Some mechanisms affecting the composition of hot Jupiters

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3D mixing in hot-Jupiter atmospheres.

Collaborators: Adam Showman, Yuan Lian

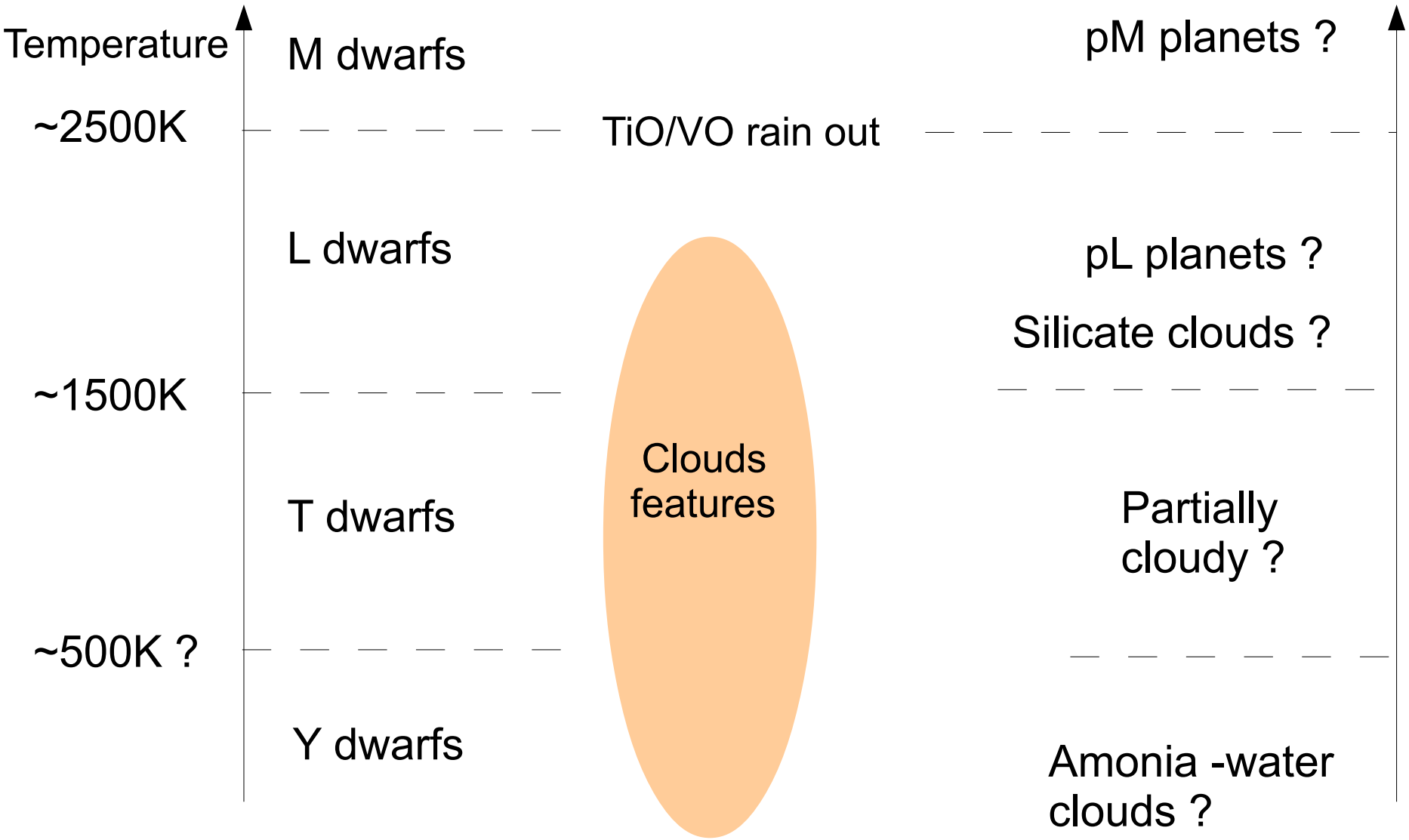
Infrared cooling of the upper atmosphere of hot planets : an analytical model.

