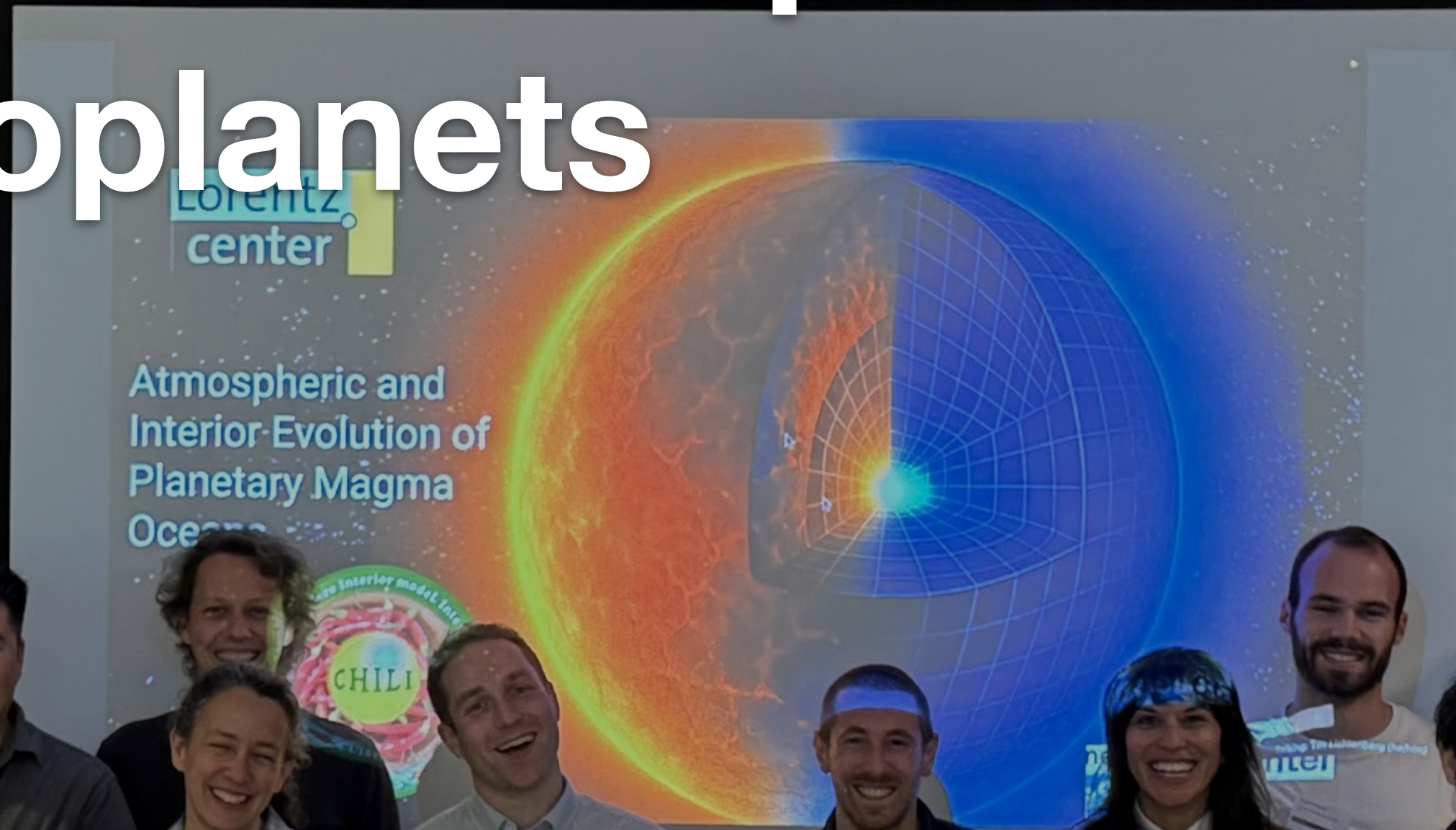


Benchmarking time-evolved coupled interior-atmosphere models of exoplanets



formingworlds.space



Social dinners, 7 pm
Mon Tim Denis ANDILEA Phil...
Tue ...
Thu ...

Laura Yoshinori Denis THE PAPER THE CODES BREAKOUT DISCUSS SIMPLE CASES IDENTIFY LIMITS COUPLED VS. WITH AS EXAMPLE HARRISON QUESTION

TIM LICHTENBERG & CHILI TEAM & FORMING WORLDS LAB



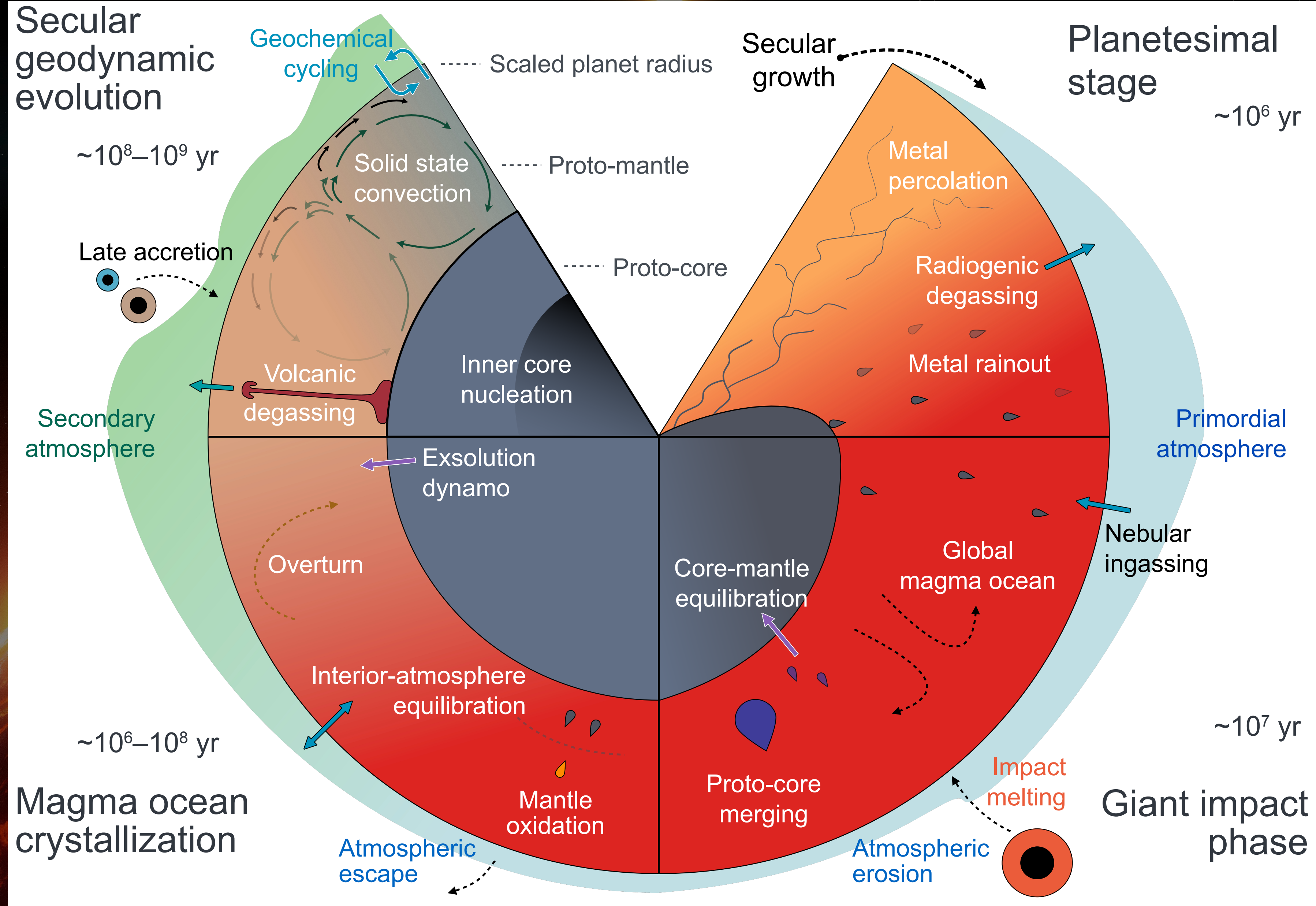
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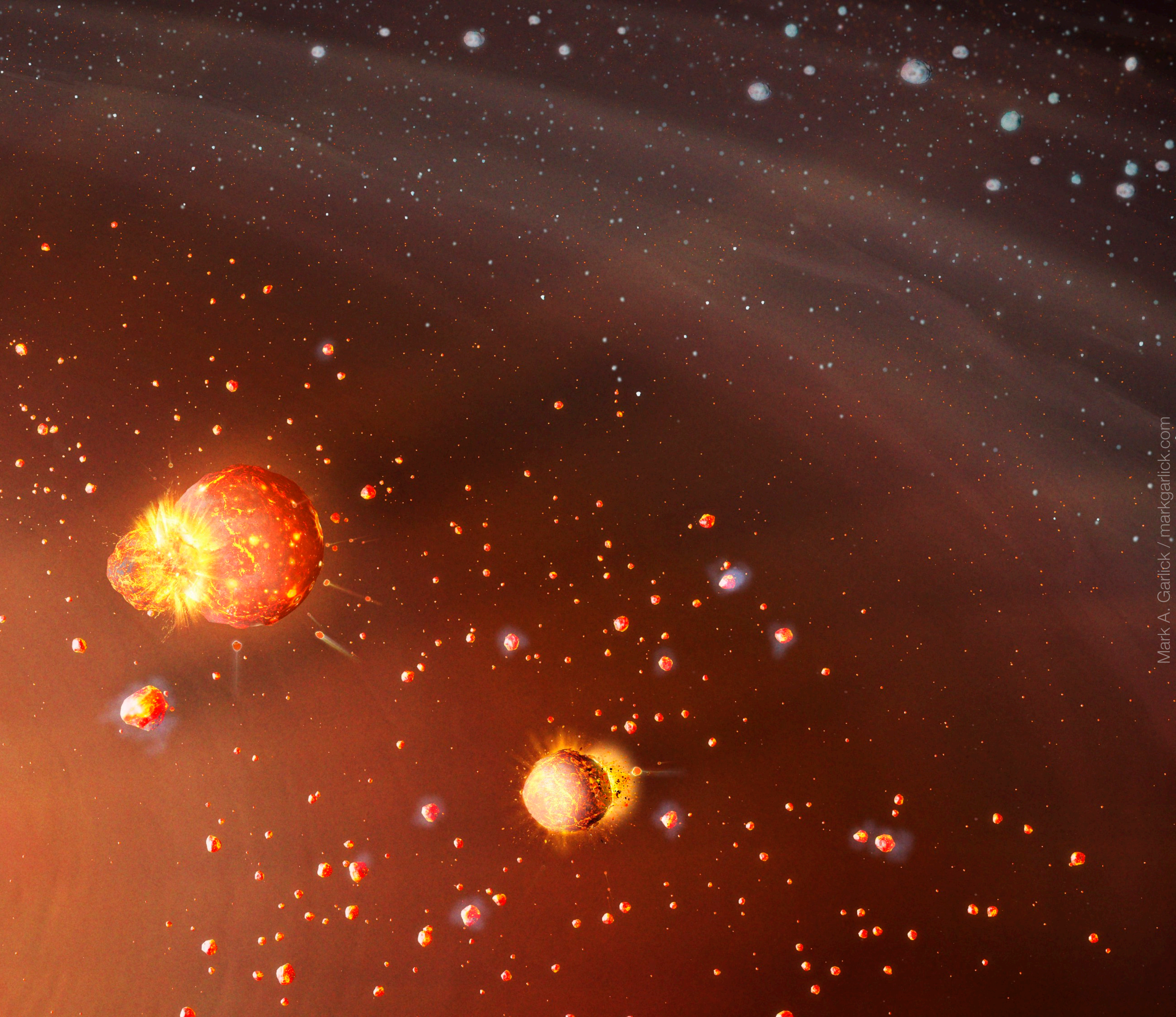
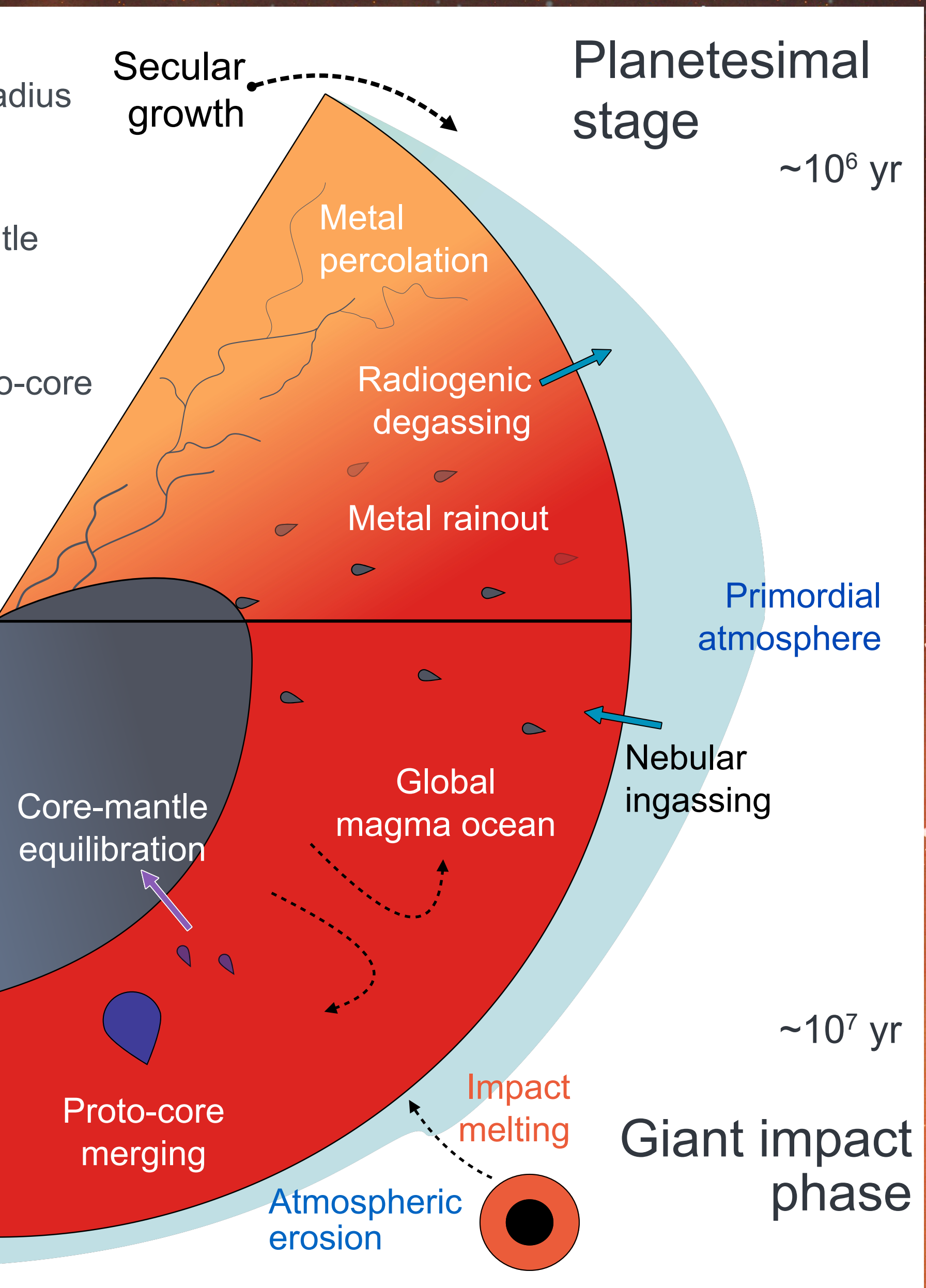
How do planetary atmospheres form?

How do low-mass exoplanets evolve?

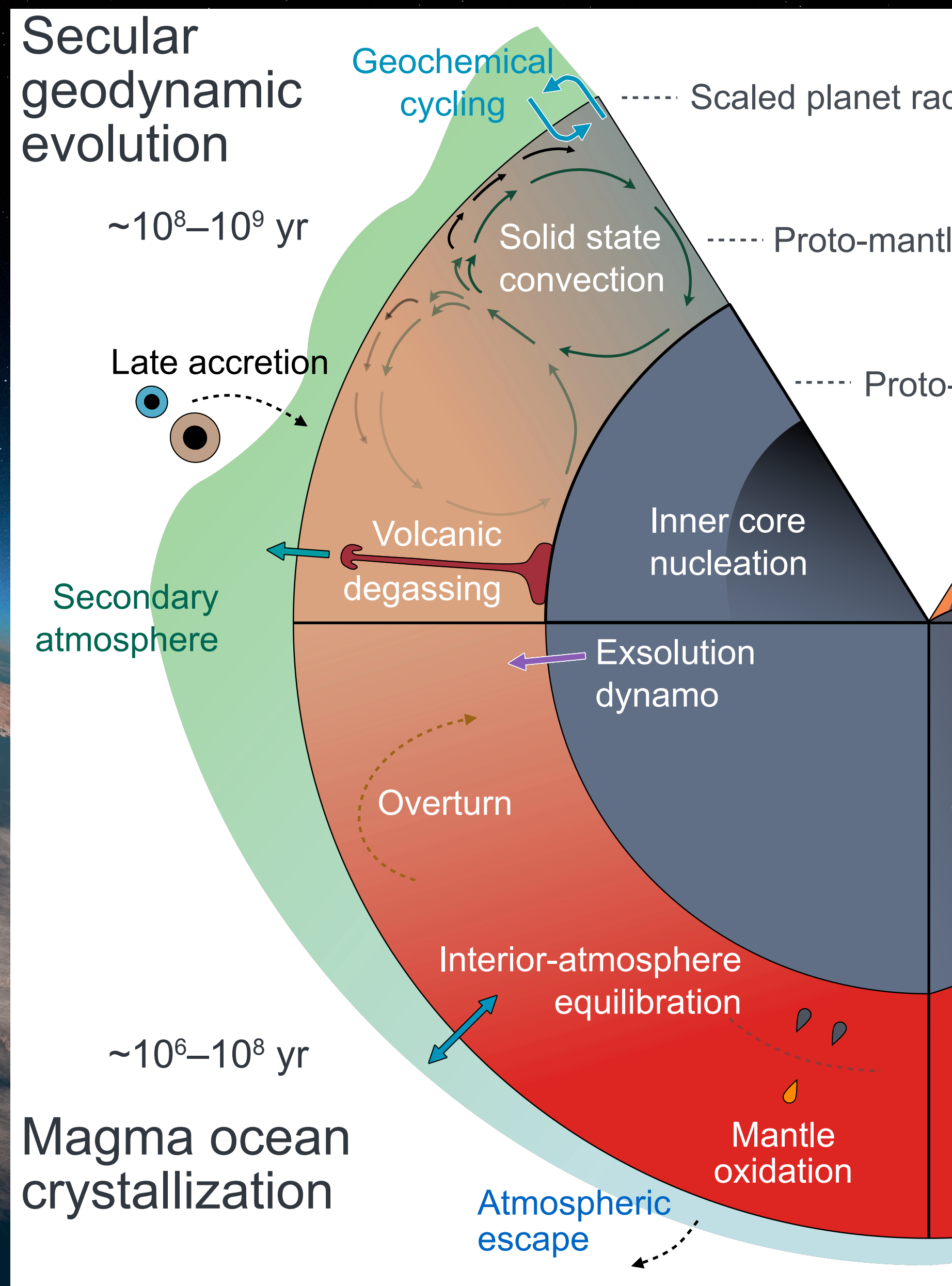
Do sub-Neptunes have sharp surfaces?

Planets are born from magma

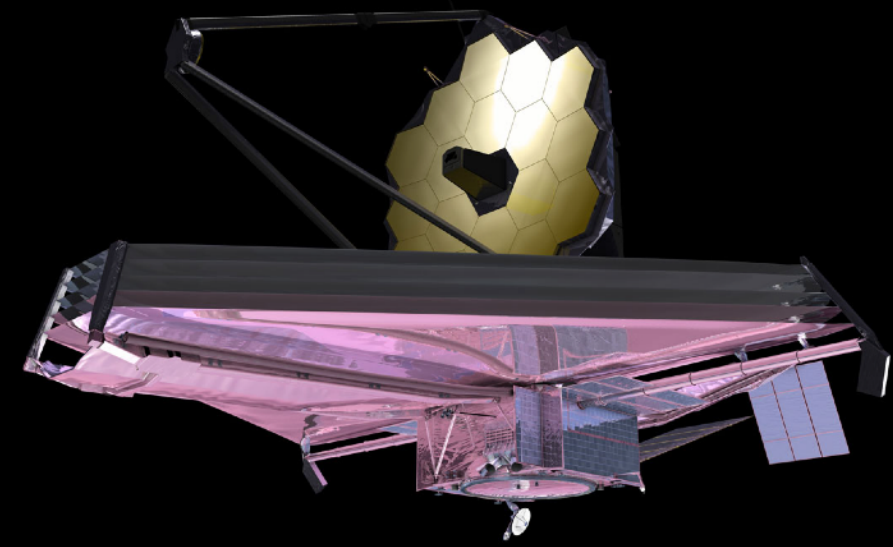




Mark A. Garlick / markgarlick.com



Possible sub-Neptune interior regimes



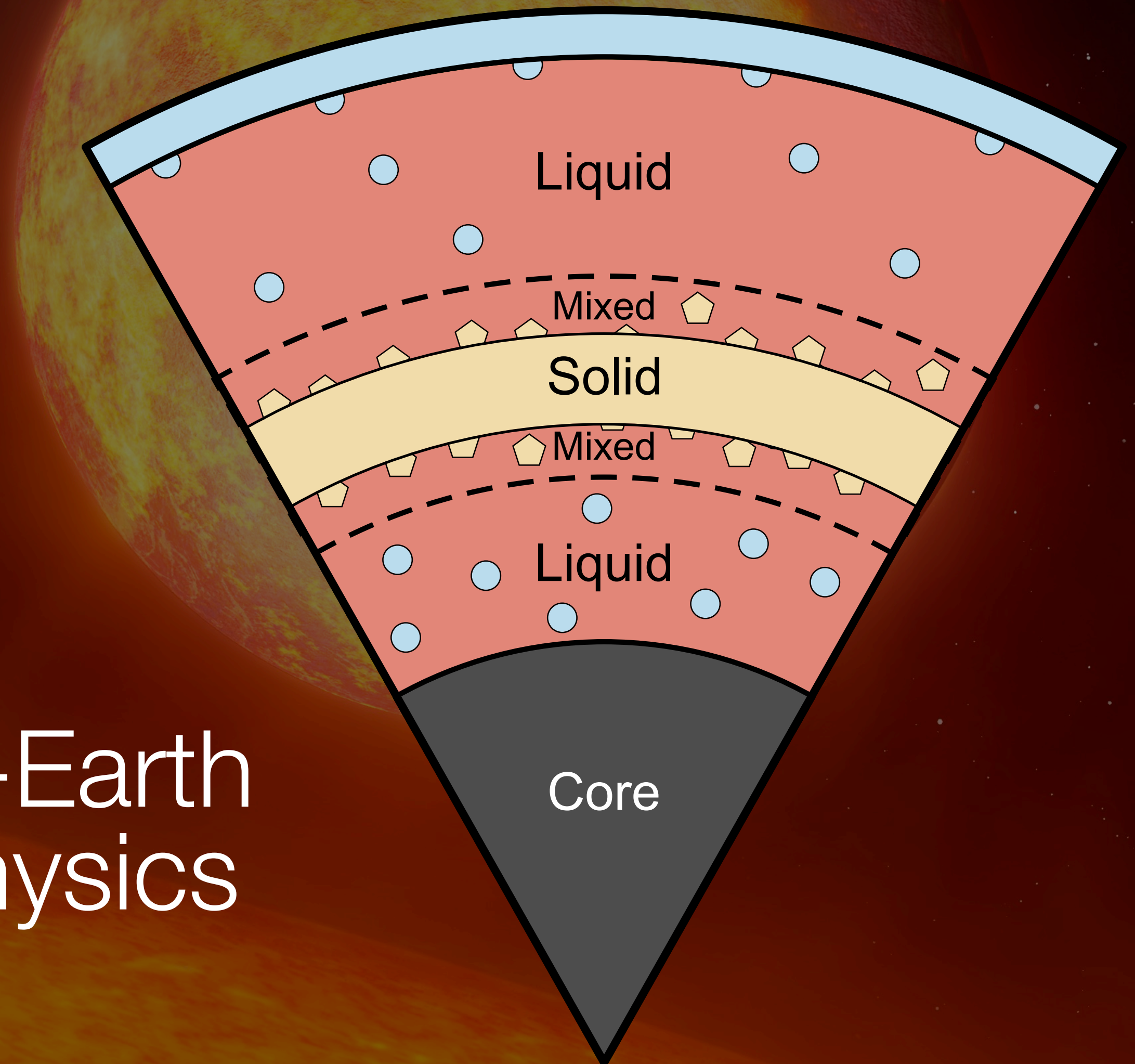
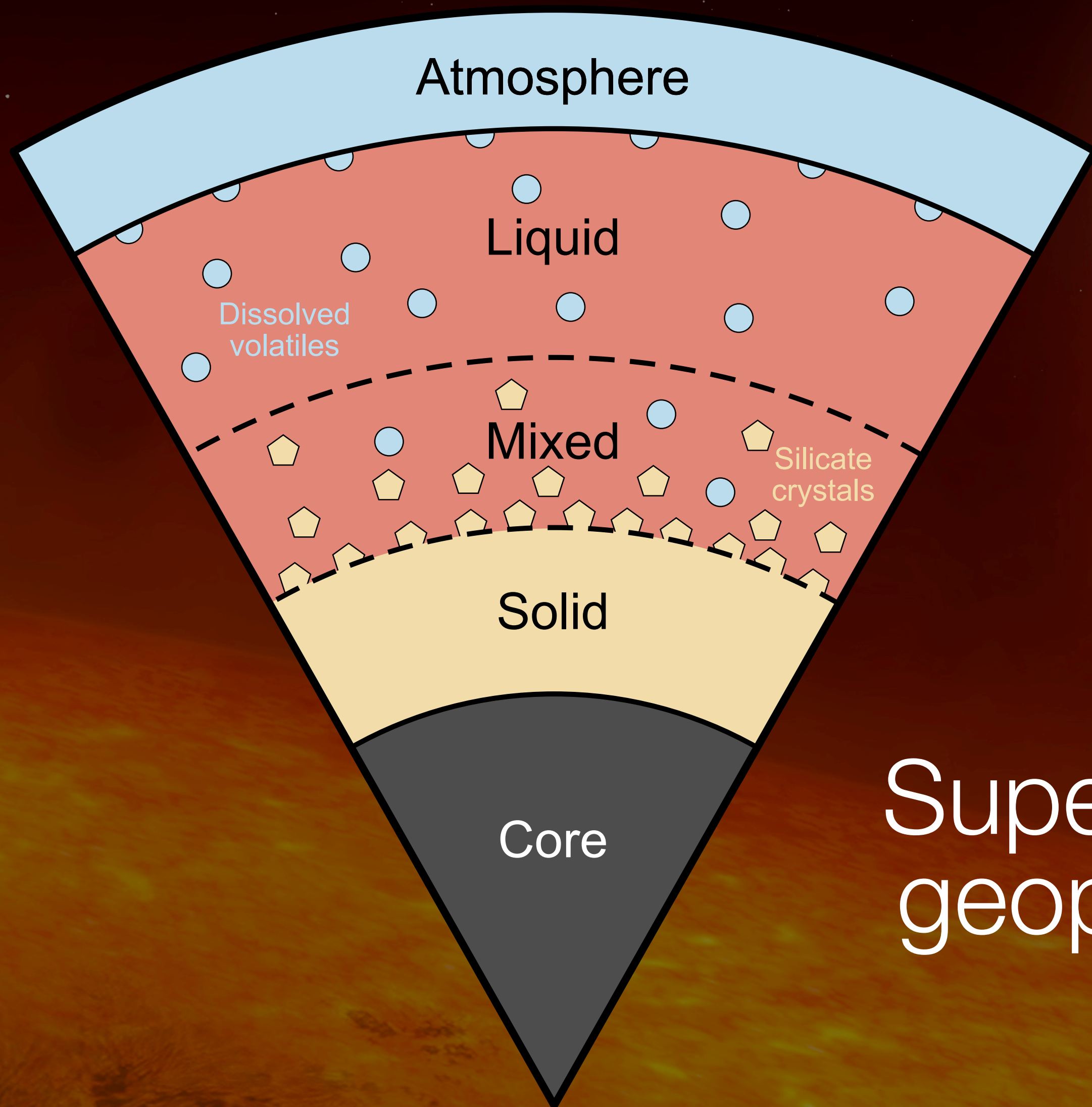
**James Webb
Space Telescope**

Gas dwarf

**Water
world**

**Globally
supercritical**

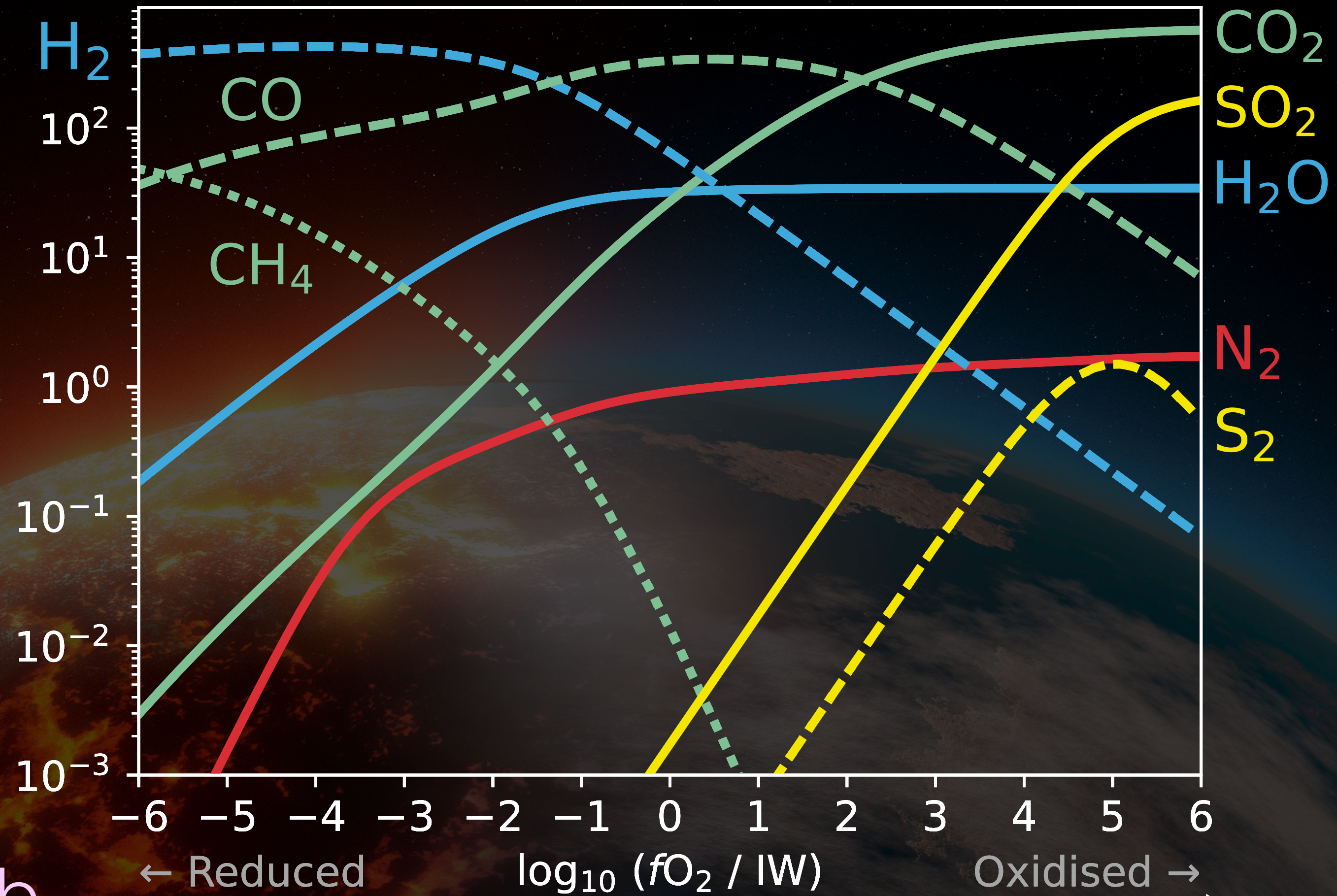
Possible super-Earth crystallisation regimes



Super-Earth
geophysics

Lava world atmospheres are fed from interior

Outgassed atmosphere partial pressure (bar)



C
H
N
S

~sub-
Neptune

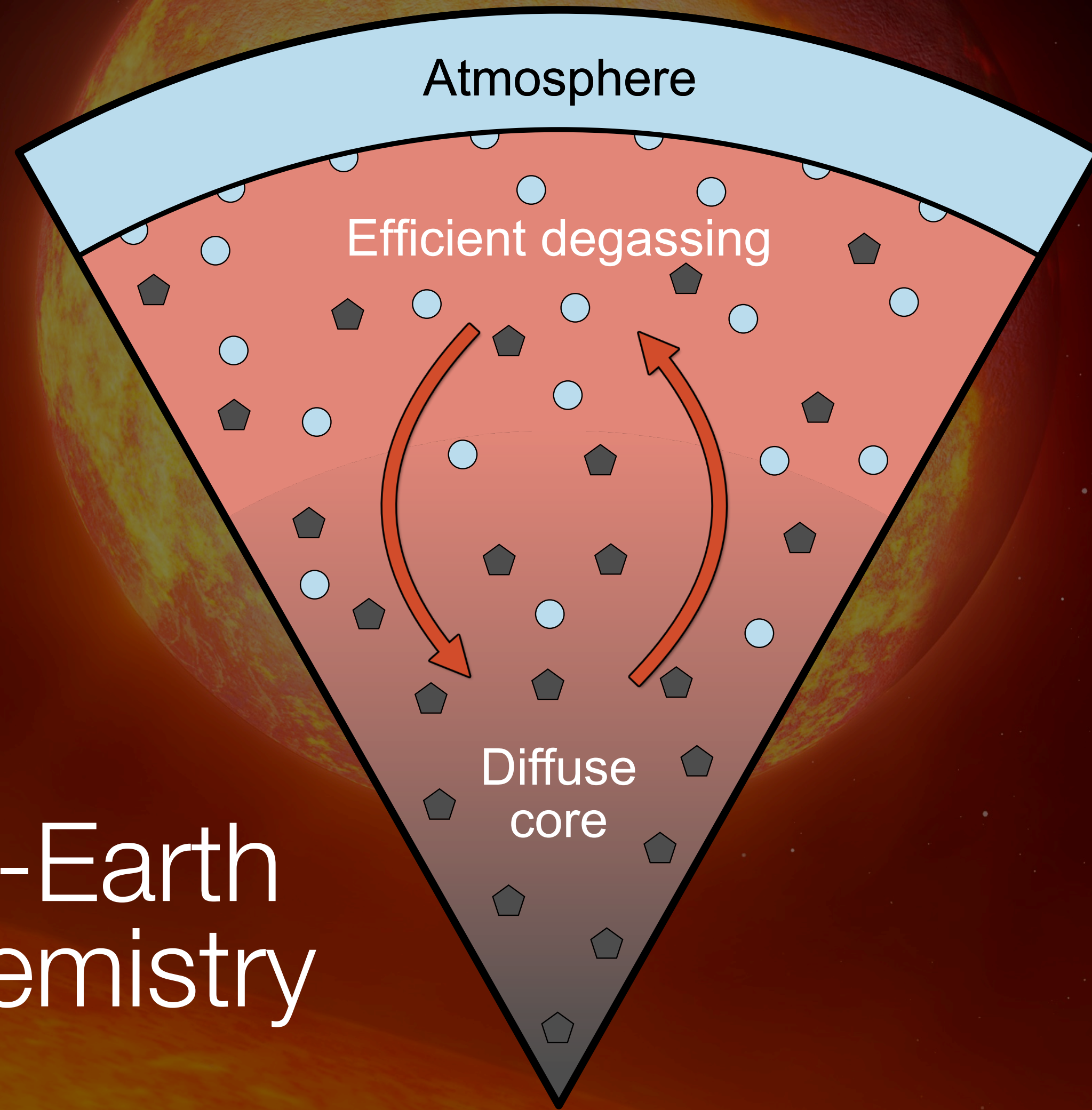
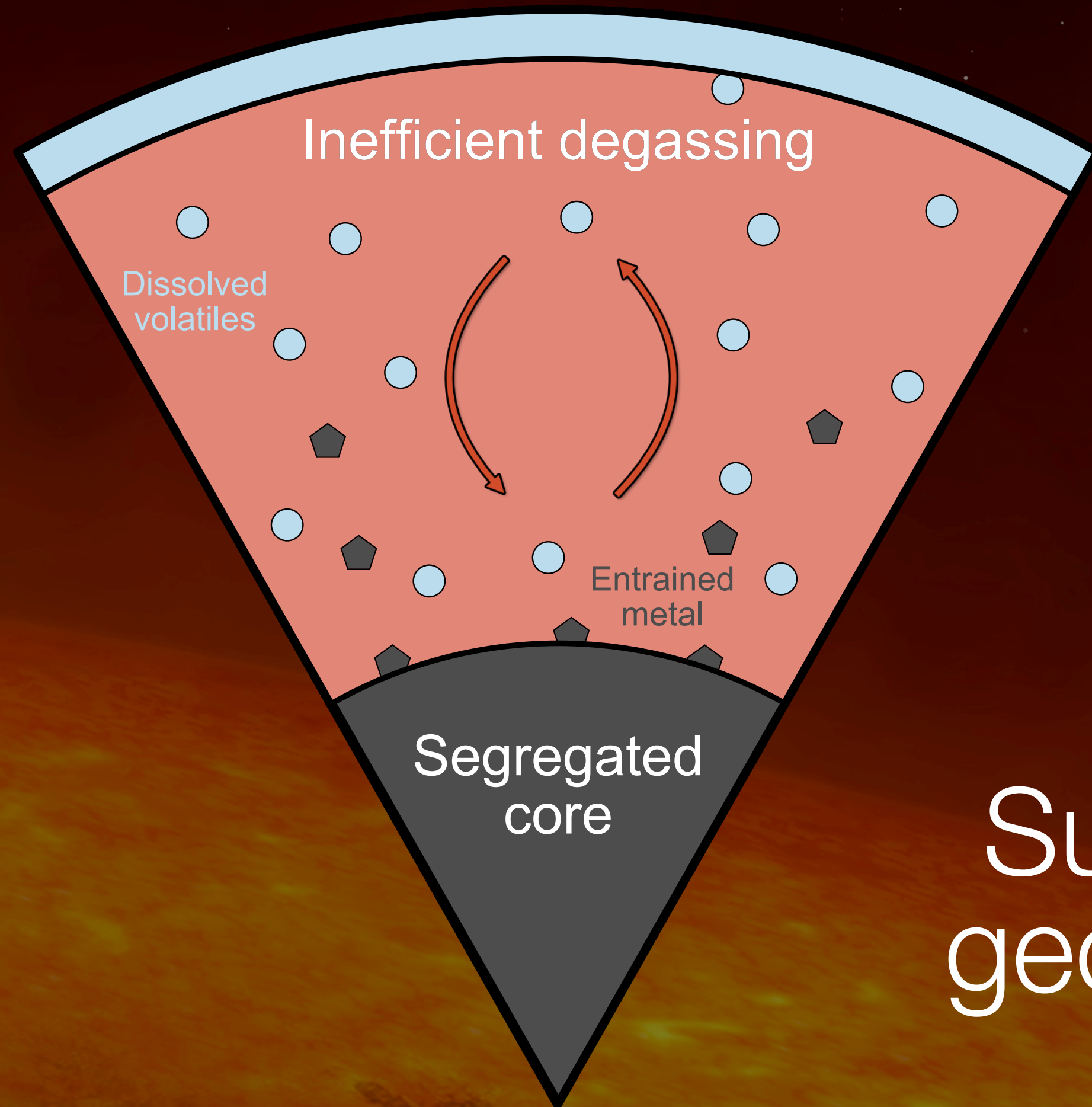
Oxidation state ~ interior geochemistry

