What controls the temperature of planetary atmospheres?

Jérémy Leconte


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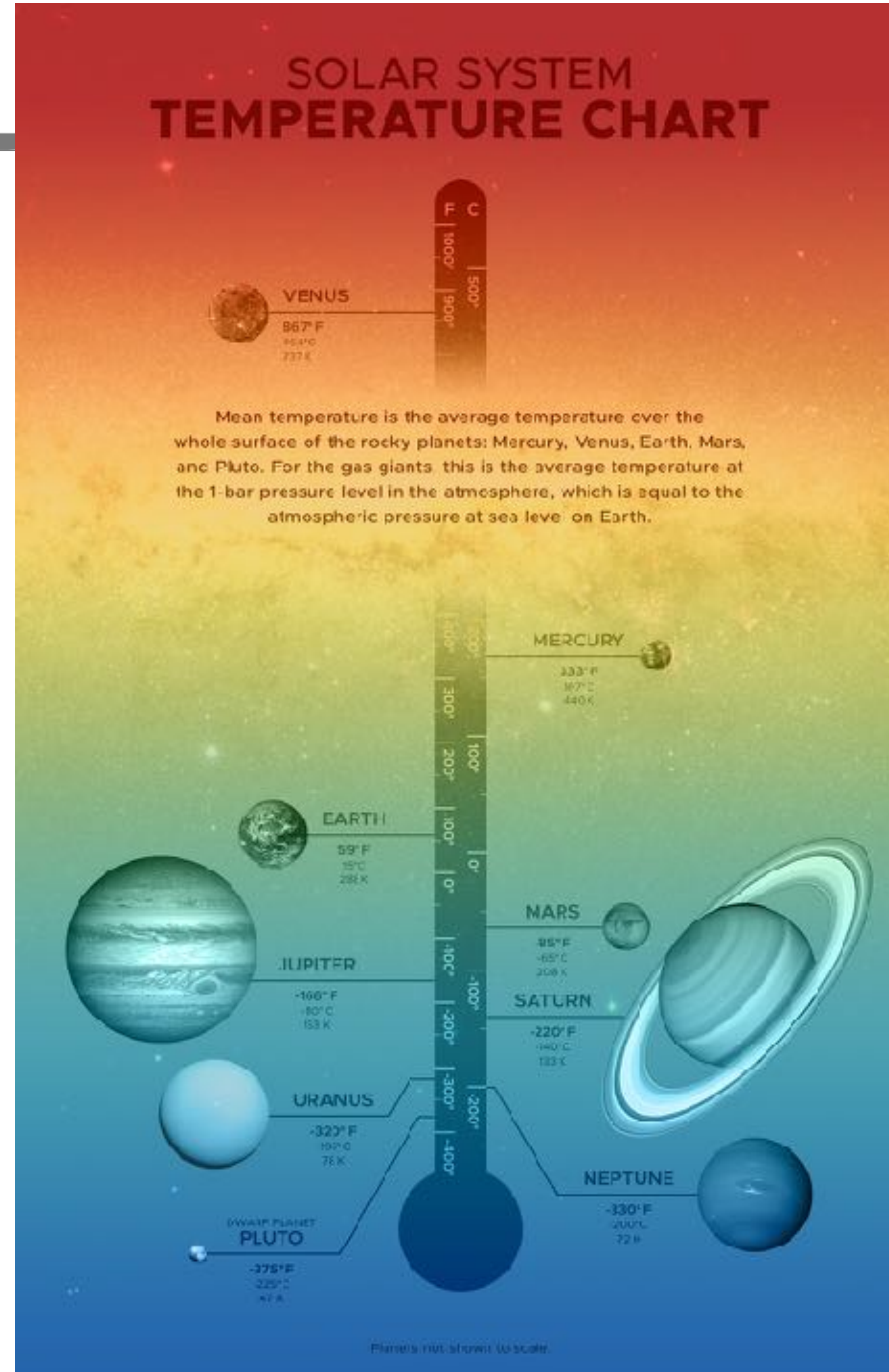
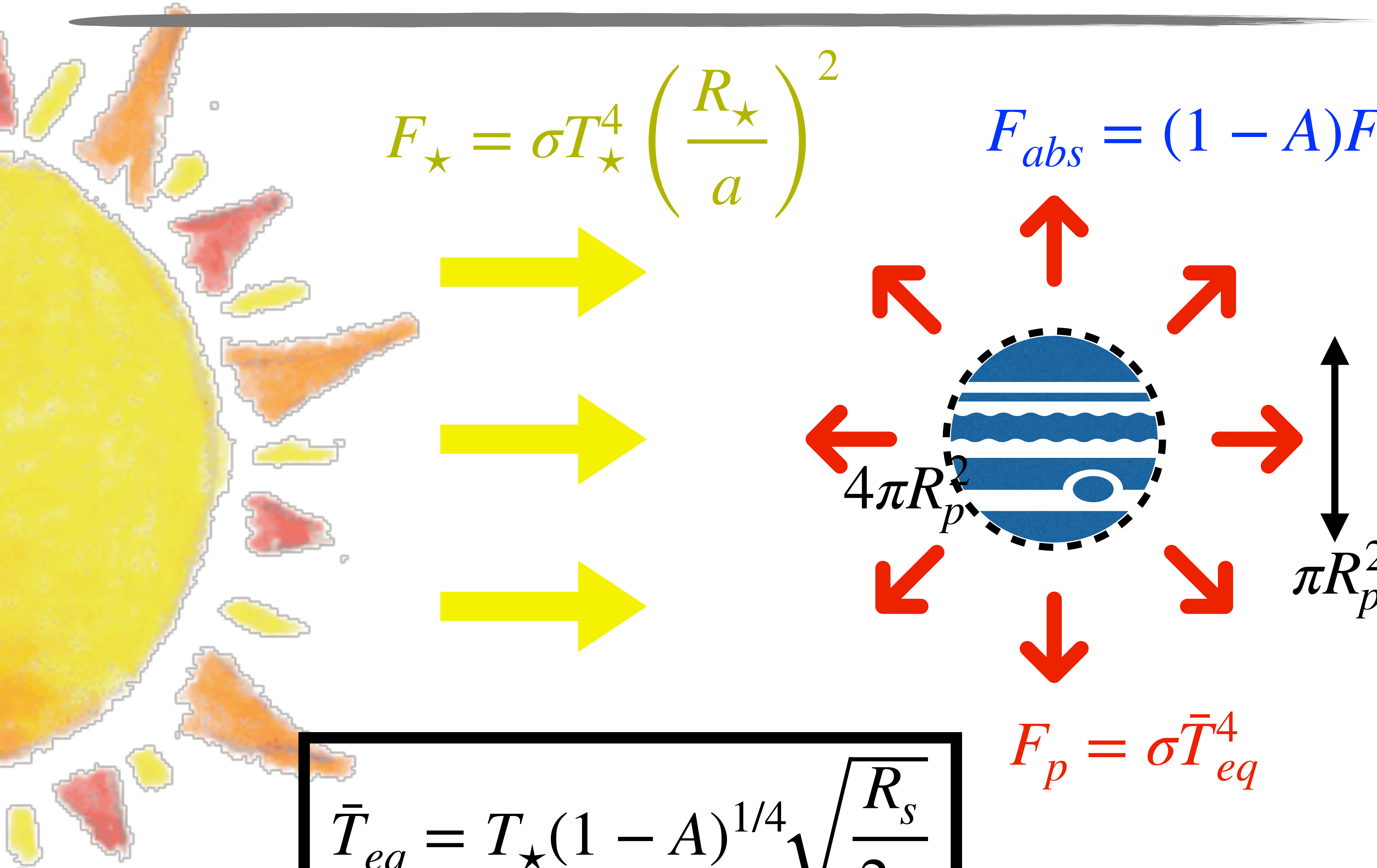
Zeroth order : Insolation



Zeroth order : Equilibrium temperature

$$F_\star = \sigma T_\star^4 \left(\frac{R_\star}{a}\right)^2$$

$$F_{abs} = (1 - A) F_\star$$



$$F_p = \sigma \bar{T}_{eq}^4$$

$$\bar{T}_{eq} = T_\star (1 - A)^{1/4} \sqrt{\frac{R_s}{2a}}$$

Is the equilibrium temperature equal to the average temperature?

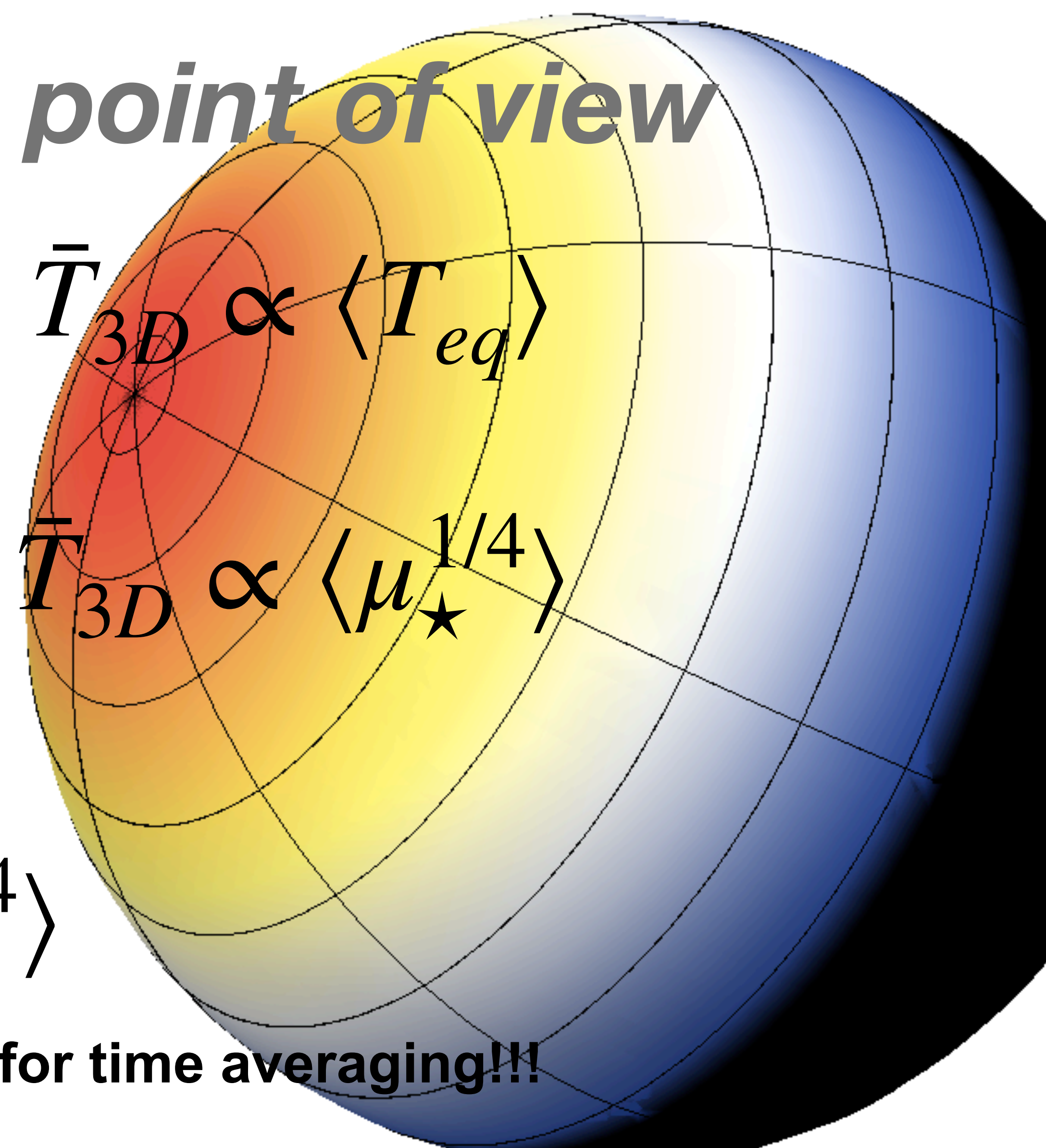
Will the average temperature be higher or lower than the equilibrium temperature?

