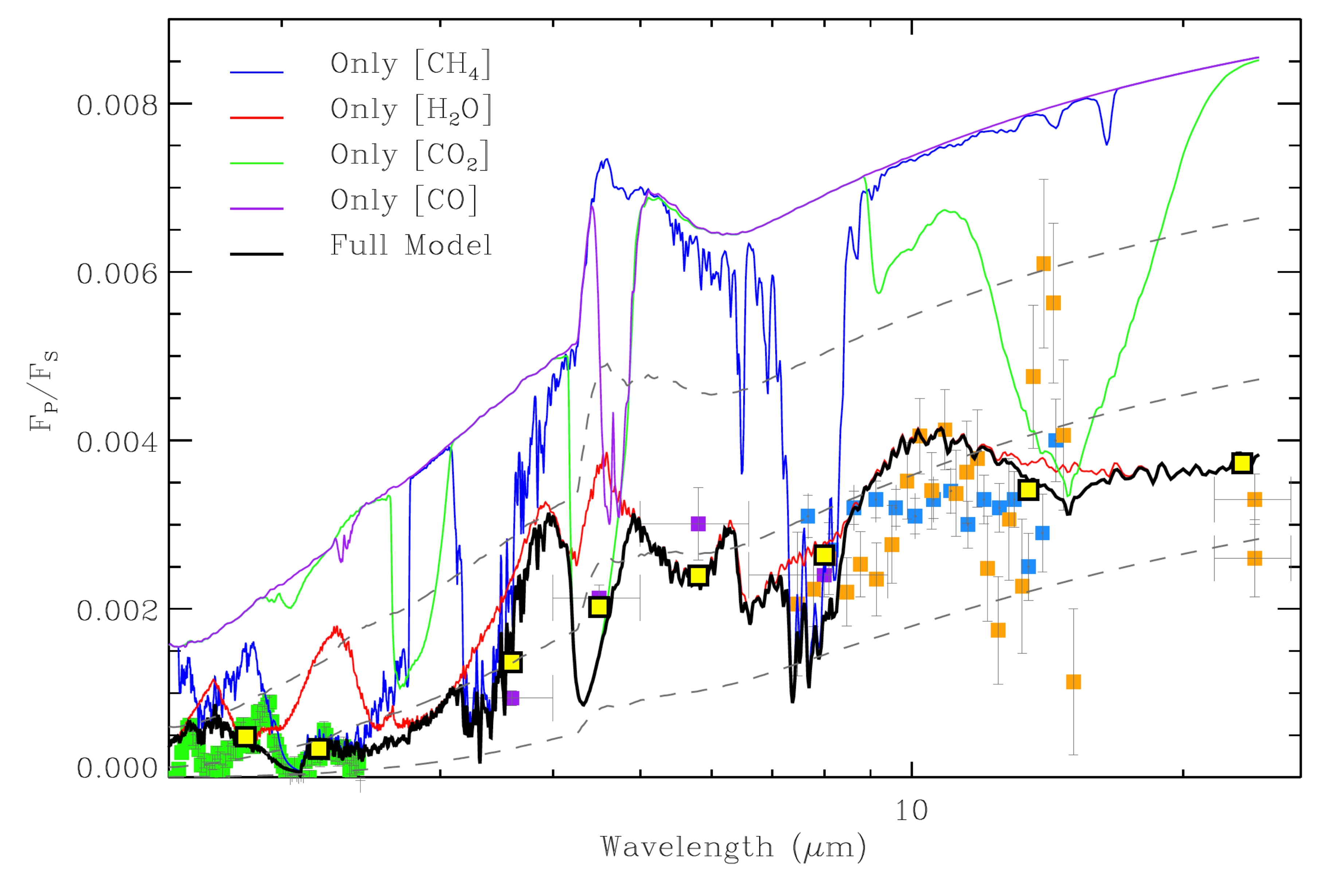
Full Model of XO-2b agrees

$P_T/P_o \sim e^{-4}$
$P_T/P_o \sim 0.02$

$P_T = 0.03$
$P_O = 0.9$
$P_T/P_o = 0.03$



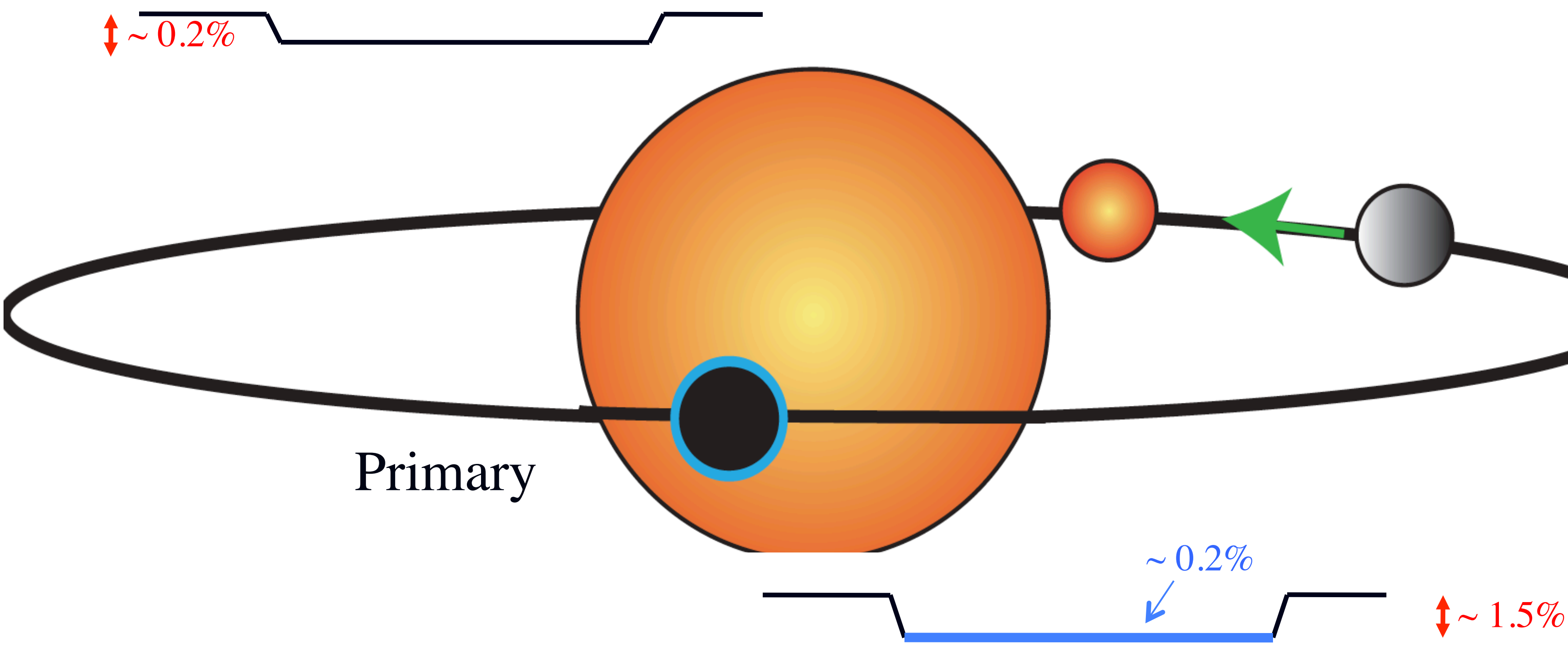
The atmospheric opacity mainly controls the ~T=0.5 pressure level



Only [CH4]
Only [H2O]
Only [CO2]
Only [CO]
Full Model
0.008
0.006
0.004
0.002
0.000
F_P/F_S
10
Wavelength (μm)