~terrestrial

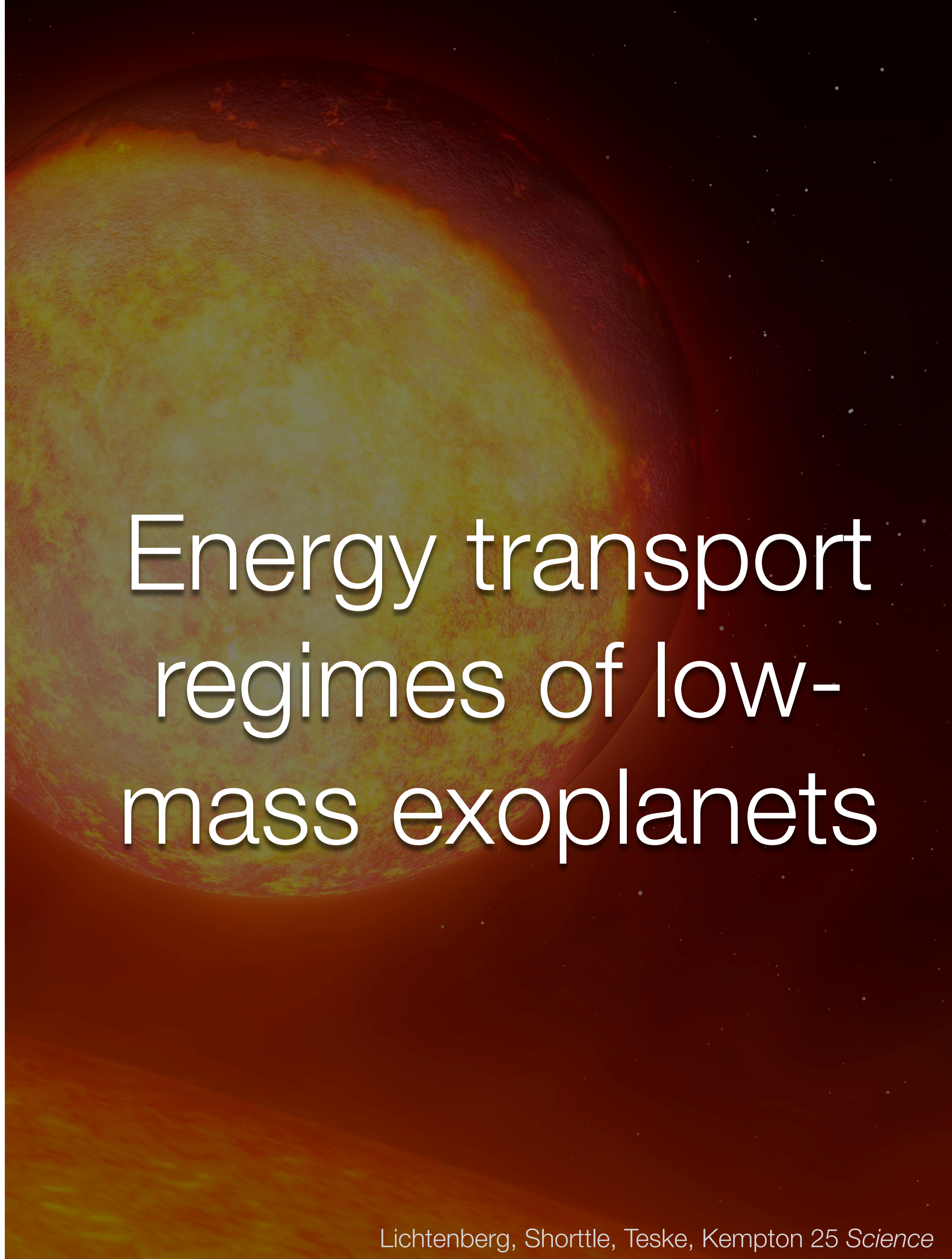
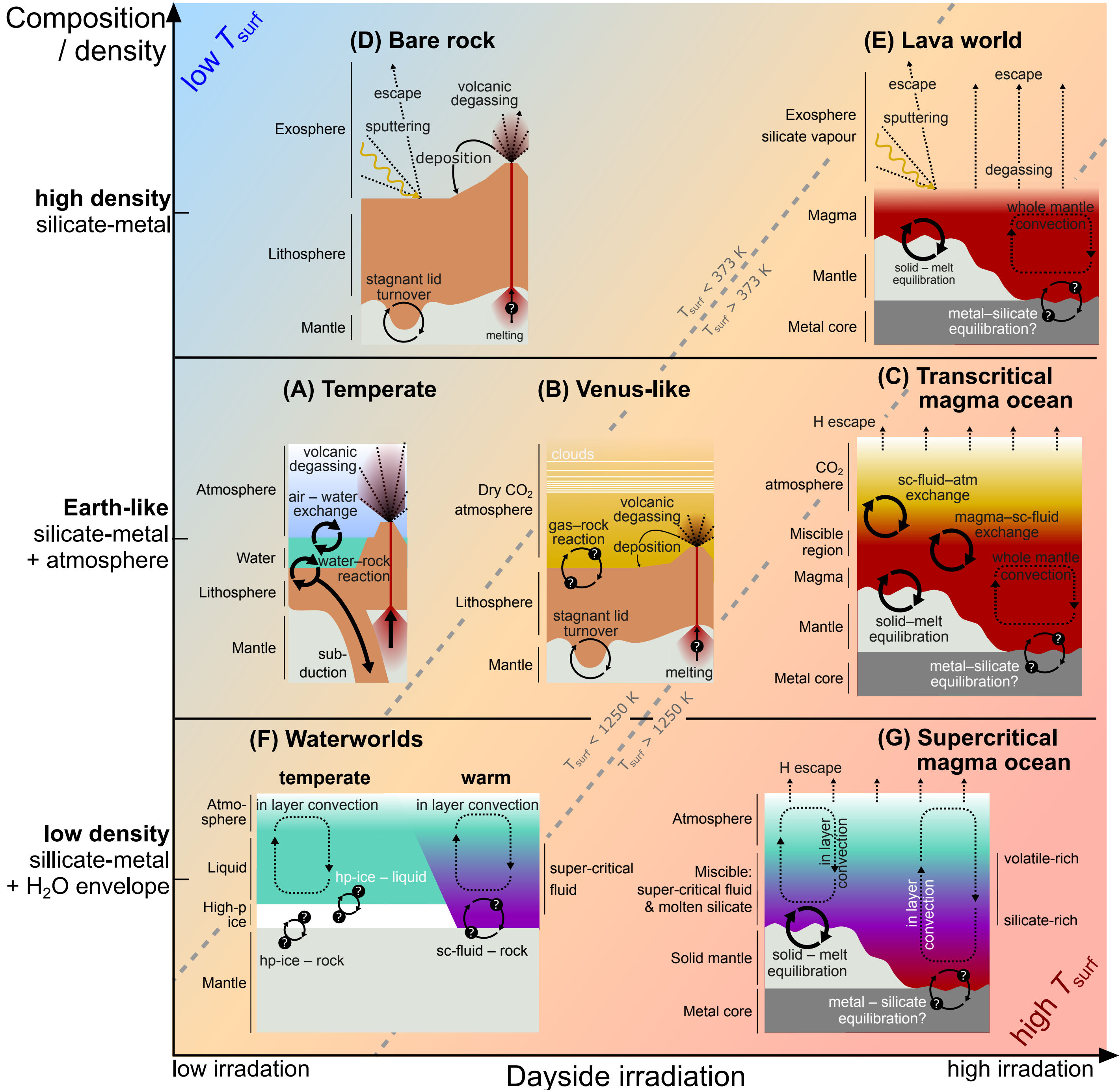


Harrison Nicholls

Possible super-Earth crystallisation regimes



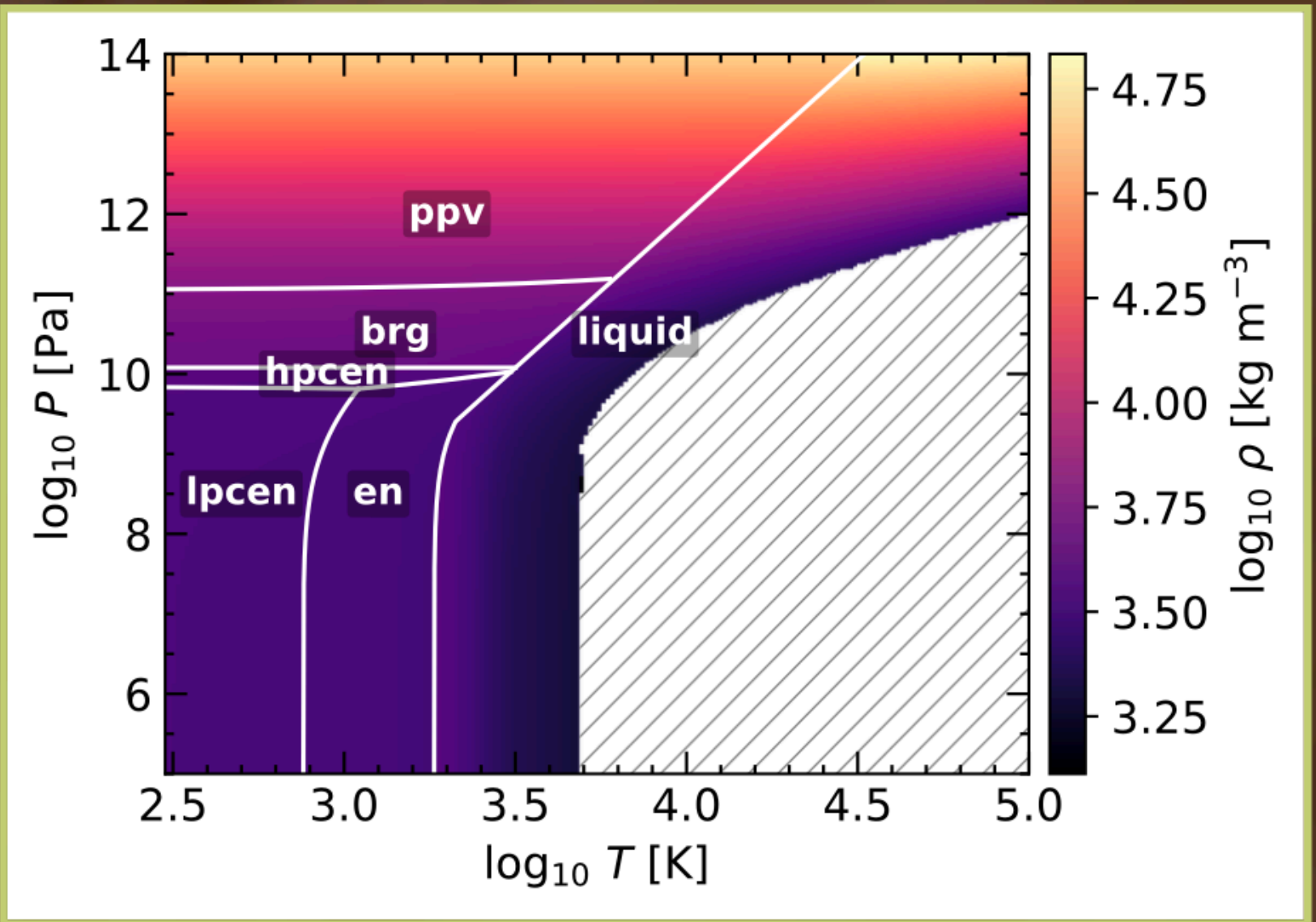
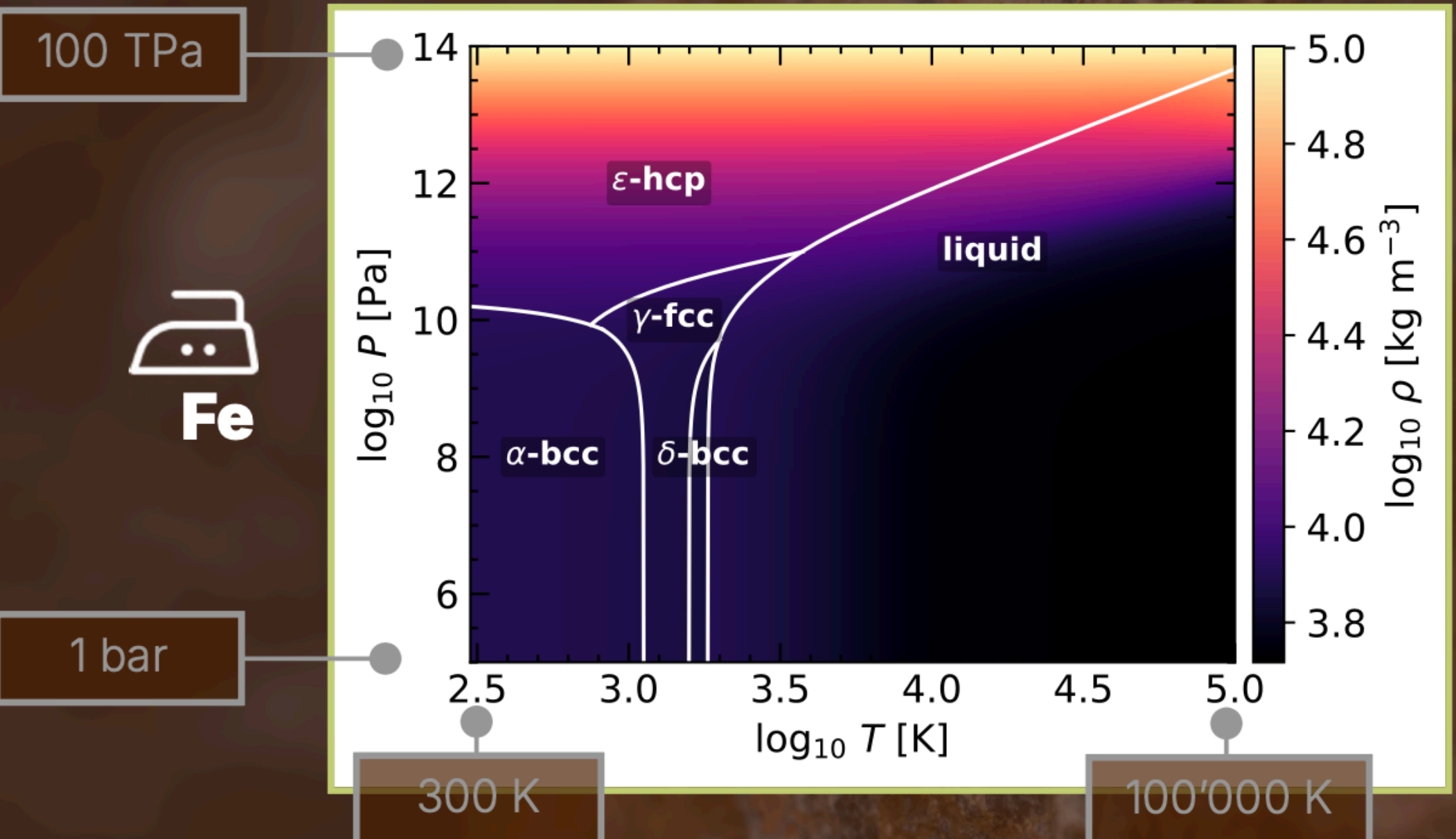
Super-Earth geochemistry



Energy transport regimes of low-mass exoplanets

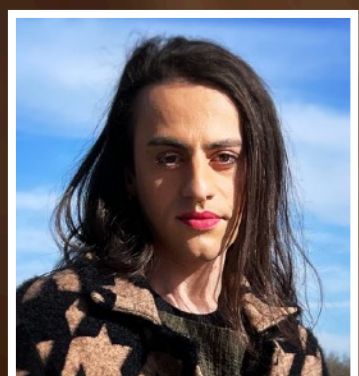
EoS phase coverage affect evolution models

Full Phase Coverage

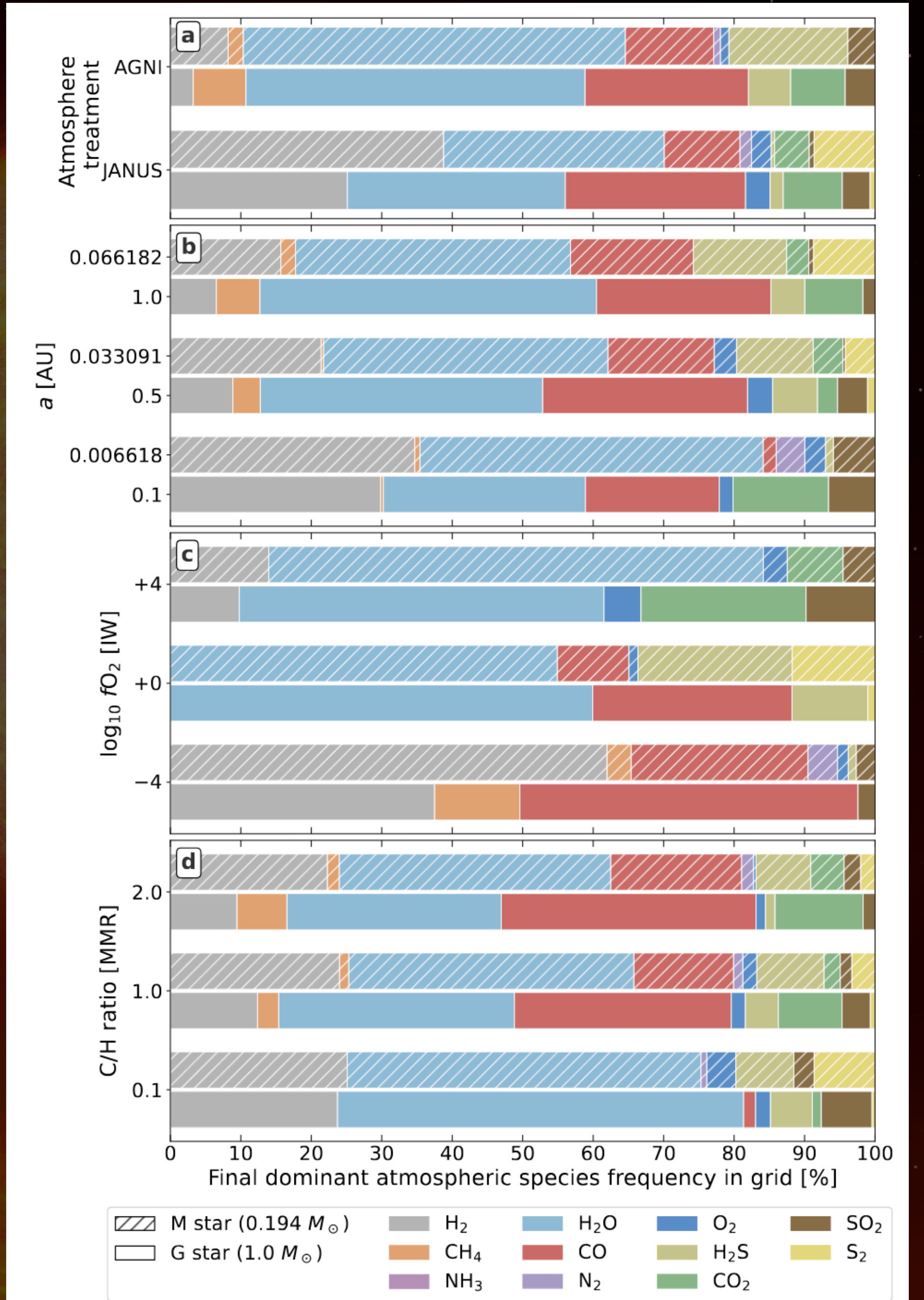
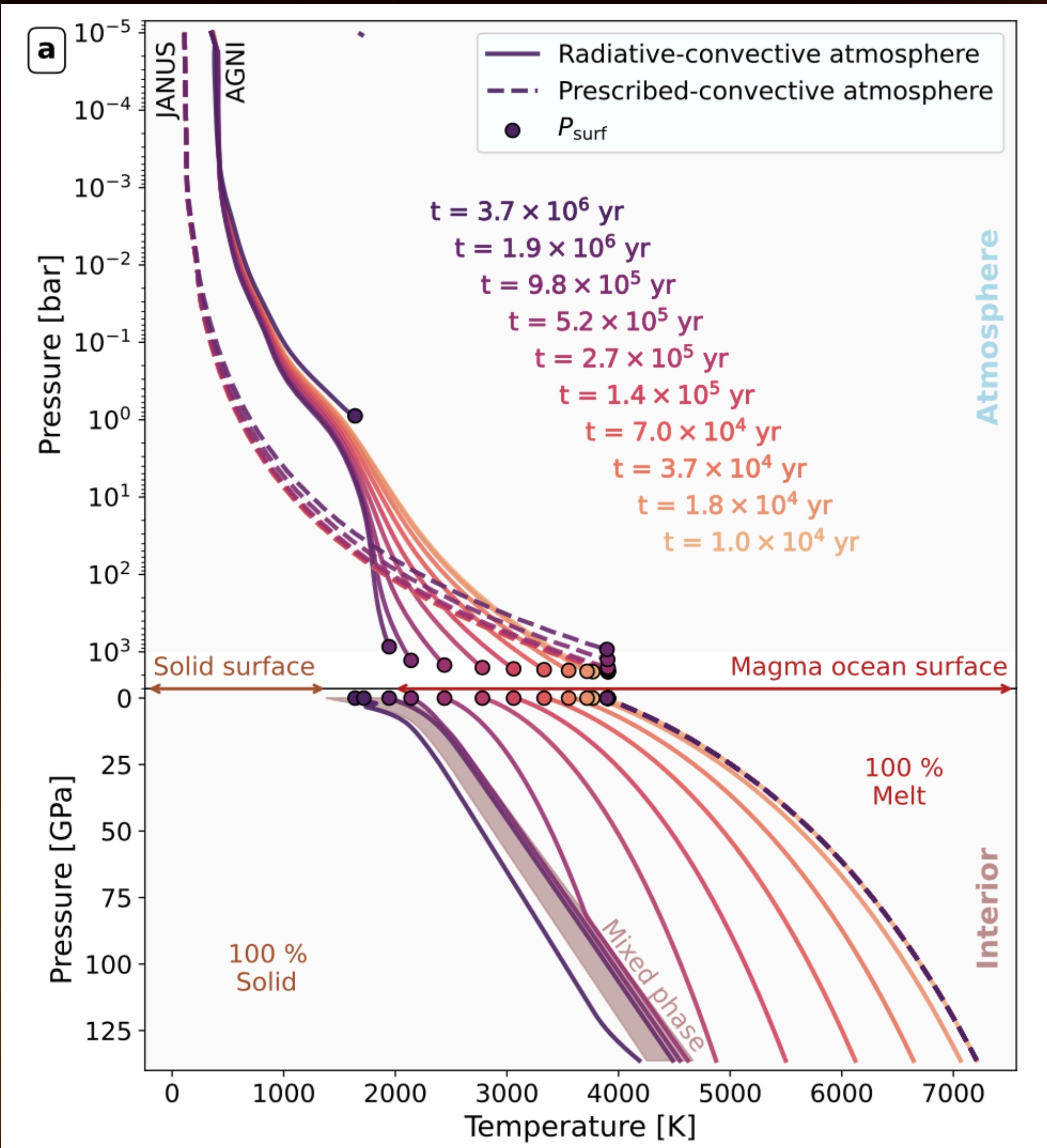


Thermodynamic consistency:
 $\Delta \equiv 1 - \rho^2 \partial S / \partial P|_T / \partial \rho / \partial T|_P$

$|\Delta| < 1\% \rightarrow$ consistent (Haldemann+20)
 Fe: **98% below 1%** (median = 1.4×10^{-7})
 MgSiO₃: **100% below 1%** (median = 3.5×10^{-8})

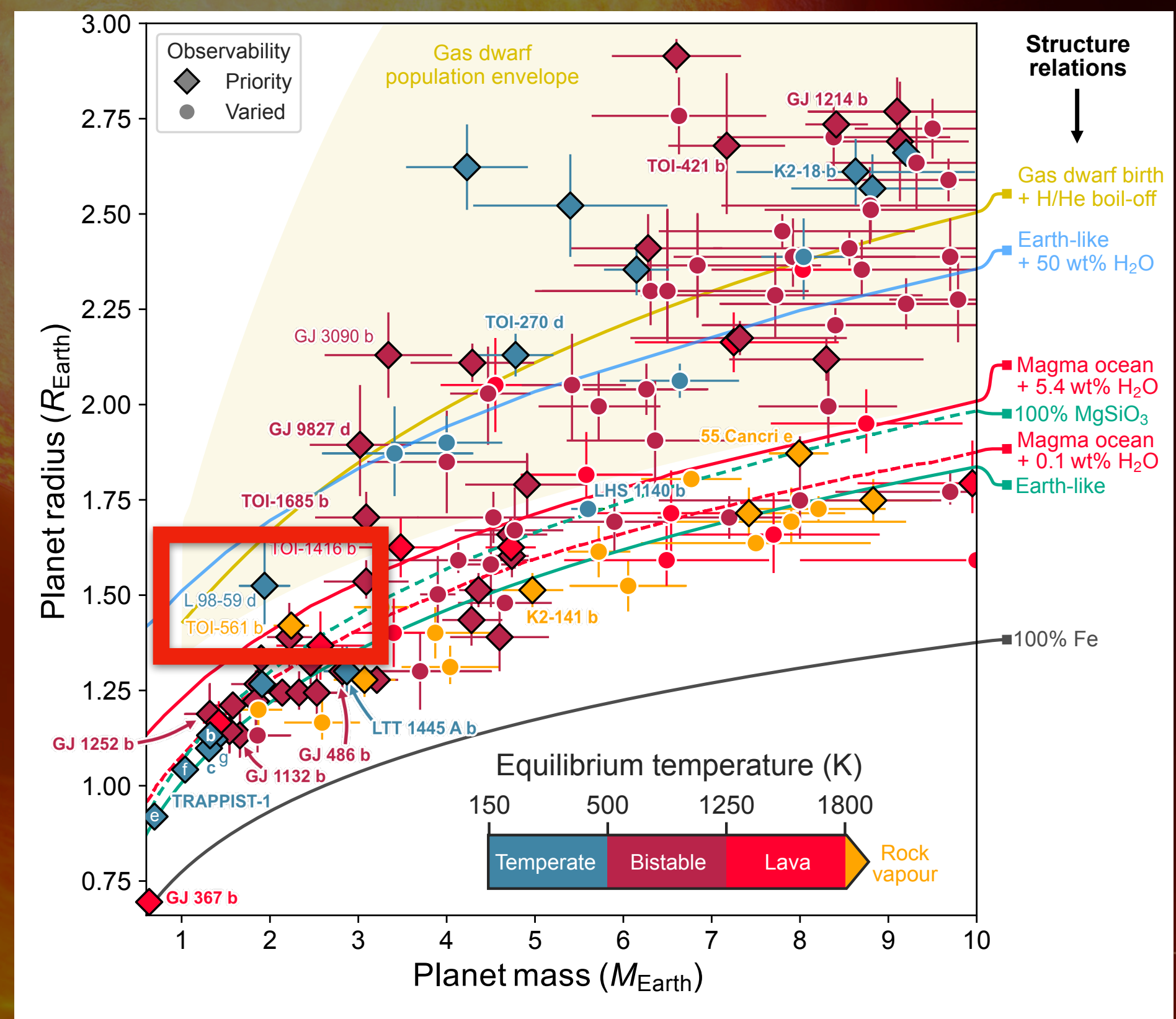
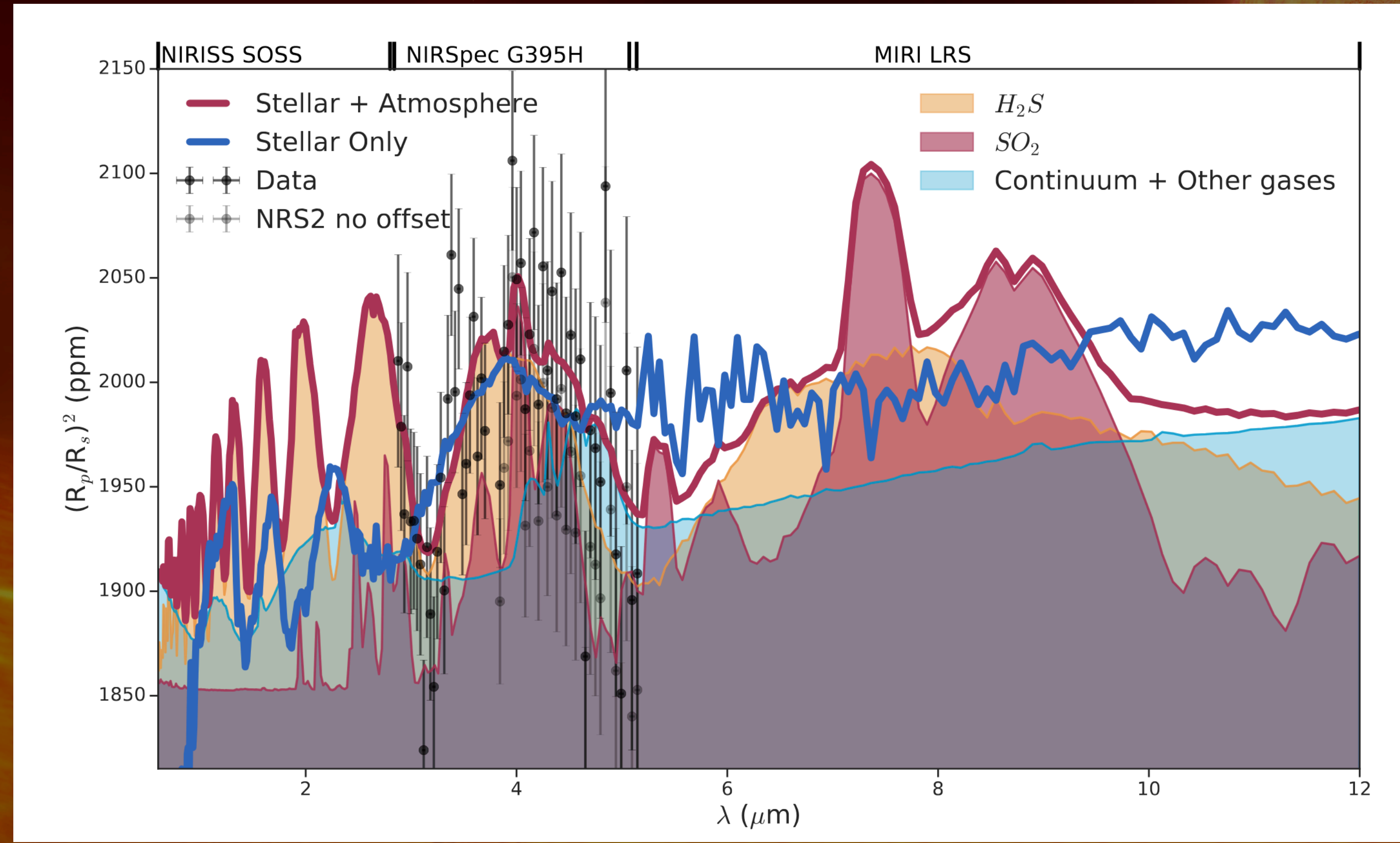


Atmospheric energy transport one determinant for MO freeze-out



Emma Postolec

Link between volatile-rich super-Earths & sub-Neptunes: L 98-59 d



Banerjee+24, Gressier+24 (JWST)

+ H₂S detection from the ground, IGRINS/Gemini South (Cheverall+26 MNRAS)

Present-day super-Earth L 98-59 d was born as volatile-rich transition planet *(not a gas dwarf, not a water world)*



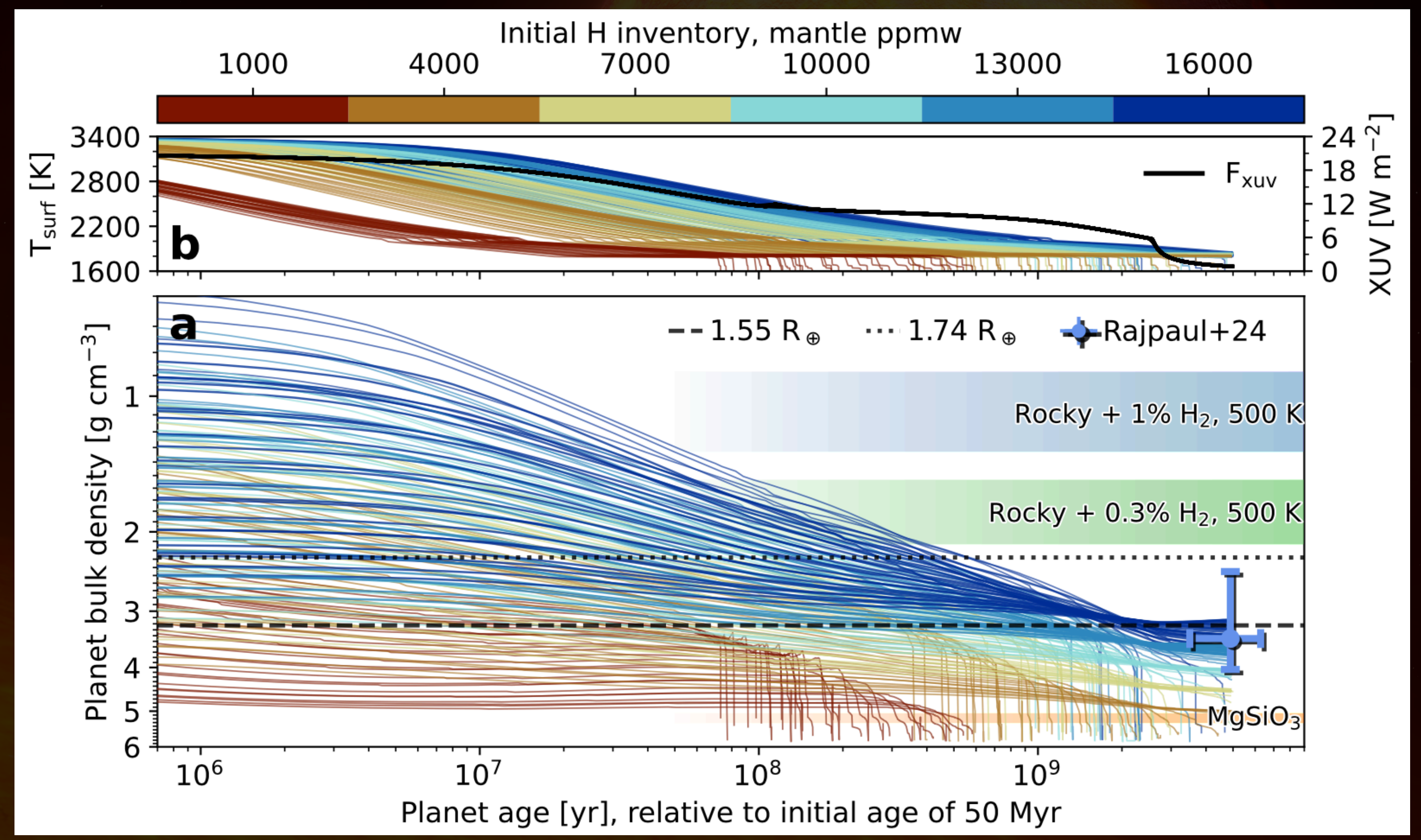
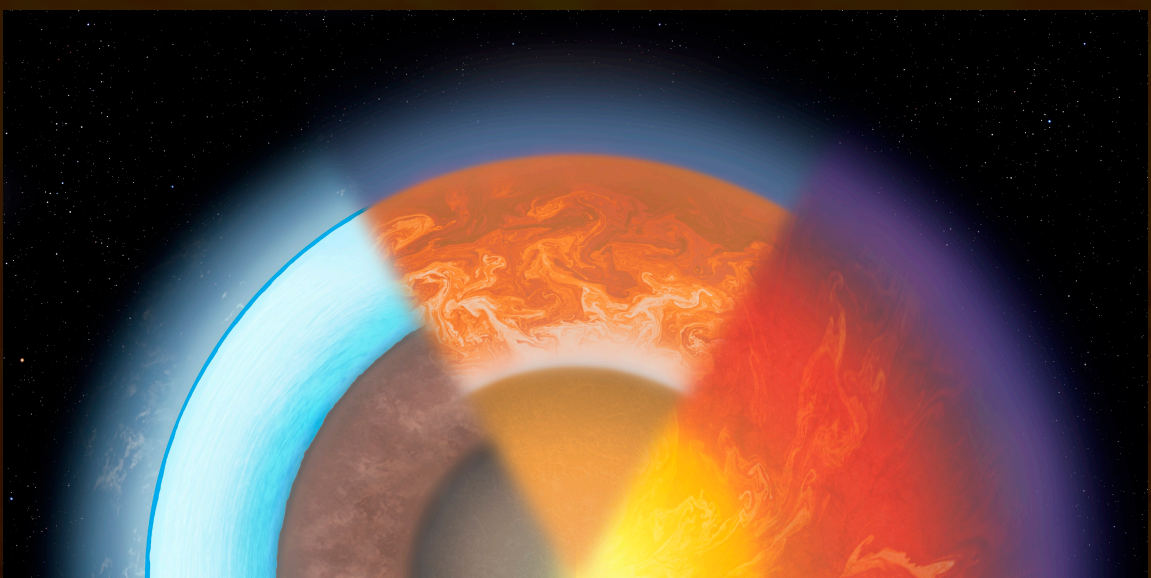
Harrison Nicholls



