Geophysical evolution during rocky planet formation

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SIMONS FOUNDATION

Lorentz Center Workshop ‘The Volatile Content of Planets that Form Early’, December 2021

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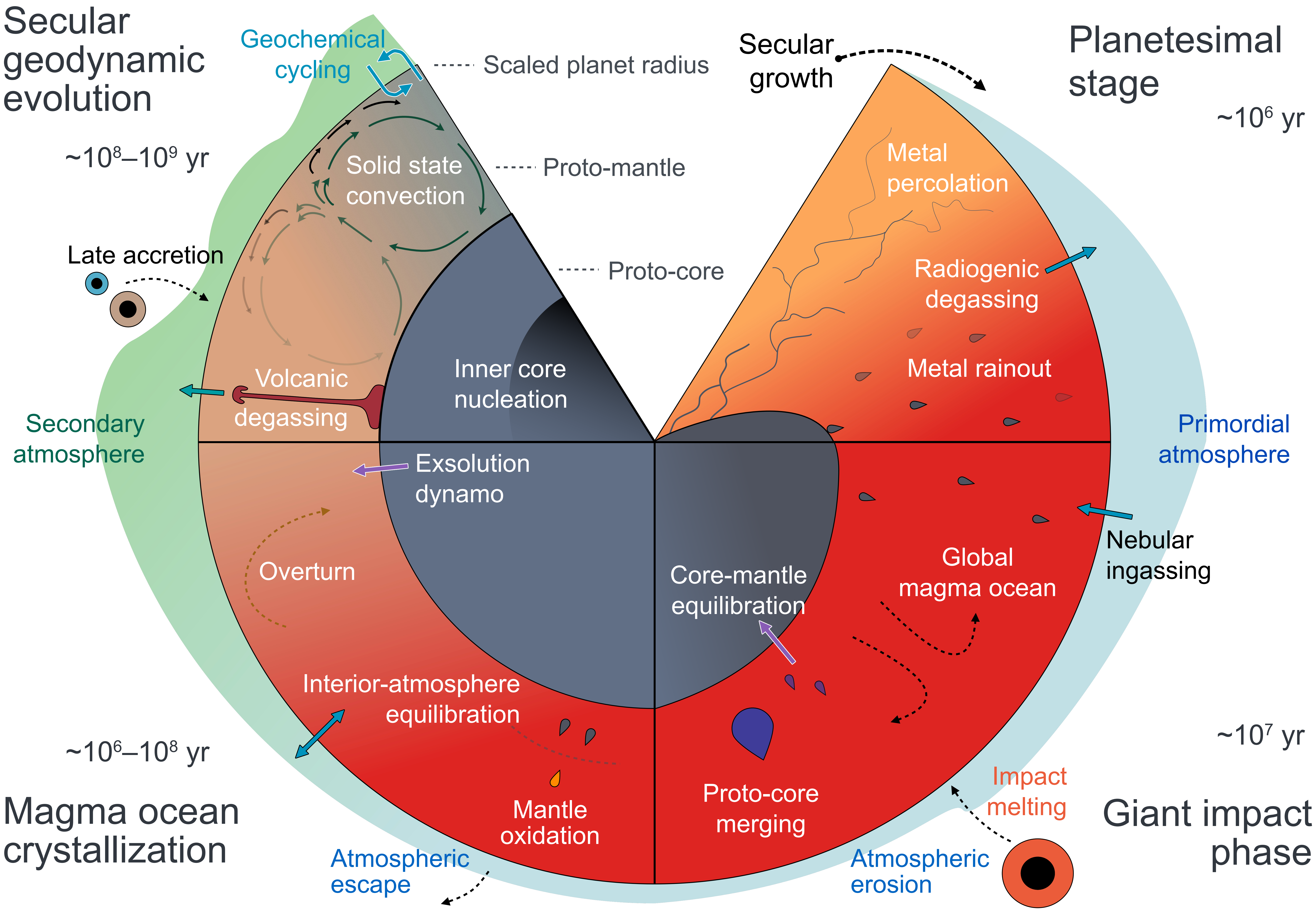
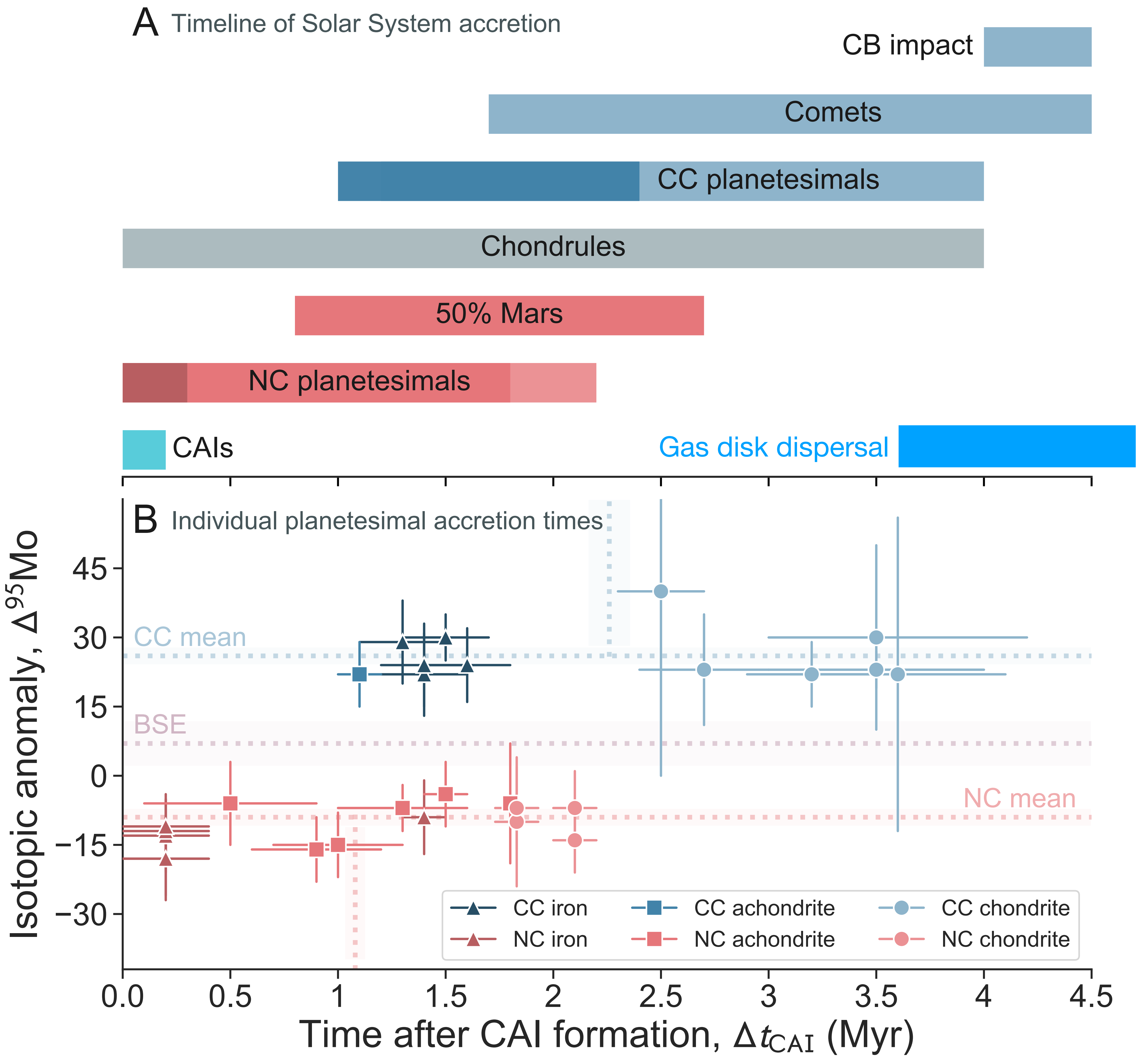
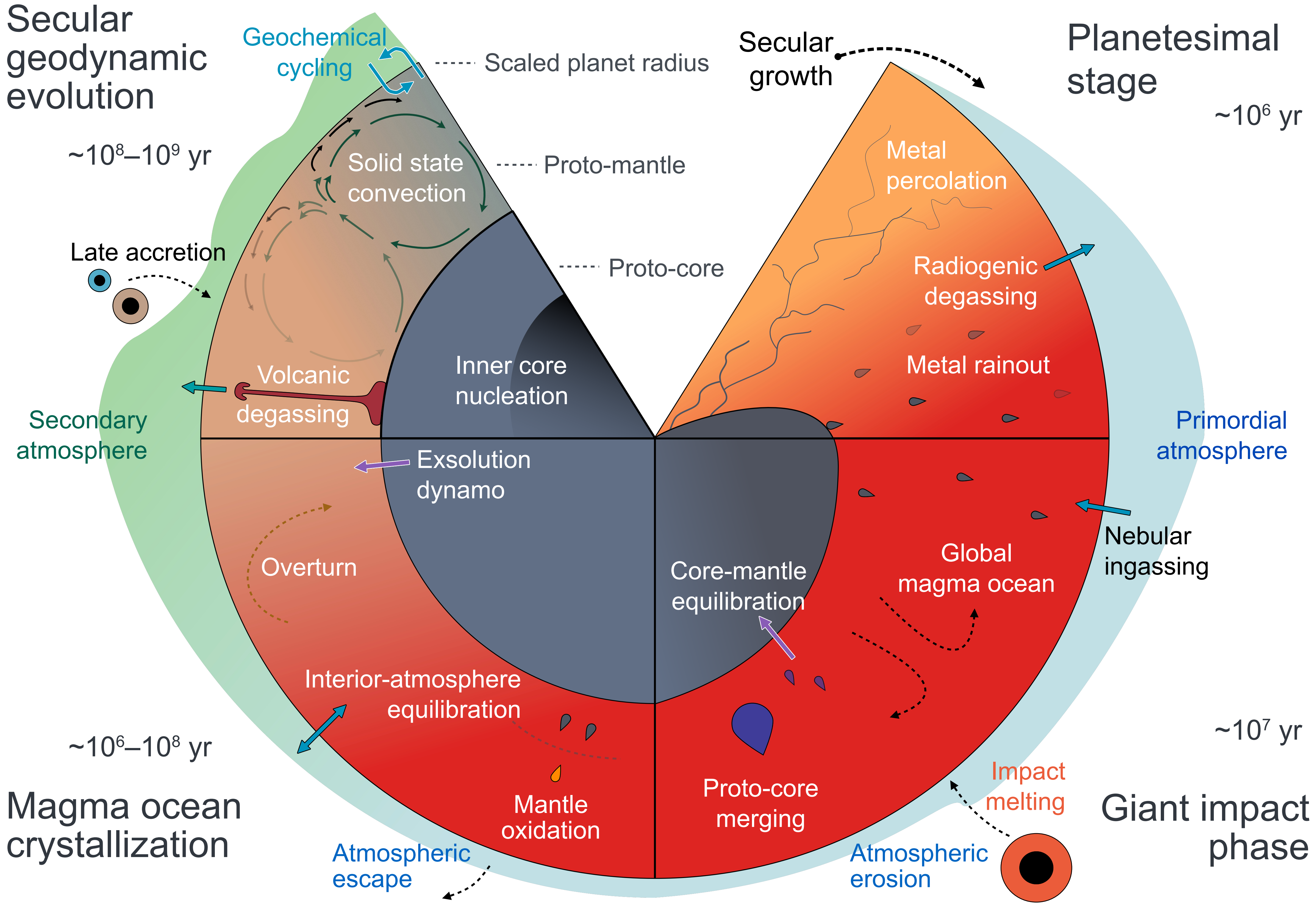


Lichtenberg, Schaefer, Nakajima, Fischer, *Protostars & Planets VII*

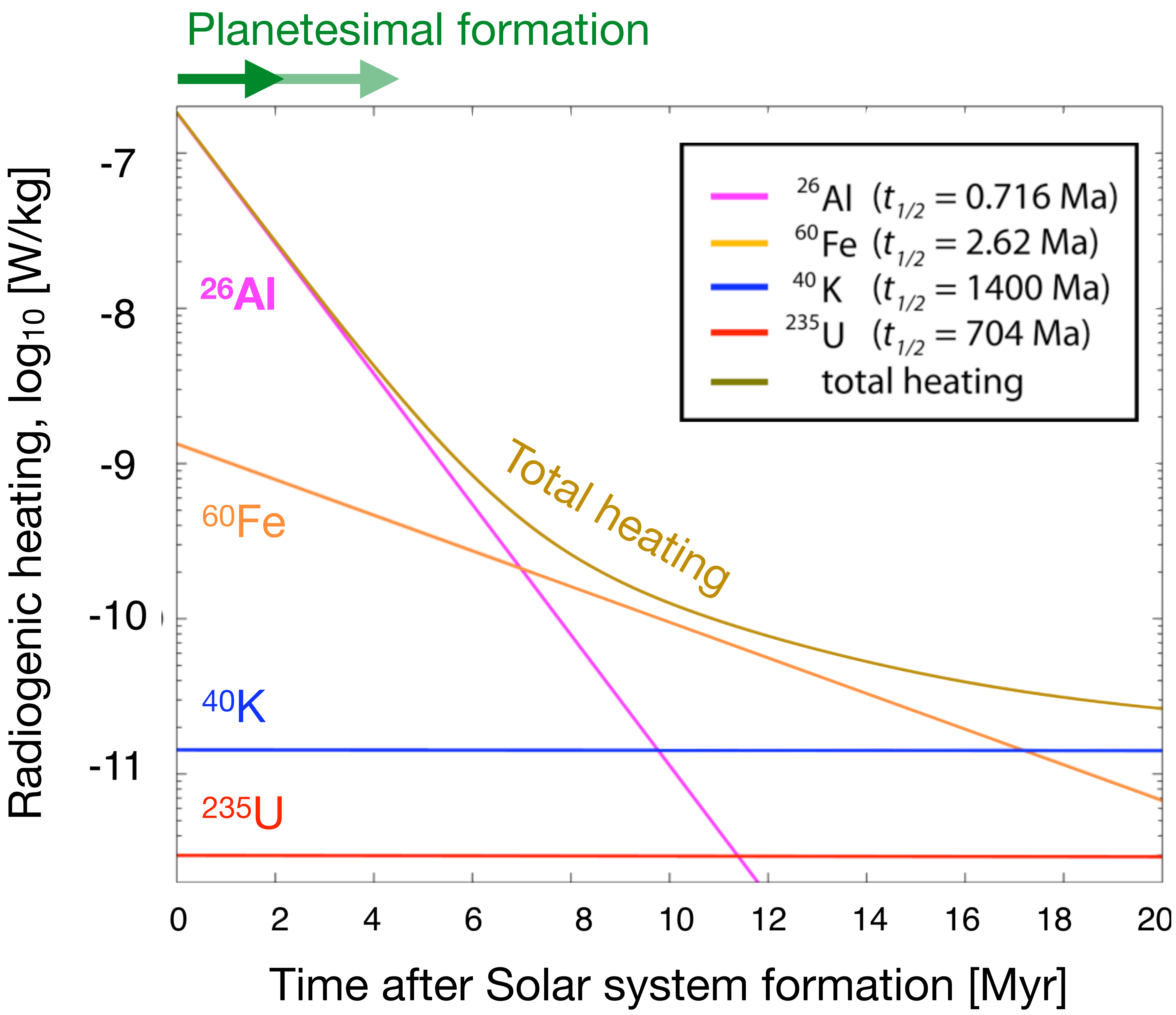
Temporal fragmentation of planet formation

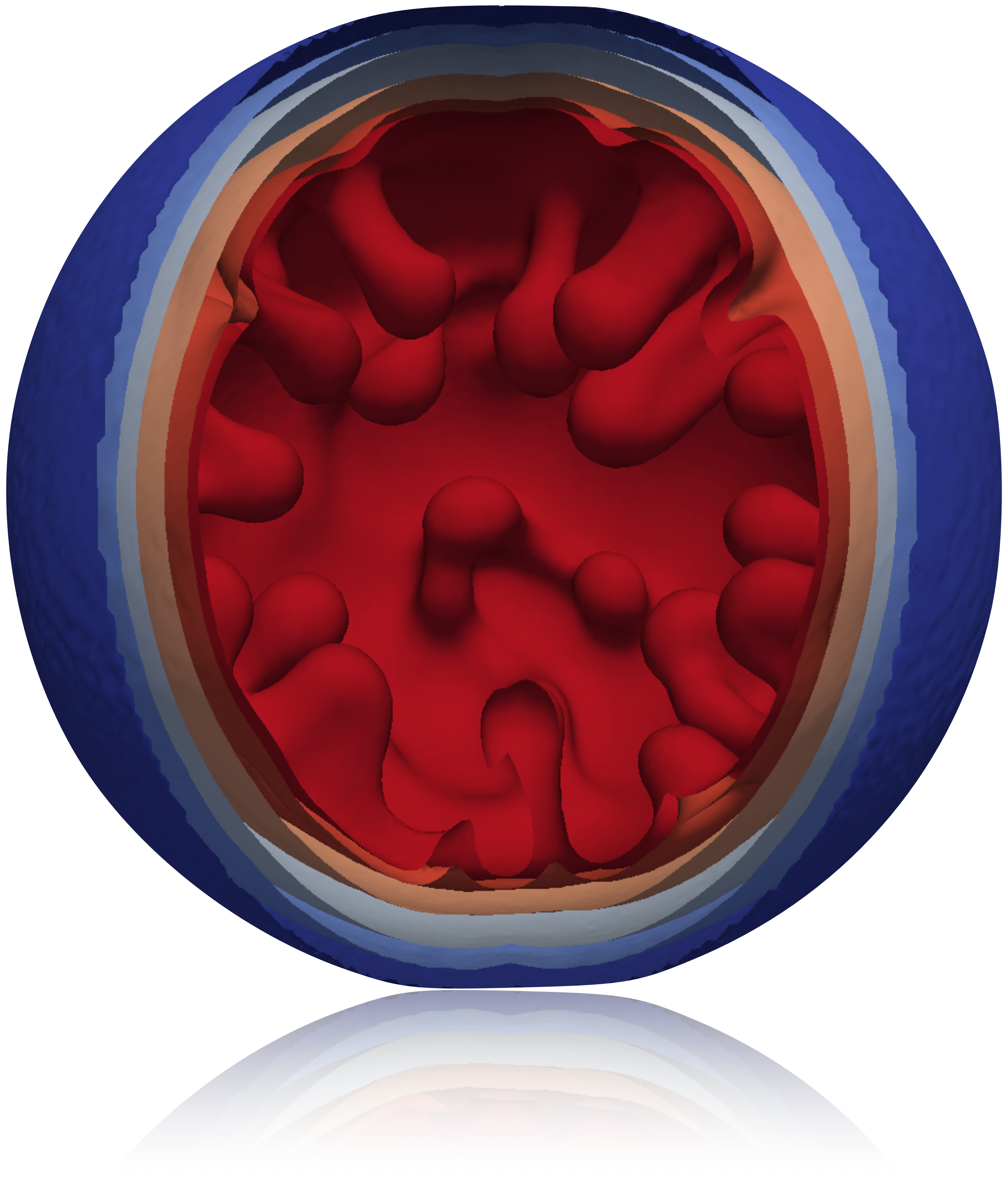




Lichtenberg, Schaefer, Nakajima, Fischer 22, *Protostars & Planets VII*

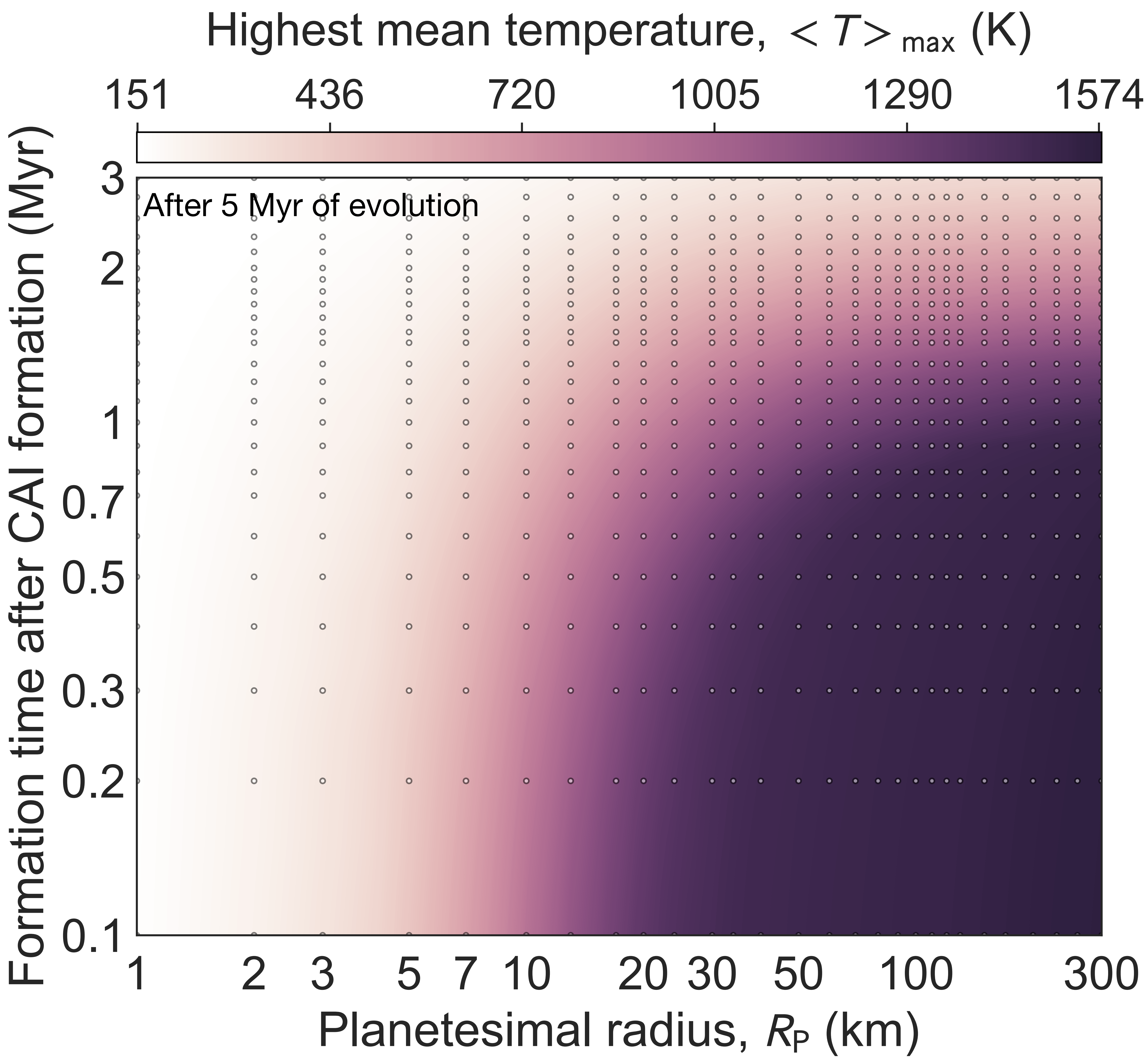
Compositional evolution from radiogenic heating



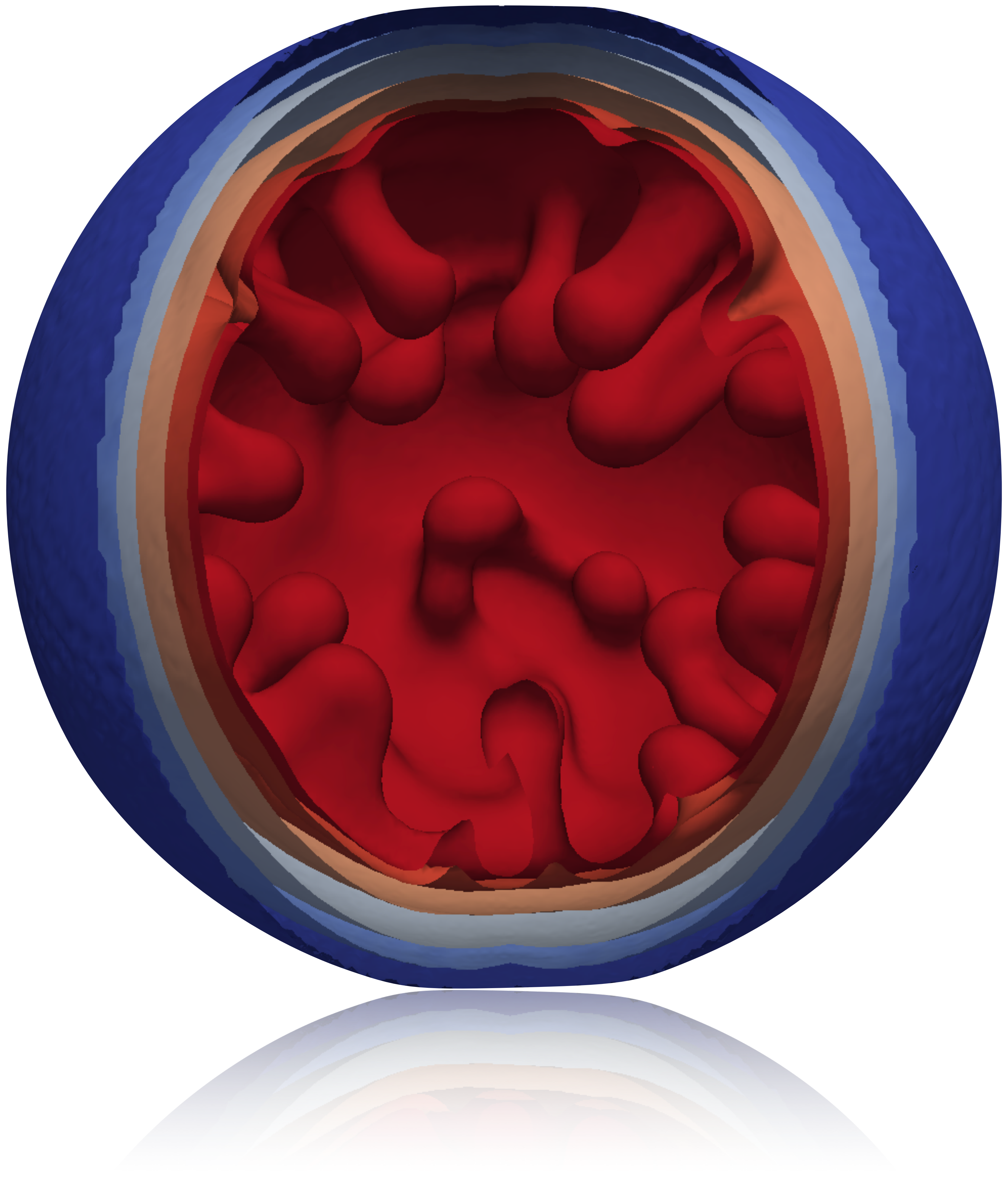


Lichtenberg+ 16a, 18, 19a,b

Radiogenic heating drives thermal evolution

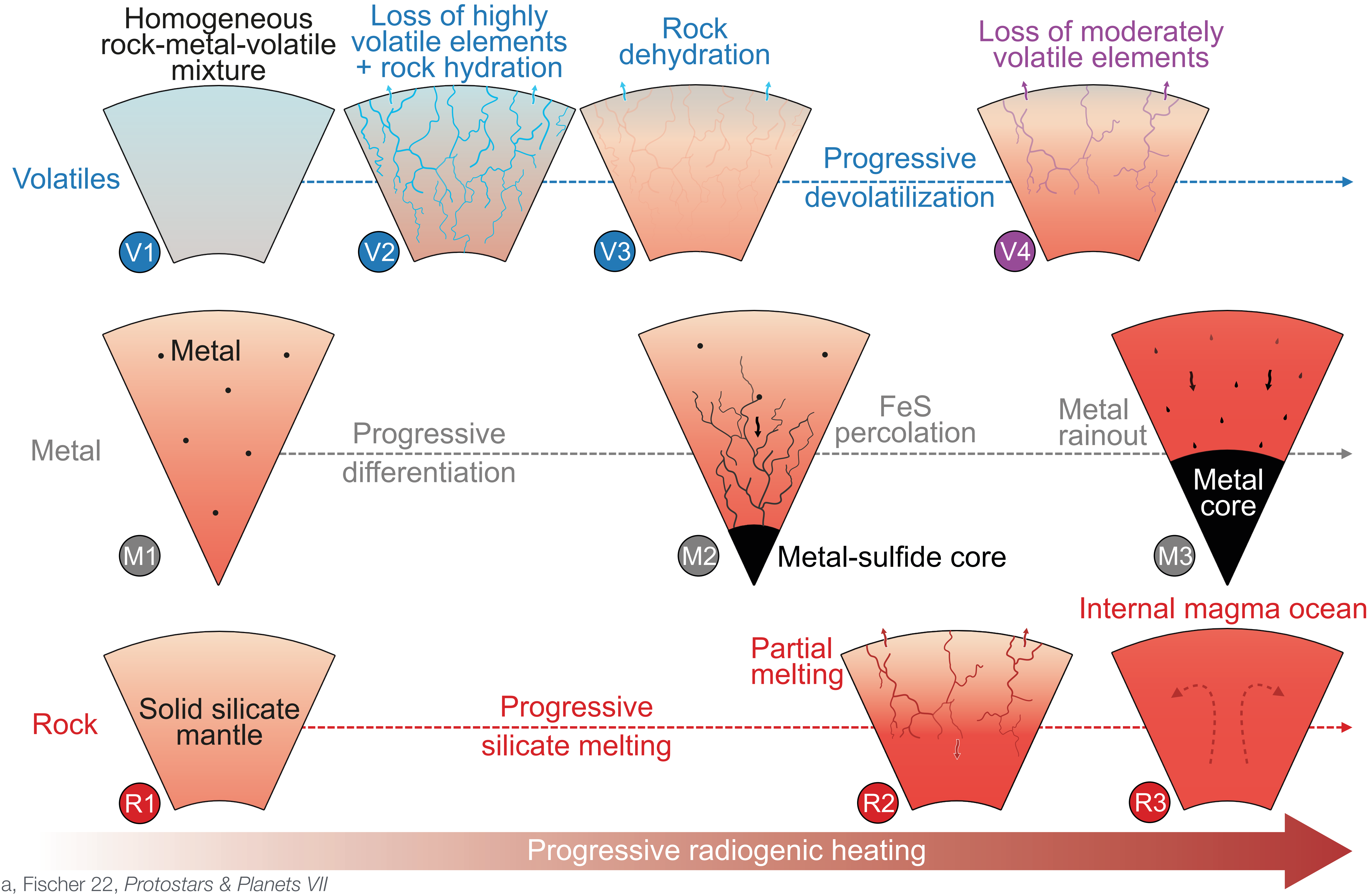


Lichtenberg, Drążkowska+ 21



Lichtenberg+ 16a, 18, 19a,b

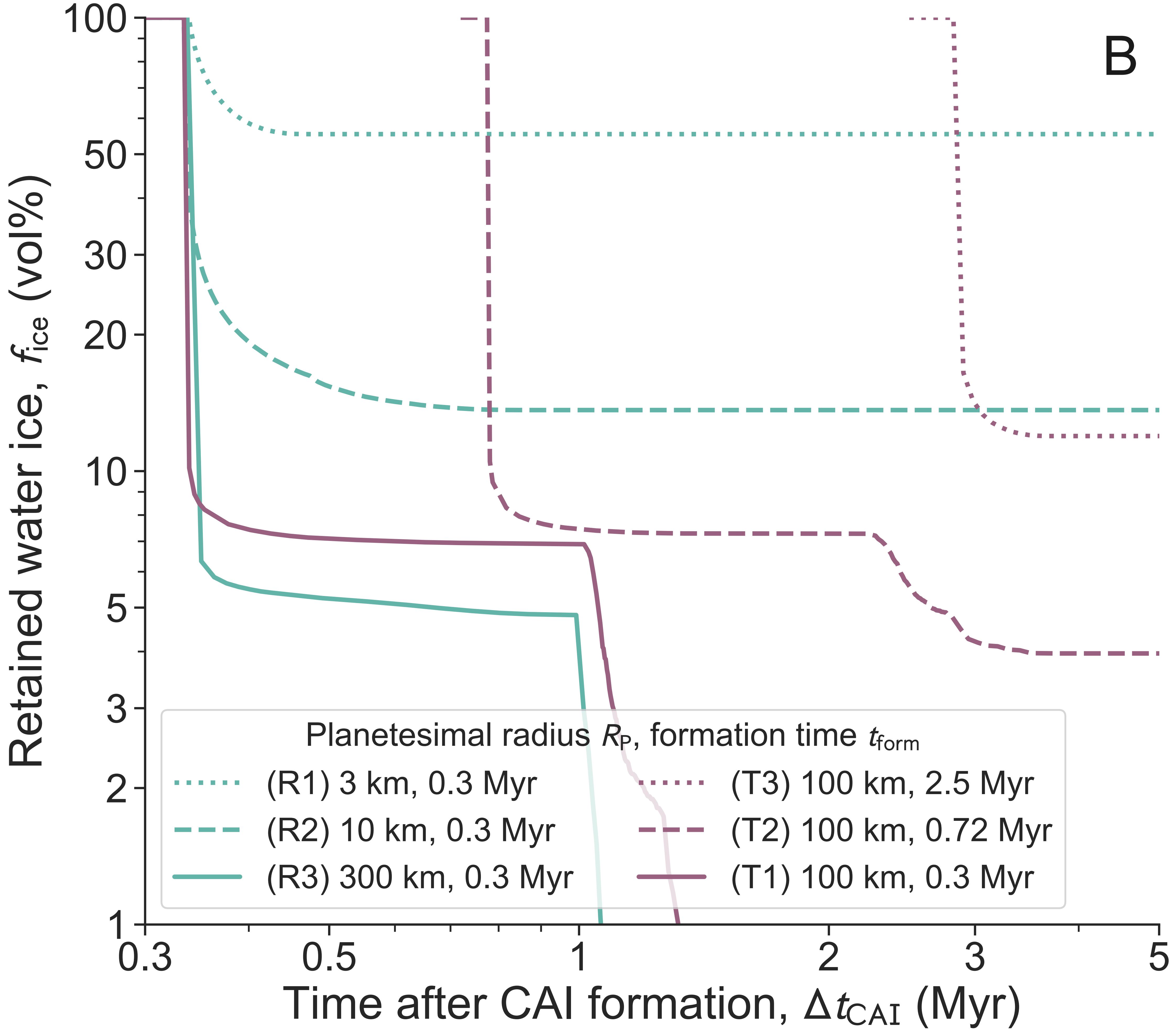
Thermal and compositional evolution **highly time sensitive**



