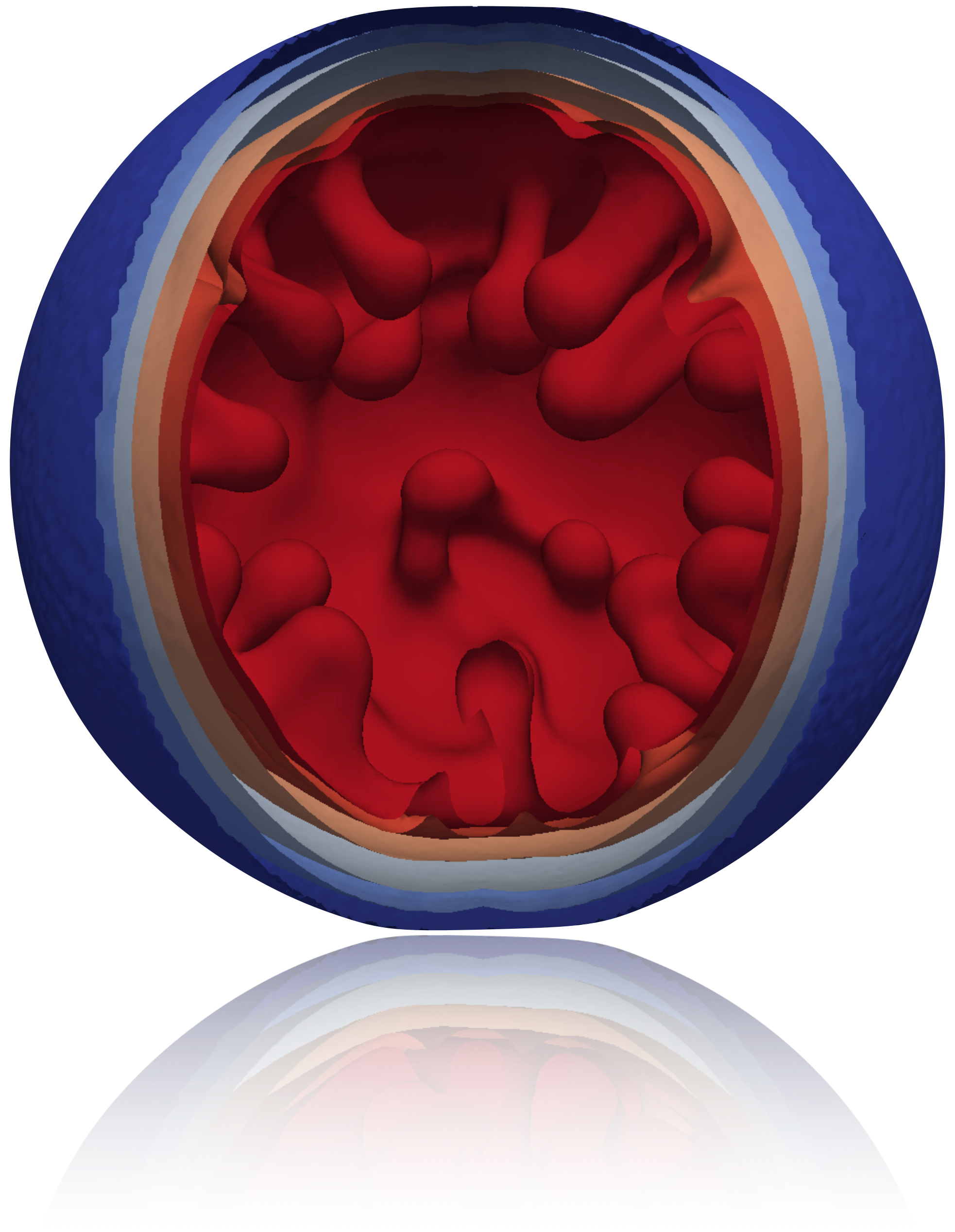
Geophysical evolution during rocky planet formation

Tim Lichtenberg



ETH Zurich: Taras Gerya, Maria Schönbächler, Sascha Quanz, Patrick Sanan; **U Bern**: Dan Bower, Yann Alibert, Christoph Mordasini, Remo Burn

U Oxford: Mark Hammond, Shang-Min Tsai, Raymond Pierrehumbert
BGI Bayreuth: Gregor Golabek
U Michigan: Michael Meyer
U Sheffield: Richard Parker

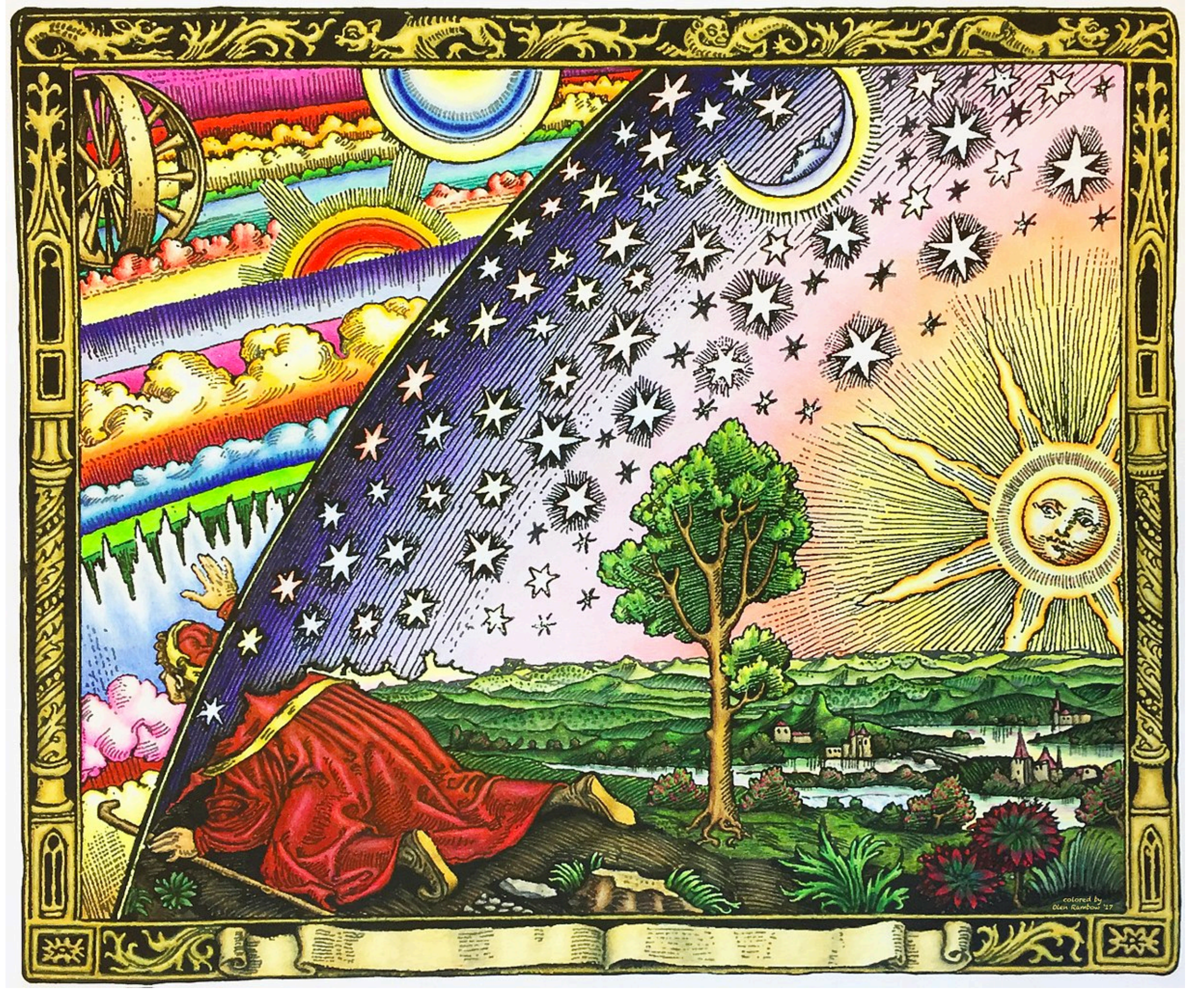
LMU Munich: Joanna Drążkowska
ELSI/Tokyo Tech: Irene Bonati
U Zurich: Tom Hands, Miles Timpe
U Heidelberg: Kees Dullemond

