Thermal evolution of magma oceans and concurrent H_2O/CO_2 atmosphere formation.

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Research questions:
1) How does the atmosphere affect the duration of the magma ocean?
2) What is the composition of the atmosphere and the volatile partitioning between the atmosphere and the interior at the end of the magma ocean stage?

Magma ocean description

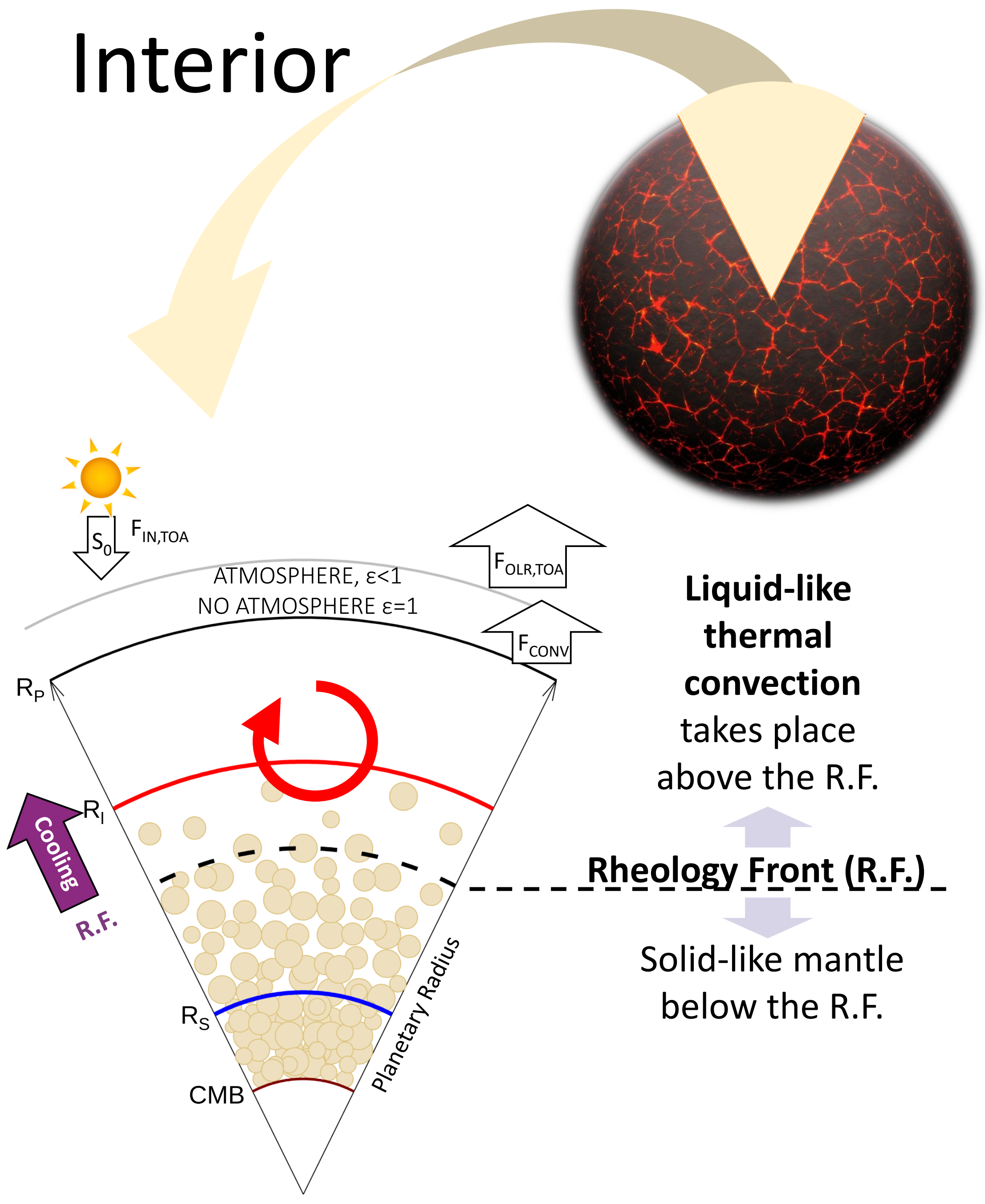
During the accretion of the terrestrial planets, in the Hadean period (4.55-3.9 Ga), **one or more** magma ocean stages are likely to have occured, due to the **energy** delivered by **impactors** and the energy provided by the **decay of radioactive elements** [1,2]. During this stage, **vigorous convection** of the molten silicates is expected. Simultaneously, the **volatiles** that degass create the bulk of the **secondary atmosphere**. The stage ends when the rheology front that separates the liquid/solid rheology, reaches the planet surface.