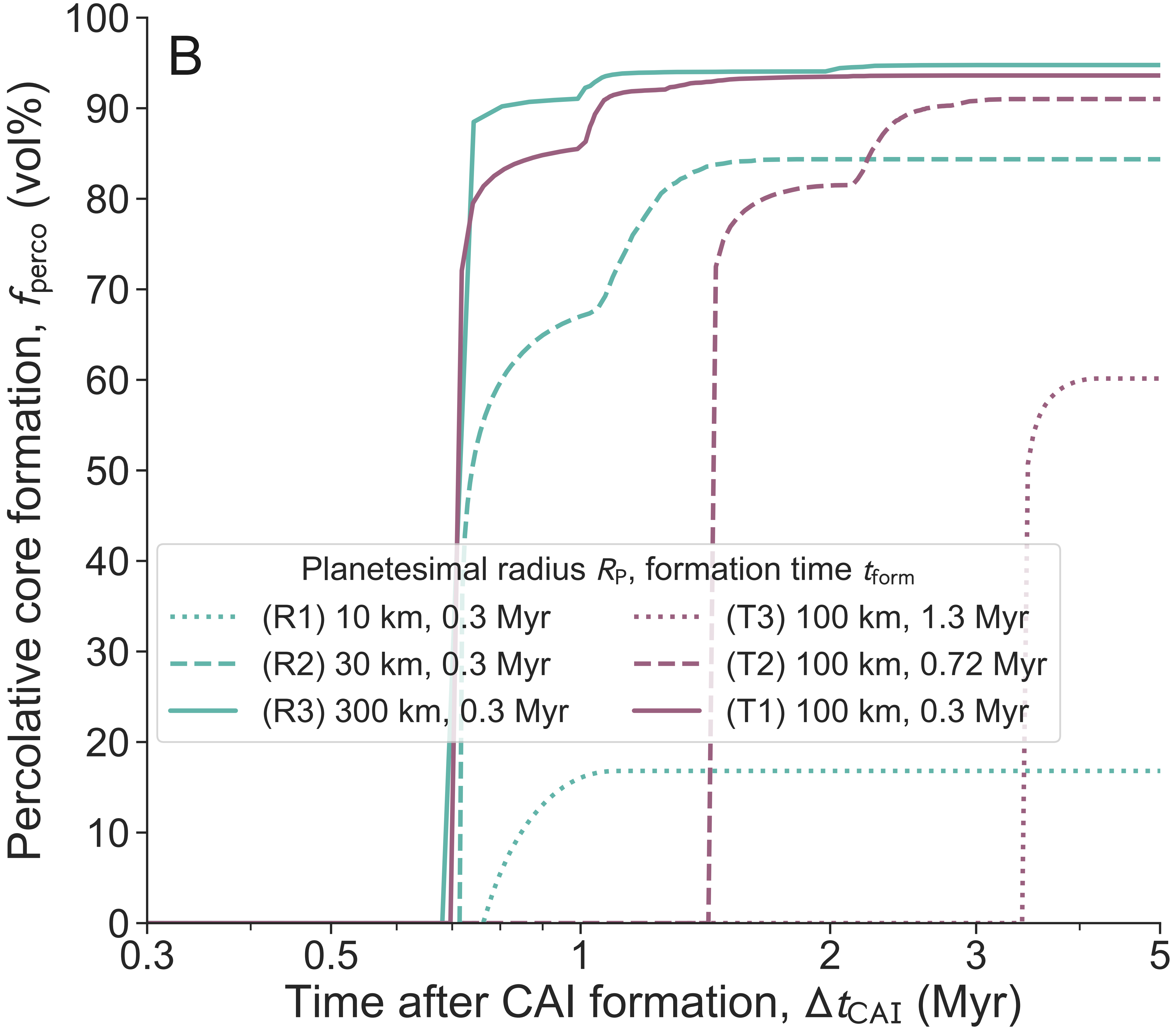
Lichtenberg, Schaefer, Nakajima, Fischer 22, *Protostars & Planets VII*

Thermal and compositional evolution **highly time sensitive**

Planetesimal dehydration

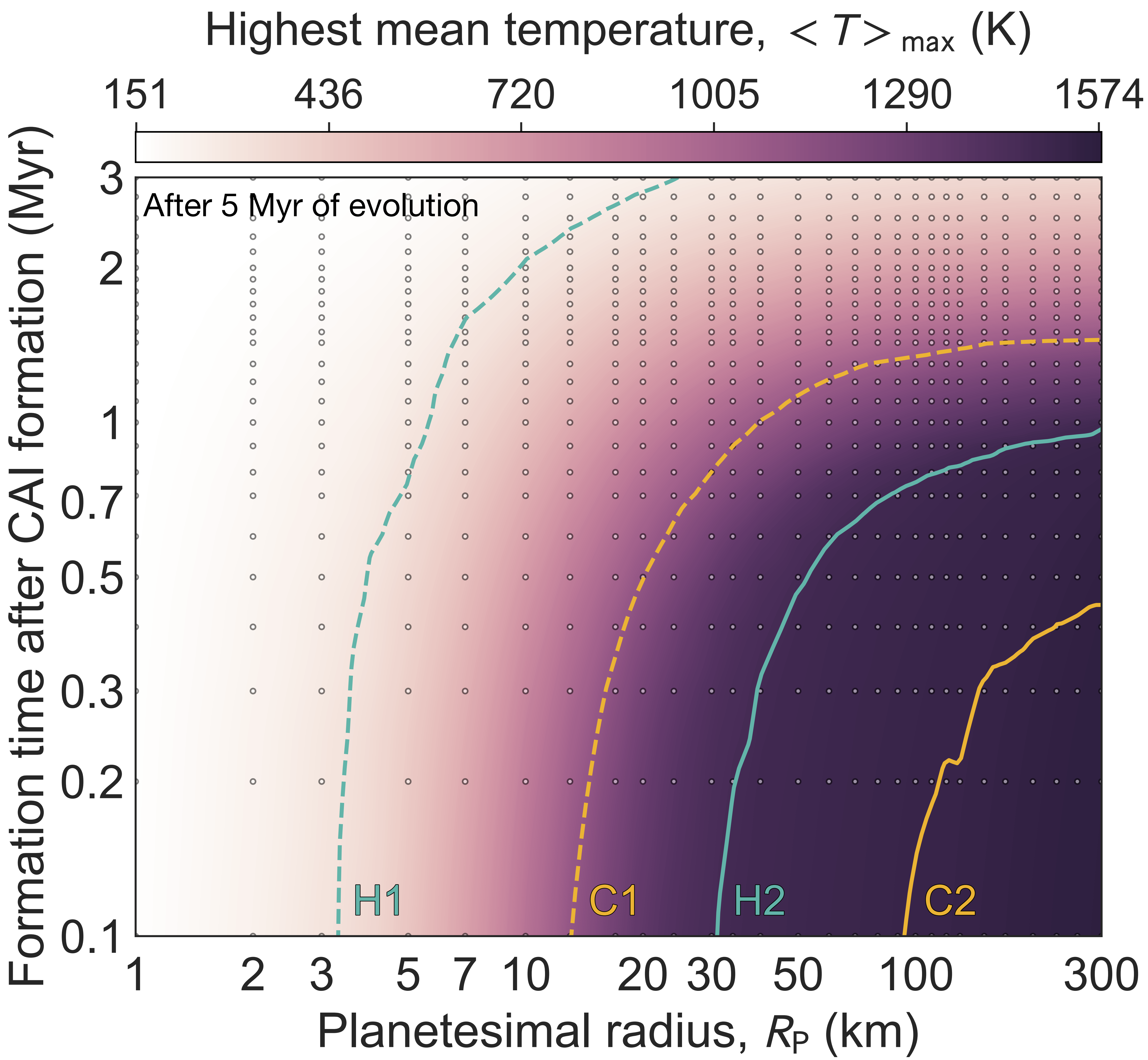


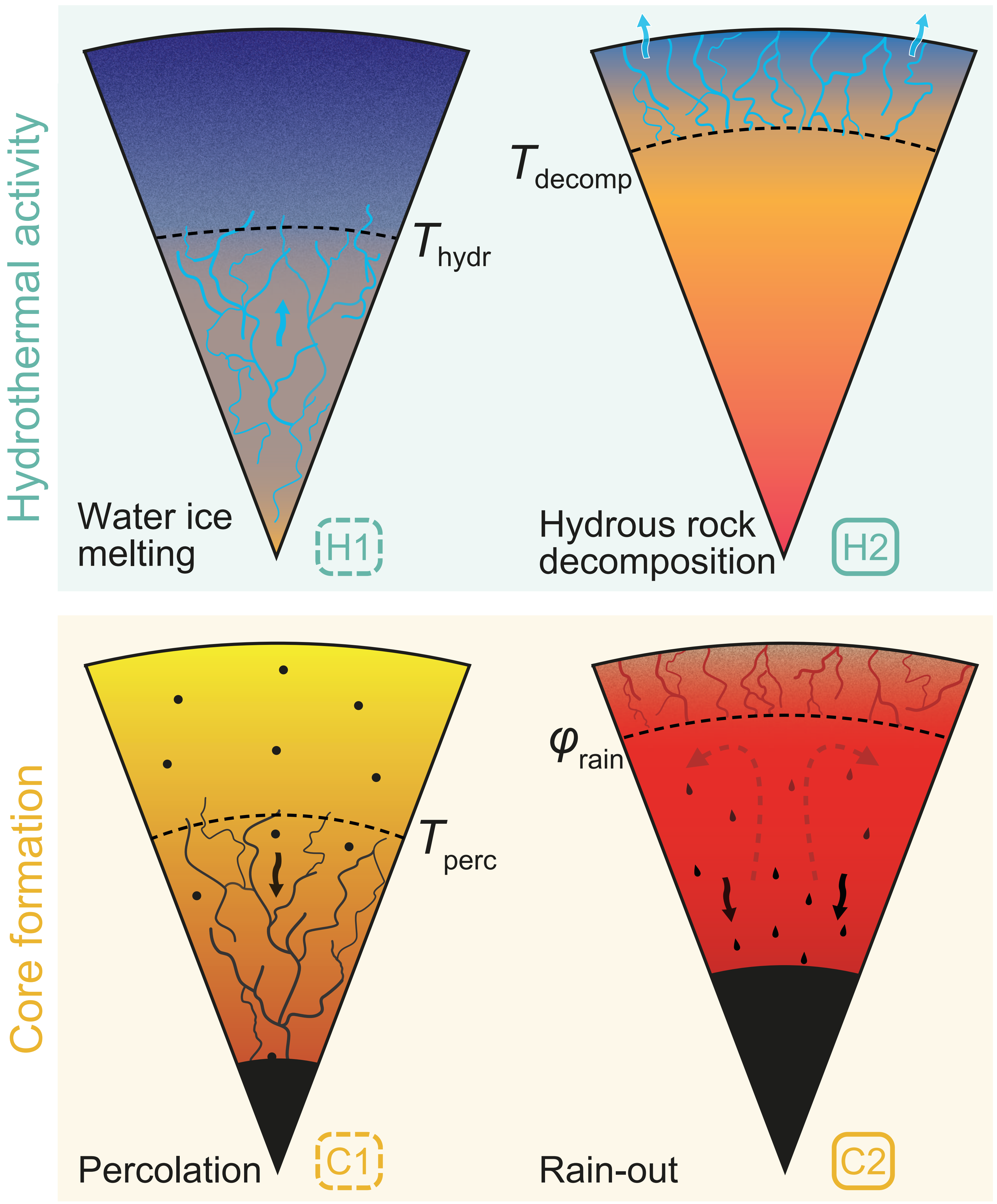
Initial core formation



Lichtenberg, Drążkowska+ 21

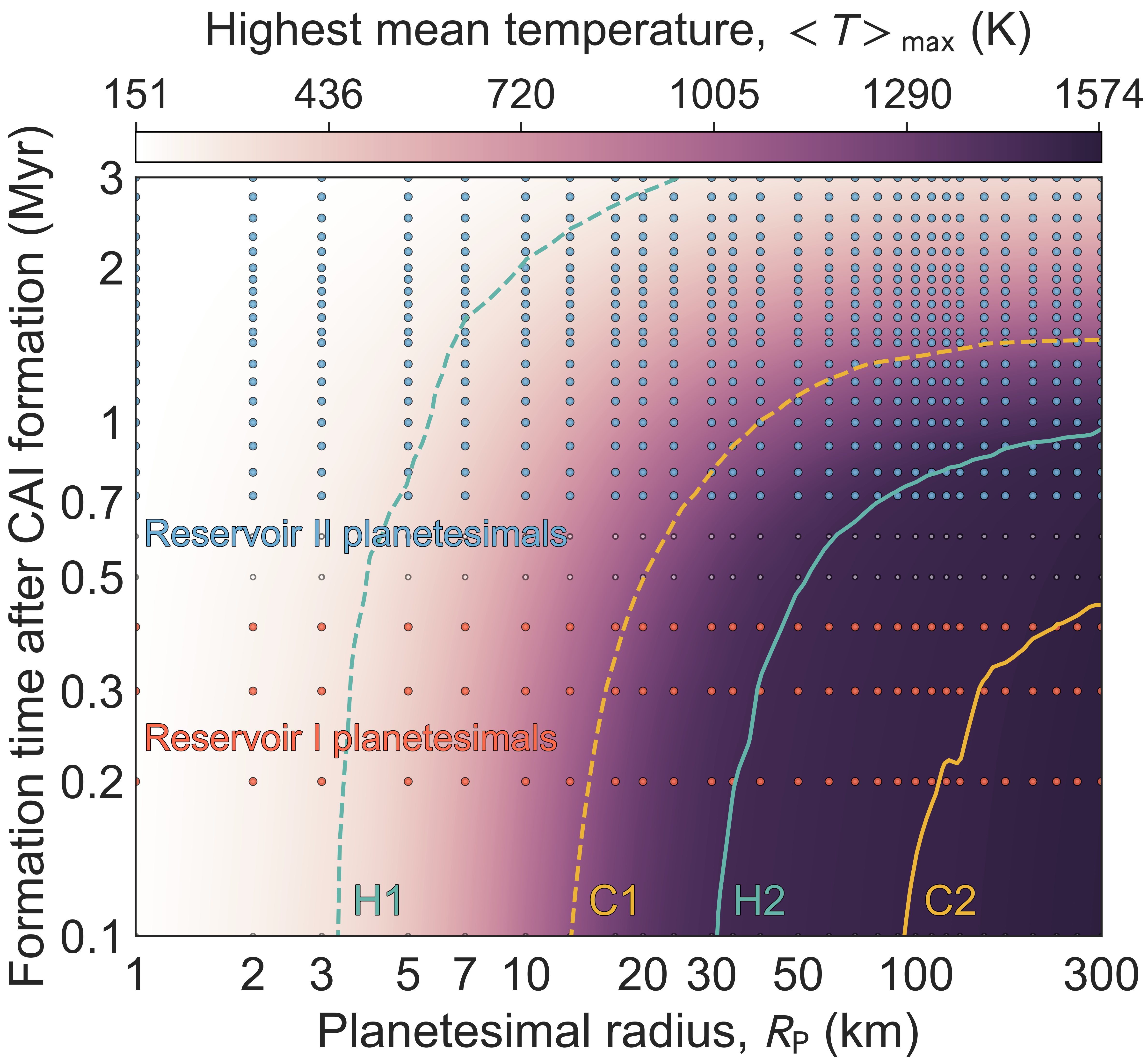
Compositional bifurcation by radiogenic heating

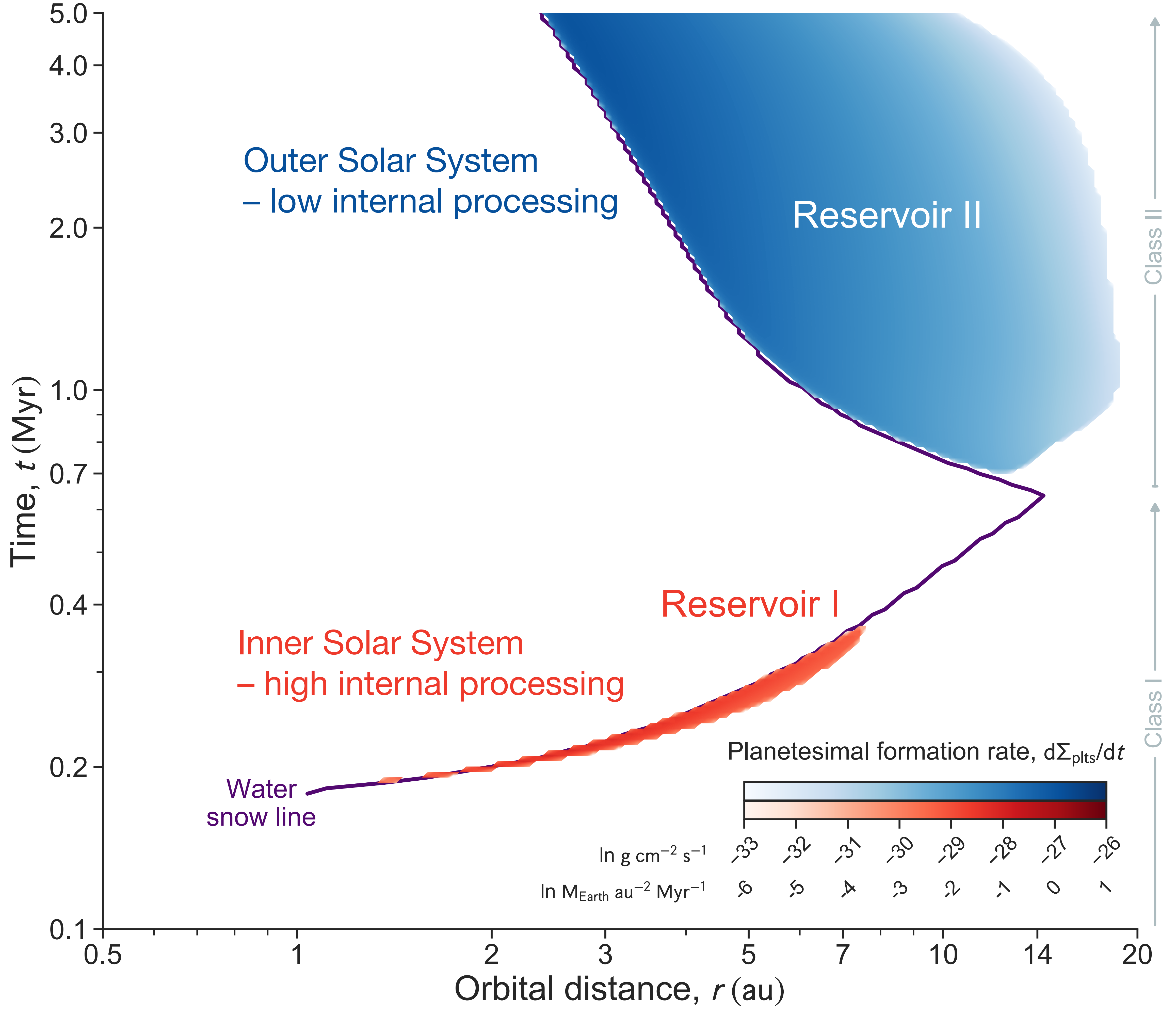




Lichtenberg, Drążkowska+ 21

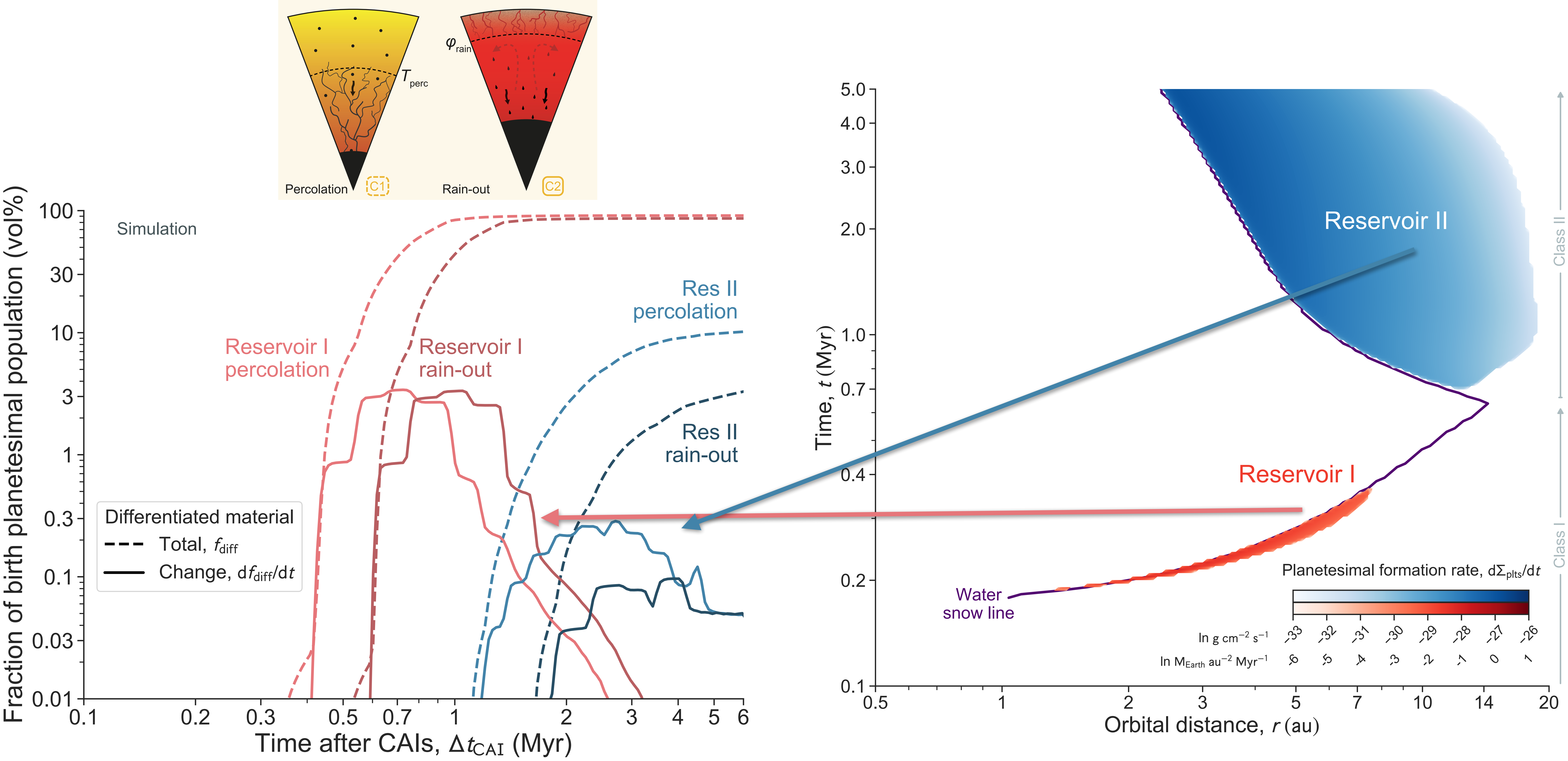
Compositional bifurcation by radiogenic heating





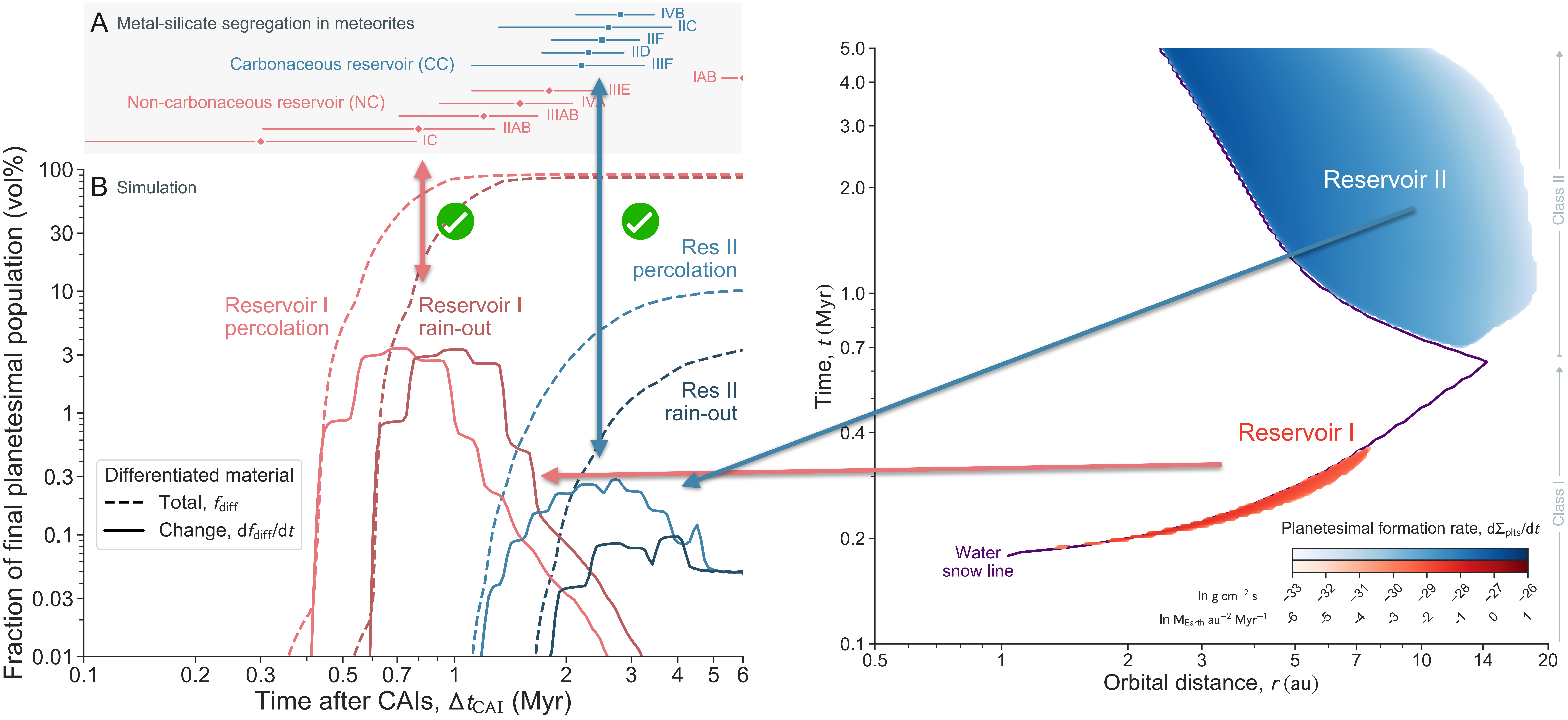
Lichtenberg, Drążkowska+ 21

Iron core formation: meteorites vs. model



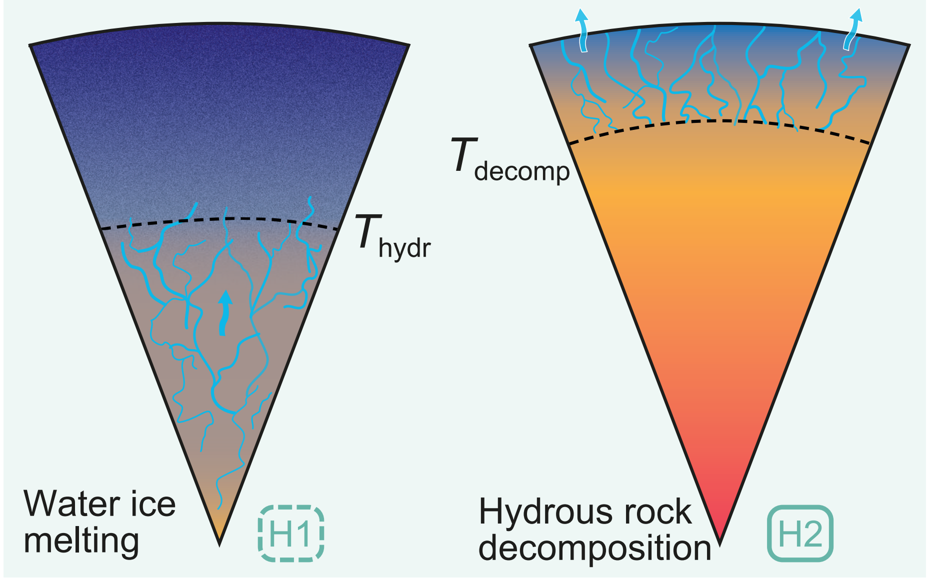
Lichtenberg, Drążkowska+ 21

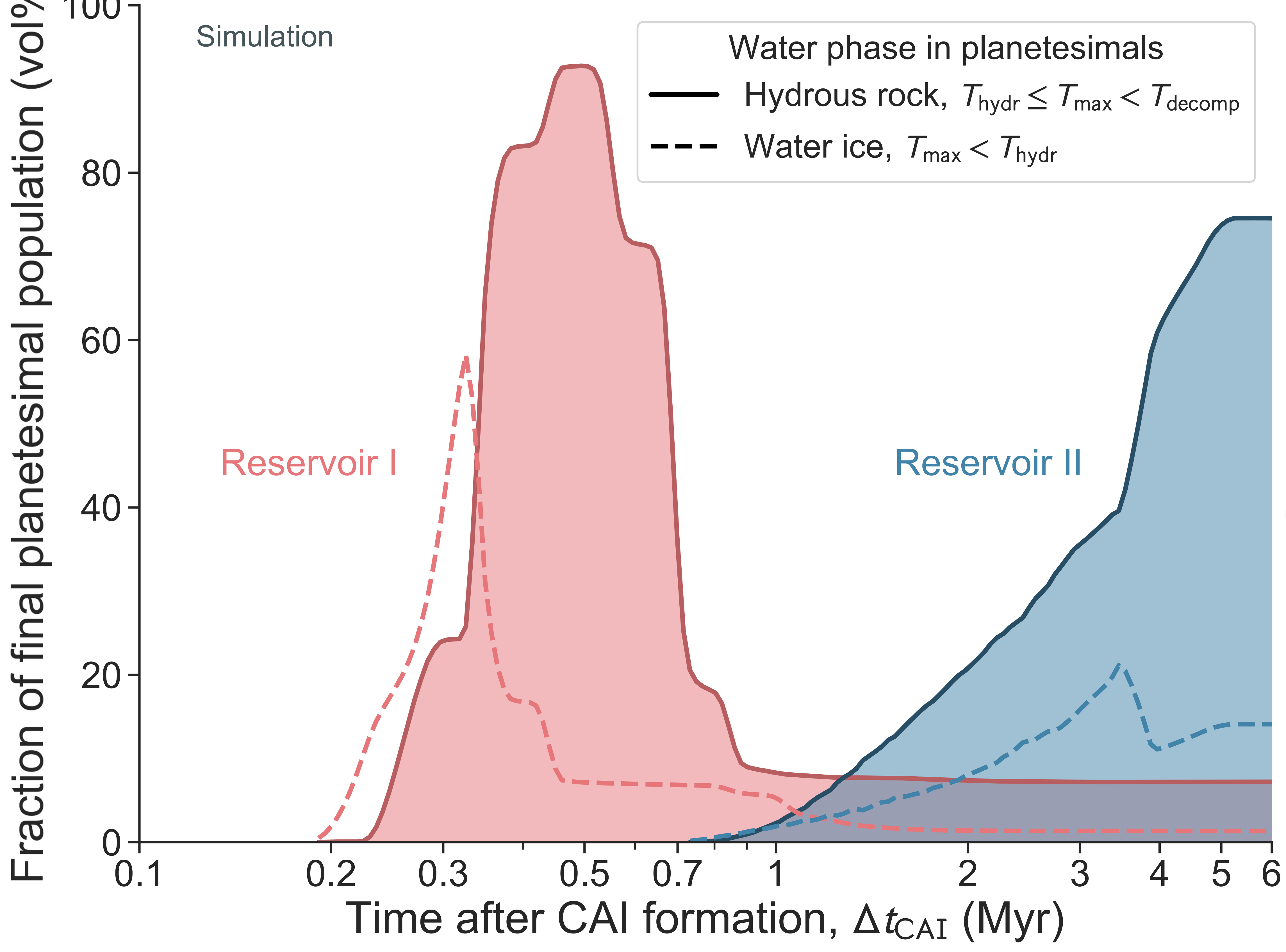
Iron core formation: meteorites vs. model