Collaborators: Tristan Guillot, Jonathan Fortney

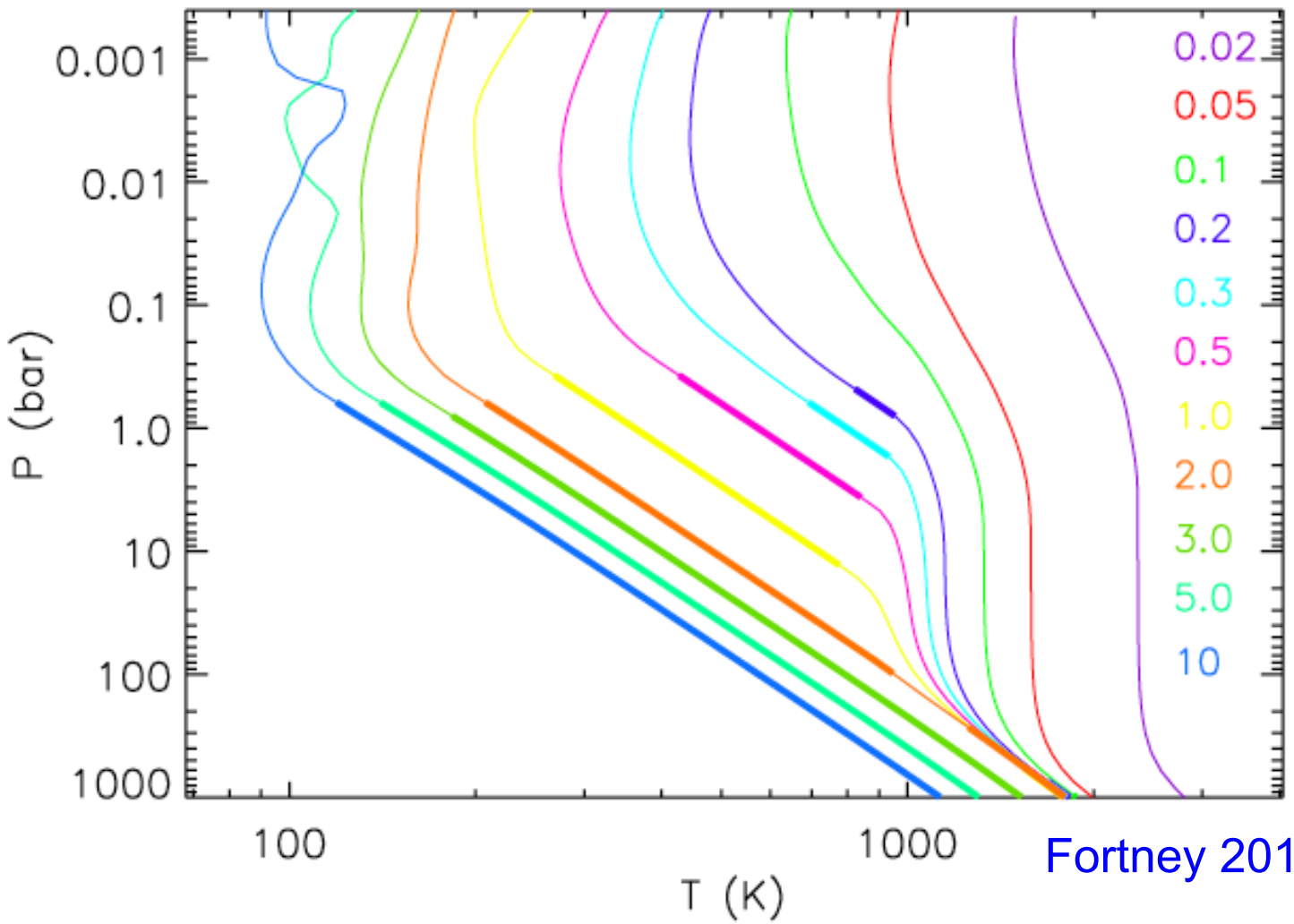
ISIMA

International Summer Institute for Modeling in Astrophysics

Cool stars vs hot planets



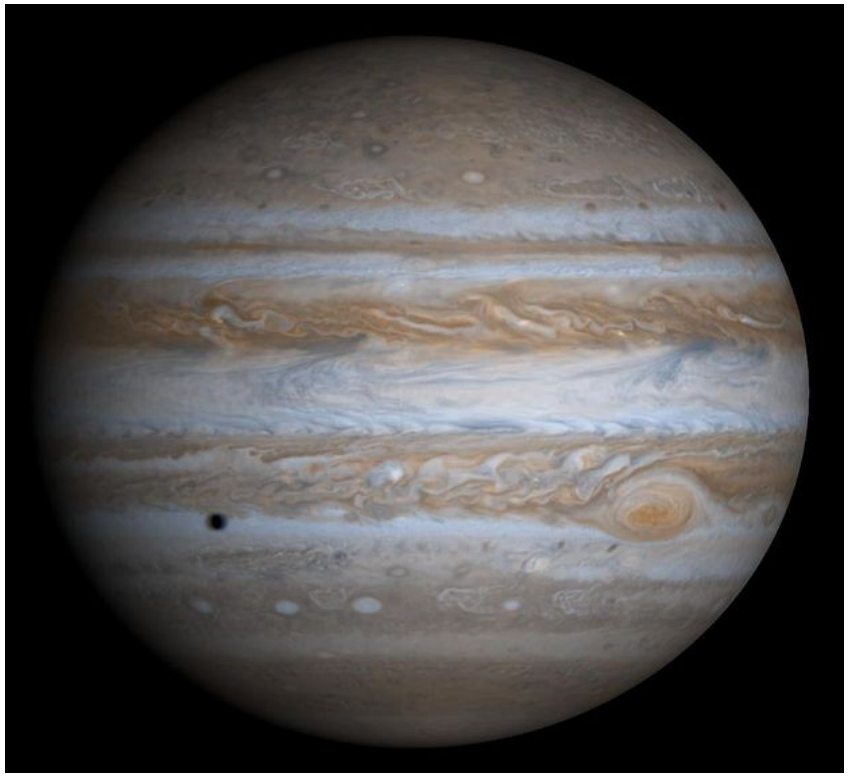
Radiative vs convective

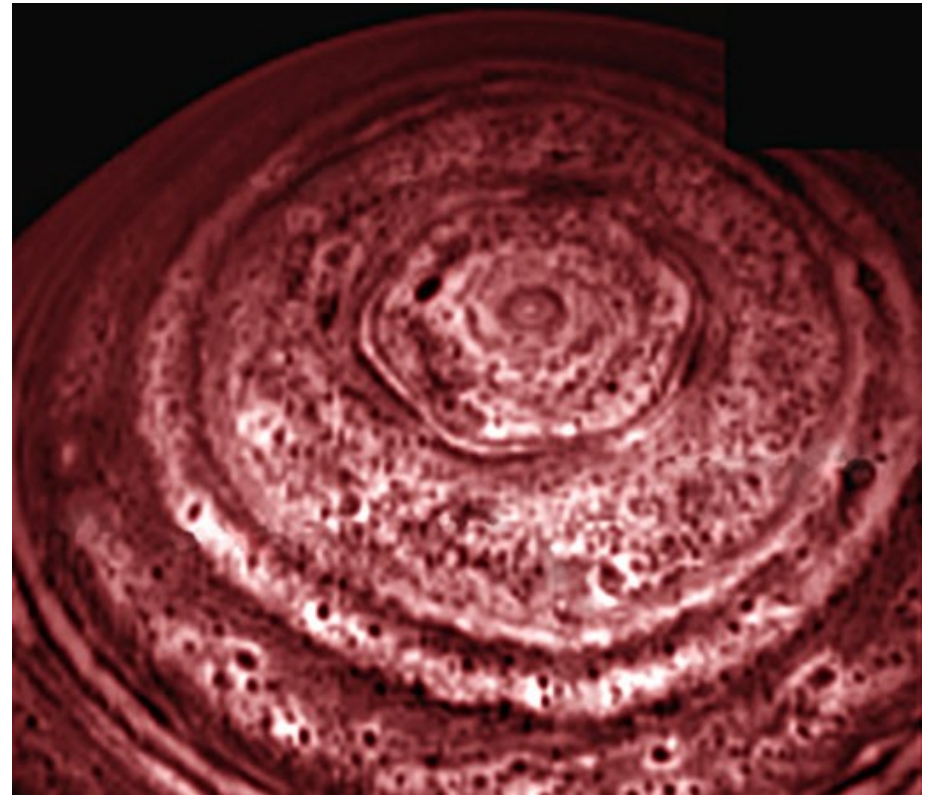


Fortney 2010

Hot Jupiters are heated from above !
→ Radiative atmosphere

Hot Jupiters vs Jupiter

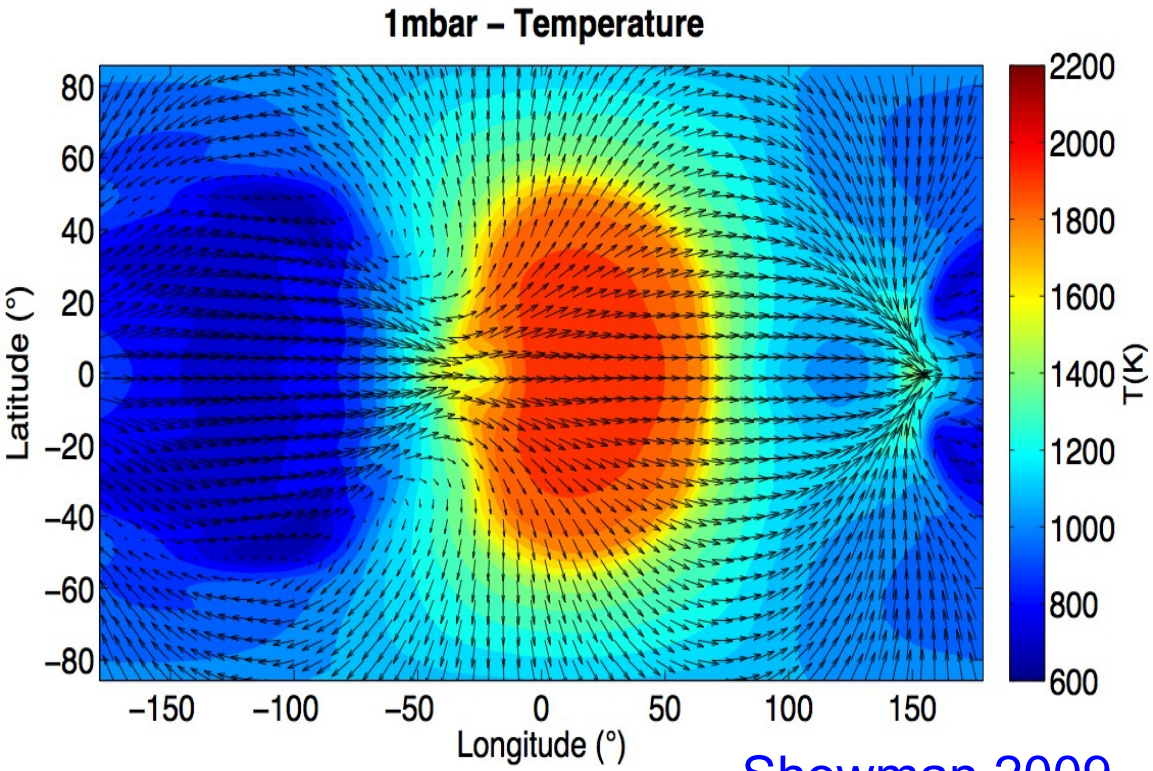




Rhines length - Balance between horizontal east/west velocities and coriolis gives the size of the jets.

Deformation radius - Balance between gravity wave propagation and Coriolis forces gives the size of the eddys.

Hot Jupiters vs Jupiter

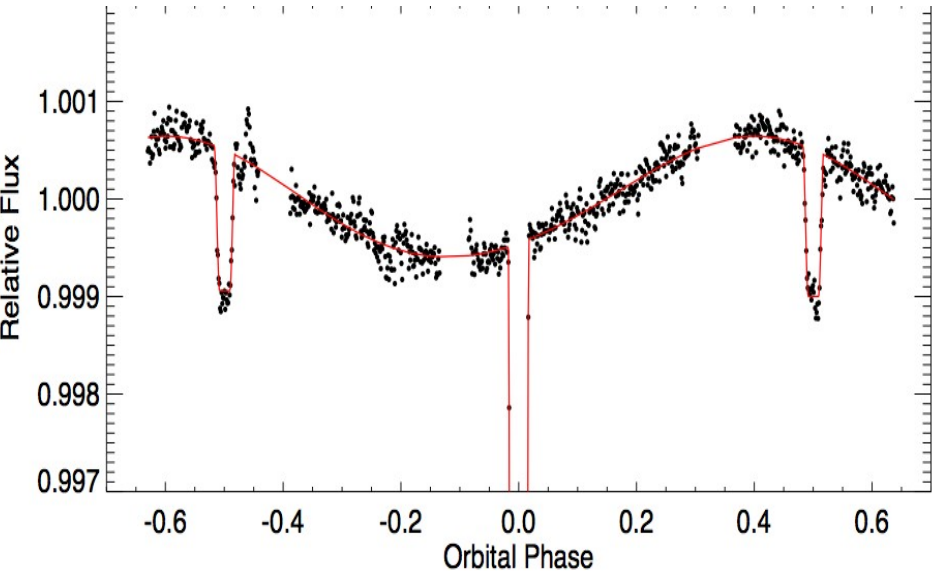


Showman 2009

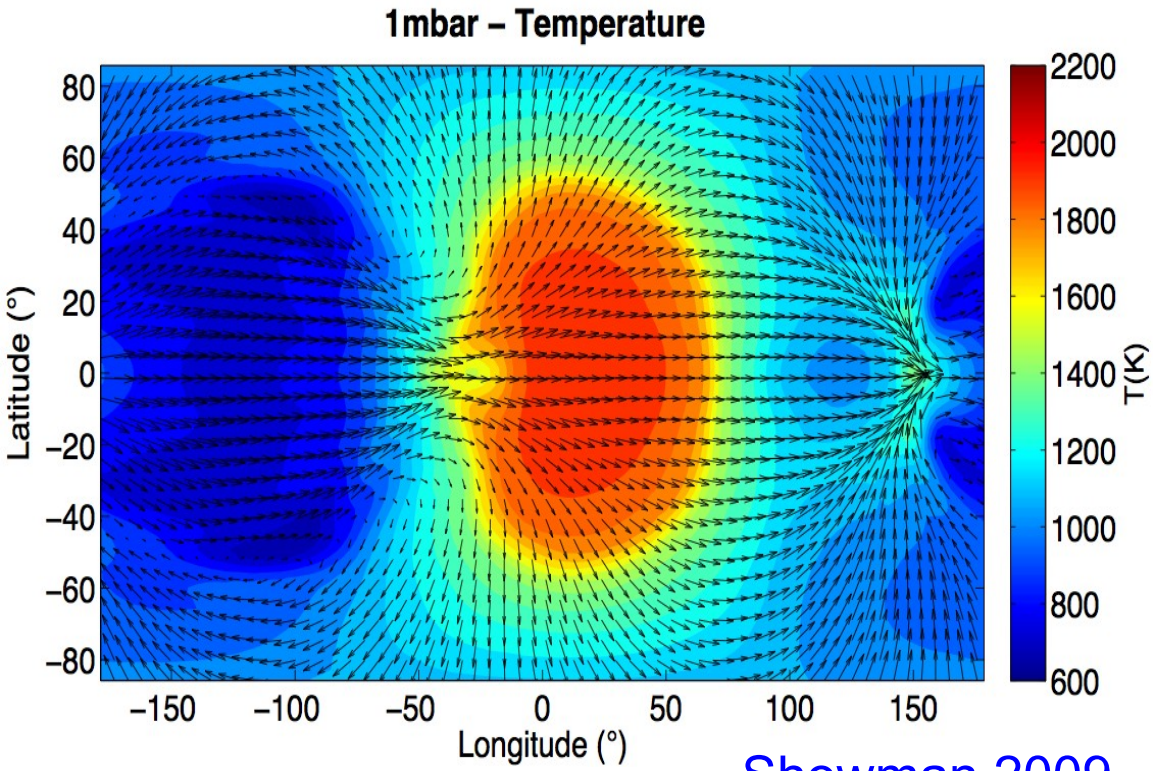
We are lucky : Rhines scale and deformation radius in hot Jupiters are comparable to the planetary radius !

Flow pattern are global, planetary scale.