Relevance to habitability

Constraining the outgassed volatiles during this stage, helps us estimate the **greenhouse effect** at the surface and also define the **compositional background** on which **atmospheric loss processes** were driven by the host star, **i. e. the XUV-active faint Young Sun [2].**

Constraining the duration of the magma ocean stage provides the boundary conditions required for the study of solid state convection development, that is essential for the **initialisation of plate tectonics on planets, a catalyst for habitability [3].**

Interior

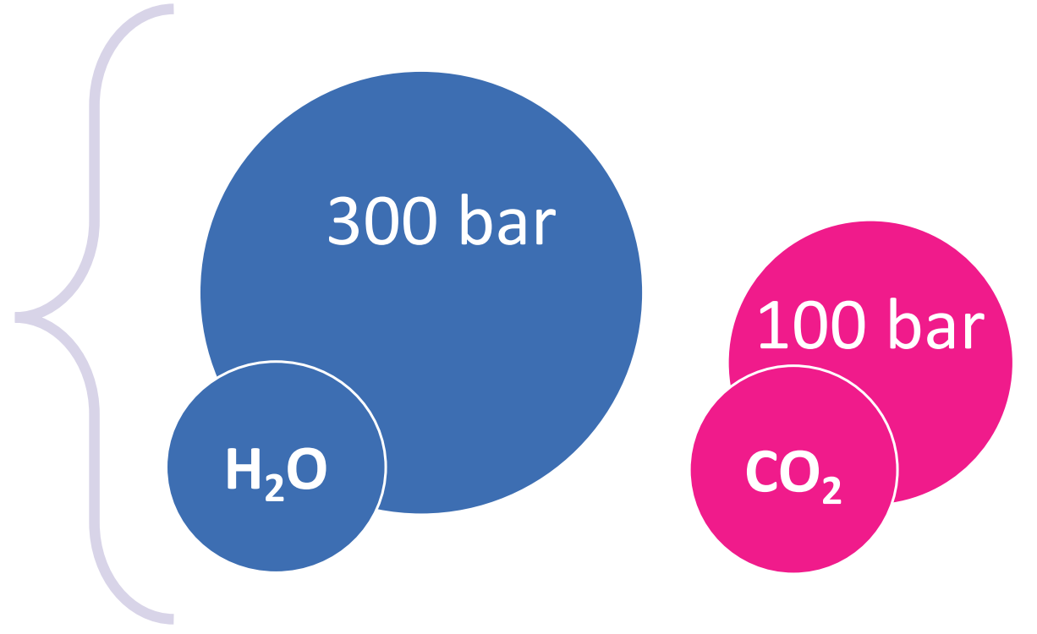


Liquid-like thermal convection takes place above the R.F.

Rheology Front (R.F.)

Solid-like mantle below the R.F.

The **reference** volatile abundances for the **Earth** are taken from **today's observed reservoirs** of one water ocean and of the carbon dioxide amount that resides in the carbonates of the crust [4].



Atmosphere

We use **two alternative approaches** in order to model the **atmospheric thermal blanketing** of a magma ocean:

I. Grey

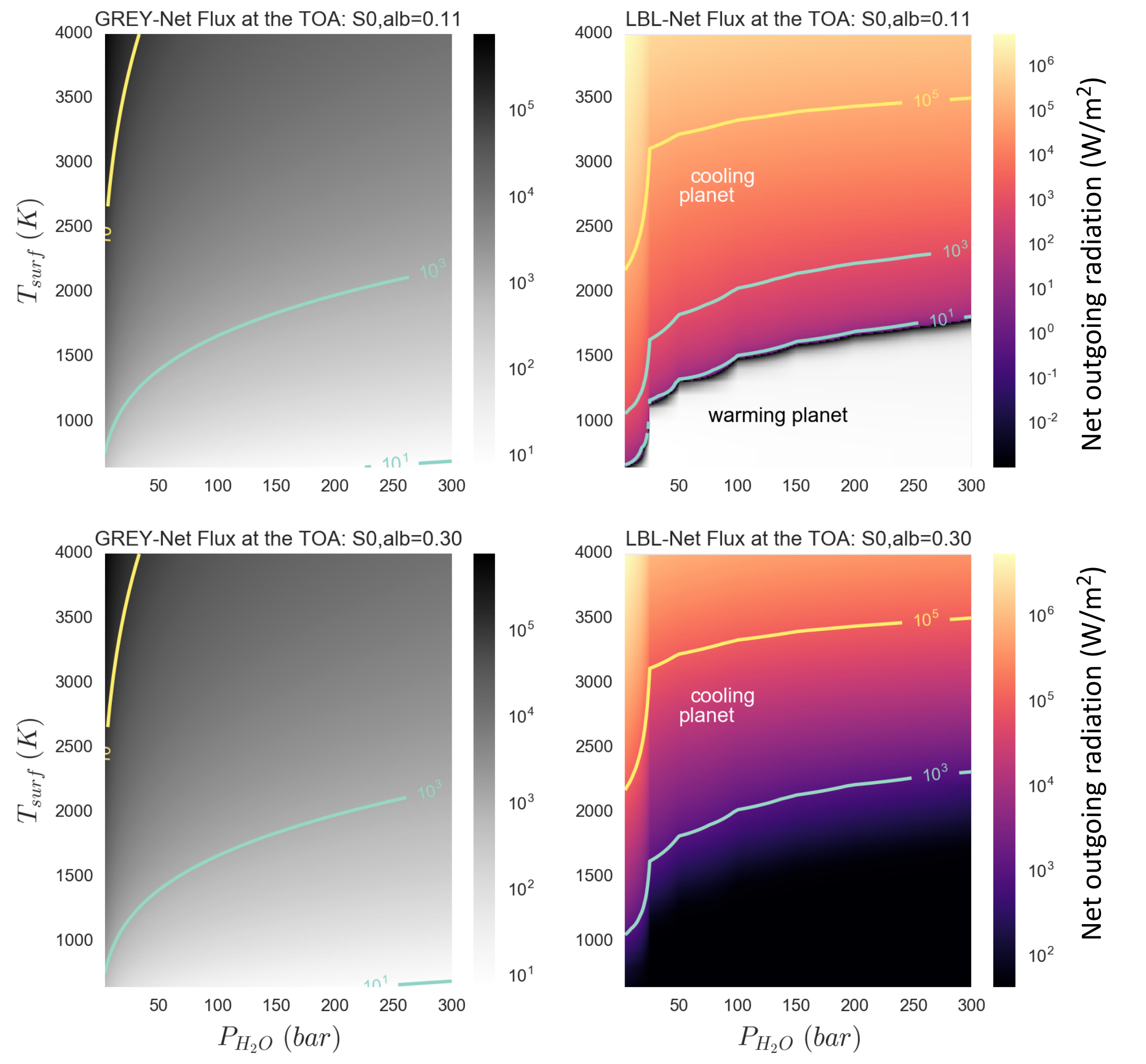
$$F_1 = \sigma\varepsilon(Tsurf^4 - Teq^4)$$

In the examined (T_{surf},P_{H2O}) range, the above F_1 values with grey emissivity ε, are always positive, therefore **planetary cooling** is ensured for different incoming insolation values (See below).