Claire Guimond



Emma Postolec



Present-day super-Earth L 98-59 d was born as sulfur-rich transition planet *(not a gas dwarf, not a water world)*



Harrison Nicholls

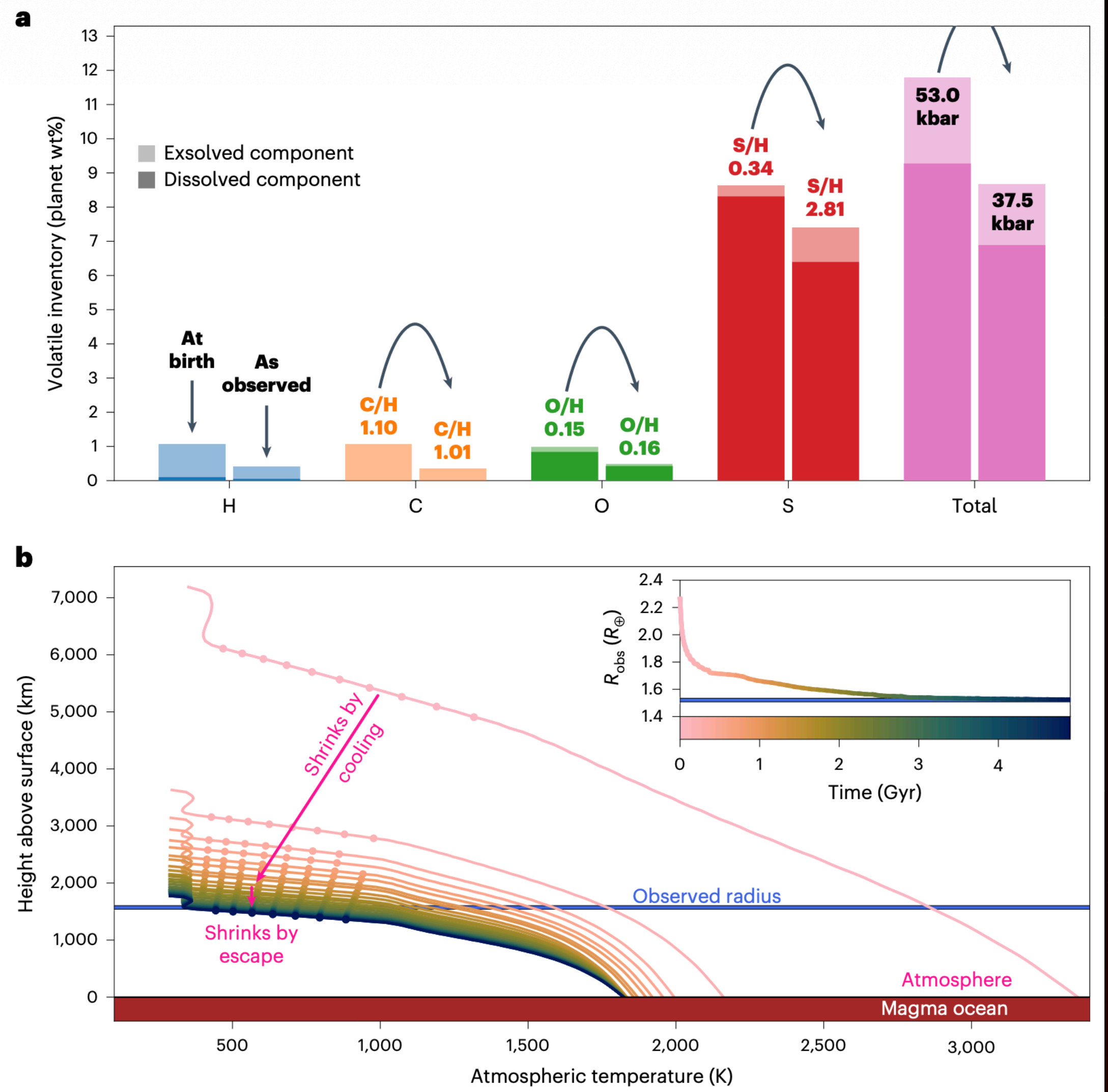
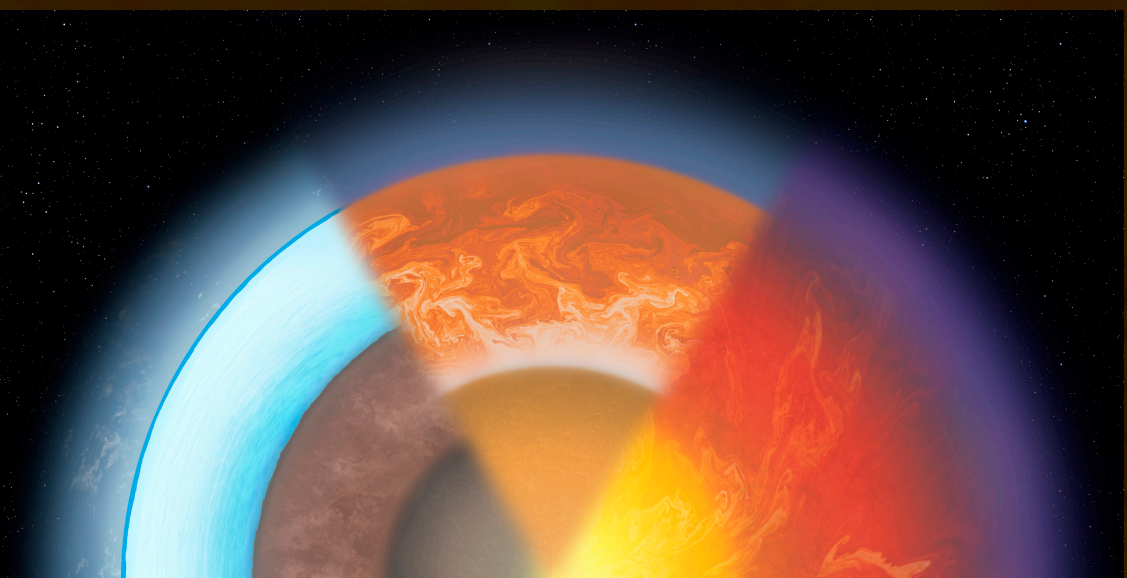


Claire Guimond



Emma Postolec

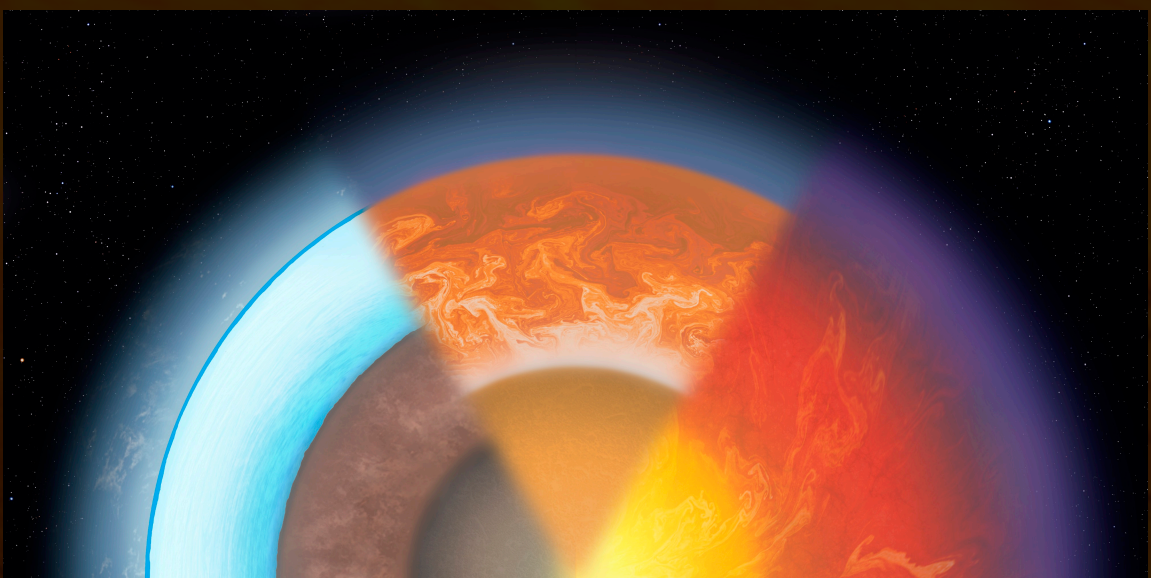
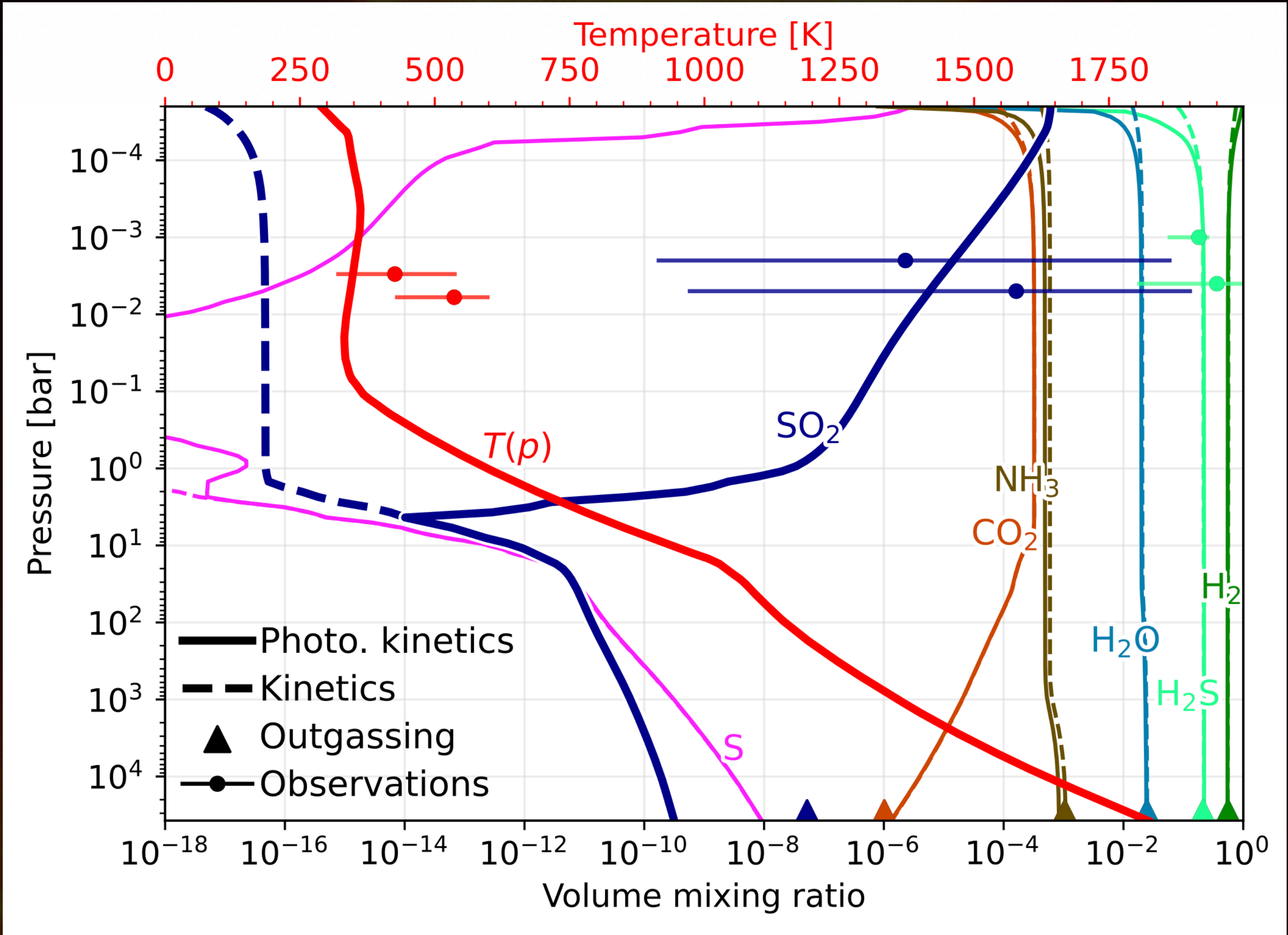
Active photochemistry in super-Earth-sized exoplanet, fed by volatile-rich & reduced magma ocean



Present-day super-Earth L 98-59 d was born as sulfur-rich transition planet *(not a gas dwarf, not a water world)*



Active photochemistry in super-Earth-sized exoplanet, fed by volatile-rich & reduced magma ocean



Ultra-hot super-Earth TOI-561 b hosts secondary atmosphere



Anjali
Piette



Diana
Valencia



Tim
Lichtenberg



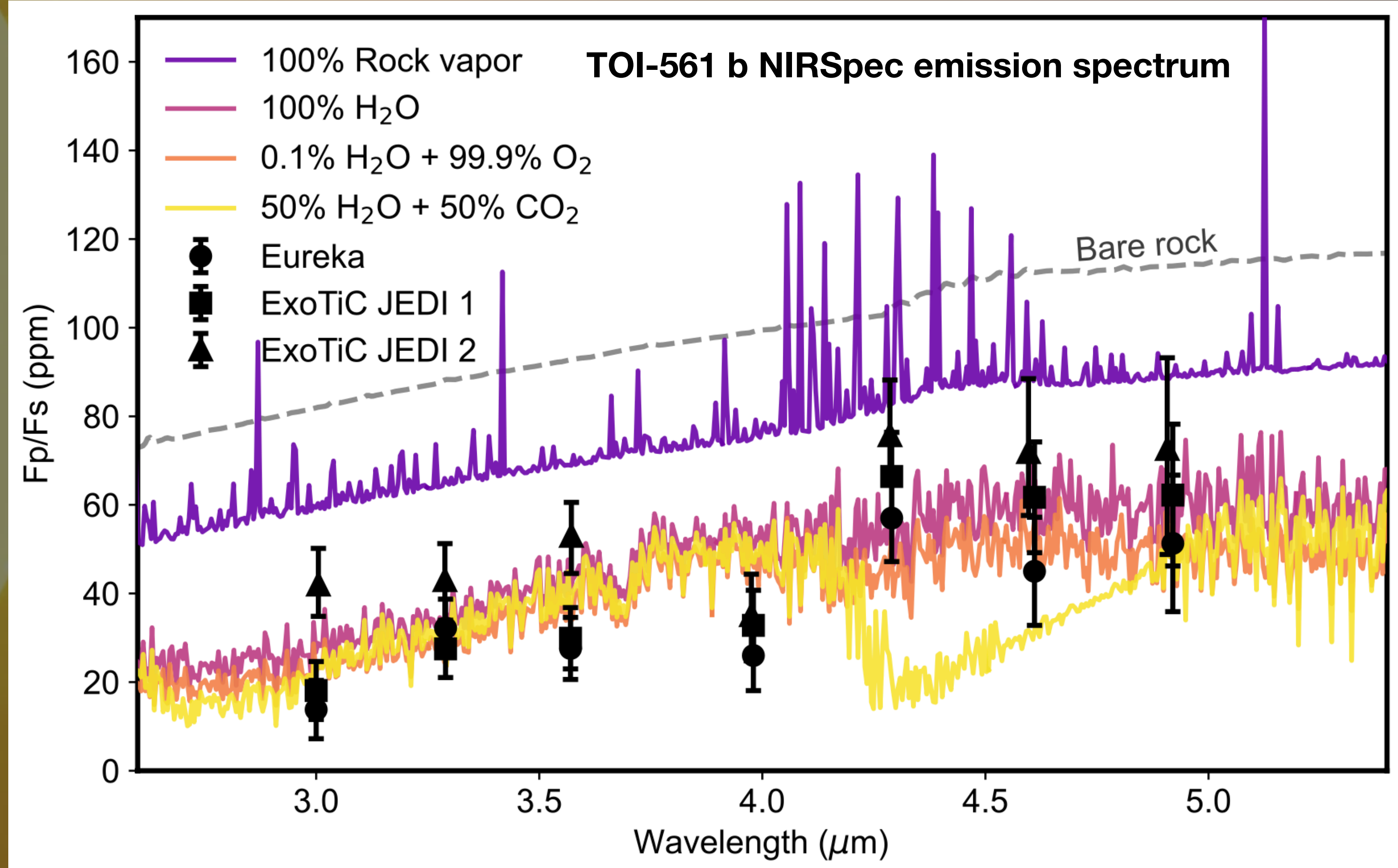
PI:
Johanna
Teske



Lisa
Dang



Raymond
Pierrehumbert



Nicole Wallack



Alex McGinty



Emma Postolec



Mark Hammond



Bo Peng



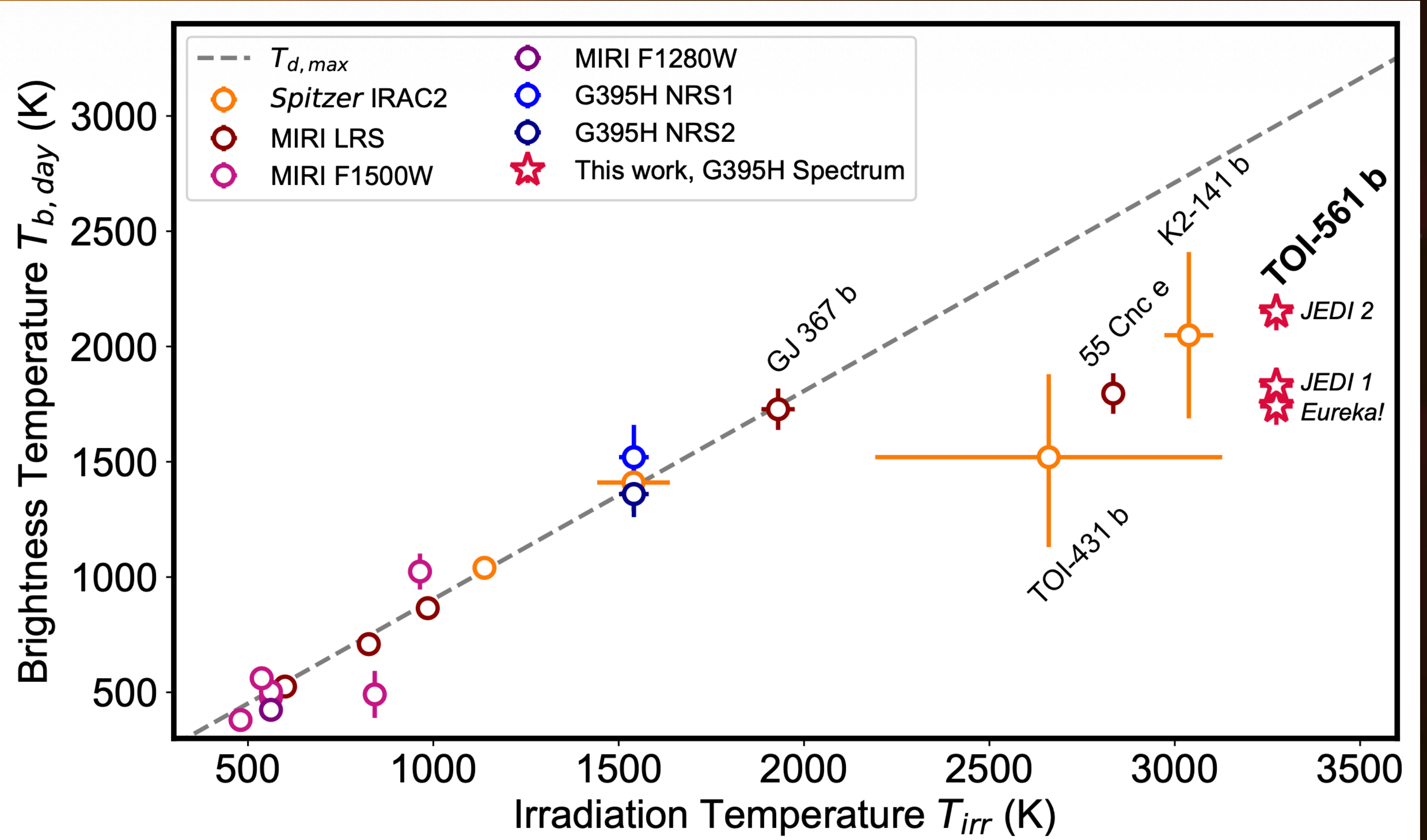
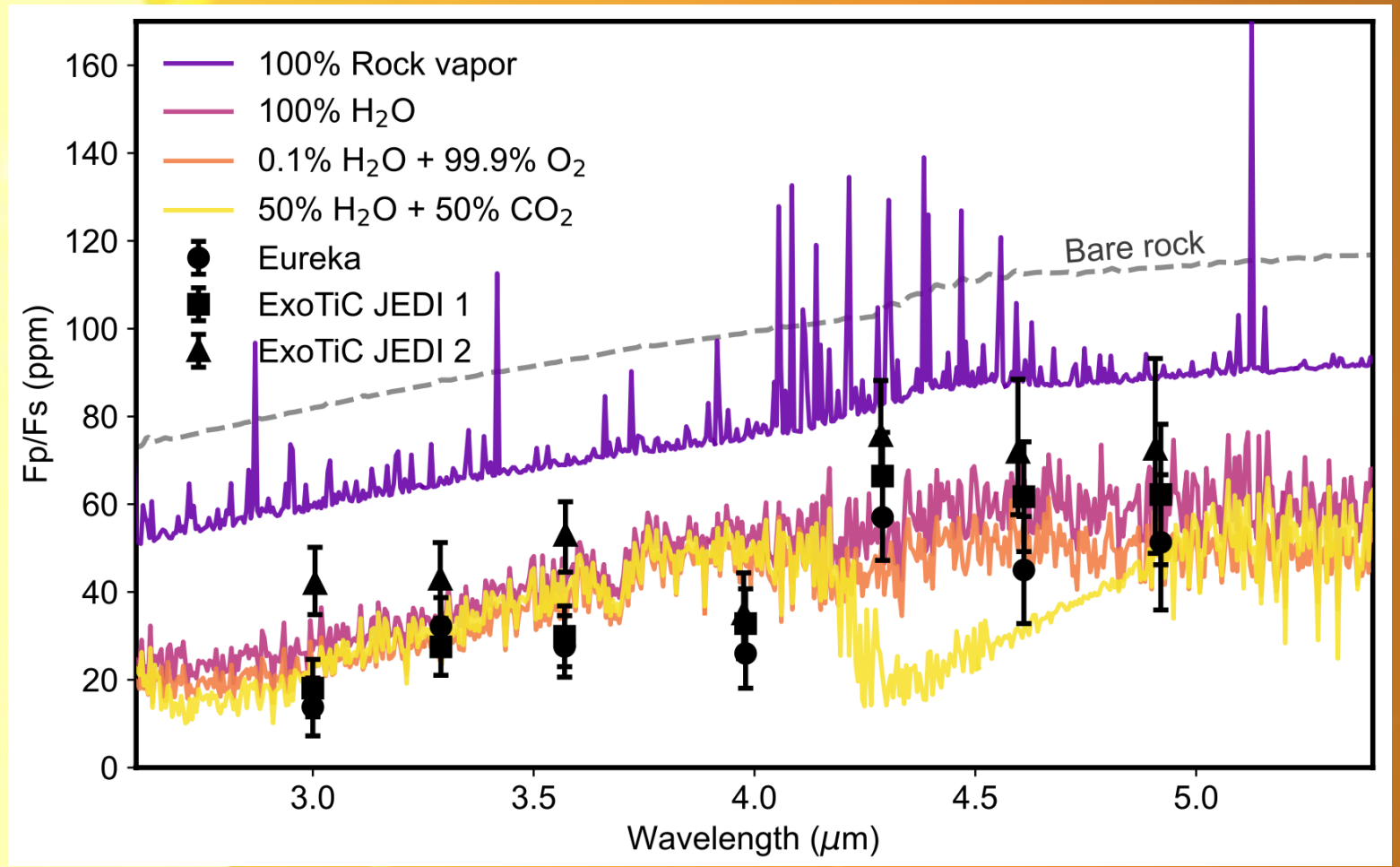
Mykhaylo Plotnykov



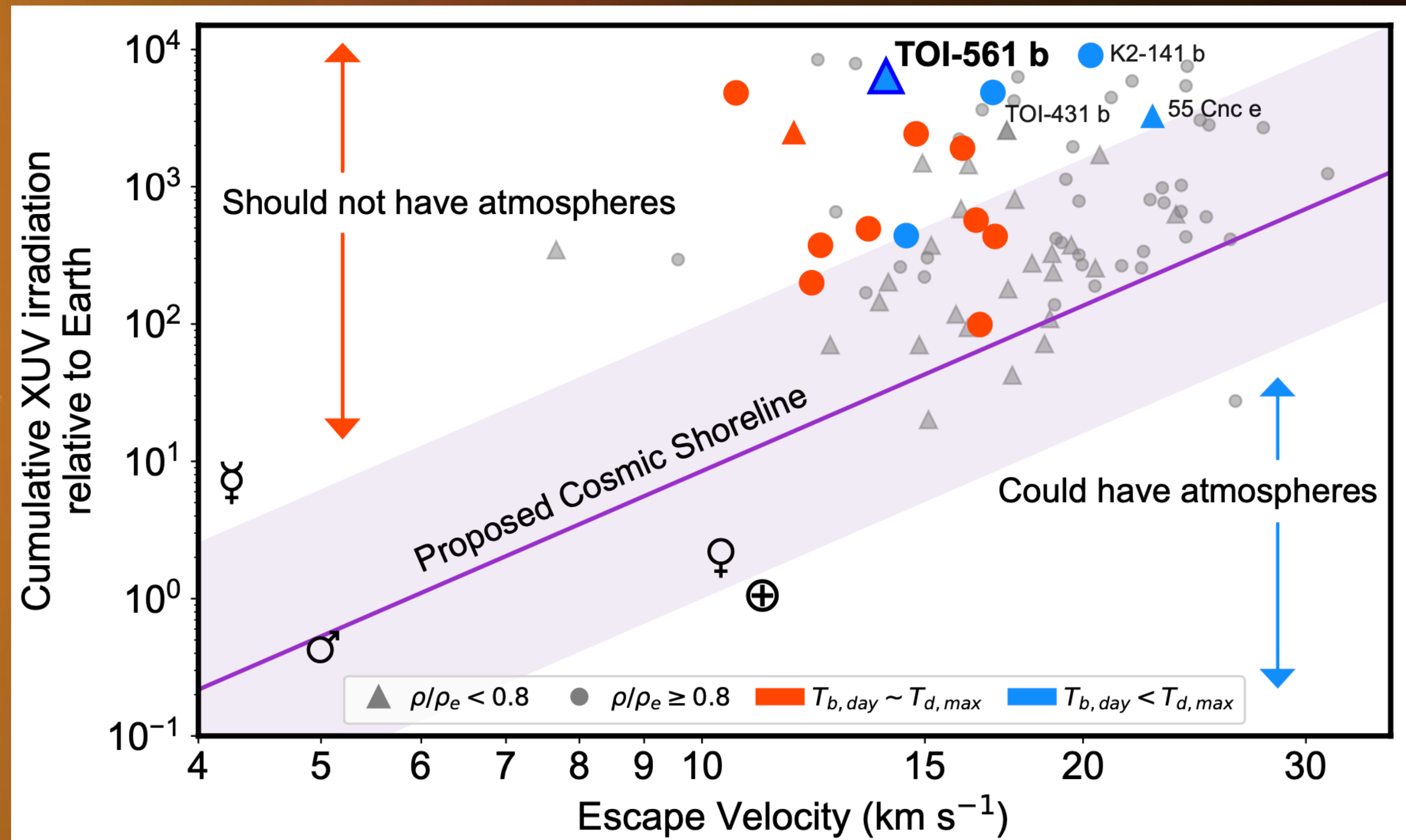
Samuel Boucher

**Early-career researchers in
TOI-561 b JWST/NIRSpec Team**

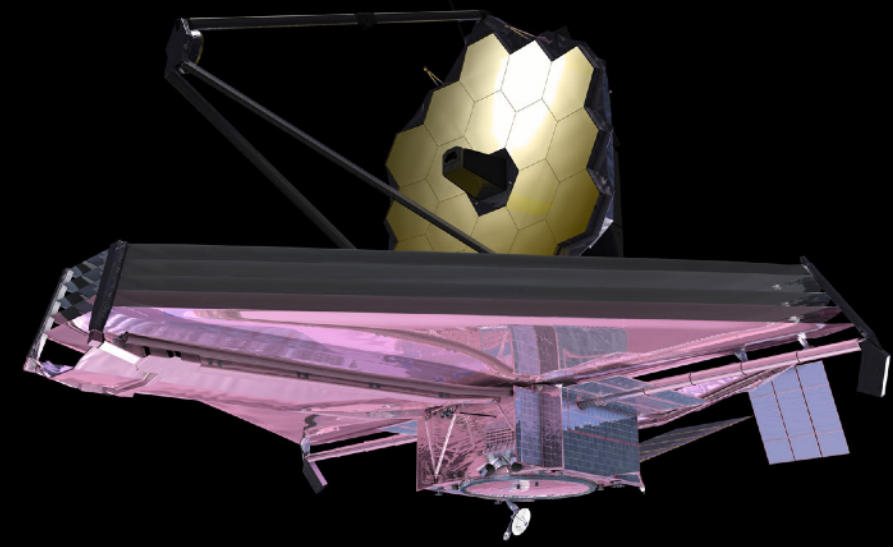
Ultra-hot super-Earth TOI-561 b hosts secondary atmosphere



TOI-561 b & 55 Cnc e falsify the “cosmic shoreline” hypothesis



Possible sub-Neptune interior regimes

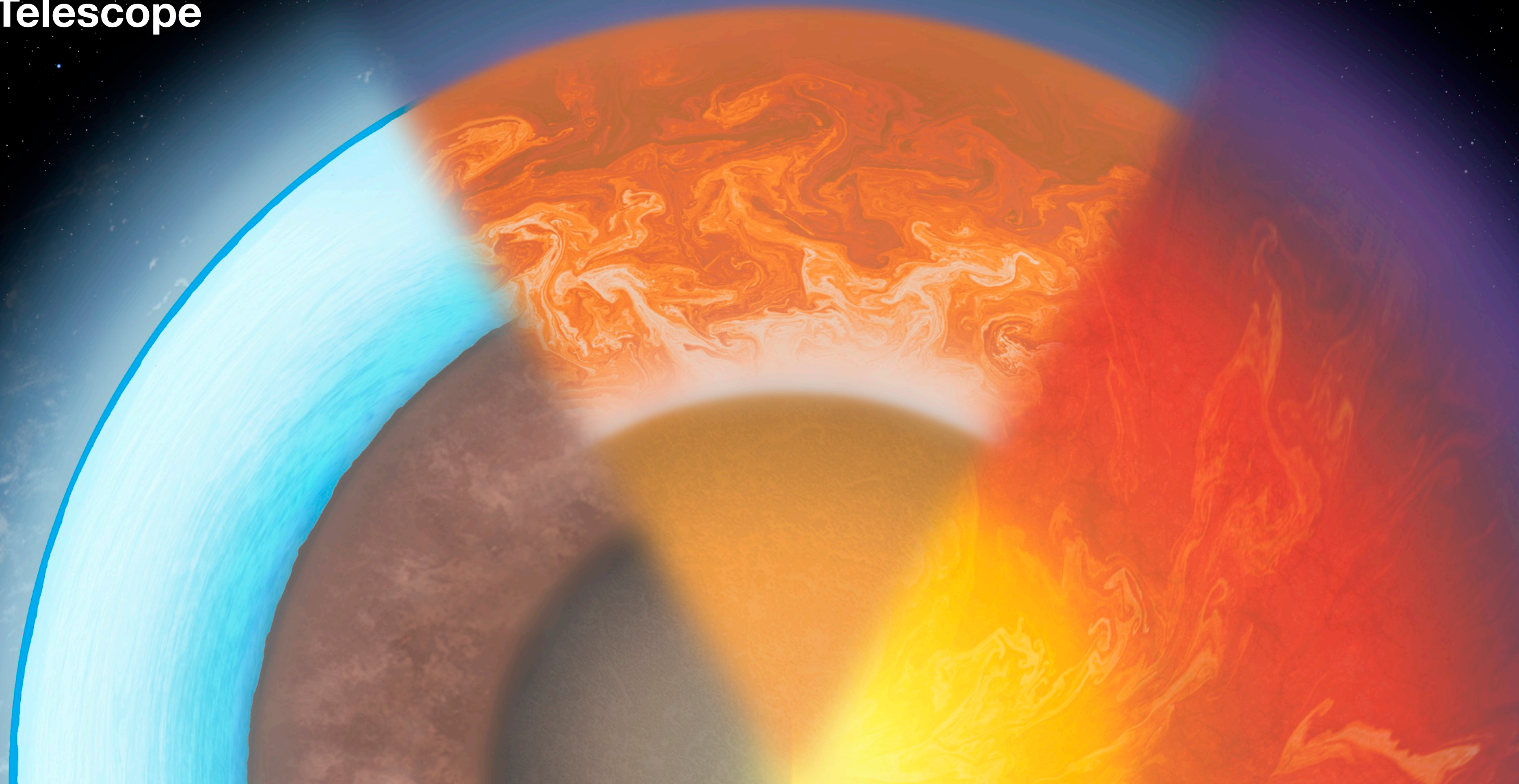


**James Webb
Space Telescope**

Gas dwarf

**Water
world**

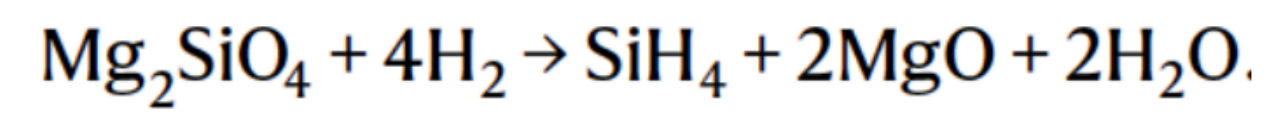
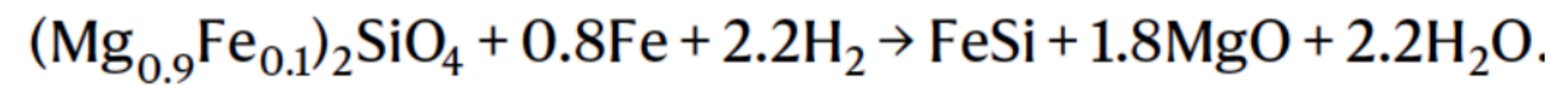
**Globally
supercritical**



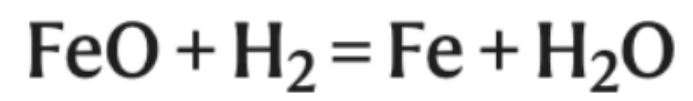
Evolving composition

Volatile production in the interior

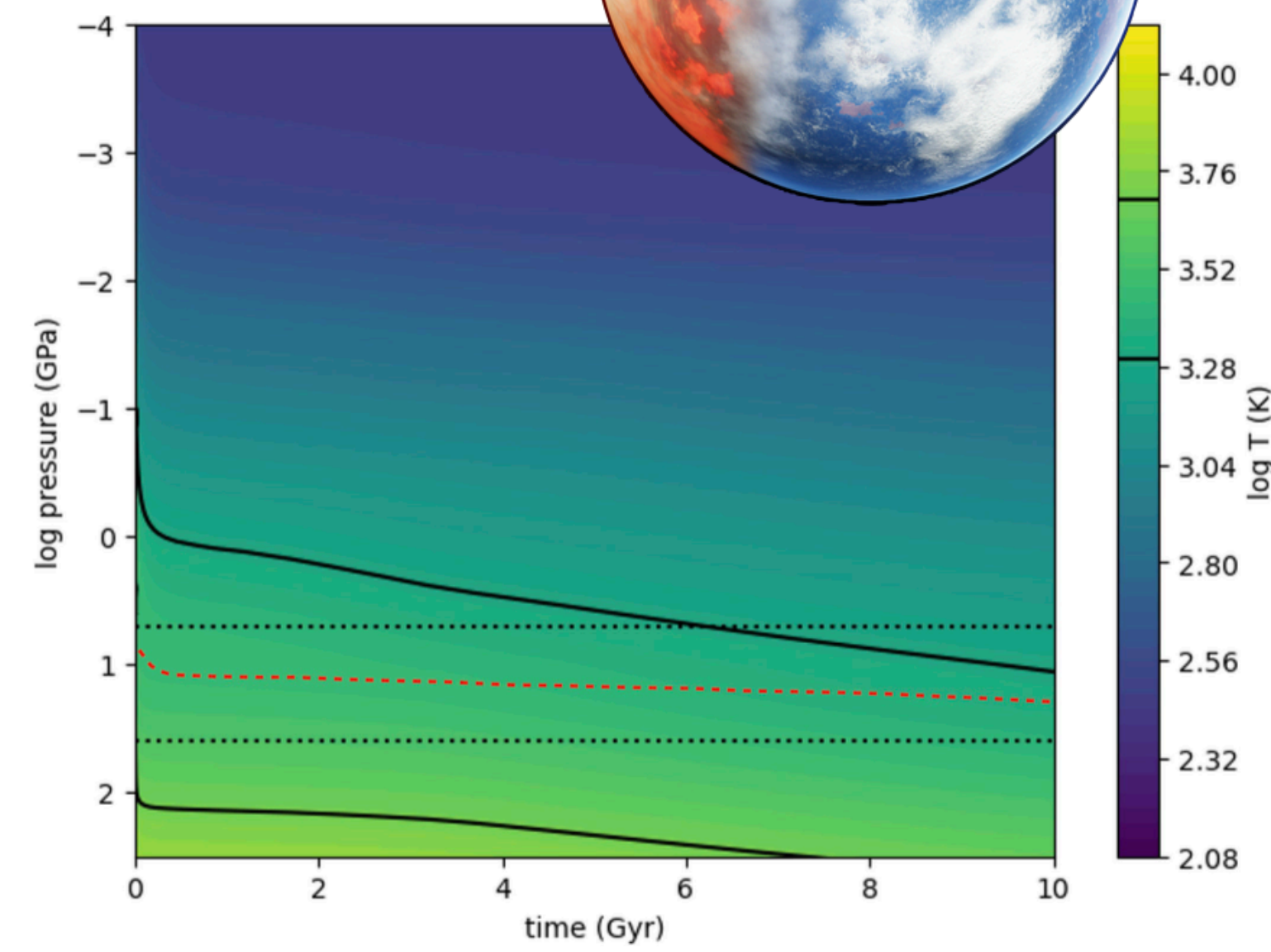
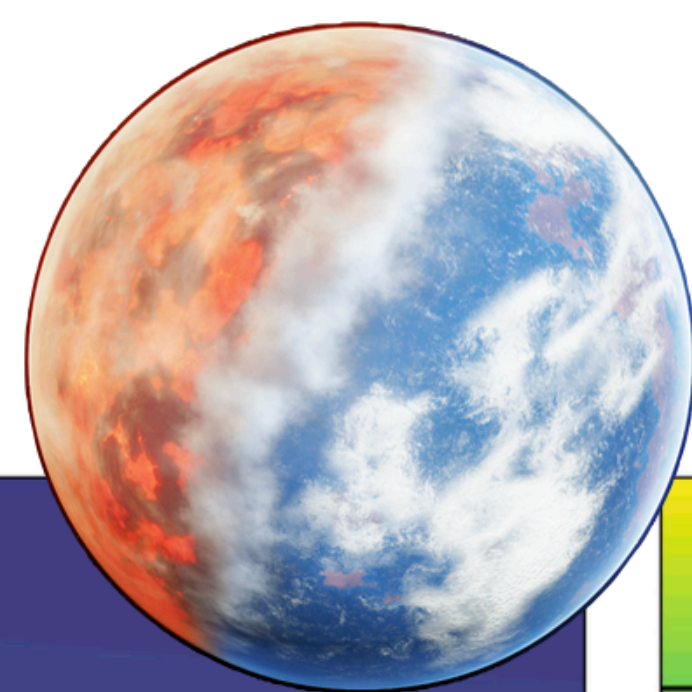
With and without Fe involvement:



