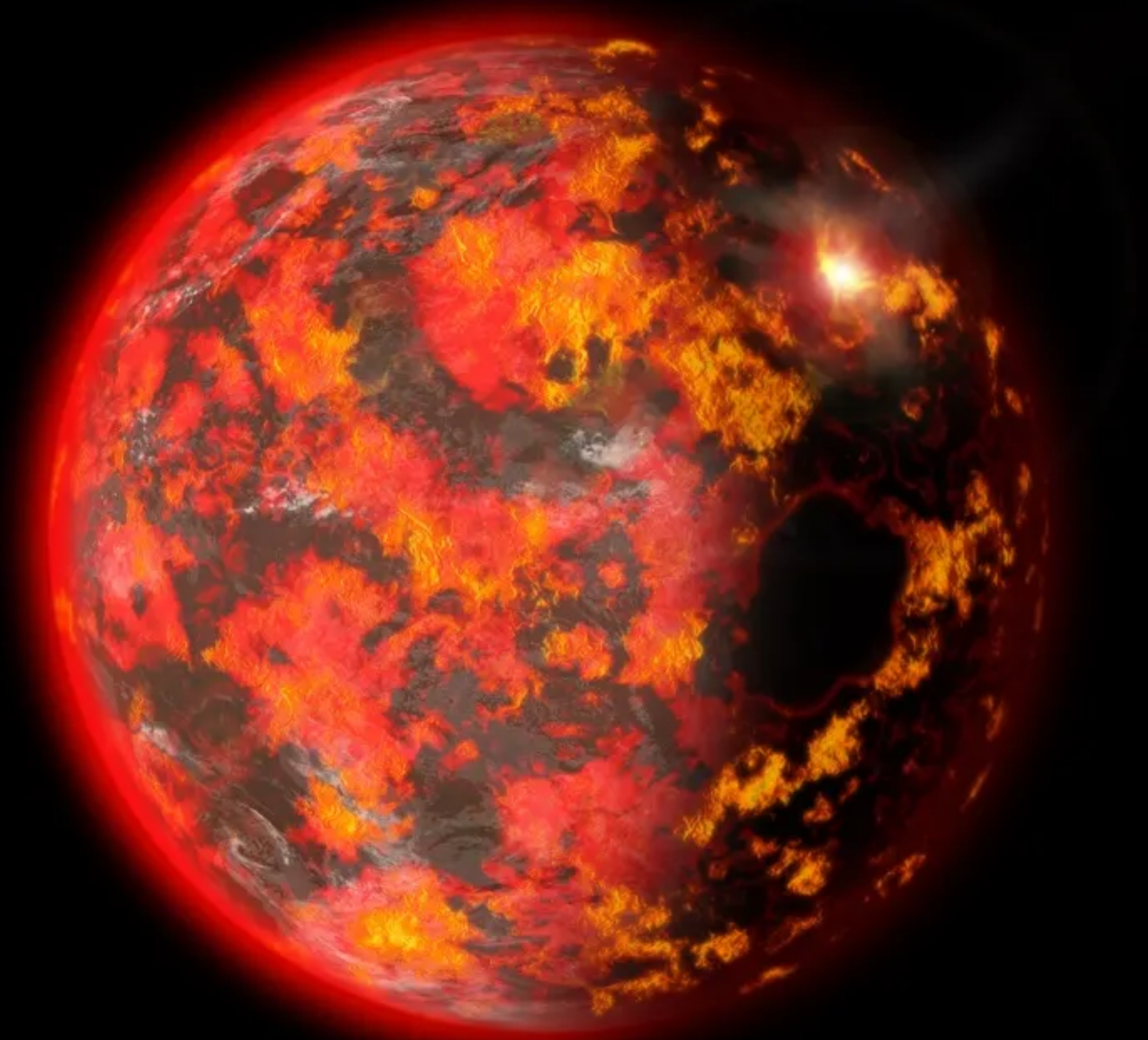
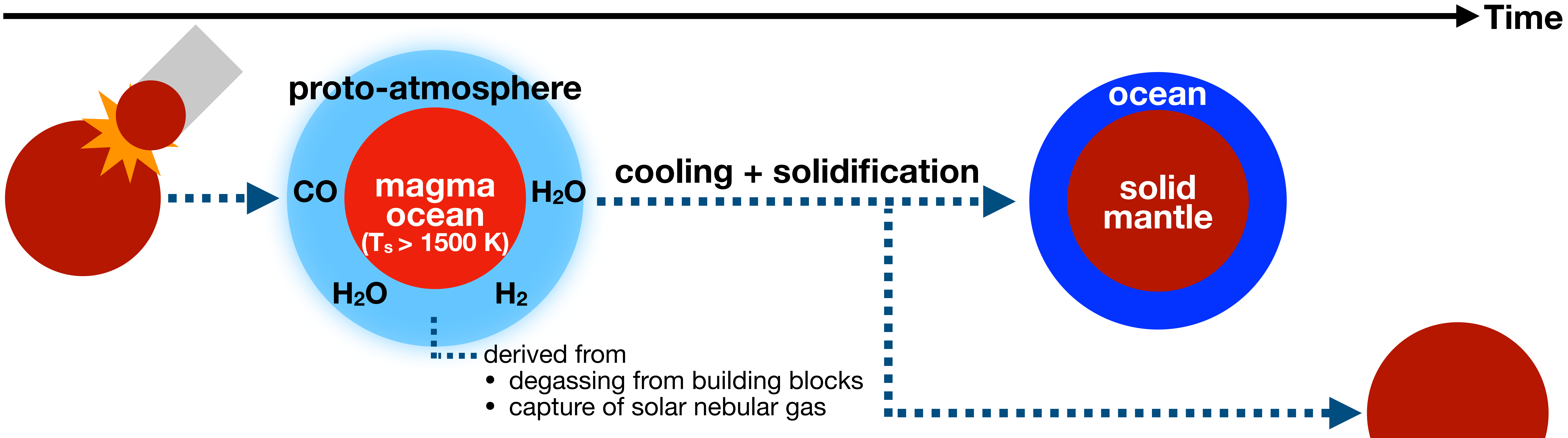
# Scattering blanketing effect of Earth's proto-atmosphere on planetary radiation and magma ocean cooling

Tatsuya Yoshida[1], Kirara Arima[2], Takeshi Kuroda[1], Naoki Terada[1], Kiyoshi Kuramoto[2]
[1]Tohoku University, [2]Hokkaido University



# Terrestrial planets just after giant impact

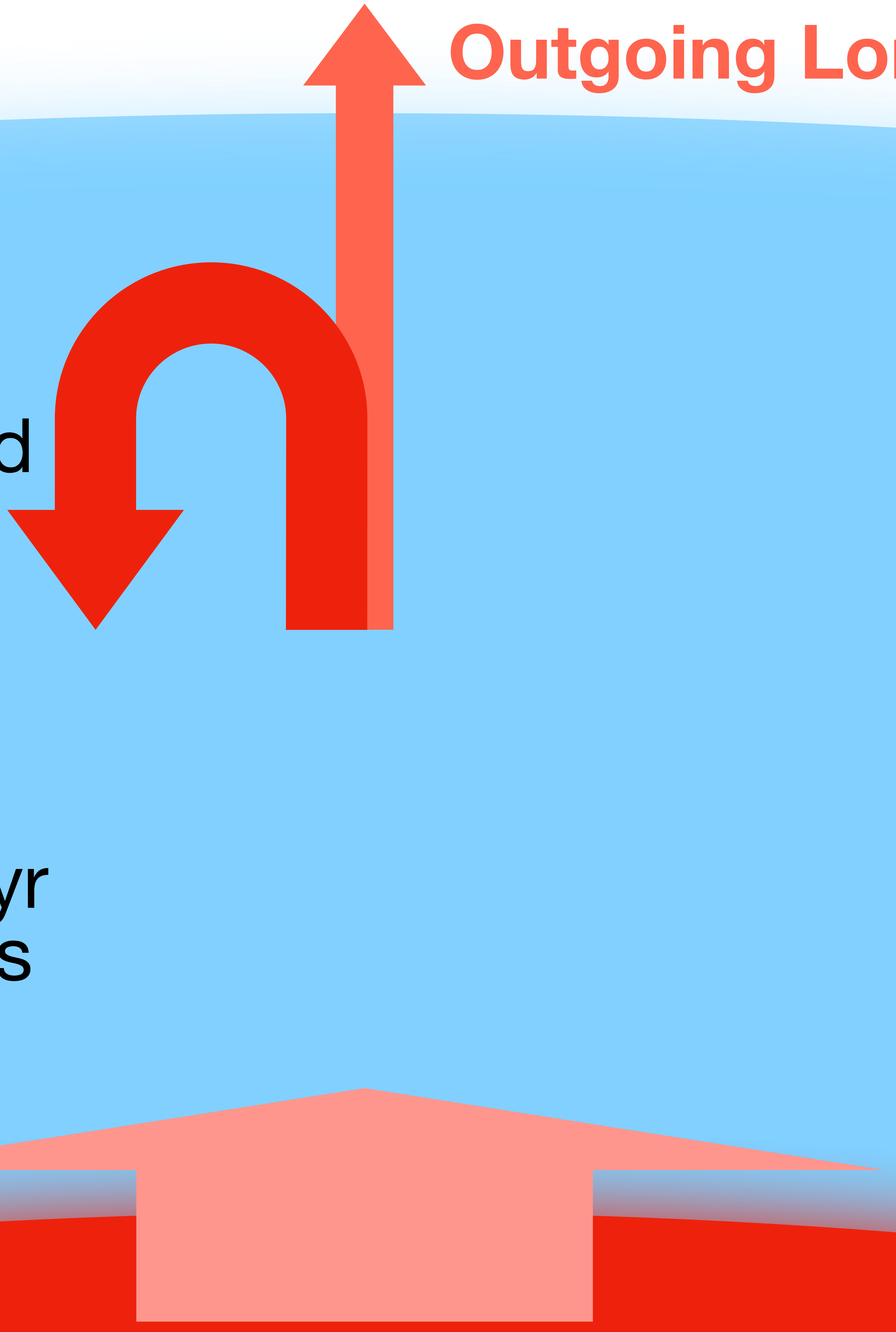



- The magma ocean cooling process is crucial in determining the surface environment (Hamano et al., 2013)
- **What factors determine the cooling timescale?**

# Blanketing Effect of proto-atmosphere

## Blanketing effect through radiative absorption

- Thermal radiation absorbed
  → OLR & MO cooling suppressed
- Effect of $H_2O$ atmosphere
  - MO lifetime ~1 Myr at Earth
    (e.g., Hamano et al., 2013; Lebrun et al., 2013)
- Effect of $H_2$ atmosphere
  - MO lifetime becomes > 100 Myr as long as $H_2$ with ~$1M_{TO}$ exists
    (Lichtenberg et al., 2021)
    - due to $H_2$-$H_2$ CIA



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Outgoing Longwave Radiation (OLR)

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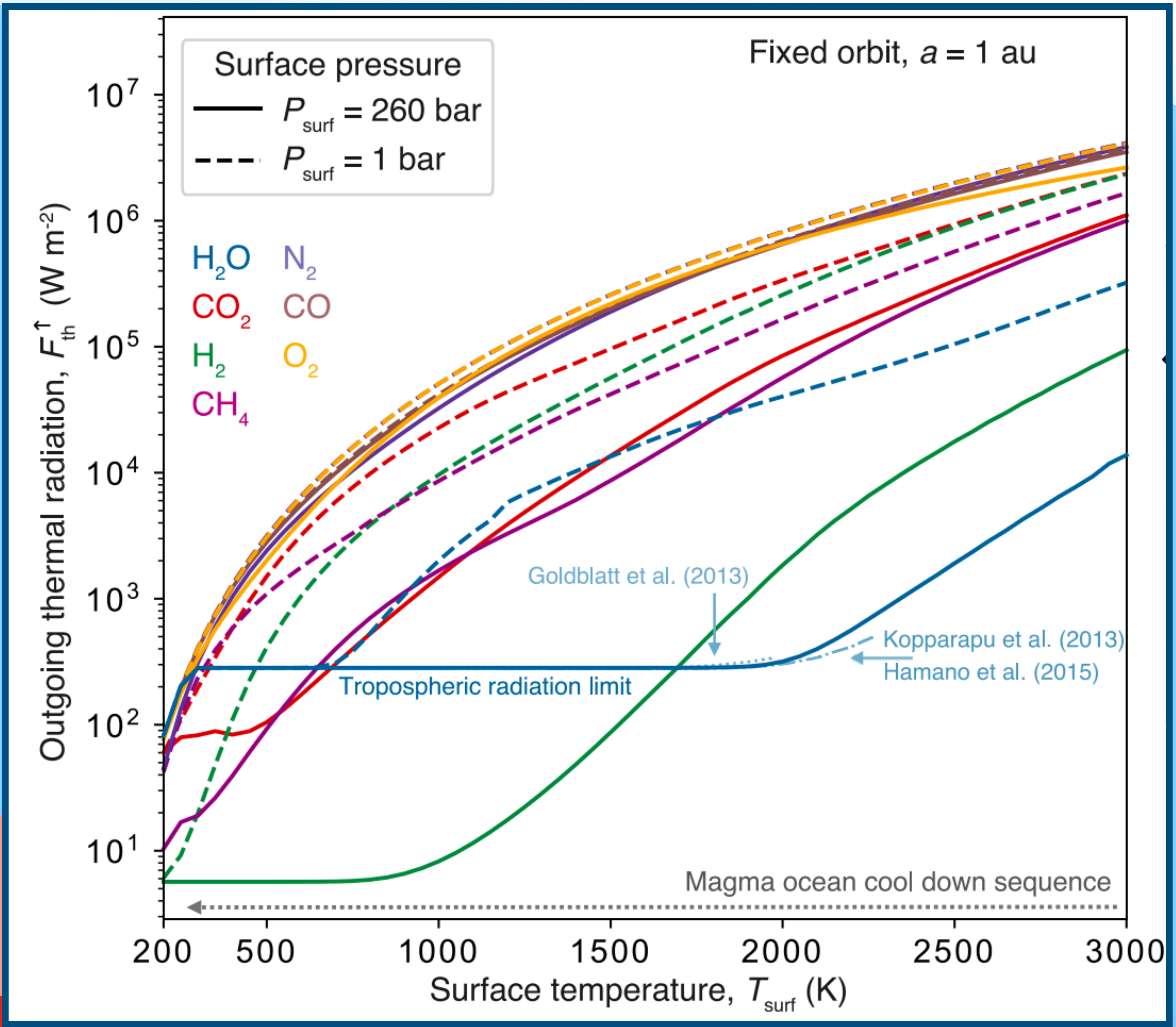


Internal heat

Lichtenberg et al. (2021)

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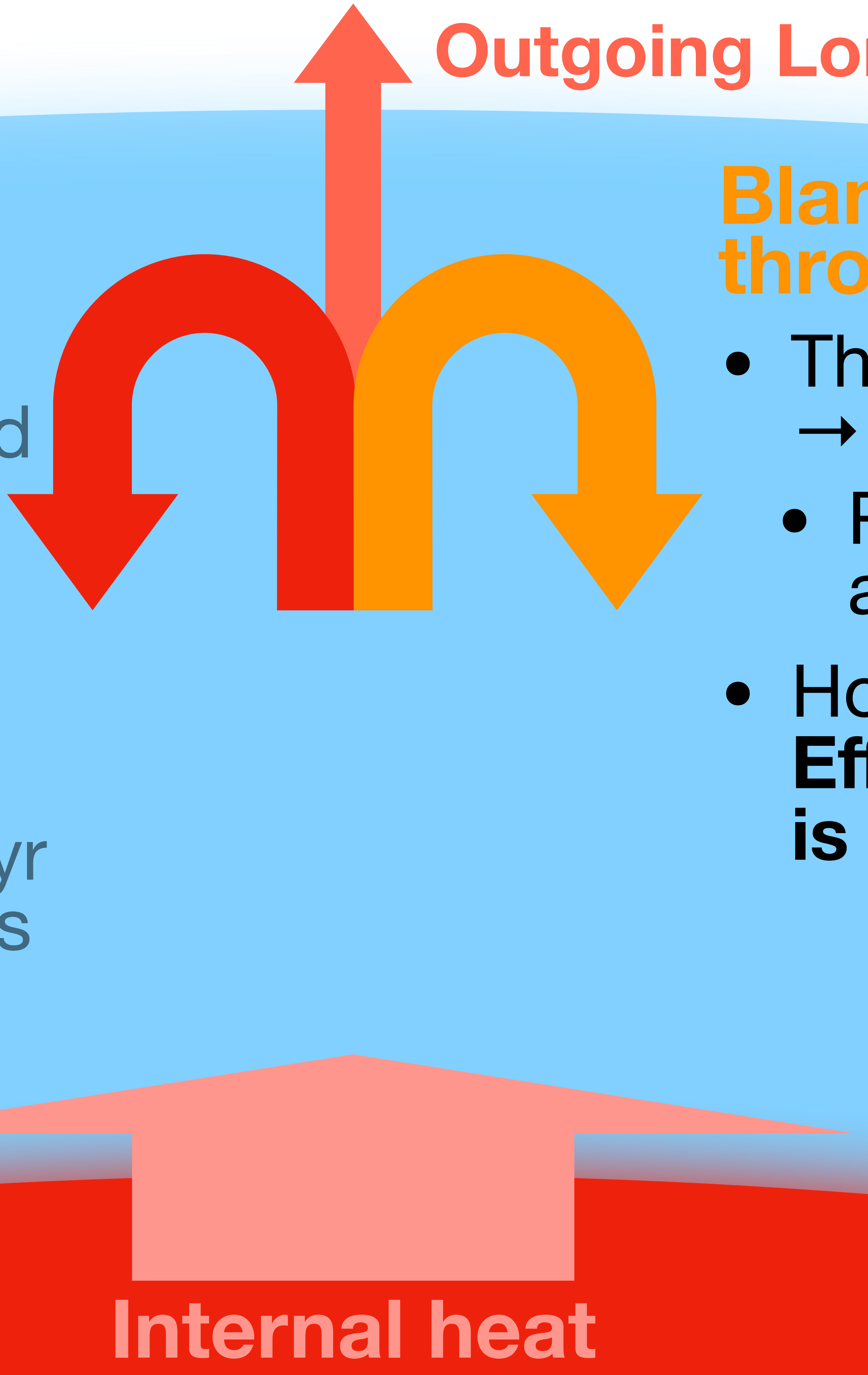
- Effect of $H_2$ atmosphere
  - $H_2$ can be a major species on proto-Earth
    - $H_2O$ reduction by Fe ($H_2O$+Fe→$H_2$+FeO)
    - Capture of the solar nebular gas

Internal heat

# Blanketing Effect of proto-atmosphere

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- Thermal radiation scattered → OLR & MO cooling suppressed
  - Rayleigh scattering dominates absorption at short wavelengths
- However… **Effect on OLR and MO cooling is uncertain**

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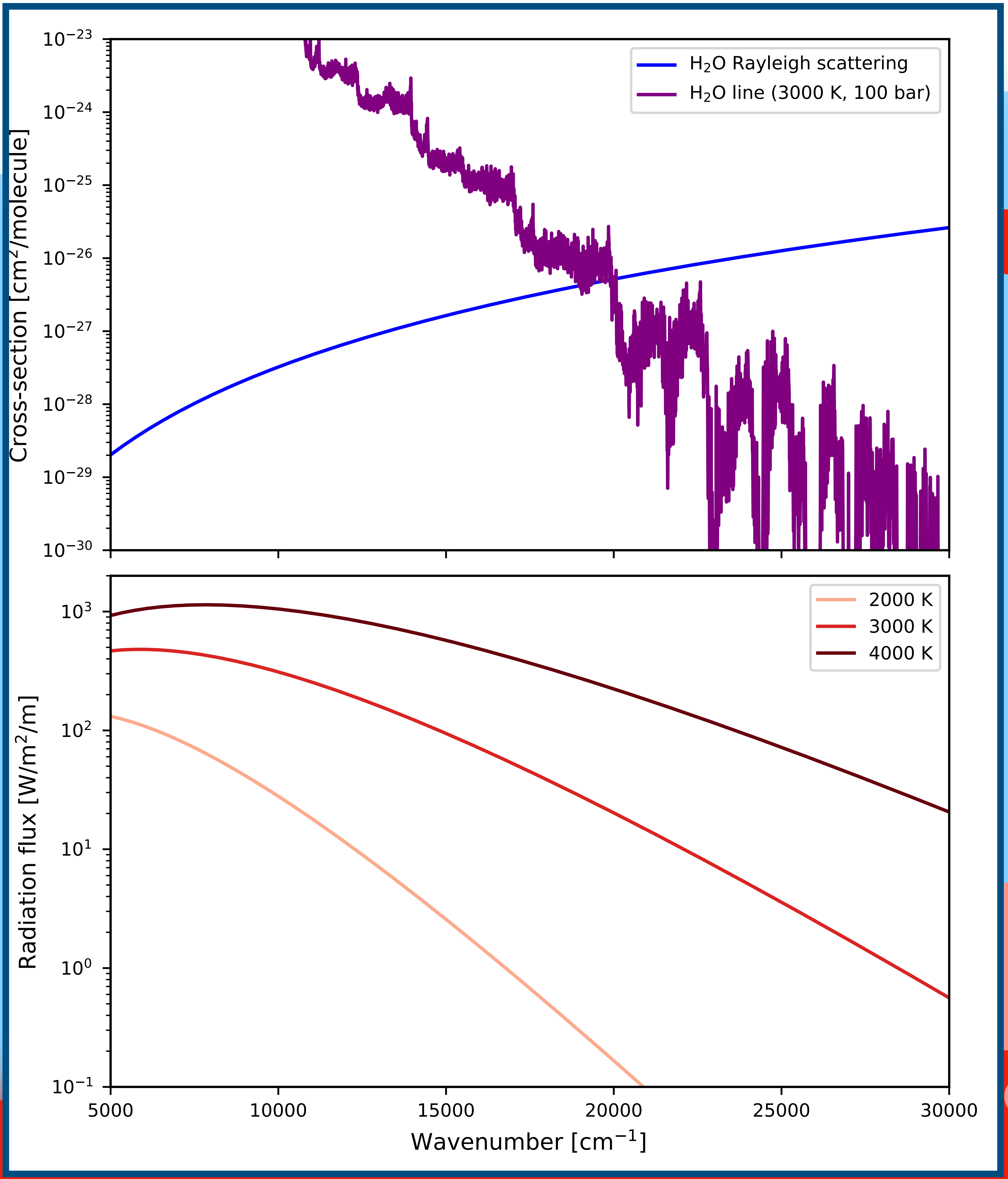