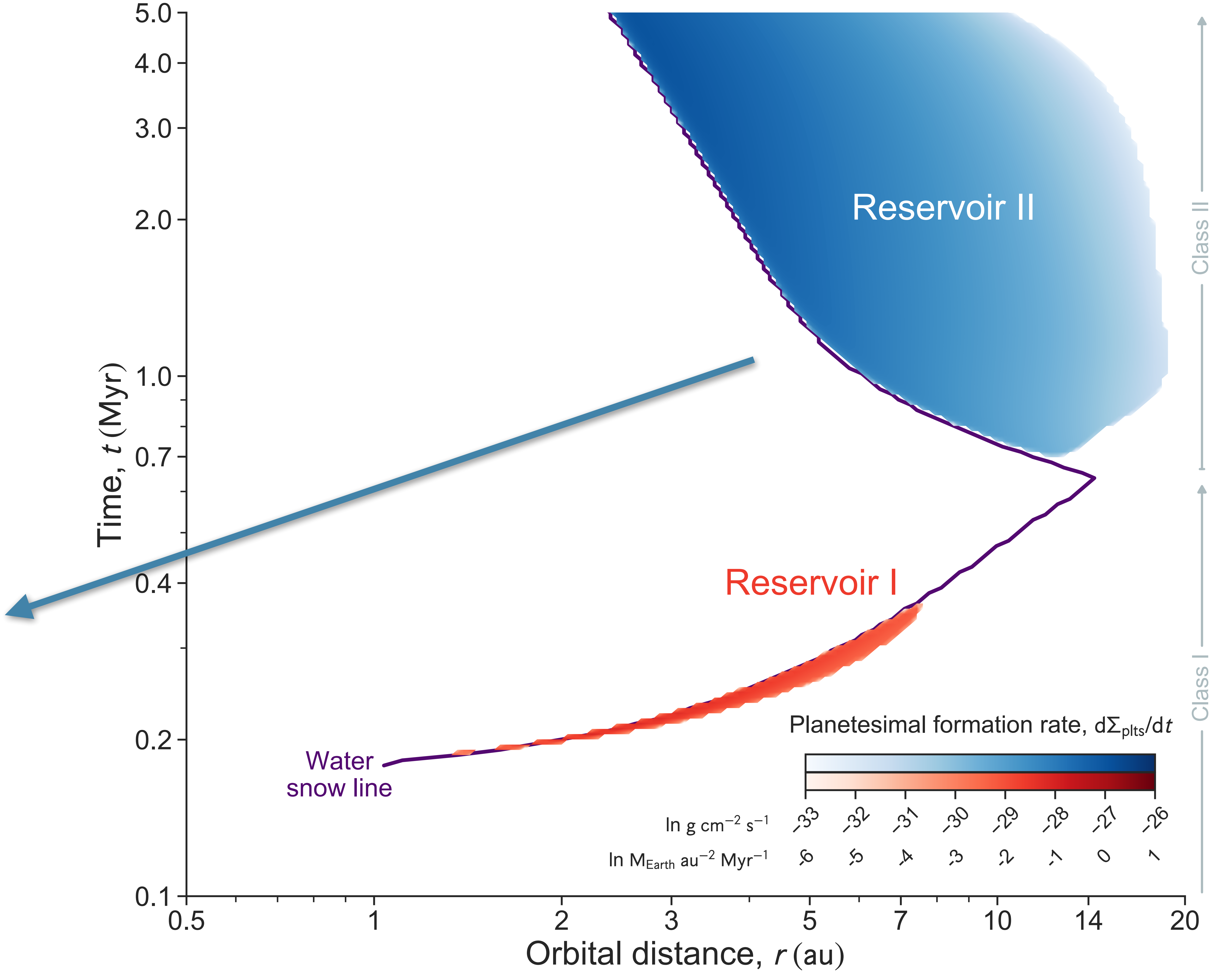


Lichtenberg, Drążkowska+ 21

Aqueous alteration: meteorites vs. model

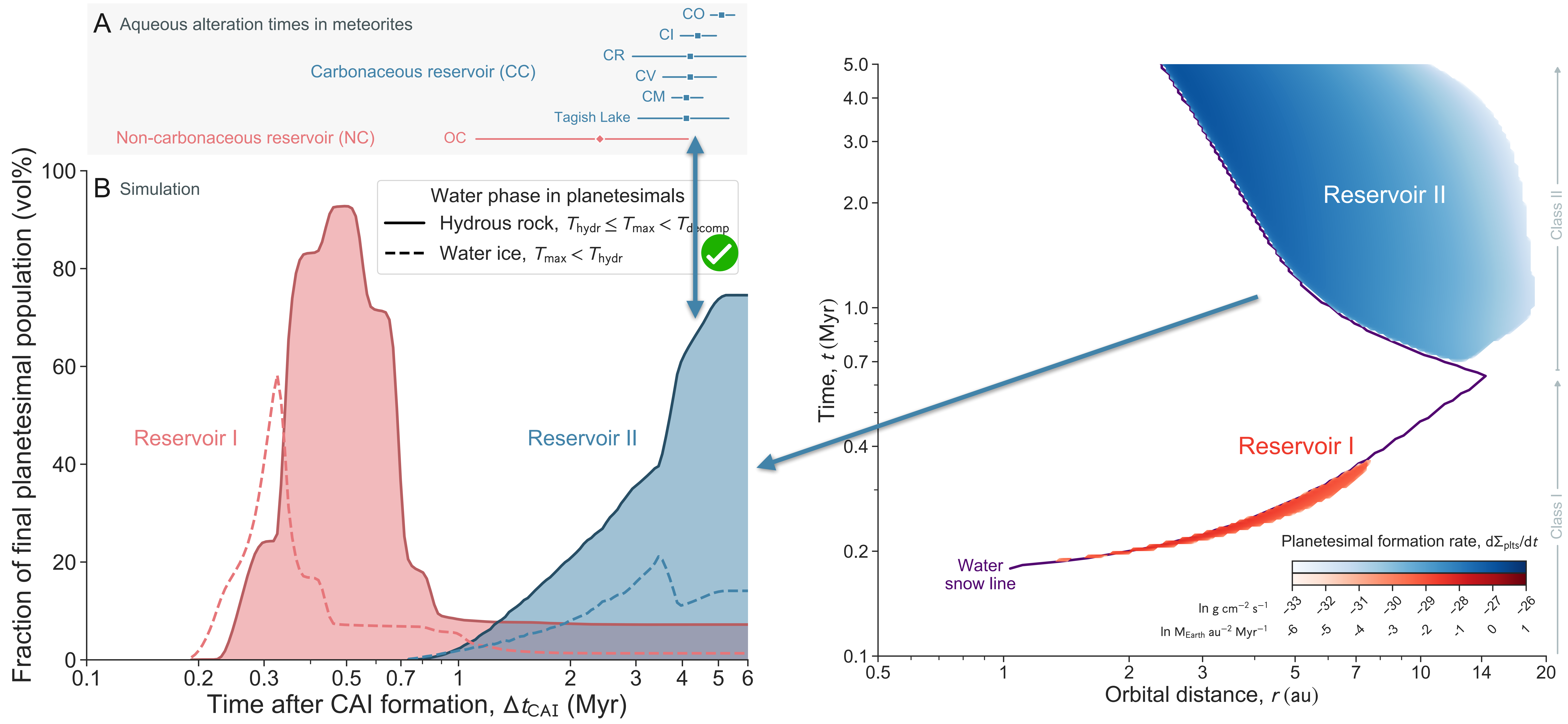






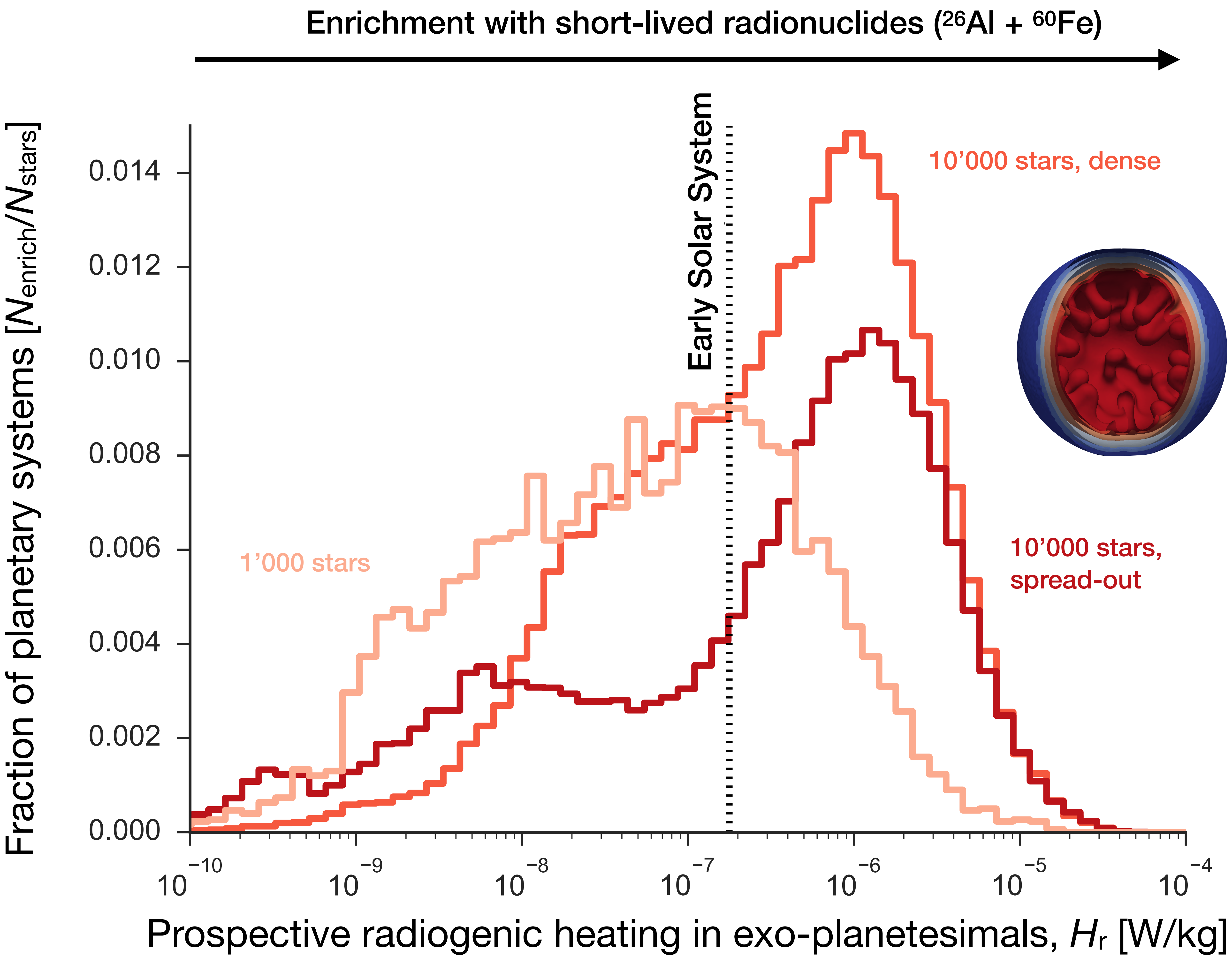
Lichtenberg, Drążkowska+ 21

Aqueous alteration: meteorites vs. model

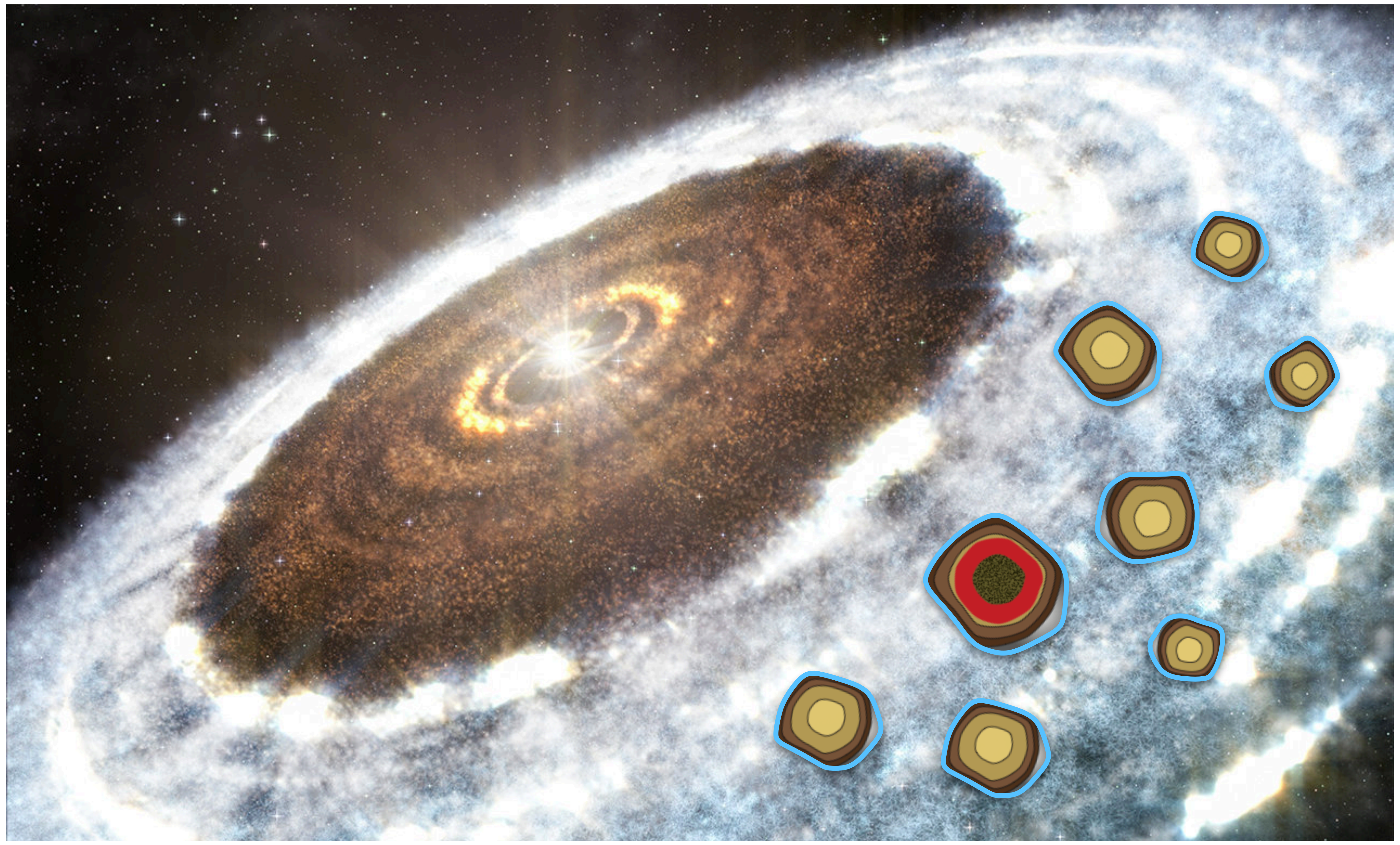


Lichtenberg, Drążkowska+ 21

^{26}Al variability across planetary systems



^{26}Al-heated icy planetesimals forming planets

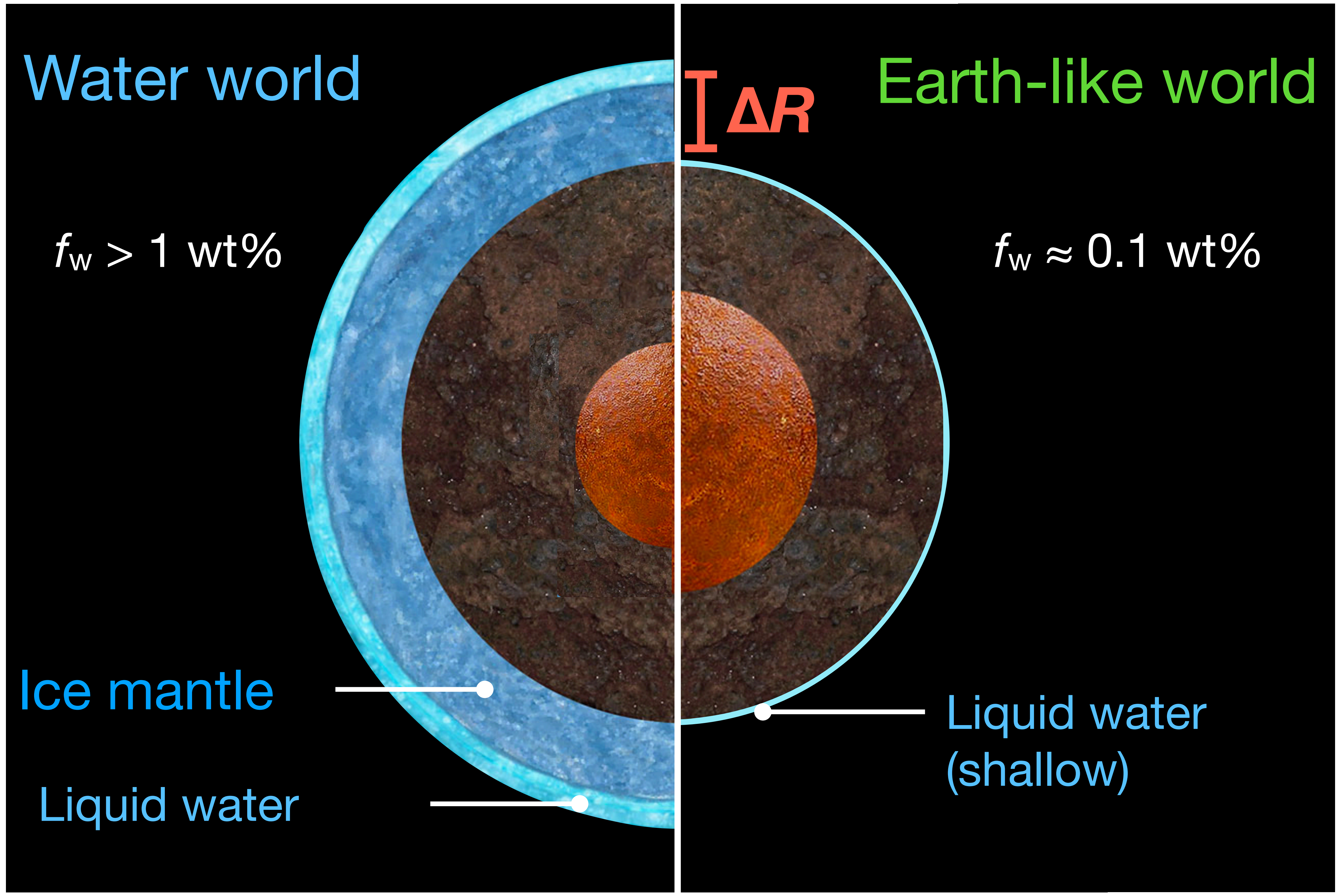


≈ 10^2—10^8 × Earth’s present-day interior radiogenic heating

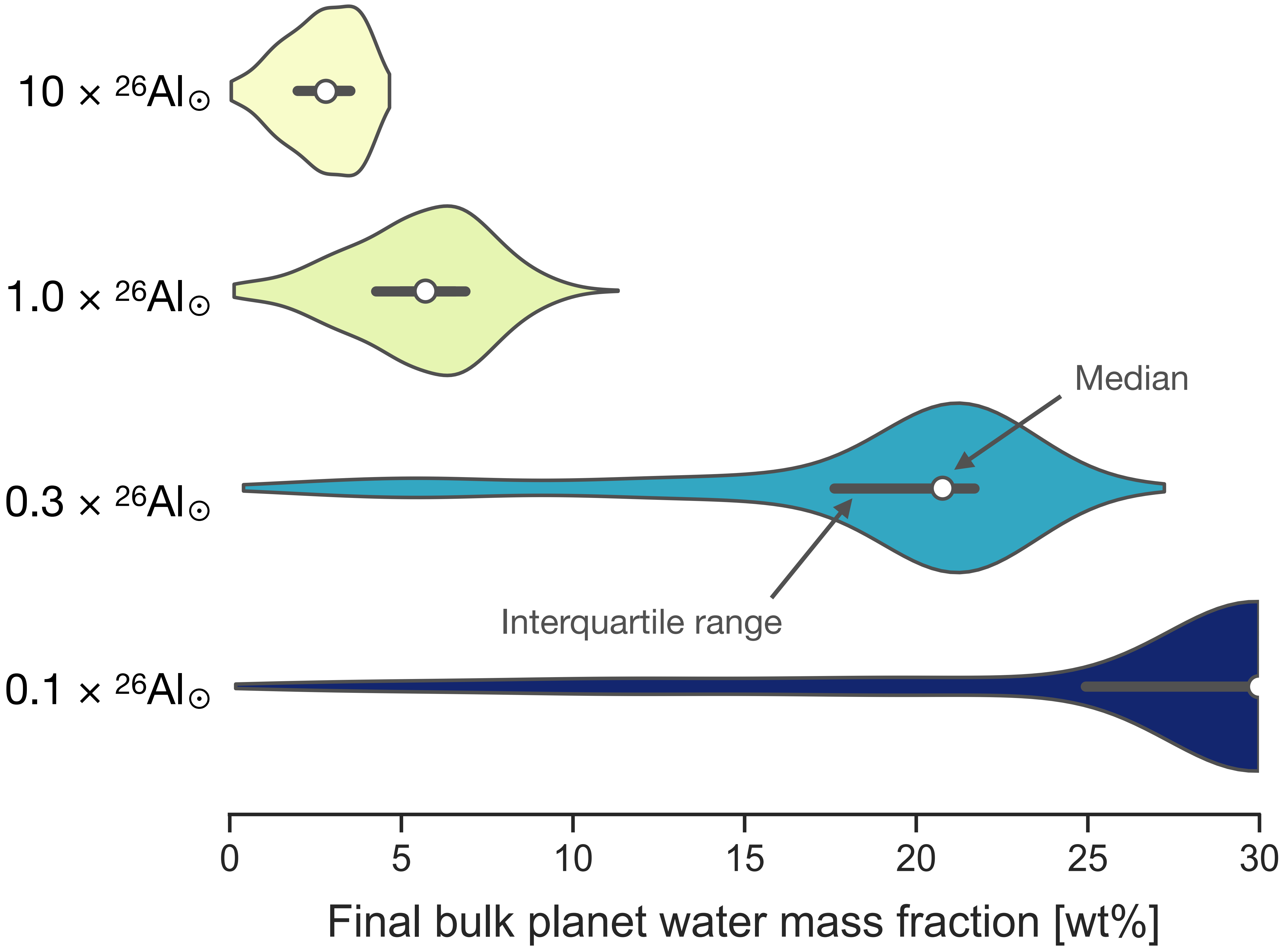
Lichtenberg+ 16b, Parker+ 14,15,17,20, Gaidos+ 09, Pfalzner+ 15, Kuffmeier+ 16, Fujimoto+18, Lugaro+ 18, Reiter+ 20, Forbes+ 21, Fatuzzo & Adams 21

A. Angelich (NRAO/AUI/NSF)/ALMA (ESO/NAOJ/NRAO)

^{26}Al shapes exoplanet *water* budget



Synthetic exoplanet populations

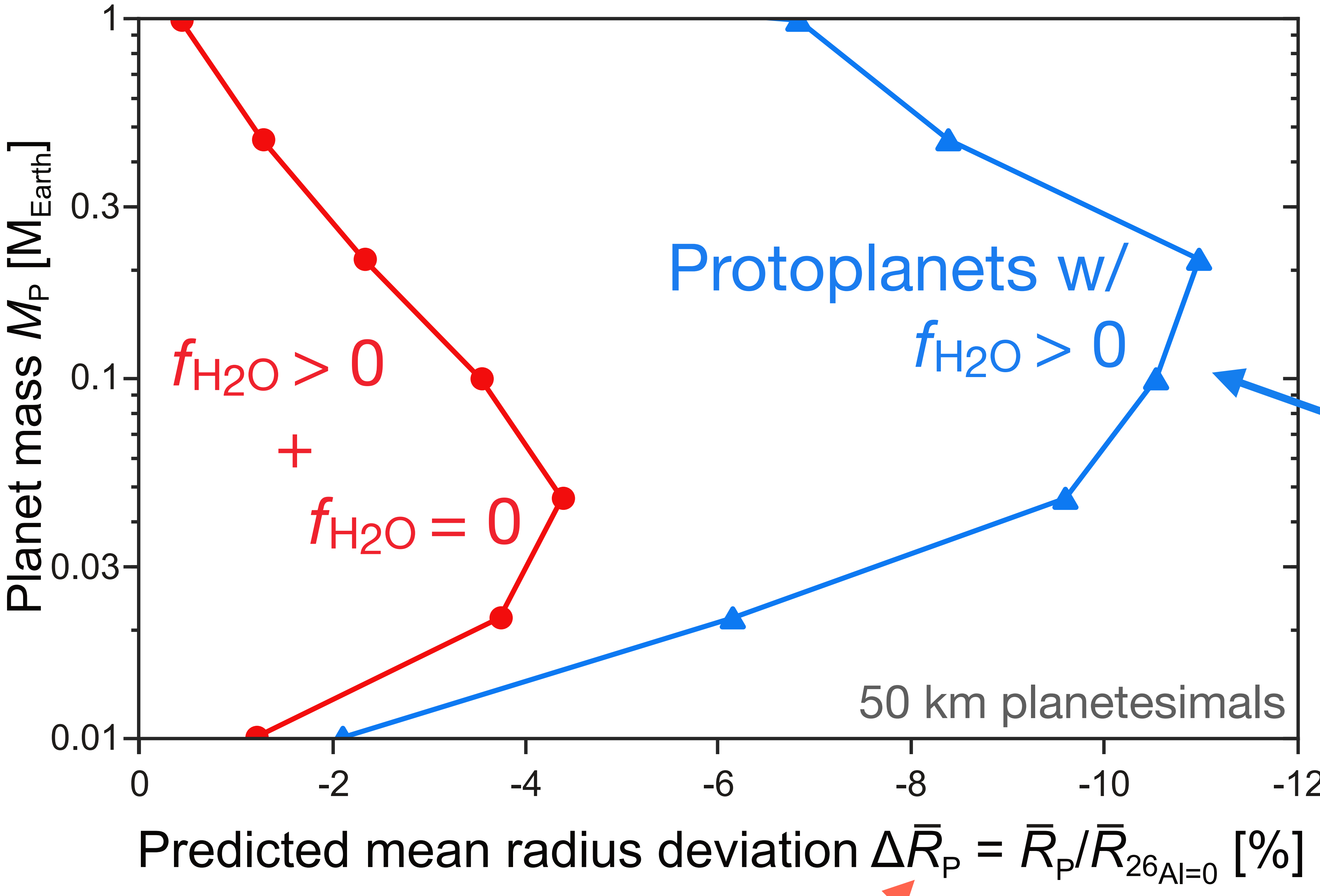


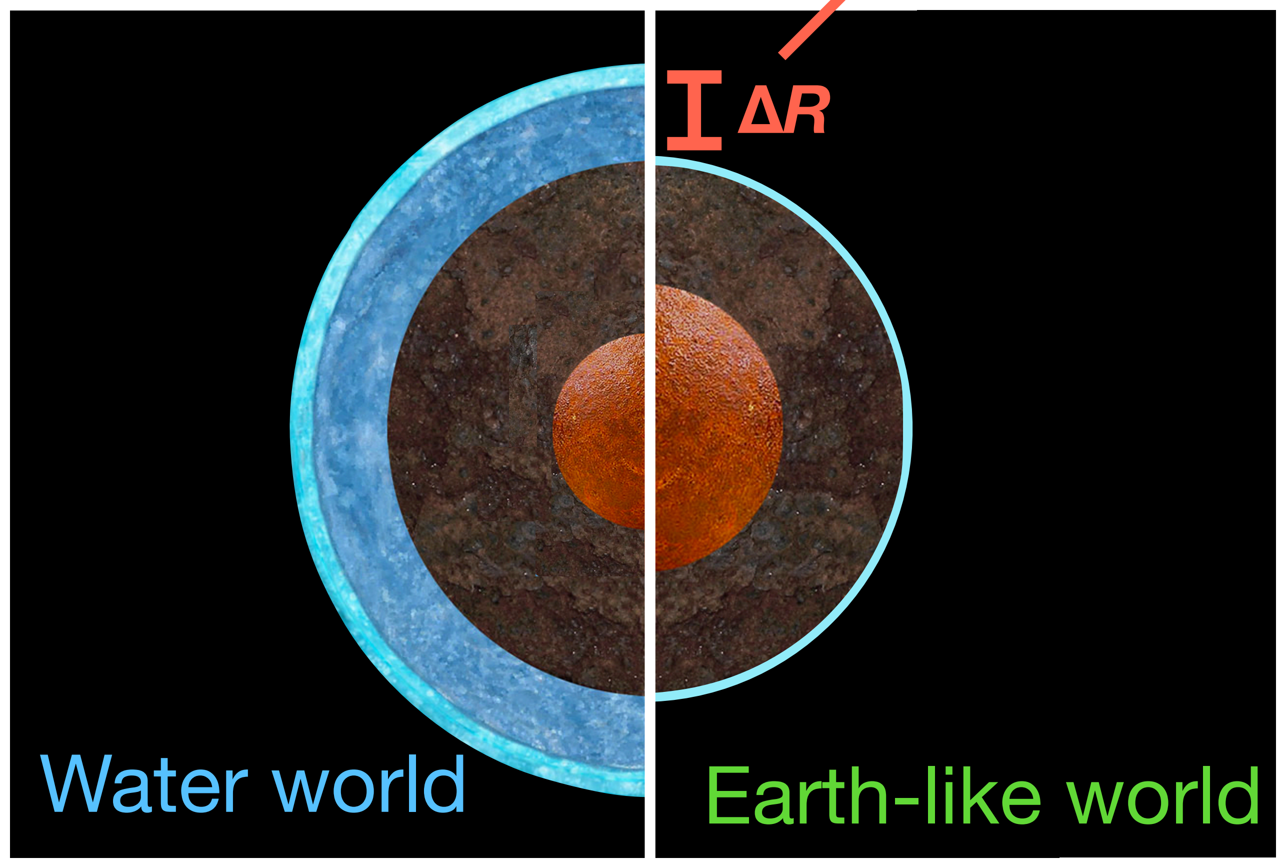
Leger+ 04, Sotin+ 07, Alibert 14, Noack+ 16/17

Lichtenberg+ 19b

^{26}Al shapes exoplanet *water* budget

Solar ^{26}Al versus no ^{26}Al heating

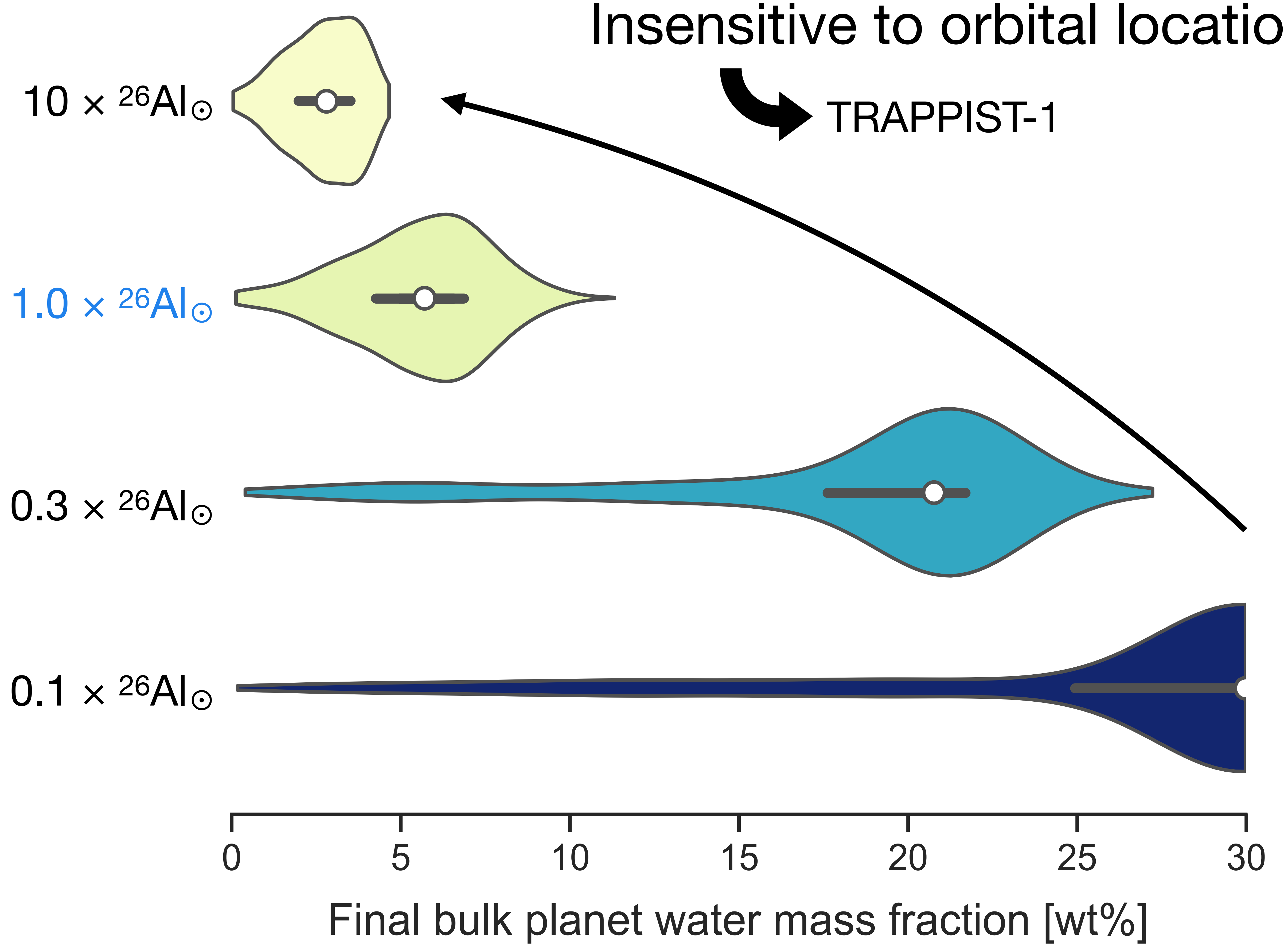




Intra-system size correlation

Insensitive to orbital location

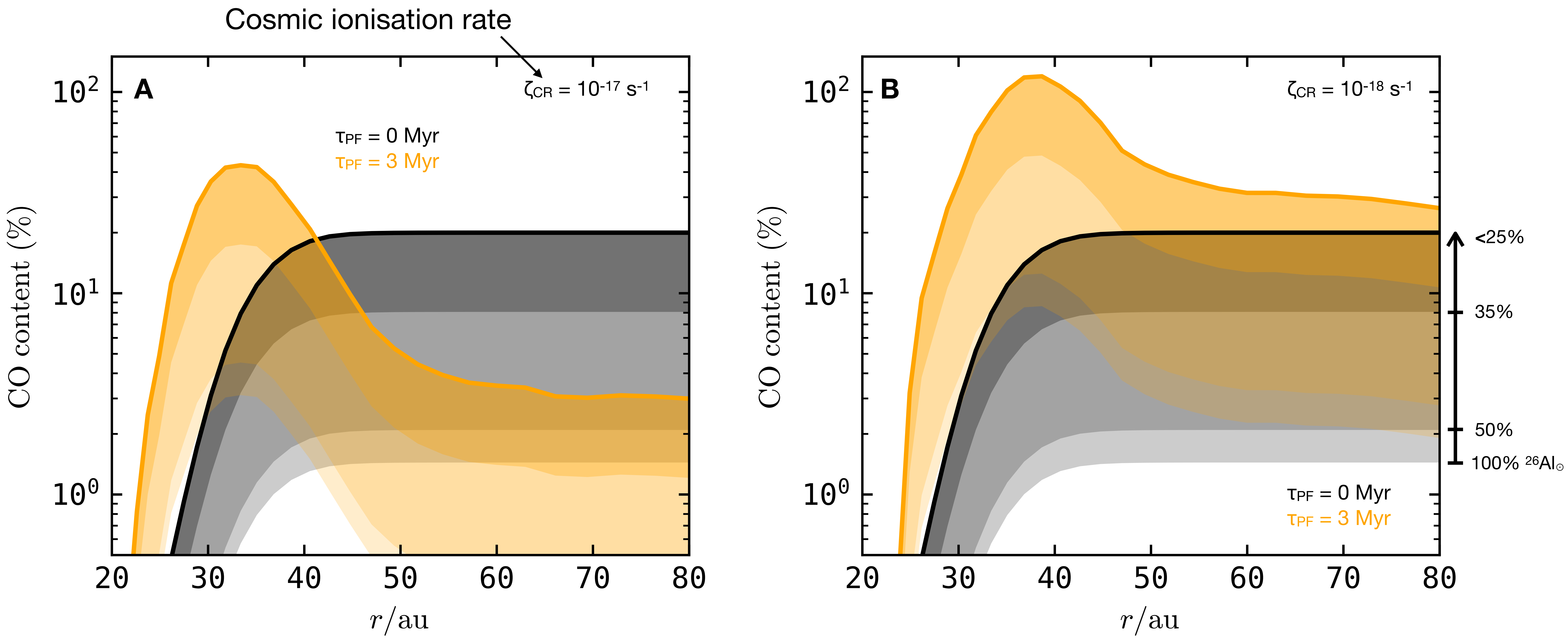
TRAPPIST-1



Lichtenberg+ 19b

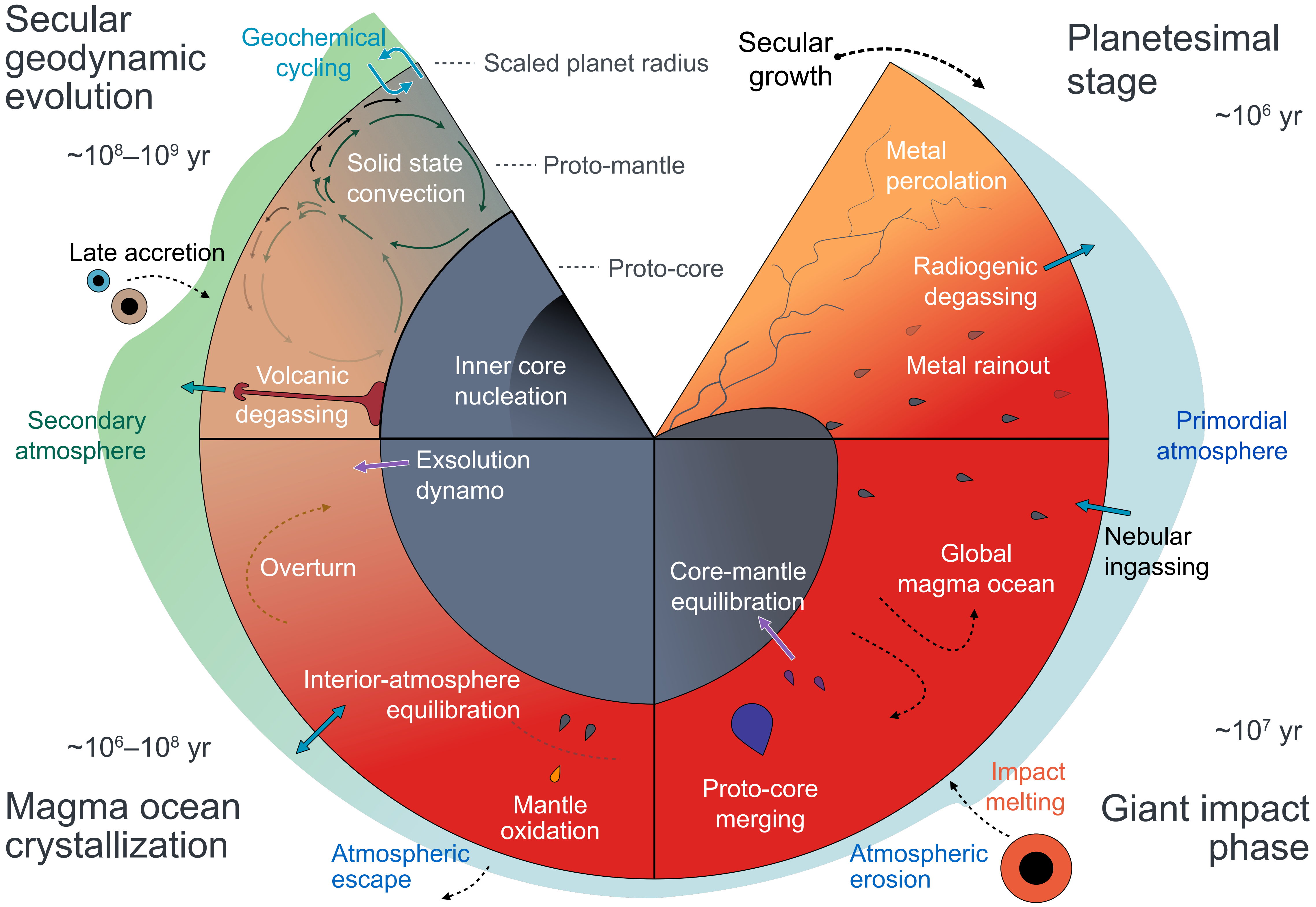
^{26}Al shapes exoplanet *carbon fractionation*

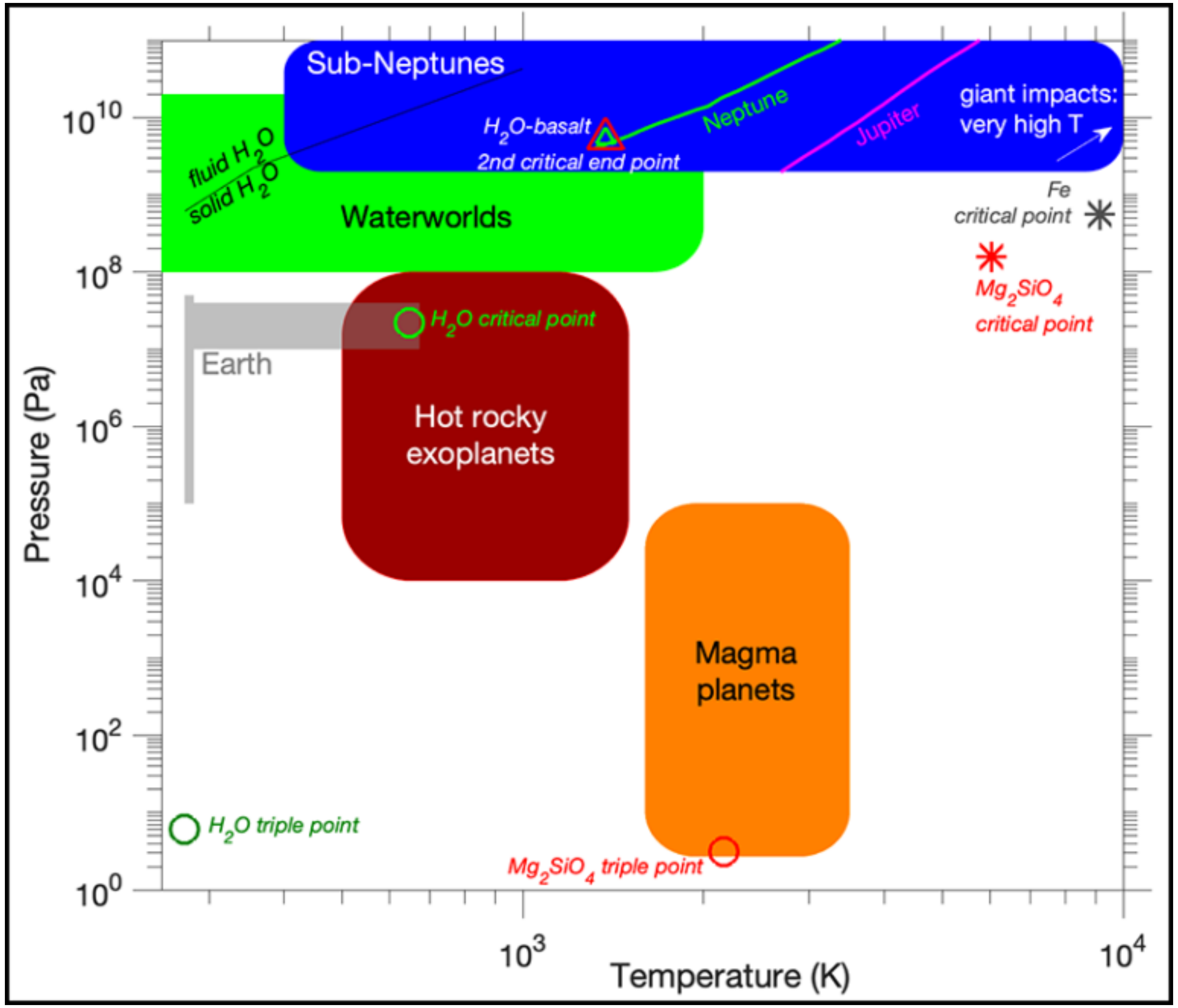
Final volatile (in this case CO) content of evolved planetesimals can be ***very*** different from that of microscopic dust grains at *t=0*, depending sensitively on radial location & both disk processes and thermal evolution of planetesimals.



