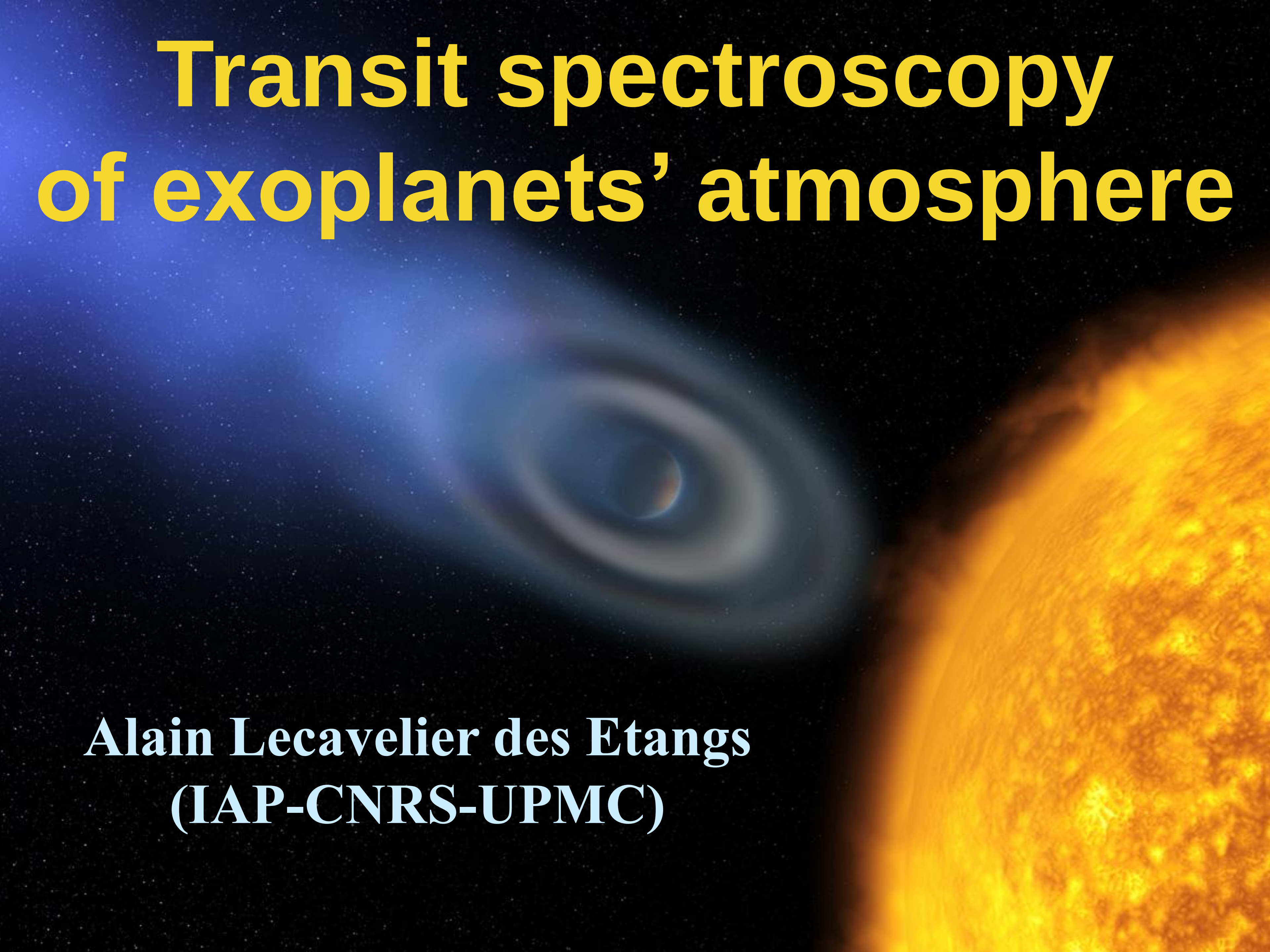
# Transit spectroscopy of exoplanets' atmosphere



Alain Lecavelier des Etangs
(IAP-CNRS-UPMC)

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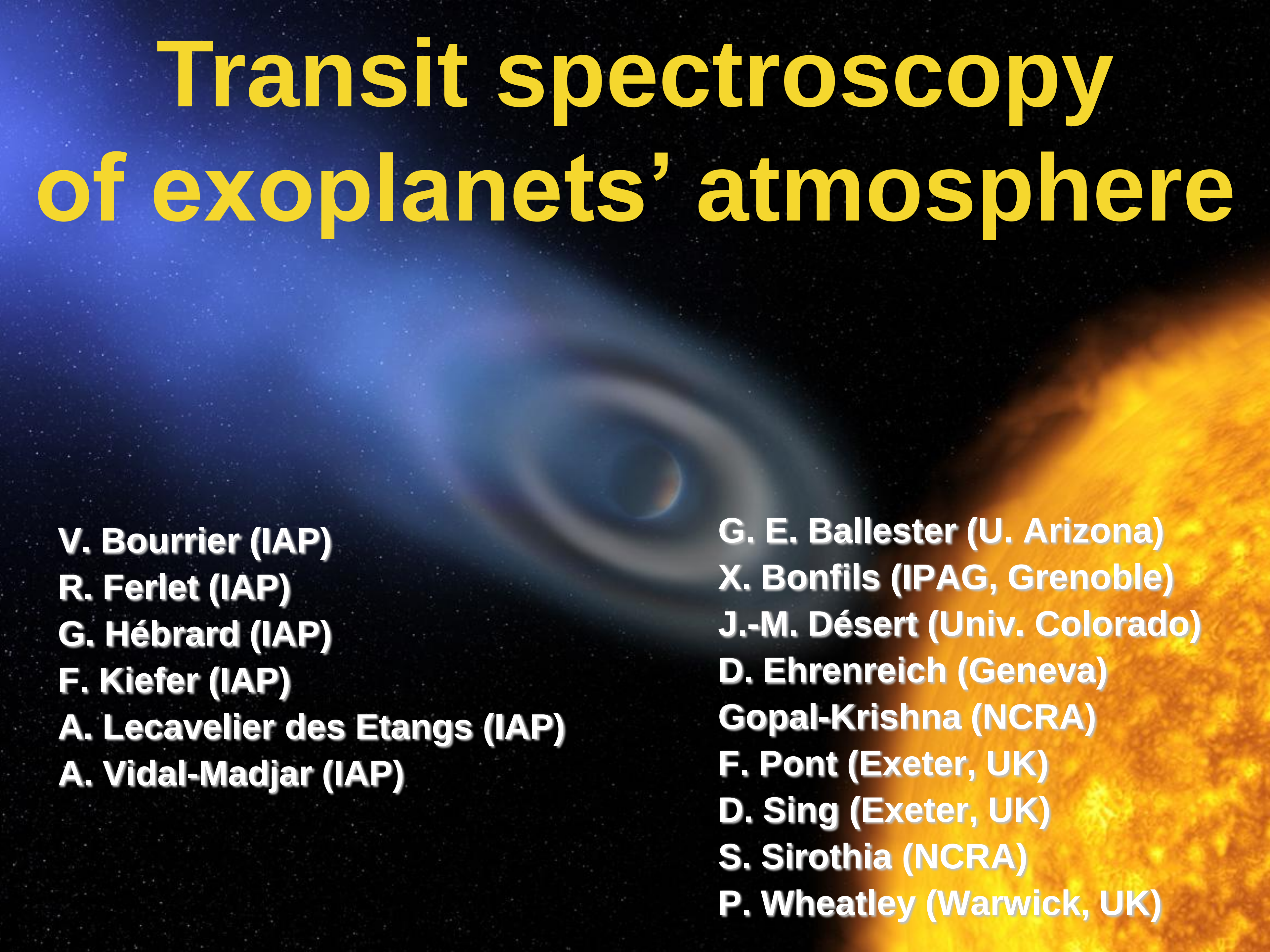

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S. Sirothia (NCRA)
P. Wheatley (Warwick, UK)

# Outline

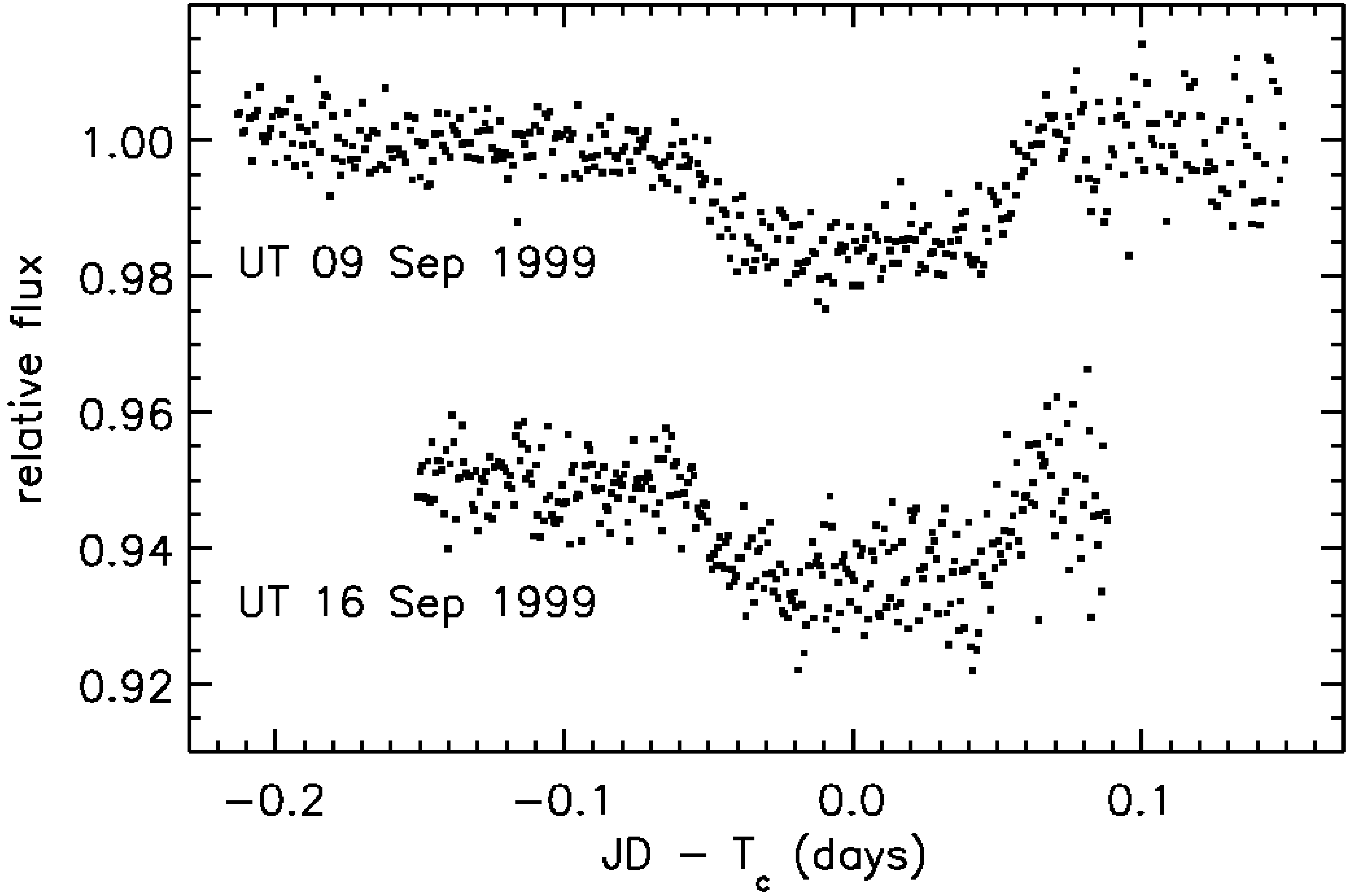
## What can be done, what cannot be done.

- !! No direct measurement of absolute abundances using transit absorption spectroscopy !!

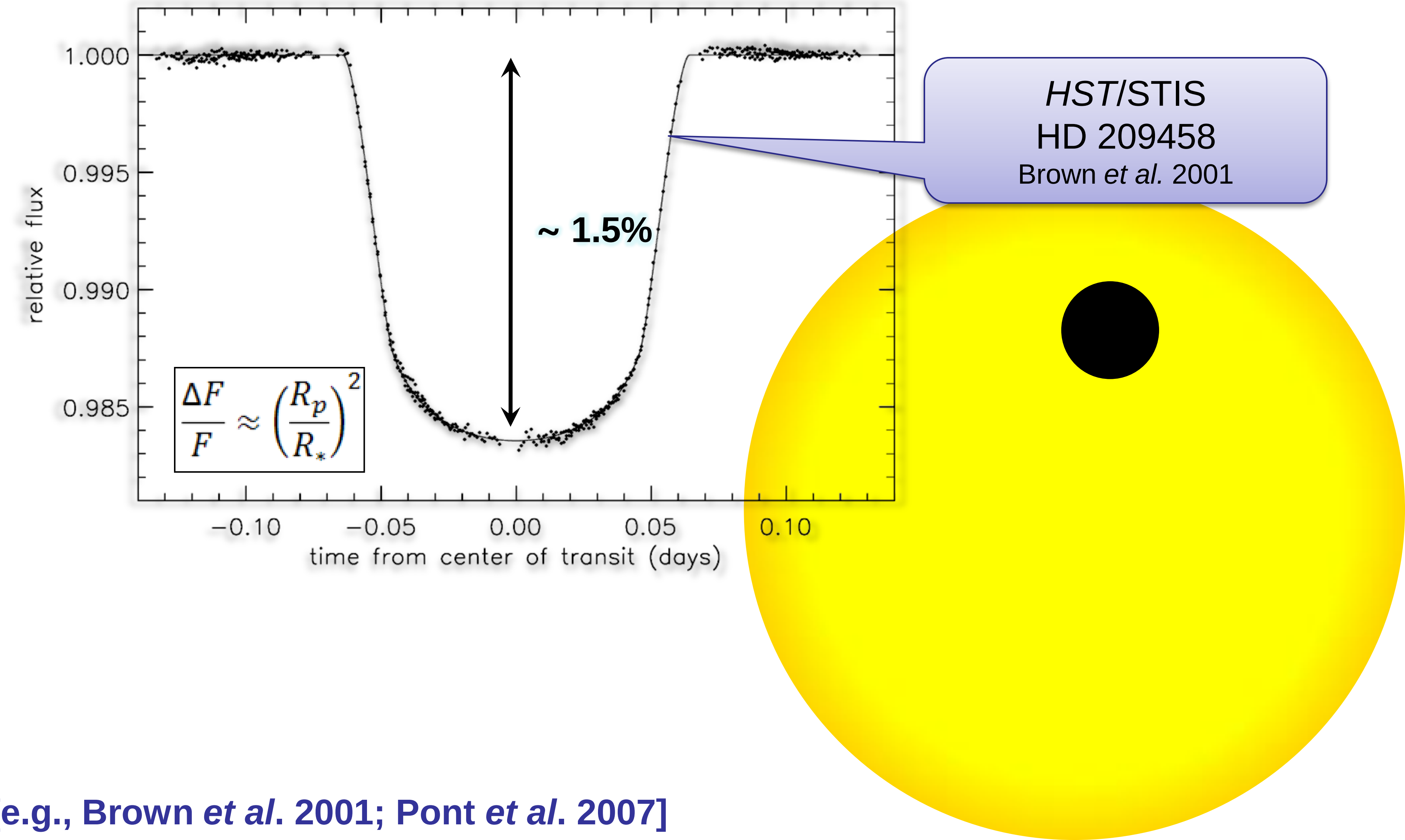
| | |
|---|---|
| Temperature | (T) |
| Variations of Temperature as a func. of altitude | (dT/dz) |
| Pressure | (P) |
| Relative abundance | ($N_1/N_2$) |
| Variations of abundances with altitude | (dN/dz) |

# Transit of HD 209458b

(Charbonneau et al. 2000)