II. Line-by-line

$$F_1 = OLR(Tsurf, P_0) - \frac{S_0(1-alb)}{4}$$

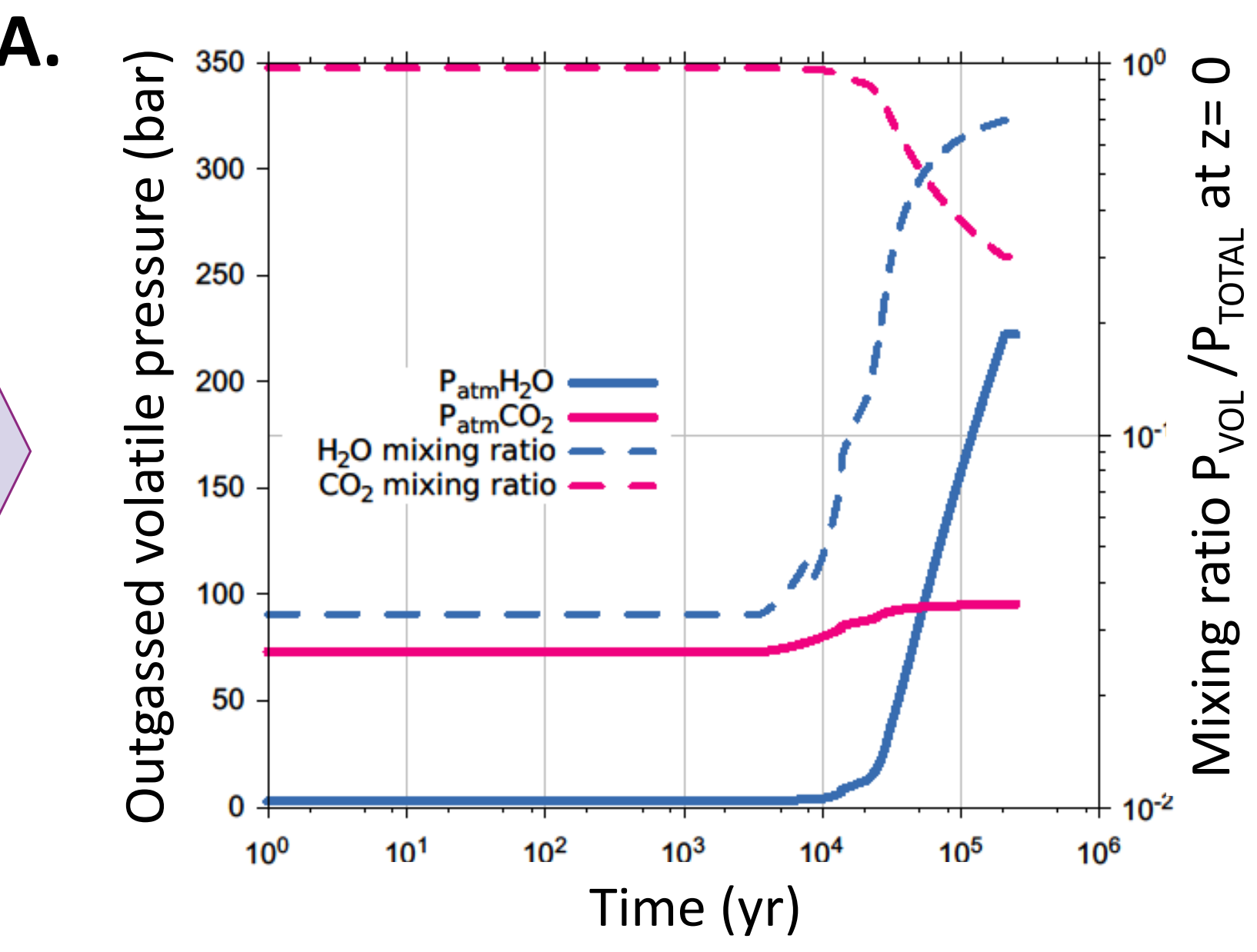
The above net outgoing flux F_1 **depending on the incoming insolation**, can take either positive or negative **values,** for which the planetary energy balance results in **cooling or warming** (See below).