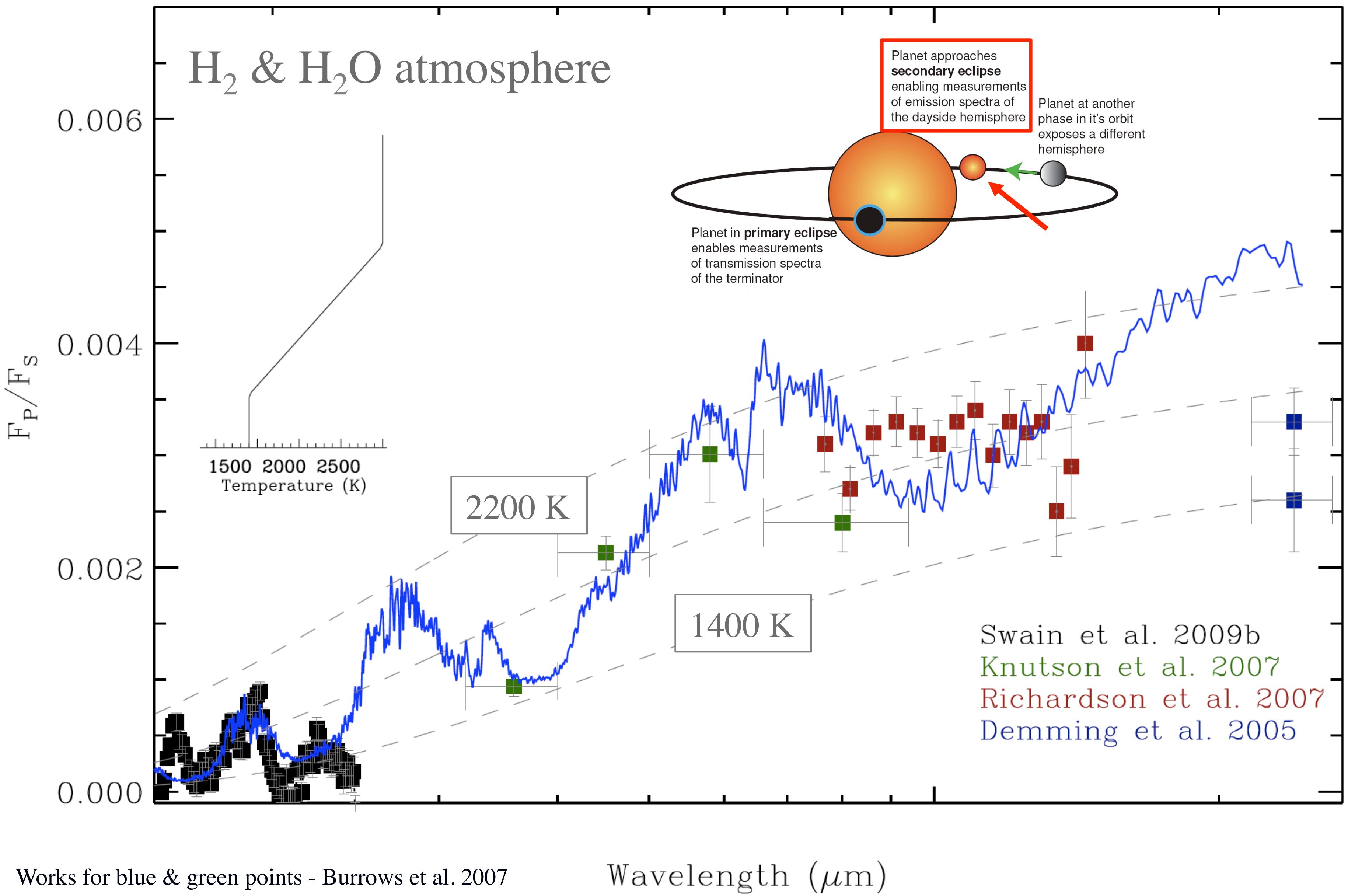
Exoplanets: Constraints from observations

What are their radii?
What are their compositions?
What are their thermal structures?



Caitlin Griffith (University of Arizona)
Giovanna Tinetti (UCL), Mark Swain (JPL), Pieter Deroo (JPL), K. Cunha (UofA), S. Schuler (UofA) Richard Freedman (NASA Ames)

Emission Spectra of HD209458b



Works for blue & green points - Burrows et al. 2007

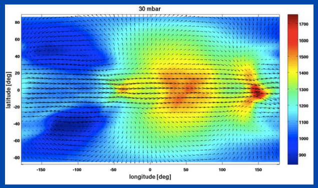
But wait…

Could this study indicate a heavy species enrichment – an indication of an accretion origin for HD209458b?

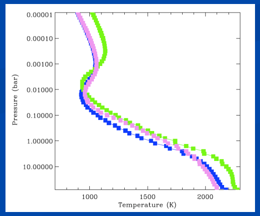
Maybe.

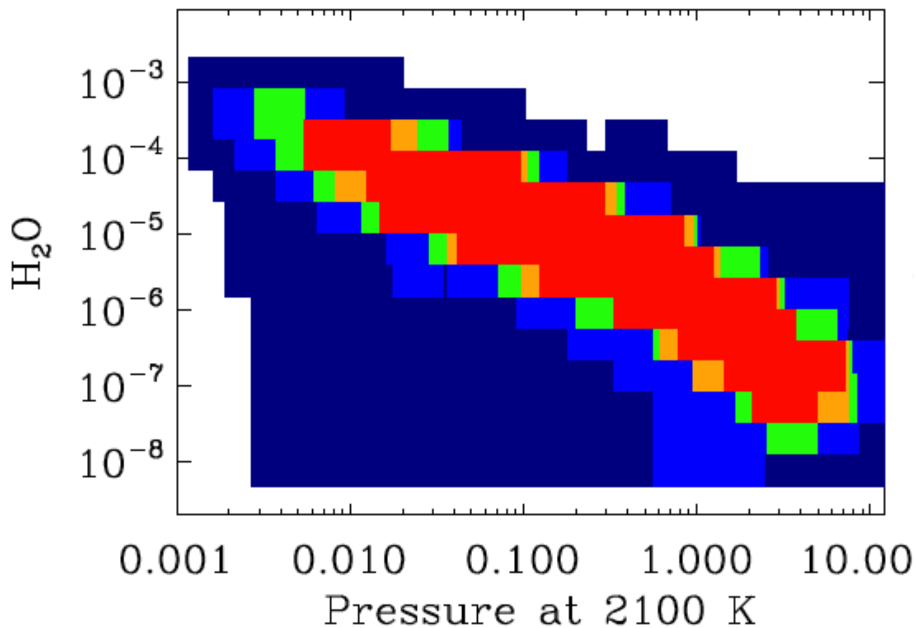
But we still need to:

1)Assess physical viability of temperature profiles.
2)Evaluate uncertainties of CH_4 absorption
3)Explore spectral details with more observations
4)Determine the composition of the host star