# Primary transit provides the « radius » of the planet.



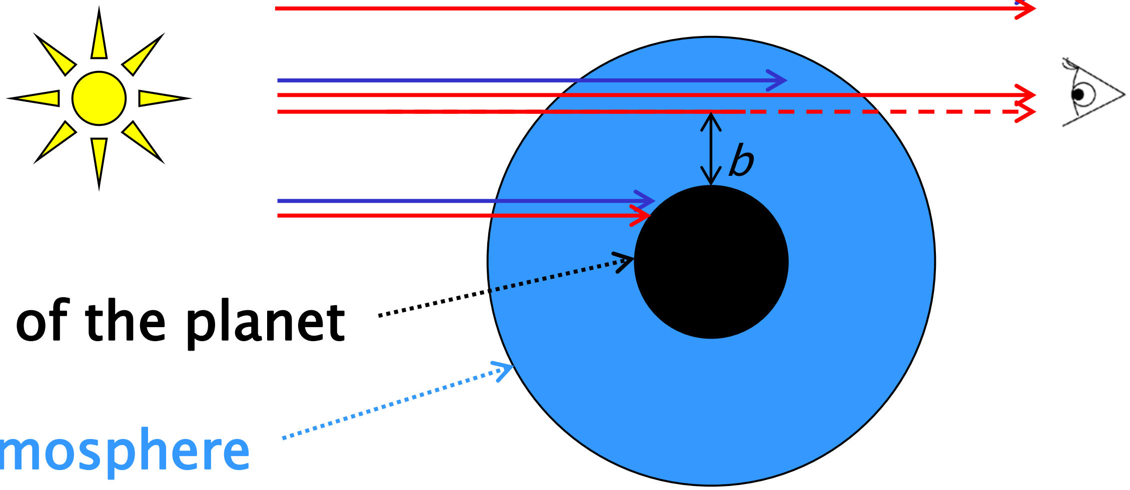
$$\frac{\Delta F}{F} \approx \left(\frac{R_p}{R_*}\right)^2$$

*HST*/STIS
HD 209458
Brown *et al.* 2001

**[e.g., Brown *et al*. 2001; Pont *et al*. 2007]**

# Spectroscopic transits of atmospheres

Light might be absorbed as a function of wavelength (λ) and impact parameter (*b*)



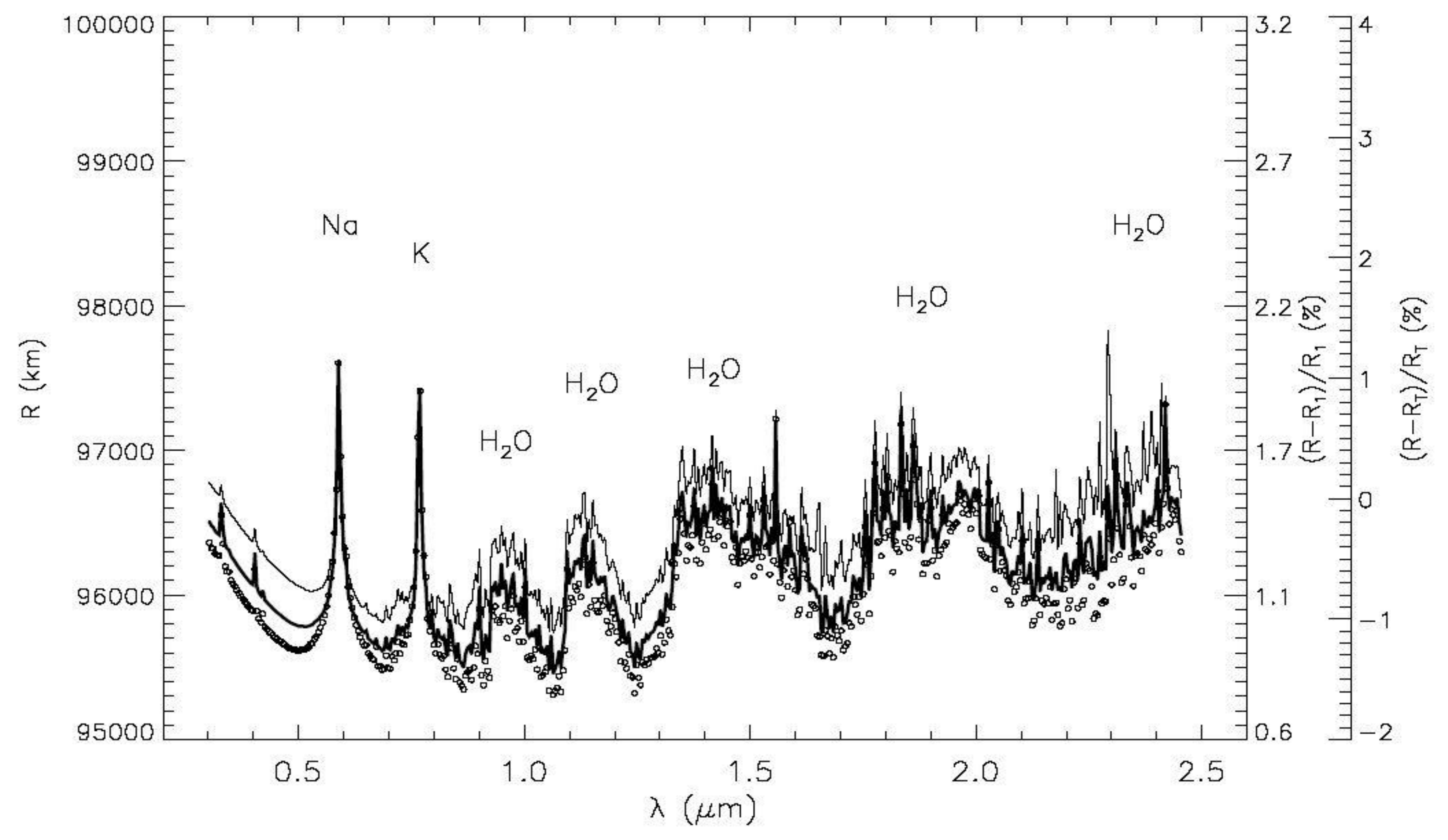
**Optically thick disk of the planet**

Planet + atmosphere

The planet looks larger when observed at highly absorbed wavelengths → $R_P \equiv R_P(\lambda)$

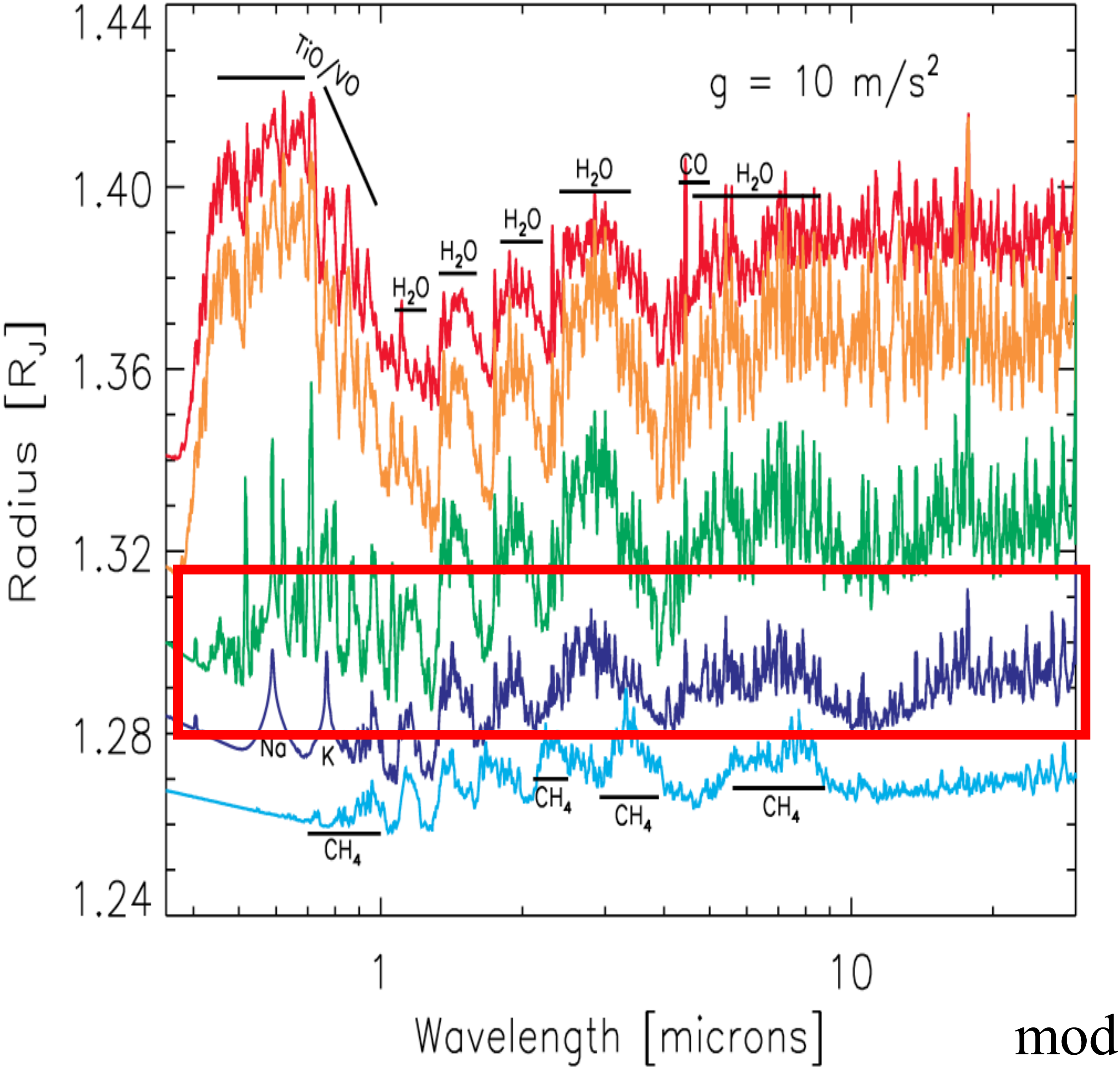
Seager & Sasselov 2000, ApJ 537, 916
Hubbard et al. 2001, ApJ 560, 413
Brown 2001, ApJ 553, 1006

# Radius as a function of wavelength for a Hot-Jupiter



(Hubbard et al. 2001)

# R(λ) for various atmospheres



models from J. Fortney

# Atmospheric signatures of exoplanets

**UV**

- HI 121.6 nm
- OI 130.5 nm CII 133.5 nm
- SiIV 139.8 nm
- SiIII 140.1 nm
- Mg II 280.0 nm, MgI 285.3 nm

**visible**

- Rayleigh $H_2$ 300-500 nm
- Haze ($MgSiO_3$ / $Al_2O_3$) 300-2000 nm
- Na I 589.2-589.8 nm
- K I 768.4 nm
- TiO-VO 600-800 nm

**IR**

- $CH_4$ 1.6 - 2.3 - 3.3 - 3.5-8 μm
- $H_2O$ 1.8 - 6-8 μm
- $CO_2$ 4 μm
- CO 2.3 - 4.5 μm

$$\boxed{\frac{\Delta F}{F} \approx \left(\frac{R_p}{R_*}\right)^2}$$

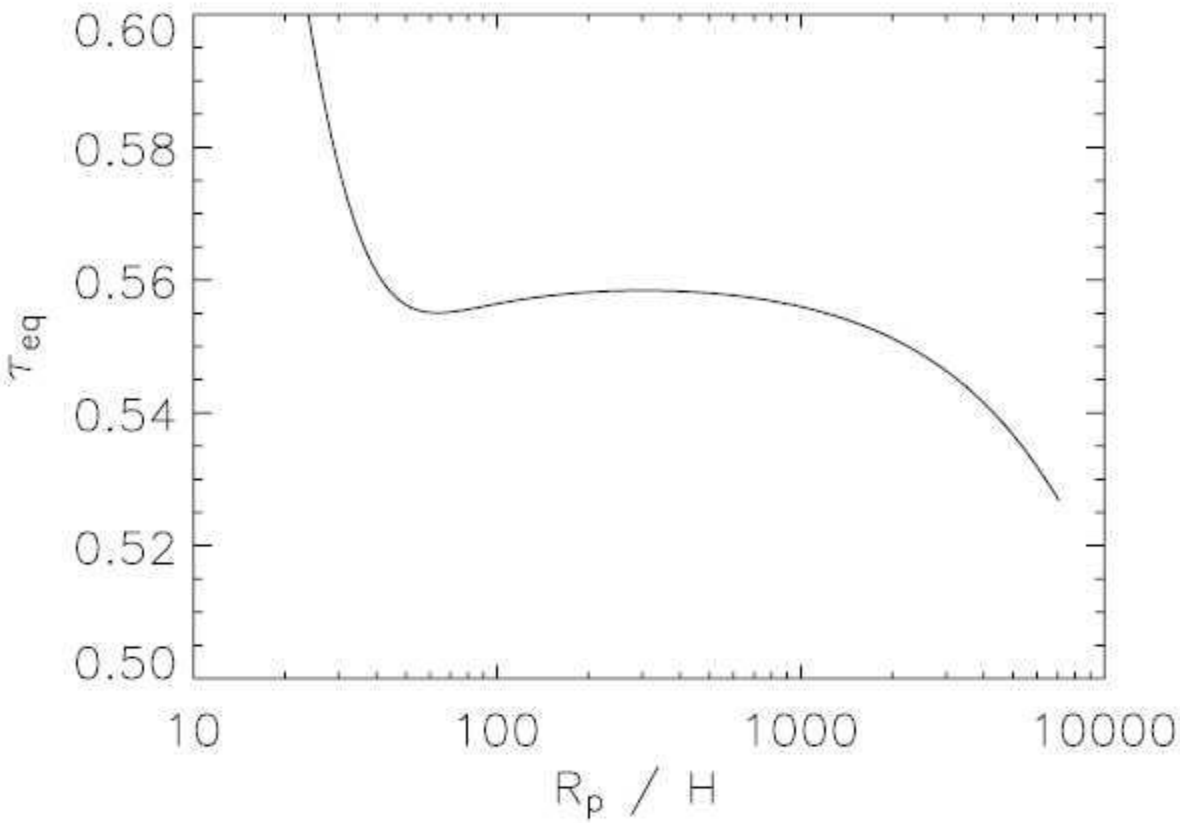
$$R_p(\lambda) = H\ ln\left(\frac{\xi_{abs}P_{z=0}\sigma_{abs}}{\tau_{eq}\mu g}\sqrt{\frac{2\pi R_p}{H}}\right) + Cste$$

# $\tau_{eq} \sim 0.56$

(Lecavelier des Etangs et al. 2008a)

$$\tau(\lambda, z) \approx \sigma(\lambda) n(z) \sqrt{2\pi R_{\rm planet} H}$$ (Fortney et al. 2005)

$$\boxed{R_p(\lambda) = R_{planet} + z(\tau = \tau_{eq})}$$



$$\boxed{\frac{\Delta F}{F} \approx \left(\frac{R_p}{R_*}\right)^2}$$

$$R_p(\lambda) = H \ln\left(\frac{\xi_{abs} P_{z=0} \sigma_{abs}}{\tau_{eq} \mu g} \sqrt{\frac{2\pi R_p}{H}}\right) + Cste$$

$$H = kT/\mu g = kTR_p^2/G\mu M_p \qquad \sigma = \sigma\,(\lambda)$$

$$\boxed{\frac{1}{F}\frac{d\Delta F}{d\lambda} = \frac{3k}{2\pi}\frac{T}{GR_*^2 \mu \rho}\frac{d\ln\sigma}{d\lambda}}$$

# Measurement of physical quantities

- Detection/Non-detection
  !! No direct measurement of absolute abundances using absorption spectroscopy !!
- Temperature (T)
- Variations of Temperature as a func. of altitude (dT/dz)
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# ~~ABUNDANCE~~ and pressure *via* absorption spectroscopy

