New Insights into Exoplanet Interiors:
Connecting Theory with Measurements from Space and Lab

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Department of Astronomy Colloquium, Tsinghua University, May 2025

ARCO
Astrophysics Research Center
of the Open university

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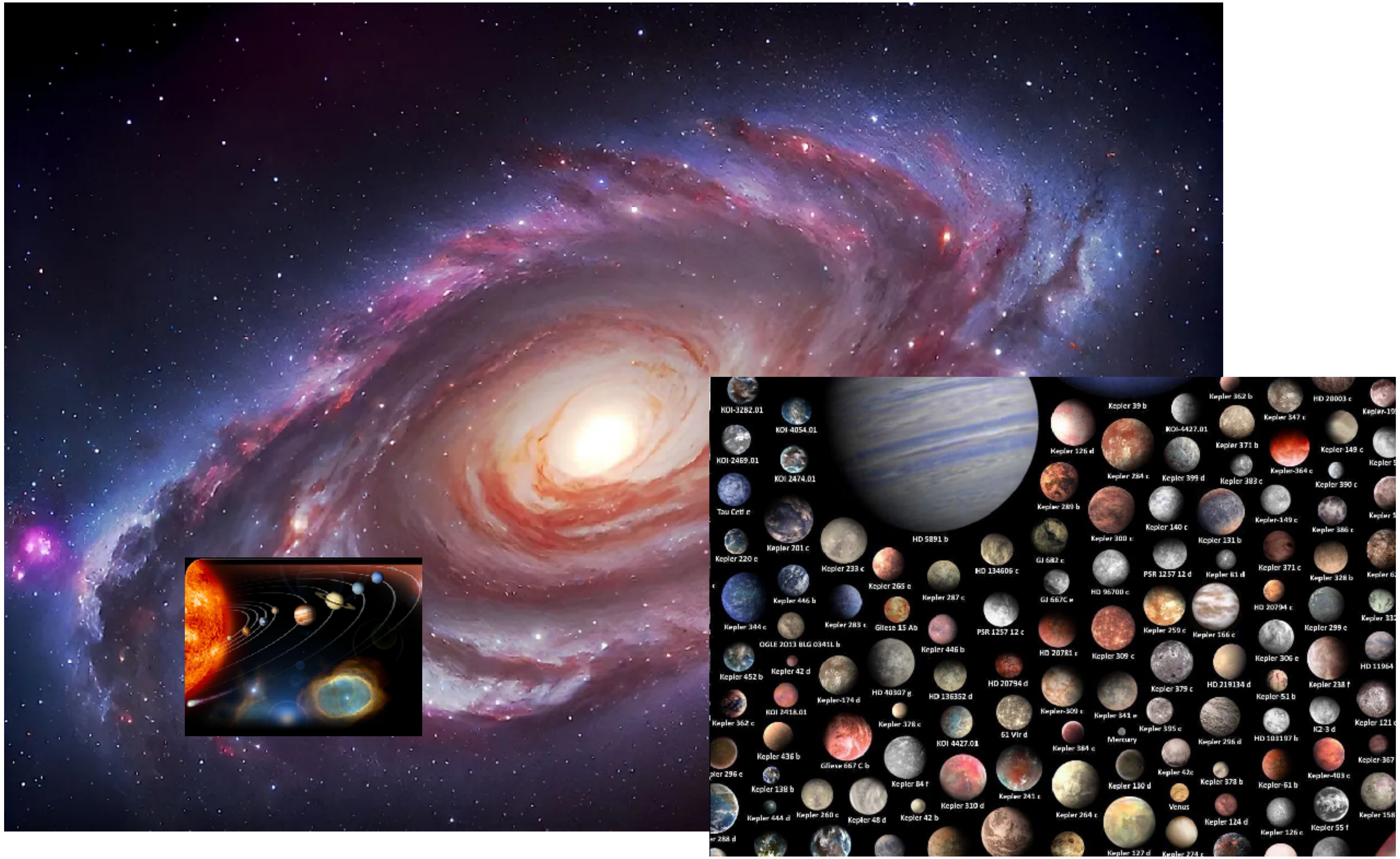
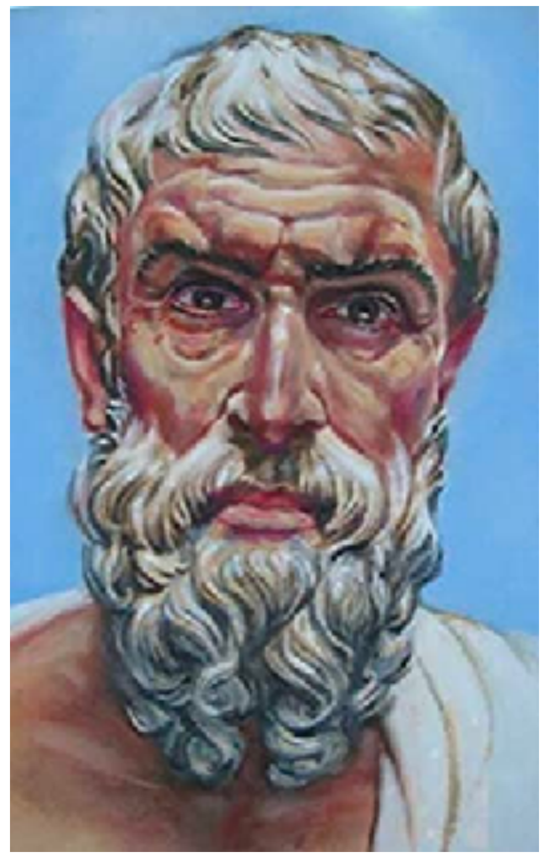
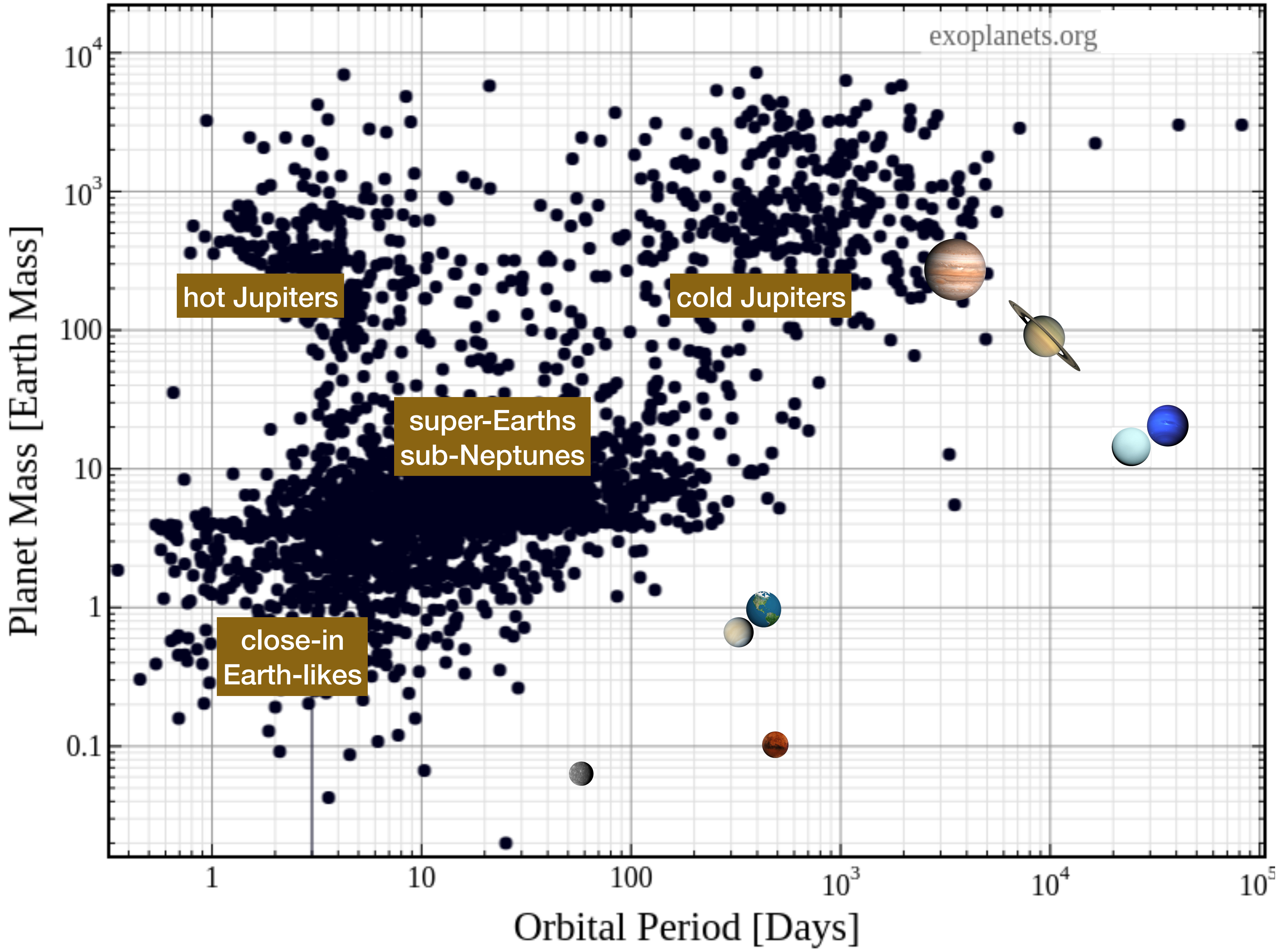
Exoplanets (extra solar worlds)





