The study of exo-climates with EChO

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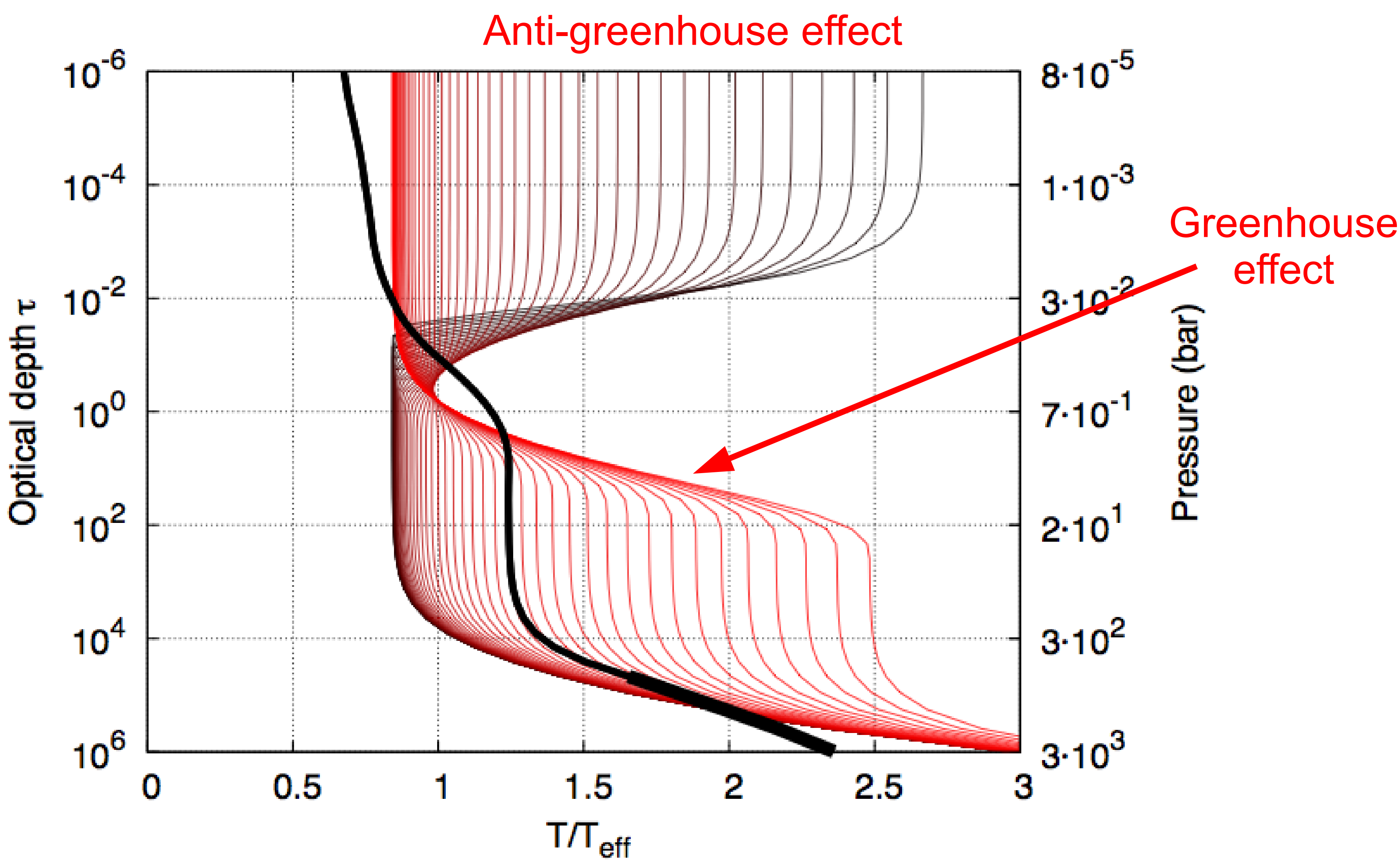
am Showman
nathan Fortney
ark Marley

A fast model for studying the diversity of exo-atmospheres

1D models of the atmosphere

Semi-grey model : 1 band in the visible, 1 in the infrared



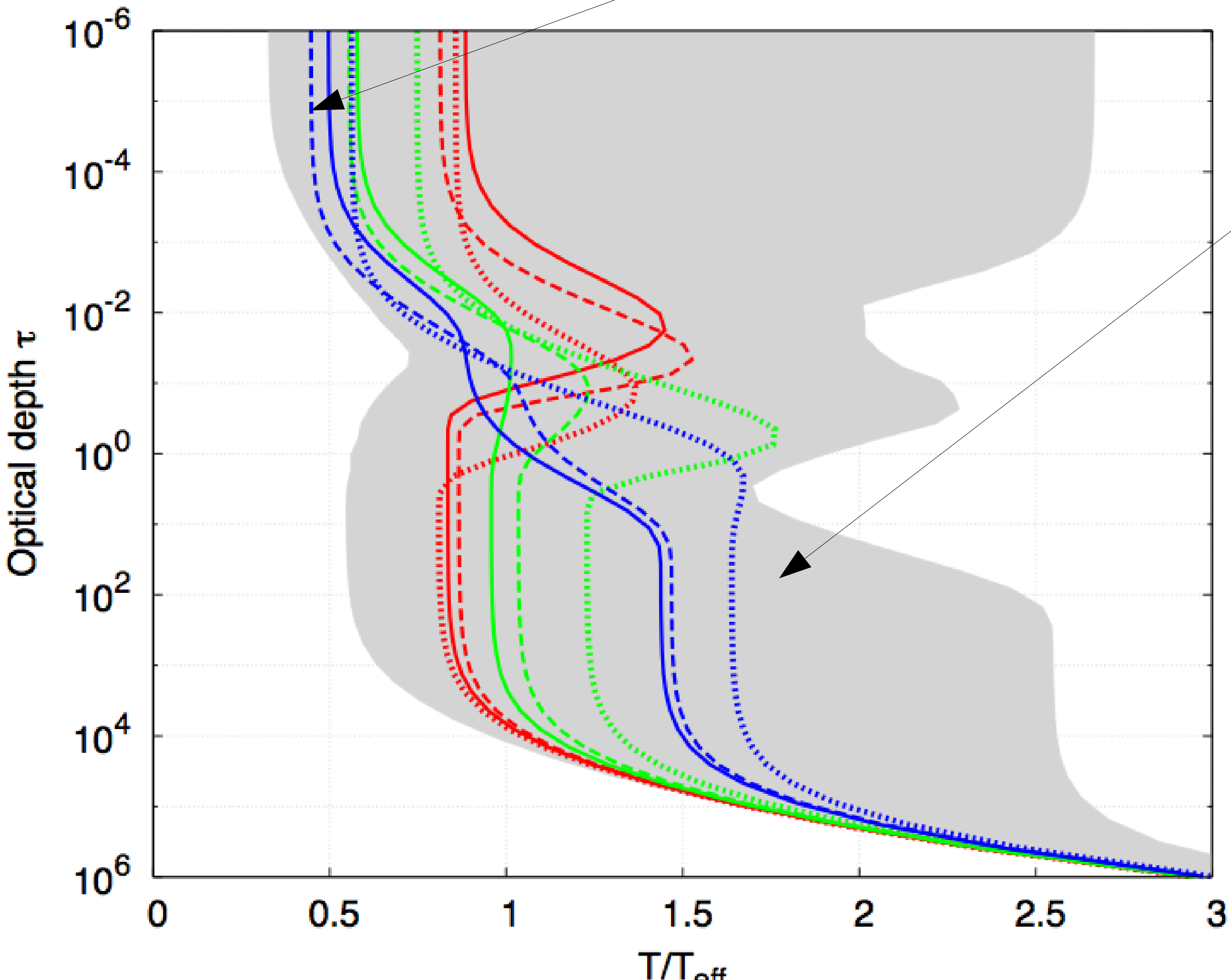
Parmentier & Guillot 2013 – in prep.

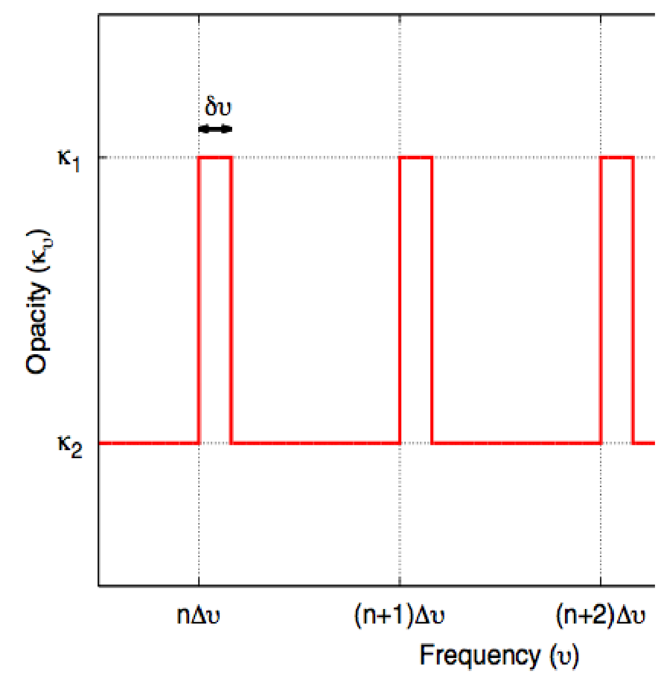
1D models of the atmosphere

Non-grey model : 1 band in the visible, 2 in the infrared

Significant cooling of the upper atmosphere

Significant warming of the lower atmosphere





Parmentier & Guillot 2013 – in prep.

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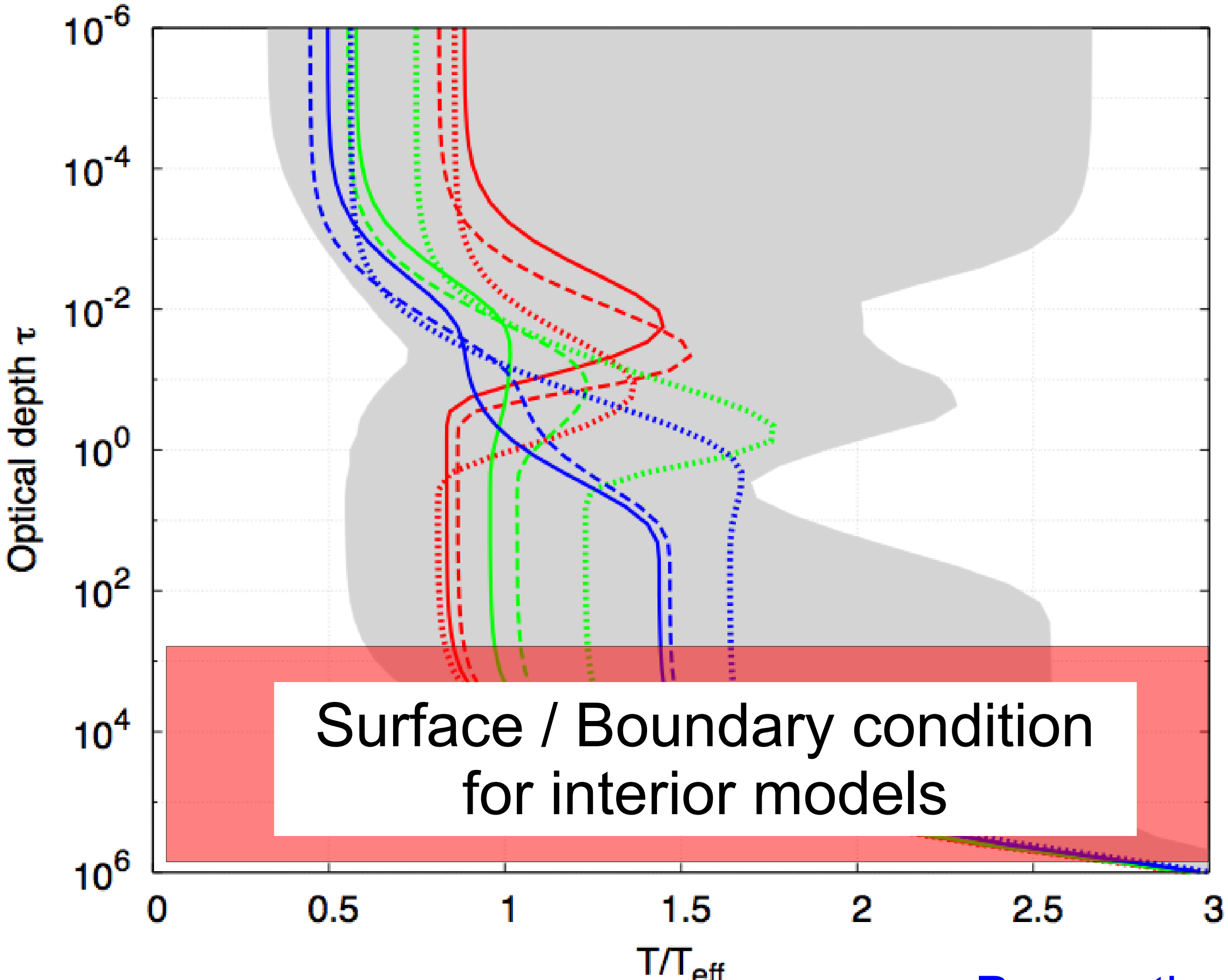

Evolution ?
Cooling rates ?
Liquid/solid/superfluid water ?
Magma ocean ?

Parmentier & Guillot 2013 – in prep.

1D models of the atmosphere

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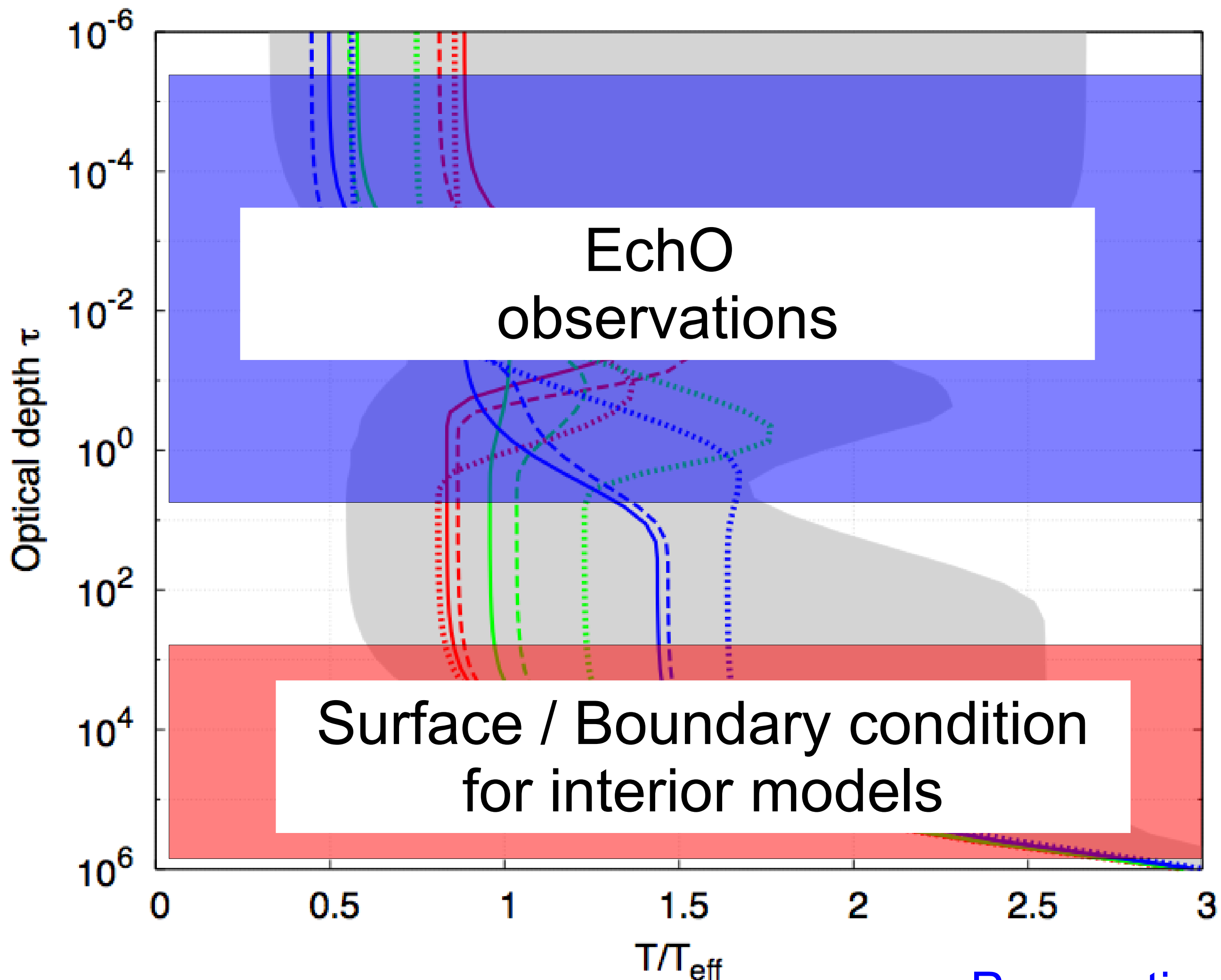