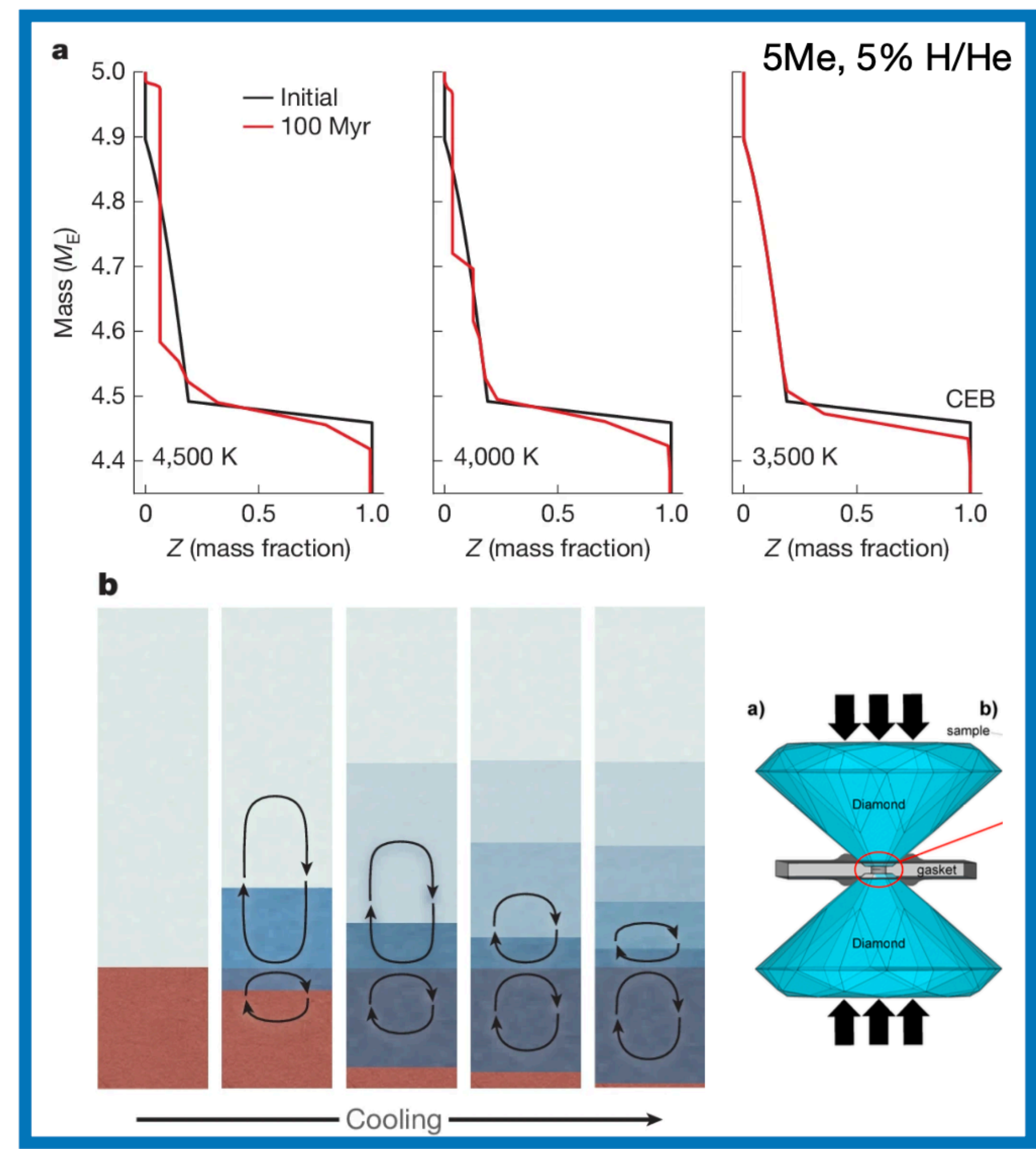
Horn et al. 2025



Miozzi et al. 2025



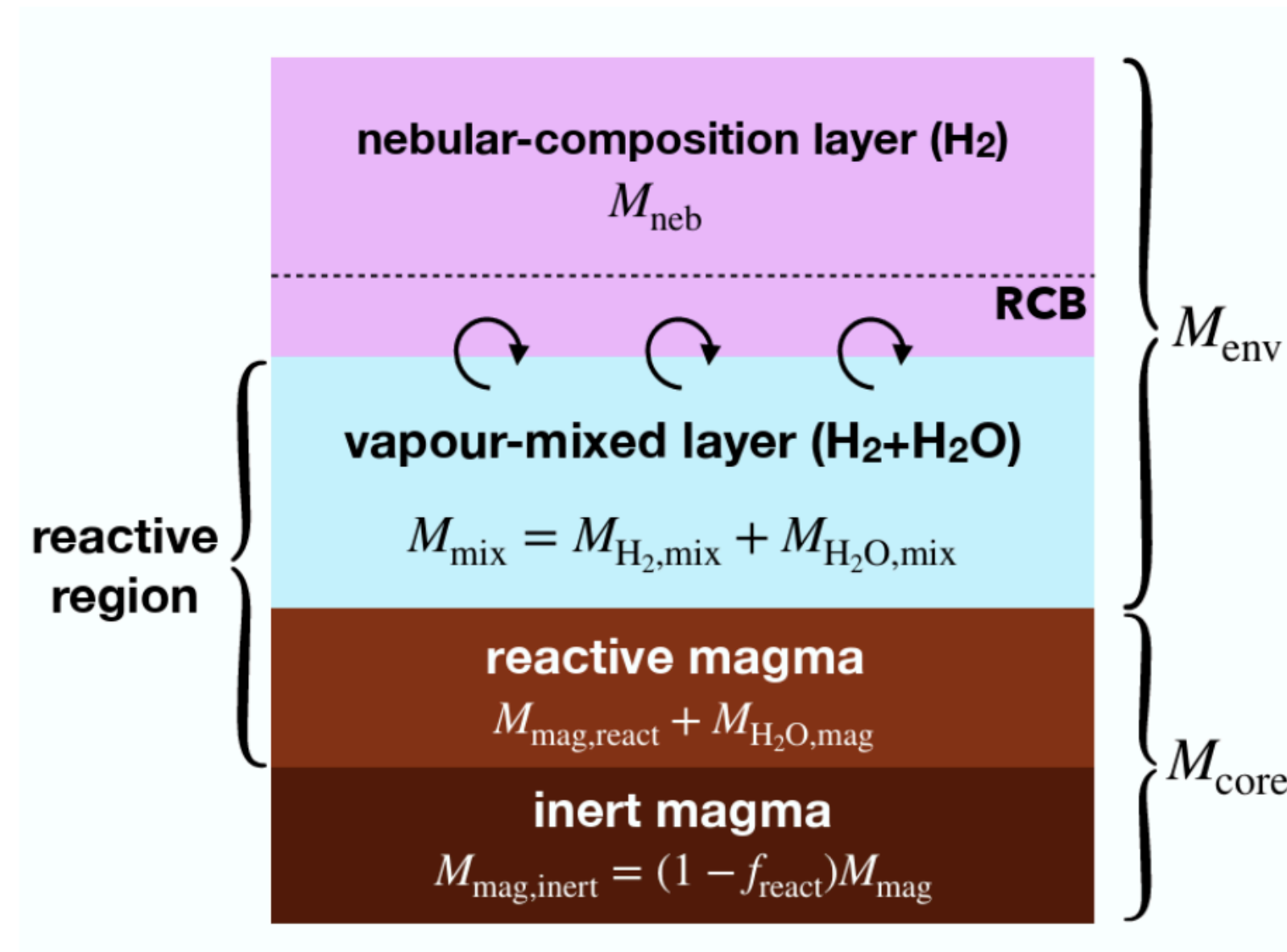
Water production found in lab is much more than the eq. chemistry levels
Convection near the core is not always suppressed by the Z gradients



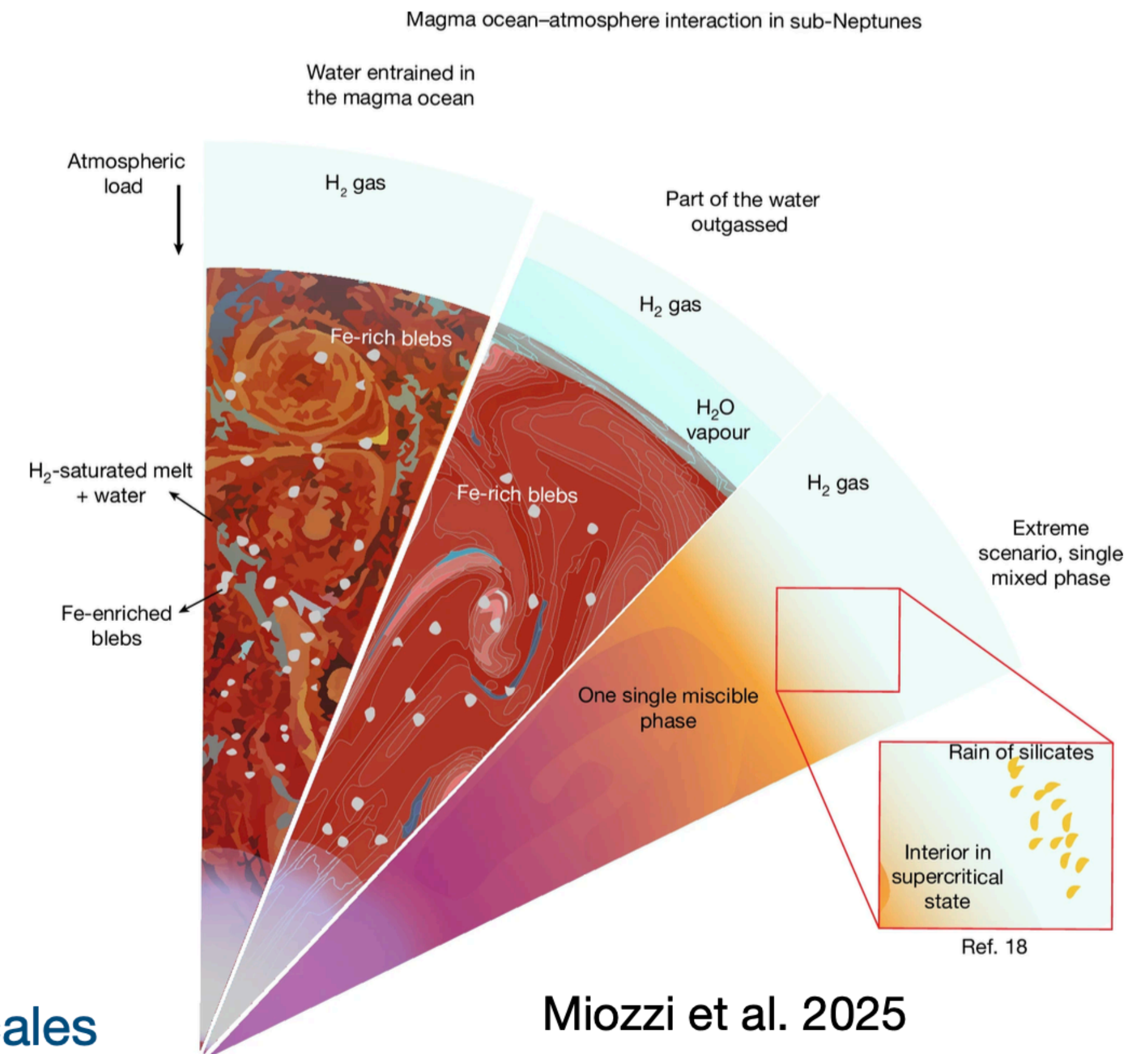
Horn, Vazan, et al. 2025, Nature

Evolving composition

Work in progress



Kimura & Lichtenberg 2026



Miozzi et al. 2025

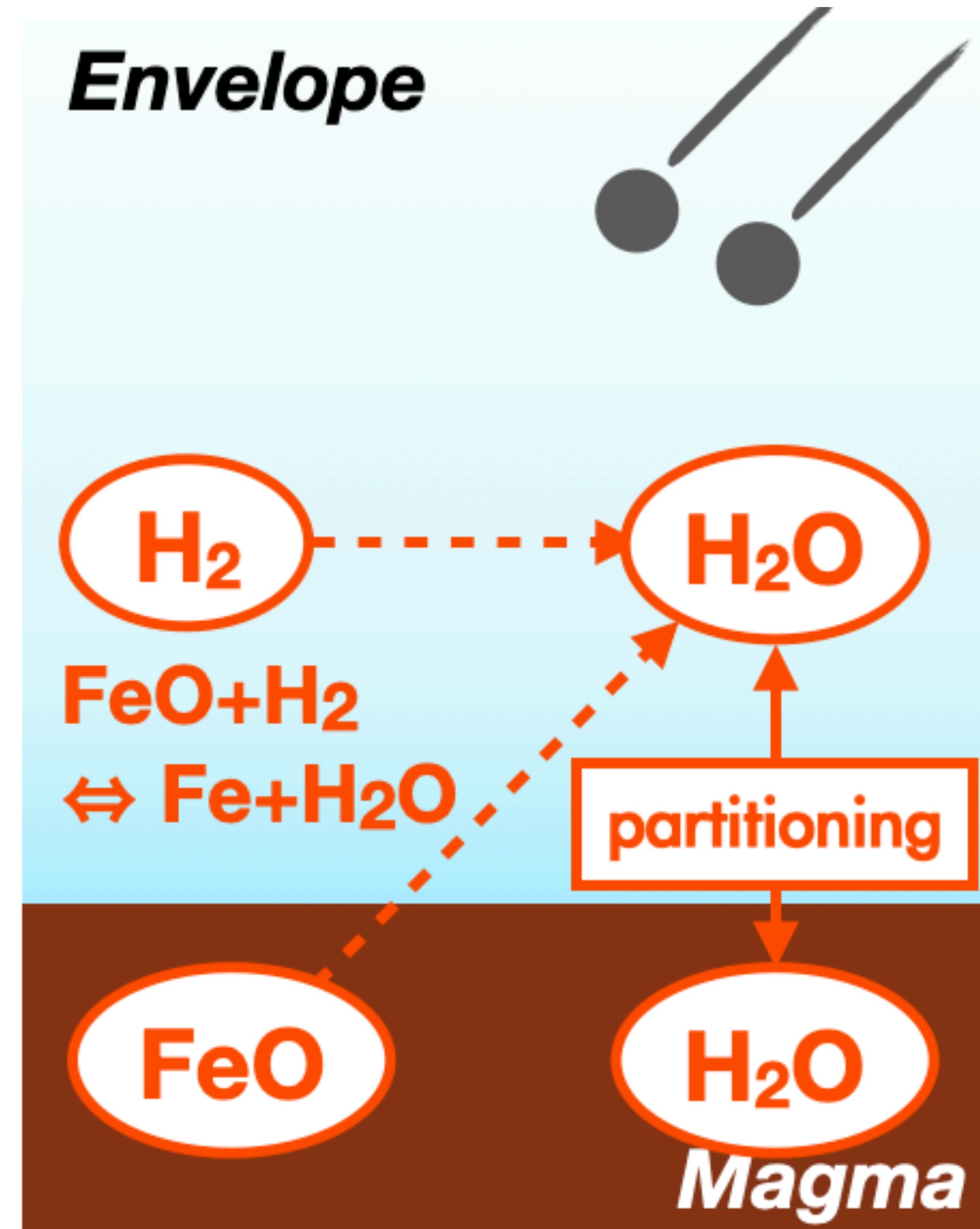
Efficiency of the products spread, and the H supply?
 physical mixing (convection) and chemical mixing (miscibility) + timescales

More modelling (and lab) work is needed - for what planetary types and conditions these processes are applicable?

Magma-Atmosphere Interaction during Formation

- How does the magma-gas interaction affect the envelope formation process?
- How do formation parameters impact on the final properties of super-Earth/sub-Neptunes?

Self-consistently calculate planet growth, envelope formation, water enrichment, partitioning & escape



Enrichment & Partitioning Model

Escape models from Yoshida & Guides 2025

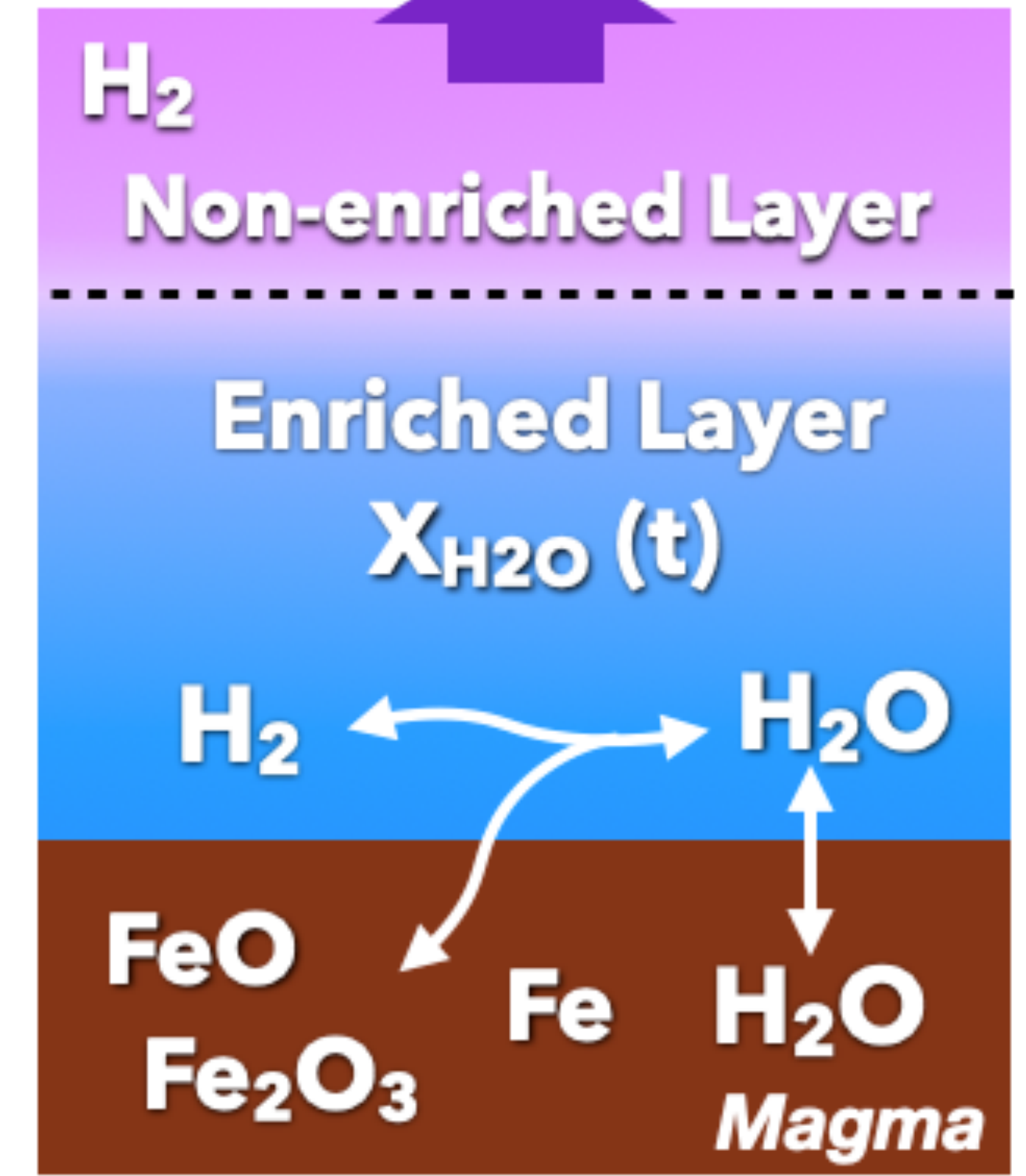
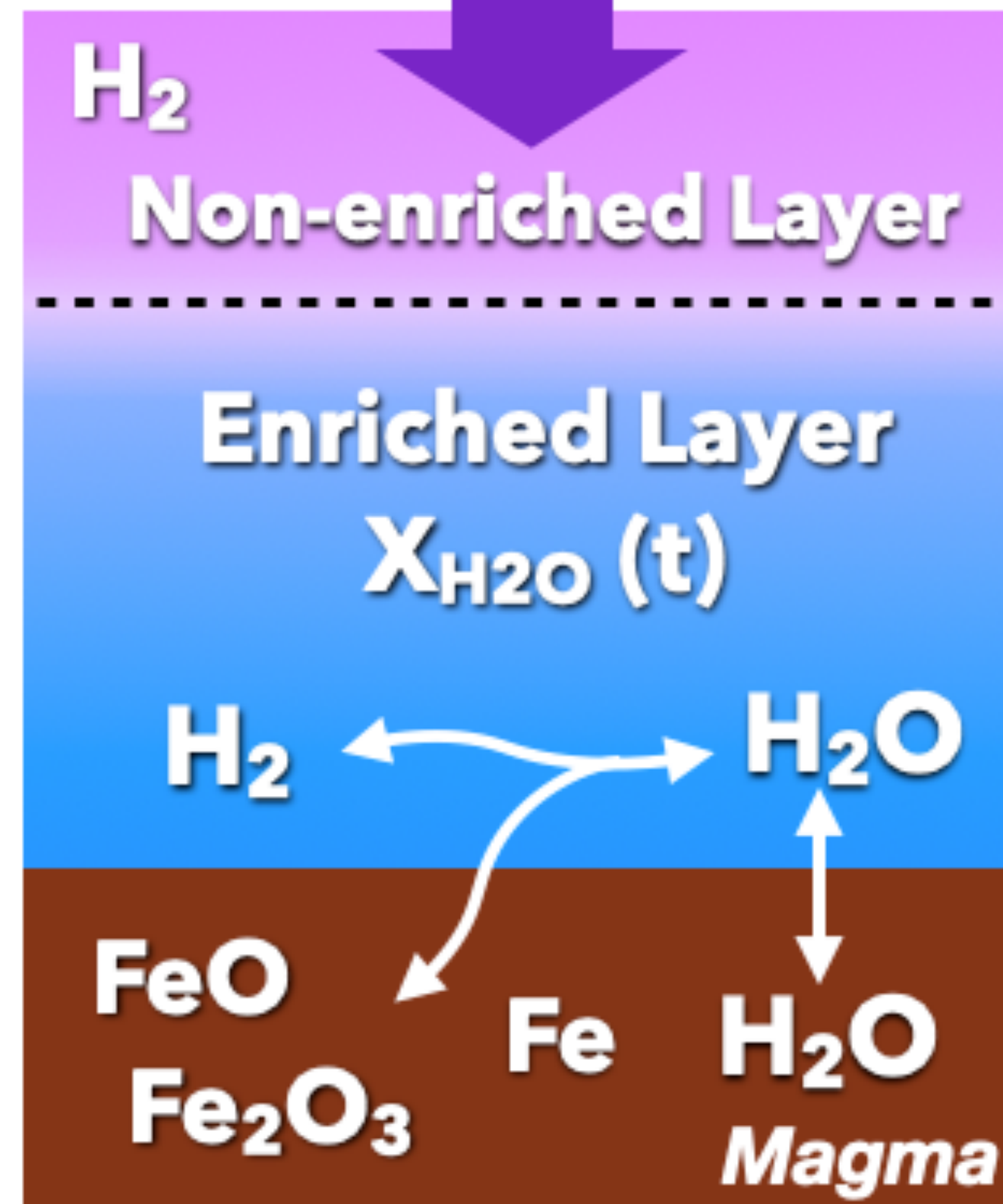
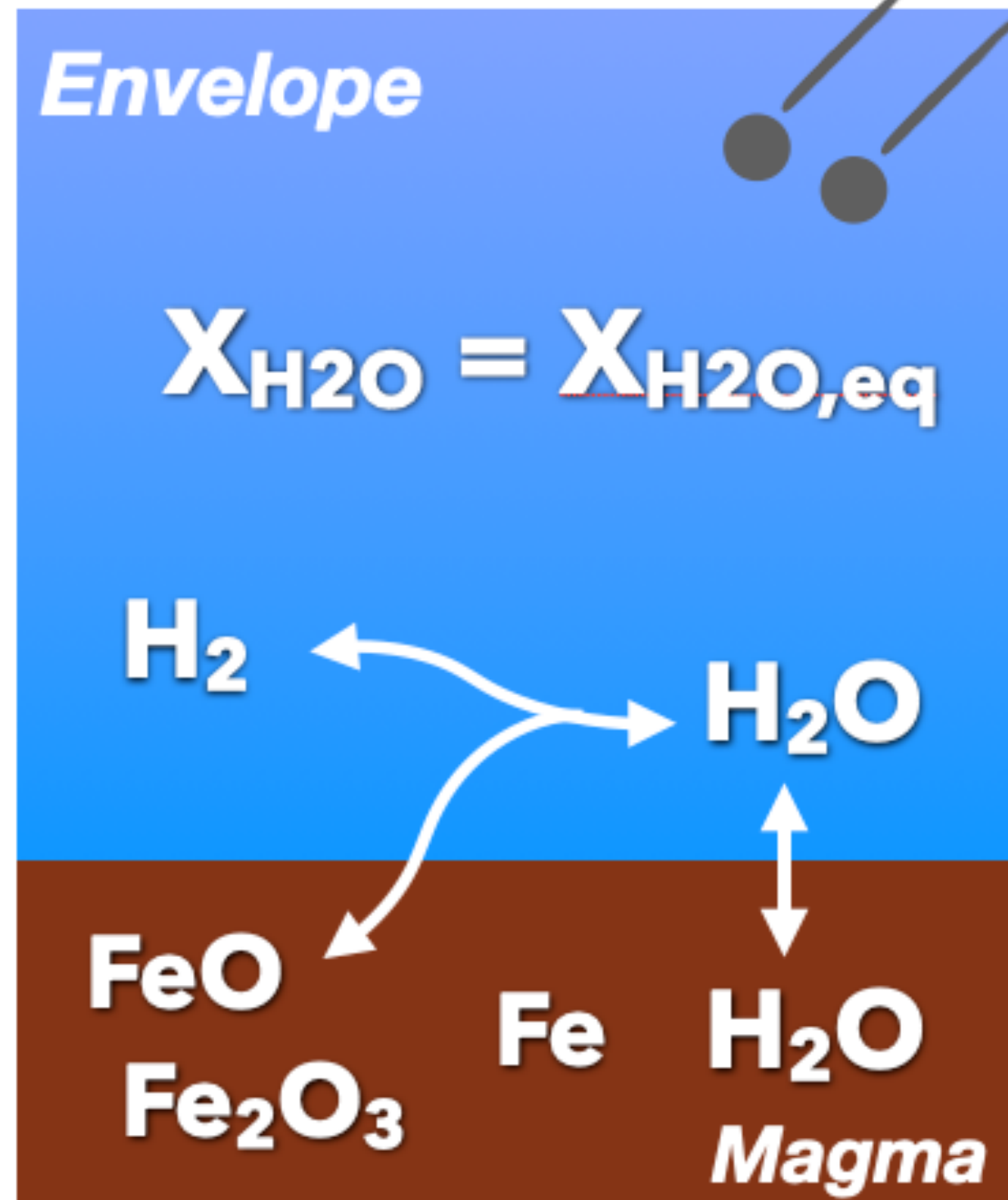
isolation

$$M_{\text{core}} = M_{\text{iso}}$$

gas accretion

disk
dissipation

escape

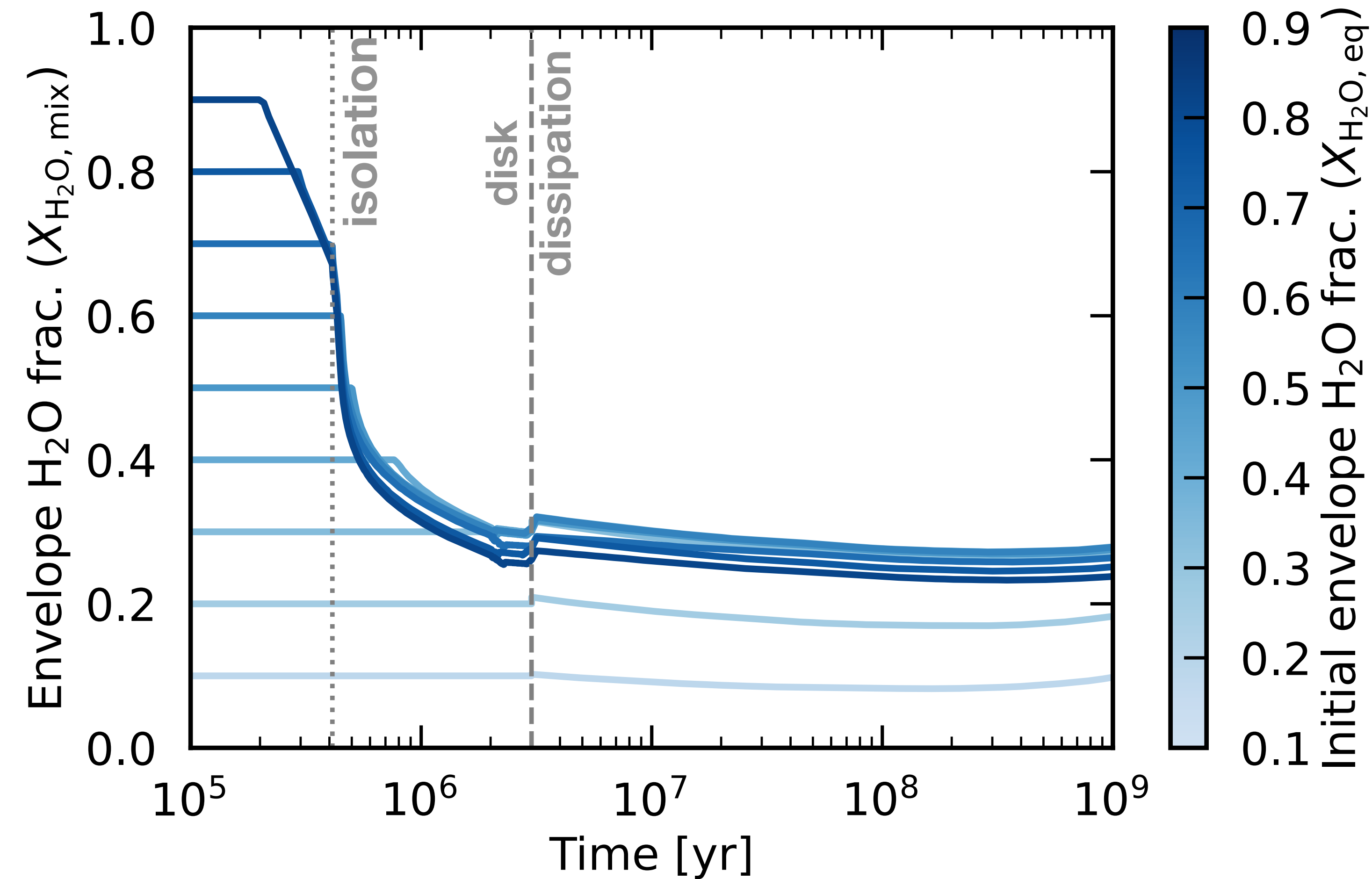


Enriched layer is equilibrated with magma
until O in magma is exhausted

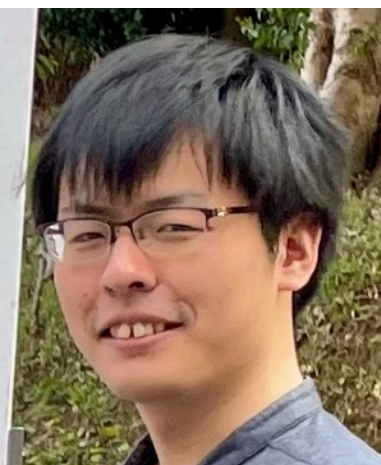
Time

Effects of initial atmospheric $X_{\text{H}_2\text{O}}$ on final $X_{\text{H}_2\text{O}}$

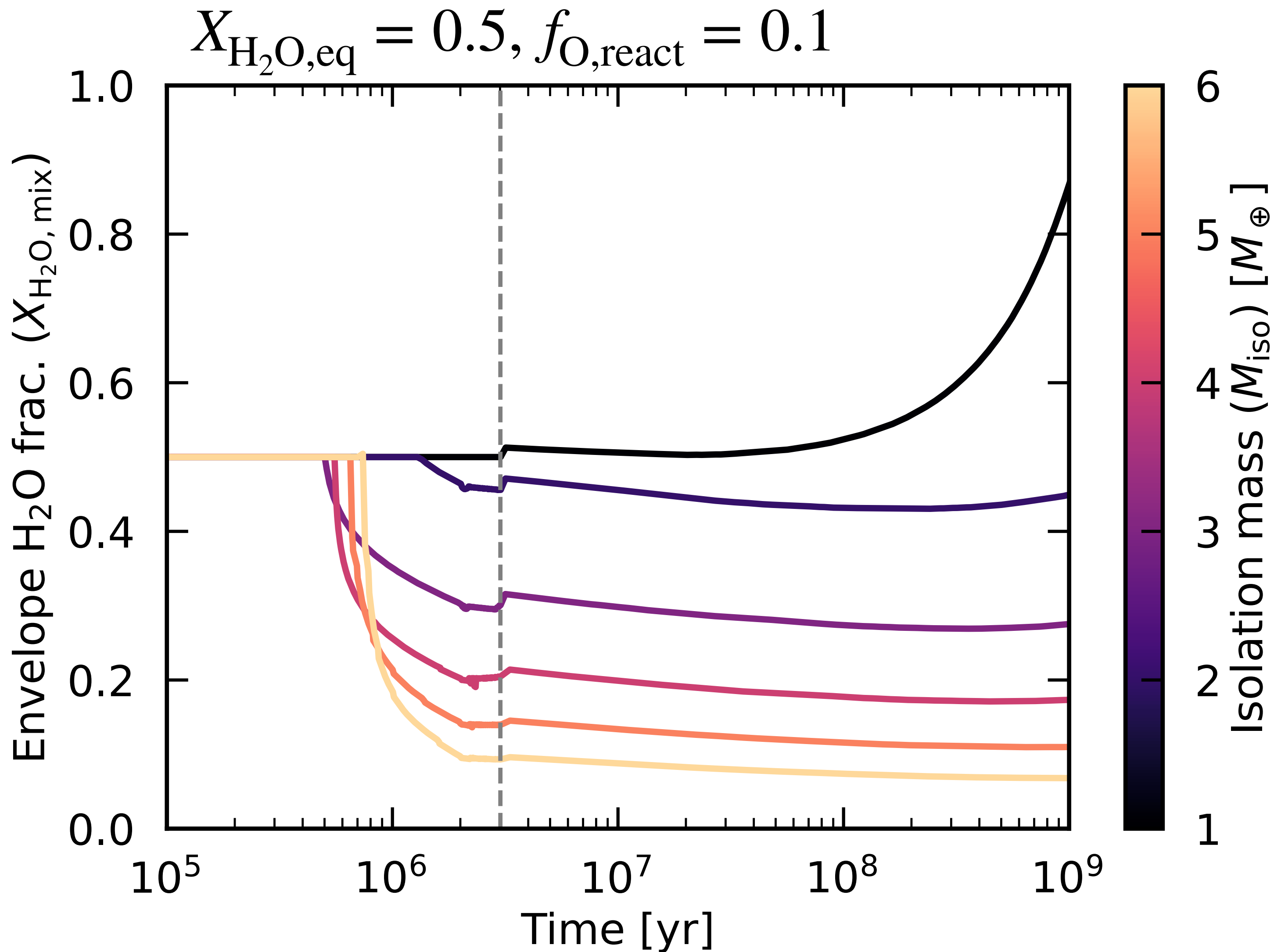
$$M_{\text{iso}} = 3M_{\oplus}, f_{\text{O,react}} = 0.1$$



- Oxygen in magma is exhausted during the evolution
- **Final composition hardly depends on the initial state**
- **It is hard to keep the envelope highly enriched with water**



Effects of planet mass on final $X_{\text{H}_2\text{O}}$



- **Larger planet has smaller $X_{\text{H}_2\text{O}}$** due to more efficient gas accretion

