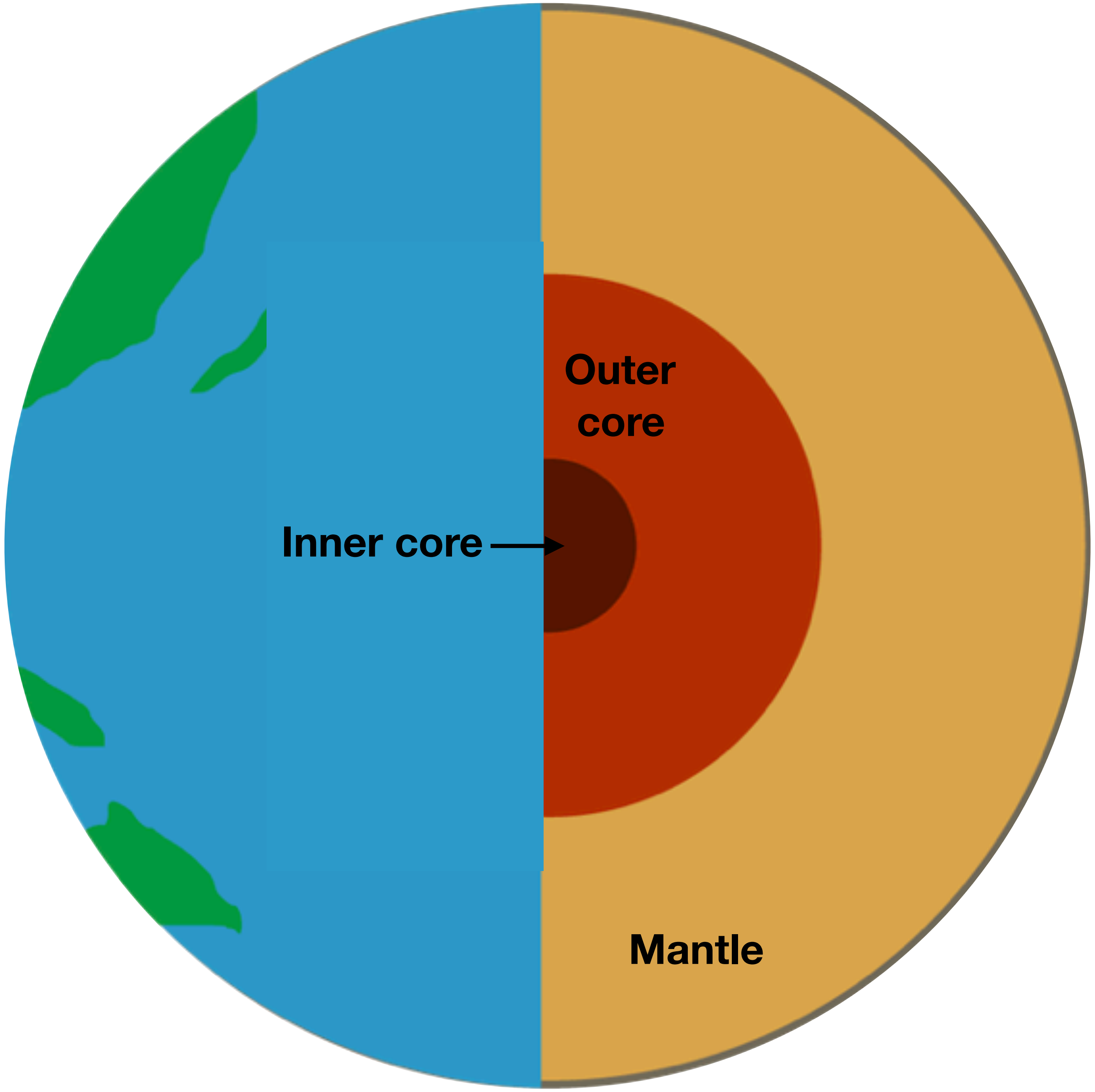
The effect of CO_2 ice condensation on the habitability of rocky planets

Irene Bonati, Ramses Ramirez

Planetary Seminar

4 July 2019

My usual research field



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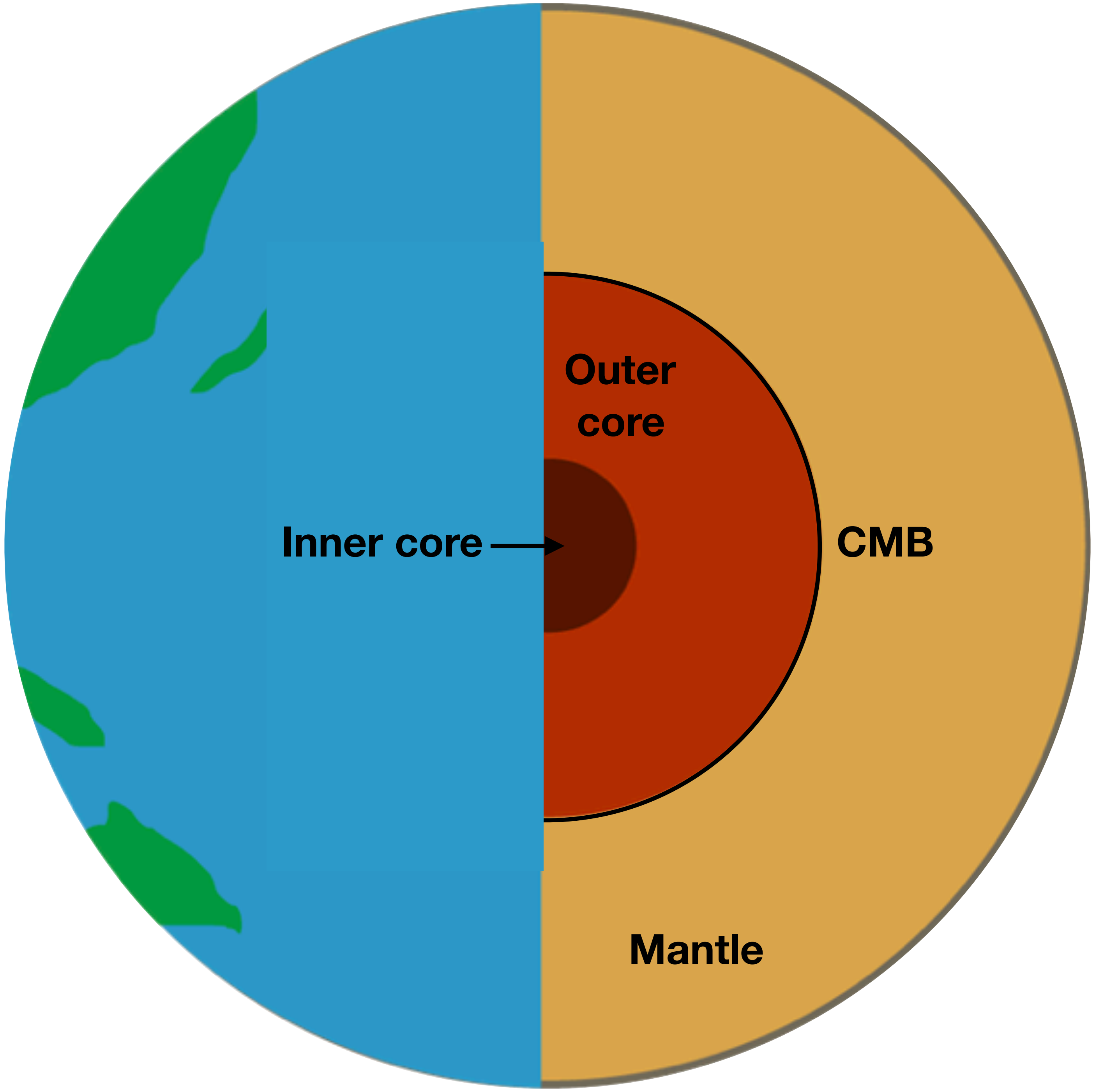
CMB: Core-Mantle Boundary



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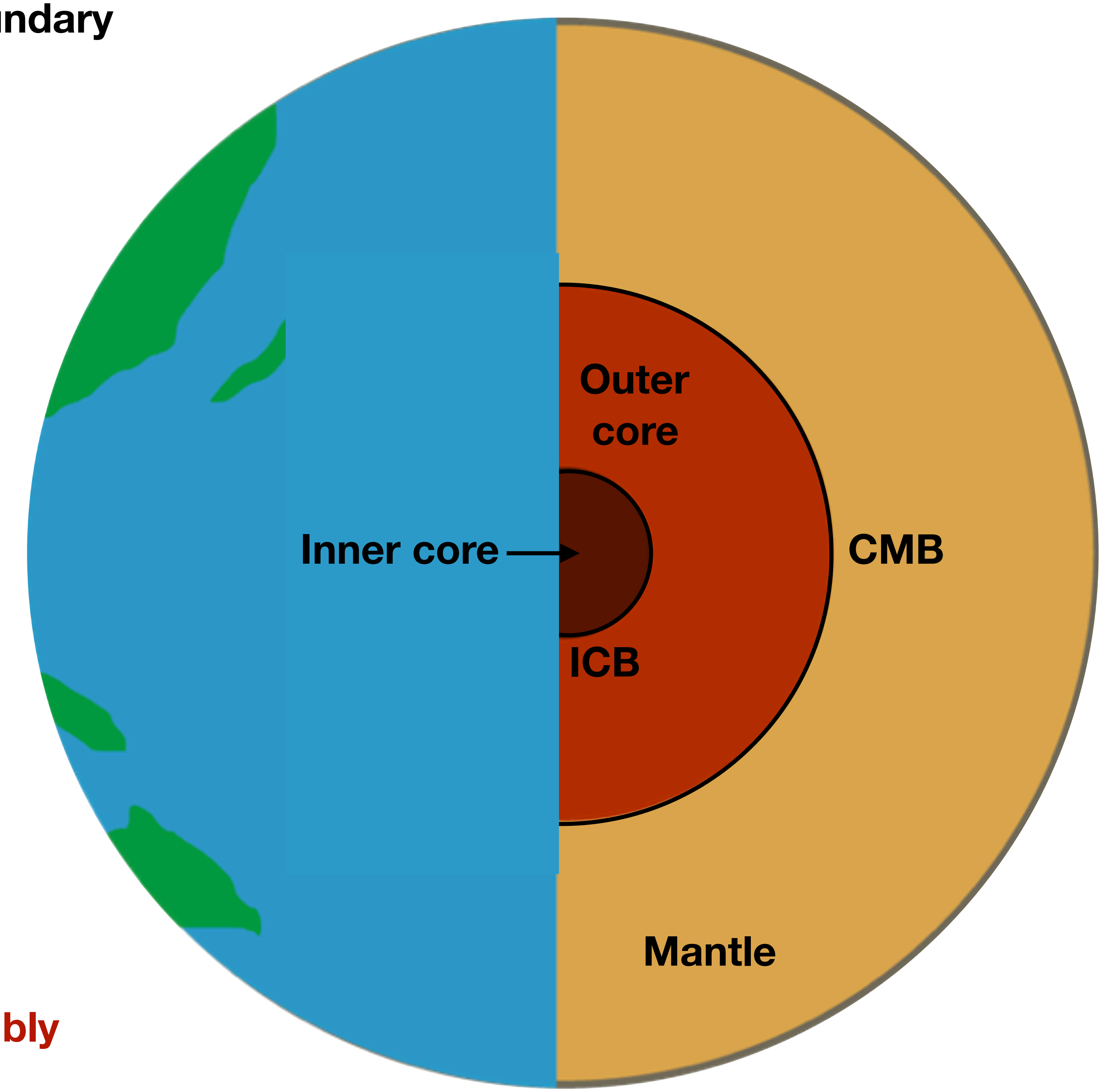

This project

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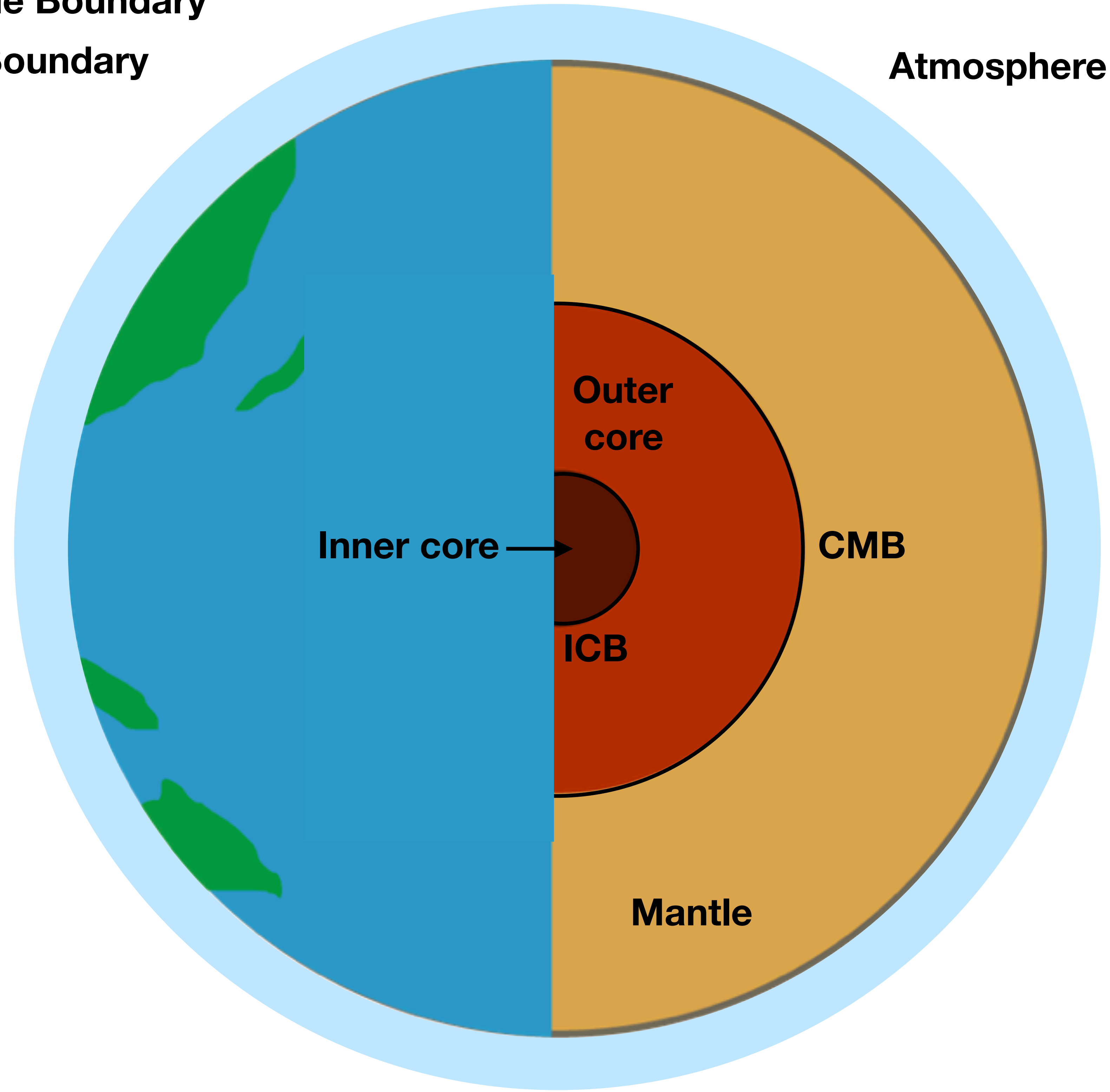