+



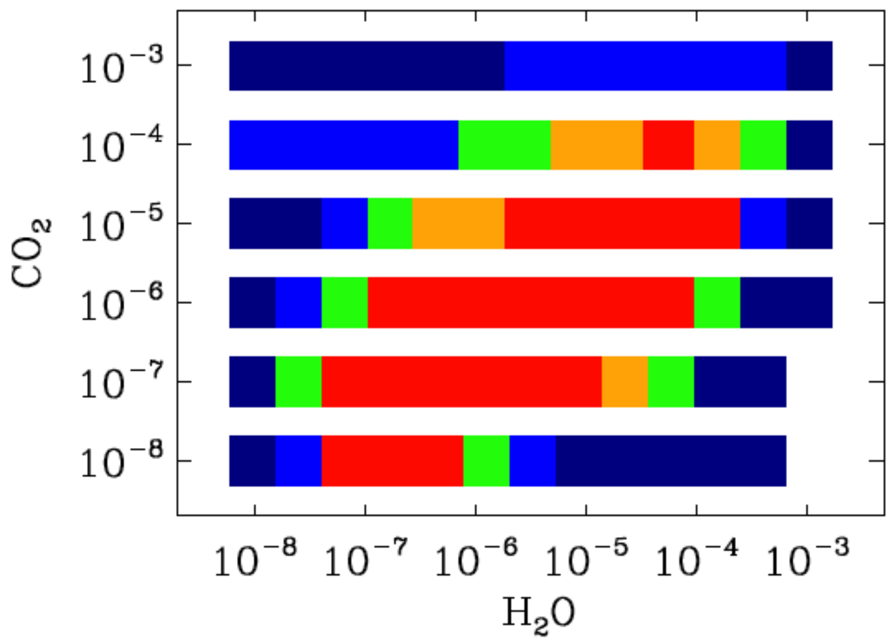


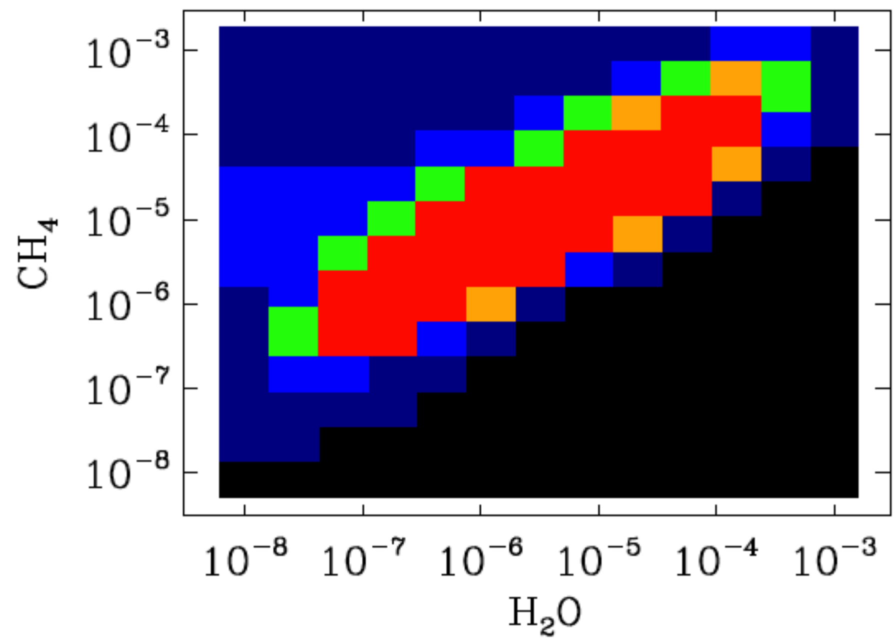
$7x10^{-8} < [H_2O] < 5x10^{-4}$

$5x10^{-7} < [CH_4] < 3x10^{-4}$

$[CO_2] < 10^{-4}$

$5x10^{-3} < P_{2100K} < 8$

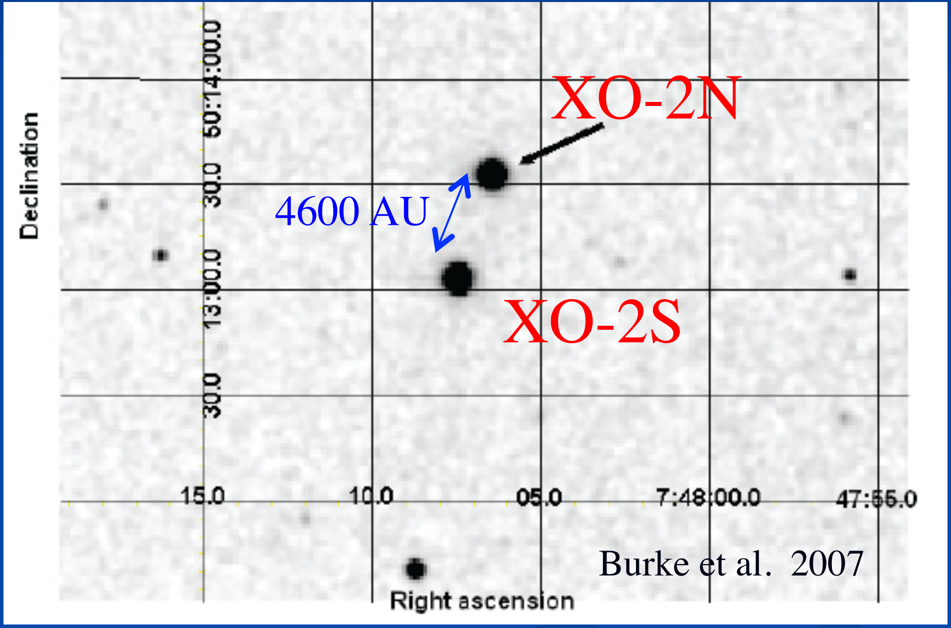




Transiting Exoplanets Data:
Breaking degenerate solutions

Caitlin Griffith
J. Turner, R. Zellem, J. Teske, K. Cunha, S. Schuler, V. Smith

1) Emission spectra
   - XO-2b
2) Transmission spectra
   - XO-2b
3) Cause of degeneracies
4) Breaking the degeneracies
   David & Goliath



XO-2b Planet:	Star :
0.57 M_J	KOV
0.97 R_J	Teff = 5340 K
a = 0.037 AU	d = 150 pc

Presentation at the Royal Society
March 12, 2013

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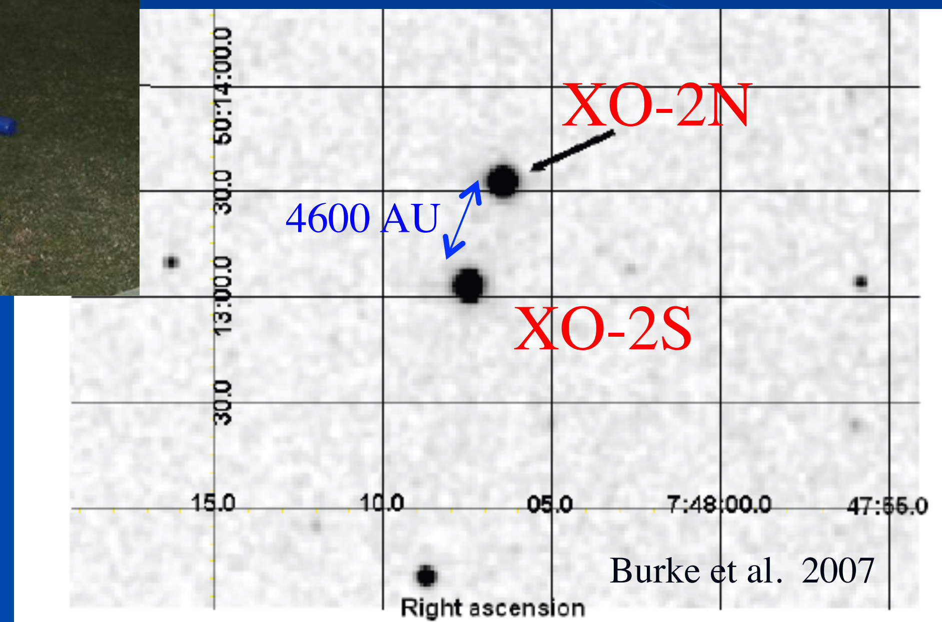

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0.57 M_J
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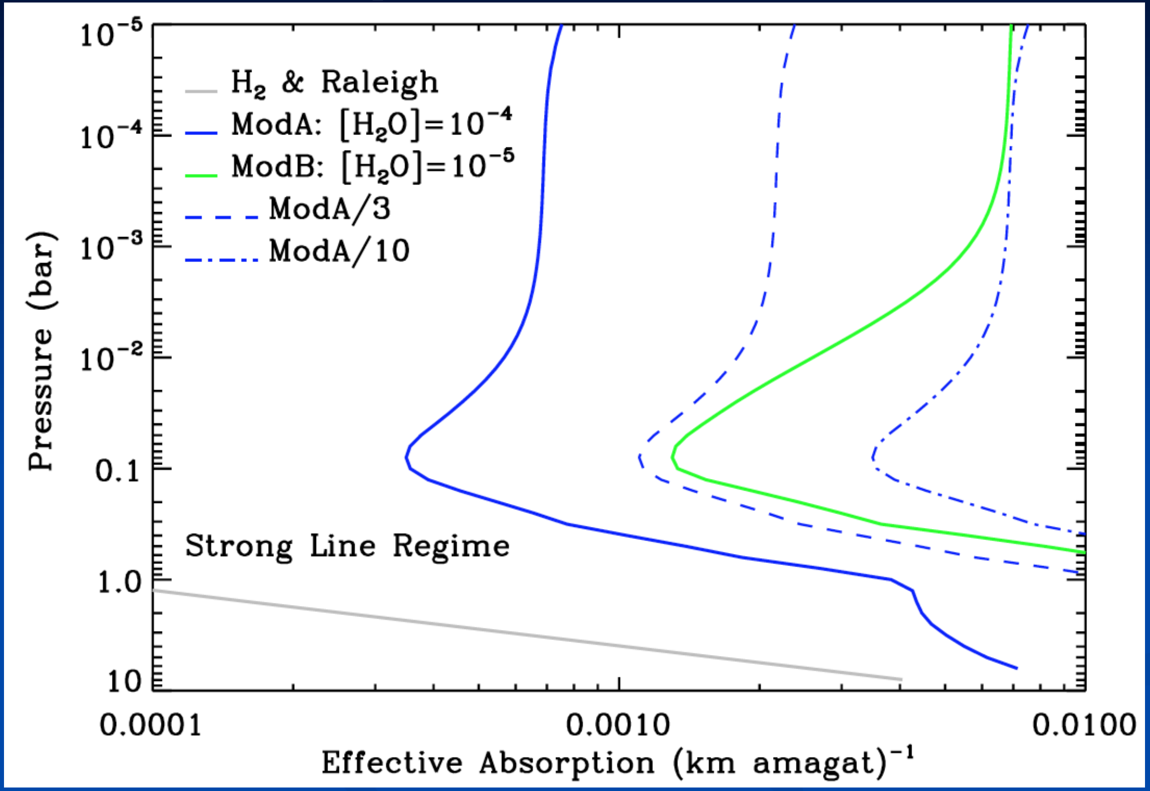
XO-2b Radius Dependence

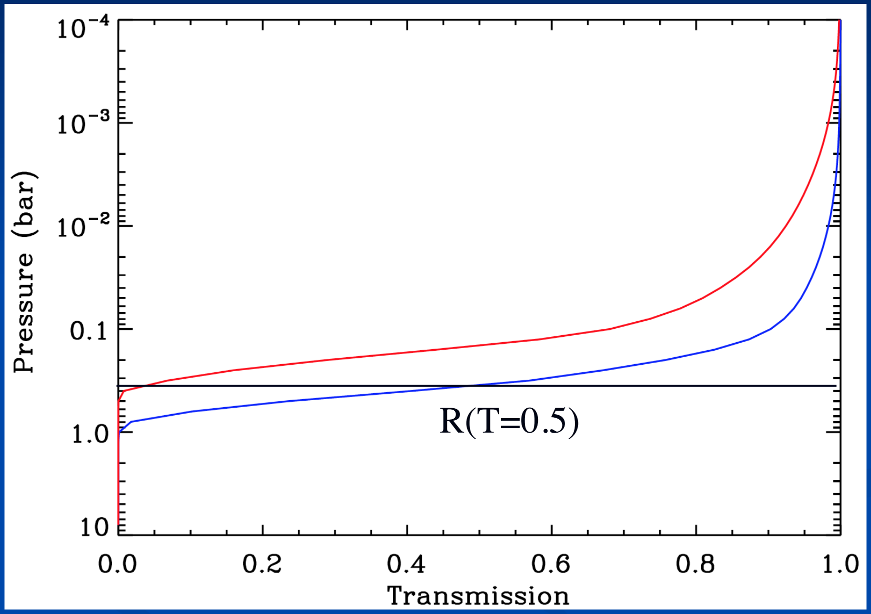
Absorption characteristics at 1.56 um



H_{XO2b} ~ 300 km. Therefore, for a 1% radius increase: $k_L/k_S = \exp(-2.2) = 0.11$
But the absorption is in the strong line regime. Thus: $[H_2O]_L/[H_2O]_S = 0.012$

Radius dependence on derived opacity

An increase in R_p shifts up the pressure & density at R



An increase in R_p shifts up the pressure & density at R. To achieve the same transmission at R, the optical depth must decrease.