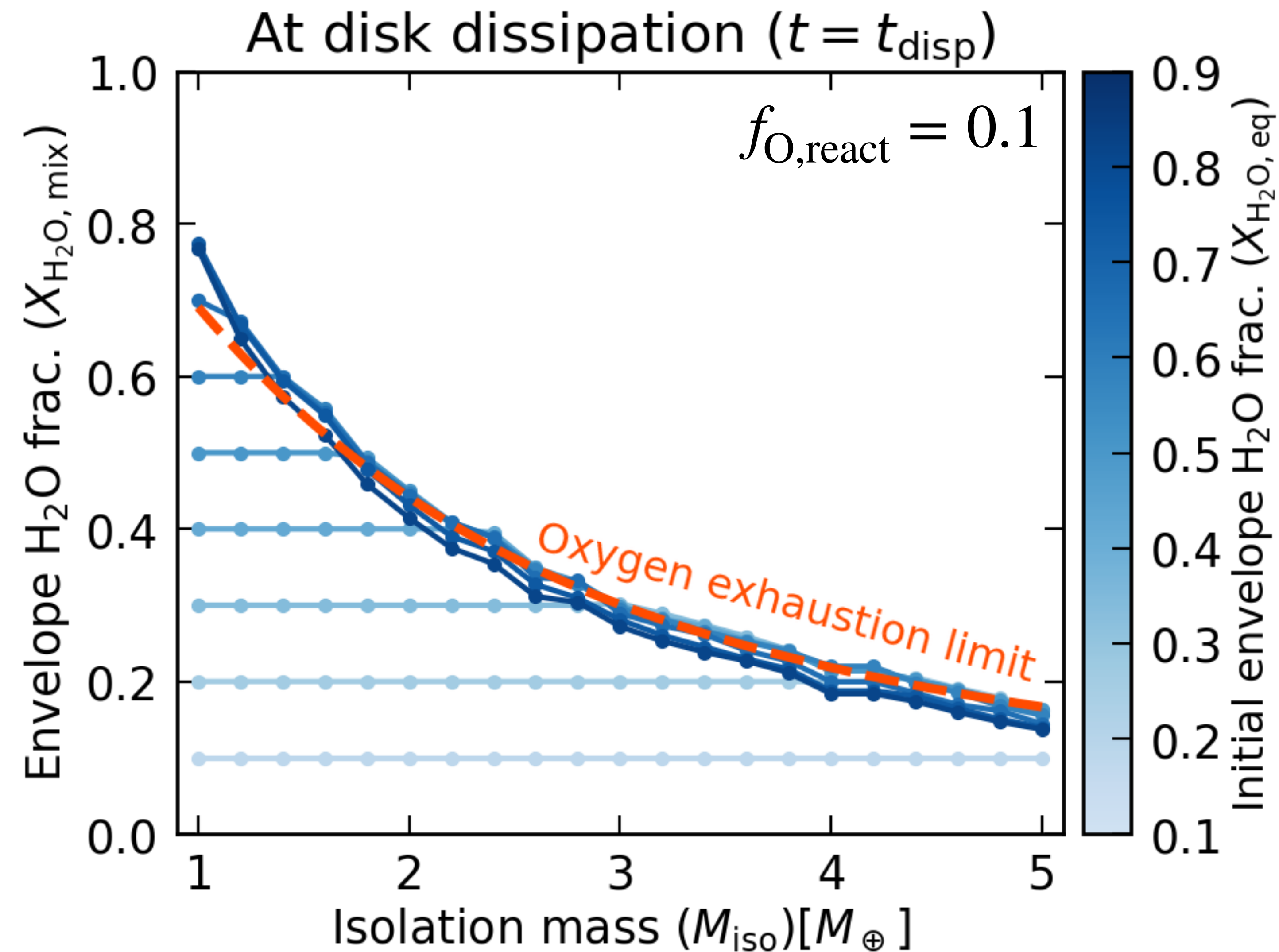
$$M_{\text{water}} \propto M_{\text{core}}$$

$$M_{\text{env}} \propto M_{\text{core}}^{3-4}$$

- Only **Earth-like-mass planet** can **keep highly-enriched state**



Planet mass and final $X_{\text{H}_2\text{O}}$

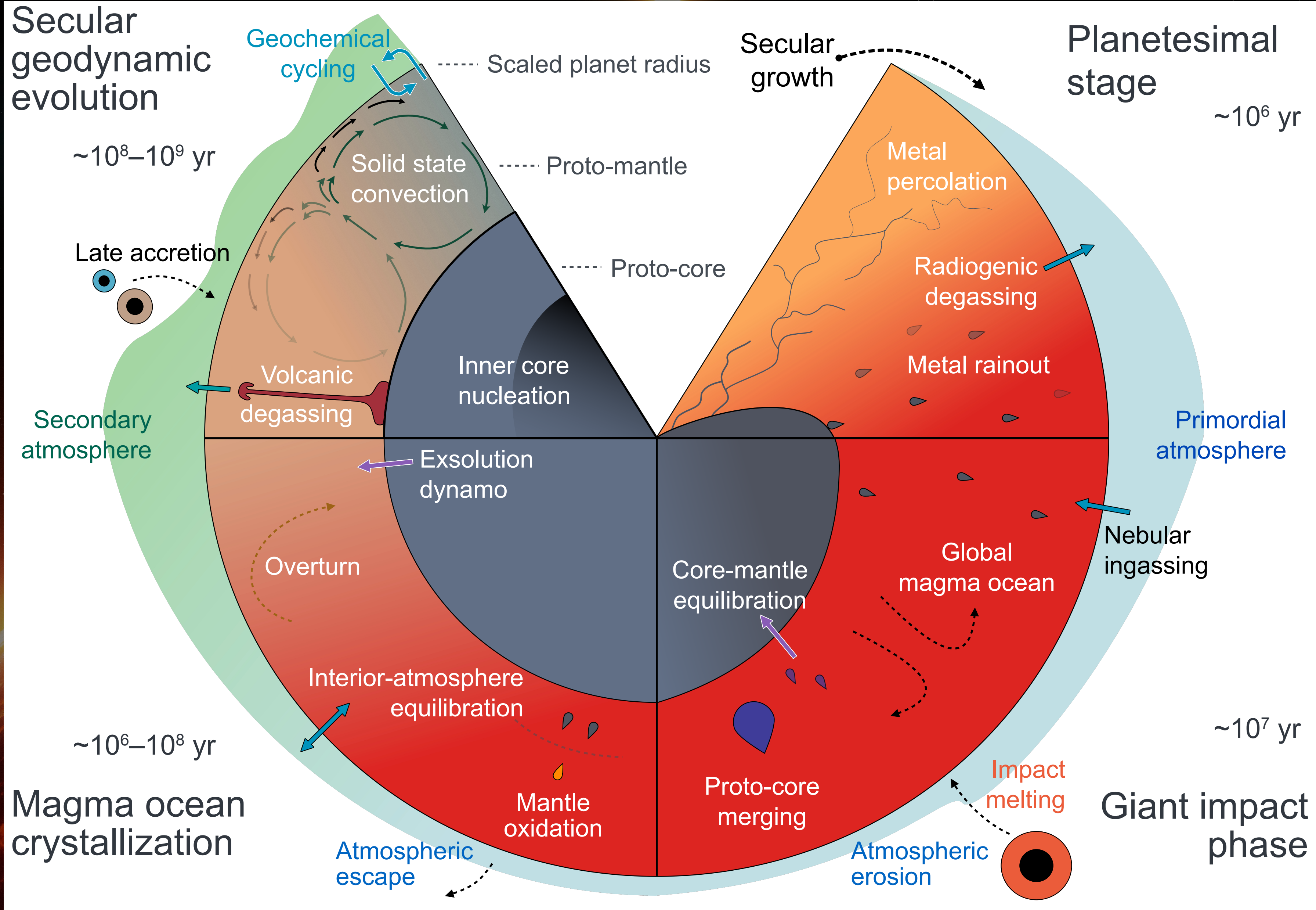


Oxygen exhaustion occurs quite commonly

- Resultant **envelope composition strongly reflects the planetary mass** at the time of disk dispersal → *a key to link the observed data to planet formation*
- **sub-Neptunes formed in-situ have much lower envelope metallicity** than those migrated from outside region

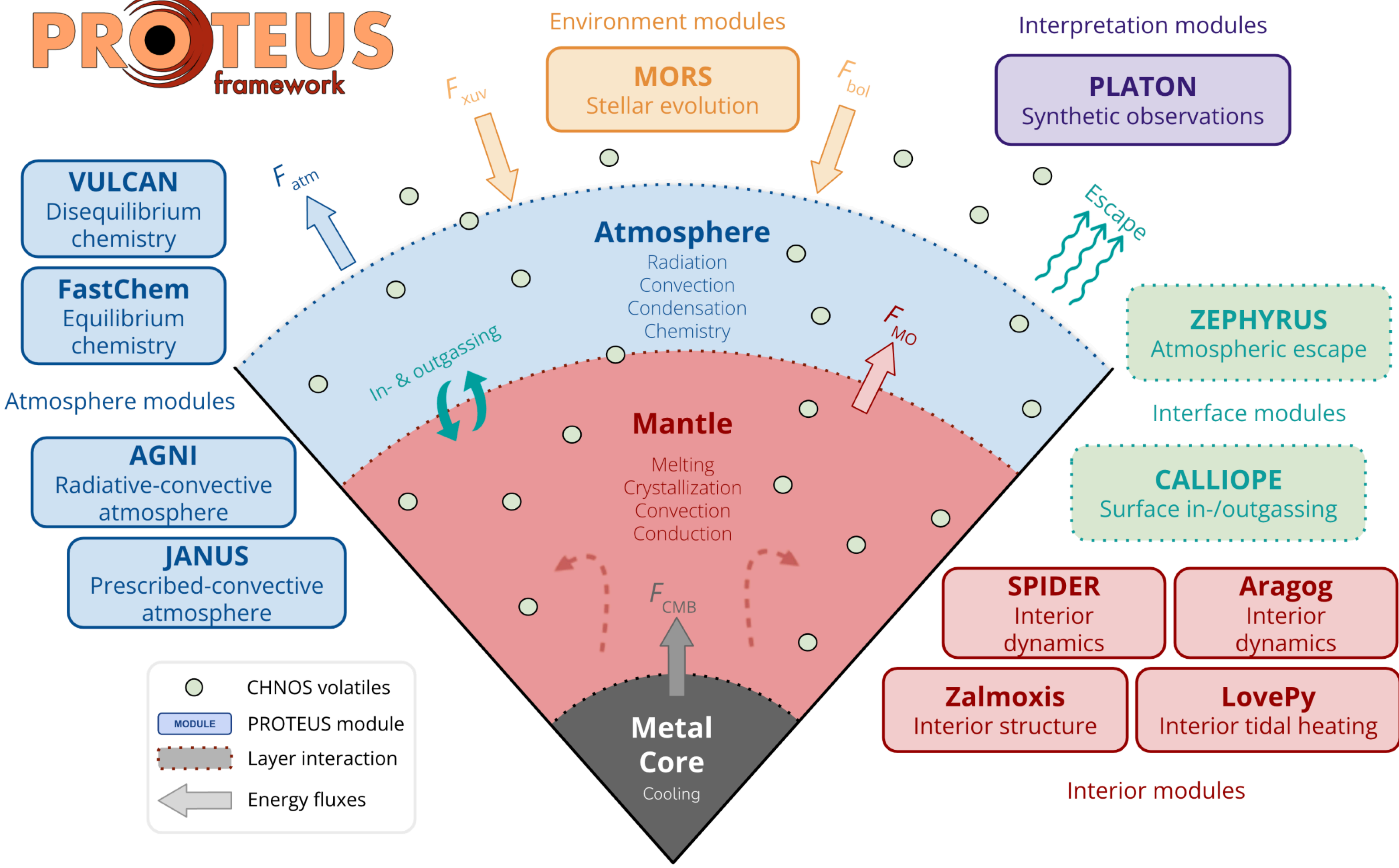


Atmosphere arise from feedback with interior

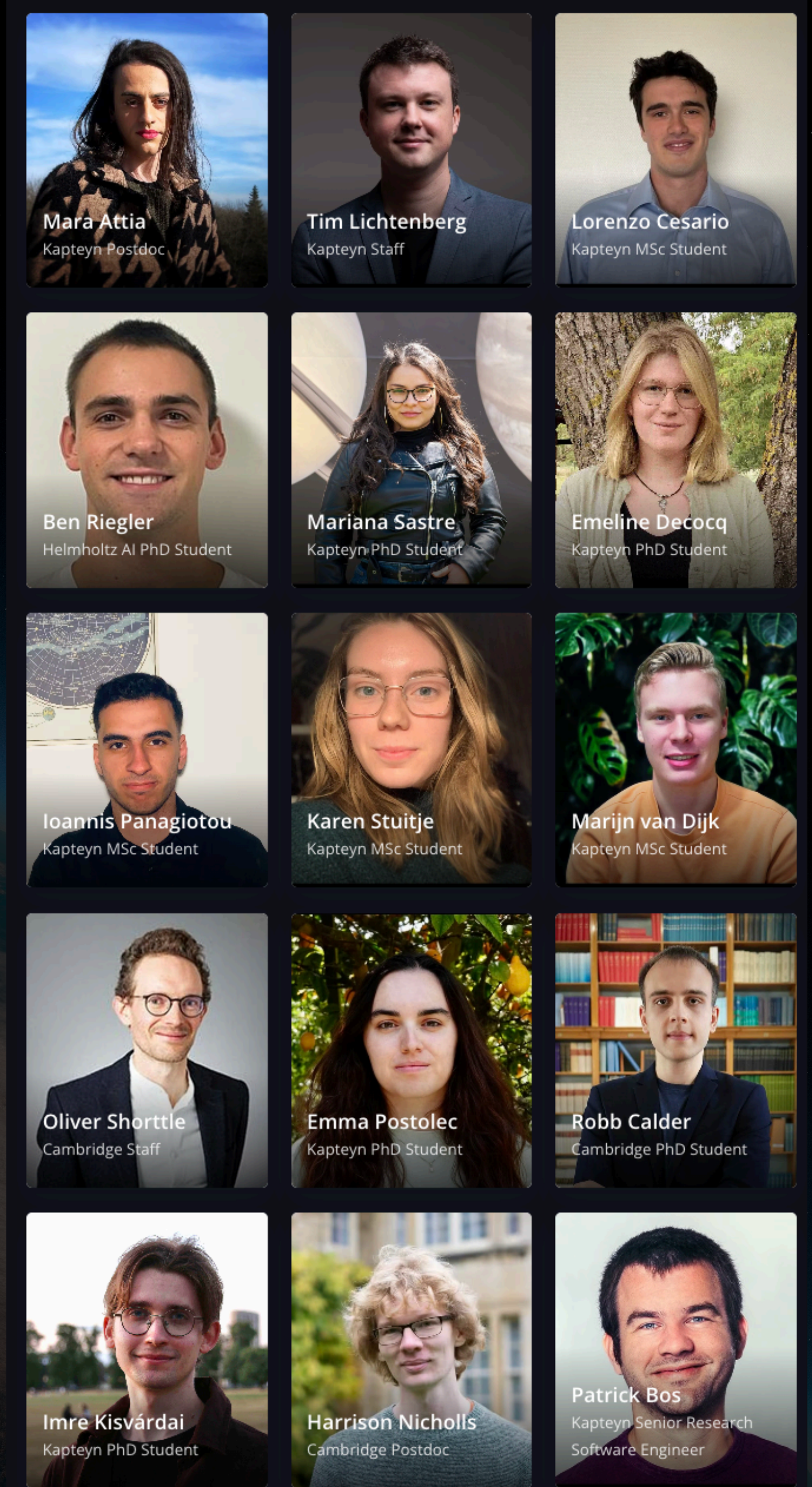


Mark A. Garlick / markgarlick.com

PROTEUS framework

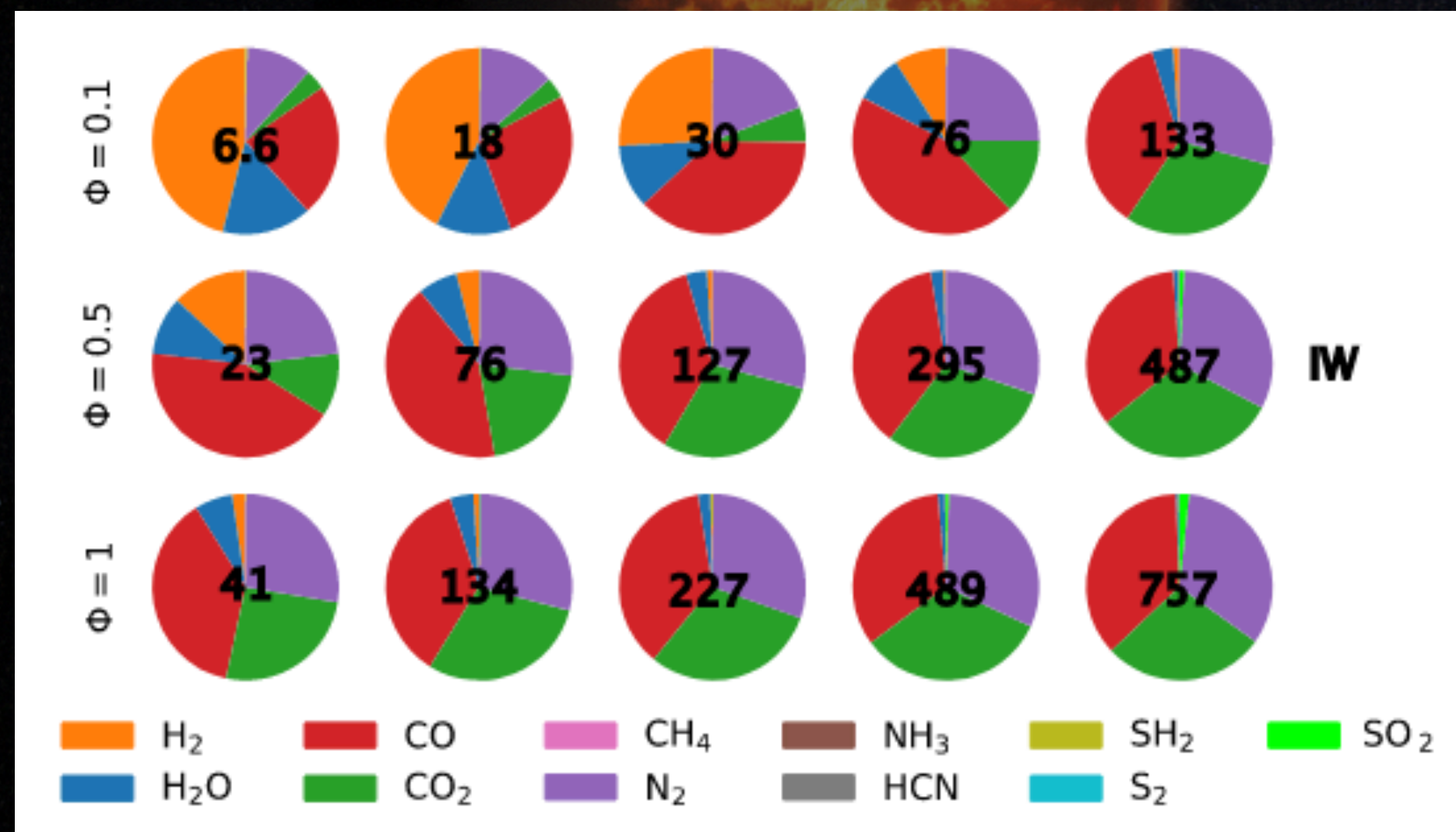


Current developers, randomised order

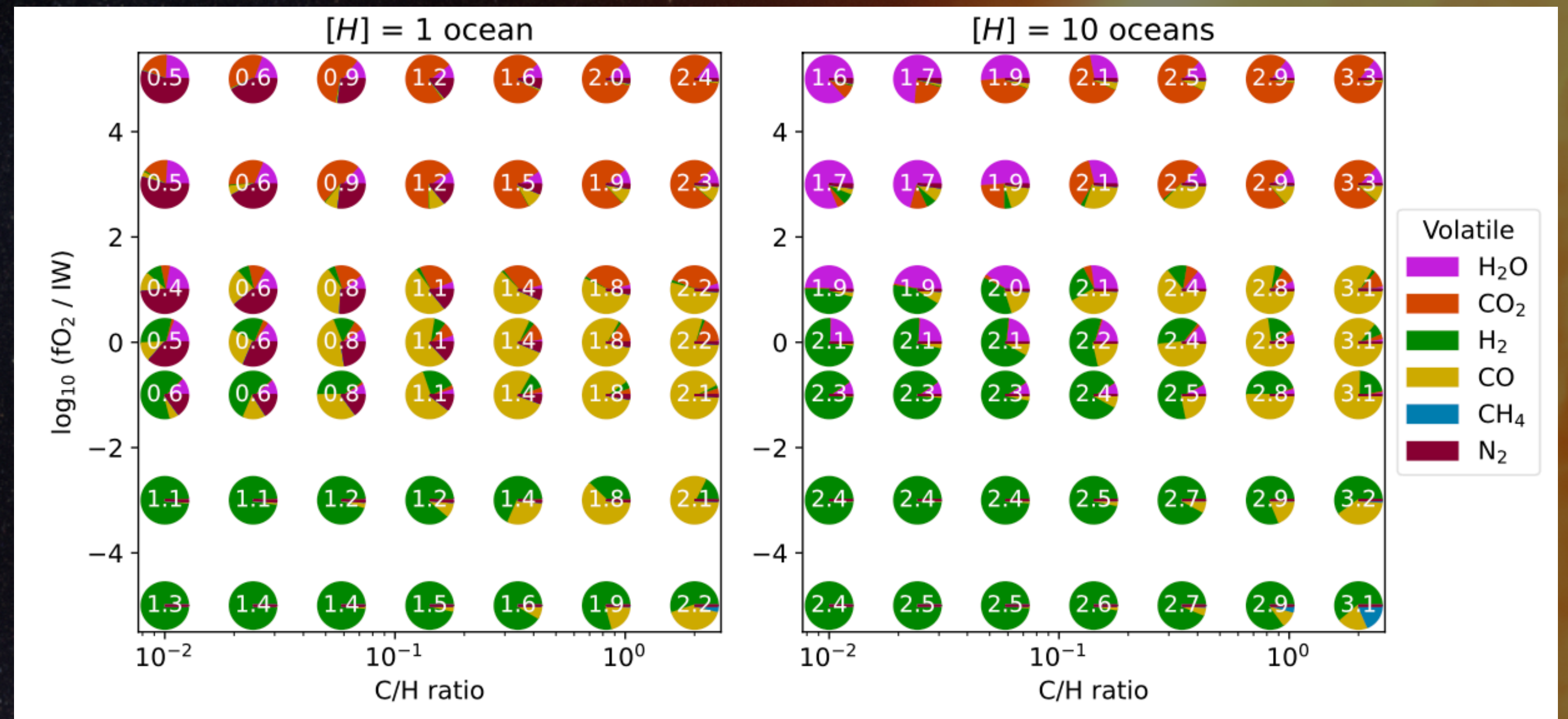


Sastre, Lichtenberg, Soucasse, Bower, Nicholls, Kamp 2026 *A&A* (subm.)
 Postolec, Lichtenberg, Soucasse, Nicholls, van der Tak 2026 *A&A* (subm.)
 Calder, Shorttle, Nicholls, Lichtenberg, Guimond 2026 *MNRAS* (in rev.)
 Nicholls, Lichtenberg, Chatterjee, Guimond, Postolec, Pierrehumbert 2026 *NatAstron*
 van Dijk, Nicholls, Lichtenberg 2026 *PSJ*
 Nicholls, Guimond, Hay, Chatterjee, Lichtenberg, Pierrehumbert 2025 *MNRAS*
 Nicholls, Pierrehumbert, Lichtenberg, Soucasse, Smeets 2025 *MNRAS*
 Nicholls, Lichtenberg, Bower, Pierrehumbert 2024 *JGRP*
 Lichtenberg, Bower, Hammond, Boukrouche, Sanan, Tsai, Pierrehumbert 2021 *JGRP*

Compositions can be highly diverse

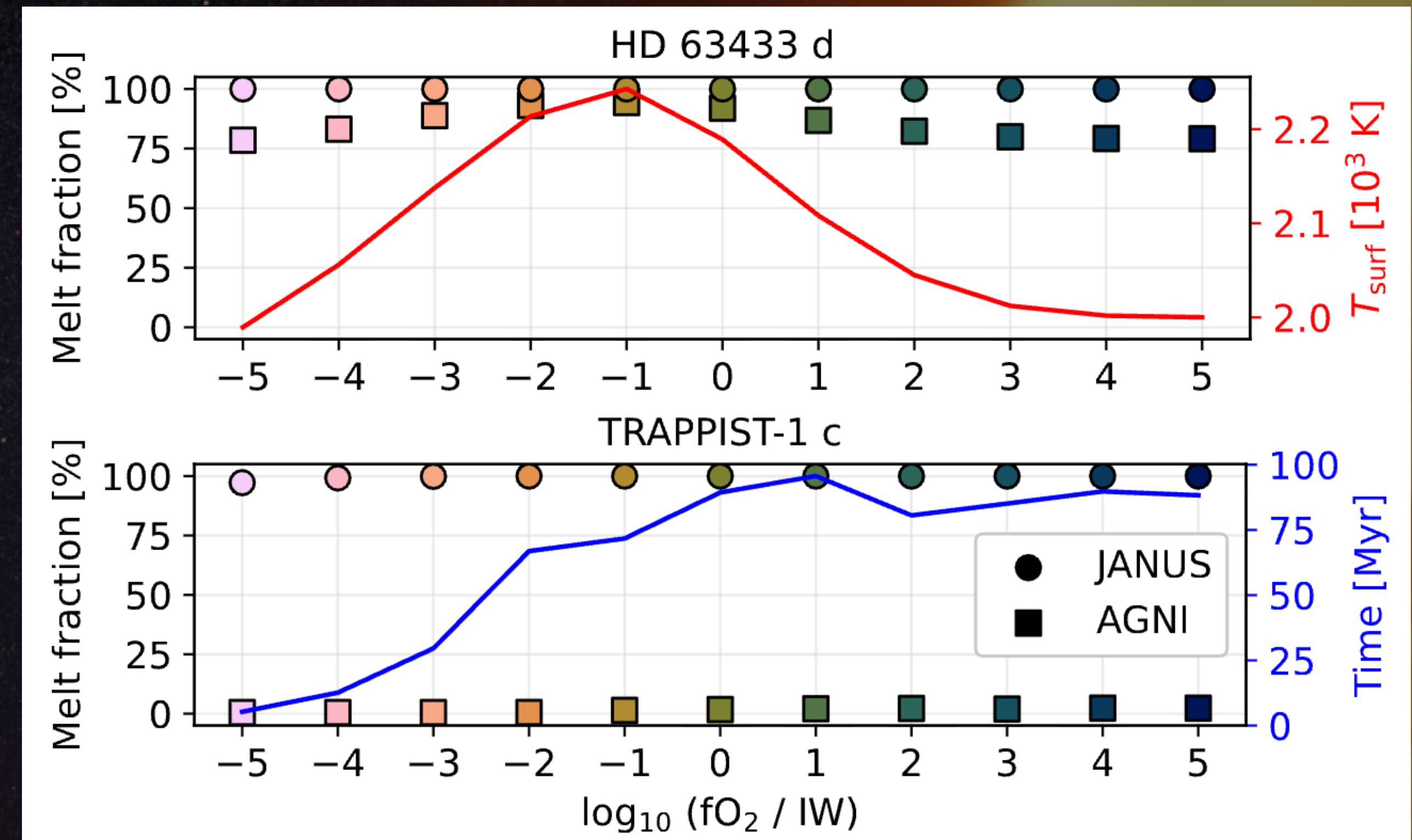
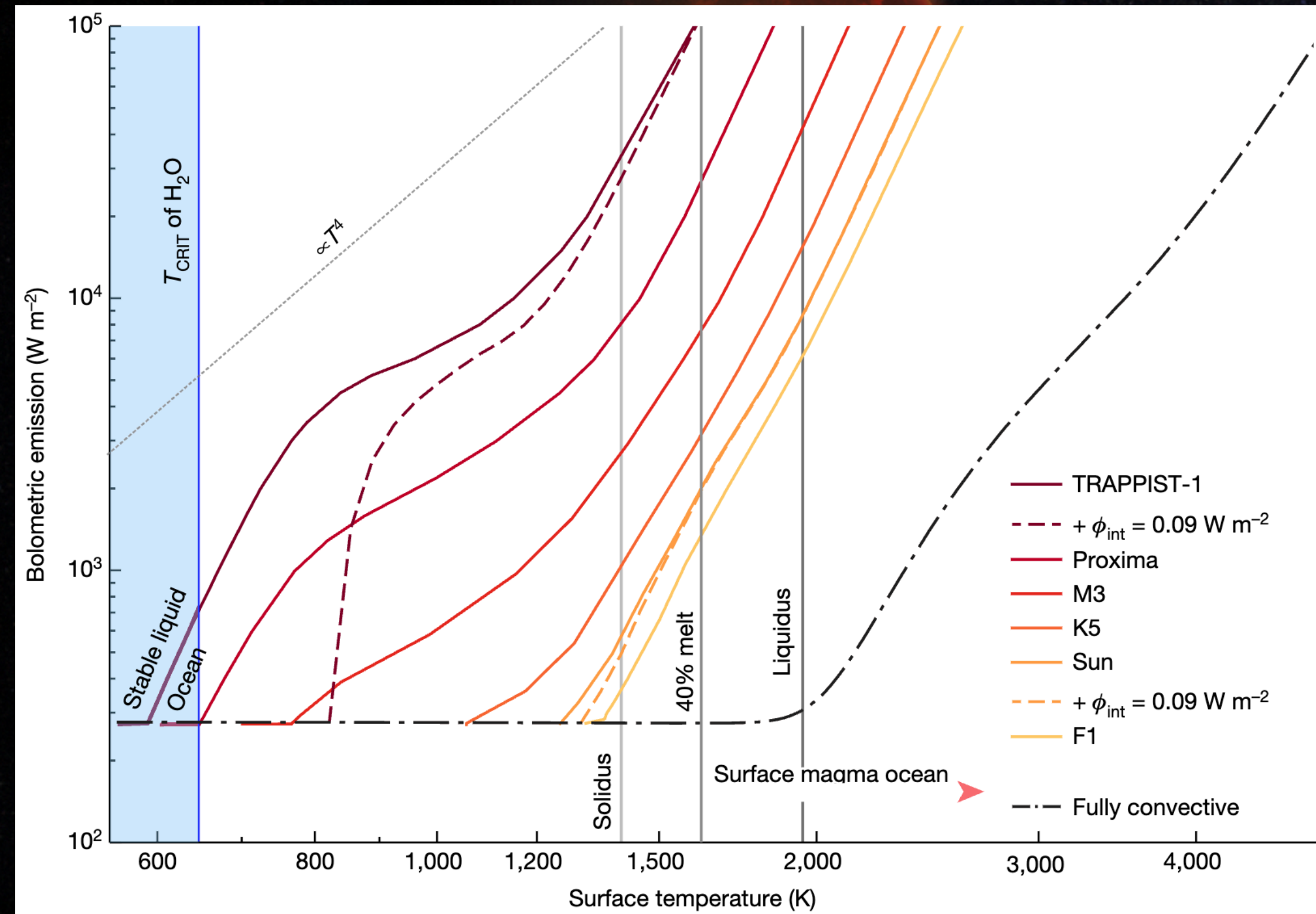


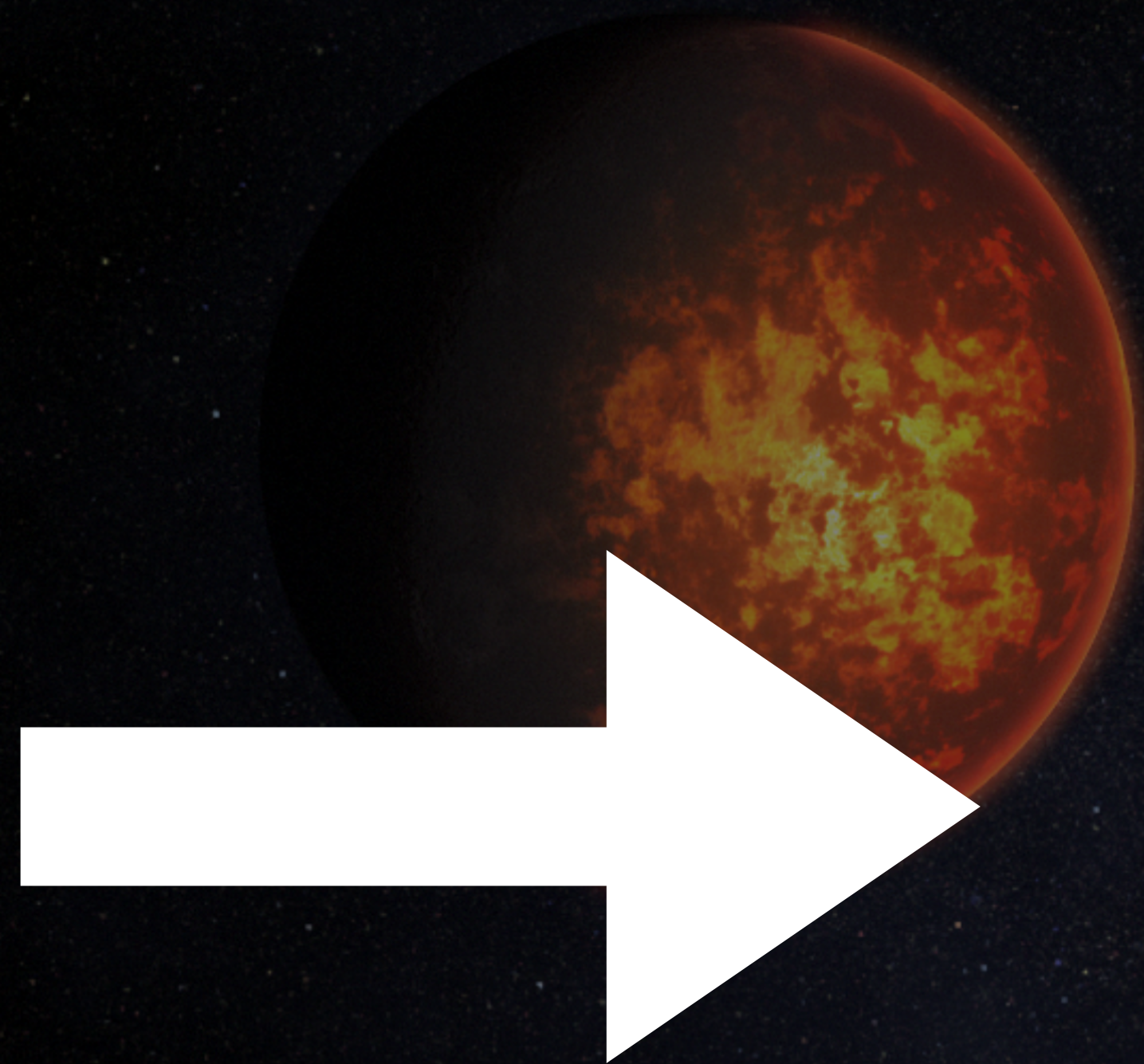
Maurice+ 24



Nicholls+ 2024

Evolution hysteresis (e.g. Venus): start molten or non-molten gives different results





We need a baseline
for intercomparison



Atmospheric and Interior Evolution of Planetary Magma Oceans

6 - 10 October 2025, Leiden, the Netherlands @lambda

<https://nexss.info/cuisines>

github.com/projectcuisines/chili

- 25 in-person participants
- Mix of plenum (hybrid) + (in-person) breakout discussions
- *Goal: write protocol draft in 5 days* 🥵
- Followed by implementation roadmap w/ regular virtual, leading to intercomparison paper(s)
- **Admin team: TL, Laura Schaefer, Josh Krissansen-Totton, Yamila Miguel, Denis Sergeev**

Topics

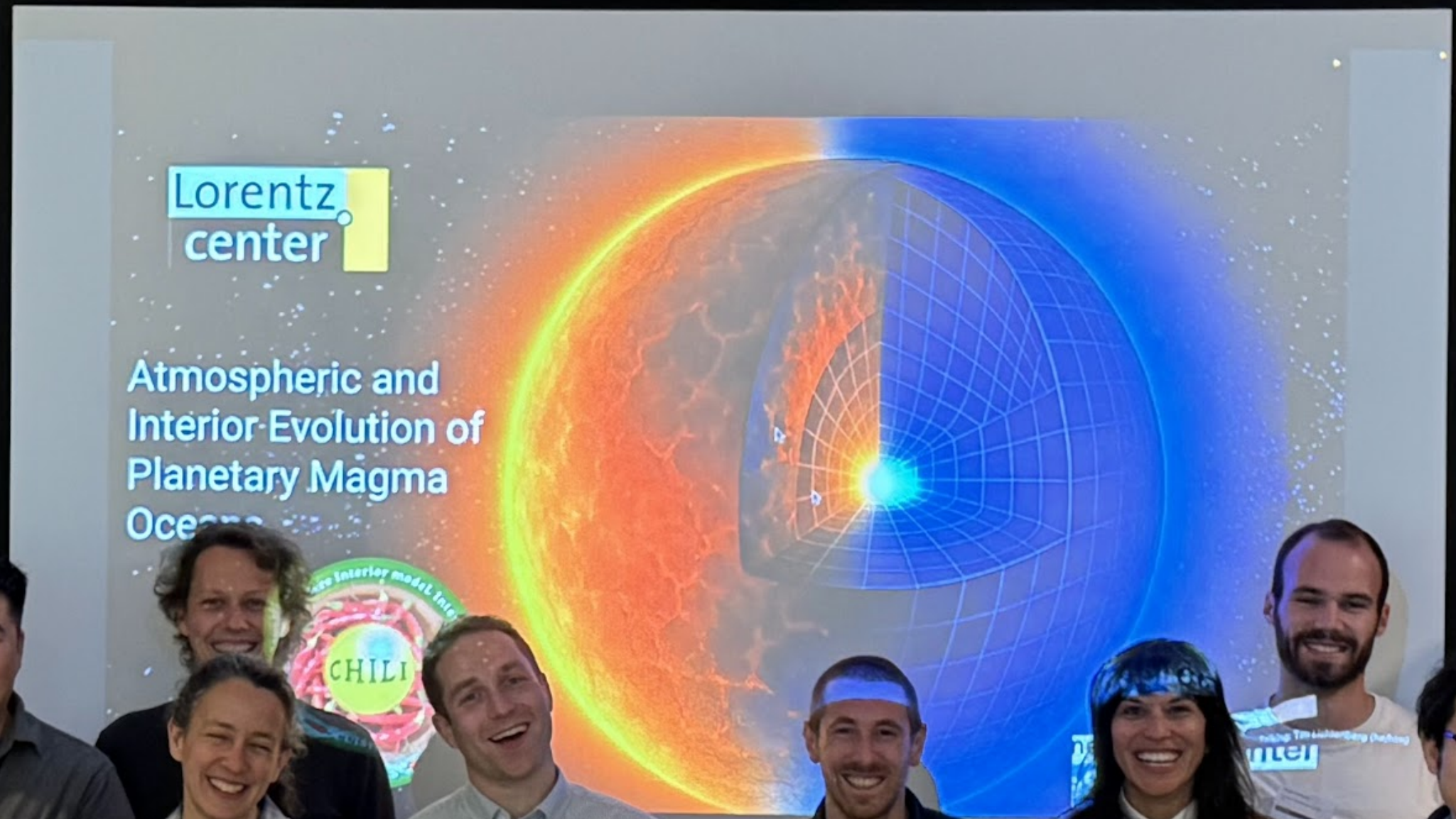
- Coupled interior-atmosphere frameworks
- Evolution of lava exoplanets
- Atmospheric formation
- Characterisation of magma ocean exoplanets with the James Webb Space Telescope

Scientific Organizers

- Tim Lichtenberg, University of Groningen
- Laura Schaefer, Stanford University
- Joshua Krissansen-Totton, University of Washington
- Yamila Miguel, Leiden University
- Denis Sergeev, University of Bristol