Epicurus
(341 BC - 270 BC):
“There is infinite amount of worlds like ours”

Observed exoplanets population



What we measure:

- Orbital period (separation)
- Radius (transit)
- Mass (radial - velocity)
- Luminosity (direct imaging)
- Atmospheric abundances (transit spectroscopy)

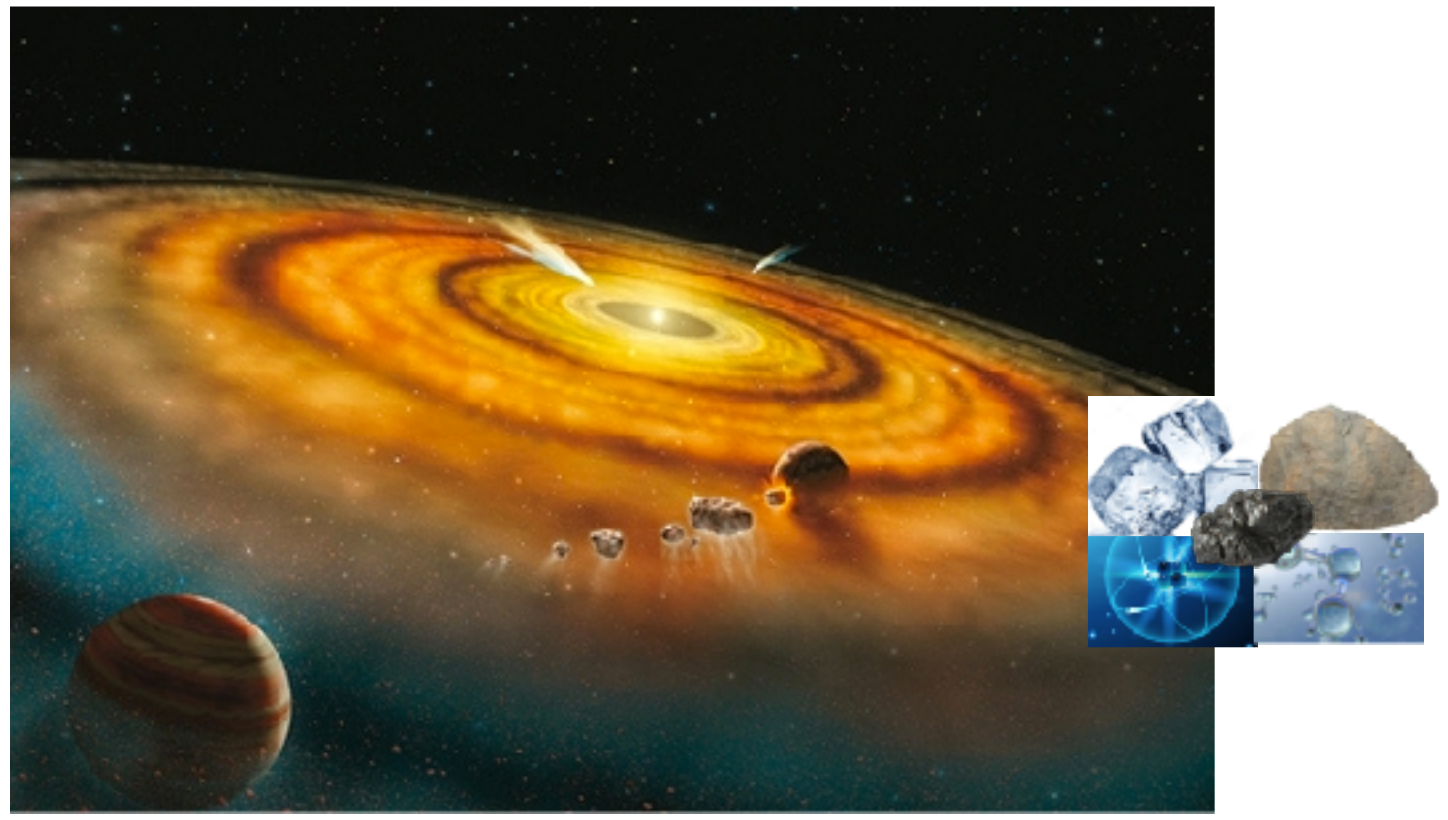
*** How do planets form?**

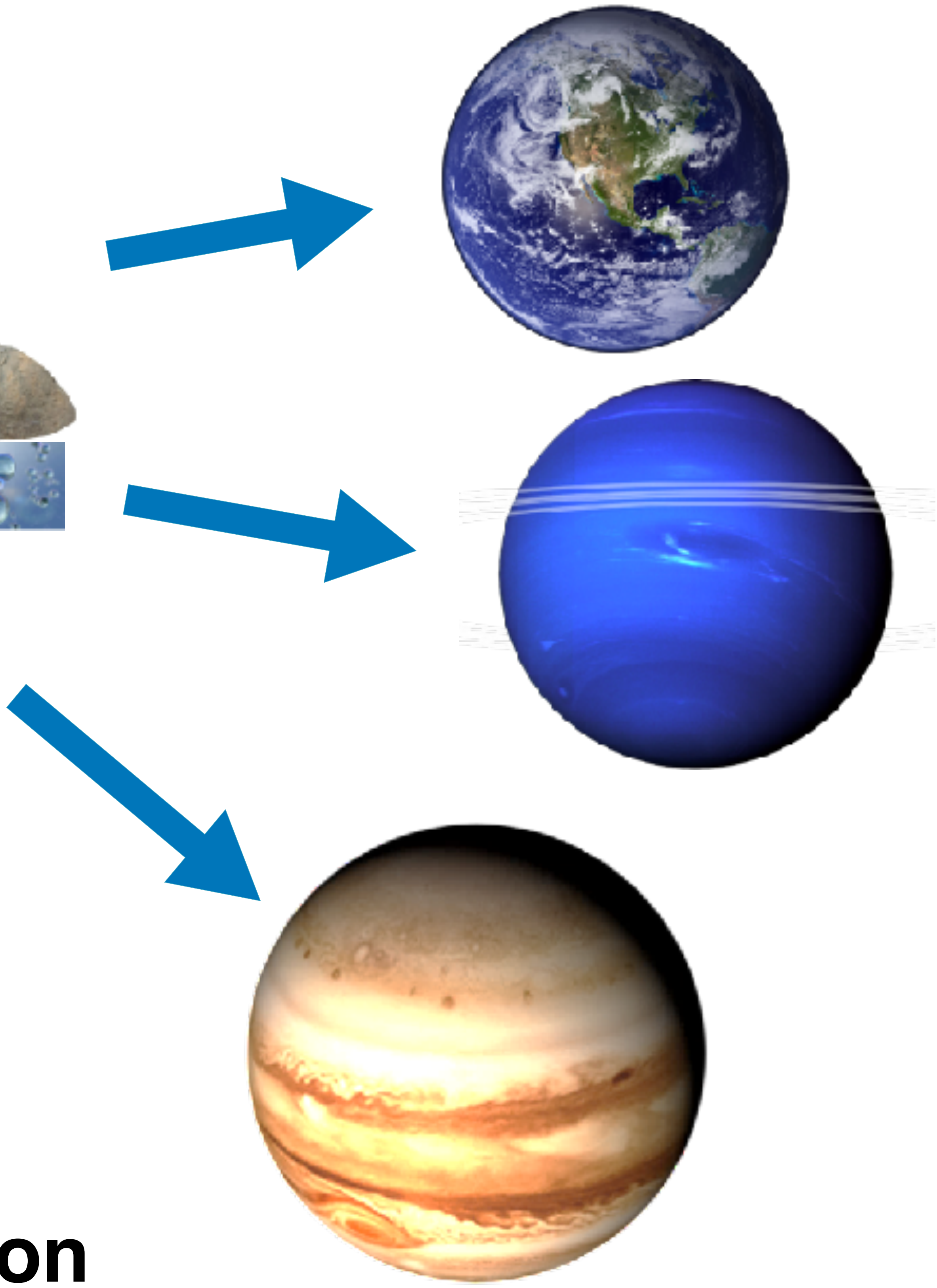
*** What are they made of?**

*** What mechanisms control diversity?**

Planetary composition

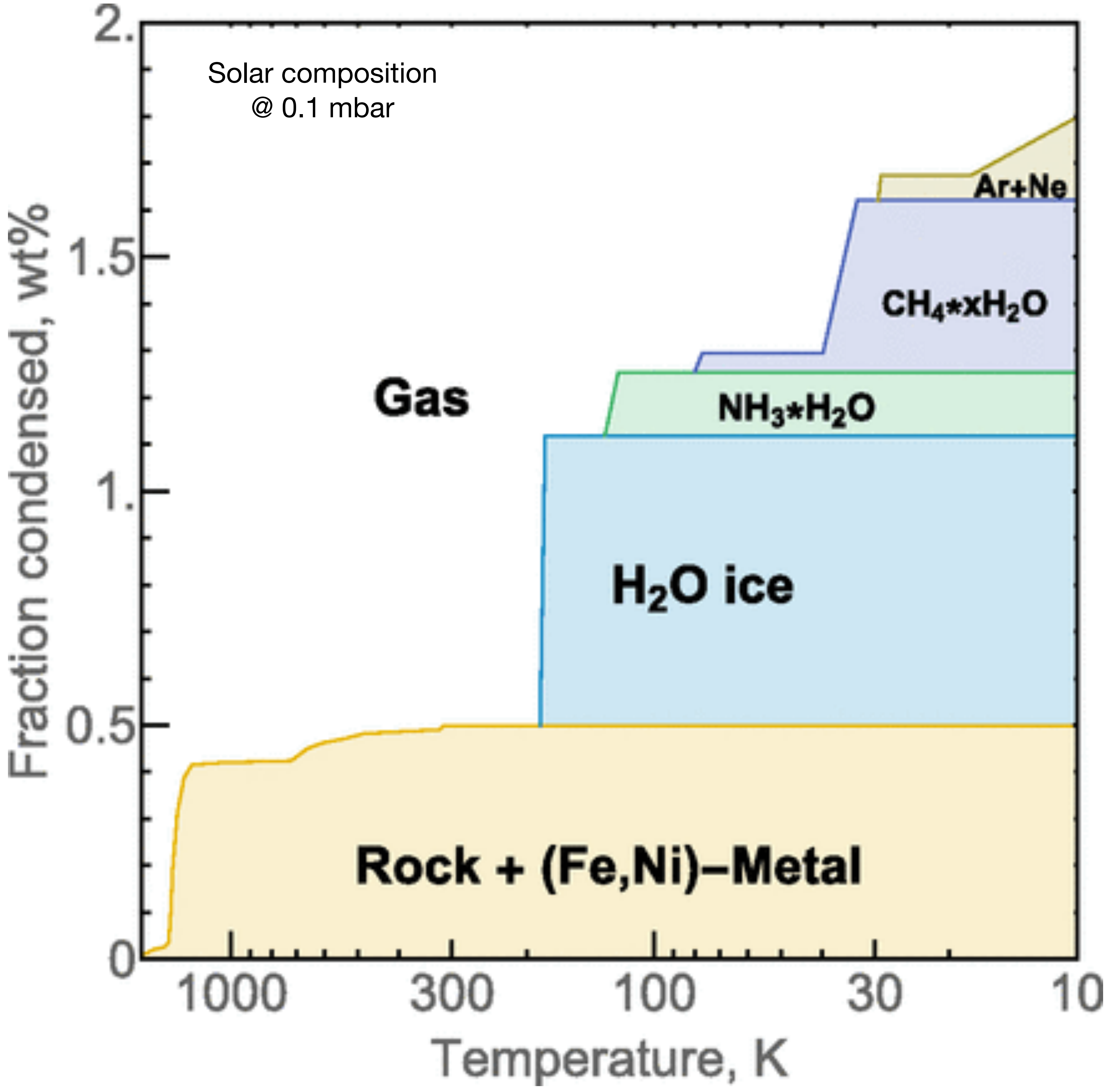
Building blocks from the protoplanetary disk