Hot Jupiters atmospheric dynamics



Knutson 2012



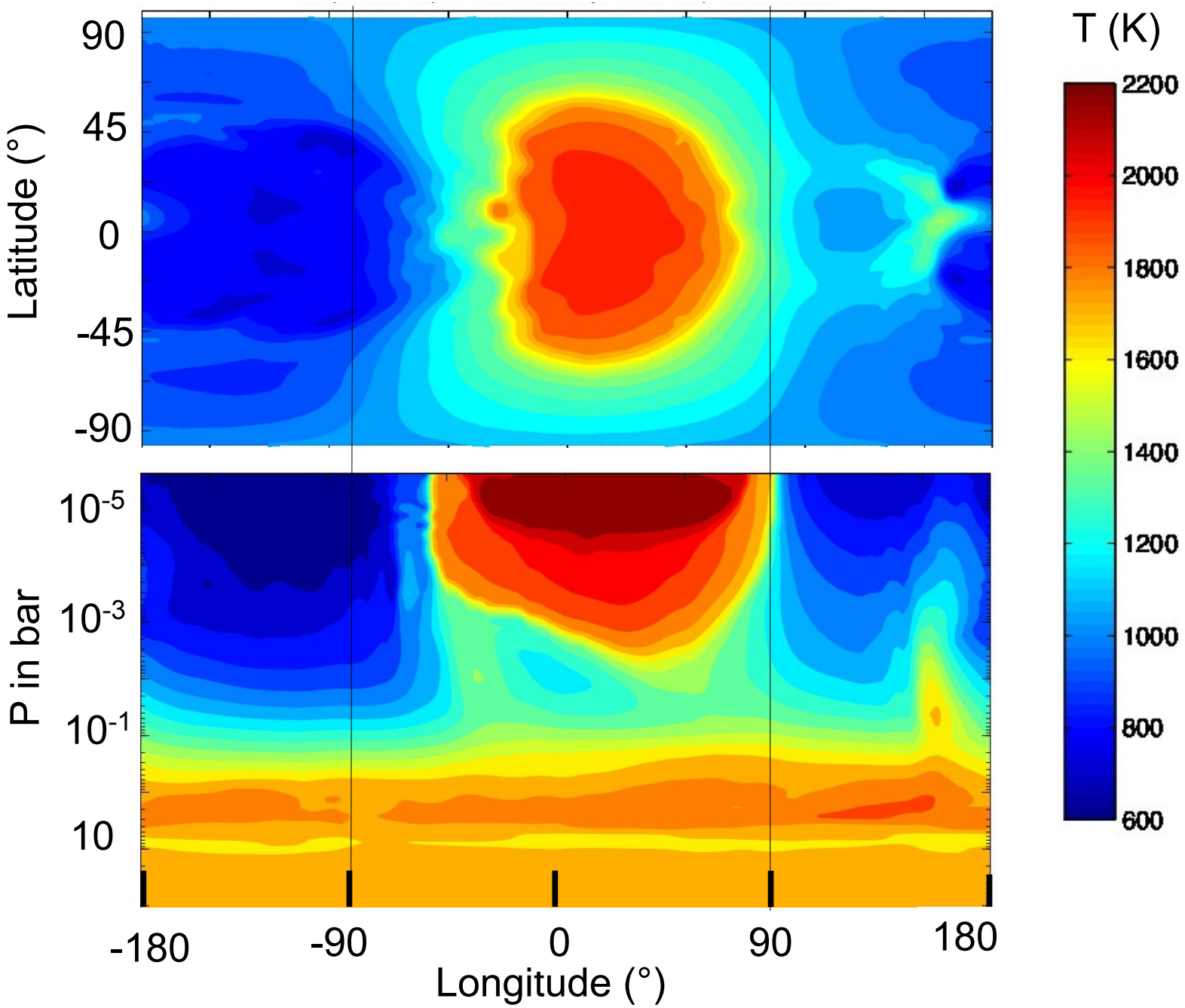
Showman 2009

Strong day/night contrast
→ Thermal light curve modulation

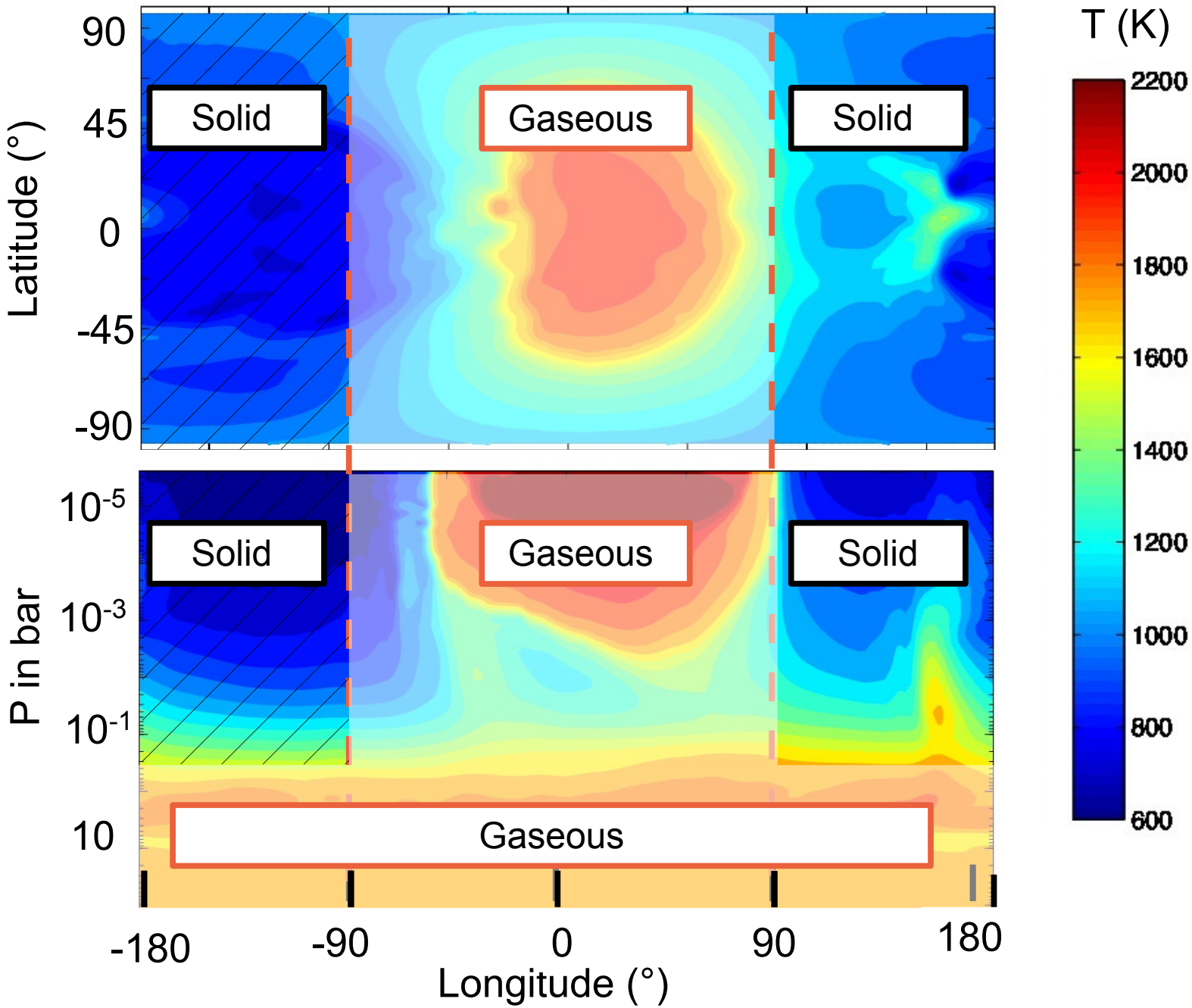
Strong eastward jet at the equator
→ Eastward shift of the hottest point.

Day to night circulation at the hight latitudes
→ Doppler shift in the lines ?
(see Snellen 2010)

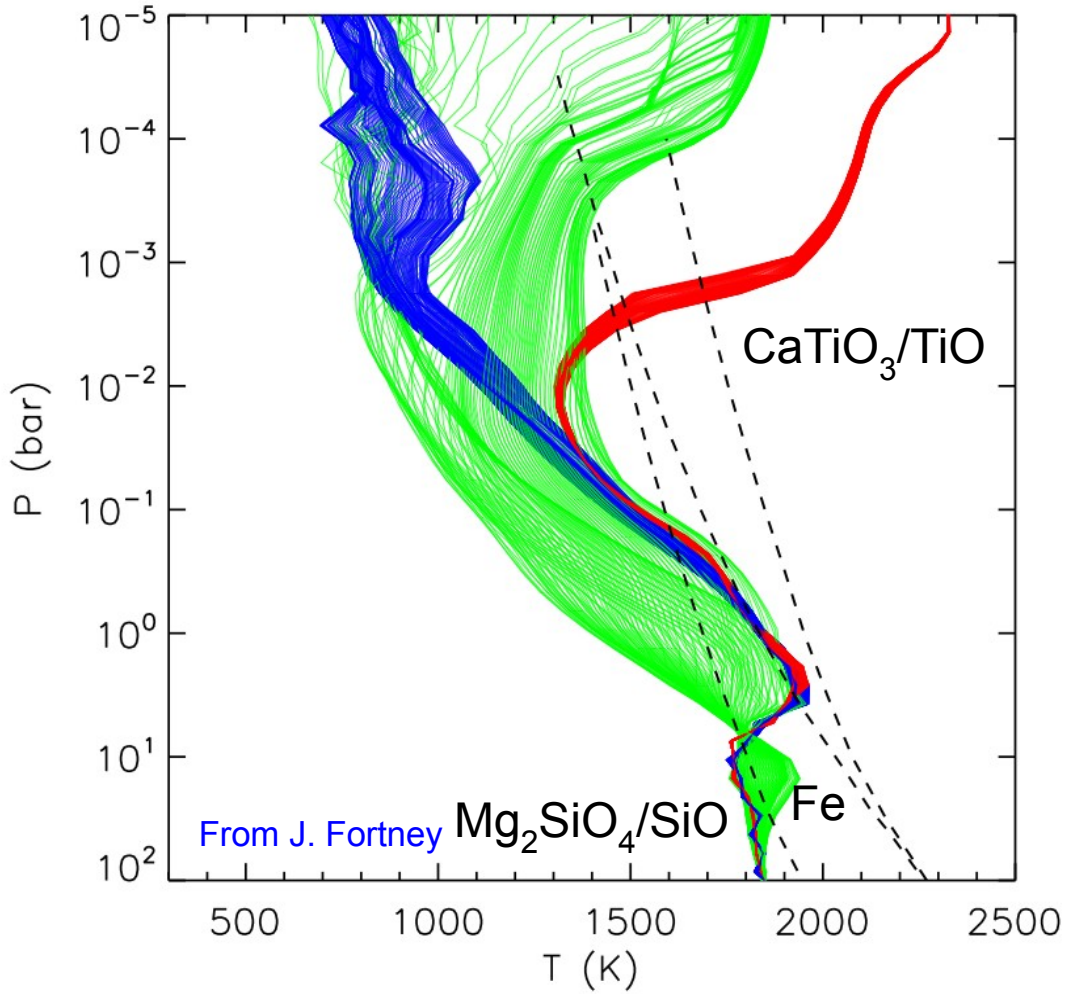
Temperature field of HD209458b



Temperature field of HD209458b



Condensates in HD209458b



Radiative atmosphere

- HD209458b as a proxy for hot-Jupiters
- Applicable to all the chemical species that condenses in the night side. Titanium oxyde or silicates clouds for example