Average temperature : systematic biases

$$\sigma T_{eq} = \left((1-A)F_\star \mu_\star\right)^{1/4}$$

$$\sigma \bar{T}_{eq} = \langle (1-A)F_\star \mu_\star \rangle^{1/4}$$

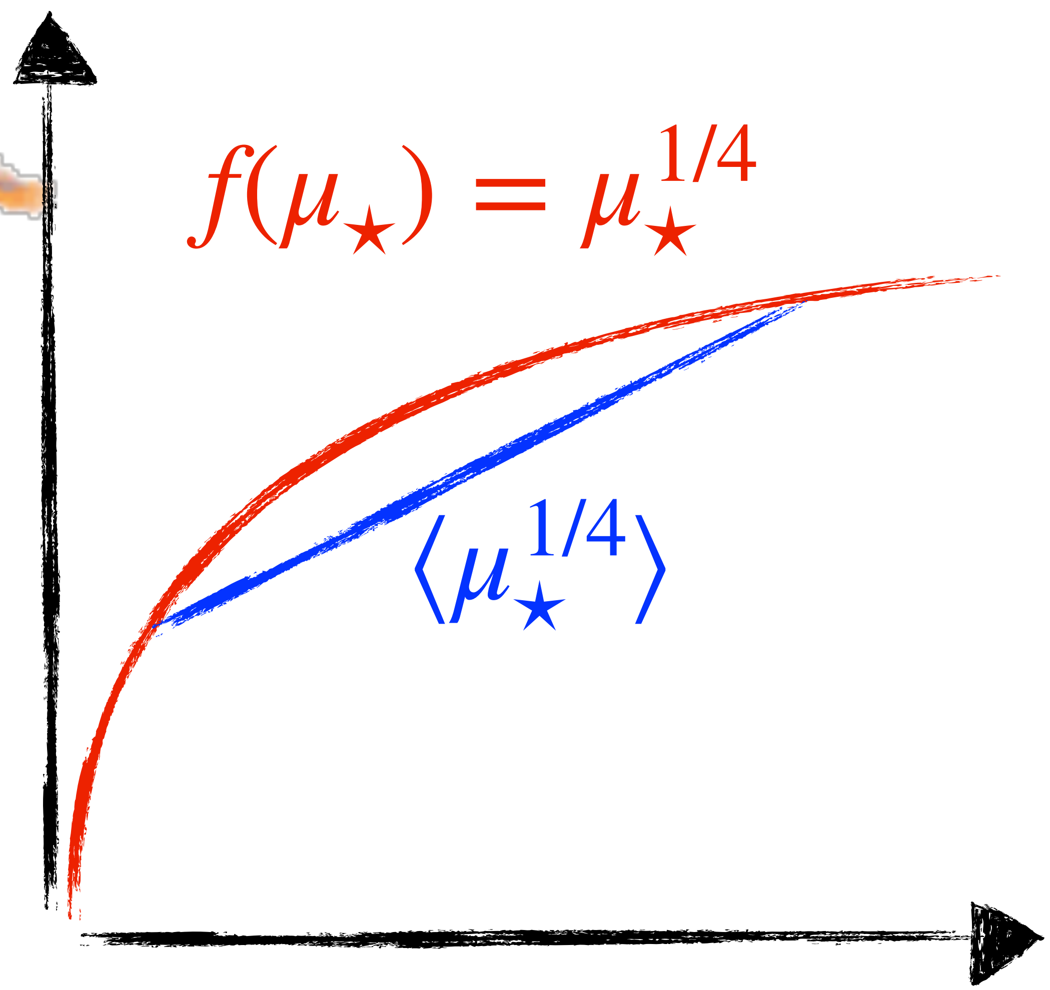
1D point of view	**3D** point of view
$T_{1D} \propto \bar{T}_{eq}$	$\bar{T}_{3D} \propto \langle T_{eq} \rangle$
$T_{1D} \propto \langle \mu_\star \rangle^{1/4}$	$\bar{T}_{3D} \propto \langle \mu_\star^{1/4} \rangle$

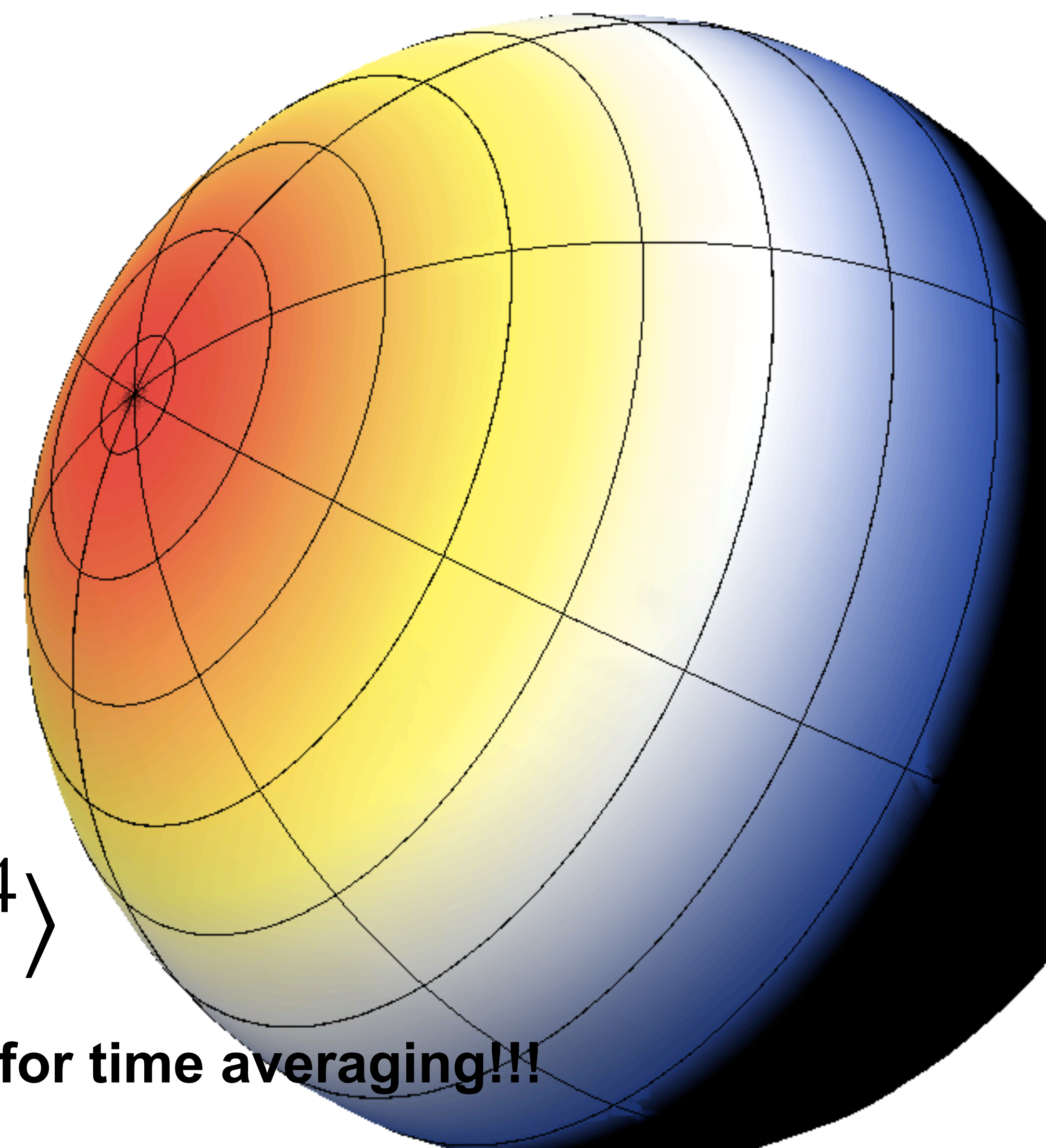


$$\langle \mu_\star \rangle^{1/4} > \langle \mu_\star^{1/4} \rangle$$

Same thing for time averaging!!!

Average temperature : systematic biases





$$\langle \mu_\star \rangle^{1/4} > \langle \mu_\star^{1/4} \rangle$$

Same thing for time averaging!!!