(Lecavelier des Etangs et al. 2008a)

$$z(\lambda) = H\ ln\left(\frac{\xi_{abs}P_{z=0}\sigma_{abs}}{\tau_{eq}\mu g}\sqrt{\frac{2\pi R_p}{H}}\right)$$

$$\xi_{\rm abs}P_{z=0} = \tau_{\rm eq}/\sigma_{\rm abs}(\lambda_{z=0}) \times \sqrt{kT\mu g/2\pi R_{\rm p}}$$

**Only partial pressure can be measured !!**
**➔ Abundance-Pressure degeneracy**

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# Temperature from observation

## Temperature using absorption spectroscopy

(Lecavelier des Etangs et al. 2008a)

$$R_p(\lambda) = H \ln\left( \frac{\xi_{abs} P_{z=0} \sigma_{abs}}{\tau_{eq} \mu g} \sqrt{\frac{2\pi R_p}{H}} \right) + \mathit{Cste}$$

**H=kT/μg=f(T)**

**σ=σ (λ)**

$$\boxed{T = \frac{\mu g}{k} \left( \frac{d \ln \sigma}{d\lambda} \right)^{-1} \frac{dR_p(\lambda)}{d\lambda}}$$

# Temperature from observation

## Temperature using absorption spectroscopy

(Lecavelier des Etangs et al. 2008a)

$$R_p(\lambda) = H \ln\left(\frac{\xi_{abs} P_{z=0} \sigma_{abs}}{\tau_{eq} \mu g} \sqrt{\frac{2\pi R_p}{H}}\right) + Cste$$

**$H = kT/\mu g = f(T)$**

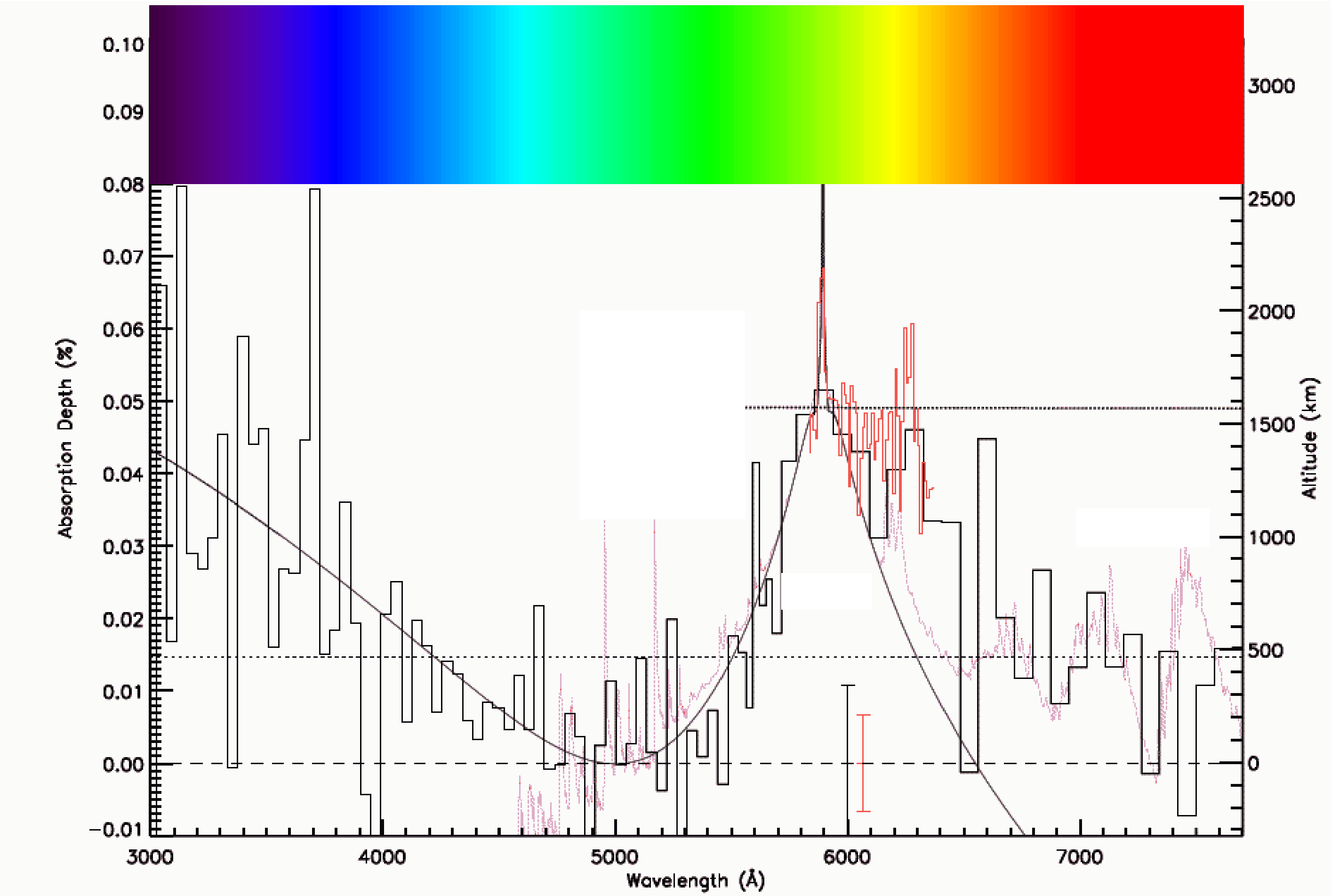
**$\sigma = \sigma(\lambda)$**

For $\sigma(\lambda) = \lambda^{\alpha}$ :

$$\boxed{\alpha T = \frac{\mu g}{k} \frac{dR_p}{d \ln \lambda}}$$

# HD209458b (Osiris):
# Atmosphere spectrum from near-UV to near-IR

(Sing et al. 2008a, 2008b, Desert et al. 2008, Lecavelier et al. 2008)



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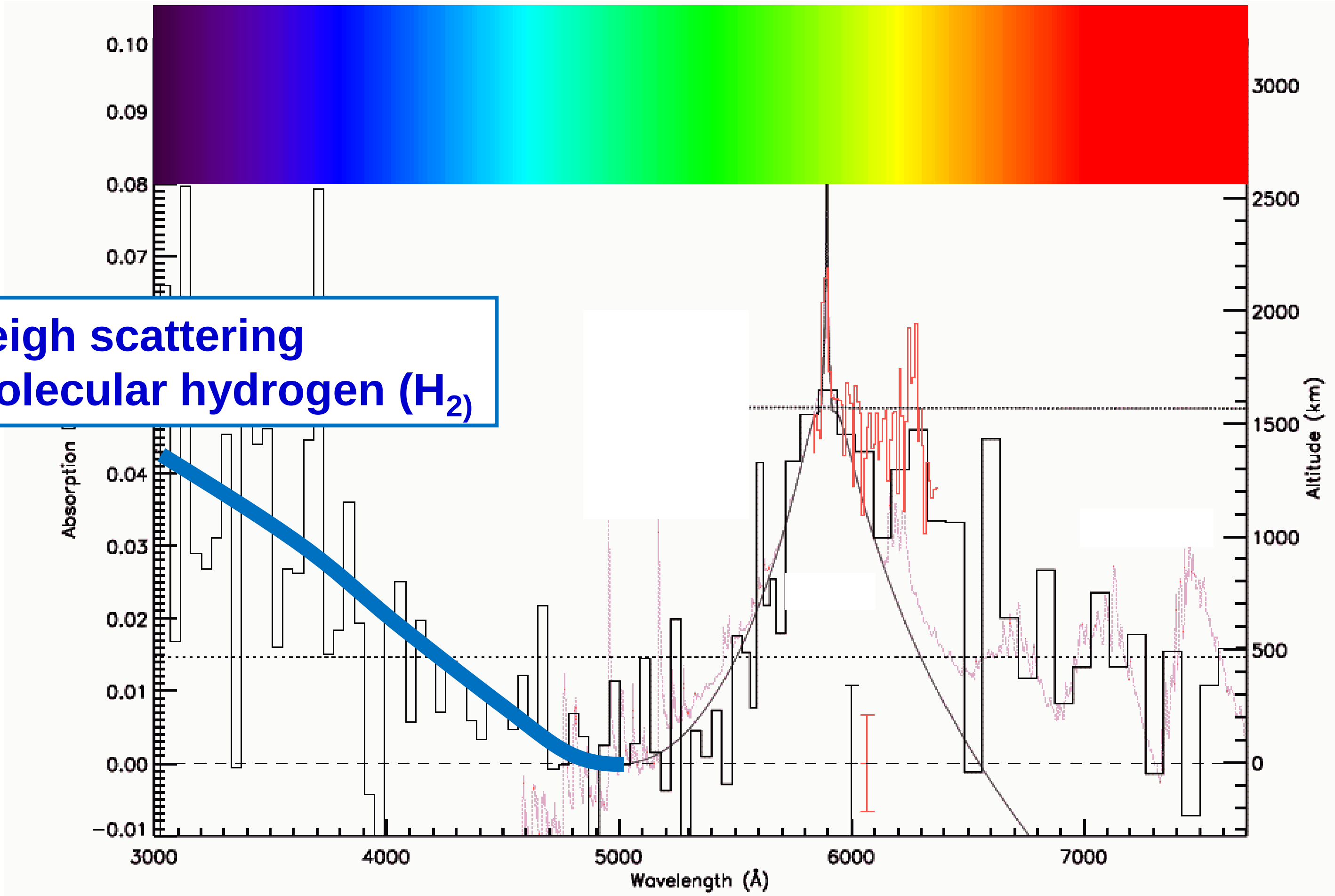

**Rayleigh scattering**
**by molecular hydrogen ($H_2$)**

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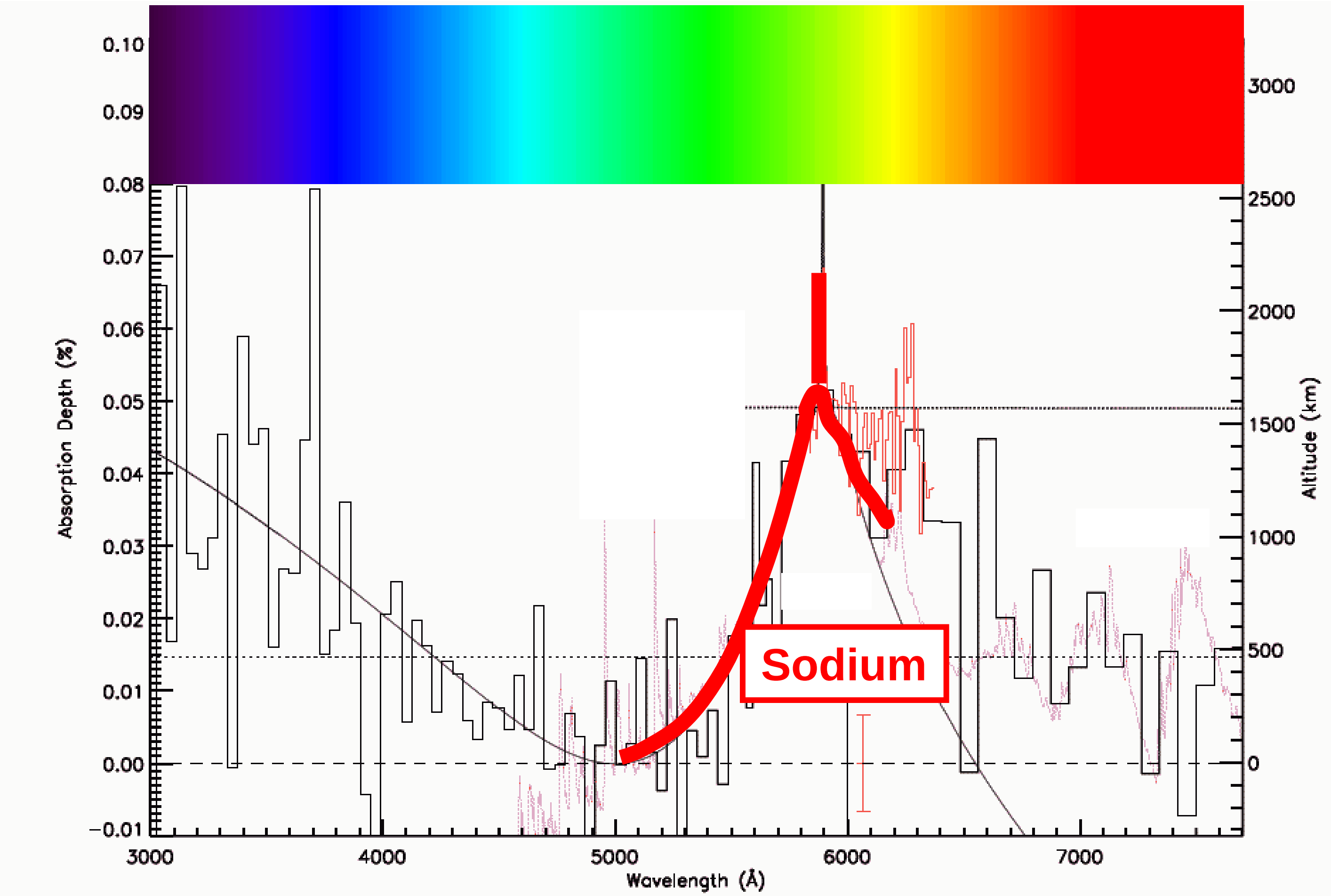
# Atmosphere spectrum from near-UV to near-IR

(Sing et al. 2008a, 2008b, Desert et al. 2008, Lecavelier et al. 2008)