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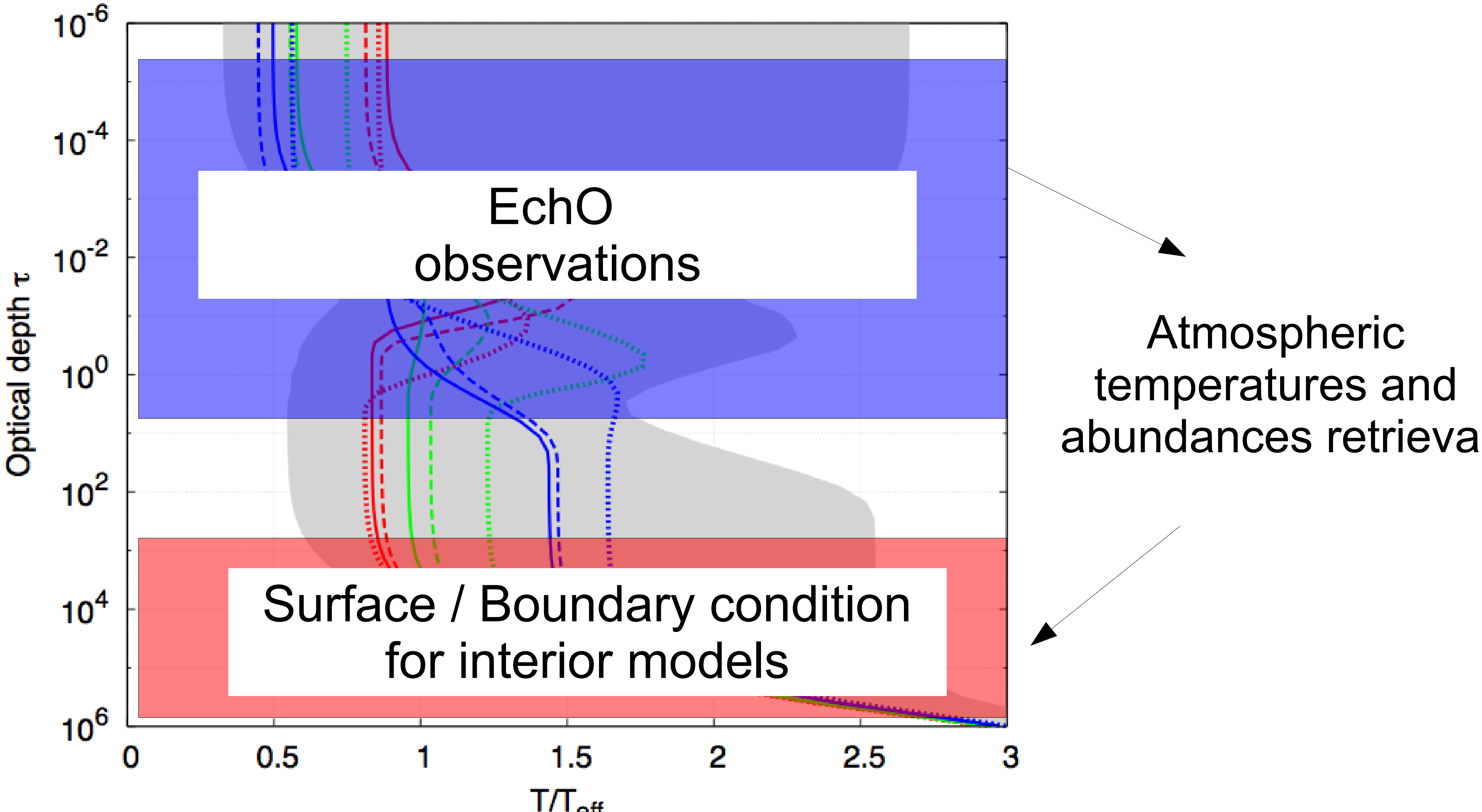
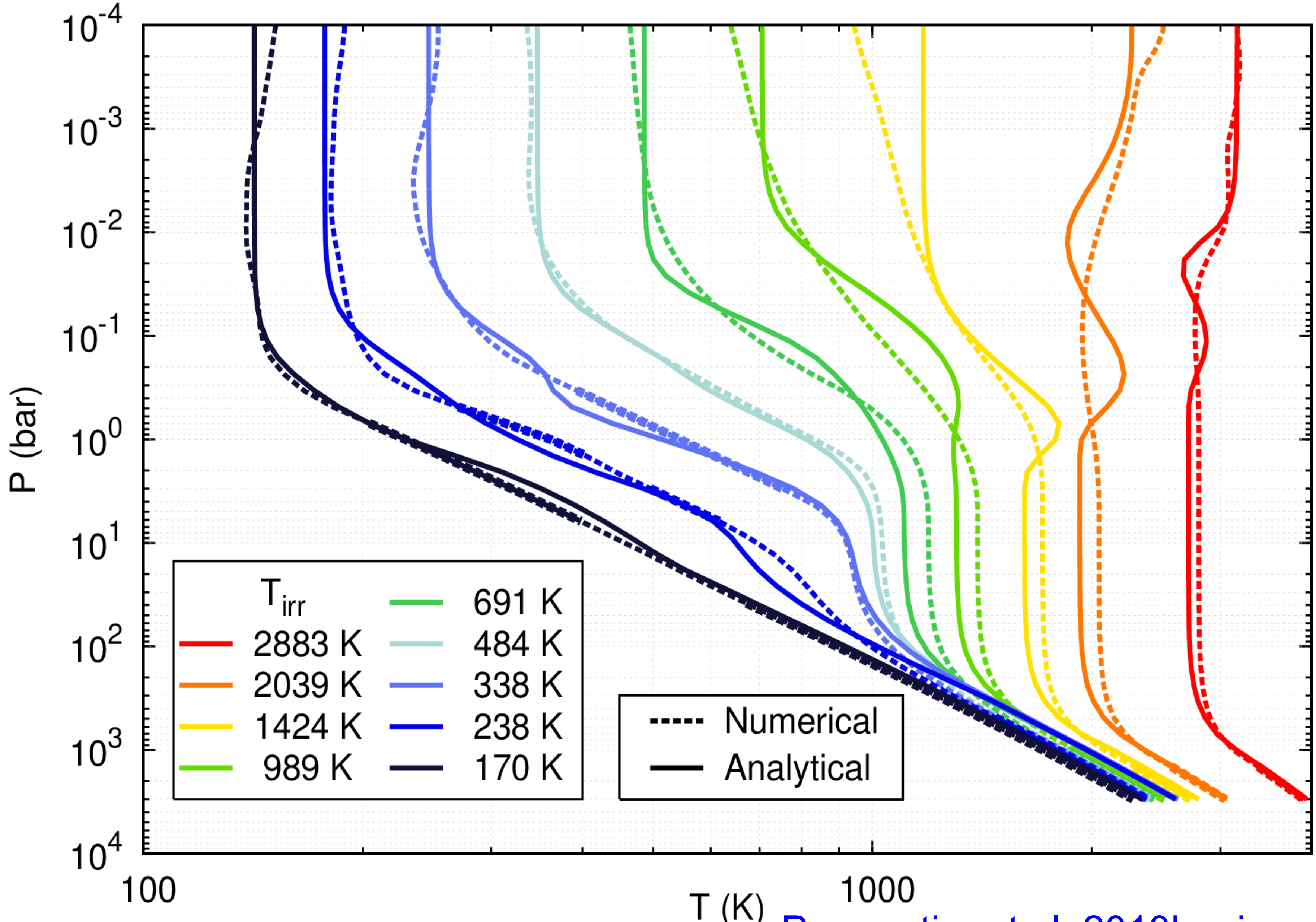


Parmentier & Guillot 2013 – in prep.

Analytical vs. Numerical : solutions

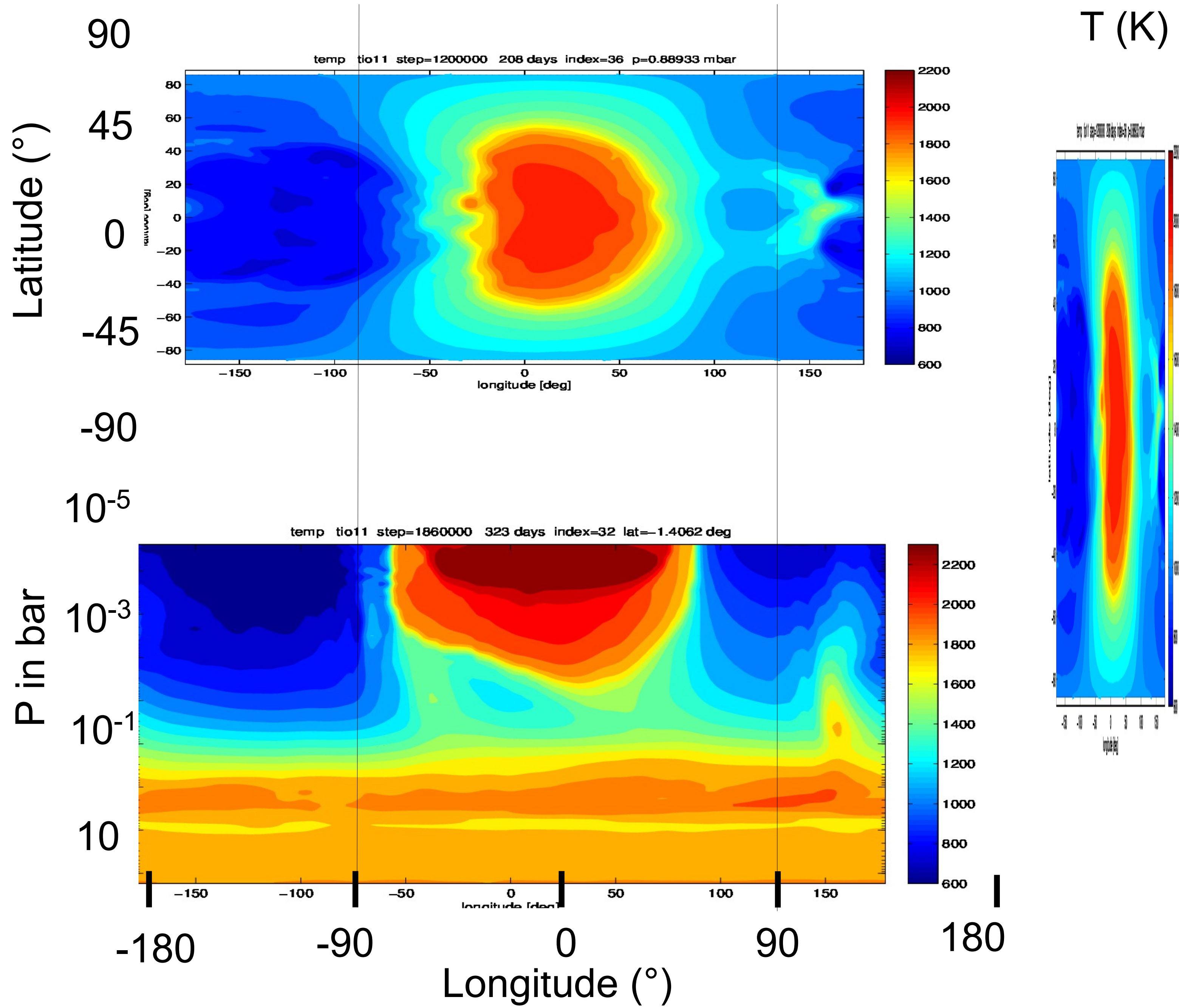
Analytical solution valid within 10% over a wide range of irradiation and gravity



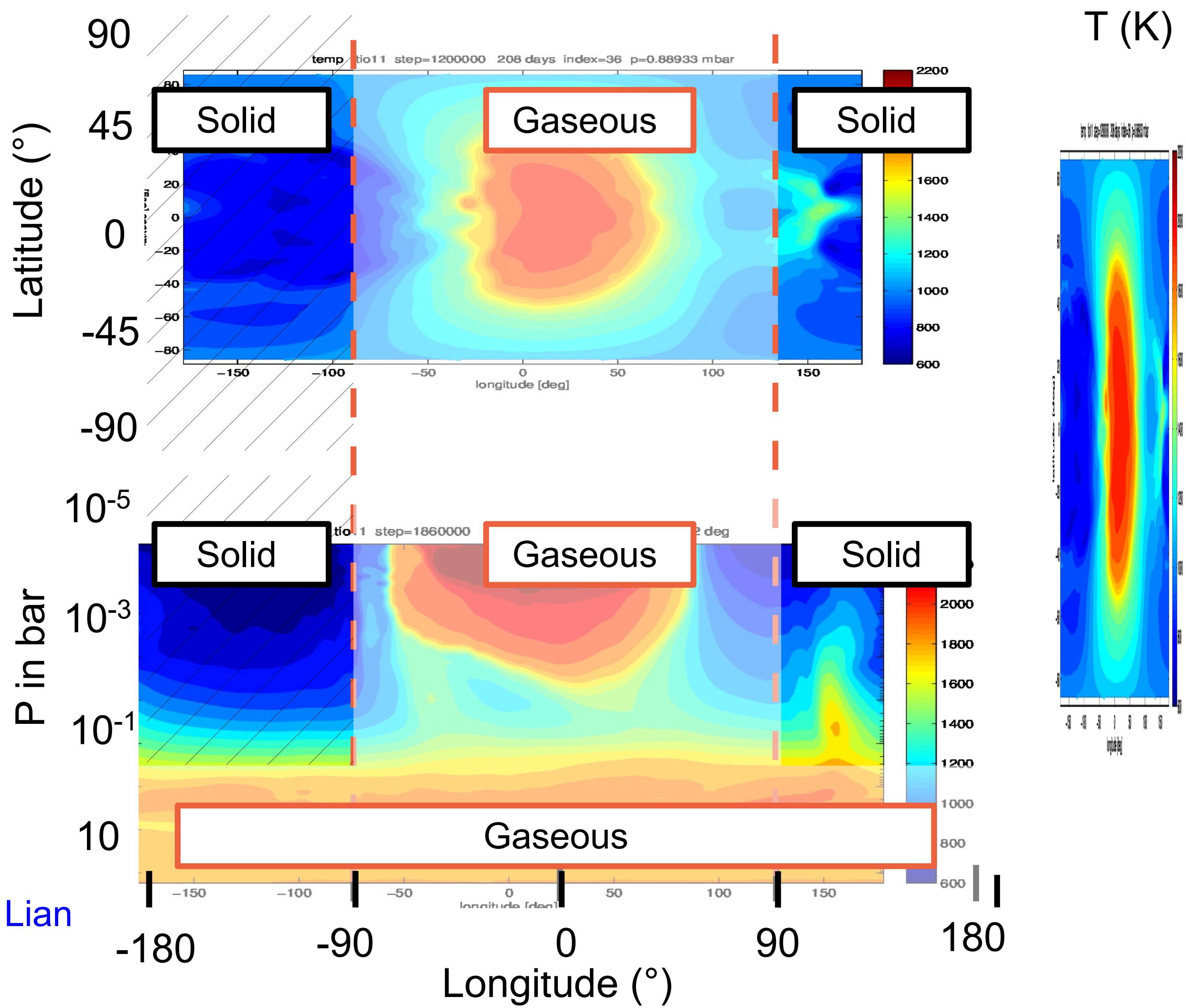
Parmentier et al. 2013b – in prep.

The importance of weather

Temperature field of HD209458b



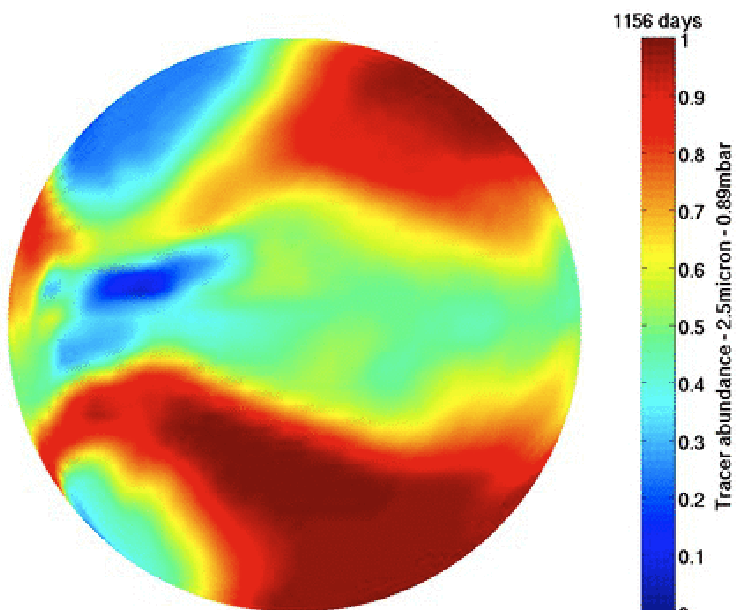
Temperature field of HD209458b



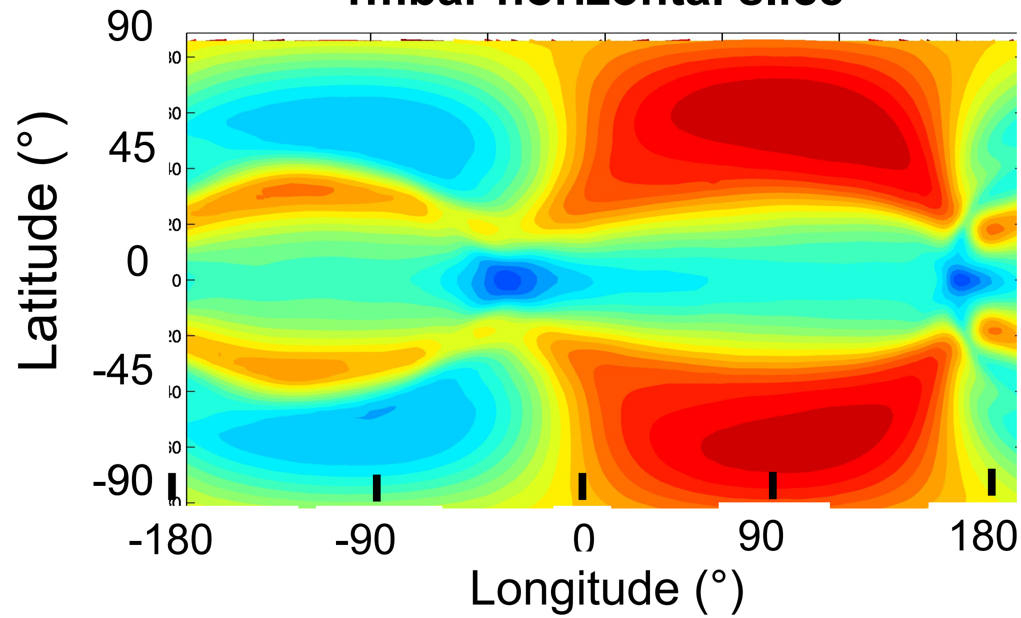
Parmentier, Showman & Lian 2013 – submitted.