The optical depth of the larger planet, τ_L, relates to that of the smaller, τ_S, as:

$$\frac{\tau_L(R)}{\tau_S(R)} = \frac{N(R)_L\ (2\pi R H_L)^{1/2}\ \kappa_L}{N(R)_S\ (2\pi R H_S)^{1/2}\ \kappa_S}$$

Assume that *H* & *k* do not change between the pressure levels sampled by the large and small planet at radius R. Then:

$$\frac{\tau_L(R)}{\tau_S(R)} = e^{(\Delta R/H)}\ \frac{\kappa_L}{\kappa_S}$$

To achieve the same T at R $\tau_L = \tau_S$ and:

$$\frac{\kappa_L}{\kappa_S} = e^{(-\Delta R/H)}$$

Consider a $1M_J$, $1R_J$, T_{eq}=1000 K, H=150 km planet.

A planet size increase of 1% is equivalent to 4.6 H.

k_L/k_S = exp(-4.6) = 0.01

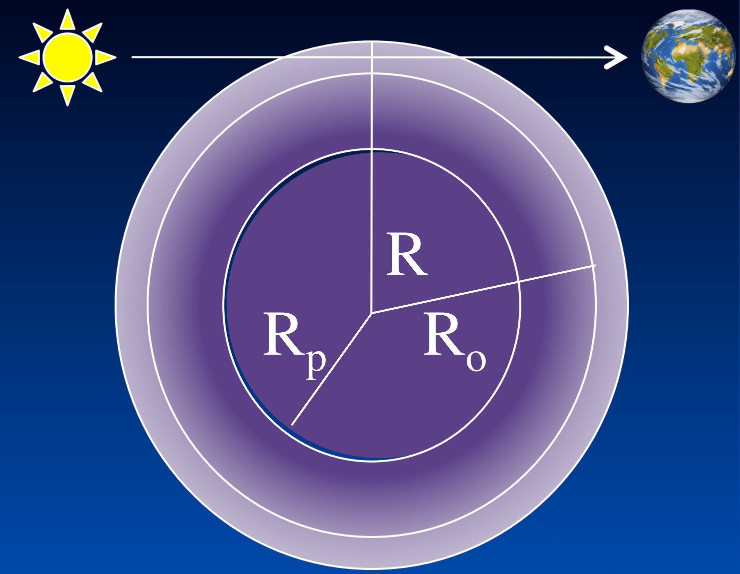
Effect on derived mixing ratio:

Weak line limit: $[H_2O]_L/[H_2O]_S = 0.01$

Strong line limit: $[H_2O]_L/[H_2O]_S = 0.0001$

-> Depends on the atmospheric scale height and absorption regime

Pressure Range



Depth of the observed light curve:

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

The right hand term can be deconstructed into 2 terms

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

Note: $T(R) = e^{-N_t(R) \sum_i \kappa_i}$

Integrate the column density along the tangent line:

$$\int_{-\infty}^{\infty} N(r)ds = N(R)\ (2\pi RH)^{1/2}$$

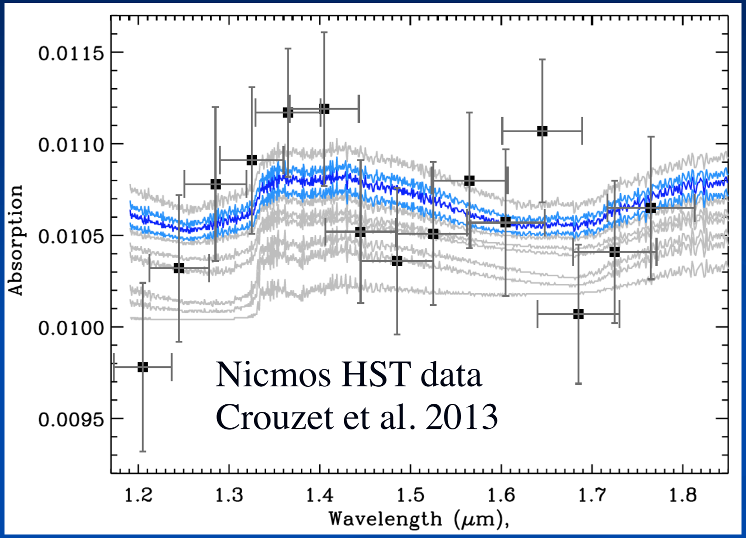
N(R) is the density at the closest distance to the planet's center, R

To find the range (R_T and R_O):

1) Specify that $T(R_T)$ is small (e.g. 0.05) and $T(R_O)$ is large (e.g. 0.95)
2) Solve for R : $T(R) = \exp\ (-N(R)\ (2\pi RH)^{1/2}\ \kappa)$
3) Approximate: $N(R_T) = N(R_O) \exp(-(R_T - R_O)/H)$

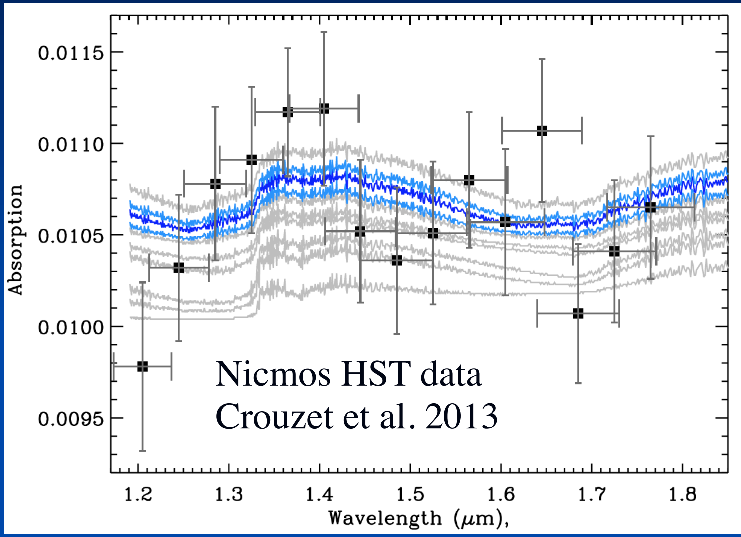
-> Answer: 4 scale heights
-> A factor 55 change in P

Transmission spectra of XO-2b



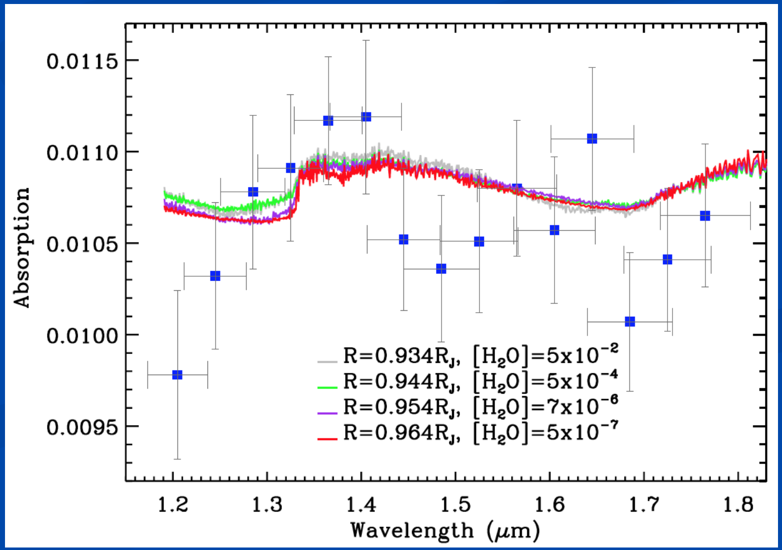
For one Rp and a temperature profile, the data indicates solutions that vary within an order of magnitude.