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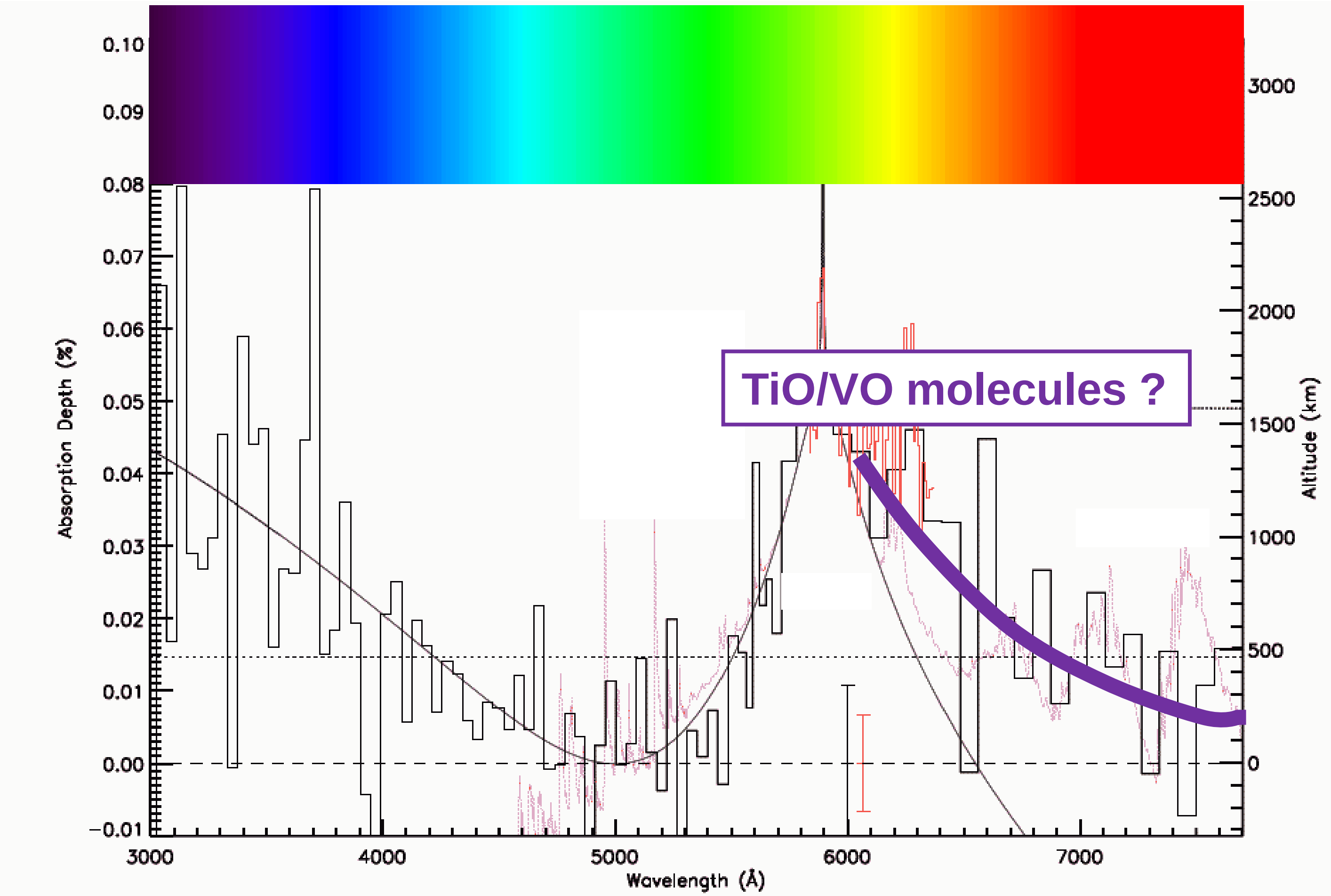
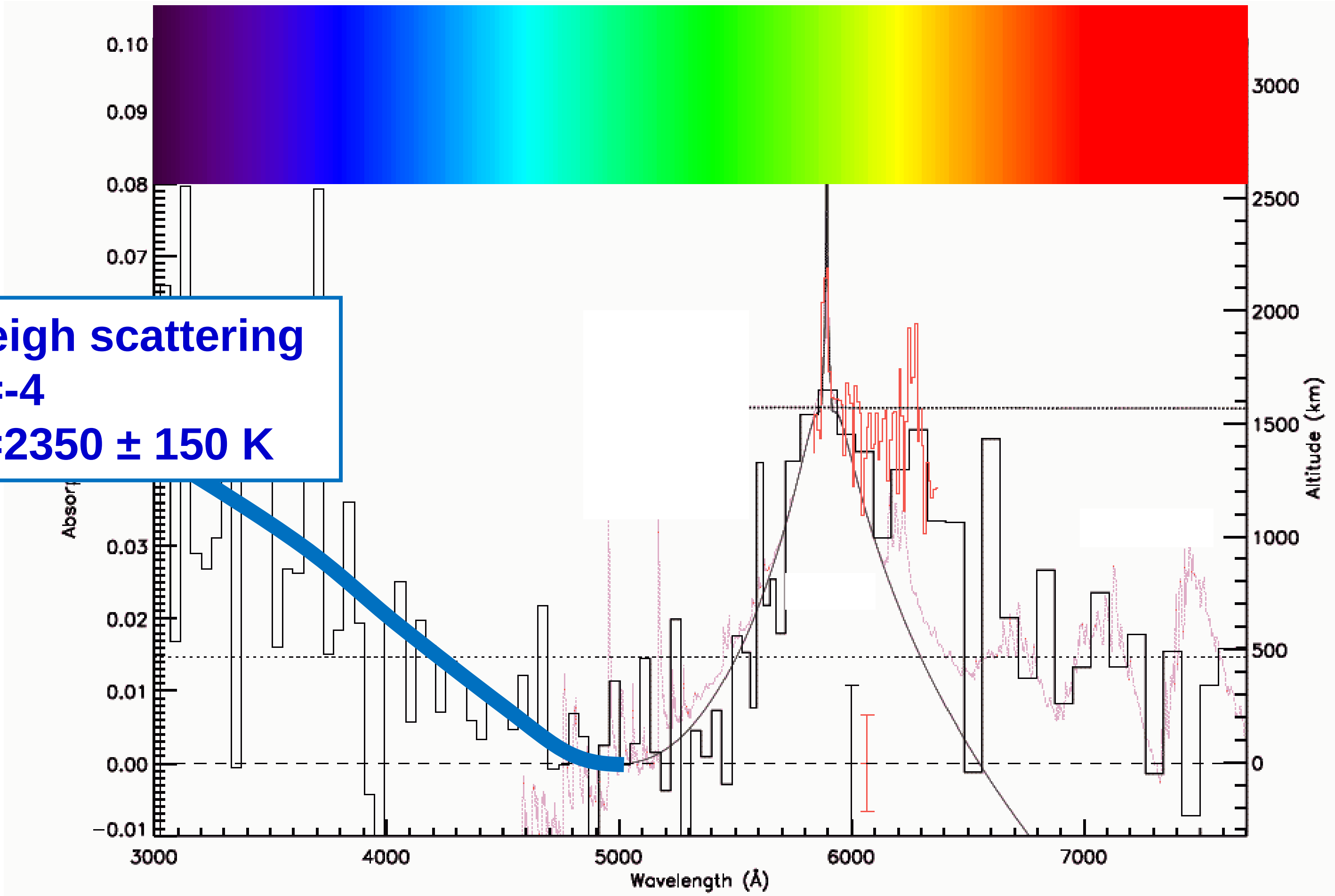


**TiO/VO molecules ?**

# Rayleigh scattering: Temperature measurement for $H_2$ in HD209458b

(Lecavelier des Etangs et al. 2008)



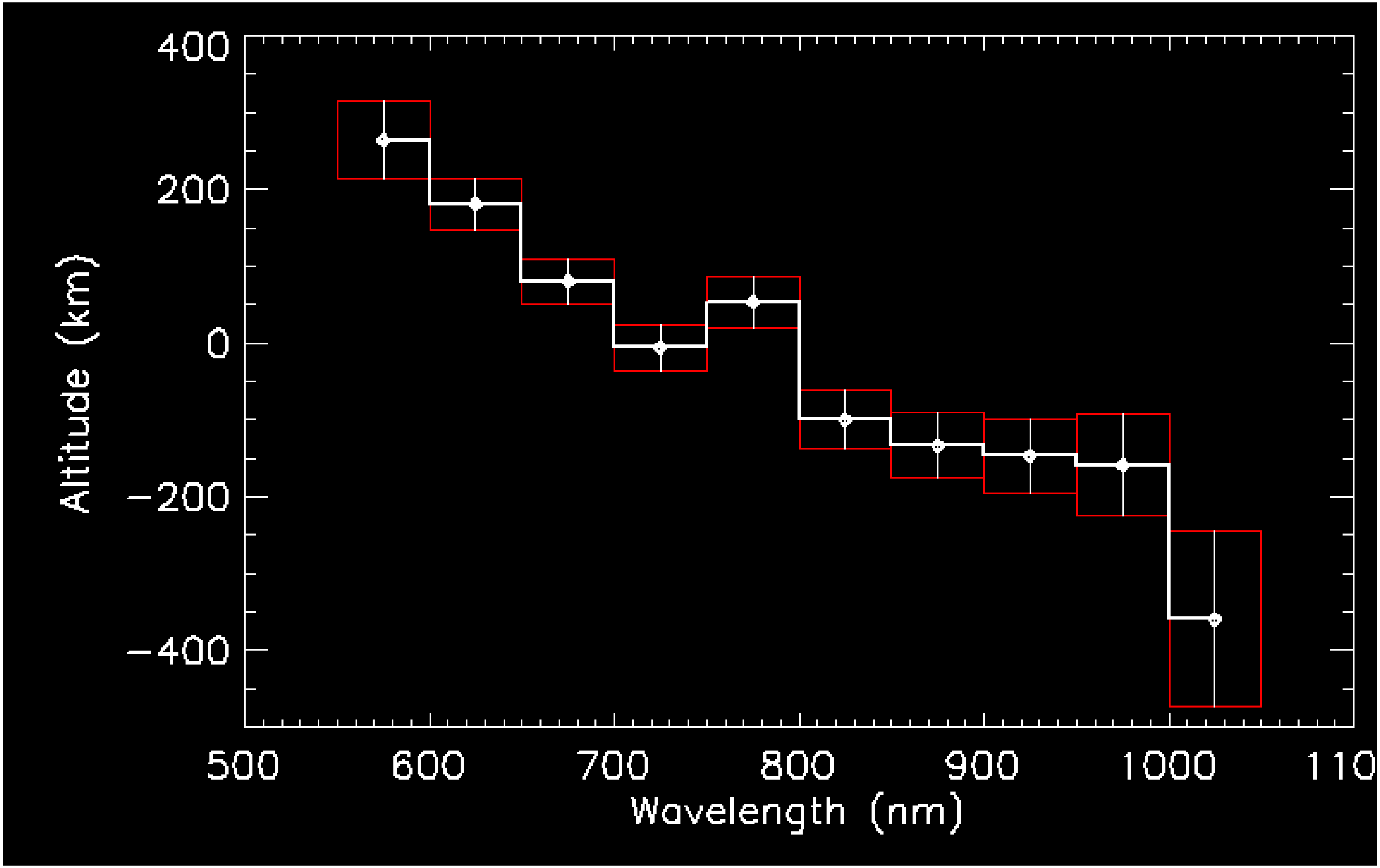
**Rayleigh scattering**

**➔ α=-4**

**➔ T=2350 ± 150 K**

# Haze in HD 189733b

(Pont et al. 2007)



# Haze in HD 189733b

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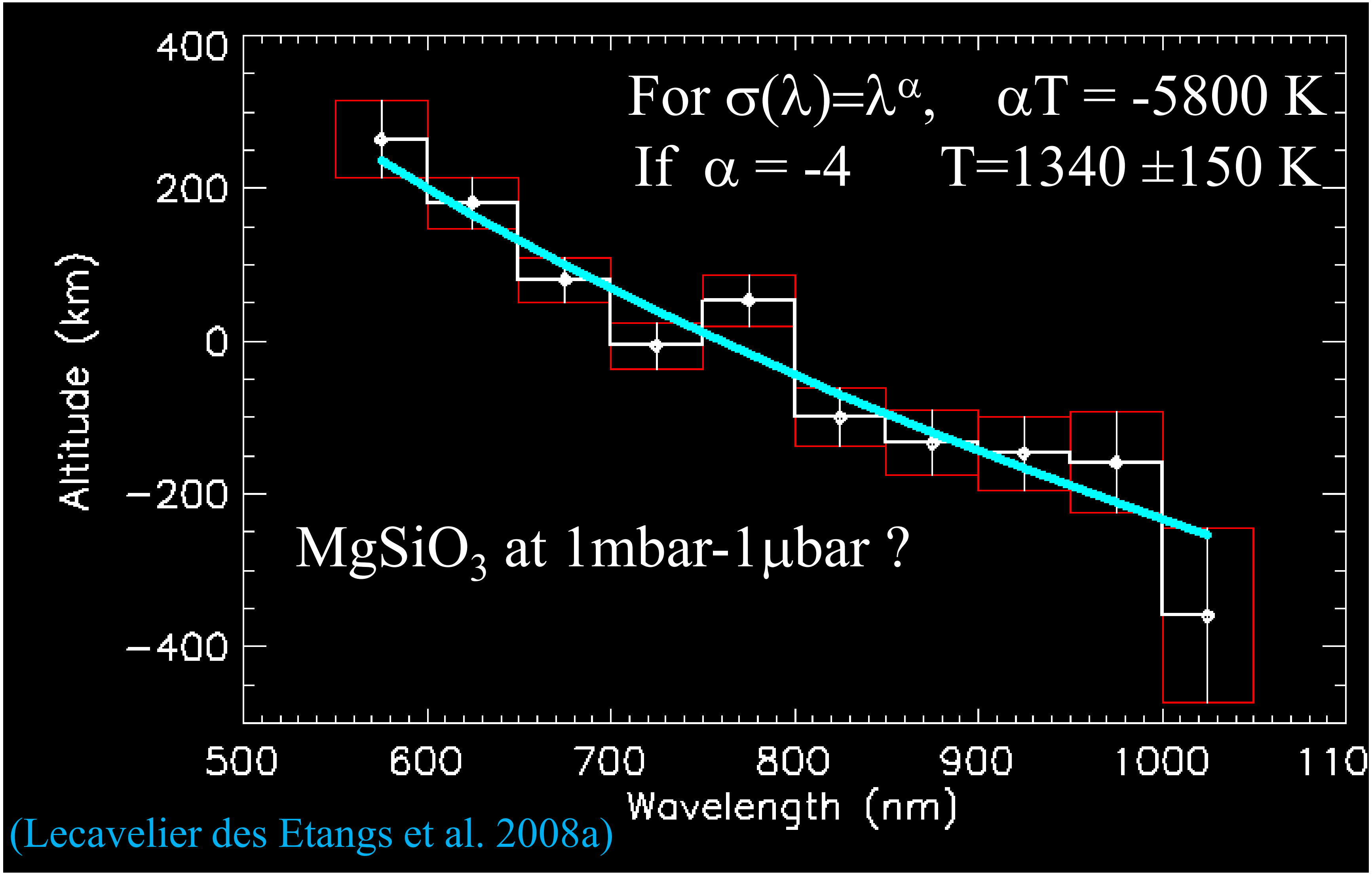

For $\sigma(\lambda)=\lambda^{\alpha}$, $\alpha T = -5800$ K

If $\alpha = -4$ T=1340 ±150 K

$MgSiO_3$ at 1mbar-1μbar ?

(Lecavelier des Etangs et al. 2008a)