Main mechanism: Core Accretion

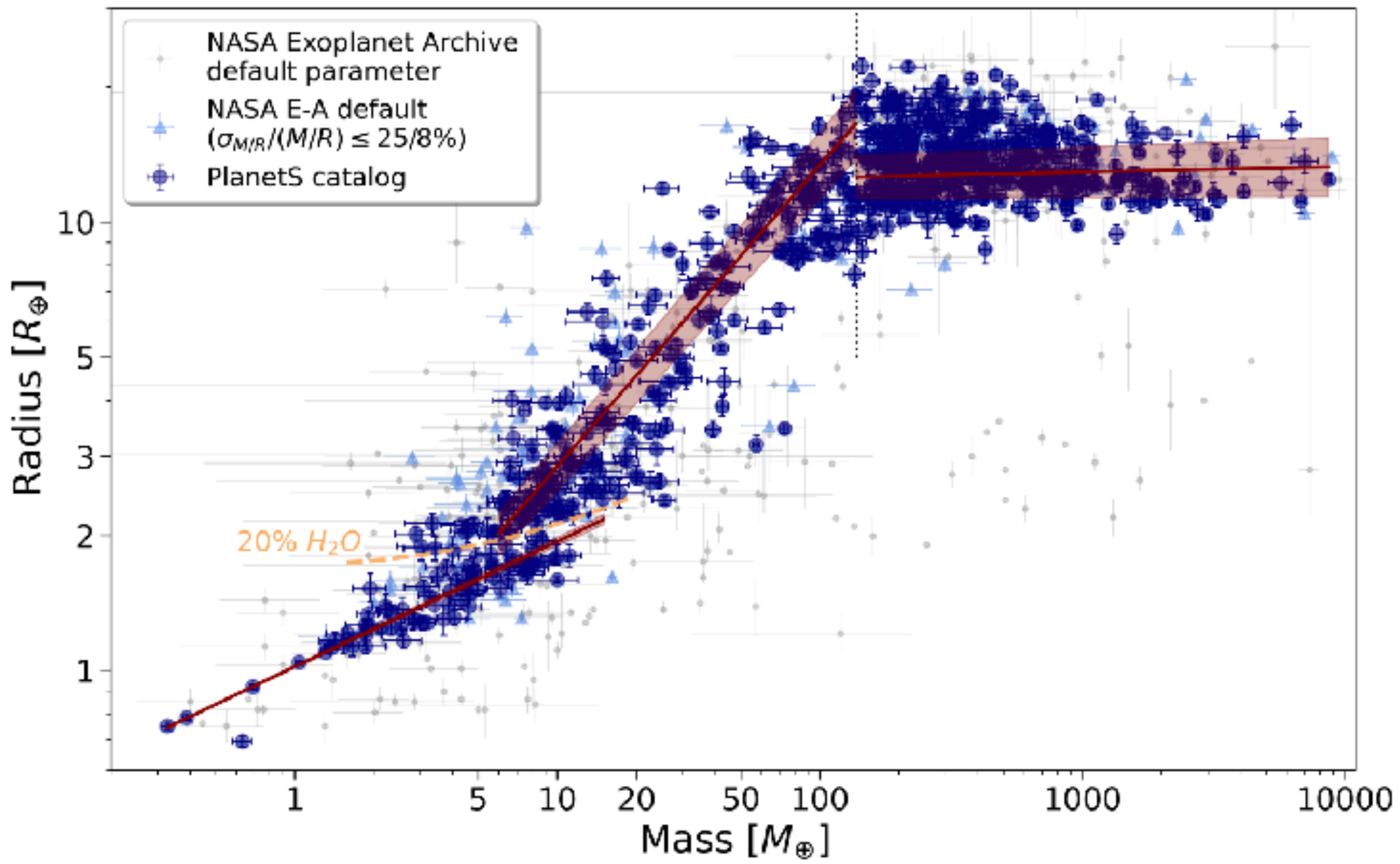
Debated mechanism: Gravitational Instability



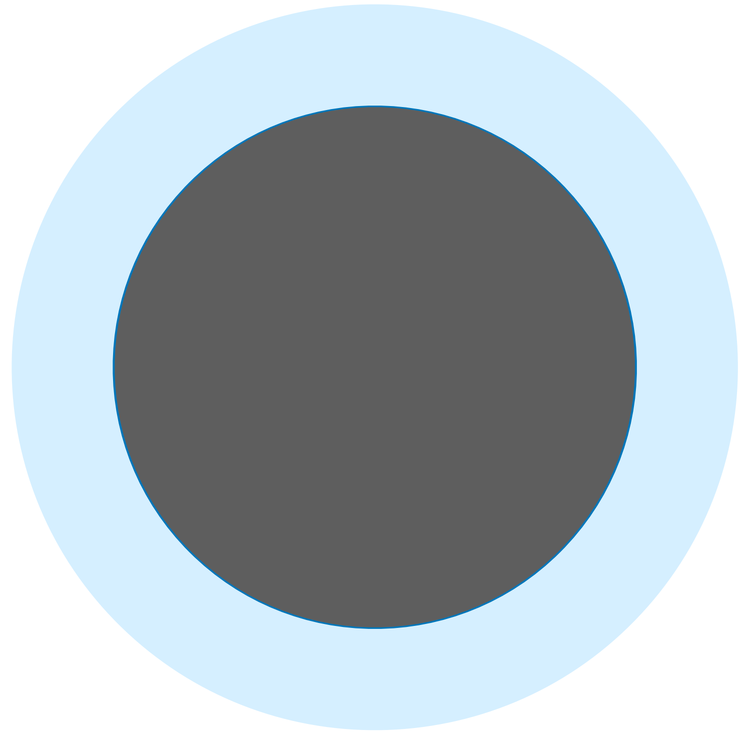
Zeng et al. 2018 (Lodders 2003)