Results : spatial variability – 2.5 µm case

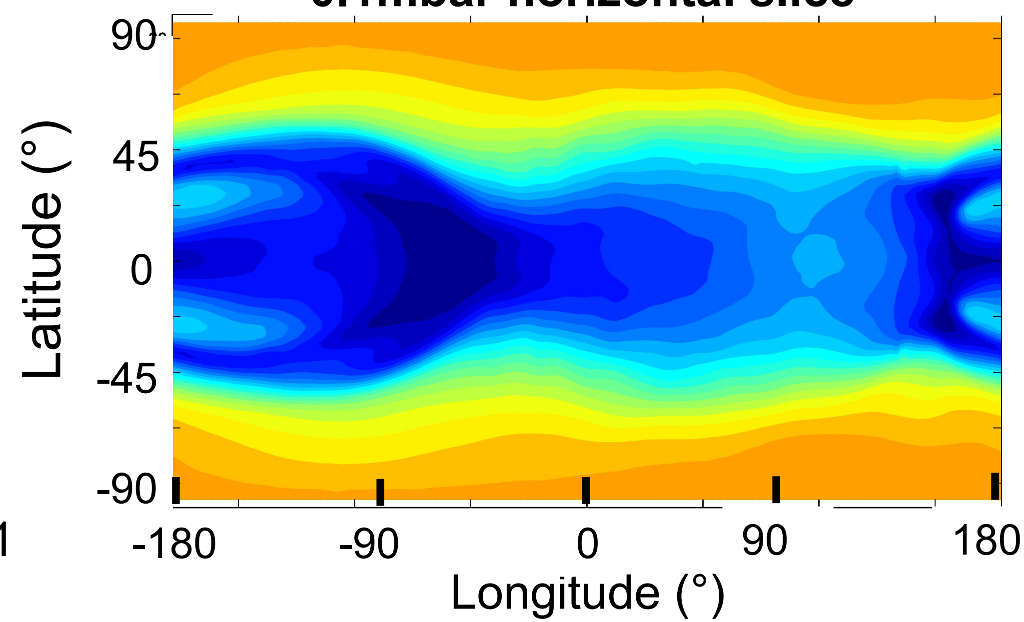
1mbar dayside time evolution

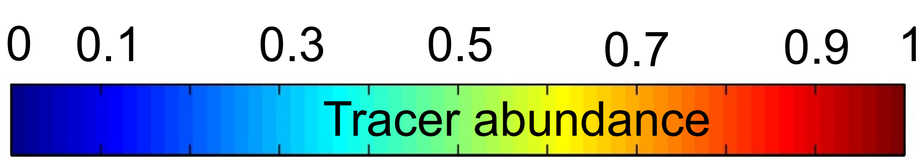


1mbar horizontal slice

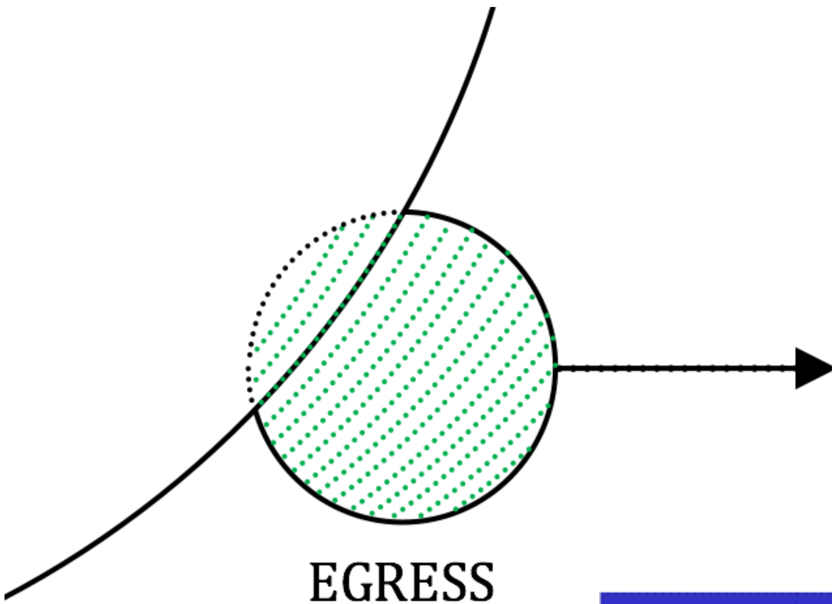


0.1mbar horizontal slice



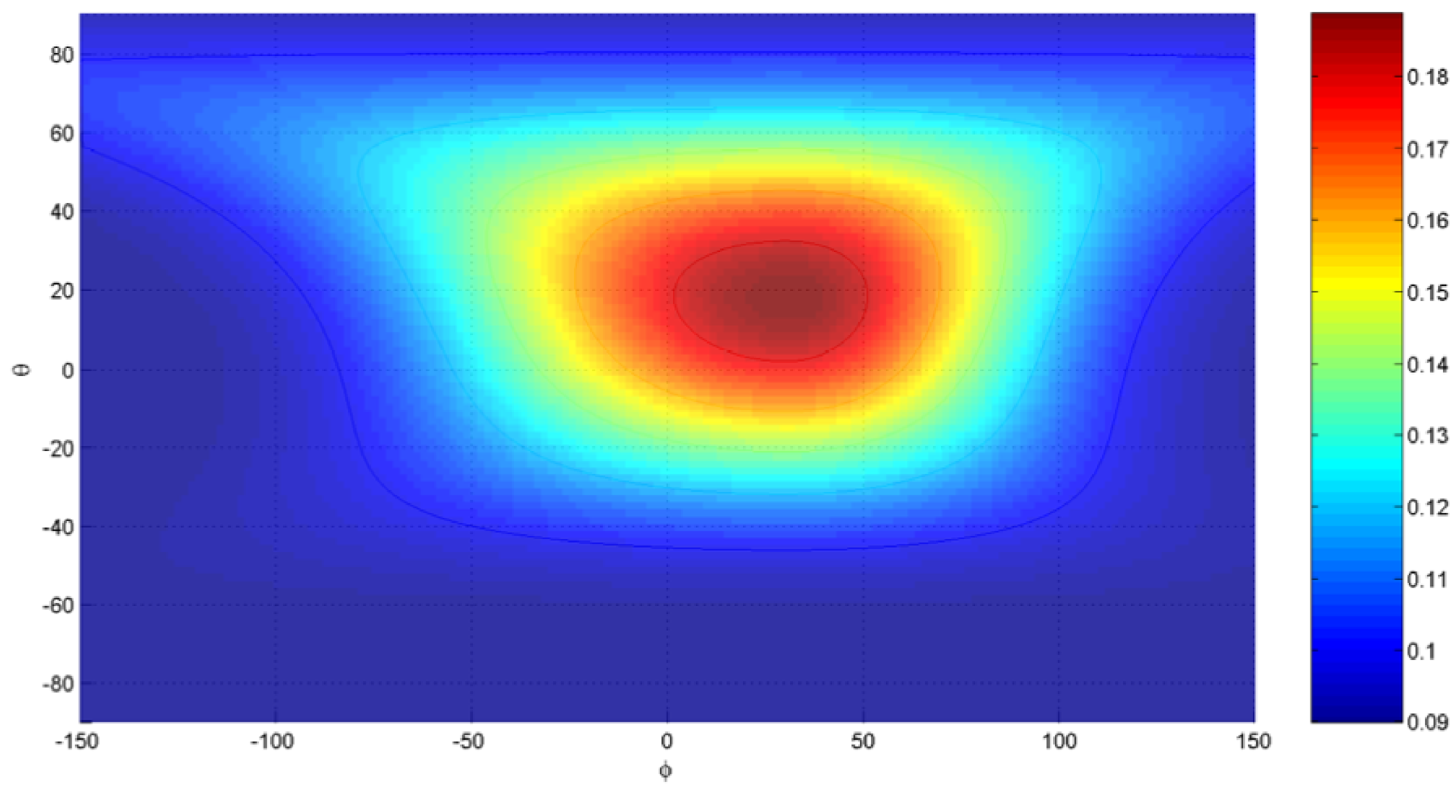


Secondary eclipse mapping



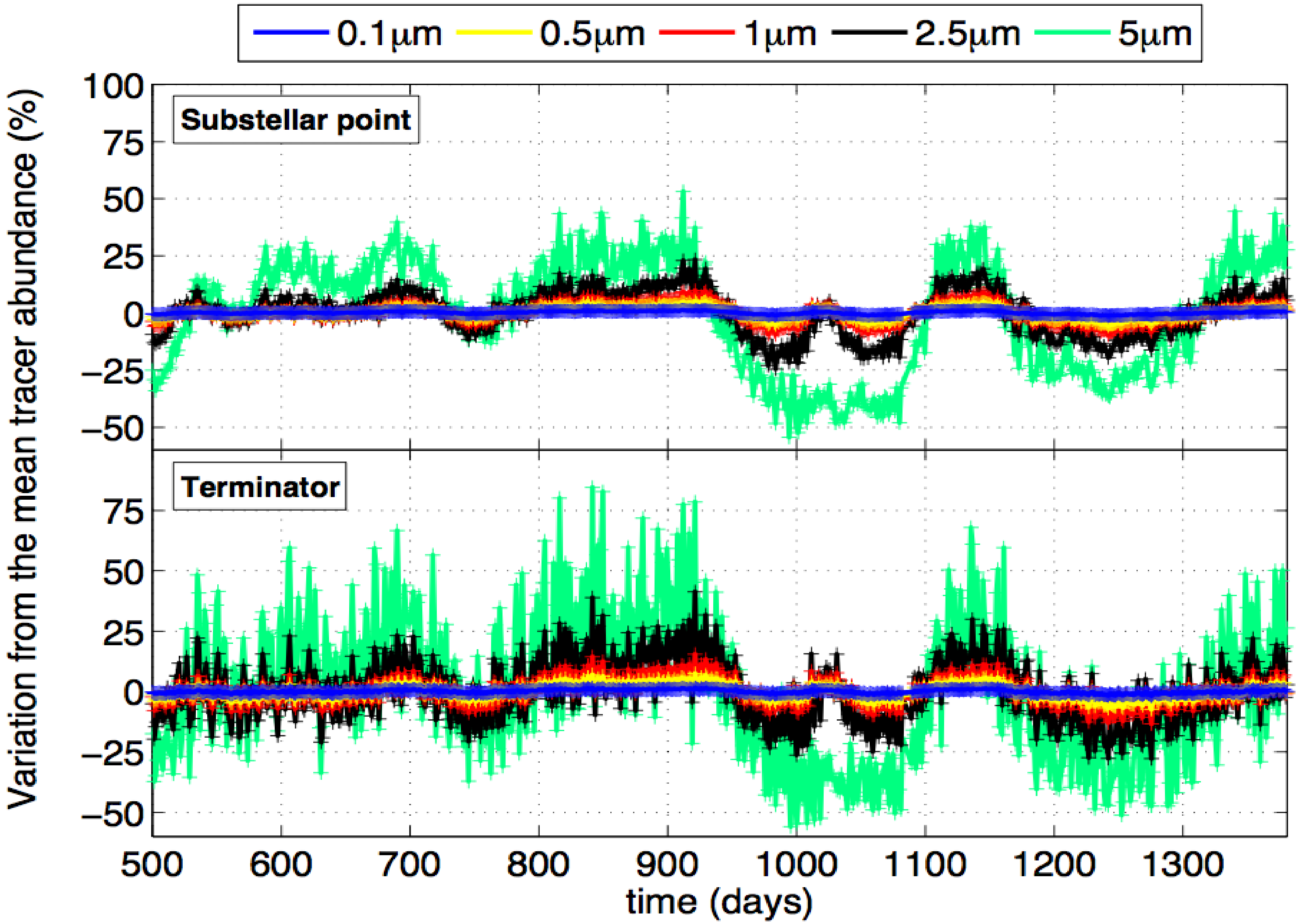
The planet disappear and reappear by slices during secondary eclipse ingress and egress. This gives an information on the north/south brightness variation.

Combined with the phase mapping, this gives information on the east/west brightness distribution, we can build 2D maps of the planet.



De Witt et al. 2012

Time variability

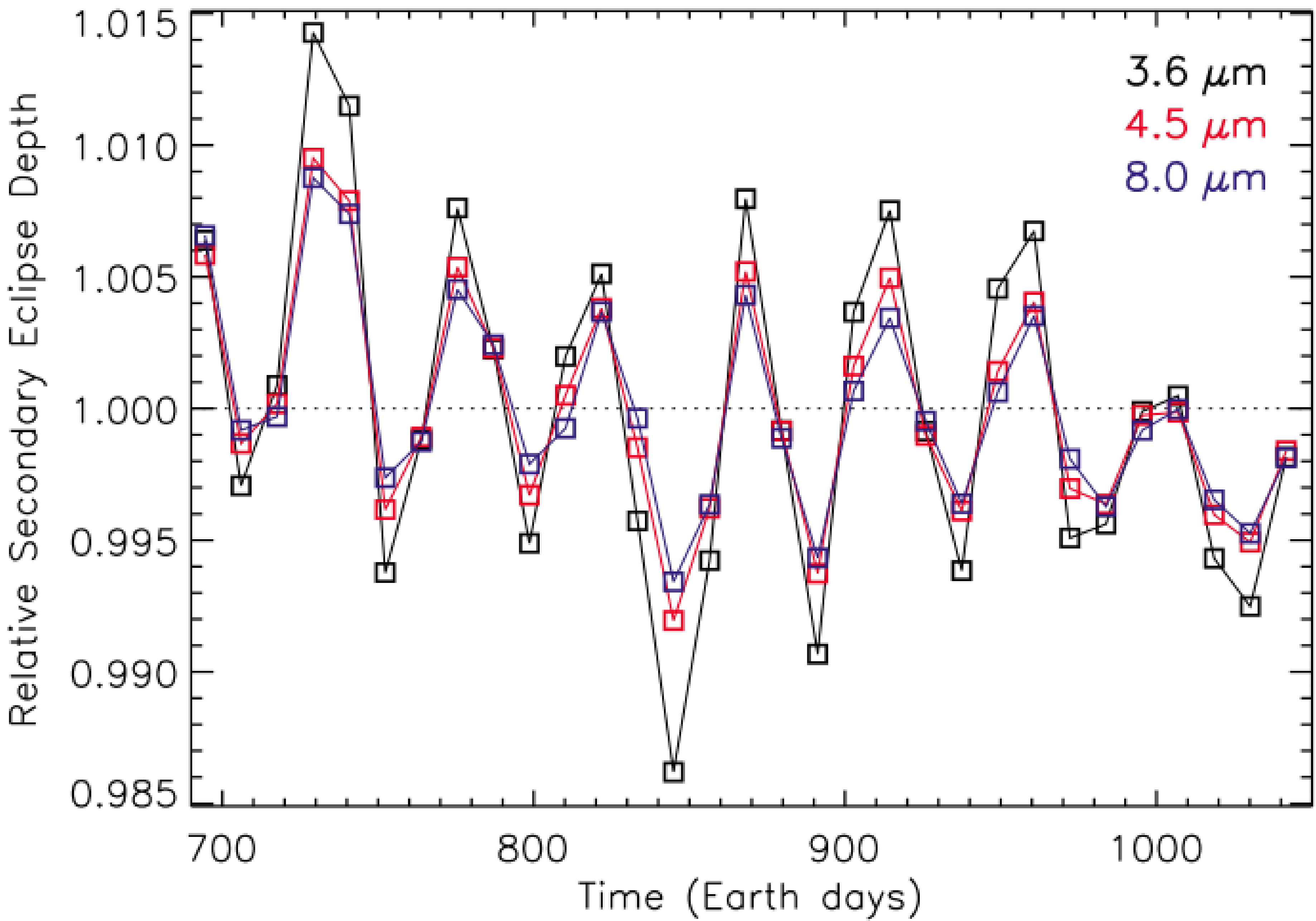


Up to 60% variability of the tracer abundance around the substellar point and the terminator in timescales of hundred of days but only 1 to 5% for sub-micrometer condensates.

→ Could lead to a spatial variation of the hottest spot or spatial variation of the albedo.

→ For TiO the effect could be amplified by switching on and off the stratosphere.