Setup

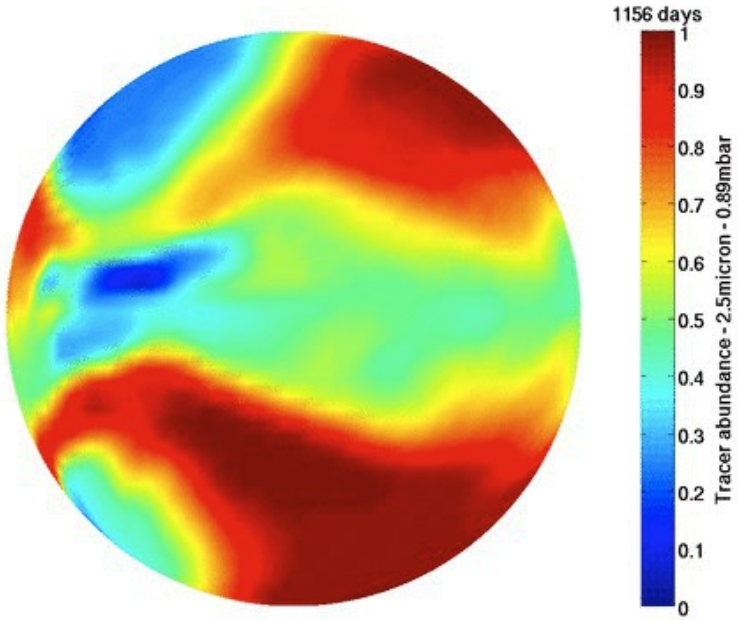
- We implement passive tracers in the MITgcm code
- In the dayside the tracers follow the fluid
- In the night side the tracers also have a settling velocity
- Settling velocity is given by the size of the particles
- The size is a parameter in the model (0.1/0.5/1/2.5/5/10μm)

→ HD209458b as a proxy for hot-Jupiters

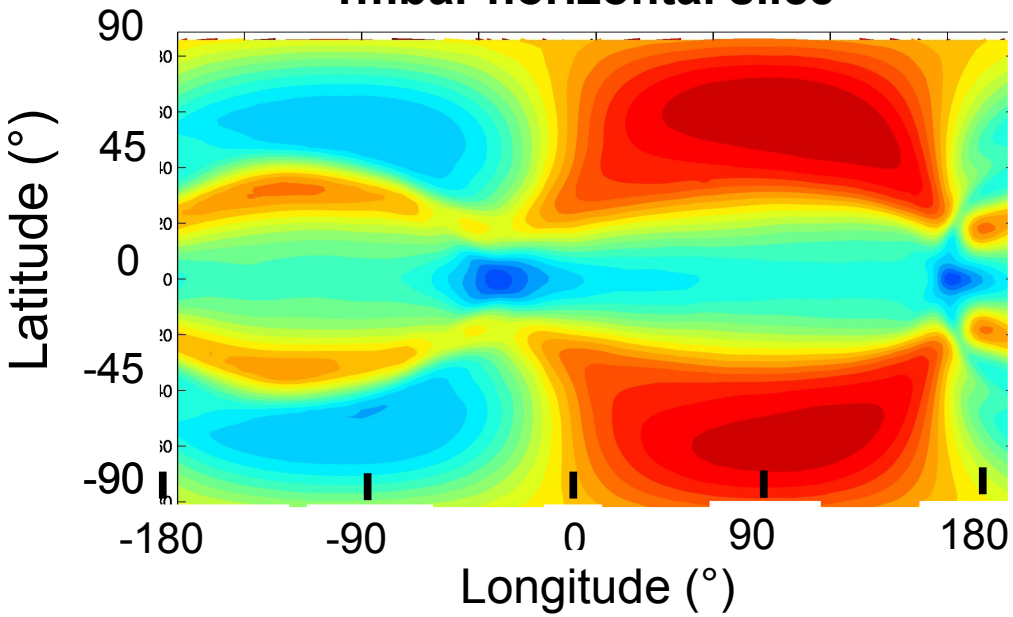
→ TiO as a proxy for species that condense in the night side