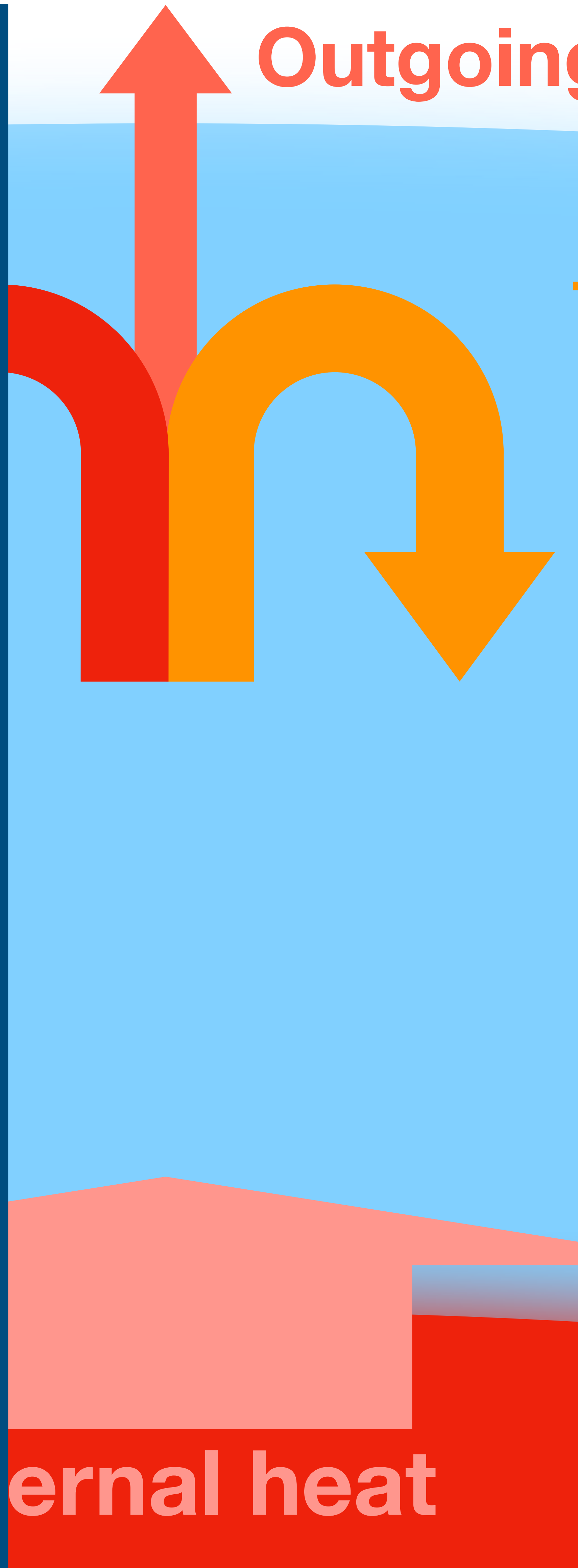


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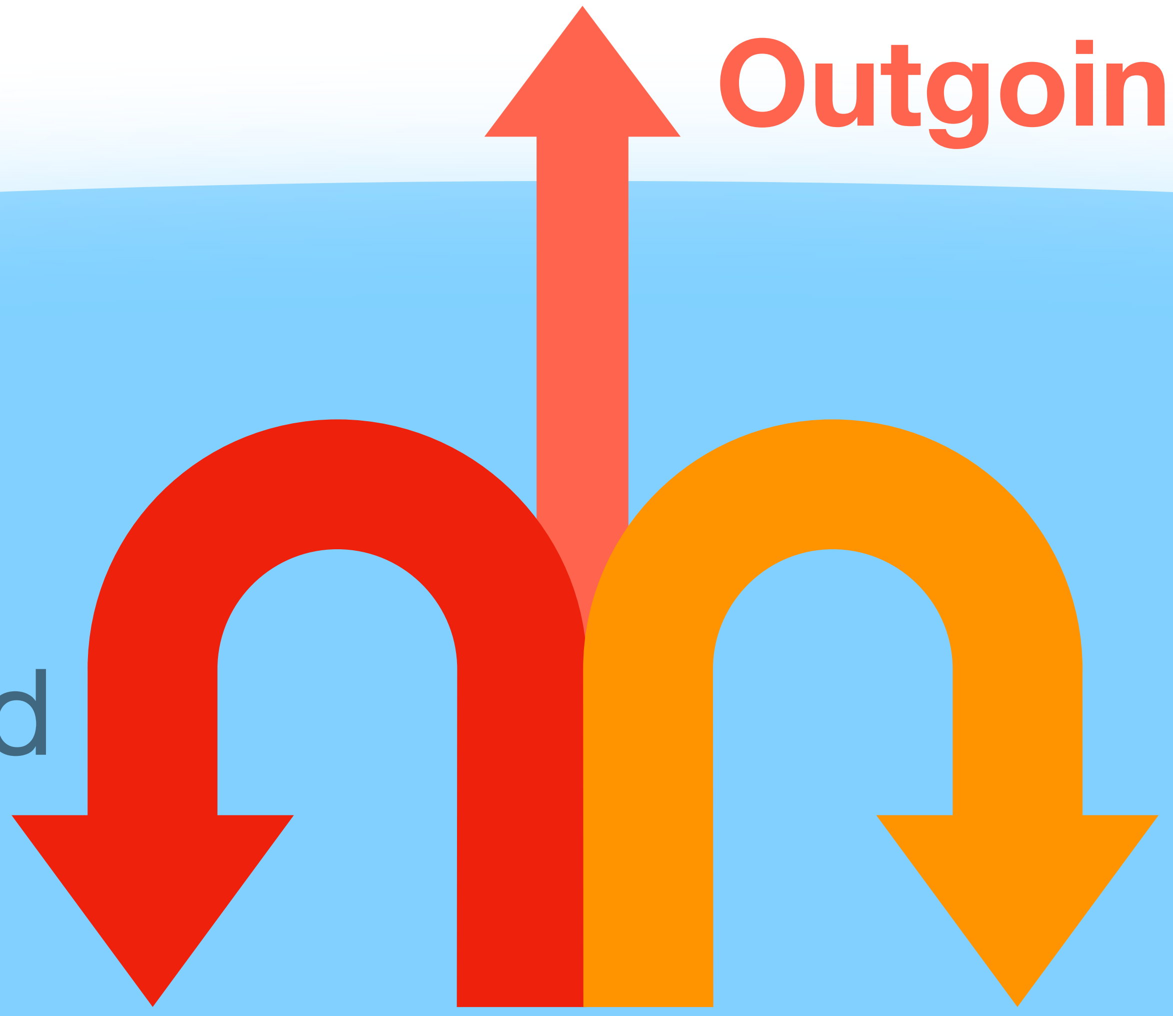


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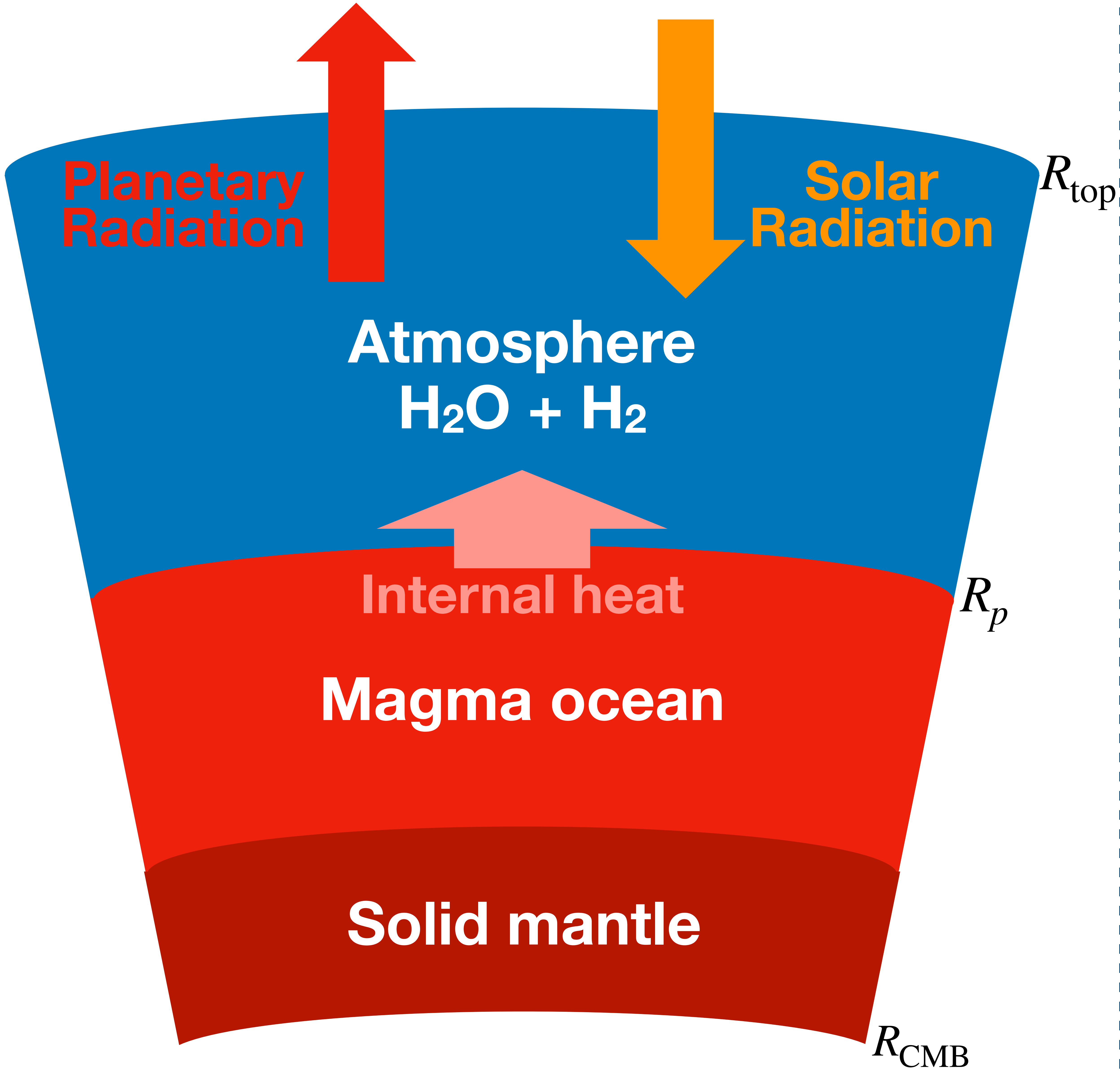
**Purpose of this study**

To clarify the scattering blanketing effect on the planetary radiation and magma ocean cooling under Earth's proto-atmosphere composed of $H_2O$ and $H_2$

Internal heat

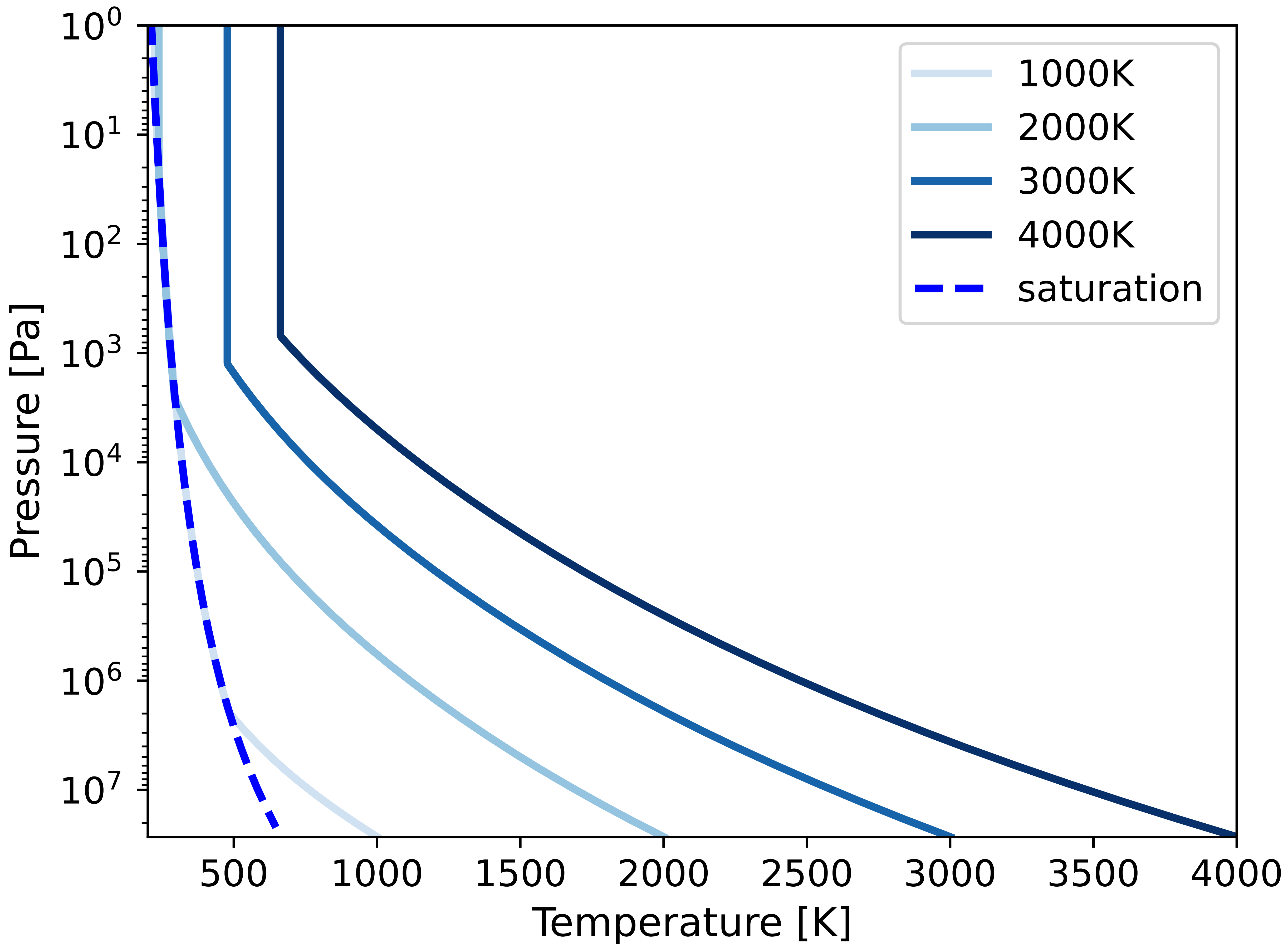
# Atmosphere-Interior model




## Atmospheric structure

- Composition and mass
  - $H_2O$ (non-ideal gas) + $H_2$ (ideal gas)
  - Mass of $H_2O$ and $H_2$: free parameters
- Hydrostatic
- Temperature profile
  - Surface temperature: varied (200-4000 K)
  - following the adiabatic lapse rate
    - $H_2O$-saturated region: moist adiabat
    - unsaturated region: dry adiabat
  - constant at the skin temperature
- Boundary
  - Top: Altitude at 1 Pa
  - Bottom: Planetary surface

# Atmosphere-Interior model




pure $H_2O$ atmosphere ($N_{H2O}=N_{TO}$)

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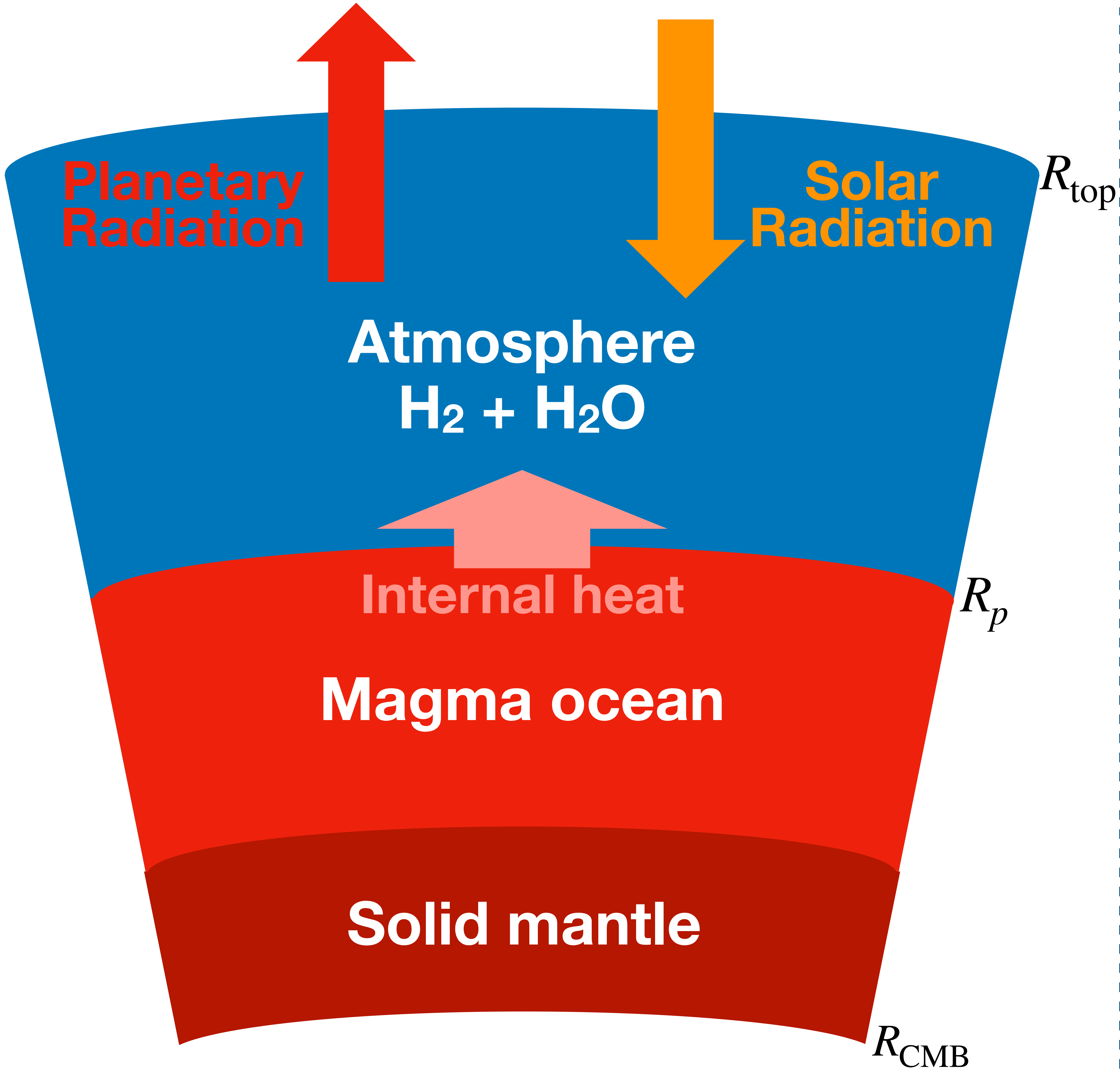