Lichtenberg & Krijt (2021), *ApJL*

Exoplanets as a window into *hothouse climates*

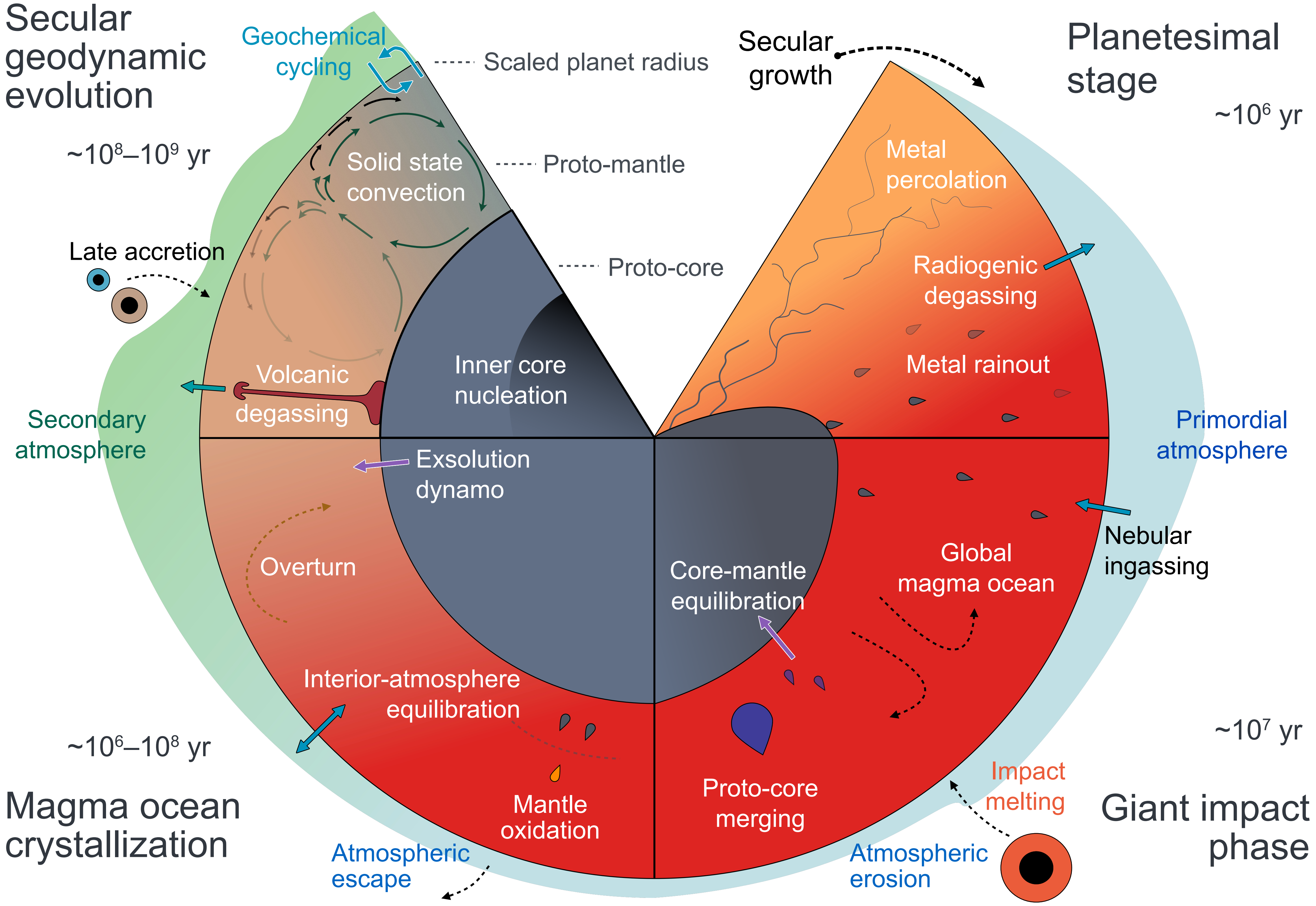


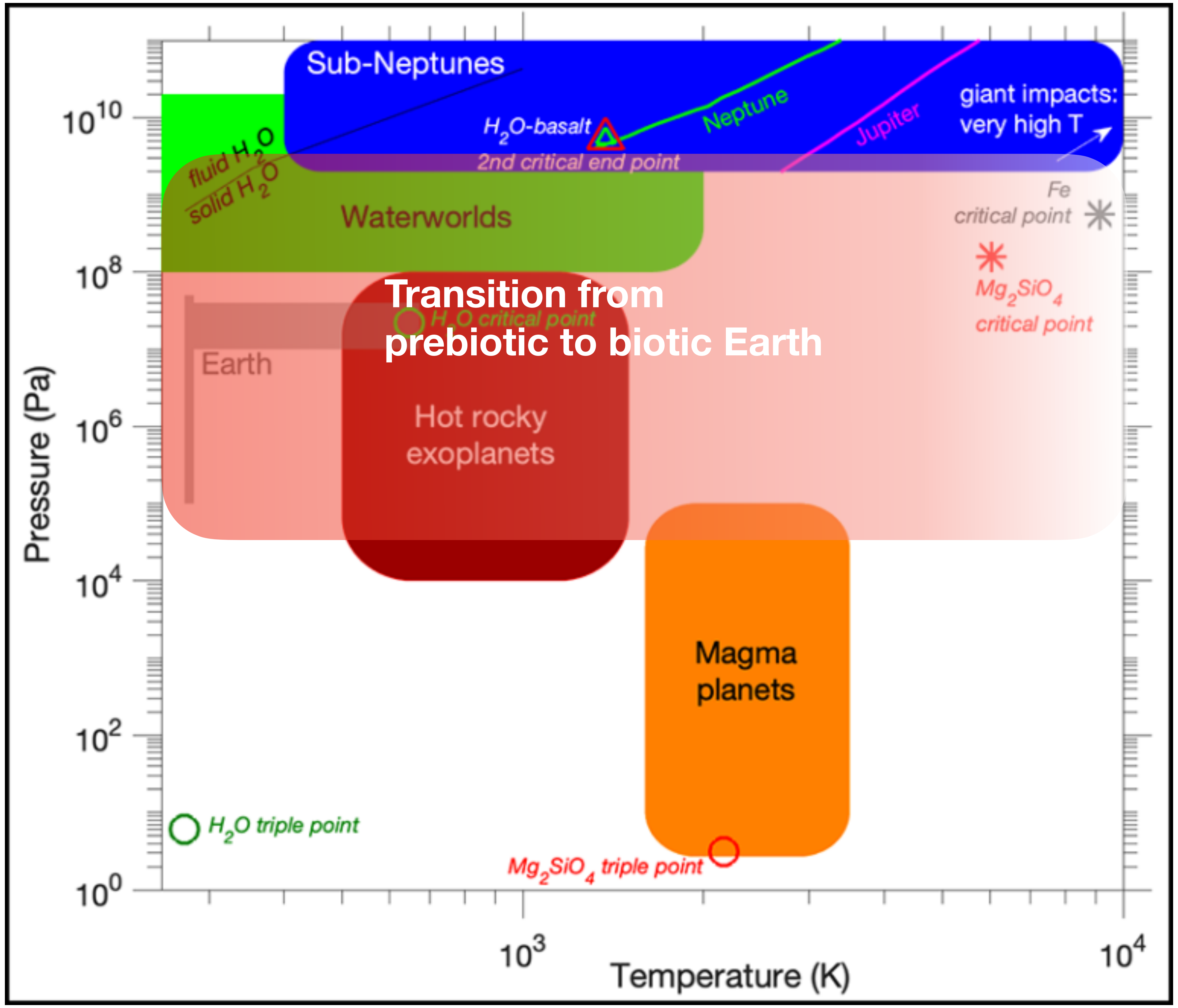


Lichtenberg, Schaefer, Nakajima, Fischer 2022, *Protostars & Planets VII*

Kite, Kreidberg+ 21, Eos

Exoplanets as a window into *hothouse climates*

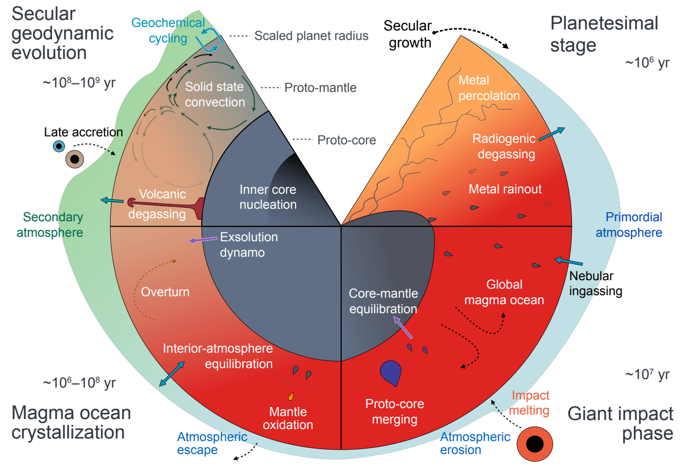


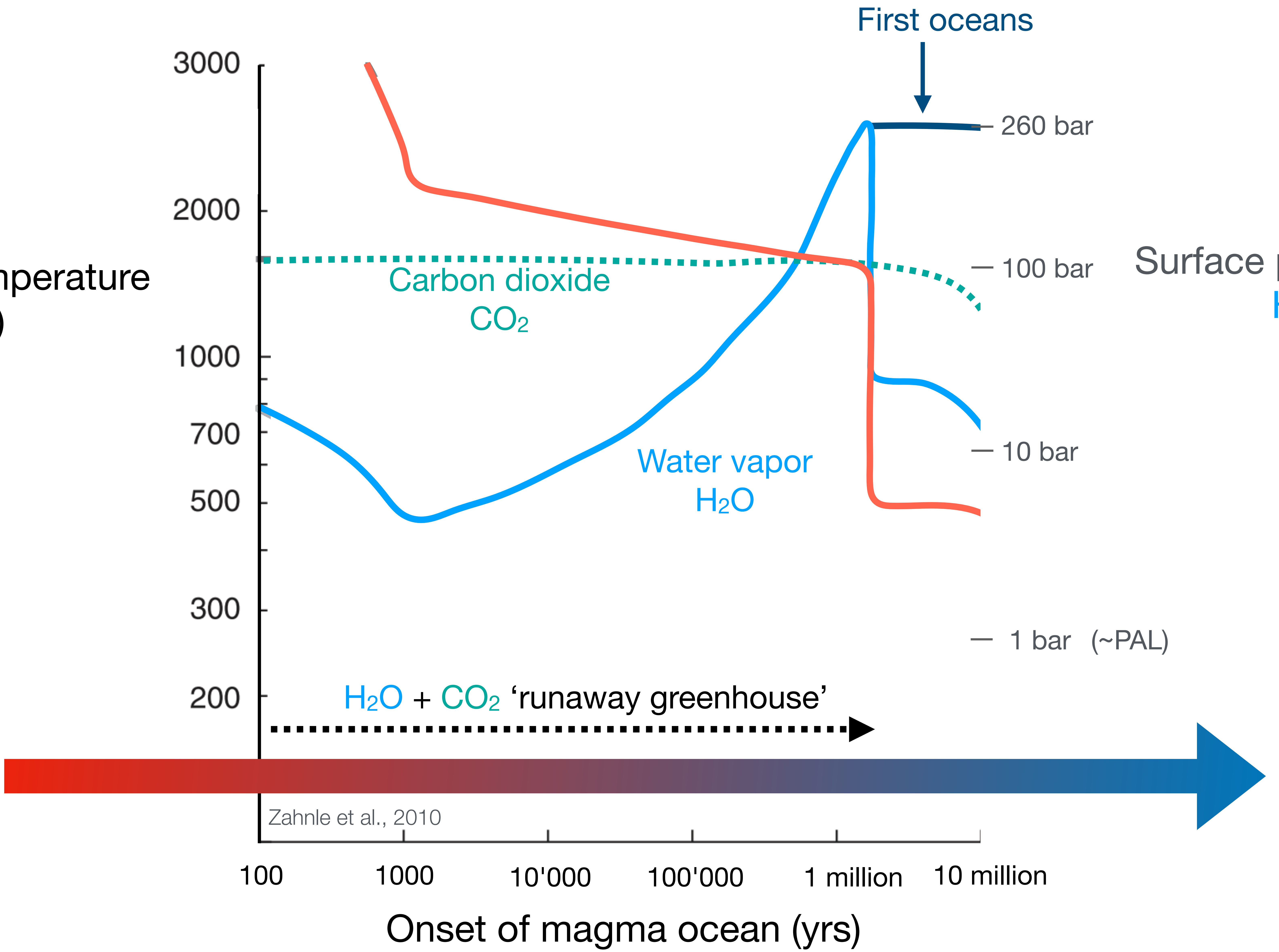


Lichtenberg, Schaefer, Nakajima, Fischer 2022, *Protostars & Planets VII*

Kite, Kreidberg+ 21, Eos

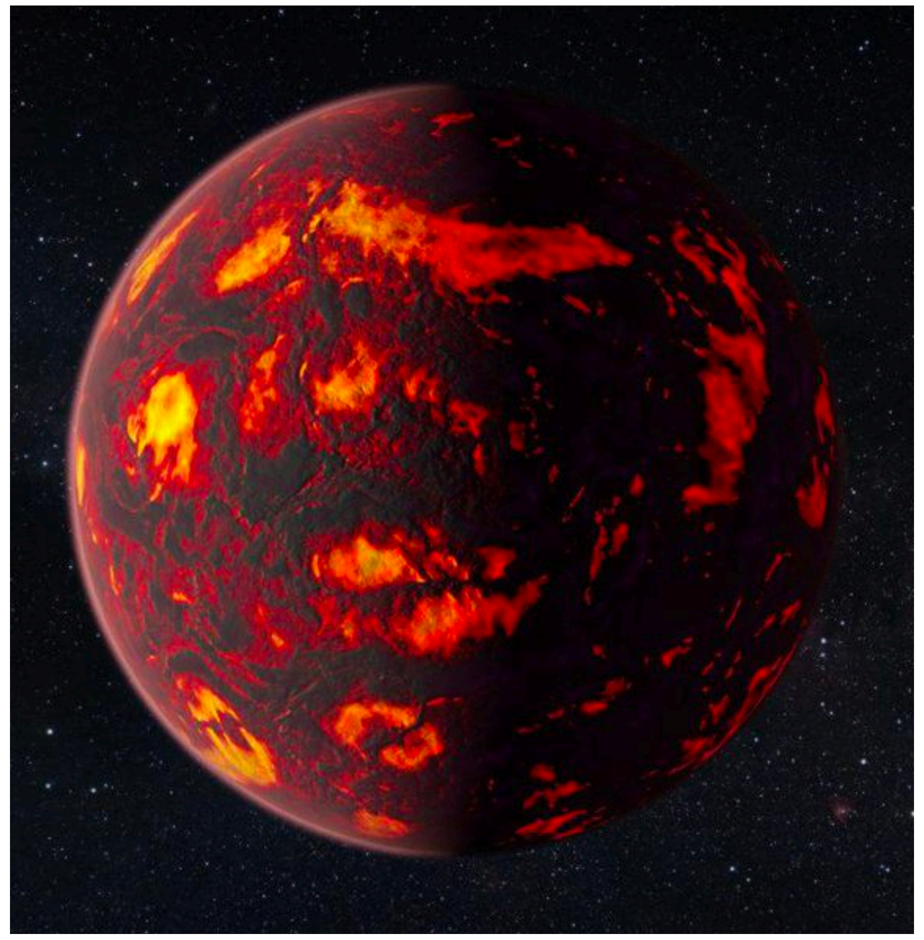
From magma- to water oceans





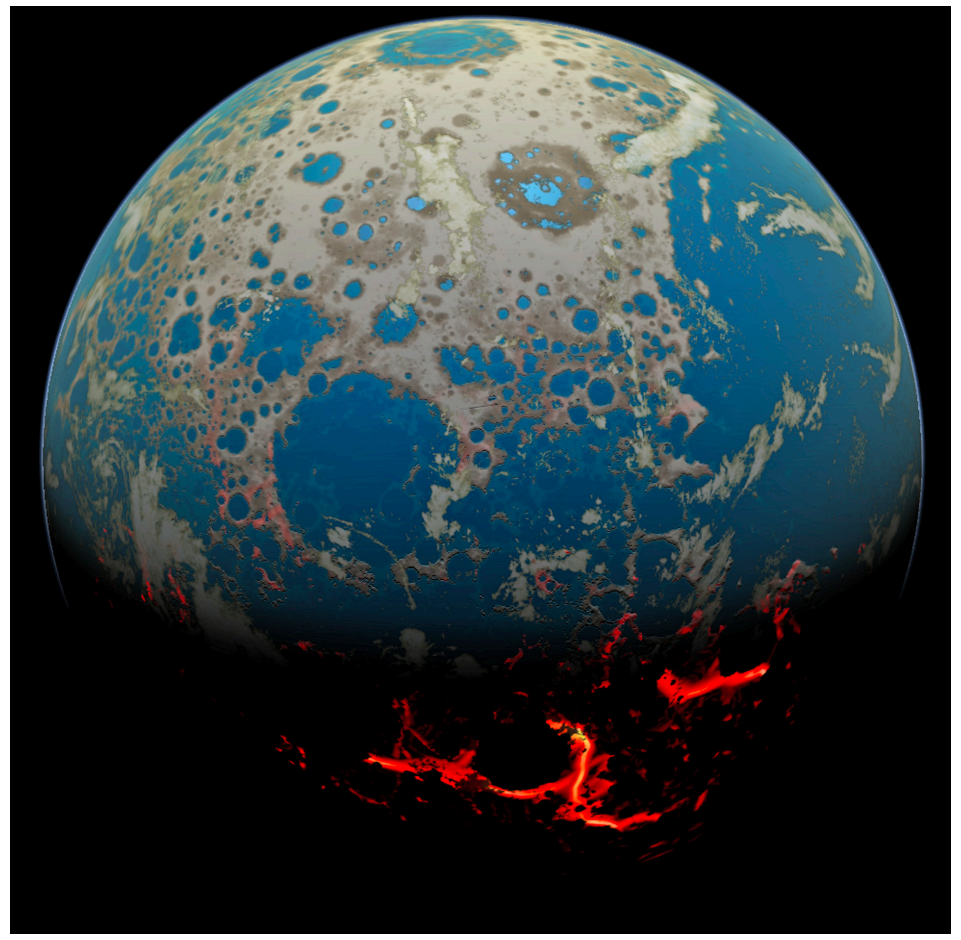
Zahnle et al., 2010

Magma ocean



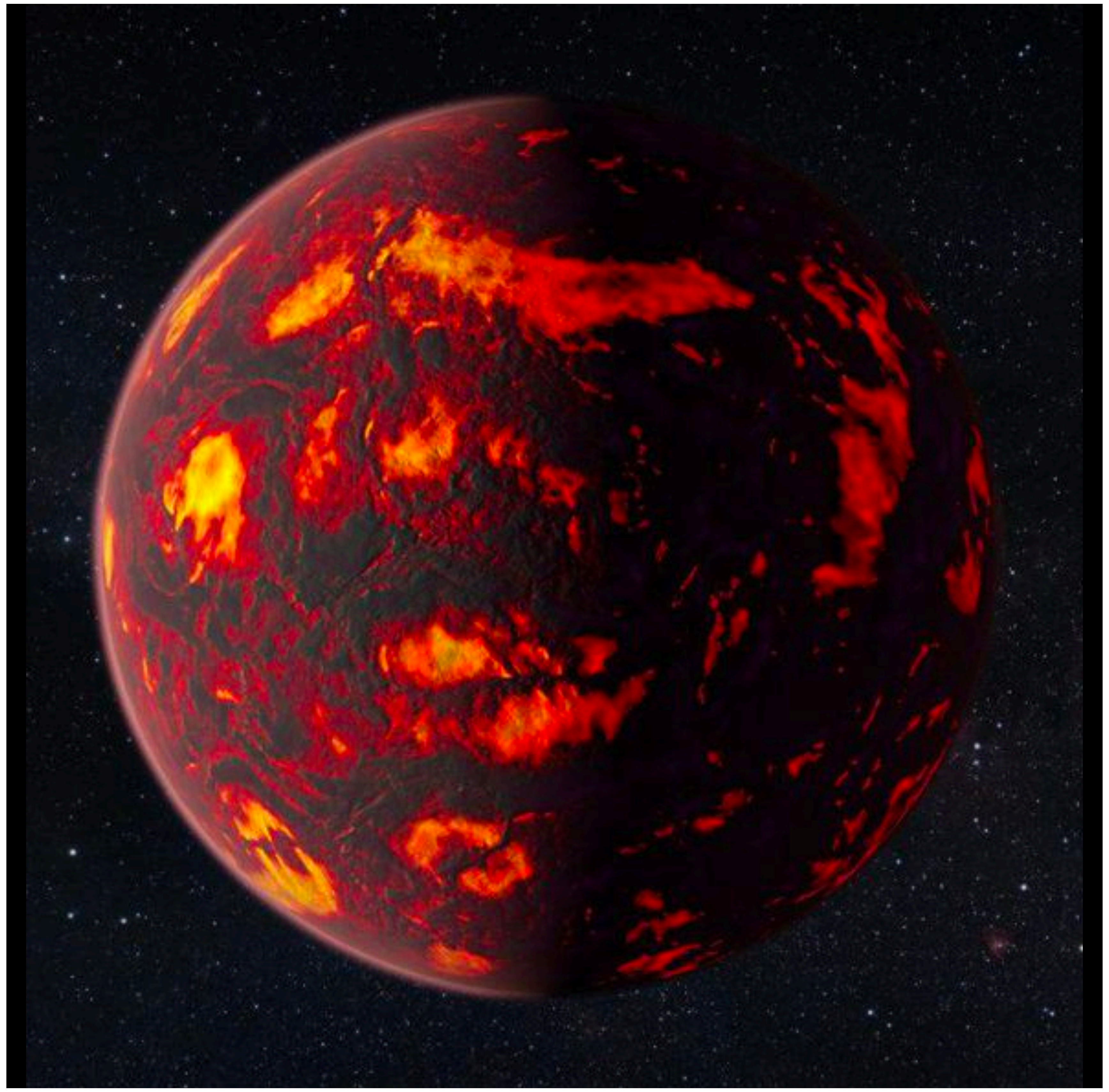
ESO

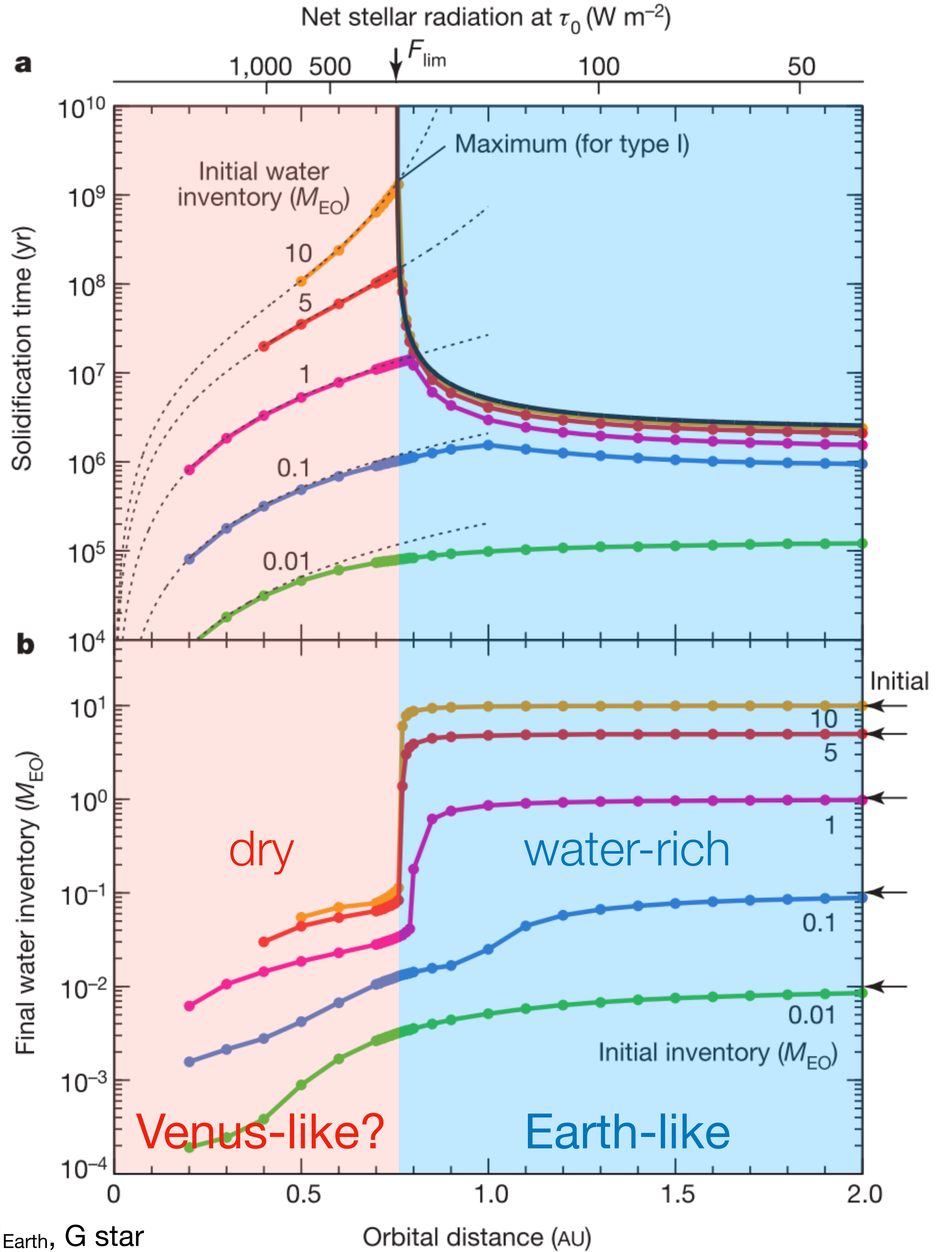
Habitable planet



SwRi/S. Marchi

Orbital split between clement and magma worlds