Average temperature : systematic biases

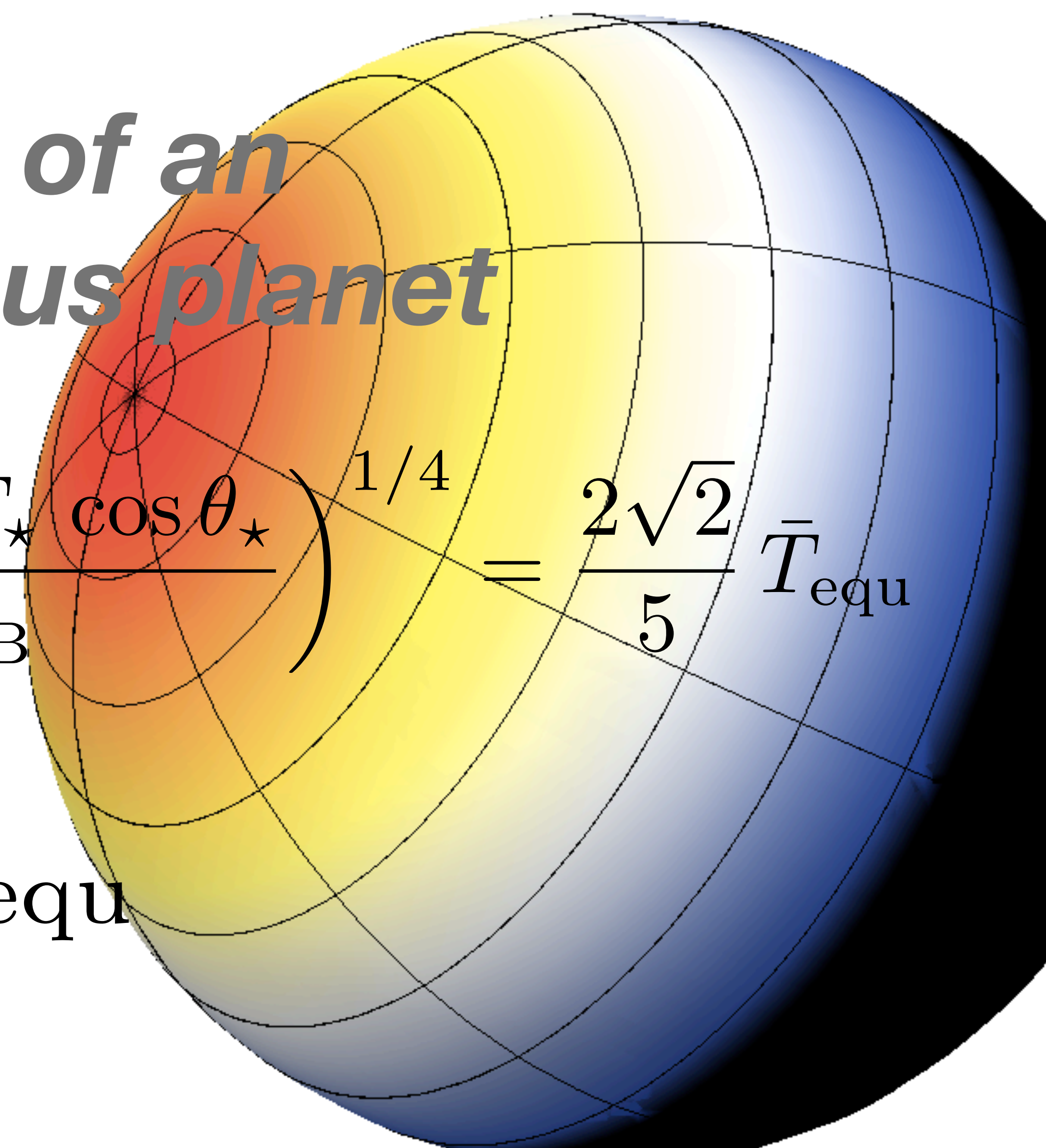
Inhomogeneous insolation

$$\bar{T}_{\mathrm{1d}} \geqslant \bar{T}_{\mathrm{3d}}$$

Extreme case of an airless synchronous planet

$$\bar{T}_{\mathrm{s}} = \frac{1}{4\pi}\int_0^{2\pi} \mathrm{d}\phi \int_0^{1} \mathrm{d}\cos\theta_\star \left(\frac{(1-A)\,F_\star\,\cos\theta_\star}{\sigma_{\mathrm{SB}}}\right)^{1/4} = \frac{2\sqrt{2}}{5}\,\bar{T}_{\mathrm{equ}}$$

$$\bar{T}_{\mathrm{s}} \approx 0.57\,\bar{T}_{\mathrm{equ}}$$



Leconte et al. (2013)

Can the average temperature be higher than the equilibrium temperature?

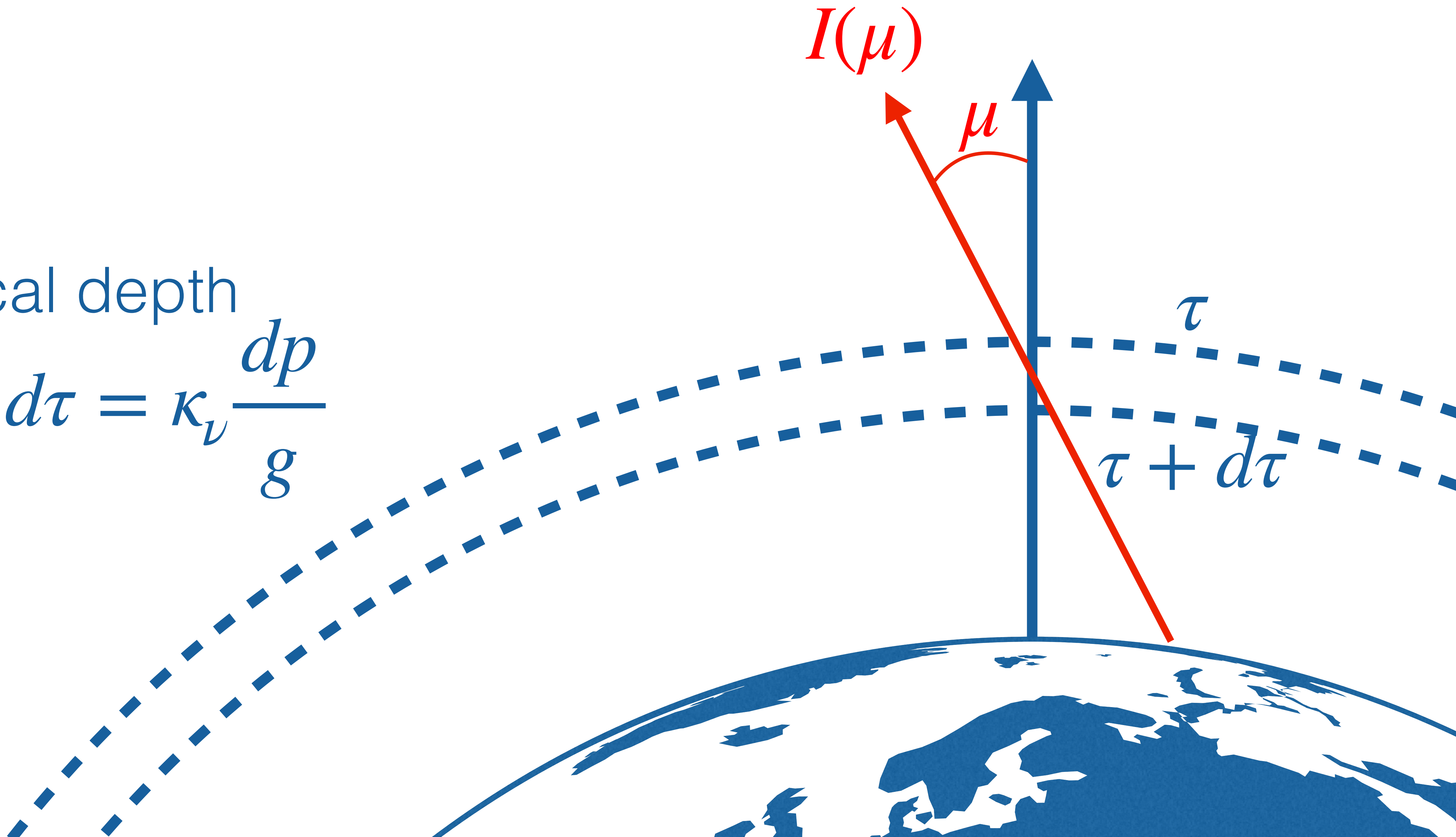
Radiative transfer 101

$$\mu \frac{\partial I_\nu(\mu,\phi)}{\partial \tau_\nu} = I_\nu(\mu,\phi) - S_\nu(\mu,\phi) - \frac{\omega_0}{4\pi}\int_0^{2\pi}\int_0^{1} P_\nu(\mu,\mu',\phi,\phi') I_\nu(\mu',\phi')\, d\phi'\, d\mu'$$