Results : spatial variability - 2.5µm case

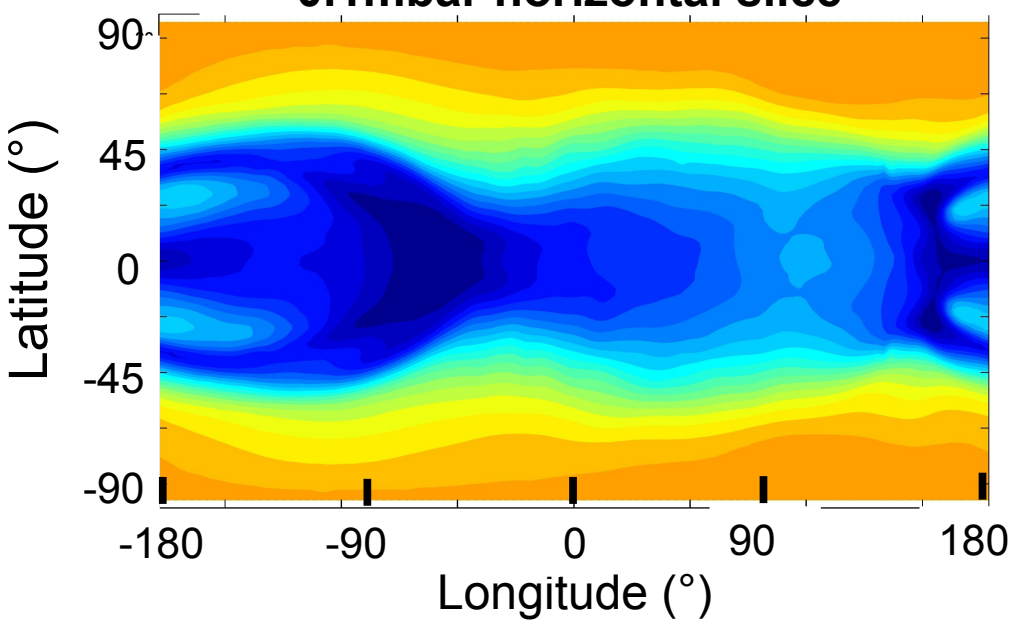
1mbar dayside snapshot

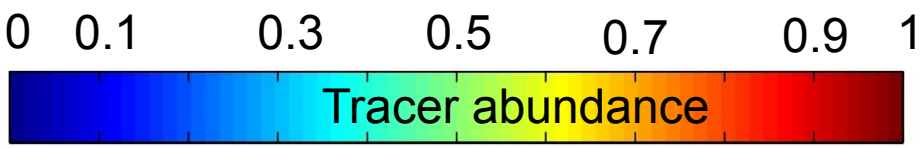


1mbar horizontal slice

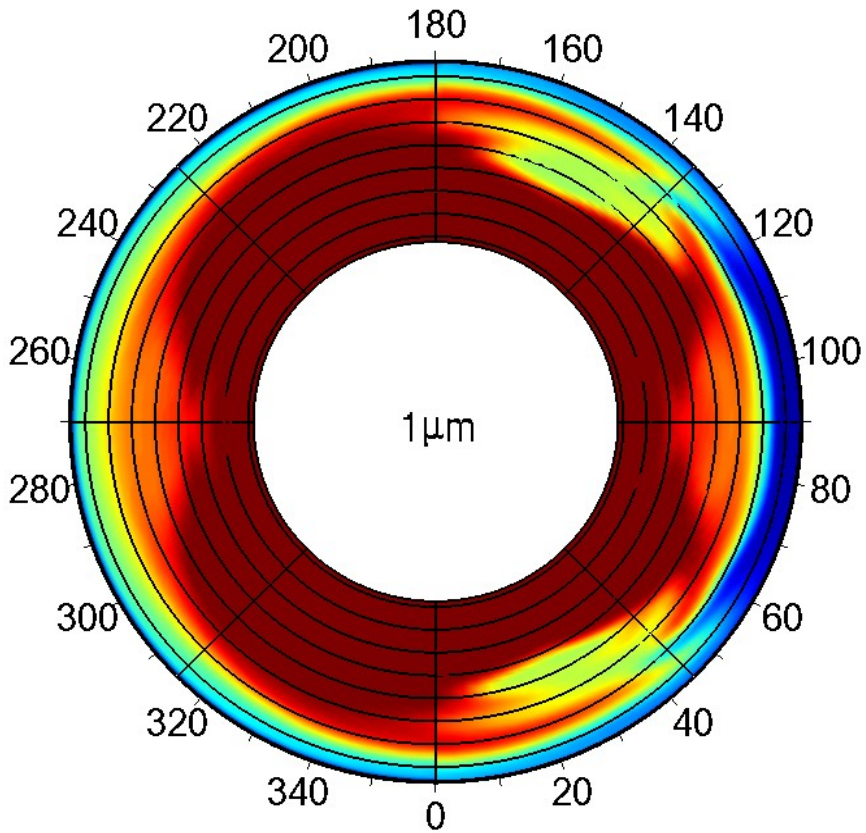


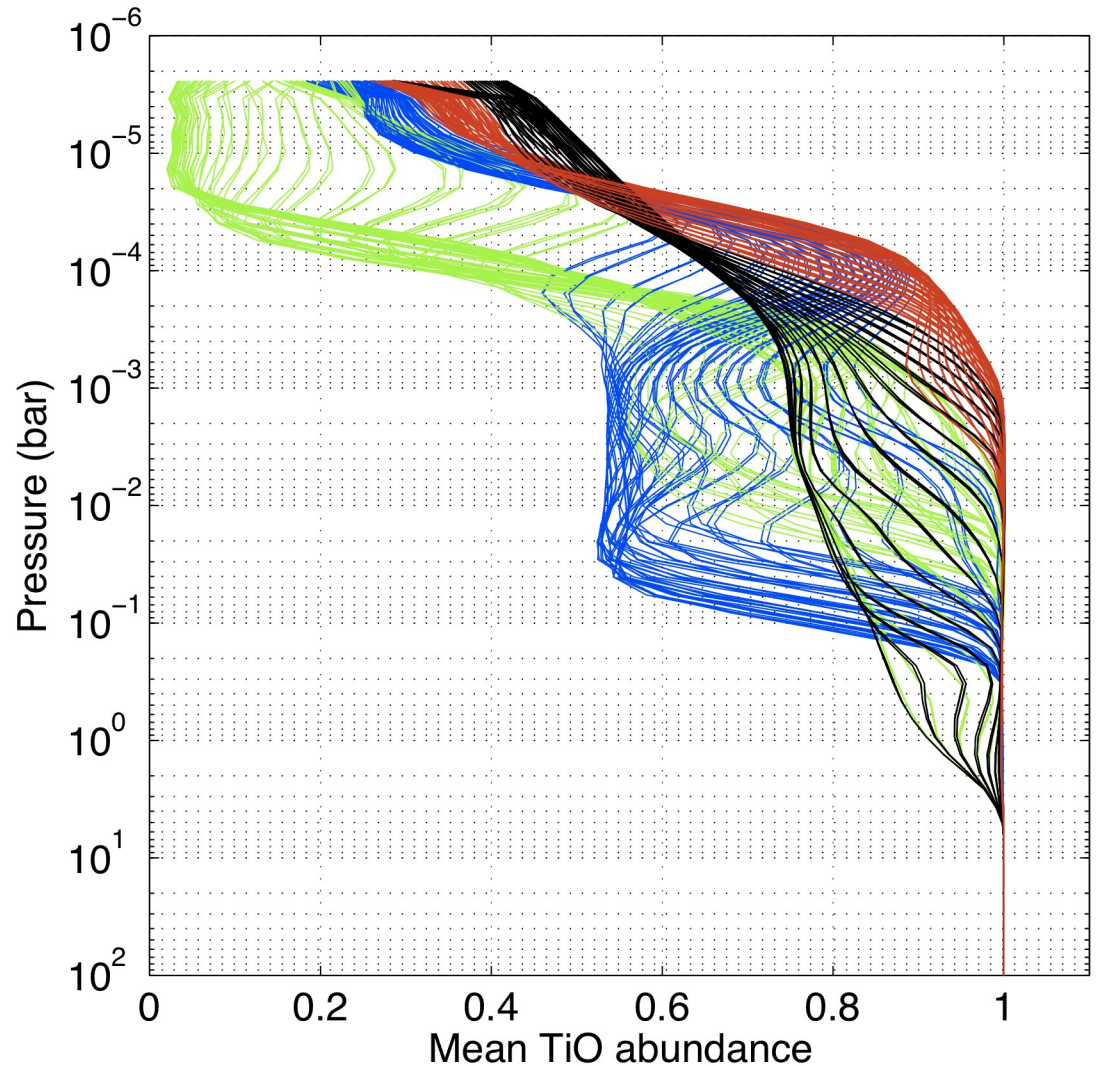
0.1mbar horizontal slice



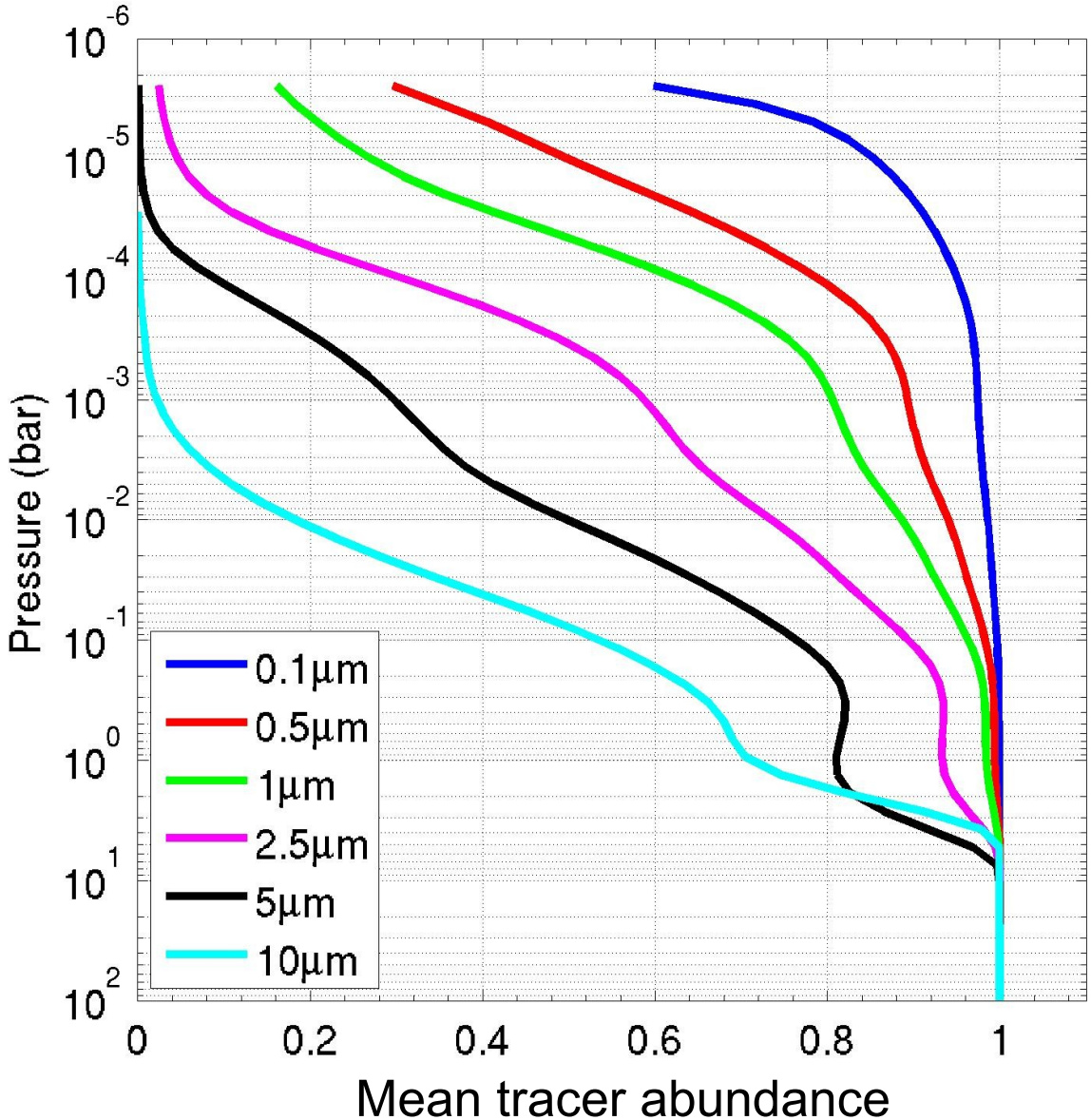


Results : Limb profiles 1μm case



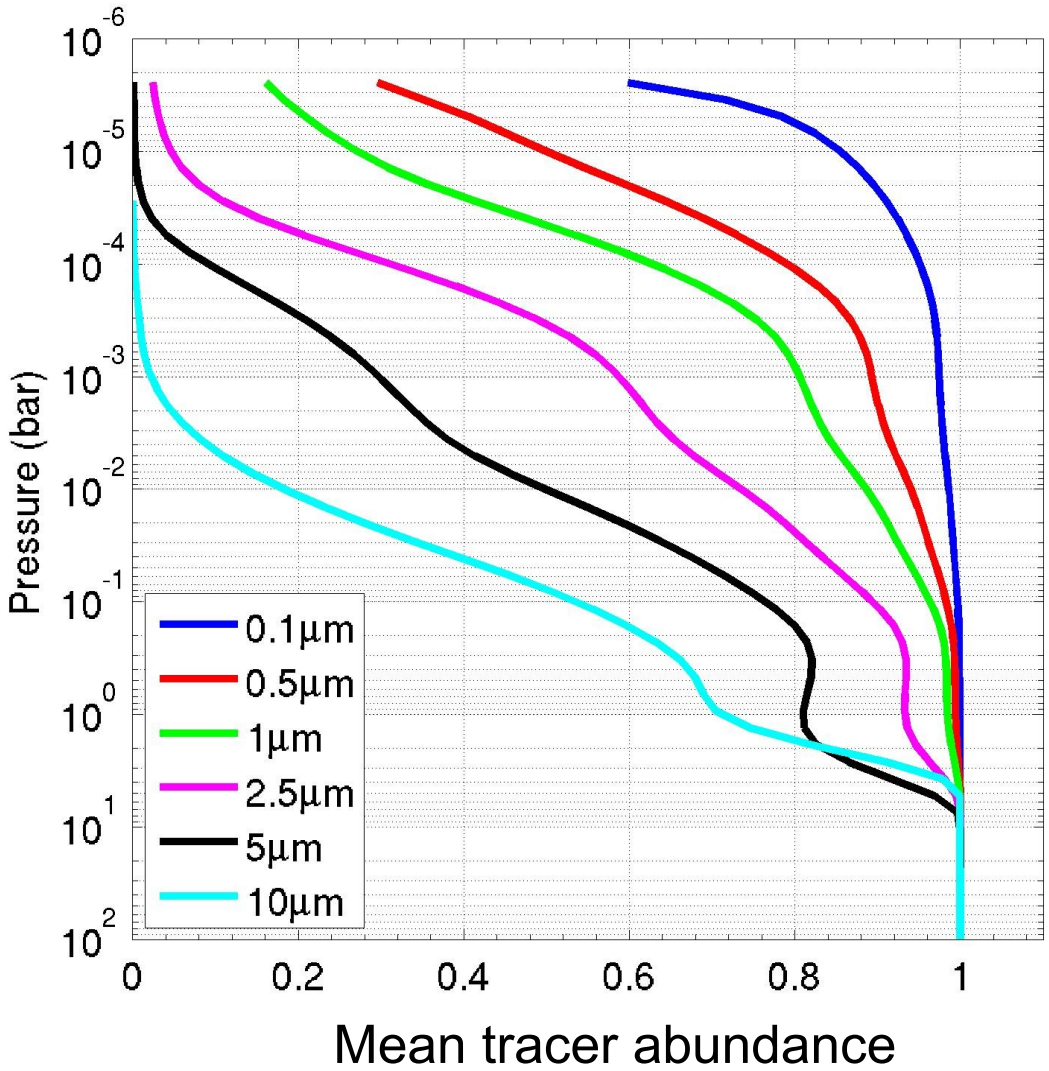


Results : Averaged tracer abundance



tracer abundance is not zero → vertical mixing happens

Results : Averaged tracer abundance



How can we quantify the amount of mixing ?

$$\frac{\partial \chi}{\partial t} - \frac{1}{\rho}\frac{\partial}{\partial z}\left(\rho K_z \frac{\partial \chi}{\partial z}\right) = \frac{1}{\rho}\frac{\partial \rho V_s \chi}{\partial z}$$