XO-2b – larger scale height: not so bad

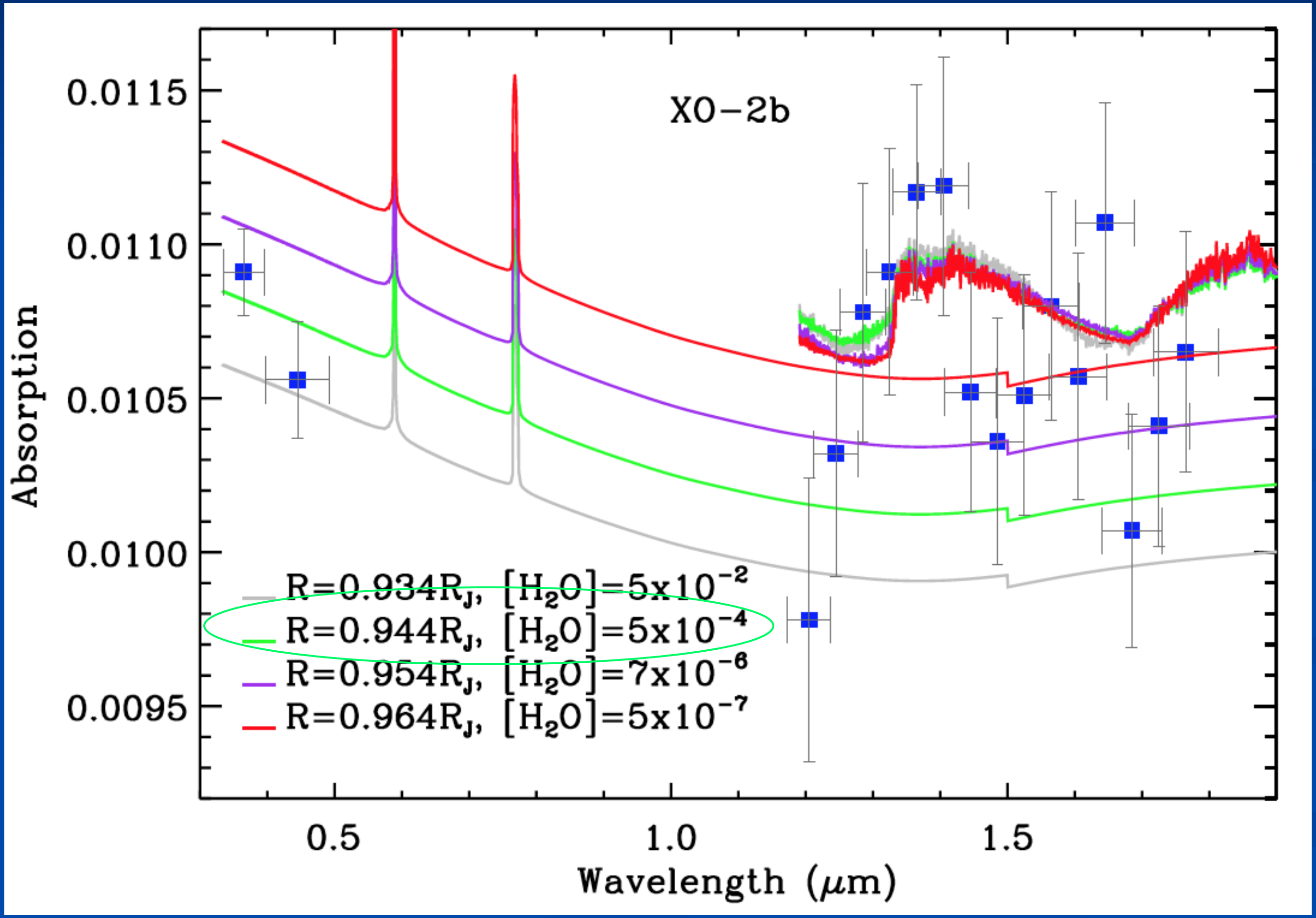


One Rp: solutions range 1 order of magnitude

Radii increased by 1%

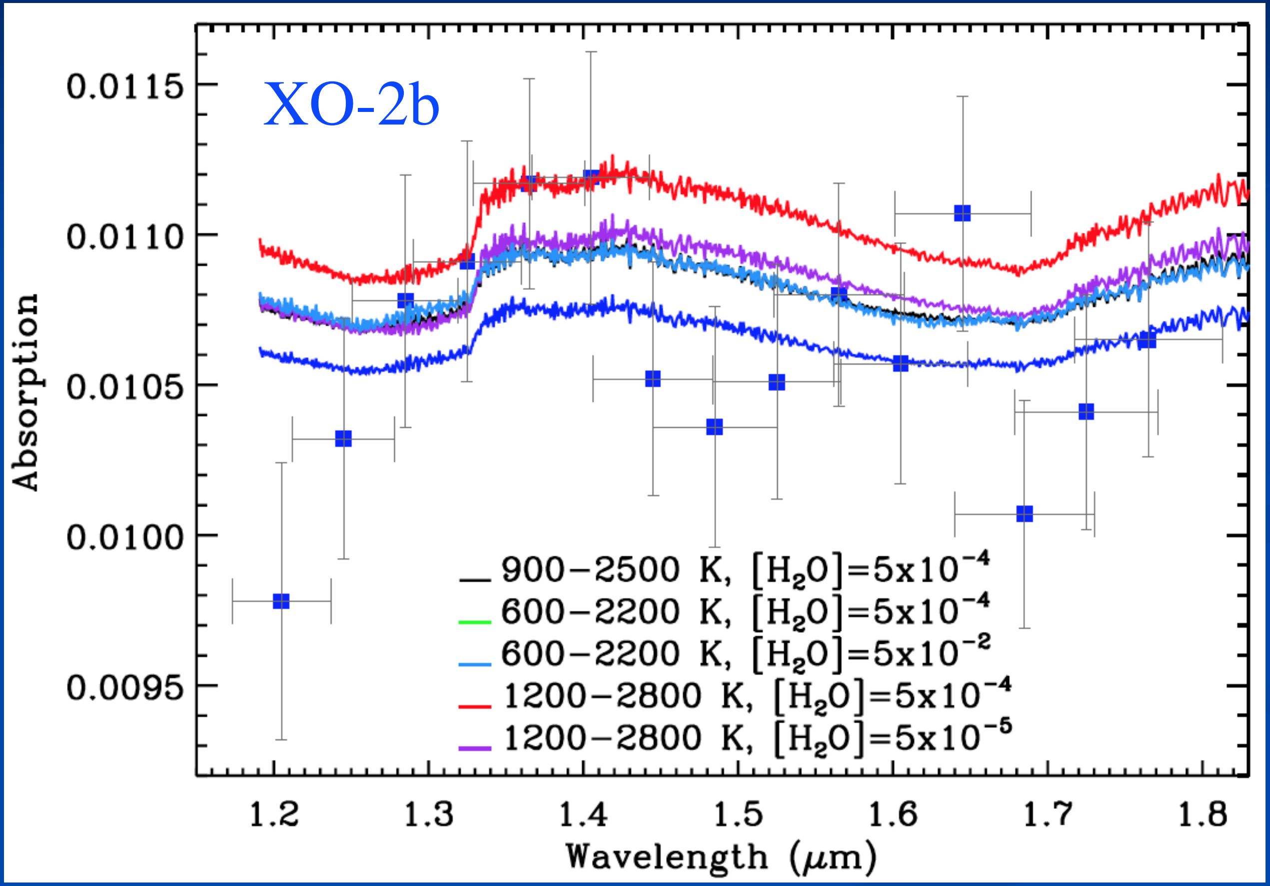


Ground-based photometry leverages HST & SPITZER data



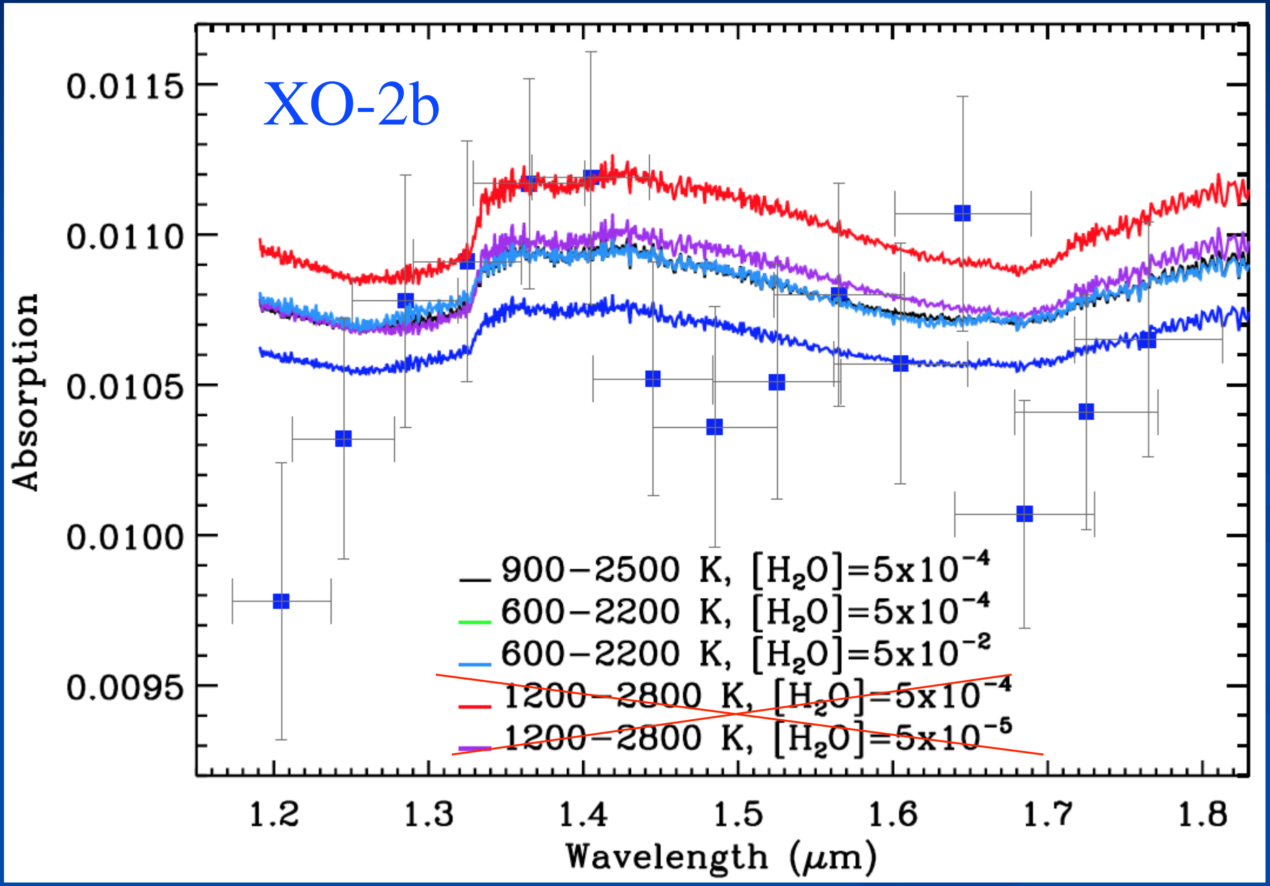
For a single temperature profile $4x10^{-4} < [H_2O] < 3x10^{-3}$