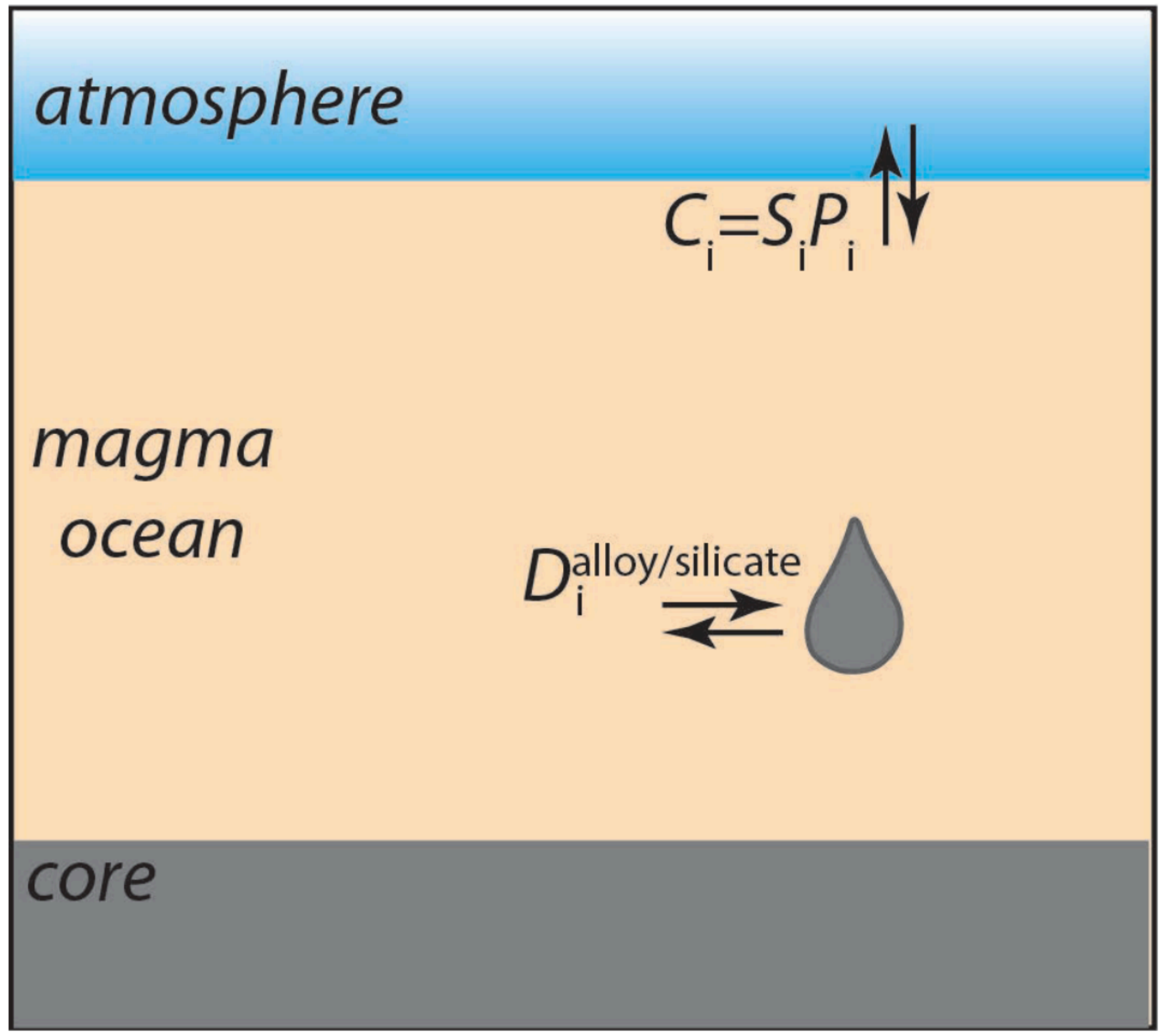


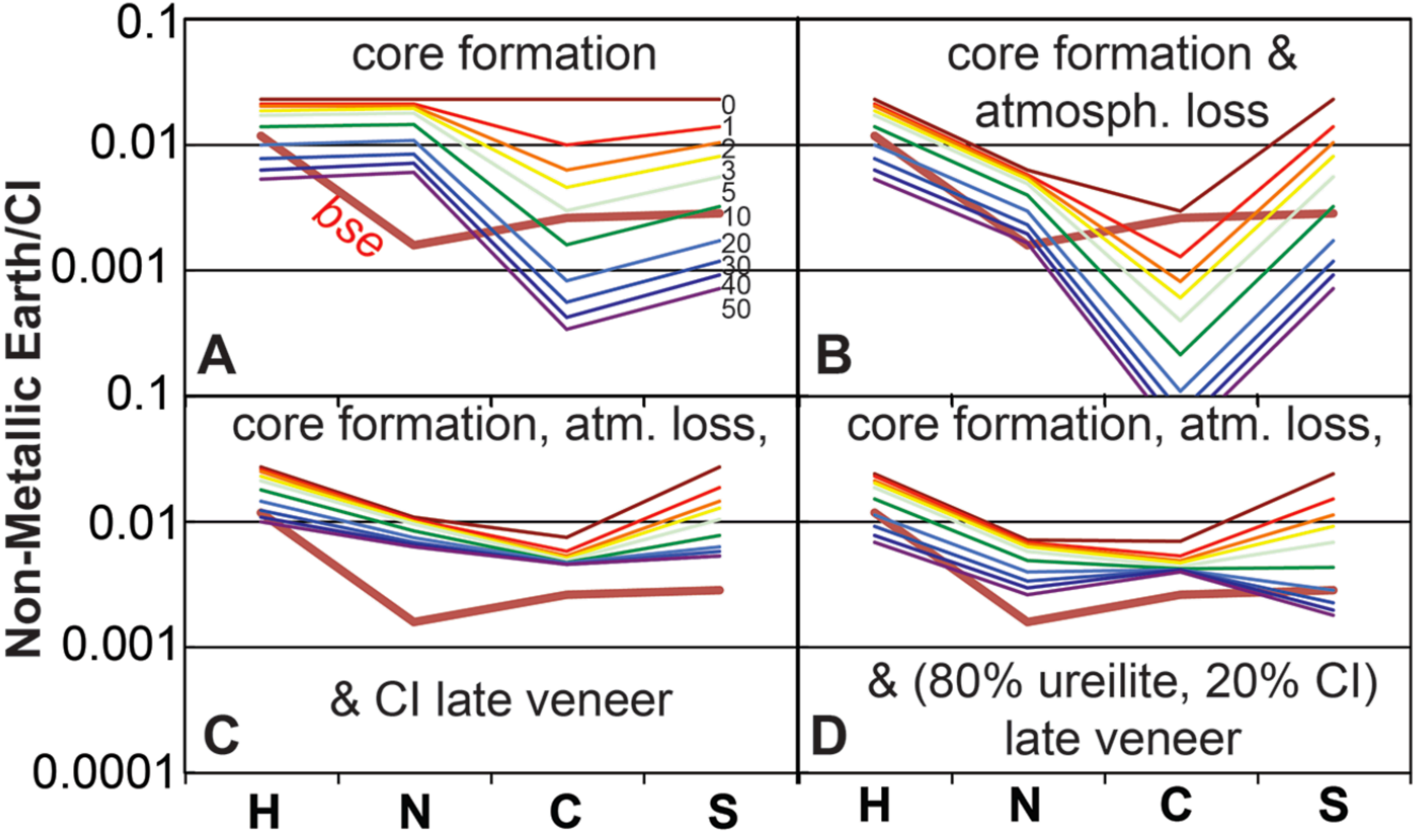
1 M_{Earth}, G star

NASA; SwRi/S. Marchi

Hamano+ 13, *Nature*

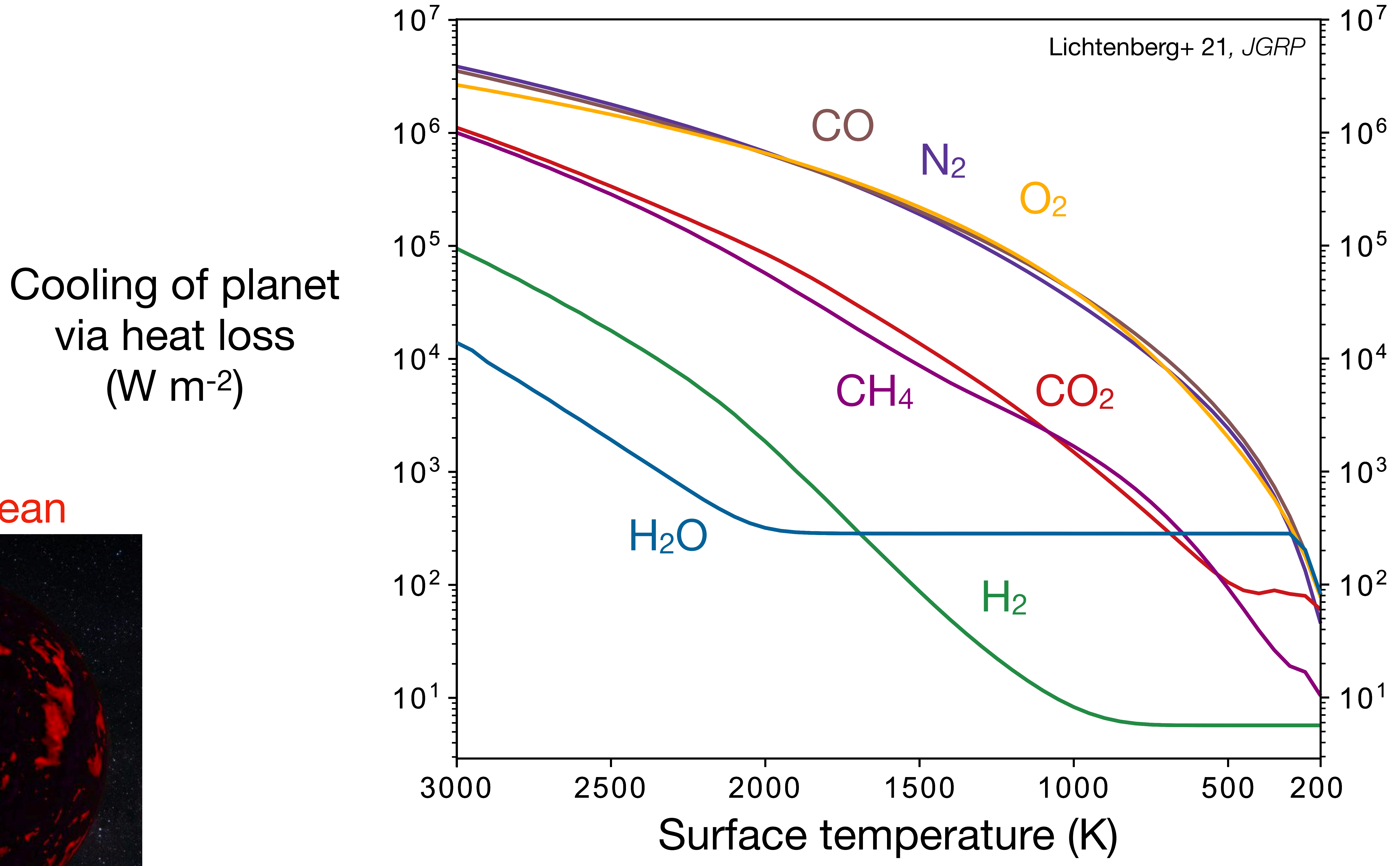
Volatile species fractionation



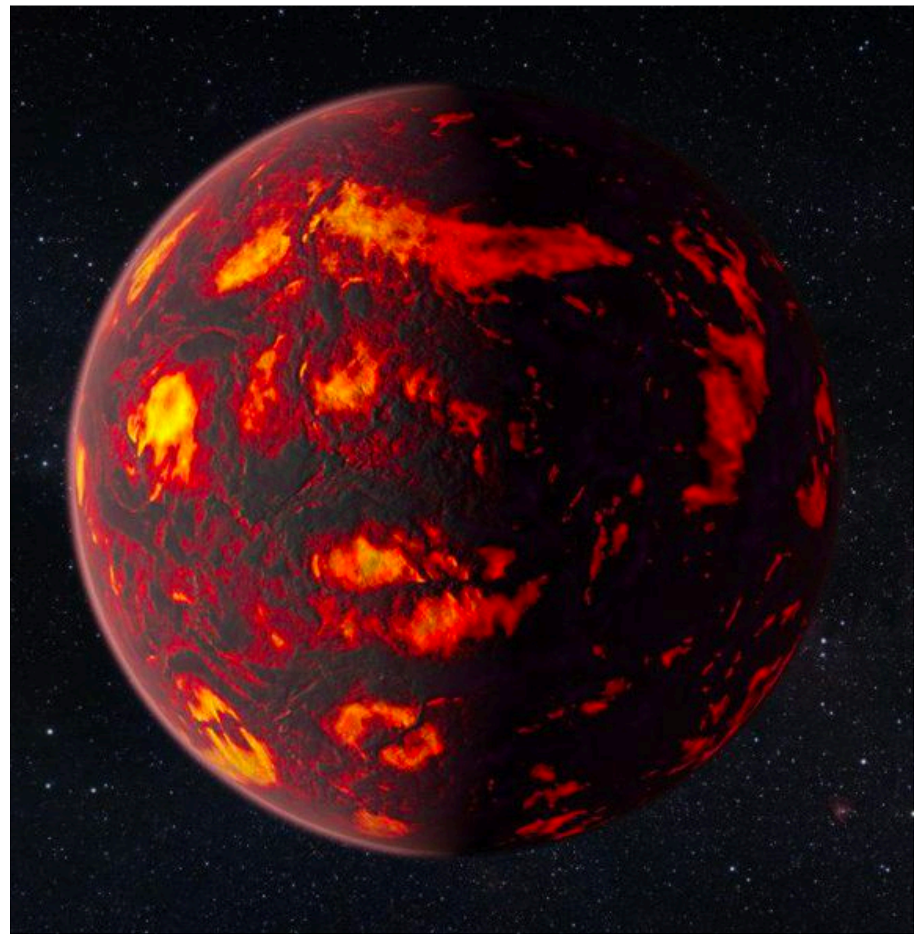


Hirschmann 16

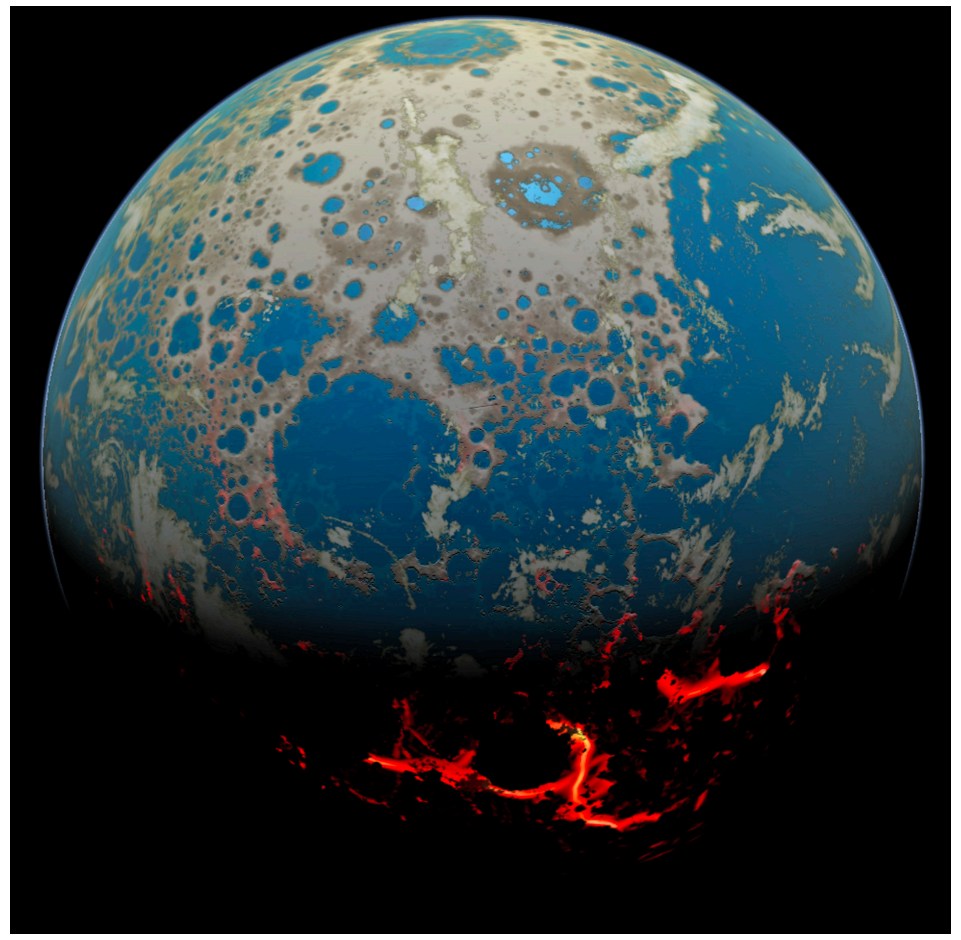
Volatile fractionation controls planet solidification



Magma ocean

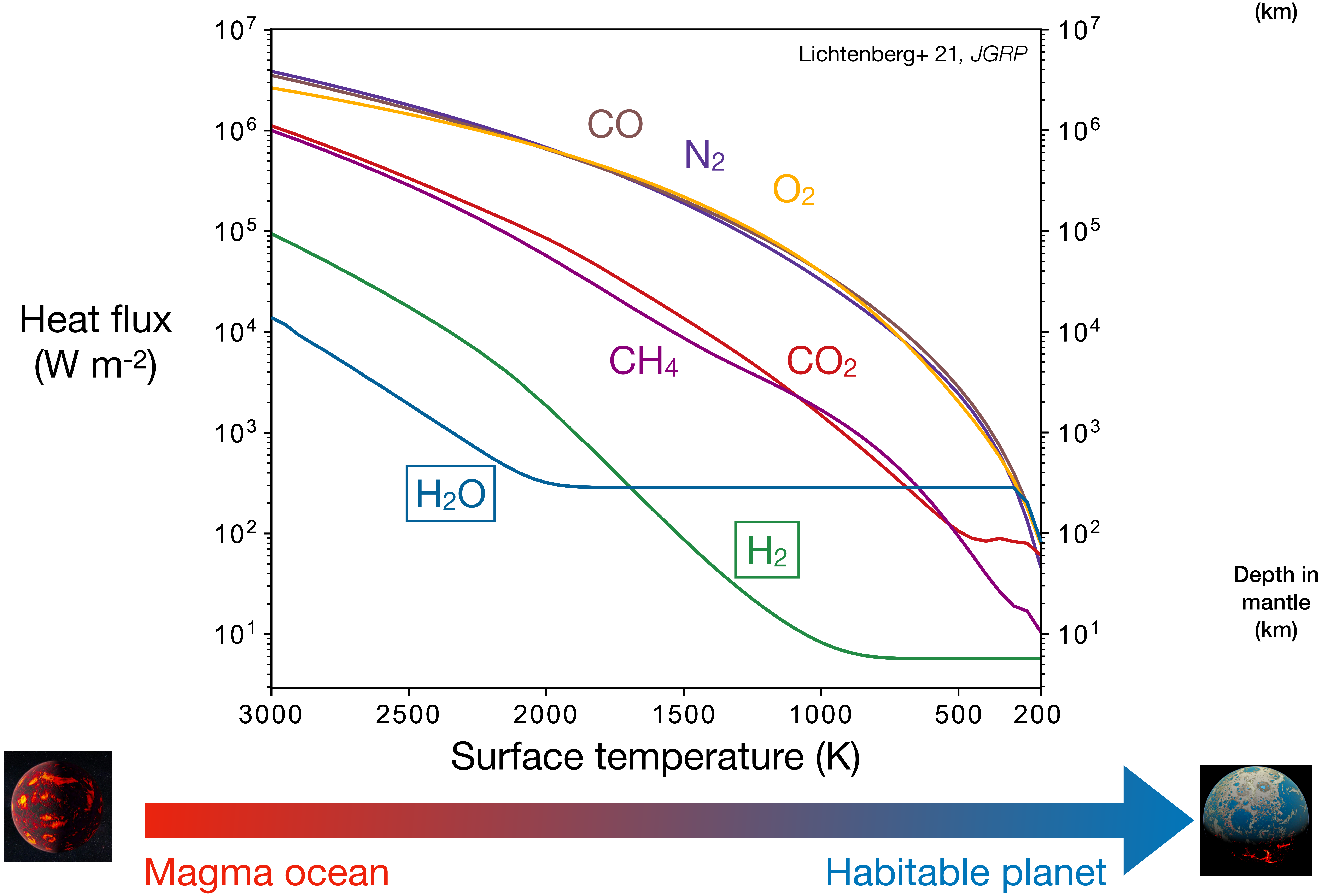


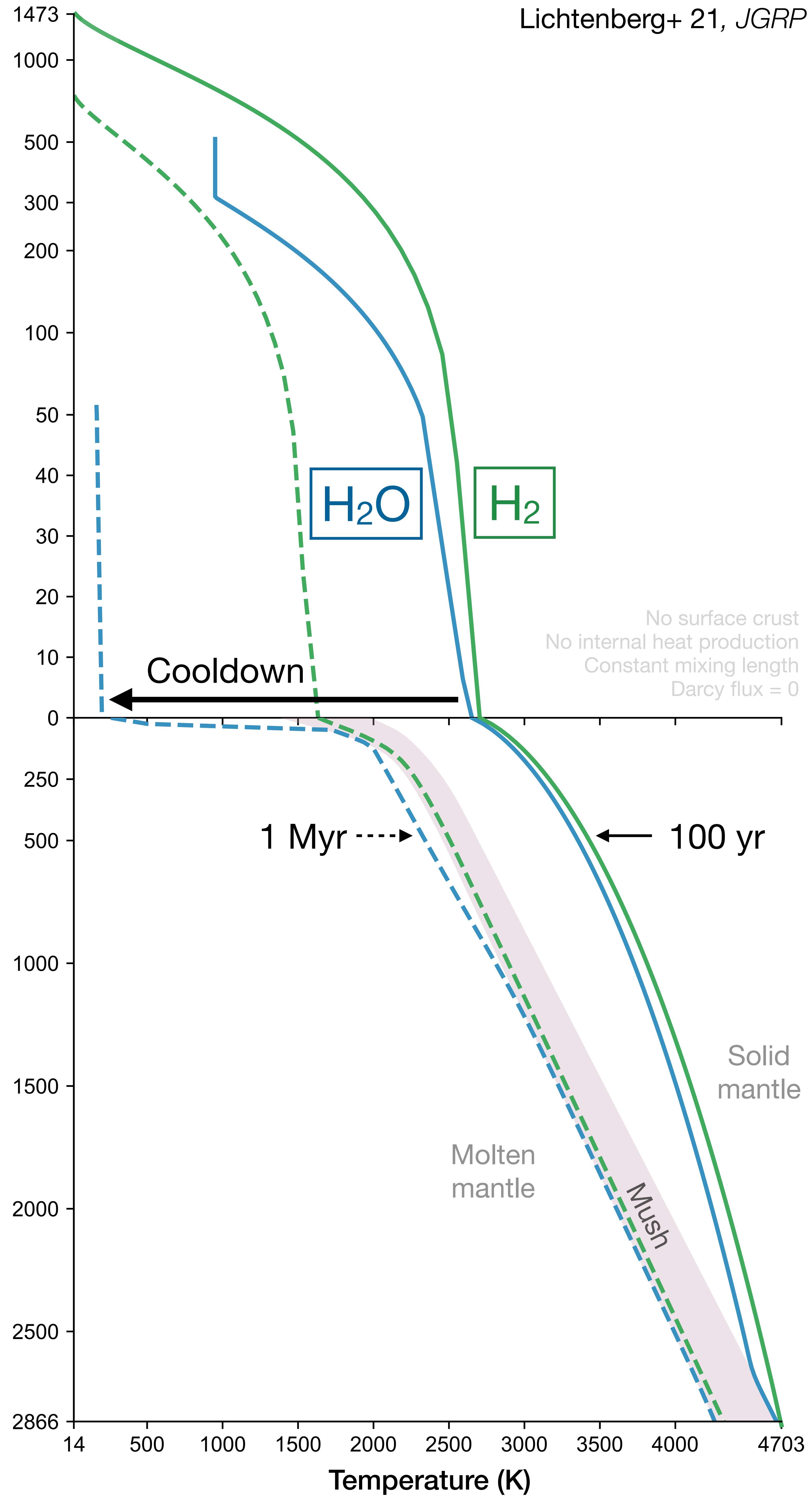
Habitable planet



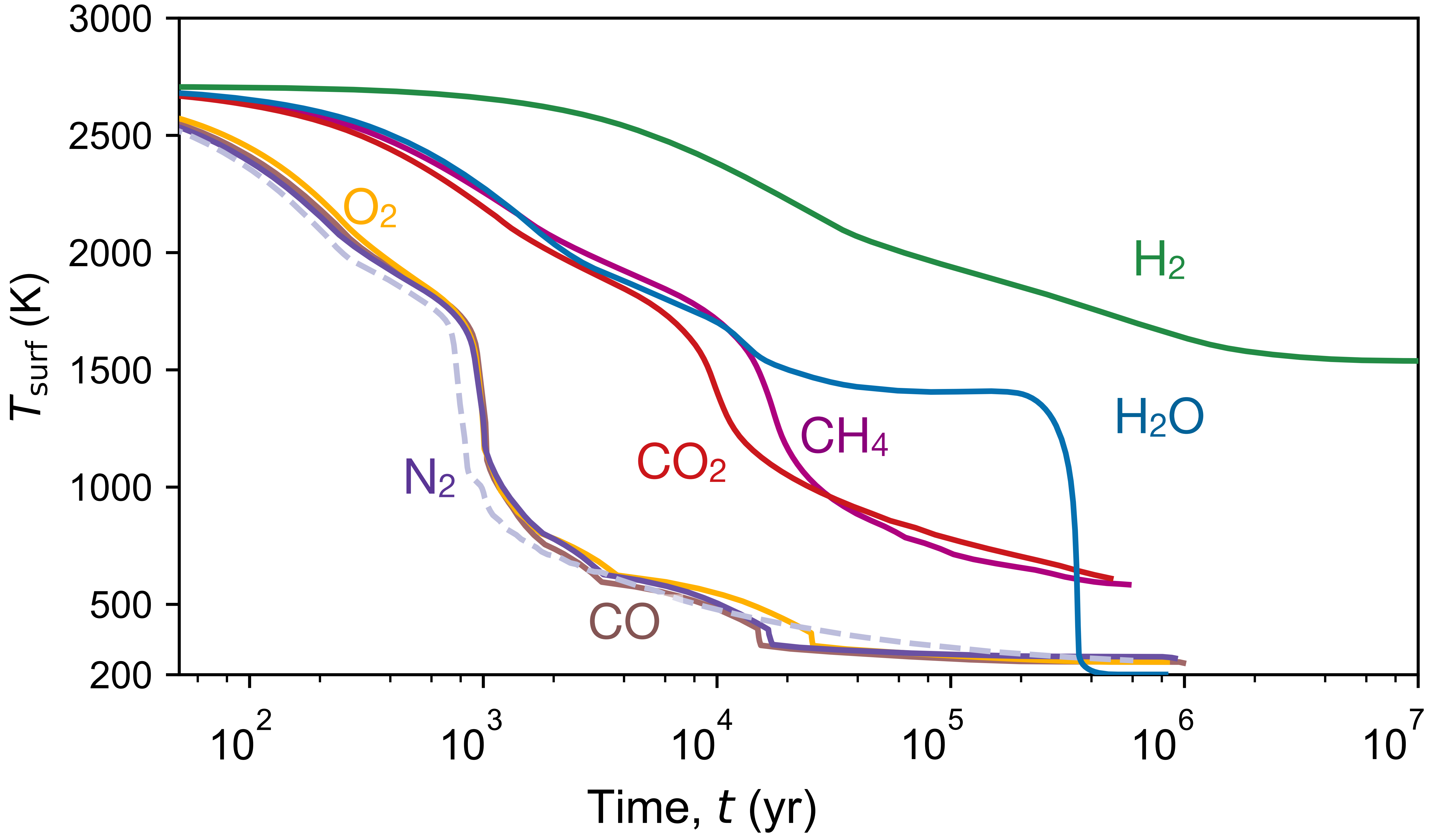
SwRi/S. Marchi

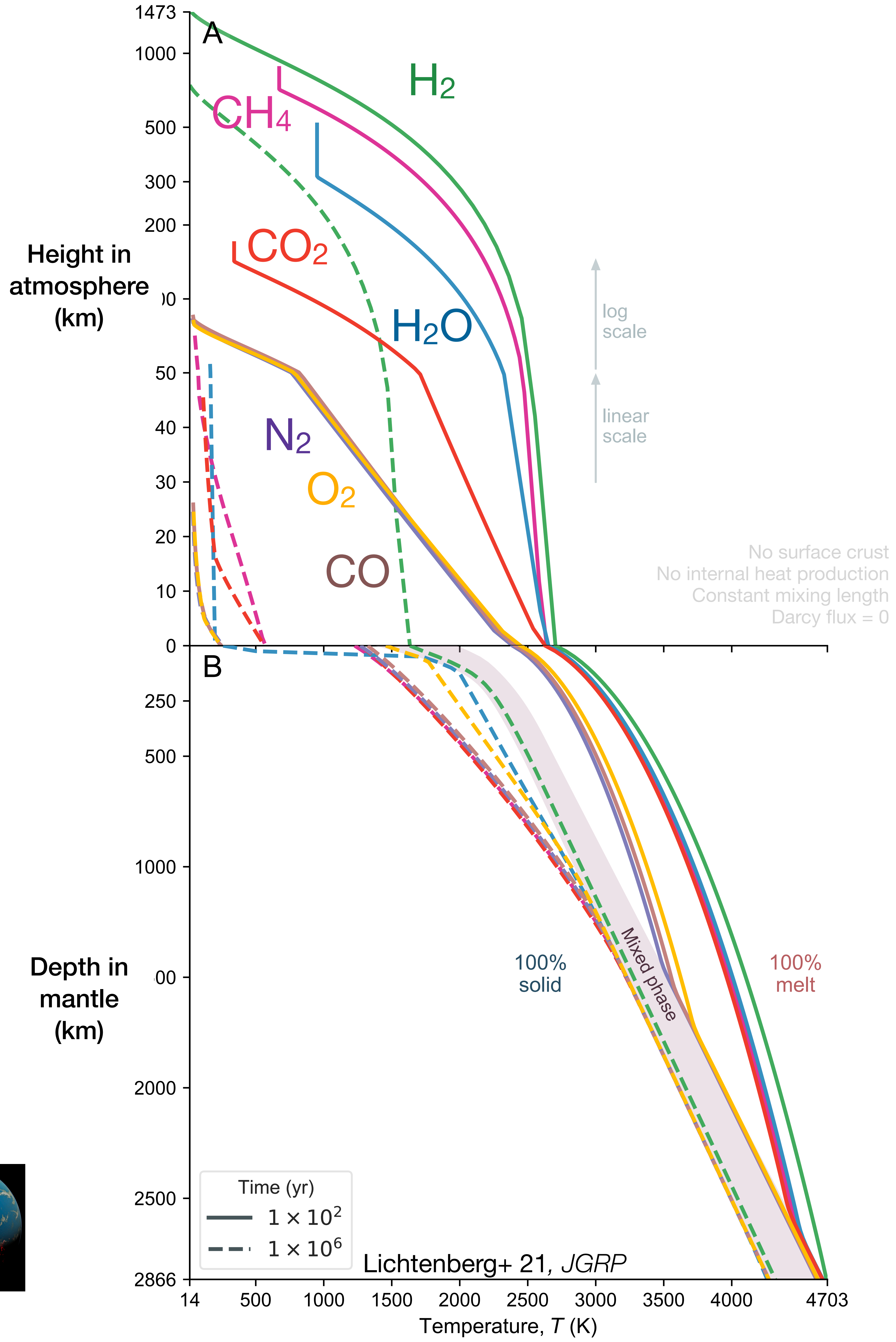
Worlds with varying volatiles *solidify differently*





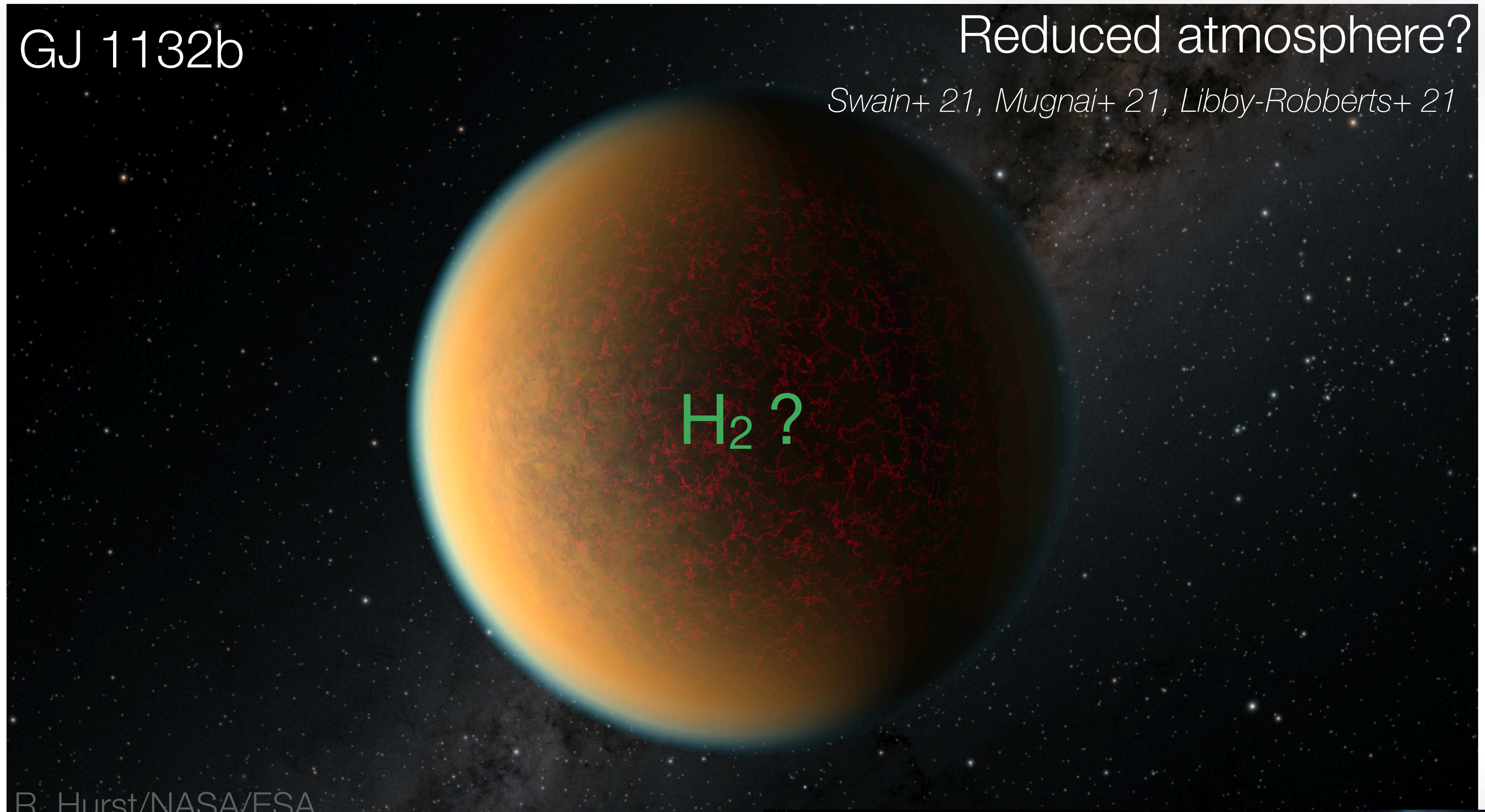
Worlds with varying volatiles *solidify differently*





Lichtenberg+ 21, *JGRP*

Sub-Neptune opportunity



GJ 1132b

Reduced atmosphere?