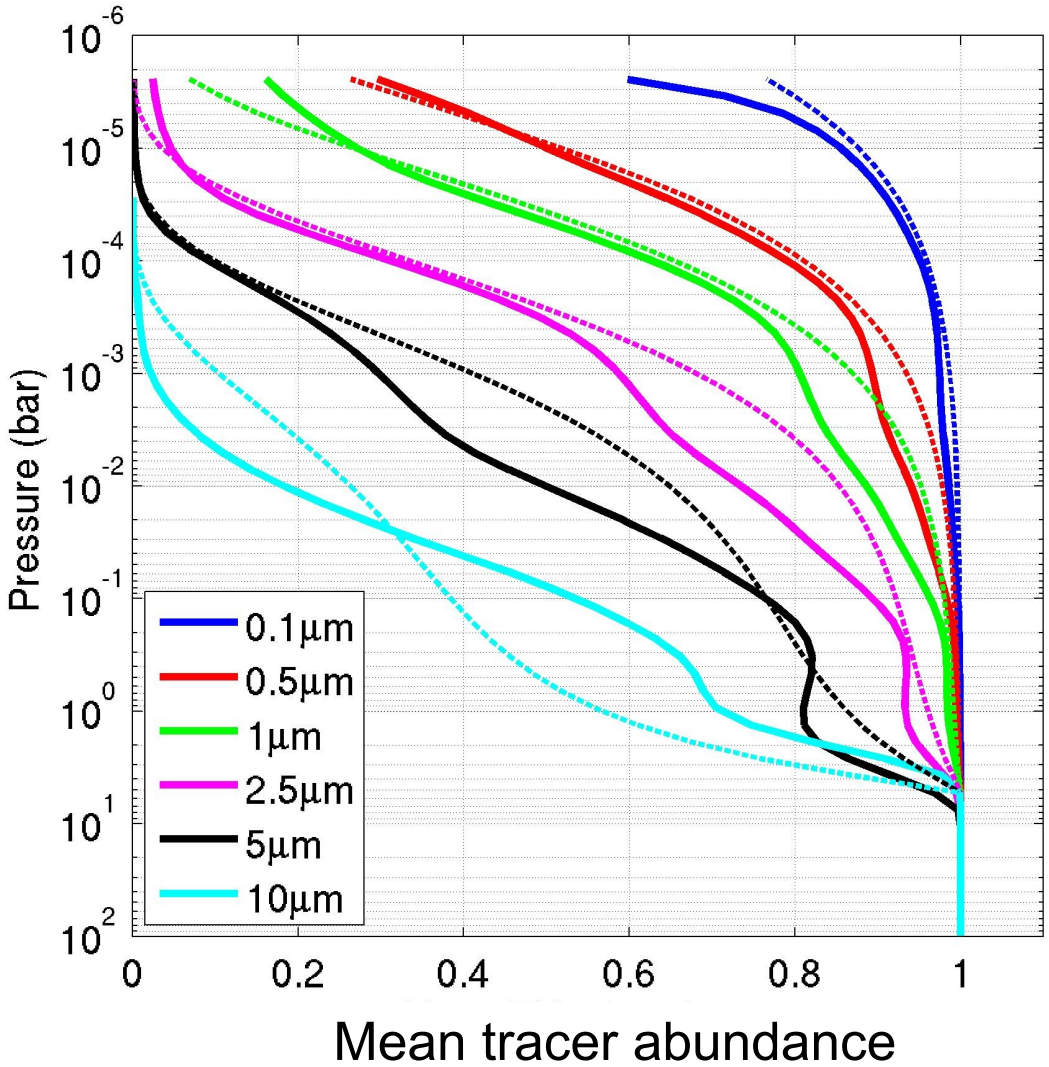
Steady state + horizontal average

$$\frac{-1}{\rho}\frac{\partial}{\partial z}\left(\rho K_z \frac{\partial \chi}{\partial z}\right) = \frac{1}{2}\frac{1}{\rho}\frac{\partial \rho V_s \chi}{\partial z}$$

Integrating one time

$$K_z \frac{\partial \chi}{\partial z} = \frac{1}{2} V_s \chi$$

Results : Estimating Kz

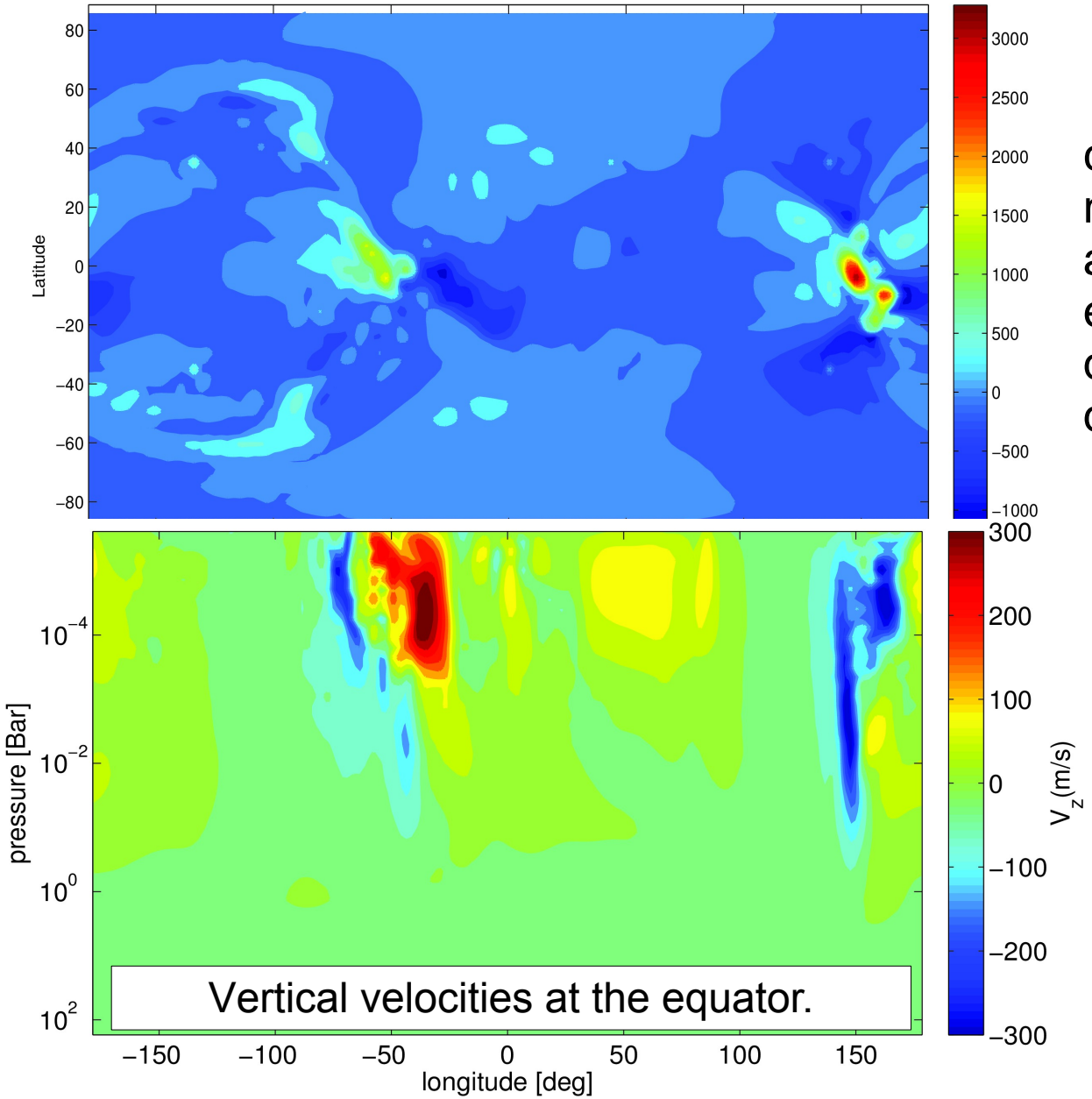


$$K_z = \frac{5 \times 10^4}{\sqrt{P_{\mathrm{bar}}}} \mathrm{m}^2/\mathrm{s}$$

$$< \chi > = \chi_0 e^{\frac{\tau_{d_0}}{\tau_s} \frac{1}{\sqrt{P_0}} \left(\sqrt{P} - \sqrt{P_1} \right)} e^{-\frac{\tau_{d_0}}{\tau_s} \frac{1}{\sqrt{P_0}} \frac{1.617 k_B T}{\sqrt{2} \pi a d^2} \left(\frac{1}{\sqrt{P}} - \frac{1}{\sqrt{P_1}} \right)}$$

Results : Geometry of the mixing

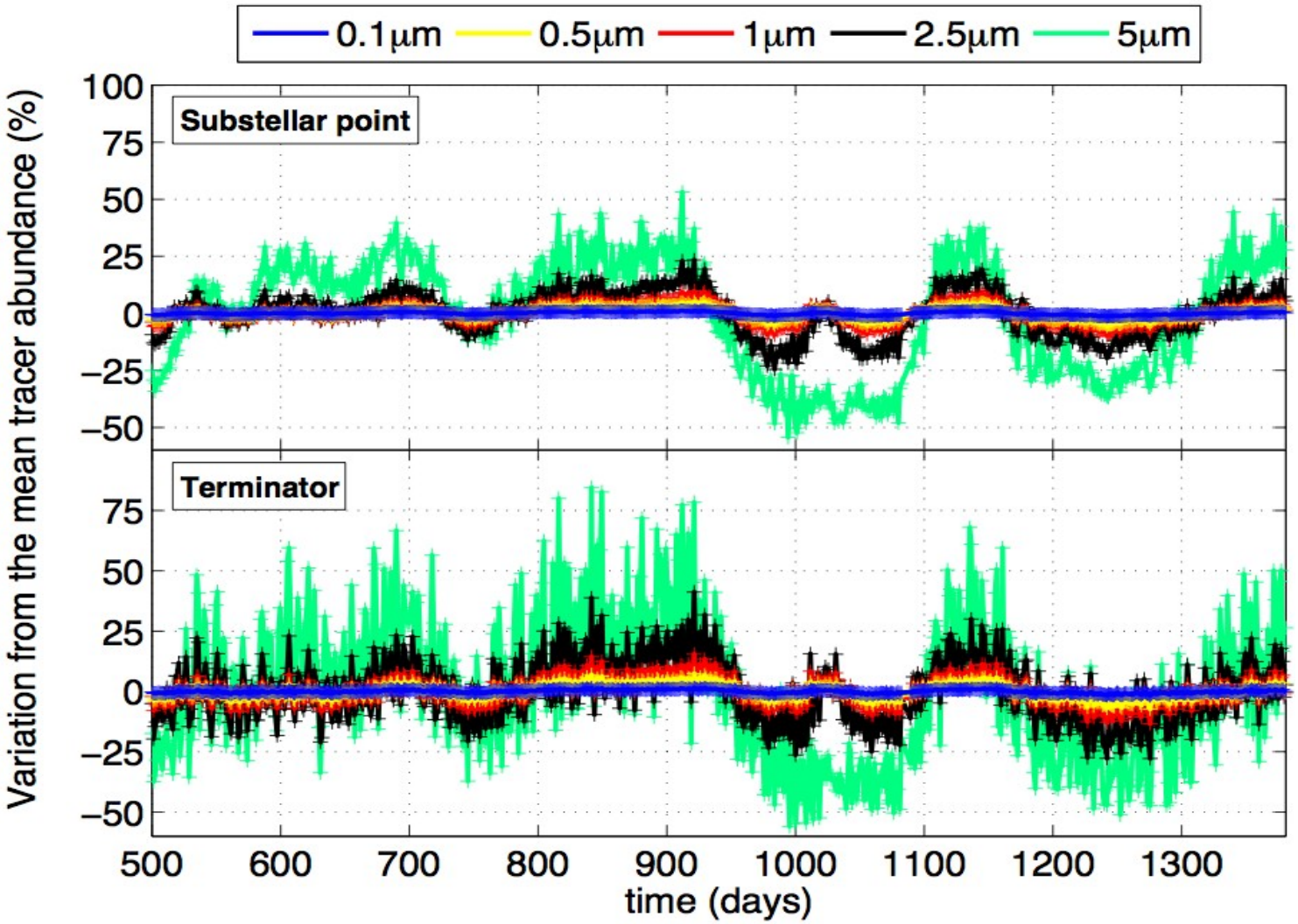
Contribution to the upward mixing



$\frac{\rho V_z(\chi - \langle\chi\rangle)}{\langle\rho V_z \chi\rangle}$ is the local contribution to the upward mixing. Positive values are either an upward flux of material enhanced in tracer or a downward flux of material depleted in tracer.