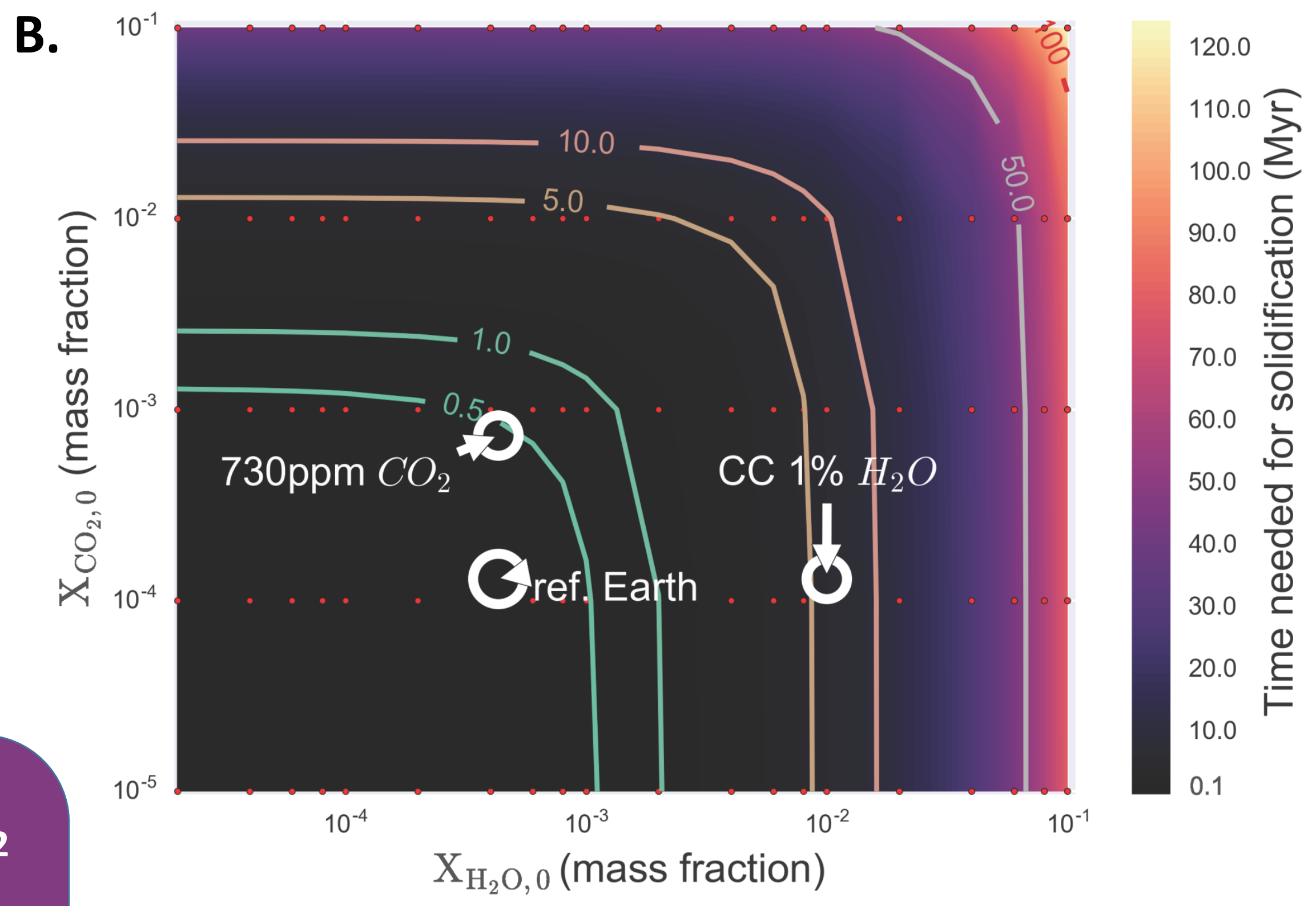
I. Results Grey atmosphere H_2O/CO_2

H_2O
CO_2

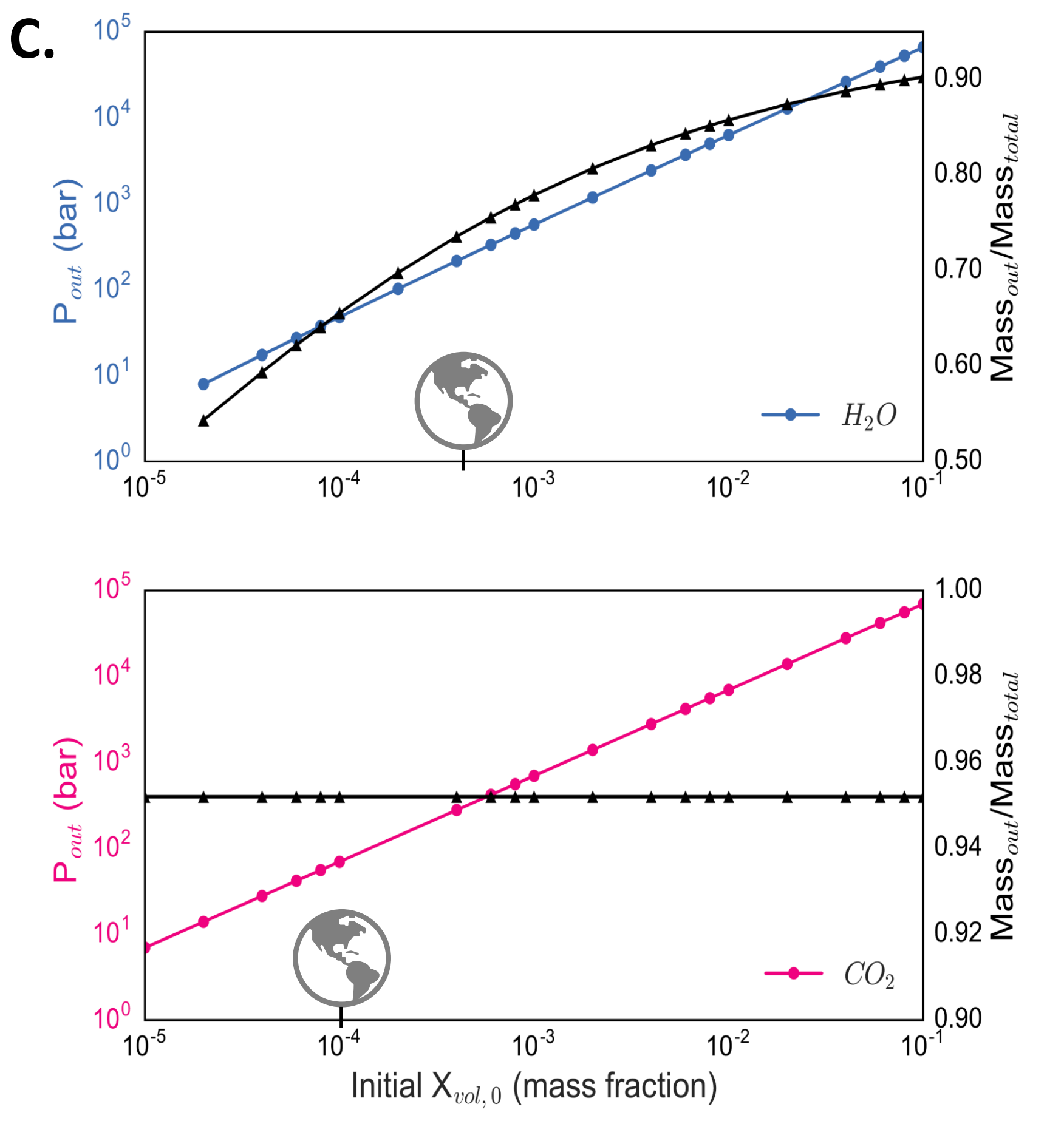
A.



B.



C.