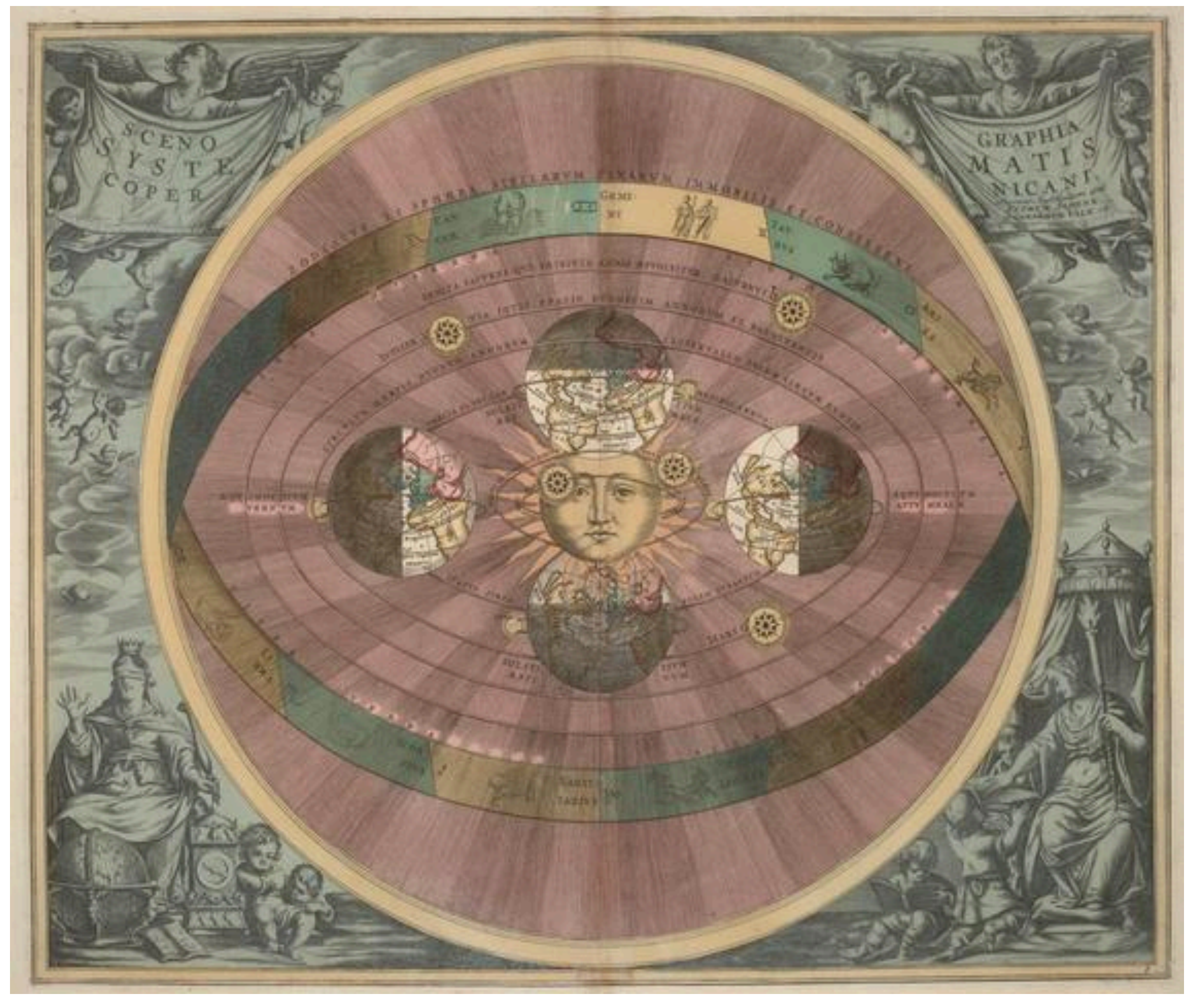
UNIVERSITY OF OXFORD

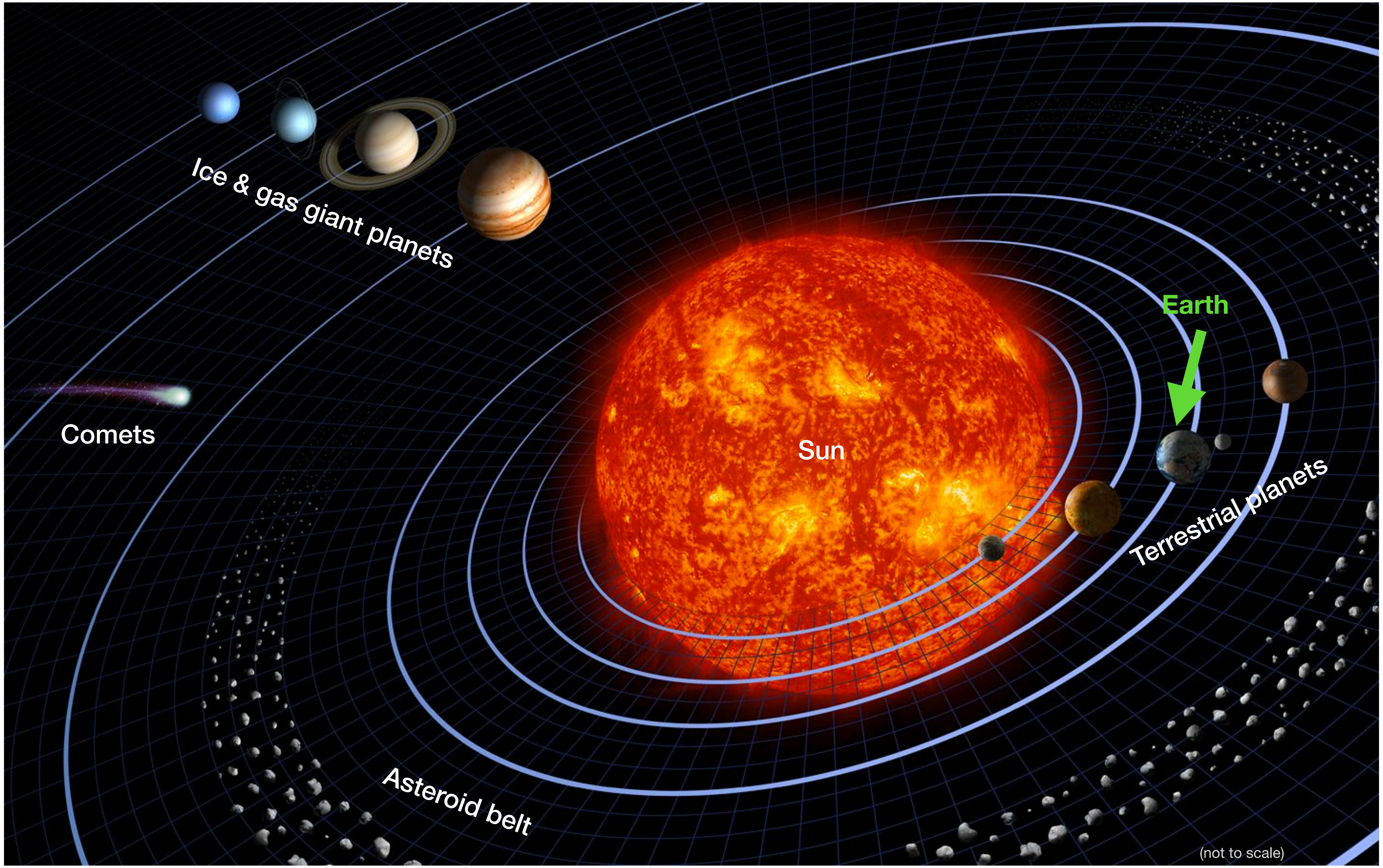
SIMONS FOUNDATION

Origins Institute, McMaster University, Hamilton, 8 November 2019

The Solar System: our home in the universe





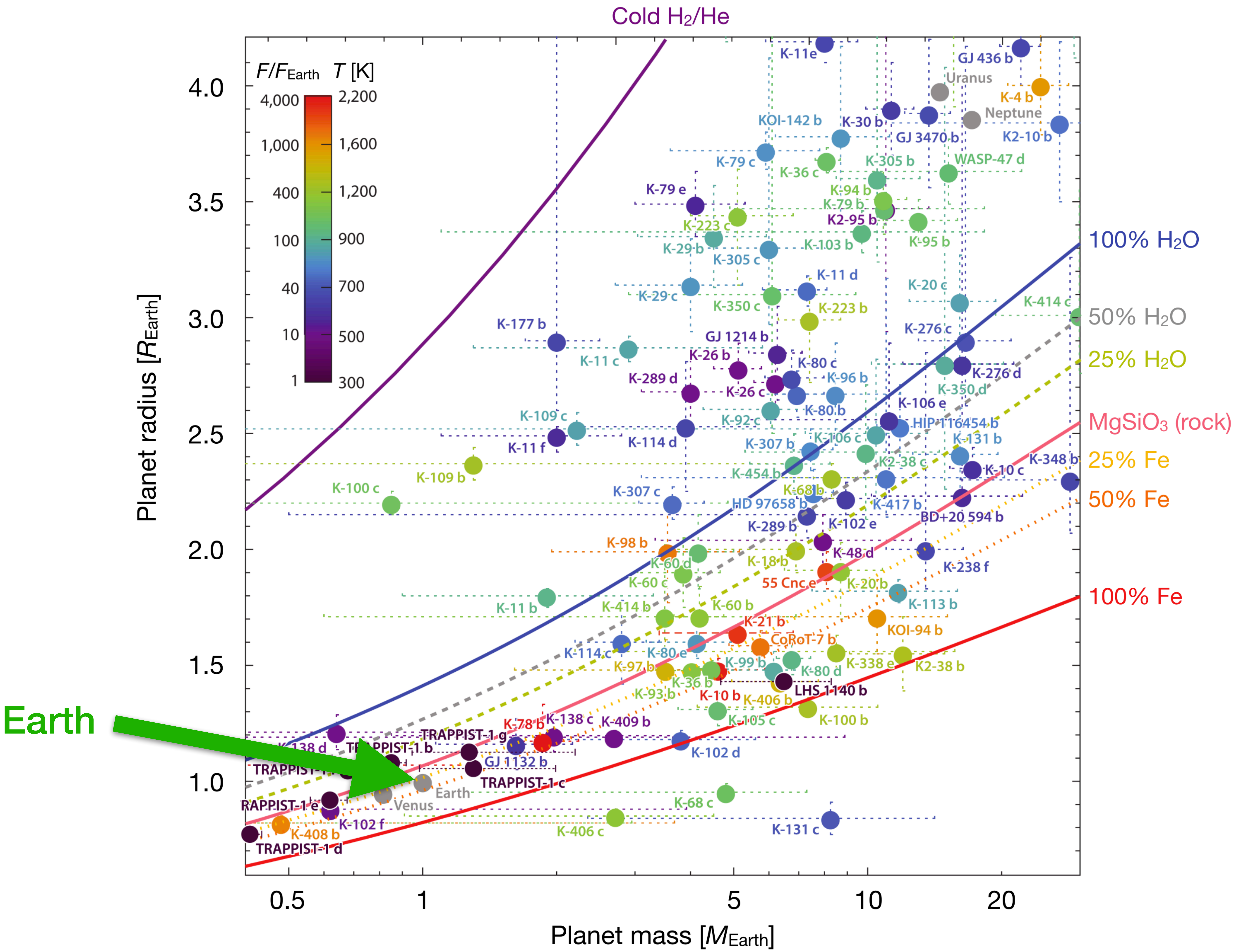


Harmonia Macrocosmica; L'atmosphère: météorologie populaire

NASA/JPL-Caltech

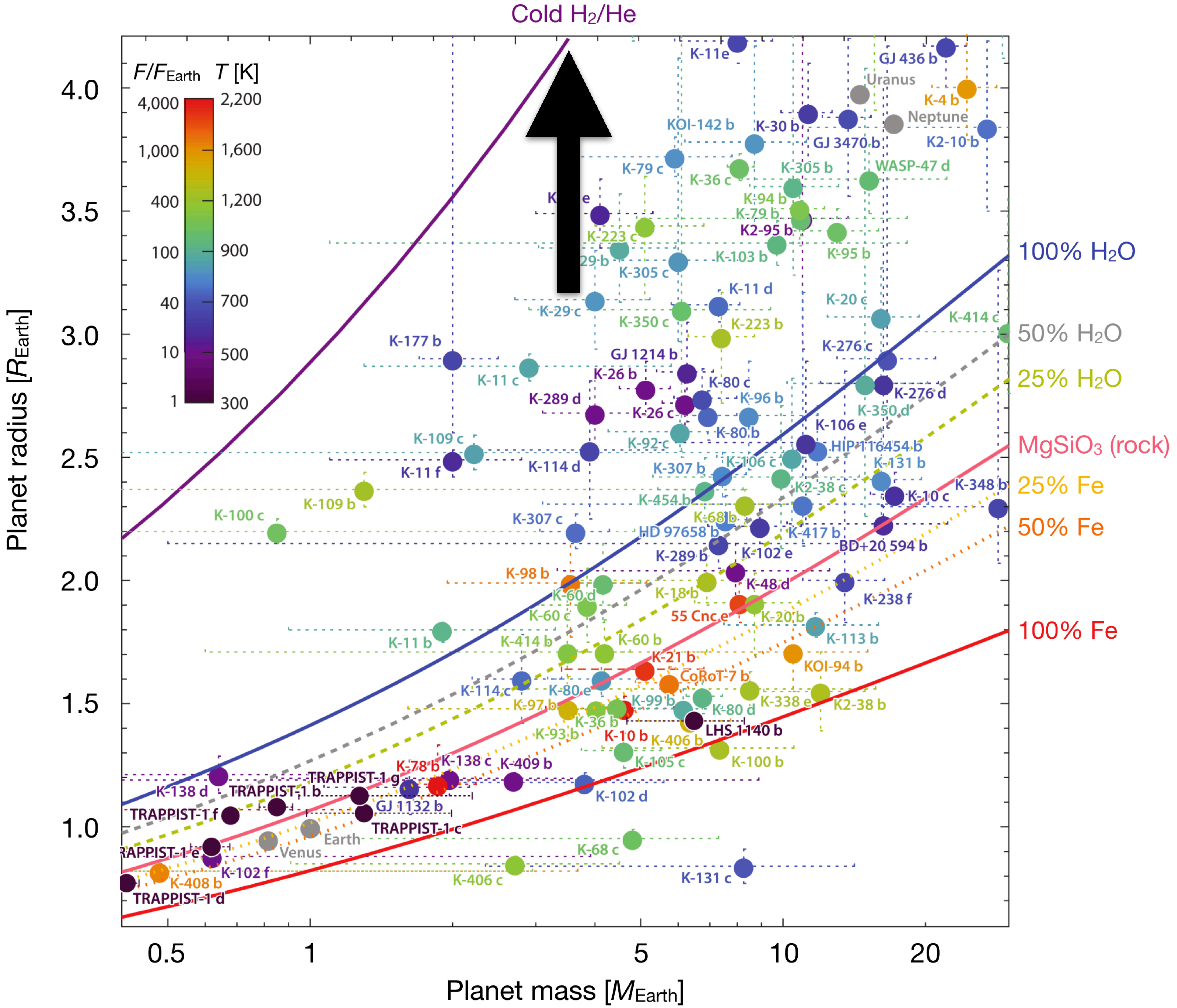
ESO/M. Kornmesser

Exoplanet diversity

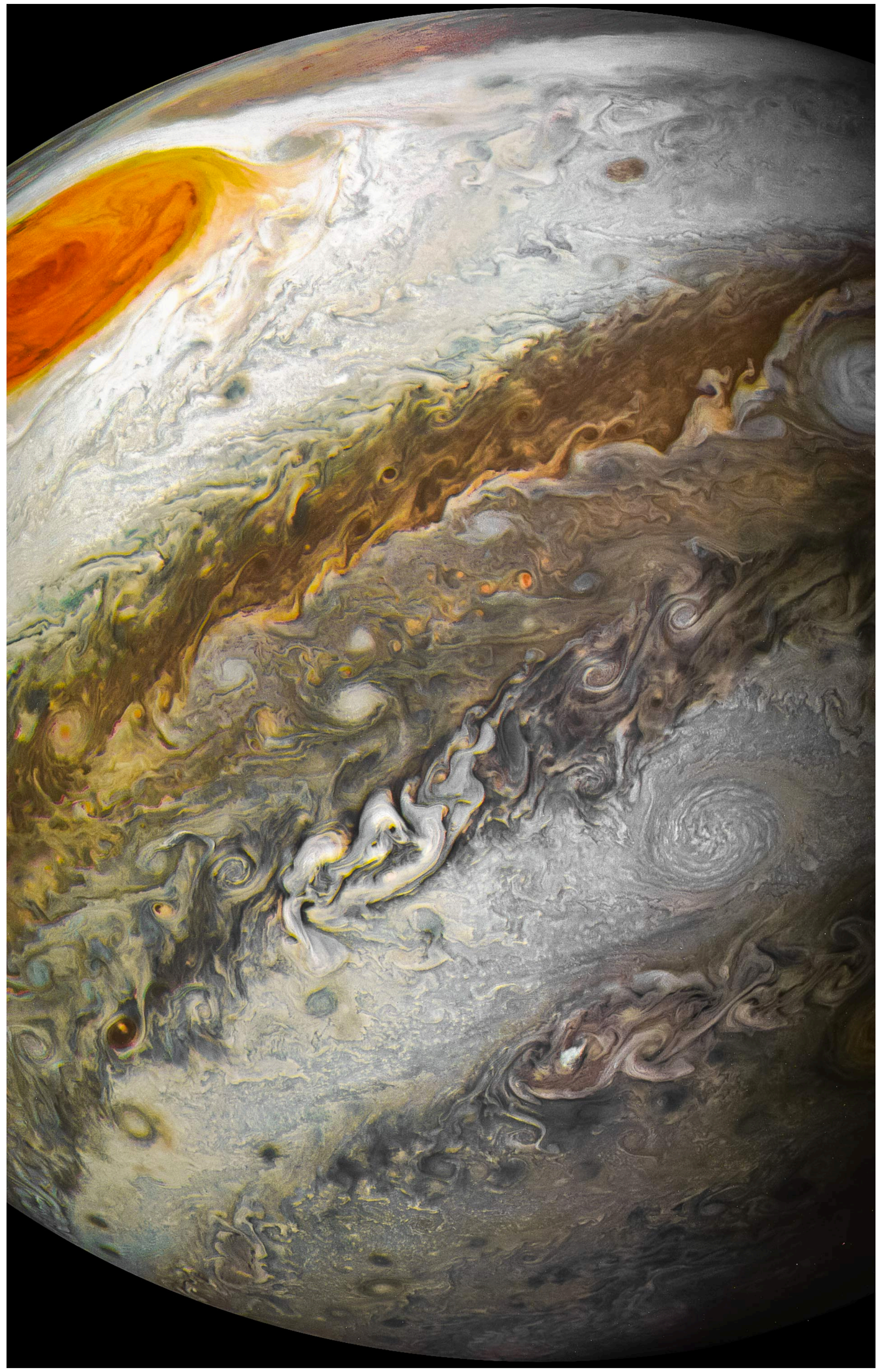


Modified from Kaltenegger 17

Planet composition



Jupiter-like

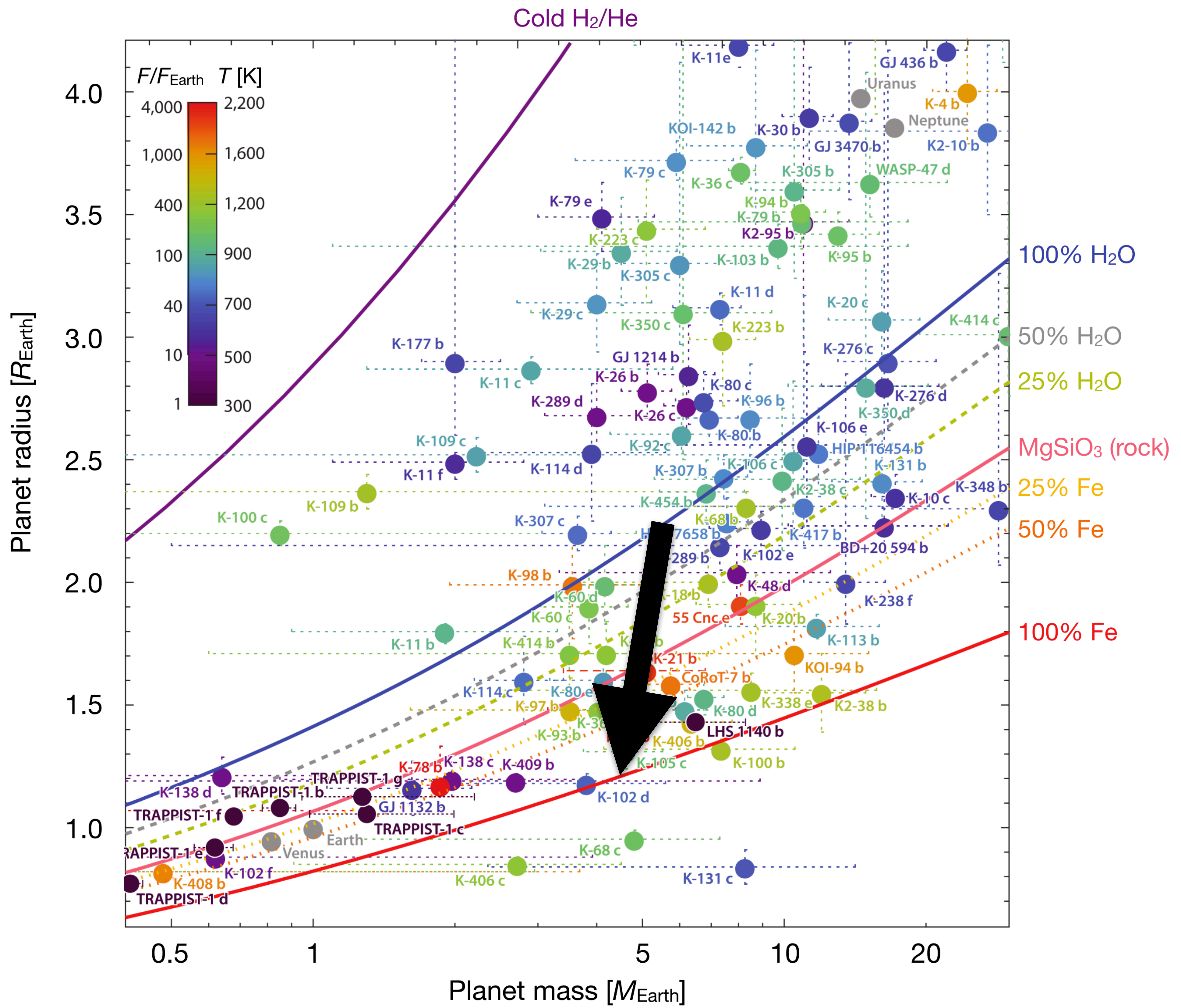


H₂/He

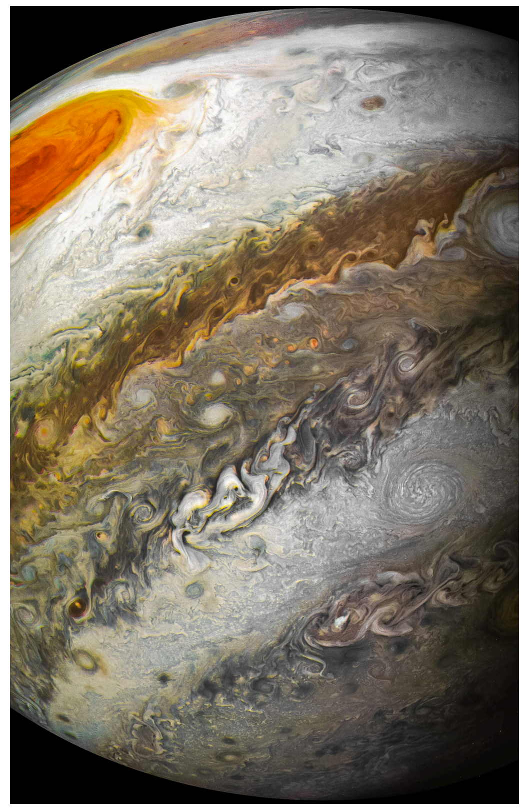
Modified from Kaltenegger 17

NASA/JPL-Caltech

Planet composition



Mercury-like

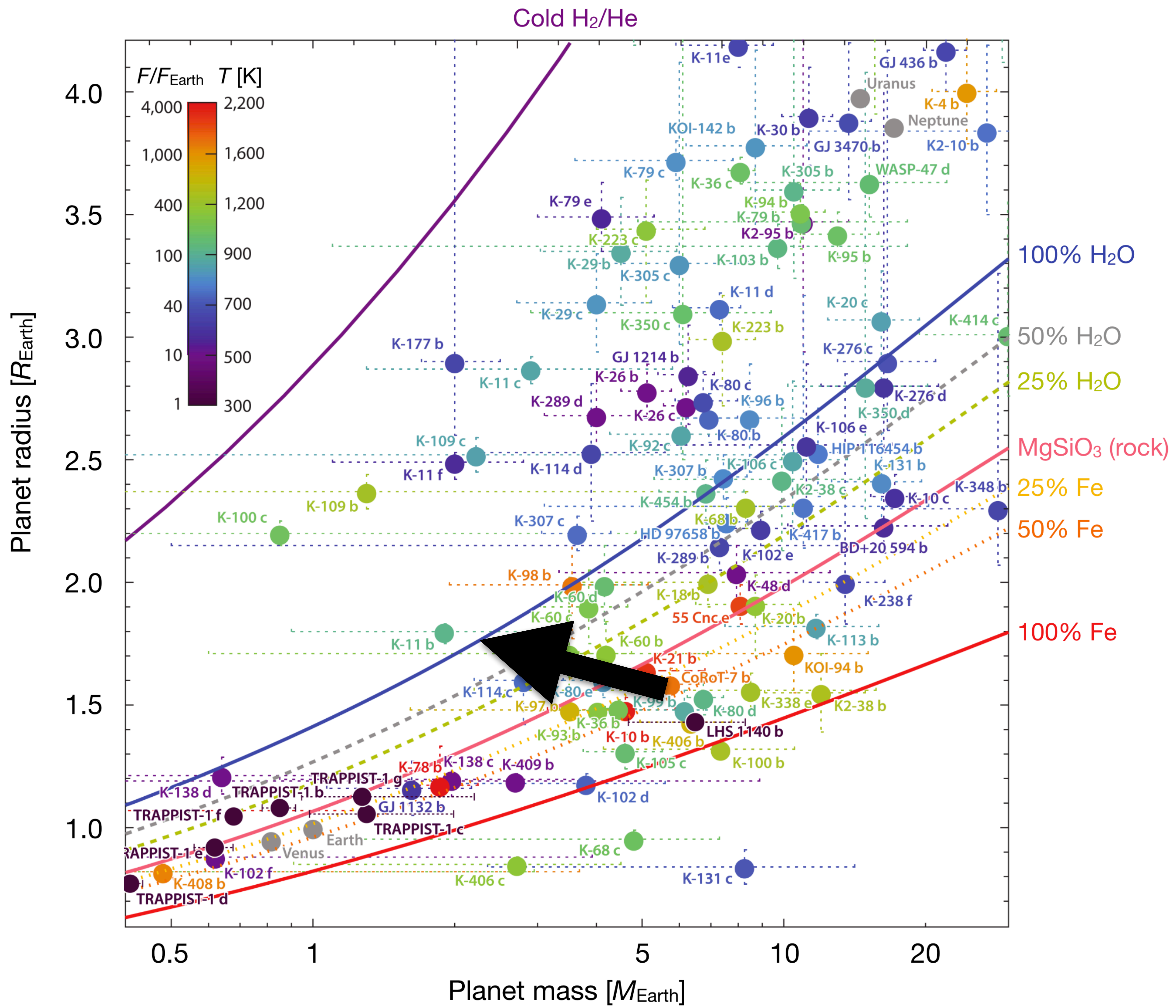


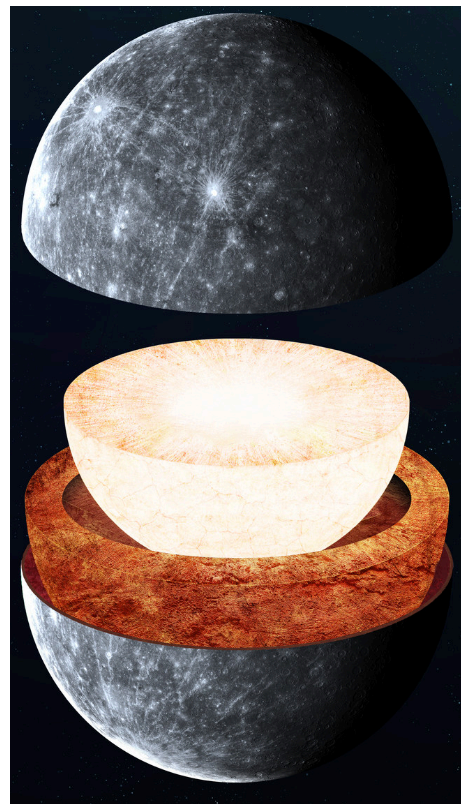
H_2/He

Modified from Kaltenegger 17

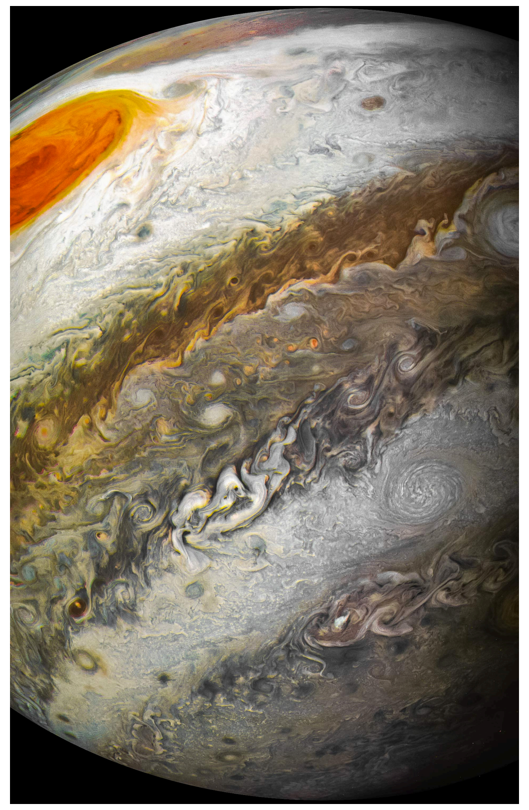
Vadim Sadovski; NASA/JPL-Caltech

Planet composition

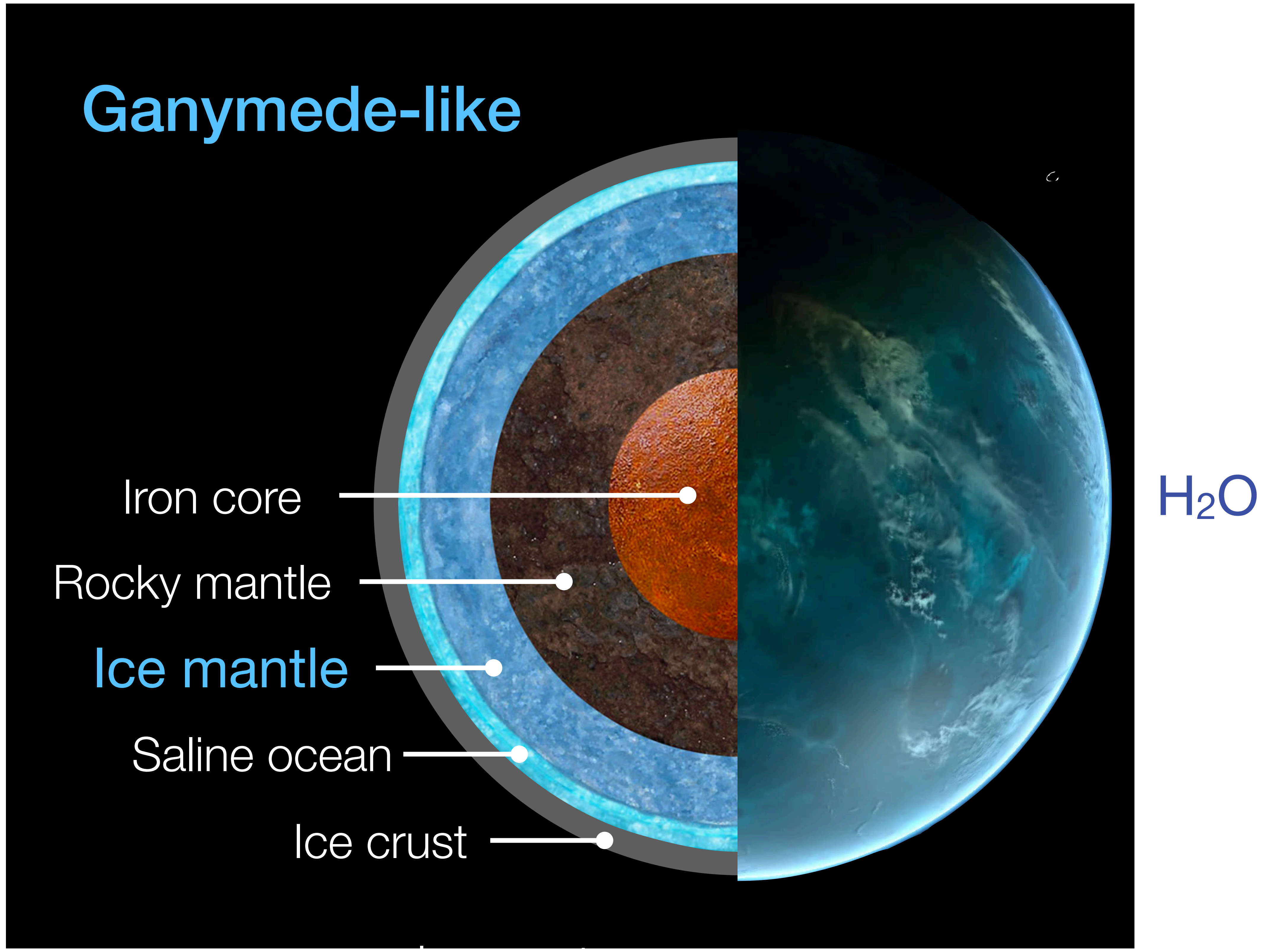




Si+Fe



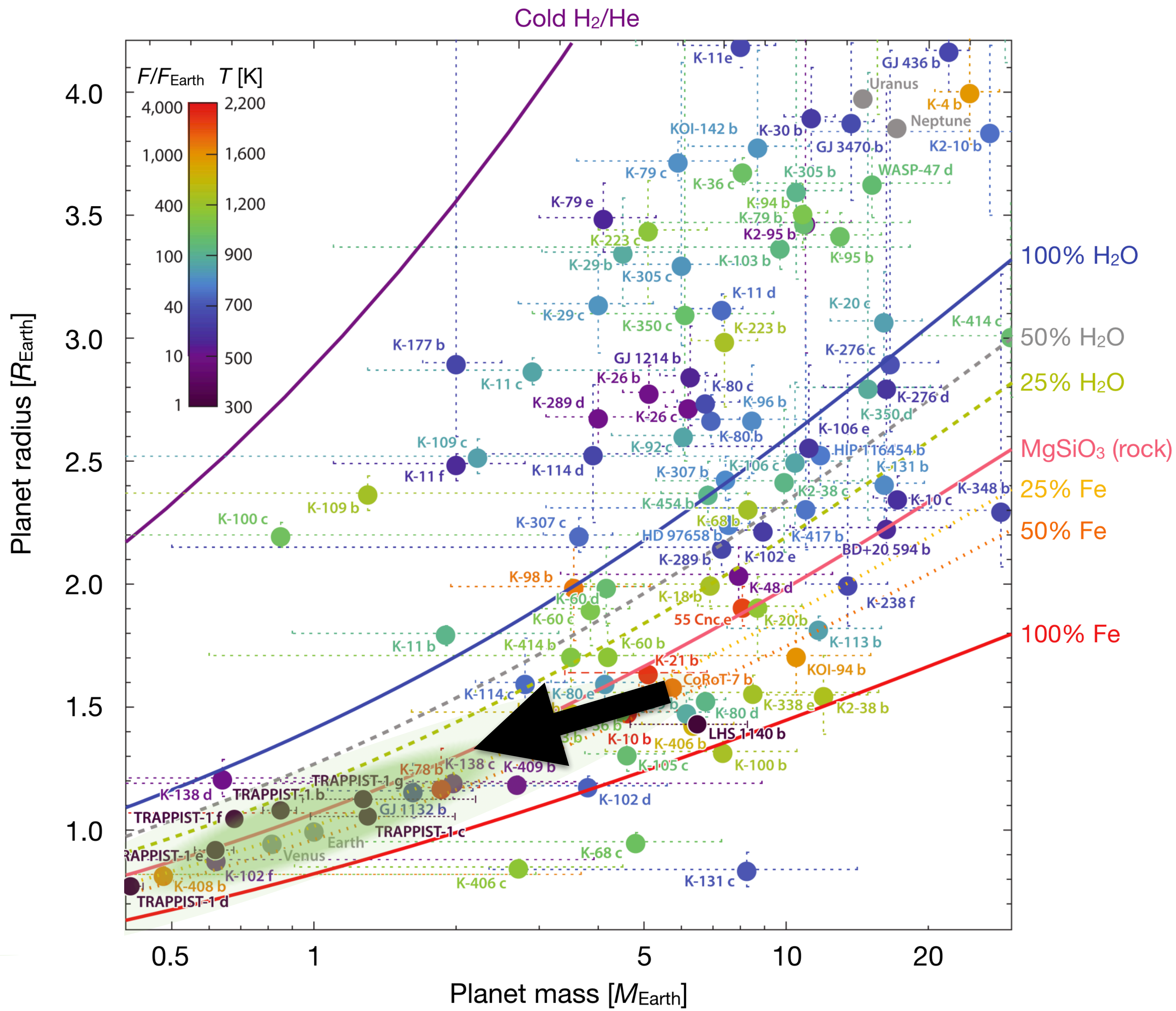
H2/He

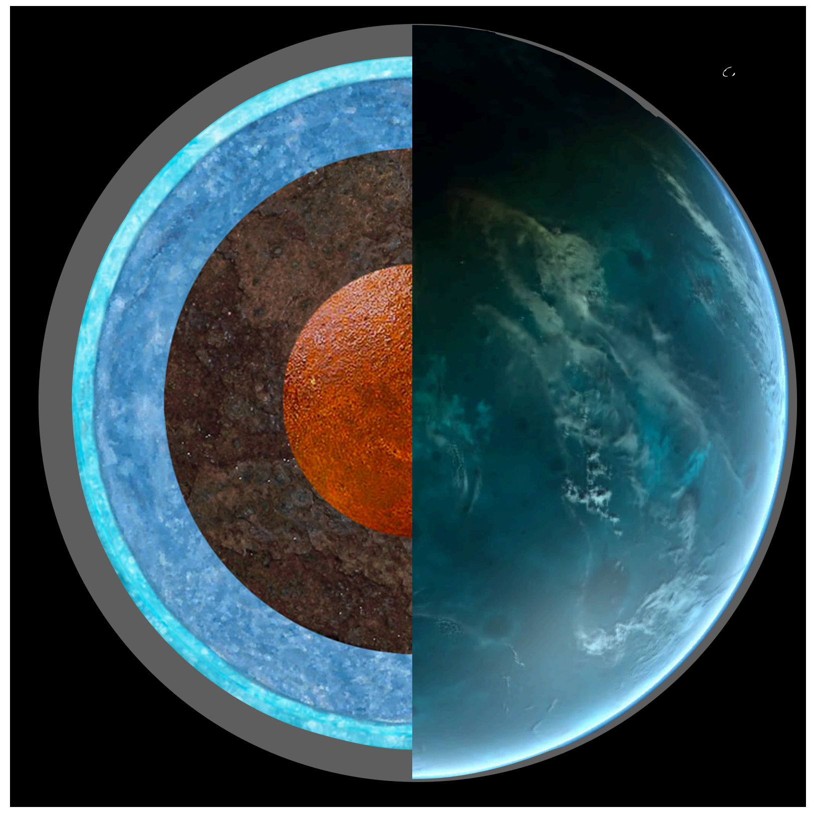


Modified from Kaltenegger 17

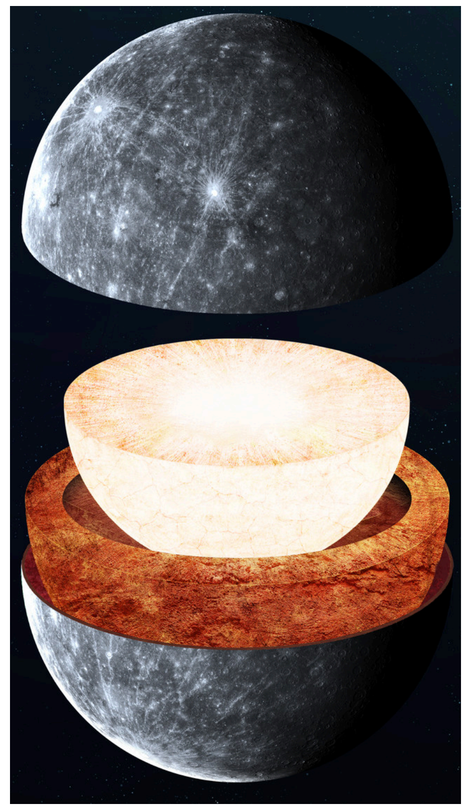
Vadim Sadovski; NASA/JPL-Caltech

Planet composition

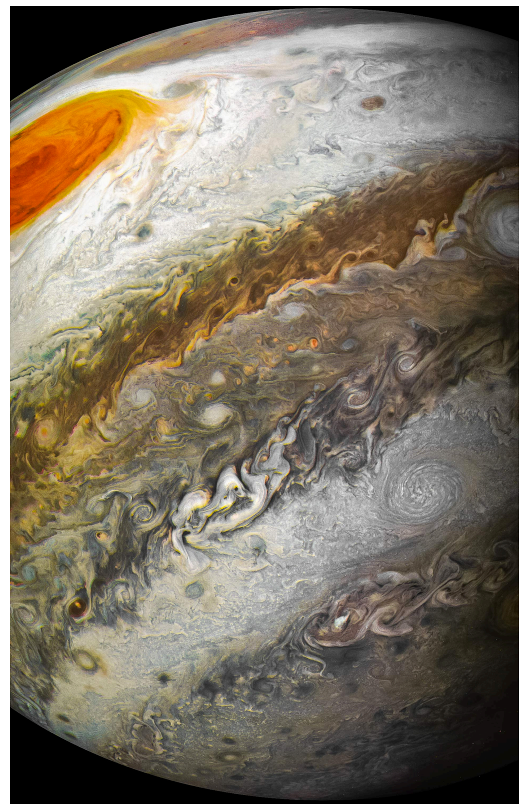




H_2O



Si+Fe



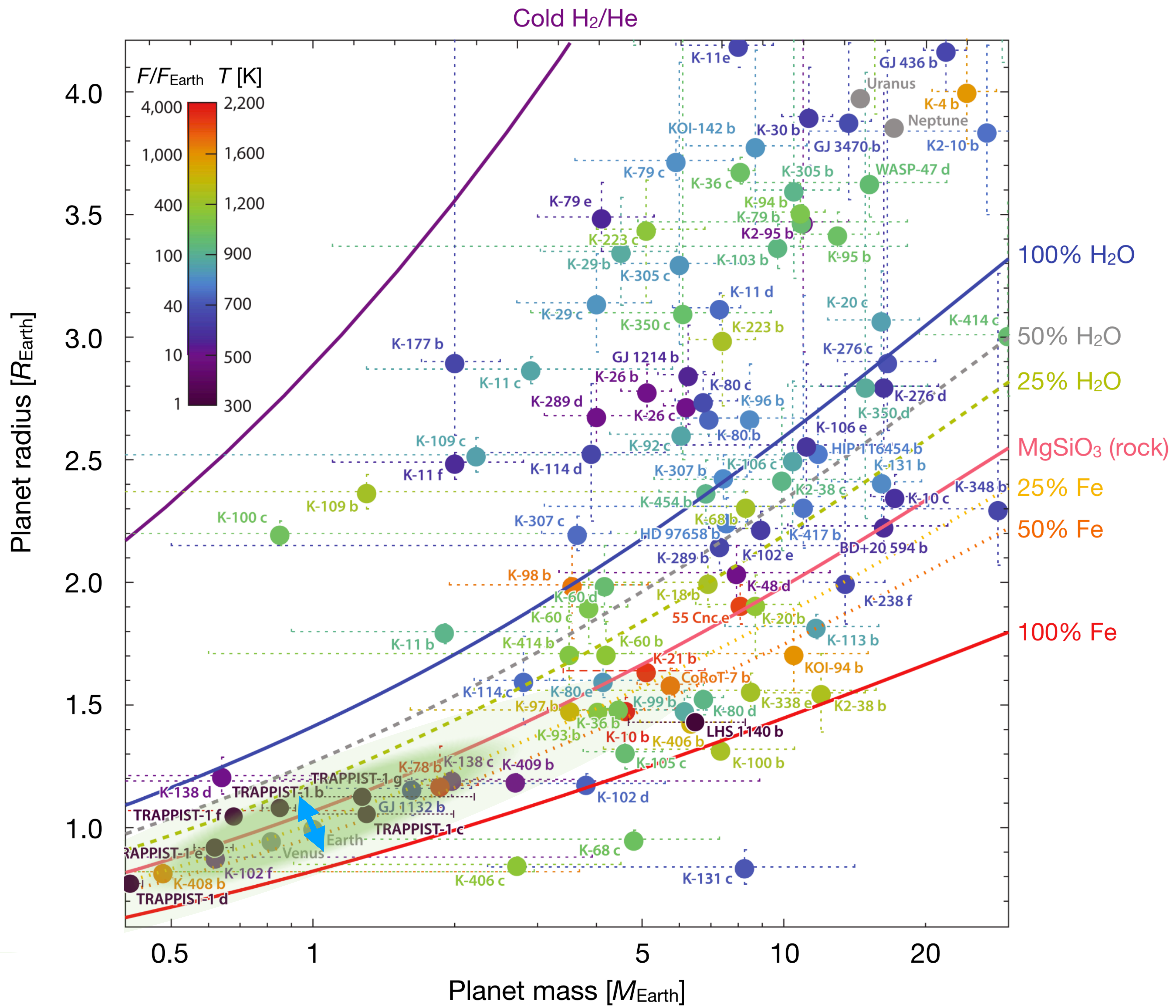
H_2/He

‘Earth-like’ mixture

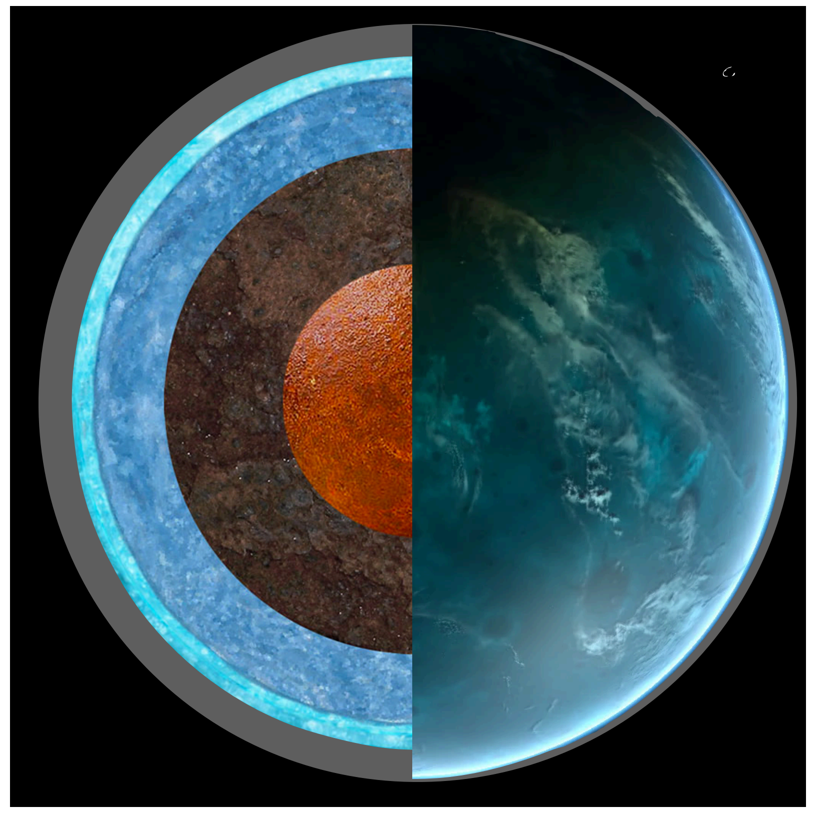
Modified from Kaltenegger 17

Meyer+ 08; Vadim Sadovski; NASA/JPL-Caltech

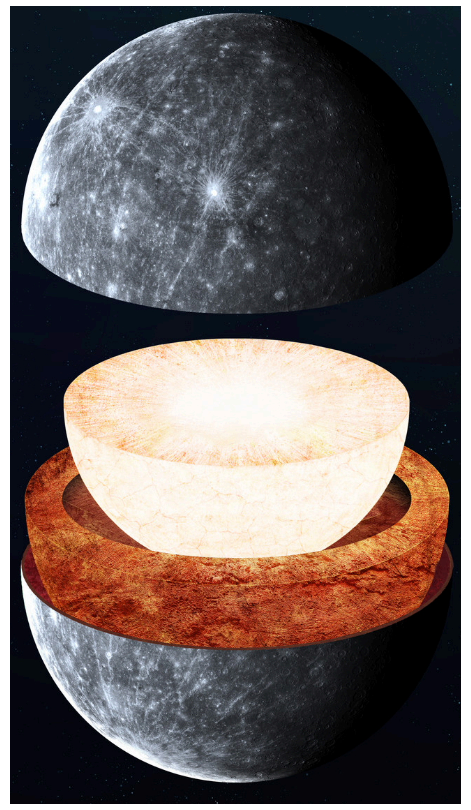
Volatile ‘oversaturation’?



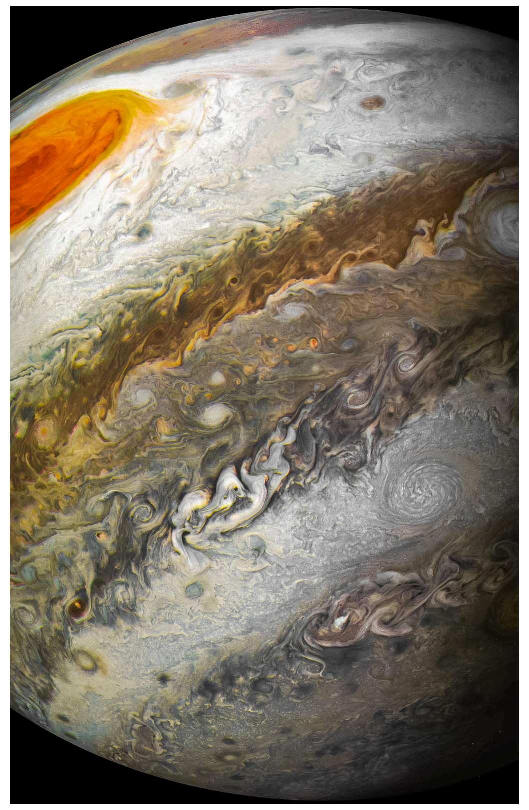
Modified from Kaltenegger 17



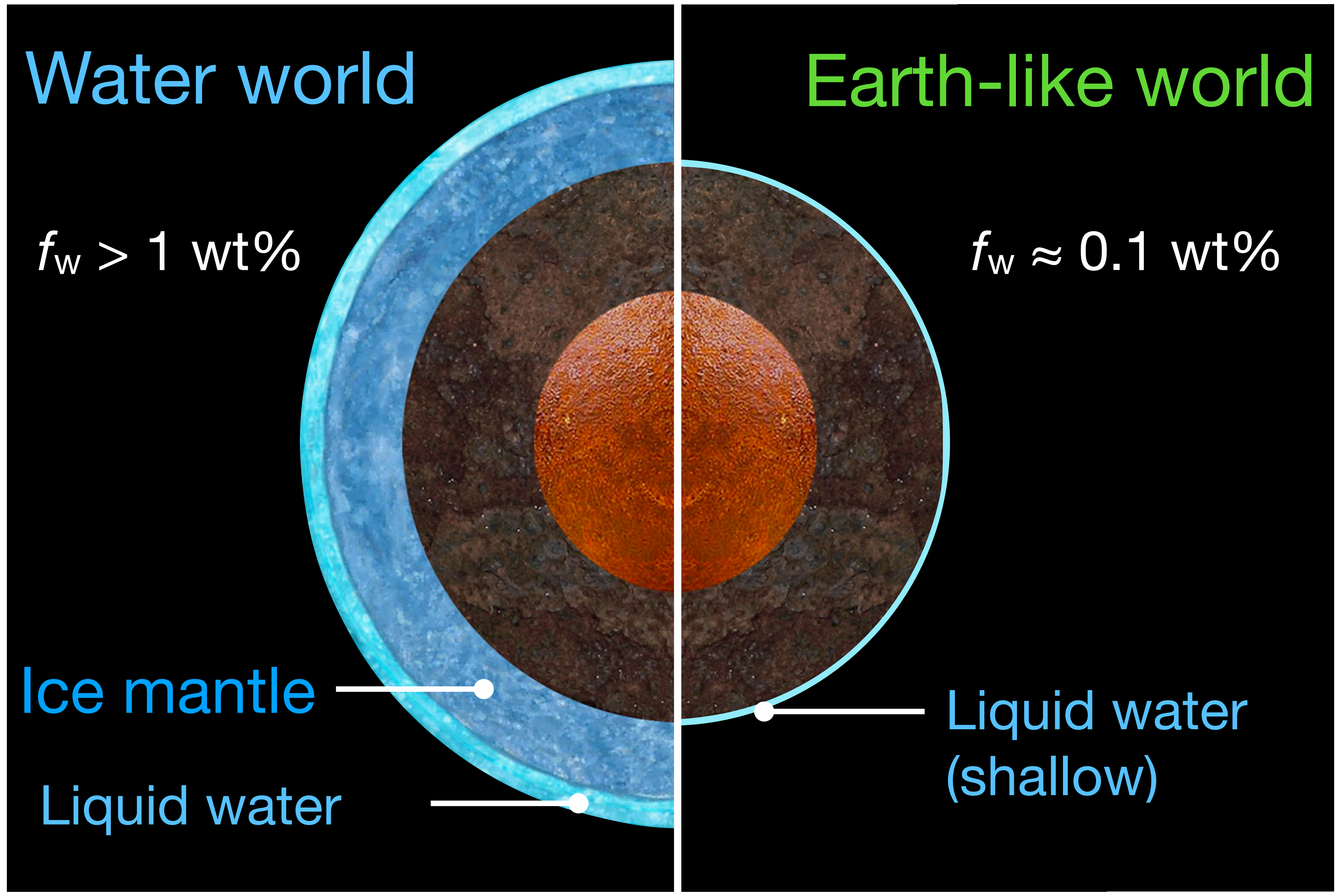
H_2O



Si+Fe



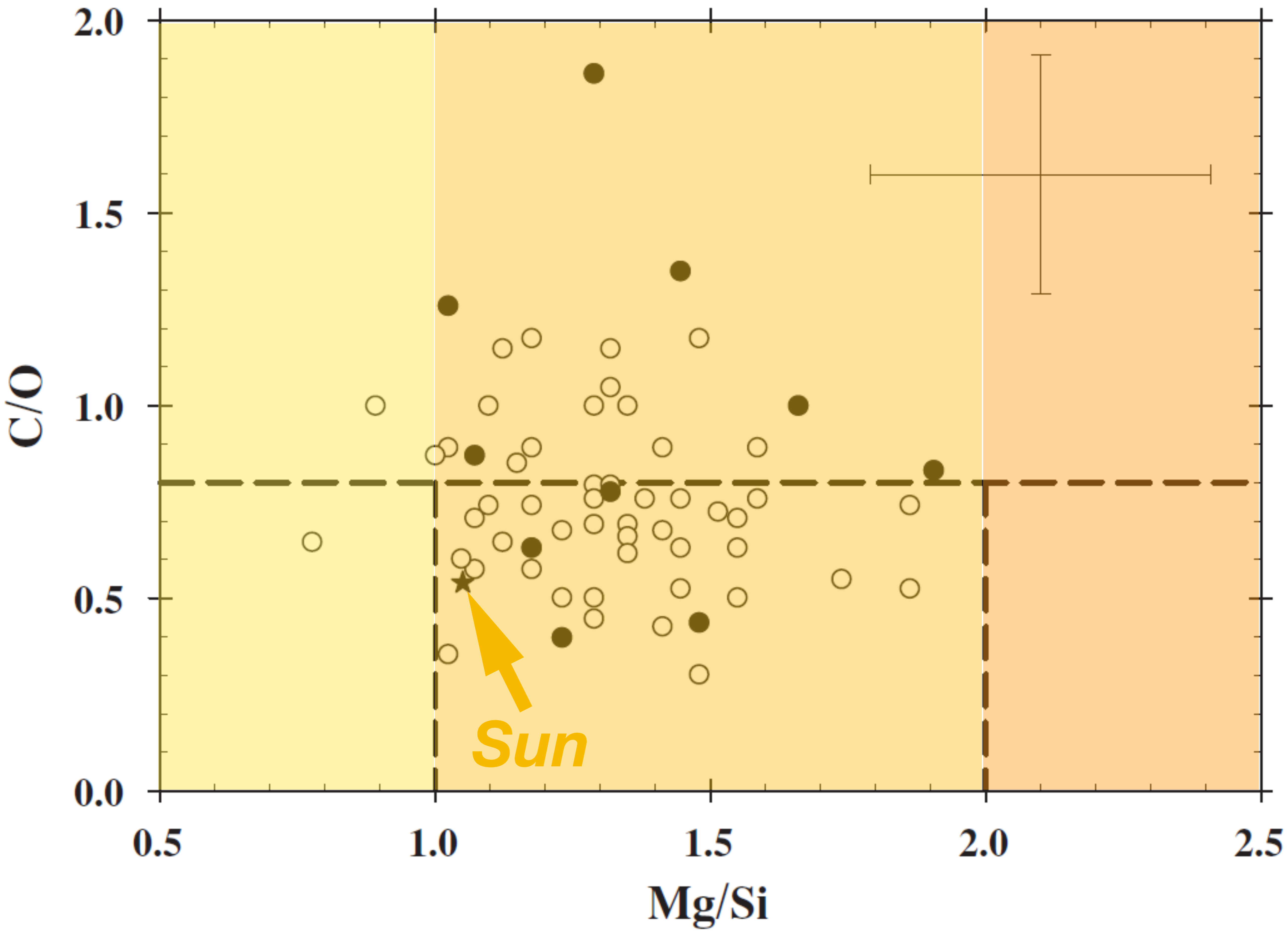
H_2/He



Limited storage in terrestrial core+mantle

Sotin+ 07; Meyer+ 08; Vadim Sadovski; NASA/JPL-Caltech

Star–planet composition relation?

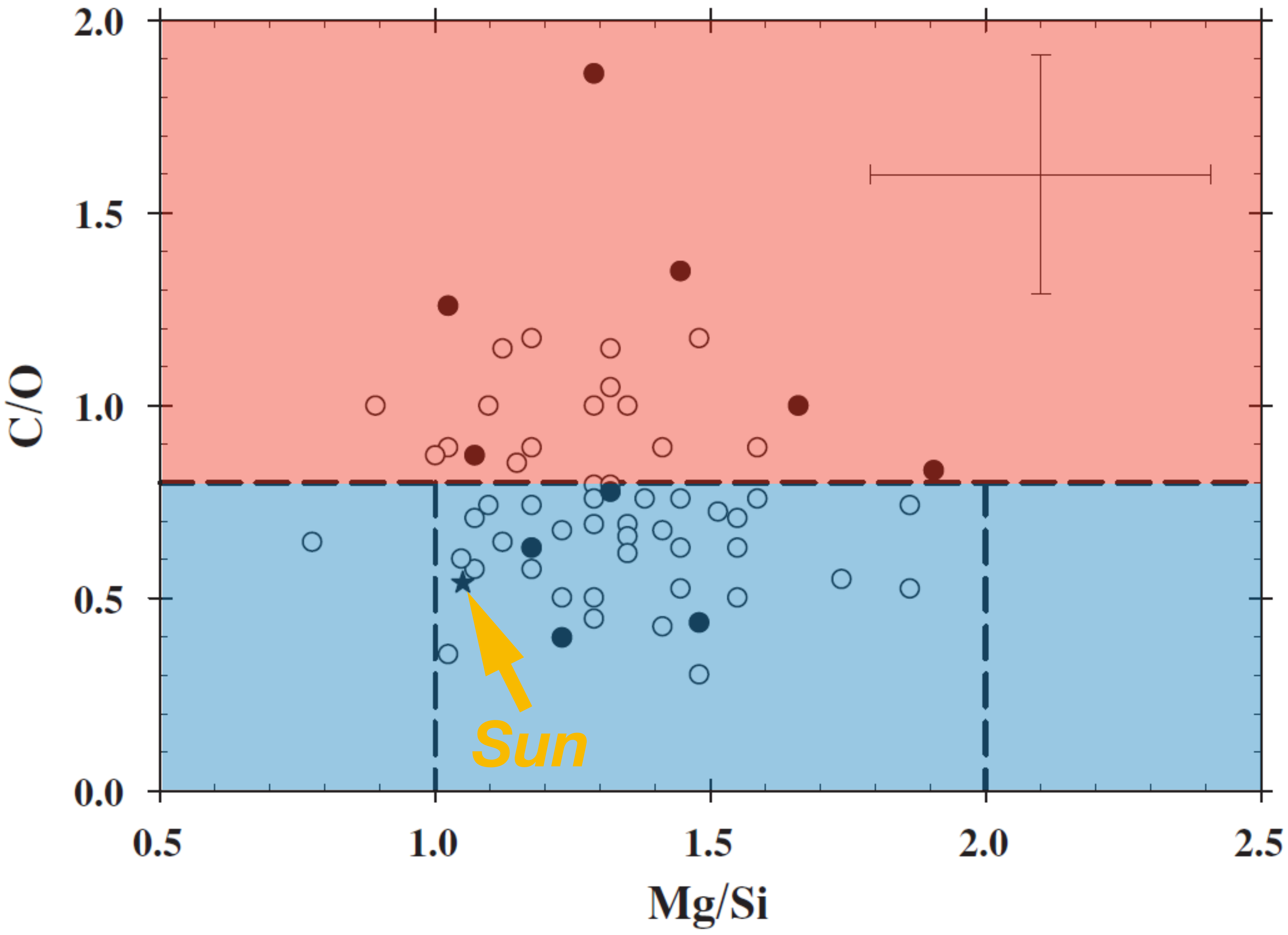


Bulk:

- **Mg/Si < 1:**
  ➡ Pyroxenes/Feldspars
- **1< Mg/Si < 2:**
  ➡ Olivine/Pyroxenes
- **Mg/Si > 2:**
  ➡ Olivine/MgO/MgS

Bond+ 10

Star–planet composition relation?



Atmosphere:

- **C/O < 0.8:**

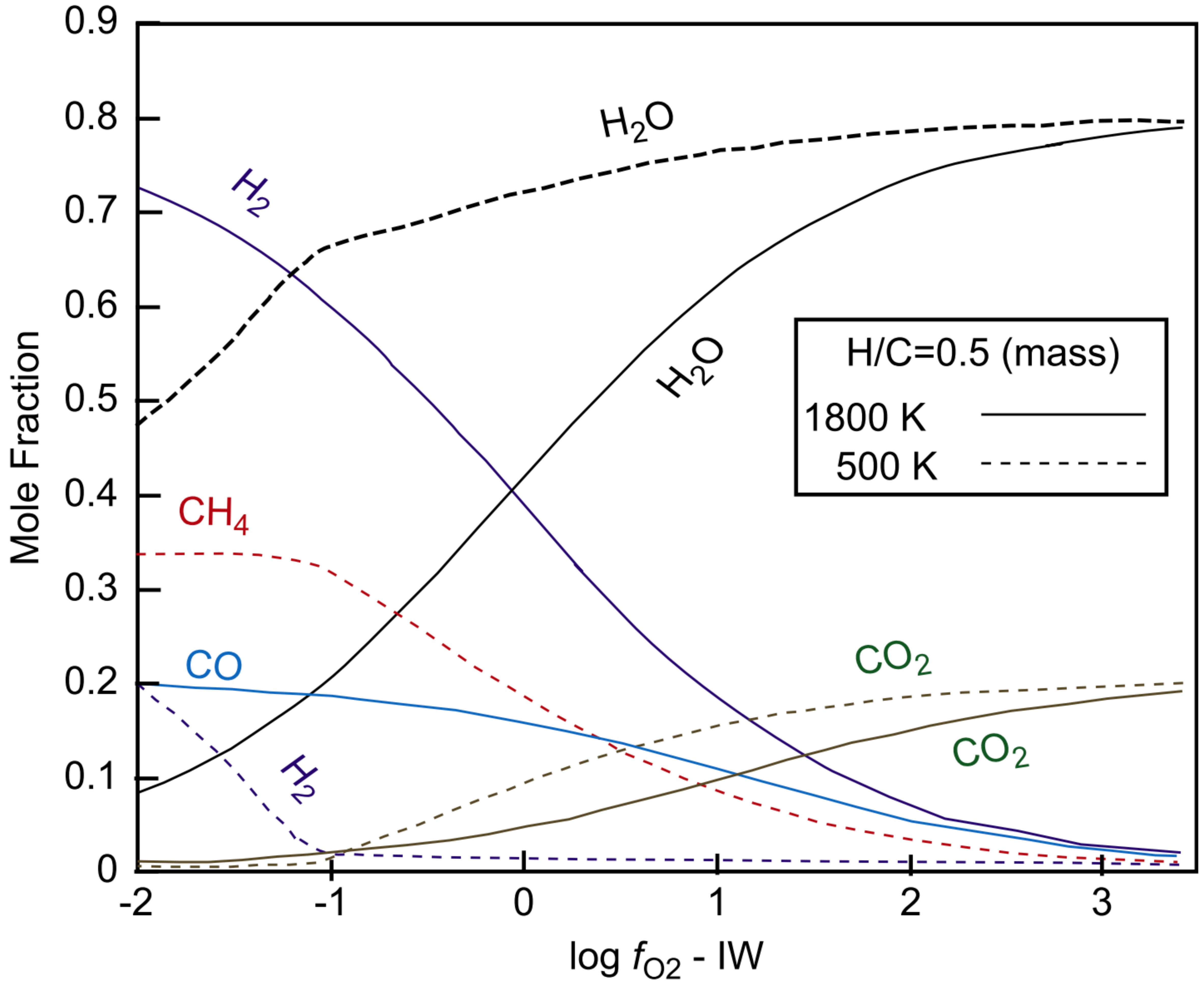
➡ Atmosphere dominated by H_2O and CO_2

- **C/O > 0.8:**

➡ Atmosphere dominated by CO and CH_4

Bond+ 10

Composition determines climatic setting

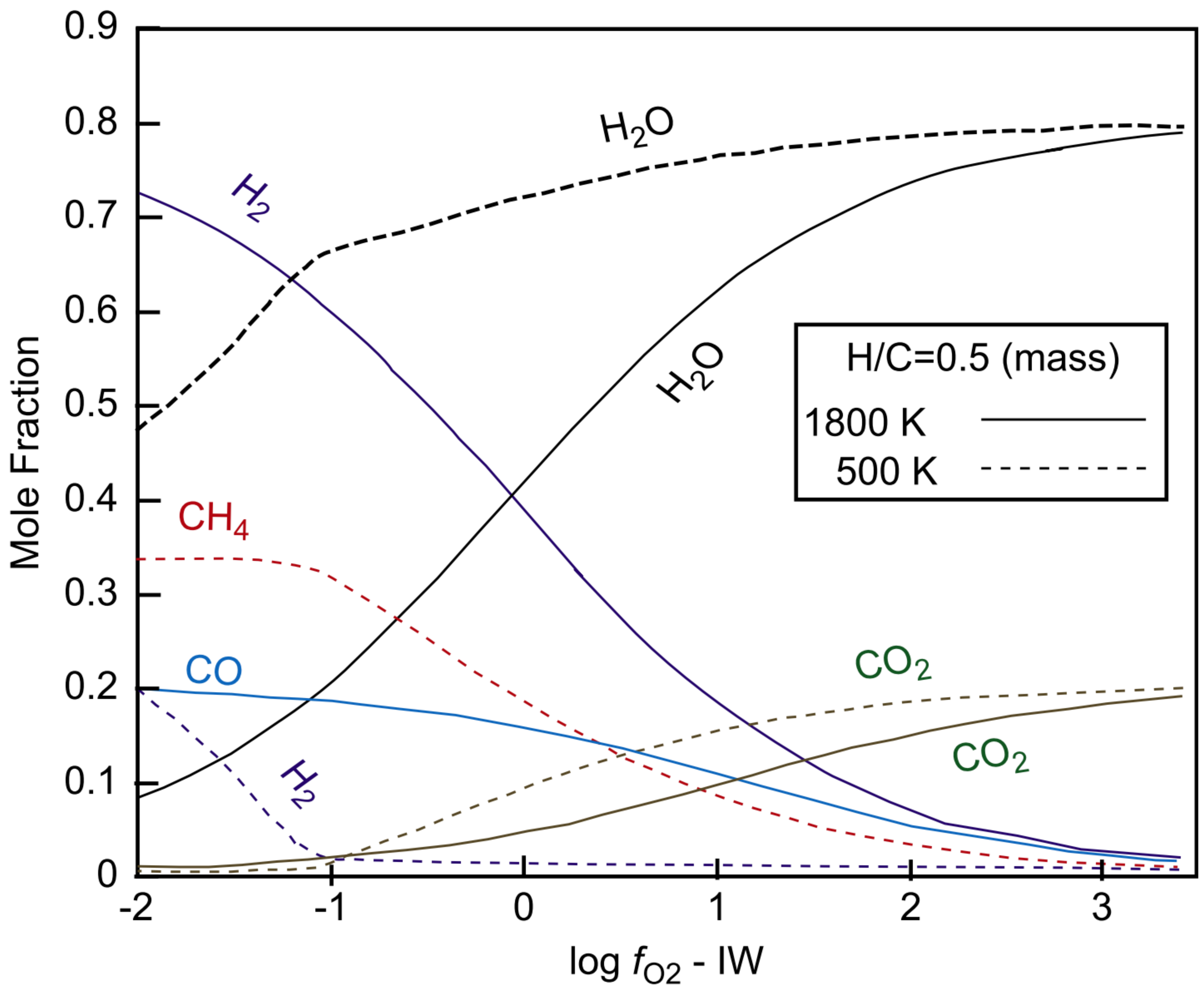


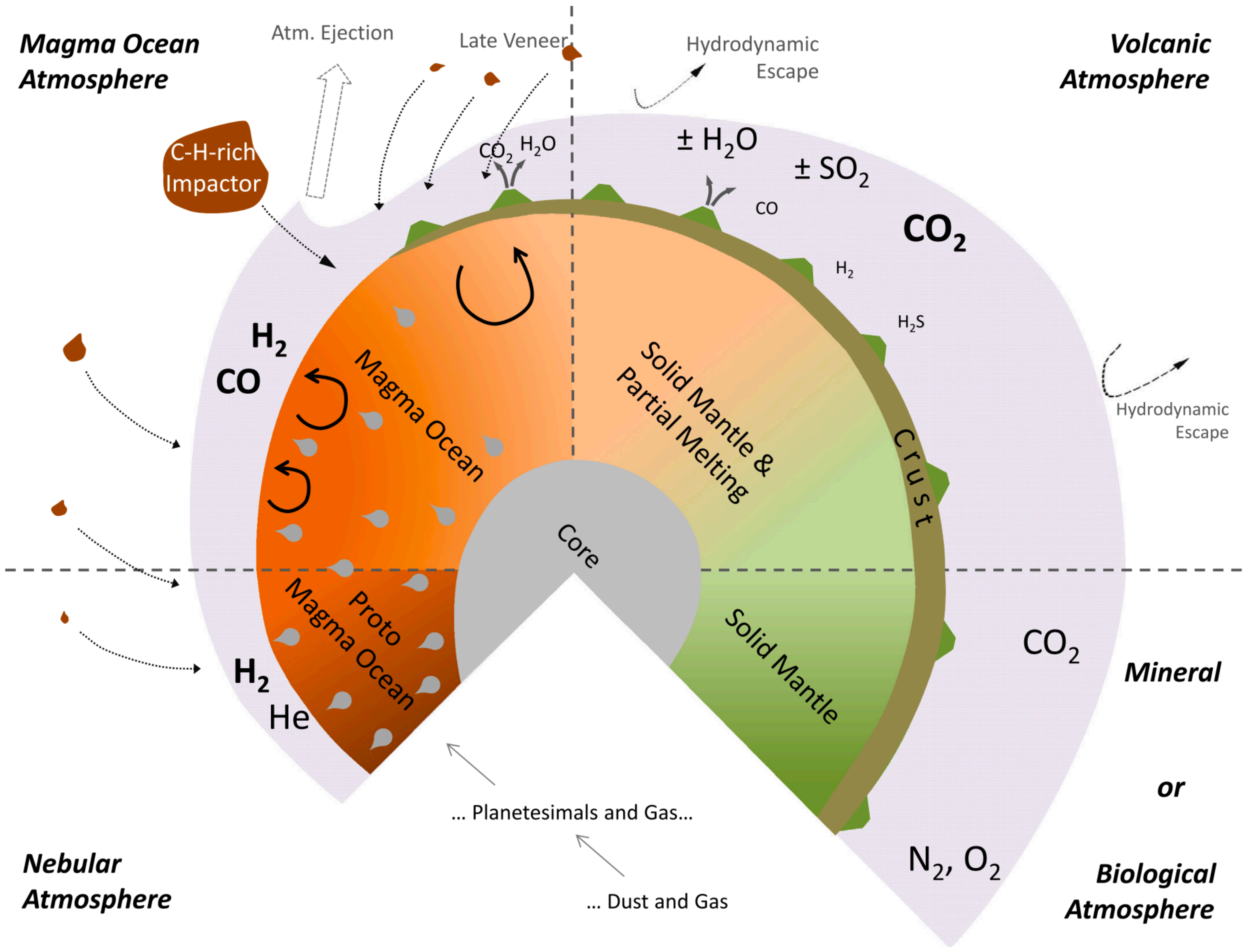
Atmosphere:

- **C/O < 0.8:**
  - ➡ Atmosphere dominated by H_2O and CO_2
- **C/O > 0.8:**
  - ➡ Atmosphere dominated by CO and CH_4