## Interior's structure

- Hydrostatic
- Temperature profile
  - following the adiabatic lapse rate
    - considering the latent heat in the partially molten zone
- Phase change
  - Solidus and liquidus temperature
    - fitting to the experimental data of peridotite is adopted (e.g., Nikolaou et al., 2019)
  - Melt fraction
    - $\phi = (T - T_{sol})/(T_{liq} - T_{sol})$
- Boundary
  - Top: Planetary surface
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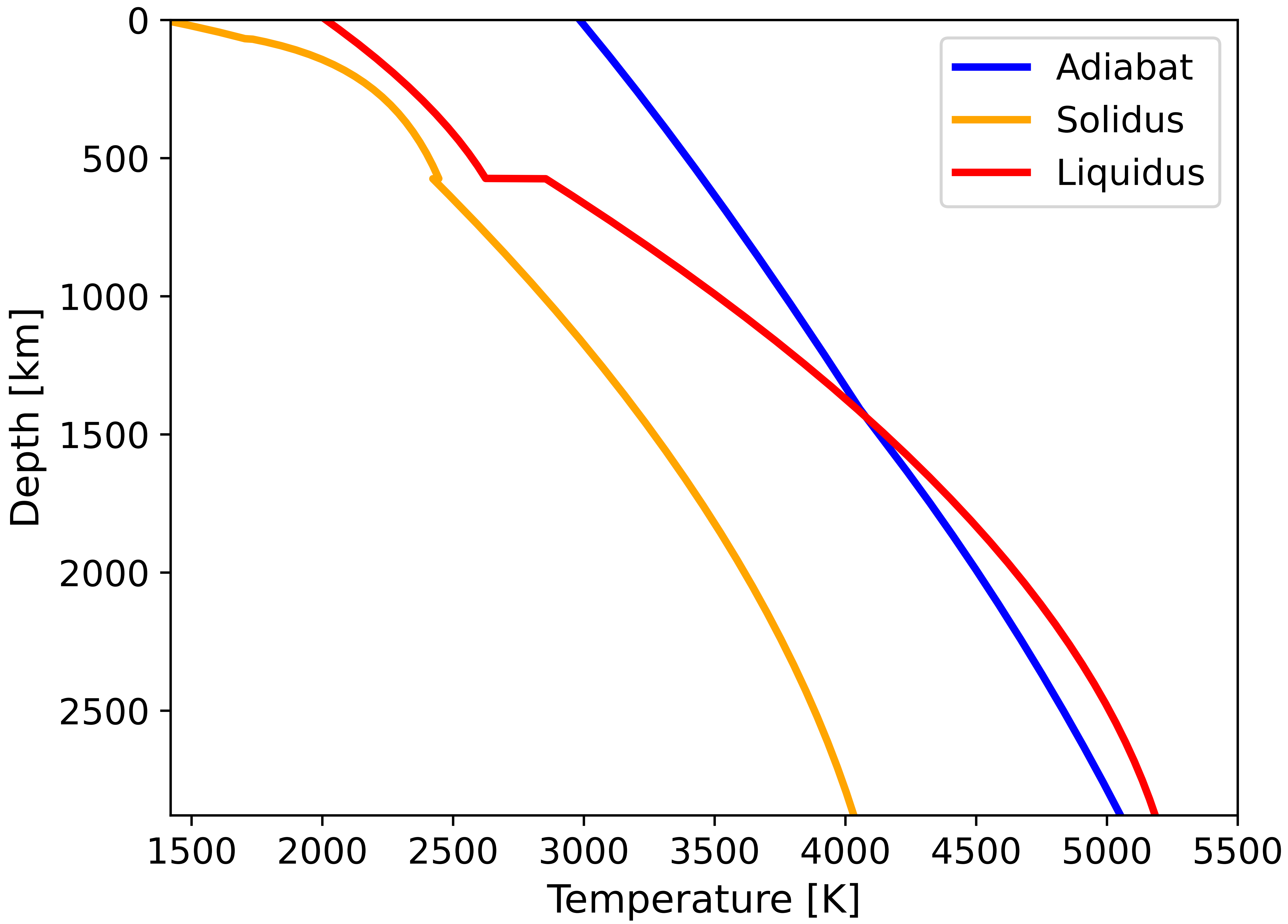
# Atmosphere-Interior model

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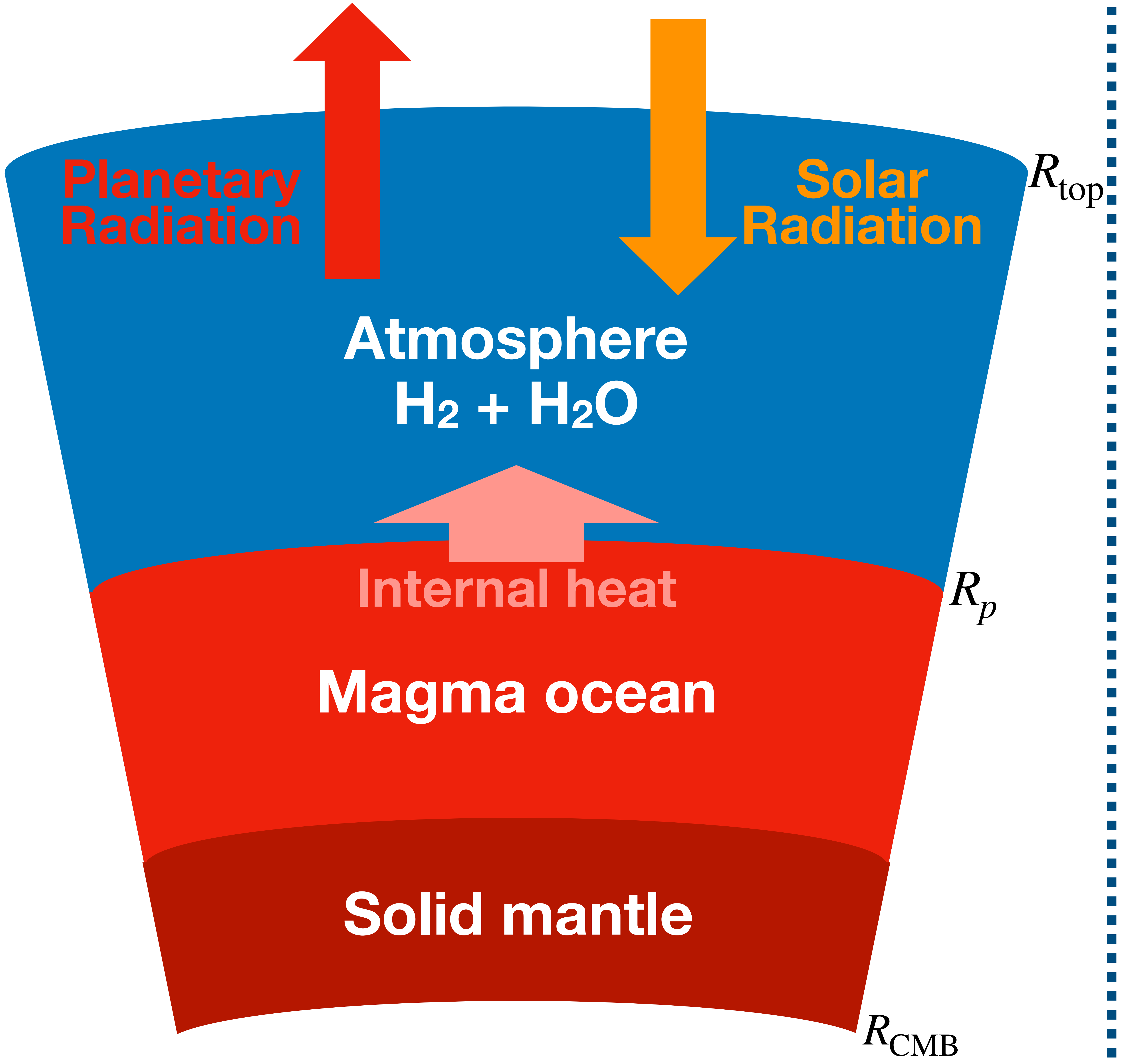


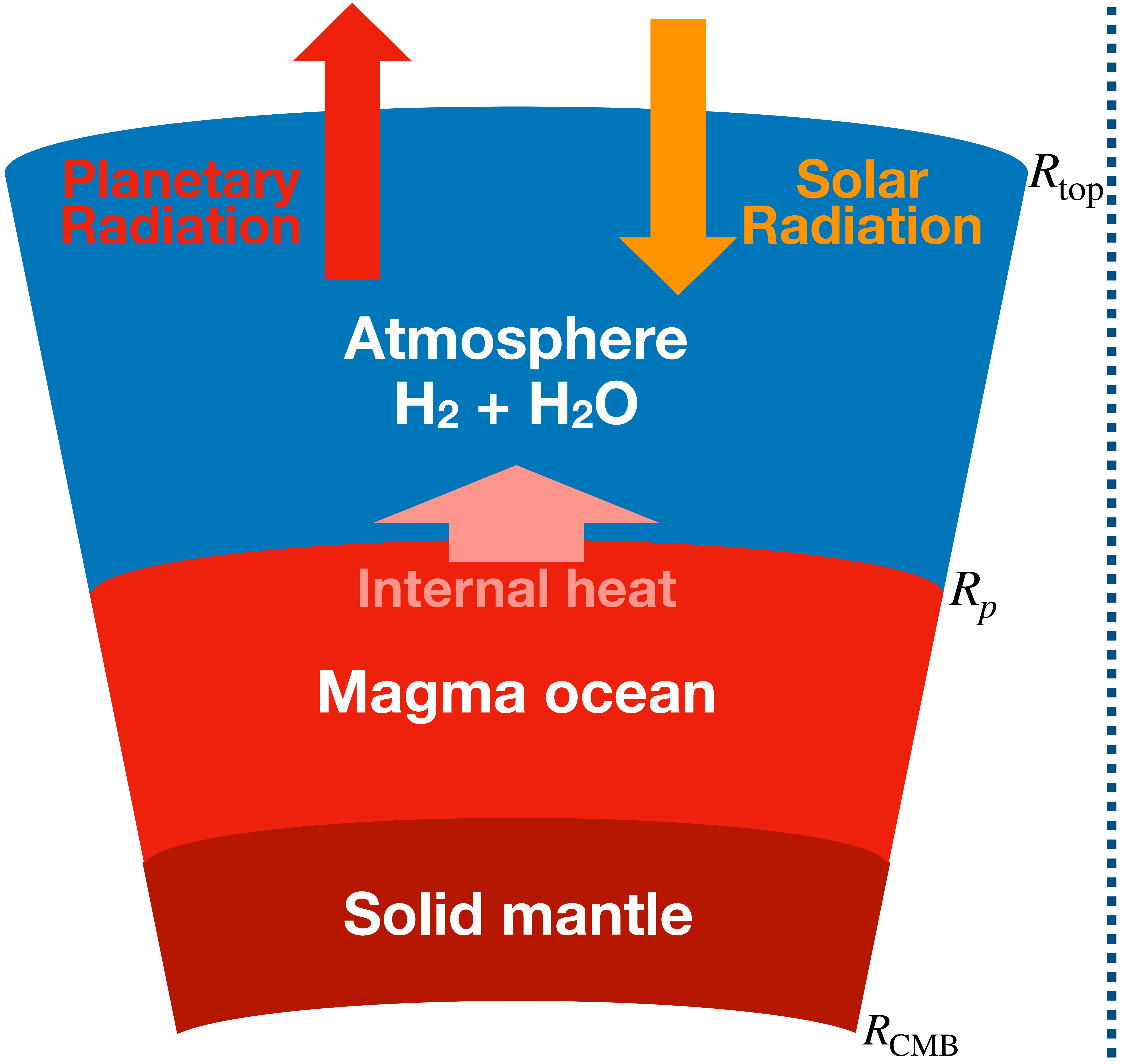

## Partitioning of volatiles

- $$k_i X_i M_{sol} + X_i M_{liq} + \frac{4\pi R_p^2}{g}\frac{\mu_i}{\bar{\mu}} P_i(X_i) = X_0 M_0$$
  - Solubility equilibrium between atmosphere and melt
  - Constant distribution coefficient between melt and solid (=0.01)

## Thermal evolution

- $$r^2 \rho \left( C_p + \Delta H \frac{d\phi}{dt} \right) \frac{dT}{dt} = \frac{\partial}{\partial r}[r^2 (F_{Sun} - F_{OLR})]$$
  - The heat flux from the magma ocean is given by the difference between OLR and incoming net solar radiation
  - Solar flux: 0.7 times the present (Gough, 1981)
  - Surface albedo: 0.2 (Kasting, 1993; Kopparapu et al., 2013)

# Atmosphere-Interior model

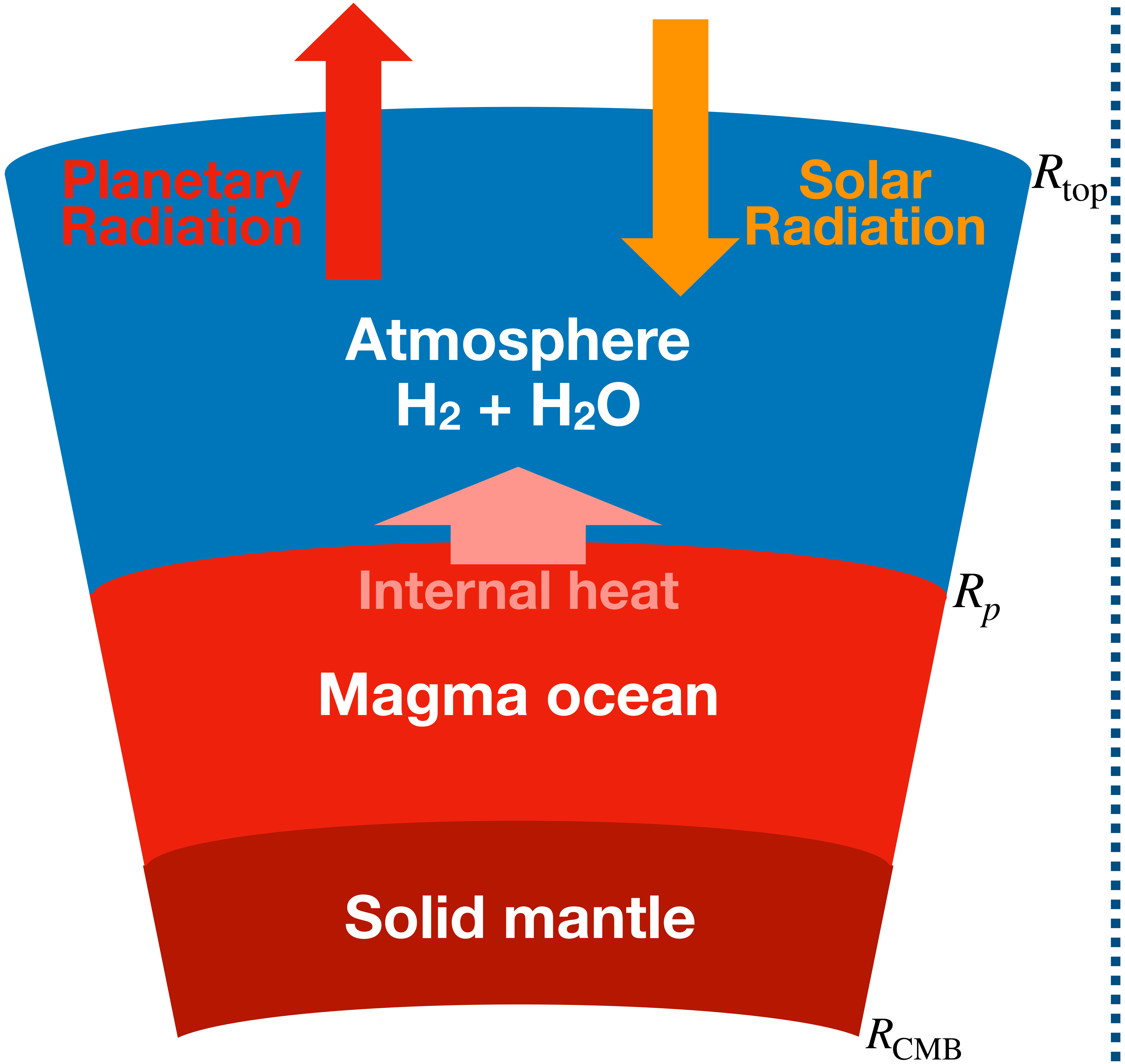



## Radiative transfer

$$\begin{cases} \dfrac{\partial F_\nu^+}{\partial \tau_\nu} = \gamma_1 F_\nu^+ - \gamma_2 F_\nu^- - S_\nu^+ \\ \dfrac{\partial F_\nu^-}{\partial \tau_\nu} = \gamma_2 F_\nu^+ - \gamma_1 F_\nu^- + S_\nu^- \end{cases}$$

- **Absorption**
  - $H_2O$ line absorption
    - Range: 1-30000 $cm^{-1}$
    - Voigt line profile
    - referring to HITEMP (Rothman et al., 2010)
  - $H_2O$ continuum absorption
    - Range: 1-20000 $cm^{-1}$
    - applying the MT_CKD model (Mlawer et al., 2012; 2023)
  - $H_2$-$H_2$ collision-induced absorption
    - Range: 1-20000 $cm^{-1}$
    - referring to Borysow's database (Borysow et al., 2001)

# Atmosphere-Interior model

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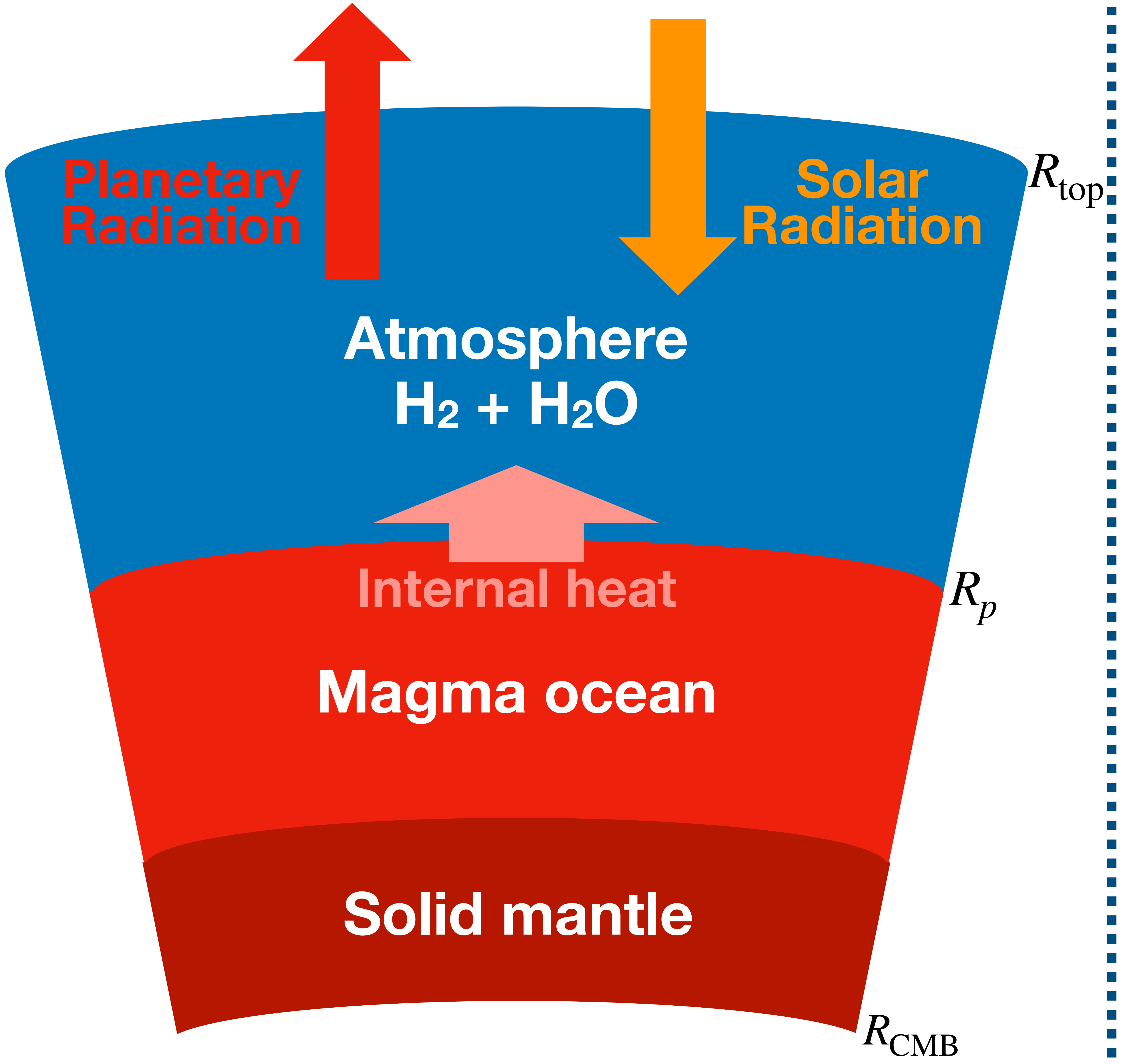
- **Scattering**
  - Rayleigh scattering by $H_2$ and $H_2O$
- **Planetary albedo**
  - (Upward scattered solar flux at the top) ÷ (Incoming solar flux)