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Earth’s climate history

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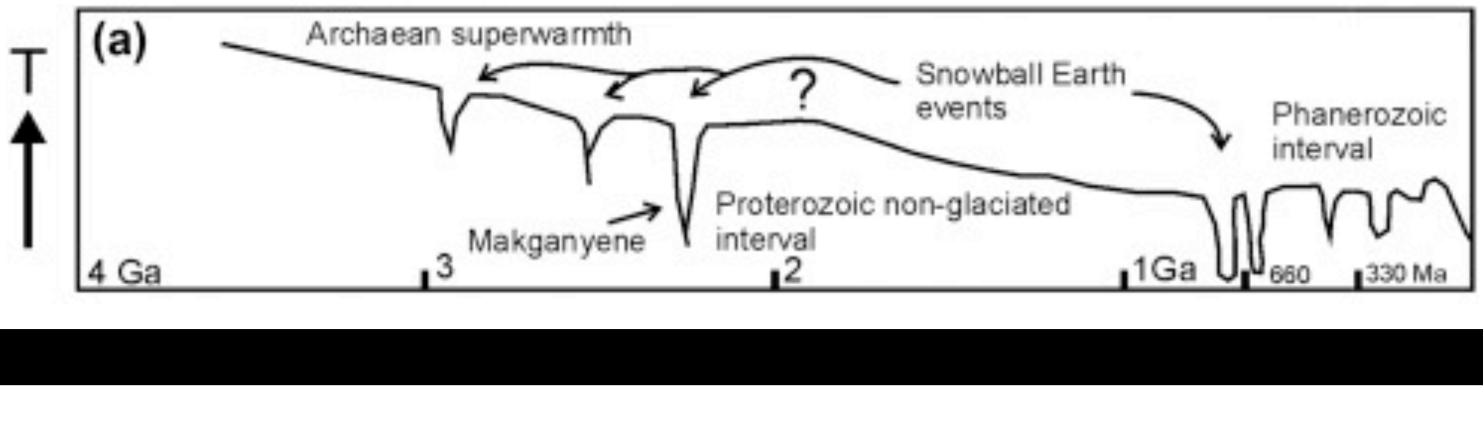
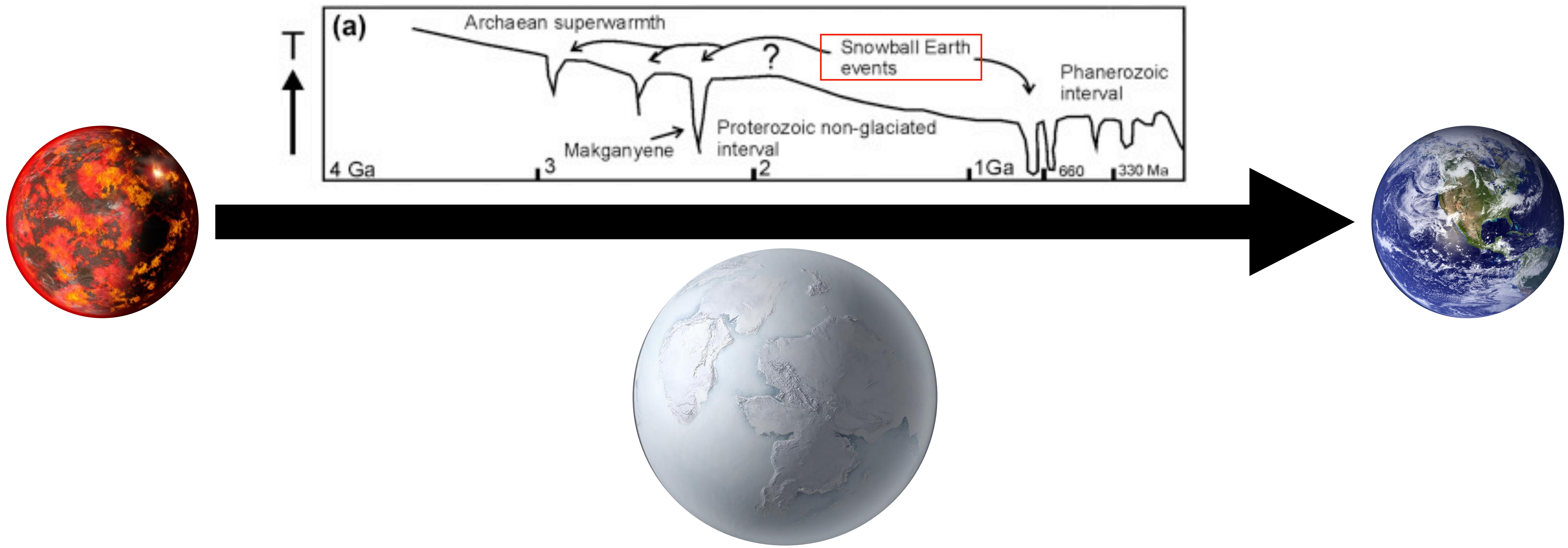


Earth's climate history



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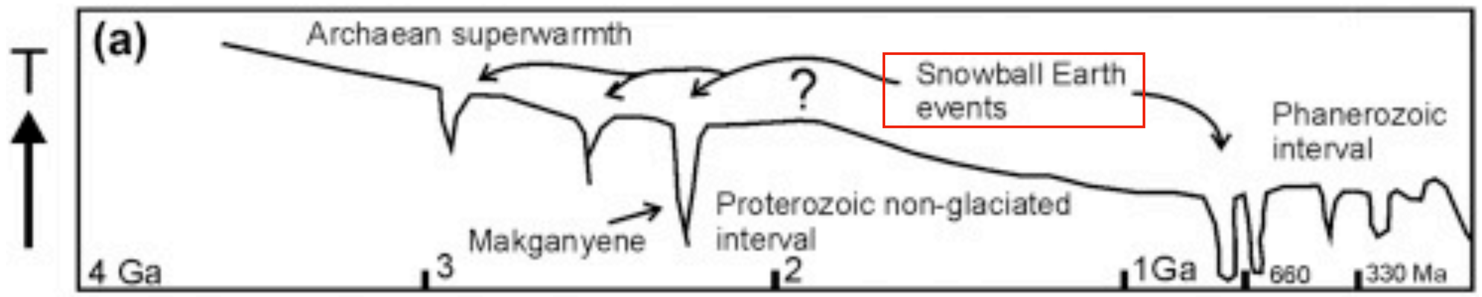

Rodinia

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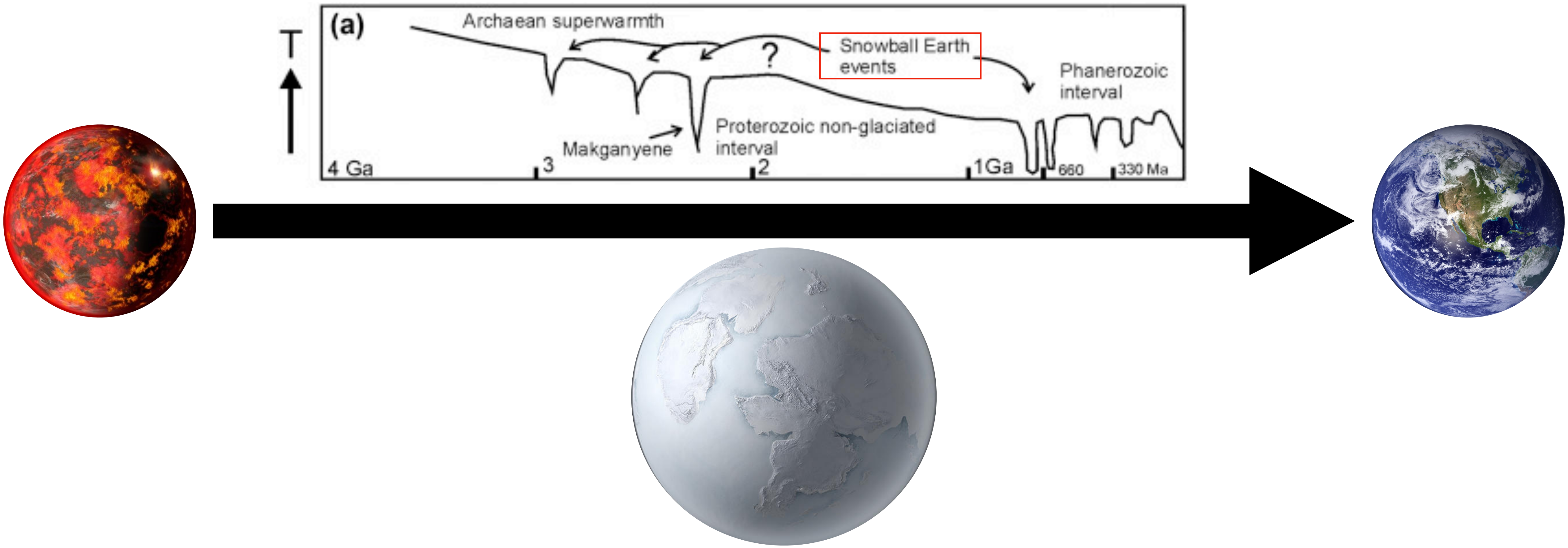

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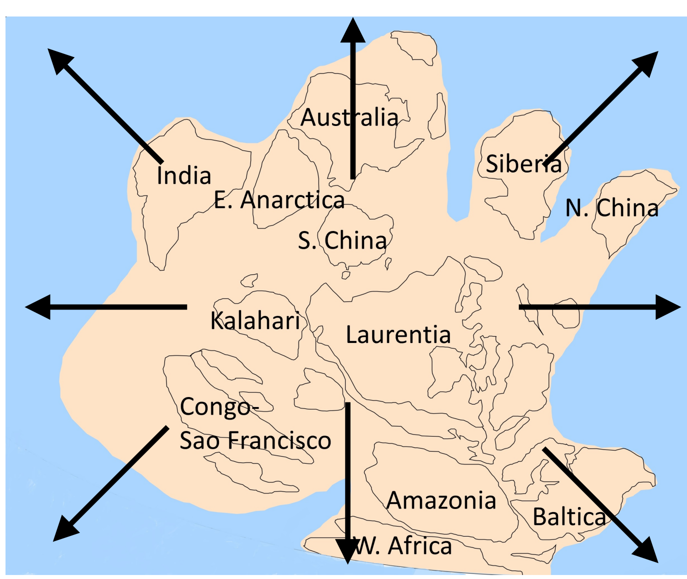

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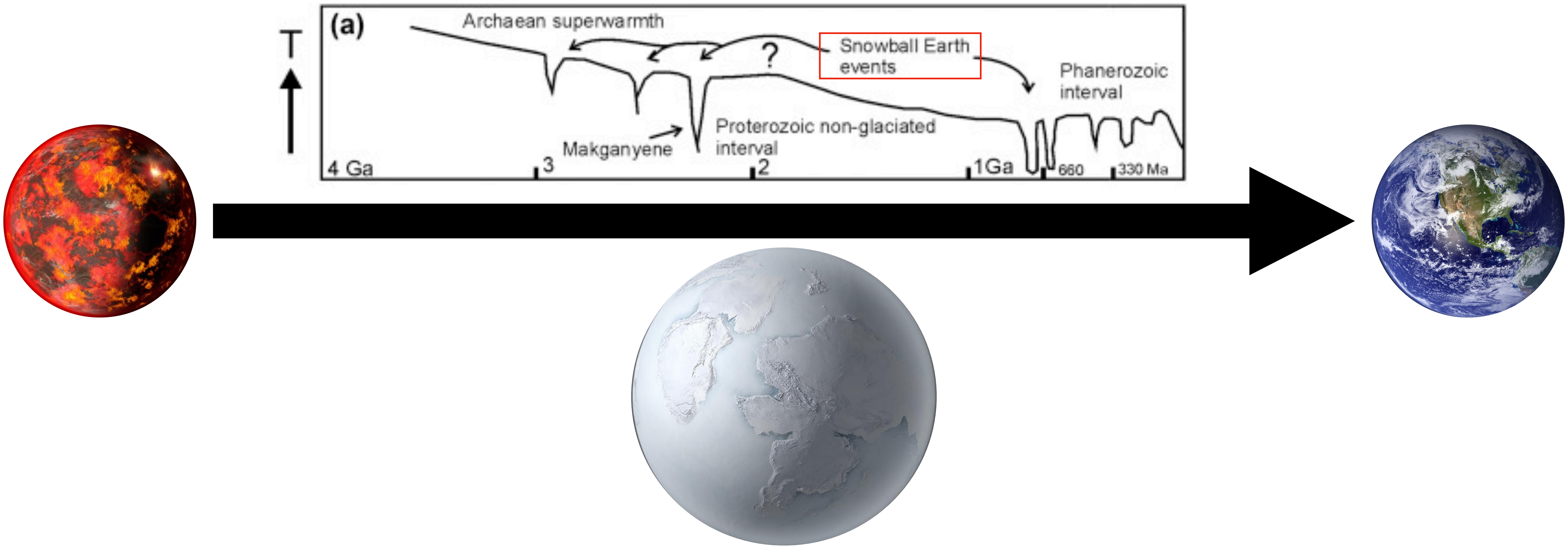

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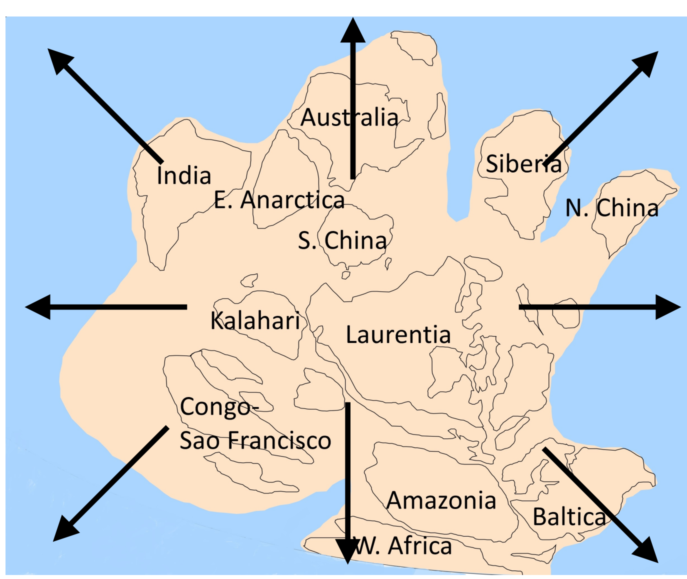
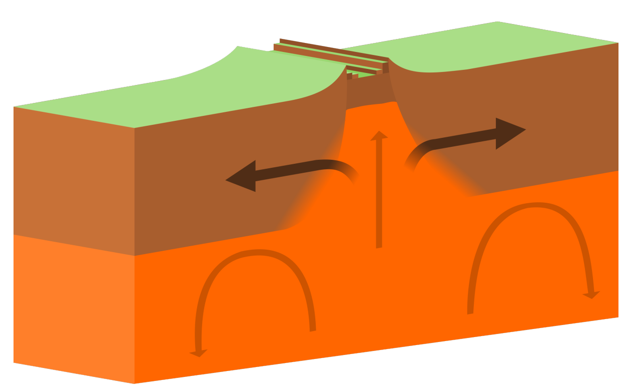