The Lorentz Center organizes international workshops for researchers in all scientific disciplines. Its aim is to create an atmosphere that fosters collaborative work, discussions and interactions. For registration see: www.lorentzcenter.nl

github.com/projectcuisines/chili



Social dinners, 7 pm

Mon	Tue	Thu
Tim		
Denis		
ANDREA		
Philipp		
E		

Laura
Yoshinori
Denis
THE PAPER
THE CODES
BREAkout DISCUSSION
- SIMPLE CASES
- IDENTIFY LIMITS
- COUPLED VS.
WITH AS EXAMPLE
QUESTION



CHILI Protocol



- **1 protocol paper: defines the mechanics & tests**
- **1 paper on Earth/Venus evolution**
- **1 paper on TRAPPIST-1 exoplanets**
- **1 paper on “static model” spectra**

Coupled atmoSPHERE Interior modeL Intercomparison (CHILI) Protocol Version 1.0: A CUISINES Intercomparison Project of Magma Ocean Models

TIM LICHTENBERG ¹, LAURA SCHAEFER ², JOSHUA KRISSENSAN-TOTTON ³, YAMILA MIGUEL ^{4,5},
DENIS E. SERGEEV ⁶, PHILIPP BAUMEISTER ⁷, JESSICA CMIEL ⁸, LEONI J. JANSSEN ⁴, T. GIANG NGUYEN ⁹,
YOSHINORI MIYAZAKI ¹⁰, HARRISON NICHOLLS ^{11,12}, ALEXANDRA PAPESH ³, HUGO PELISSARD ¹³, BO PENG ¹⁴,
JUNELLIE PEREZ ¹⁵, EMMA POSTOLEC ¹, MARIANA SASTRE ¹, ARNAUD SALVADOR ^{16,17}, HANNO SPREEUW ¹⁸,
ANDREA ZORZI ¹⁴, THOMAS J. FAUCHEZ ^{19,20,21}, KEIKO HAMANO ²², JÉRÉMY LECONTE ¹³, MAXIME MAURICE ²³,
LENA NOACK ⁷ AND LAURENT SOUCASSE ^{18,24}

¹Kapteyn Astronomical Institute, University of Groningen, P.O. Box 800, 9700 AV Groningen, The Netherlands

²Department of Earth & Planetary Sciences, Stanford University, Stanford, CA 94305

³Department of Earth and Space Sciences / Astrobiology Program, University of Washington, Seattle, WA 98105, USA

⁴Leiden Observatory, Einsteinweg 55, 2333 CC Leiden, The Netherlands

⁵SRON Netherlands Institute for Space Research, Leiden, The Netherlands

⁶School of Physics, University of Bristol, HH Wills Physics Laboratory, Tyndall Avenue, Bristol BS8 1TL, UK

⁷Department of Earth Sciences, Freie Universität Berlin, Malteserstrasse 74-100, 12249 Berlin, Germany

⁸Harvard Paulson School of Engineering and Applied Sciences, 29 Oxford Street, Cambridge, MA 02138, USA

⁹Department of Physics, McGill University, 3600 rue University, Montréal, QC H3A 2T8, Canada

¹⁰Department of Earth and Planetary Sciences, Rutgers University, Piscataway, NJ 08854, USA

¹¹Institute of Astronomy, University of Cambridge, Madingley Road, Cambridge CB3 0HA, United Kingdom

¹²Atmospheric Oceanic and Planetary Physics, University of Oxford, Parks Road, Oxford OX1 3PU, United Kingdom

¹³Laboratoire d'astrophysique de Bordeaux, Univ. Bordeaux, CNRS, B18N, allée Geoffroy Saint-Hilaire, 33615 Pessac, France

¹⁴Stanford University, Department of Earth and Planetary Sciences, 450 Jane Stanford Way, Stanford, 94305, CA, USA

¹⁵Department of Earth & Planetary Sciences, Johns Hopkins University, Baltimore, Maryland, USA

¹⁶Institute of Space Research, German Aerospace Center (DLR), Rutherfordstr. 2, 12489 Berlin, Germany

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Evolutionary models

Static models

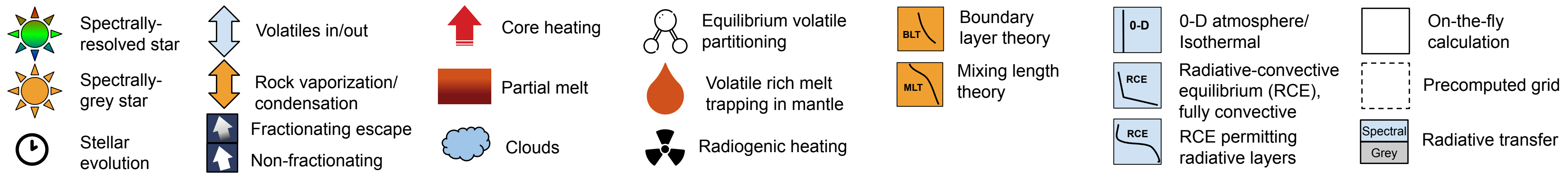
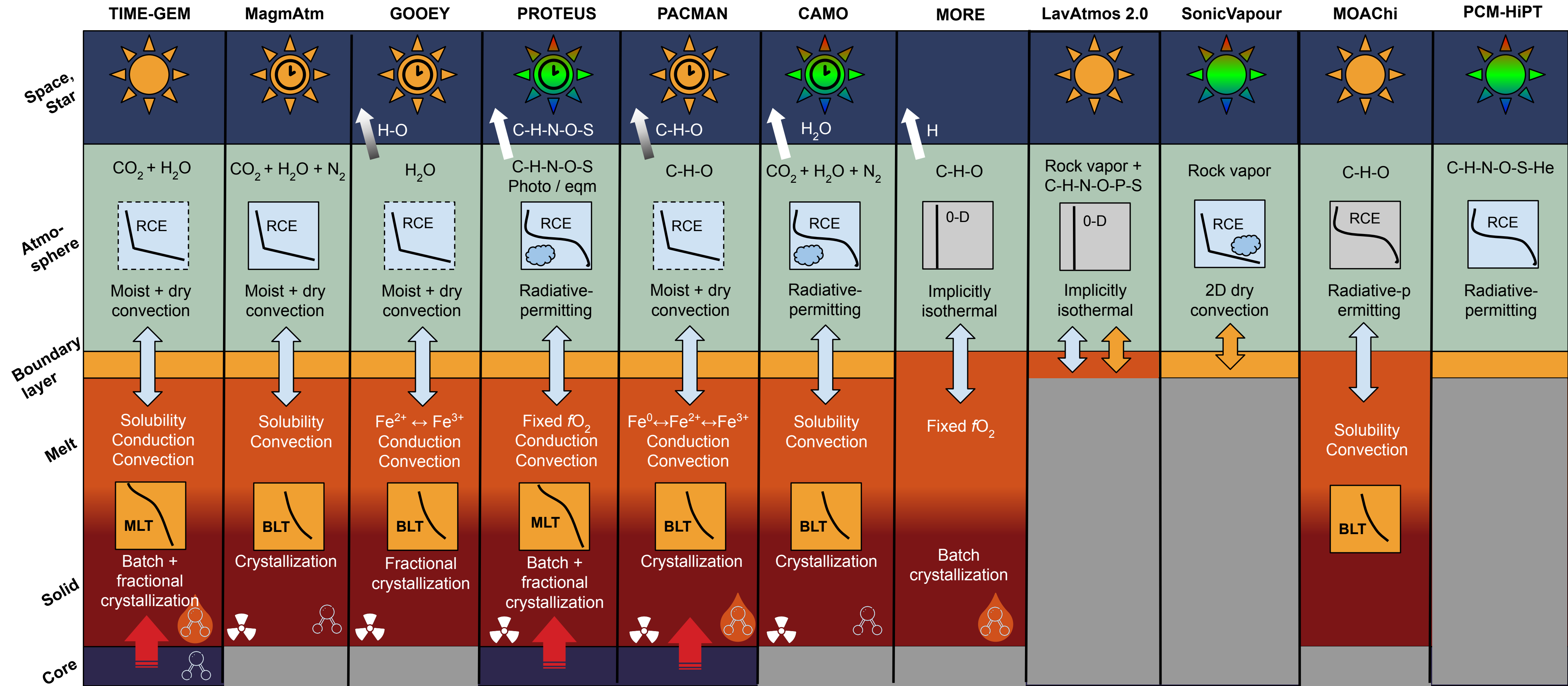


Table 2. Initial parameters for nominal Earth and Venus

Parameter	Earth	Venus	Grid samples
Starting simulation time [Myr]	50	50	–
Stellar mass [M_{\odot}]	1.0	1.0	–
Orbital period [days]	365.26	224.7	–
Eccentricity	0	0	–
Semi-major axis [AU]	1	0.723	–
Stellar irradiance [$\text{W}\cdot\text{m}^{-2}$]	920	1760	–
Bond albedo	0.1	0.1	–
Planet mass [M_{\oplus}]	1	0.815	–
Planet radius [R_{\oplus}]	1	0.95	–
Core radius [fraction]	0.55	0.55	–
$T_{\text{mantle}}^{\text{init}}$	fully molten	fully molten	–
Mantle composition	BSE	BSE	–
Initial oxygen fugacity at 1600 K*	IW+4	IW+4	–
H [kg] / H ₂ O [kg]	4.7×10^{20} / 4.2×10^{21}	4.7×10^{20} / 4.2×10^{21}	$[1.6, 7.8, 16] \times 10^{20}$ / $[1.4, 7.5, 14] \times 10^{21}$
C [kg] / CO ₂ [kg]	2.73×10^{20} / 1×10^{21}	2.73×10^{20} / 1×10^{21}	$[1.36, 2.73, 5.44] \times 10^{20}$ / $[0.5, 1, 2] \times 10^{21}$

NOTE—*Users should ensure that final mantle oxygen fugacity is equivalent to the IW+4 buffer.

Table 4. Initial parameters for exoplanet model comparison

Parameter	Value	References
Starting simulation time [Myr], TRAPPIST 1-b	50	–
TRAPPIST 1-e	50	–
TRAPPIST 1- α	1000	–
Stellar mass [M_{\odot}]	0.09	E. Agol et al. (2021)
Orbital period [days], 1-b	1.510	E. Agol et al. (2021)
1-e	6.101	E. Agol et al. (2021)
1- α	0.02136	fictitious lava world
Eccentricity	0	–
Semimajor axis [AU], 1-b	1.154×10^{-2}	E. Agol et al. (2021)
1-e	2.925×10^{-2}	E. Agol et al. (2021)
1- α	6.75×10^{-4}	–
Bond albedo	0.1	K. Hamano et al. (2015)
Planet mass [M_{\oplus}]	1.0	–
Planet radius [R_{\oplus}]	1.0	–
Core radius [fraction]	0.55	W. F. McDonough & S. s. Sun (1995)
$T_{\text{mantle}}^{\text{init}}$	fully molten	–
Mantle composition	BSE	C. P. A. van Buchem et al. (2023)
Initial oxygen fugacity at 1600 K	IW+4	–
H [kg] / H ₂ O [kg]	4.7×10^{20} / 4.2×10^{21}	–
C [kg] / CO ₂ [kg]	2.73×10^{20} / 1×10^{21}	–

NOTE—Stellar and orbital parameters are adopted from E. Agol et al. (2021). The hypothetical planet 1- α uses parameters defined in this work. Volatile inventories and oxidation state assumptions follow K. Hamano et al. (2015).

Table 5. Characteristic evolutionary ages. Snapshots taken at a subset of these times will generate input parameters for the static models. Not all of these times will necessarily be important in all planet cases; they serve as reference points for the interface between the evolutionary and static models. Evolutionary models should store output variables at times close to these ages where possible.

τ_3	τ_4	τ_5	τ_6	τ_7	τ_8	τ_9
10^3 yrs	10^4 yrs	10^5 yrs	10^6 yrs	10^7 yrs	10^8 yrs	10^9 yrs

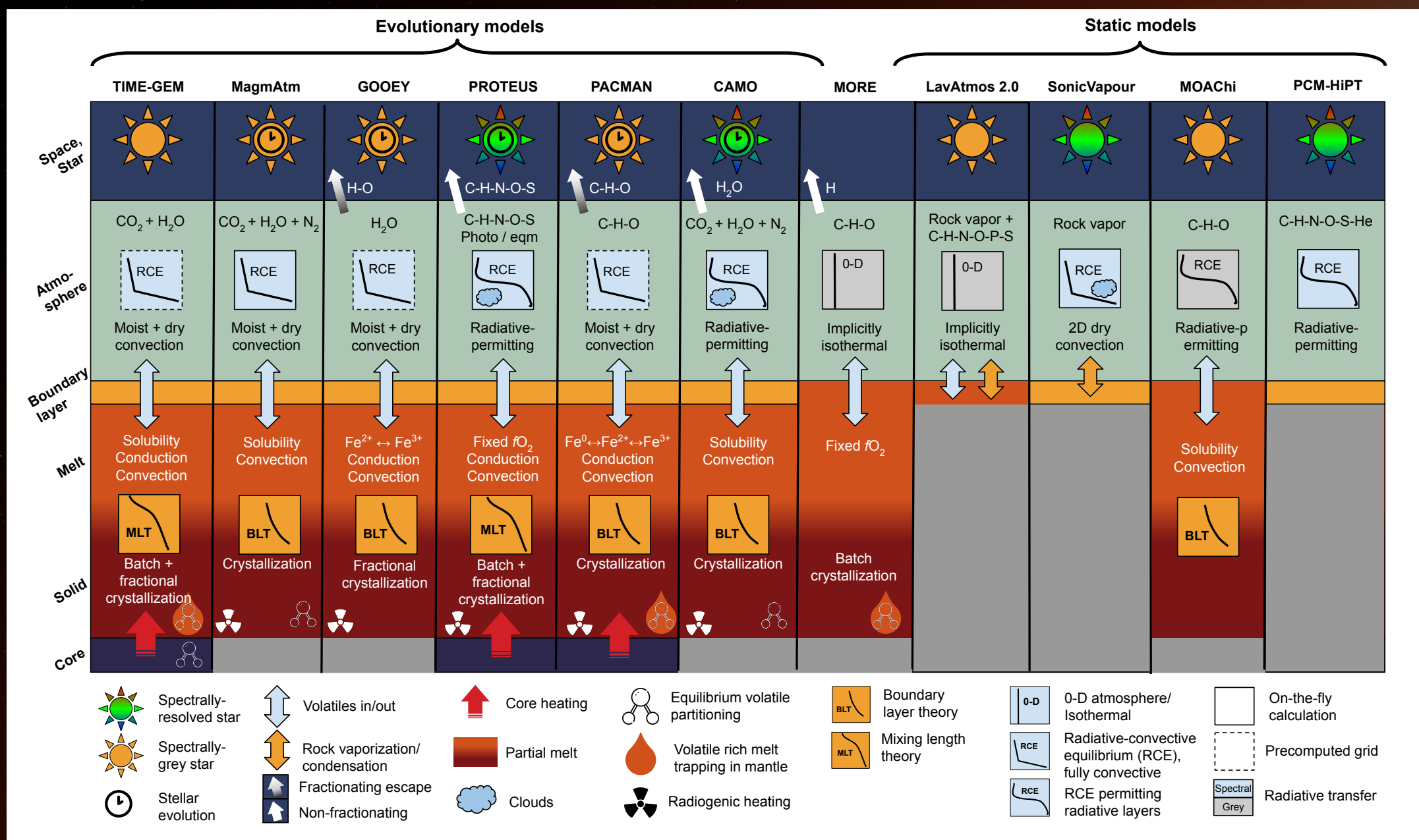
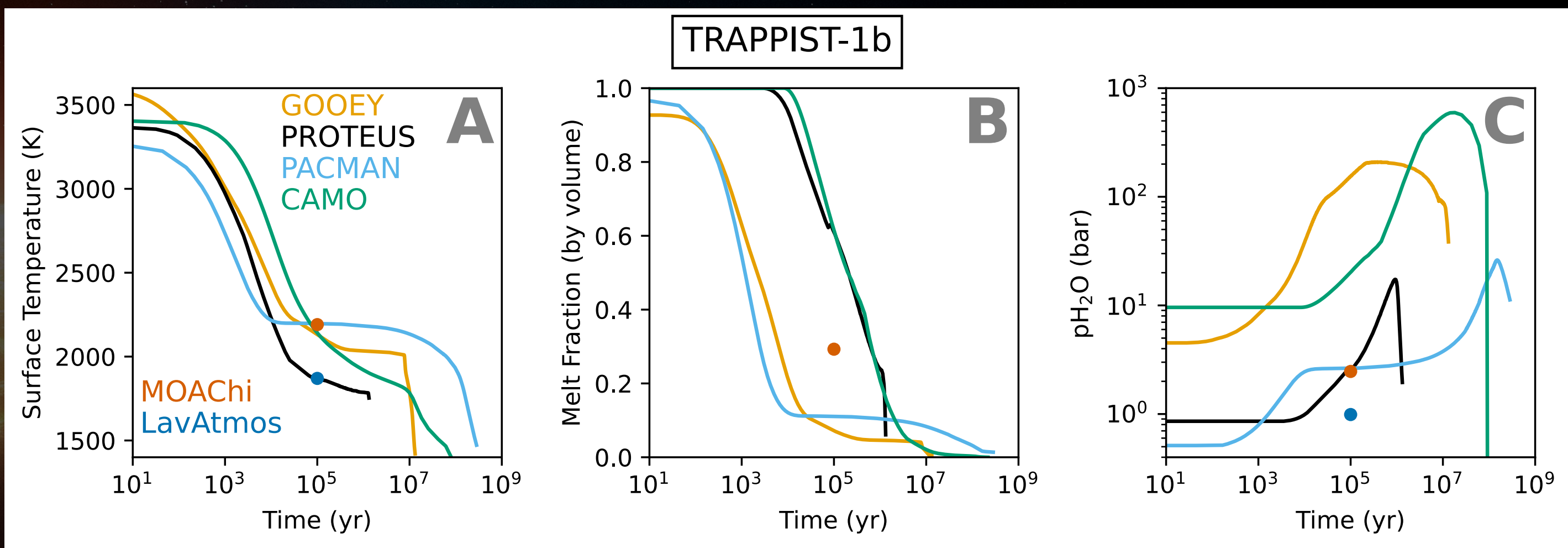
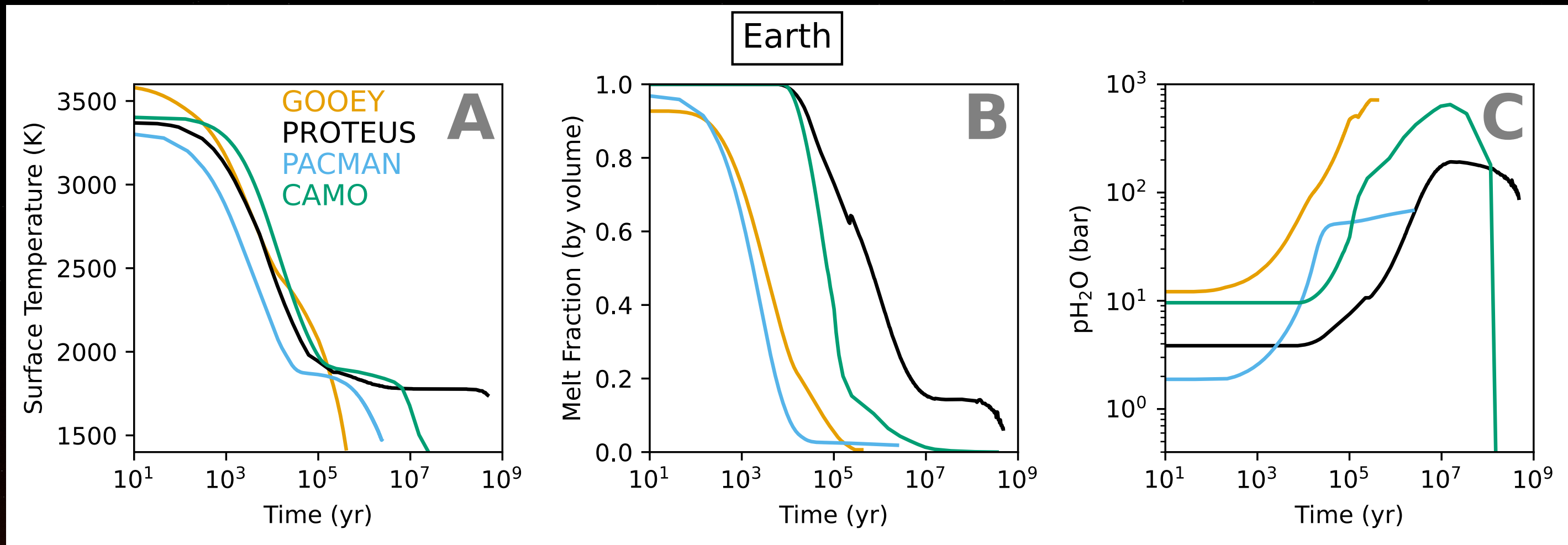
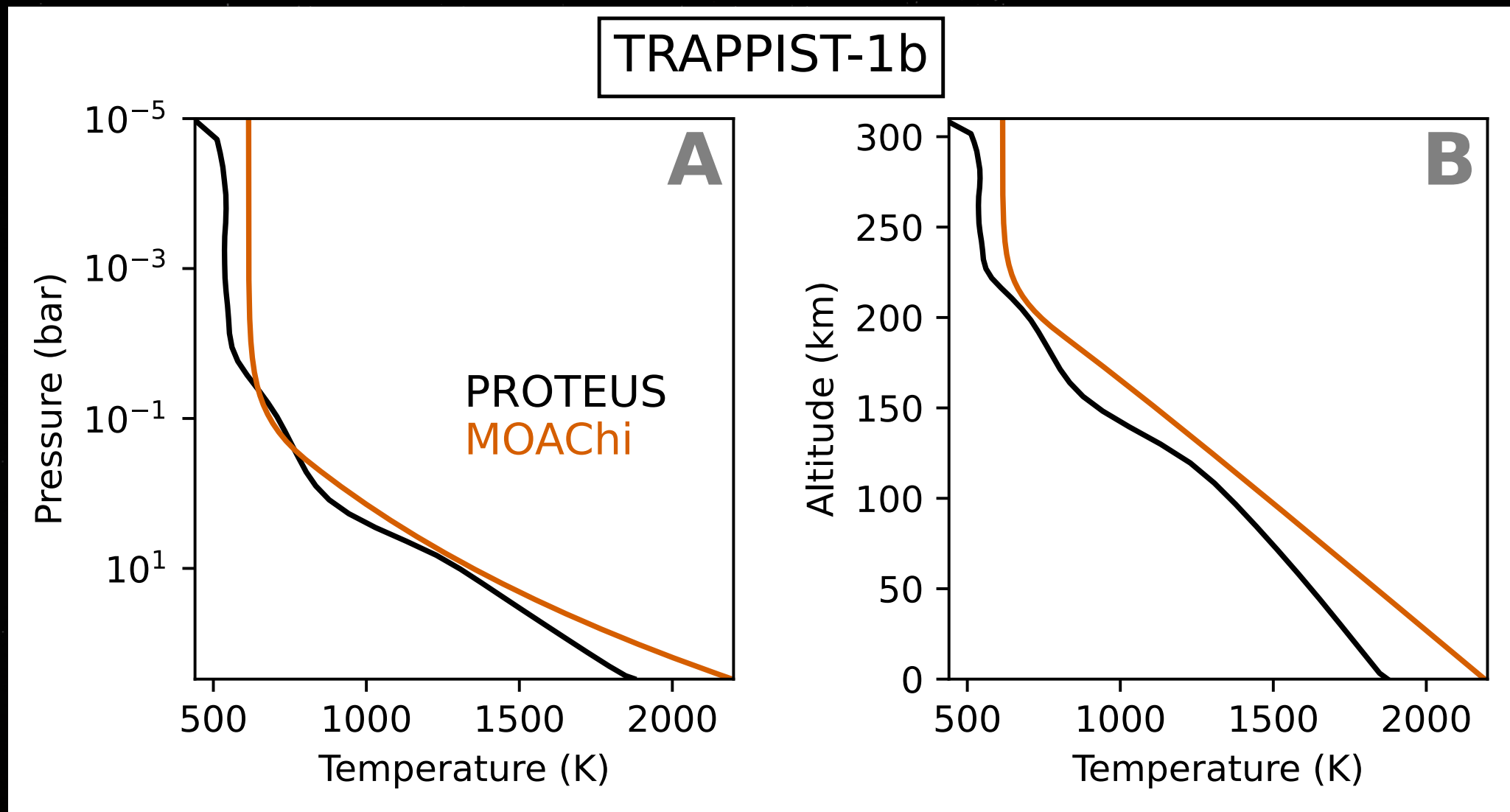
	(i) Magma ocean surface chemistry models	(ii) Atmospheric structure models
Required inputs from evolutionary models	$p_{\text{surf}}, T_{\text{surf}}$ At least $p_{\text{H}_2\text{O}}$, ideally bulk atmospheric C/H/O ratios.	$F_{\text{surf}}, F_{\text{ASR}}, p_{\text{surf}}$ At least $*p_{x,\text{norm}}$, ideally bulk atmospheric C/H/O ratios.
Required outputs from static models	p_x	$p(z), p_x(z), T(z)$

Table 6. Required inputs and outputs for static magma ocean chemistry and atmosphere models. *Normalized atmospheric partial pressures of individual species in bars (Equation 1).**Table 3.** Scalar output variables required from participating evolutionary models at each step of their time-integration. Other calculated variables are free to be recorded alongside these.

Output variable	Description	Units
t	Time relative to initialization	yr
T_{surf}	Surface mantle-atmosphere temperature	K
T_{pot}	Effective mantle potential temperature	K
F_{surf}	Surface geothermal heat flux	W m^{-2}
F_{OLR}	Outgoing longwave radiation (OLR)	W m^{-2}
F_{ASR}	Absorbed stellar radiation (ASR)	W m^{-2}
Φ_v	Volumetric whole-mantle melt fraction	–
$f\text{O}_2$	Oxygen fugacity of solid mantle & melt	bar, bar
d_{CBL}	Thickness of surface conductive boundary layer	m
m_{C}	Mass of carbon atoms in atmosphere, solid, and melt	kg, kg, kg
m_{H}	Mass of hydrogen atoms in atmosphere, solid, and melt	kg, kg, kg
m_{O}	Mass of oxygen atoms in the atmosphere	kg
p_{surf}	Total surface pressure	bar
p_x	Partial pressure H ₂ O, CO ₂ , CO, H ₂ , CH ₄ , O ₂	bar $\times 6$
μ	Mean molecular weight of the bulk atmosphere	kg mol^{-1}
R_{trans}	Effective photospheric-transit radius	m
R_{solid}	Radius of solidification/rheological front	m
ν	Characteristic viscosity of the whole mantle	Pa s

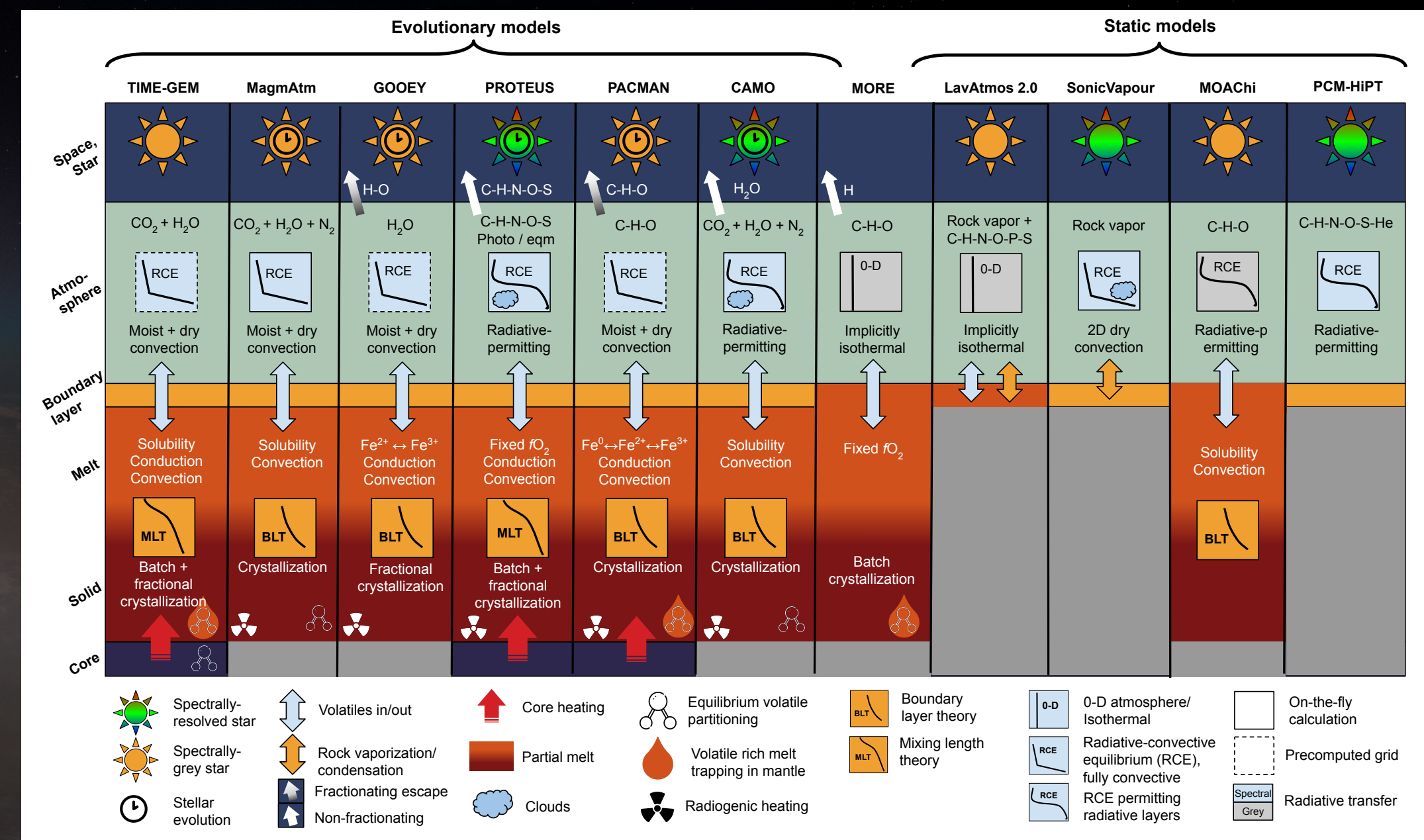
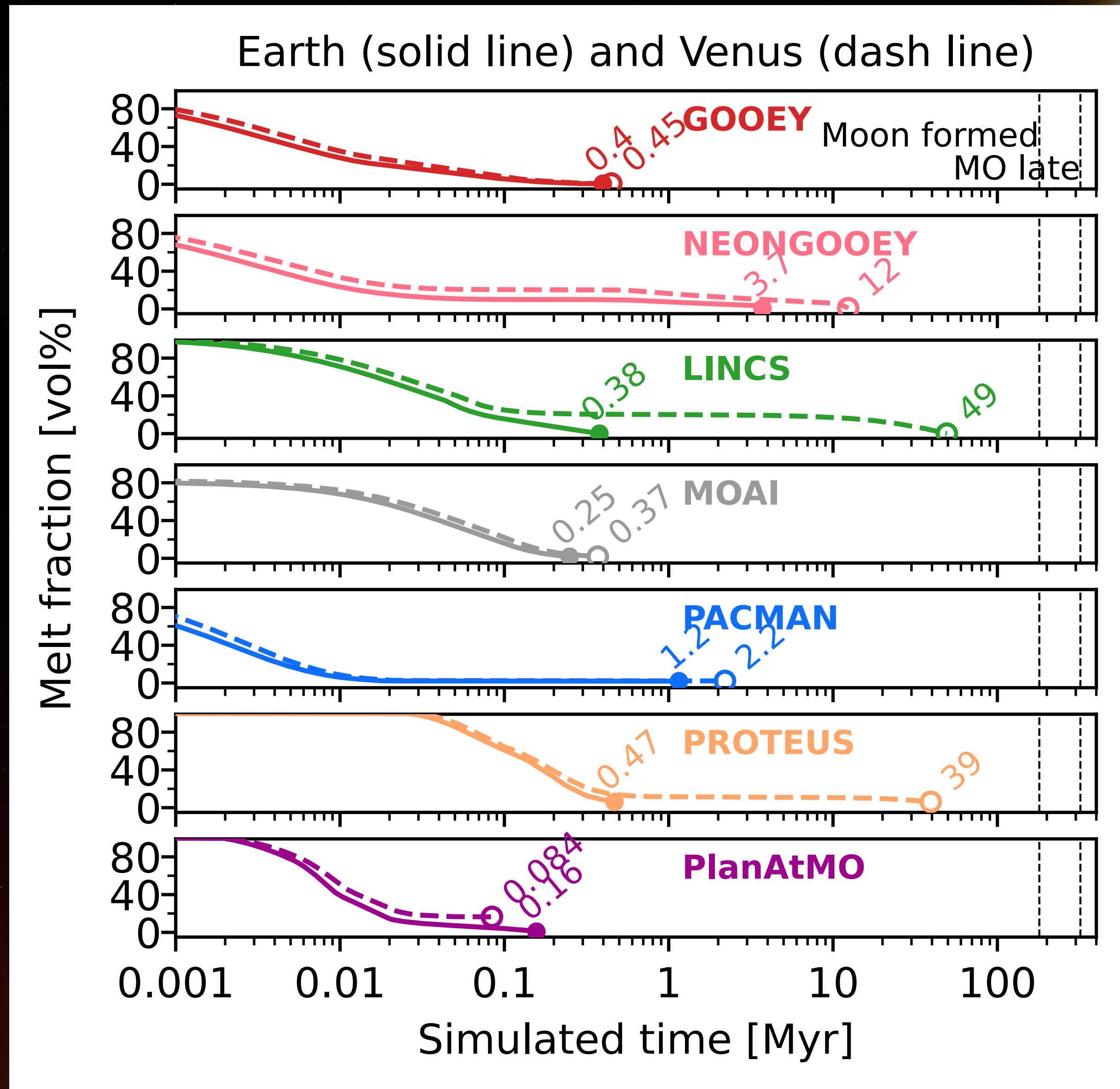