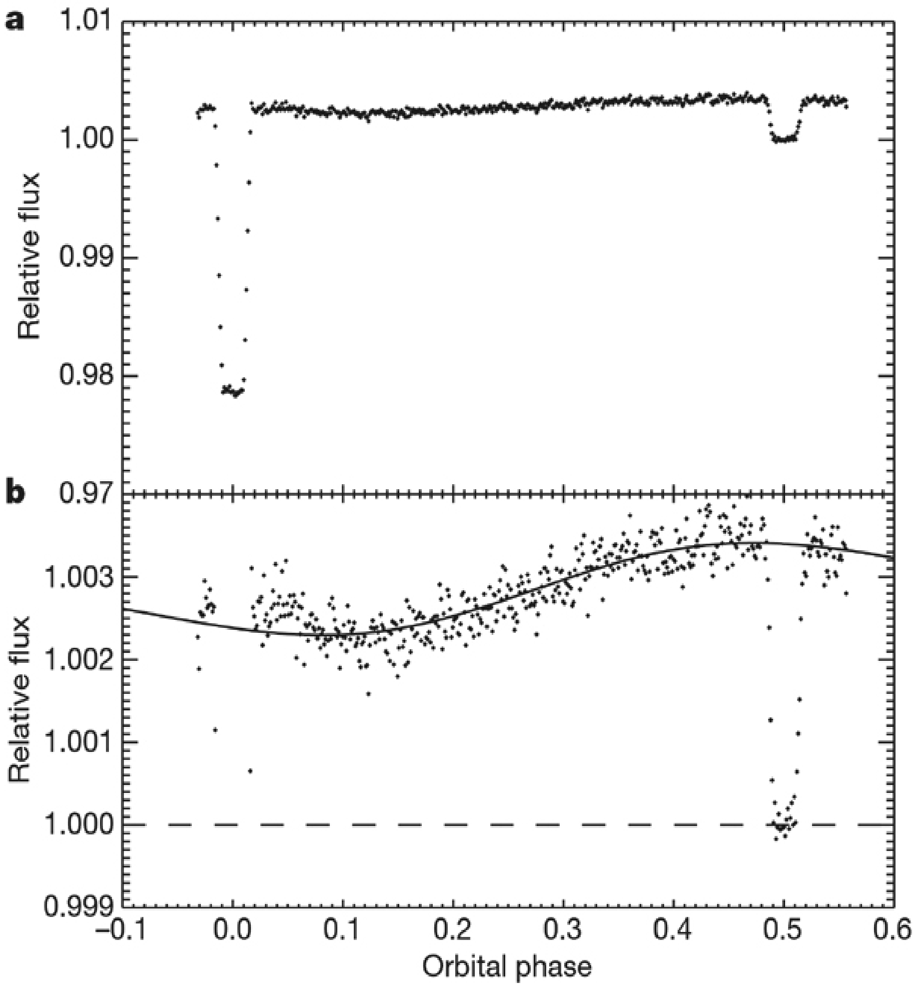
Time variability

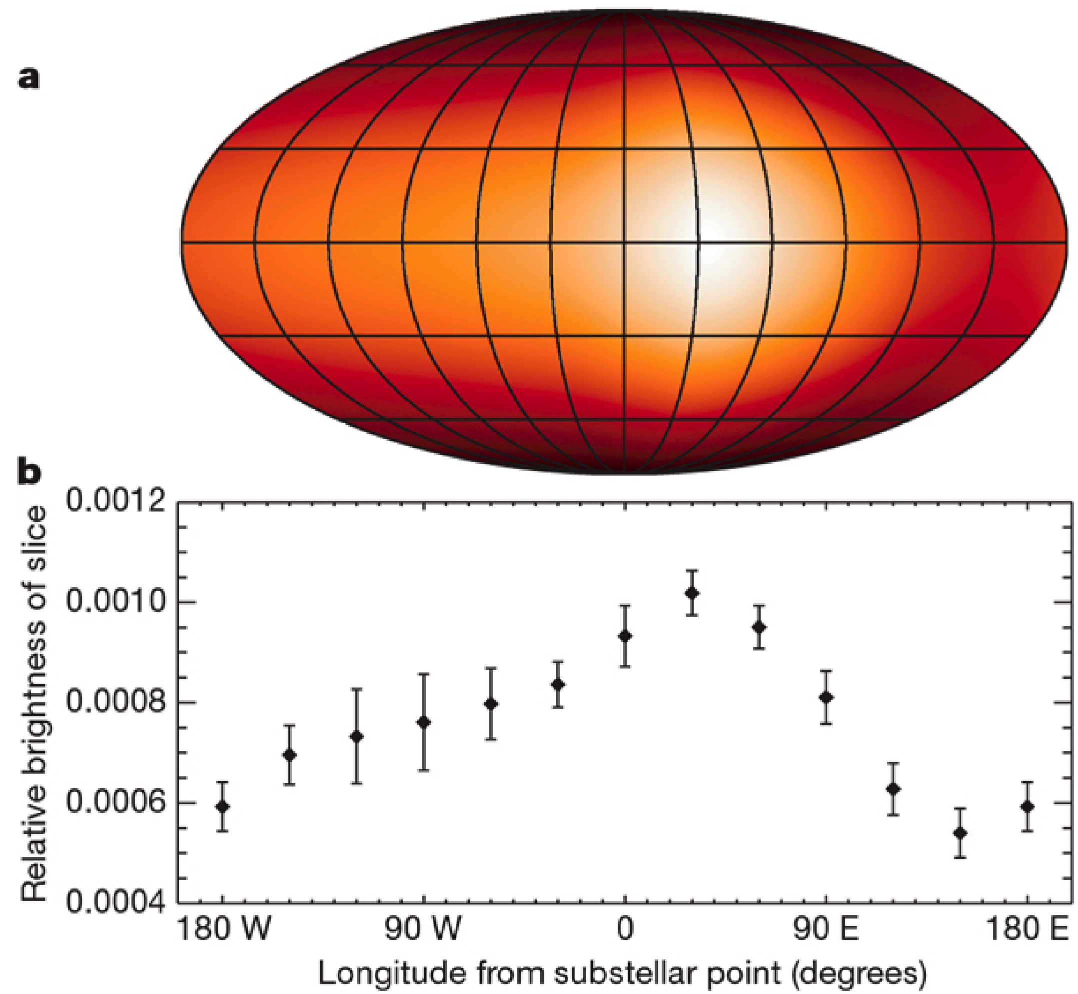


Phase curves

Phase curves

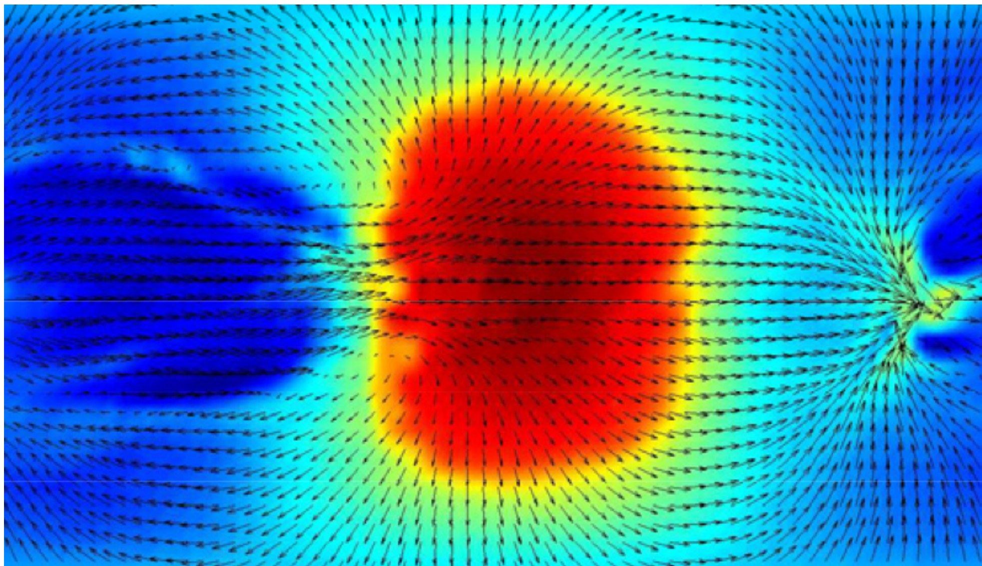
One phase curve gives us the longitudinal temperature variations at one level.



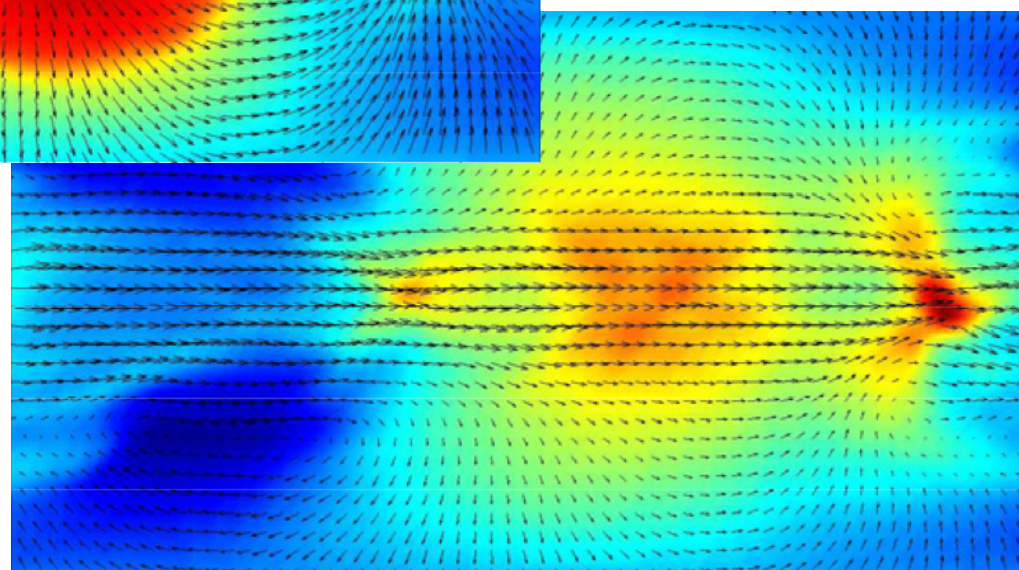


Knutson 2007

Spectral resolution is vertical resolution



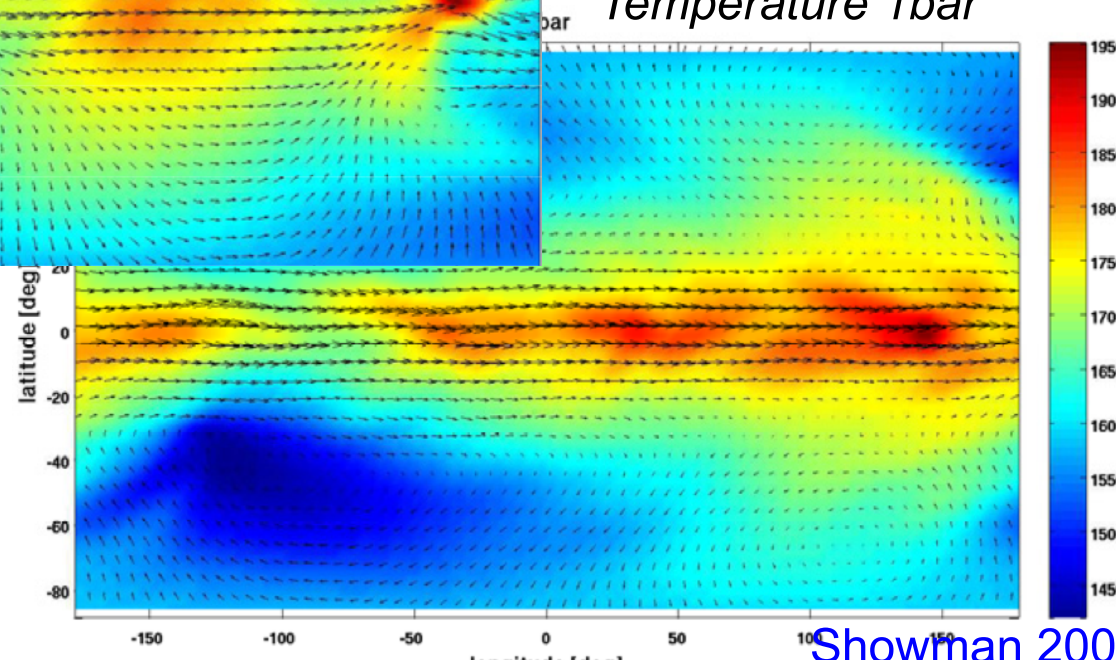
Temperature 1mbar



Temperature 30mbar

Increasing optical depth

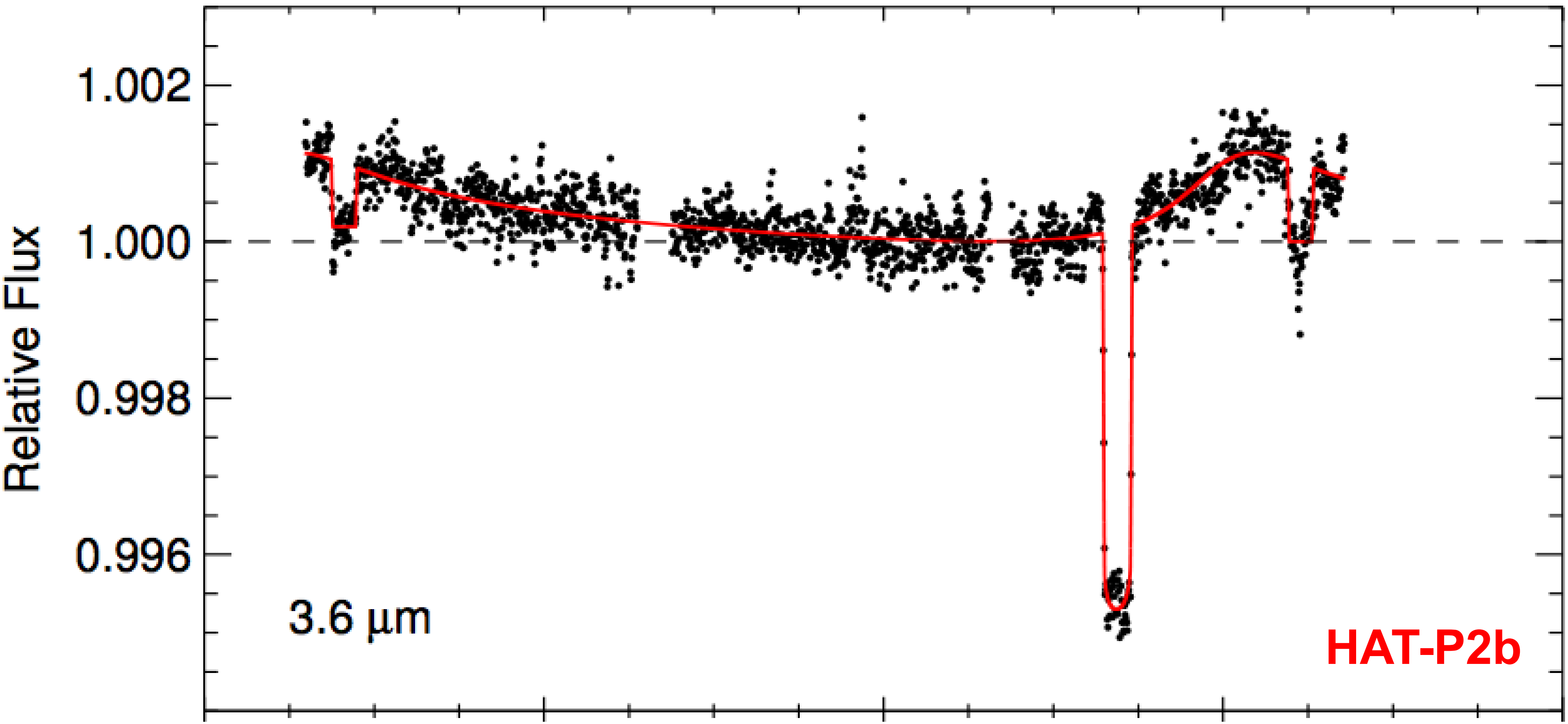
Temperature 1bar



Showman 2009

EChO will probe the 3D structure of planetary atmospheres

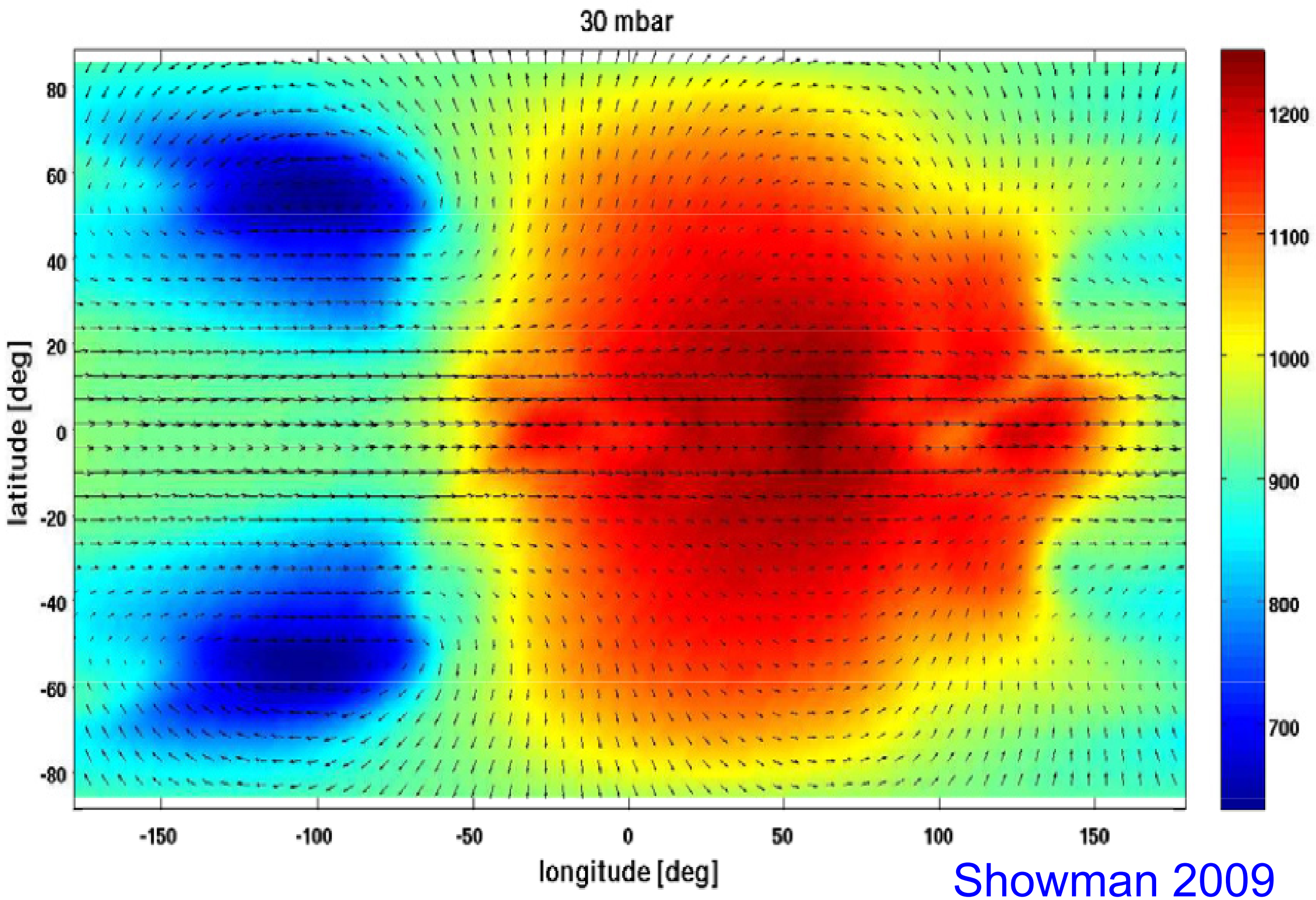
Measuring radiative timescales : the power of eccentric planets



Lewis et al. 2013

We need a survey of those !