Basaltic lavas, fast erosion



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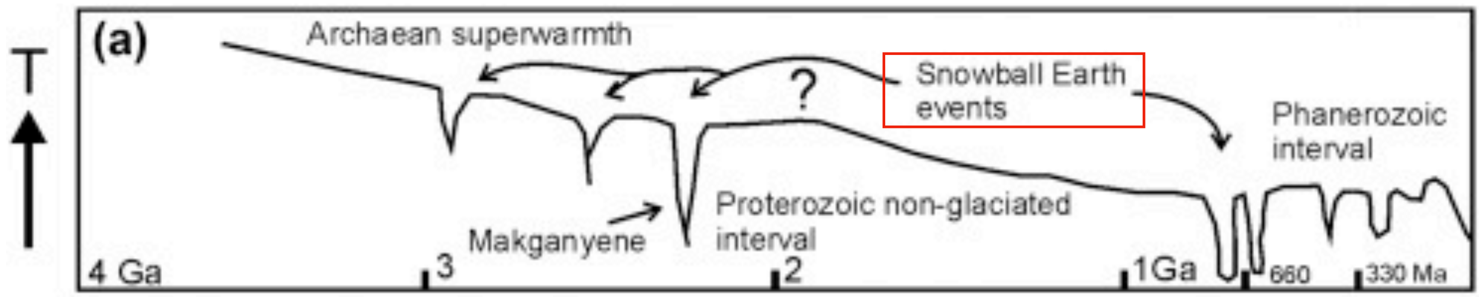

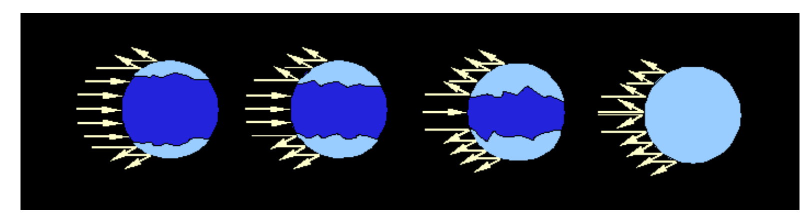

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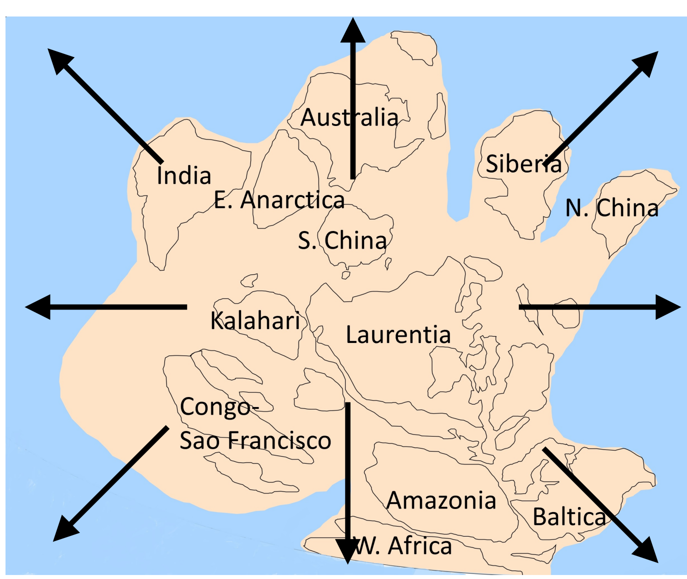

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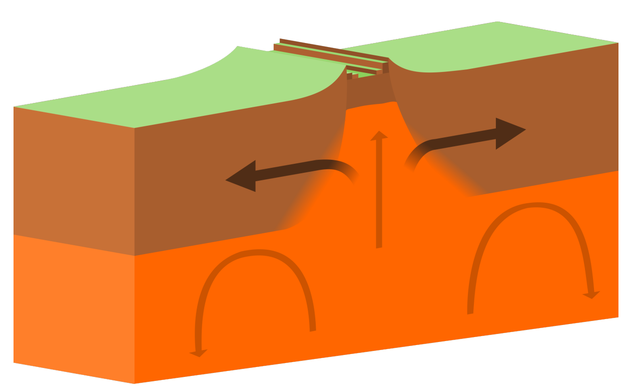
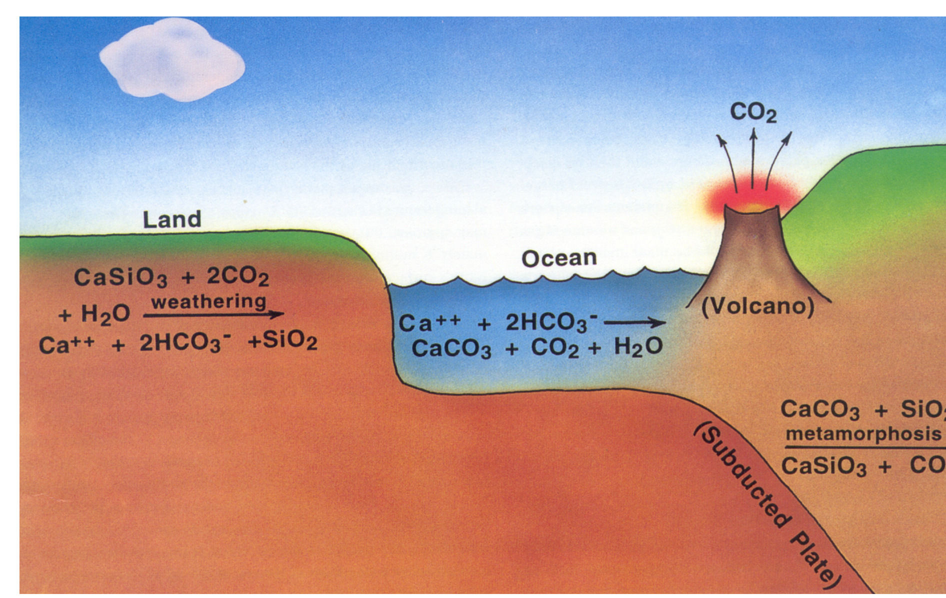
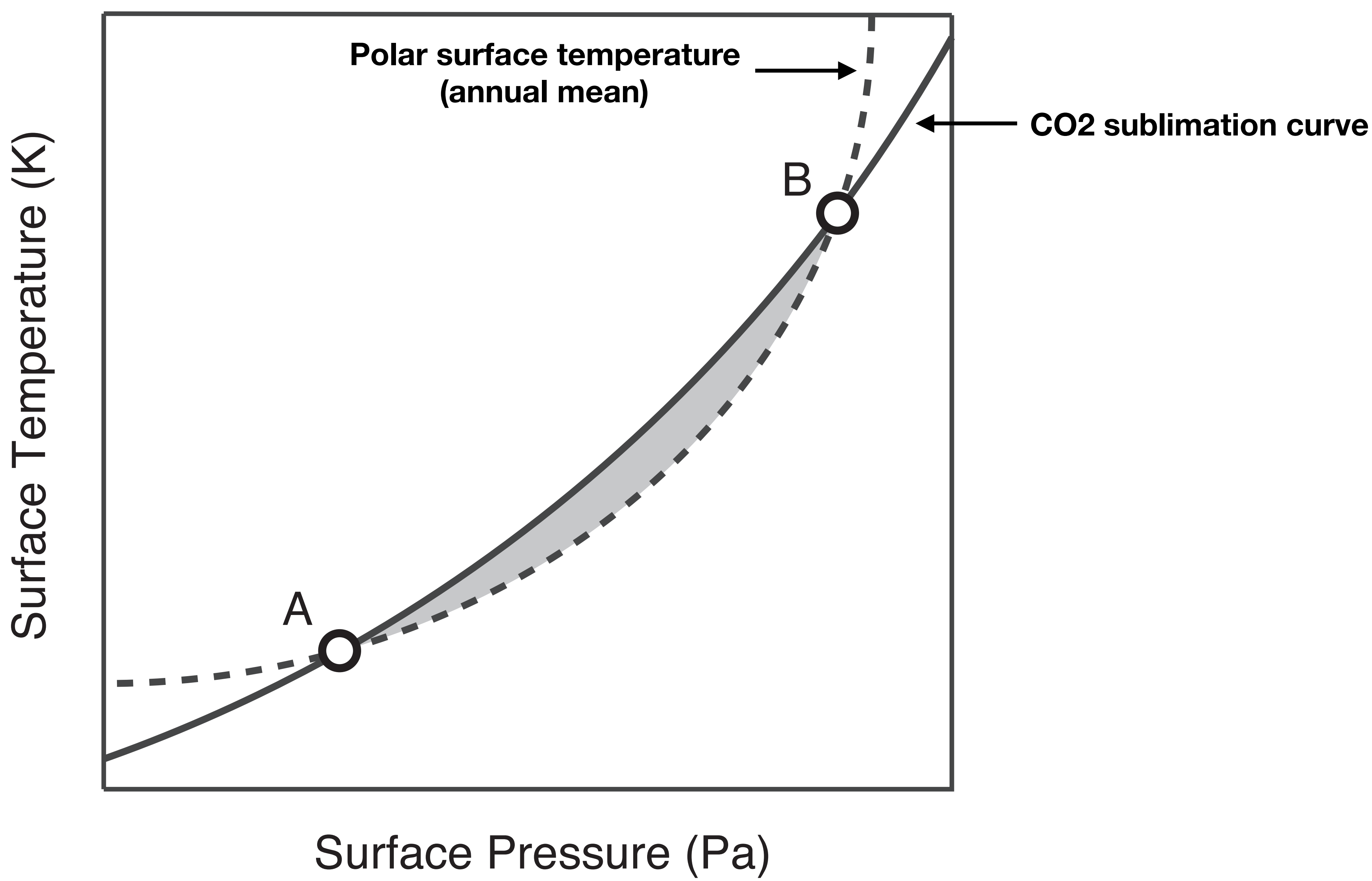




CO2 ice condensation

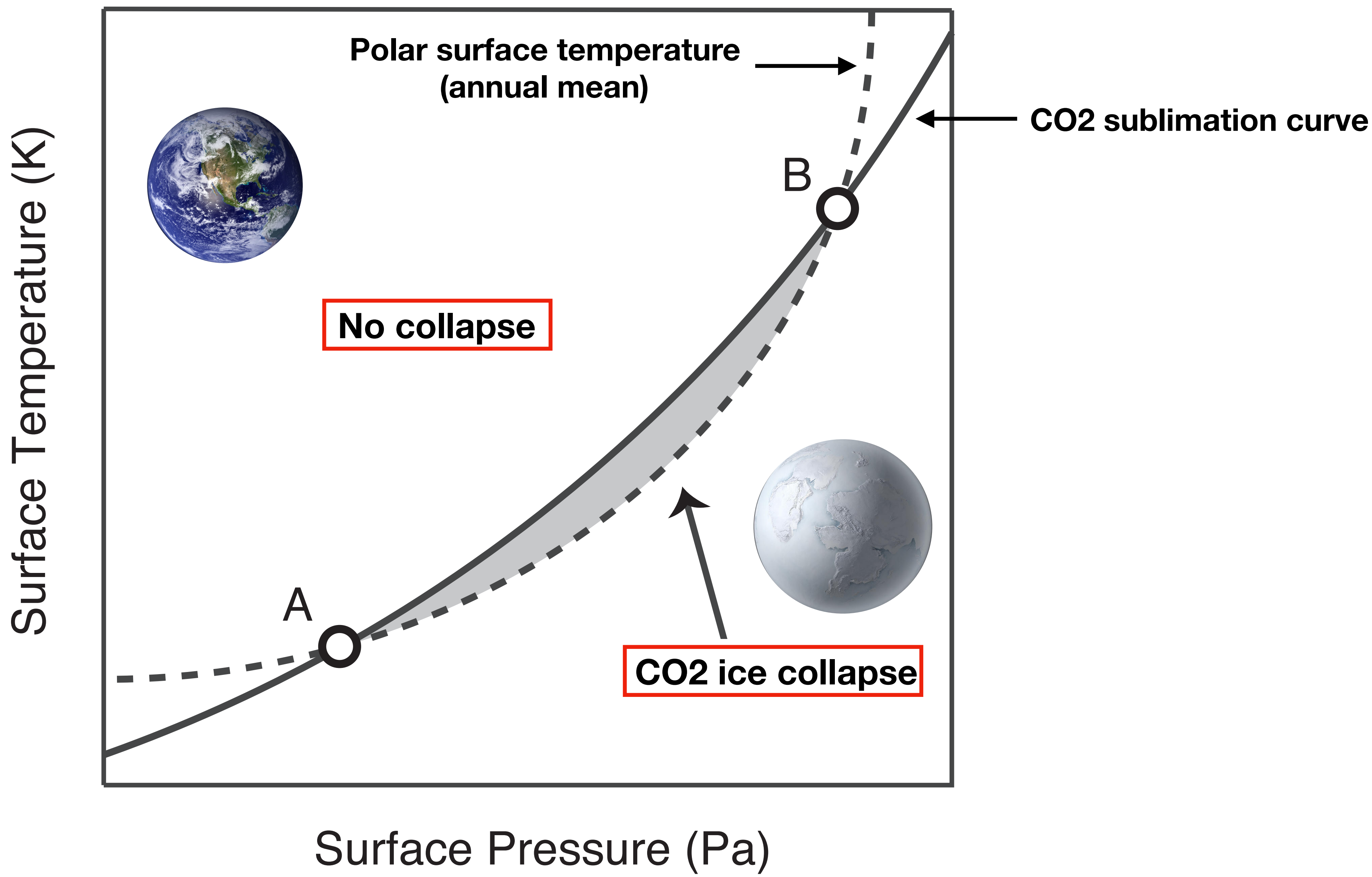
- Depending on the atmospheric CO2 pressure, planets might experience CO2 ice condensation.



Modified after Soto+2015

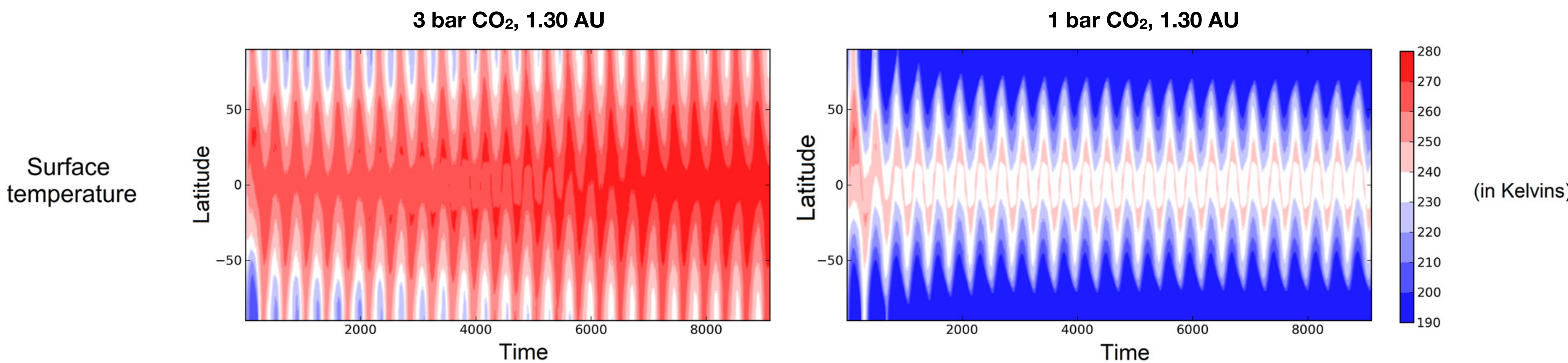
CO2 ice condensation

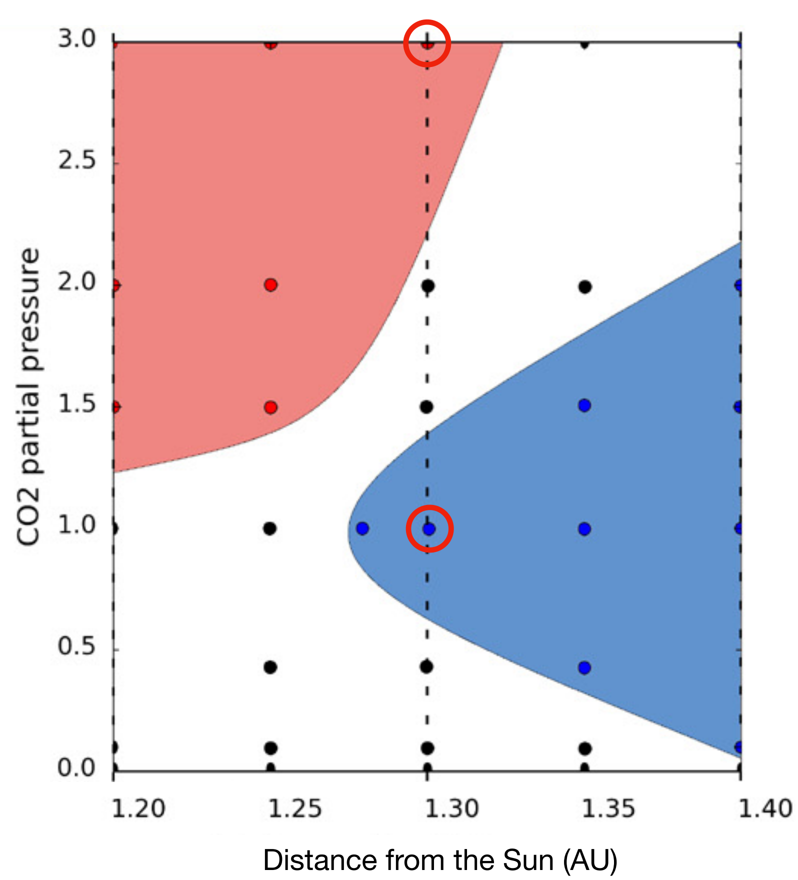
- Depending on the atmospheric CO_2 pressure, planets might experience CO_2 ice condensation.