# Atmosphere-Interior model

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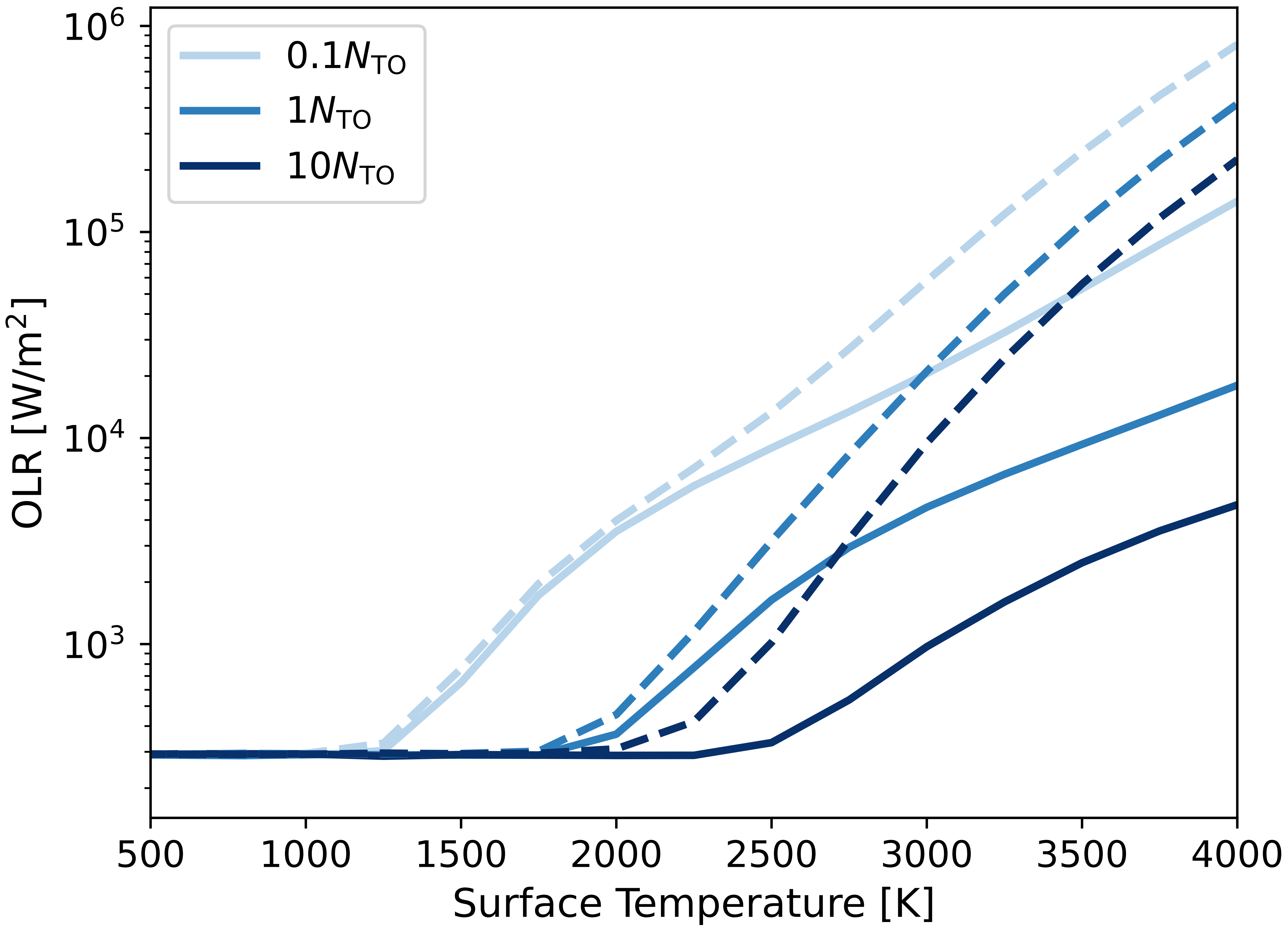
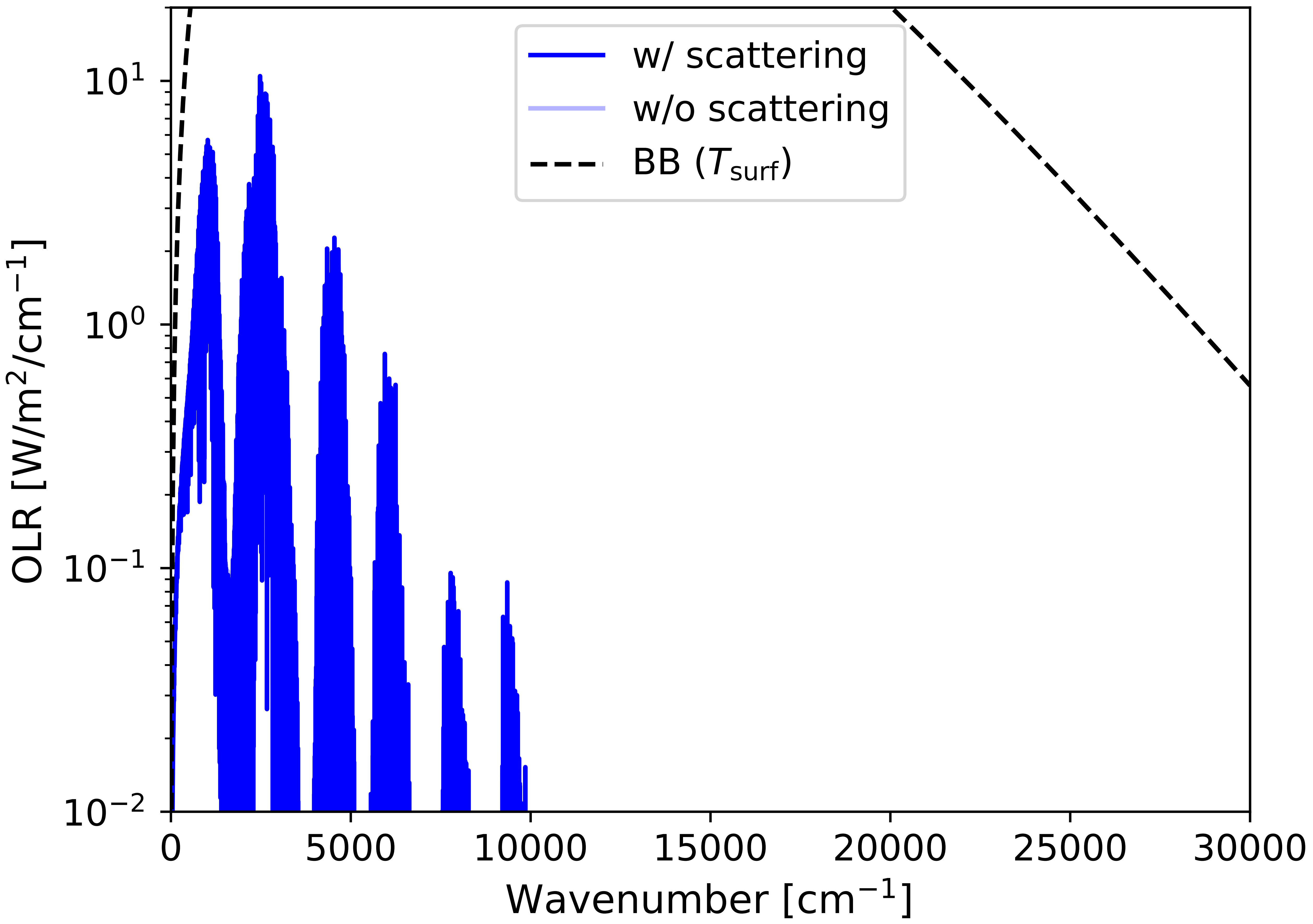
- **Calculation method**
  - Line-by-line calculation (Wordsworth et al., 2017)
    - Range: 1-30000 $cm^{-1}$
    - Resolution: 1 $cm^{-1}$
  - The atmosphere is vertically divided into 500 layers from the ground to the top
    - The grids are equally spaced on a logarithmic scale of pressure
    - The pressure at the top is 1 Pa

# OLR (pure $H_2O$ atmosphere)

## Total



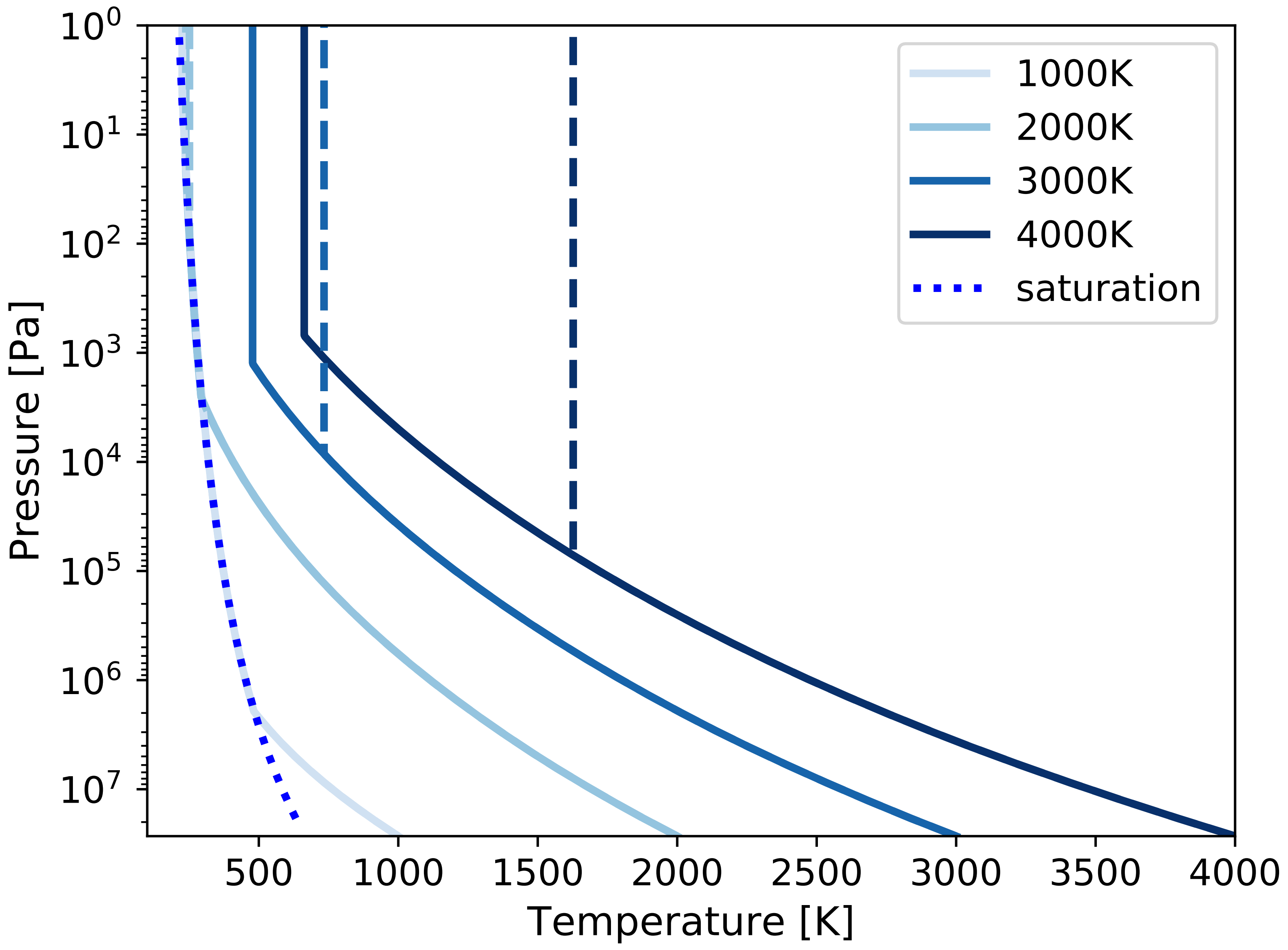

## Per wavenumber ($1N_{TO}$, 3000 K)



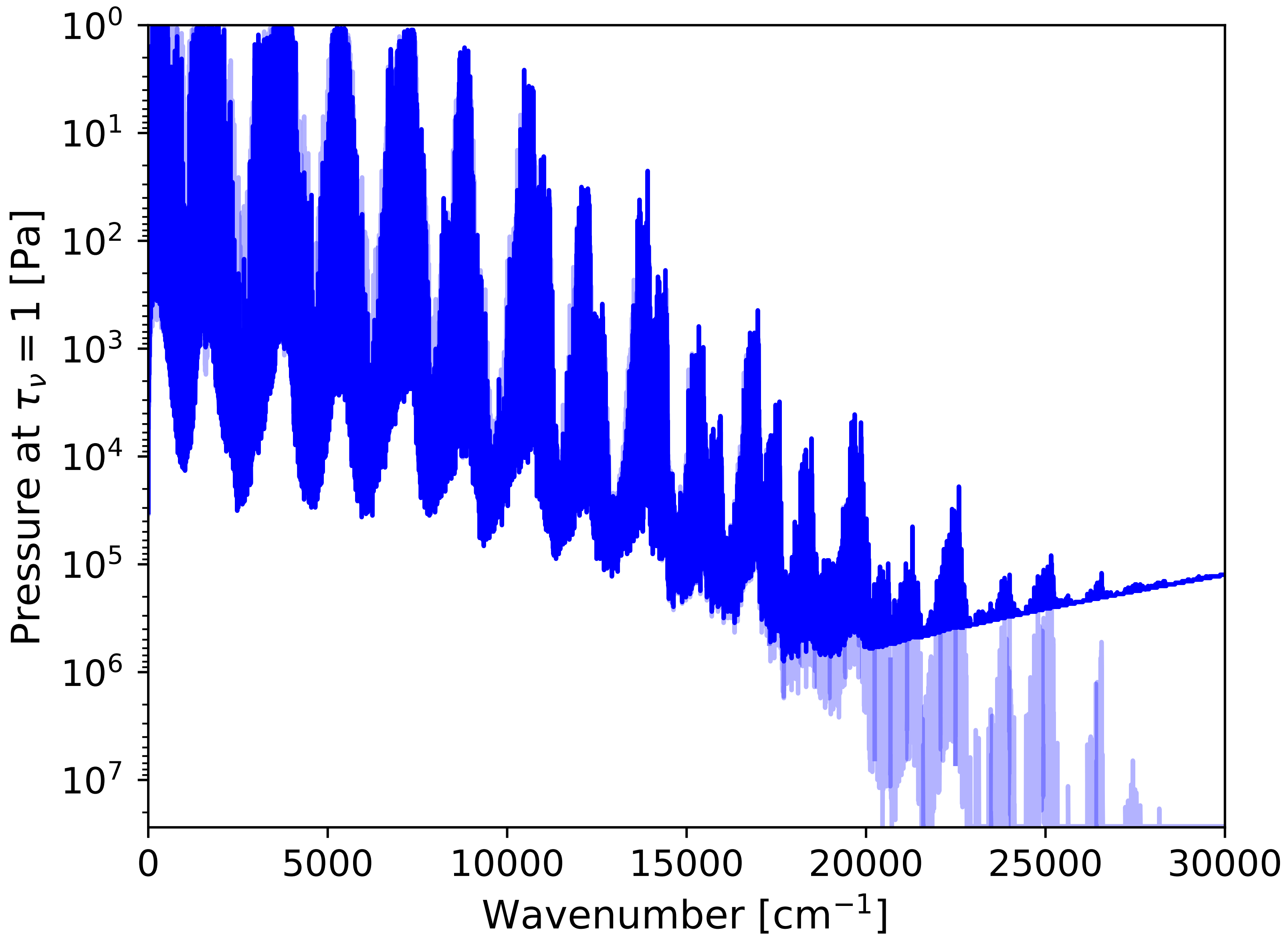

- **The scattering blanketing effect becomes significant as surface P and T increase**
  - High P → Scattered doward flux increases
  - High T → Thermal radiation flux increases in high wavenumbers, where Rayleigh scattering is effective

# Vertical profile (pure $H_2O$ atmosphere, $1N_{TO}$)

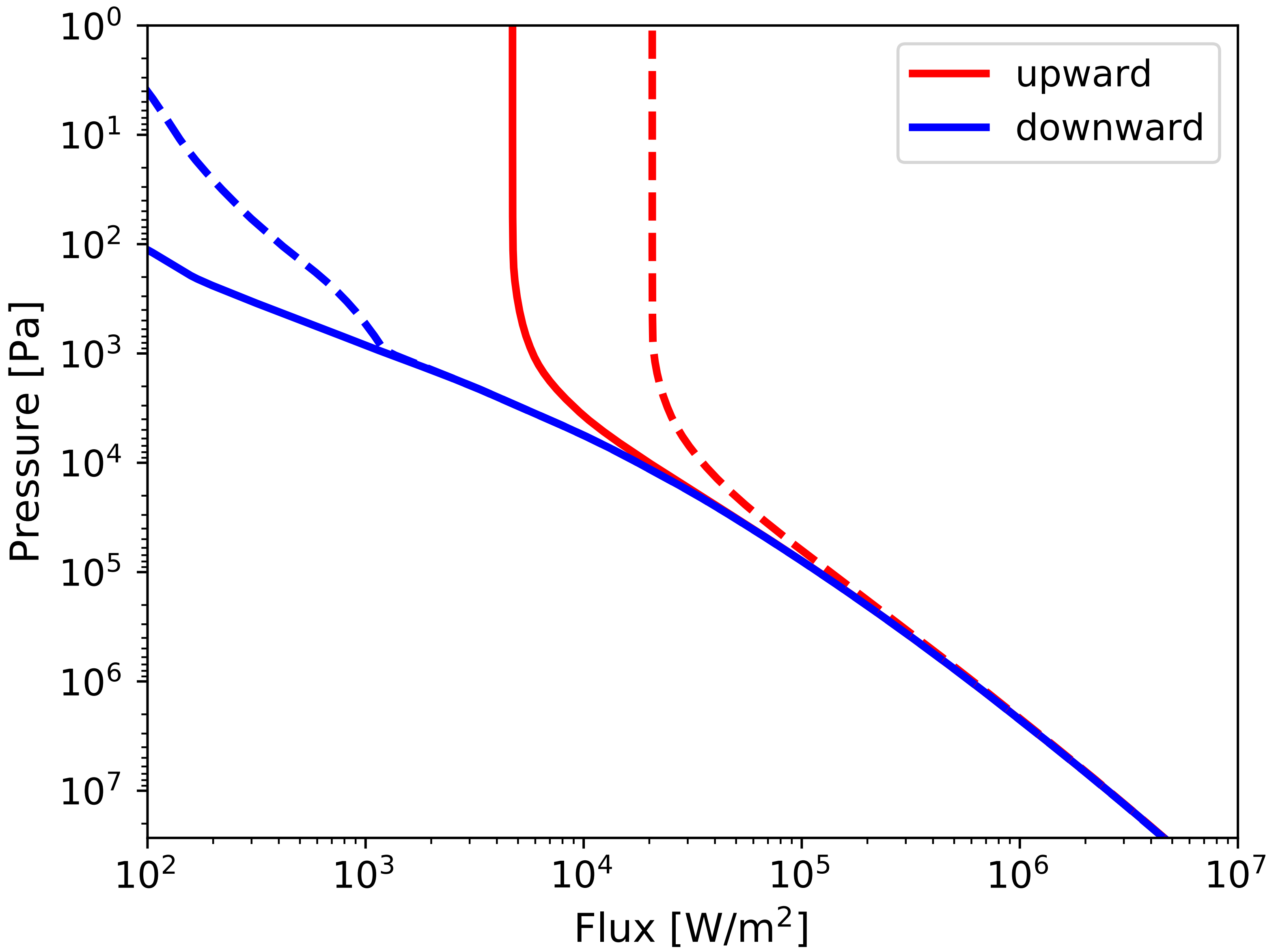
## Temperature




## Optical depth




## Planetary radiation flux



# OLR (pure $H_2$ atmosphere)

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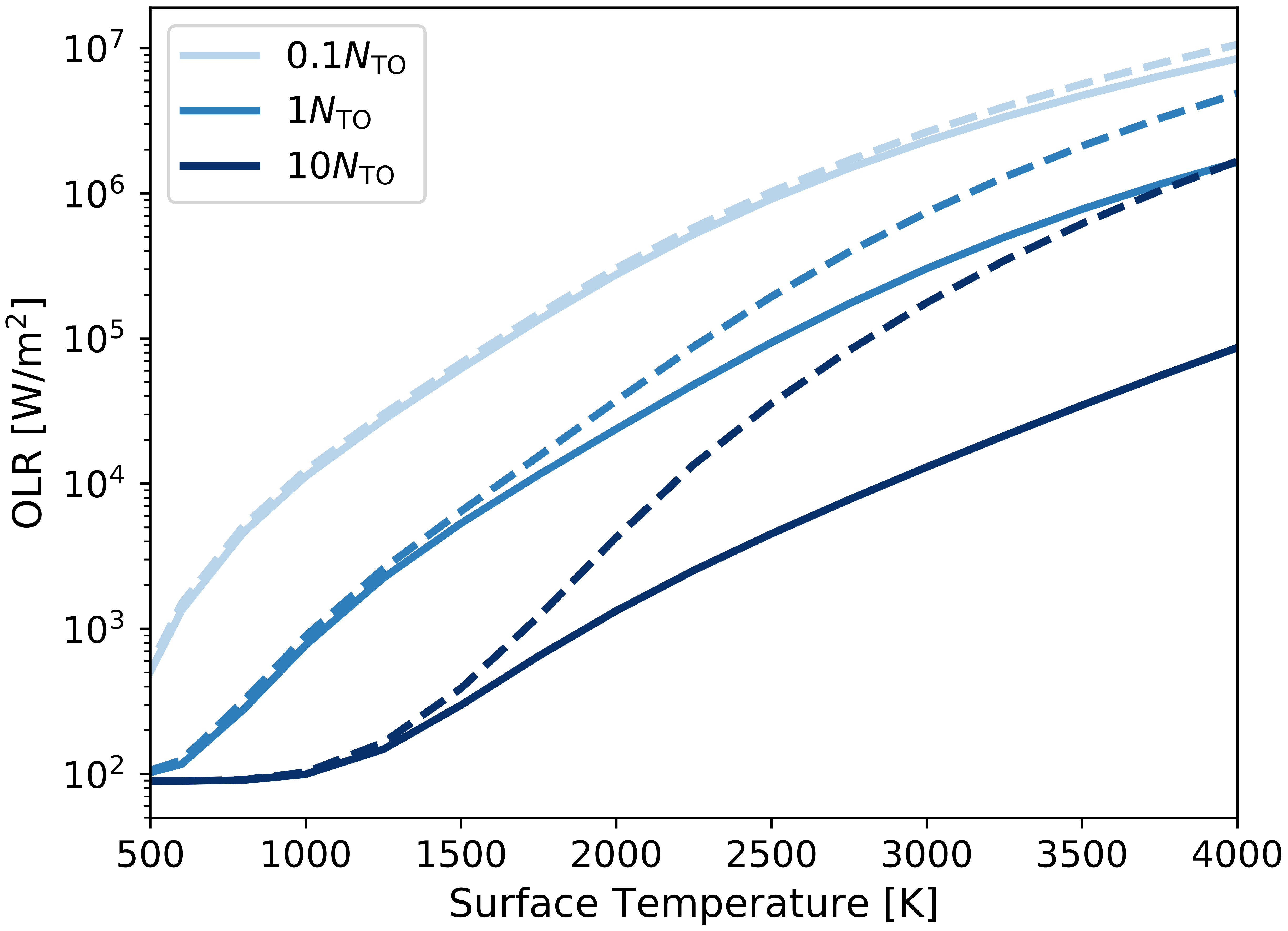