Temperature dependence



Yet there are constraints on the temperature profile

Temperature dependence



Observations indicate $[H_2O] \geq 2x10^{-4}$, the solar abundance equilibrium value

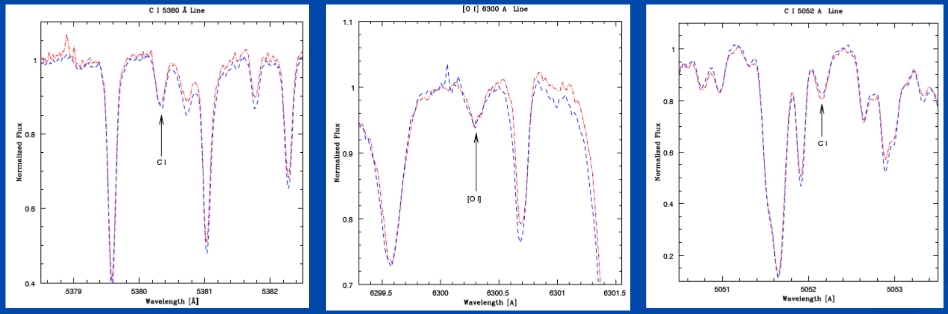
System elemental abundances

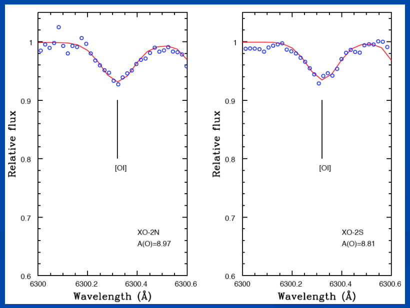
We know [Fe/H], [C/H], [O/H] and [C/O] of XO-stars.

Carbon and Oxygen Abundances in the Hot Jupiter Exoplanet Host Star XO-2B and its Binary Companion

J. K. Teske, S. C. Schuler, K. Cunha, V. Smith, C.A. Griffith

Submitted to ApJ Letters



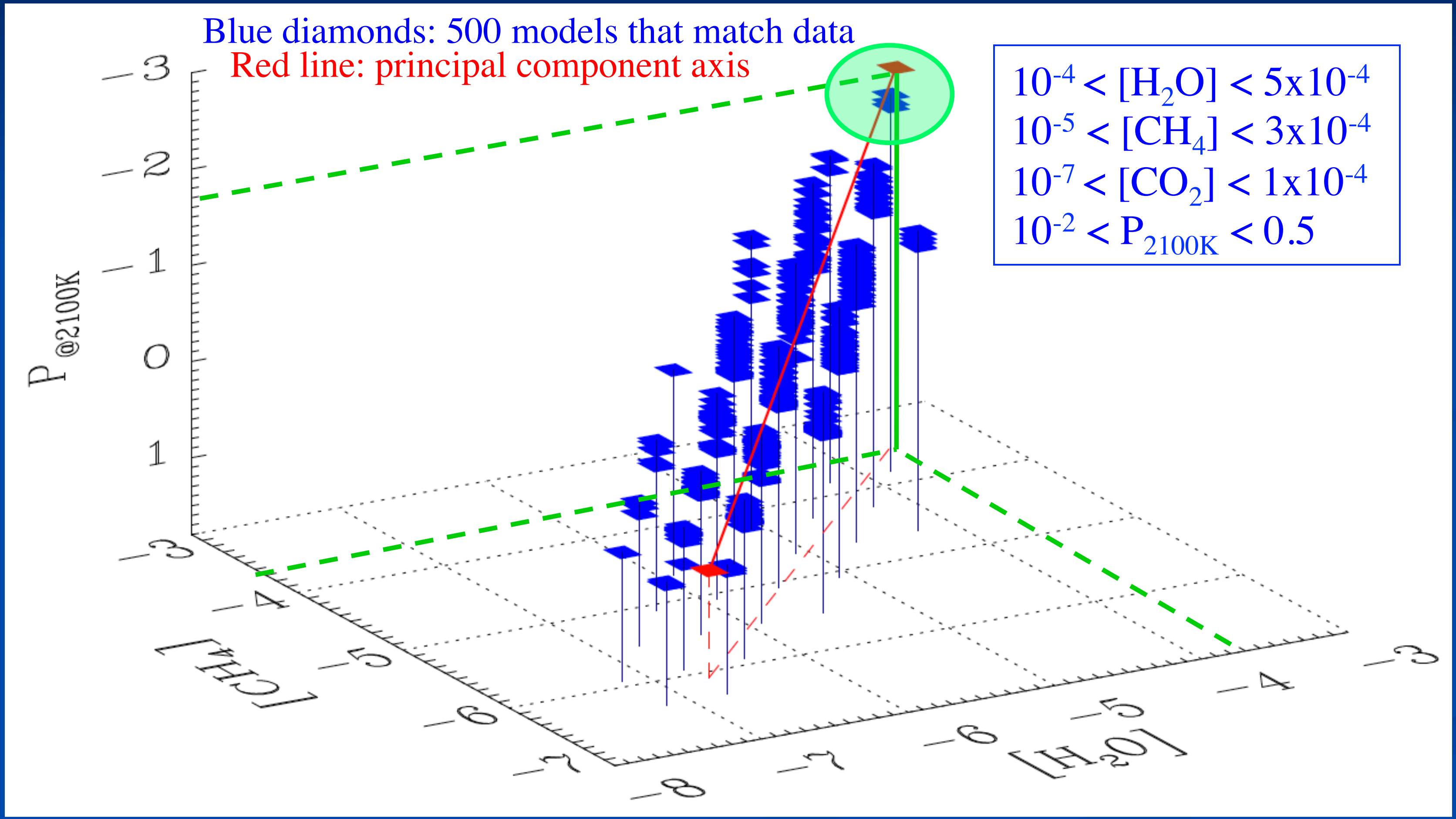


Parameter*	XO-2S	XO-N
[Fe/H]	0.28±0.14	0.39±0.14
[Ni/H]	0.38±0.04	0.44±0.04
[O/H]	0.18±0.15	0.34±0.16
[C/H]	0.26±0.11	0.42±0.12
C/O	0.60±0.19	0.60±0.20

- [Fe/H] values agree with Burke et al. 2007, Ammler-von Eiff et al. 2009 & Torres et al. 2012
- [Ni/H] values by Teske et al. 2013 are smaller than Burke et al. values.

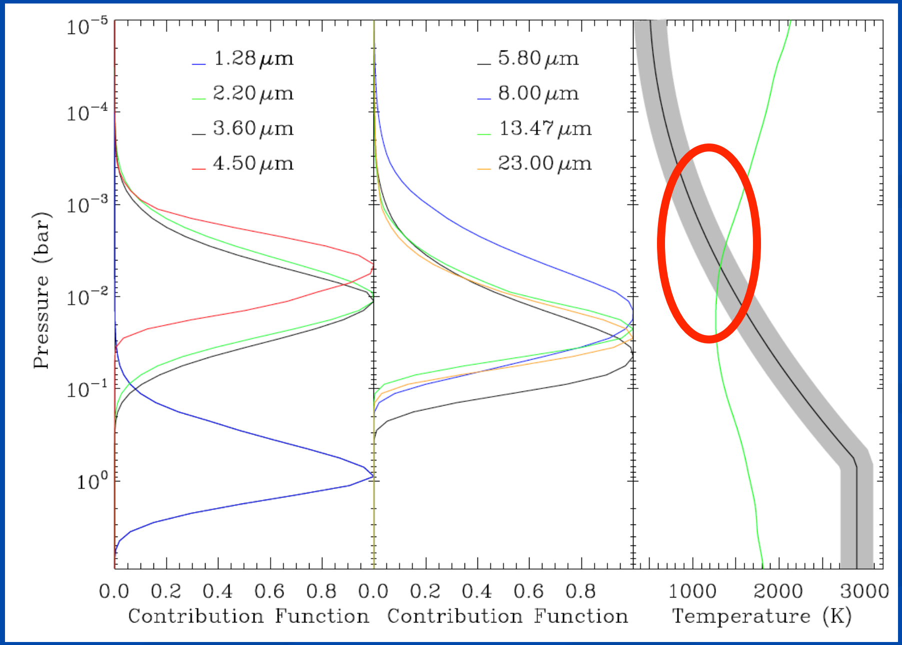
Combine 1st and 2nd transits:

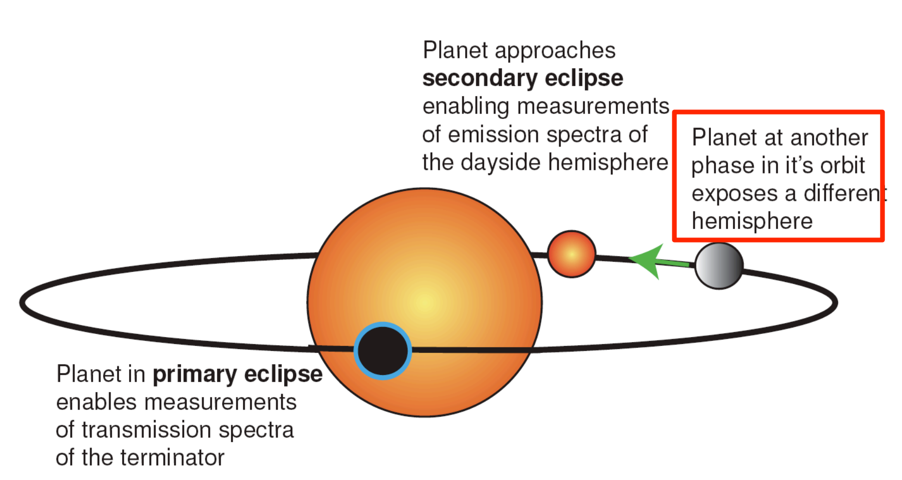
HD209458b



Constraints on temperature

Moses et al. 2011





Full phase measurements at
Two spitzer wavelengths.