Modified after Soto+2015

CO_2 ice condensation

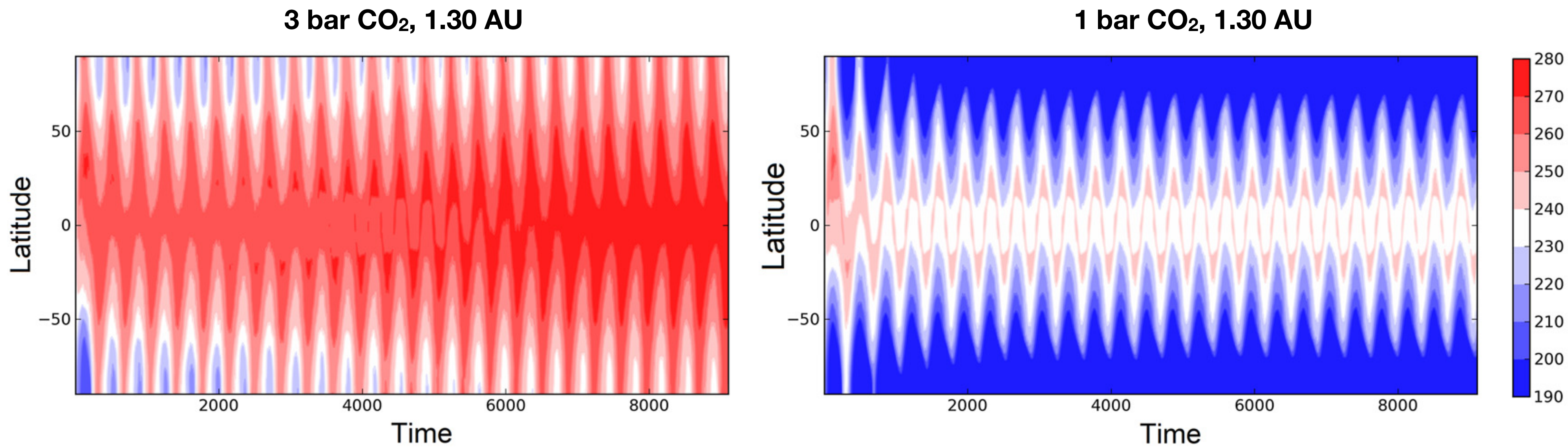




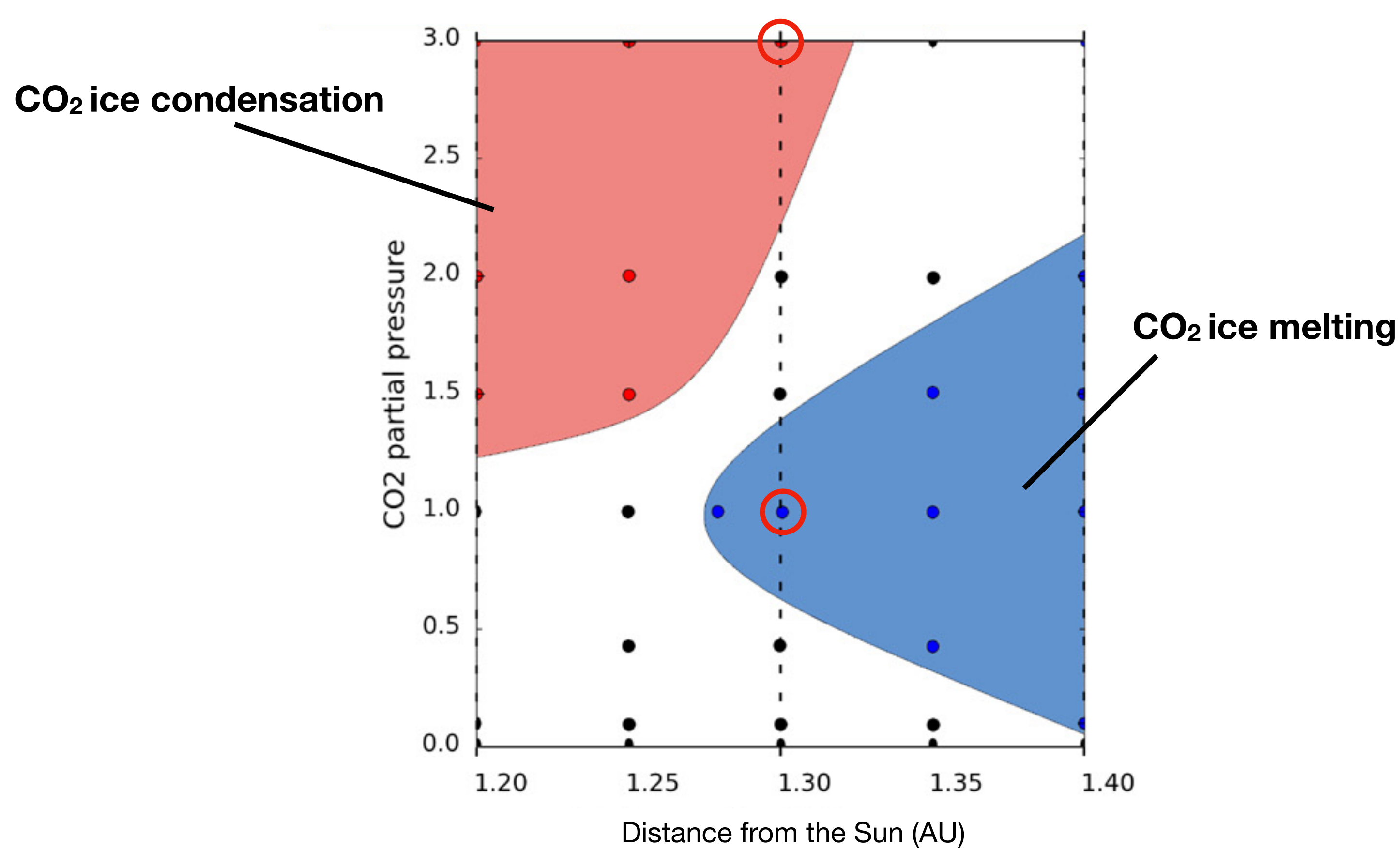
Turbet+2017

CO_2 ice condensation

Surface temperature



(in Kelvins)

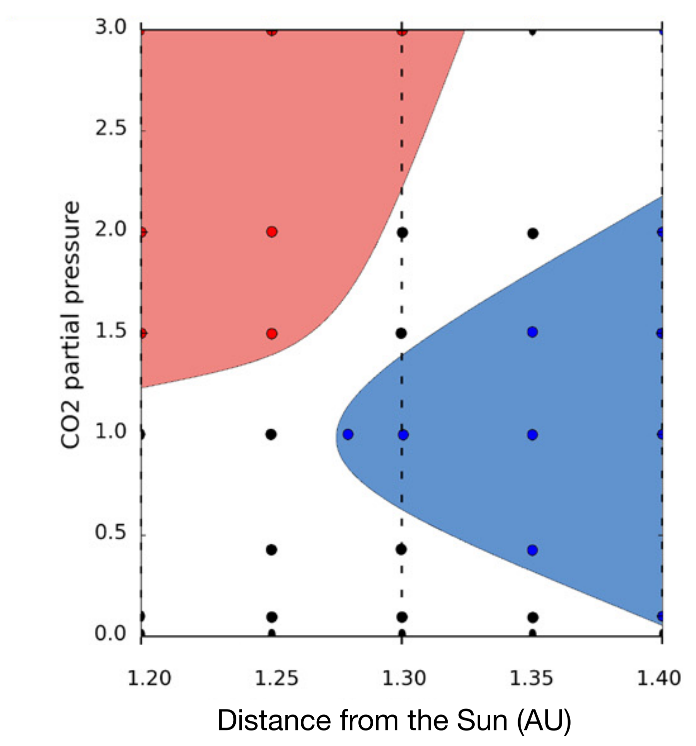


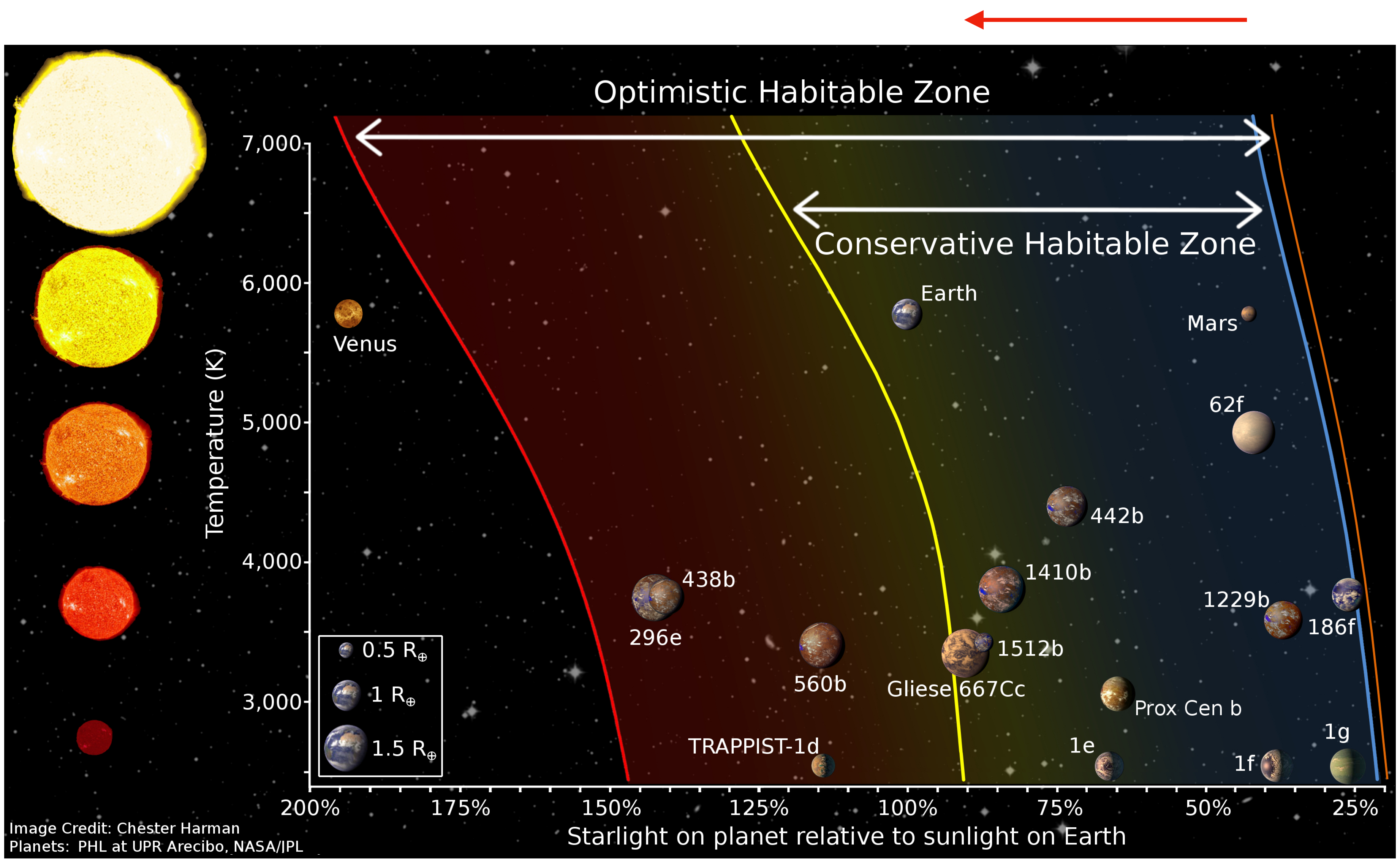
Turbet+2017

Habitable zone

- Such a result would modify the outer limit of the habitable zone*.

***Habitable: surface water is stable on the planetary surface, it does not mean anything else than that!**





Turbet+2017

Kopparapu+2014

However...

What previous studies didn't consider:

- Heat transport by a dynamic ocean
- Effect of water vapor
- **What happens to planets that are initially warm? Is their fate determined by the atmospheric pressure of CO_2?**
- **What happens to planets orbiting other star types (e.g., M-stars)?**

Energy balance model (EBM)

- **Principle**: Planets in thermal equilibrium radiate as much energy to space as they receive from their star.
- Energy fluxes in a given region are balanced by dynamic fluxes transporting heat away or to the region.
- Planet is subdivided into 36 latitude belts

- **Radiative energy balance**: $C\frac{\partial T(x,t)}{\partial t} - \frac{\partial}{\partial x} D(1-x^2)\frac{\partial T(x,t)}{\partial x} + I = S(1-A)$

C: heat capacity

T: zonally averaged surface temperature

x: sin(latitude)

D: heat diffusion coefficient (heat transport efficiency)

I: Outgoing infrared flux to space

S: absorbed fraction of incident solar flux

A: albedo (top of atmosphere)

Energy balance model (EBM)

- CO_2 ice sublimation + condensation
- Carbonate-silicate cycle (weathering rates)
- Atmosphere: 1 bar N_2 + variable amounts of CO_2 and H_2O
- Water vapor and CO_2 clouds
- Ice-albedo feedback
- Ocean and continents (no topography)

- **Heat transport**: $$\left(\frac{D}{D_0}\right) = \left(\frac{p}{p_0}\right)\left(\frac{c_\mathrm{p}}{c_{\mathrm{p}_0}}\right)\left(\frac{m_0}{m}\right)^2\left(\frac{\Omega_0}{\Omega}\right)^2$$

D: heat diffusion coefficient (heat transport efficiency; $D_0 = 0.58\ Wm^{-2}K^{-1}$)

p : atmospheric pressure ($p_0 = 1\ bar$)