Dasgupta & Hirschmann 10,12; Hirschmann/+ 10,12,16,18

Composition determines climatic setting

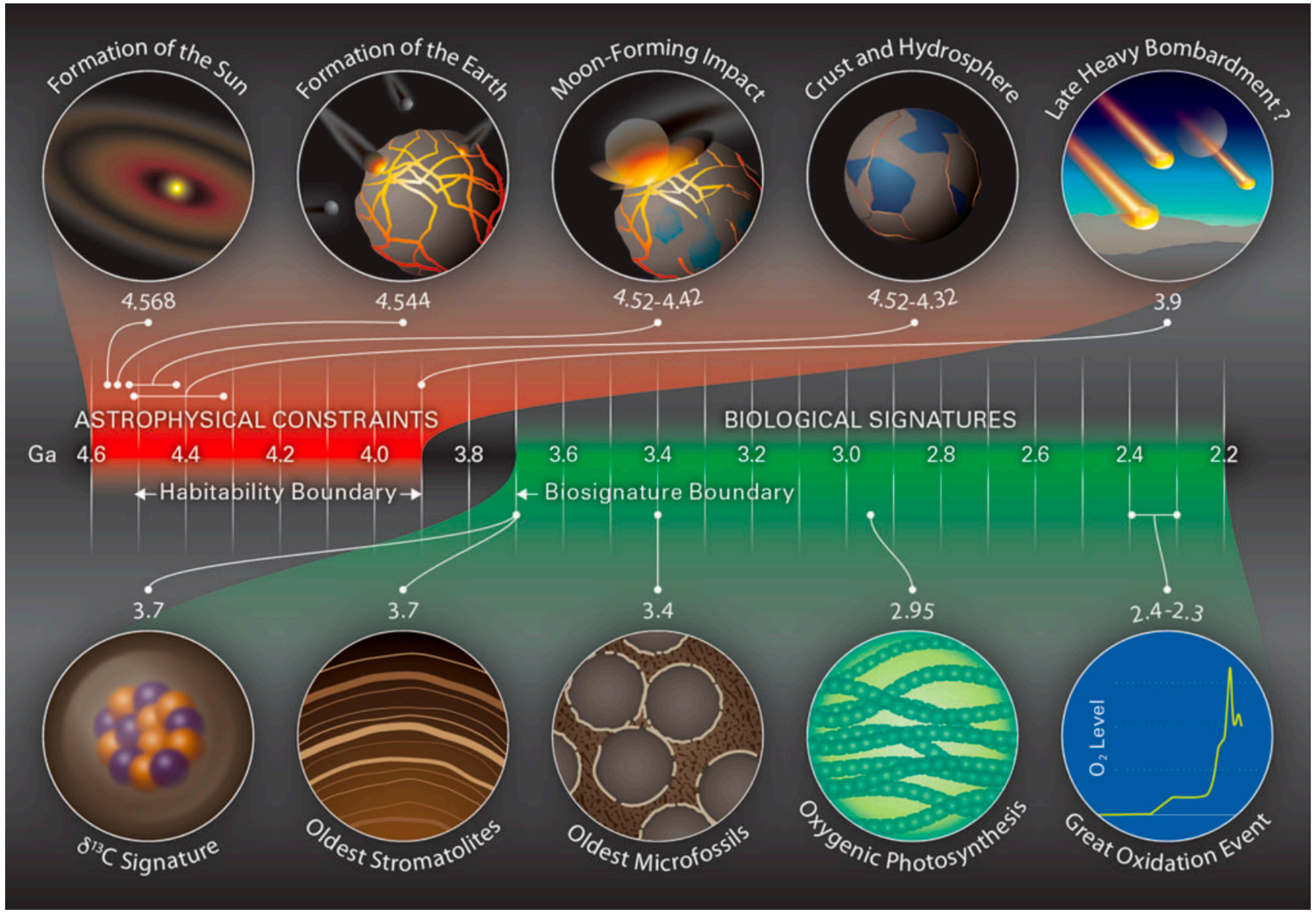


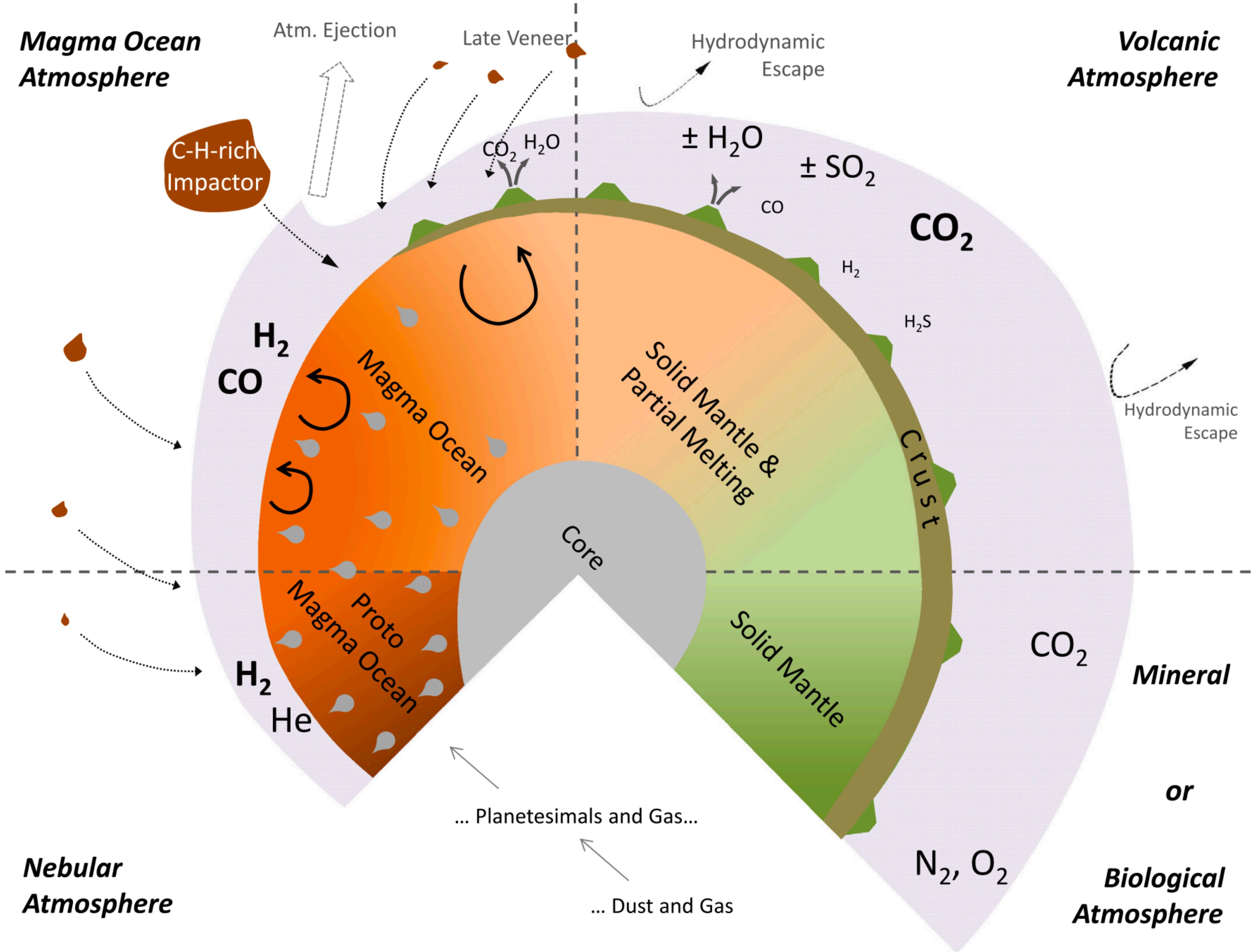


Dasgupta & Hirschmann 10,12; Hirschmann/+ 10,12,16,18

Gaillard & Scaillet 14

Composition determines climatic setting

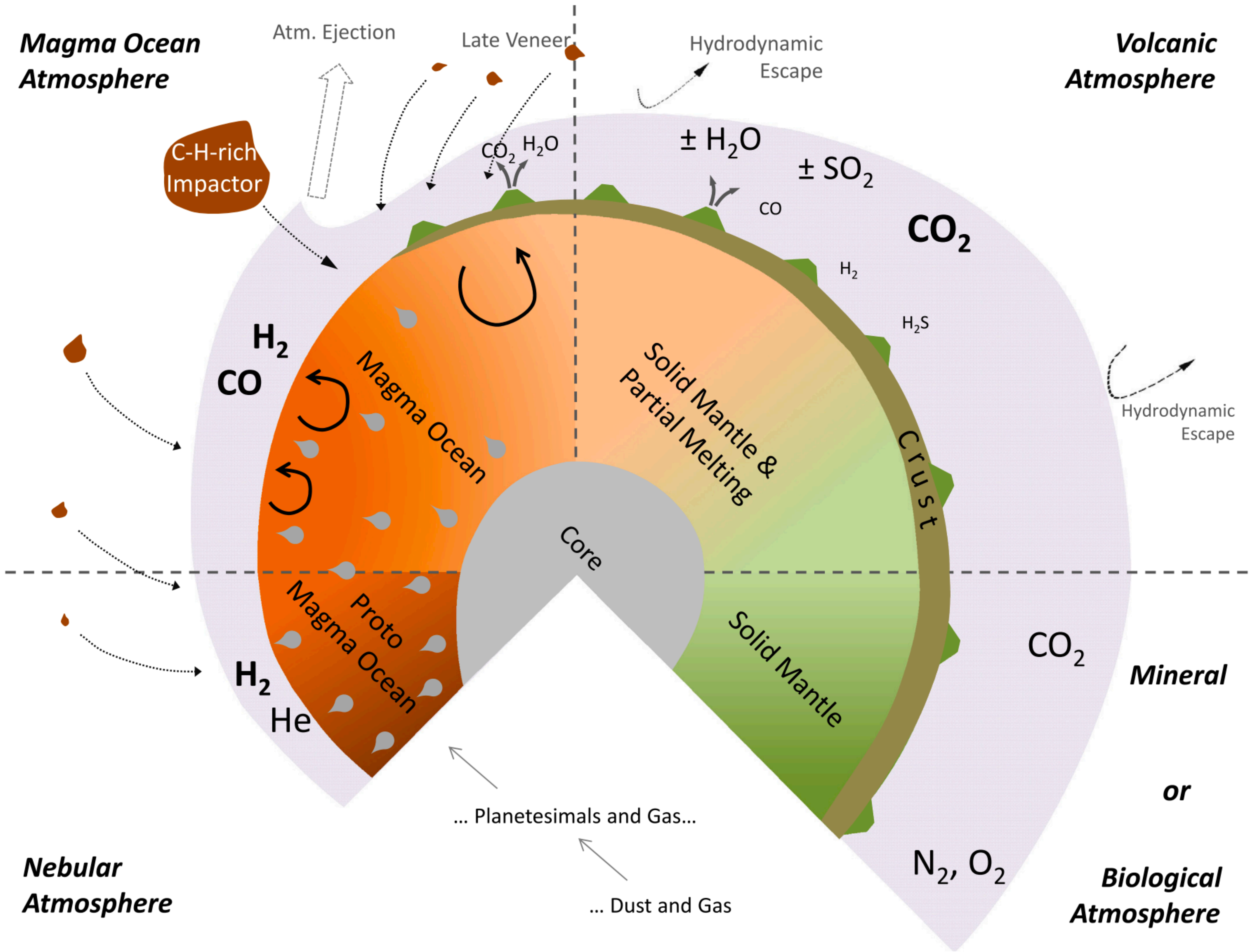


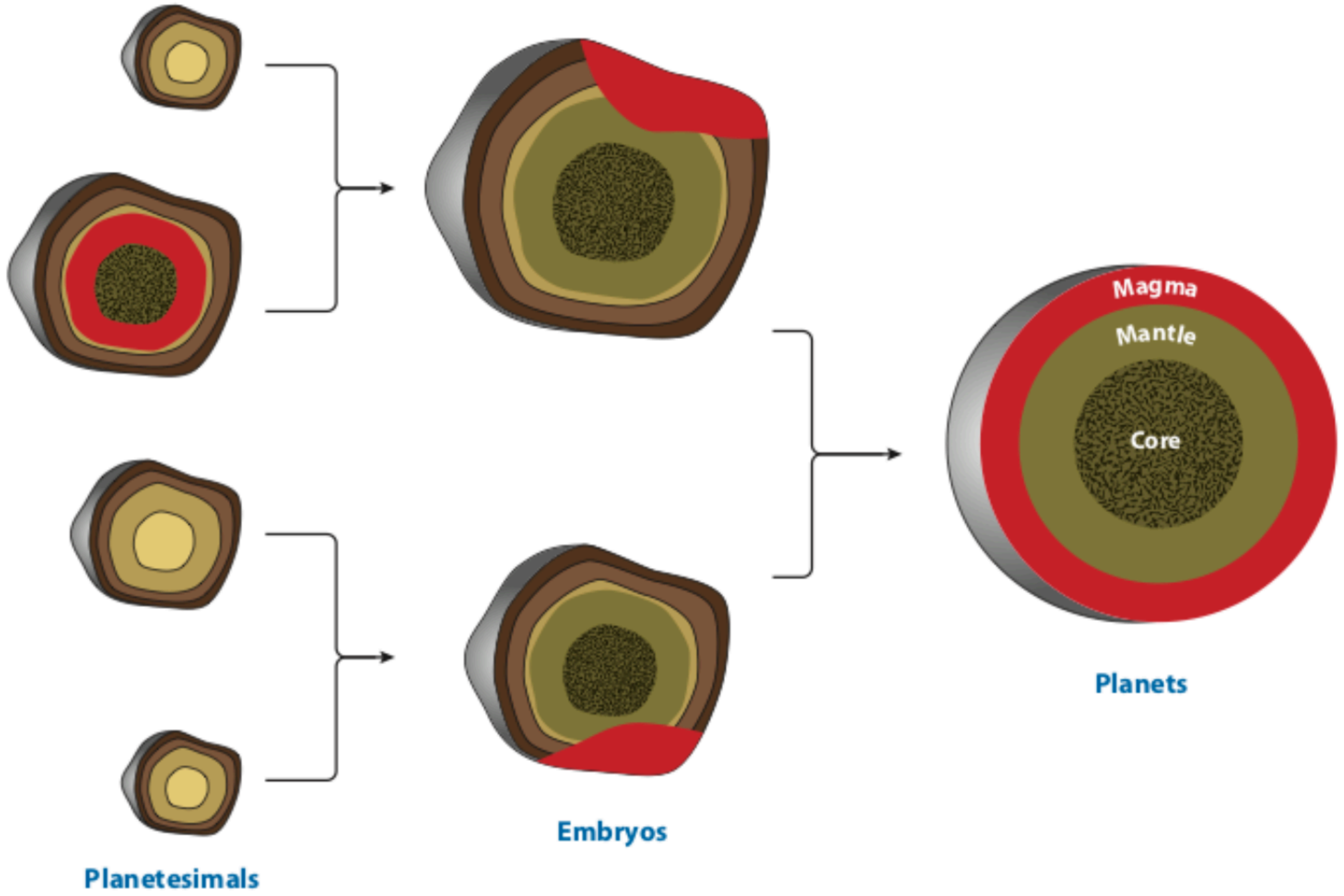


Pearce, Tupper, Pudritz, Higgs 18

Gaillard & Scaillet 14

Geophysical evolution during accretion

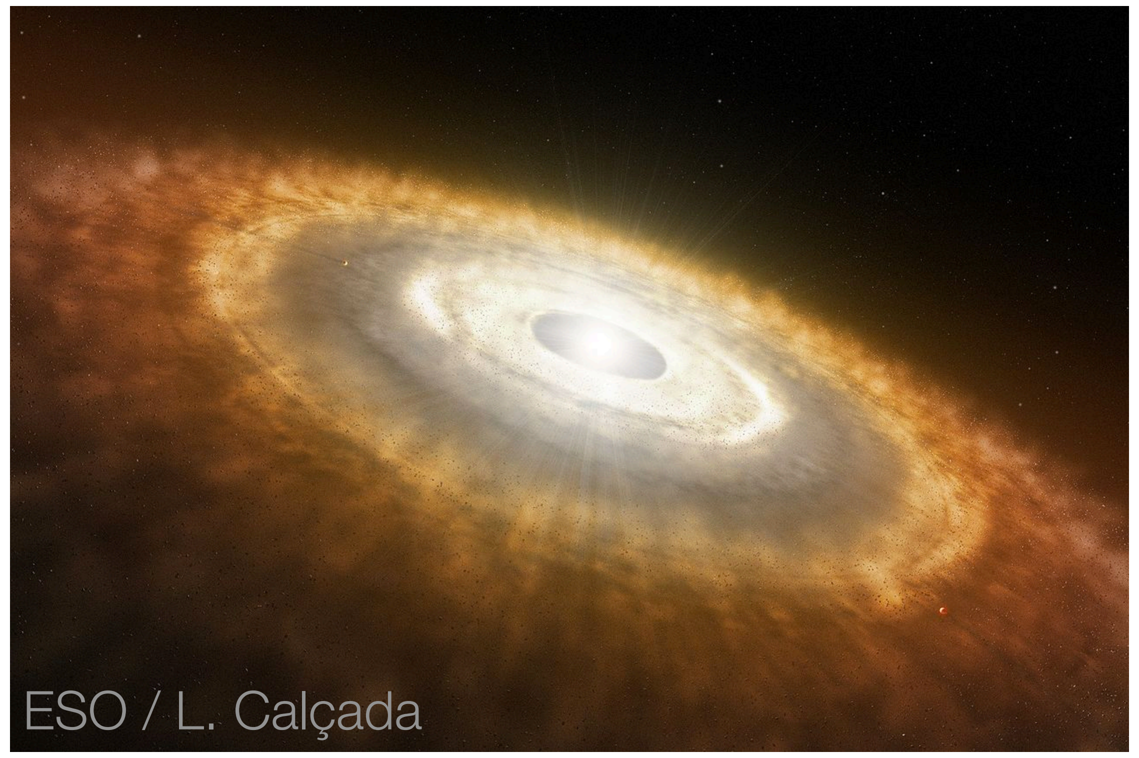


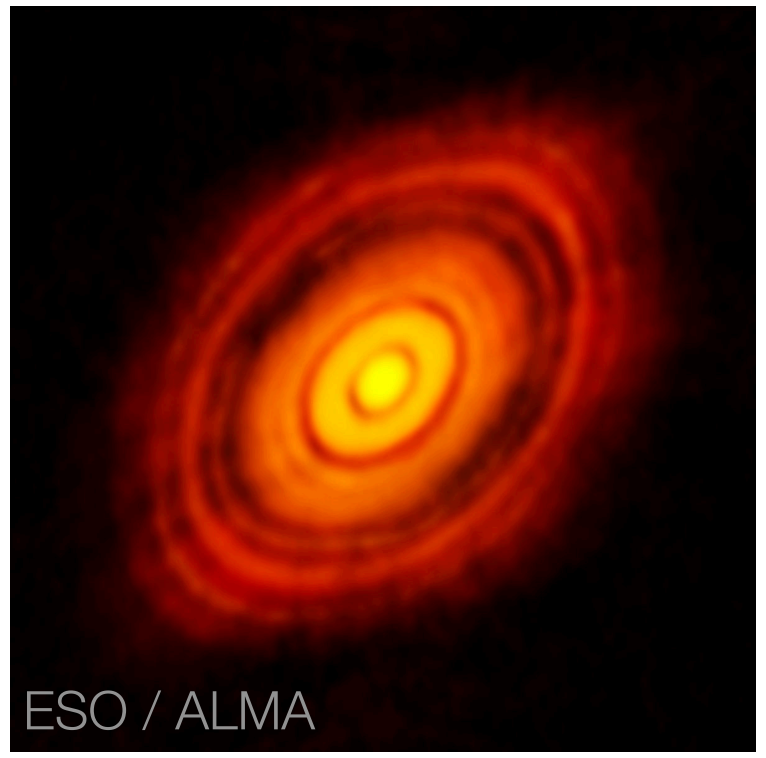


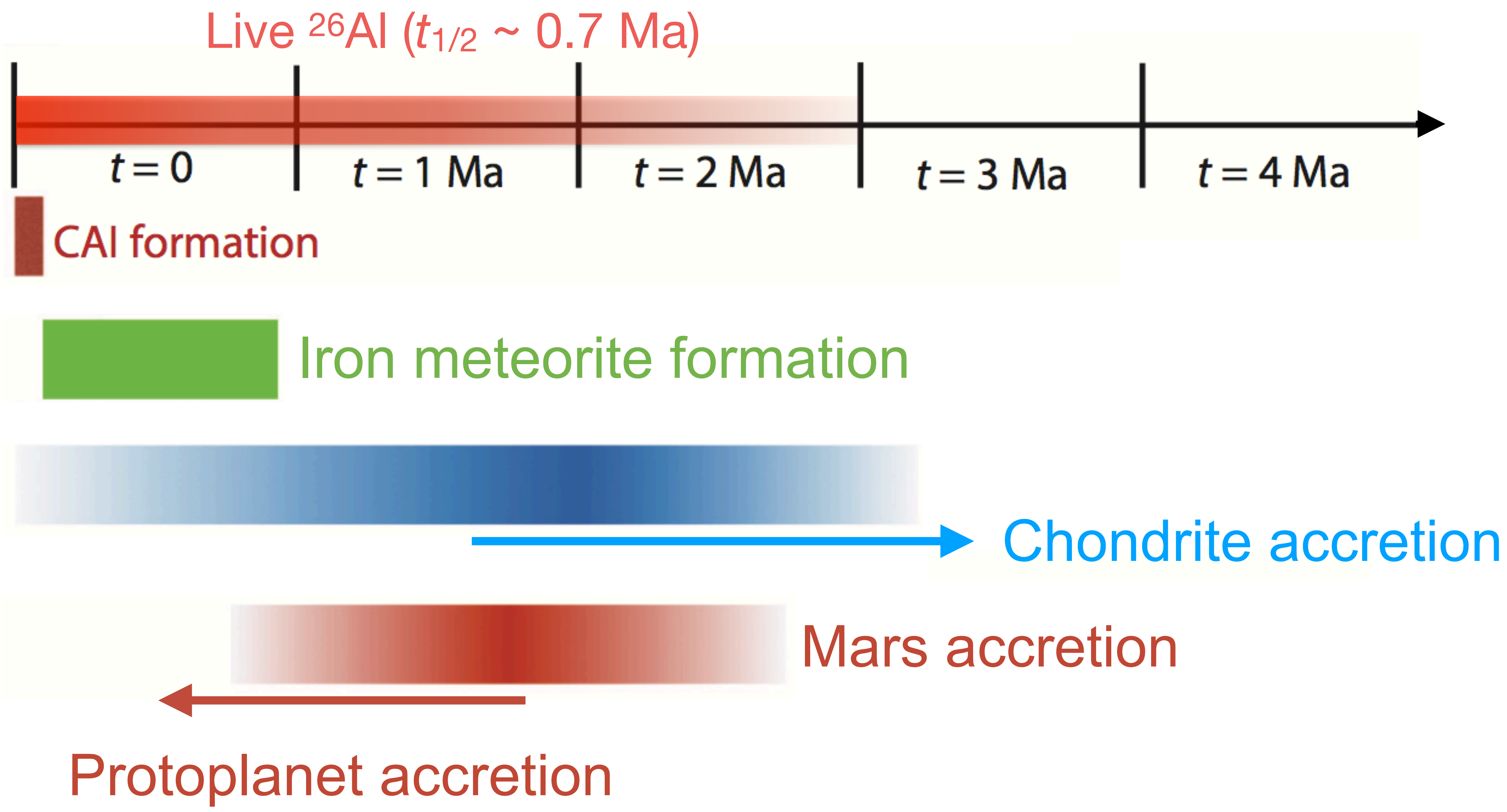
Gaillard & Scaillet 14

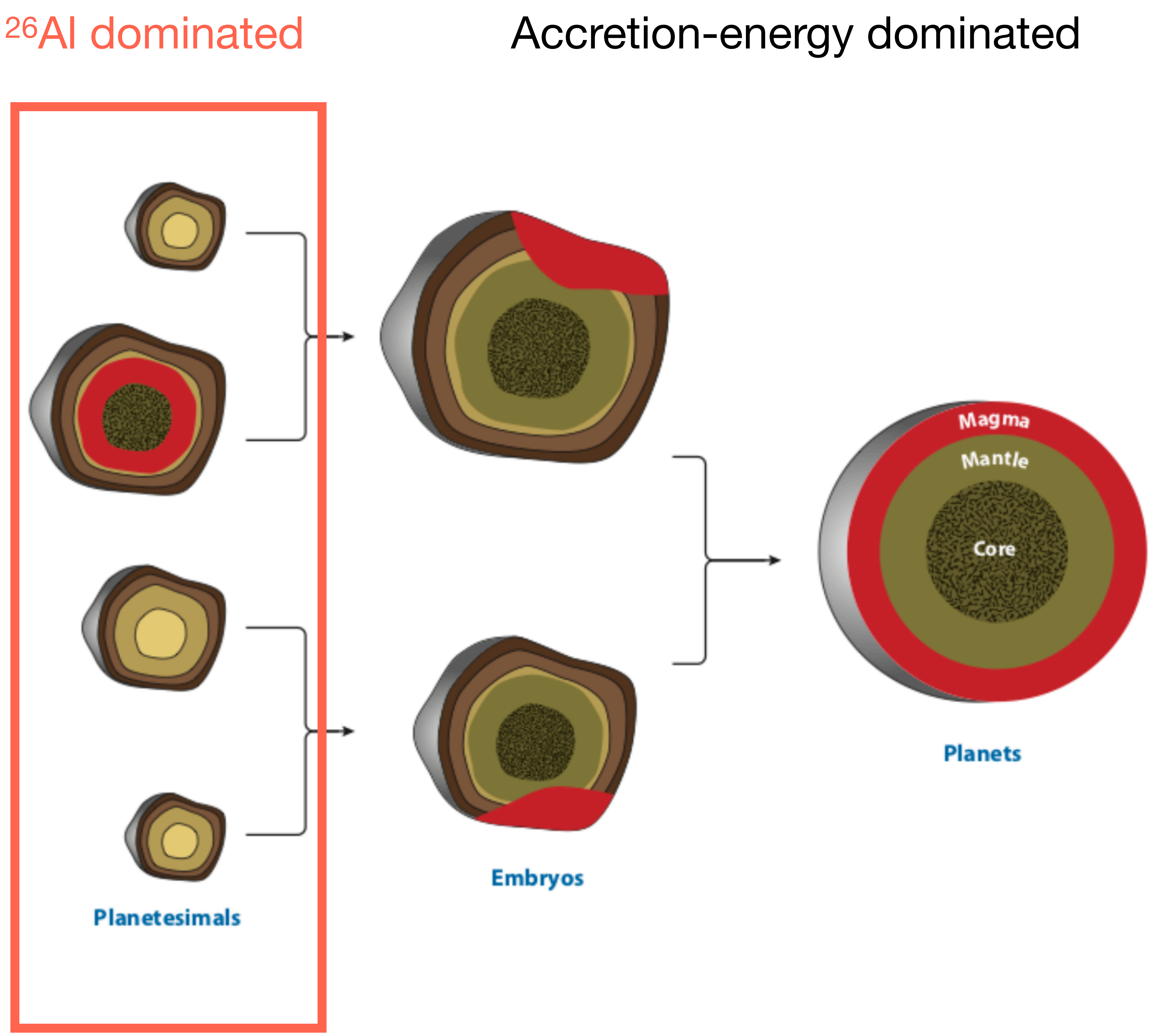
Elkins-Tanton 10, Weiss & Elkins-Tanton 17

Geophysical evolution during **early** accretion



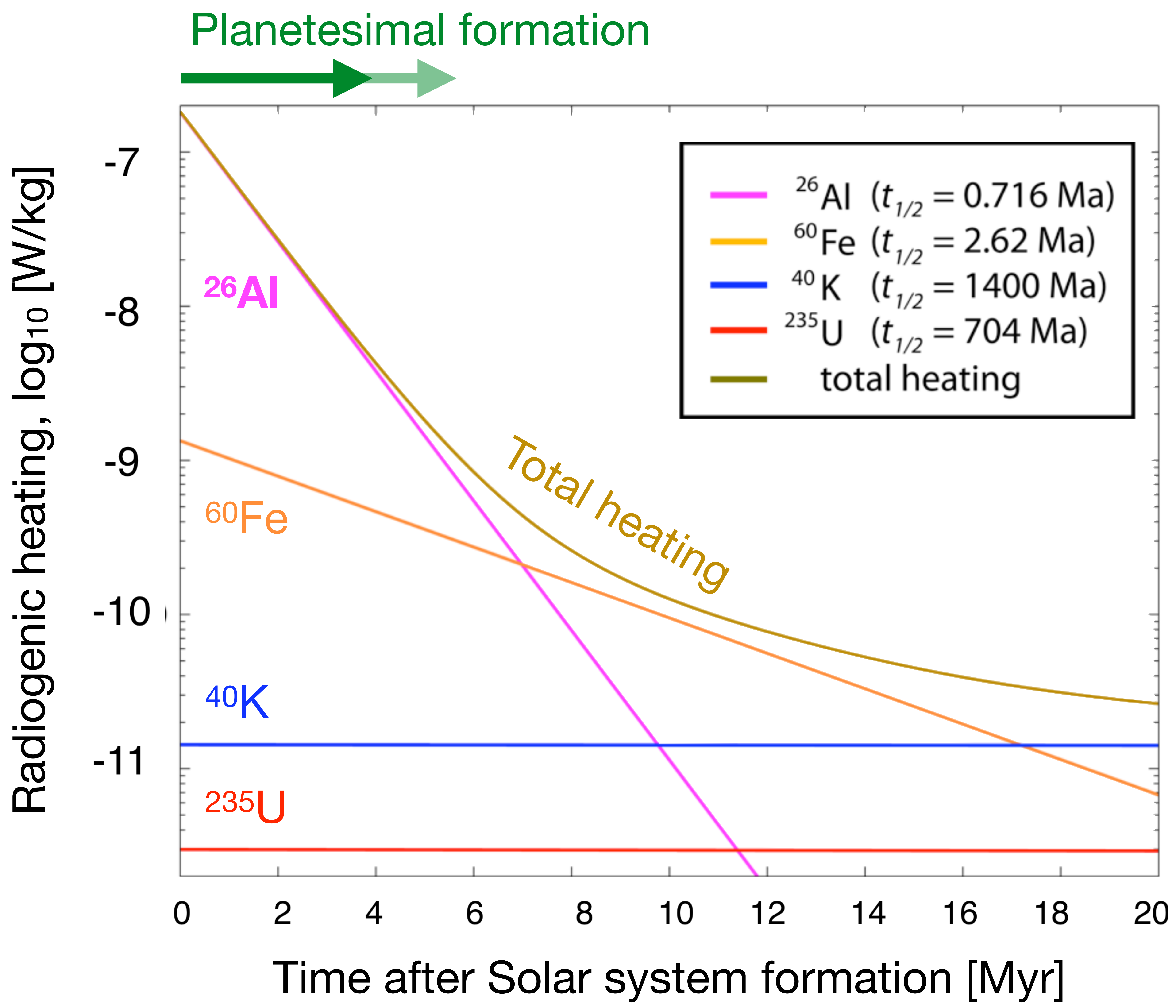






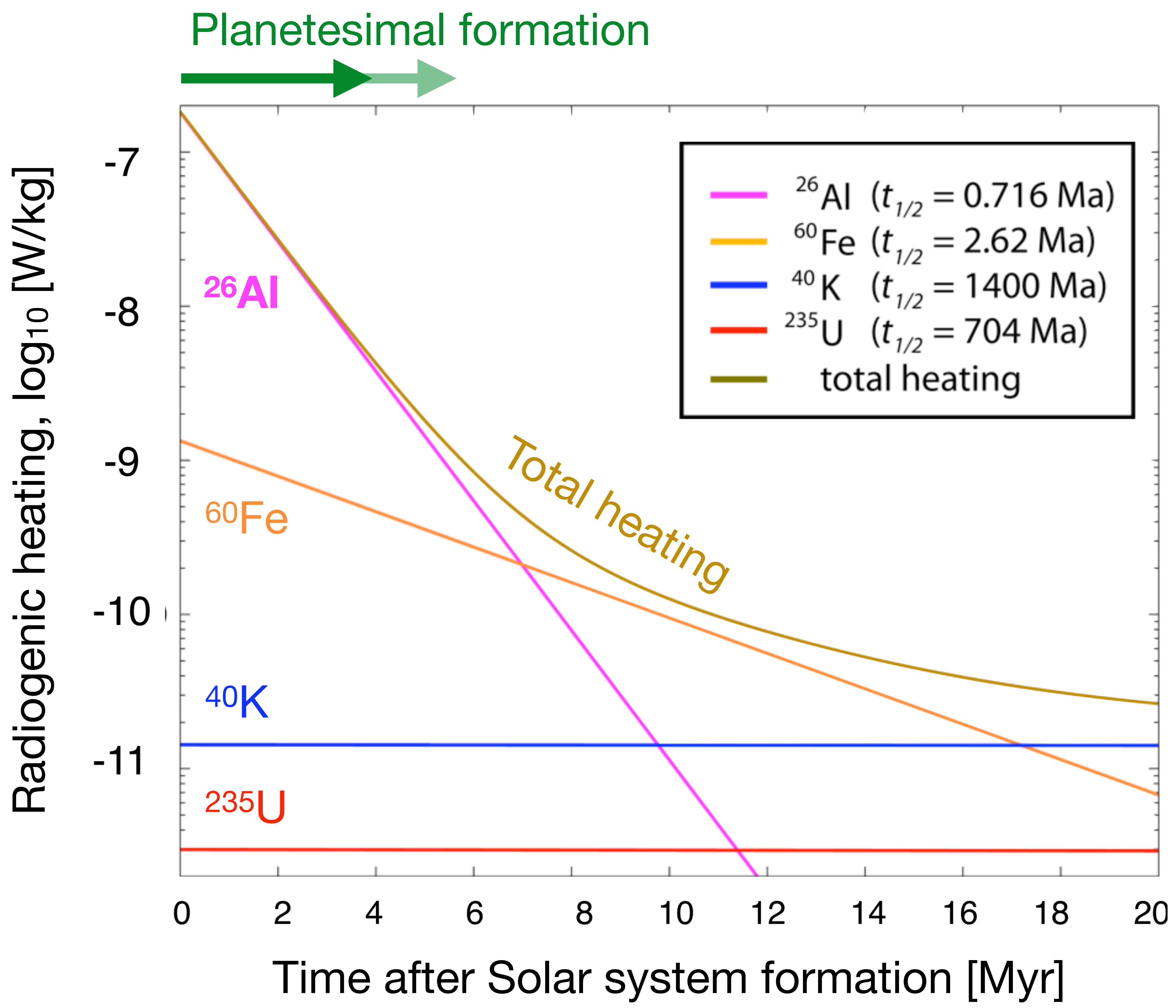
Elkins-Tanton 10, Weiss & Elkins-Tanton 17

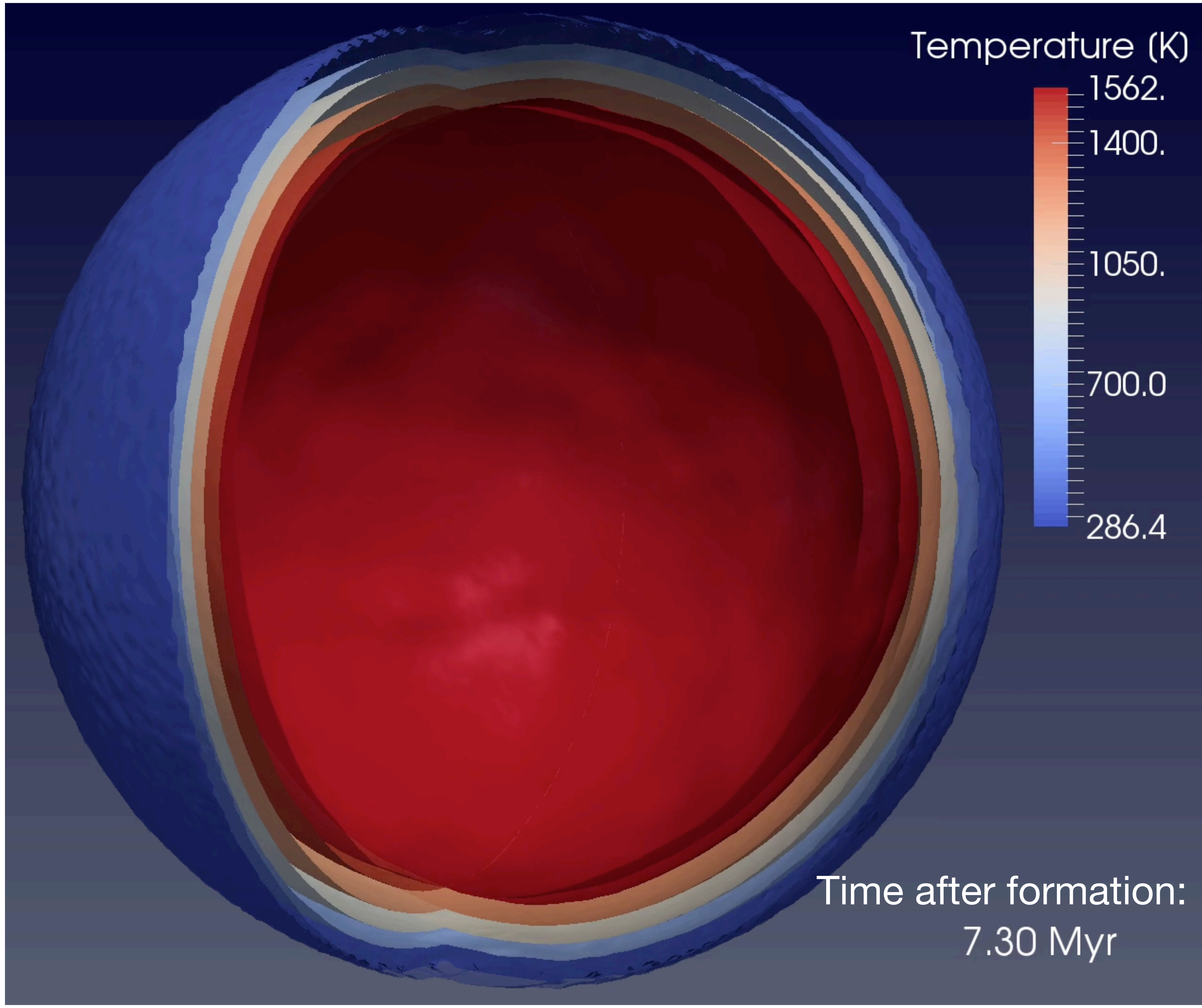
Radiogenic heating drives thermal evolution



Lichtenberg+ 16a,18,19a,b

Planetesimal interior evolution

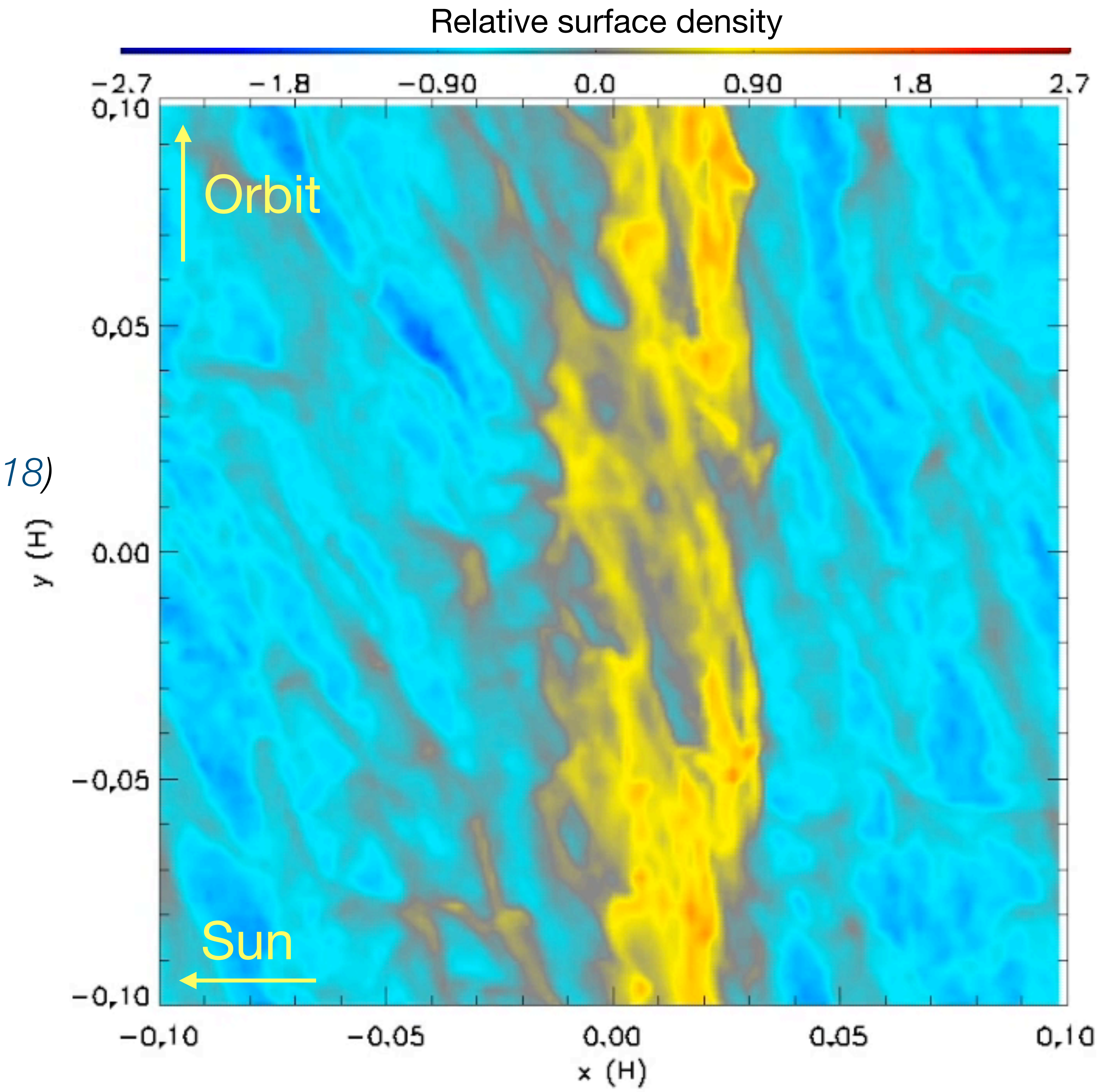




Lichtenberg+ 16a,18,19a,b

Estimates for planetesimal birth function

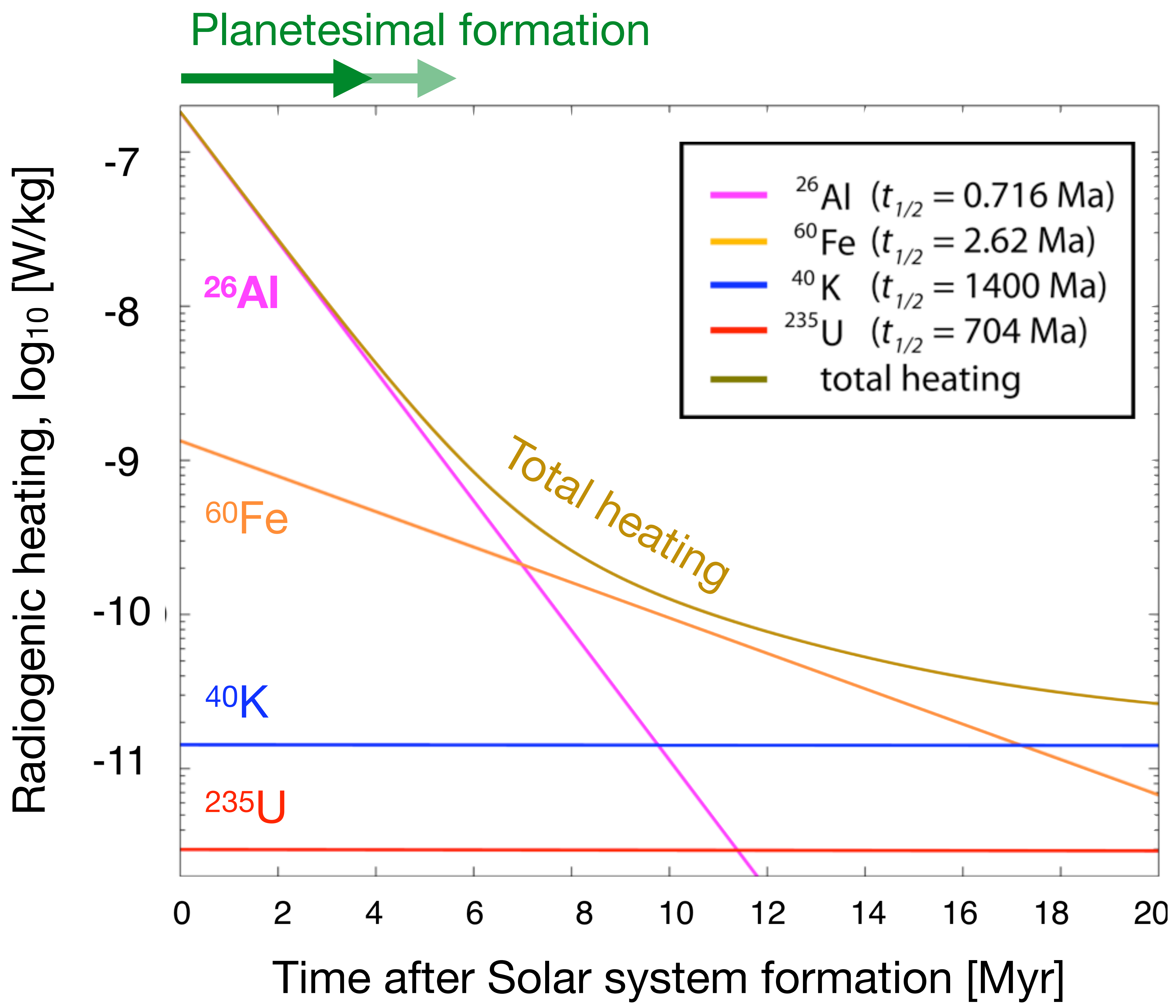
- R_{plts} = 10—100 km (*Cuzzi+ 08*)
- R_{plts} = 100—1000 km (*Morbidelli+ 09*)
- R_{plts} = 50—200 km (*Chambers 10*)
- $R_{plts} \leq$ 25—200 km (*Johansen+ 15, Simon+ 16,17, Abod+ 18*)
  - $dN/dR_{plts} \sim R^{-2.8}$
  - $dN/dM_{plts} \sim M^{-1.6}$
- $R_{plts} \geq$ 50 km (Morbidelli+ 09, Delbo+ 17, Singer+ 19)
- $M_{plts} \sim 10^{17}$—10^{21} kg ~ 10^{-4}—10^{0} M_{Ceres}