Visible vs IR phase curve

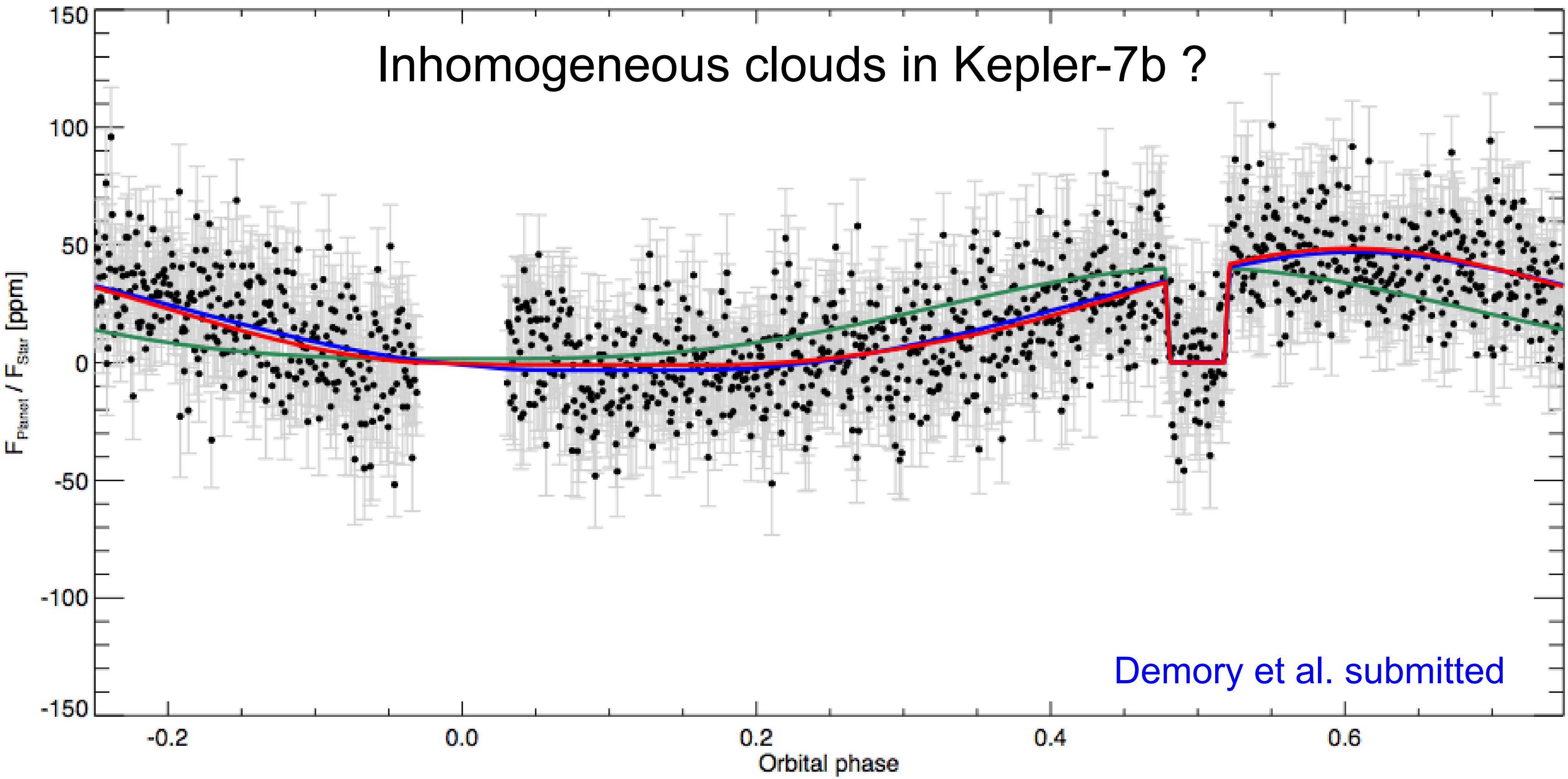


Showman 2009

→ Hot spot shifted to the east → peak of the emission **before** the secondary eclipse

→ Clouds shifted to the west → peak of the reflection **after** the secondary eclipse

Visible vs IR phase curve



→ Hot spot shifted to the east → peak of the emission **before** the secondary eclipse

→ Clouds shifted to the west → peak of the reflection **after** the secondary eclipse

Conclusion

→ EChO will constrain the P-T profiles and chemical abundances for a large number of planets. We provide an analytical model, fast and accurate to study the diversity of exoplanets.

→ Close-in, tidally locked planets are very important targets, because we know the geometry of the system ! Eccentric planets tell us about the thermal inertia of atmospheres.

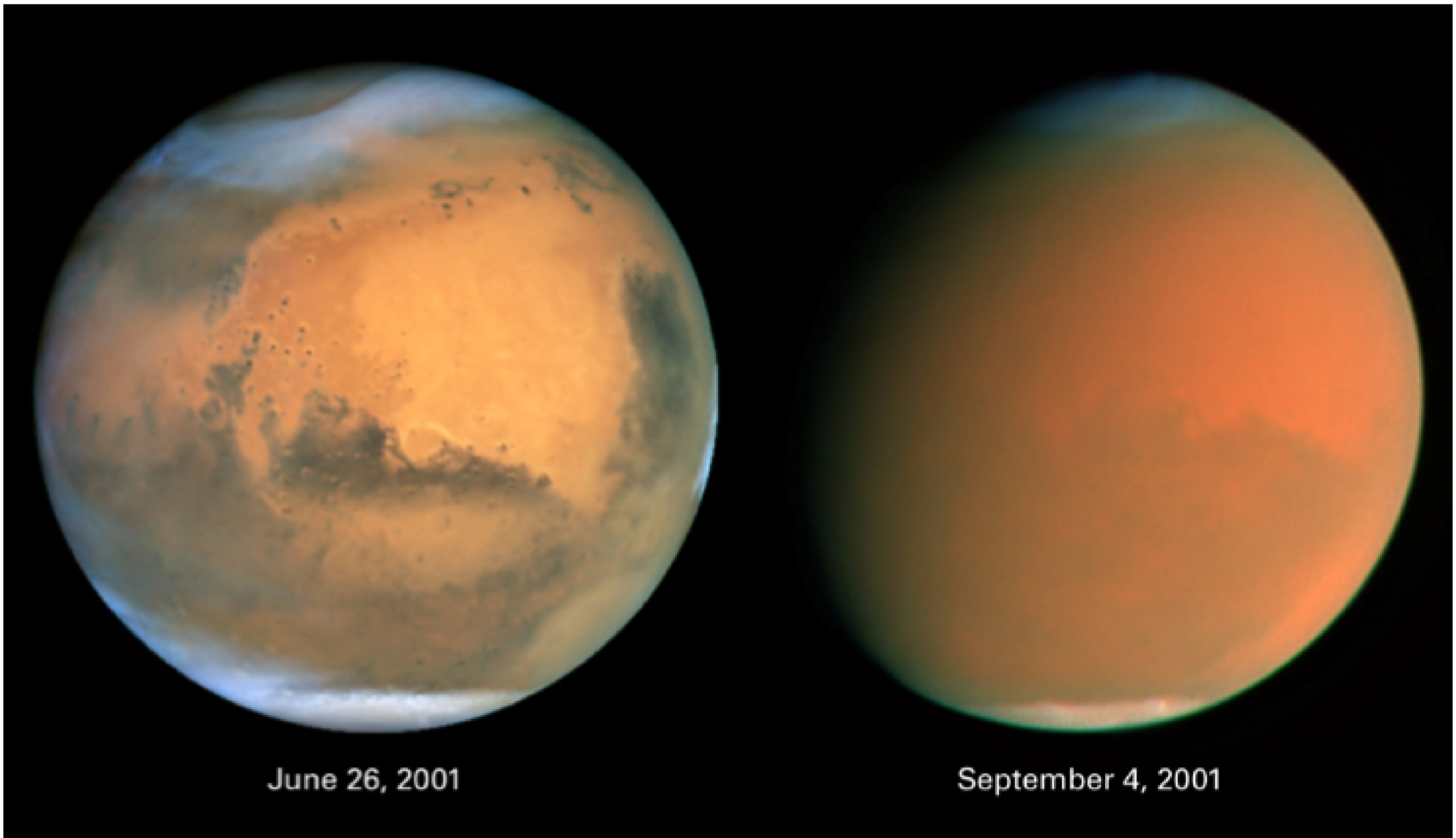
→ EChO will give us a global understanding of the atmosphere
+ Spatially : Phase curve/ secondary eclipse mapping
+ Spectroscopically : different wavelength at the same time
+Temporally : Observe a target several times.

Going down in mass

Earth and super-earth in the HZ of M dwarfs

→ Tidally locked
→ Atmospheric circulation dominated by large scales

Similar to Hot Jupiters

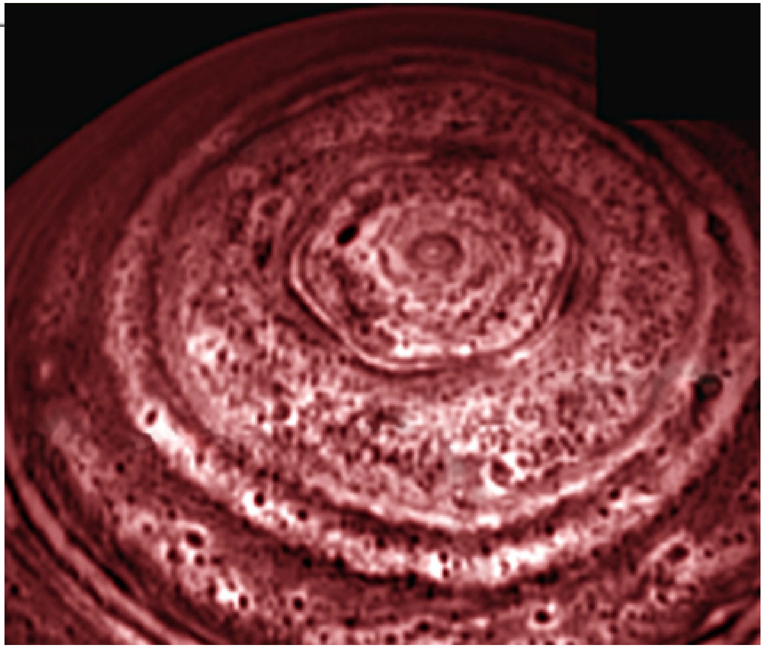


→ Planet wide effects ?

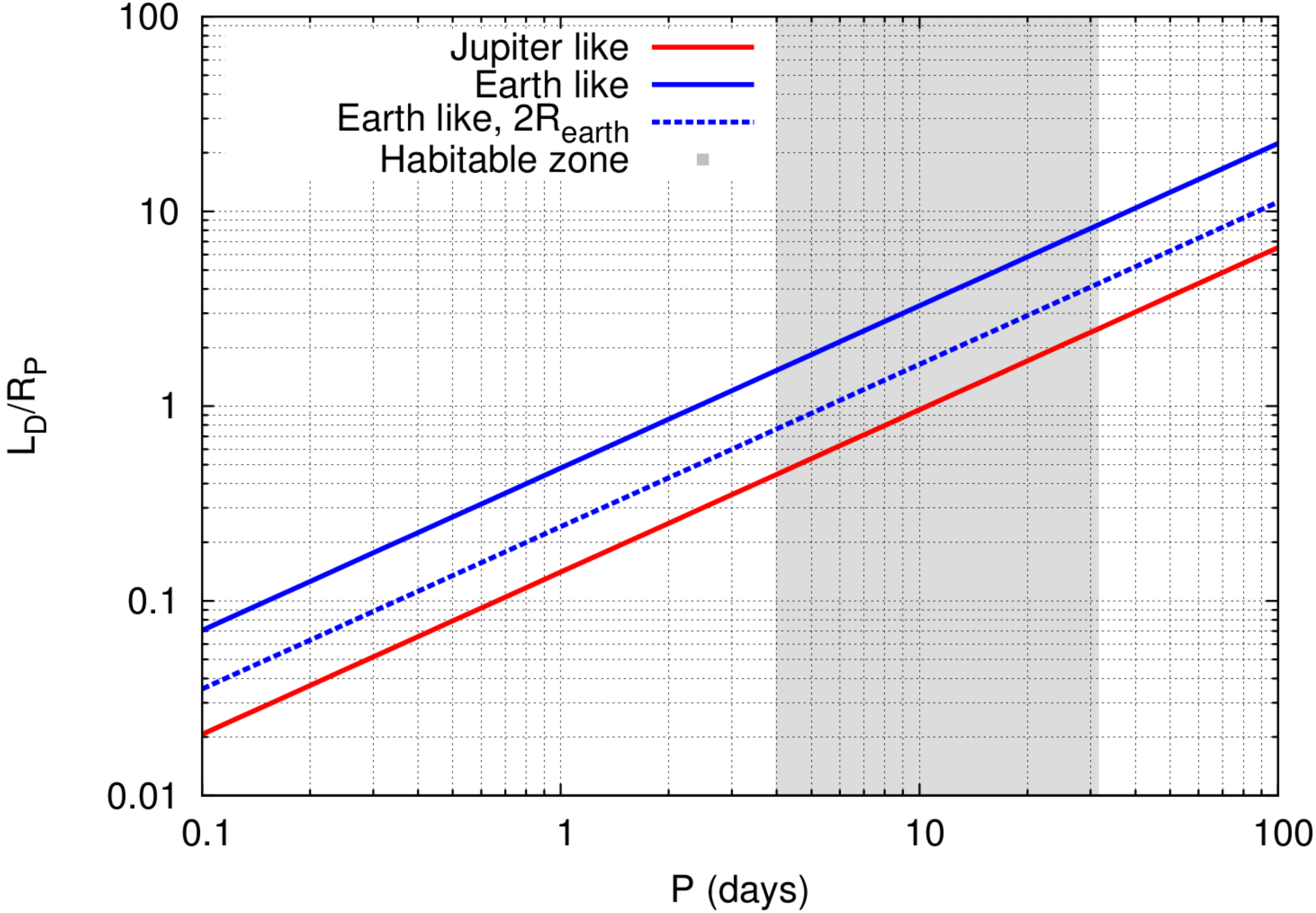
Deformation radius

Deformation radius is set as the balance between gravity waves and coriolis forces

	L_D (km)	L_D/a
Venus	400,000	70
Earth atmosphere	2000	0.3
Earth oceans	50	0.01
Mars	2000	0.6
Titan	25,000	10
Jupiter and Saturn	2000	0.03
Uranus and Neptune	2500	0.1
HD 189733b	25,000	0.3
GJ 1214b (H_2 atm)	10,000	0.6
GJ 1214b (CO_2 atm)	2000	0.1



Deformation radius for a planet around the M dwarf Gliese 581



→ Atmospheres should dominated by large scales.

Earth and super-earth in the HZ of M dwarfs

→ Tidally locked
→ Atmospheric circulation dominated by large scales

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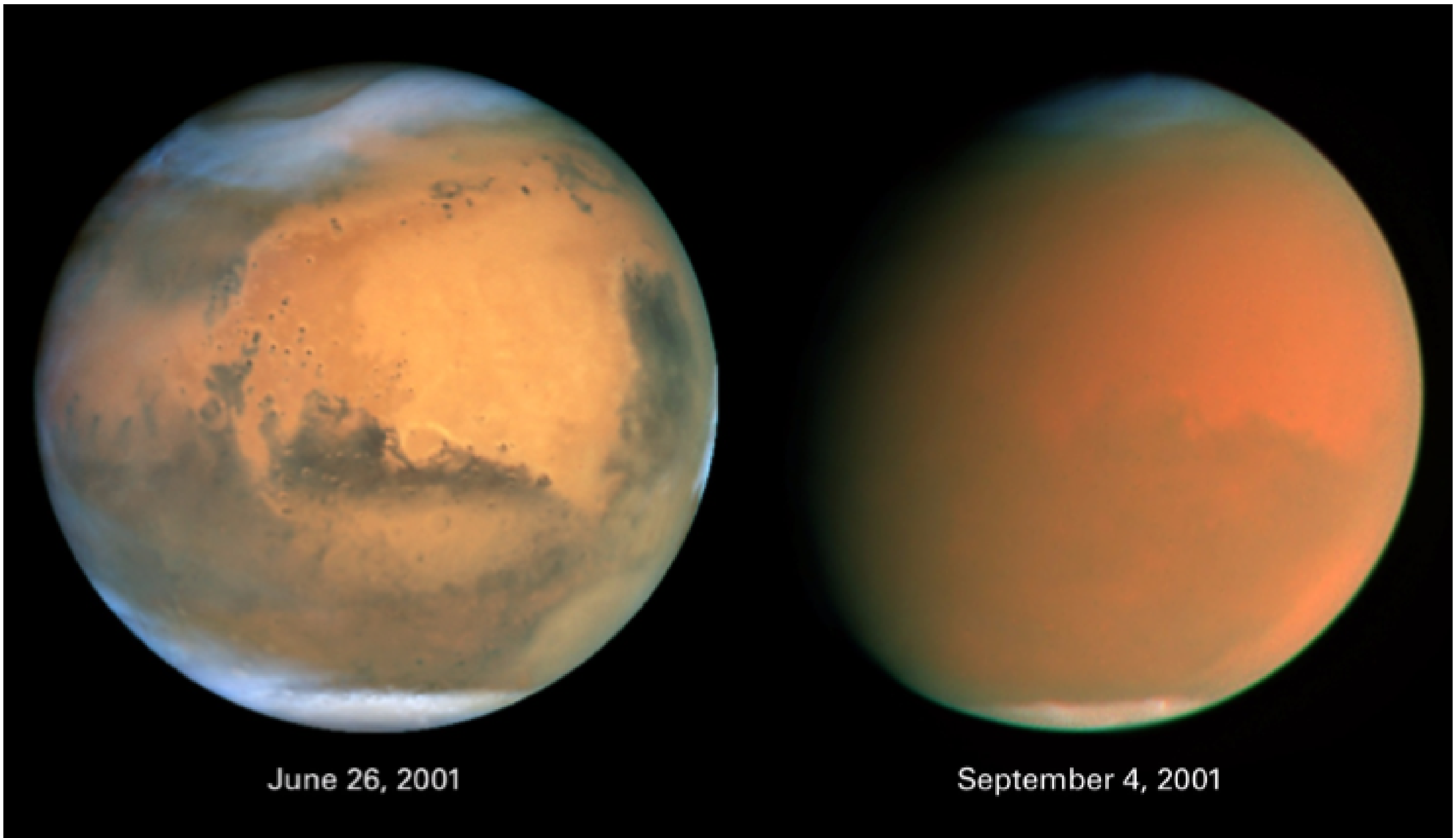
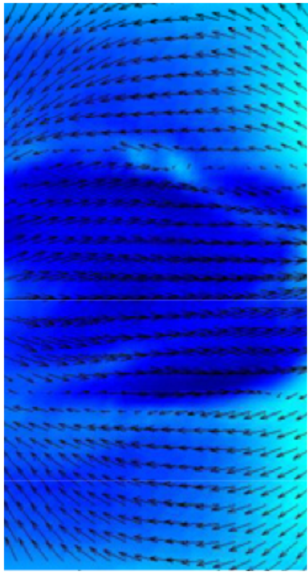
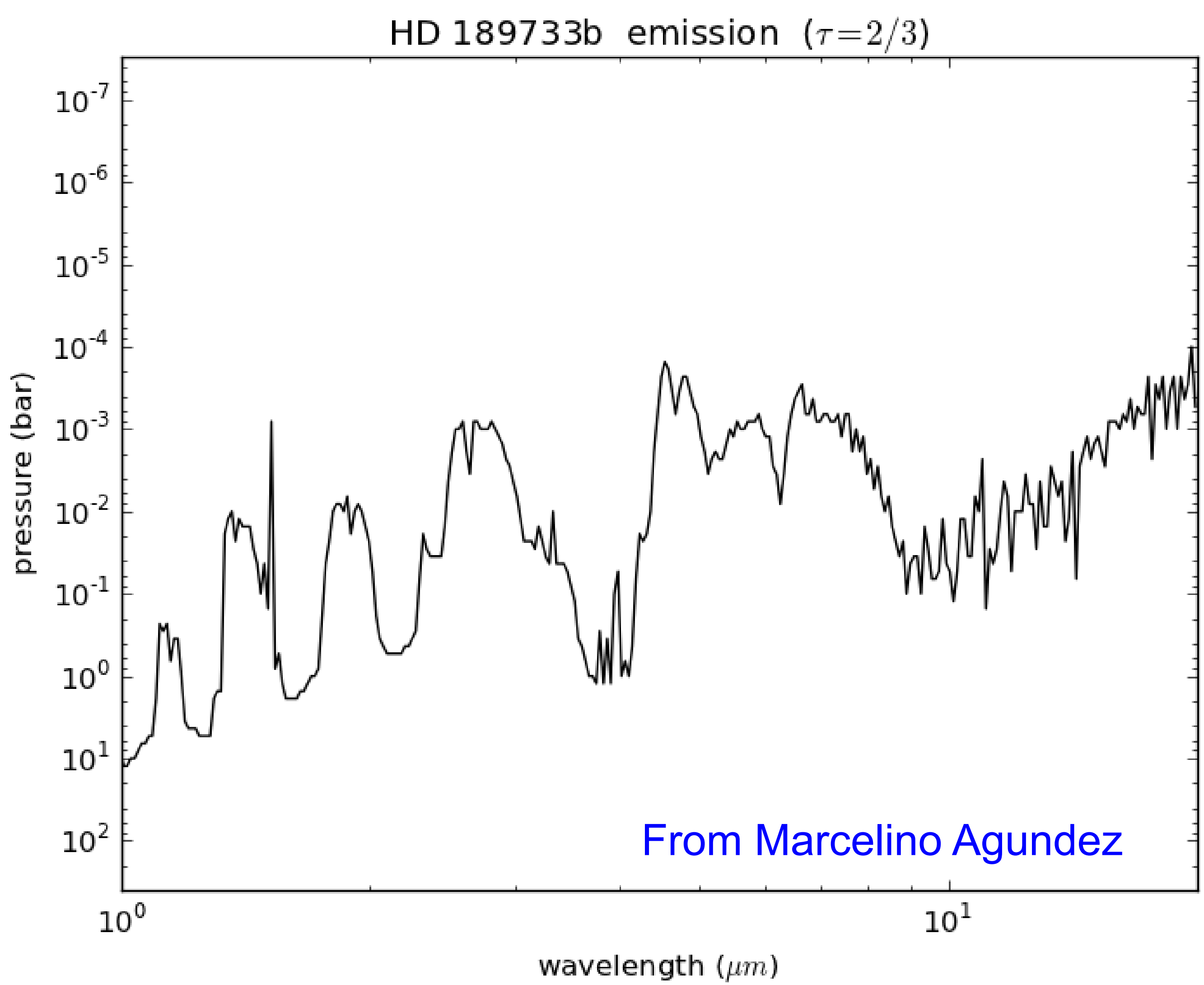