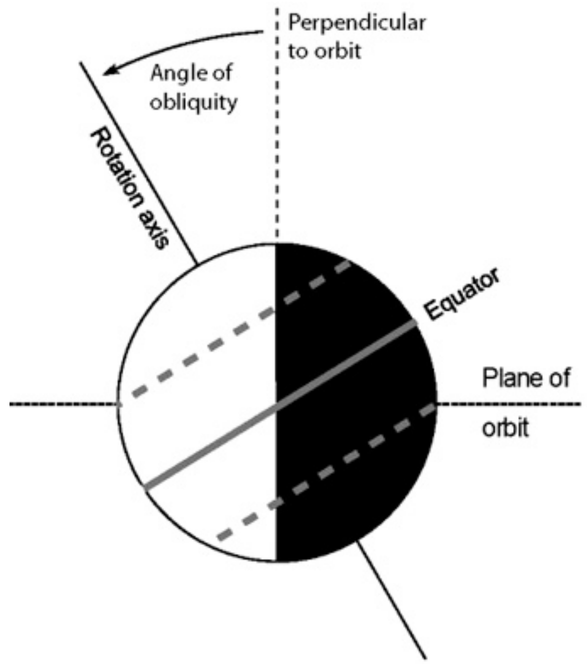
c_p: heat capacity ($c_{p0} = 10^3\ g^{-1}kgK^{-1}$)

m: atmospheric mass ($m_0 = 28\ kg$)

Ω: rotation rate ($\Omega_0 = 7.27e{-5}\ \ rad\ s^{-1}$)

Parameter space

- **Initial CO_2 atmospheric pressure**: 0.01 - 3 bar
- **Obliquity**: 0 deg, 23.5 deg (Earth), 45 deg
- **Water fraction**: 100% water, Earth-like, 100% land



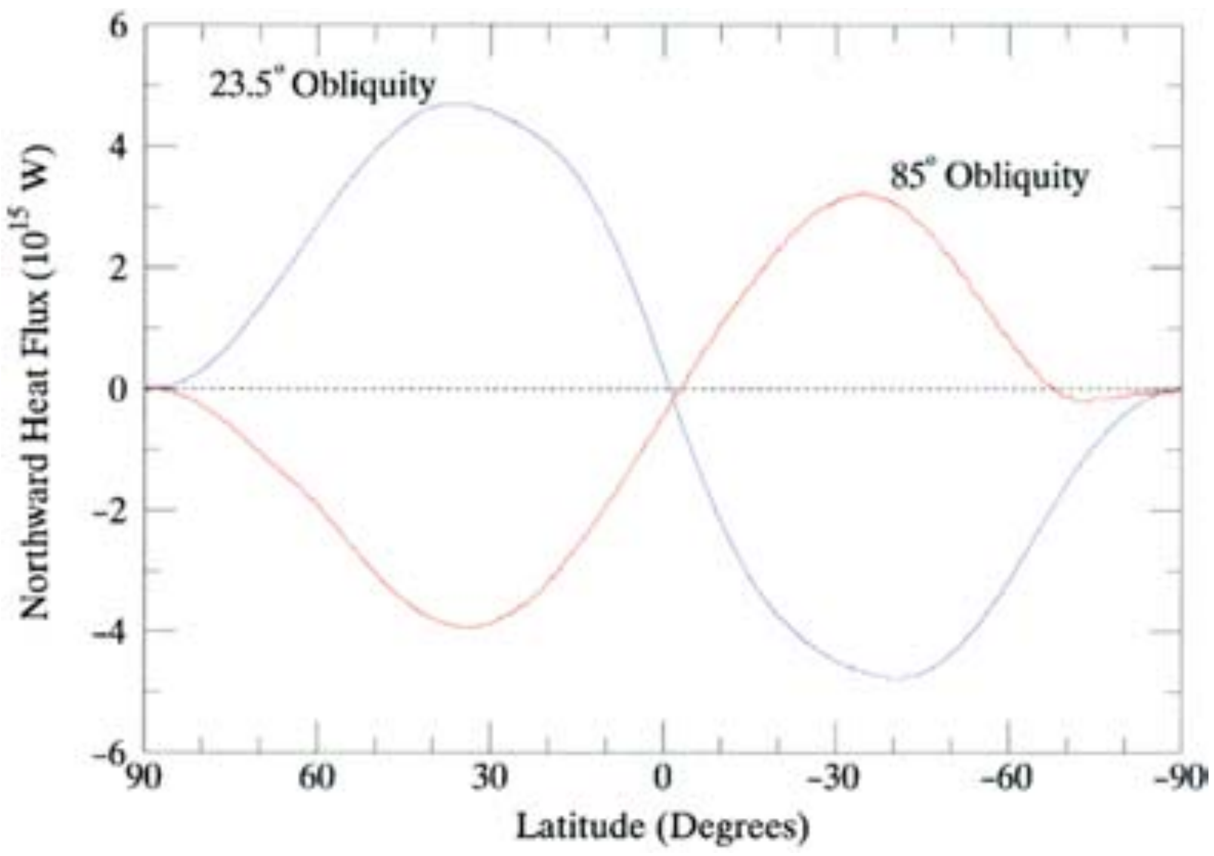
Cold start
T= 230 K everywhere (ice)
Low thermal diffusion coefficient
No water vapor clouds
High albedo

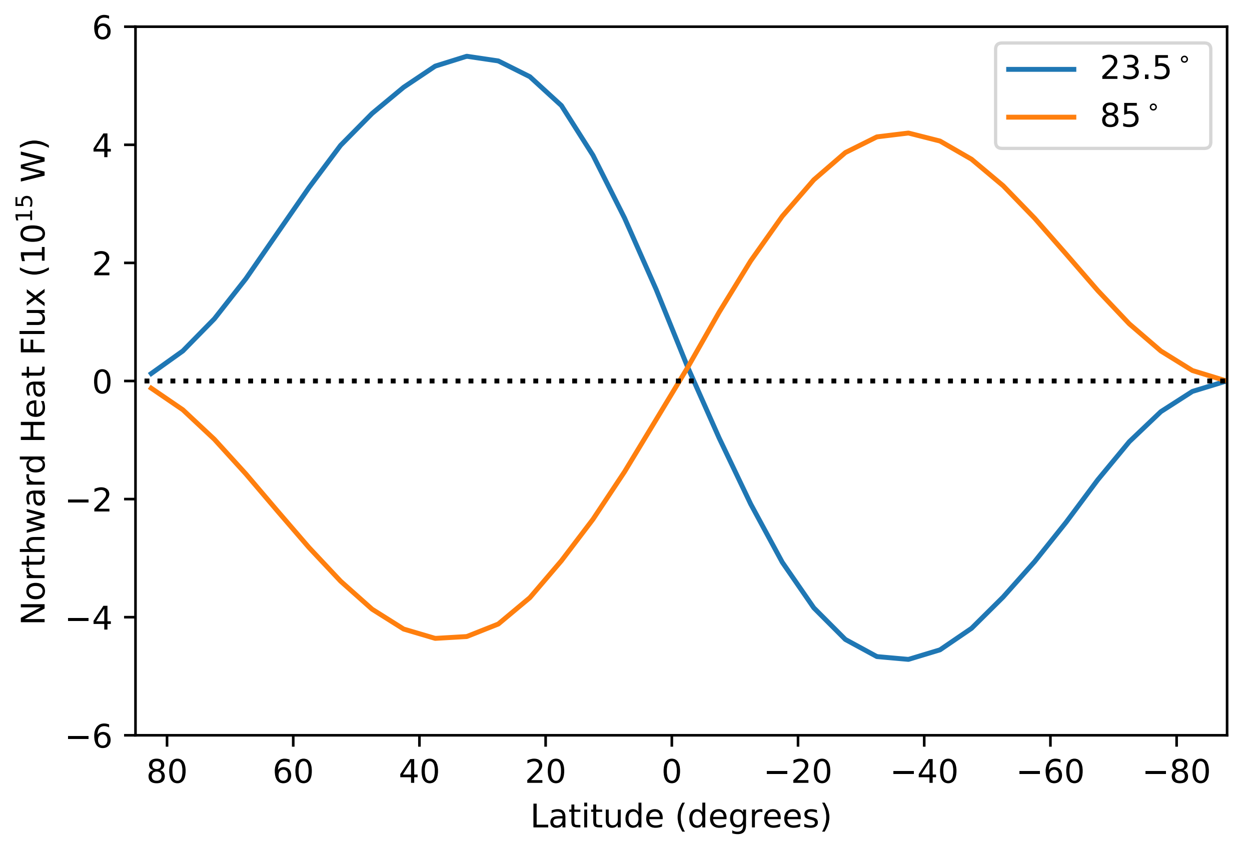
Warm start
T= 280 K everywhere
High thermal diffusion coefficient
Water vapor clouds are present
Low albedo

Validation - Meridional heat transport

$$\mathcal{F}_\lambda = 2\pi R \cos\lambda F_\lambda = 2\pi R^2 D \cos^2\lambda \frac{\partial T}{\partial x}$$

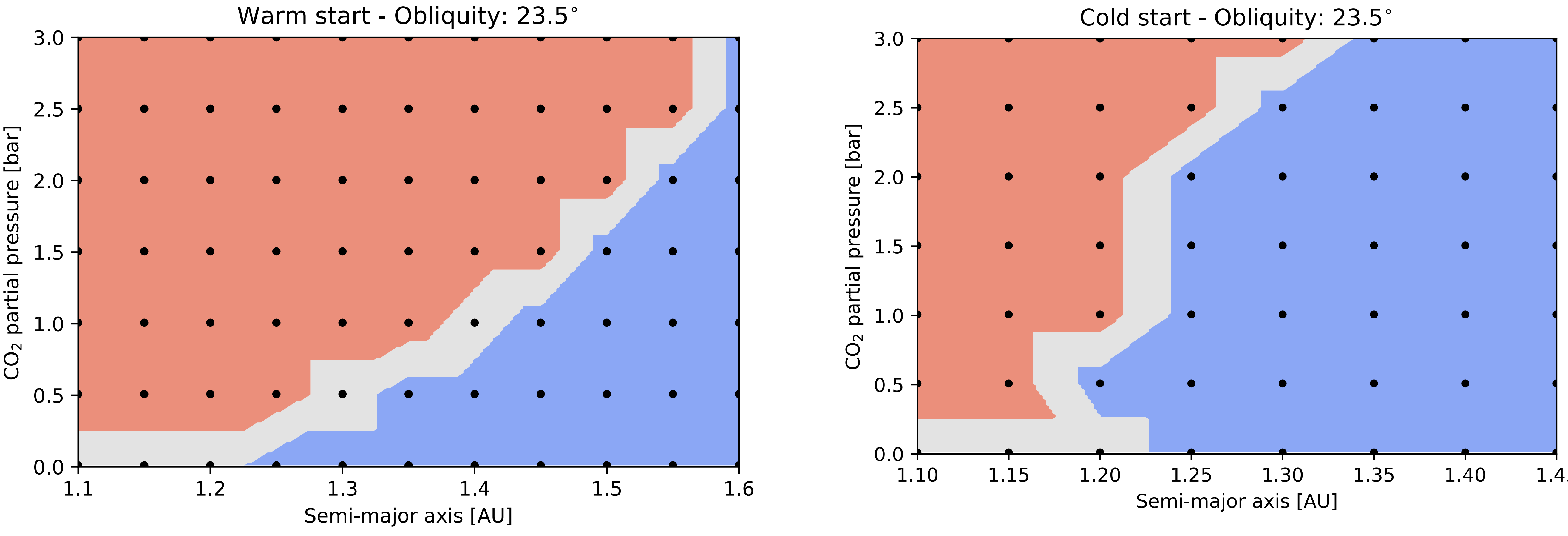
Fλ : Latitudinal energy transport per unit length
R: planetary radius
D: heat diffusion coefficient
λ : Latitude
dT/dx: temperature gradient between latitude belts





Williams+2003

Results - Steady-state solutions



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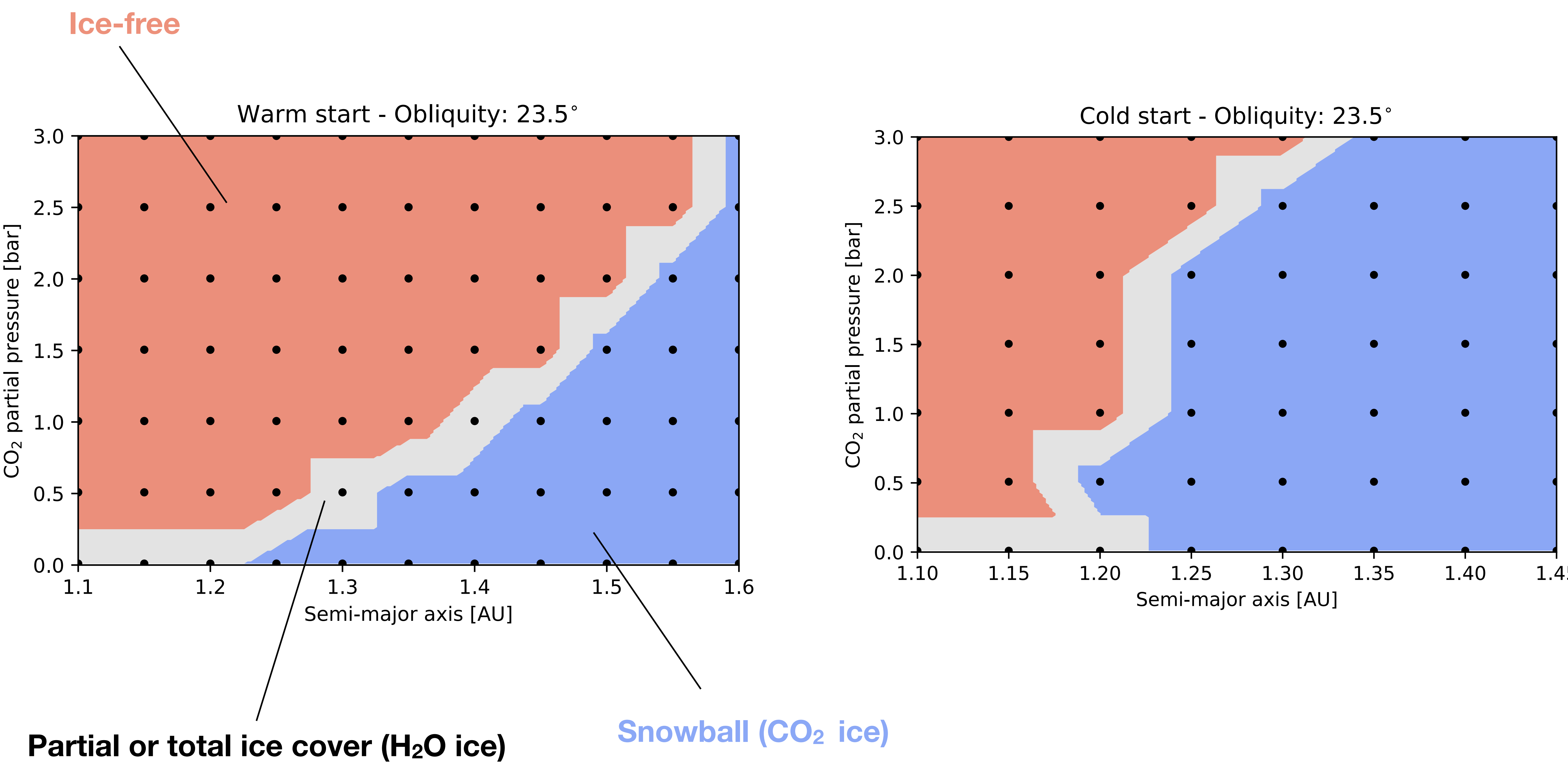