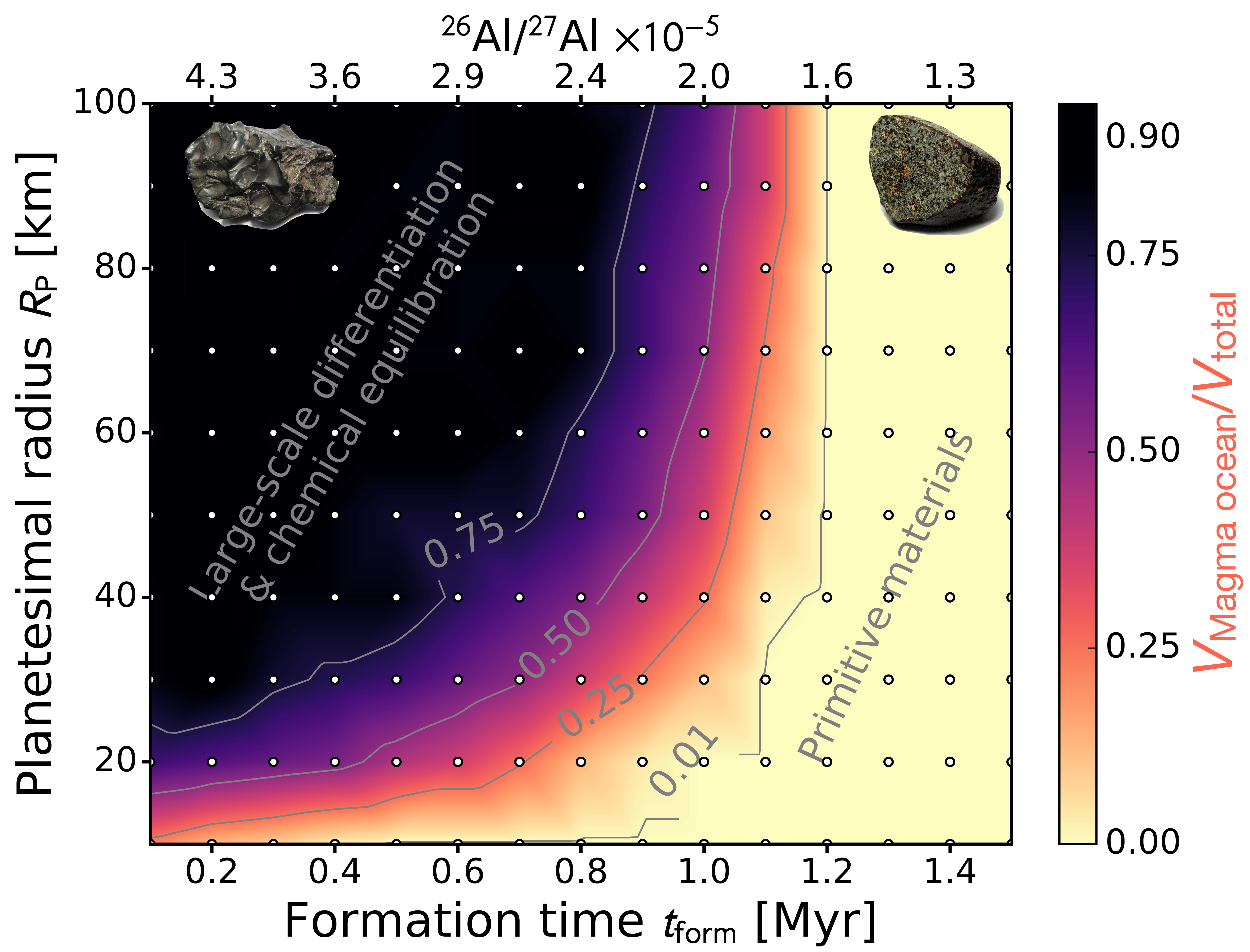


Streaming instability *Vortices/Turbulent concentration* *Asteroid belt inversion* *Kuiper belt cratering record*

Simon+ 16,17

Planetesimal interior evolution

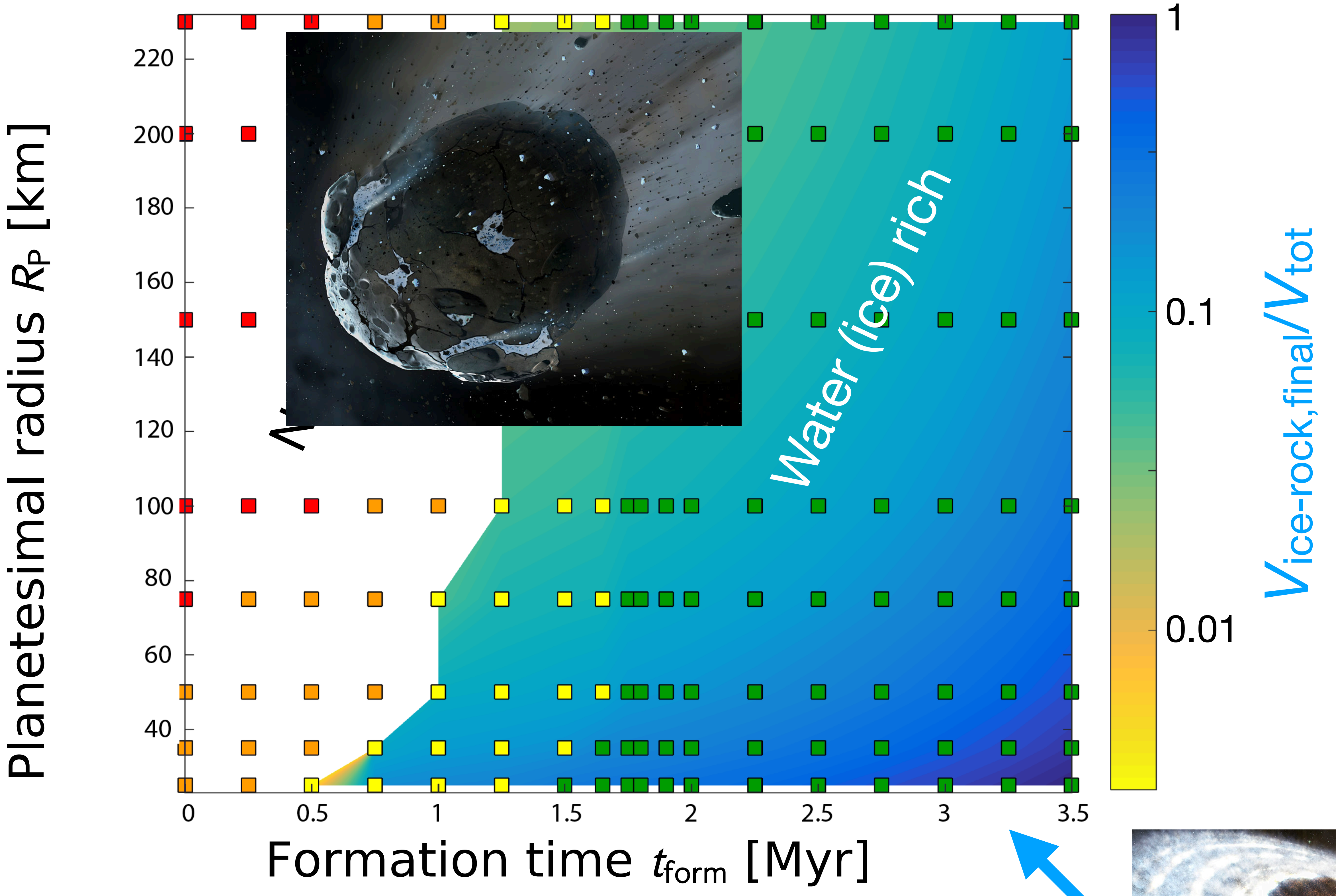




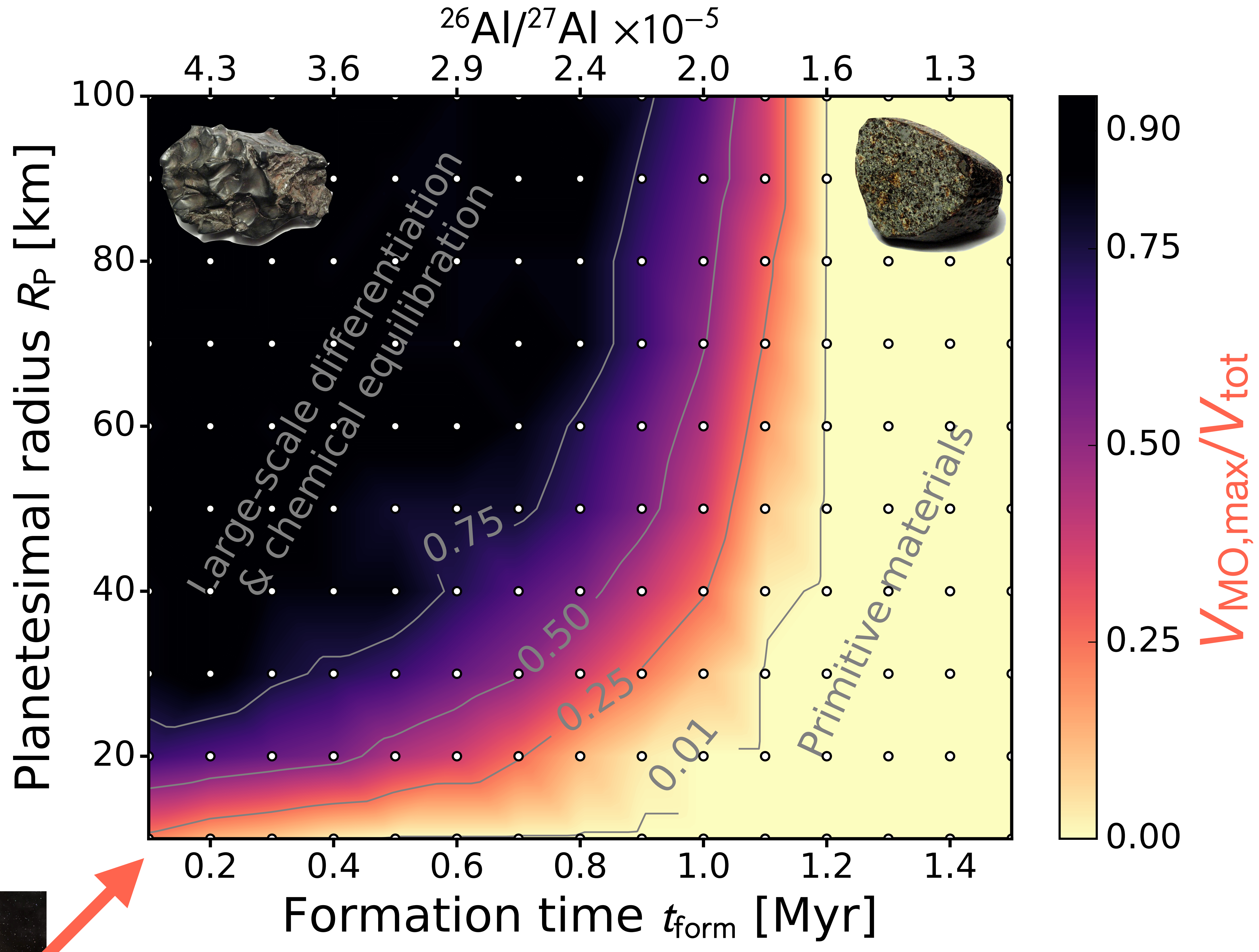
Lichtenberg+ 18

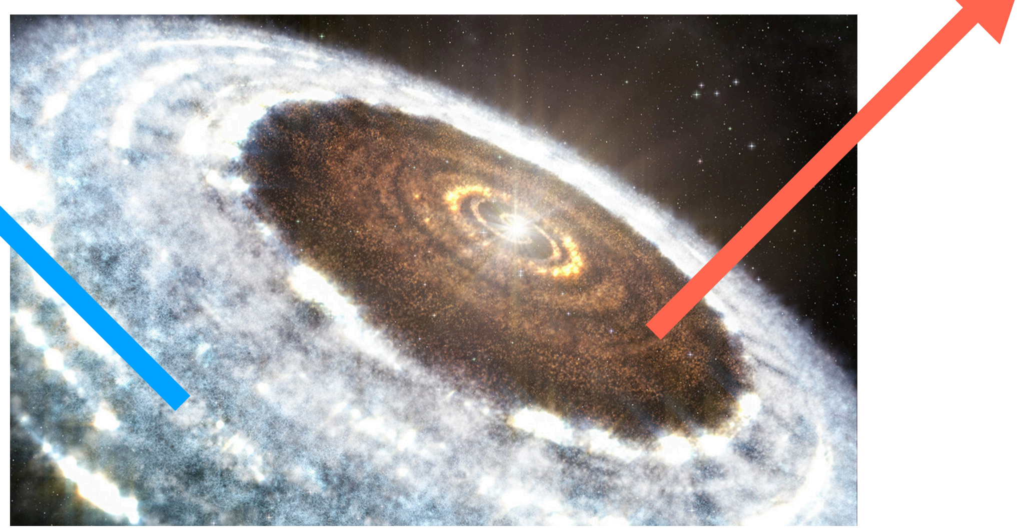
Volatile retention/loss & differentiation

Retained water ice in planetesimals



Magma ocean volume

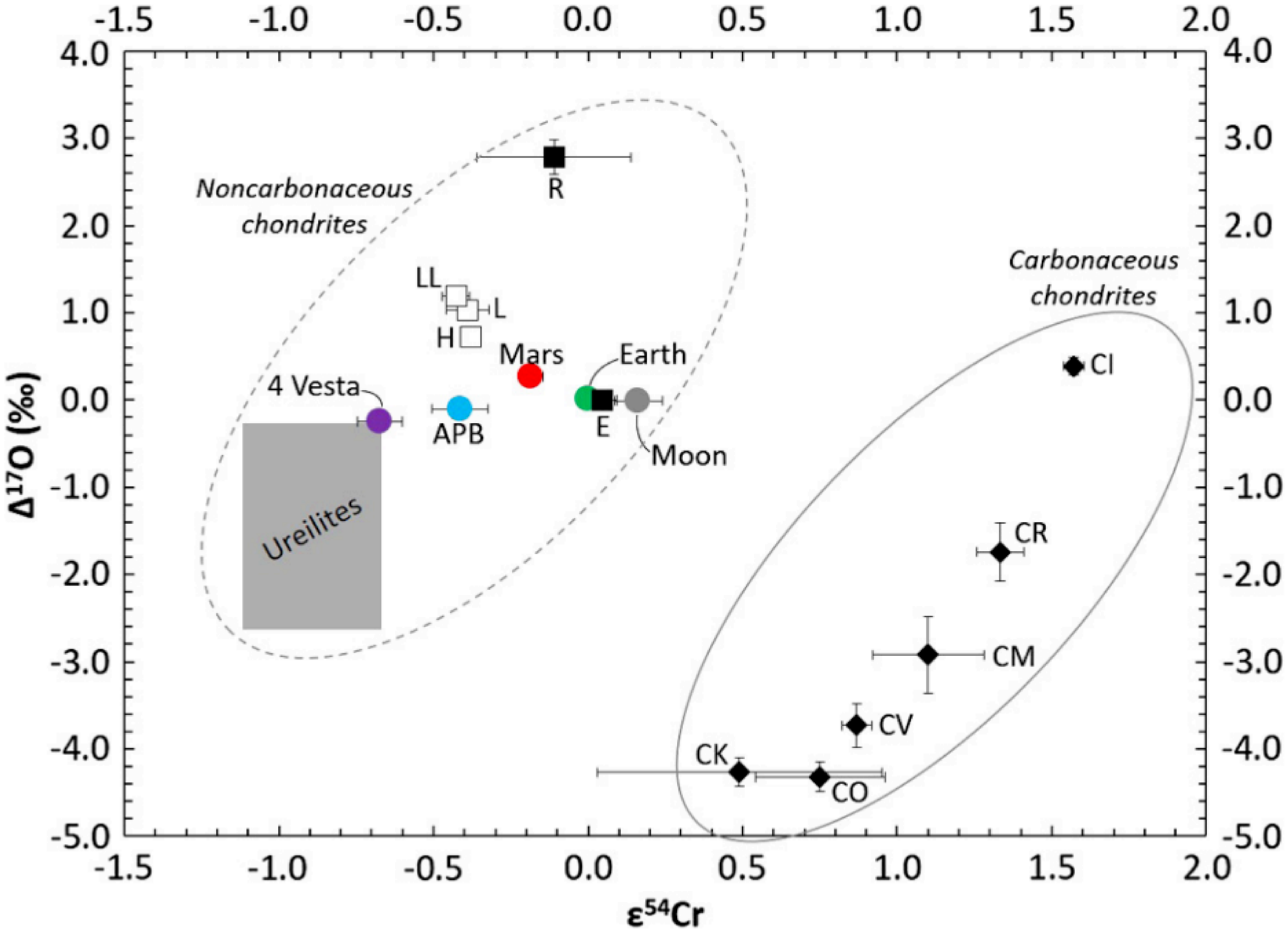


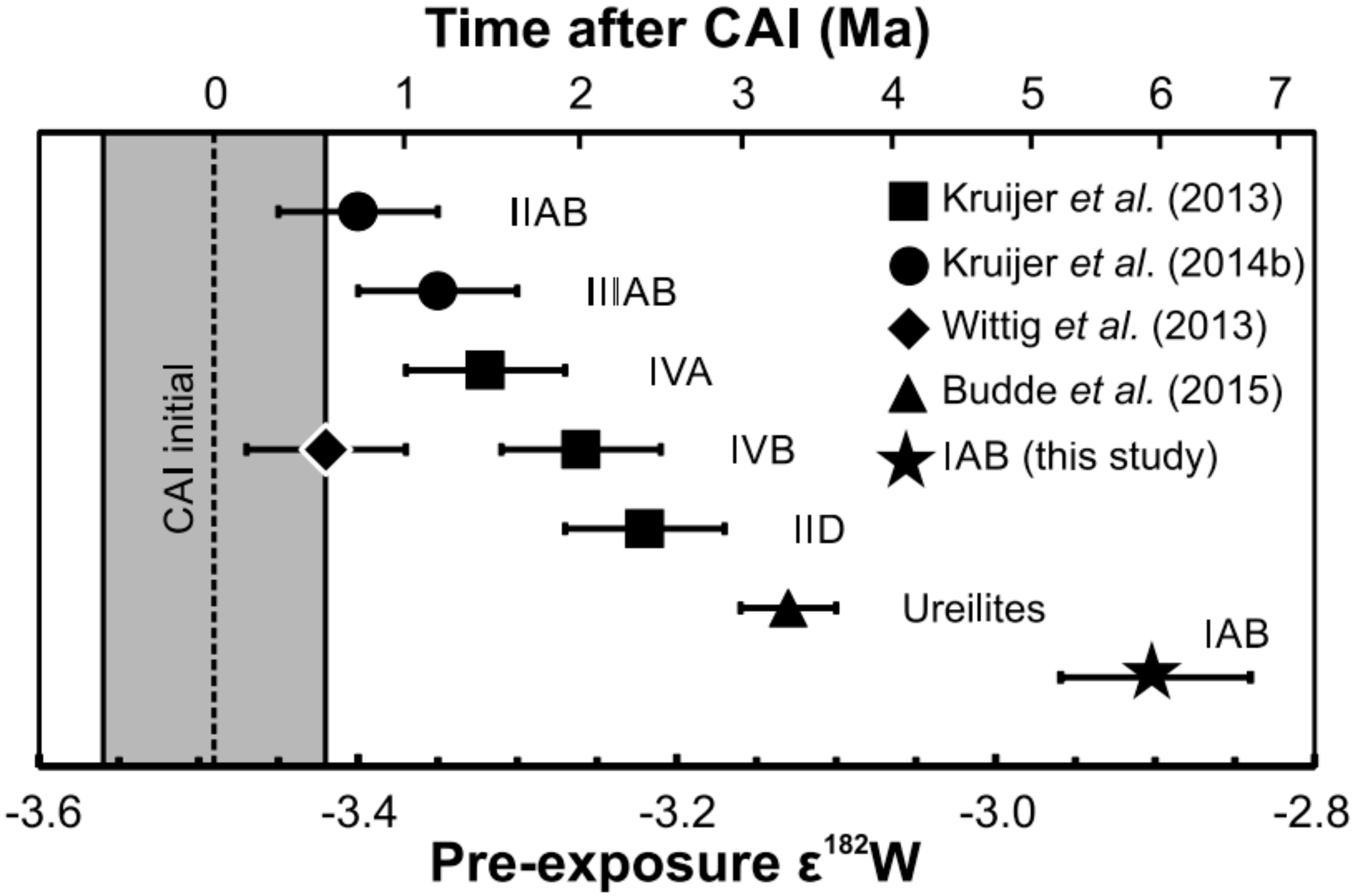


Modified from Monteux, Golabek+ 18; ESA/NASA/M.A.Garlick

Lichtenberg+ 18

Early accretion in the Solar System: distinct reservoirs, rapid core formation, compositional trend with orbit

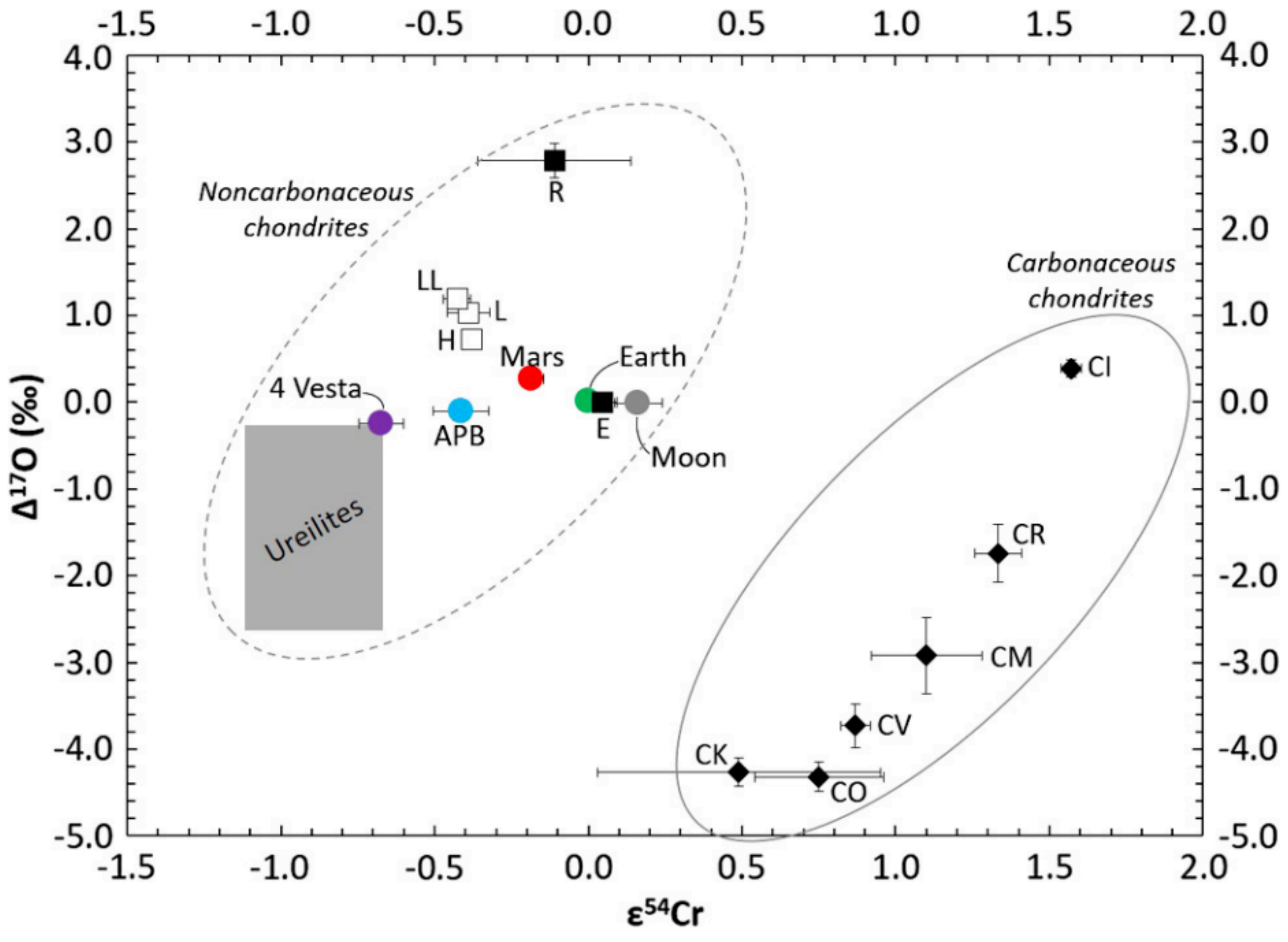


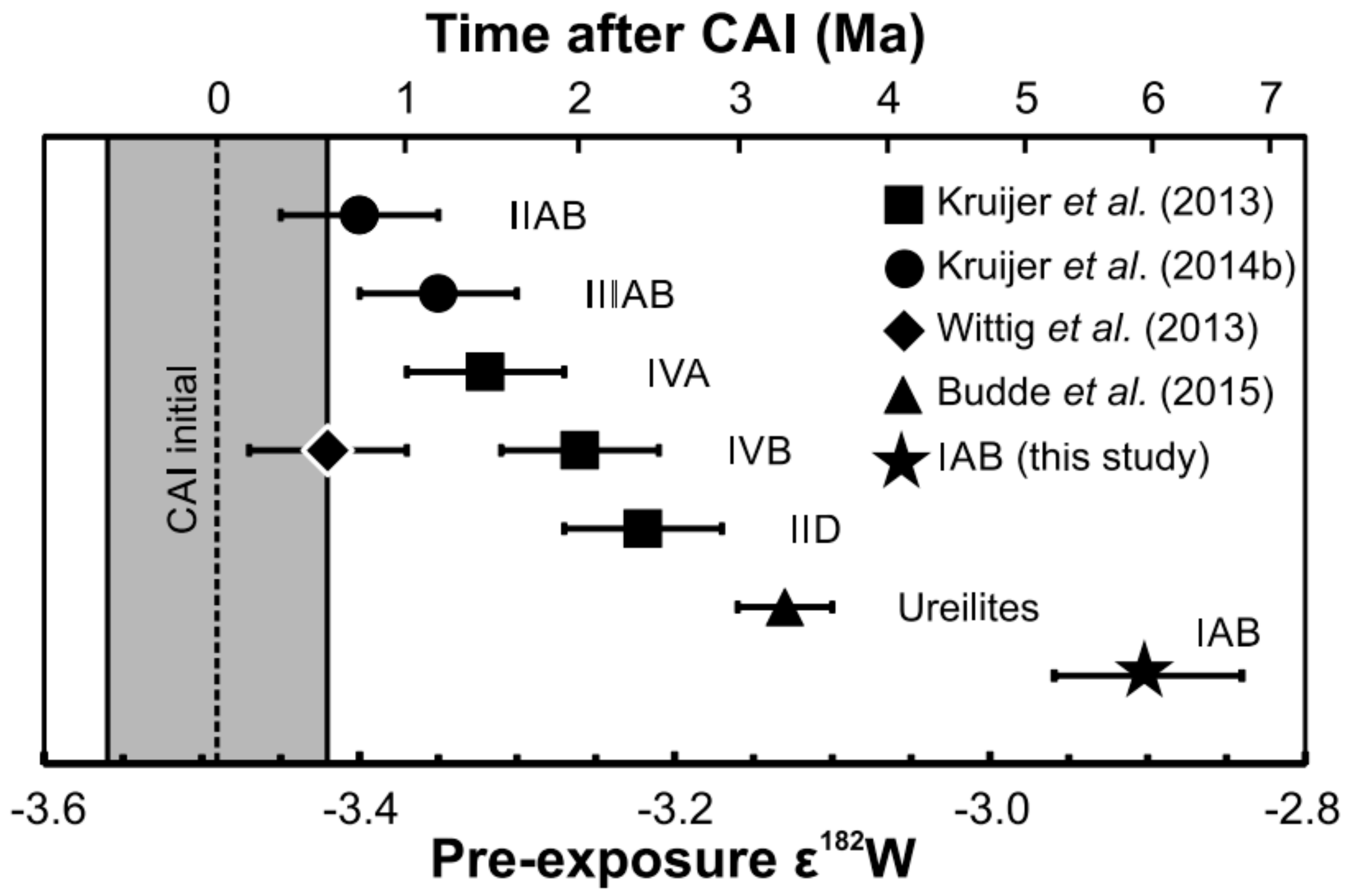


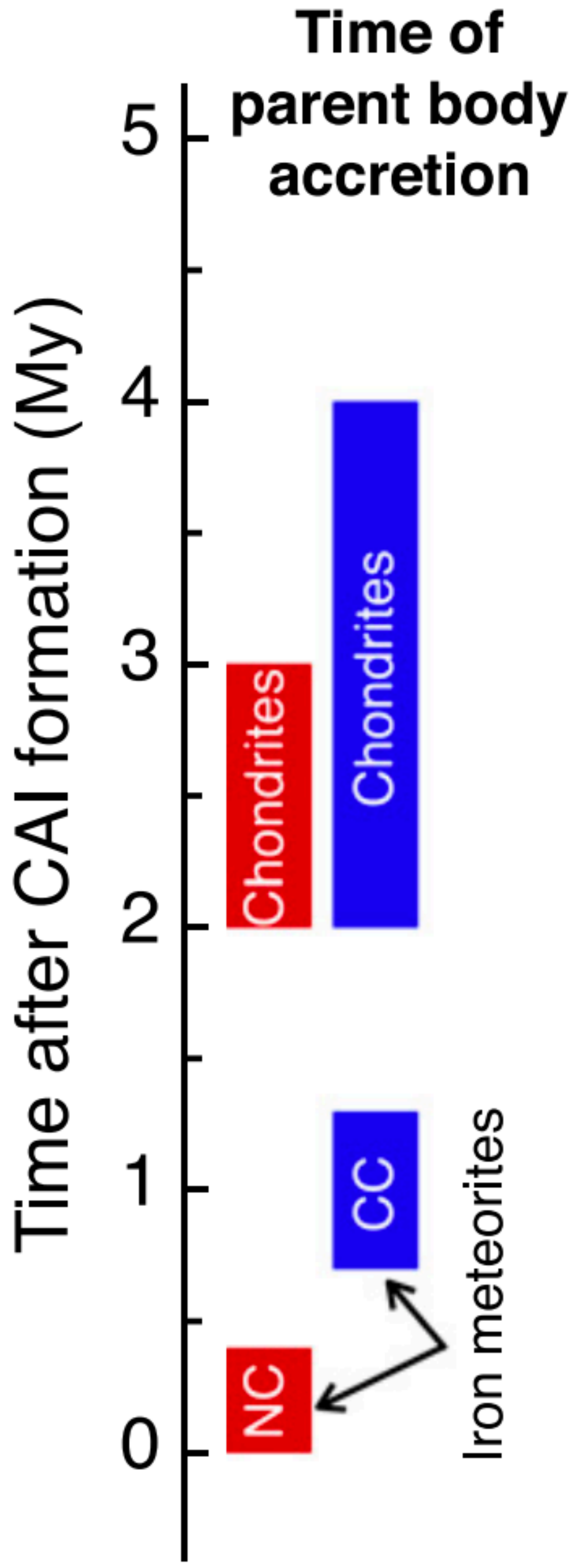
Trinquier+ 07, 09; Warren 11

Hunt, Cook, Lichtenberg+ 18

Early accretion in the Solar System: distinct reservoirs, rapid core formation, compositional trend with orbit



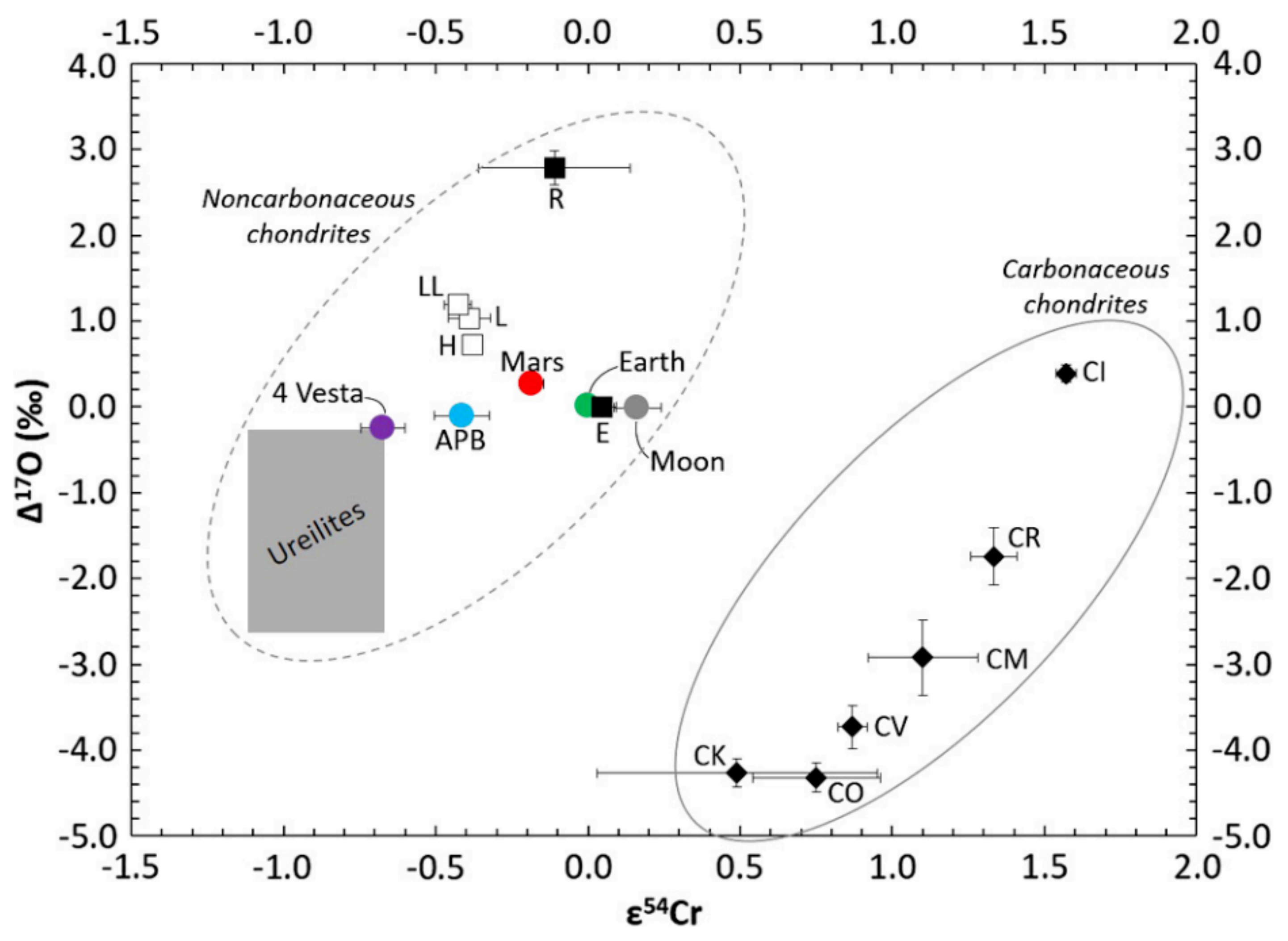


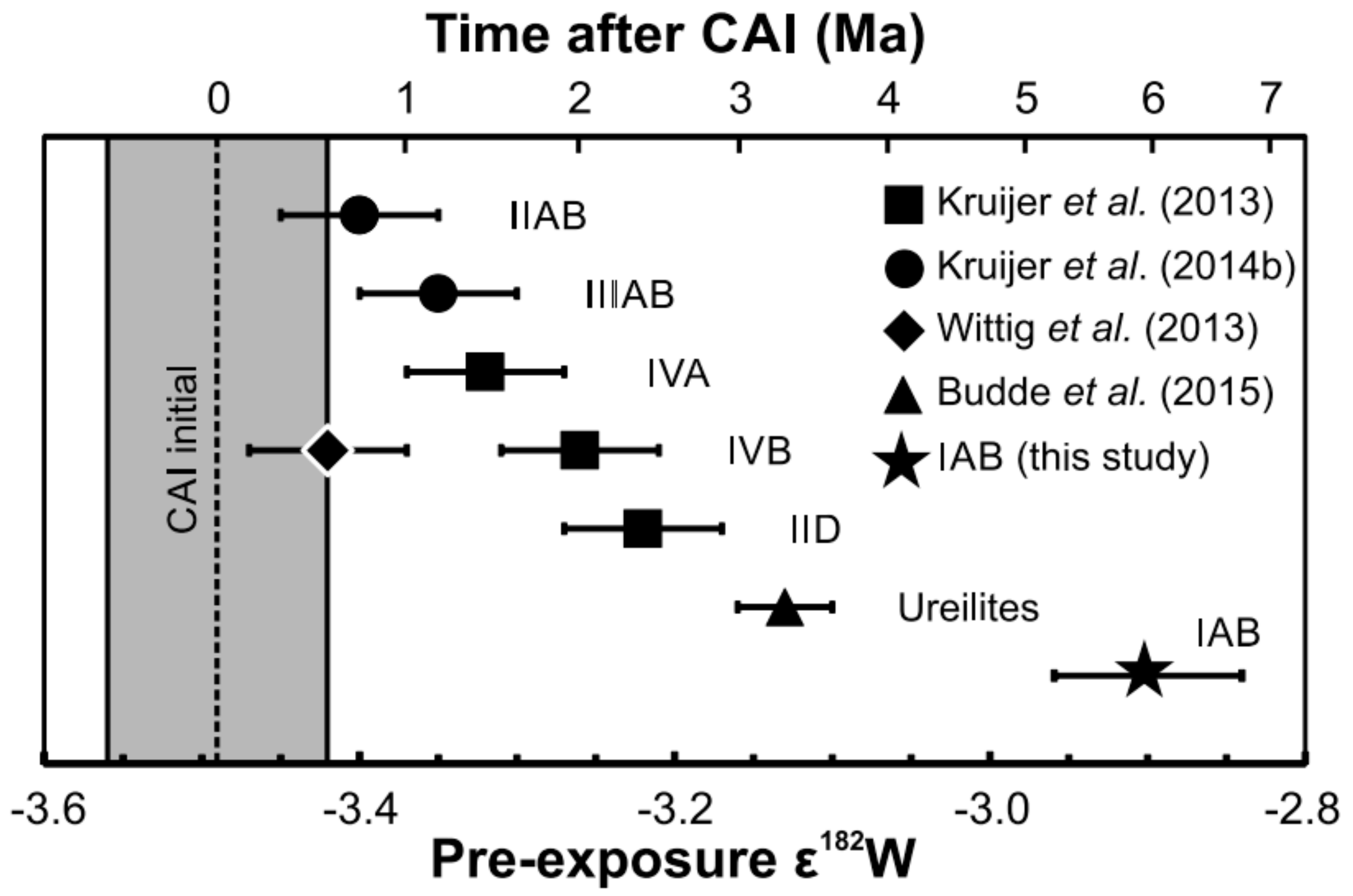


Warren 11, Hunt+ 18

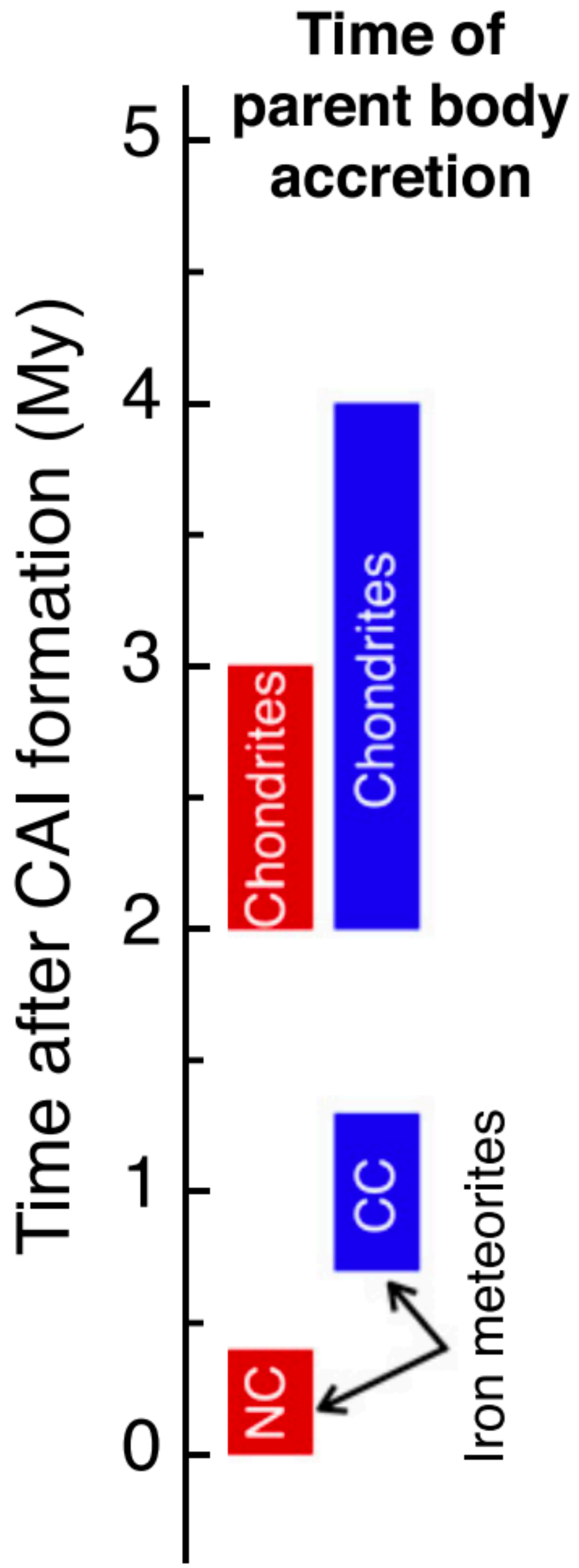
Kruijer+17

Early accretion in the Solar System: distinct reservoirs, rapid core formation, compositional trend with orbit