Swain+ 21, Mugnai+ 21, Libby-Robberts+ 21

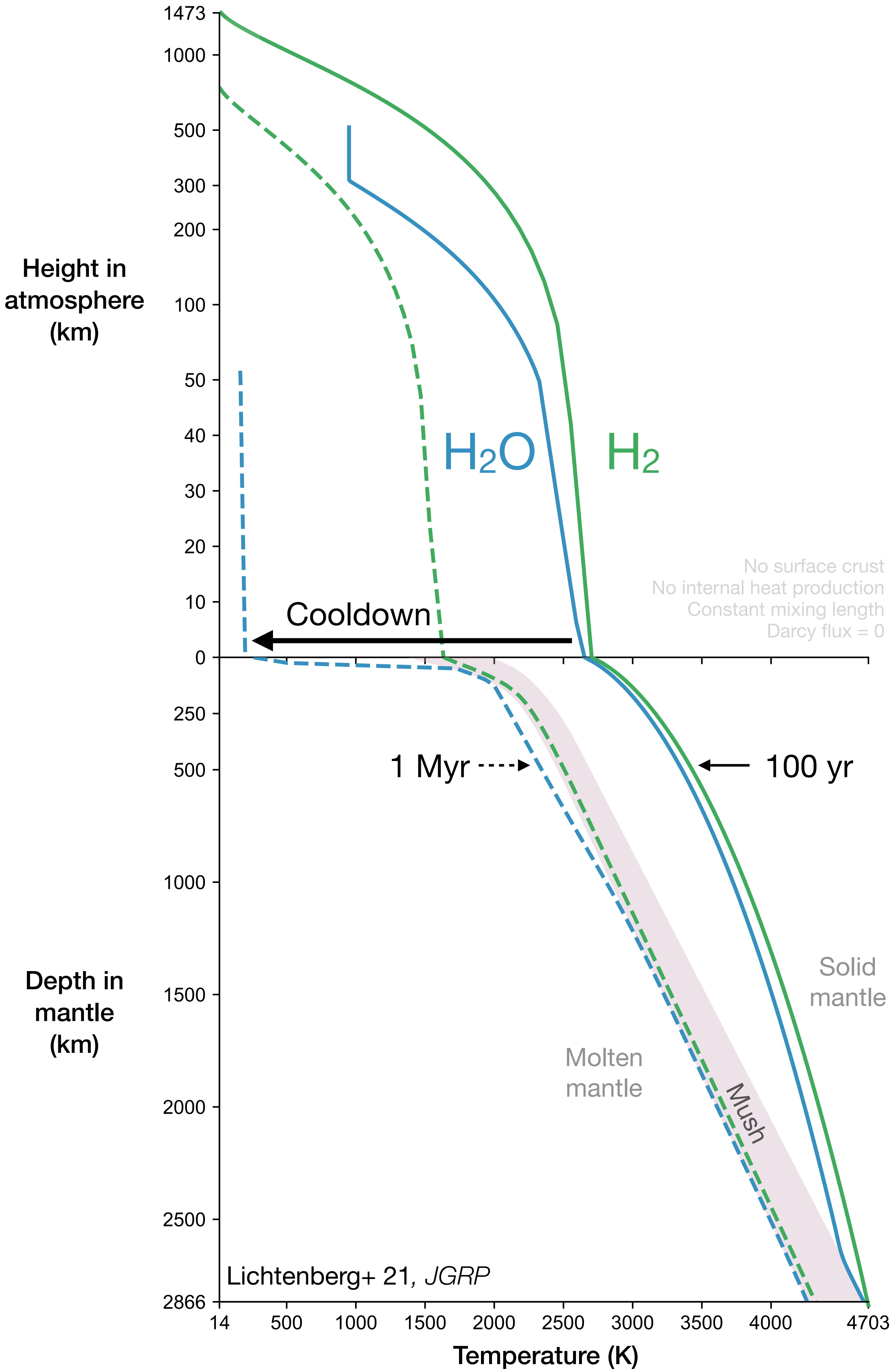
R. Hurst/NASA/ESA

K2-18b

Water-rich atmosphere

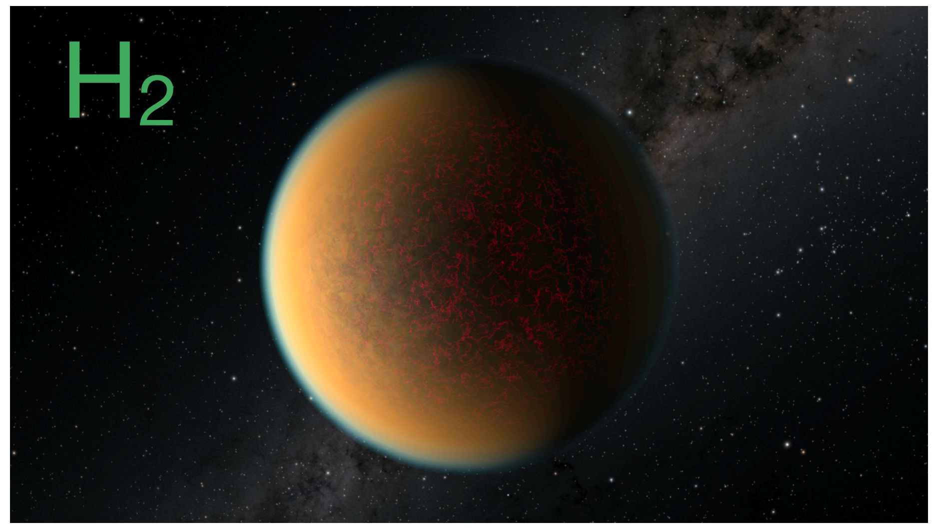
Benneke+ 19, Tsiaras+ 19

Esa/Hubble, M. Kornmesser

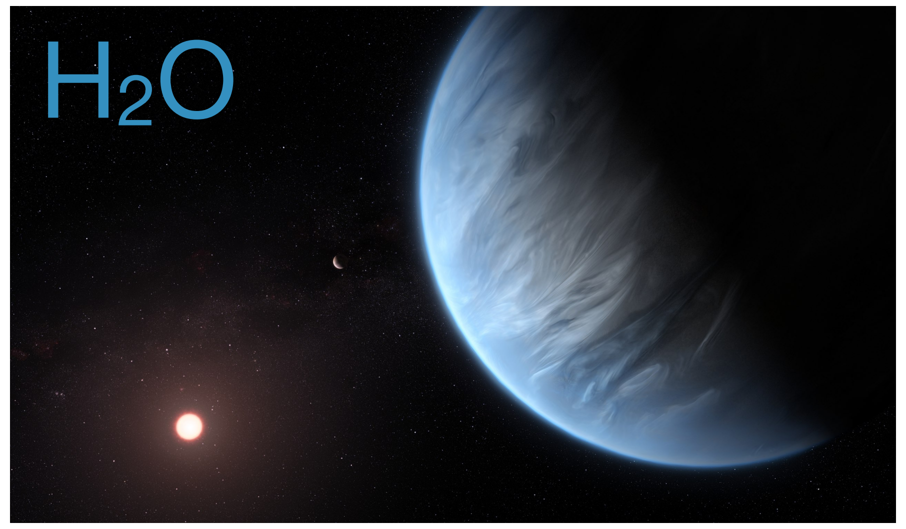


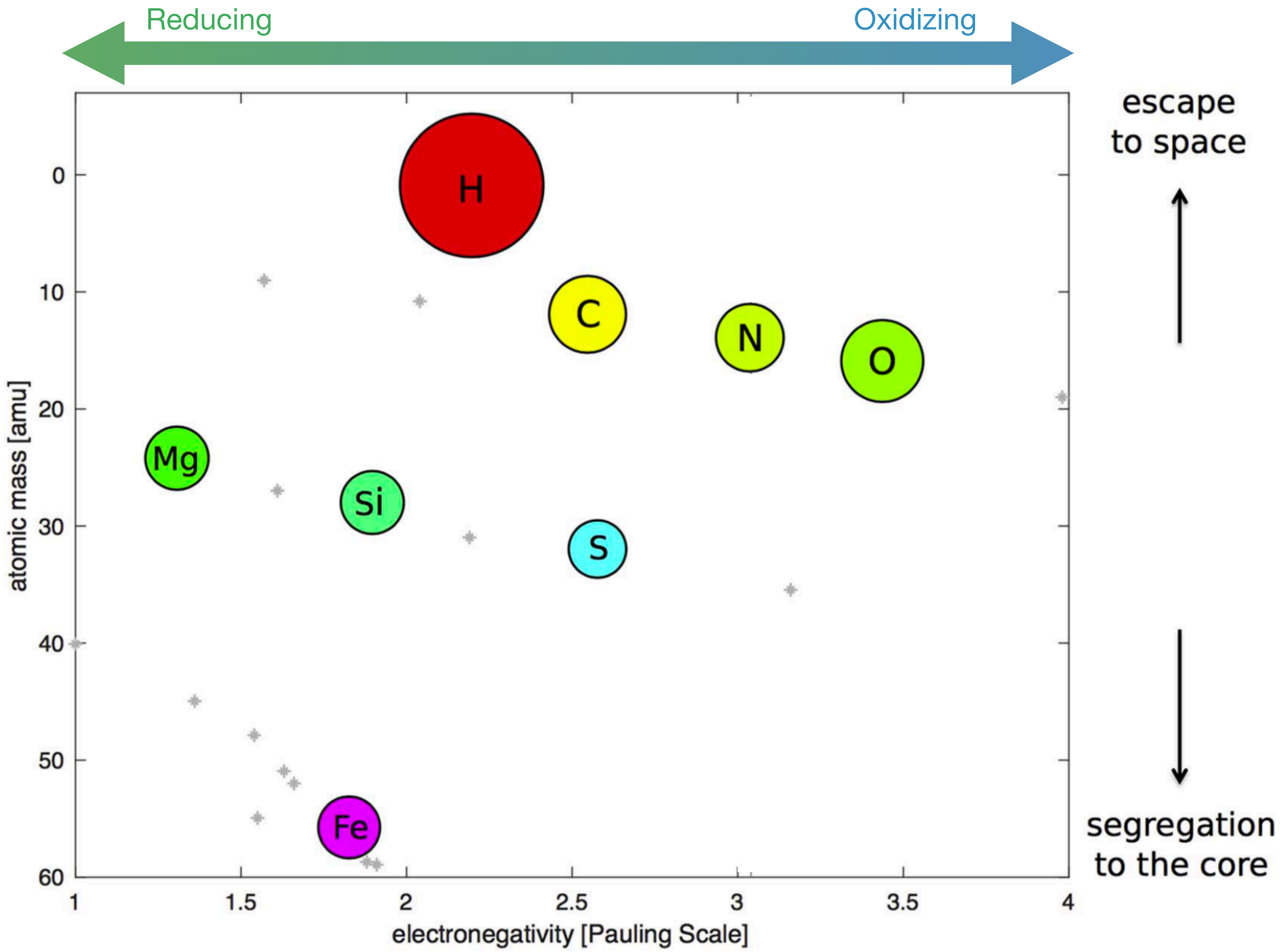
Lichtenberg+ 21, *JGRP*

Redox-controlled climates

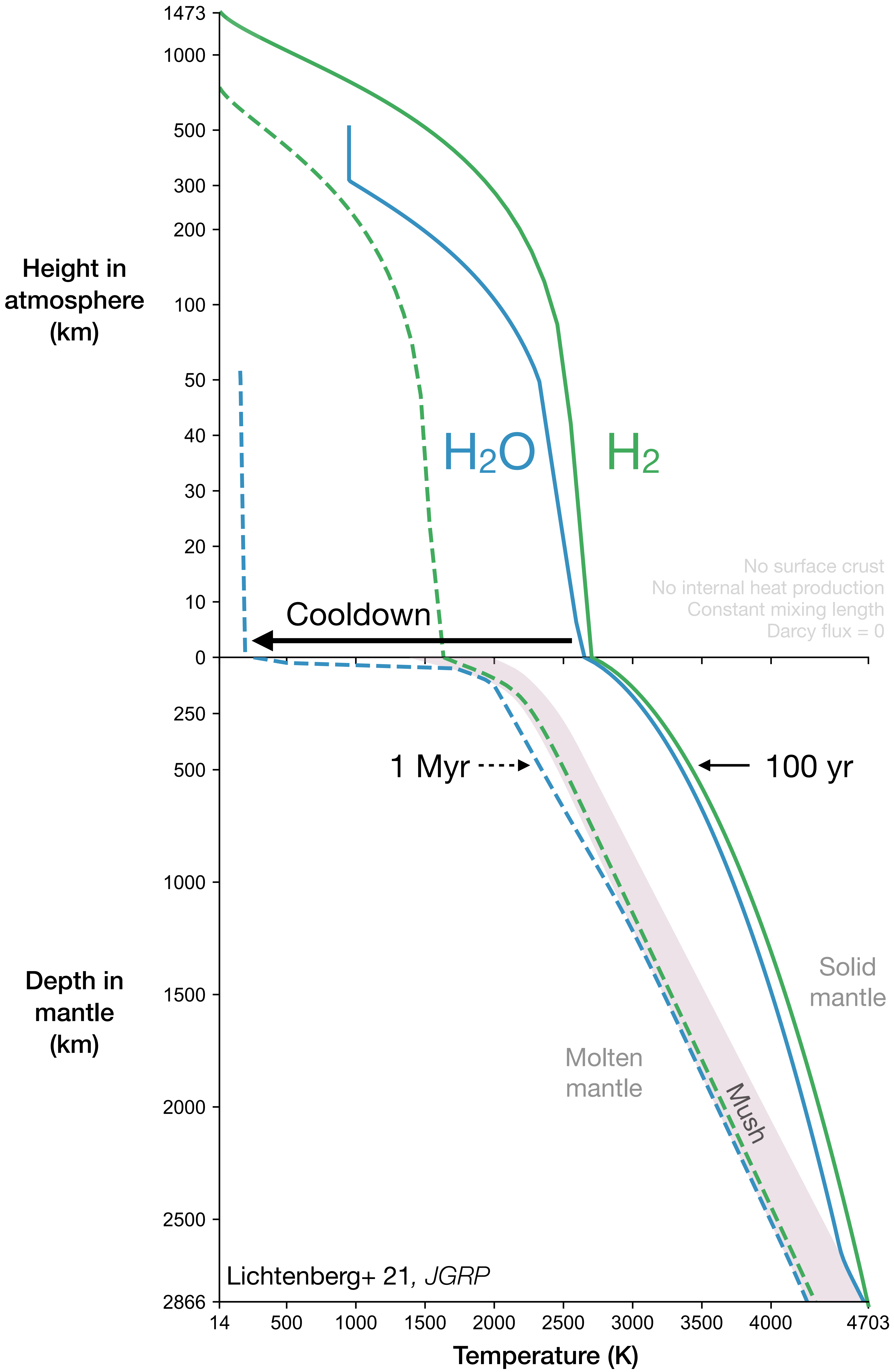


Redox state:
planet-scale
electronegativity





Wordsworth+ 18, *AJ*



Lichtenberg+ 21, *JGRP*

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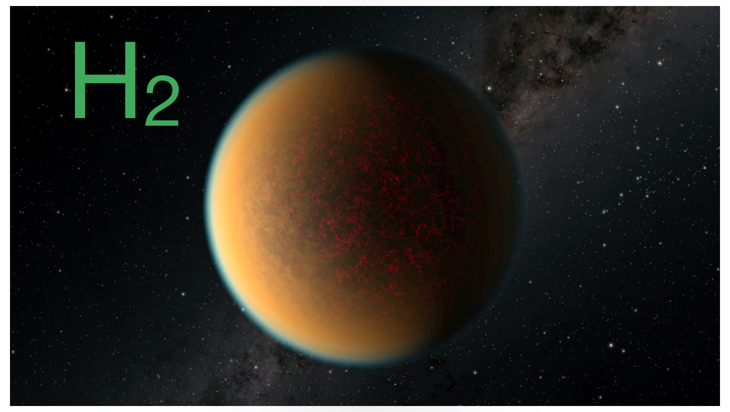
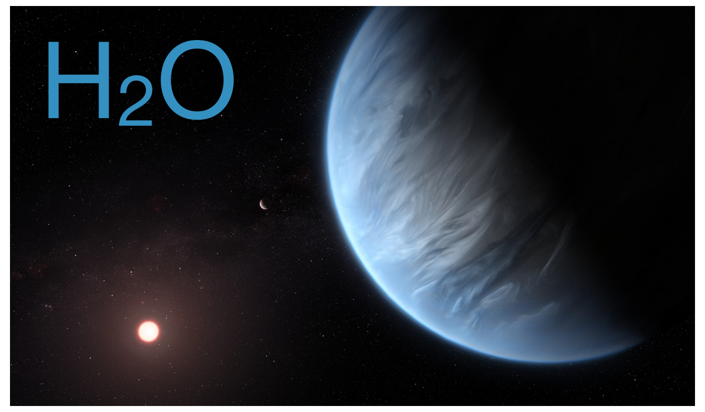
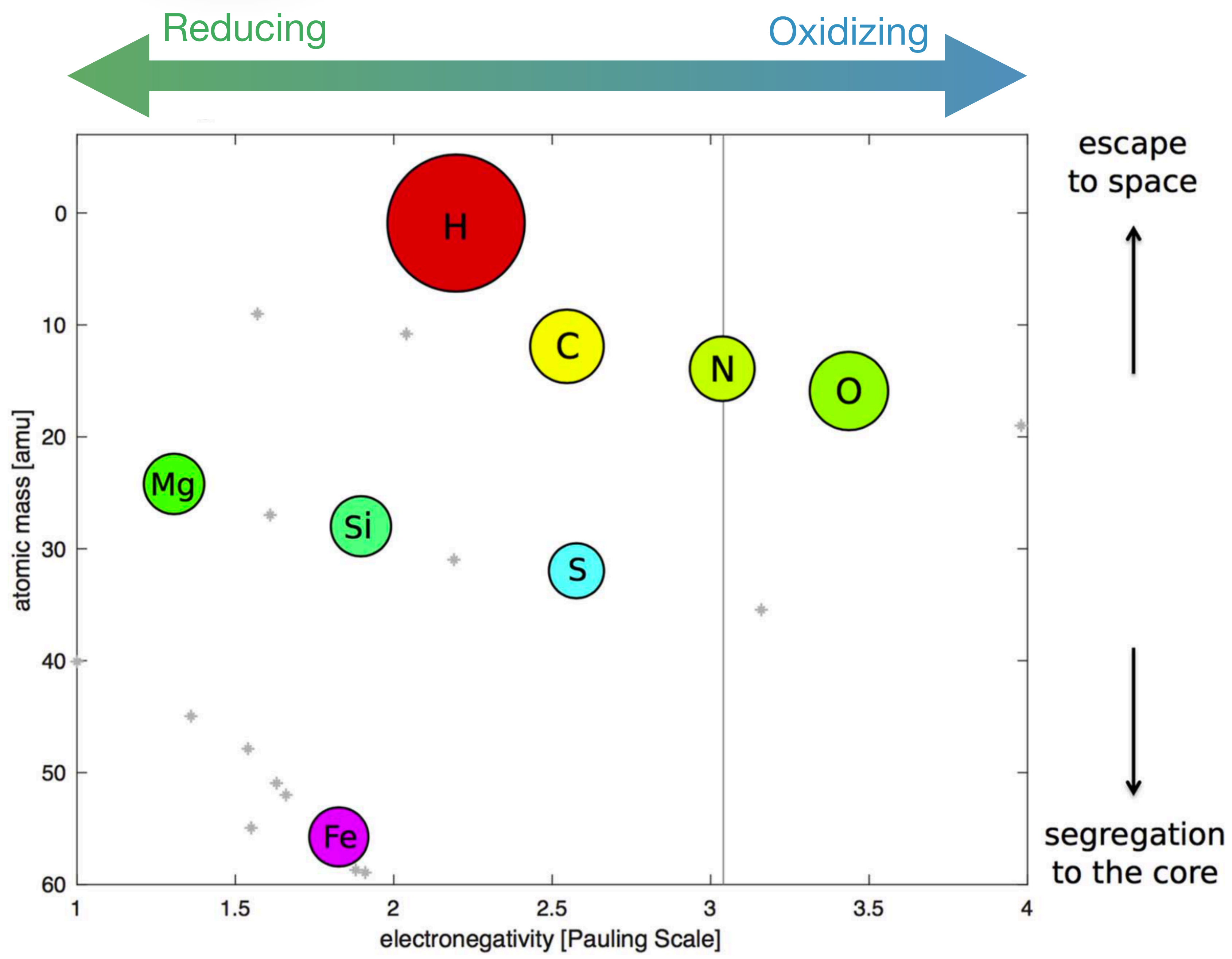
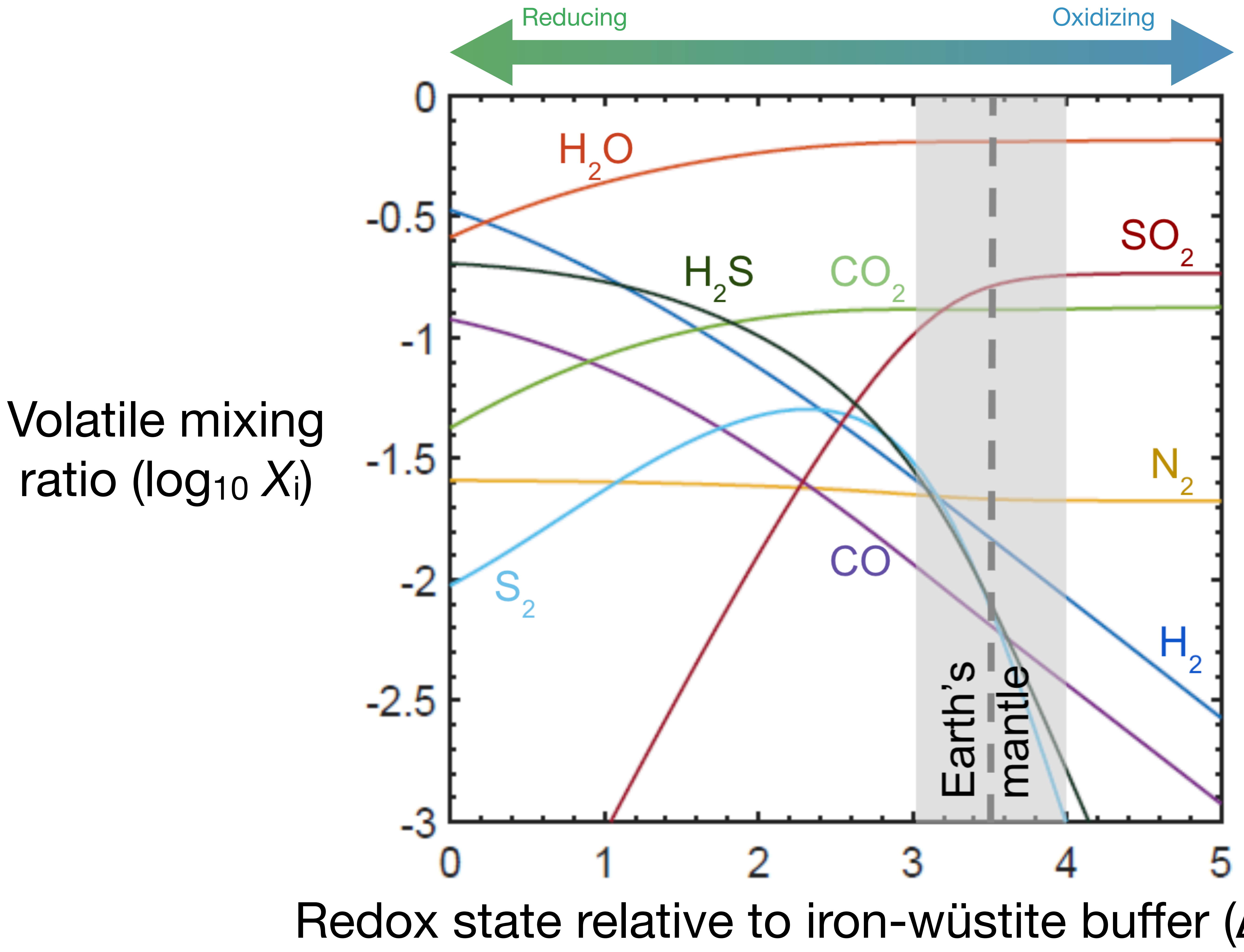






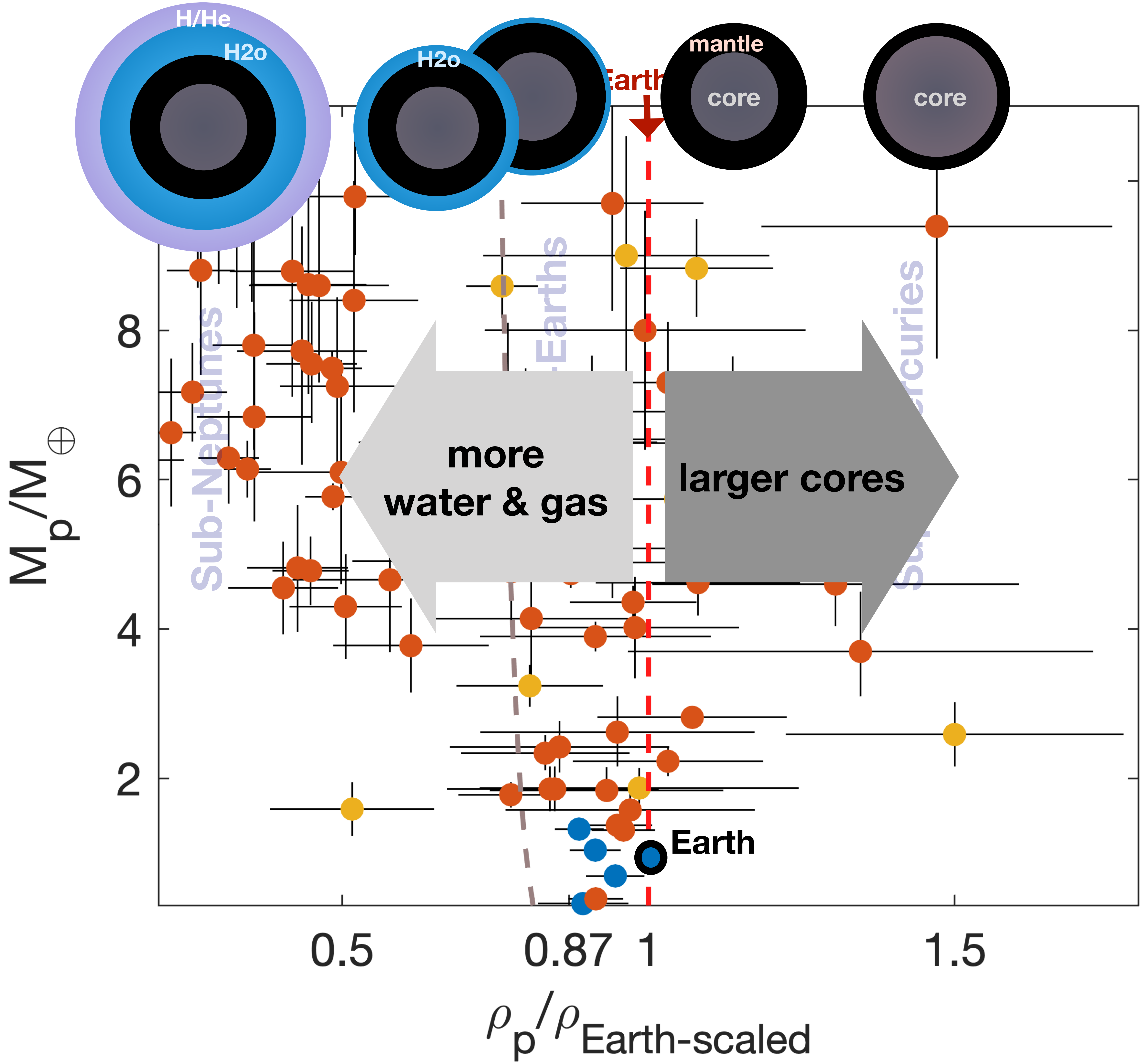


$P_{\mathrm{surf}} = 1$ bar
$T_{\mathrm{surf}} = 1400$ K

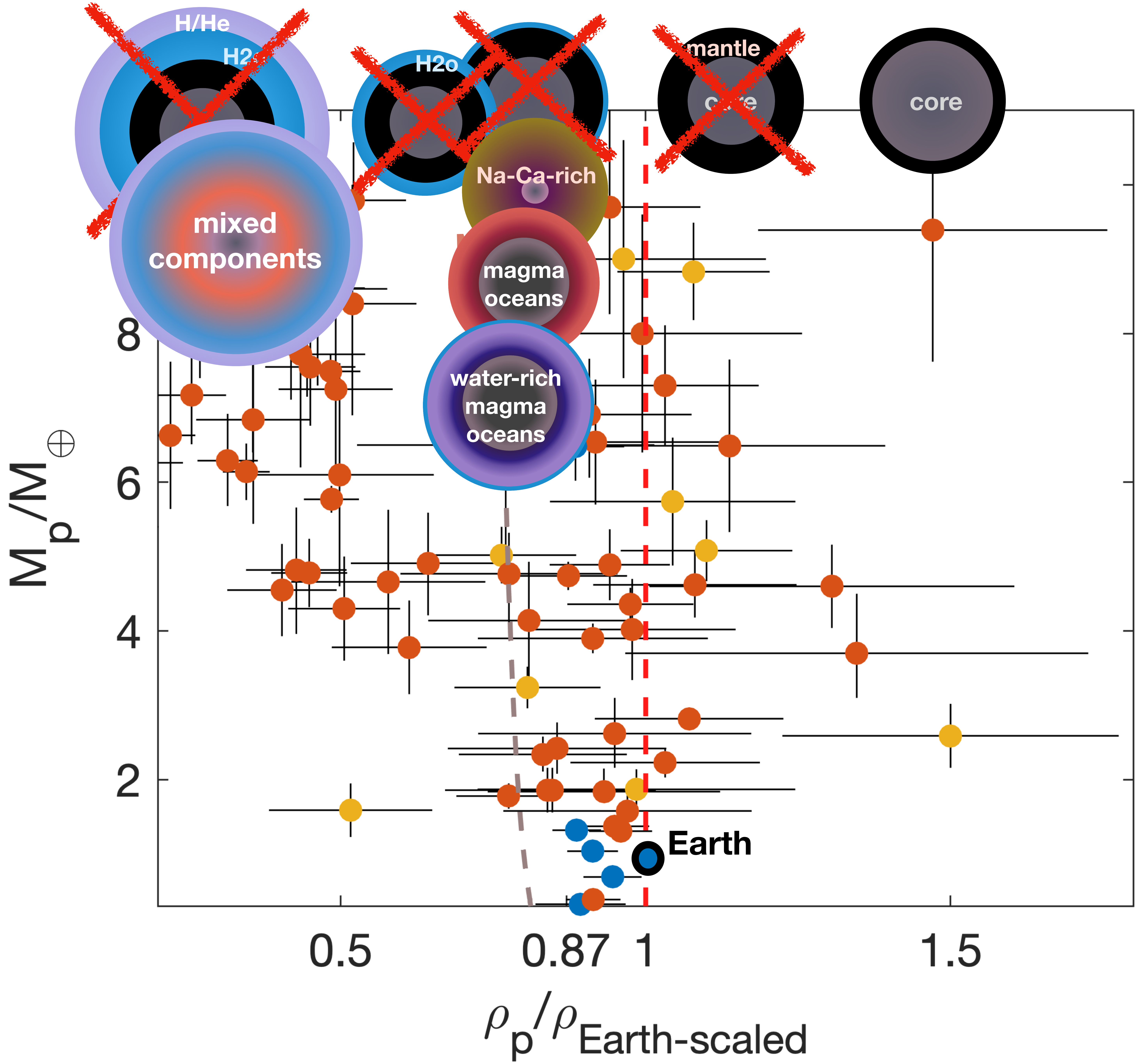
IW: $2(1-x)\,Fe + O_2 = 2\,Fe_{1-x}O$

Wordsworth+ 18, *AJ*

Lichtenberg+ 22, *Protostars & Planets VII*



Credit: C. Dorn



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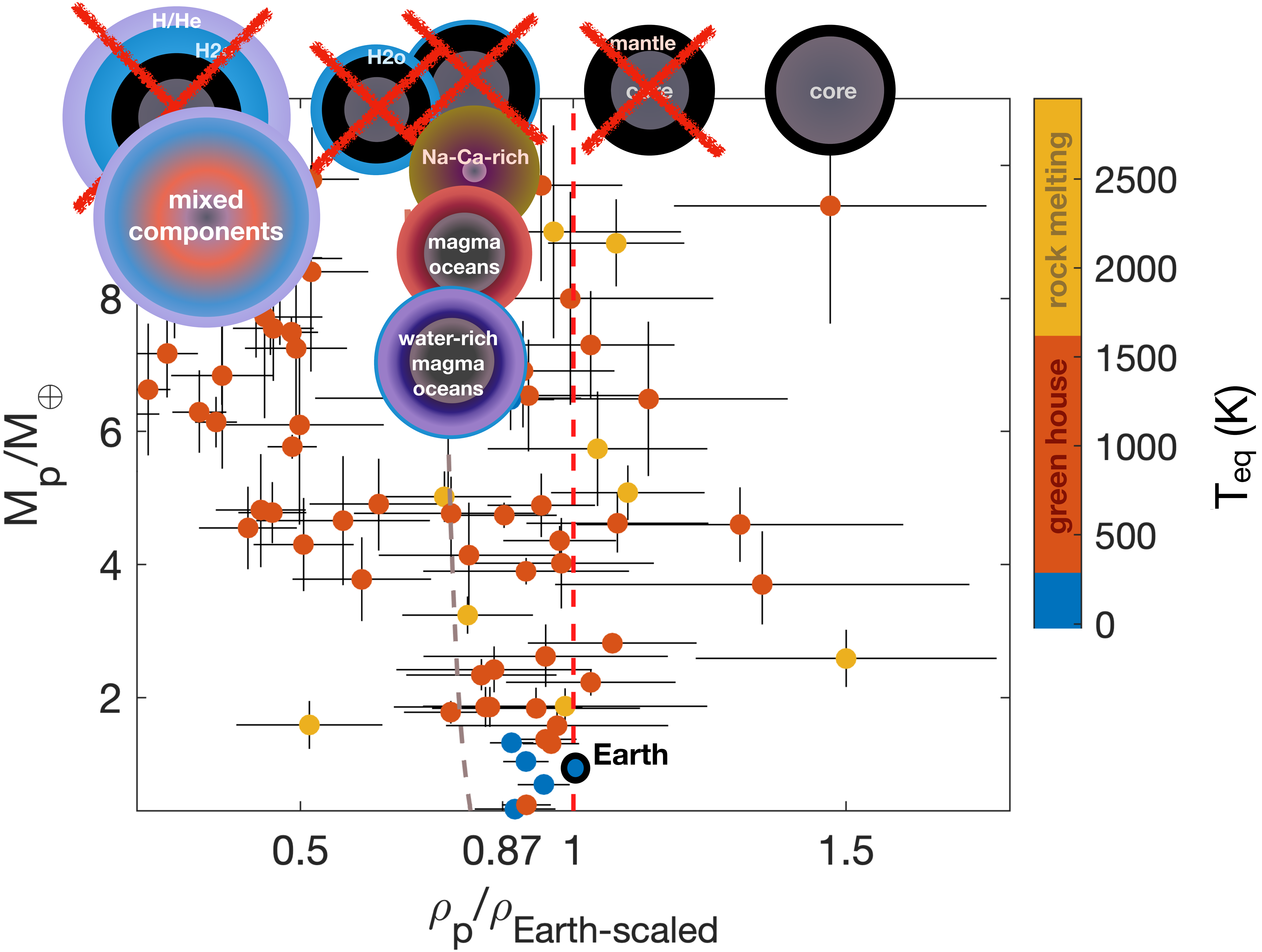
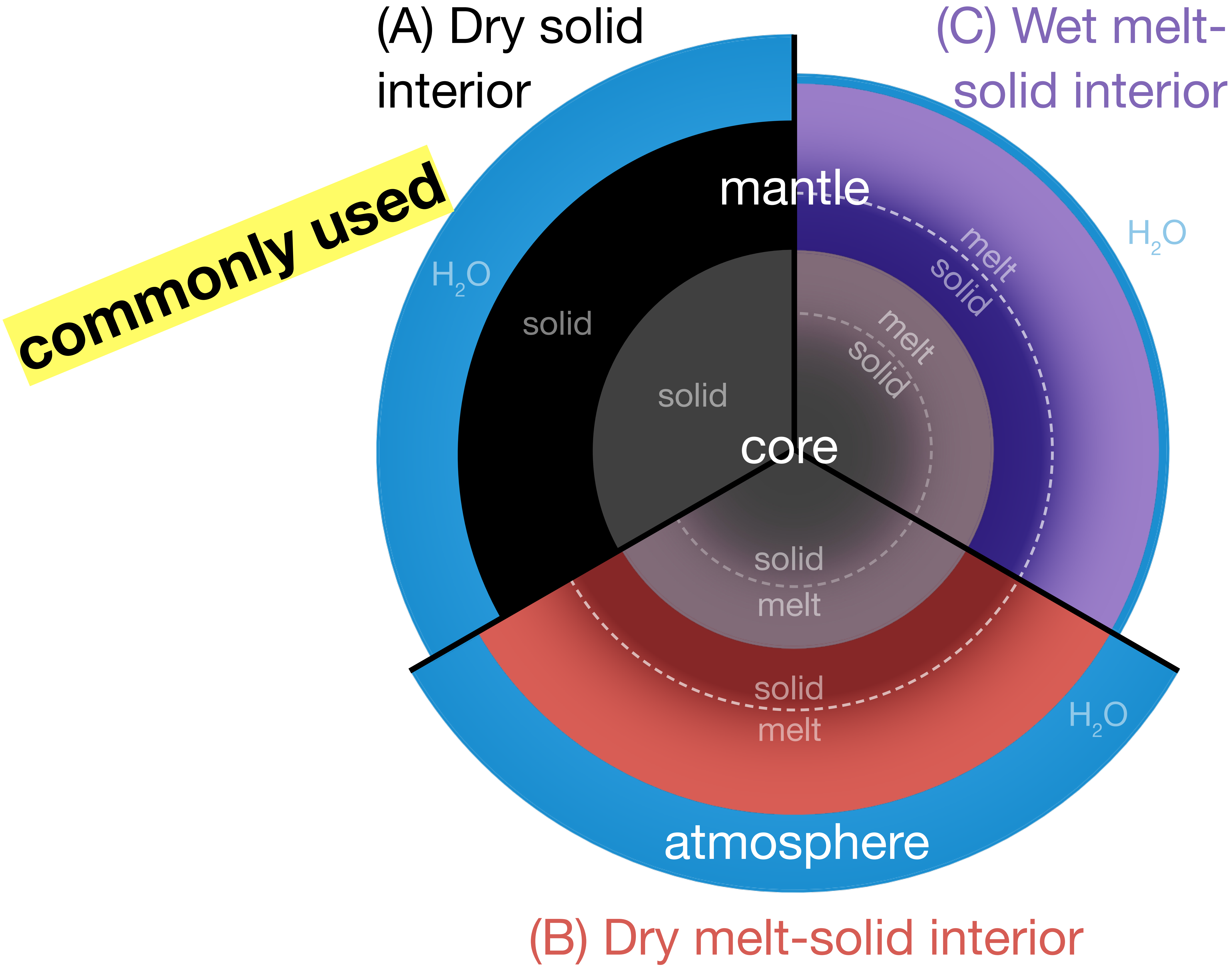
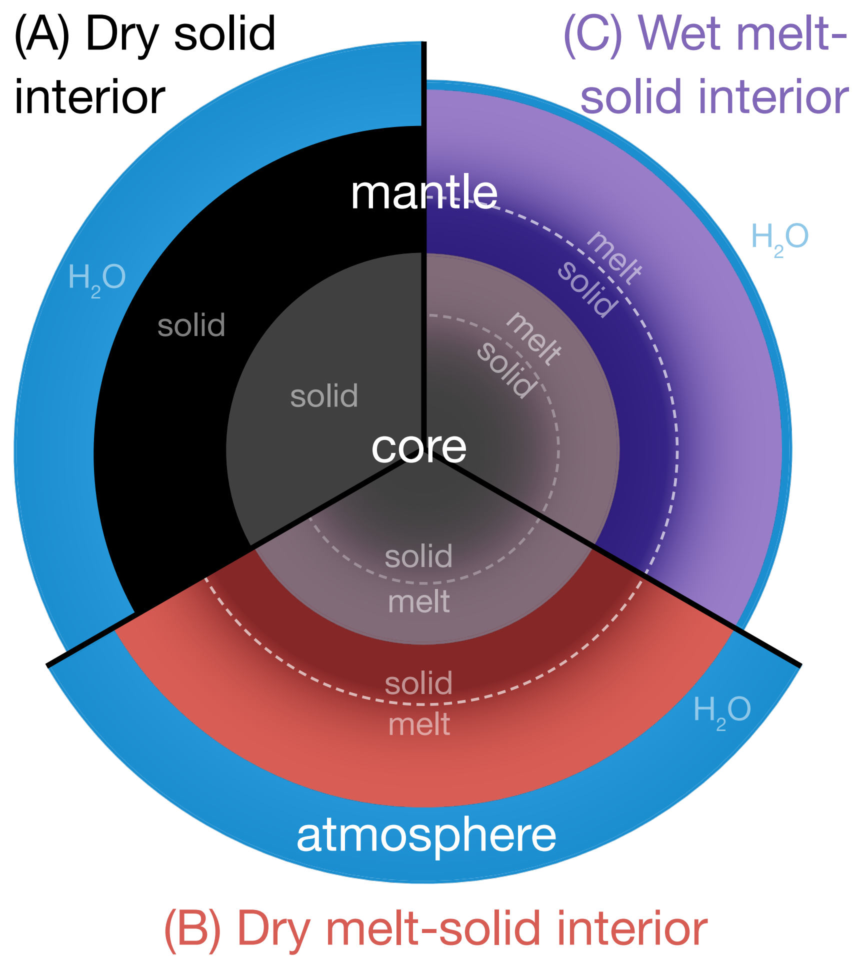