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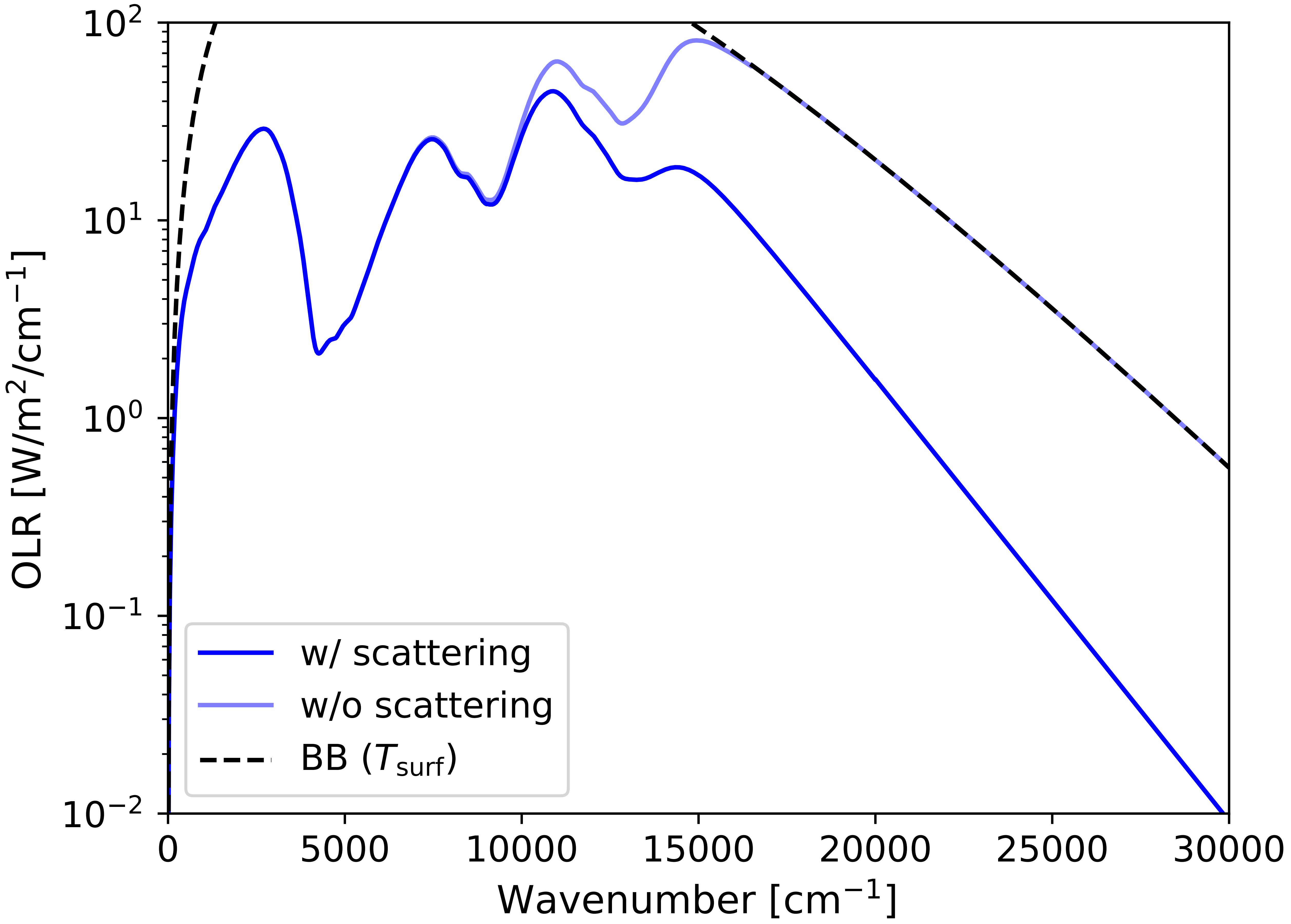


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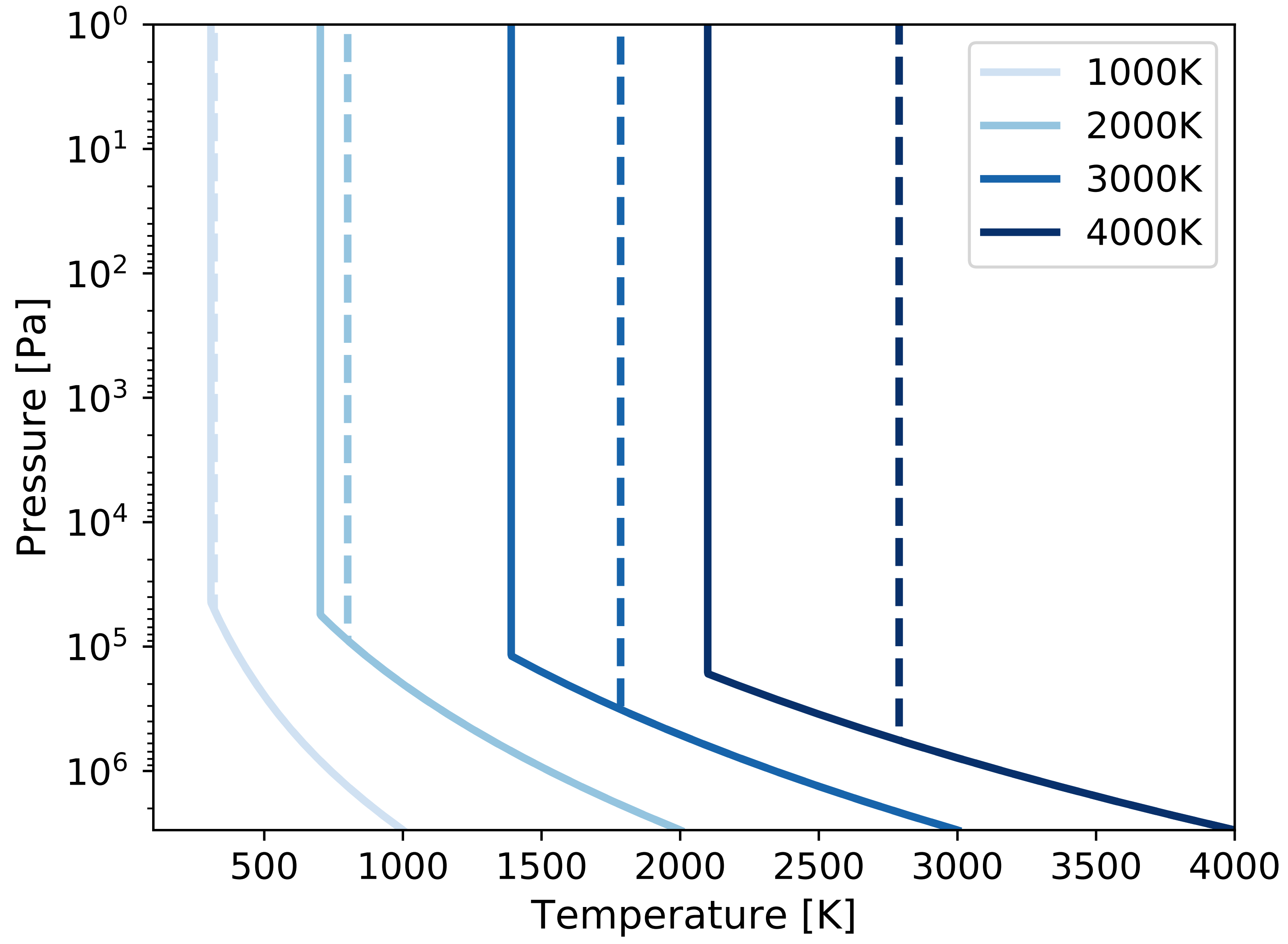


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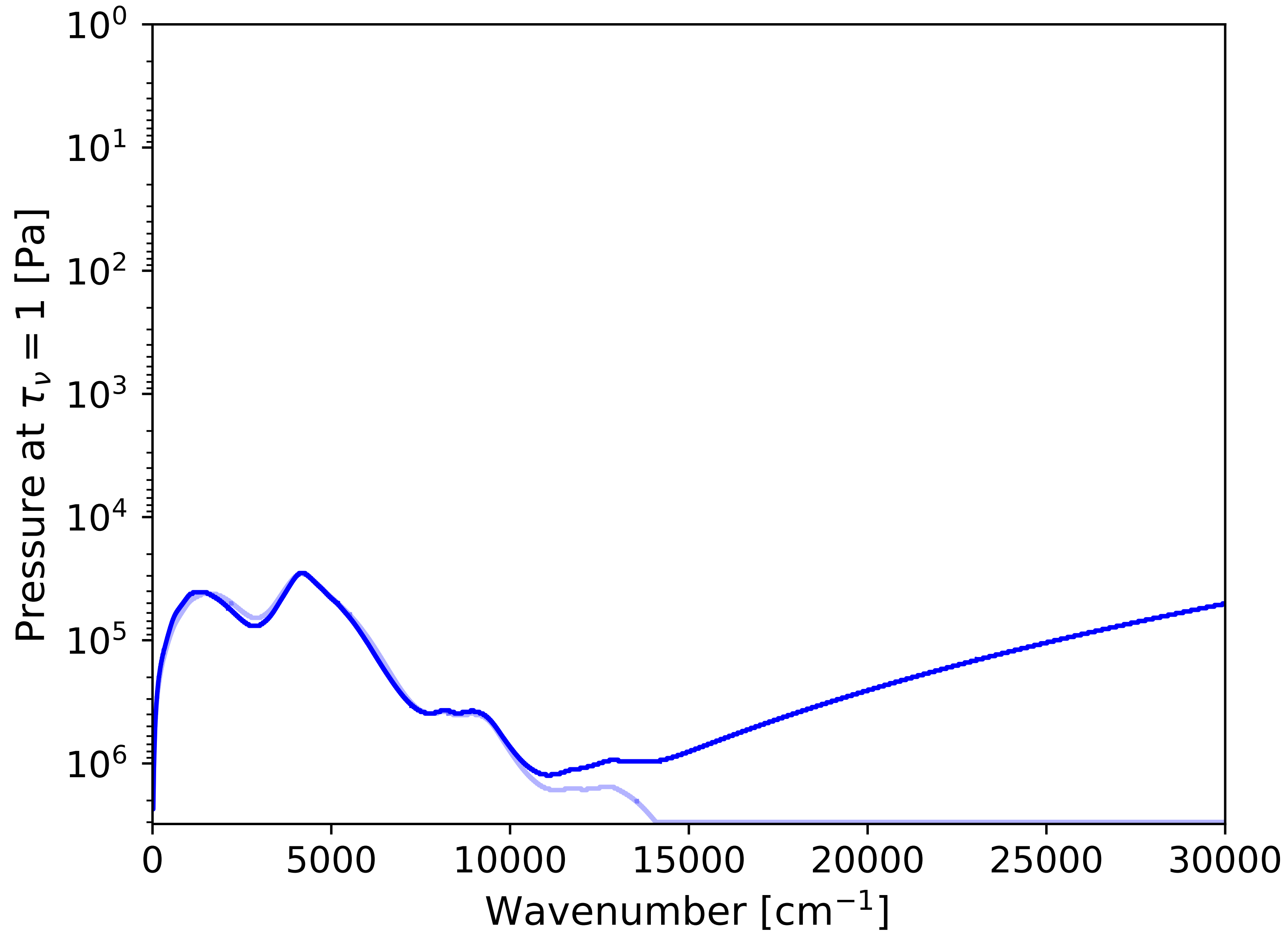
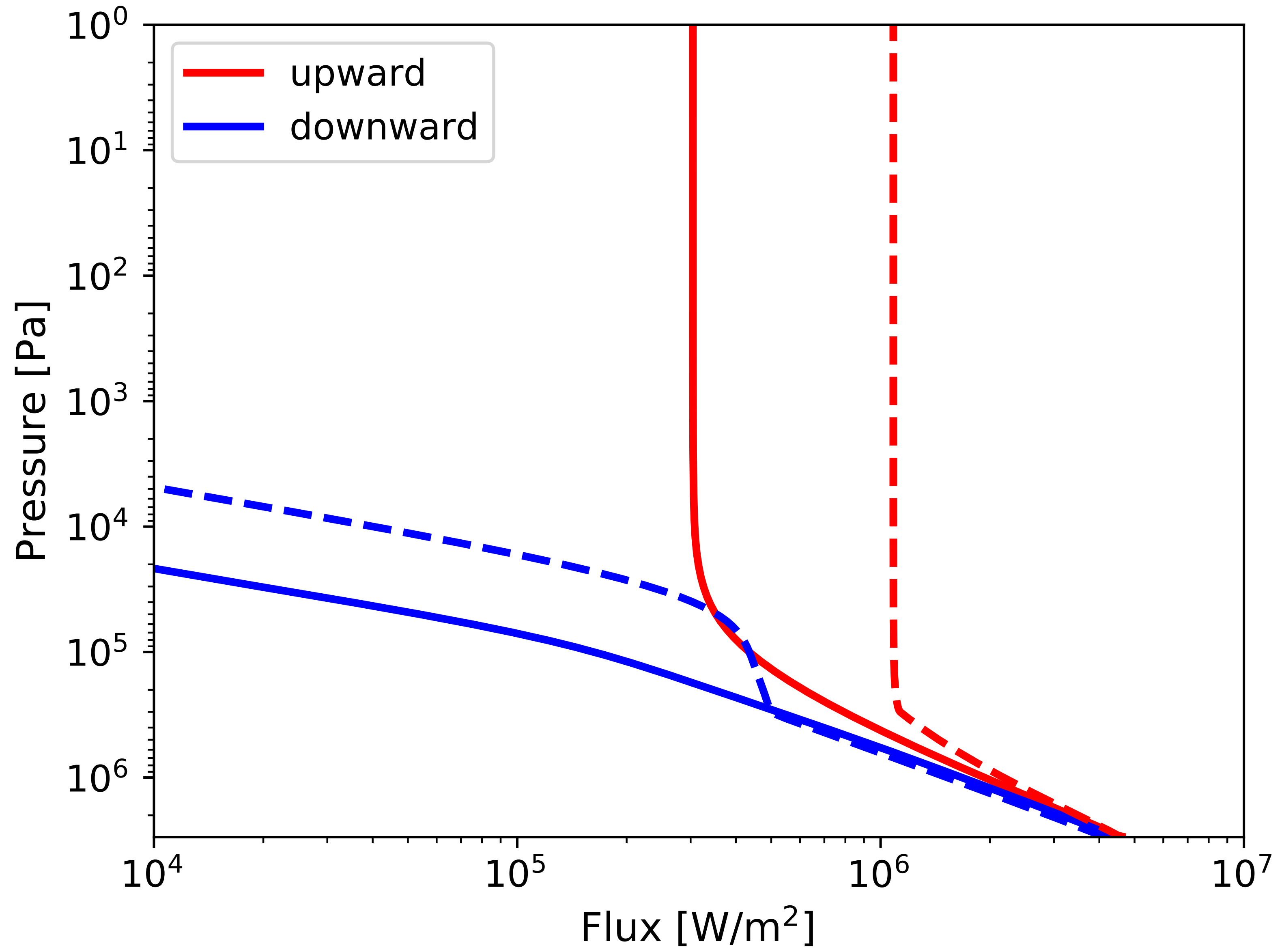
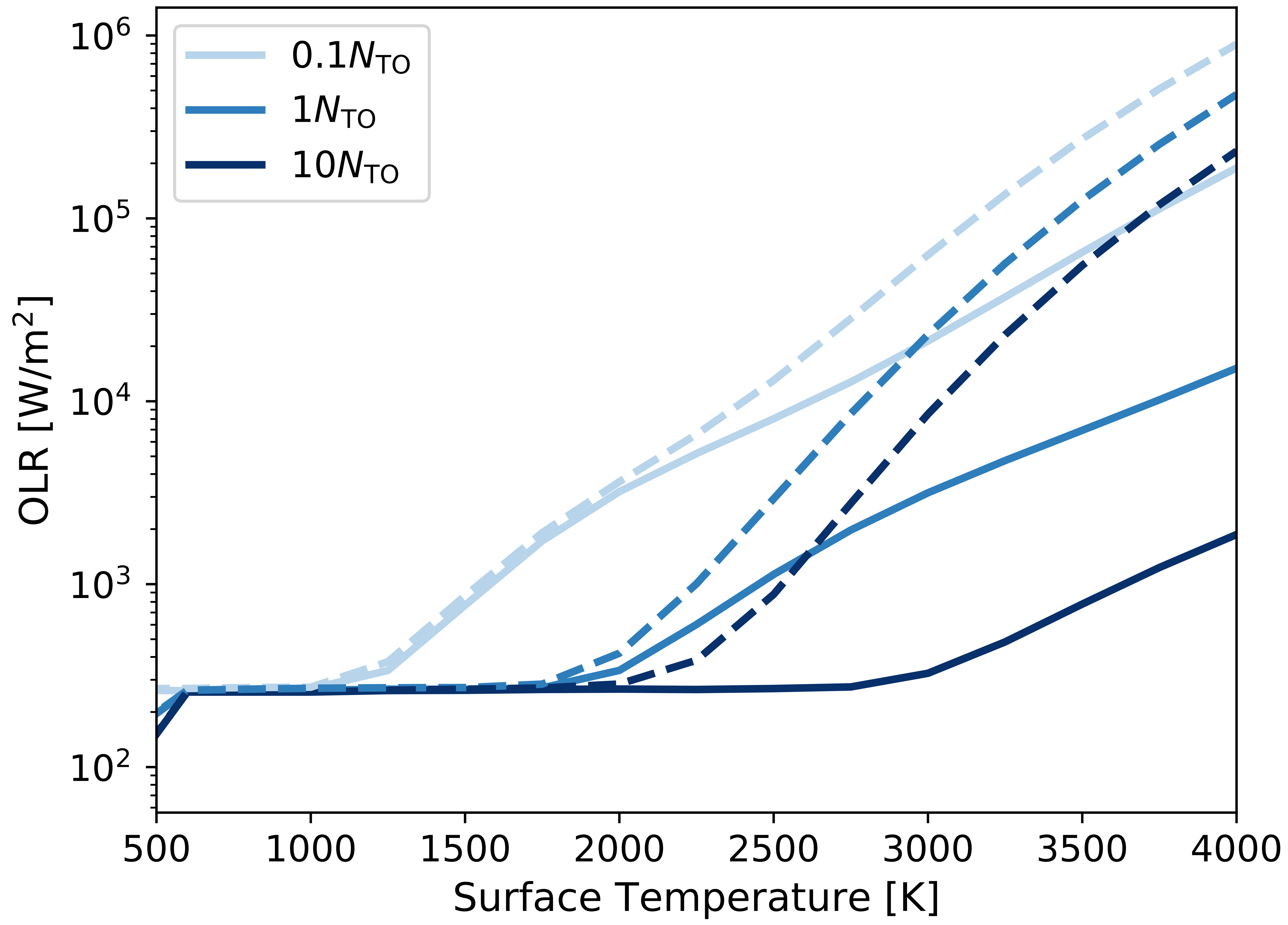