→ **Planet wide effects ?**

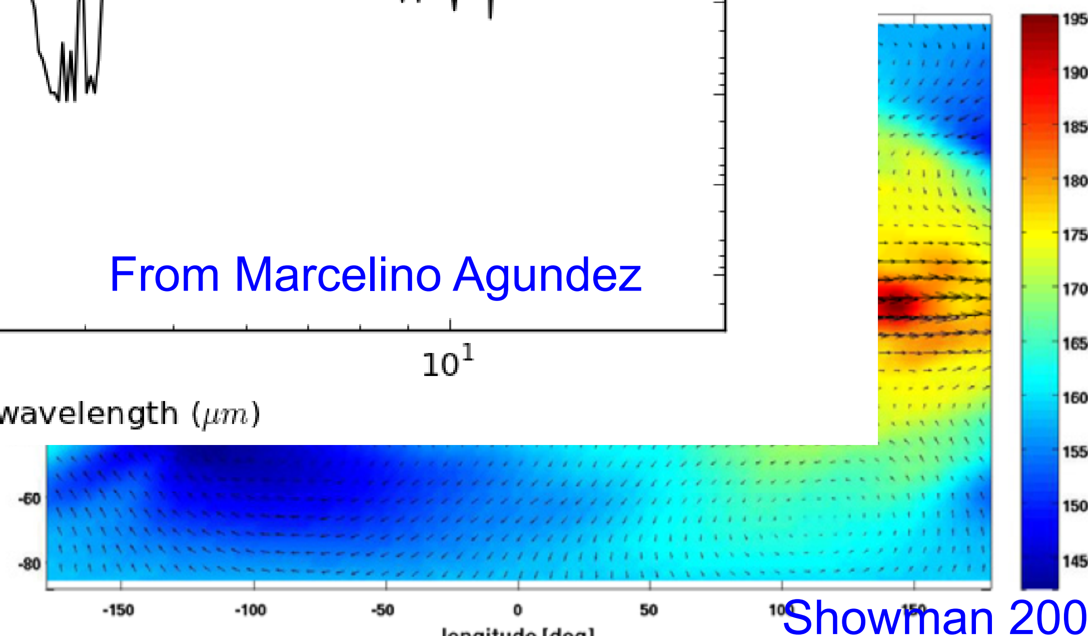
Multi wavelength phase curves



Temperature



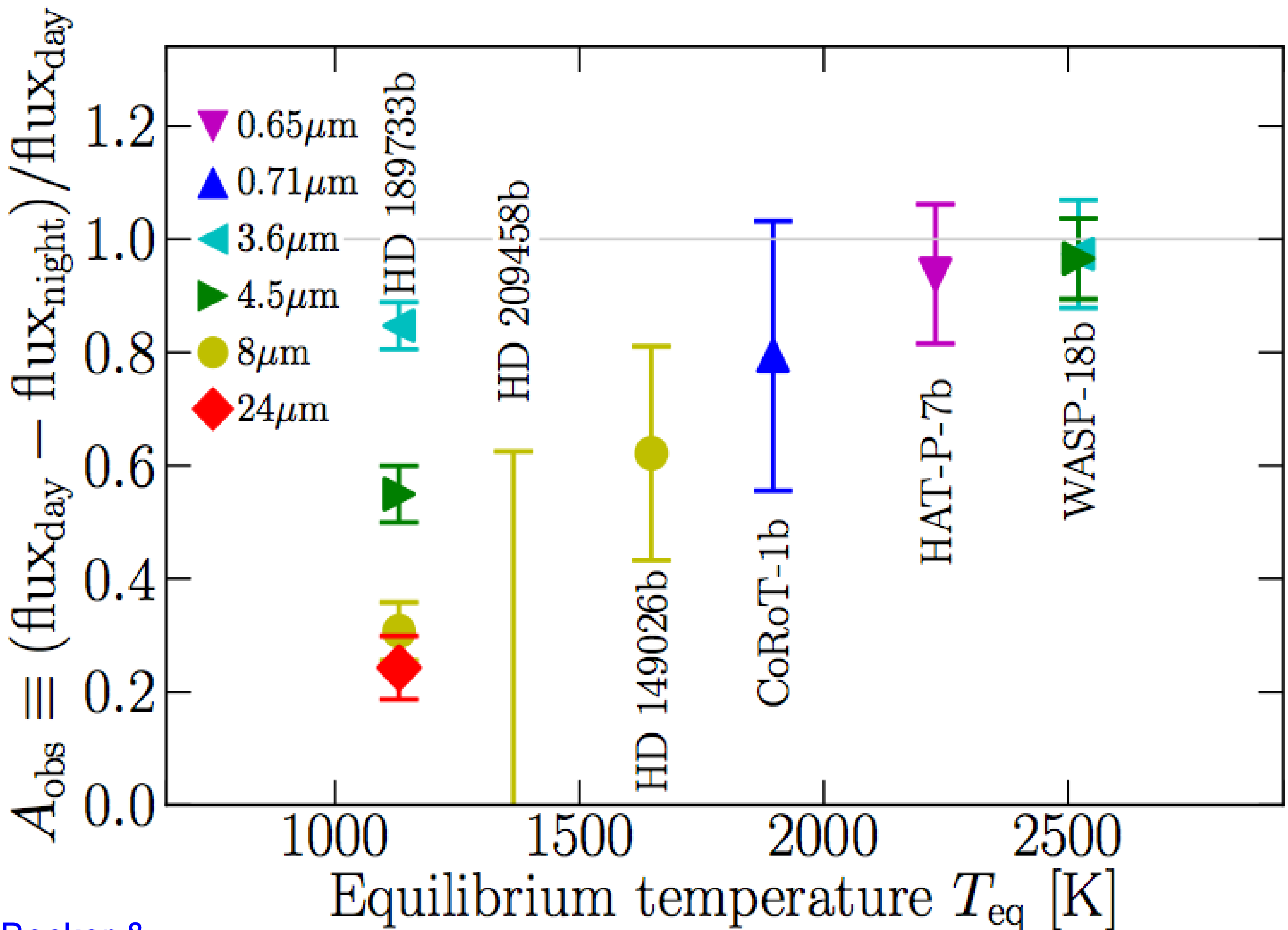
bar



Showman 2009

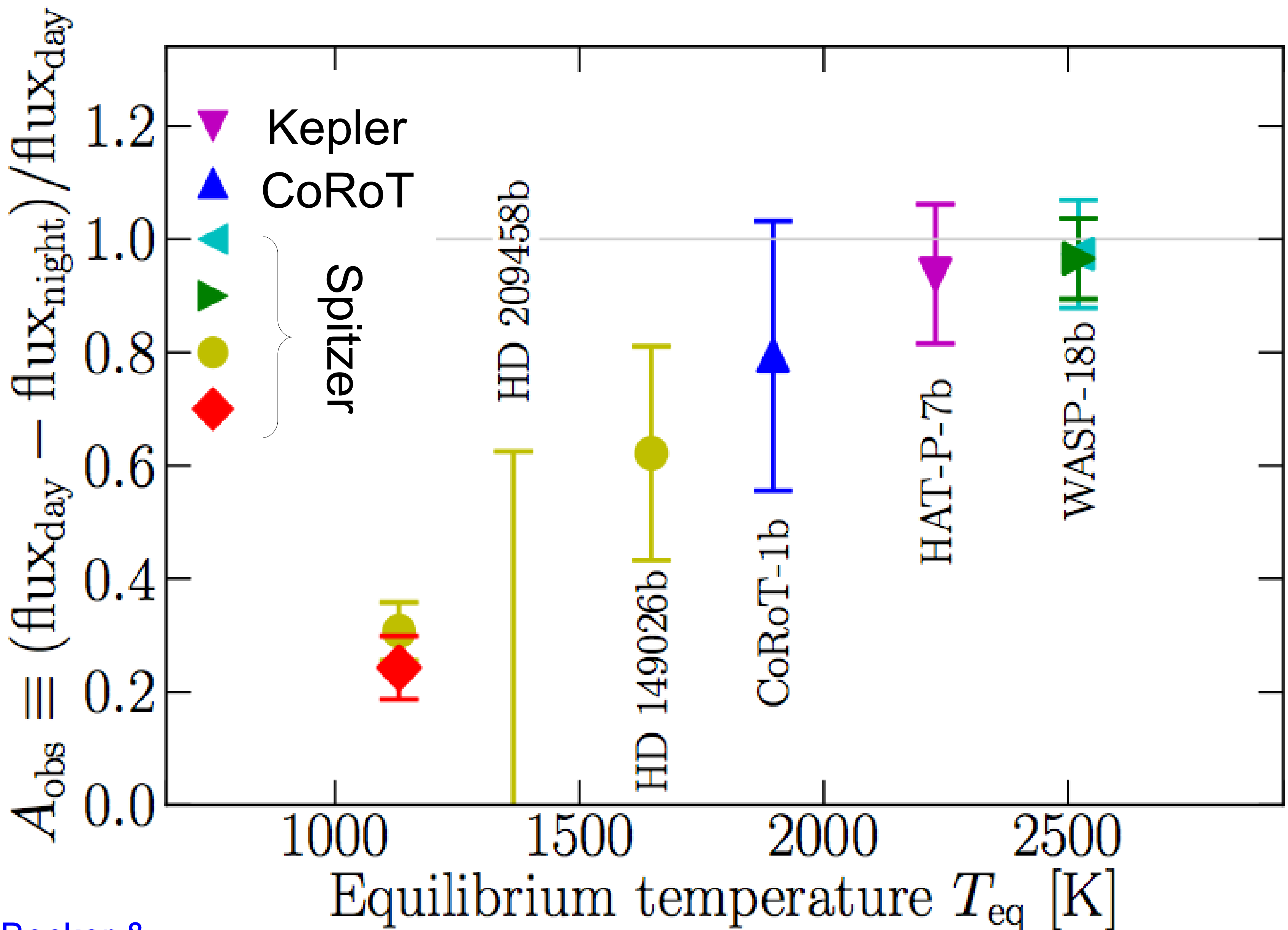
EChO w
structure of planetary atmospheres

An emergent trend ?



Perez-Becker &
Showman 2013

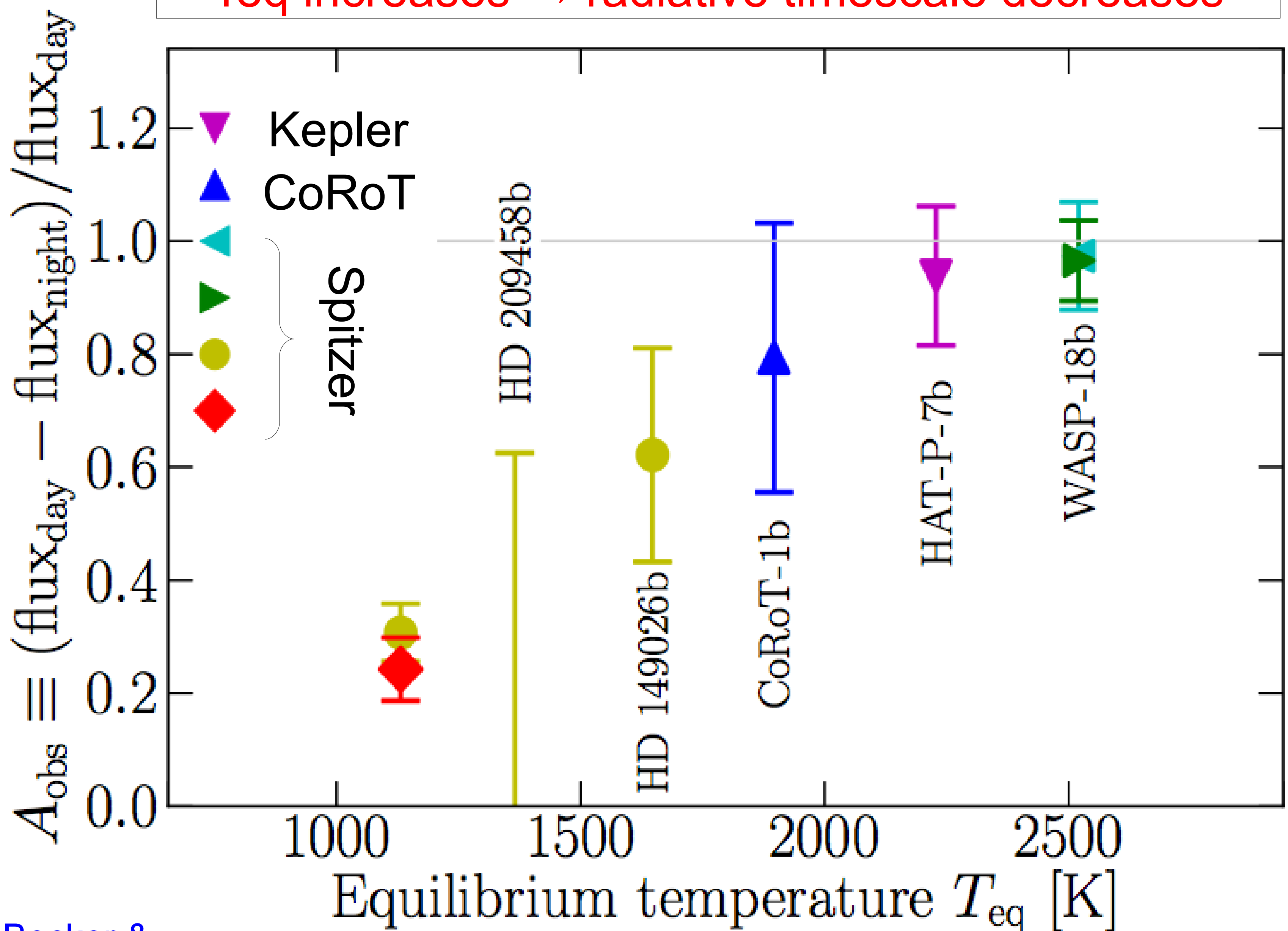
An emergent trend ?



Perez-Becker &
Showman 2013

An emergent trend ?

Teq increases → radiative timescale decreases



Perez-Becker & Showman 2013

Conclusion

→ EChO will constrain the P-T profiles and chemical abundances. Understanding the atmosphere is crucial for interior models !

→ EChO will give us a global understanding of the atmosphere
+ Spatially : Phase curve/ secondary eclipse mapping
+ Spectroscopically : different wavelength at the same time
+Temporally : Observe a target several times.

→ Habitable earth like planet around M stars should have an atmospheric circulation dominated by large scales. Leading to large scale patterns observable by EChO.