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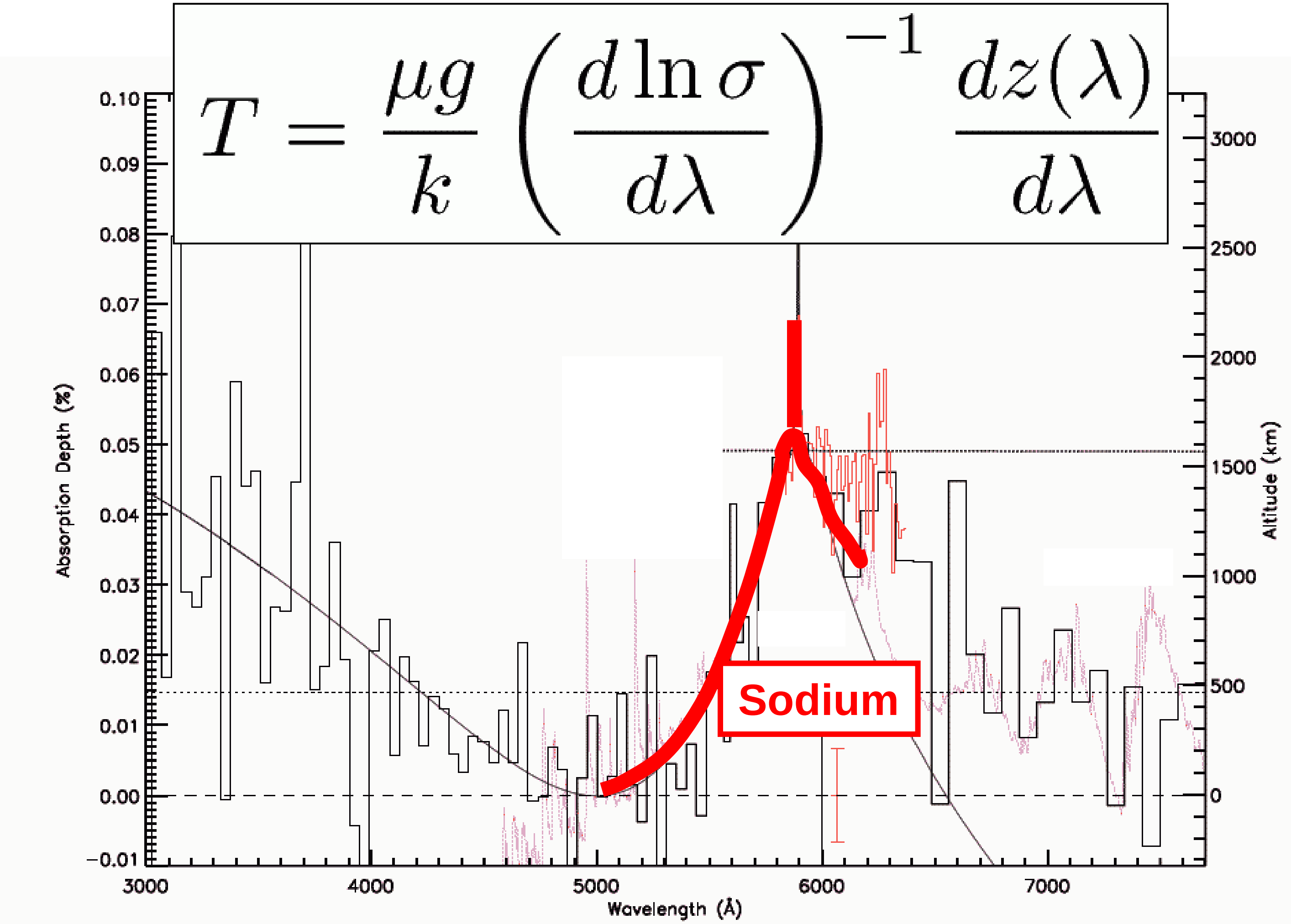
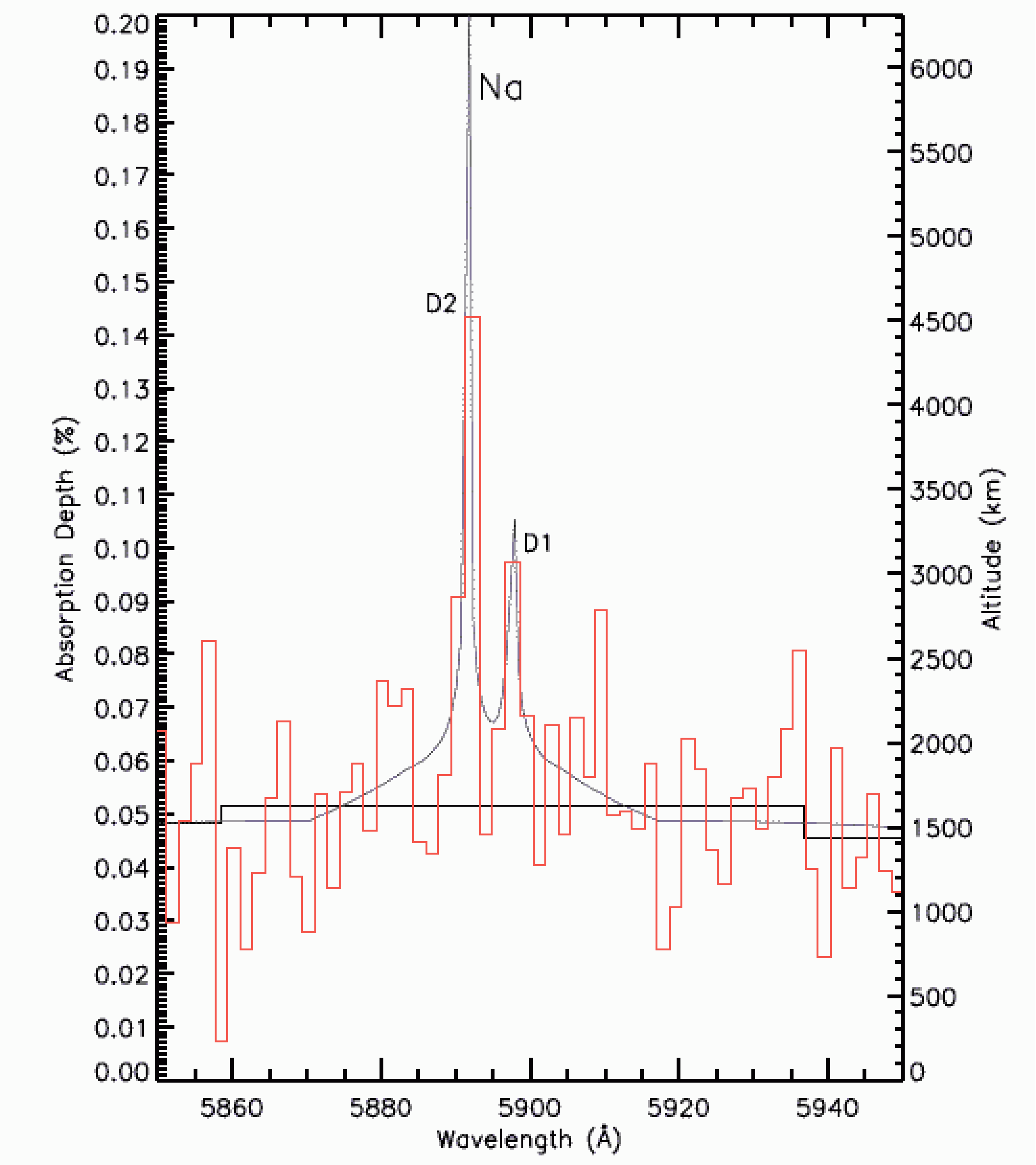


$$T = \frac{\mu g}{k} \left( \frac{d \ln \sigma}{d\lambda} \right)^{-1} \frac{dz(\lambda)}{d\lambda}$$

# Core of the sodium doublet

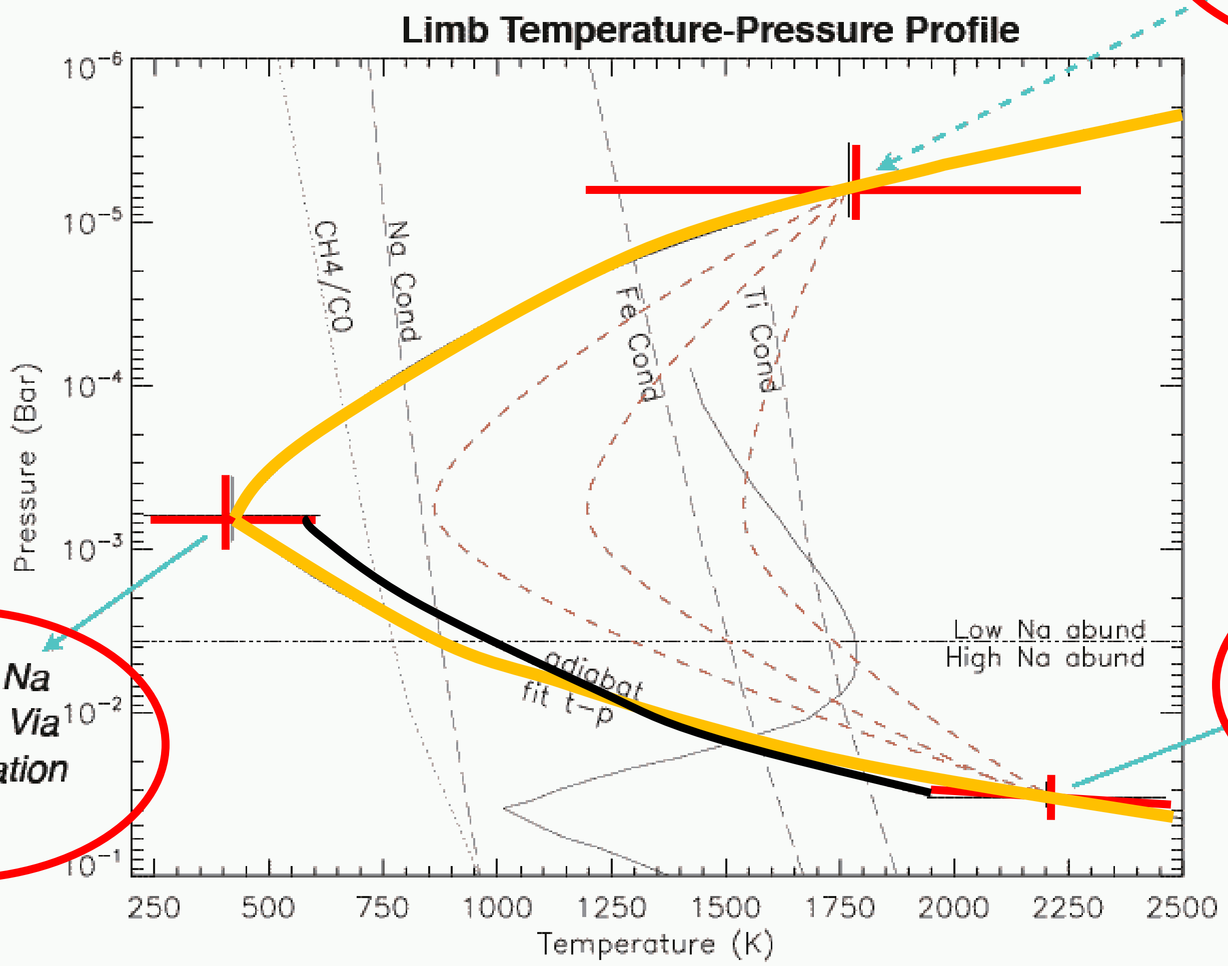
(Sing et al. 2008a, 2008b)



# T-P Profile 10 mbar-10μbar

(Sing et al. 2008a; 2008b; Vidal-Madjar et al. 2012)

Na core indicates hot high-altitude temperatures



HD209458b

*Assumes Na Depletion Via Condensation*

Measured By $H_2$ Rayleigh Scattering.

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# ~~ABUNDANCE~~ and pressure *via* absorption spectroscopy

(Lecavelier des Etangs et al. 2008a)

$$z(\lambda) = H \; ln \left( \frac{\xi_{abs} P_{z=0} \sigma_{abs}}{\tau_{eq} \mu g} \sqrt{\frac{2\pi R_p}{H}} \right)$$

$$\xi_{\mathrm{abs}} P_{z=0} = \tau_{\mathrm{eq}} / \sigma_{\mathrm{abs}}(\lambda_{z=0}) \times \sqrt{kT\mu g / 2\pi R_{\mathrm{p}}}$$

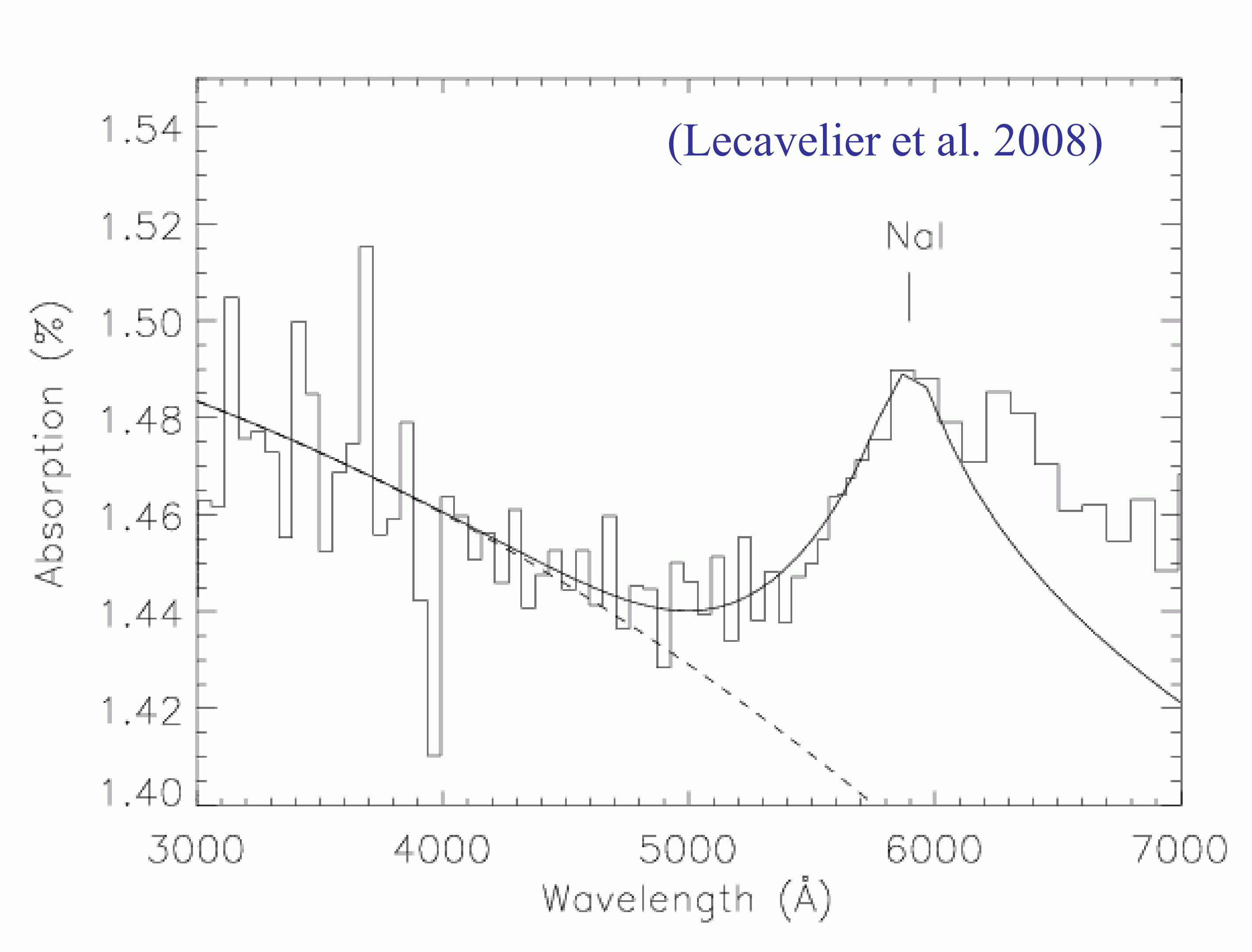
**Only partial pressure can be measured !!**
**➔ Abundance-Pressure degeneracy**

Exception for $H_2$: $\xi_{\mathrm{H}_2} \sim 1$ ➔ Measurement of total pressure!

$$P_0 = \tau_{\mathrm{eq}} / \sigma_0 \times \sqrt{kT\mu g / 2\pi R_{\mathrm{p}}}$$

# Rayleigh scattering from $H_2$
# ➔Temperature – Pressure at z=0

(z=0 for $R_p^2/R_{star}^2=1.453\%$)



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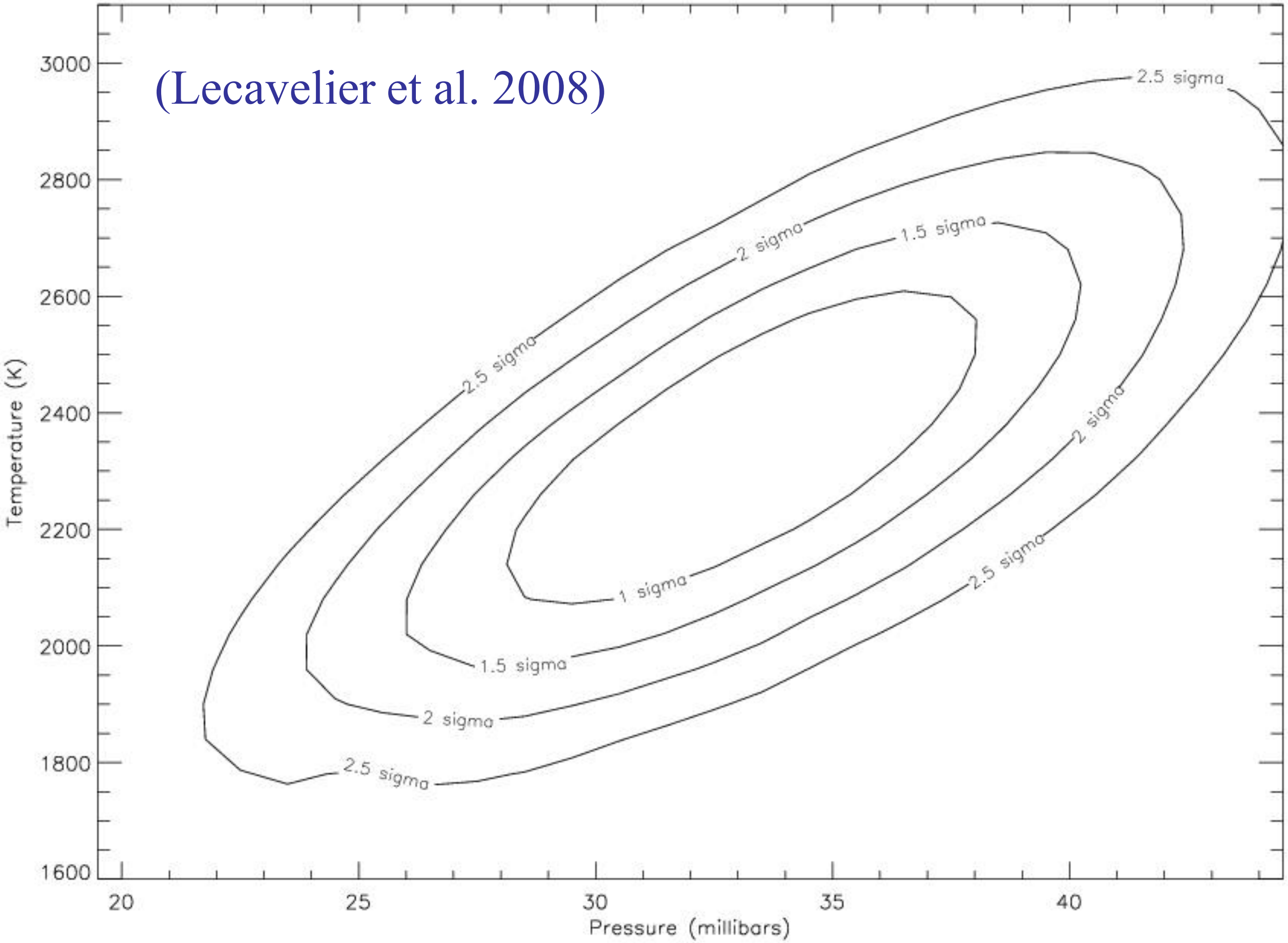
(z=0 for $R_p^2/R_{star}^2$=1.453%)