## Planetary radiation flux



# OLR ($H_2$-$H_2O$ atmosphere, $N_{H2}/N_{H2O}$=1)

## Total

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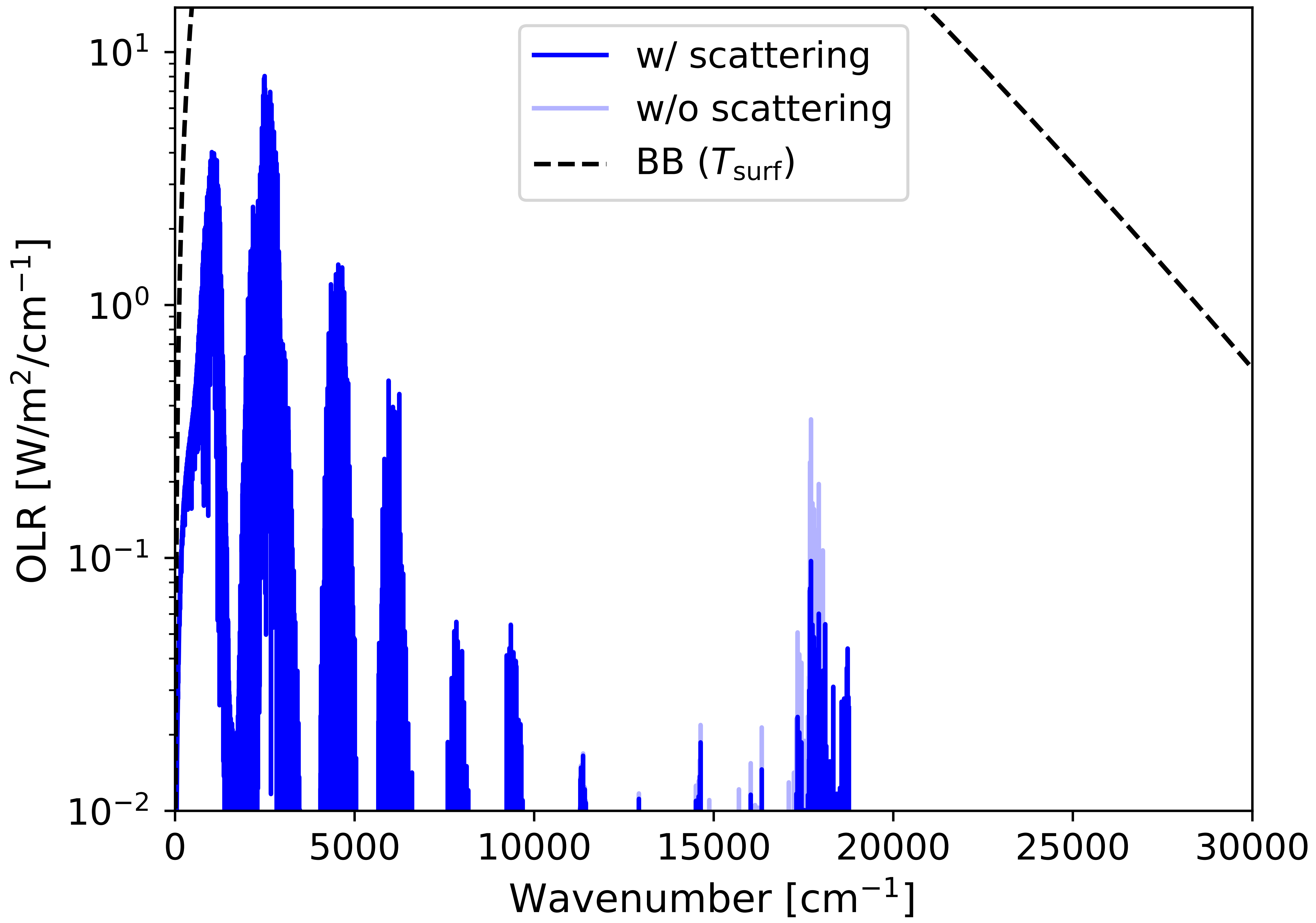


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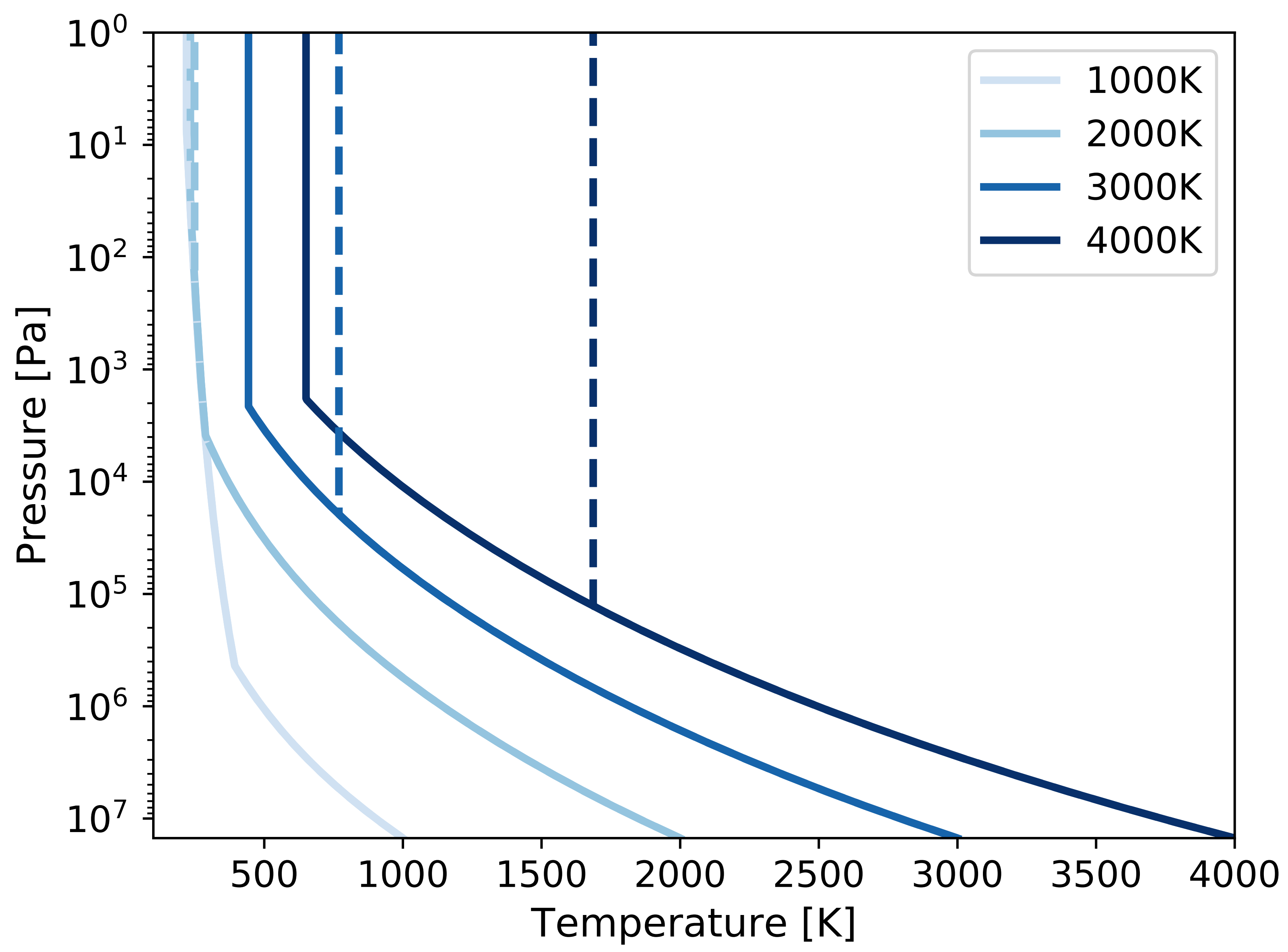


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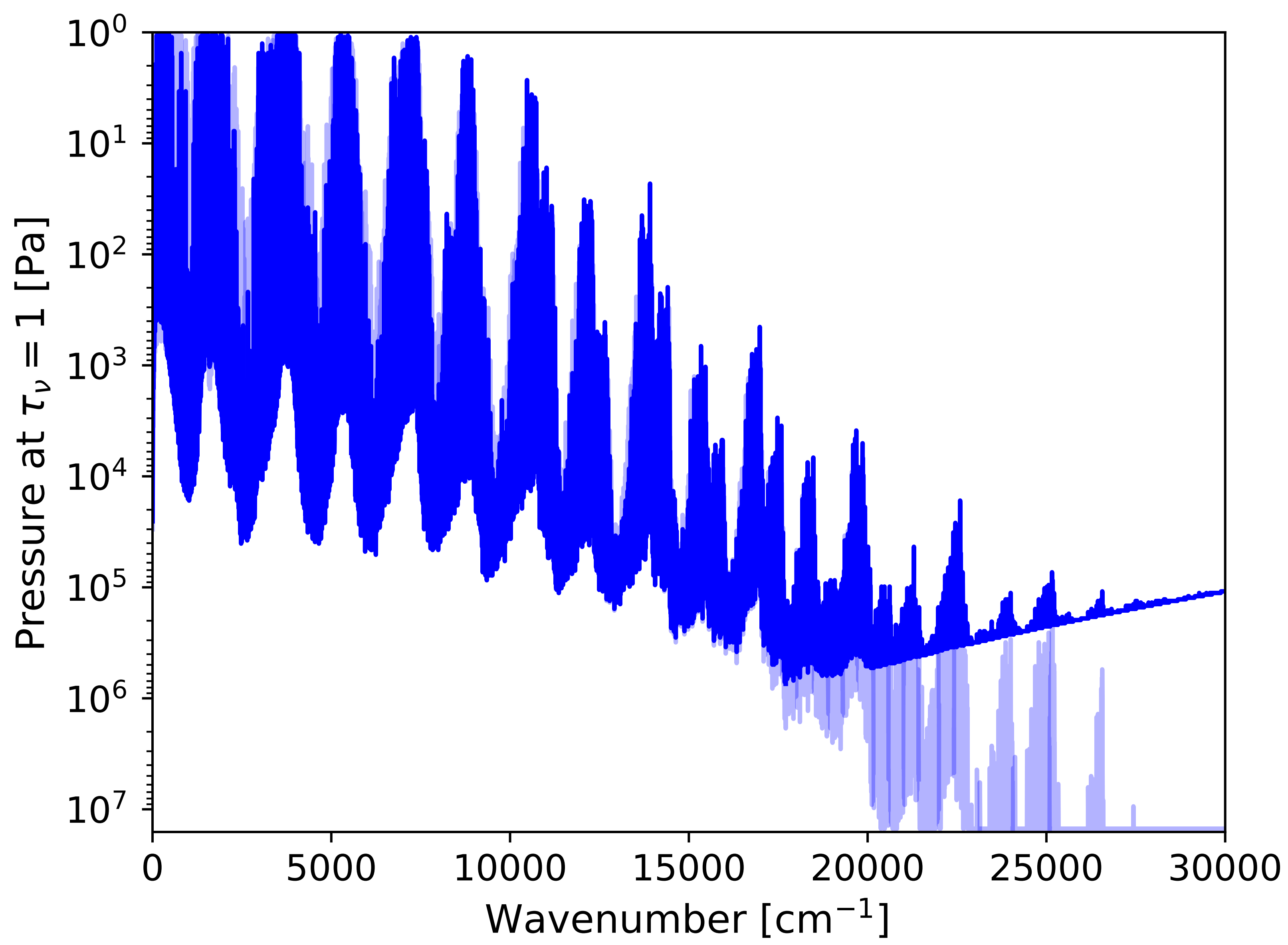


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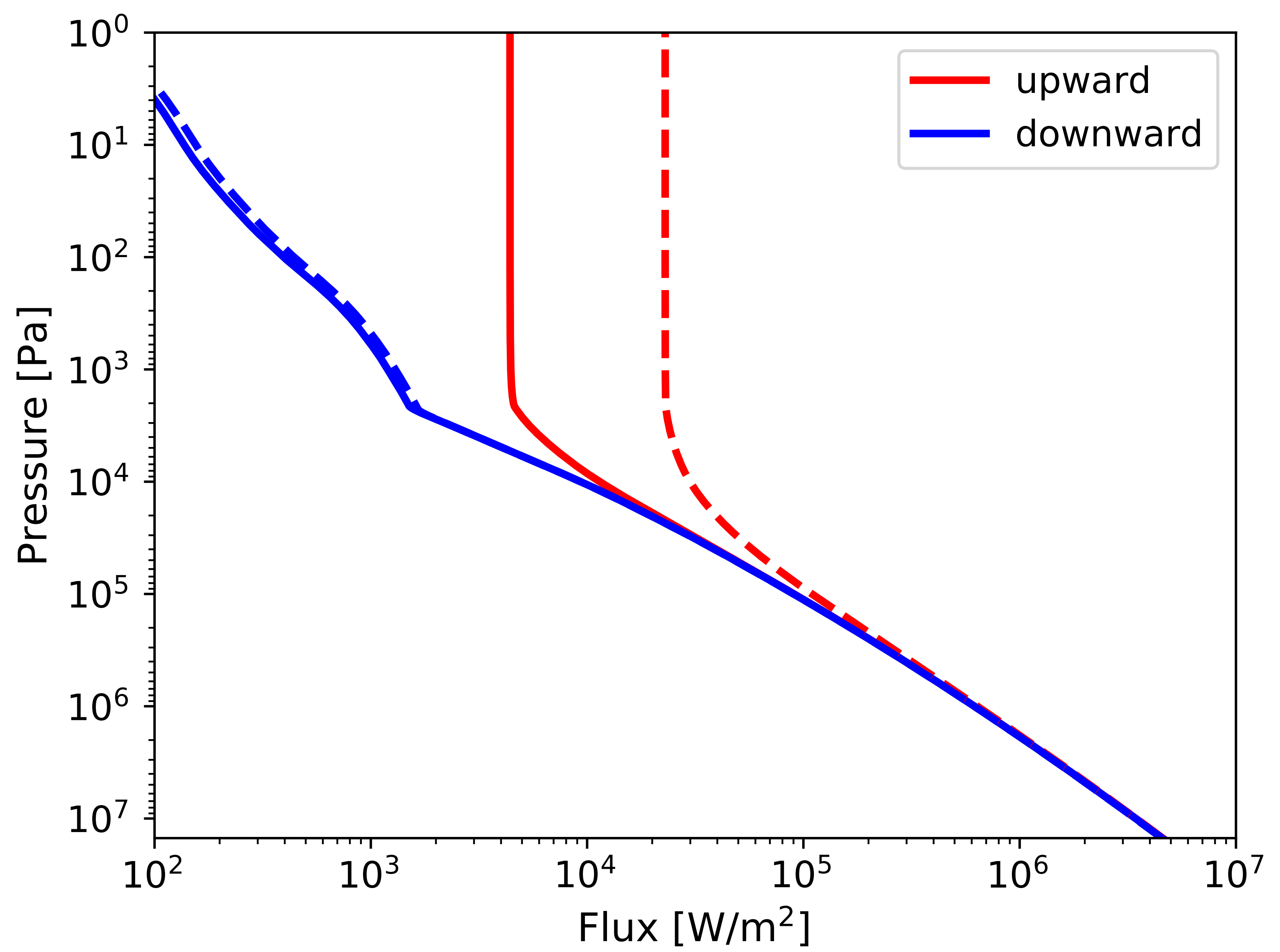
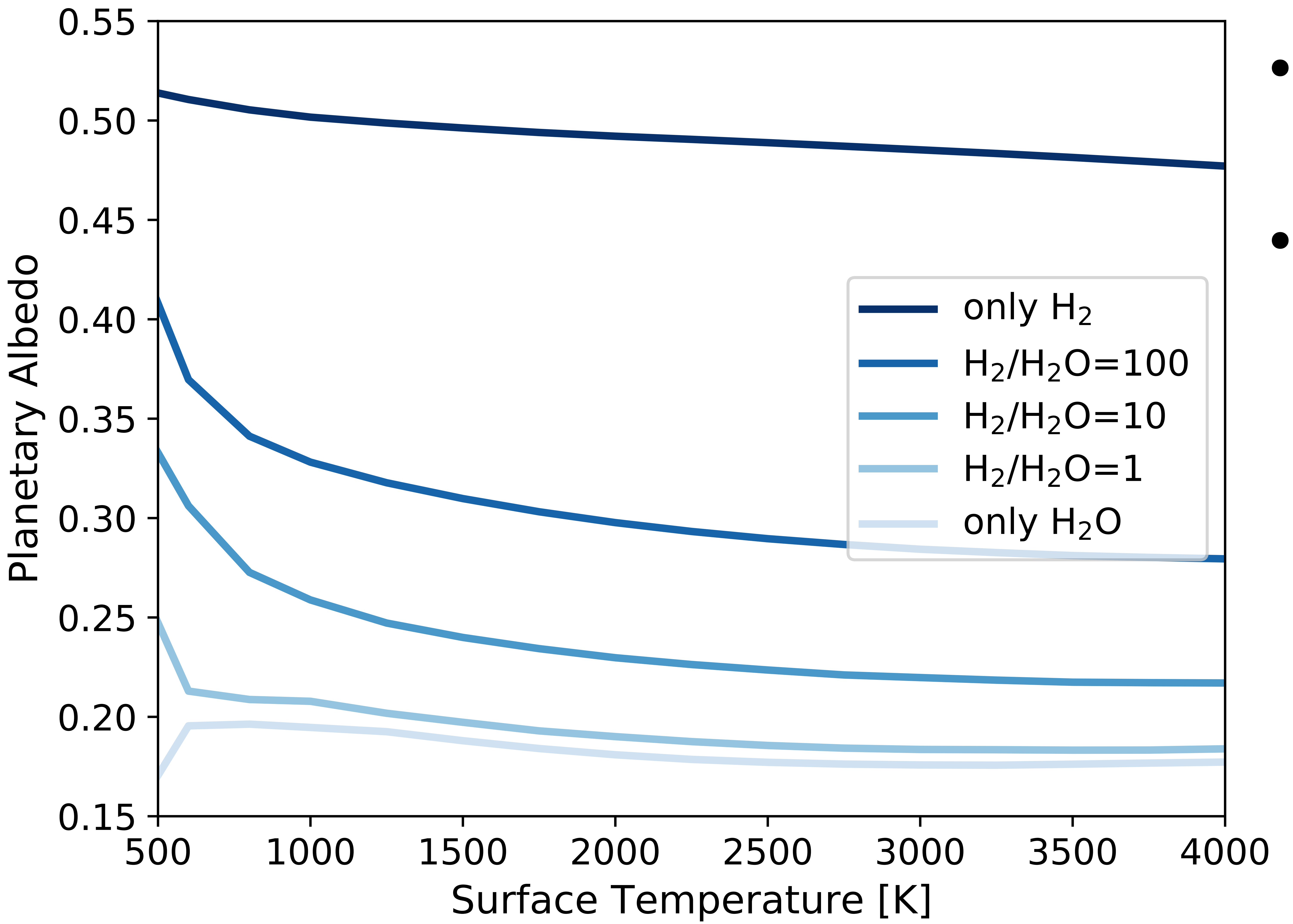


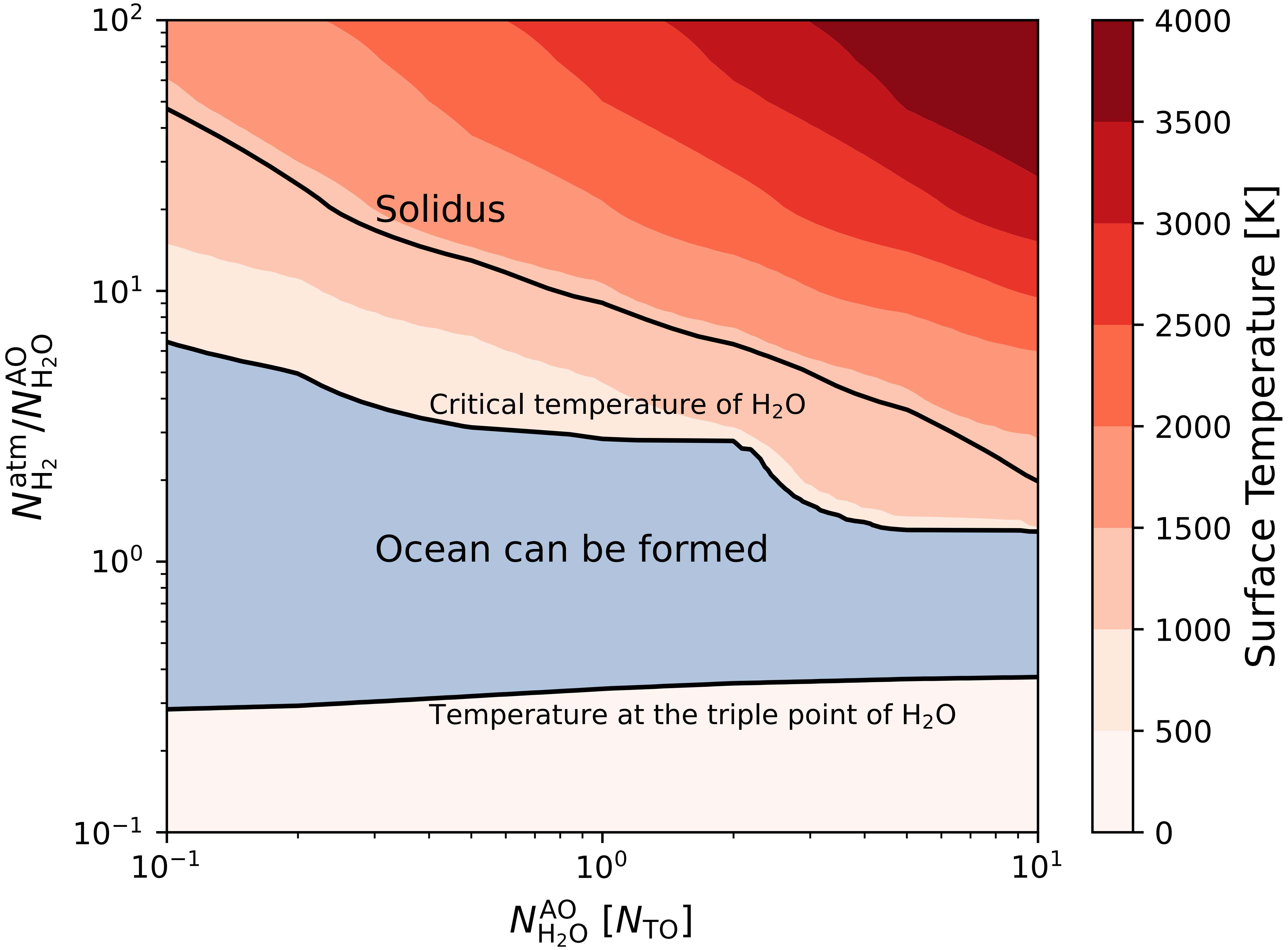
# Planetary albedo ($N_{H2}+N_{H2O}=N_{TO}$)