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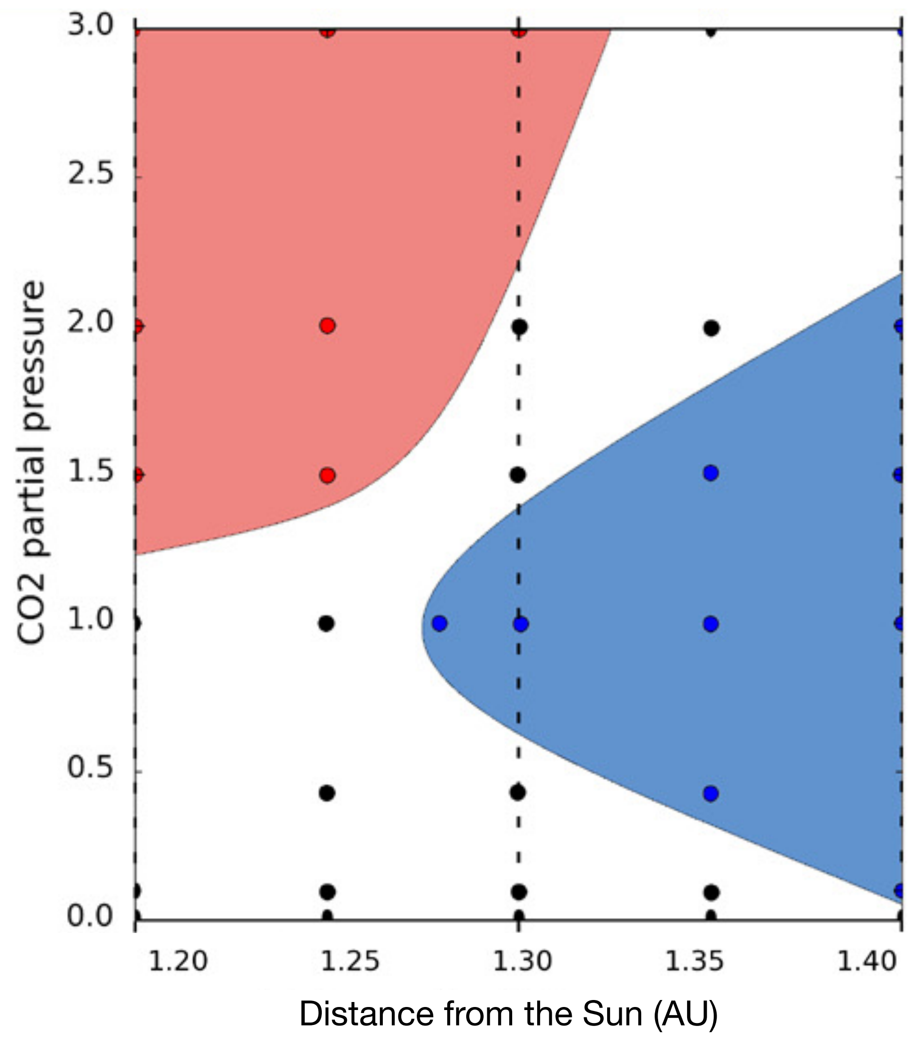
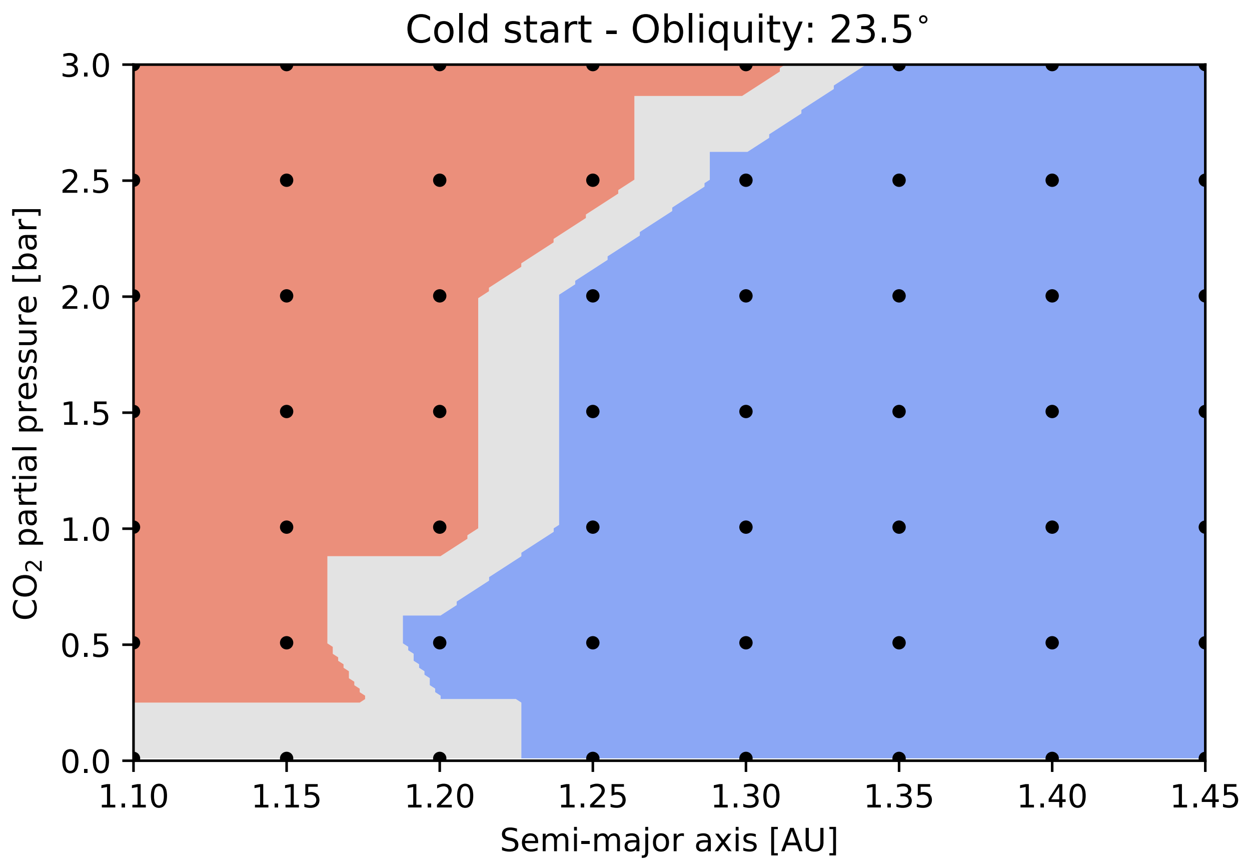
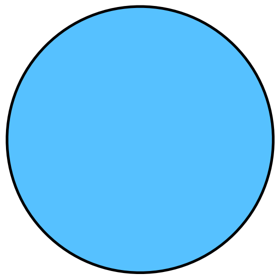
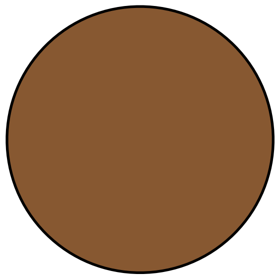
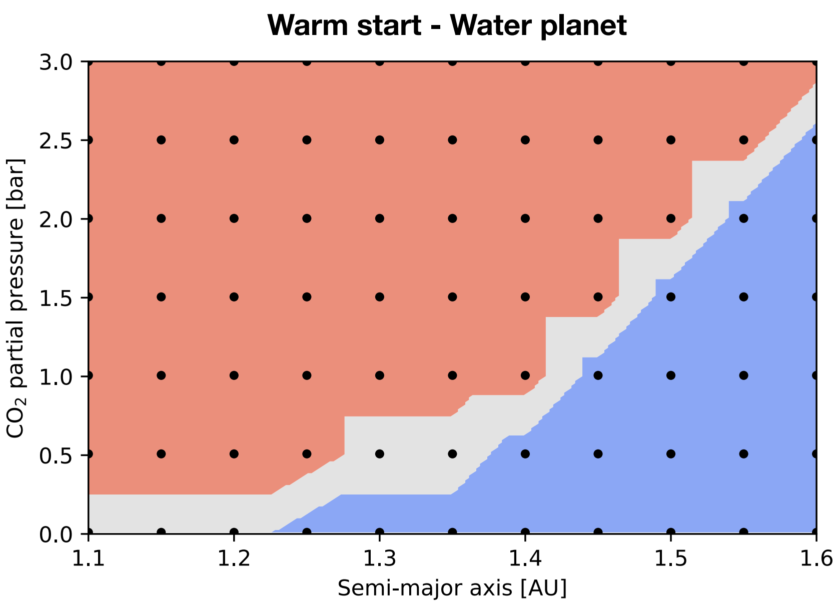


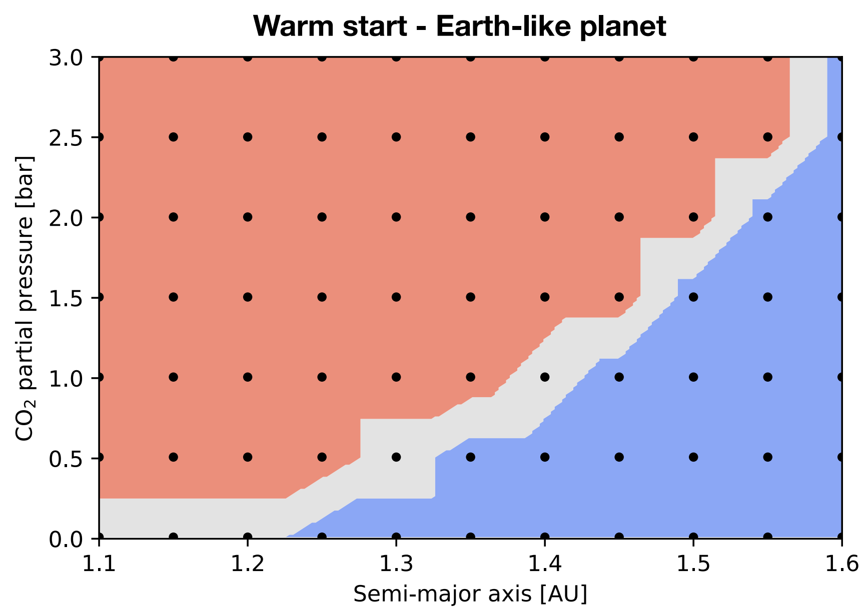


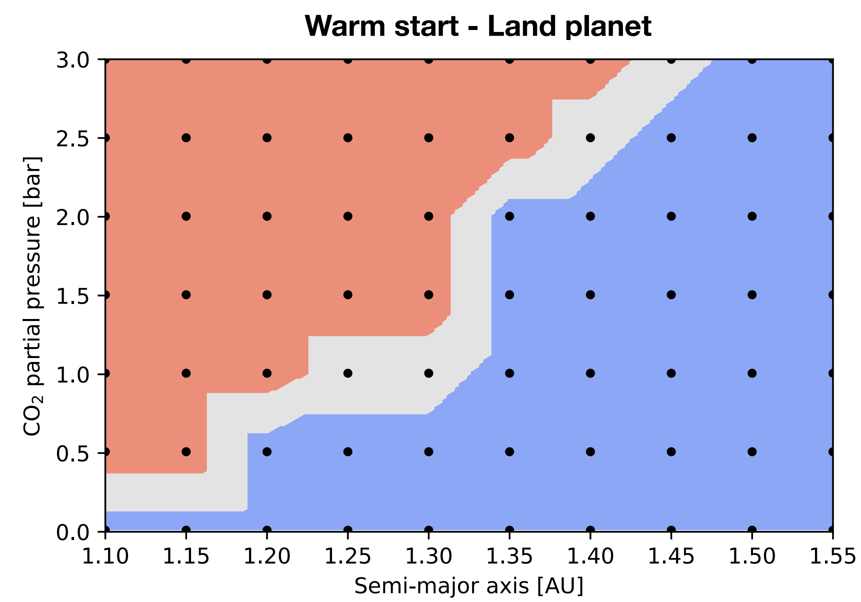
Results - Effect of water fraction



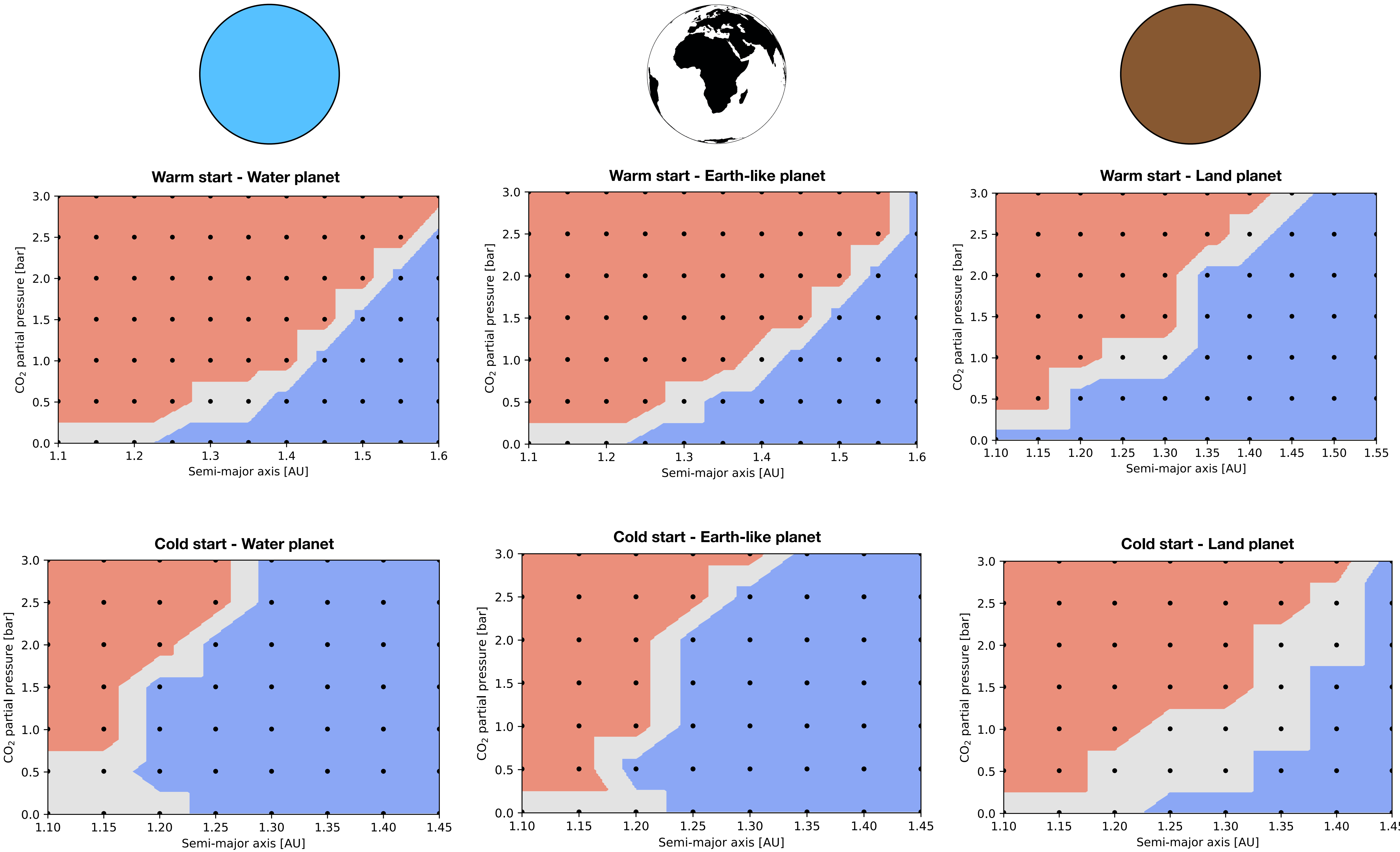






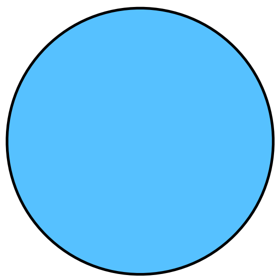


Results - Effect of water fraction



Results - Effect of water fraction

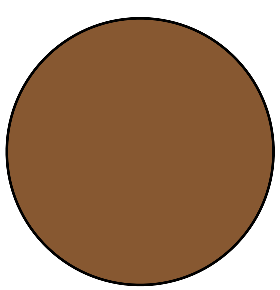
Water planet



Warm start: More water vapor than in continental case
Heat transfer more efficient —> **Warmer**