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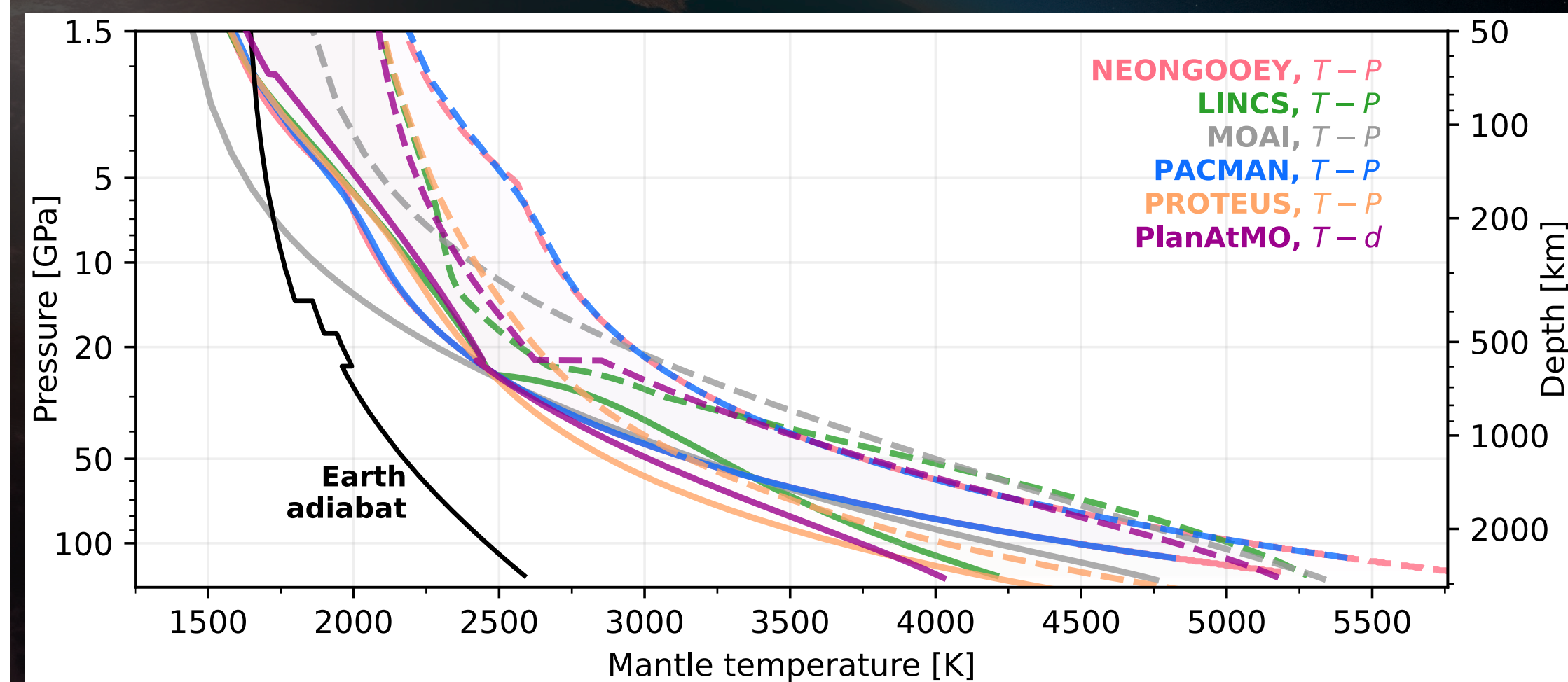
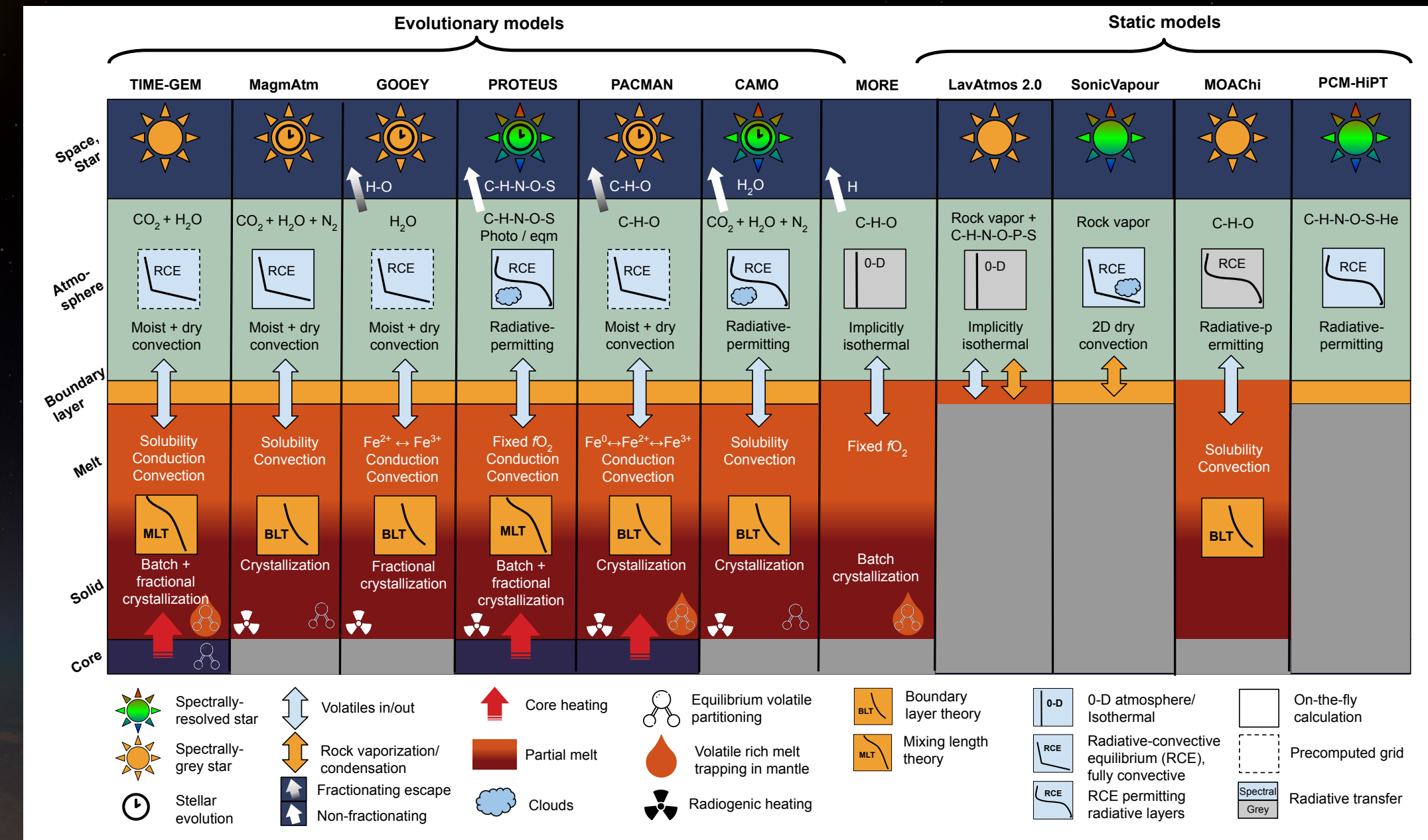
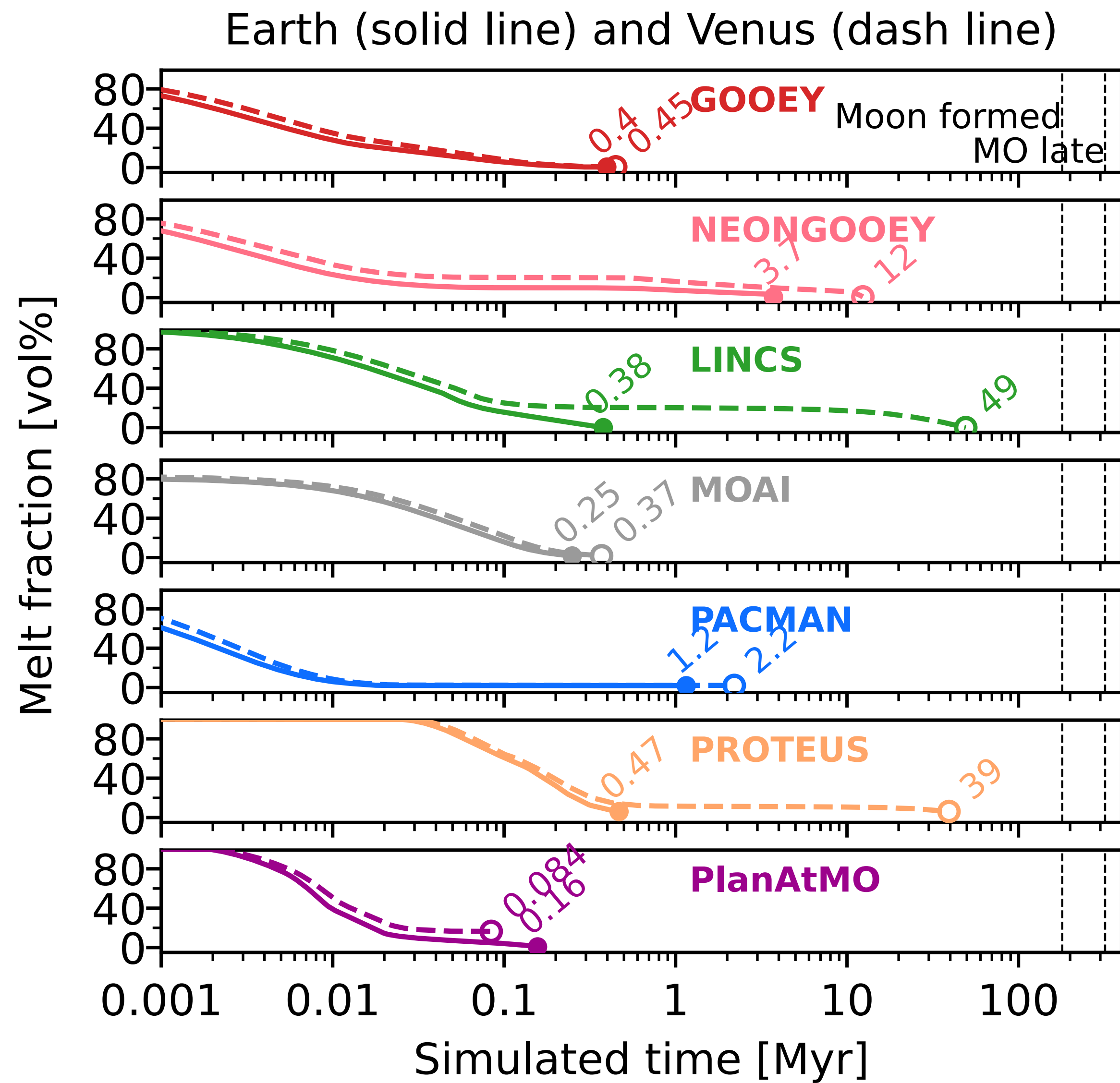


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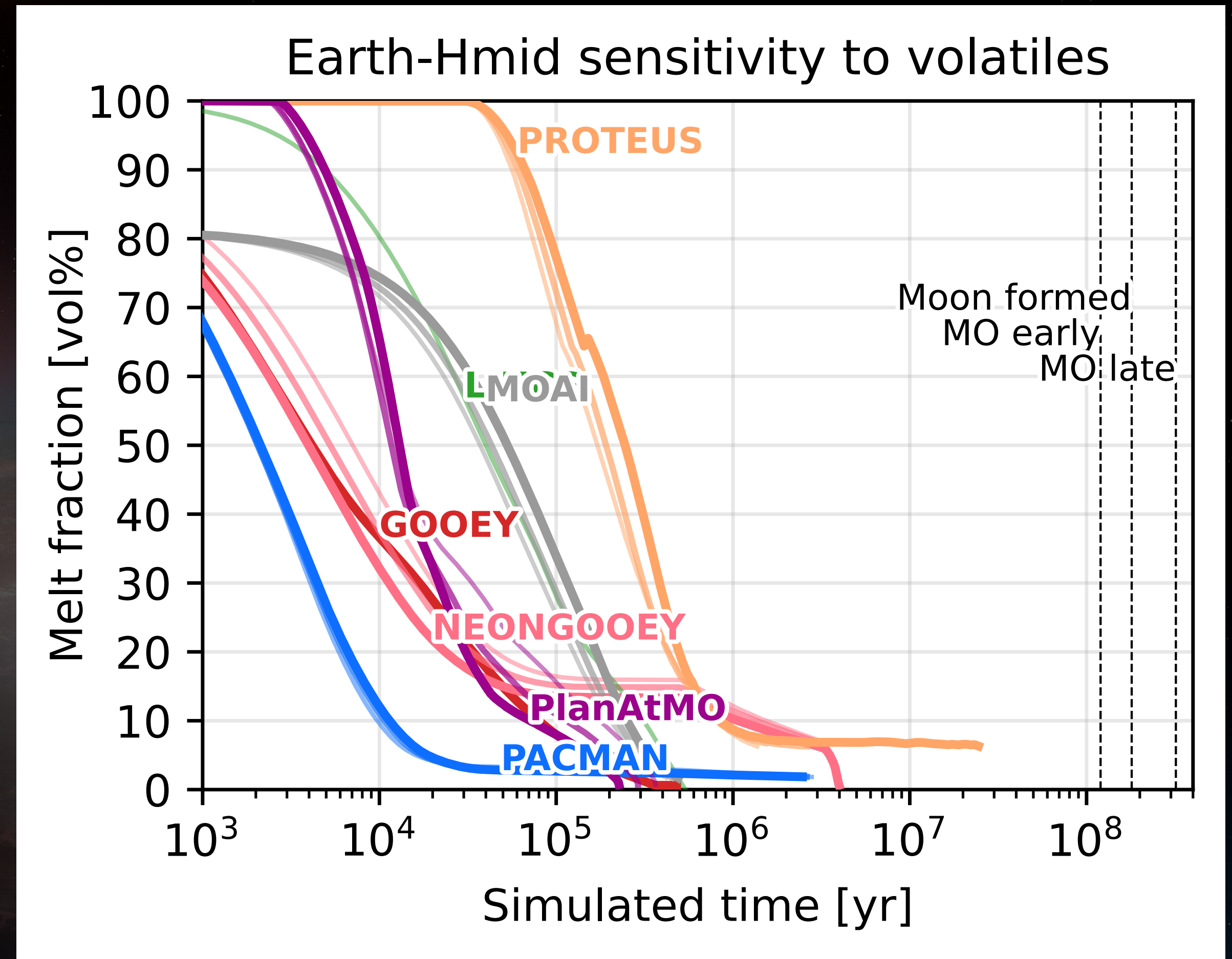
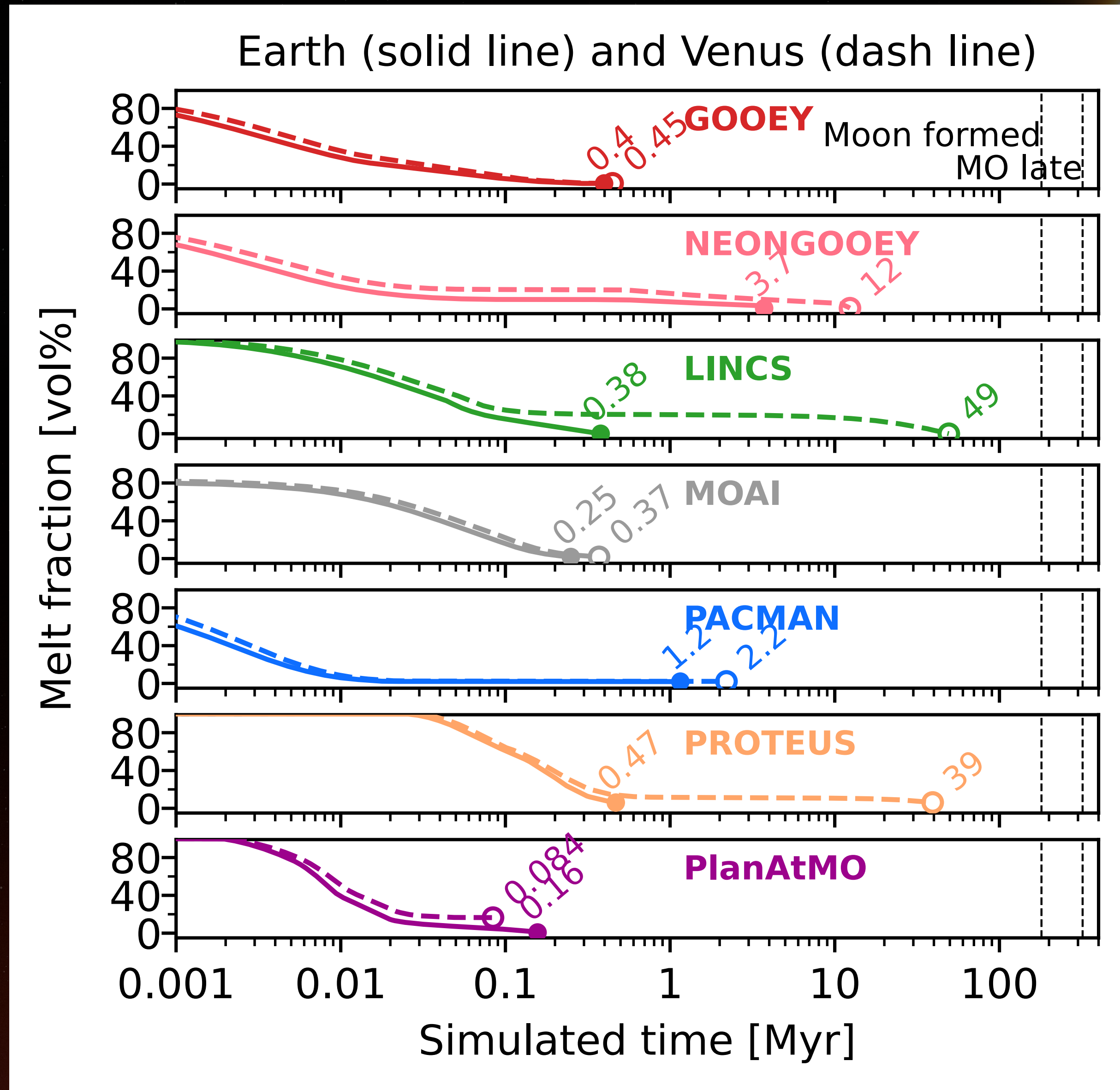
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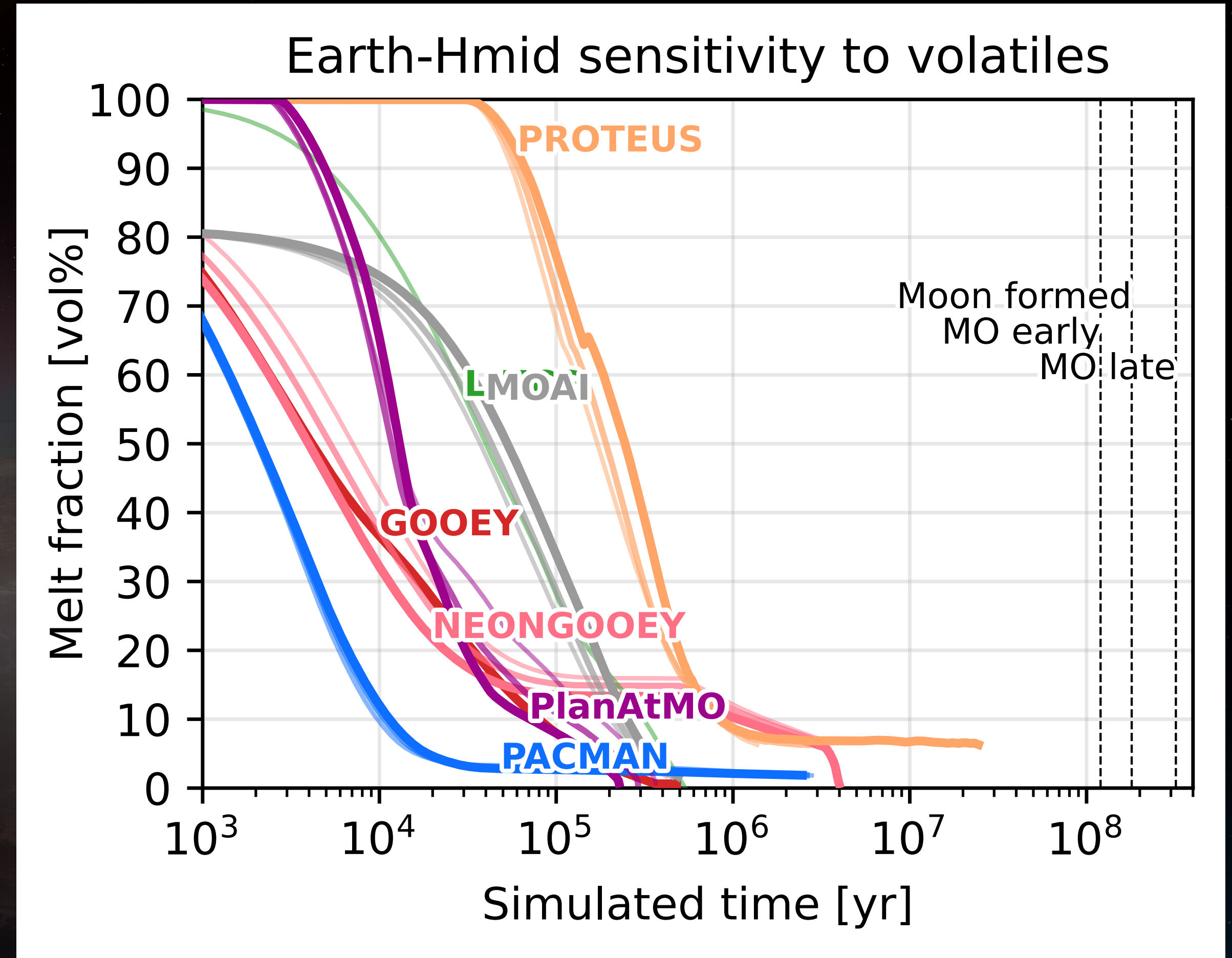
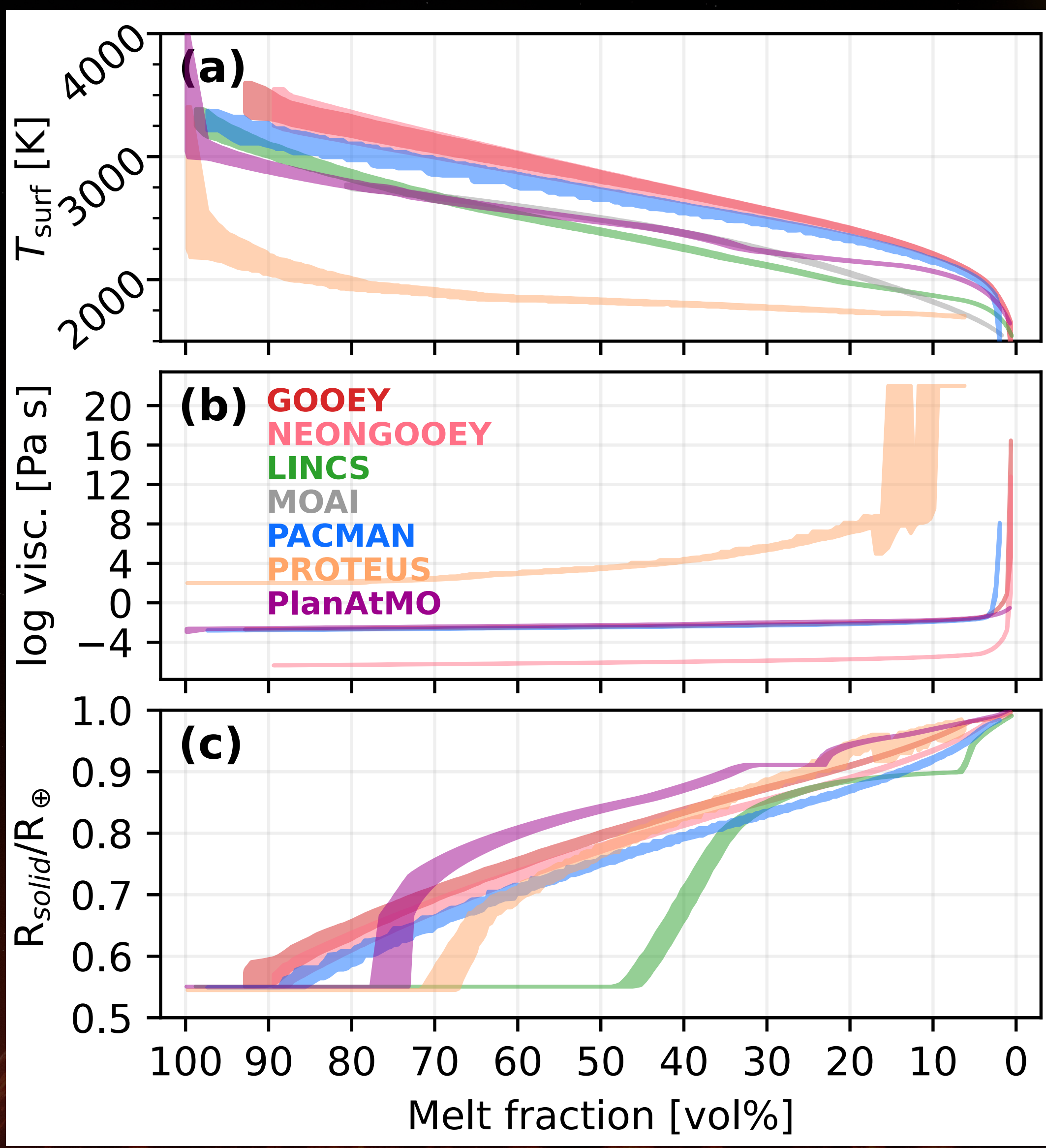
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CHILI Earth-Venus comparison