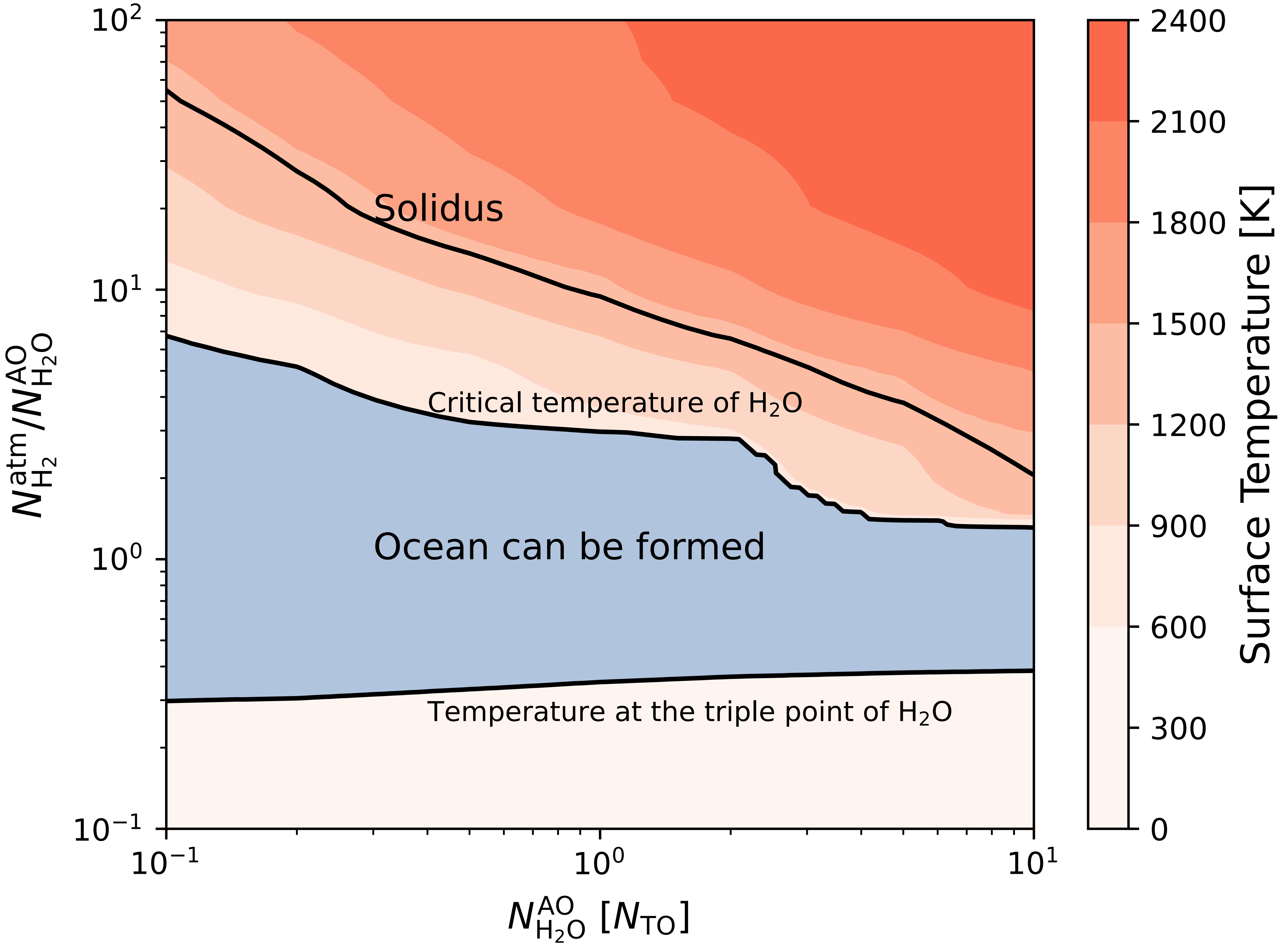

- (Planetary Albedo)
  = (Upward scattered solar flux)
  ÷ (Incoming solar flux)
- Planetary albedo increases with $H_2$ mixing ratio
  - due to a decrease in absorption of stellar radiation by $H_2O$

# Equilibrium surface temperature

## w/ scattering

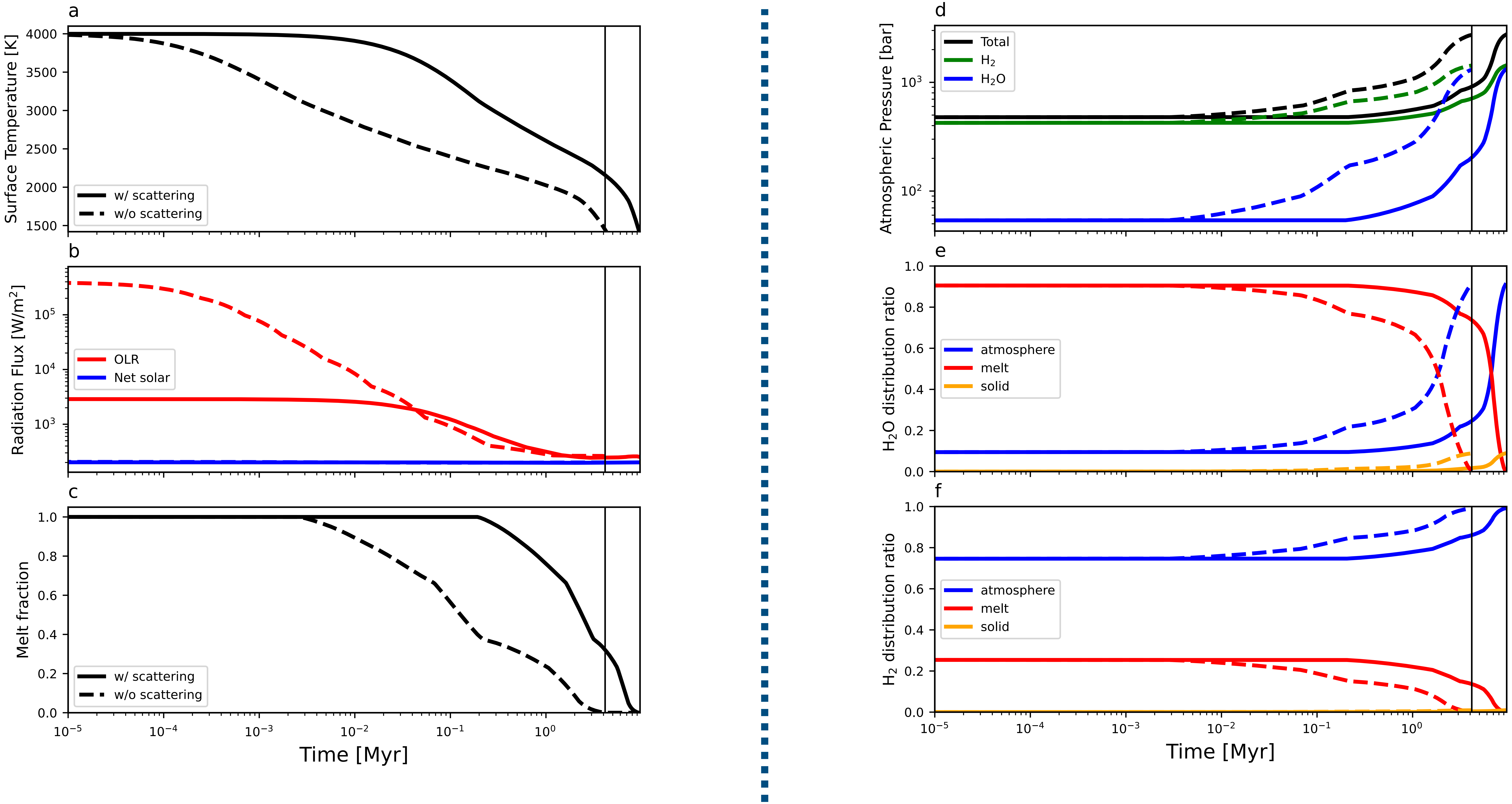



## w/o scattering



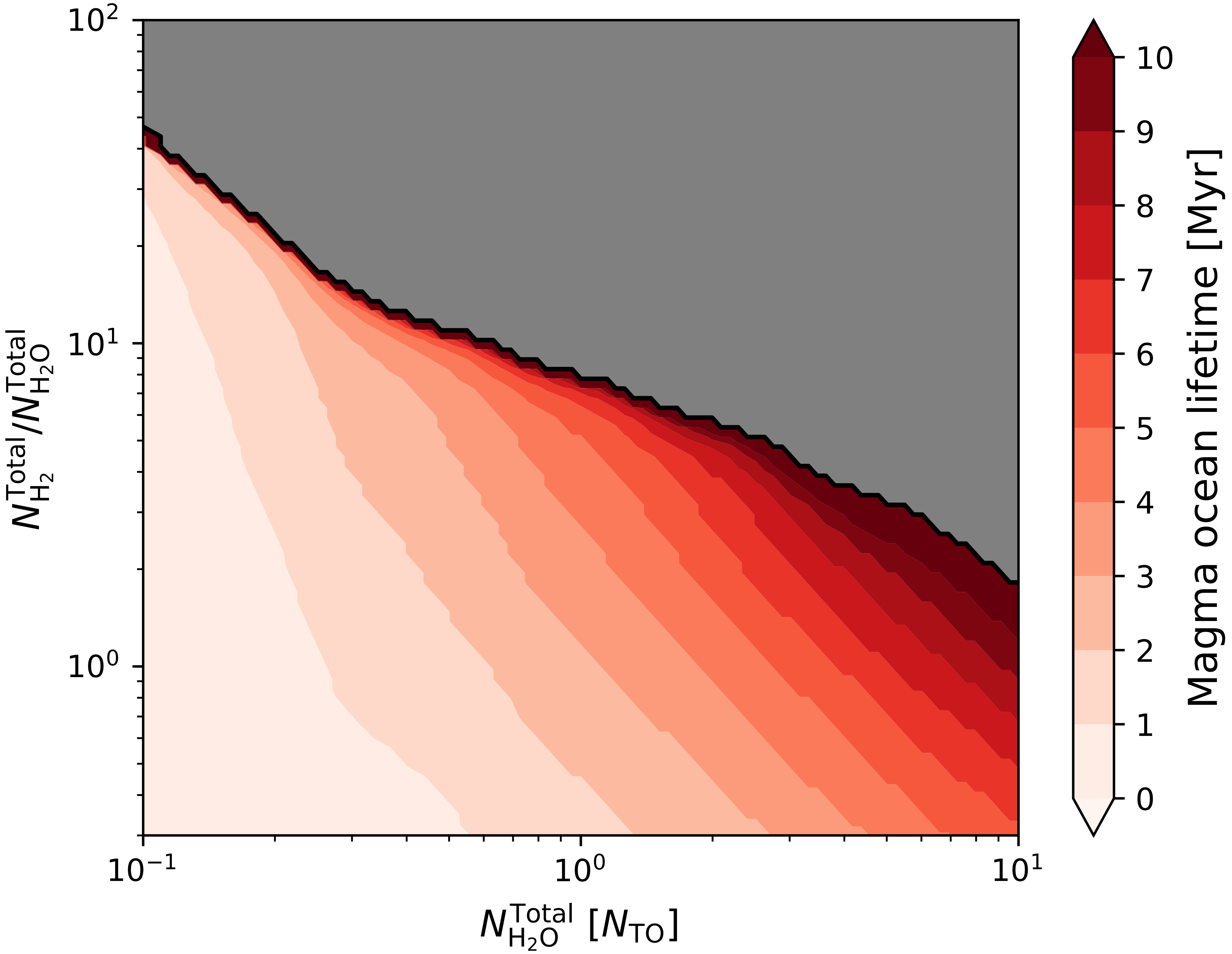

- (OLR) = (net absorbed solar flux)
- Equilibrium temperature increases with the amounts of $H_2O$ and $H_2$
- The scattering effect further increases the equilibrium temperature

# Example of the atmosphere-interior evolution ($N_{H2O}=N_{H2}=10N_{TO}$)



# Magma ocean lifetime

## w/ scattering

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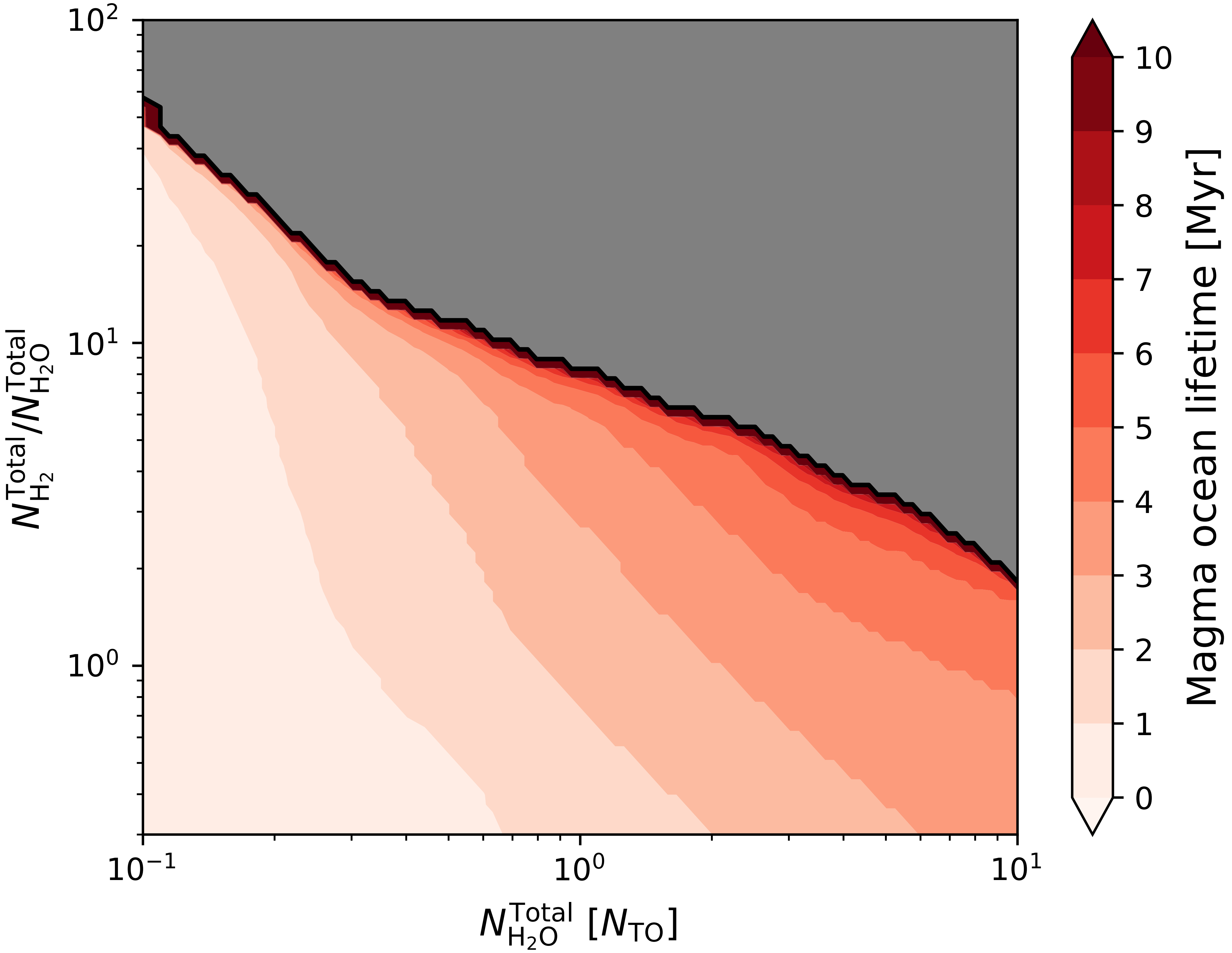
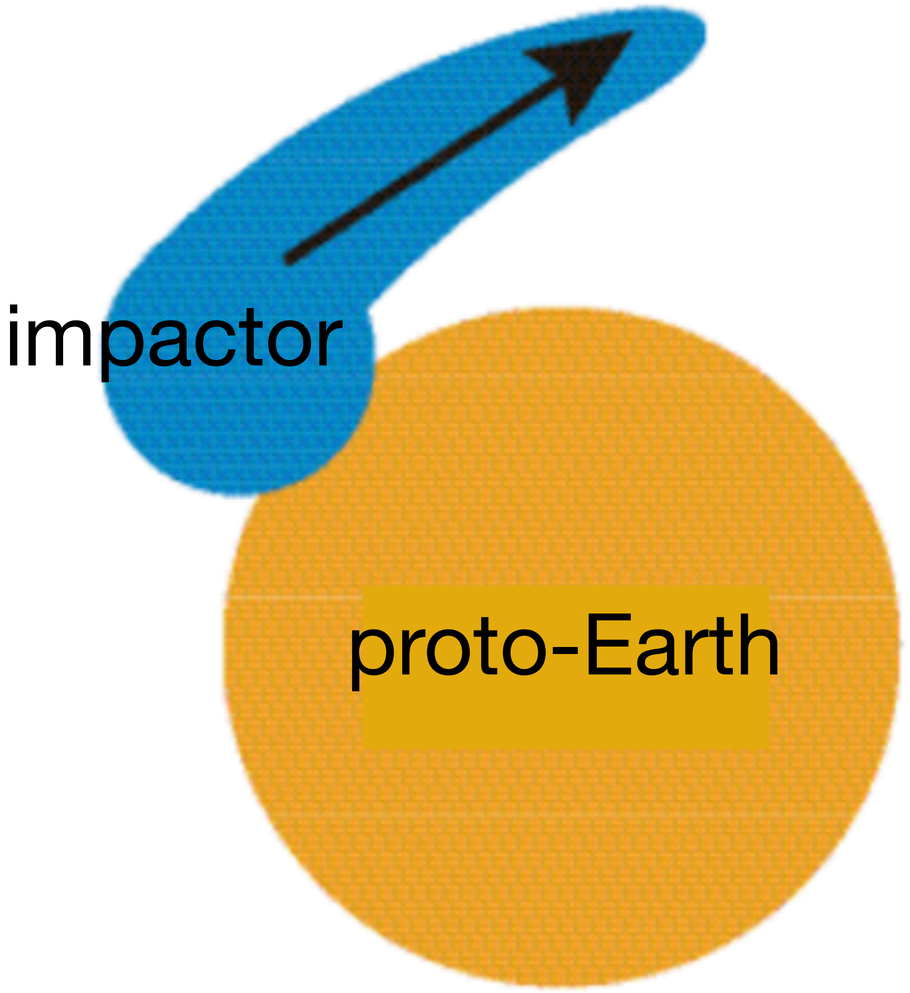


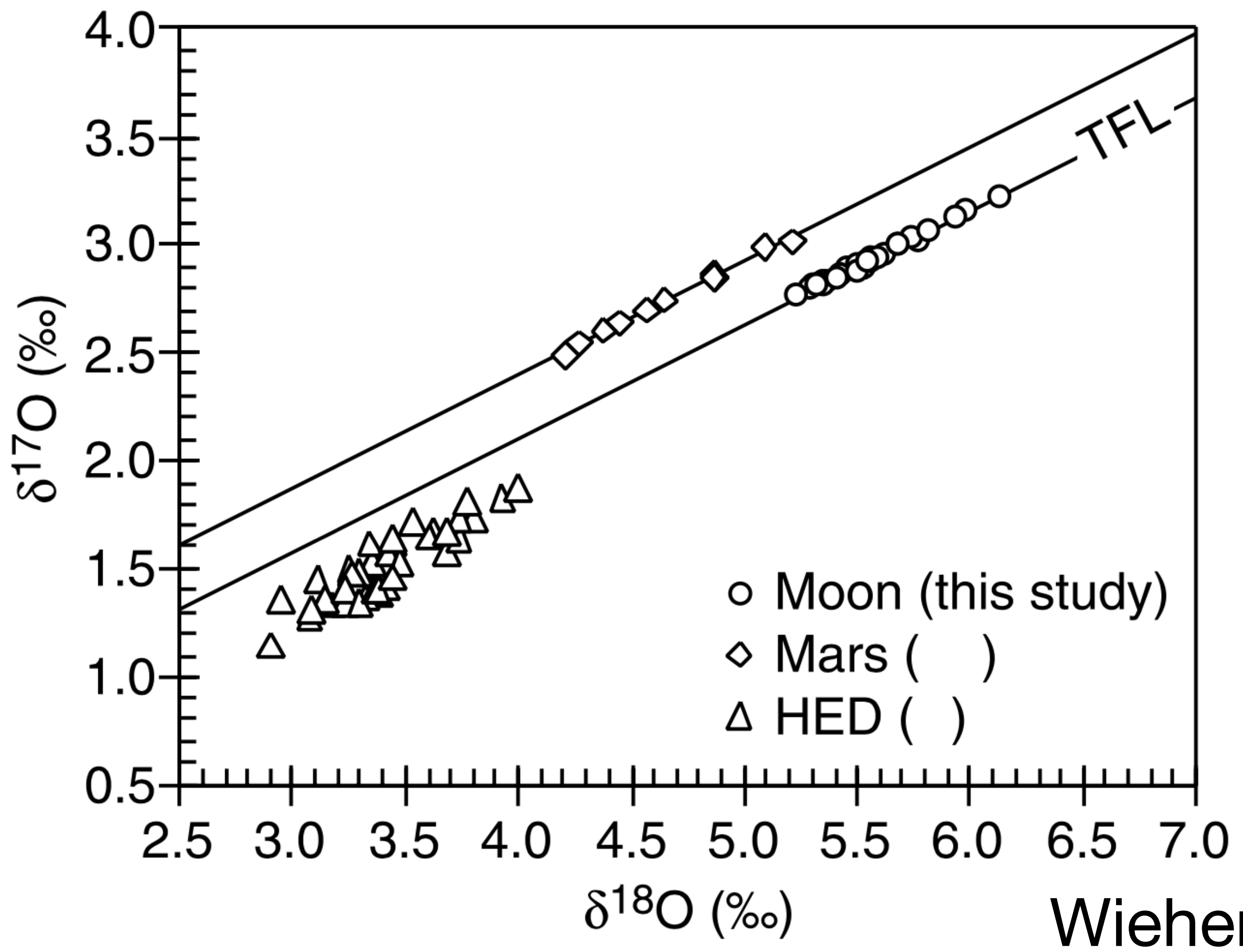

- The scattering blanketing effect prolongs the magma ocean lifetime especially when the total amounts of $H_2O$ and $H_2$ are high