Cold start: More water means more ice
Efficient ice-albedo feedback —> **Colder**

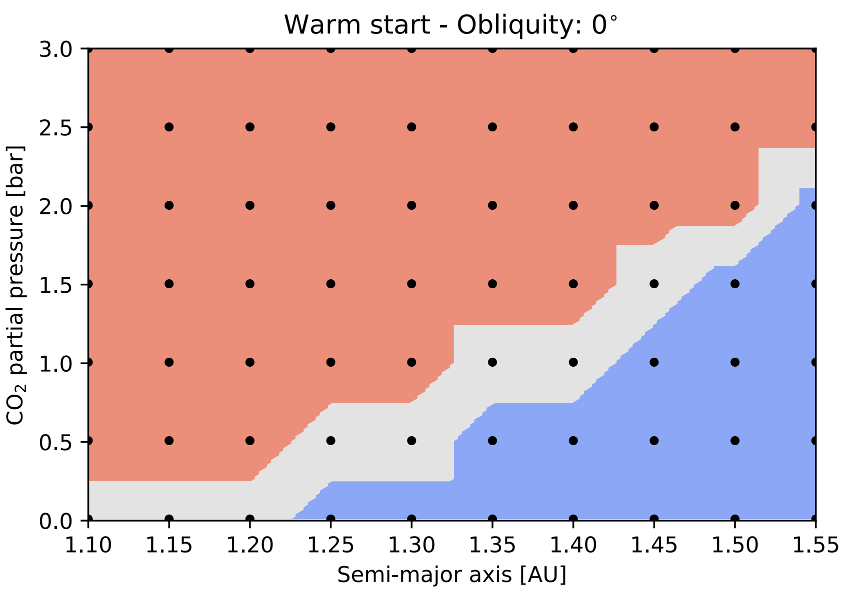
Land planet

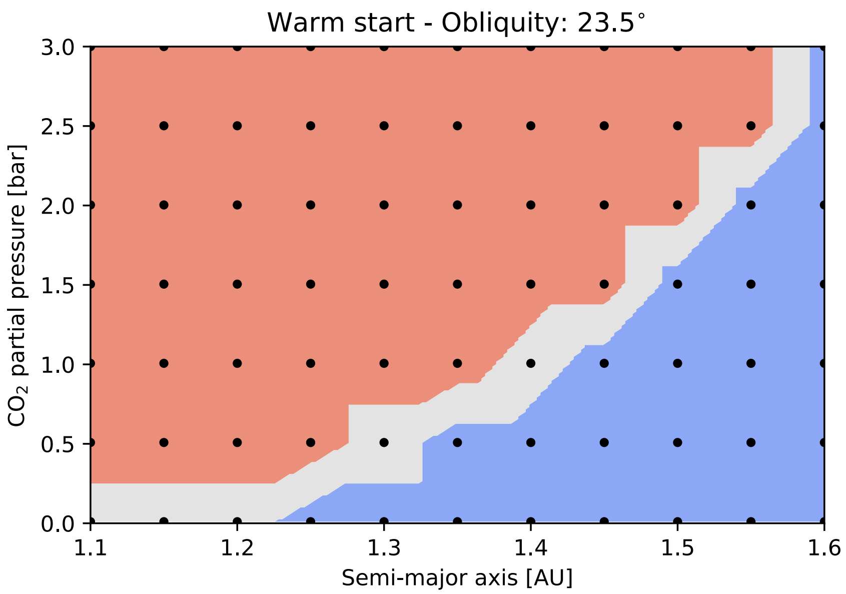


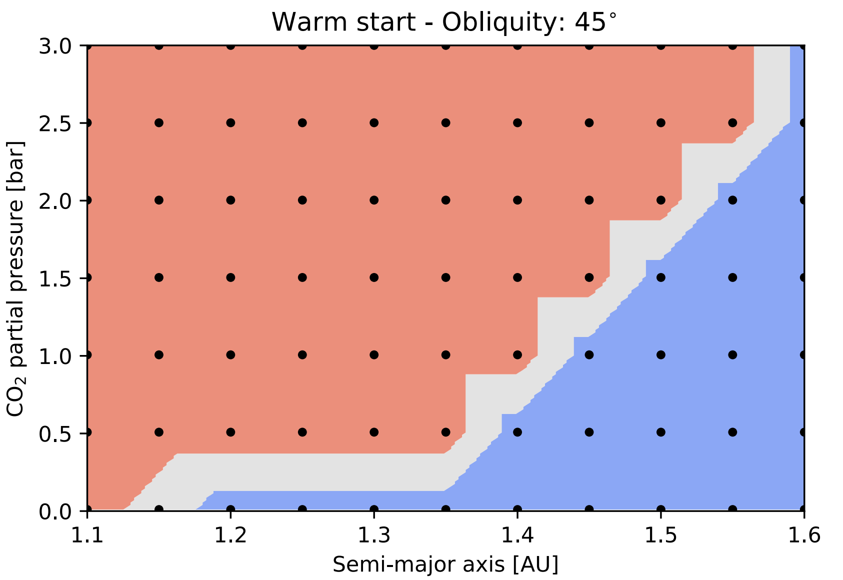
Warm start: Less water vapor present
Heat transfer is less efficient —> **Colder**

Cold start: Lower albedo (for given ice coverage on land)
Planet tends to heat up faster —> **Warmer**

Results - Effect of obliquity







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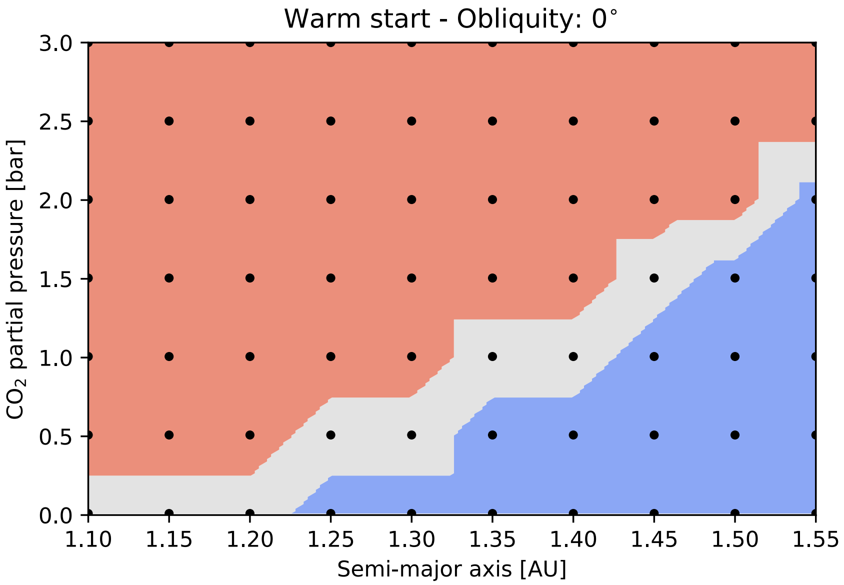
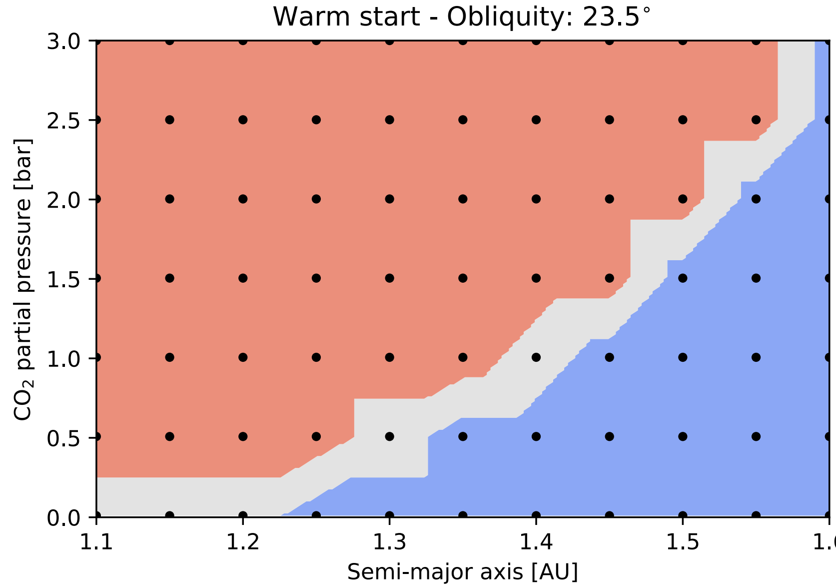
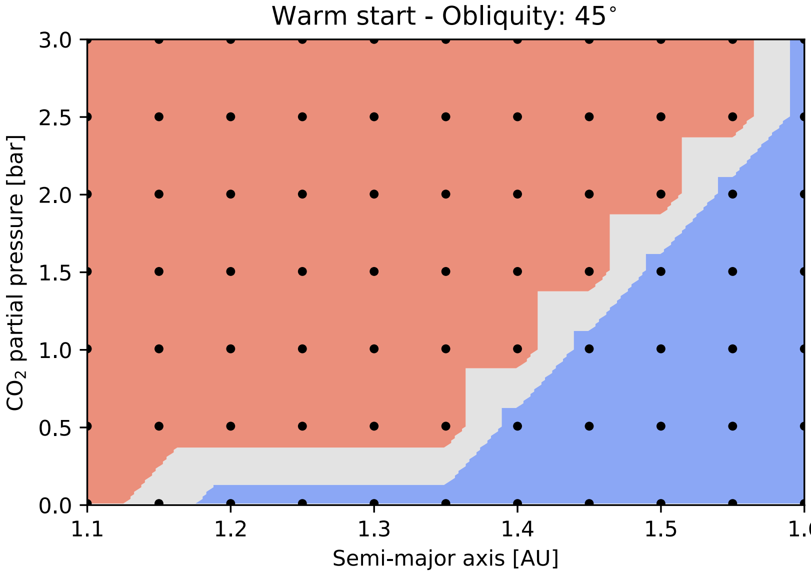
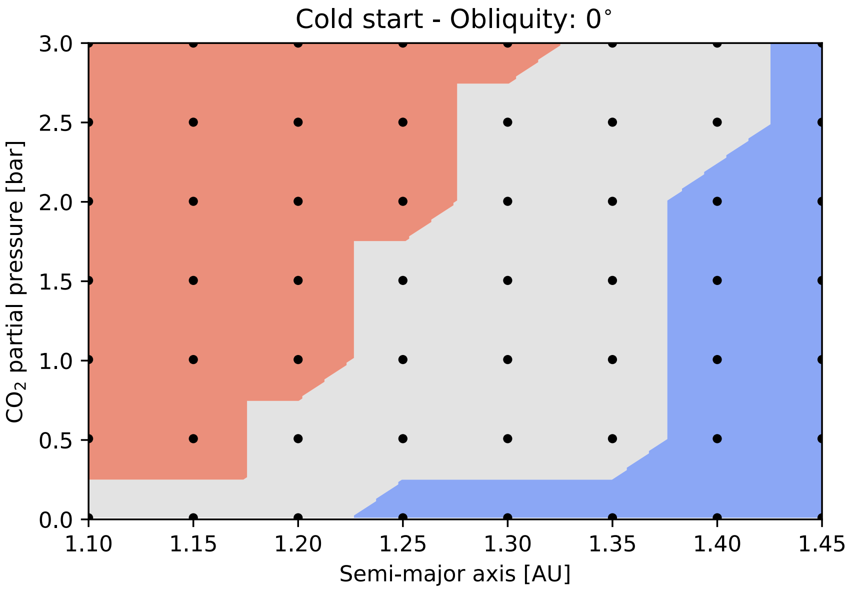
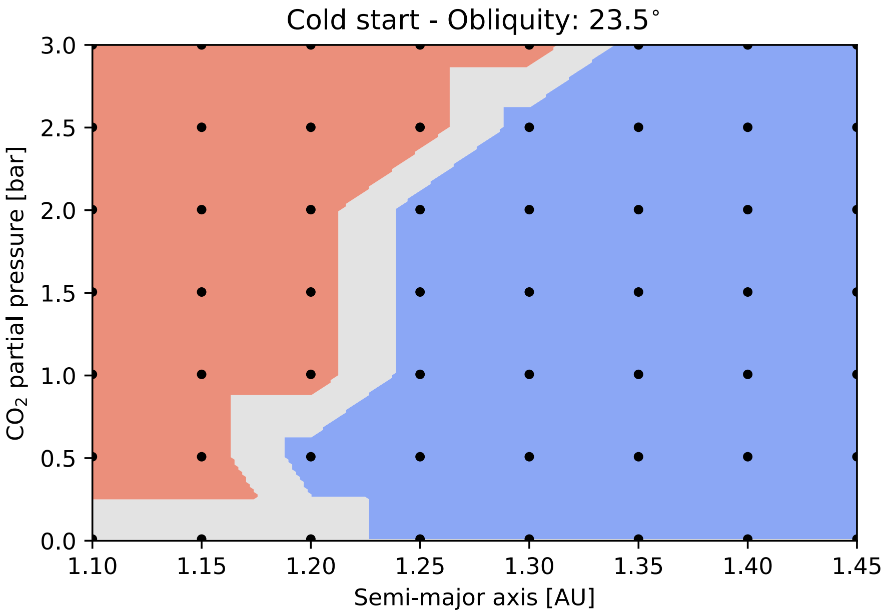
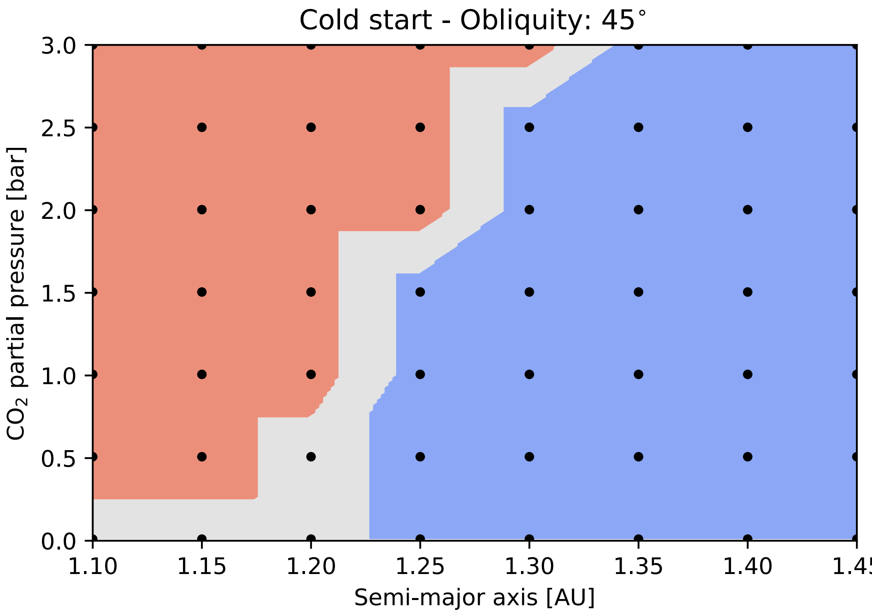