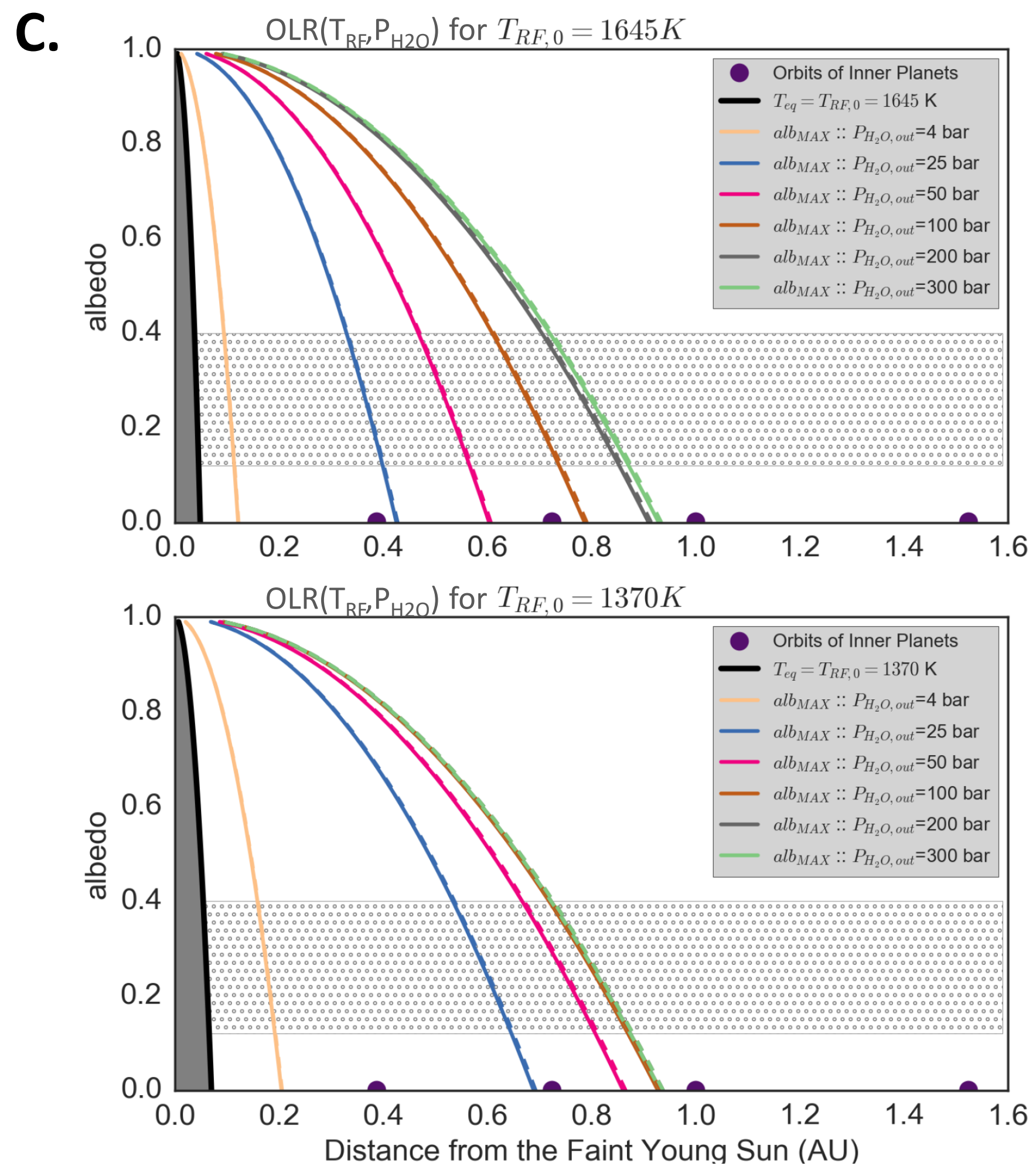


A. During magma ocean evolution the atmospheric composition **changes qualitatively from CO_2 to H_2O - dominated** [5].

B. The duration of the magma ocean for **the reference Earth volatile abundances** is less than **1 Myr**.