# Implication for the Moon’s origin

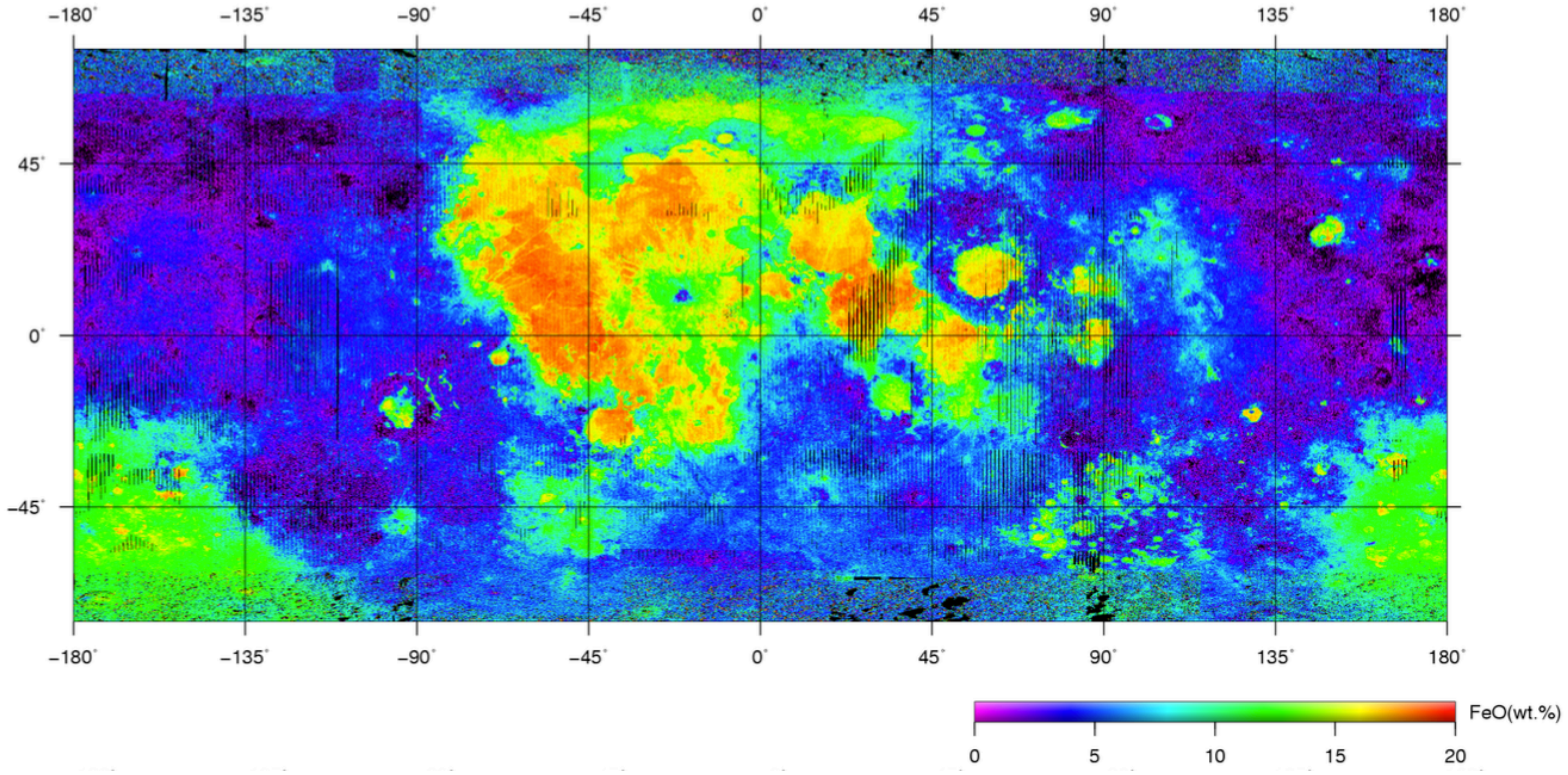
## Classical giant impact model




- Most of the building materials of the Moon are from the impactor (e.g., Canup, 2004)
  - ✘ Similarity in the isotopic composition between the Earth and the Moon (e.g., Zhang et al., 2012)
  - ✘ Enrichment of FeO in the basalts and the bulk Moon than in the Earth’s mantle (Khan et al., 2006)




Wiehert et al. (2001)




Ohtake et al. (2016)

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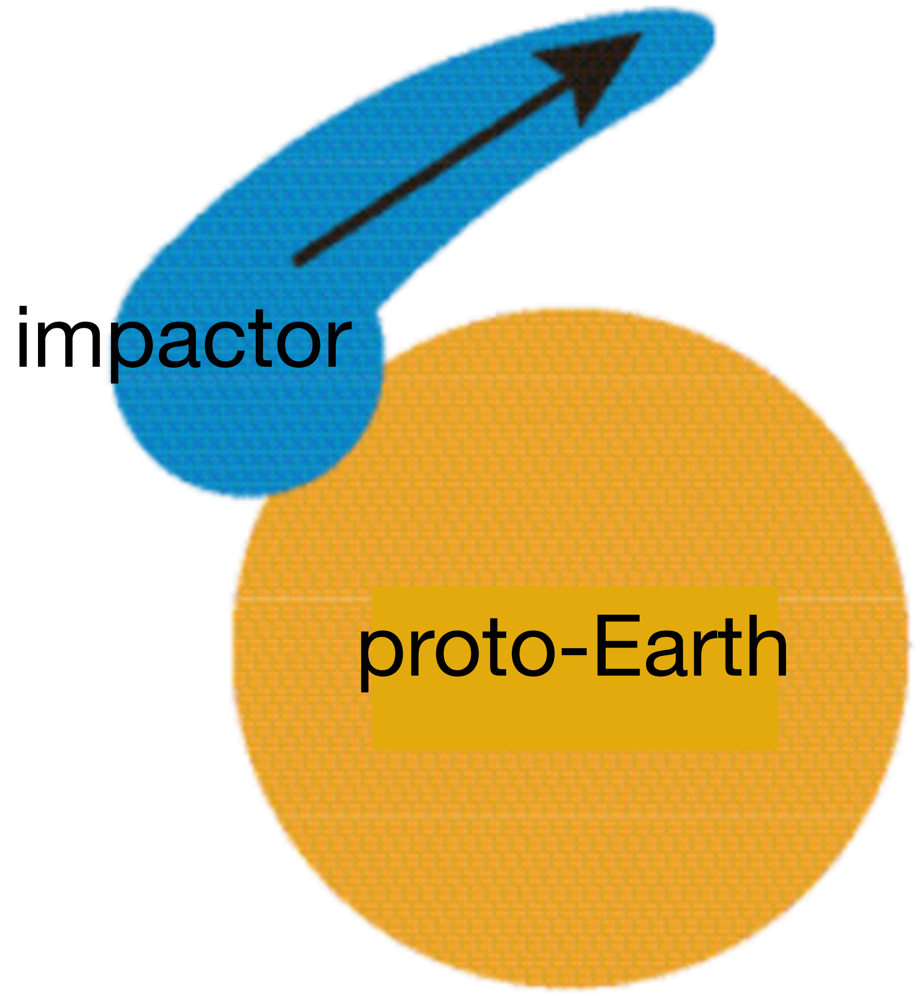


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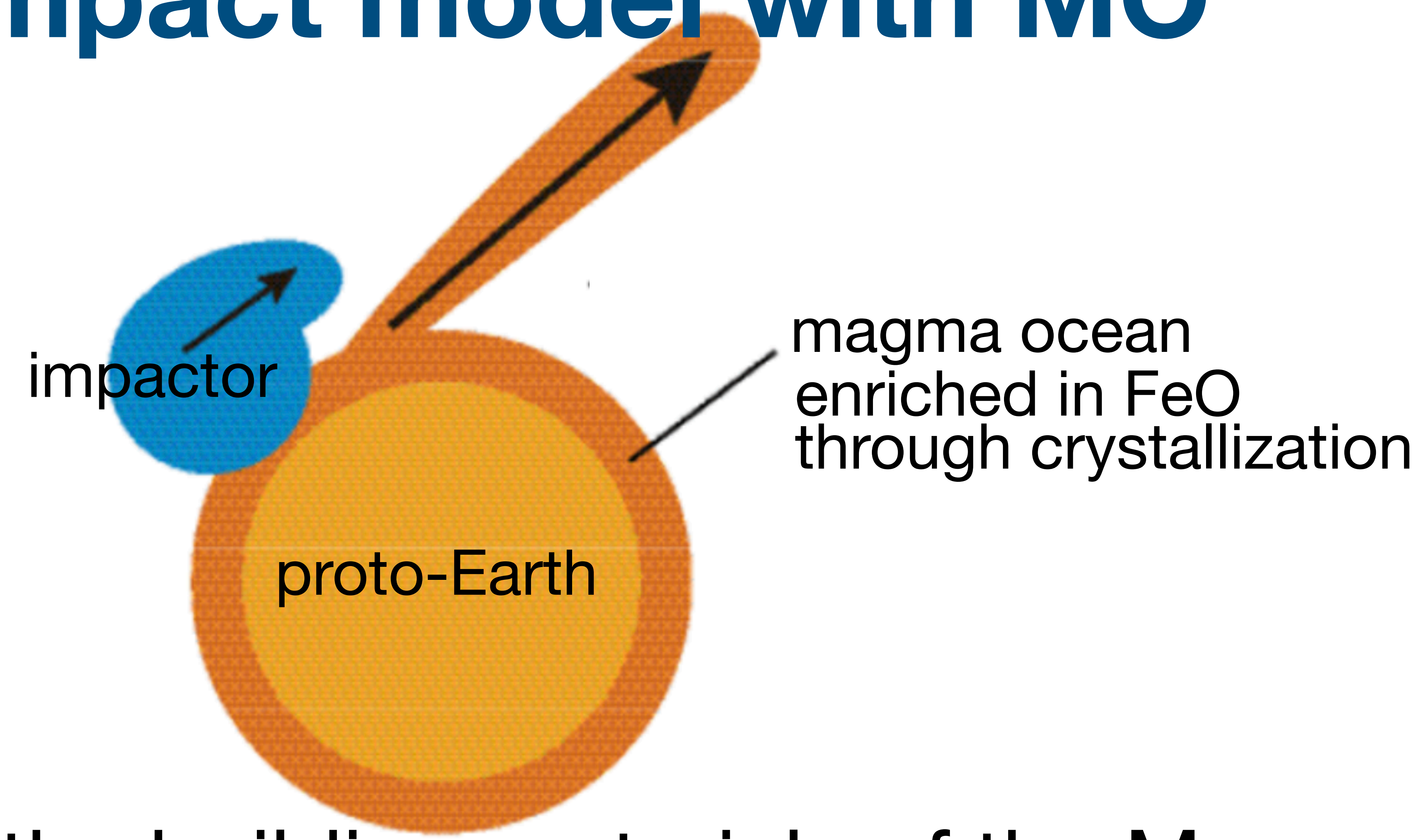
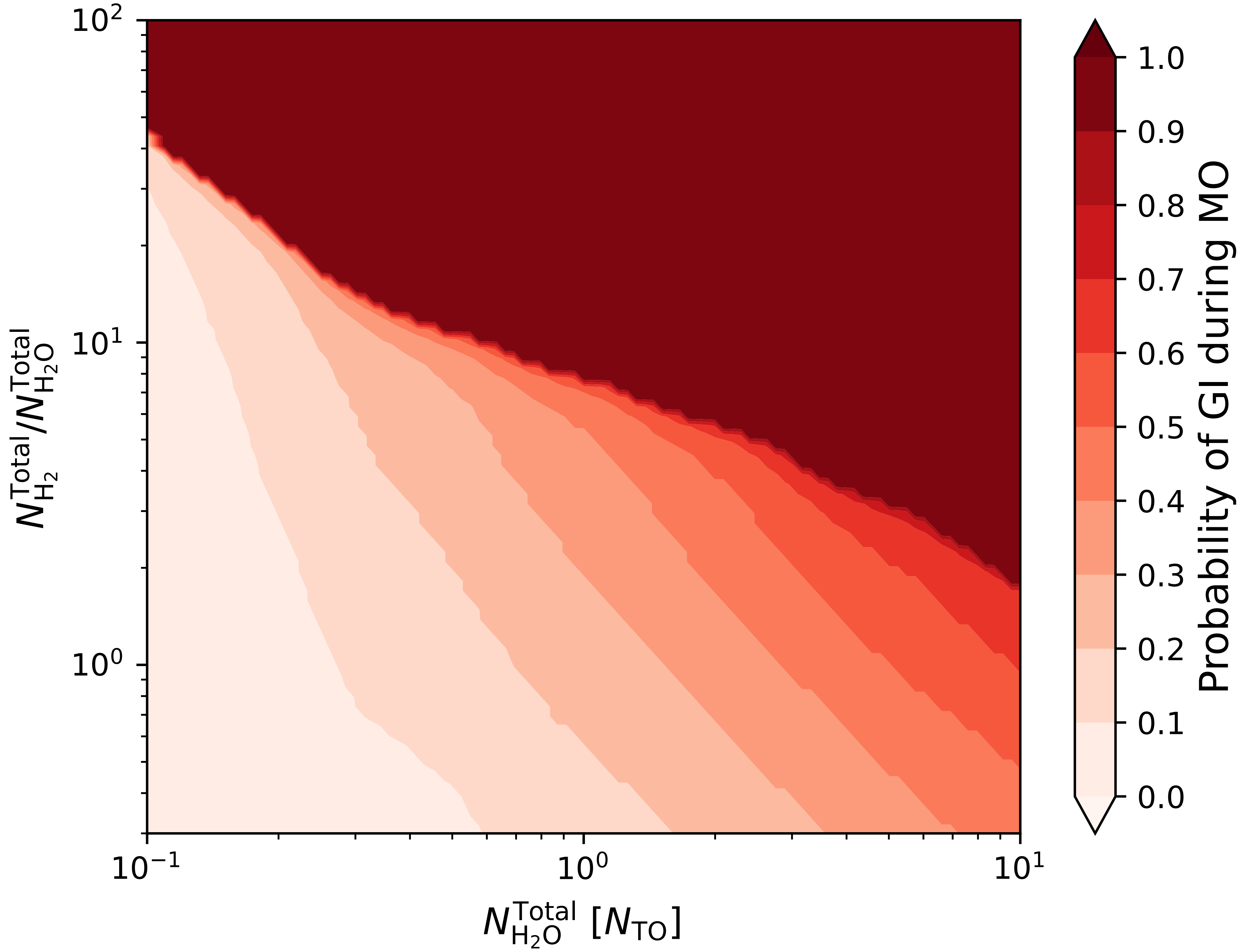
## Giant impact model with MO




- Most of the building materials of the Moon are from the Earth's MO (Karato, 2014; Hosono et al., 2019)
  - ✓ consistent with the similarity in the isotopic composition between the Earth and the Moon
  - ✓ Enrichment of FeO in the basalts and the bulk Moon than in the Earth's mantle through the crystallization differentiation

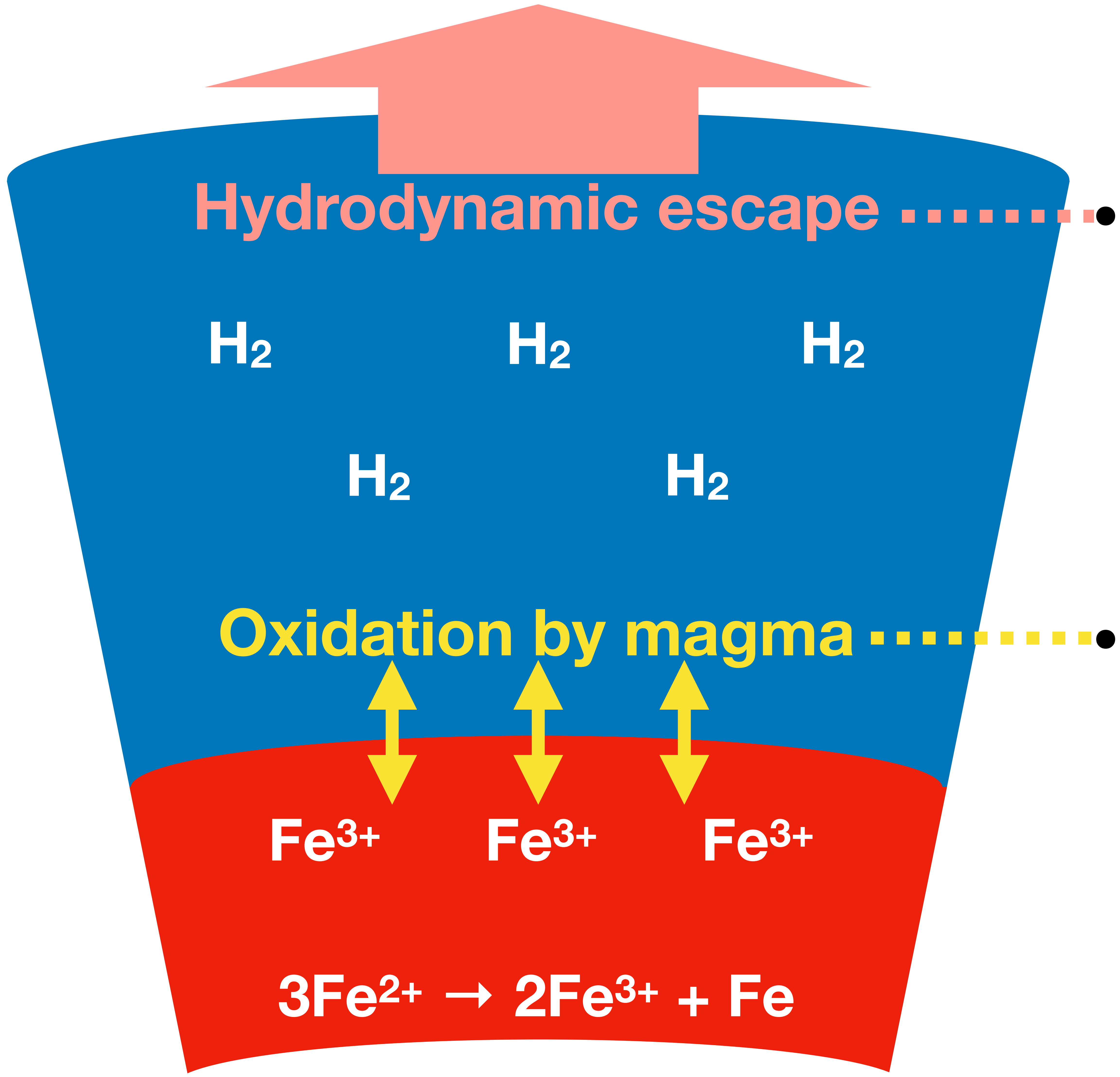
# Implication for the Moon's origin

## Probability of GI occuring during MO phase




- $P_{imp} = 1 - \exp\left(-\frac{\tau_{MO}}{\tau_{imp}}\right)$
  - $\tau_{MO}$ : magma ocean lifetime
  - $\tau_{imp}$ : time interval between GI (= 10 Myr)
- The prolonged magma ocean lifetime increases the probability of GI occurring during the magma ocean phase
  - supporting the magma ocean origin consistent with the chemical characteristics

# Loss processes of atmospheric $H_2$




- Escape process induced by heating of the upper atmosphere through XUV absorption
  - The escape is not fast (~1 bar/Myr) due to molecular radiative cooling (Yoshida & Kuramoto, 2020; 2021; Yoshida et al., 2022; 2024)

- Chemical reaction with the oxidized magma resulting from FeO disproportionation (e.g., Armstrong et al., 2019; Deng et al., 2020; Kuwahara et al., 2023)
  - $H_2 + Fe_2O_3 \rightarrow H_2O + 2FeO$
  - The reaction rate should be limited by the $H_2$ diffusion into the magma ocean

# Summary

- We have developed a coupled atmosphere-interior thermal evolution model that considers the balance of planetary and solar radiation
- Rayleigh scattering can significantly suppress the outgoing longwave radiation (OLR), particularly when the surface temperature and atmospheric mass are high
- The MO lifetime can be extended by the blanketing effect of proto-atmospheres
  - suggesting that the magma ocean state persisted throughout most of the giant impact phase and support the hypothesis that the Moon originated from Earth's magma ocean