Absorption Emission Scattering

Optical depth

$$d\tau = \kappa_\nu \frac{dp}{g}$$

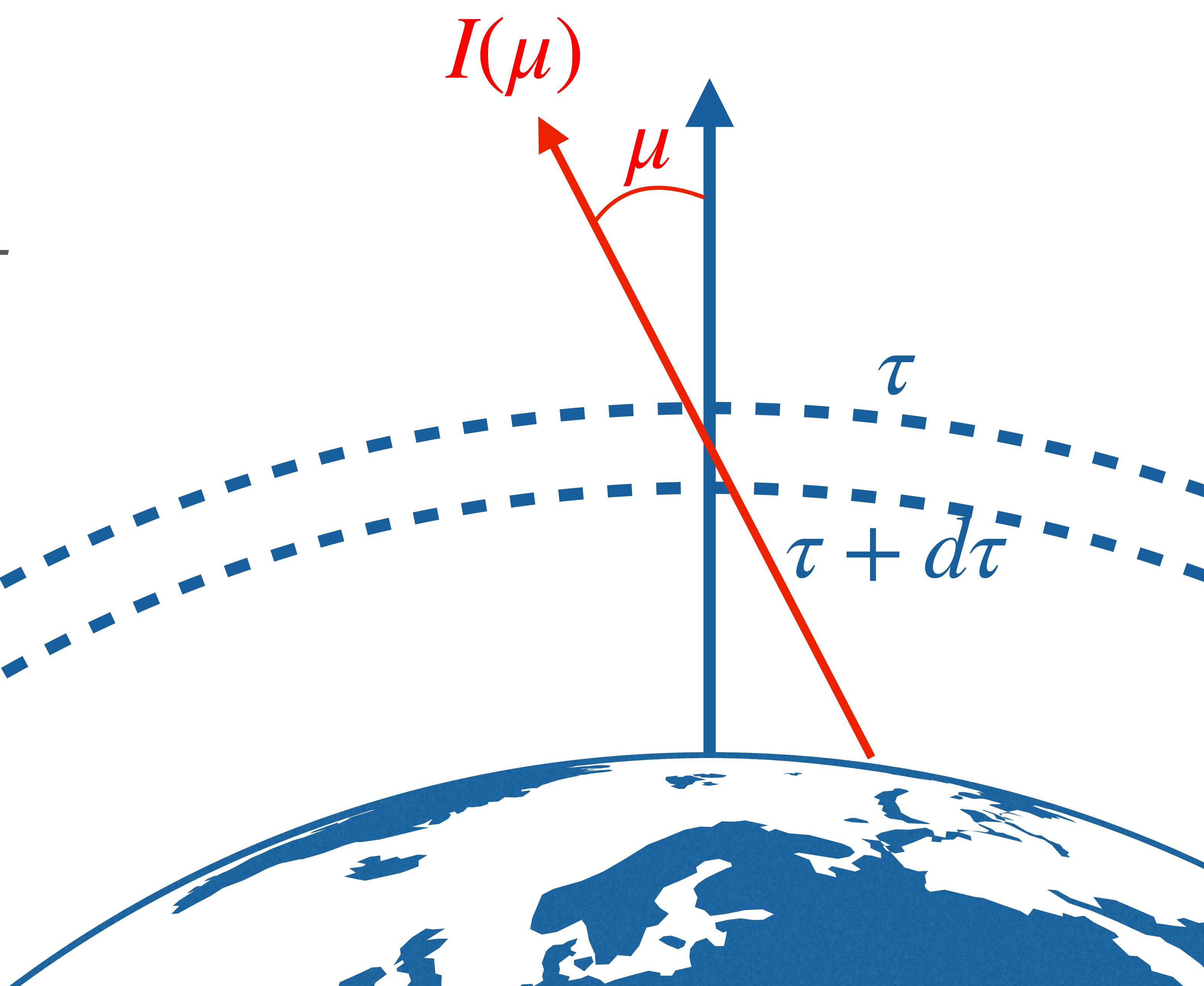


First order : Radiative Equilibrium

$$\mu \frac{\partial I_\nu(\mu,\phi)}{\partial \tau_\nu} = I_\nu(\mu,\phi) - S_\nu(\mu,\phi) - \frac{\omega_0}{4\pi}\int_0^{2\pi}\int_0^{1} P_\nu(\mu,\mu',\phi,\phi') I_\nu(\mu',\phi') d\phi' \mathrm{d}\mu'$$

Absorption Emission Scattering

- ★ *Local Thermal Eq. (LTE) implies:*
  - ★ $S_\nu = B_\nu(T)$
    - ➡ *Can compute I from T*
- ★ *Radiative equilibrium:*
  - ★ *Absorption = Emission (once averaged over all directions)*
- ★ *Allows iteration over T*



The 2-stream approximation

$$\mu \frac{\partial I_\nu(\mu,\phi)}{\partial \tau_\nu} = I_\nu(\mu,\phi) - S_\nu(\mu,\phi) - \frac{\omega_0}{4\pi}\int_0^{2\pi}\int_0^1 P_\nu(\mu,\mu',\phi,\phi') I_\nu(\mu',\phi') d\phi' \mathrm{d}\mu'$$

- ★ *Main Assumptions:*
  - ★ *Plane parallel*
  - ★ *Intensity described by upward and downward fluxes (F^+ and F^-)*
    - ➡ *Usable in a numerical model (like exo_k)*
- ★ *Additional assumptions*
  - ★ *Intensity constant over hemispheres*
  - ★ *No scattering*
  - ★ *No visible absorption*
  - ★ *gray absorber*
    - ➡ *Analytical solutions*

$$\frac{\partial F^+}{\partial \tau} = 2F^+ - 2\pi B$$

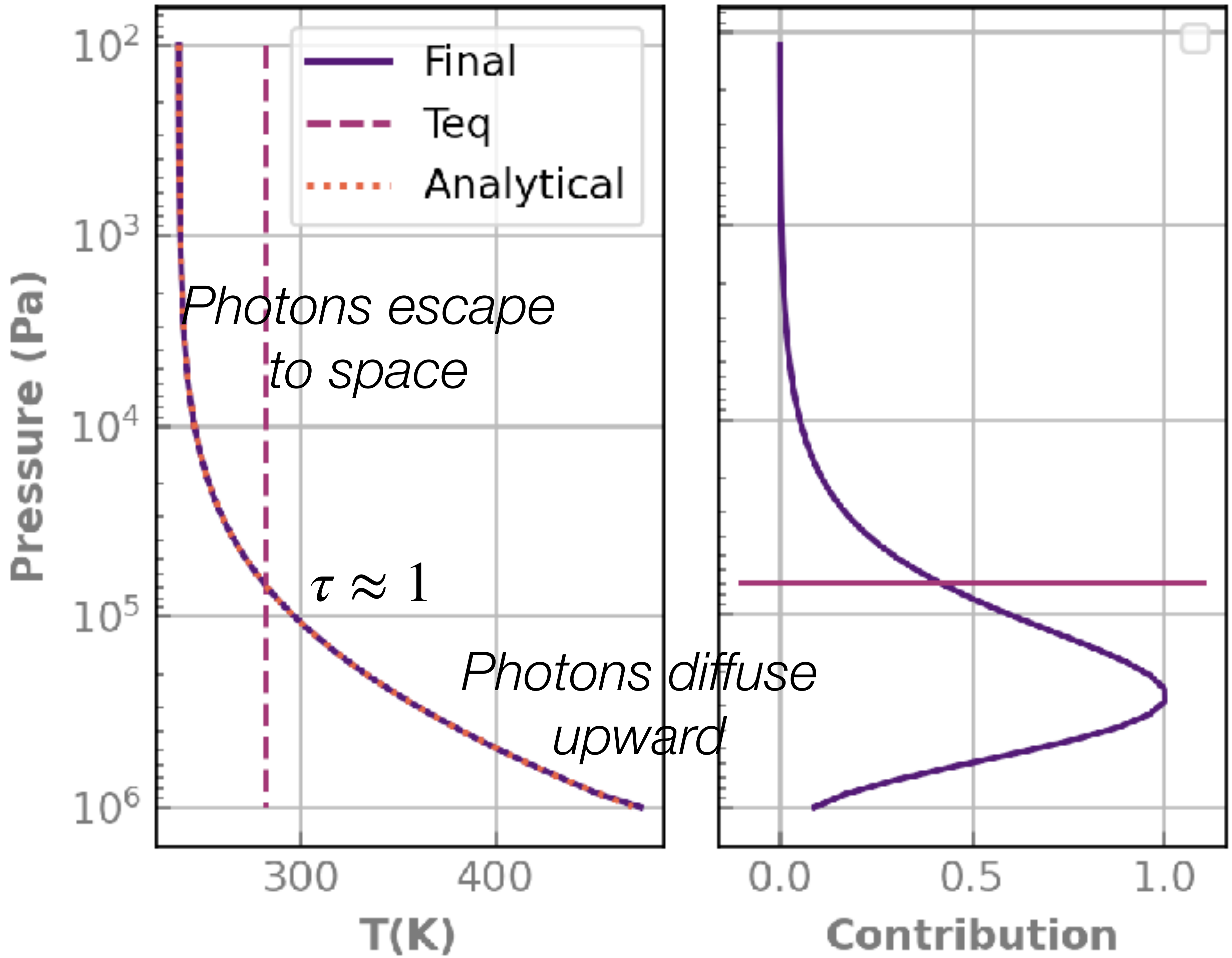
$$\frac{\partial F^-}{\partial \tau} = 2F^- + 2\pi B$$

$$T(\tau)^4 = T_{eq}^4\left(\frac{1}{2} + \tau\right)$$

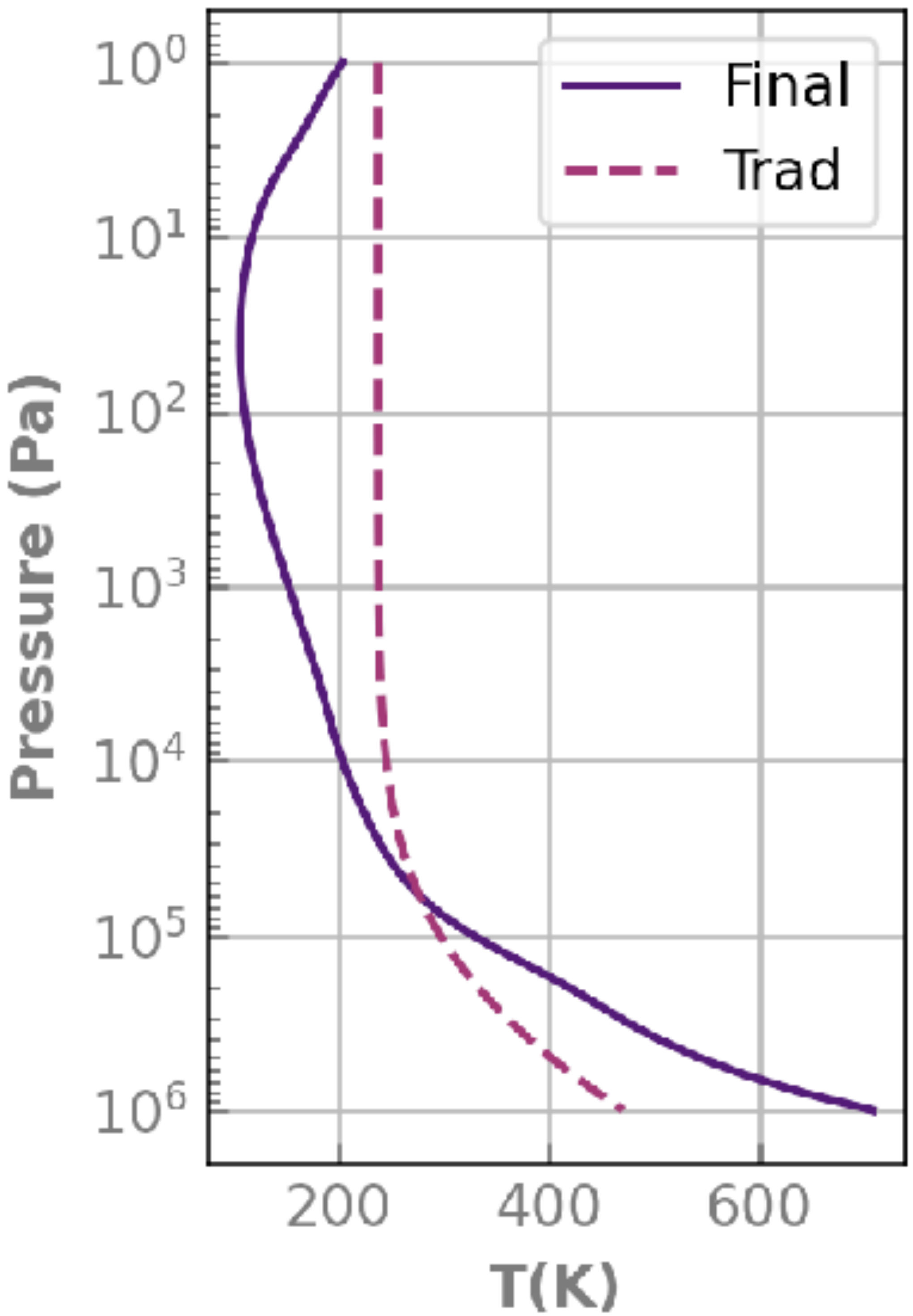
See Guillot (2010) for more detailed models