Warren 11, Hunt+ 18



Kruijer+17

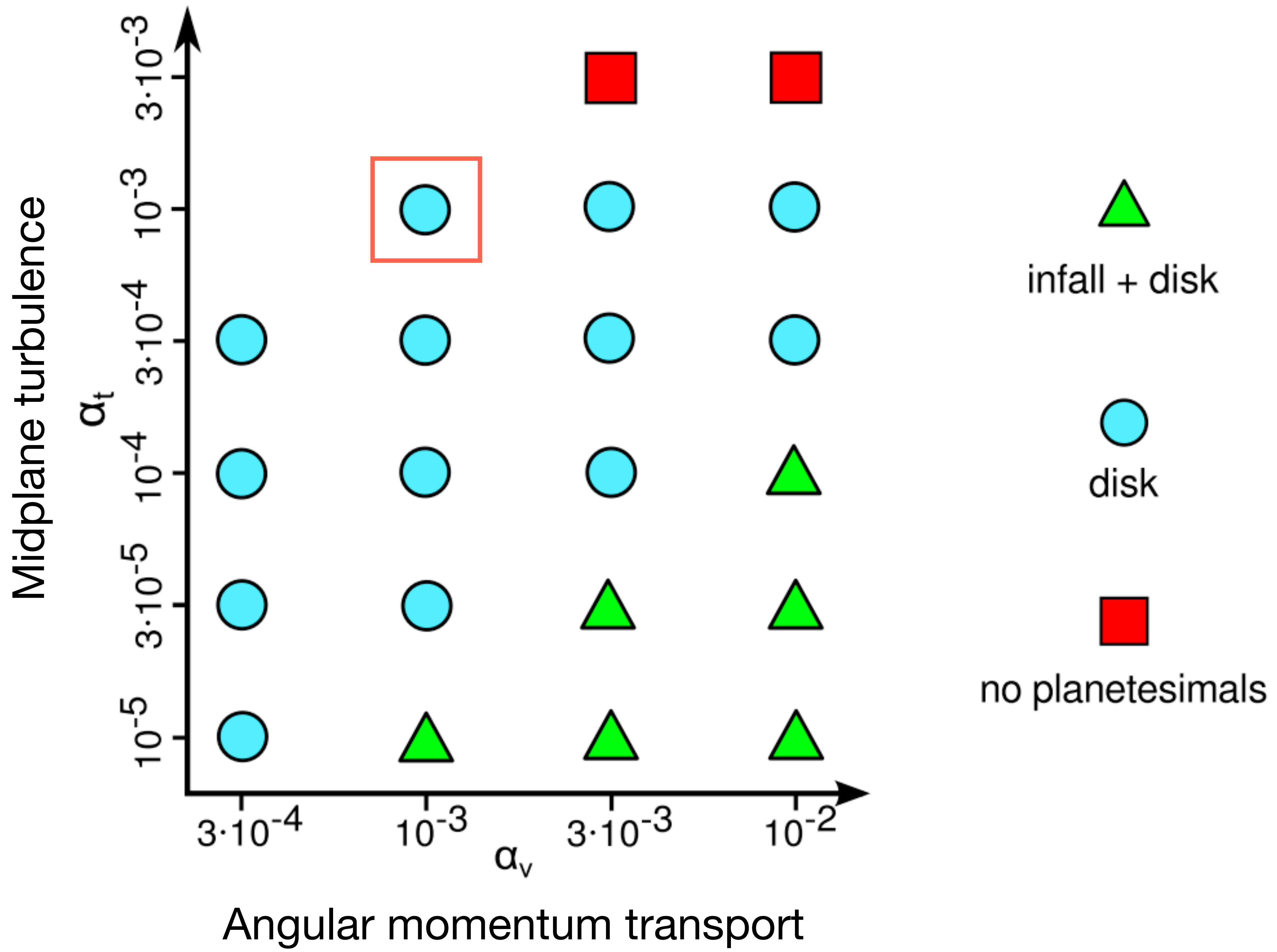
1. Isotopic + compositional dichotomy

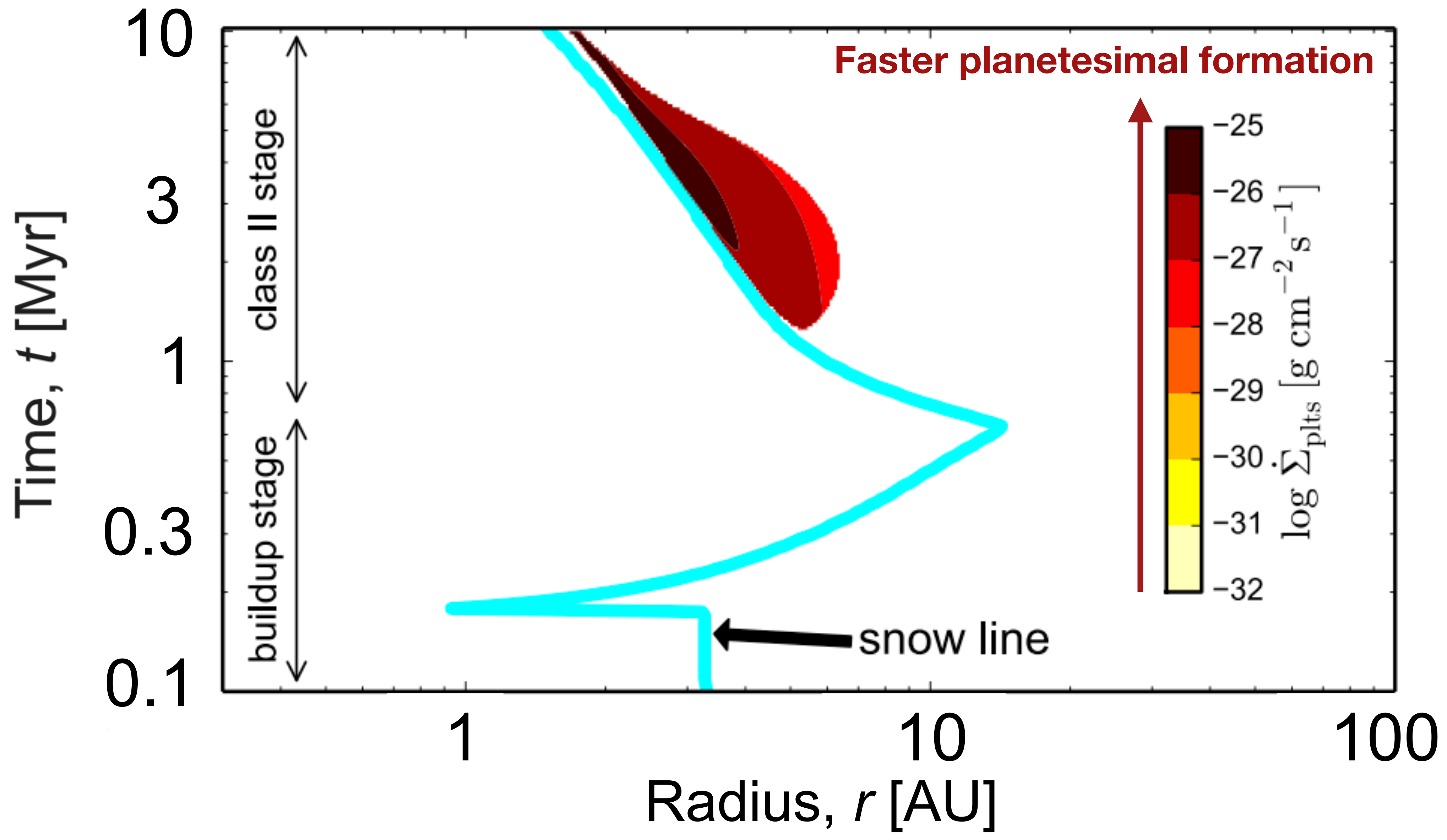
   ➡ Spatial heterogeneity

2. Timing: early vs. late(r) core formation

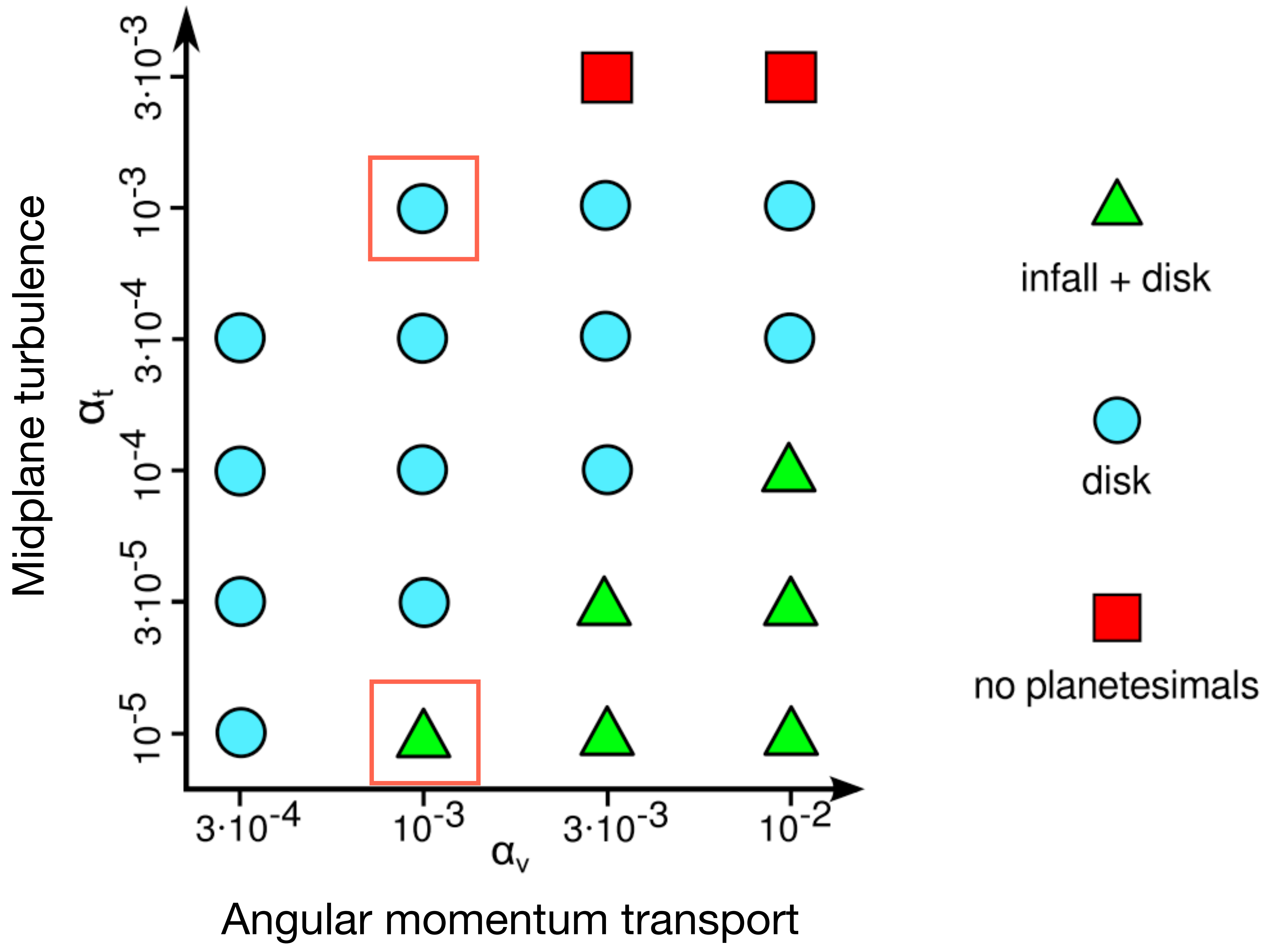
   ➡ Temporal heterogeneity

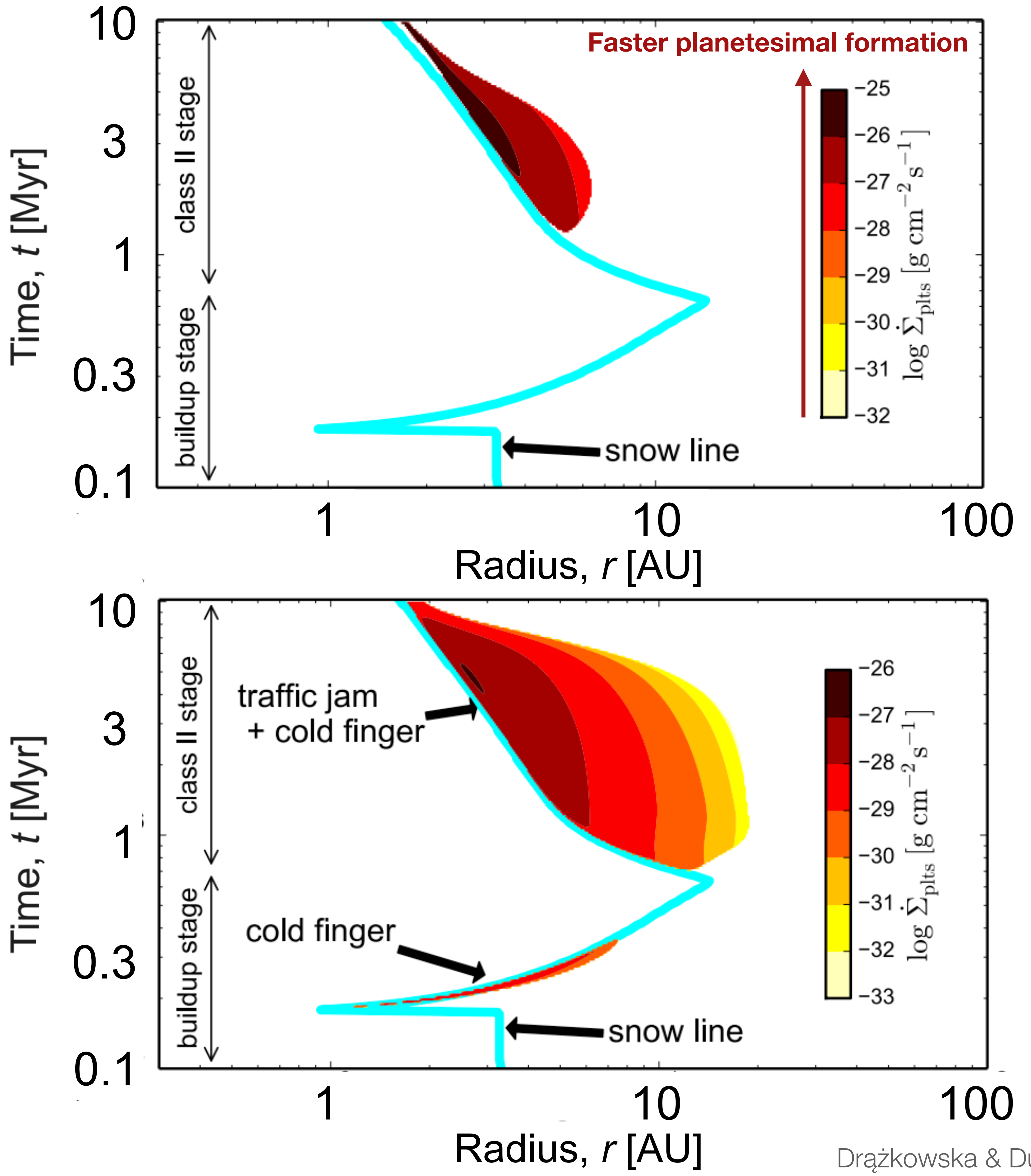
Planetesimal formation in ≈wind-driven disk





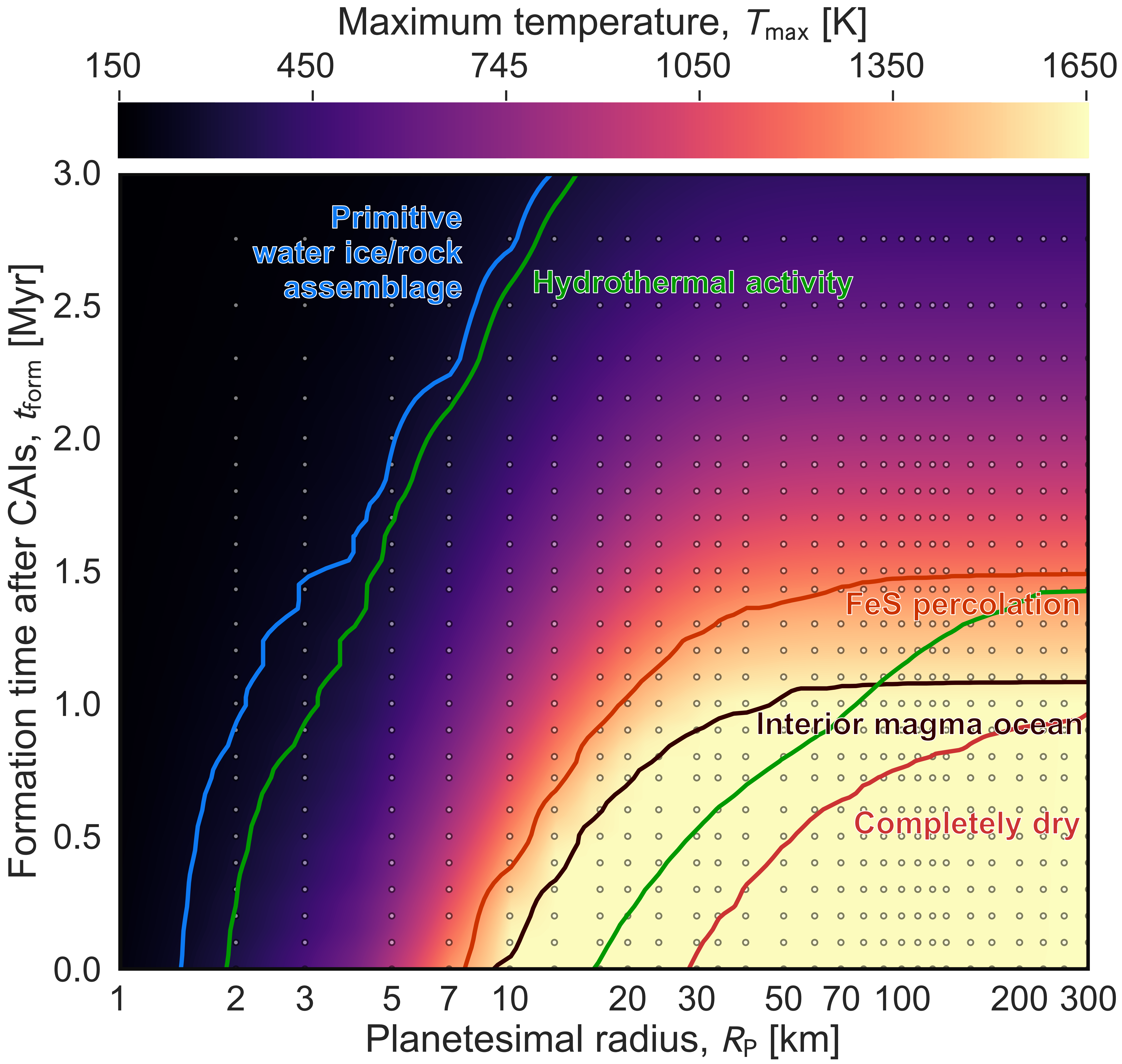
Rapid accretion in midplane-quiescent disks



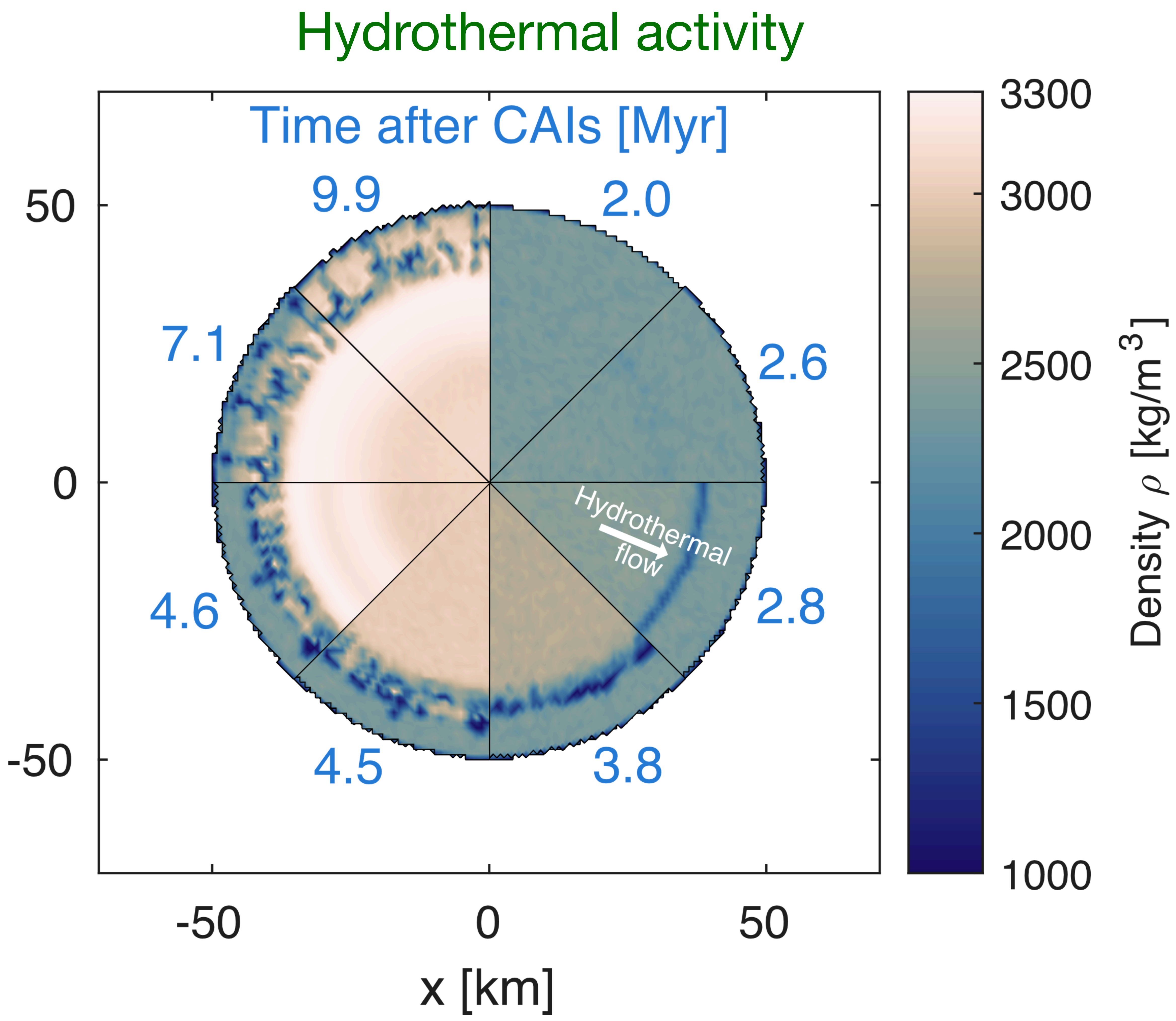


Drążkowska & Dullemond 18

Compositional bifurcation of reservoirs

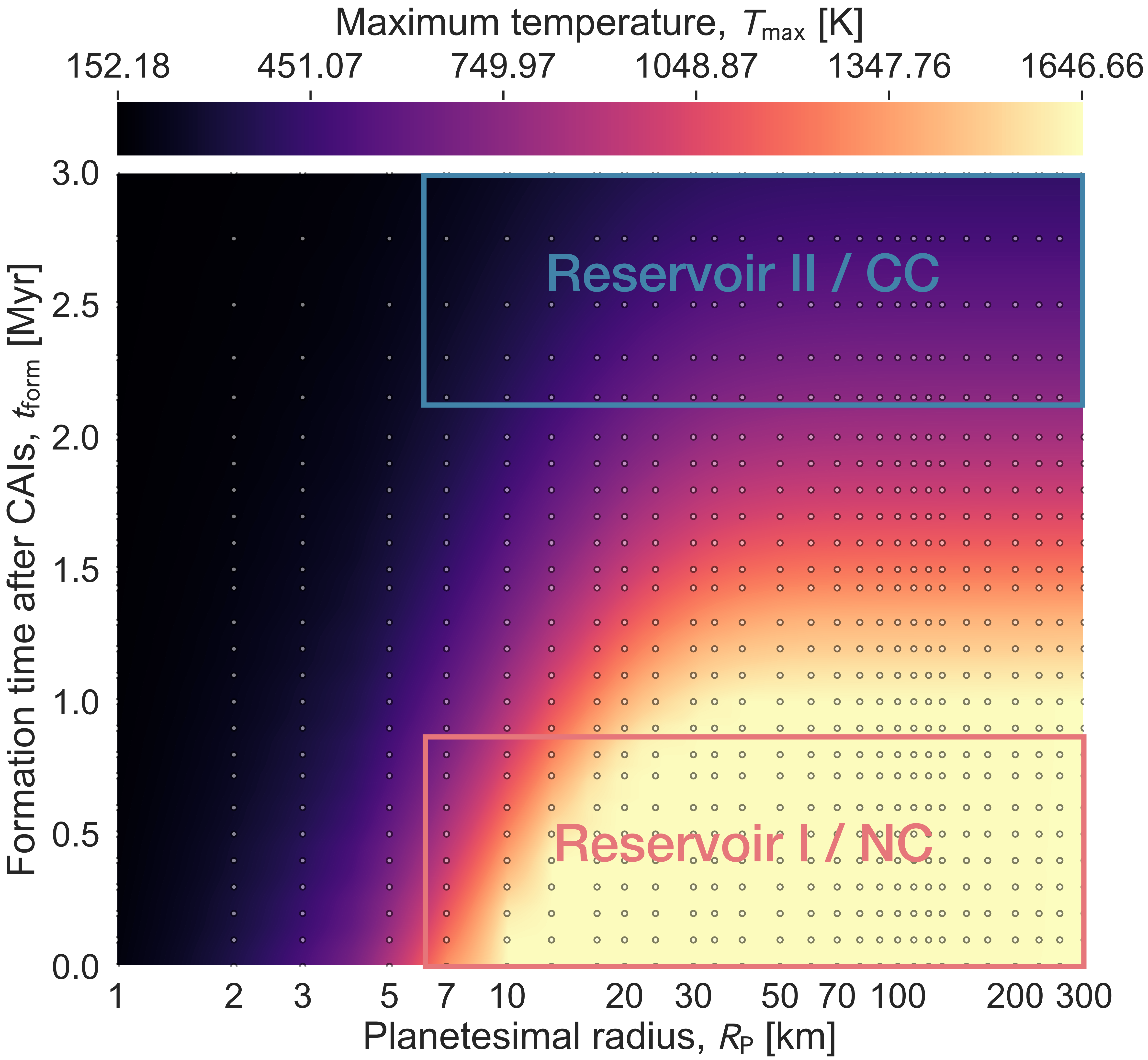


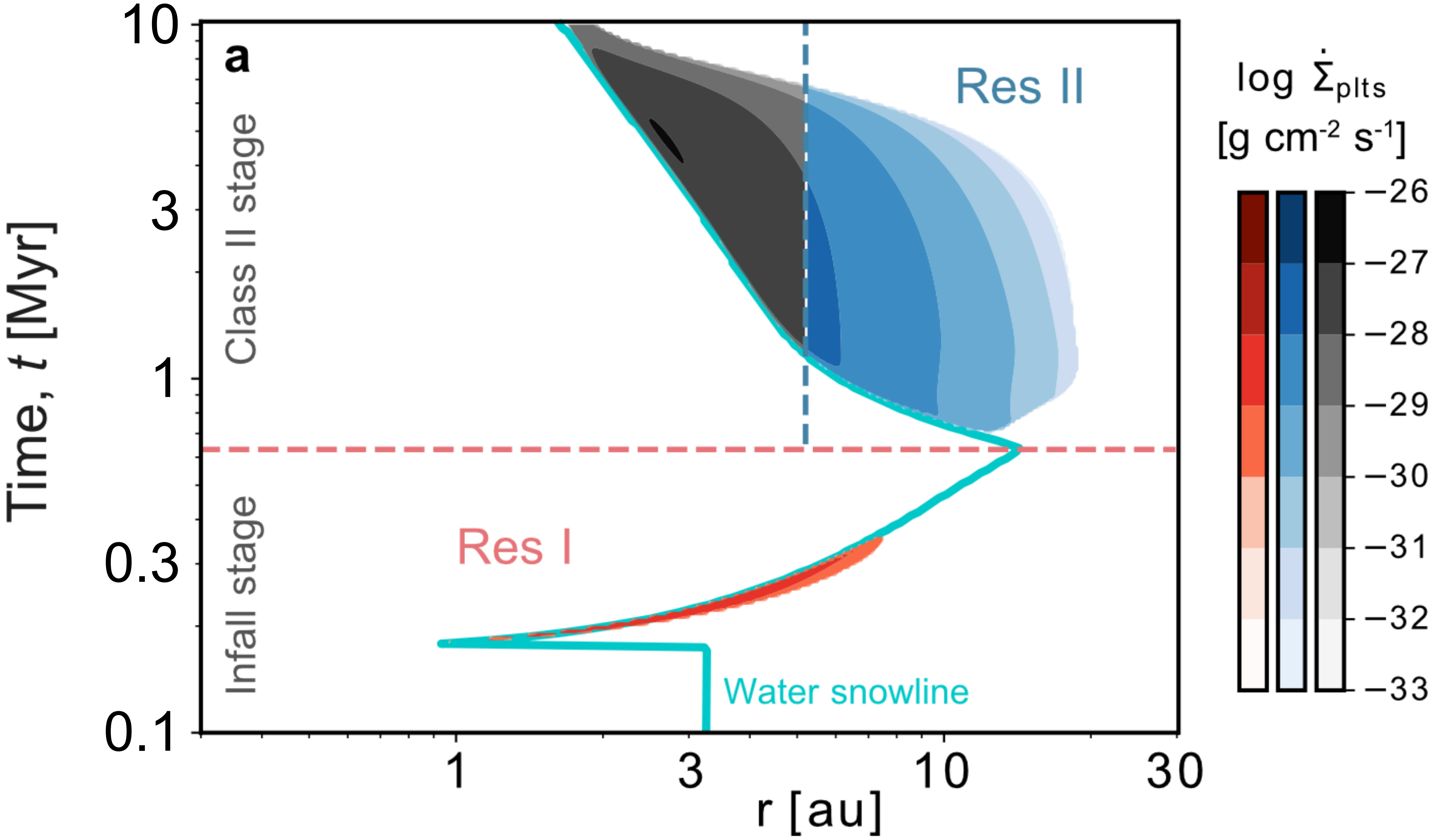
Lichtenberg & Golabek, in prep.



Lichtenberg & Gerya, in prep.

Compositional bifurcation of reservoirs



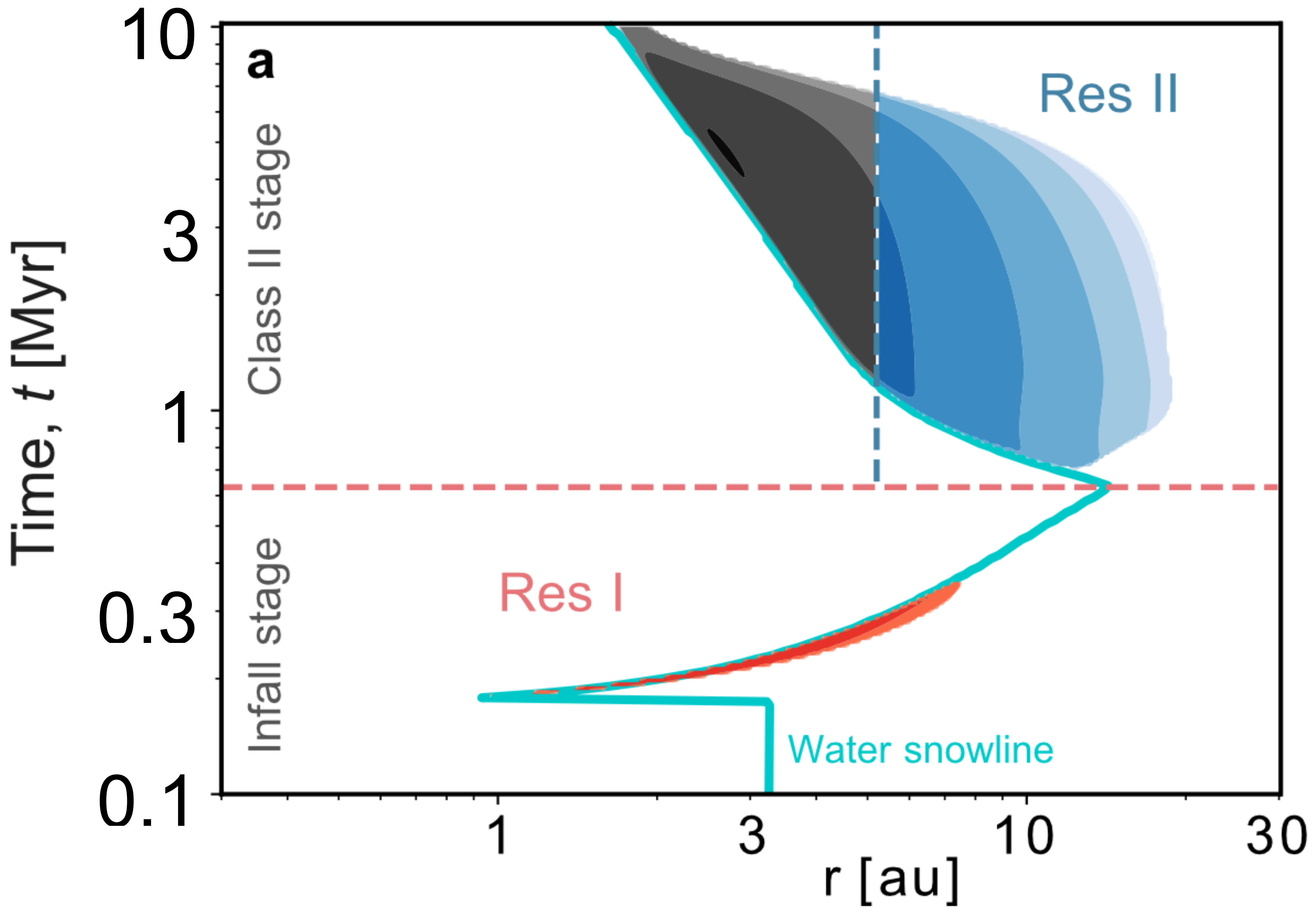


Lichtenberg, Drążkowska, Schönbächler, Golabek, Hands, in prep.

Compositional bifurcation of reservoirs

Lichtenberg, Drążkowska, Schönbächler, Golabek, Hands, in prep.

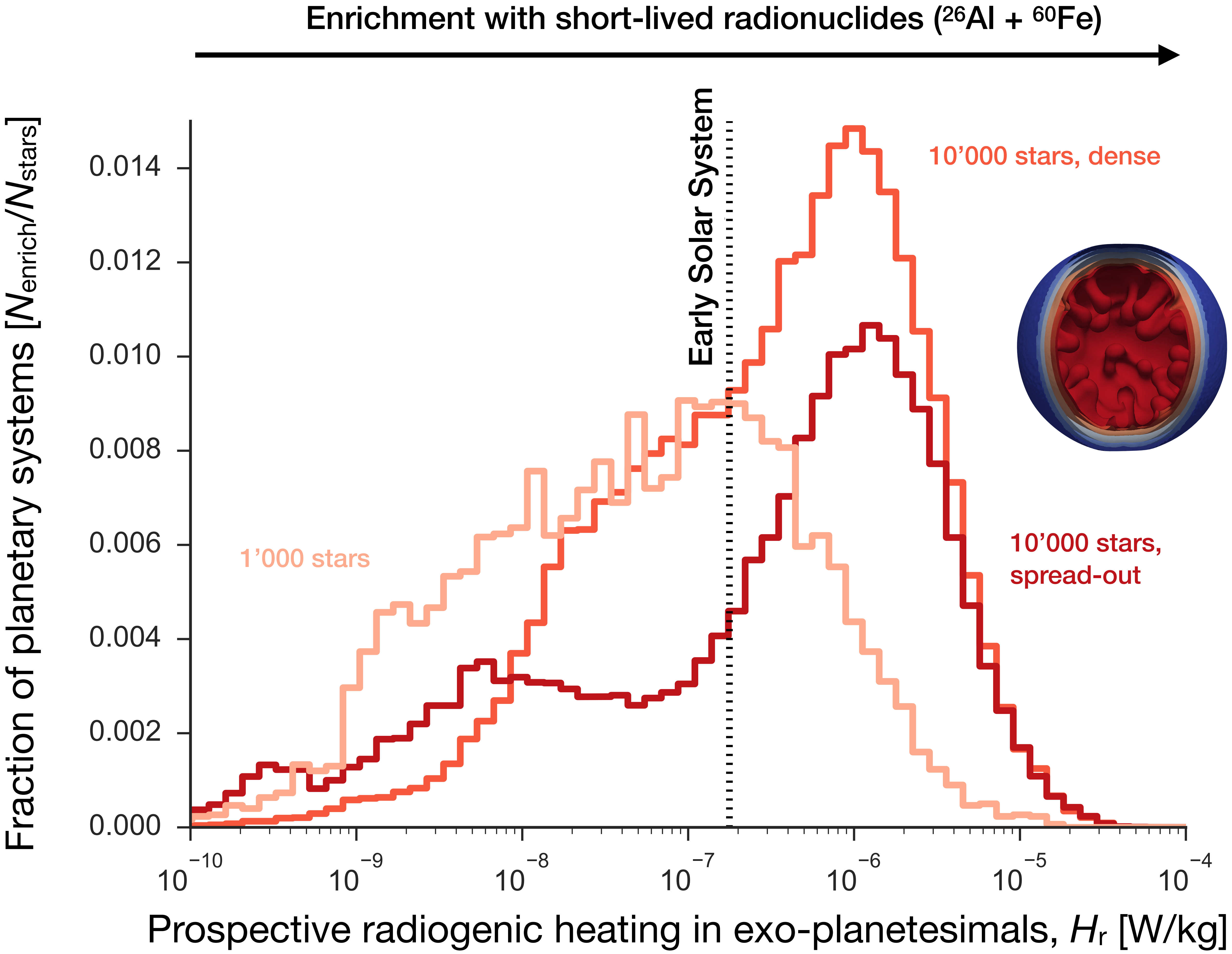
Solar System: earliest bifurcation of planetary building blocks?