(Lecavelier et al. 2008)

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# Relative abundance

$$z(\lambda) = H\ ln\left(\frac{\xi_{abs}P_{z=0}\sigma_{abs}}{\tau_{eq}\mu g}\sqrt{\frac{2\pi R_p}{H}}\right)$$

If '1' and '2' are the two main absorbers at $\lambda_1$ and $\lambda_2$:

($\xi$ is the abundance, $\sigma$ the cross section)

$$\boxed{\Delta R_p = H \ln\frac{\xi_1\sigma_1}{\xi_2\sigma_2} \quad \text{where} \quad H = \frac{kT}{\mu g}}$$

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$$\boxed{\text{if} \quad \xi_1 = \xi_2, \qquad T = \frac{\mu g \Delta R_p}{k \ln(\sigma_1/\sigma_2)}}$$

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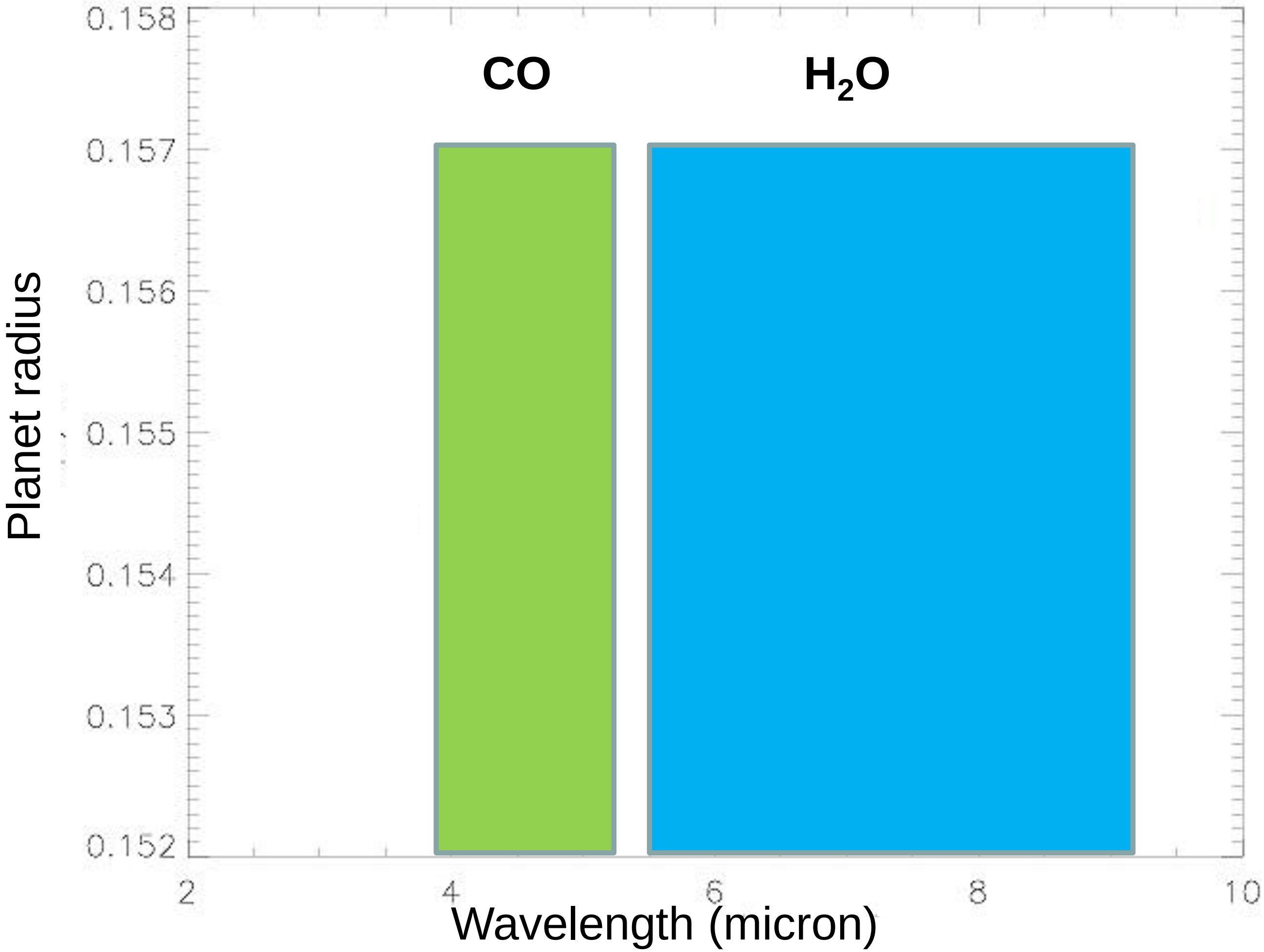
$$\text{if} \quad \xi_1 = \xi_2, \qquad T = \frac{\mu g \Delta R_p}{k \ln(\sigma_1/\sigma_2)}$$

$$\text{if} \quad \xi_1 \neq \xi_2, \qquad \frac{\xi_1}{\xi_2} = \frac{\mu g \Delta R_p}{kT \ln(\sigma_1/\sigma_2)}$$

# Spitzer observations HD189733b

(Ehrenreich et al. 2007; Désert et al. 2009)



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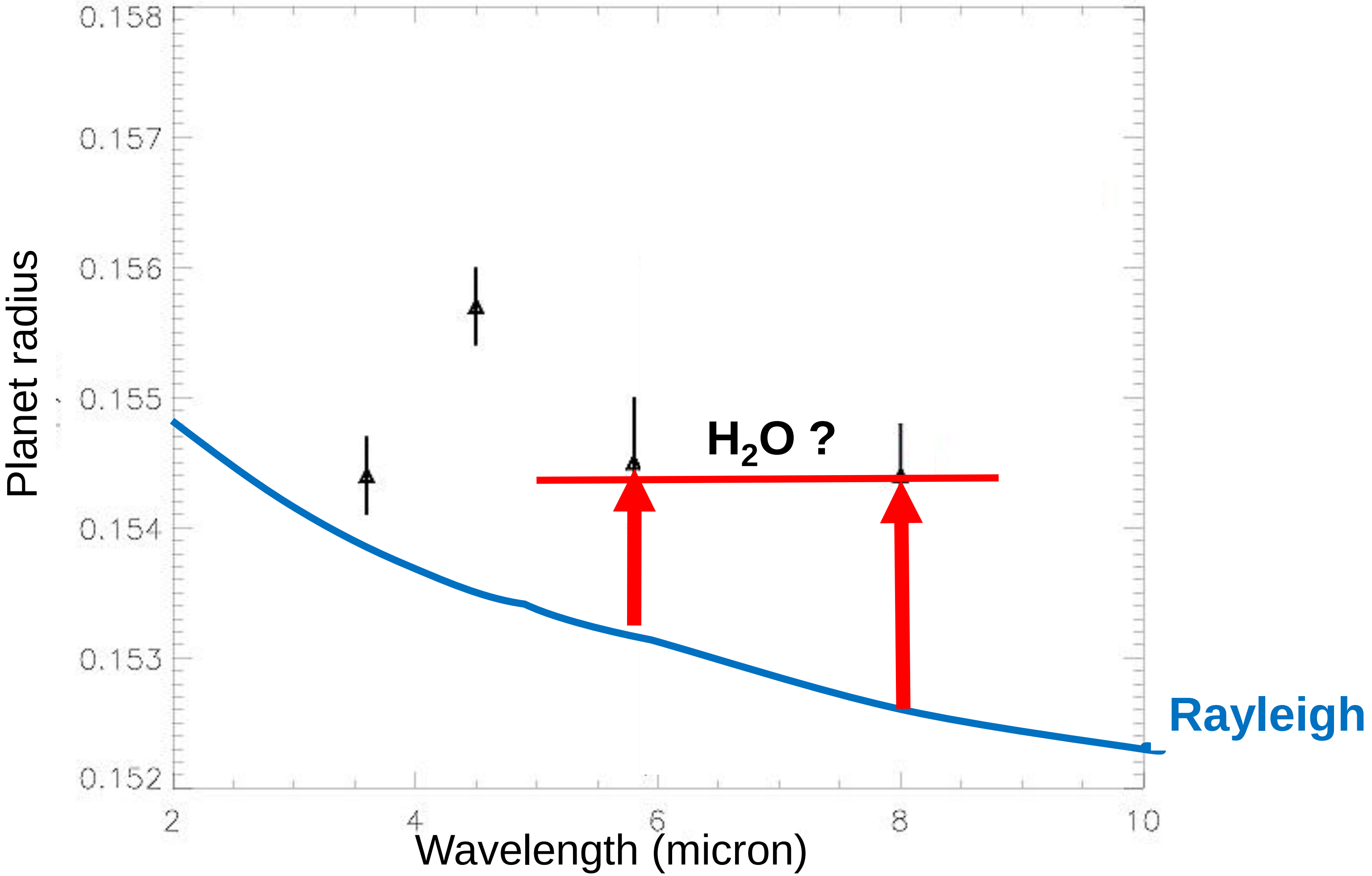

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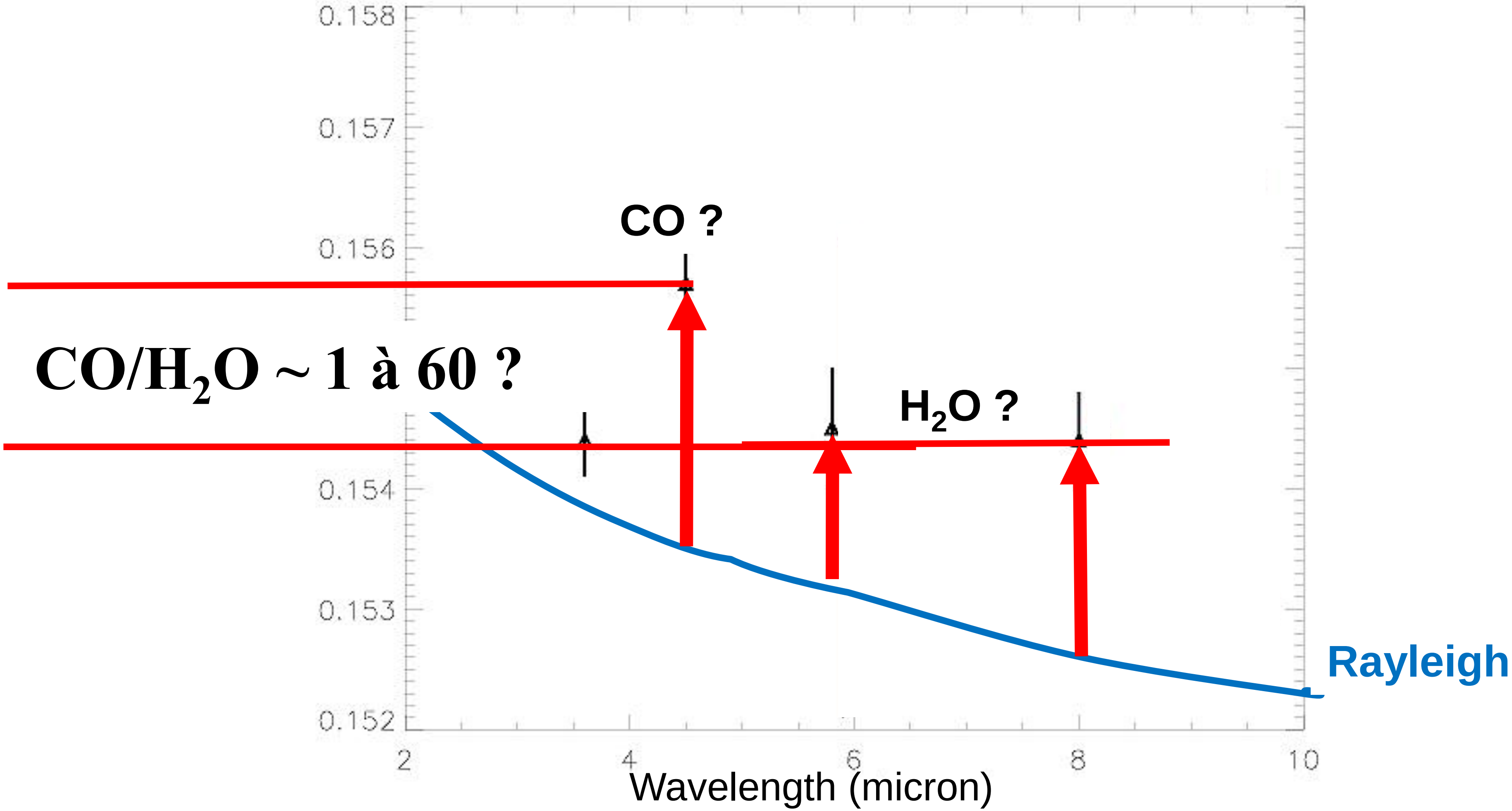

CO/$H_2O$ ~ 1 à 60 ?