C. The majority of the CO_2 degasses at the surface, whereas **up to 40-10% of H_2O is retained in the interior**, depending on its initial concentration [5].

C.



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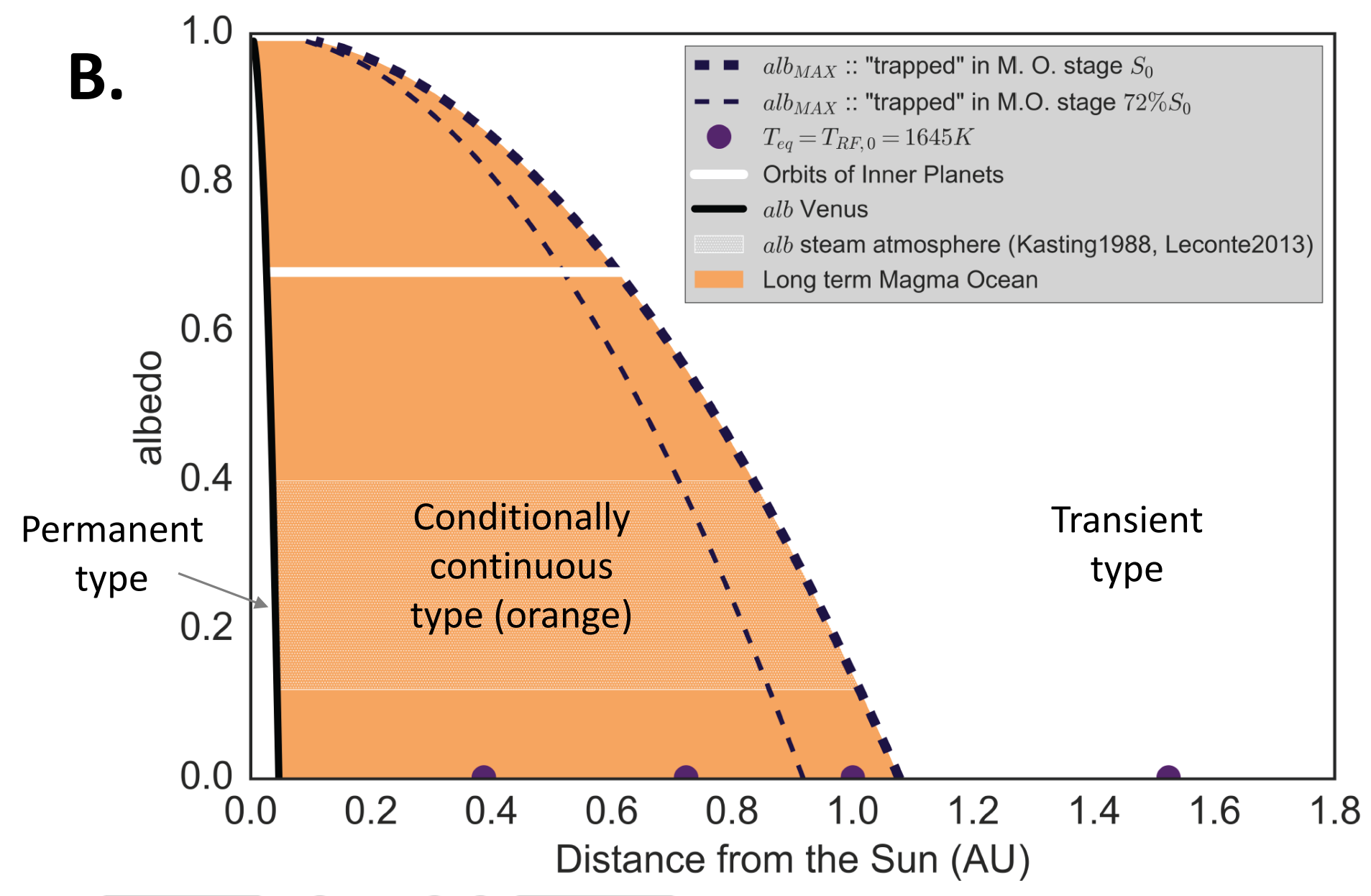