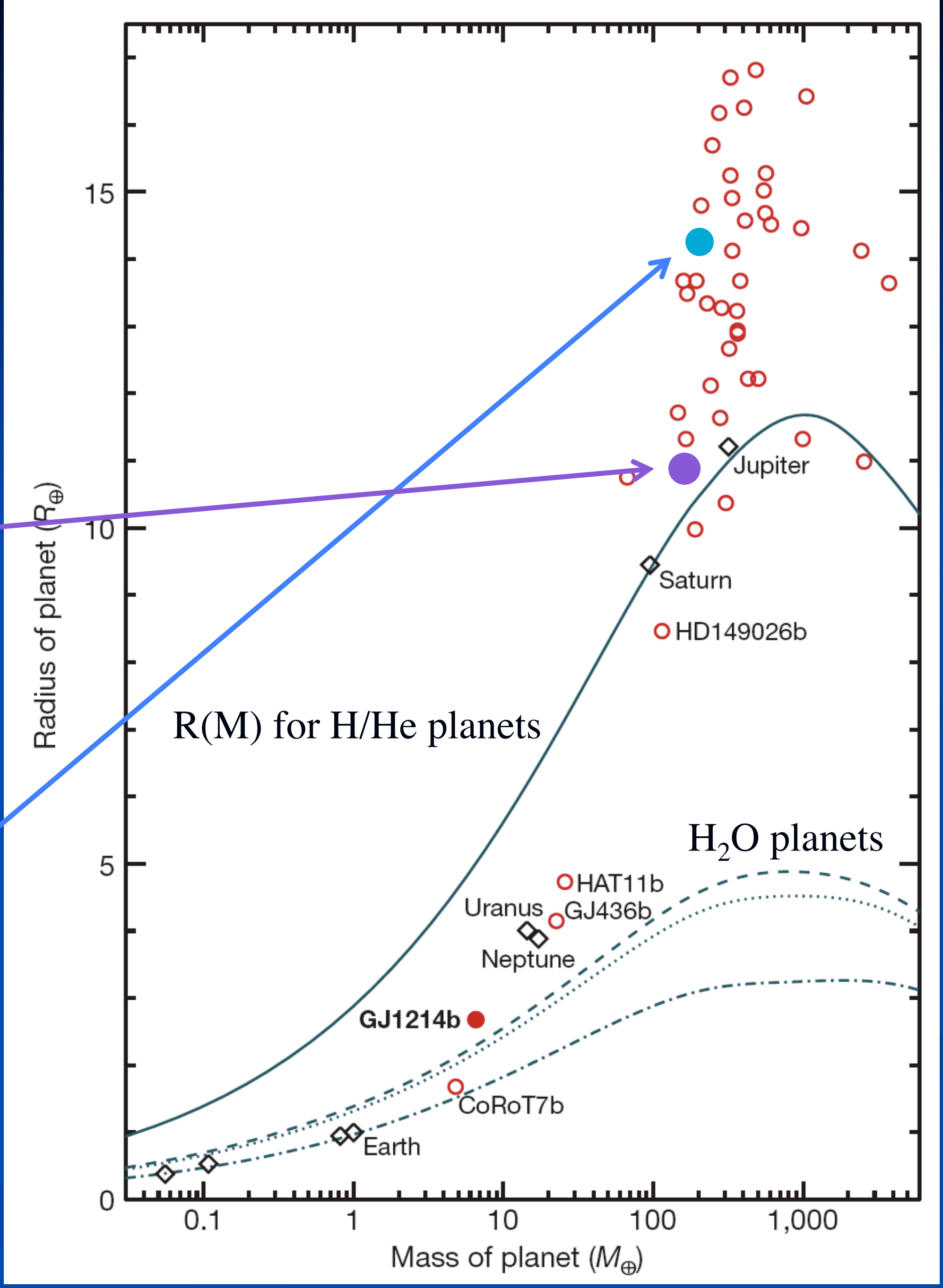
Extrasolar Planets

XO-2b

Mass: 0.57 M_J
Radius: 0.97 R_J
Parent Stars (2): KOV
V Magnitude: 11.2
$[Fe/H]_{Star}$: 0.39*
Semi-major axis: 0.037 AU

HD209458b

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



Charbonneau et al. 2009

* *Teske et al. 2013*

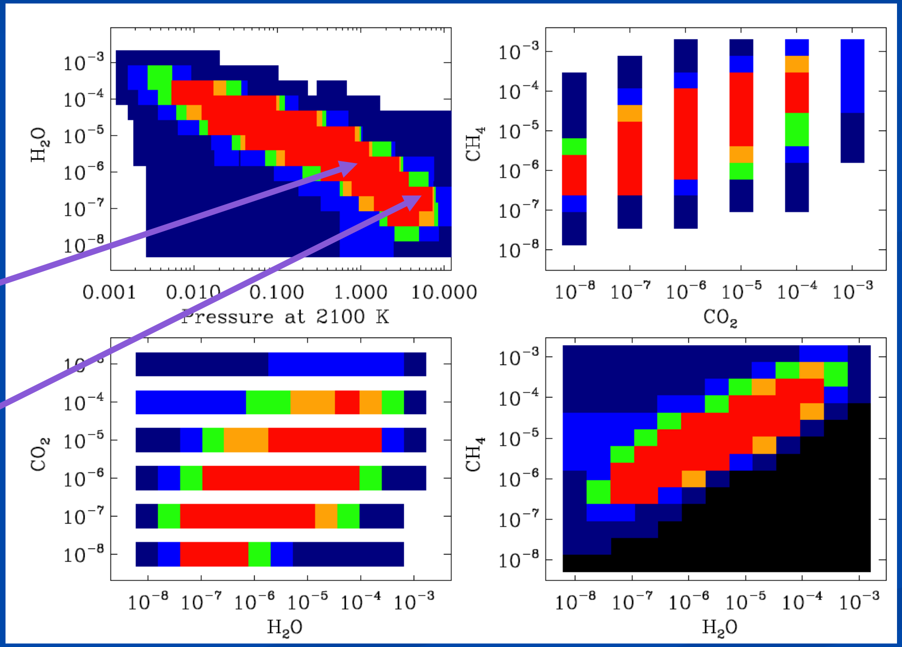
Analyses of low resolution optical to IR data of transiting planets

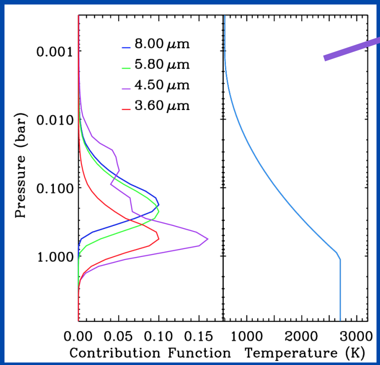
Caitlin Griffith
(University of Arizona)

Collaborators: J. Turner, J. Teske, R. Zellem, G. Tinetti, M. Swain, P. Deroo, K. Cunha, S., R. Zellem, S. Schuler, V. Smith, R. Freedman, J. Tennyson, N. Lewis, H. Knutson

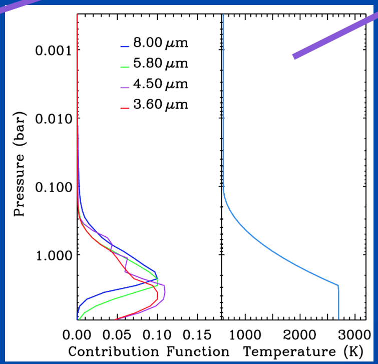
Secondary Eclipse: Dayside Emission

Temperature parametrized with 5 parameters; Composition of H_2O, CH_4, CO and CO_2 with 4