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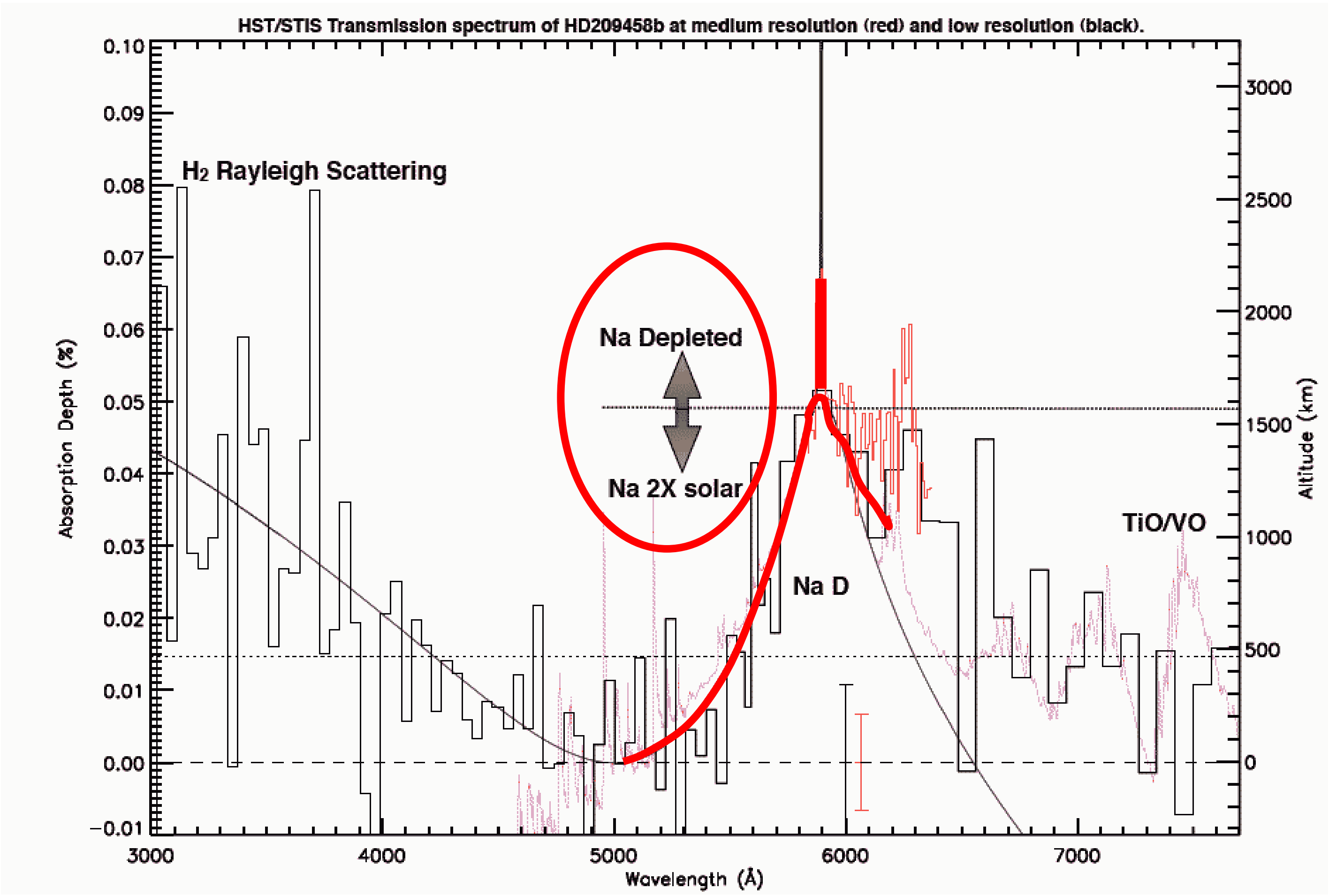
# HD 209458b:
# Sodium broad band absorption

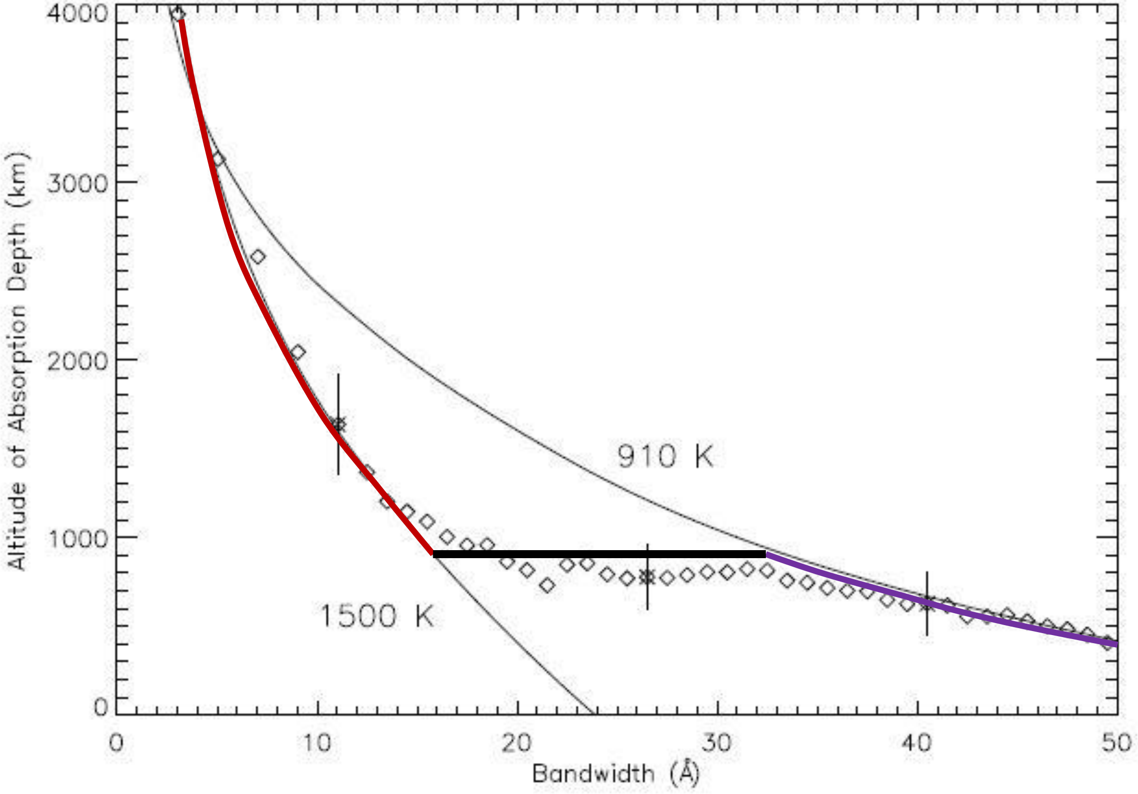
(Sing et al. 2008a, 2008b; Vidal-Madjar et al. 2011, 2012)



# Variations of abundances with altitude

(Sing et al. 2008a, 2008b; Vidal-Madjar et al. 2011, 2012)

HD209458b, d [NaI]/dz

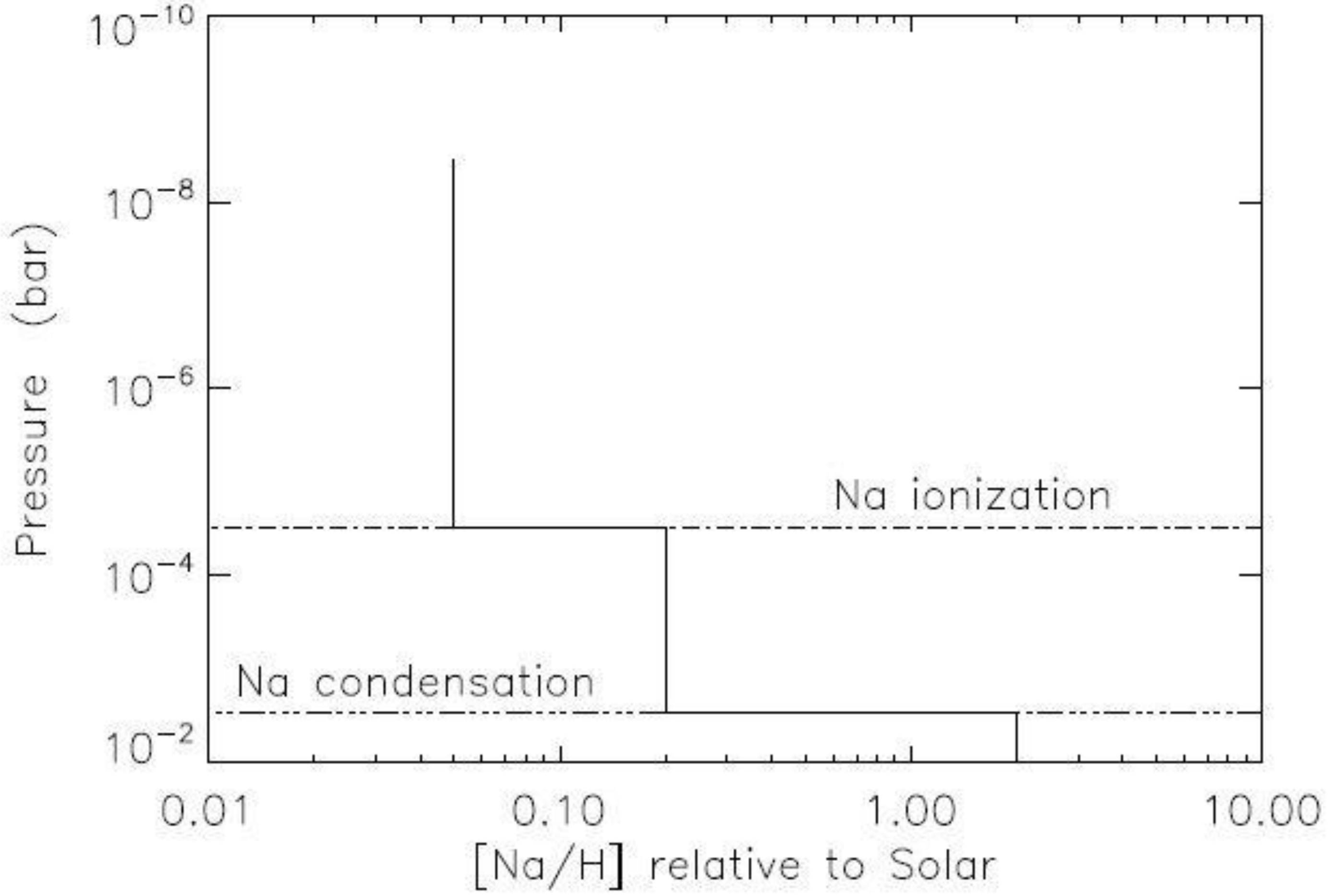


$$\left(\frac{[\mathrm{Na/H}]_1}{[\mathrm{Na/H}]_2}\right) = \left(\frac{\sigma(\lambda_2)}{\sigma(\lambda_1)}\right) \cong \left(\frac{\lambda_2 - \lambda_0}{\lambda_1 - \lambda_0}\right)^{-2} \quad \Delta\lambda_2/\Delta\lambda_1 \sim 2 \rightarrow \left(\frac{[\mathrm{Na/H}]_1}{[\mathrm{Na/H}]_2}\right) = 1/4$$

# Variations of abundances with altitude

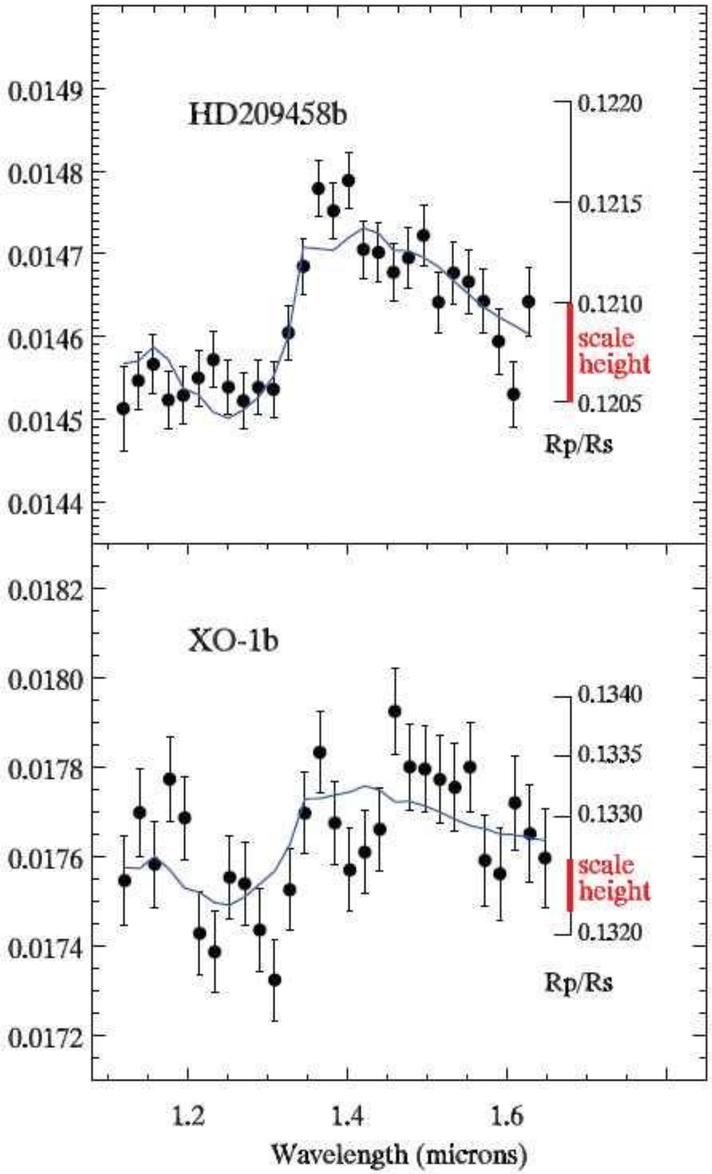
(Sing et al. 2008a, 2008b; Vidal-Madjar et al. 2011, 2012)

HD209458b, d [NaI]/dz



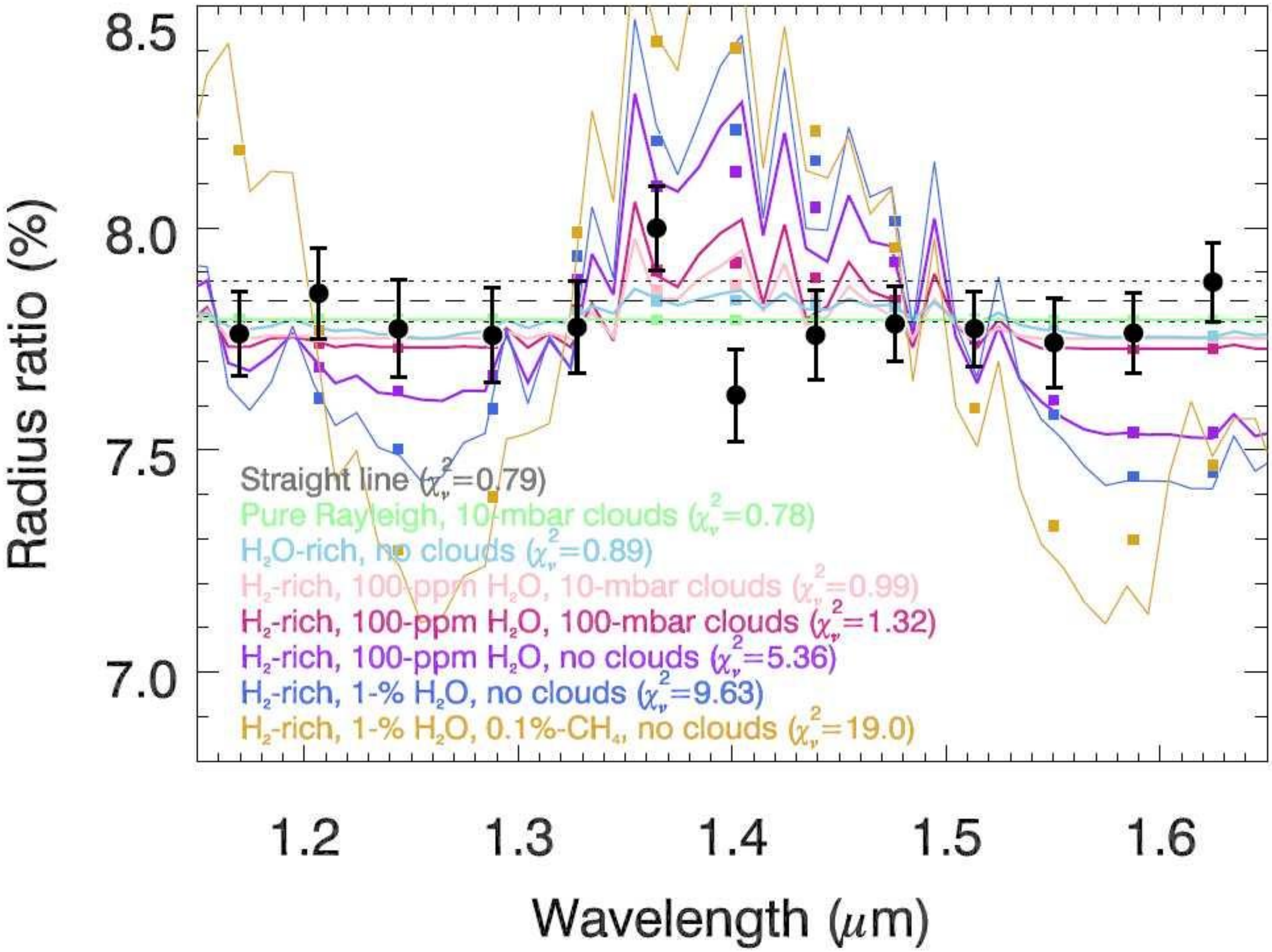
# Observation of $H_2O$ using HST/WFC-3

(e.g., Deming et al. 2013; Ehrenreich et al. 2014)