Greenhouse effect in a gray atmosphere

Parameters for K2-18b



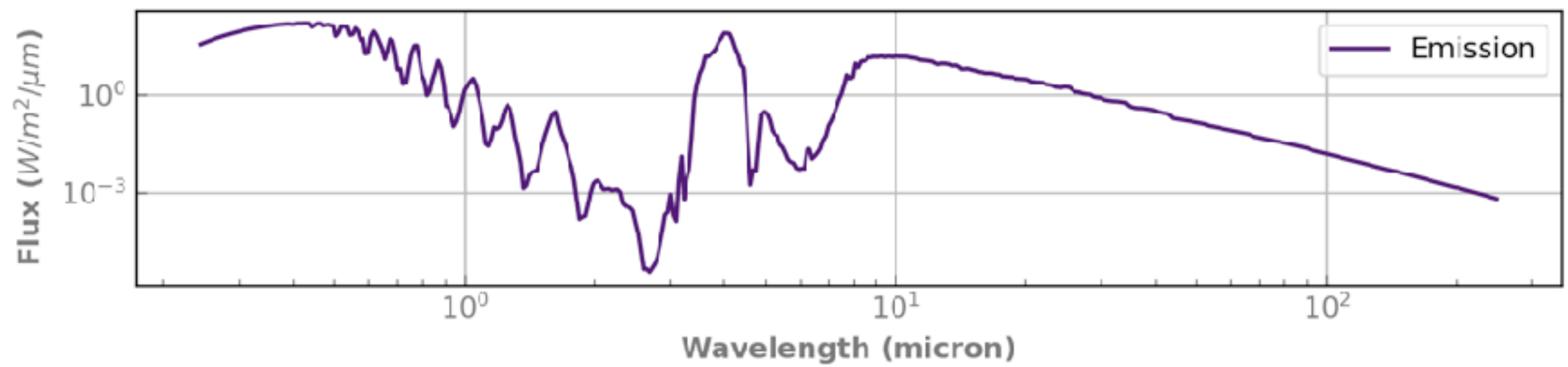
Thermal structure with real gases

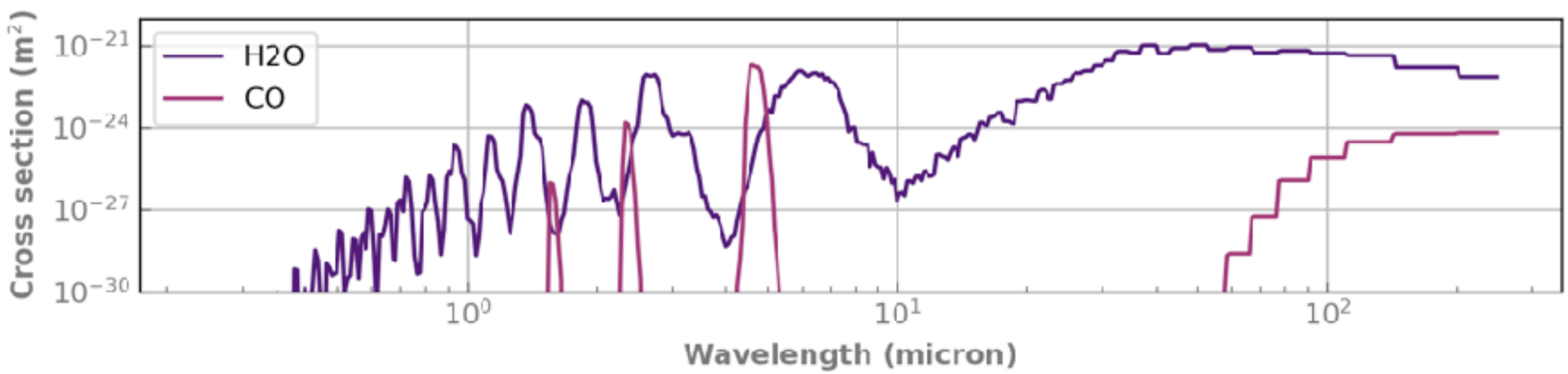


- ★ *Stratosphere is colder:*
  - ★ *Gas has opacity windows where thermal radiation can escape without heating the stratosphere*
- ★ *Troposphere is hotter*
  - ★ *Opacity increases with depth (collisional broadening)*
  - ★ *Thermal gradient needs to steepen to transport the flux upward*

How is it linked to observables?

Emission for real gas atmospheres





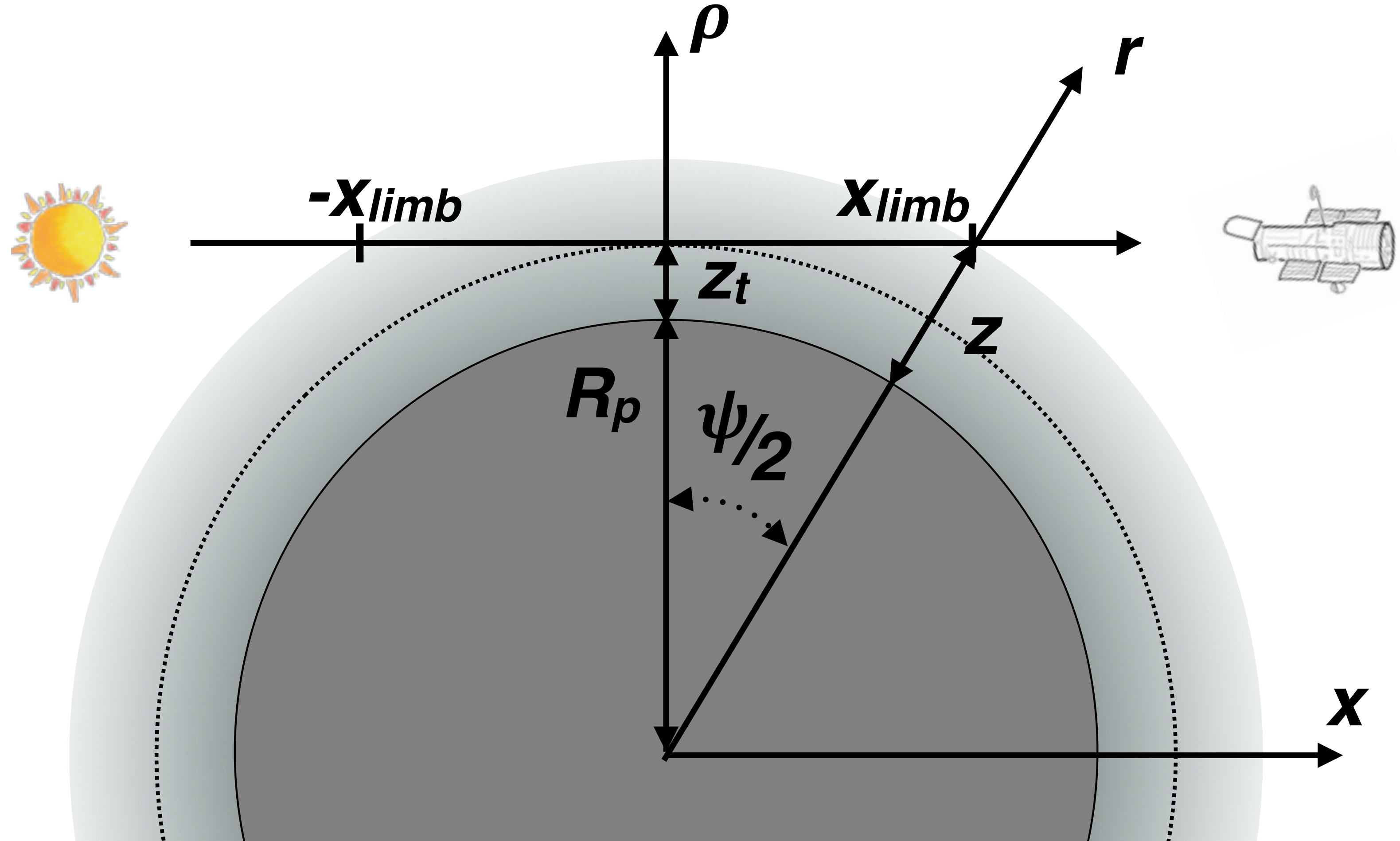
- ★ *We see the* $\tau \approx 1$ *level*
  - ★ *The more transparent the gas, the deeper we see*
  - ★ *The deeper the hotter (usually)*
  - ★ *Higher fluxes in transparent windows (and vice versa)*