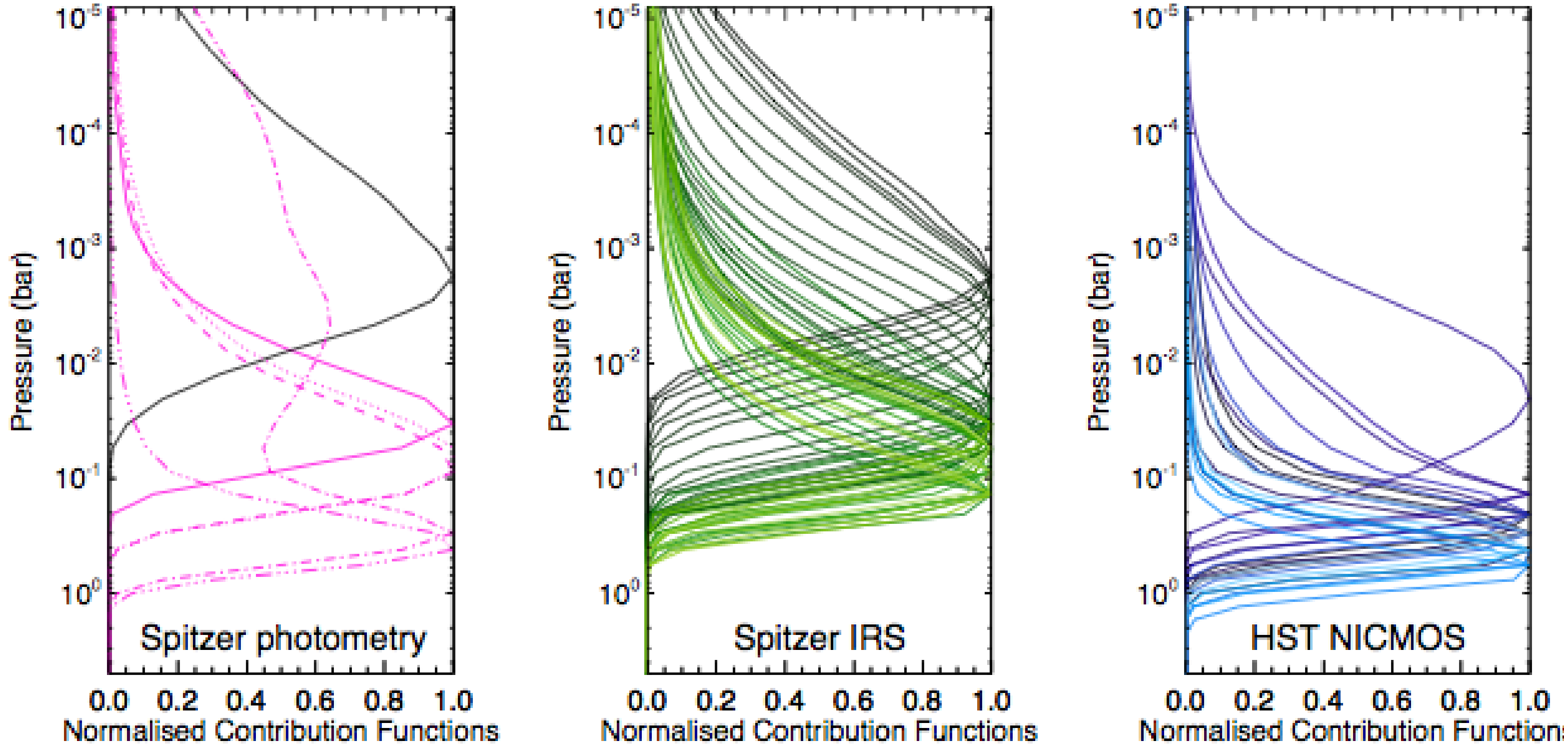


Figure 3. Contribution functions for the *Spitzer* broadband photometry (left), IRS spectroscopy (middle), and the *HST*/NICMOS spectrophotometry (right) channels. For the *Spitzer* photometry channels, each line pattern means MIPS 24 μm (solid), IRS 16 μm (solid-black), IRAC 8.0 μm (dotted), 5.8 μm (dashed), 4.5 μm (dot-dashed), and 3.6 μm (triple dot-dashed). For the *Spitzer* IRS and the *HST*/NICMOS channels, the brighter colours denote the channels at the shorter wavelengths. For all cases, emission from the lower atmosphere tends to dominate the shorter wavelength channels.

The six *Spitzer* broadband photometry channels in the range 3.6–24 μm have broadly-distributed contribution functions whose peak pressures range from 2 to 300 mbar. The contribution functions for the IRAC channels (3.6, 4.5, 5.8, and 8 μm) and MIPS (24 μm) are located in the deeper atmosphere and provide strong constraints for the temperature between 30–300 mbar. The contribution function of the IRAC 4.5 μm channel has a second peak at high altitude (3–5 mbar), being close to the peak of the IRS 16 μm channel at 2 mbar. Hence, the temperature at pressures as low as 2 mbar can be retrieved from the IRAC channels, but only if the temperature of the deep atmosphere is well constrained from the other measurements. The 47 *Spitzer* IRS spectroscopy channels between 5

Atmospheric circulation of habitable planets around M dwarf should be dominated by large scales
→ Planet wide effects

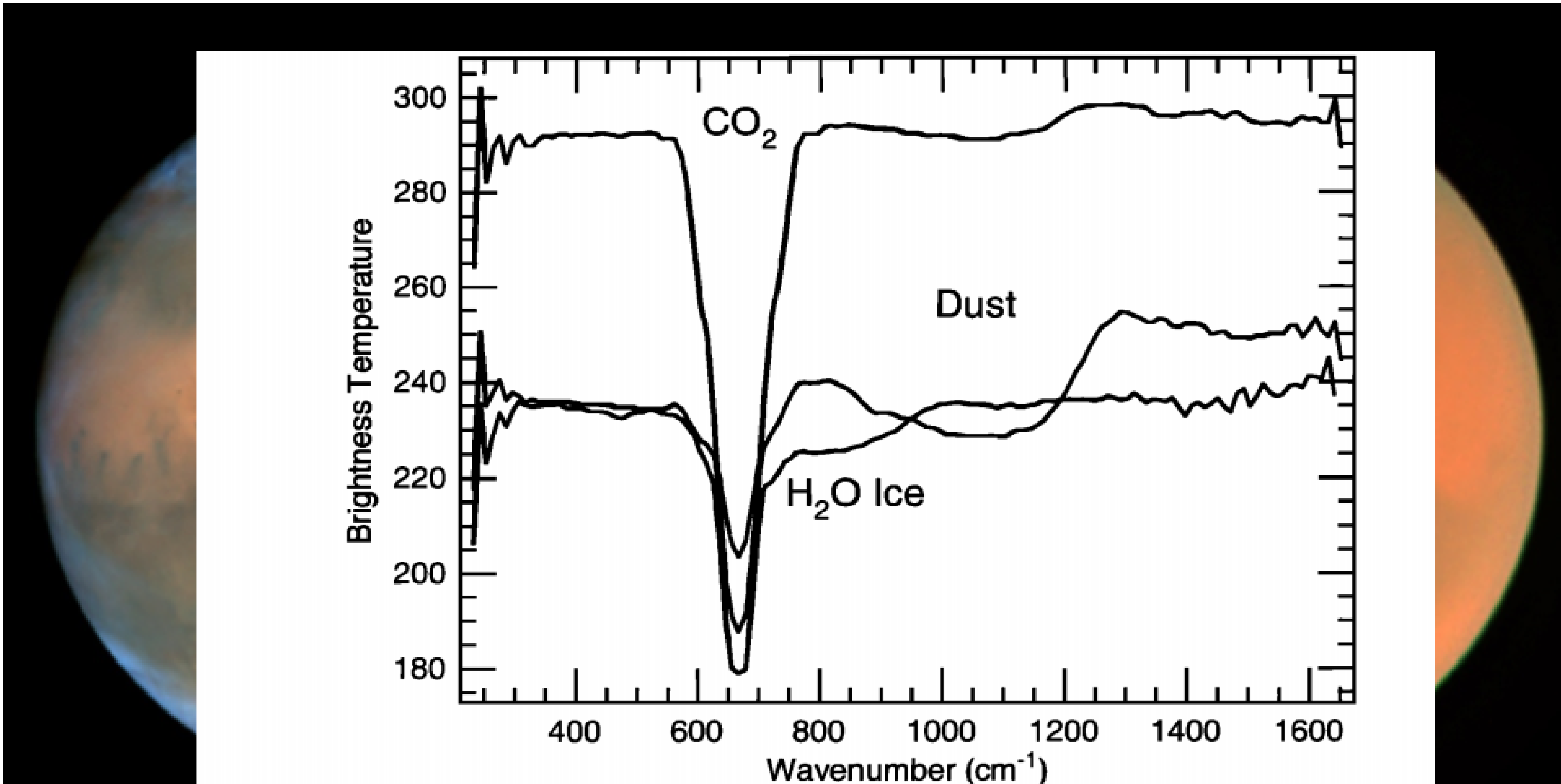


Figure 1. Examples of typical daytime Thermal Emission Spectrometer (TES) spectra. Radiances are shown in terms of equivalent brightness temperature to emphasize features. The signature of CO_2 gas, H_2O ice aerosols, and dust aerosols are all easily identified and are distinct from each other. The uppermost curve shows a hot, midday spectrum with nominal dust opacity (0.2). The two lower curves show a spectrum taken at the height of the Noachis dust storm and a spectrum taken on the flank of Arsia Mons where there were a thick H_2O cloud and low dust opacity due to the high elevation.

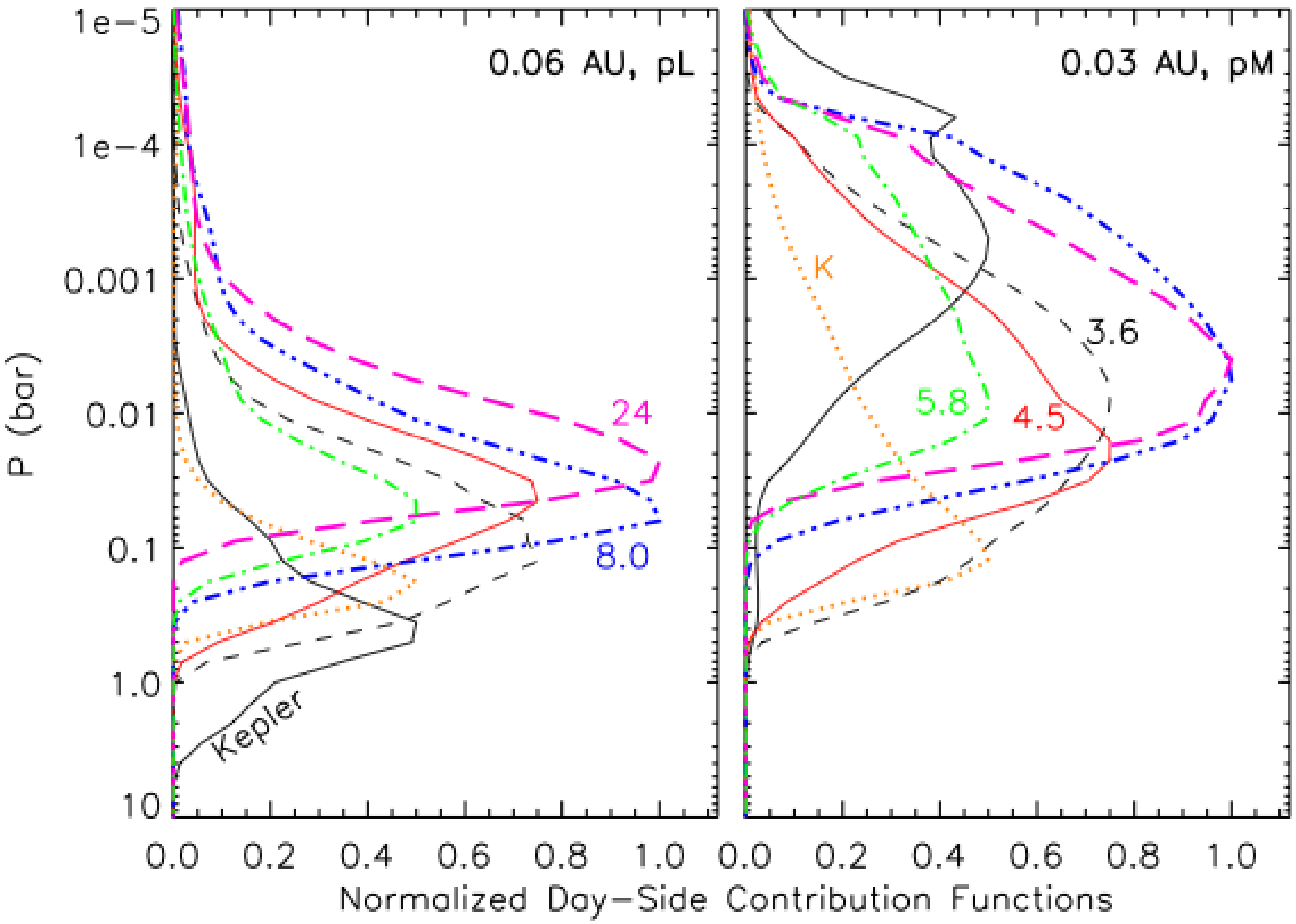
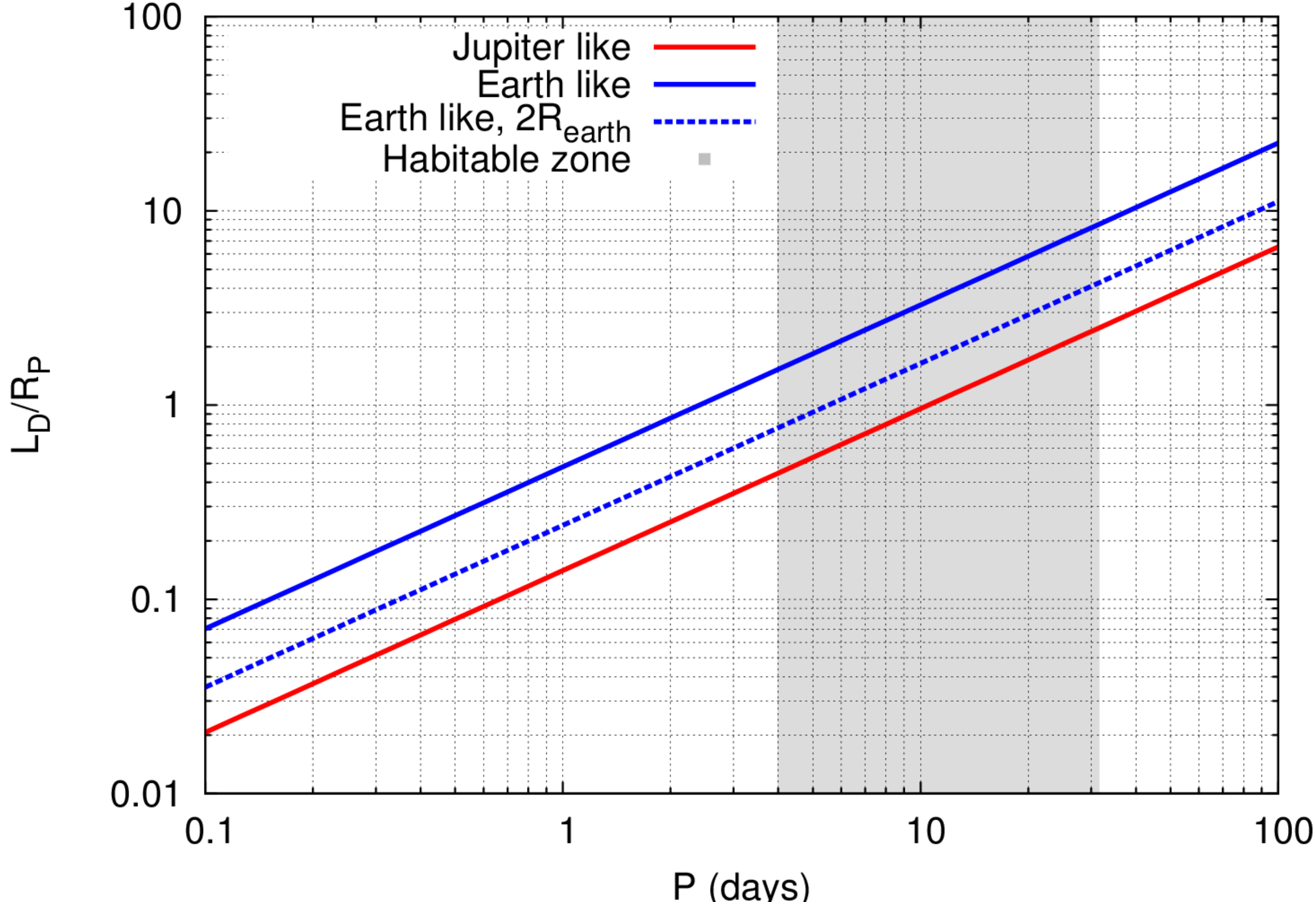


Figure 9. Contribution functions (e.g., Chamberlain & Hunten 1987; Knutson et al. 2009) calculated using our one-dimensional radiative transfer model for a generic cloud-free pL-class planet without atmospheric TiO and VO (left) and a generic pM-class planet with atmospheric TiO and VO (right). Both are for dayside conditions, and both assume solar metallicity with equilibrium chemistry. Contribution functions are calculated for various *Spitzer* broadband filters (black short dashed, red solid, green dashed-dotted, blue dashed-triple-dotted, and pink long-dashed curves for 3.6, 4.5, 5.8, 8, and 24 μm, respectively), *K* band (orange dotted curve), and the *Kepler* band at 450–900 nm (black solid curve). For clarity some of the curves have been normalized to 0.5 or 0.75 rather than 1.