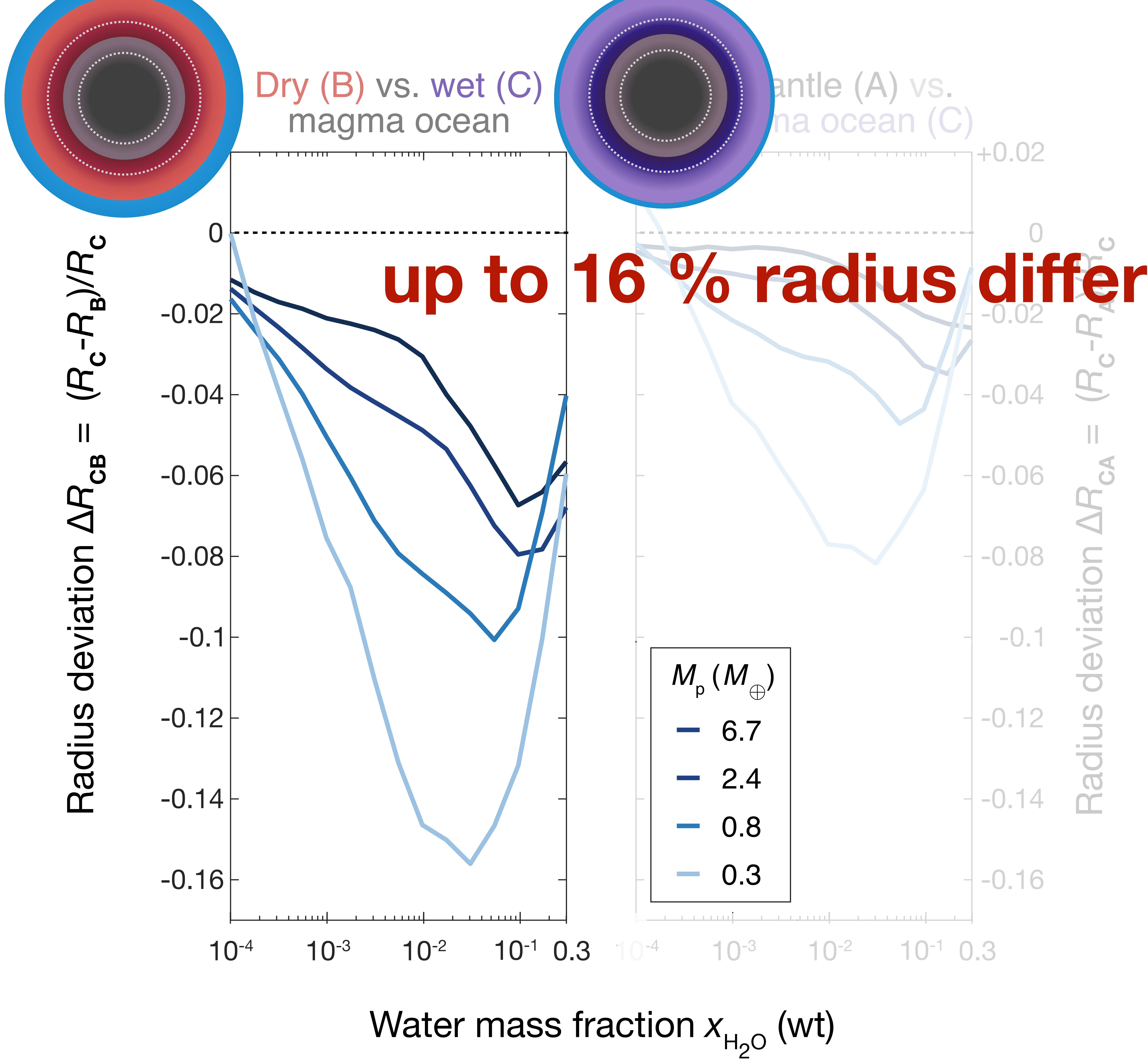
Credit: C. Dorn

Advanced interior-atmosphere models



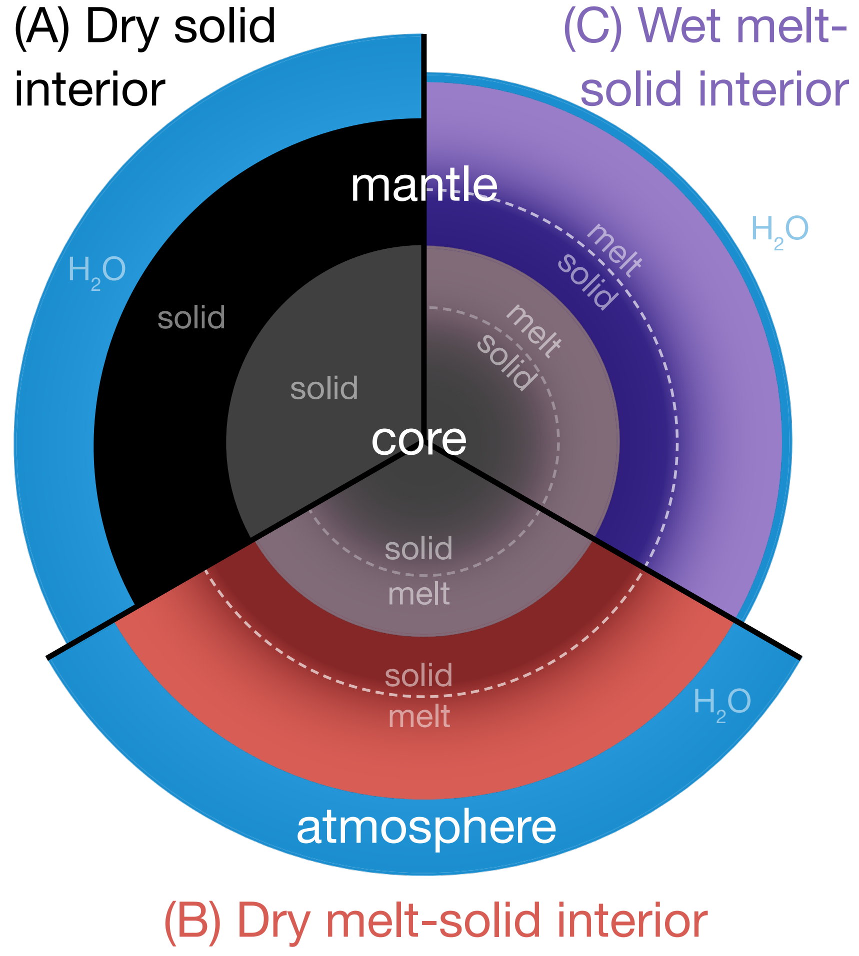
Dorn & Lichtenberg 21, *ApJL*

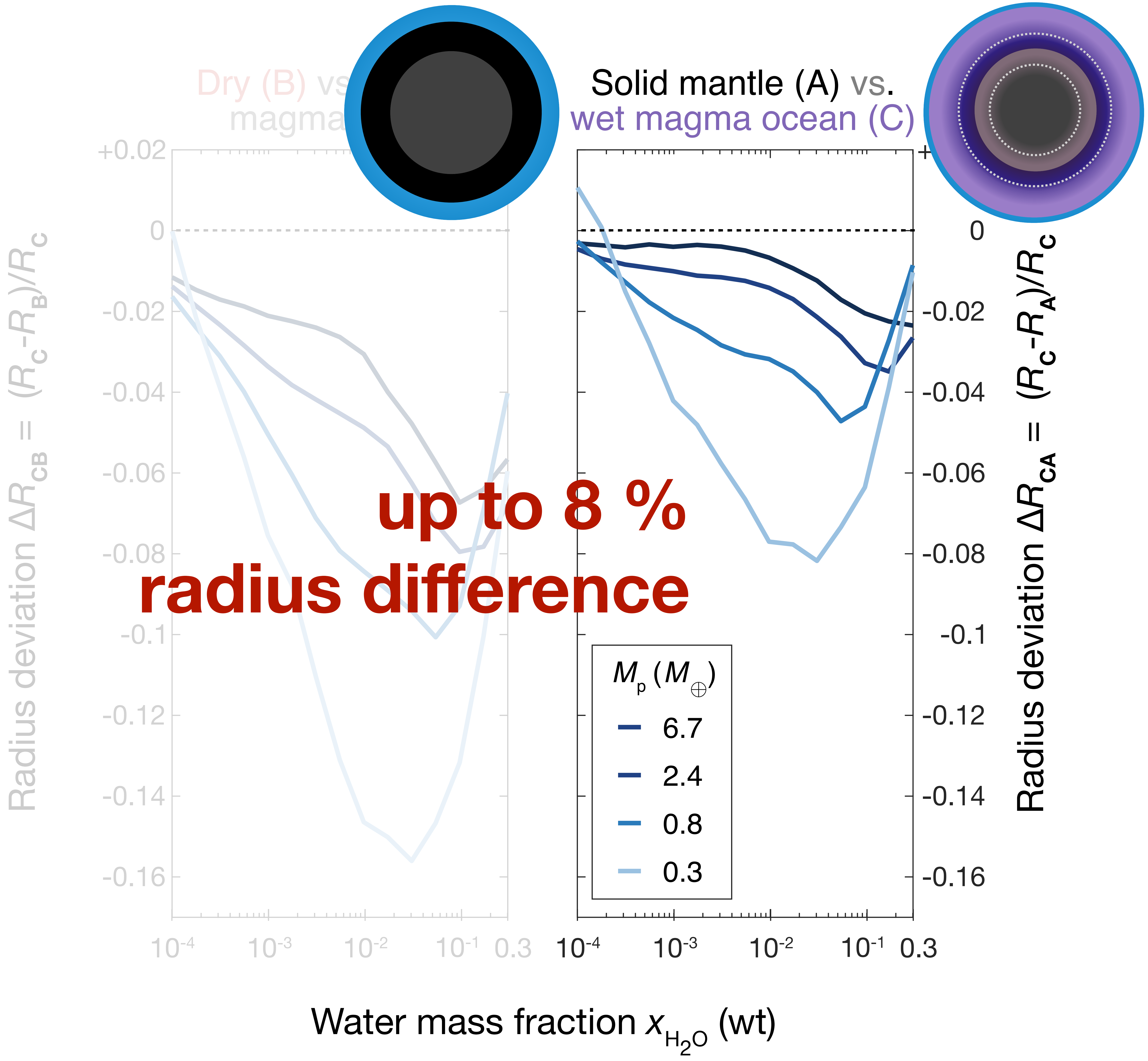




up to 16 % radius difference

Dorn & Lichtenberg 21, *ApJL*

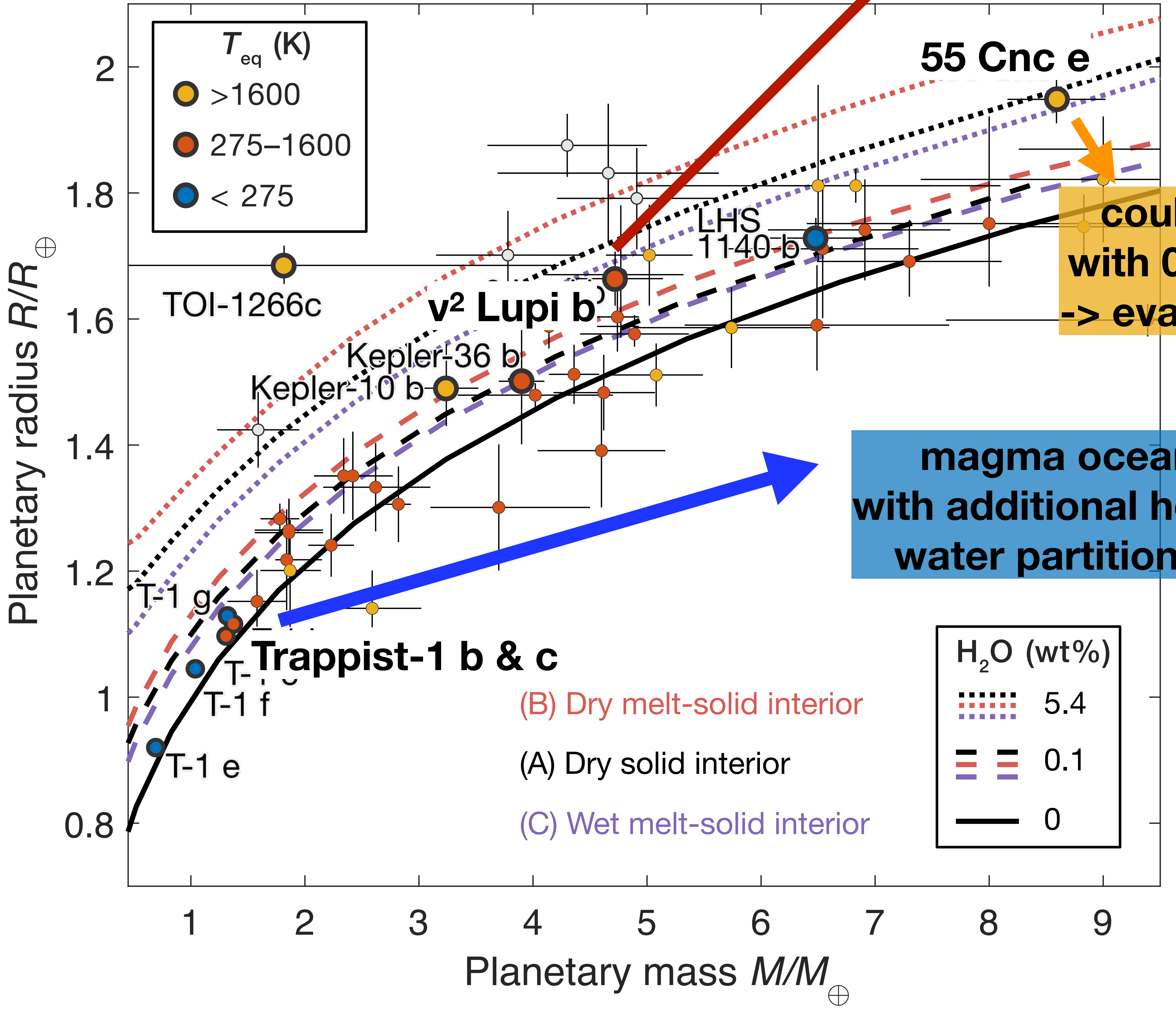




up to 8 %
radius difference

Dorn & Lichtenberg 21, *ApJL*

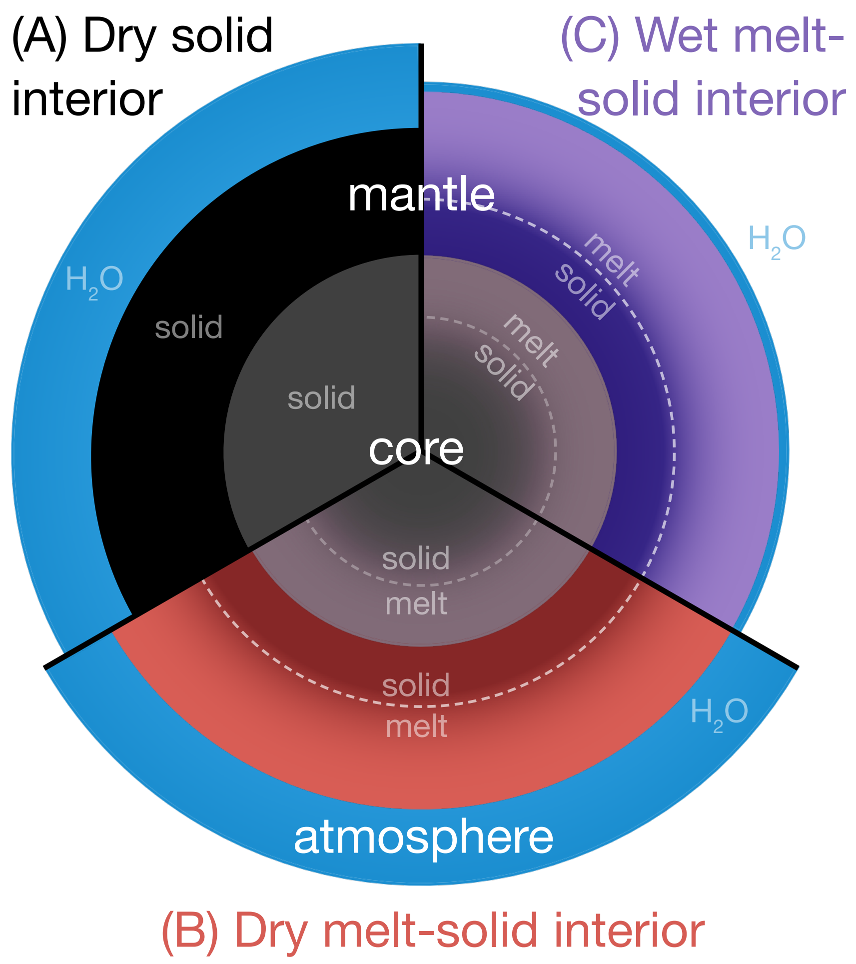
Specific planets



0.07 % steam atmosphere
& 2 % in magma ocean
very different from Delrez+2021

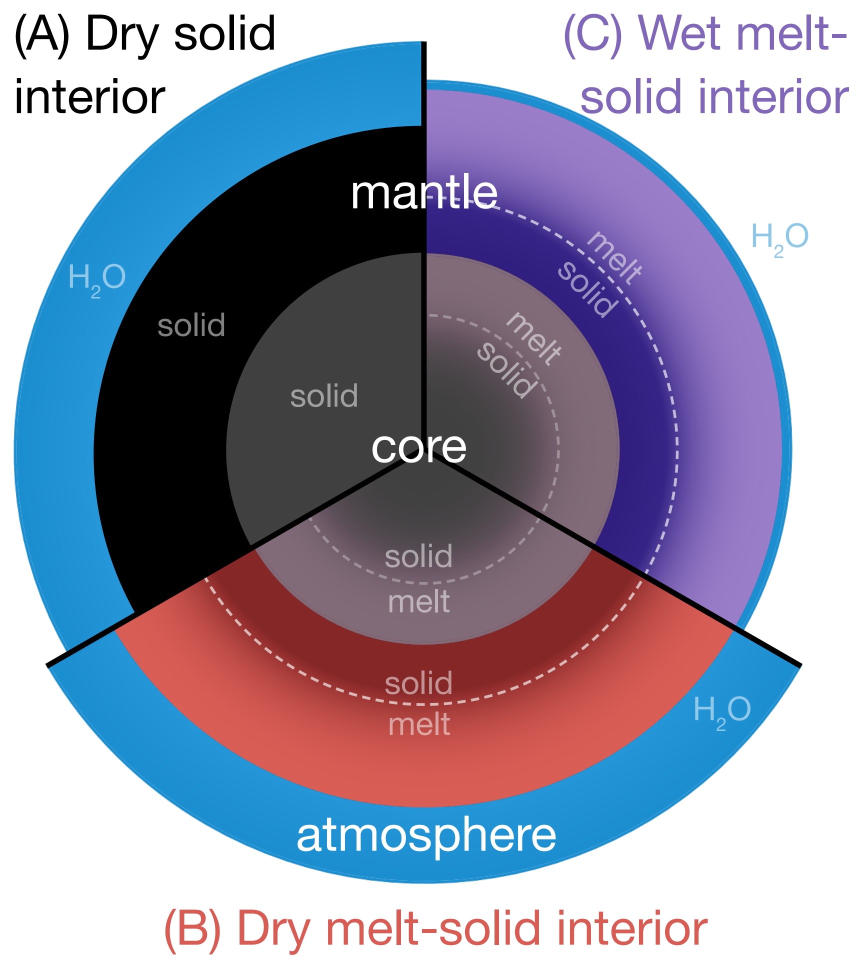
could have several % of water,
with 0.01 % steam on the surface,
-> evaporative loss model required

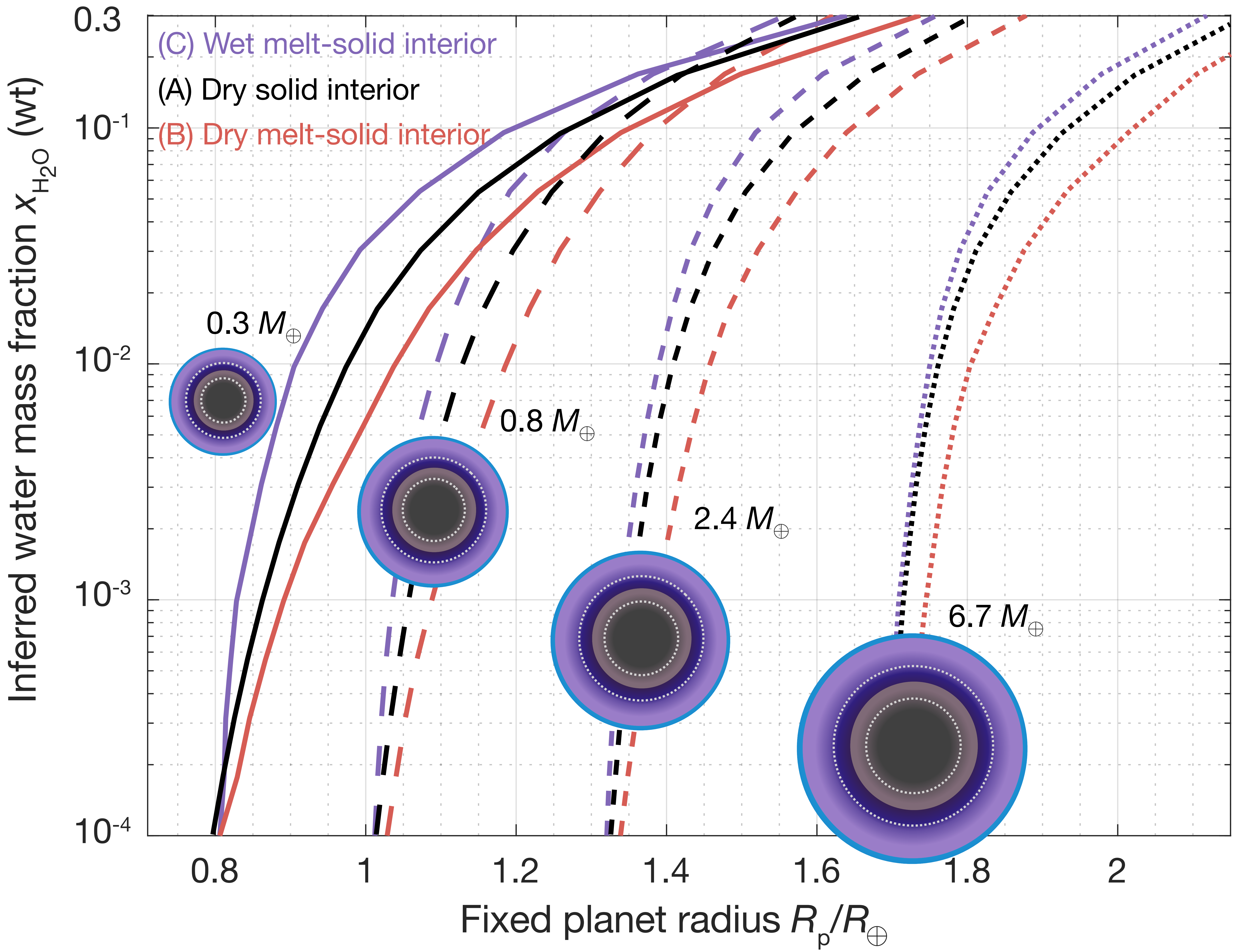
magma oceans only possible
with additional heating mechanisms
water partitioning only marginal



Dorn & Lichtenberg 21, *ApJL*

Up to 1 magnitude water budget difference





Dorn & Lichtenberg 21, *ApJL*

Redox alteration requires reservoir mixing

Iron disproportionation

$$\boxed{3\mathrm{Fe}^{2+} \rightarrow 2\mathrm{Fe}^{3+} + \mathrm{Fe}^{0}}$$

Frost+ 04, Wade & Wood 05, Frost & McCammon 08, Carlson+ 12

Endogenous water production

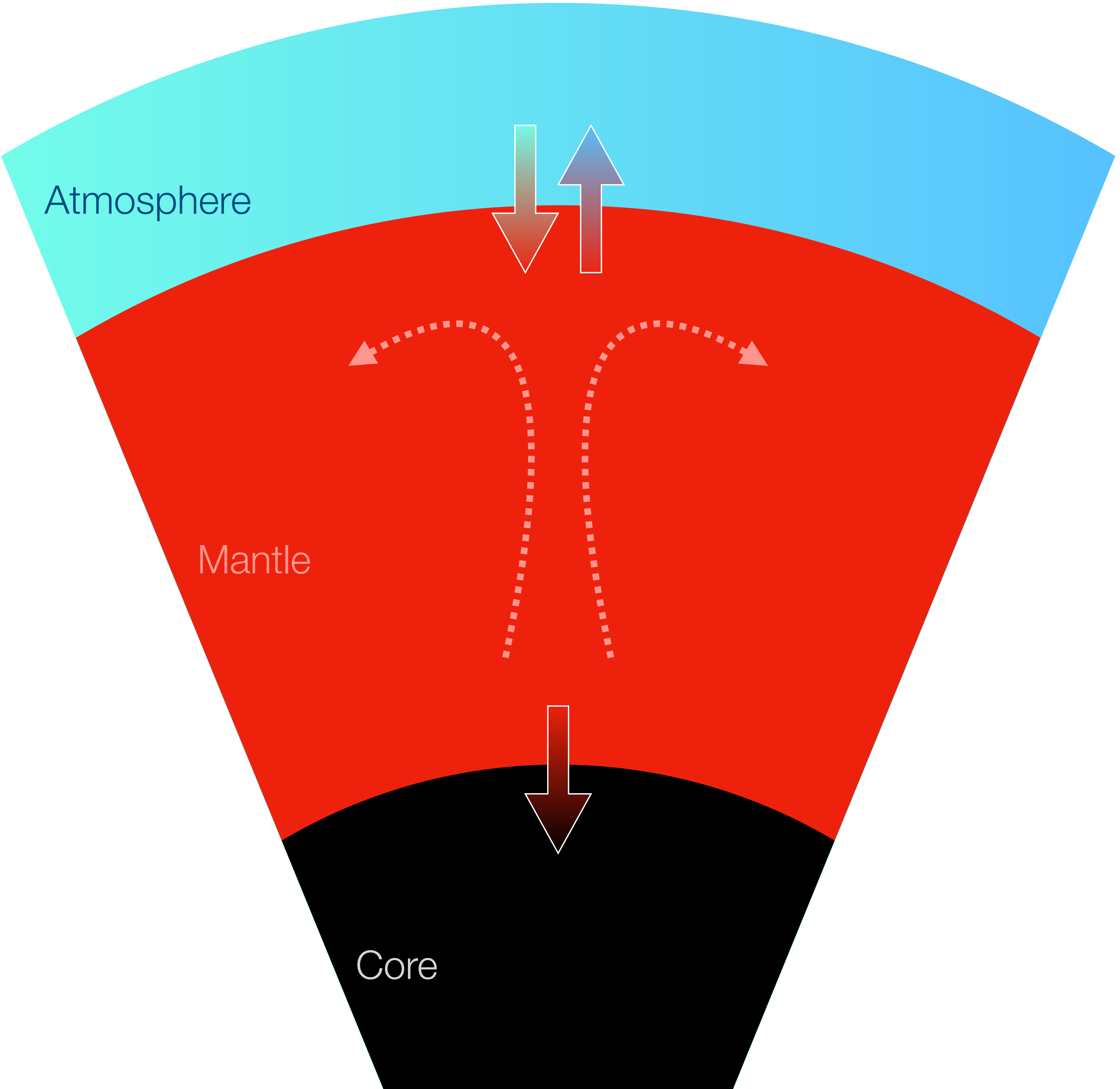
$$\boxed{\mathrm{FeO} + \mathrm{H}_2 \rightarrow \mathrm{H}_2\mathrm{O} + \mathrm{Fe}^{0}}$$

Ikoma & Genda 06, Ikoma+ 18, Olson & Sharp 18, Kite & Schaefer 21

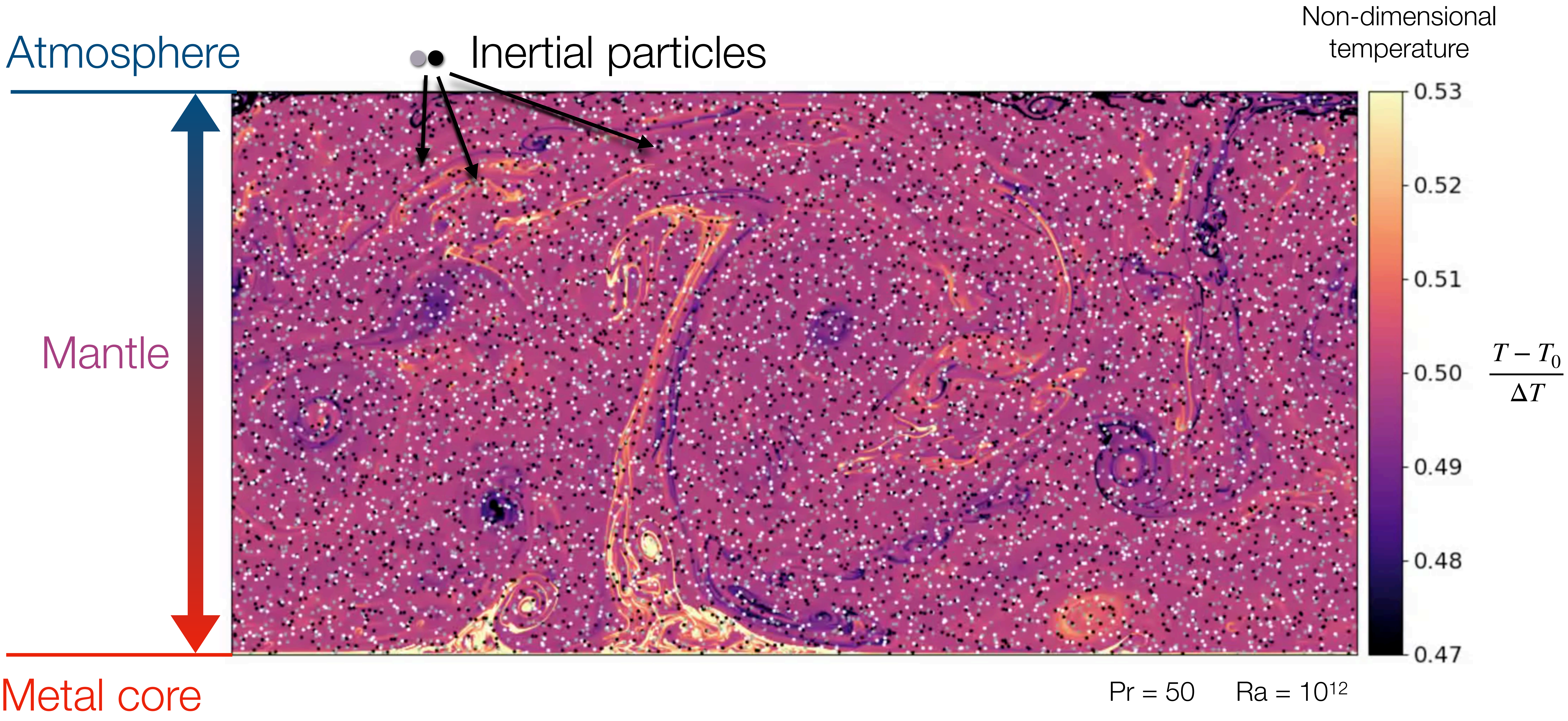
Require:

- Mixing: atmosphere-mantle
- Mixing: mantle-core

?



Particle settling in turbulent convection



Atmosphere

●● Inertial particles

Non-dimensional temperature

Mantle

Metal core

$$\frac{T - T_0}{\Delta T}$$

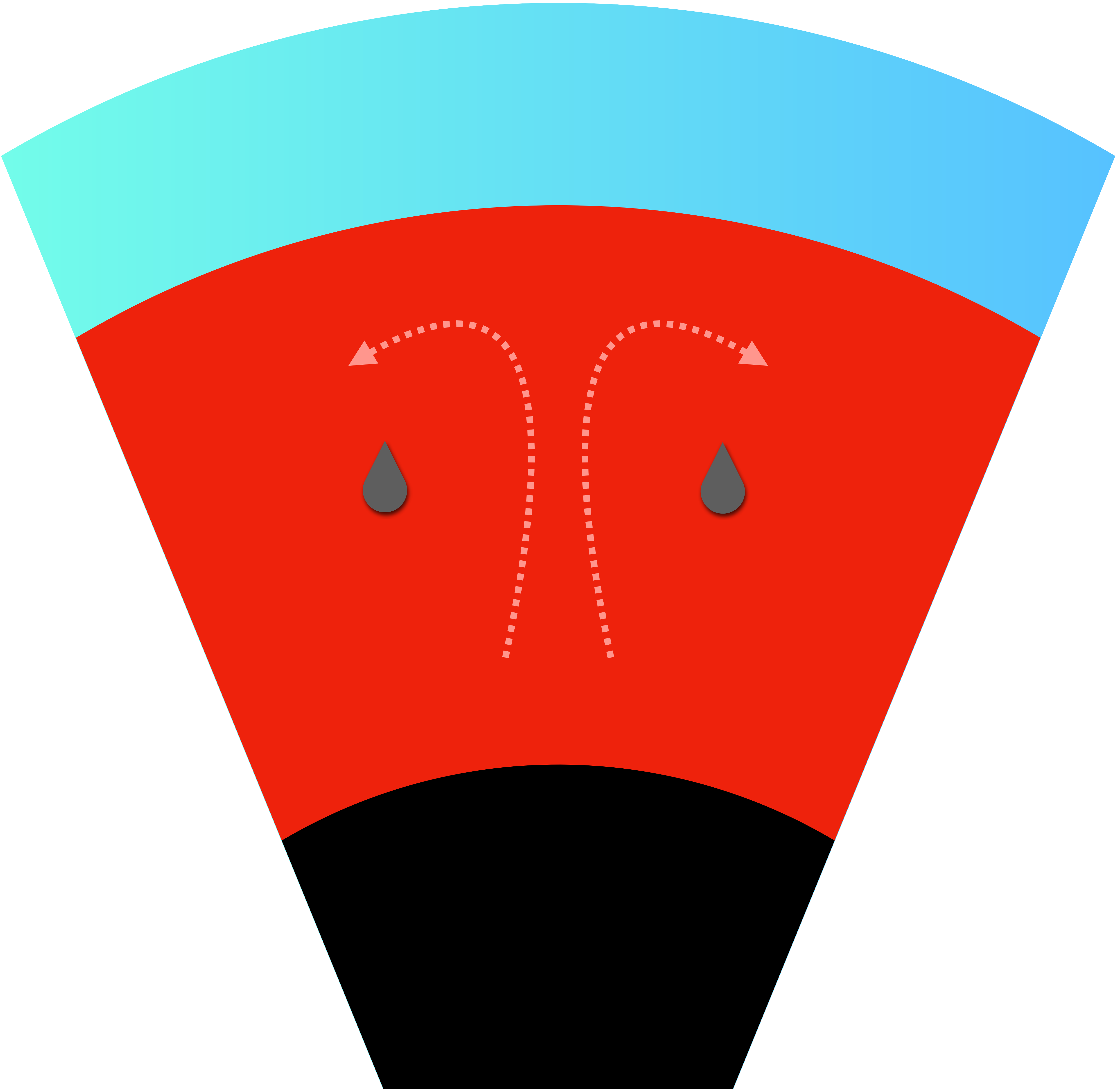
$Pr = 50$ $Ra = 10^{12}$

Patočka+ 20, Phys. Rev. Fluids

Turbulent convection in sub-Neptunes

Magma ocean depth

$$\mathrm{Ra} = \frac{\alpha \rho g \Delta T \boxed{D^3}}{\kappa \eta}$$



Turbulent convection in sub-Neptunes

Expected iron droplet sizes

Surface energy

Weber number

$$d_{\mathrm{droplet}} \approx \frac{\sigma \cdot \mathrm{We}}{\Delta\rho \cdot v_{\mathrm{magma}}^2}$$