Transmission for real gas atmospheres

★ *The atmosphere will absorb (hide) everything below the* $\tau \approx 1$ *level*

★ *The more opaque the gas, the higher the atmosphere absorbs*

★ *Higher transit depth in opaque bands (and vice versa)*



Transmission for real gas atmospheres

- ★ *The atmosphere will absorb (hide) everything below the $\tau \approx 1$ level*
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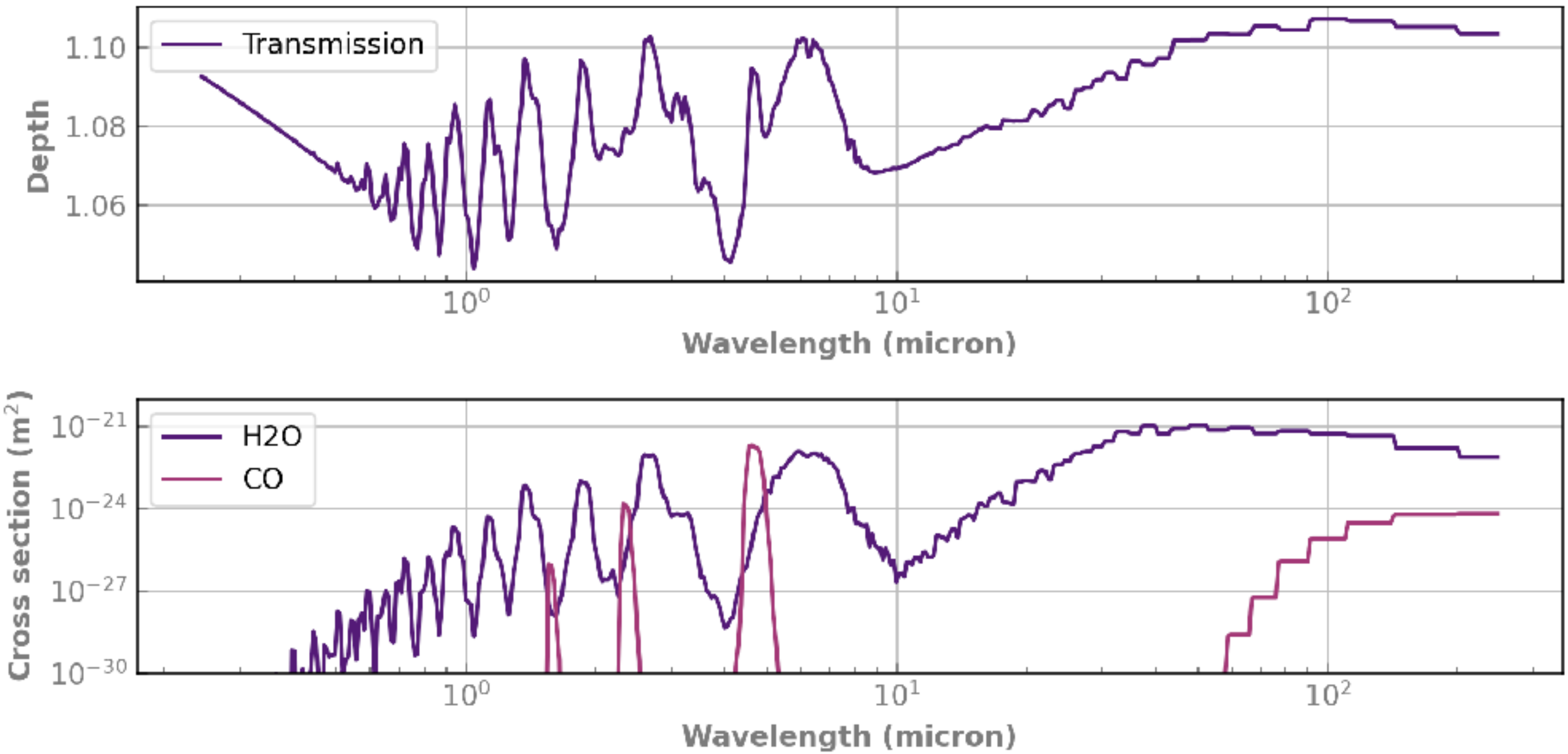
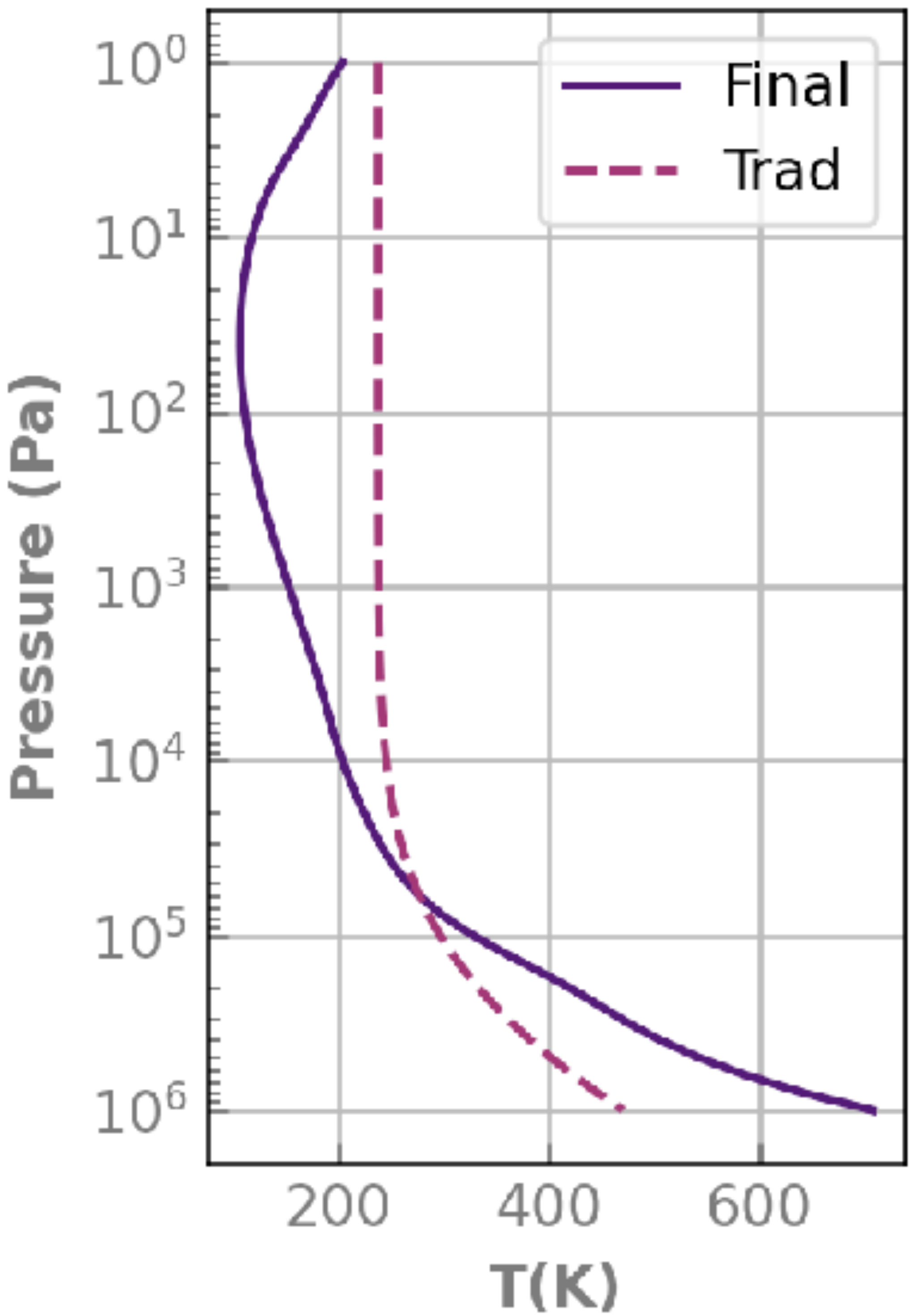
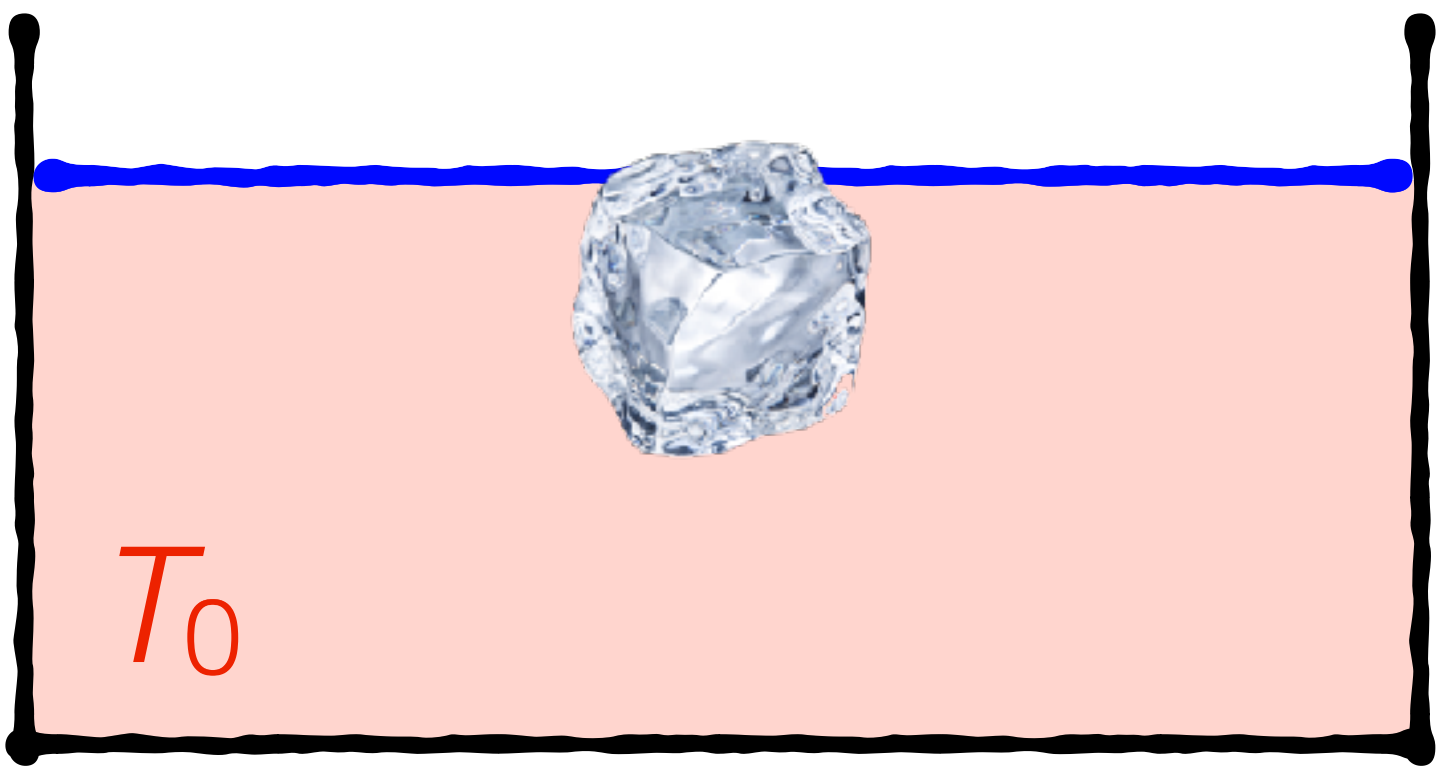
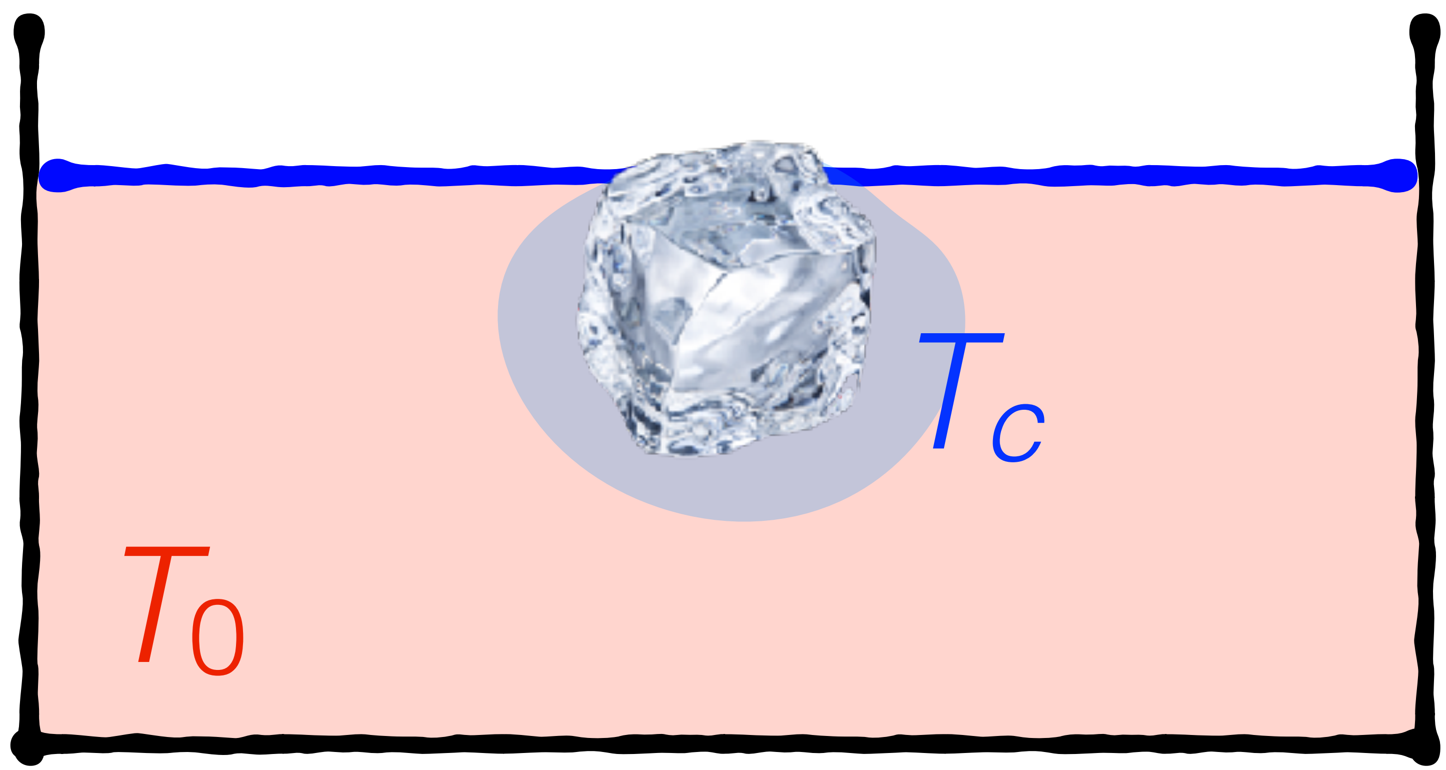