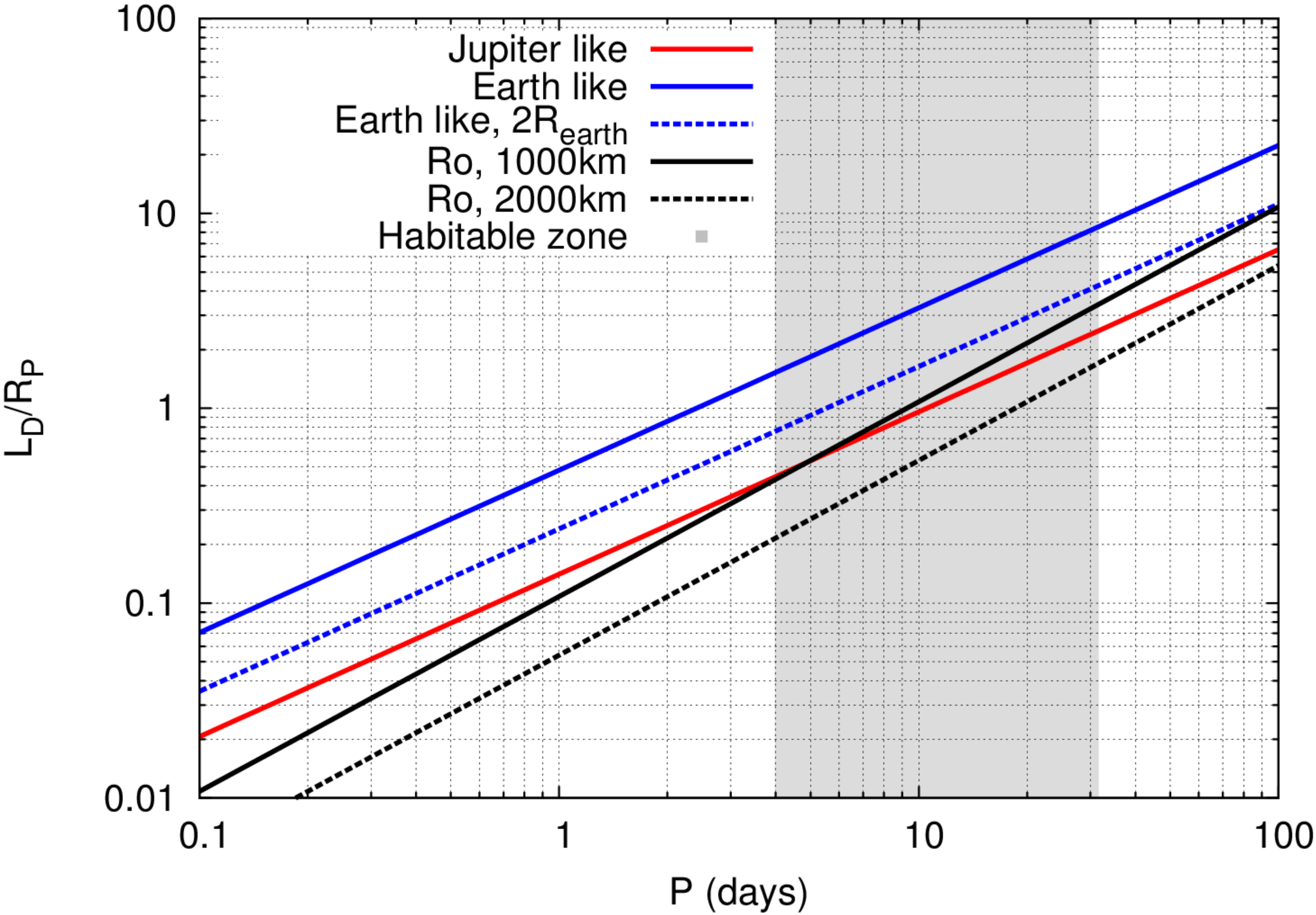
Deformation radius for a planet around the M dwarf Gliese 581

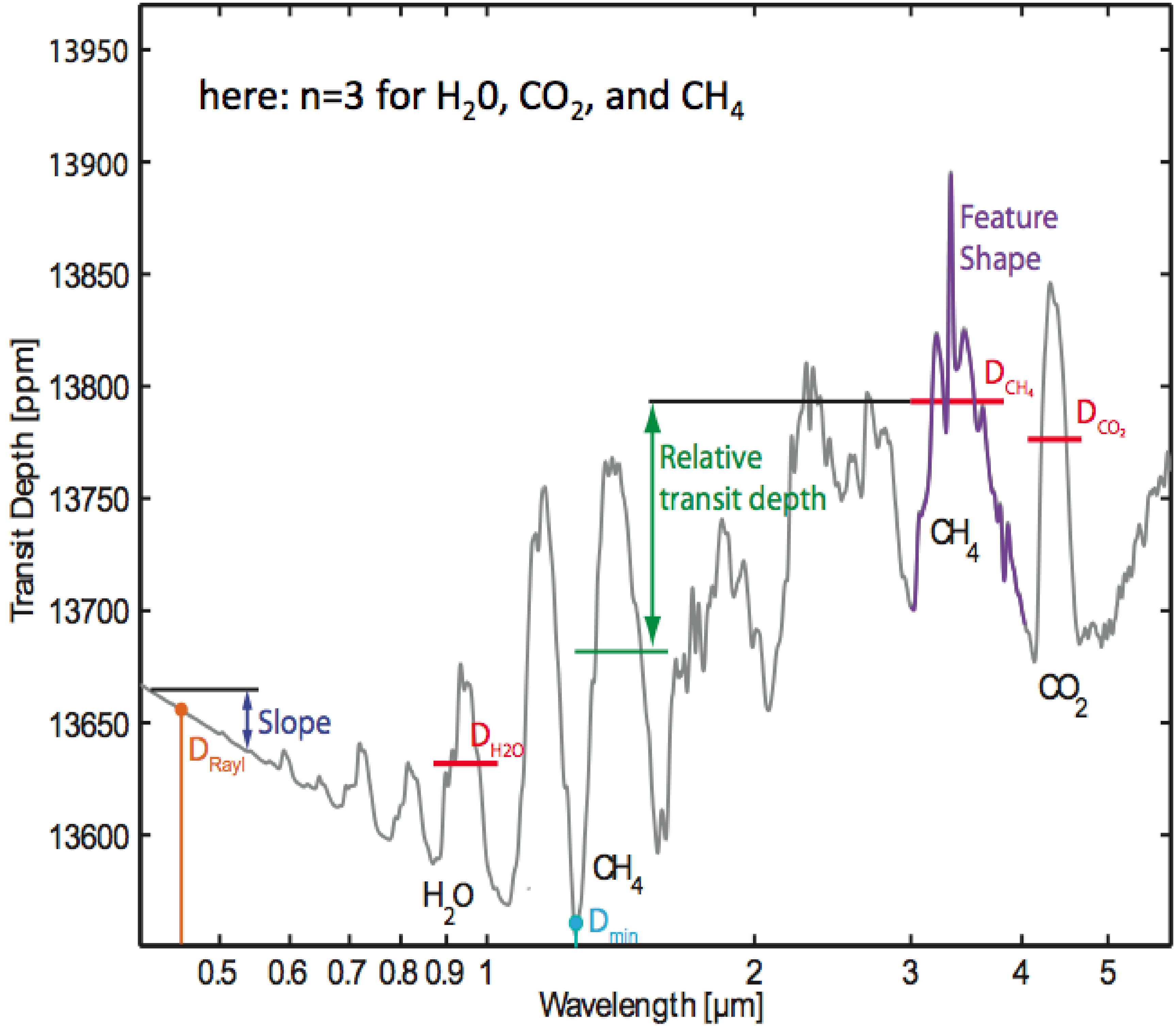


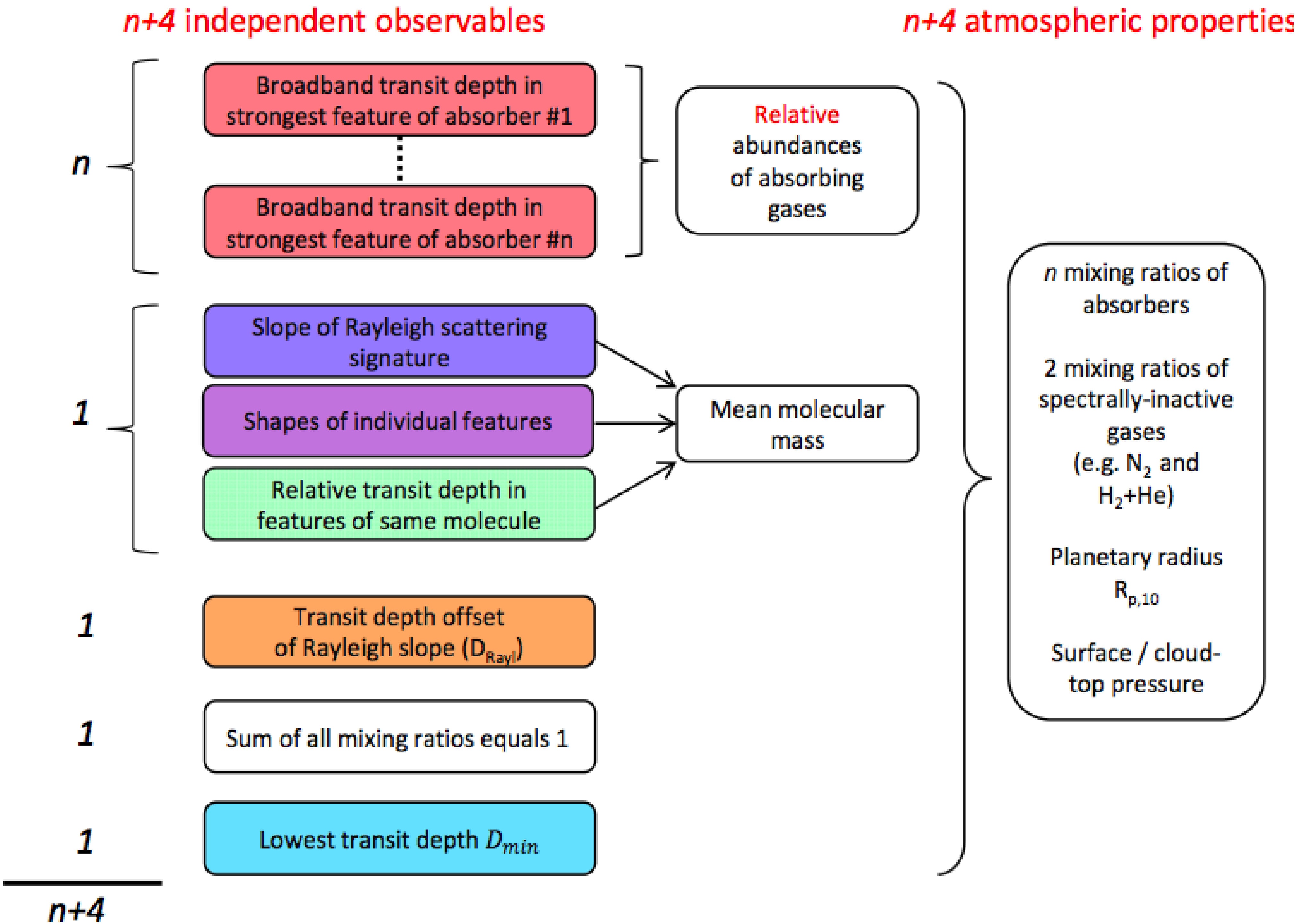
→ Atmospheres should dominated by large scales.

see also Leconte et al. 2013

Deformation radius for a planet around the M dwarf Gliese 581

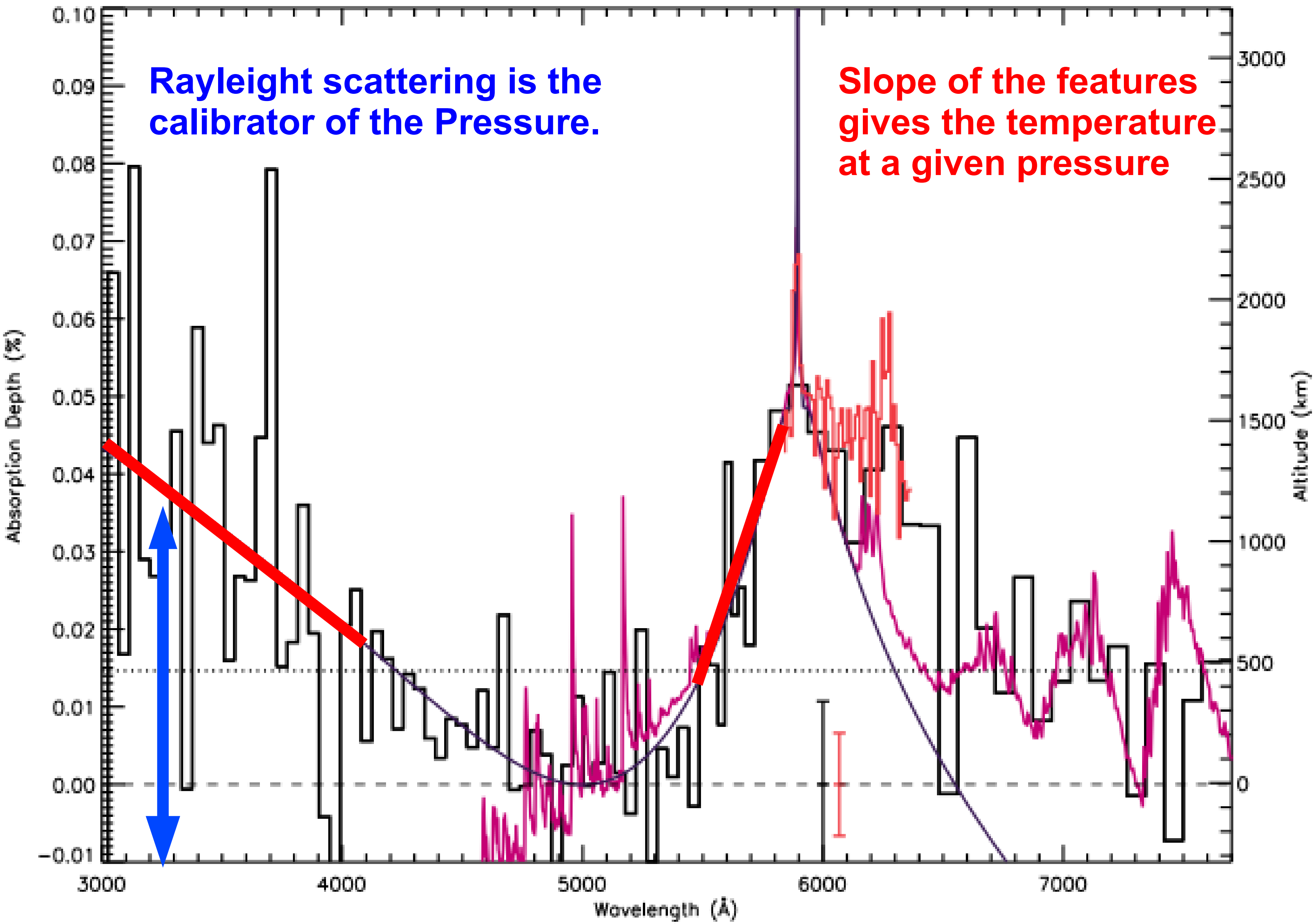



here: n=3 for H_2O, CO_2, and CH_4
Transit Depth [ppm]
13950
13900
13850
13800
13750
13700
13650
13600
Wavelength [μm]
0.5
0.6
0.7
0.8
0.9
1
2
3
4
5
Feature Shape
D_{CH_4}
D_{CO_2}
Relative transit depth
CH_4
CO_2
Slope
D_{Rayl}
D_{H2O}
H_2O
CH_4
D_{min}



n+4 independent observables
n+4 atmospheric properties
n
Broadband transit depth in strongest feature of absorber #1
Broadband transit depth in strongest feature of absorber #n
Relative abundances of absorbing gases
1
Slope of Rayleigh scattering signature
Shapes of individual features
Relative transit depth in features of same molecule
Mean molecular mass
1
Transit depth offset of Rayleigh slope (D_{Rayl})
1
Sum of all mixing ratios equals 1
1
Lowest transit depth D_{min}
n+4
n mixing ratios of absorbers
2 mixing ratios of spectrally-inactive gases (e.g. N_2 and H_2+He)
Planetary radius $R_{p,10}$
Surface / cloud-top pressure

Break the degeneracy

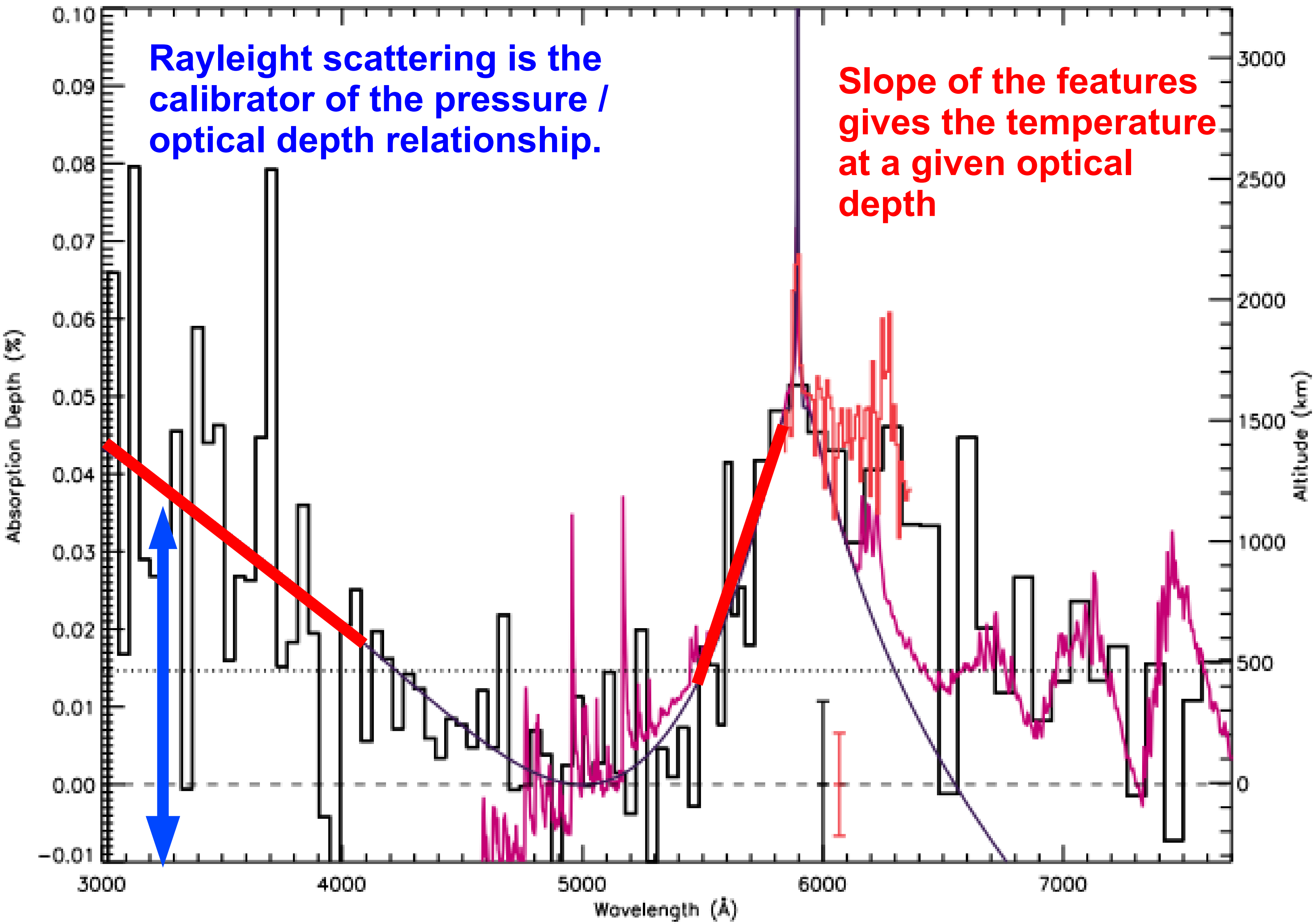


Introduction

Liant
coté lien atmosphere interieur ?
Atmosphere → necessité de connaître opacitées/abondances/temperatures
Models d'atmosphere « backwarming »
→ influence sur l'interieur ?

Dynamique atmospherique. → comprendre globalement l'atmosphere
→ Especes hors equilibre ?
→

Measuring PT profiles and absolute abundances



Sing et al. 2008