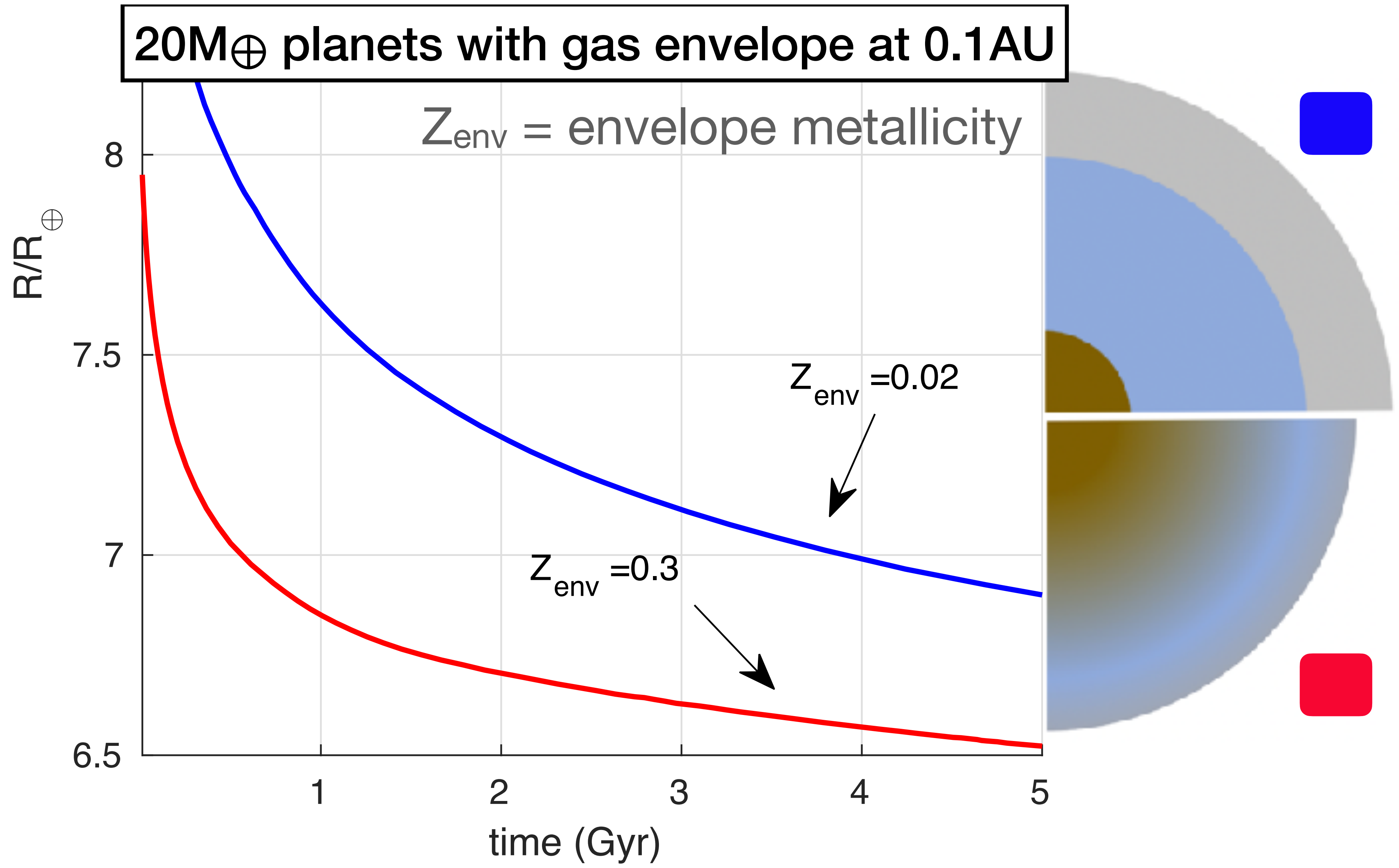
Planetary interiors

What can we tell? why do we care?



Parc et al. 2024



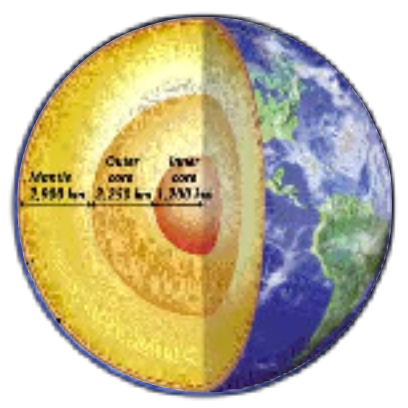
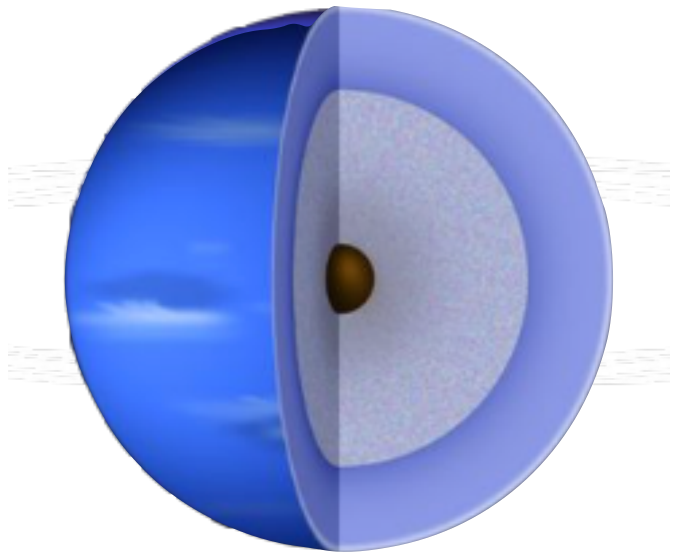
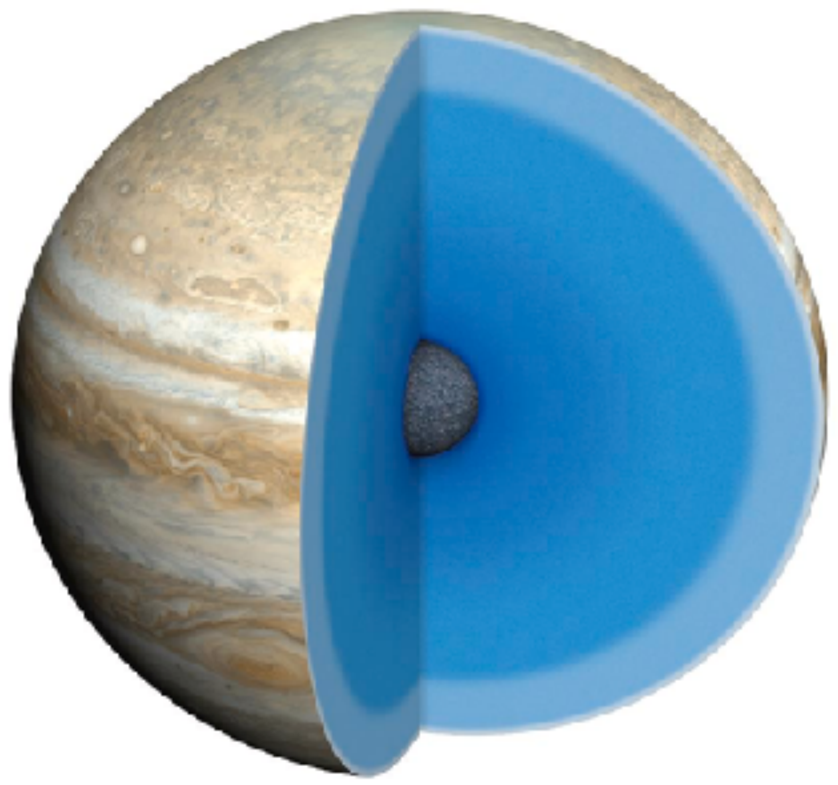
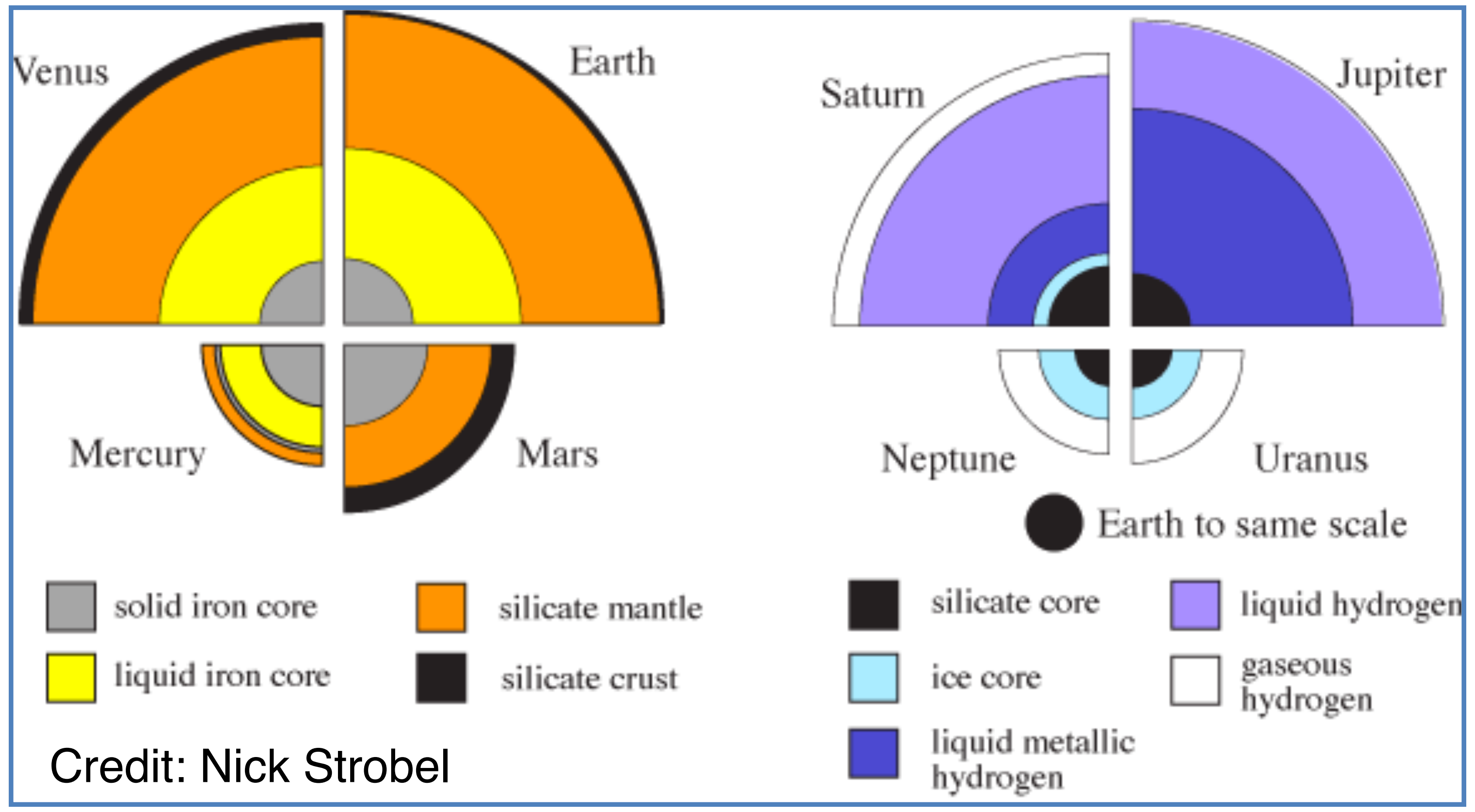