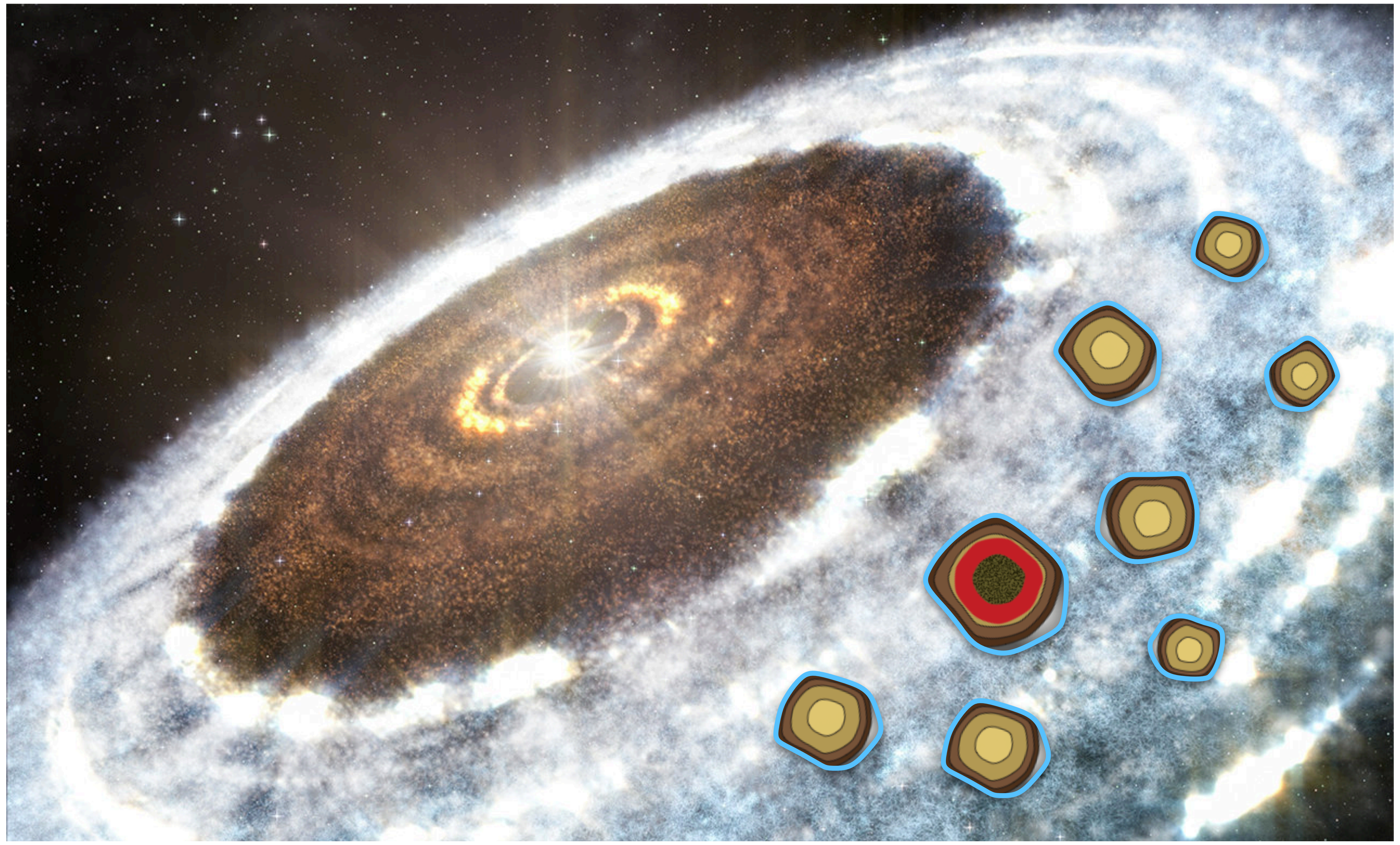
- Reservoir separation induced by protoplanet seeding
  - Not dependent on the presence of Jupiter, but *causing* its nucleation and growth
- Rocky planets seeded *before* giant planets
- Water accretion sequence to inner Solar System: water-depleted ➡ dry ➡ water-rich
  - Qualitatively reproduces latest geochemical constraints < 4 Myr (Sarafian+17a,b; Peslier+ 17; Piani+ 17,18; McCubbin & Barnes 19)
- Suggests cause for absence of super-Earths in Solar System
- Connects accretion sequence to observable disk parameters

Lichtenberg, Drążkowska, Schönbächler, Golabek, Hands, in prep.

^{26}Al variability across planetary systems



^{26}Al-heated icy planetesimals forming planets

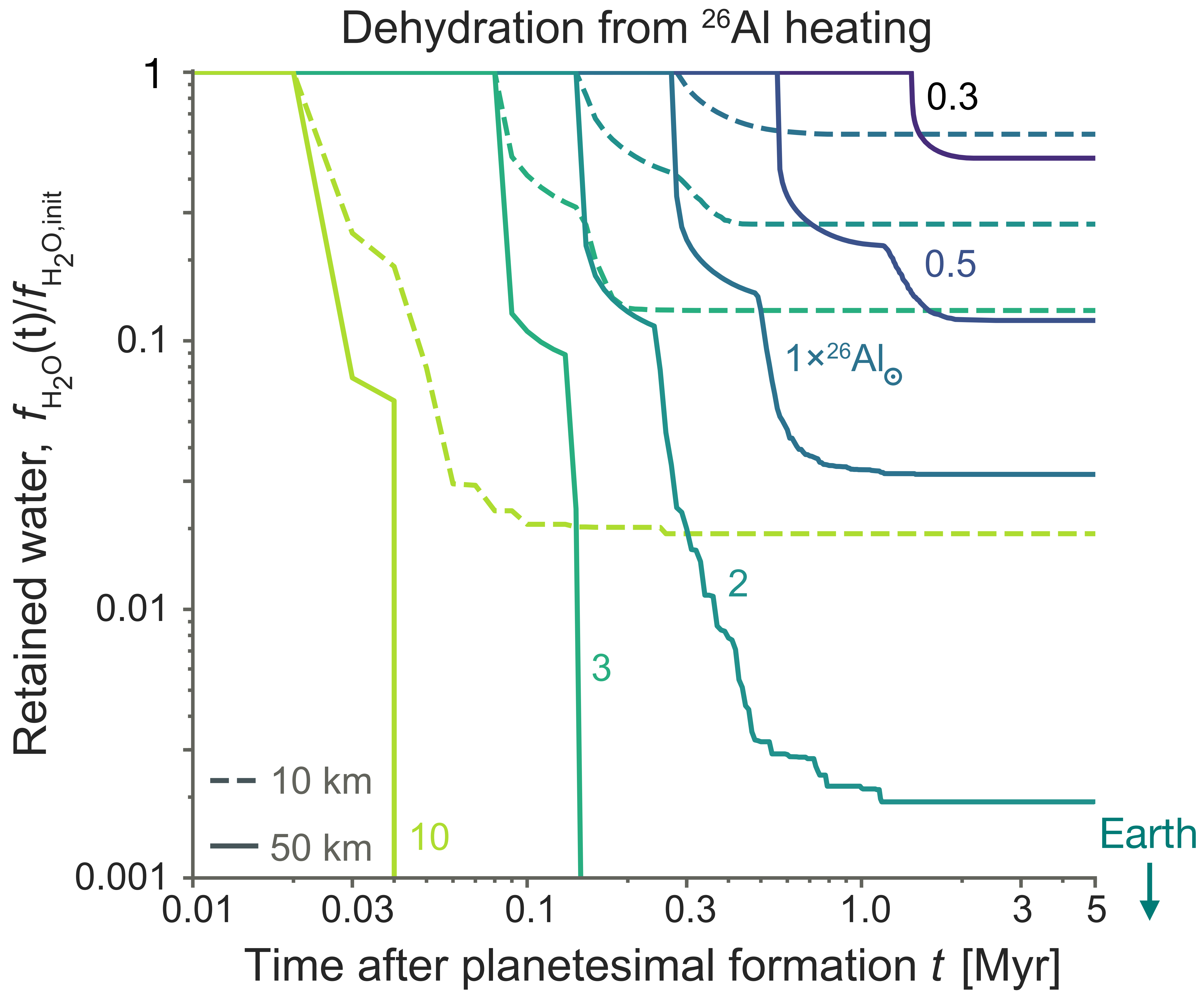


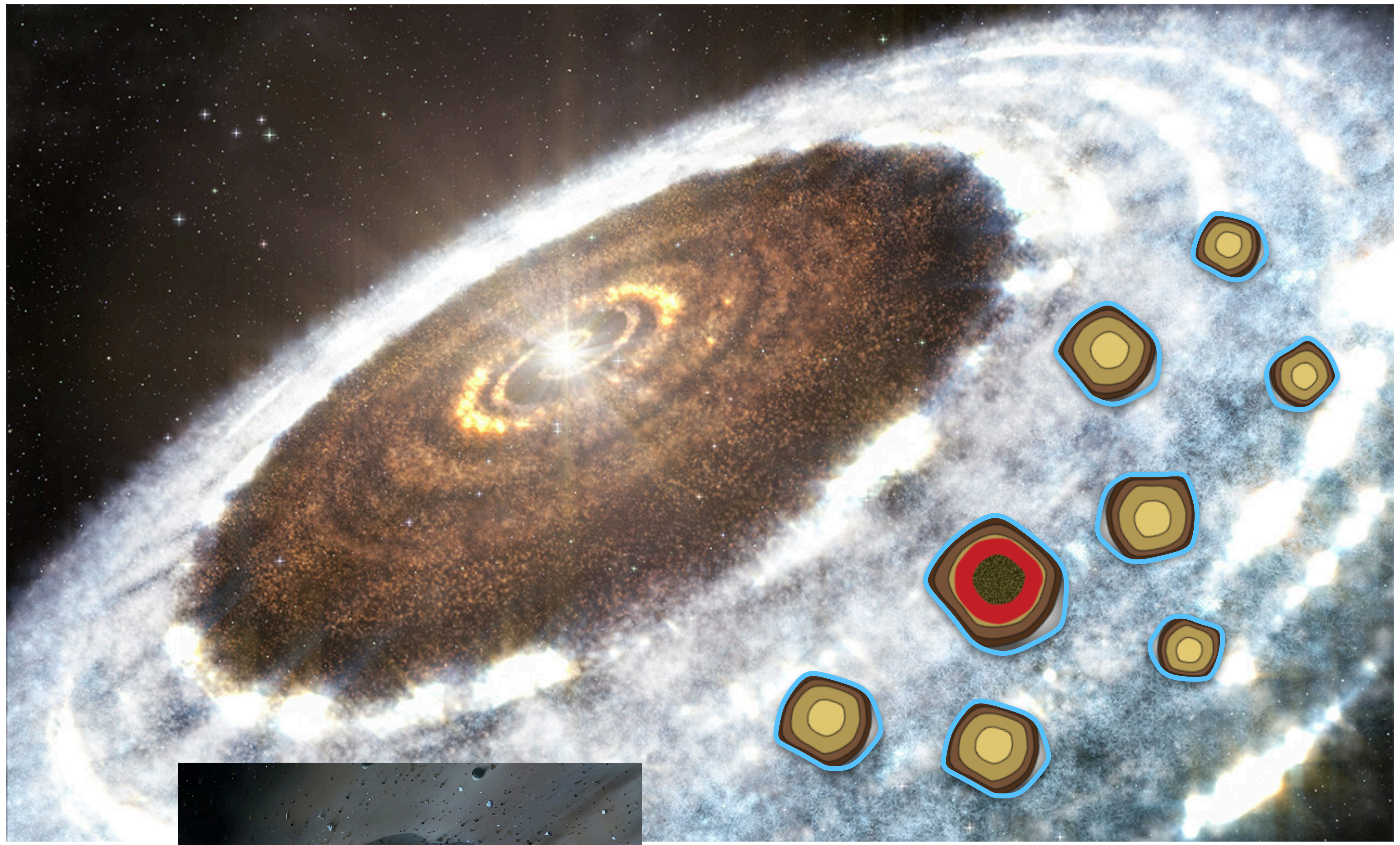
≈ 10^2—10^8 × Earth's present-day interior radiogenic heating

Lichtenberg+ 16b, Parker+ 14,15,17, Gaidos+ 09, Pfalzner+ 15, Kuffmeier+ 16, Lugaro+ 18

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

Getting rid of the water: radiogenic heating

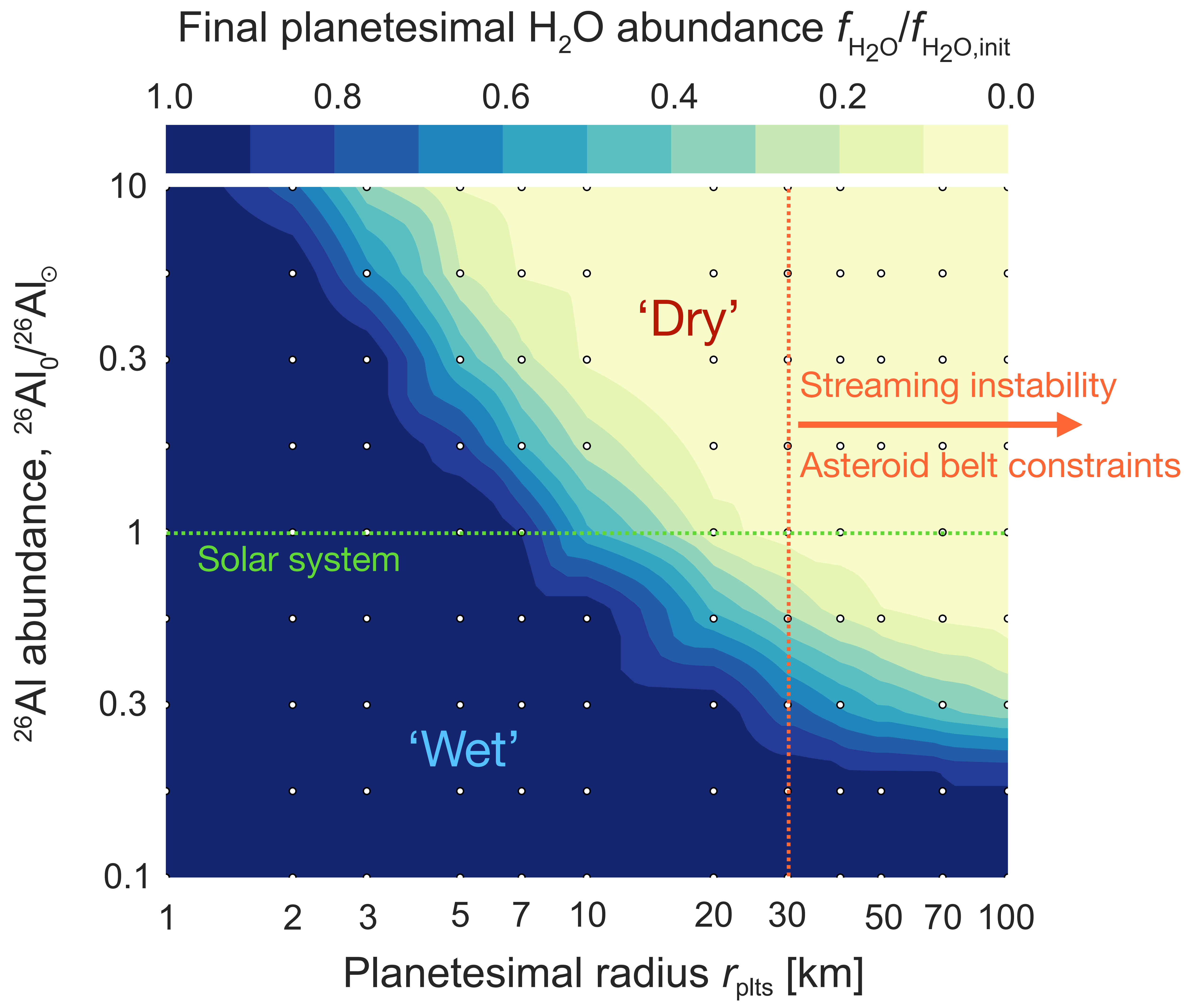




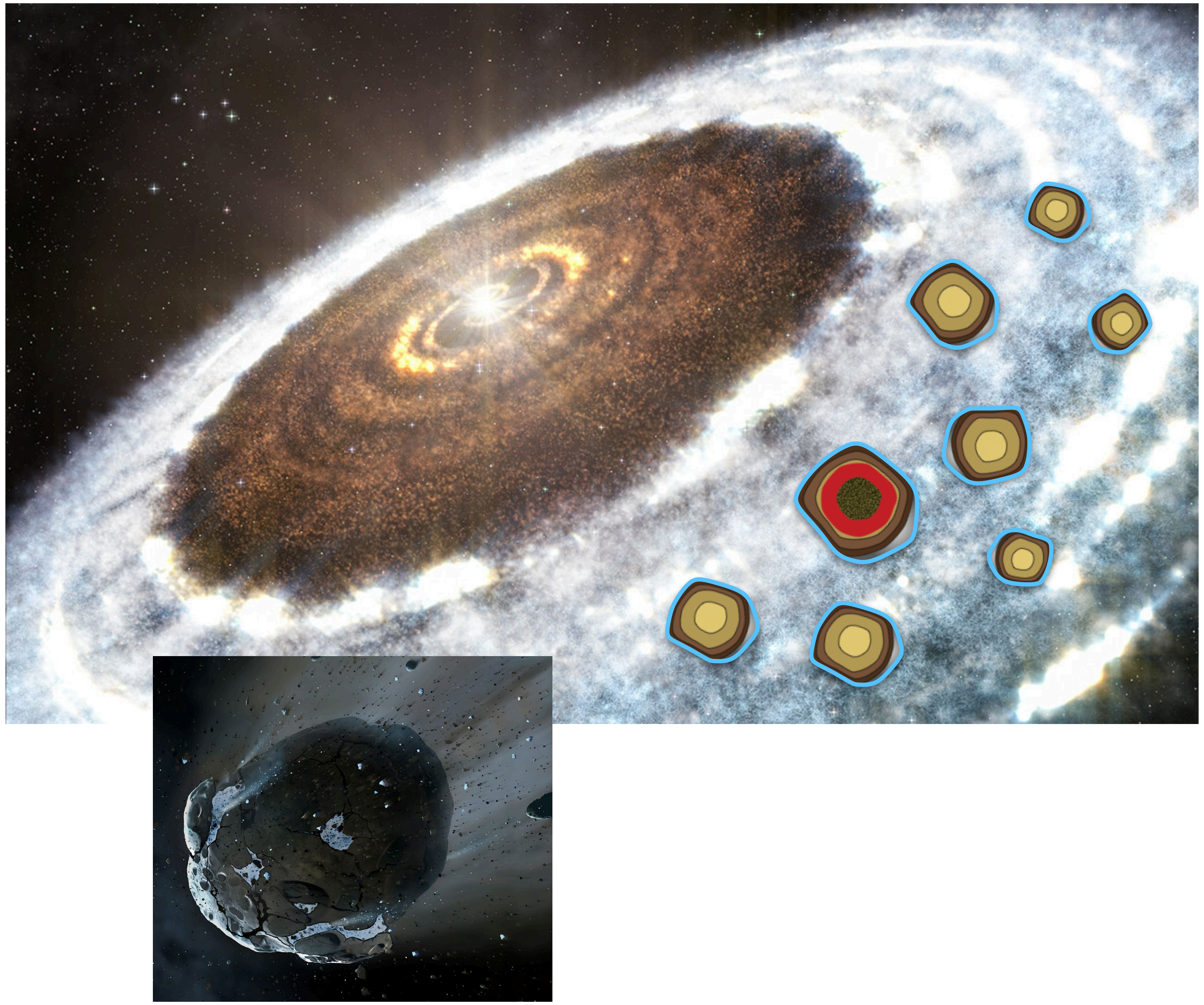
Lichtenberg+ 19b

A. Angelich (NRAO/AUI/NSF)/ALMA (ESO/NAOJ/NRAO); ESA/NASA/M.A.Garlick

Rapid dehydration of water-rich planetesimals



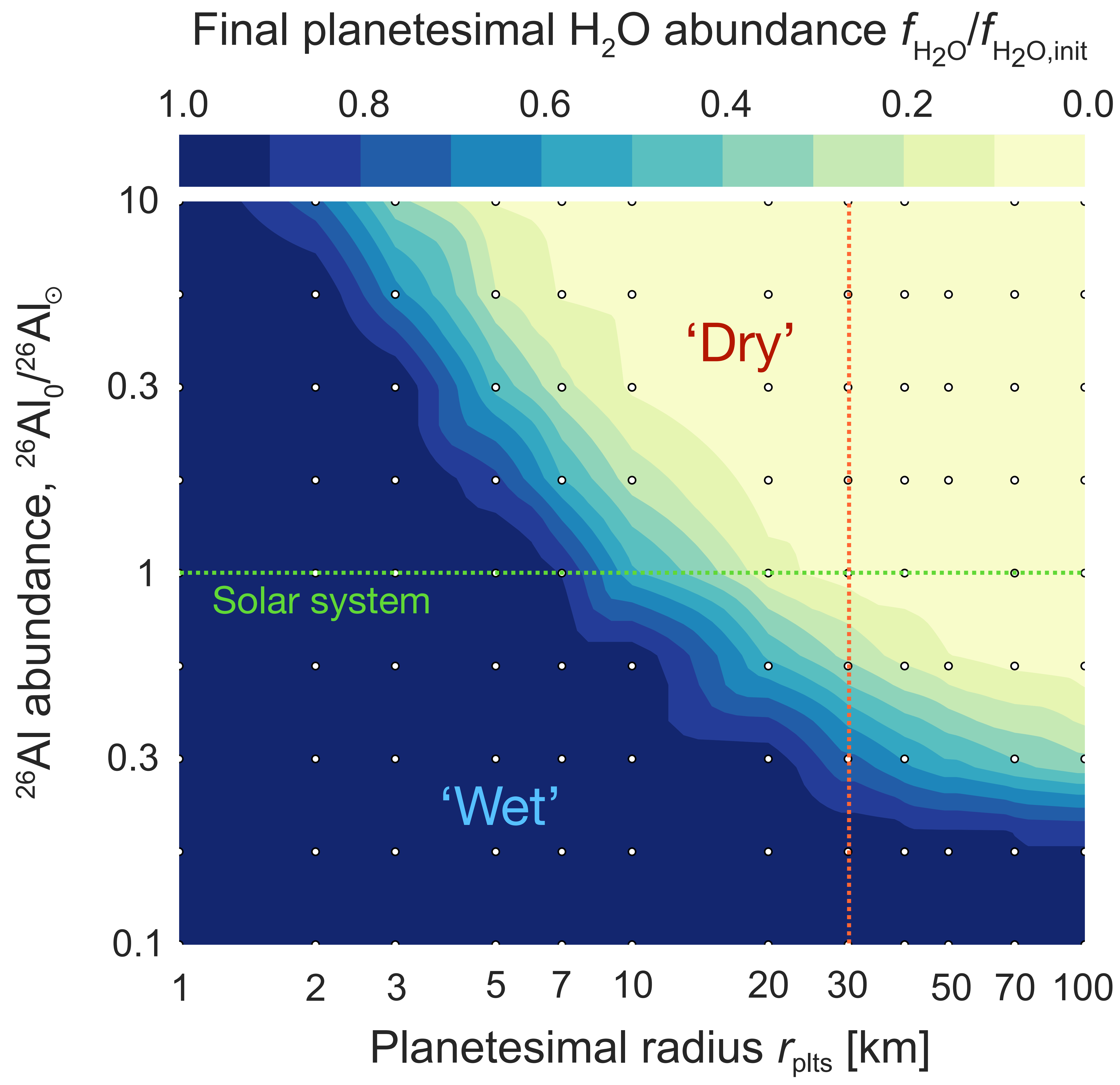
^{26}Al-heated icy planetesimals forming planets