# Observation of GJ 3470b with HST/WFC-3

(Ehrenreich et al. 2014)



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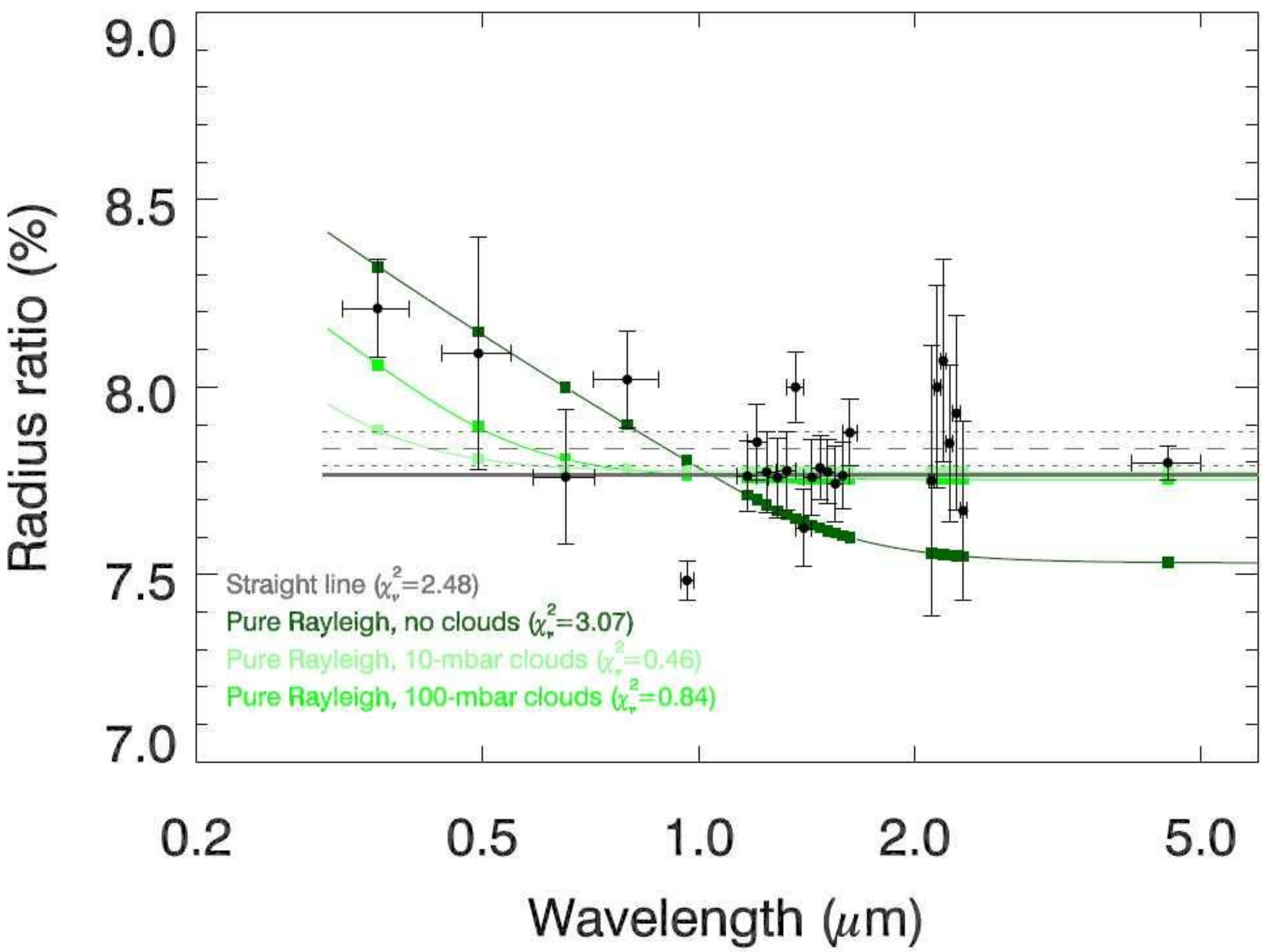
(Ehrenreich et al. 2014)



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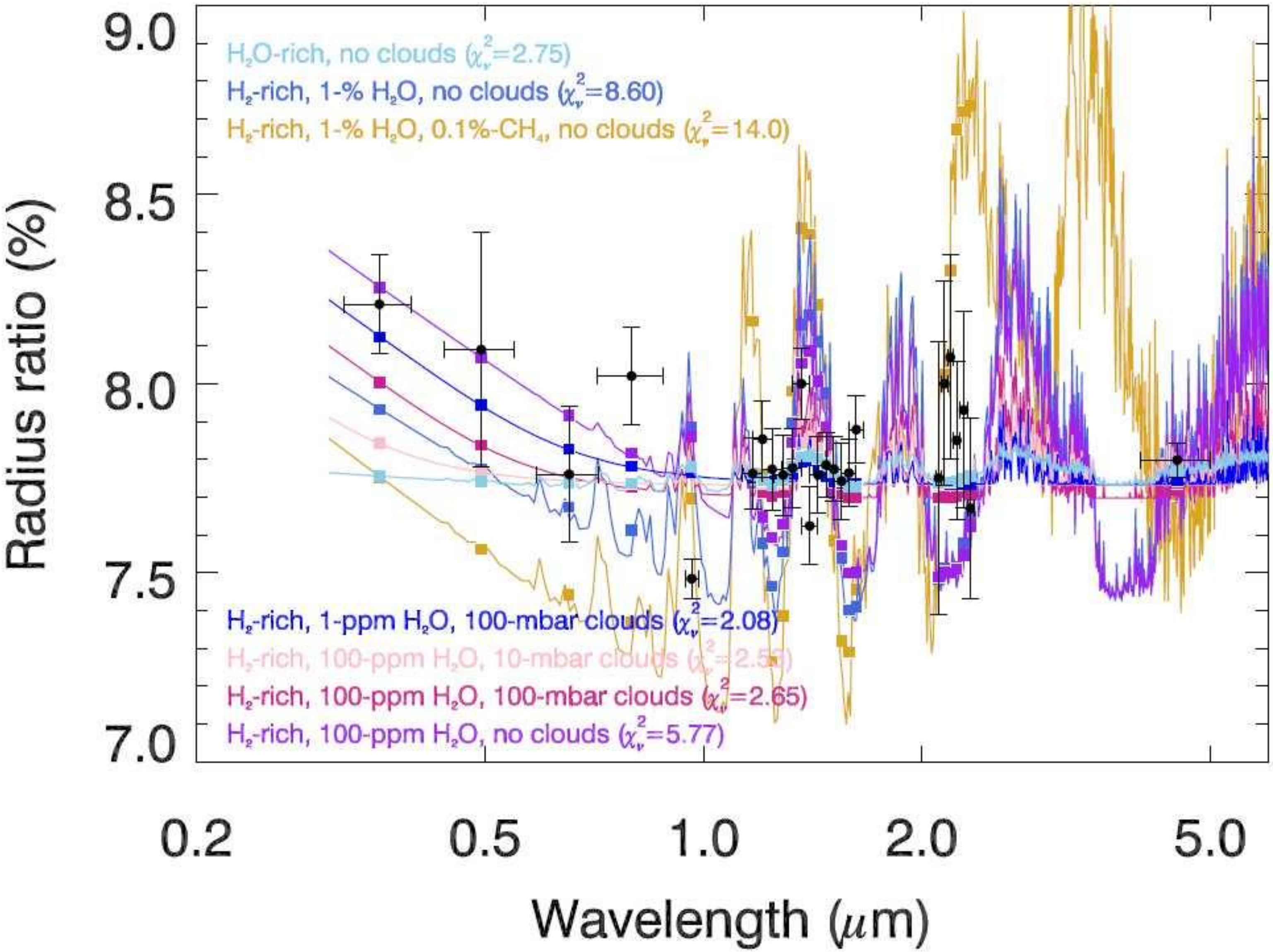

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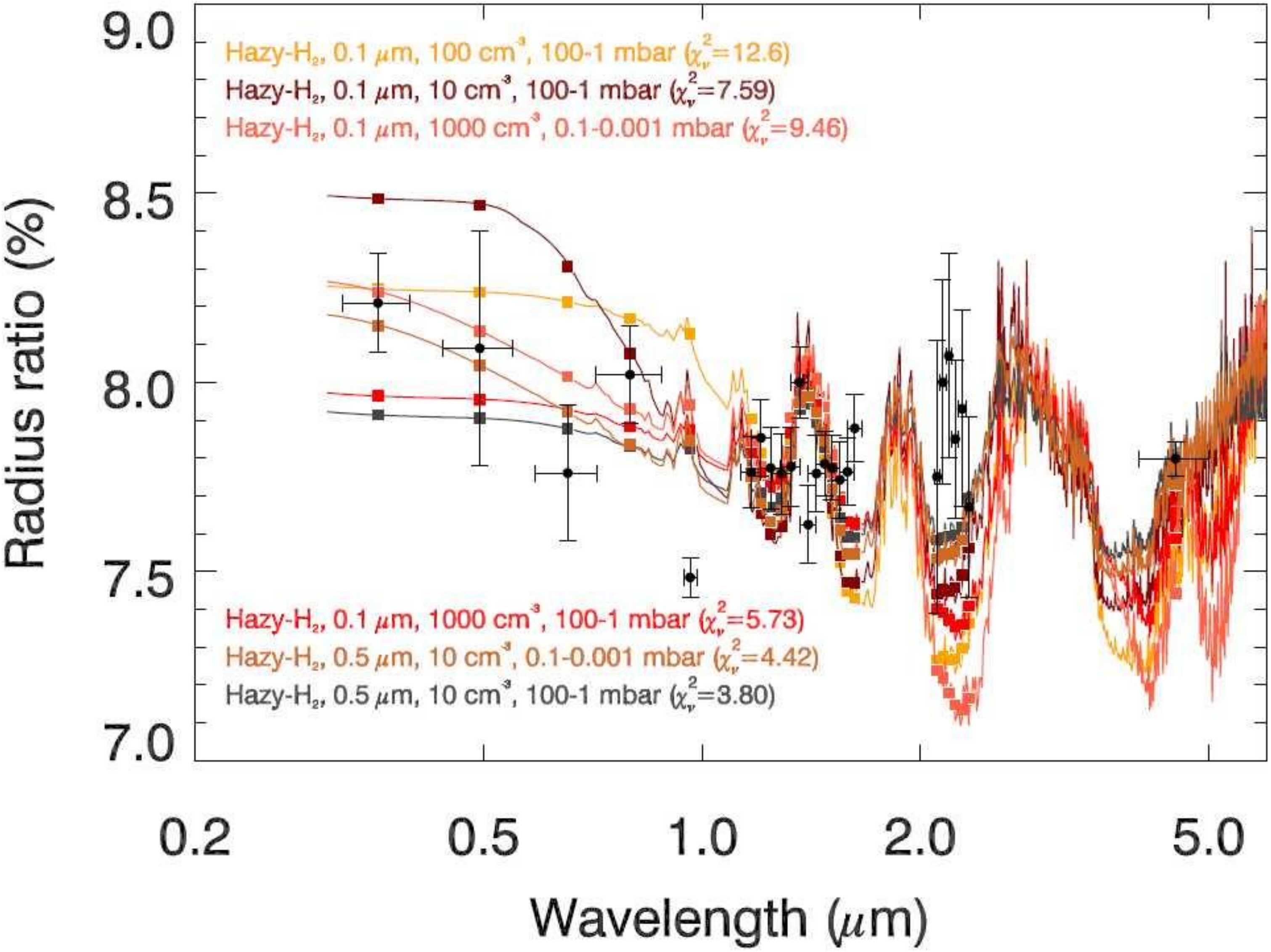

# Observation of Wasp-12 with HST

(Sing et al. 2013)

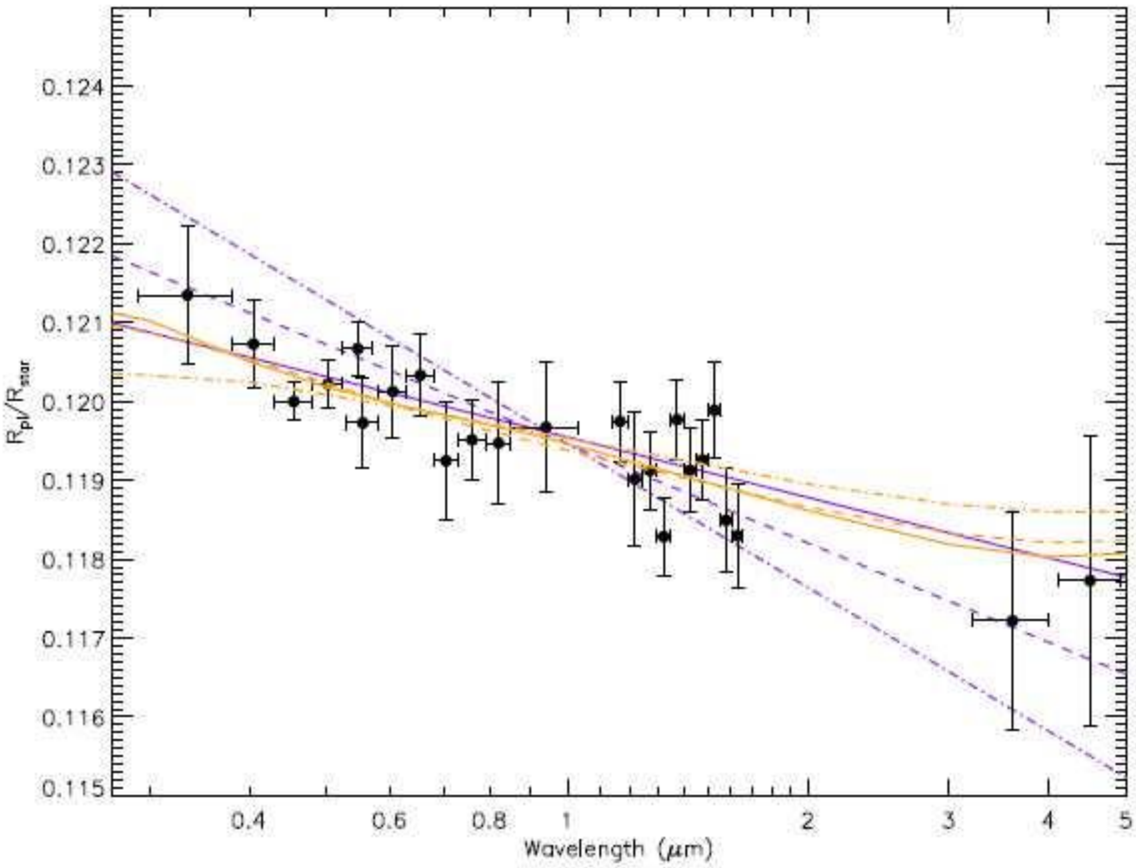

**Figure 14.** Rayleigh scattering (purple) and Mie scattering $Al_2O_3$ models (orange) plotted at different assumed atmospheric temperatures of 968 K (solid), 1450 K (dashed), and 2100 K (dot-dashed). $Al_2O_3$ Mie scattering models can provide good fits at a wide variety of temperature ranges, while Rayleigh scattering models fit best at temperatures of 882±164 K.

Pure Rayleigh

➔ T~880 ± 170K

$Al_2O_3$

➔ T=1400 ± 400 K

The end