Thermal structure with real gases



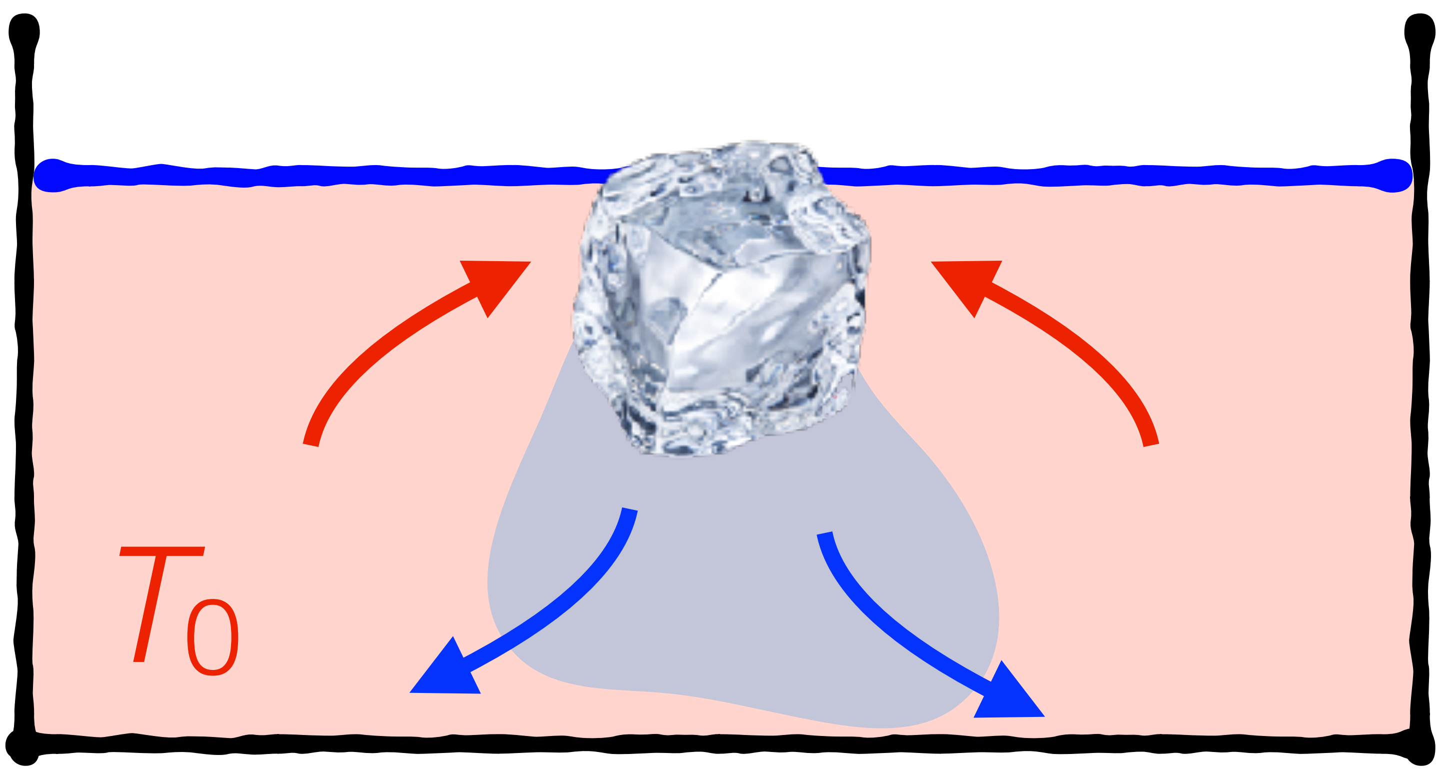
What are we forgetting?