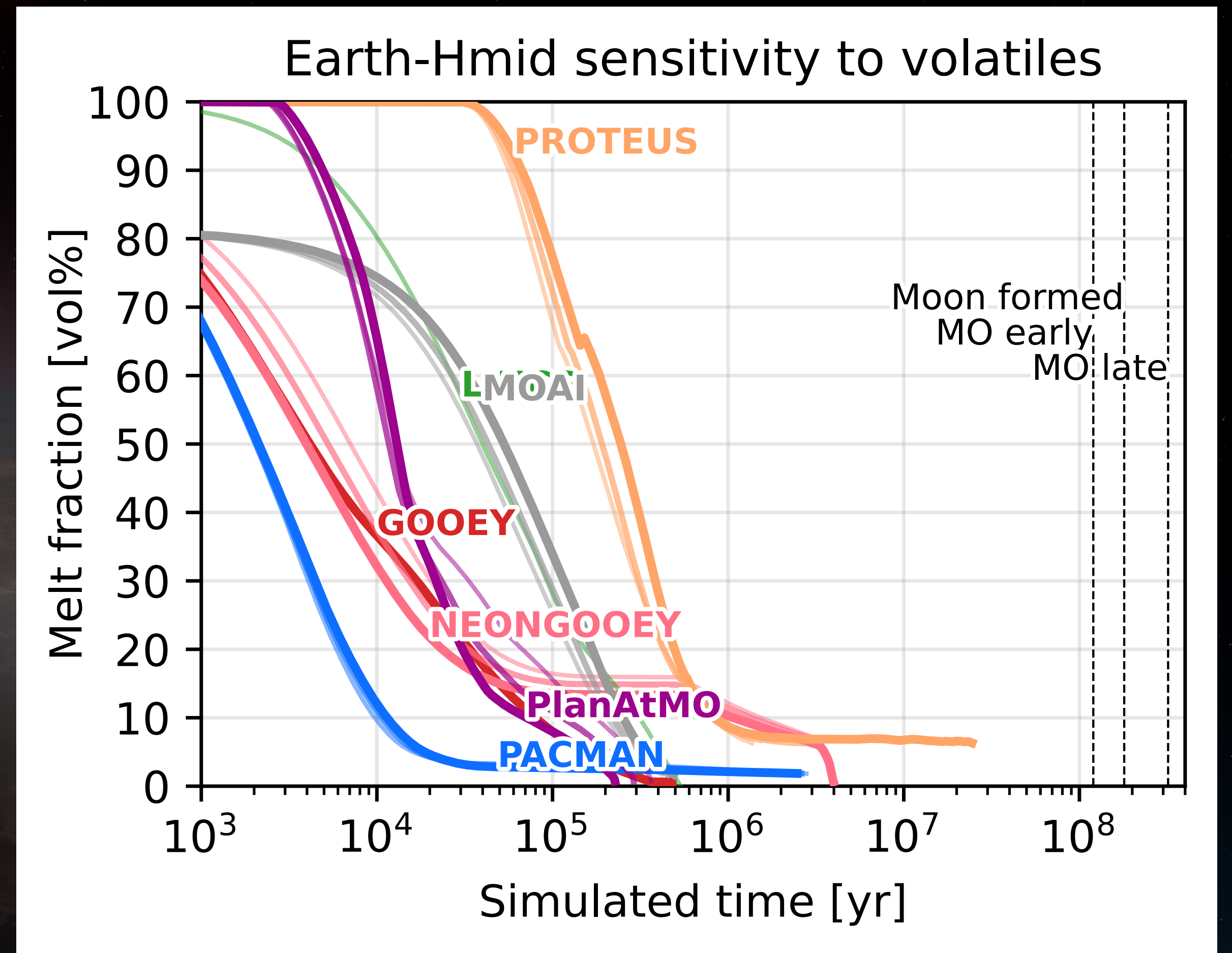
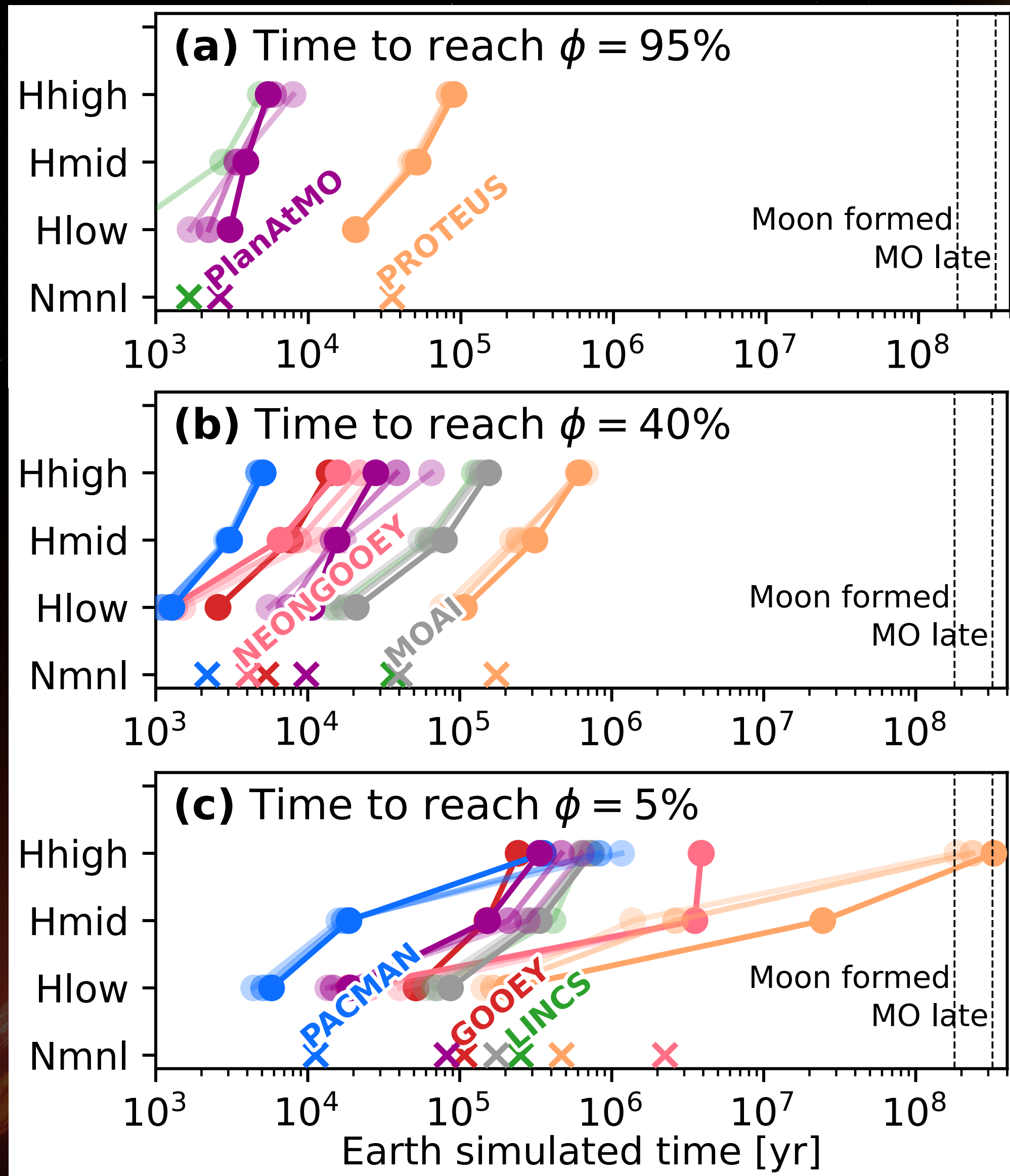
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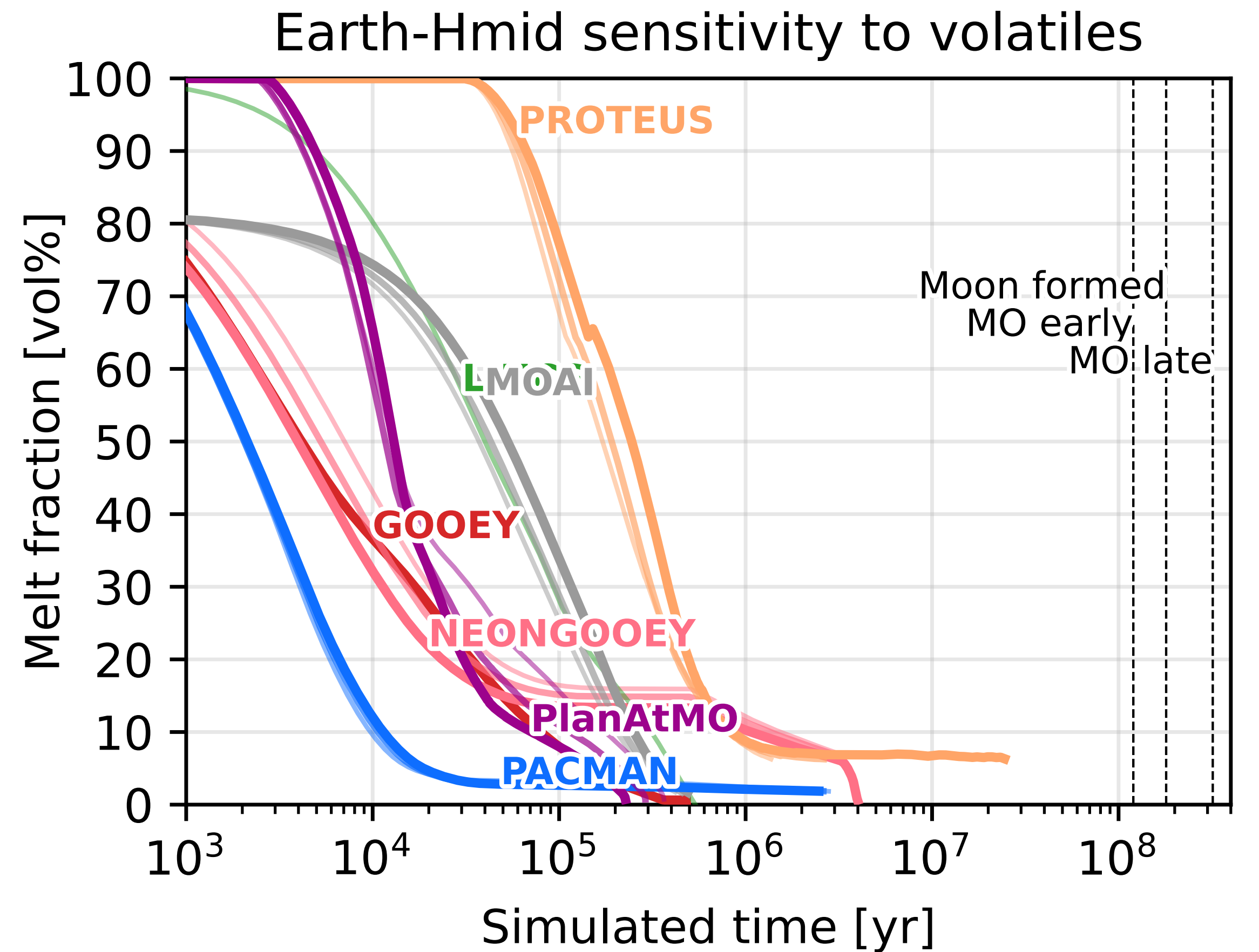
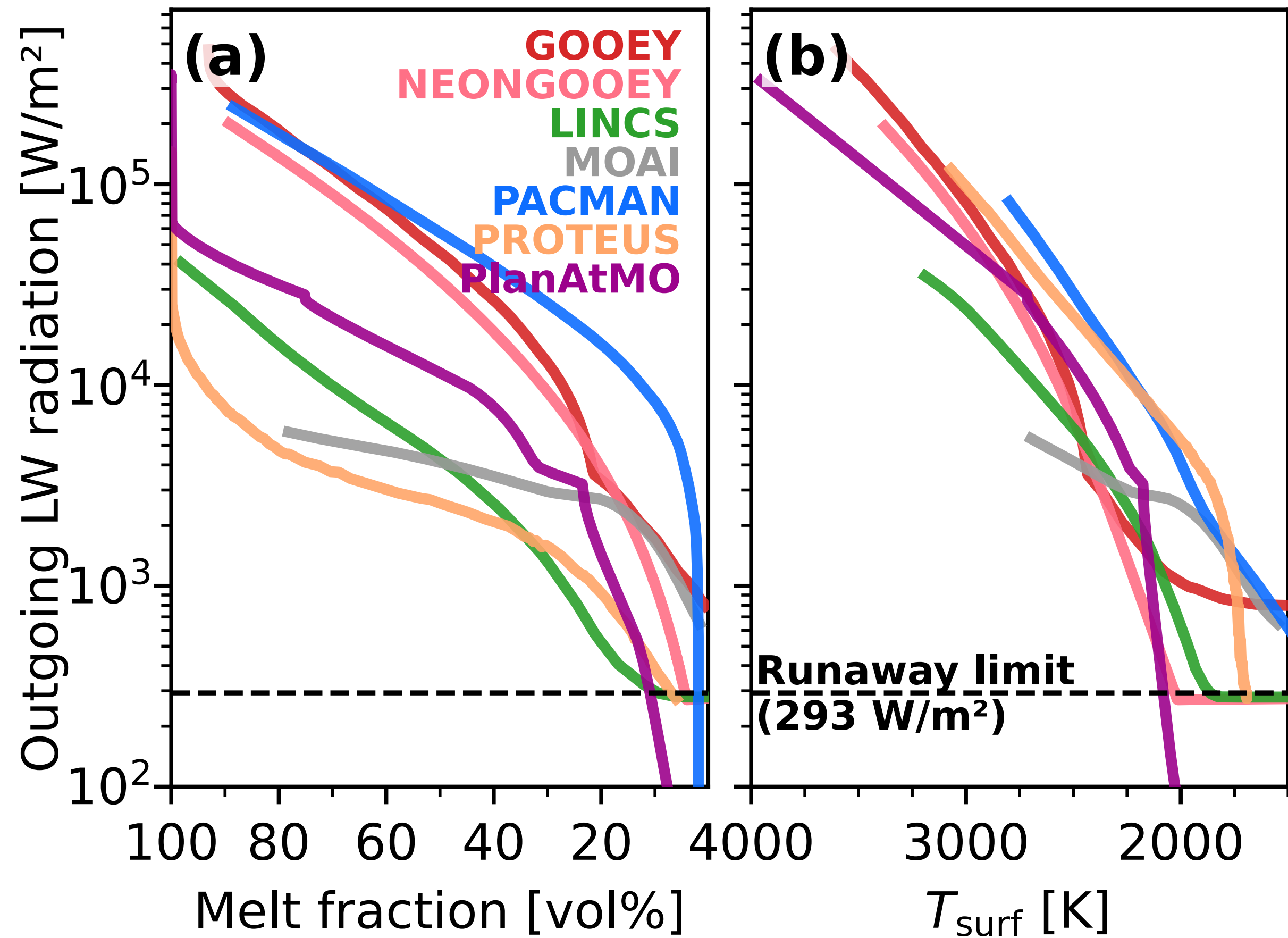
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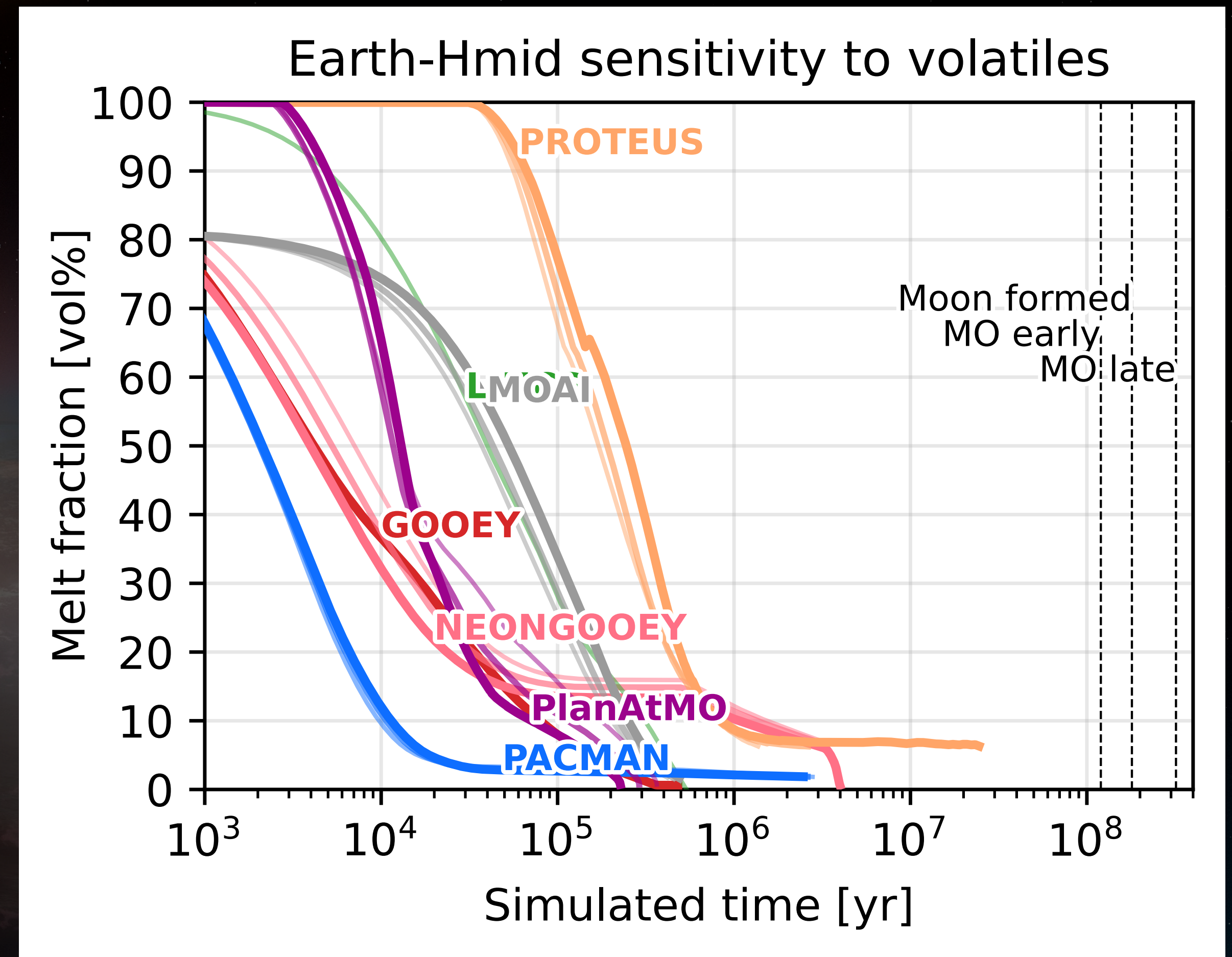
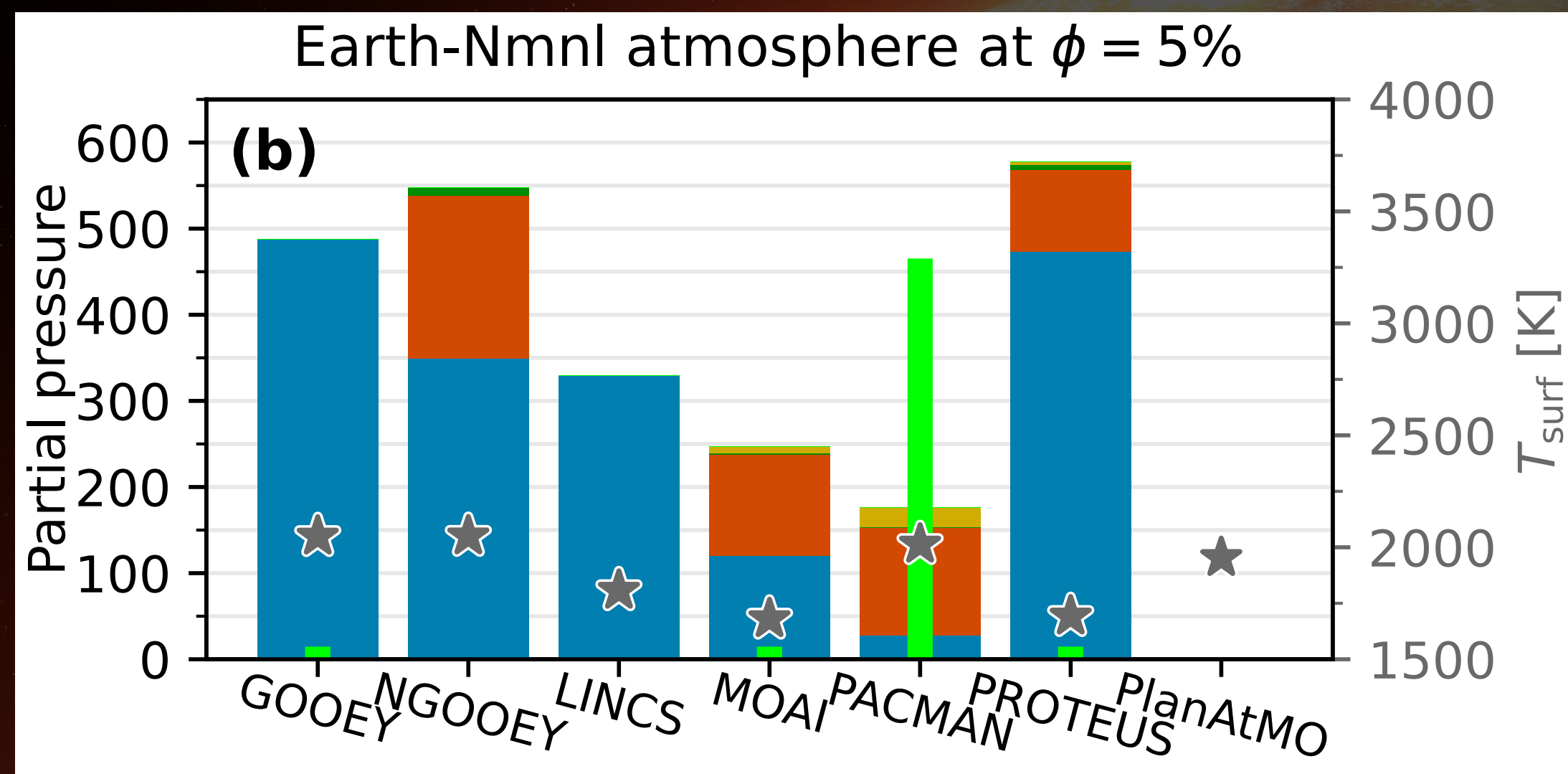
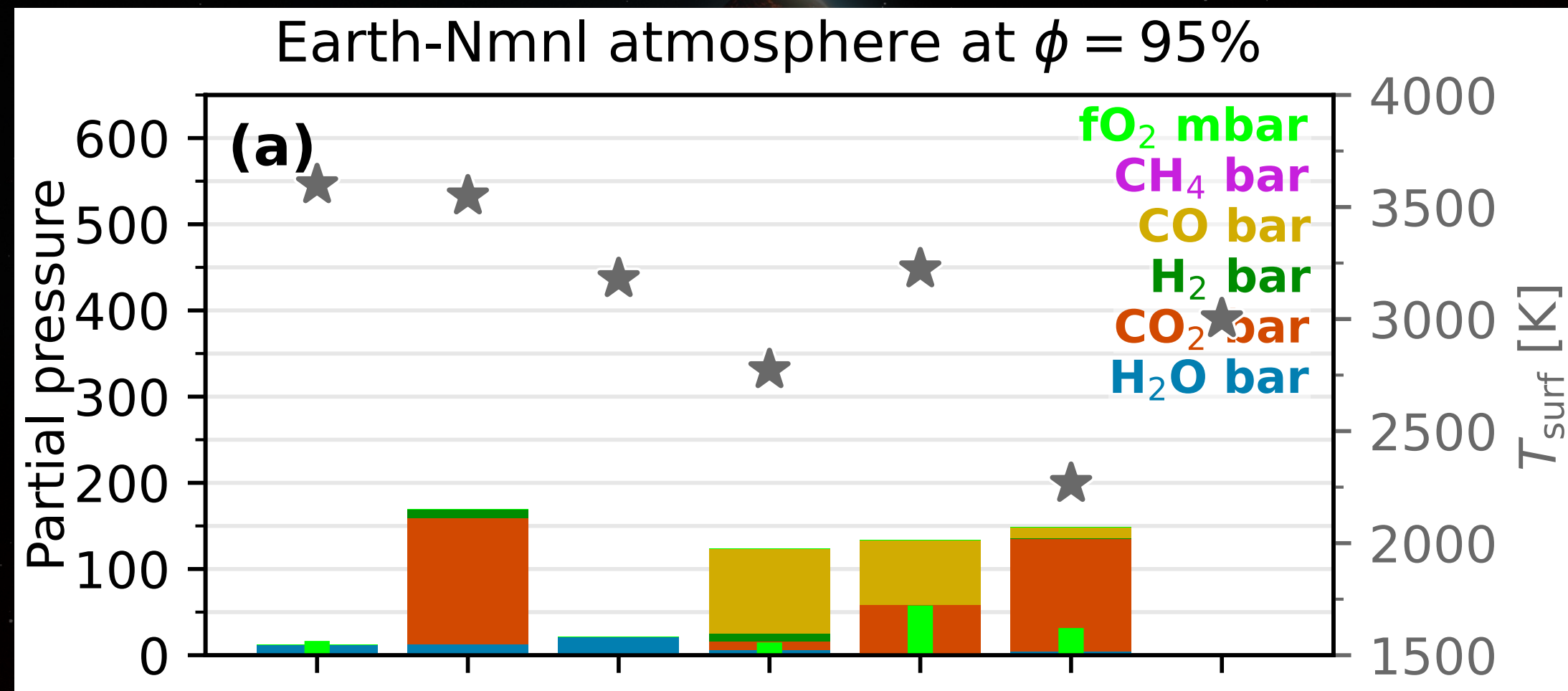
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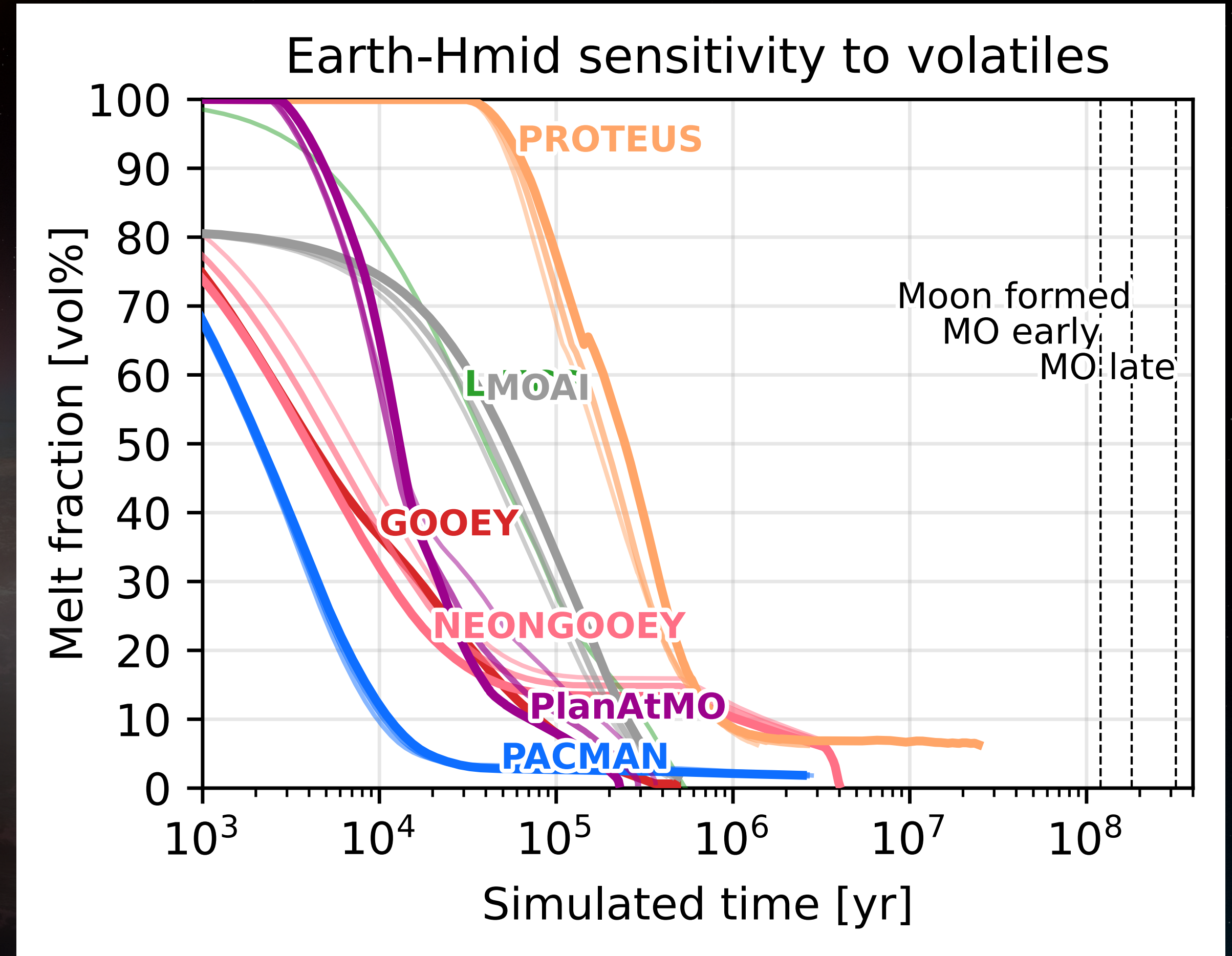
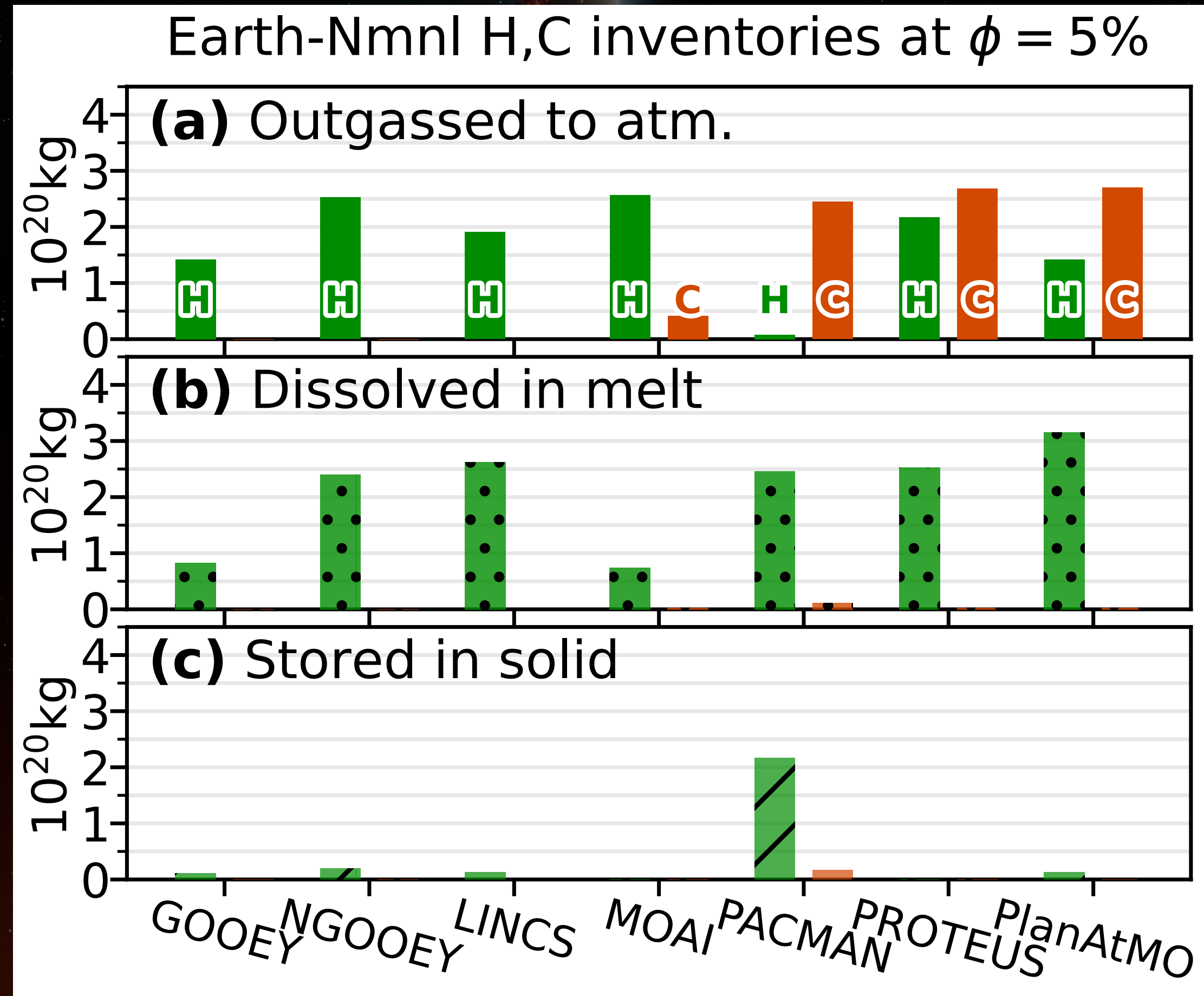
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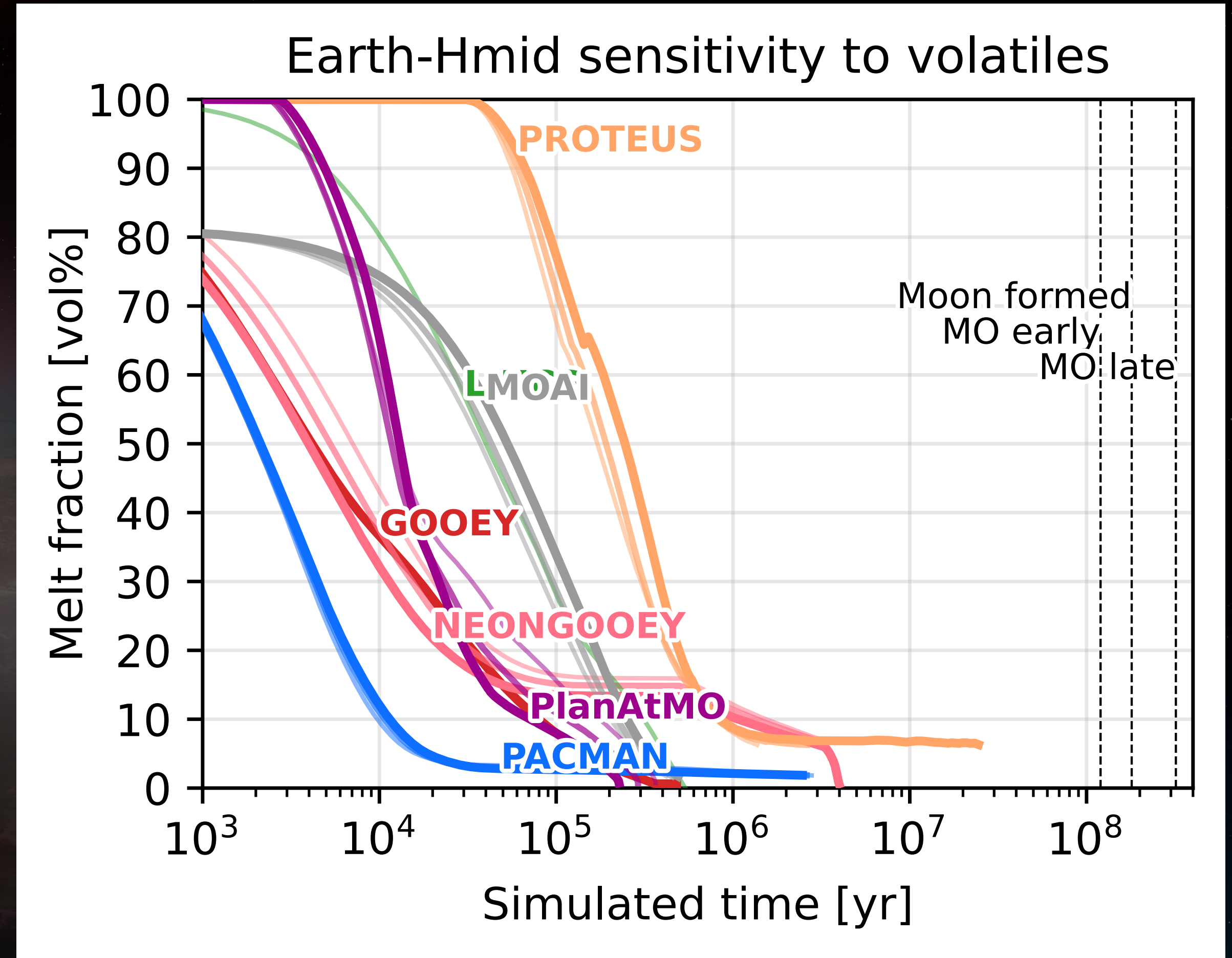
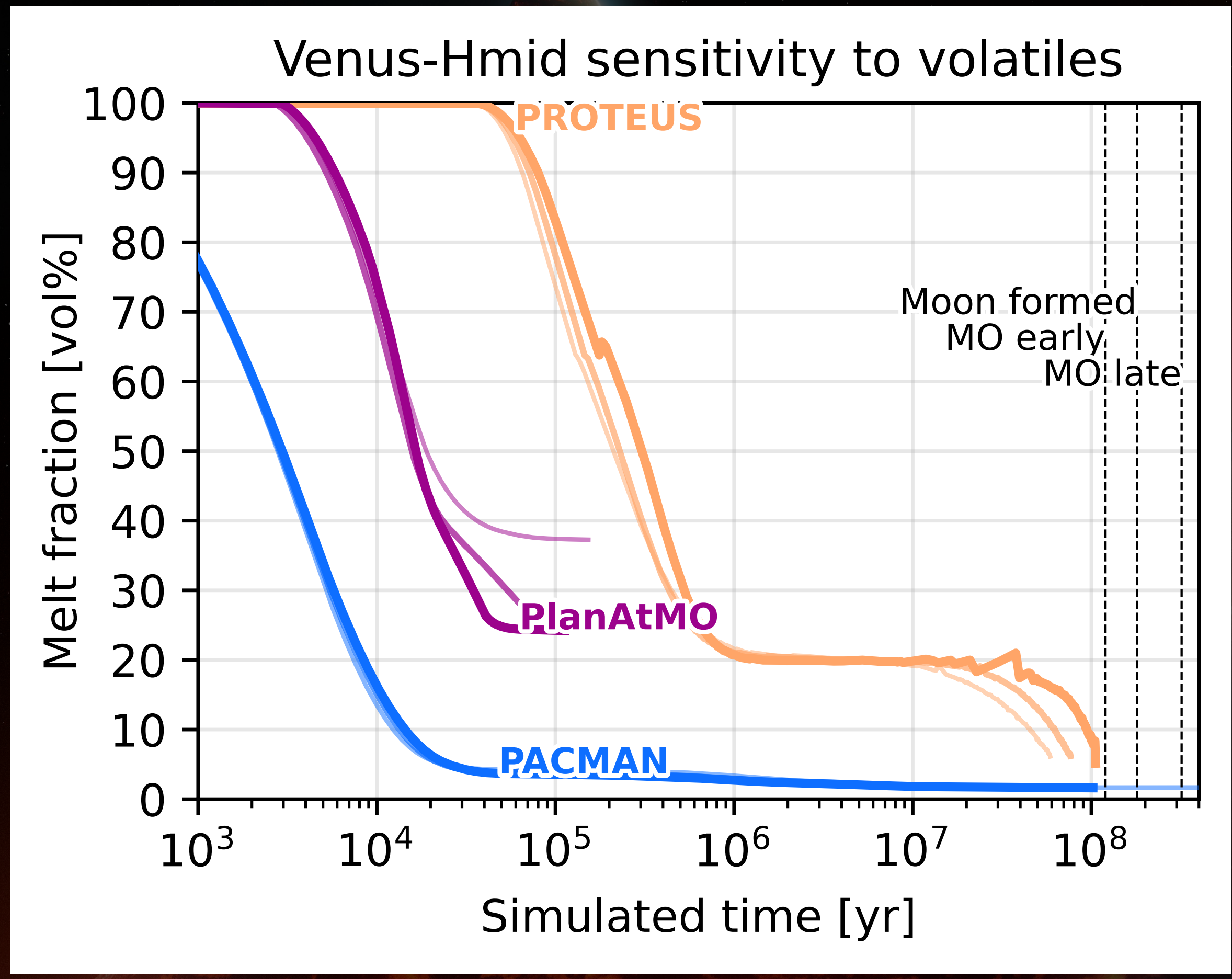
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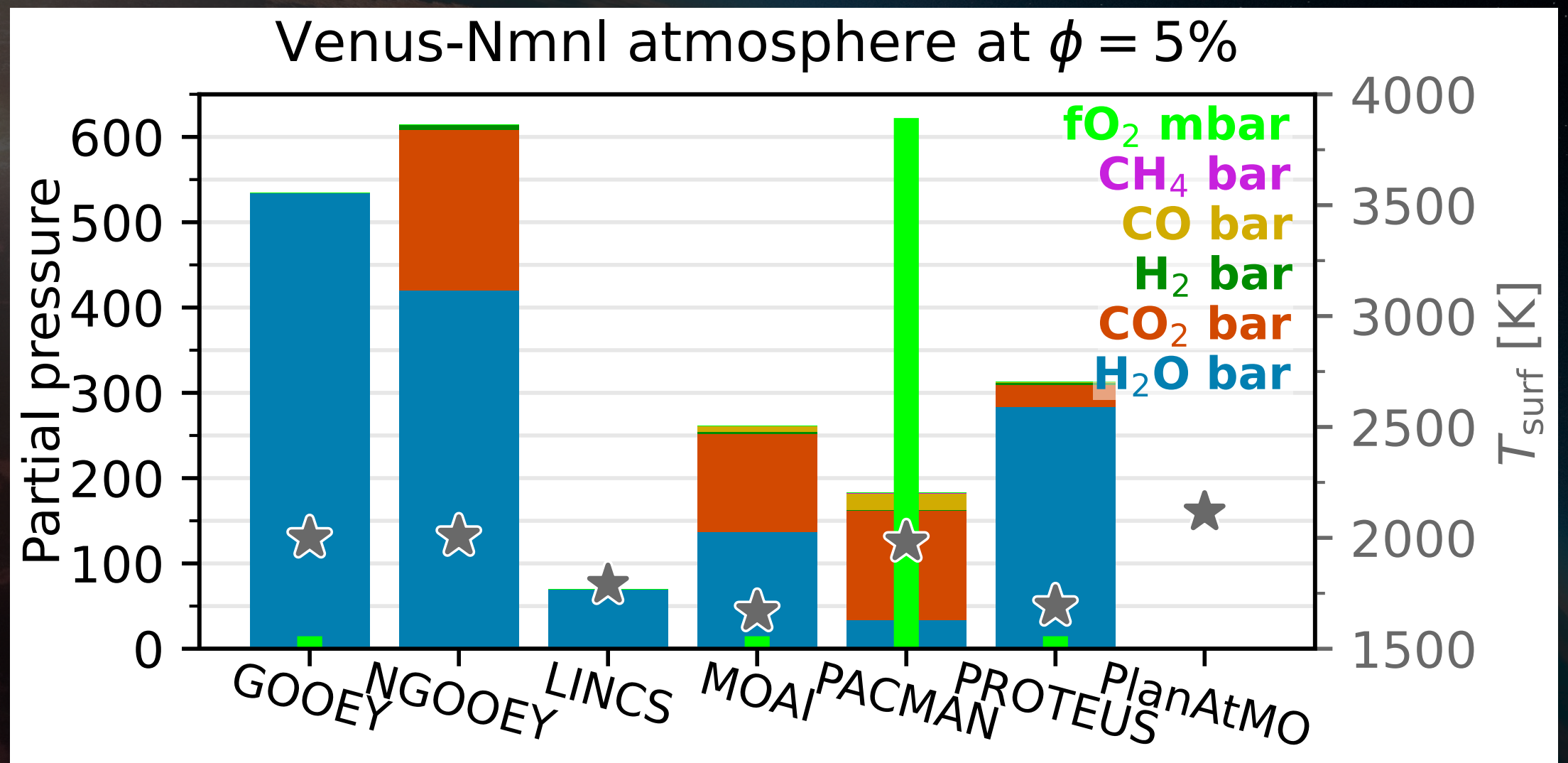
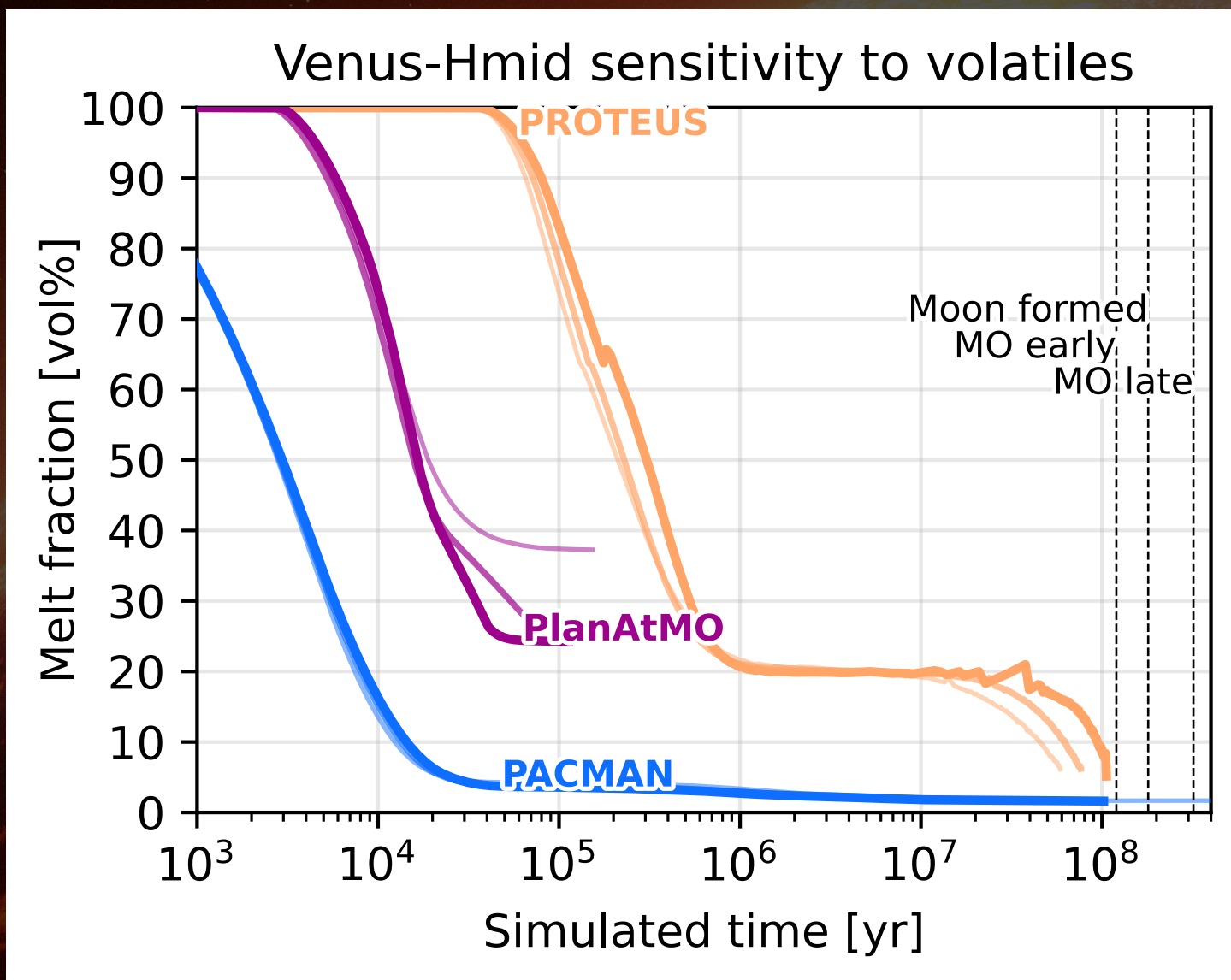
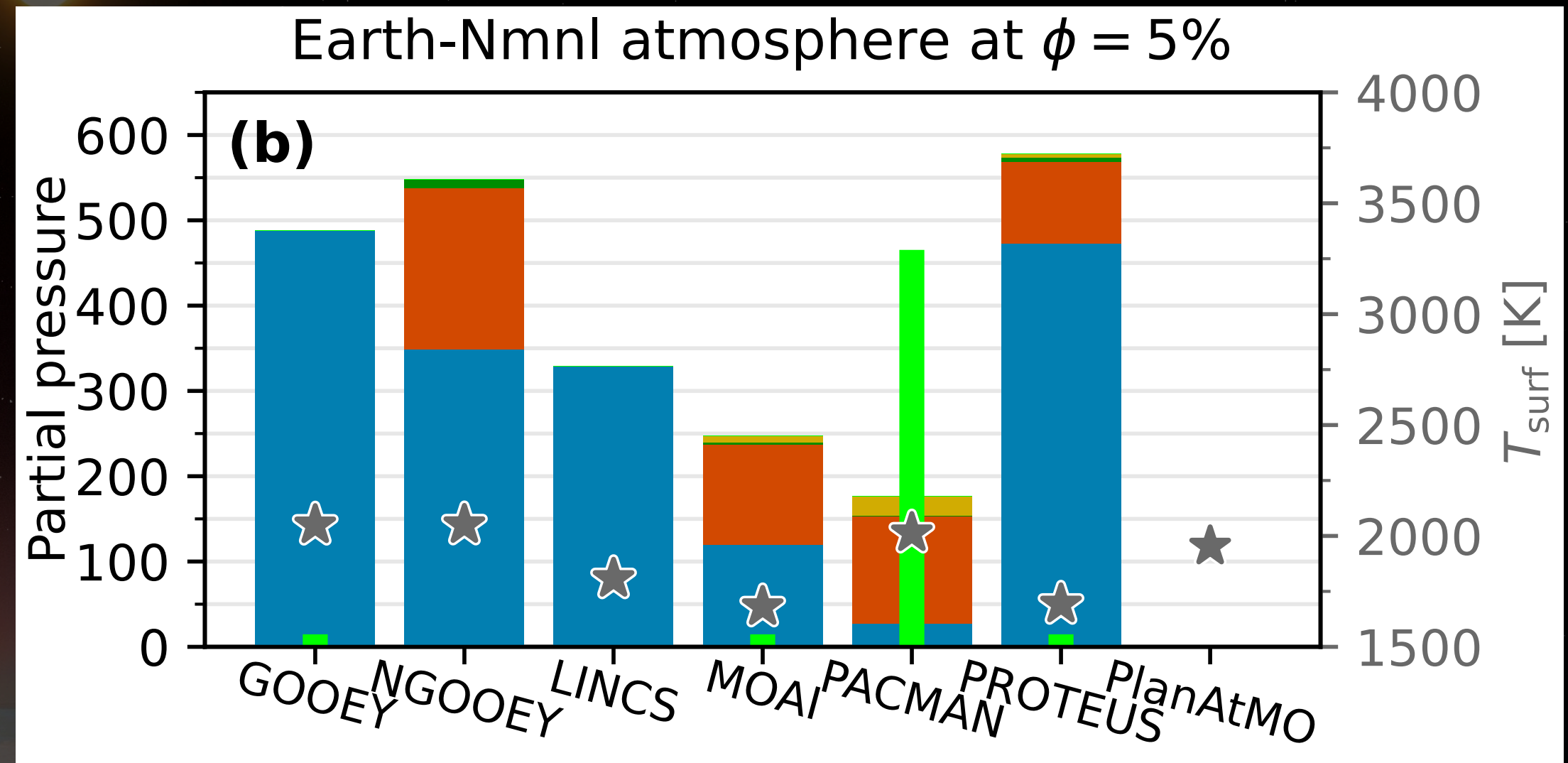
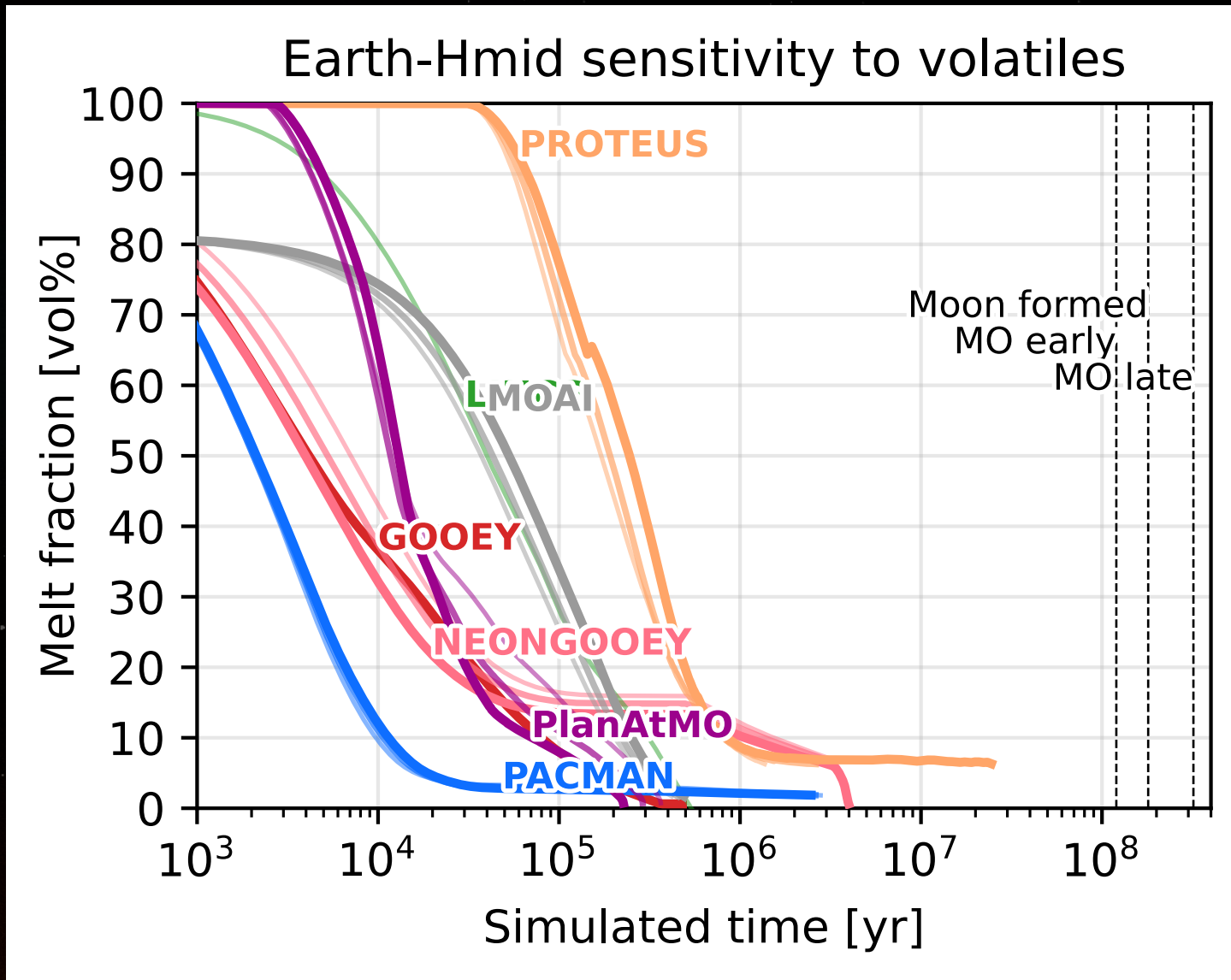
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1. Atmospheric & interior properties are co-evolving and defined by continuous feedback

2. Coupled models agree strongly on some features (e.g., rapid crystallisation of Earth in the absence of tides), but disagree on others (e.g., crystallisation time at increasing irradiation) -> digging deeper into causes

3. Next inter-comparison steps for coupled model should be larger planets: super-Earths/sub-Neptunes, where feedback effects compound