→ Mixing seems to happen principally in a few small regions where the vertical velocities are big.

Results : time variability



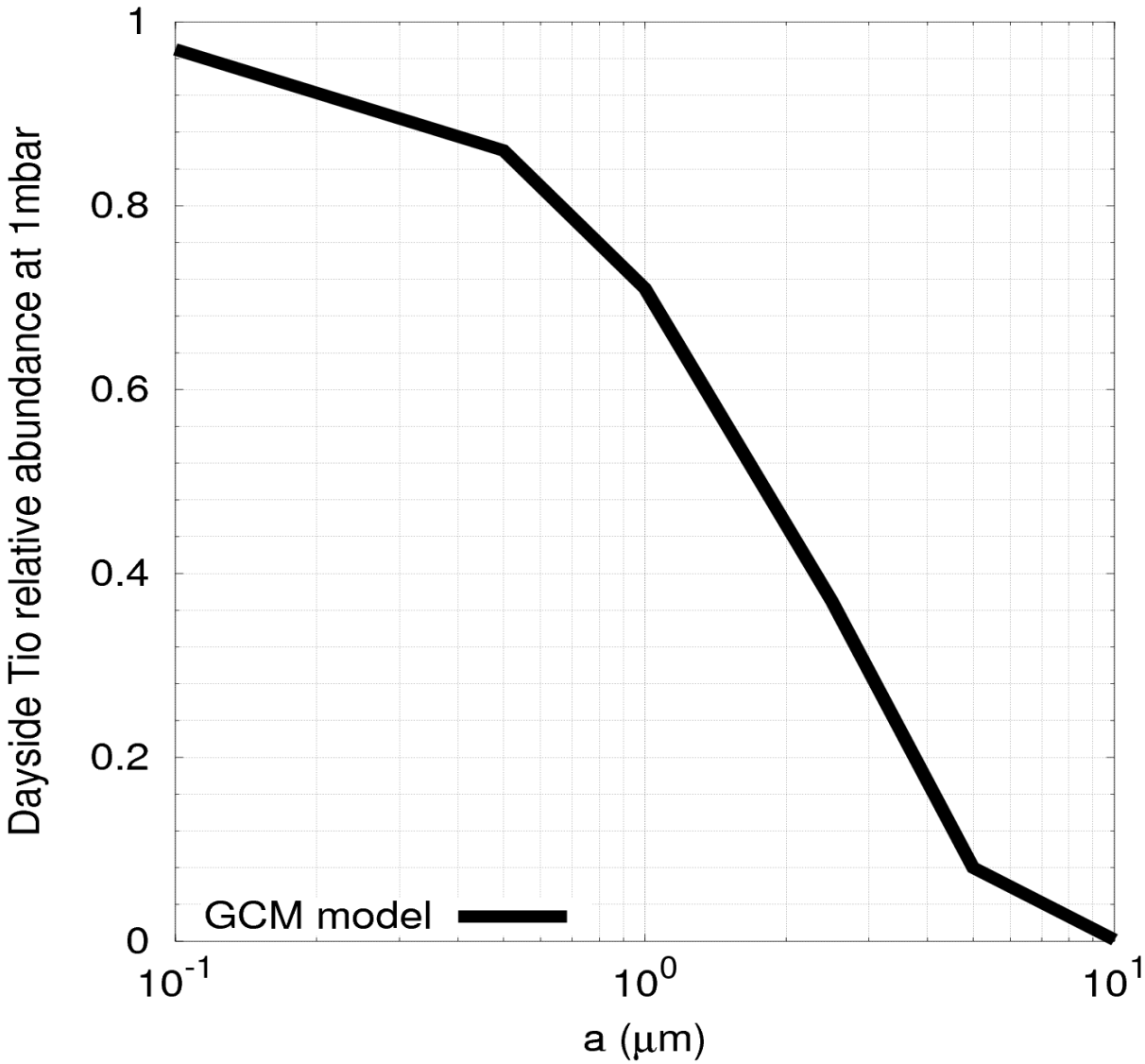
Up to 60% variability of the tracer abundance around the substellar point and the terminator in timescales of hundred of days but only 1 to 5% for sub-micrometer condensates.

→ 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.

Can TiO produce the observed stratosphere ?

Dayside abundance of TiO
at the equator at 1mbar



For condensates greater than a few micrometers, the observed atmosphere should be depleted in TiO.

Conclusions

→ Day-night cold trap is strong enough to deplete species that condense in particles **bigger than a few micrometers** in the night side.

→ The repartition of condensable species can be **inhomogeneous** over the planet and **temporally variable**. In particular, in the dayside, equatorial band is expected to me more depleted than the poles.

→ **Large scale circulation in hot-Jupiters creates mixing**. However, this mixing seems to happen principally in a few localized positions.

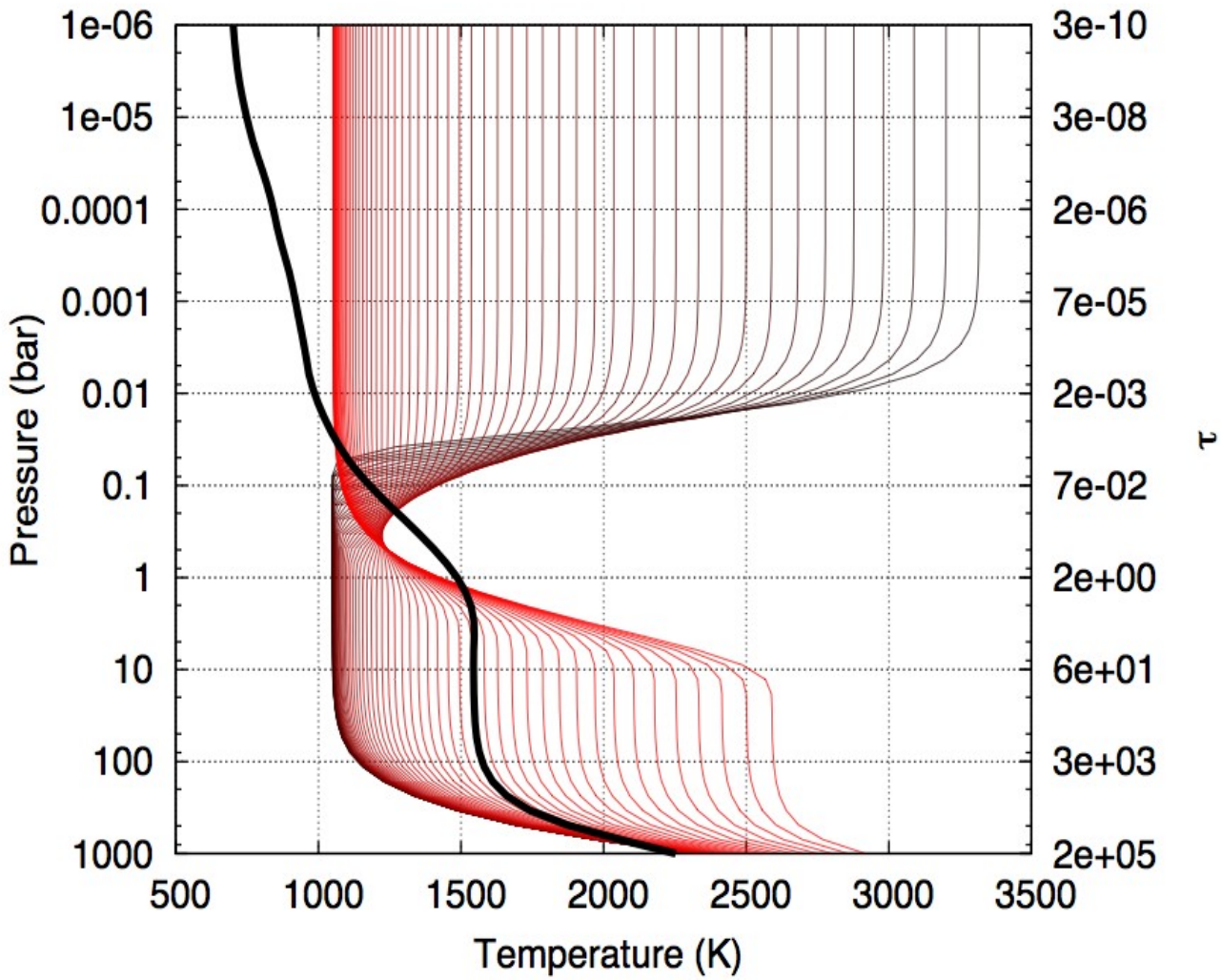
→ Although the atmosphere of Hot-Jupiters are radiative, they can be strongly mixed.