T_0

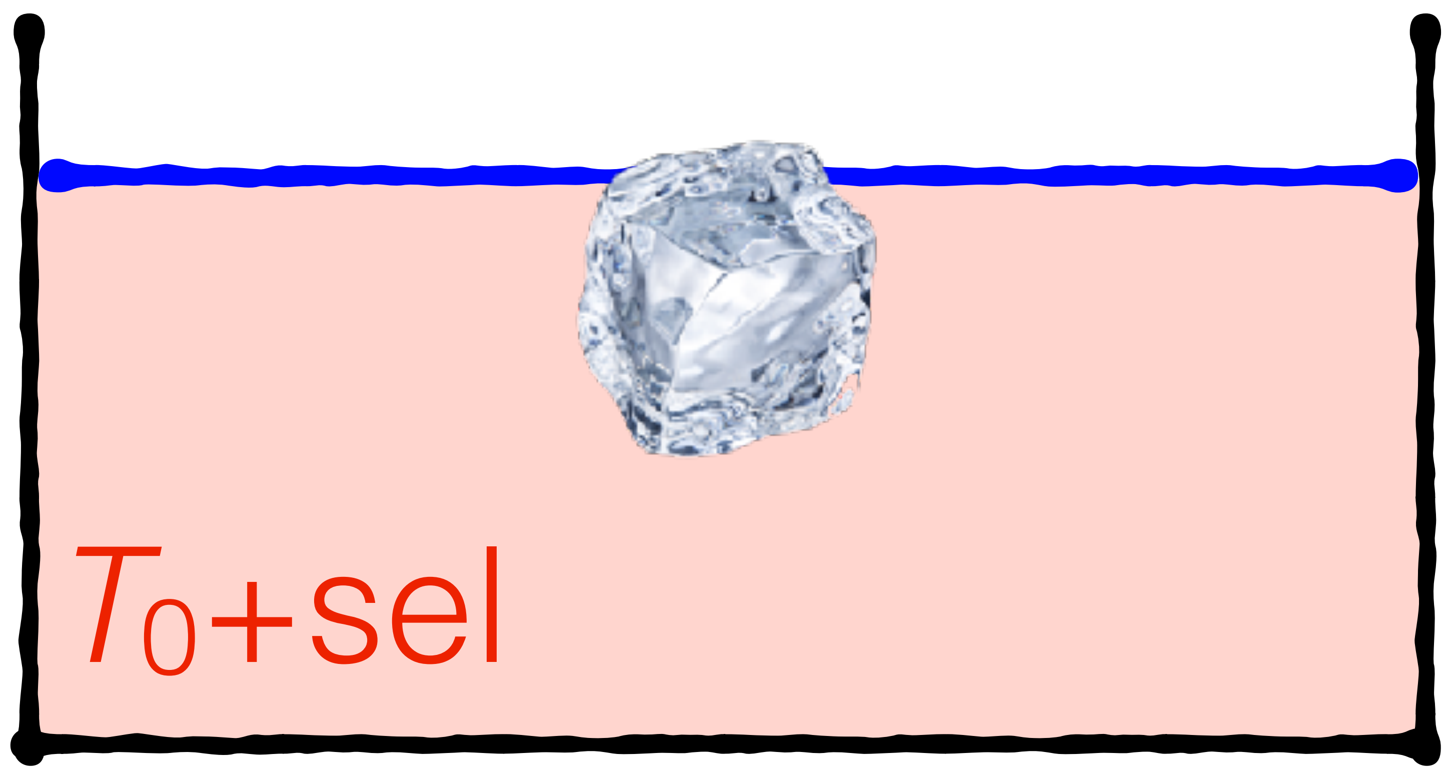


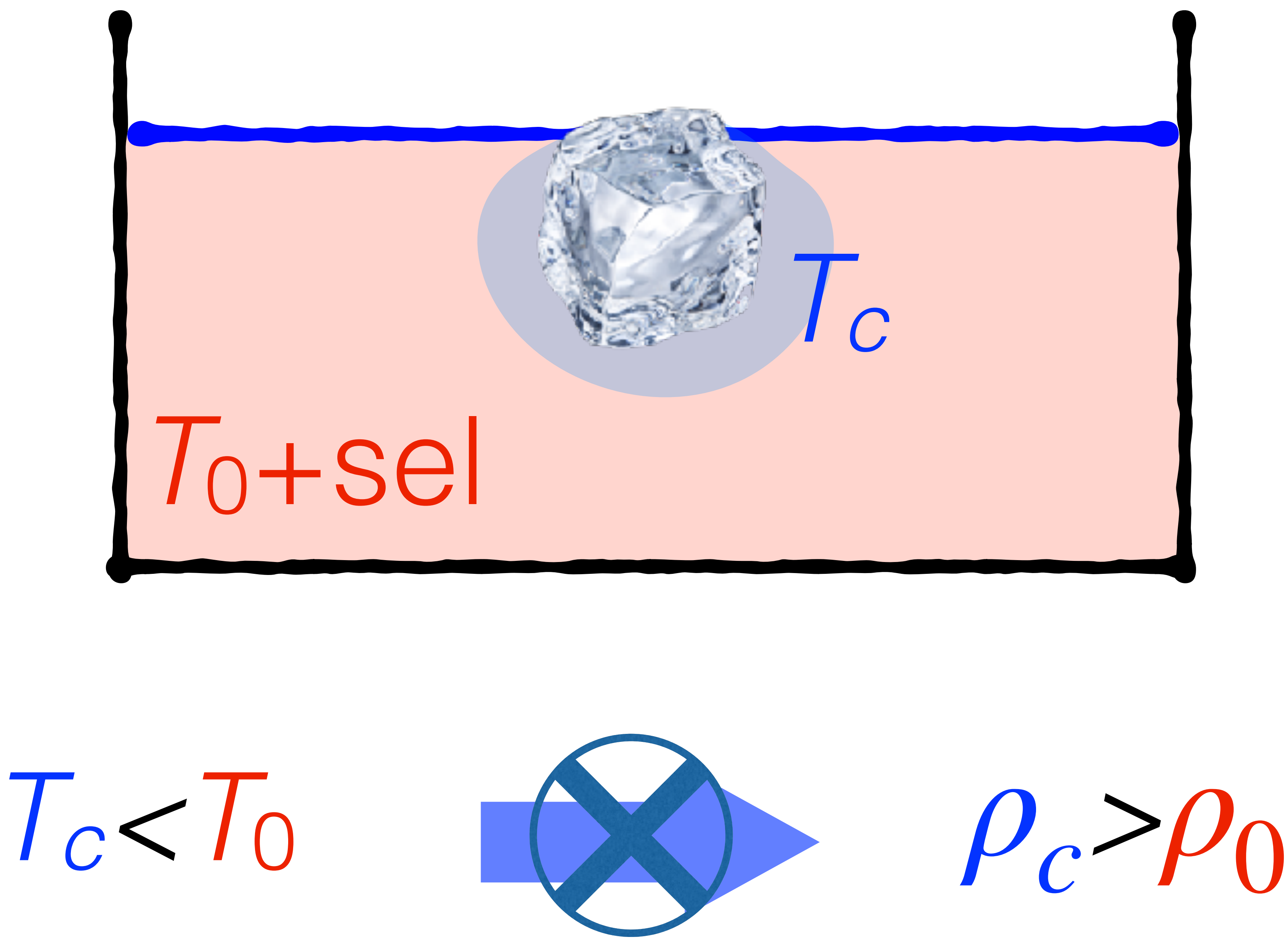
$$T_c < T_0 \;\Rightarrow\; \rho_c > \rho_0$$

Net transport of heat upward

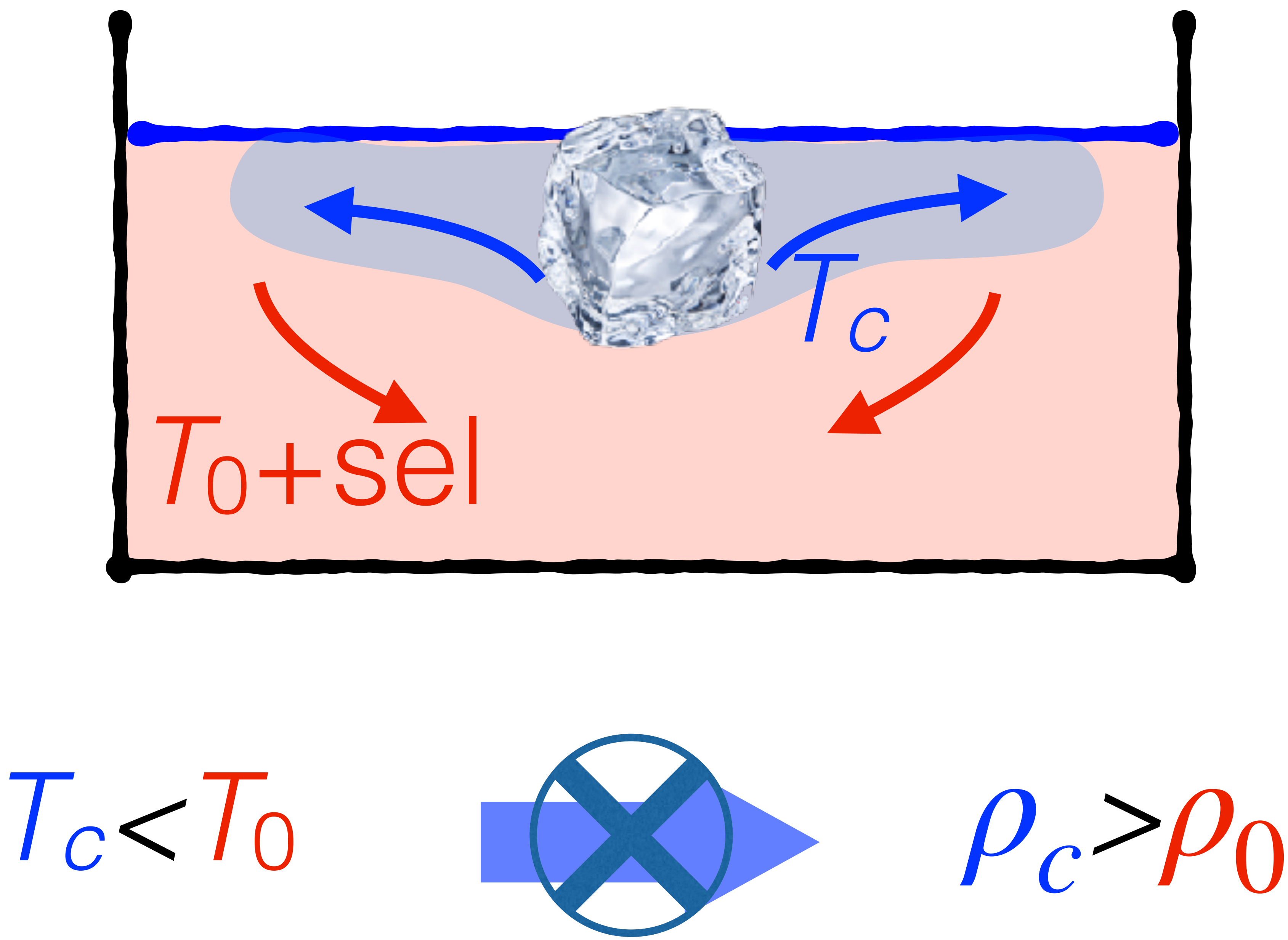


$T_c < T_0$ ⇒ $\rho_c > \rho_0$


T_0+sel



T_c
T_0+sel
$T_c < T_0$
$\rho_c > \rho_0$



T_c
T_0+sel
$T_c < T_0$
$\rho_c > \rho_0$

Thermal structure with convection