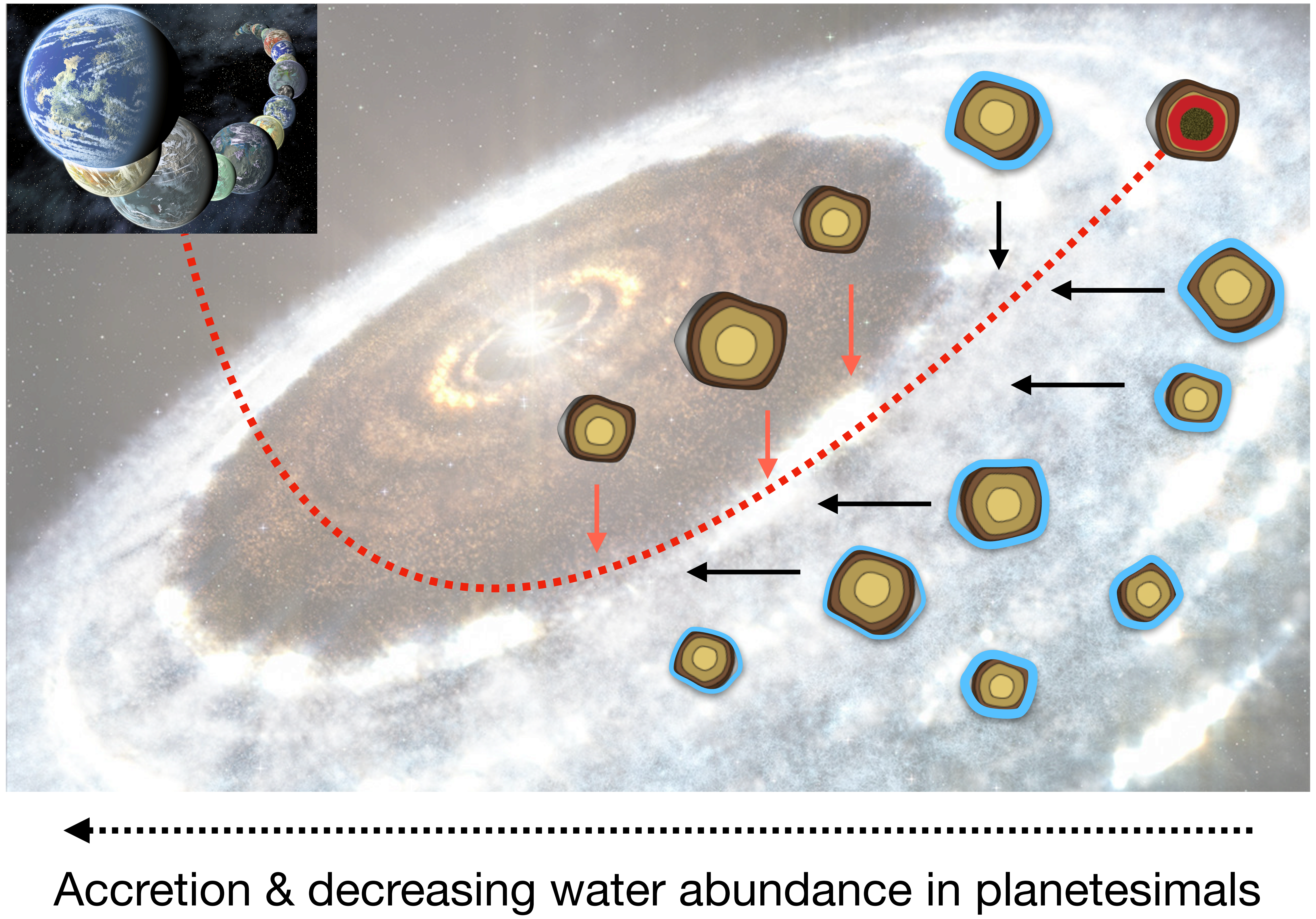
Lichtenberg+ 19b

A. Angelich (NRAO/AUI/NSF)/ALMA (ESO/NAOJ/NRAO); ESA/NASA/M.A.Garlick

^{26}Al controls bulk water content



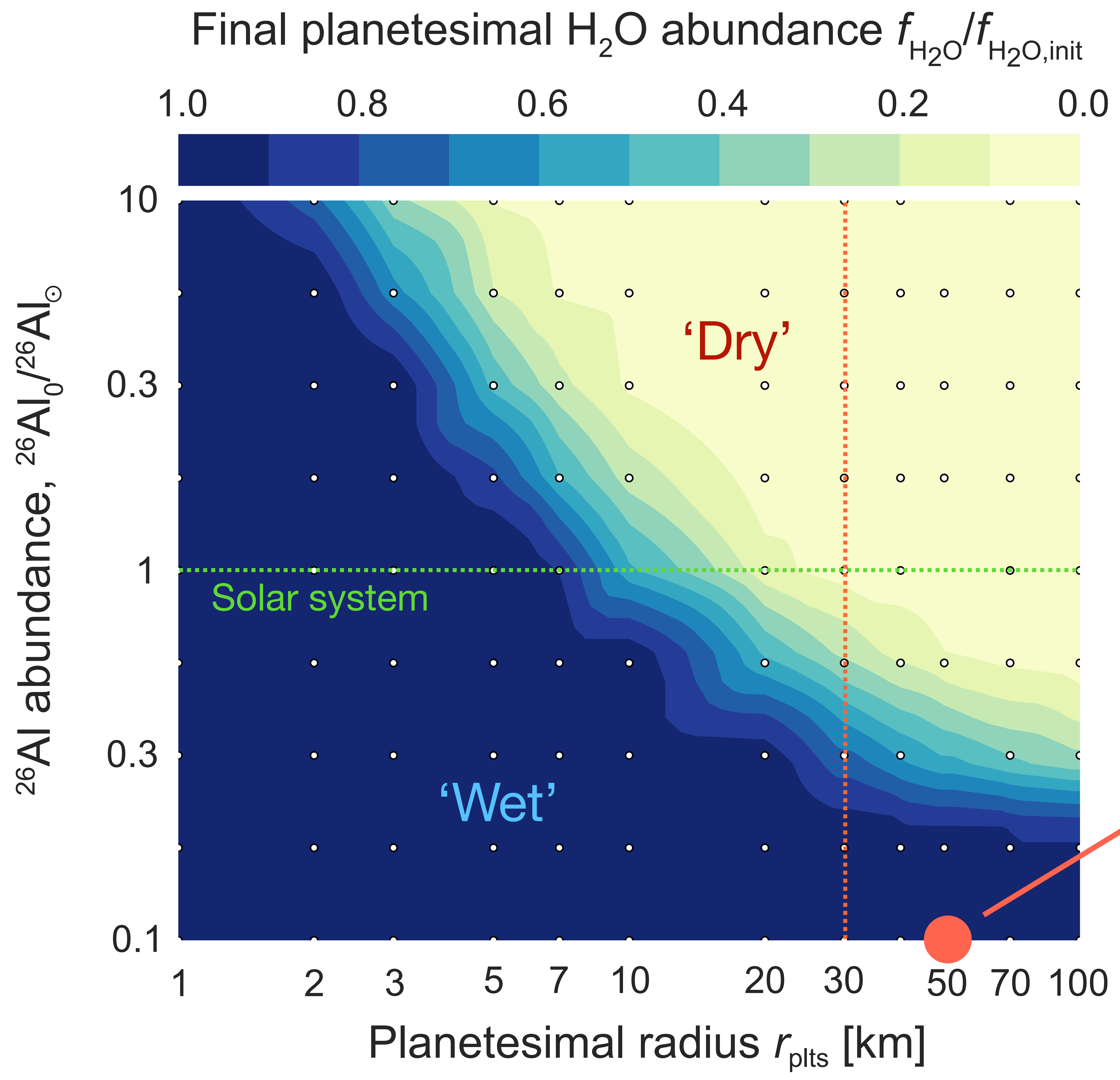
Synthetic exoplanet populations

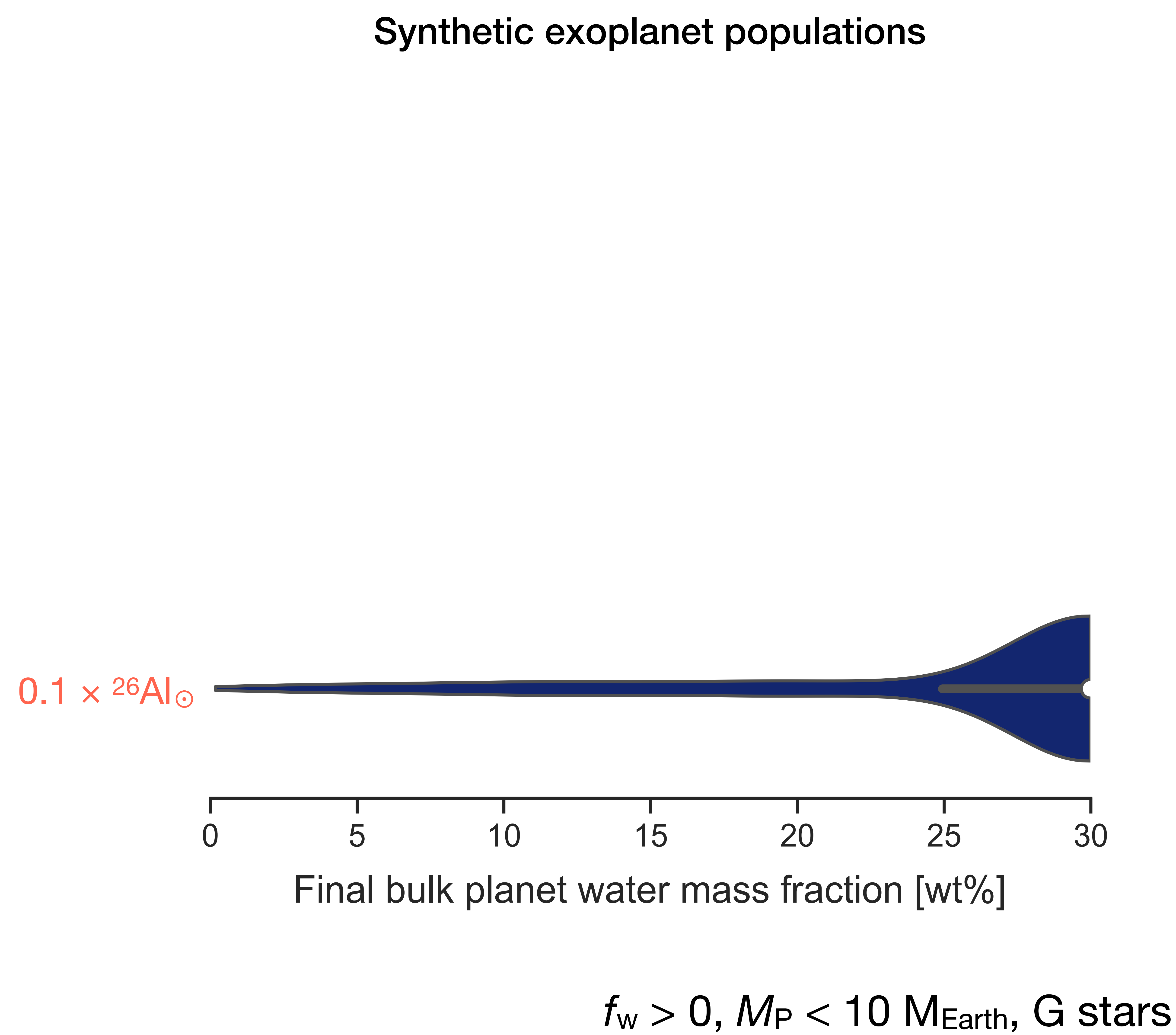


Lichtenberg+ 19b

Benz+14, PPVI

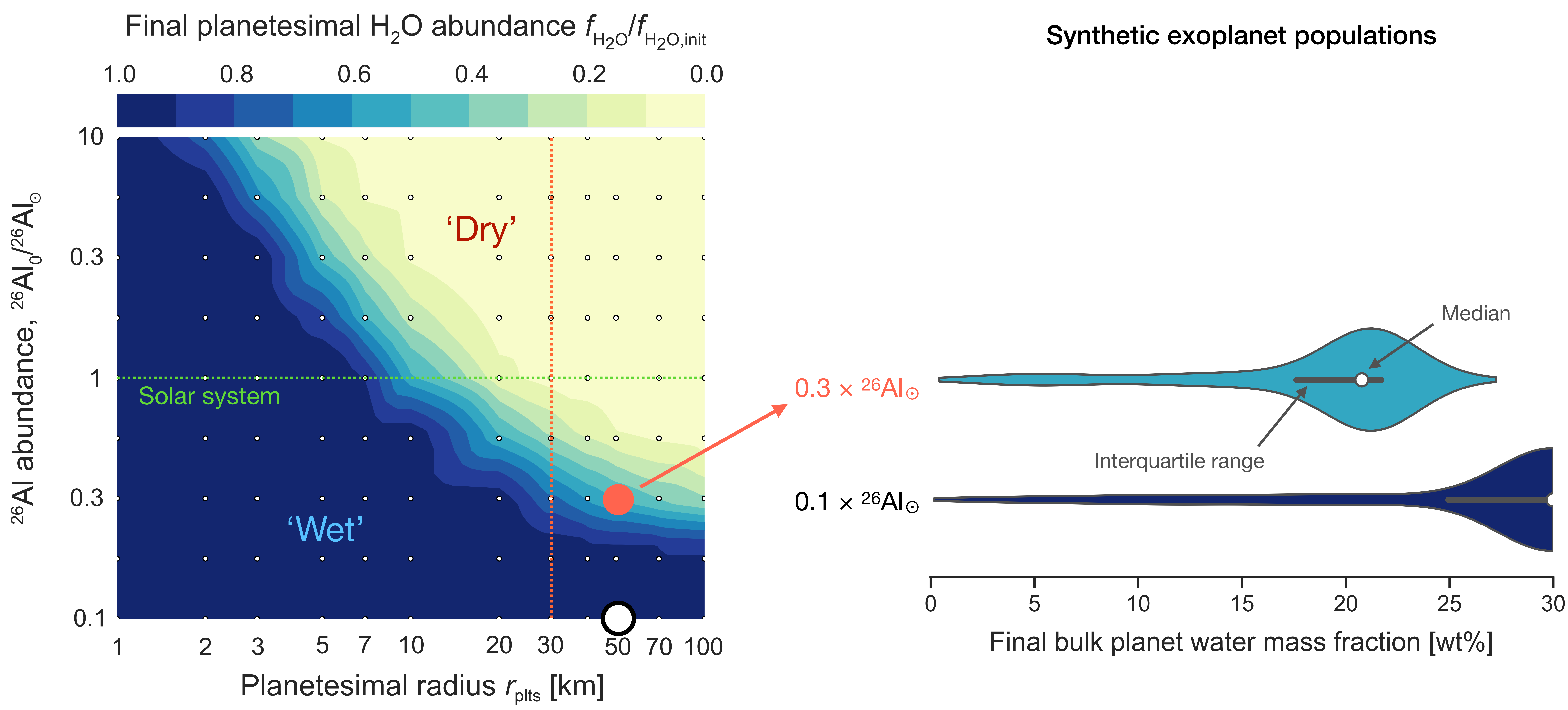
^{26}Al controls bulk water content





Lichtenberg+ 19b

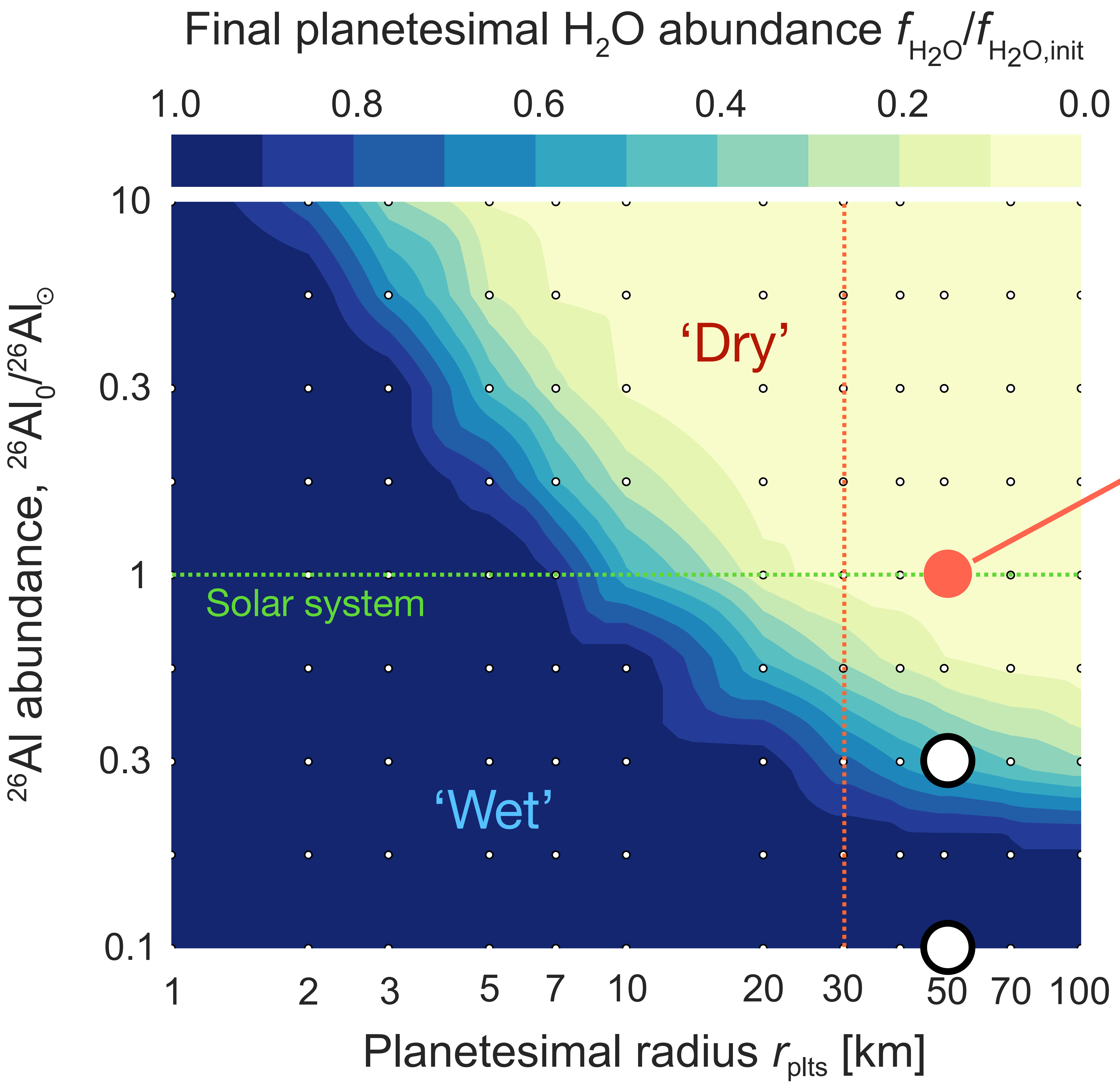
^{26}Al controls bulk water content

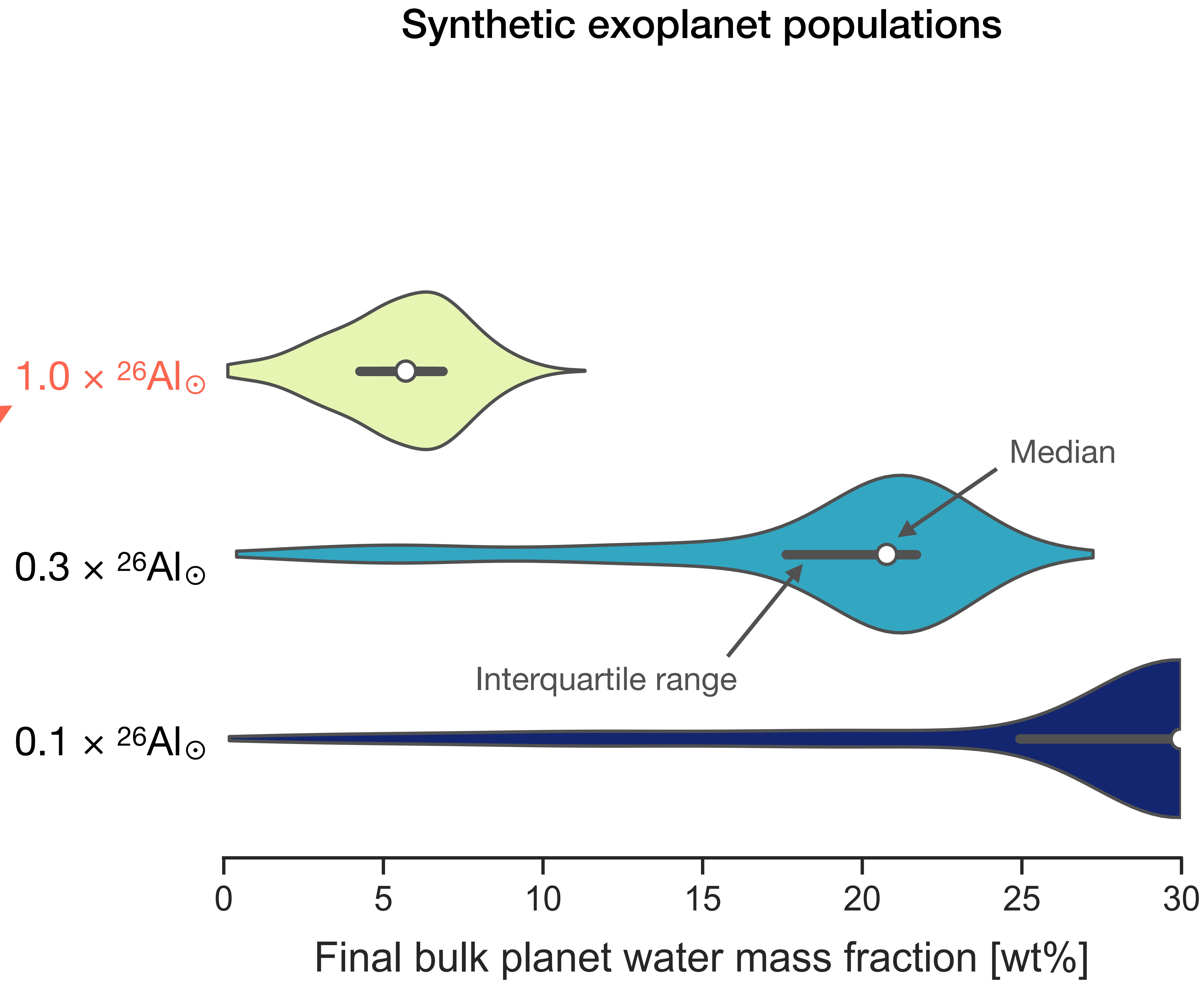


Lichtenberg+ 19b

$f_W > 0$, $M_P < 10\ M_{Earth}$, G stars

^{26}Al controls bulk water content

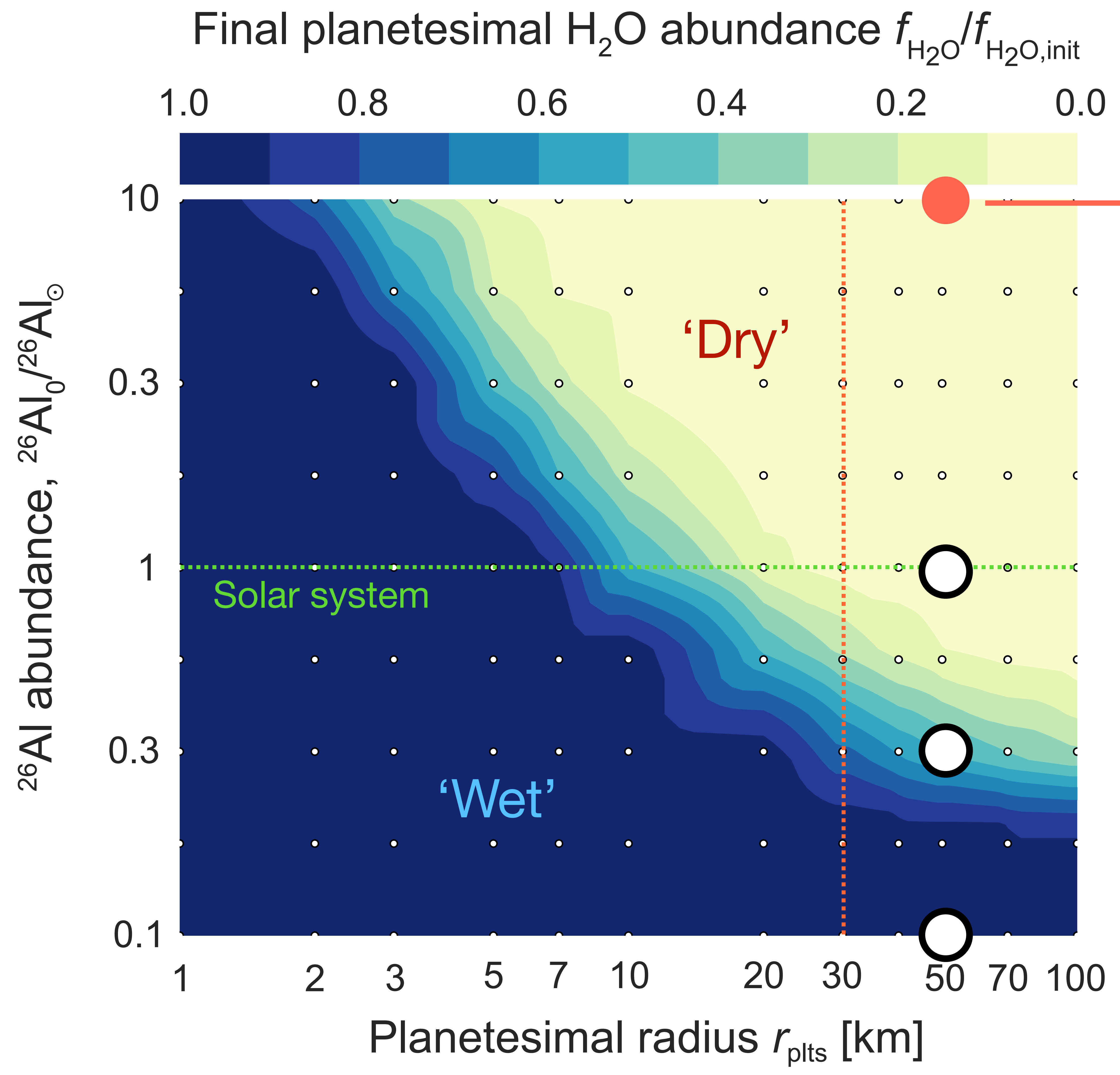


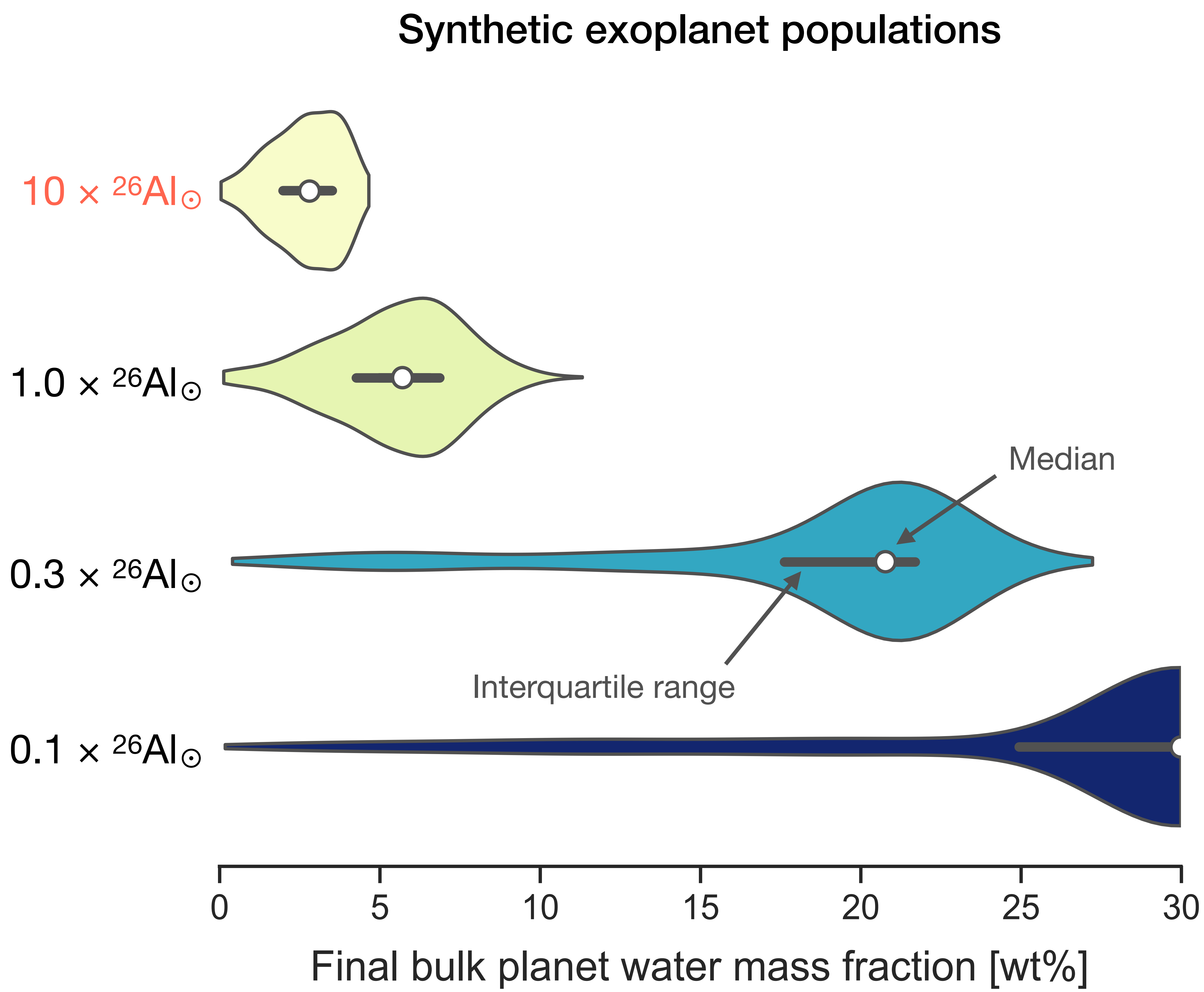


$f_W > 0$, $M_P < 10\ M_{Earth}$, G stars

Lichtenberg+ 19b

^{26}Al controls bulk water content



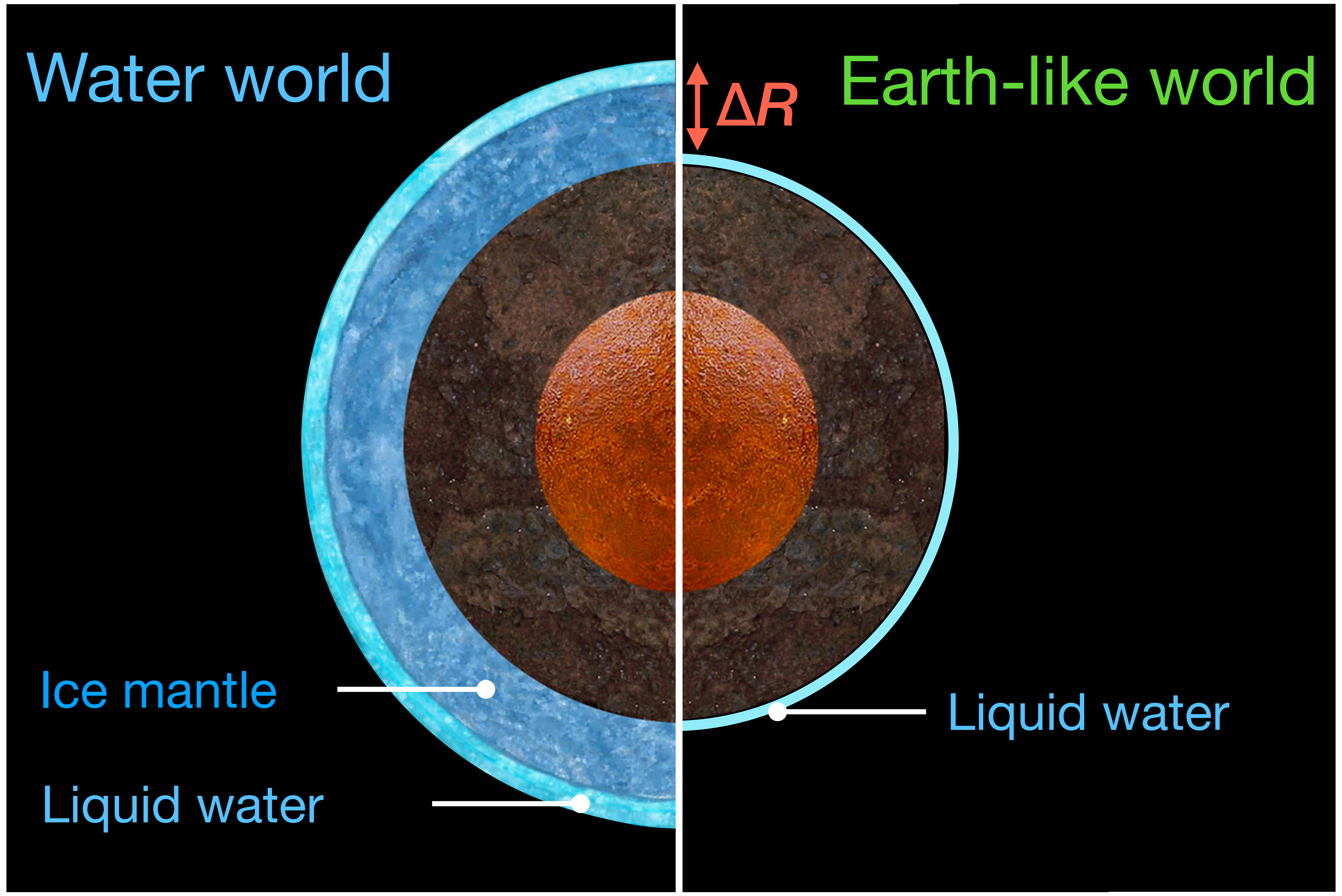


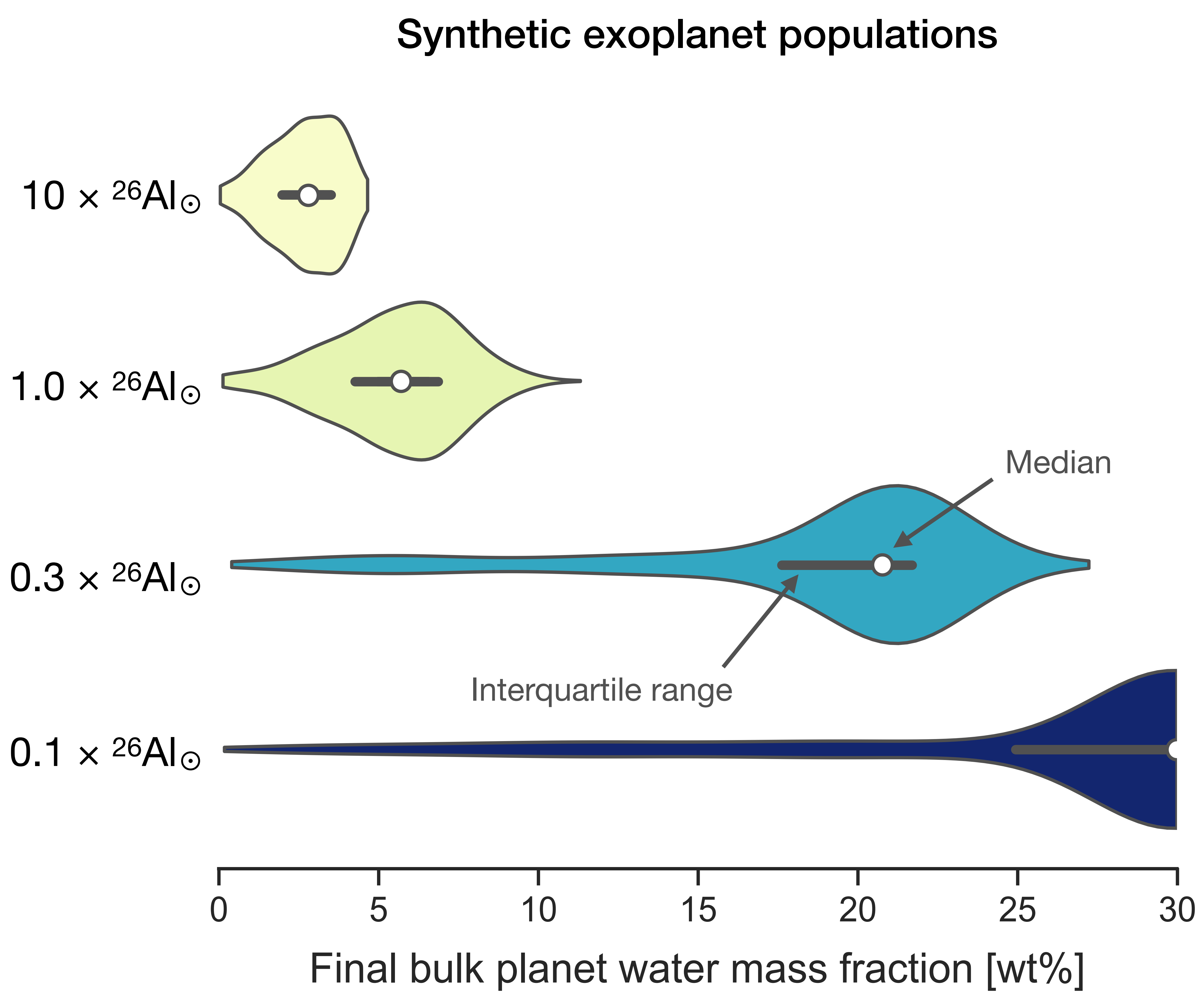
$f_W > 0$, $M_P < 10\ M_{Earth}$, G stars

Lichtenberg+ 19b

Lichtenberg+ 19b

^{26}Al shapes exoplanet structure

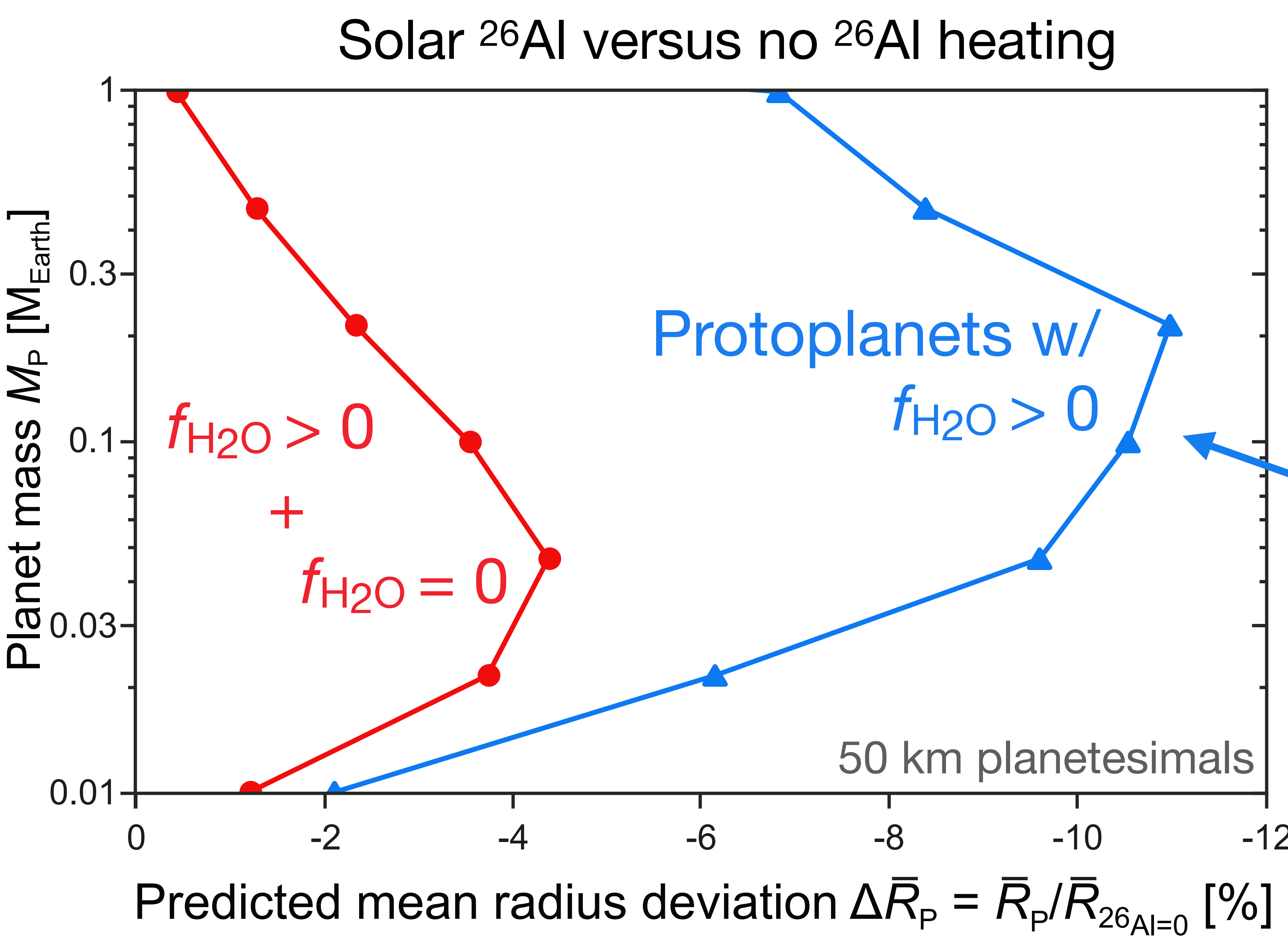


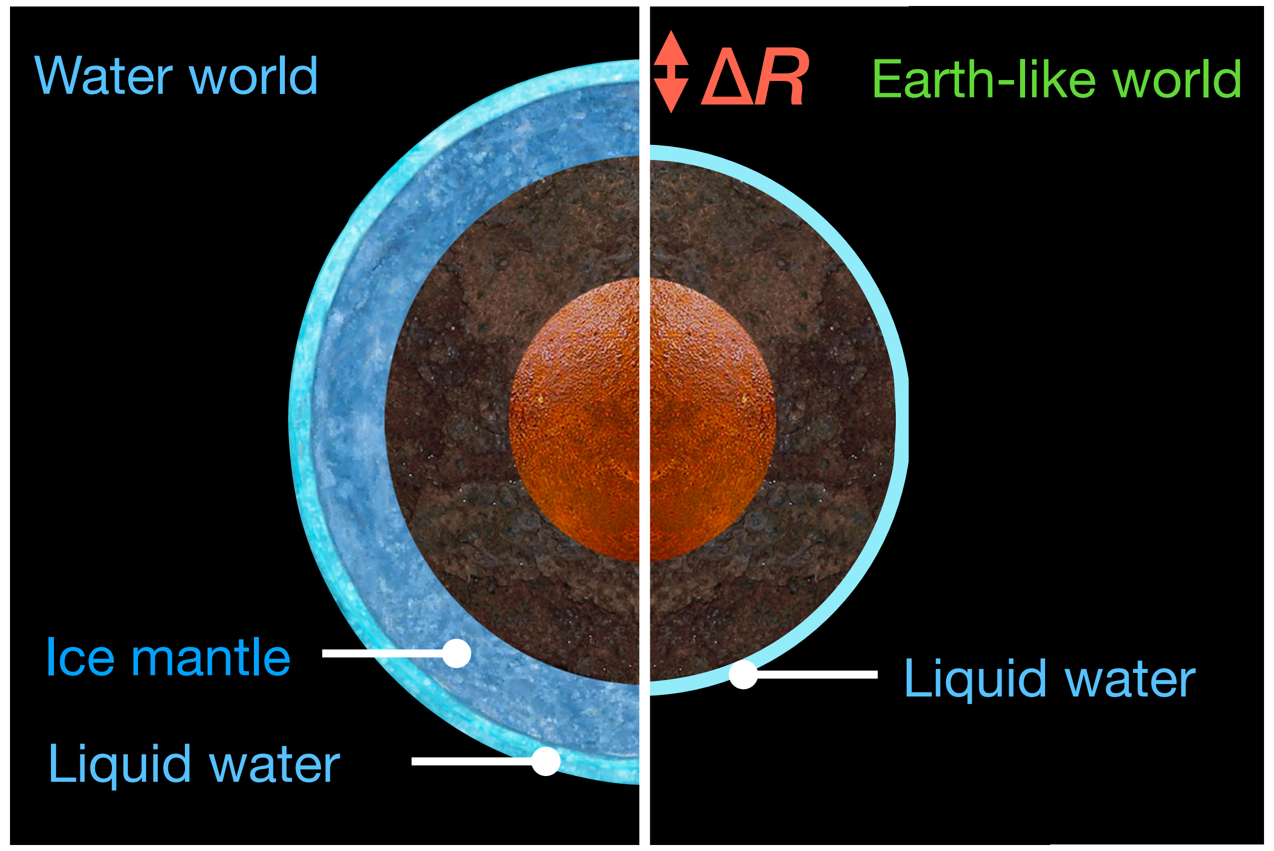


Leger+ 04, Sotin+ 07, Alibert 14, Noack+ 16/17

Lichtenberg+ 19b

^{26}Al shapes exoplanet structure

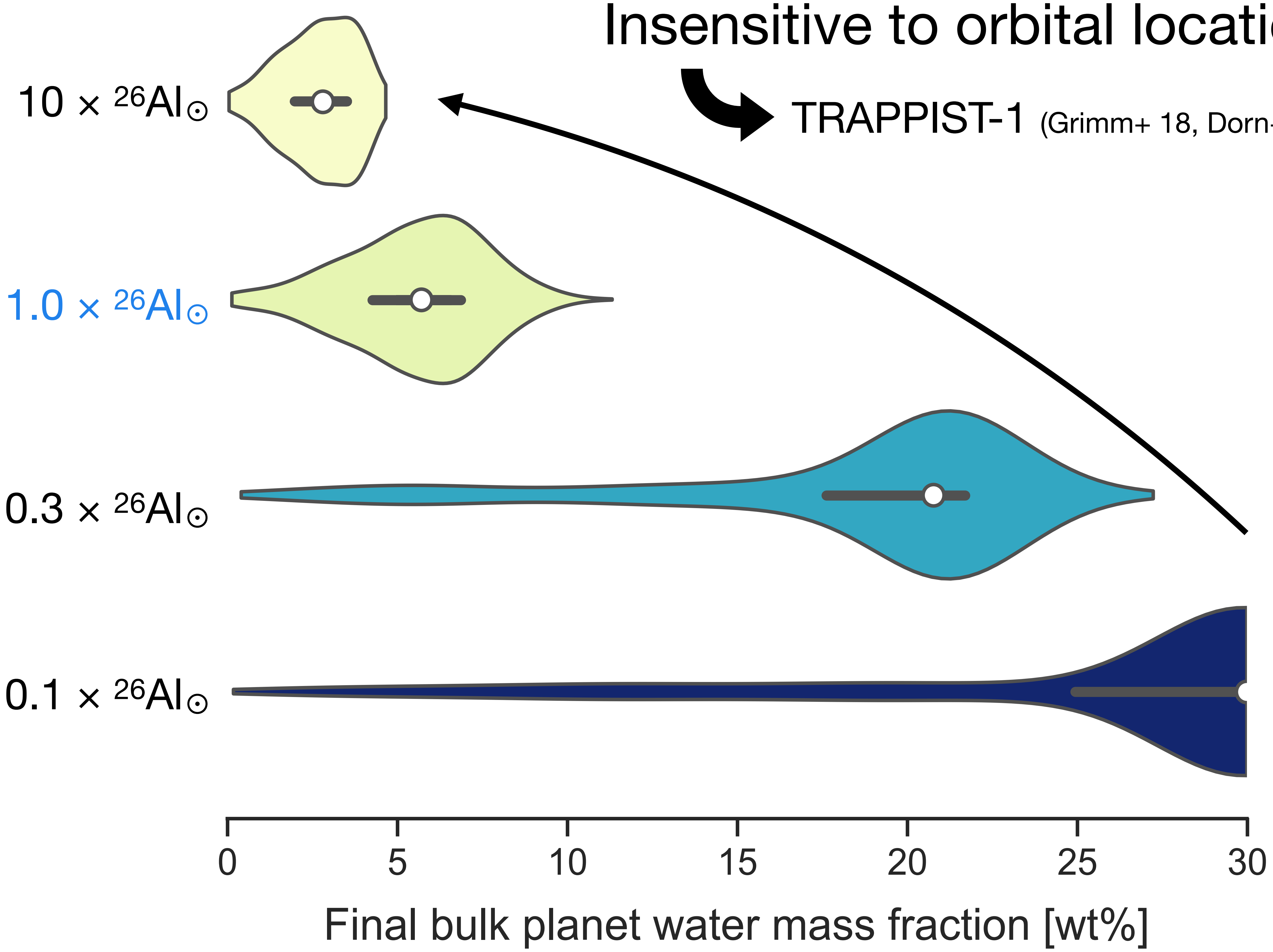




Intra-system size correlation (Weiss+ 18, Millholland+ 18)

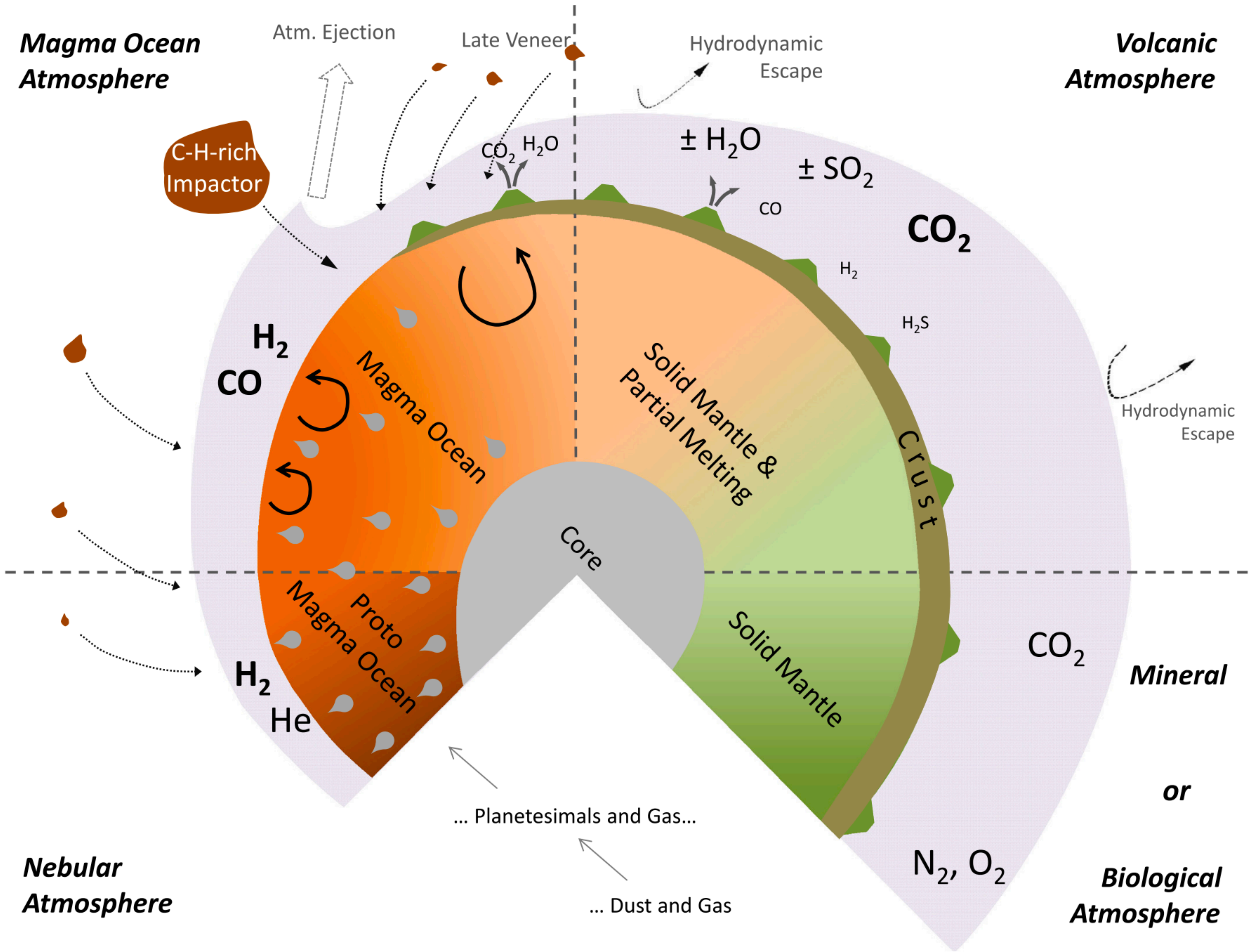
Insensitive to orbital location

TRAPPIST-1 (Grimm+ 18, Dorn+ 18)



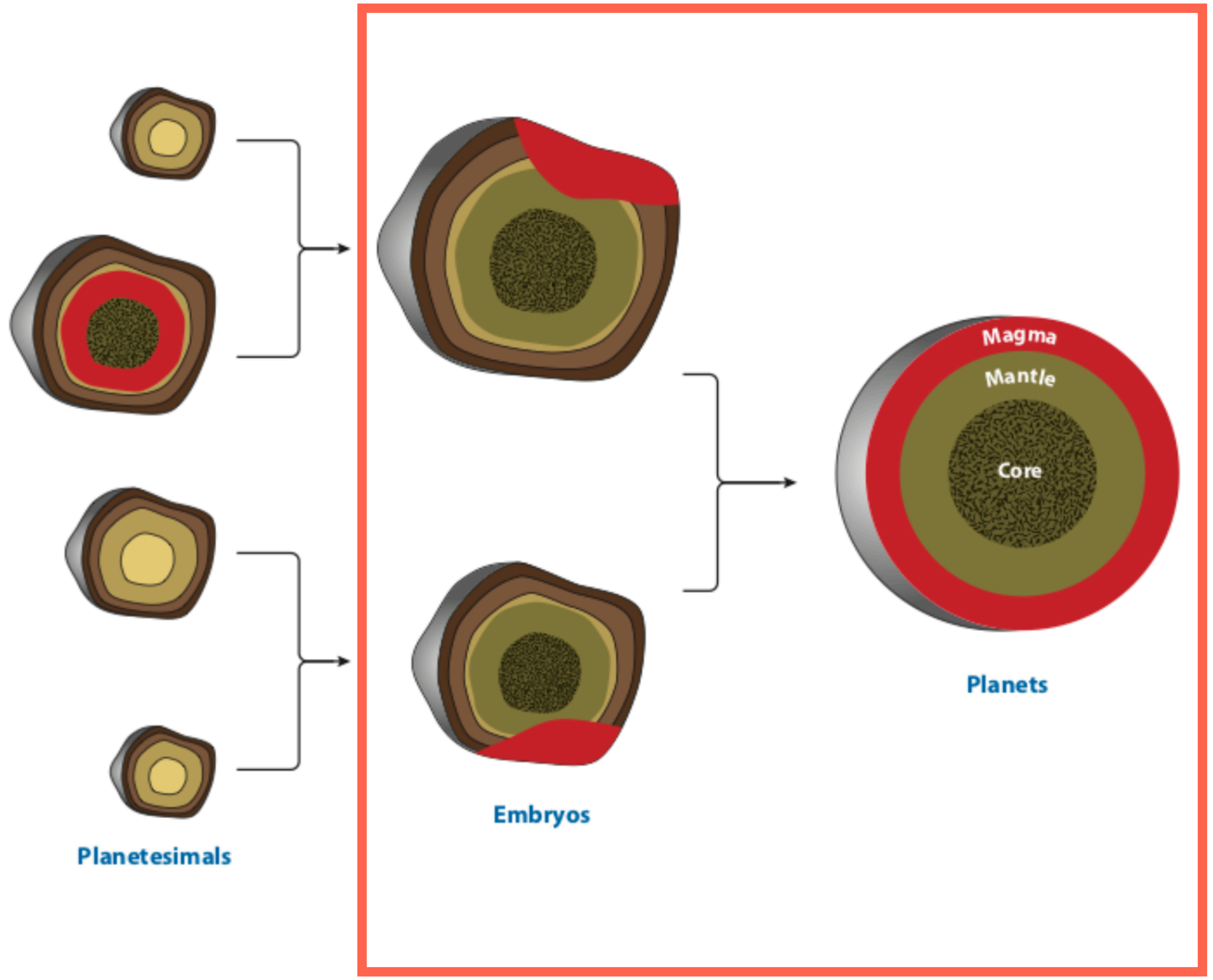
Lichtenberg+ 19b

Geophysical evolution during **late** accretion



^{26}Al dominated

Accretion-energy dominated



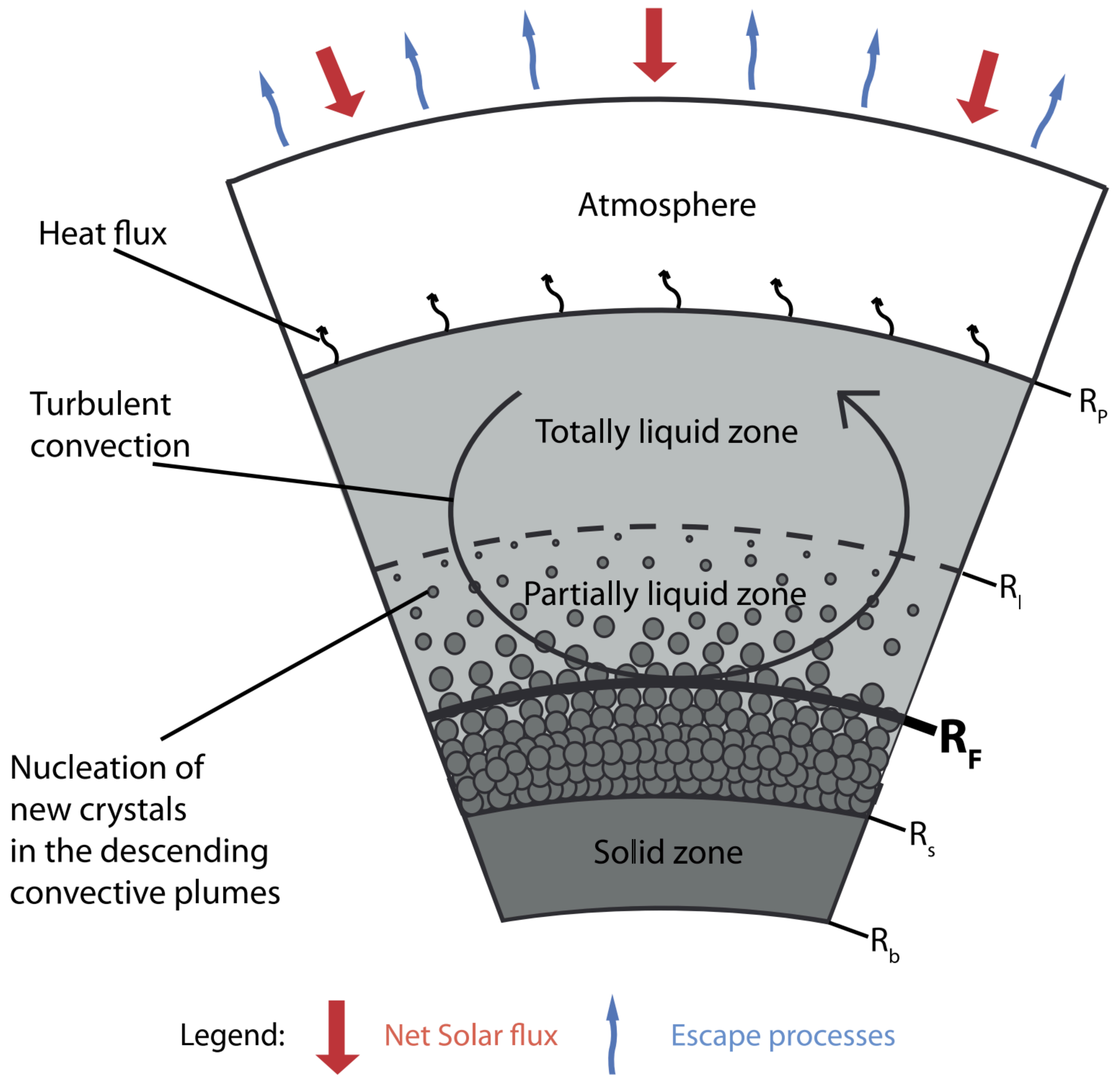
Gaillard & Scaillet 14

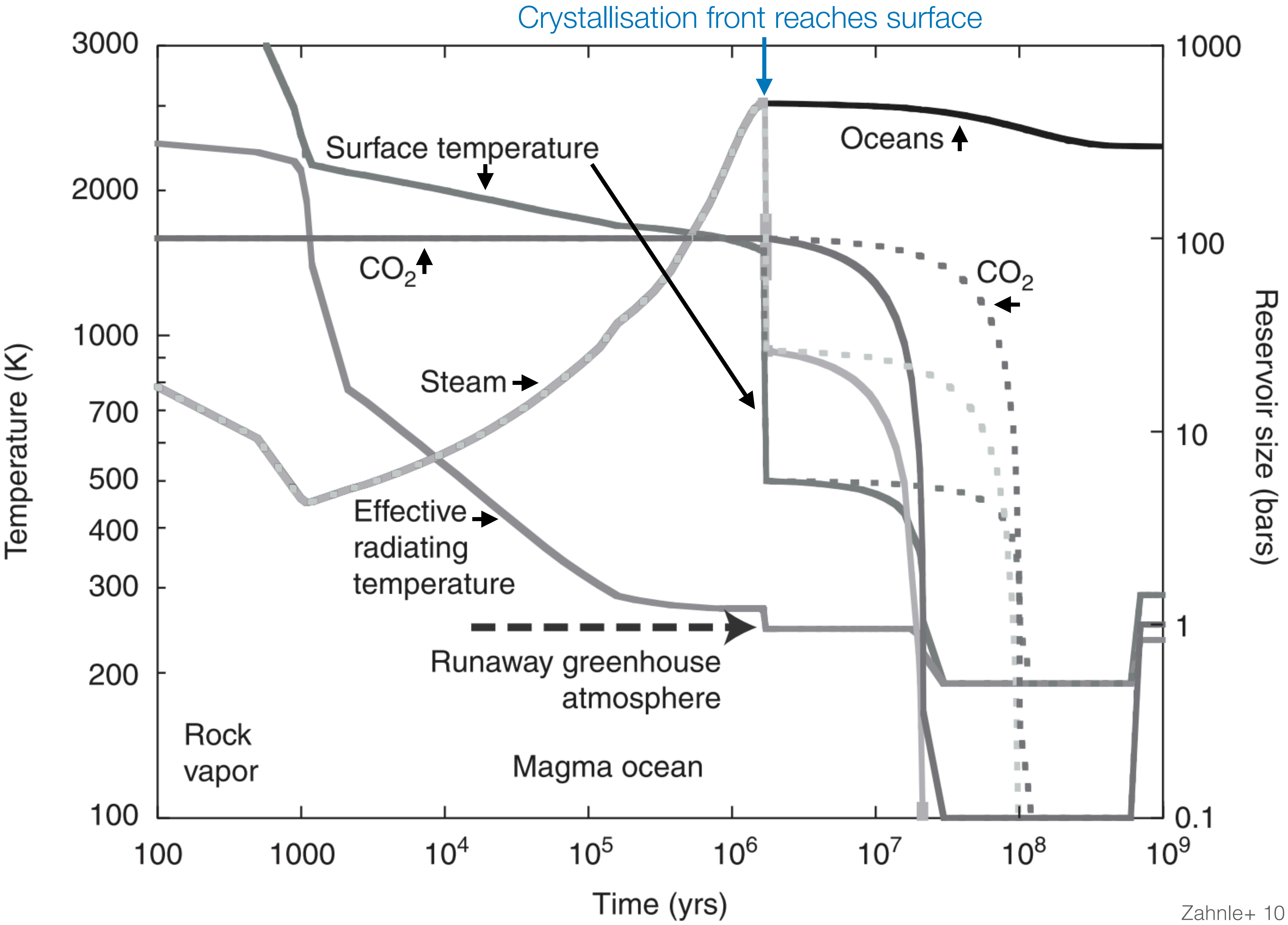
Elkins-Tanton 10, Weiss & Elkins-Tanton 17