A. Types of magma oceans

Permanent	Conditionally continuous	Transient
$T_{R.F.} < T_{EQ}$ Surface molten by the host star.	$F_{IN,TOA} >$ OLR(T_{RF},P_{H2O}) Cooling hindered by H_2O-steam and interior.	$F_{IN,TOA} <$ OLR(T_{RF},P_{H2O}) Cooling ensured at all times.

II. Results Line-by-line H_2O steam atmosphere

H_2O

All figures presented here are part of a larger study.

A. Classification of magma oceans into 3 types is suggested: 1. transient 2. conditionally continuous 3. permanent.

B. A planet at the orbital distance of Earth with outgassed atmosphere of ≈290 bar H_2O is **unlikely to have been trapped** in long-term magma ocean at 4.45 Ga.

C. By varying the solidification temperature and keeping the atmospheric water vapor constant [5], the same planet can demonstrate either a long-lived or a short-lived magma ocean.

Model details

- A parameterization [1] is used for the calculation of the convective heat flux F_2.
- An iterative convergence (T_{surf}, F_2) scheme based on [6], with tolerance $\Delta F = 10^{-1}$ W/m² is used.
- A 1D model of the interior is alternatively coupled to two atmospheric modules.
- The line-by-line [7] **H_2O steam only** atmospheric module [8] uses the temperature profile of [9]
- The grey atmospheric module for **H_2O/CO_2** after [10] and [11] is adopted.
- **Experiments**: We vary the initial volatile abundances X_0 and/or the solar incoming radiation.

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References: [1] Solomatov, *Treatise on Geophysics*, Elsevier (2015) **[2]]** Johnstone et al., *Astr. J. Letters*, 815 (2015) **[3]** Tosi et al., *Encycl. Solar Syst.*, Elsevier (2014) **[4]** Irgensoll, *Princeton Primers* (2013) **[5]** **Nikolaou et al. *ApJ 875,11 (2019)*** **[6]** Lebrun et al., *JGR: Planets*, 118 (2013) **[7]** Schreier et al., *J. Quant. Spectr. Rad. Tr.*, 137 (2014) **[8]** Katyal et al. ApJ *875, 31 (2019)* **[9]** Kasting, *Icarus*, 74, (1988) **[10]** Abe and Matsui, *JGR*, 90 (1985) **[11]** Elkins-Tanton, *EPSL*, 271 (2008)