Higher H_2O abundance
-> emission from higher levels

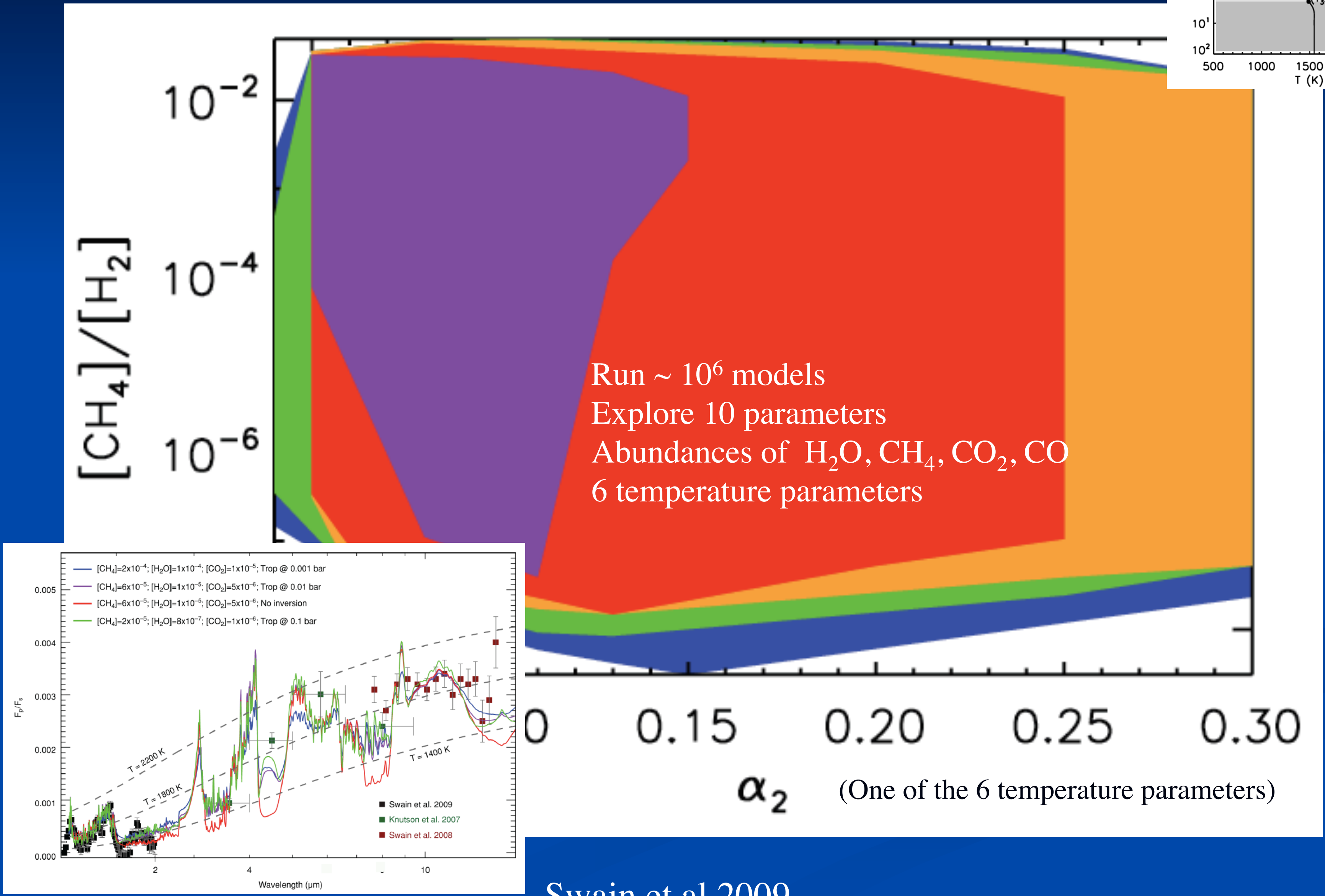


Higher H_2O abundance
-> emission from higher levels

17 million models… (why so silly?)

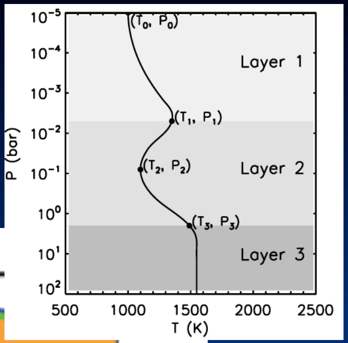
Griffith, Zellem, Tinetti, Swain, Deroo et al. 2013, in prep.

Degenerate Solutions



Run ~ 10^6 models
Explore 10 parameters
Abundances of H_2O, CH_4, CO_2, CO
6 temperature parameters

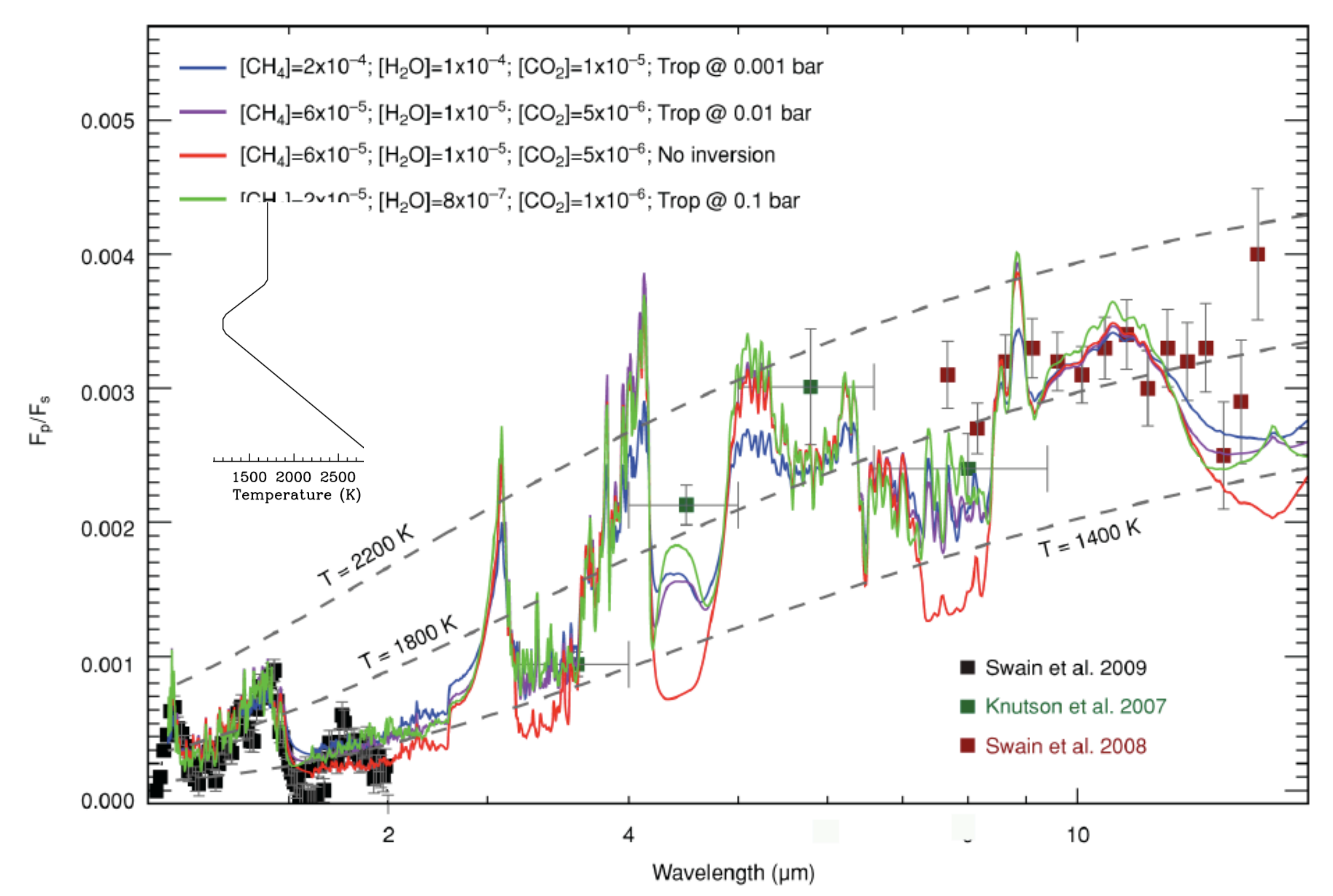
(One of the 6 temperature parameters)



Madhusudhan & Seager 2009

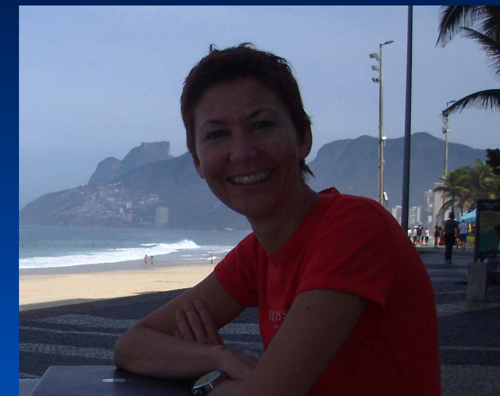
Swain et al 2009

Many combinations of temperature & composition fit the data



Swain et al. 2009

Acknowledgments…



Range of efforts

Observations: Bouwman, Beaulieu, Gomez, Waldmann

Data reduction: Waldmann, Bouwman, Beaulieu

Molecular spectroscopy: Tennyson

Radiative transfer: Koskinen, Menanger

Chemistry: Venot

Dynamics: Cho

Interior structure

Planetary Systems: Sozzetti