Molten protoplanets during late-stage accretion

Robin Canup, SwRI

Hadean Earth: from accretion to water oceans

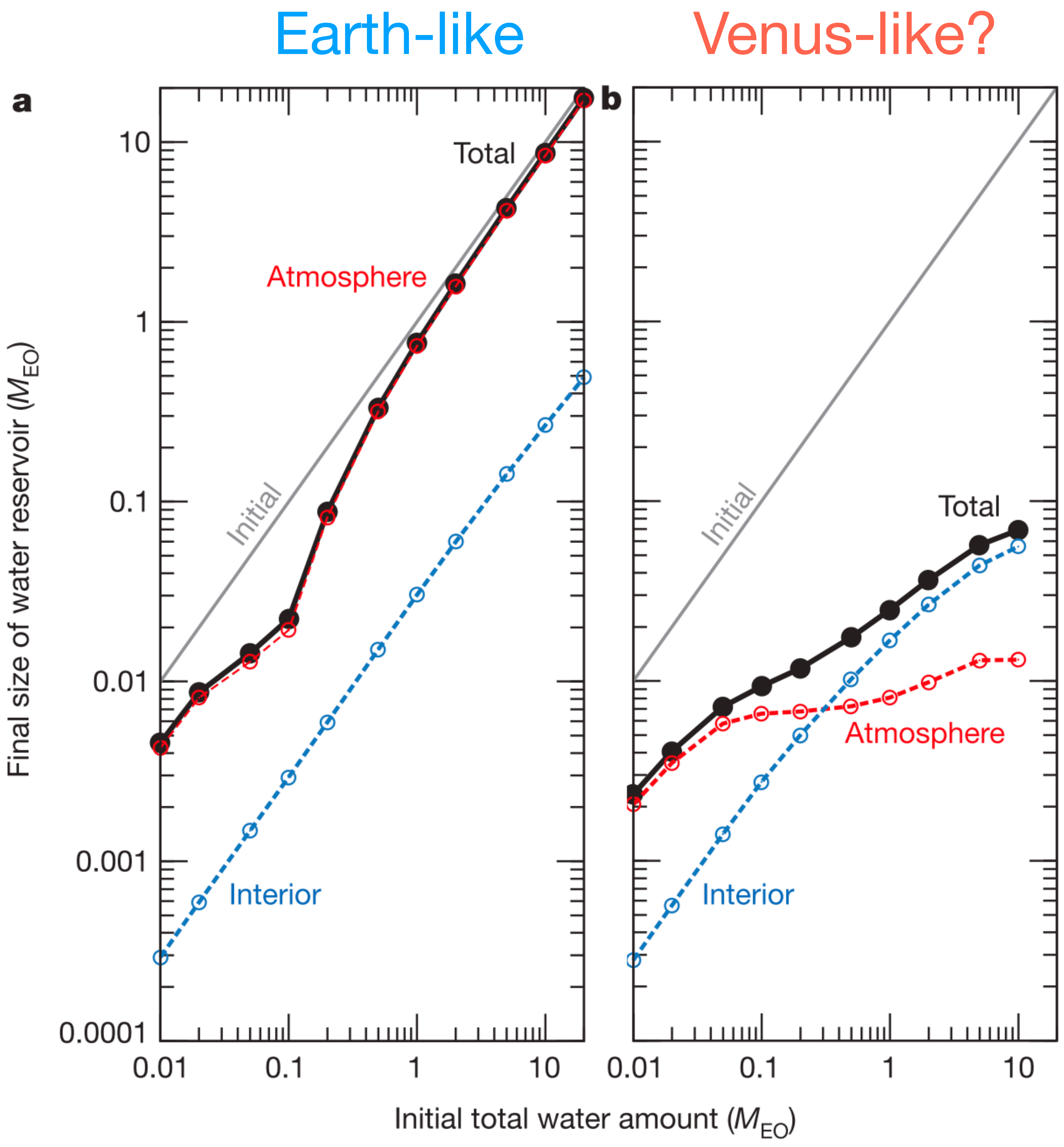




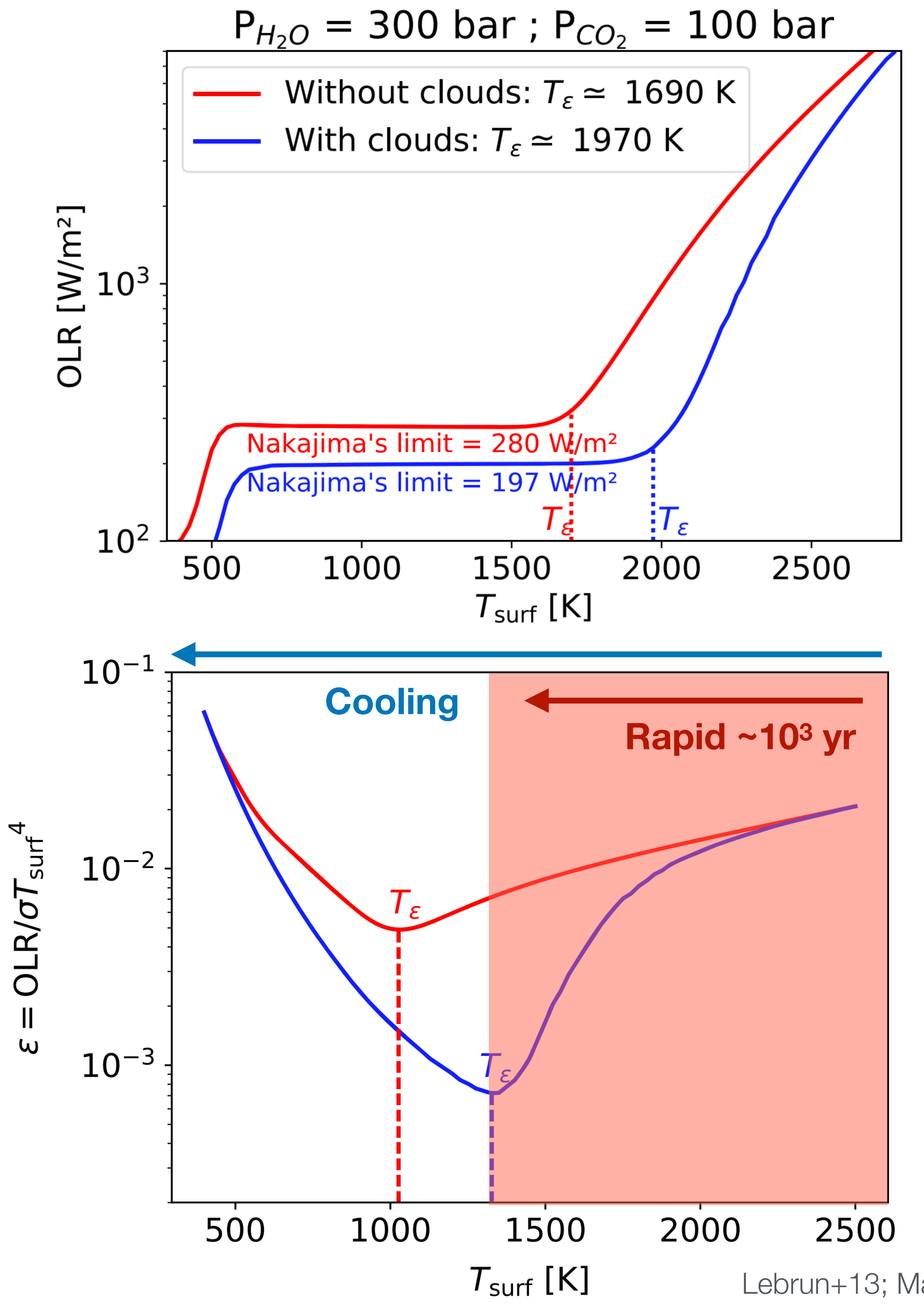
Solomatov 15; Massol+16

Zahnle+ 10

Magma ocean desiccation?



Hamano+ 13

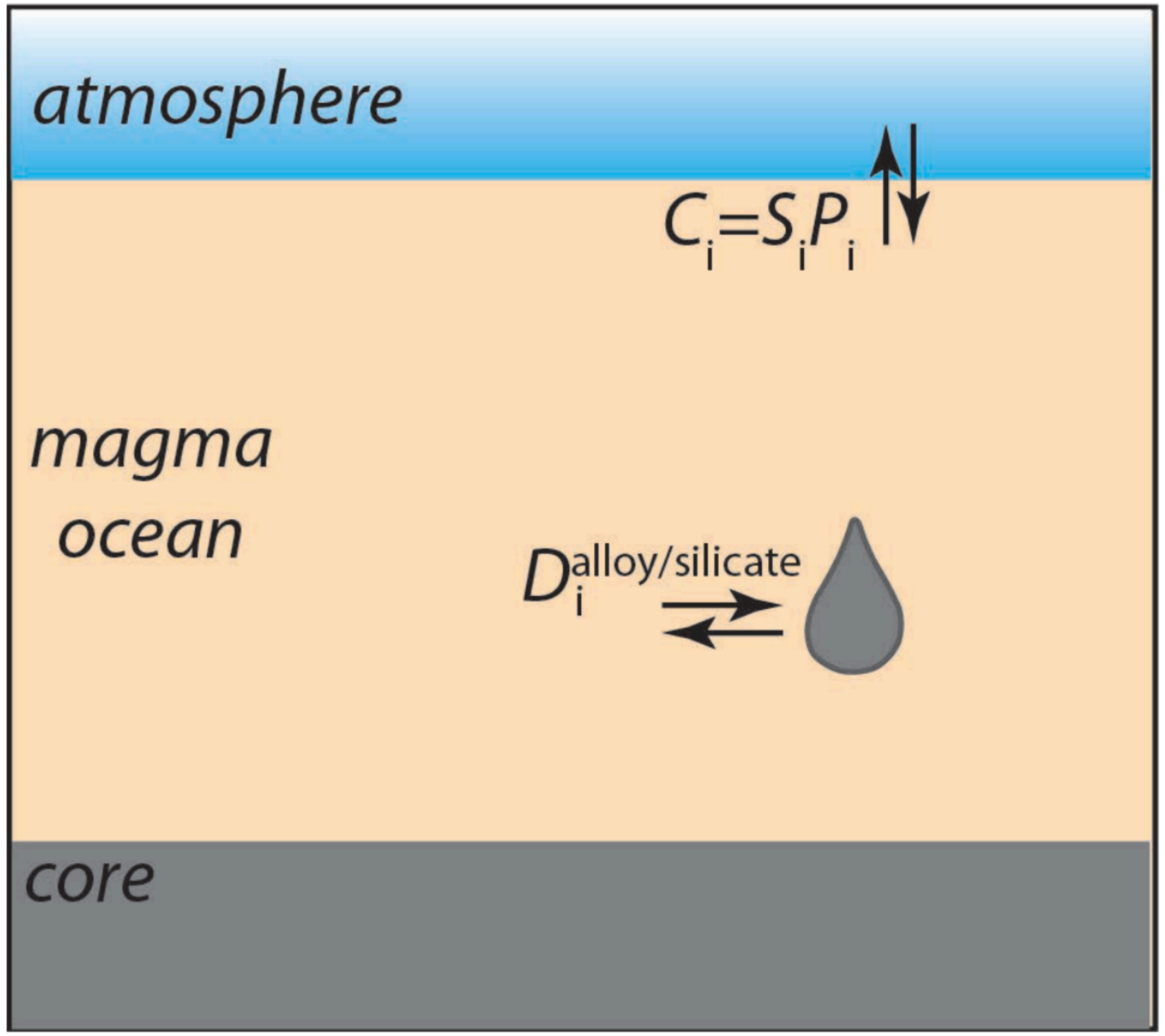


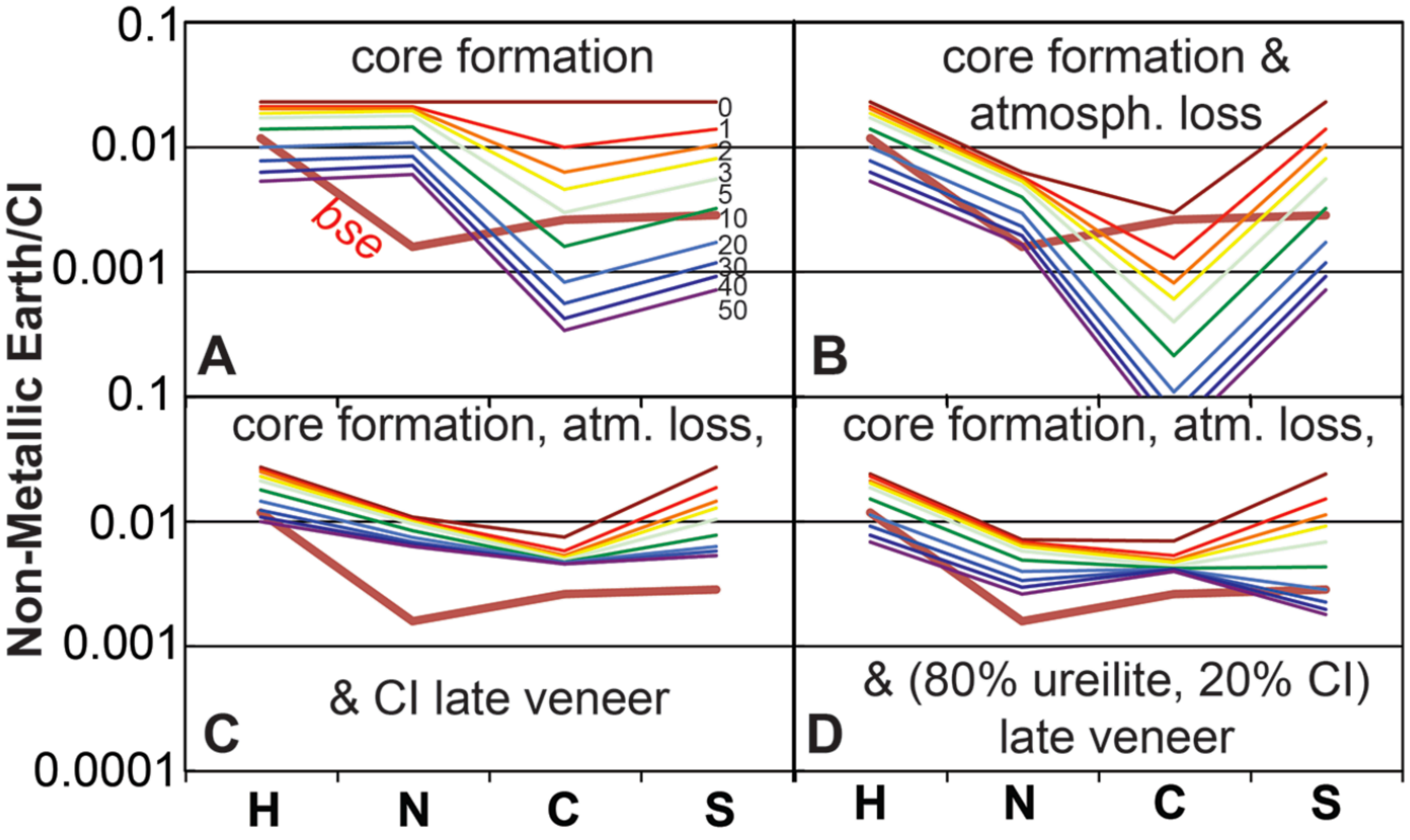
Outgoing longwave radiation (heat flux)

Effective emissivity

Lebrun+13; Marcq+12,17, Salvador+17

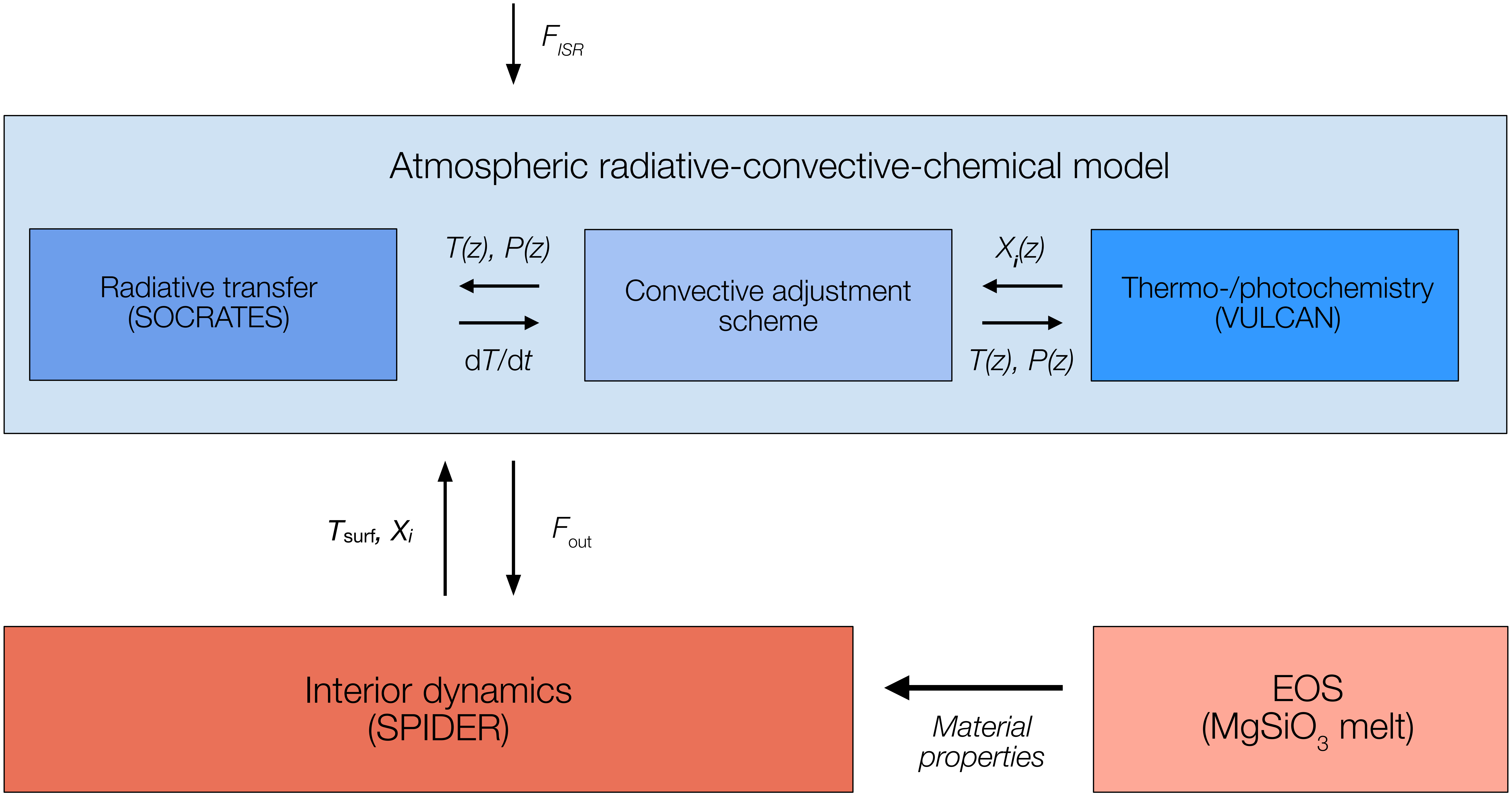
Equilibrium partitioning + *some* evolution





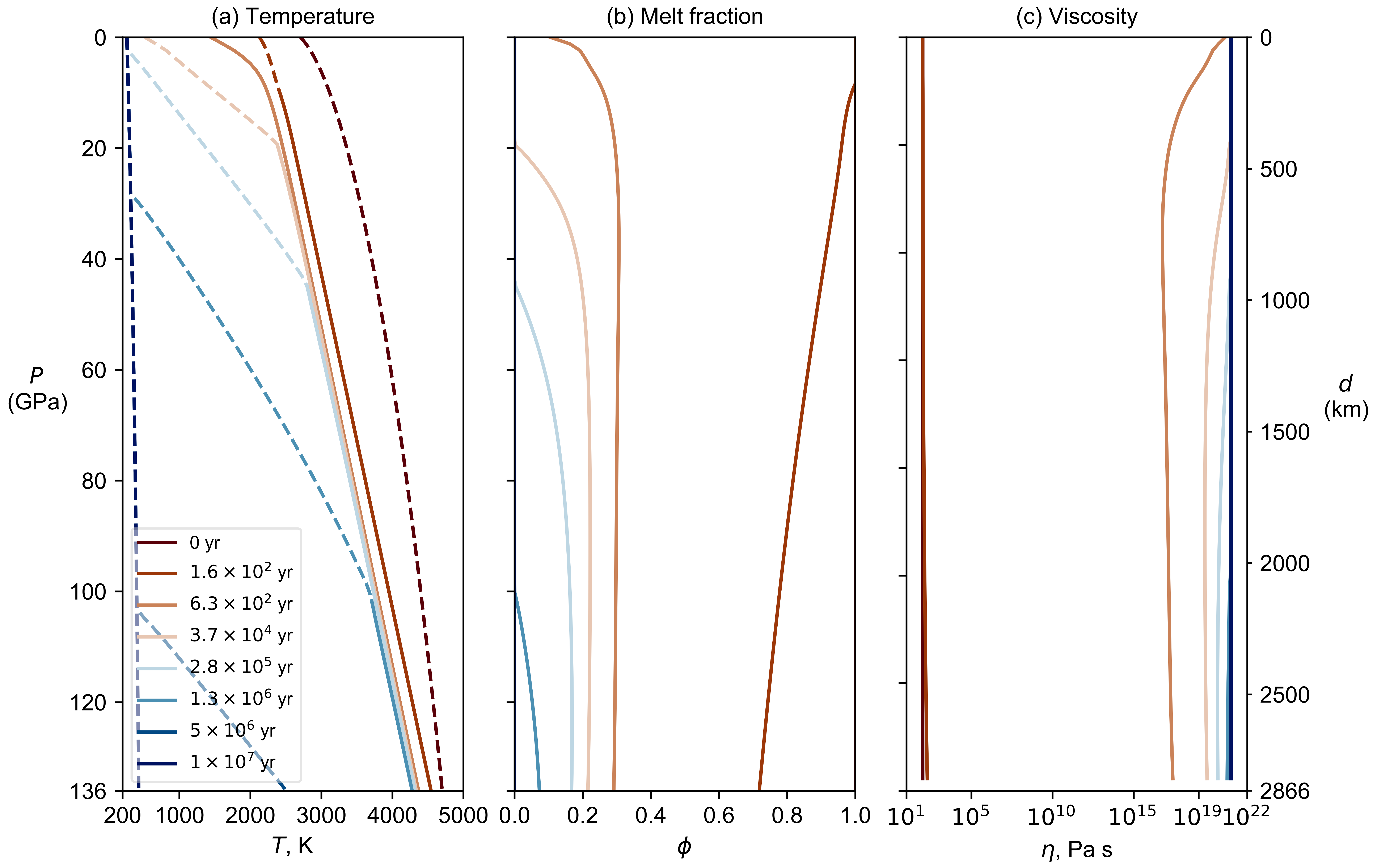
Hirschmann 16

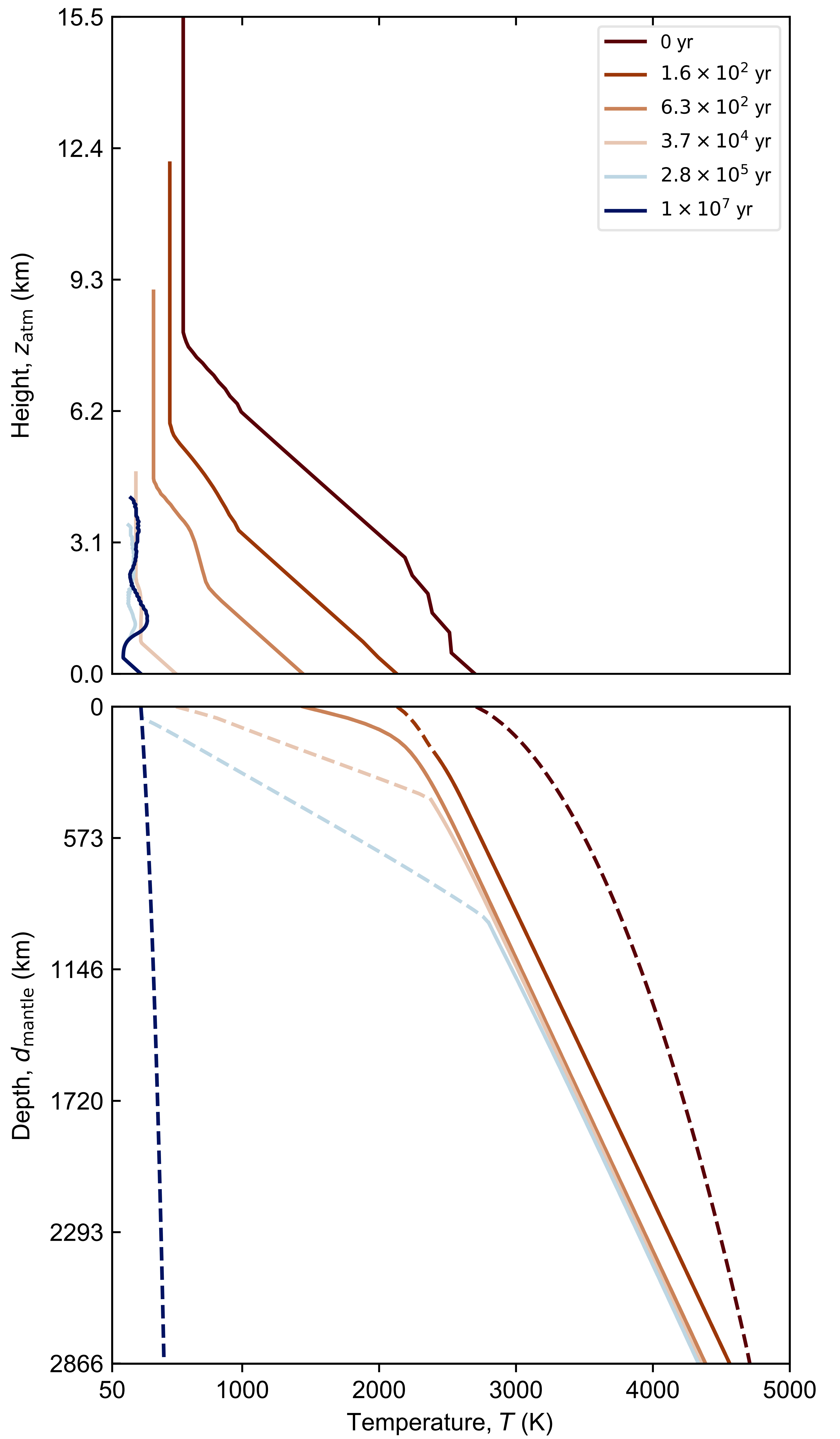
Integrated magma ocean—atmosphere model



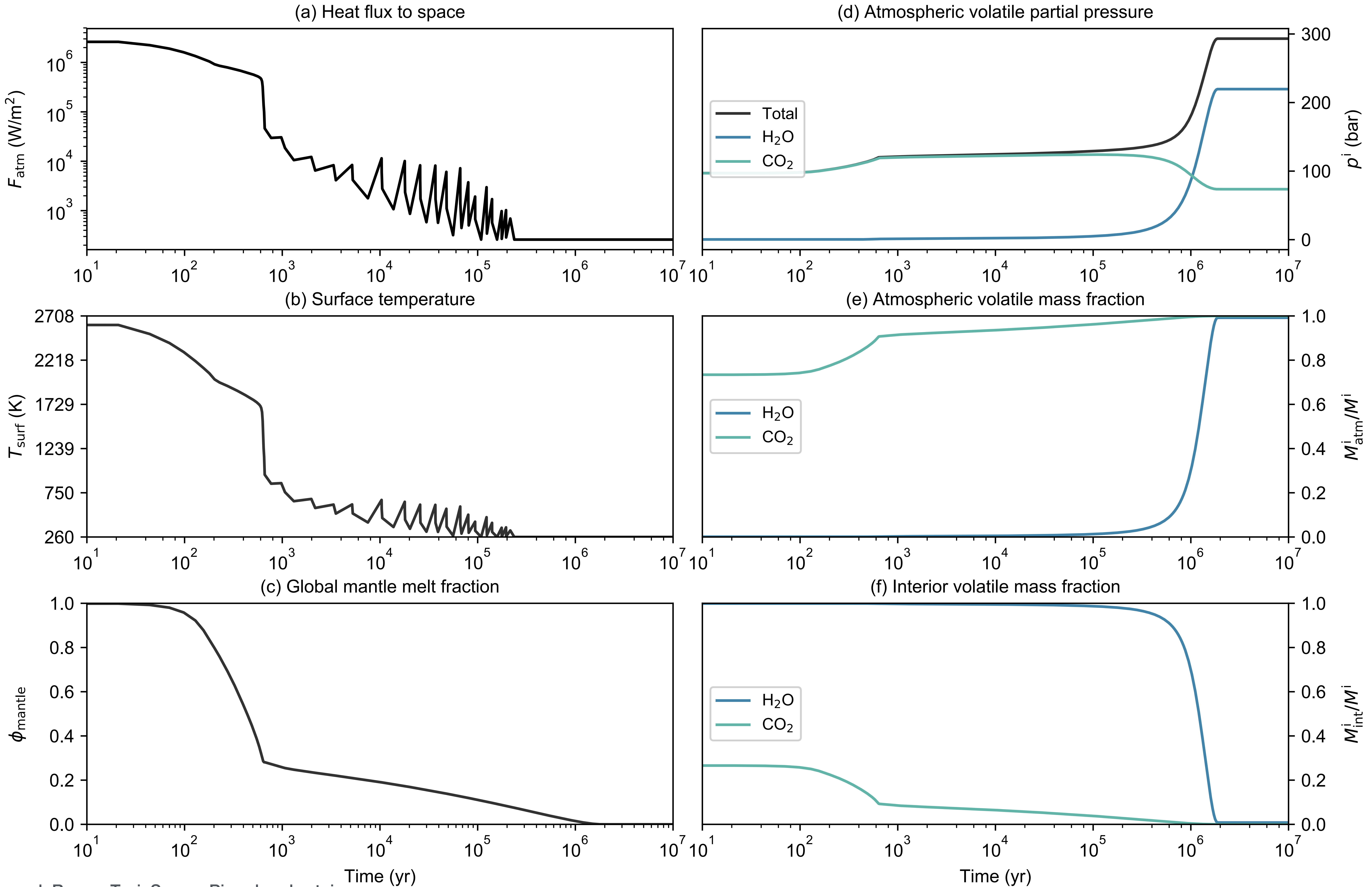
Lichtenberg, Hammond, Bower, Tsai, Sanan, Pierrehumbert, in prep.

Magma oceans from the core-mantle boundary to the top of the atmosphere





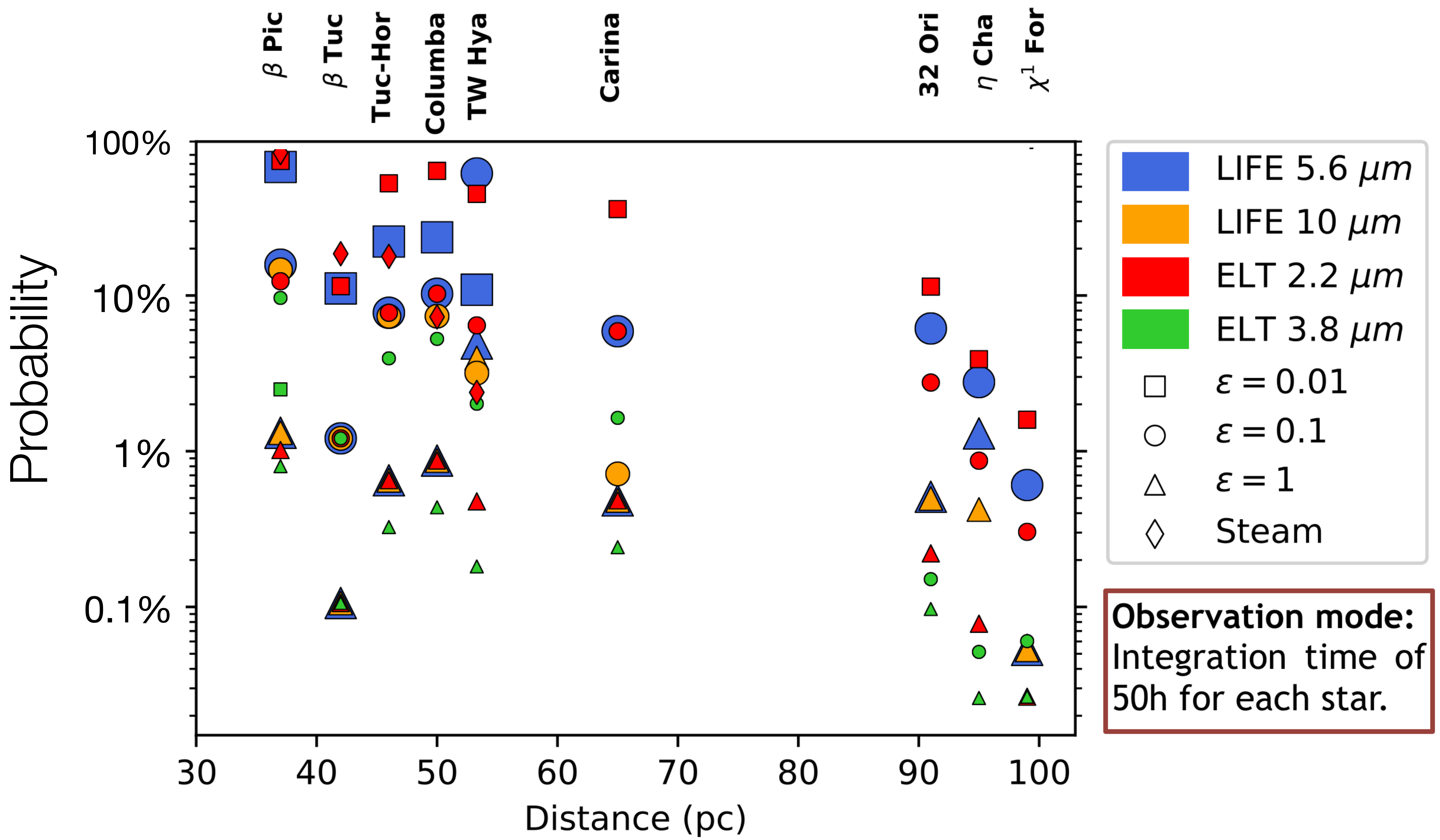
Lichtenberg, Hammond, Bower, Tsai, Sanan, Pierrehumbert, in prep.

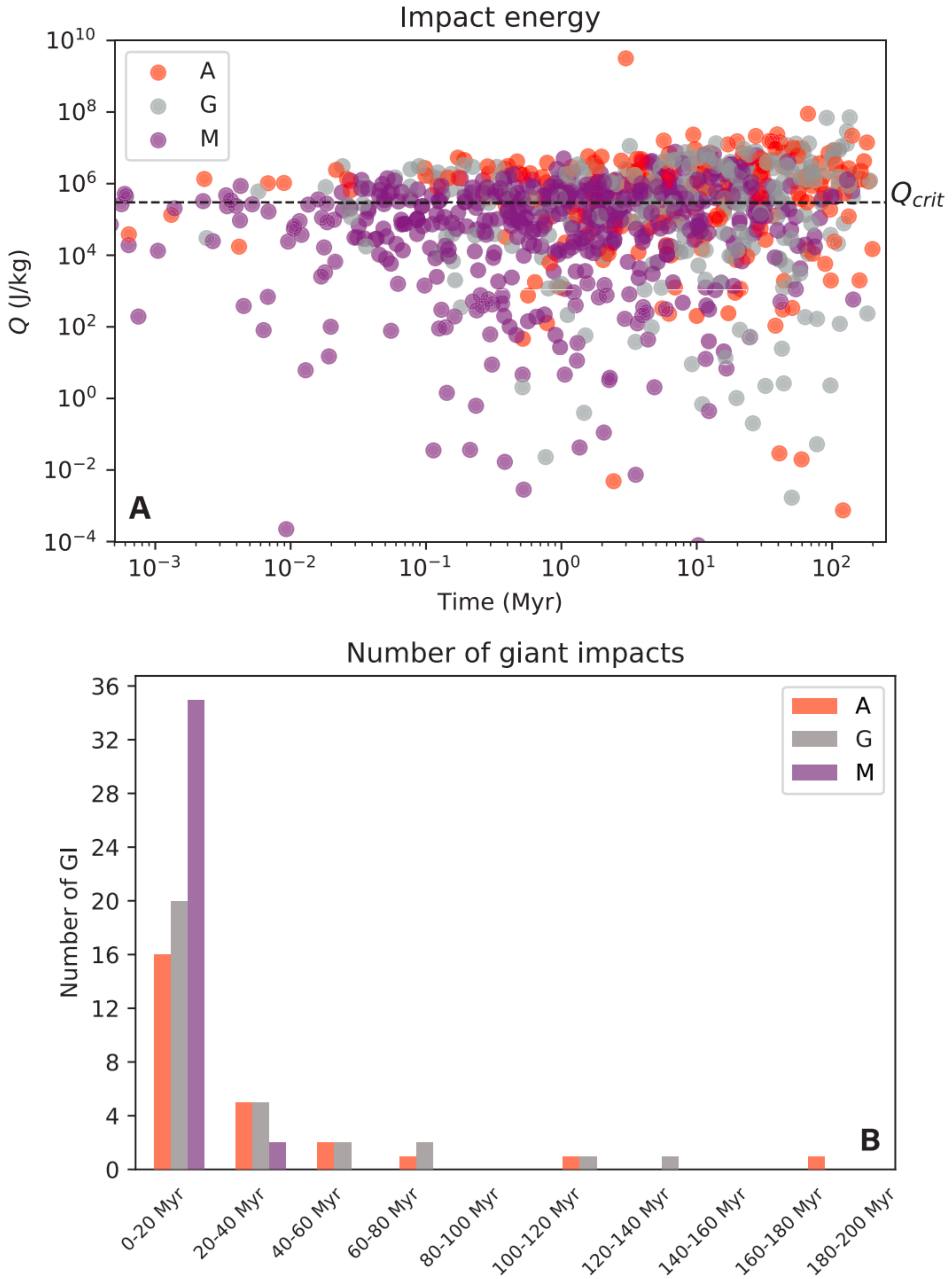


Lichtenberg, Hammond, Bower, Tsai, Sanan, Pierrehumbert, in prep.

MO-detectability with direct imaging?

Probability of detecting magma ocean planet with future direct imaging facilities





Bonati, Lichtenberg, Bower, Timpe, Quanz (A&A, 2019)

Geophysical evolution shapes young rocky planets

- Systemic ^{26}Al dichotomy across planetary systems:
  - ➡ Enriched systems form water-poor (proto-)planets
  - ➡ Not-enriched systems tend to form ocean worlds
  - ➡ In Solar System traced by inner/outer chemical and isotopic bifurcation?
- Magma ocean-atmosphere coupling shapes earliest atmospheric and upper mantle (geo-)chemistry:
  - ➡ Barrier from planet formation to early planetary evolution
- Interconnect w/ future space missions and laboratory studies?
  - ➡ Observational constraints from both solar system- (formation) and exoplanet-focused missions (evolution, atmospheric signatures)
  - ➡ Laboratory studies that help to constrain (or depend on) environmental variables, e.g., UV flux, subaerial volatile abundances?

Lichtenberg+ 2016a, Icarus
Lichtenberg+ 2018, Icarus
Lichtenberg+ 2019a, E&PSL
Lichtenberg+ 2019b, NatAstron
Lichtenberg+ 2016b, MNRAS
Hunt+ 2018, E&PSL
Bonati+ 2019, A&A