Mass-radius relation is affected by composition distribution in the interior (and by age)

A. Vazan

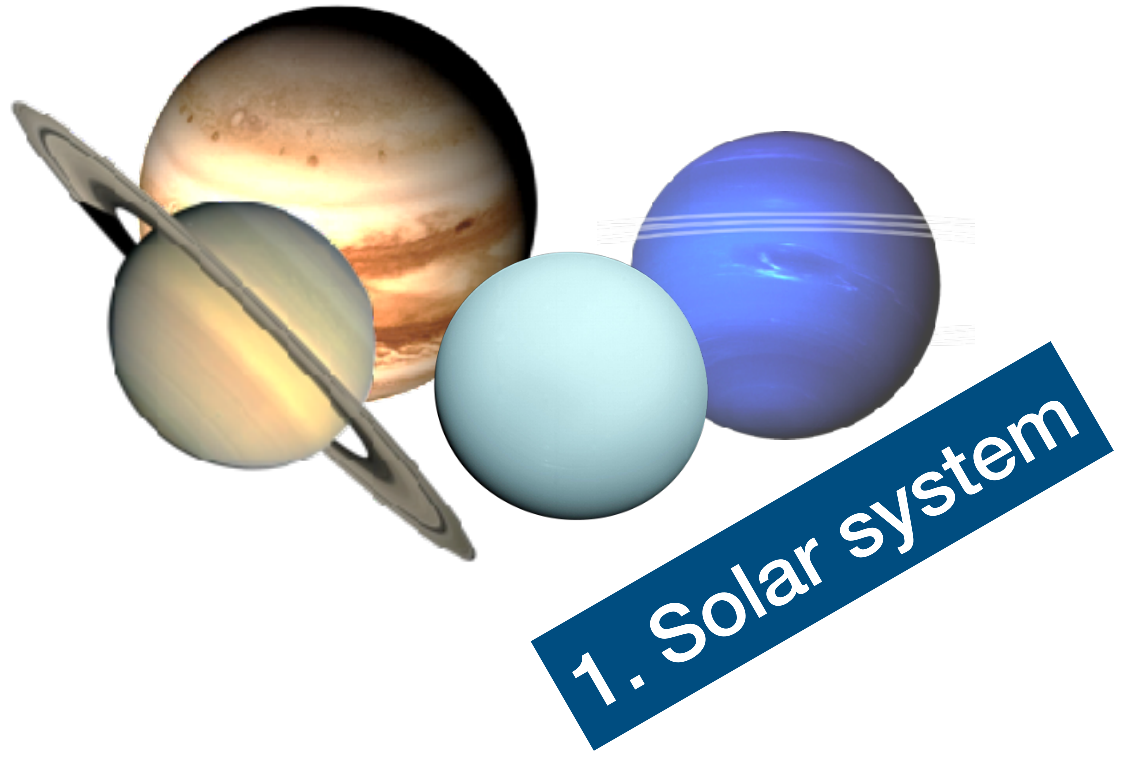
Planet interior structure

Simple is best (if it works…)

Then why not?