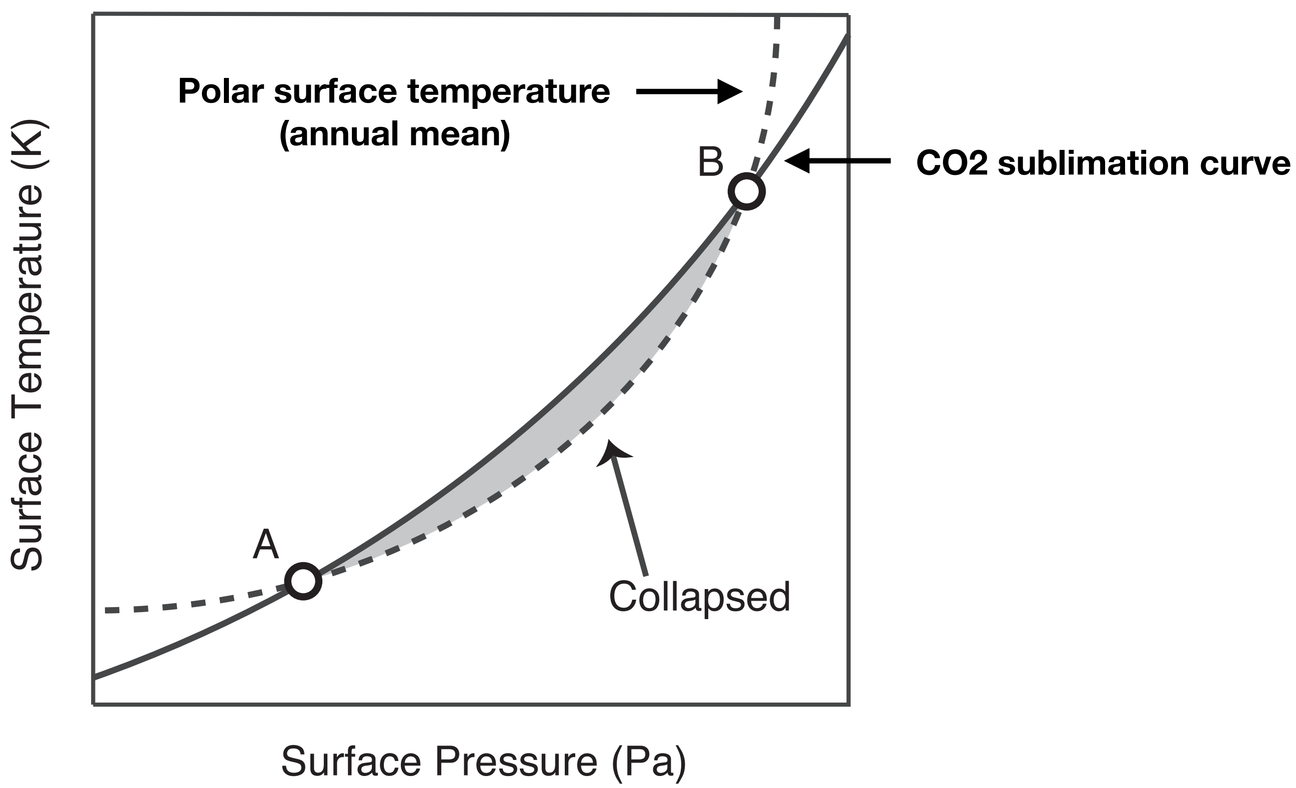


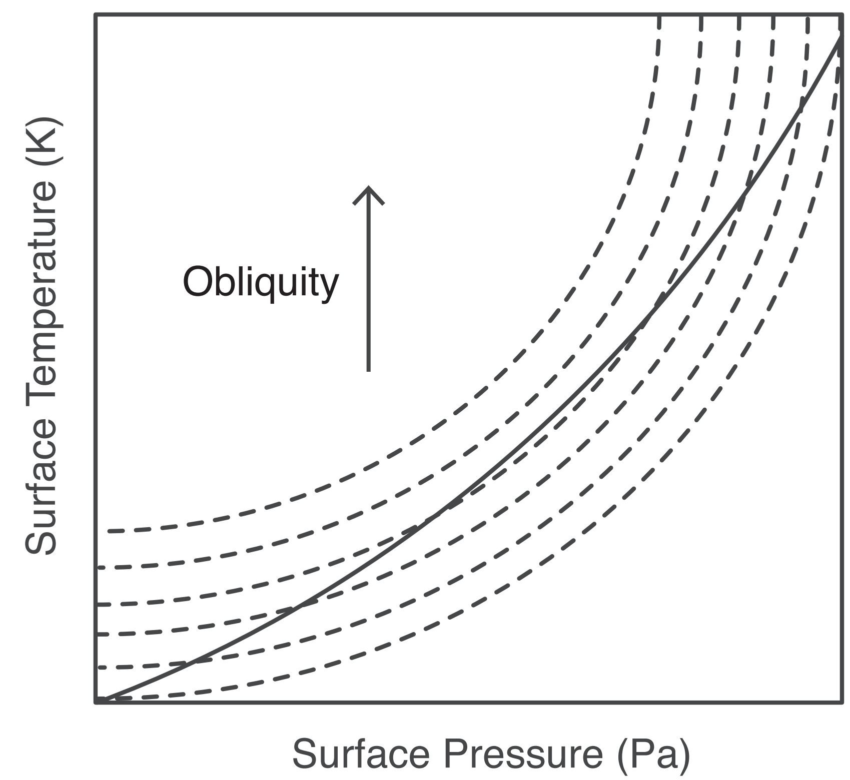






Atmospheric CO2 collapse rate





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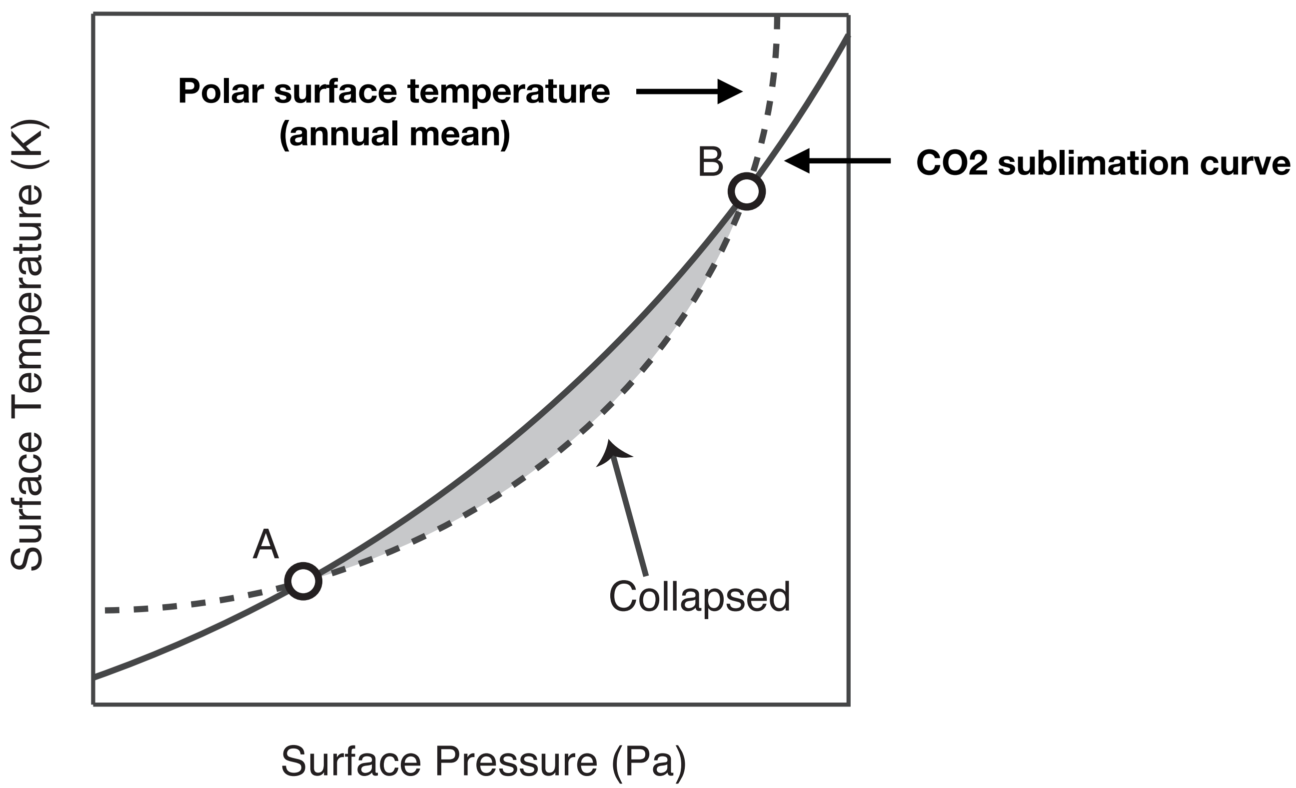
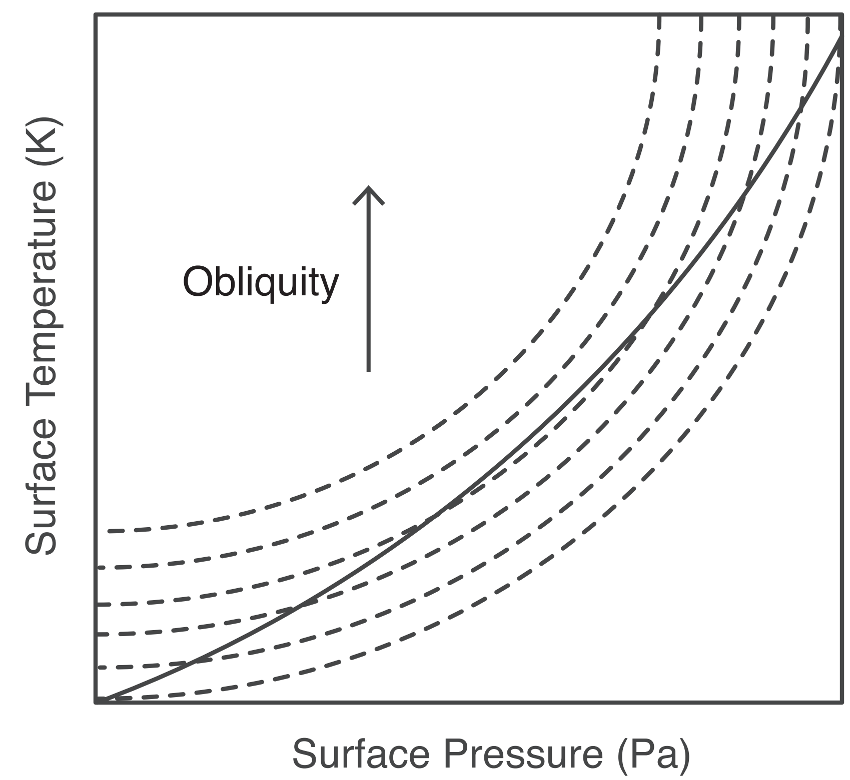




$\bar{P}_s$	Obliquity			
	0°	5°	15°	25°
6	1.4×10^{15}	1.4×10^{15}	0.3×10^{15}	NC
60	3.1×10^{15}	4×10^{15}	2.3×10^{15}	0.9×10^{15}
300	2×10^{15}	3.5×10^{15}	2.8×10^{15}	2.8×10^{15}
600	1.5×10^{15}	2.3×10^{15}	3.1×10^{15}	3×10^{15}
1200	0.9×10^{15}	1.4×10^{15}	1.3×10^{15}	0.9×10^{15}
3000	1×10^{15}	1.1×10^{15}	0.4×10^{15}	NC

Soto+2015

Results - CO2 ice as a function of time

Results - T_surf afar latitude

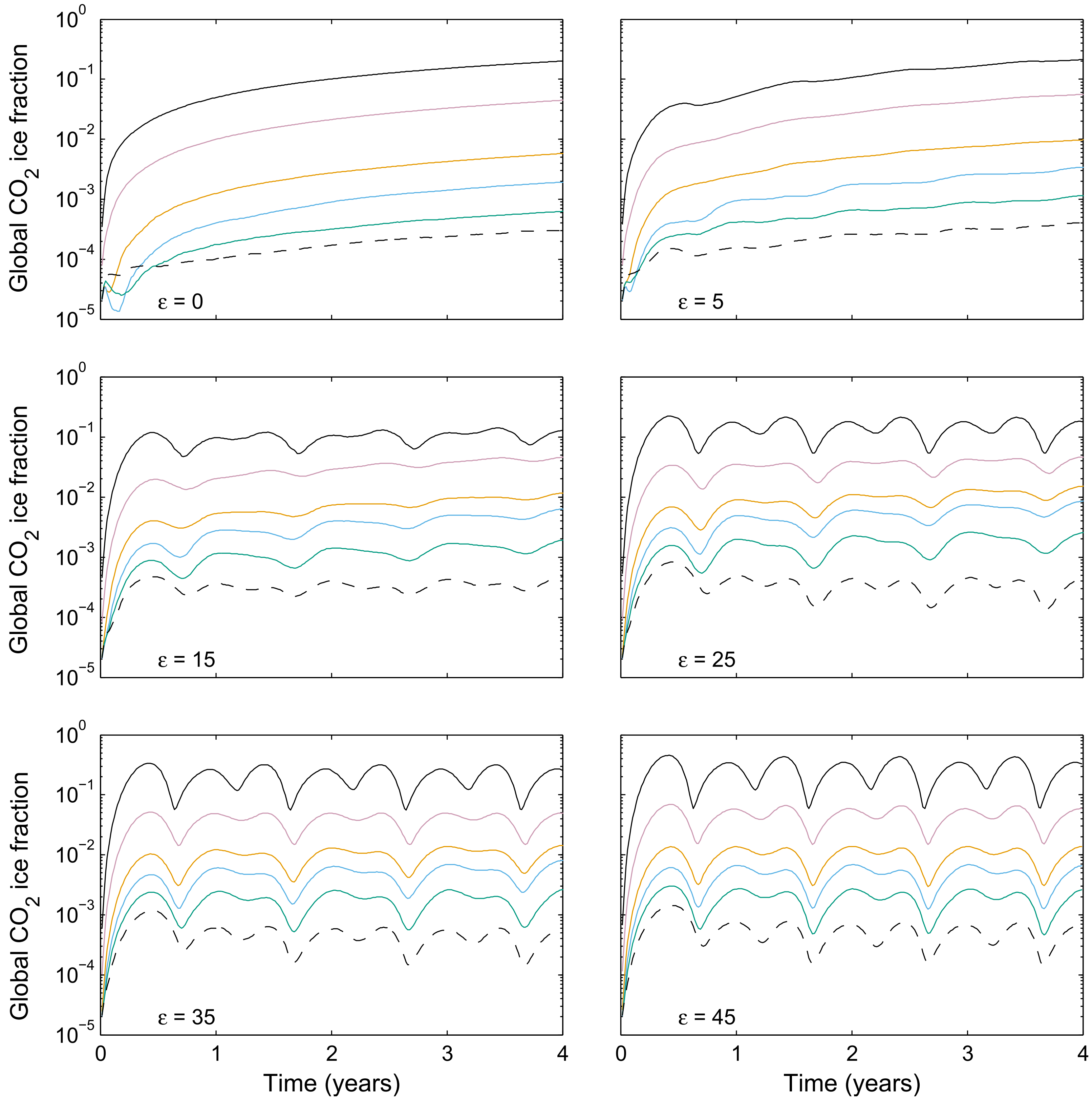
Conclusion and outlook

- Earth-like planets starting out **warm** can more easily **avoid permanent CO_2 surface ice collapse** and sustain habitable surface temperatures over longer distances from their host star.
- **Water planets** starting out **cold** display a higher tendency to CO_2 surface ice collapse due to the **increased ice fraction** and resulting **high albedo**.
- On the other hand, water planets starting out **warm** show a more efficient heat transport and result **warmer than land planets**.
- Planets at **higher obliquities** tend to be **warmer** due to the reduced temperature gradients between the equator and the poles.

Next steps

- Application to bodies orbiting M-stars
- Time evolution of CO_2 ice (seasonality)

Seasonality



Soto+2015