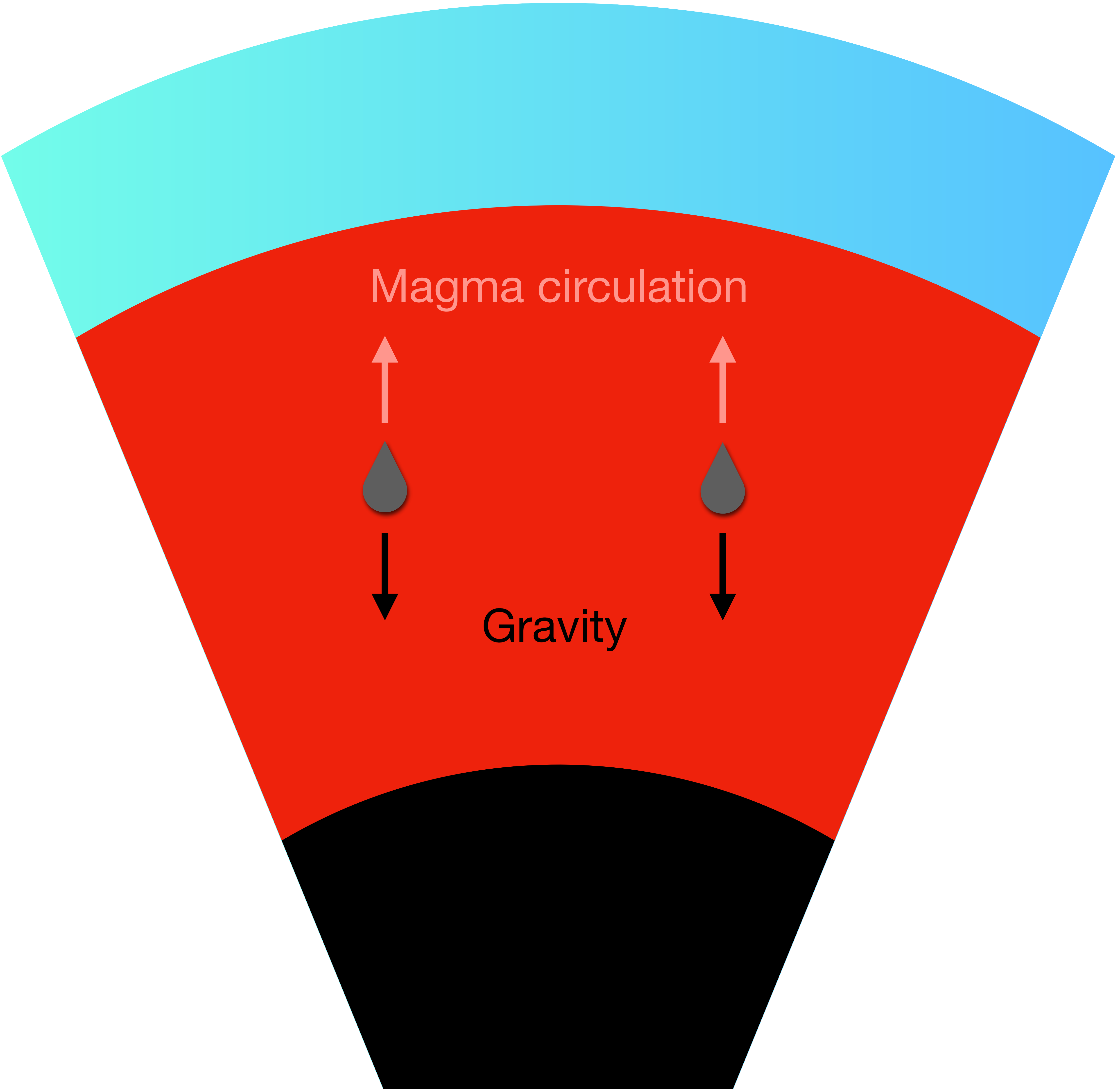
Iron-magma density difference

Fluid velocity

Size threshold for suspension

Magma density

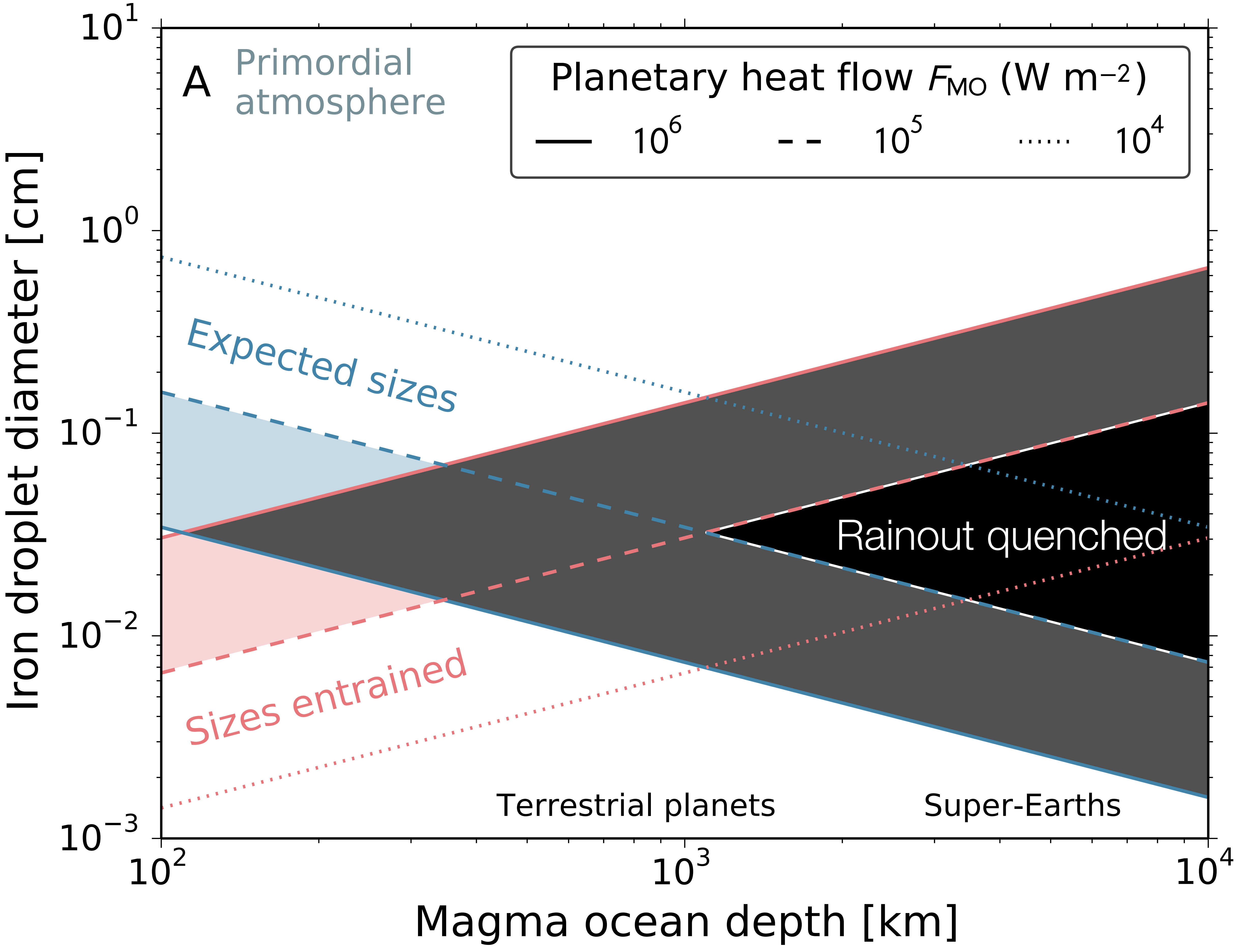
$$d_{\mathrm{crit}} \lesssim \frac{\rho_{\mathrm{magma}}(v_{\mathrm{magma}}/60)^2}{0.1\Delta\rho \cdot g}$$

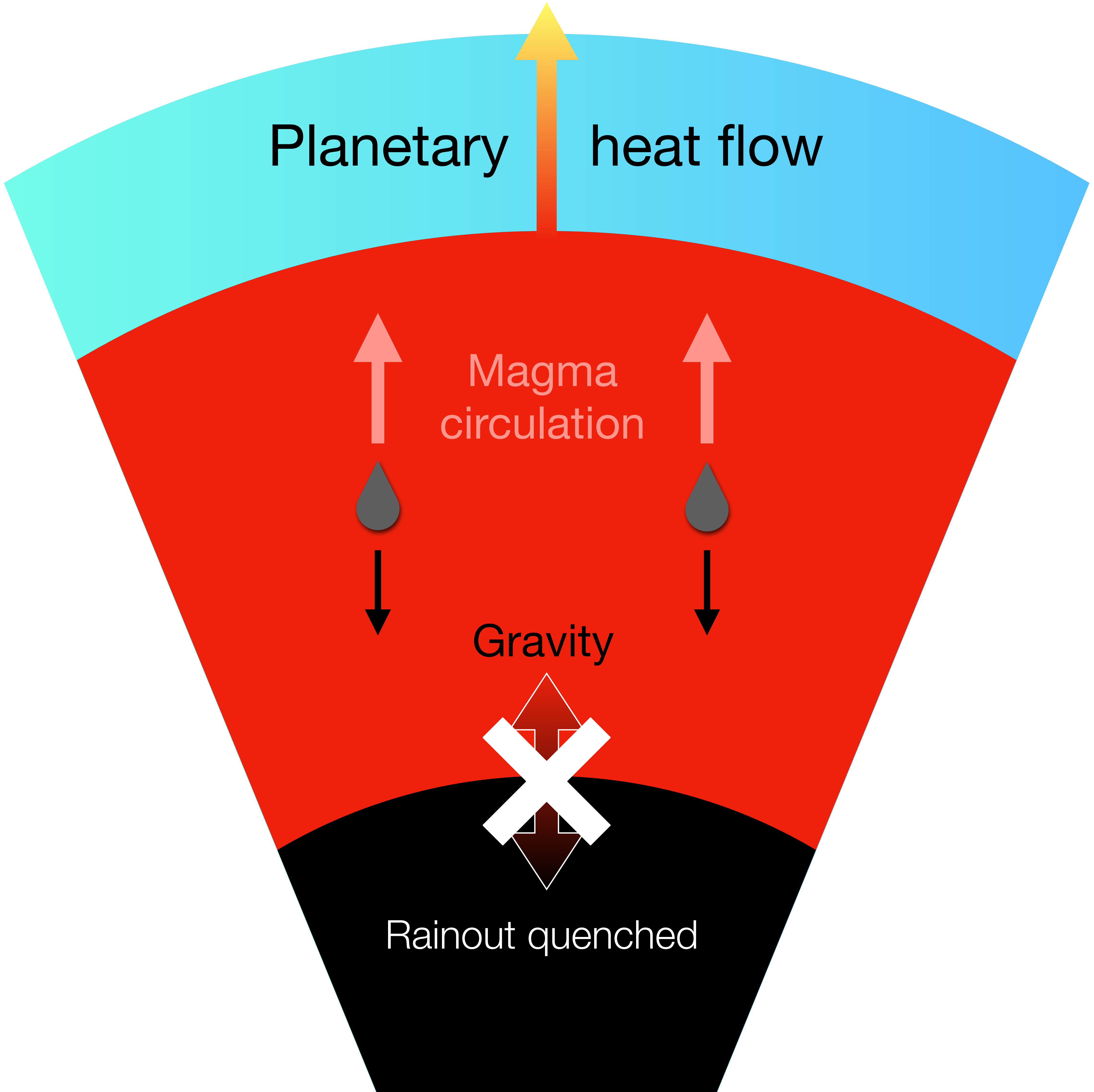


Rubie+ 03, Solomatov 15

Rainout quenching in sub-Neptune interiors

d_{droplet} **vs.** d_{crit}





Planetary heat flow

Magma circulation

Gravity

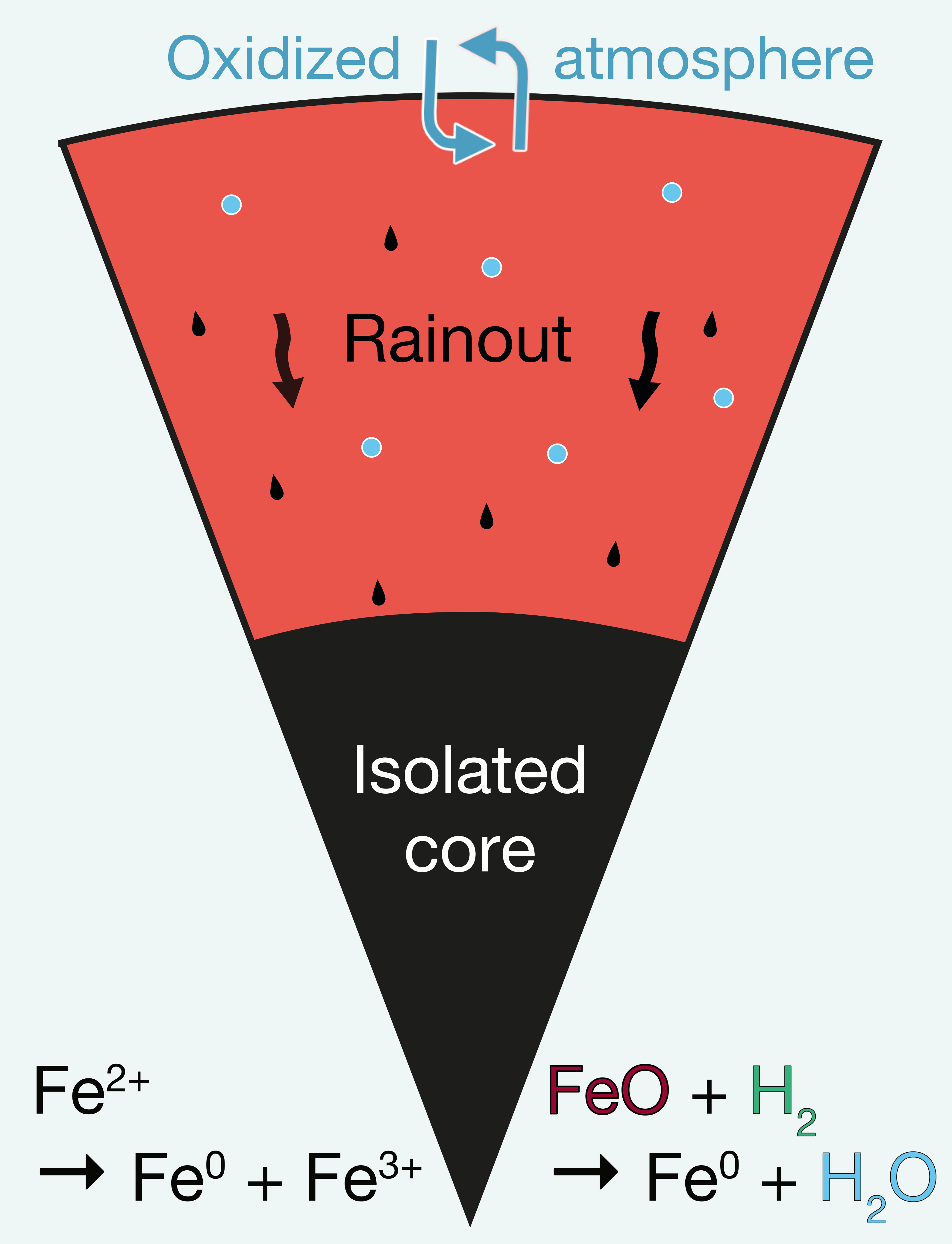
Rainout quenched

Magma circulation affects *thermal evolution*

H_2O
CO_2
SO_2

Oxidised surfaces

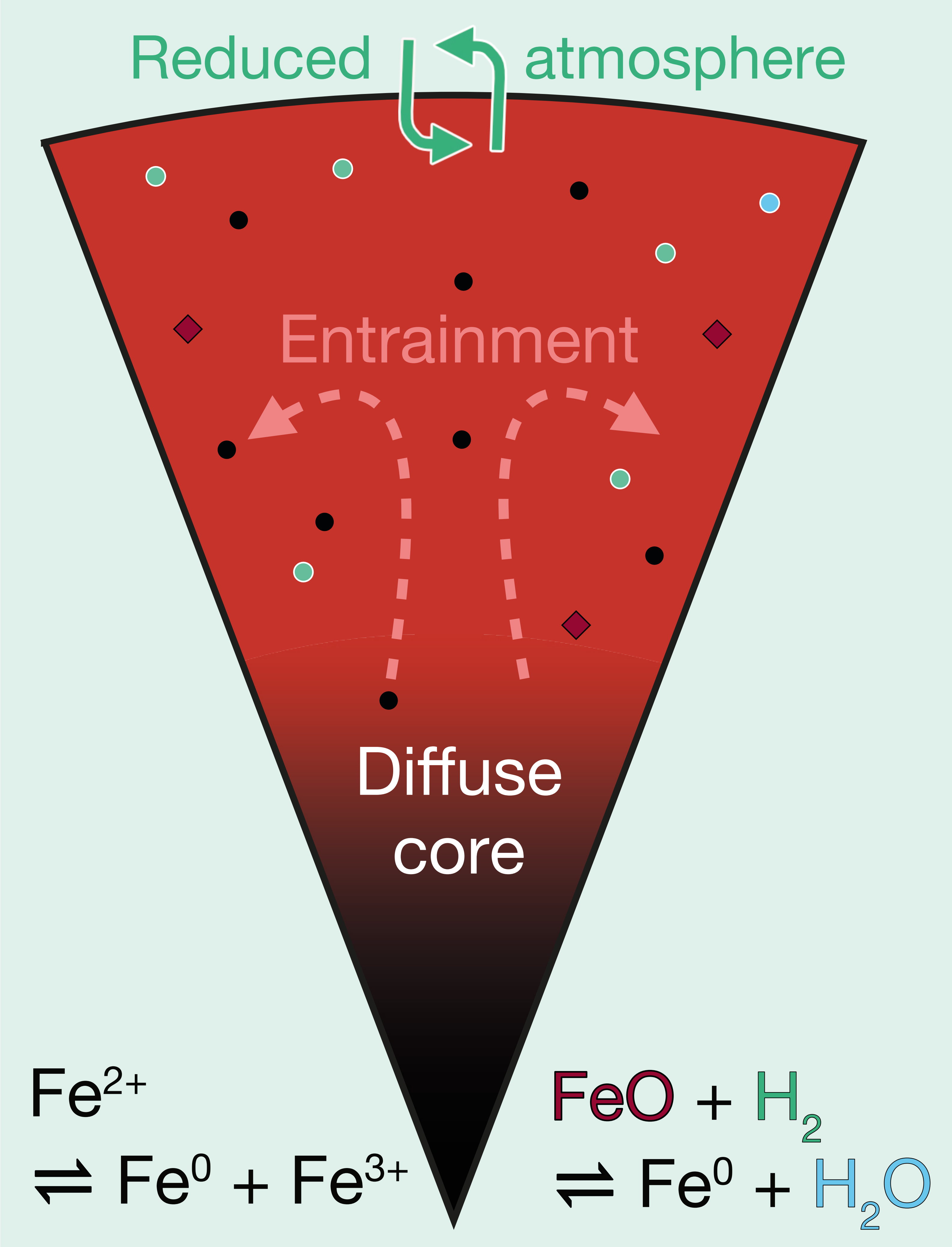
Prolongs magma ocean phase



$Fe^{2+} \rightarrow Fe^0 + Fe^{3+}$

$FeO + H_2 \rightarrow Fe^0 + H_2O$

(A) Mantle self-oxidation



$Fe^{2+} \rightleftharpoons Fe^0 + Fe^{3+}$

$FeO + H_2 \rightleftharpoons Fe^0 + H_2O$

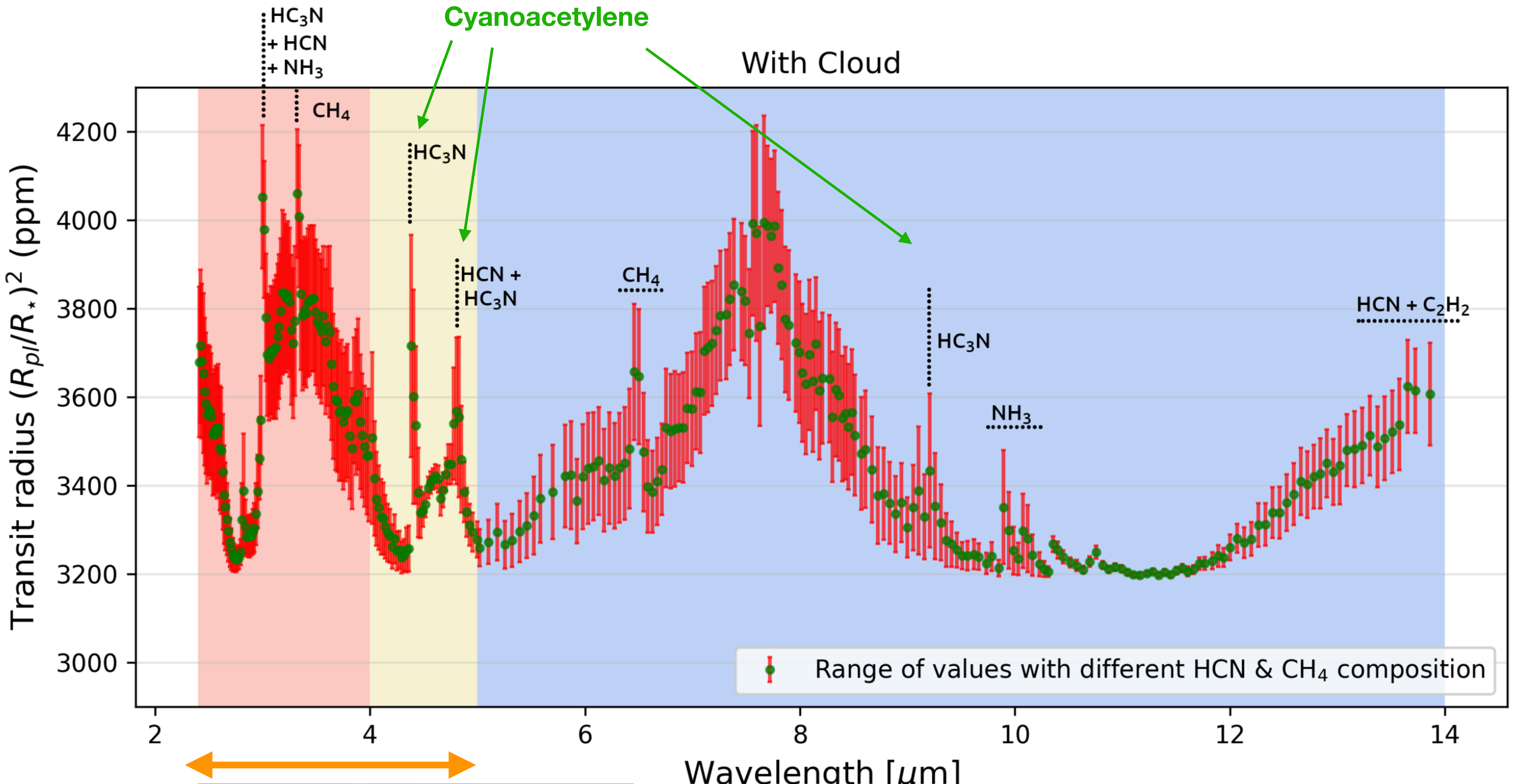
(B) Redox hysteresis

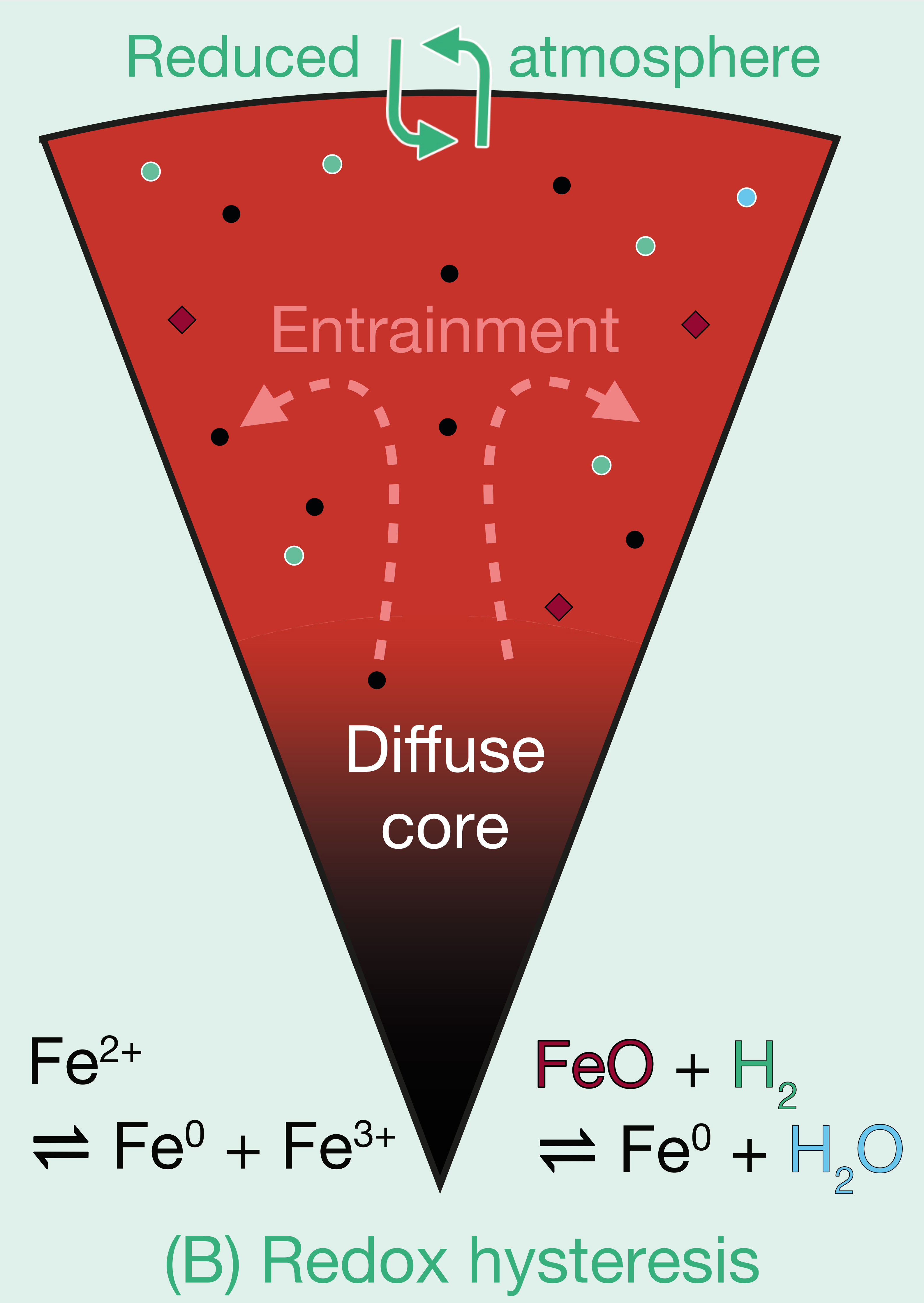
H_2
CO
CH_4

Reduced surfaces

Enhances chances for detection

Prebiotic chemistry on reduced super-Earths?





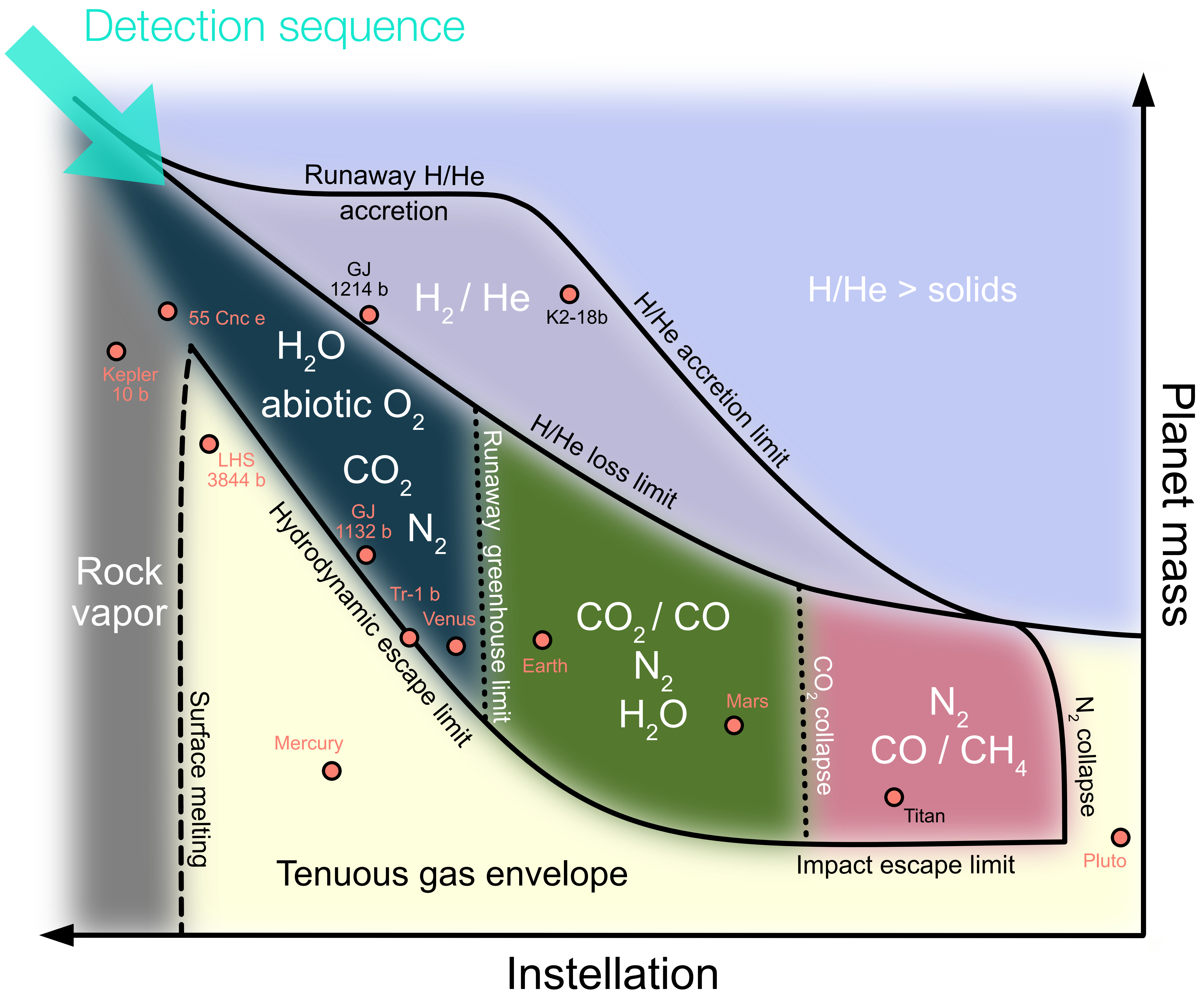
$Fe^{2+} \rightleftharpoons Fe^0 + Fe^{3+}$

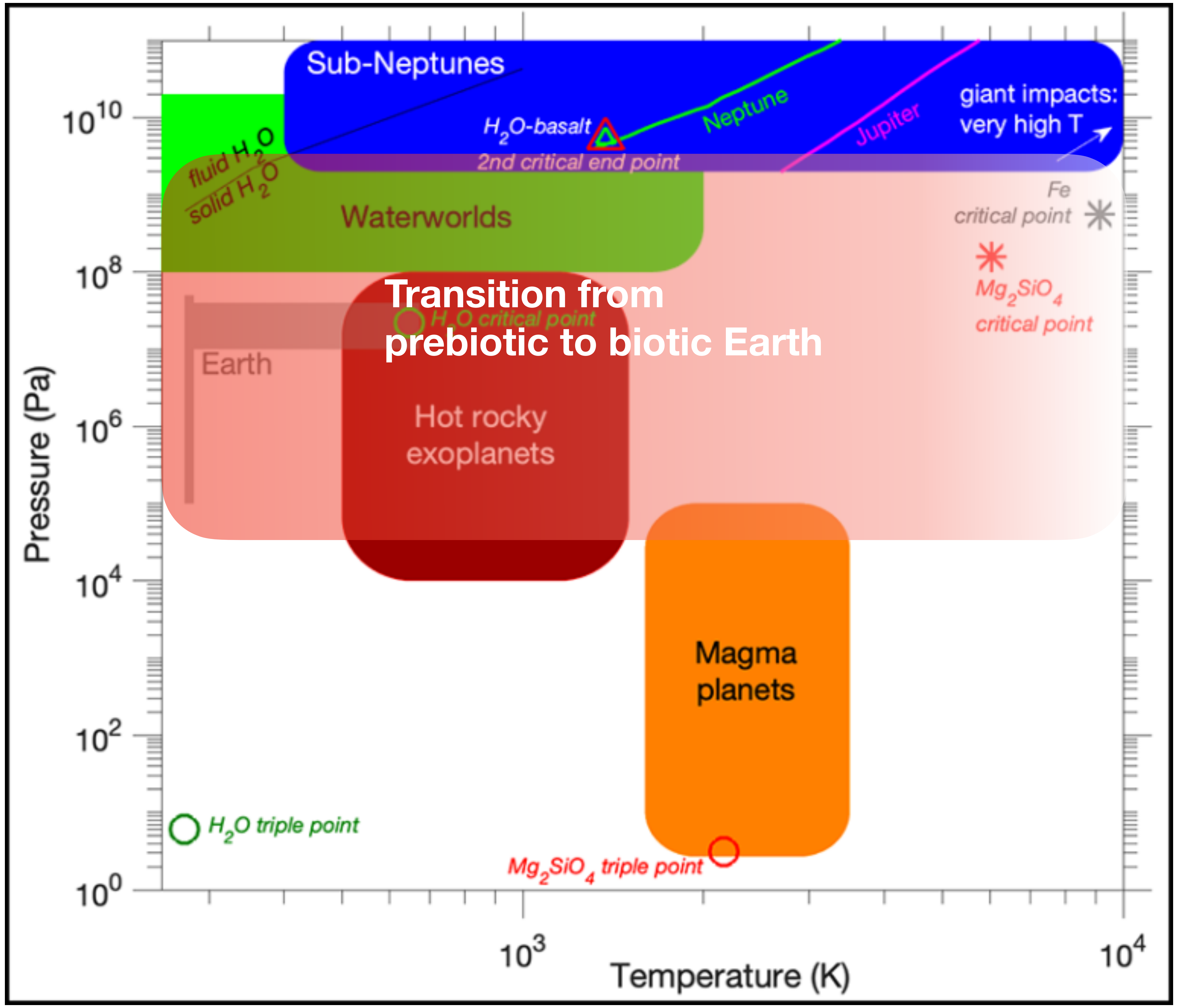
$FeO + H_2 \rightleftharpoons Fe^0 + H_2O$

(B) Redox hysteresis

Rimmer+ 21, *ApJL*

Exoplanets as a window into *climate diversity*



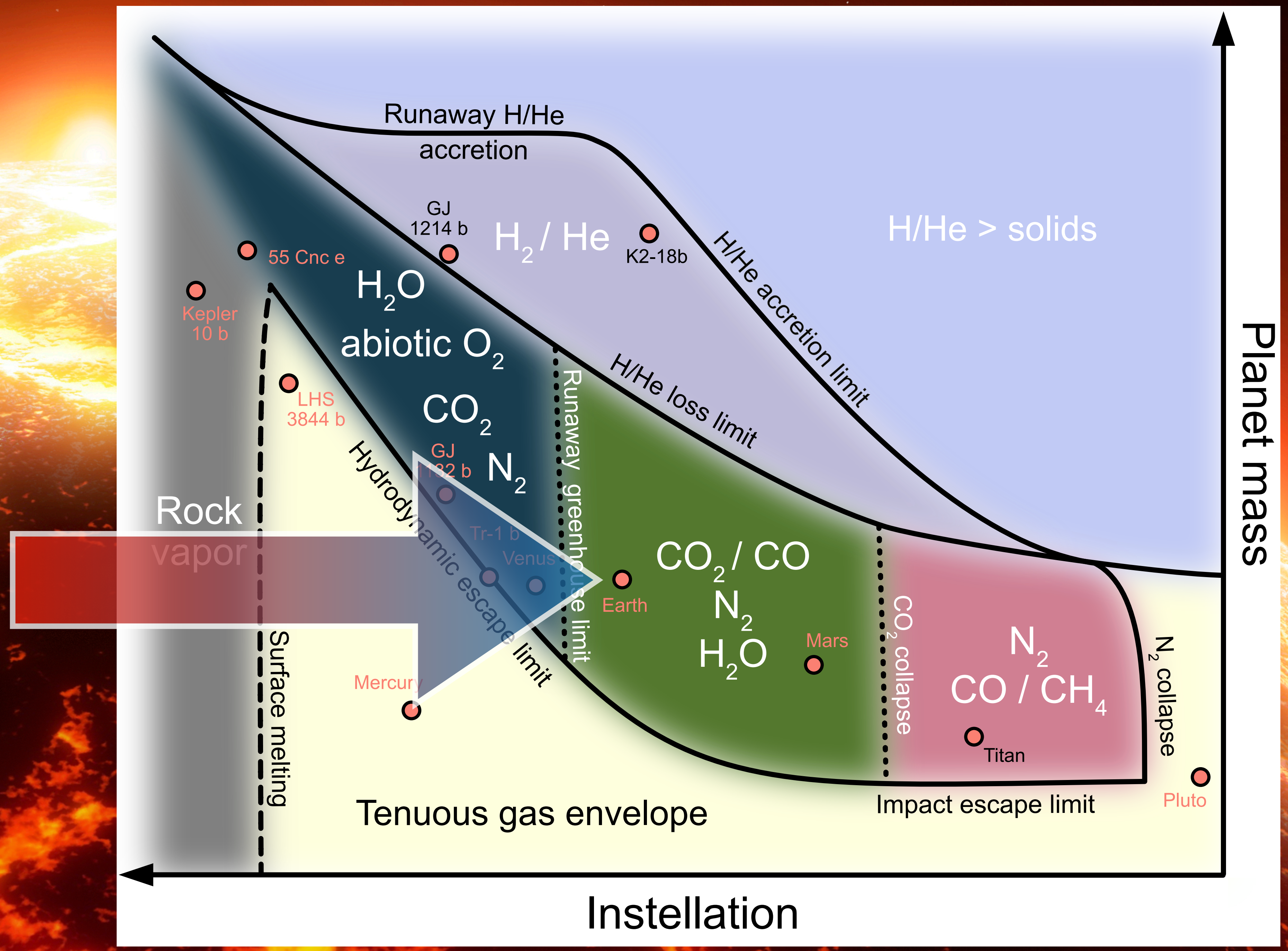


Lichtenberg, Schaefer, Nakajima, Fischer 2022, *Protostars & Planets VII*

Kite, Kreidberg+ 21, Eos

Geophysical evolution during rocky planet formation

- Timing of formation alters geophysics internal processing
- Geophysical evolution leads to order of magnitude fractionation in volatile content
- Magma ocean atmospheres are key to decipher climate diversity



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