$$K_{zz} = \frac{5\times10^4}{\sqrt{P_{bar}}}\ \mathrm{m}^2/\mathrm{s}$$

$$K_{zz} = \frac{5\times10^8}{\sqrt{P_{bar}}}\ \mathrm{cm}^2/\mathrm{s}$$

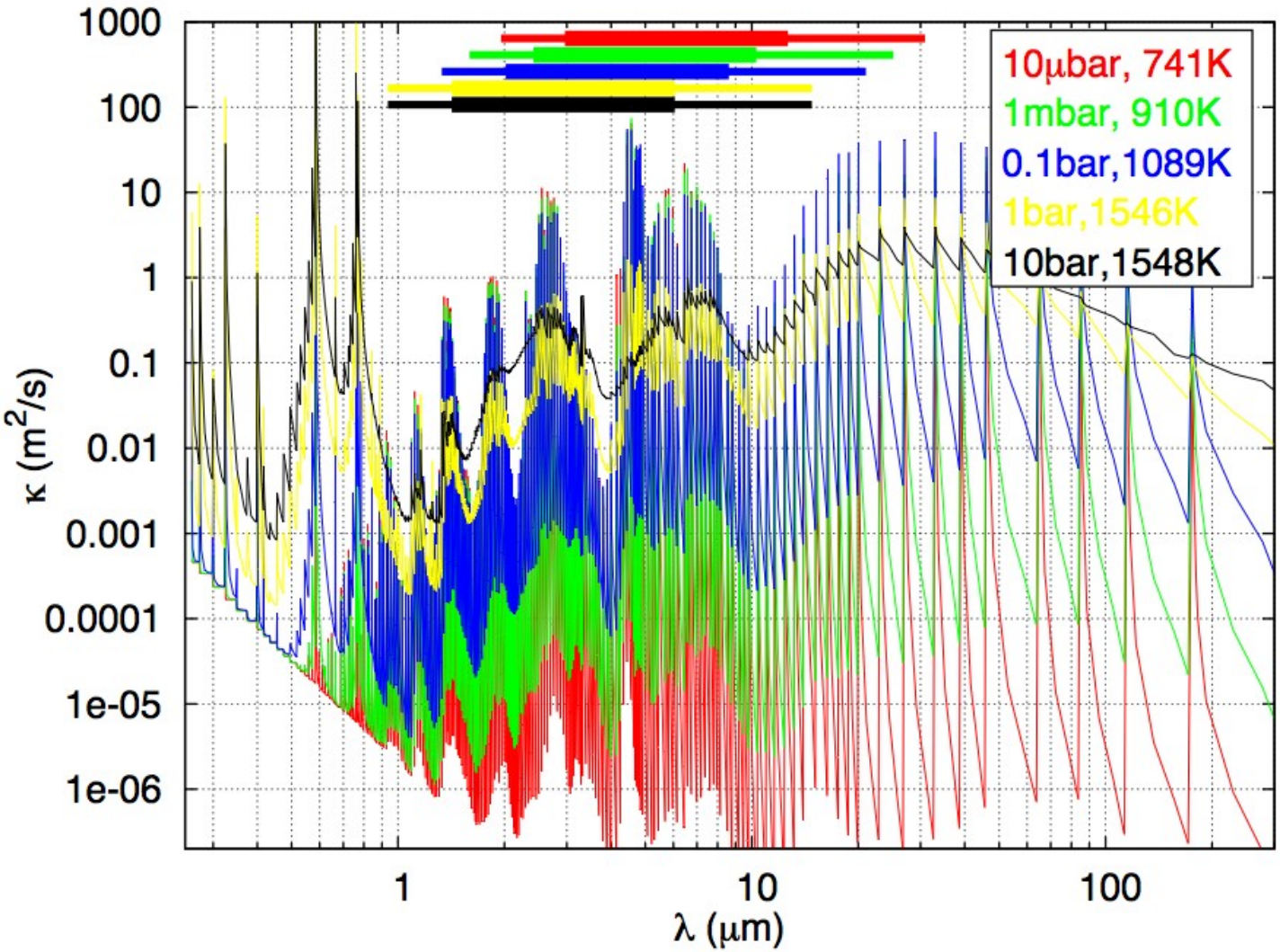
Infrared cooling of the upper atmosphere of hot planets : an analytical model

Limitation of the semi-grey models



→ The functional form of the semi-grey profile is not enough to get the cool temperatures of the upper atmosphere.

Opacities in hot-Jupiters atmospheres



Lines :

$$\frac{1}{B_\nu}\frac{\partial B_\nu}{\partial \nu} \ll \frac{1}{\kappa_\nu}\frac{\partial \kappa_\nu}{\partial \nu}$$

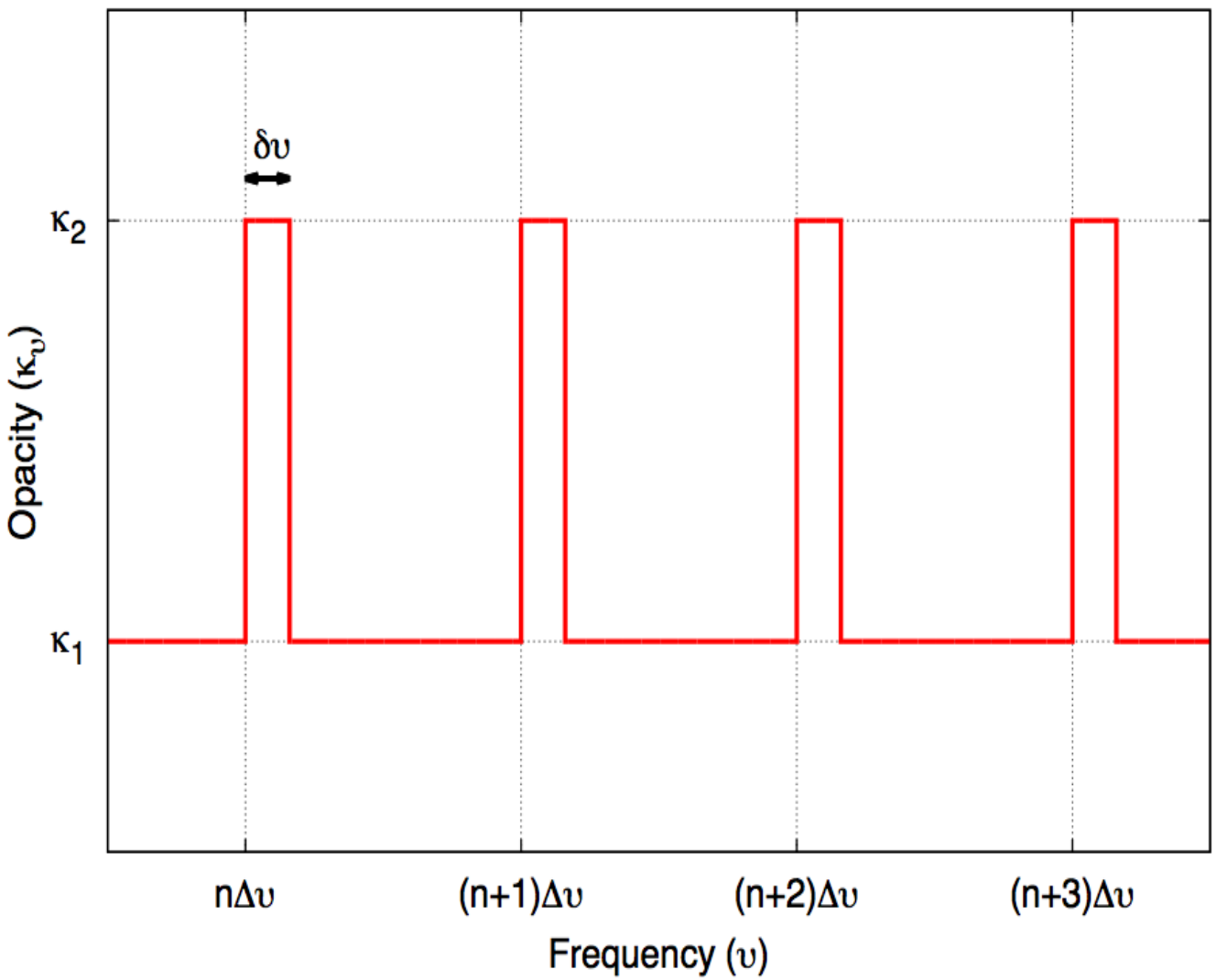
Bands :

$$\frac{1}{B_\nu}\frac{\partial B_\nu}{\partial \nu} \sim \frac{1}{\kappa_\nu}\frac{\partial \kappa_\nu}{\partial \nu}$$

→ Line dominated opacities at low pressures

→ Band dominated opacities at high pressures

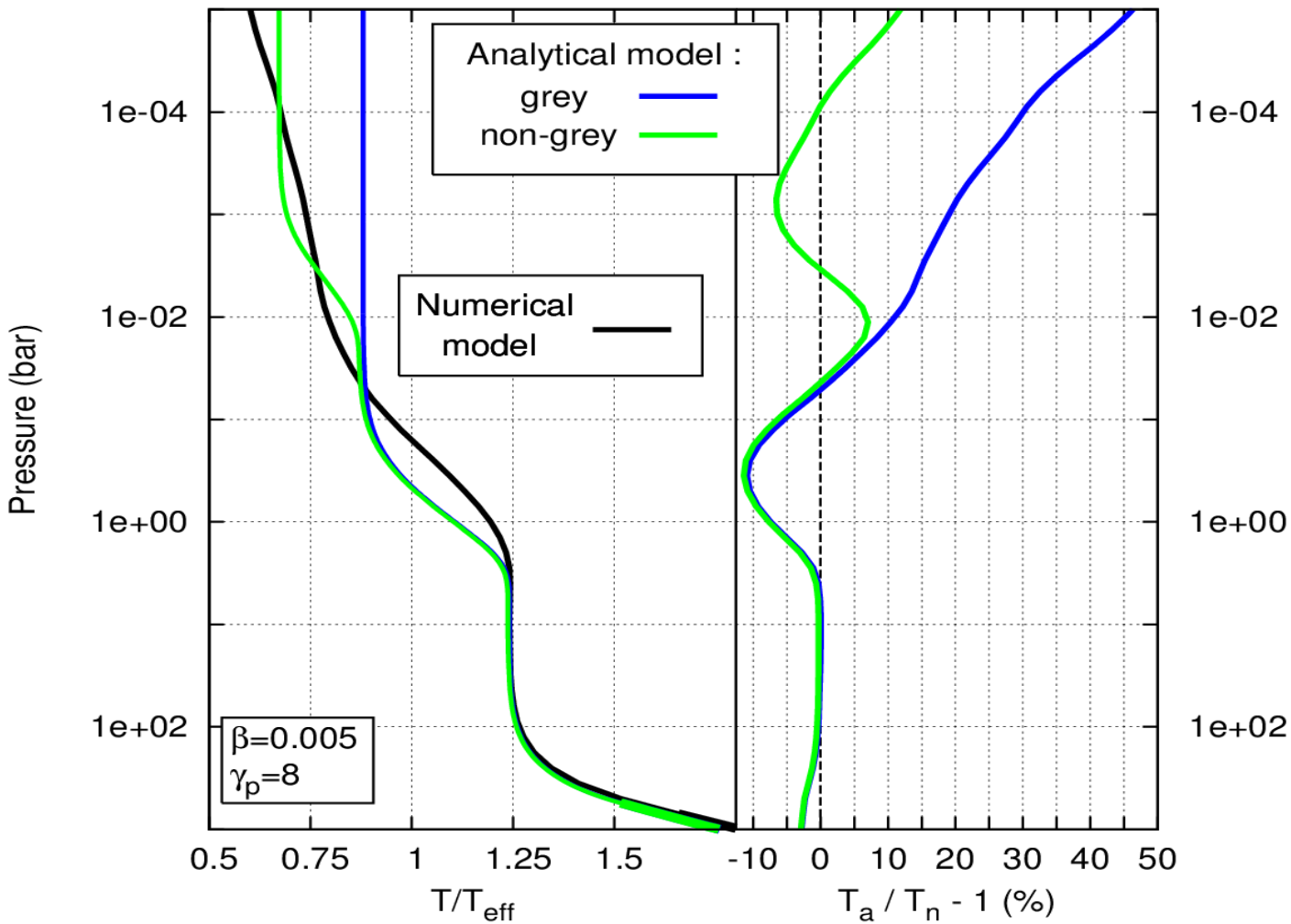
Simplifying the opacities



→ Comb like opacity such that B_ν is constant over $\delta\nu$

We only keep the lines !

Results : fitting a numerical profile



We have an analytical – self consistent model of line opacities that takes into account the cooling of the upper atmosphere