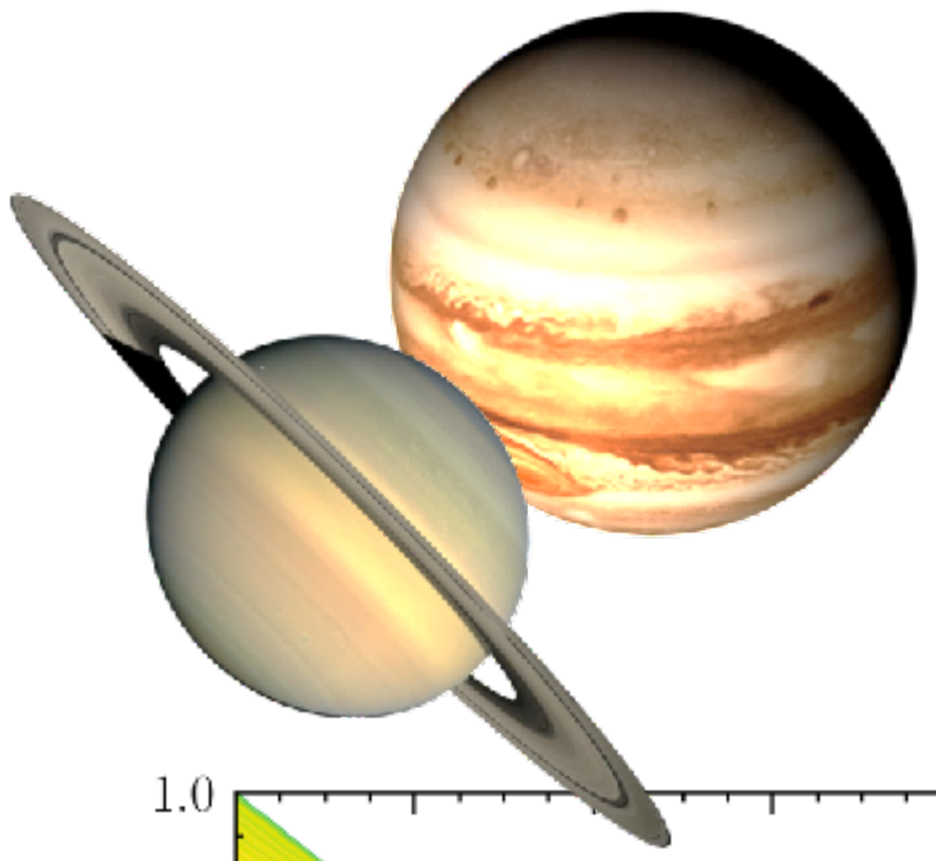
New findings challenge traditional theory:



1. Solar system

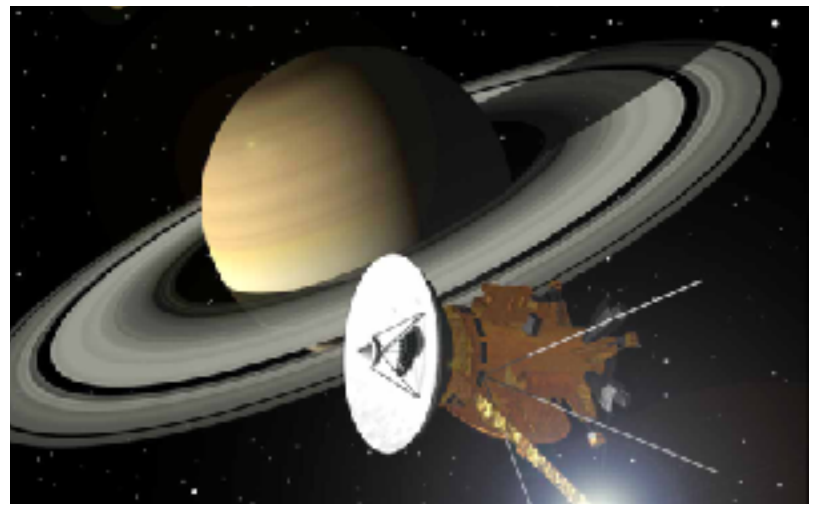
Jupiter and Saturn

Interior structure and evolution



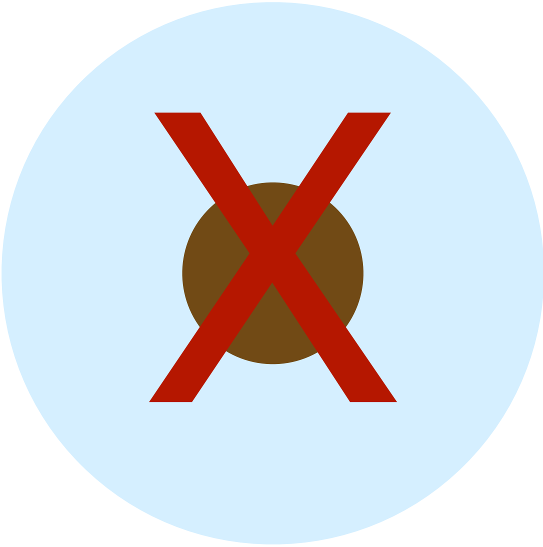
JUNO:

2016 -

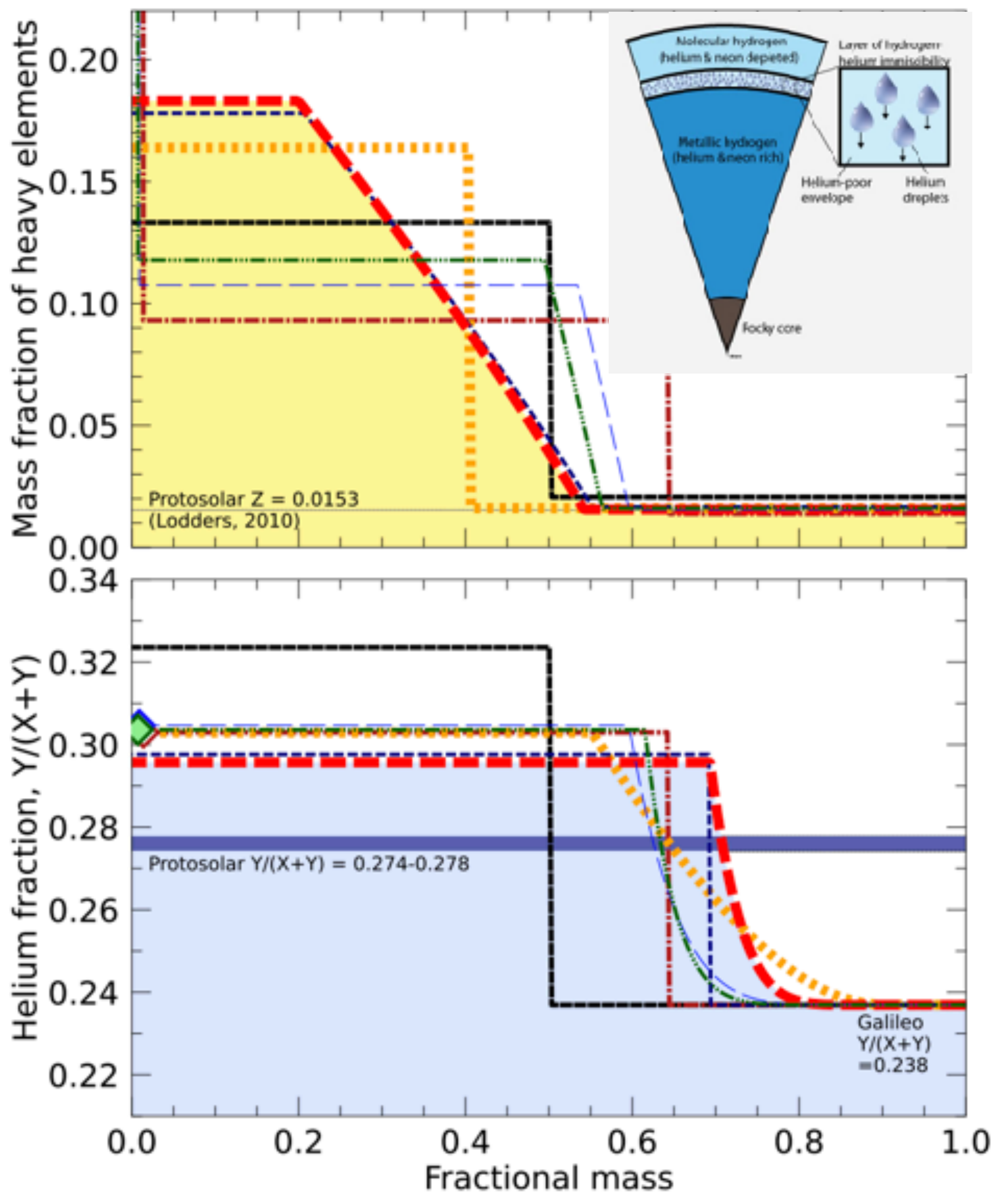


CASSINI:

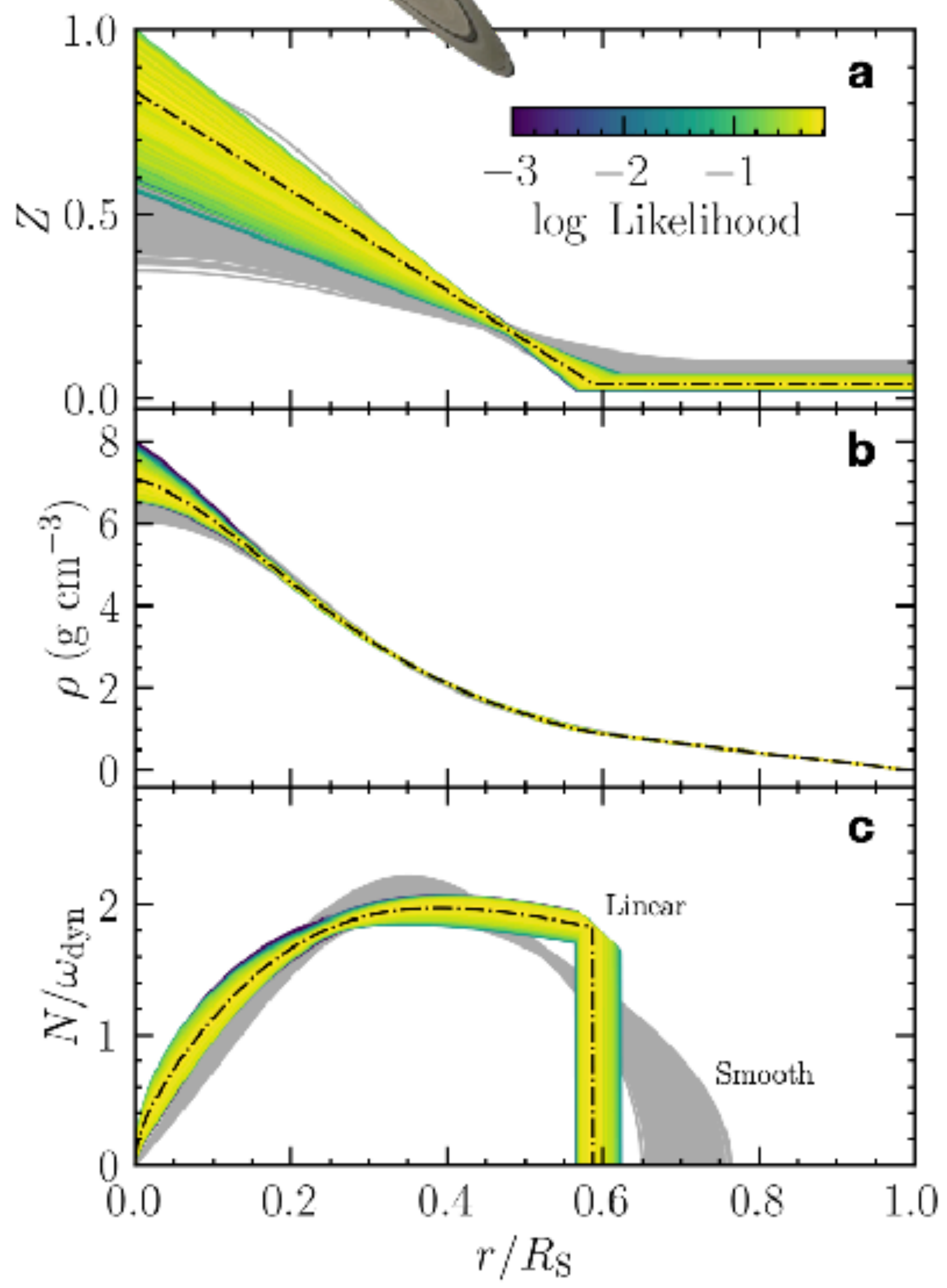
2004 - 2017



Simple core-envelope interior models are not consistent with the measurements by the **JUNO** and **CASSINI** space missions



Militzer & Hubbard 2024

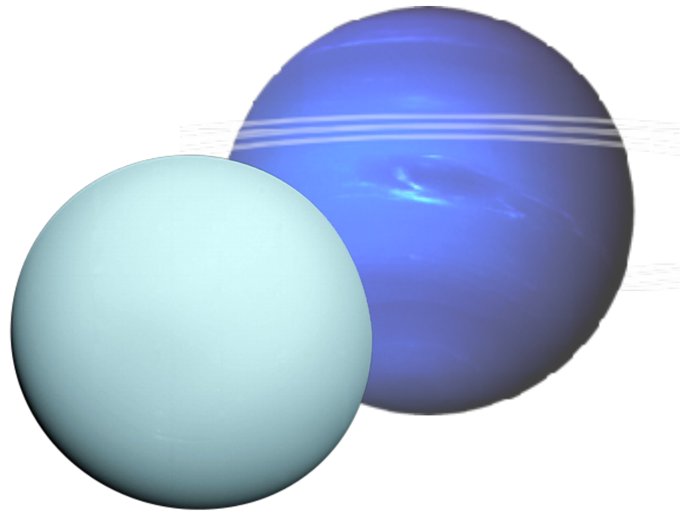


Mankovich et al. 2023

see also: Vazan et al. 2016

Uranus and Neptune

Interior structure



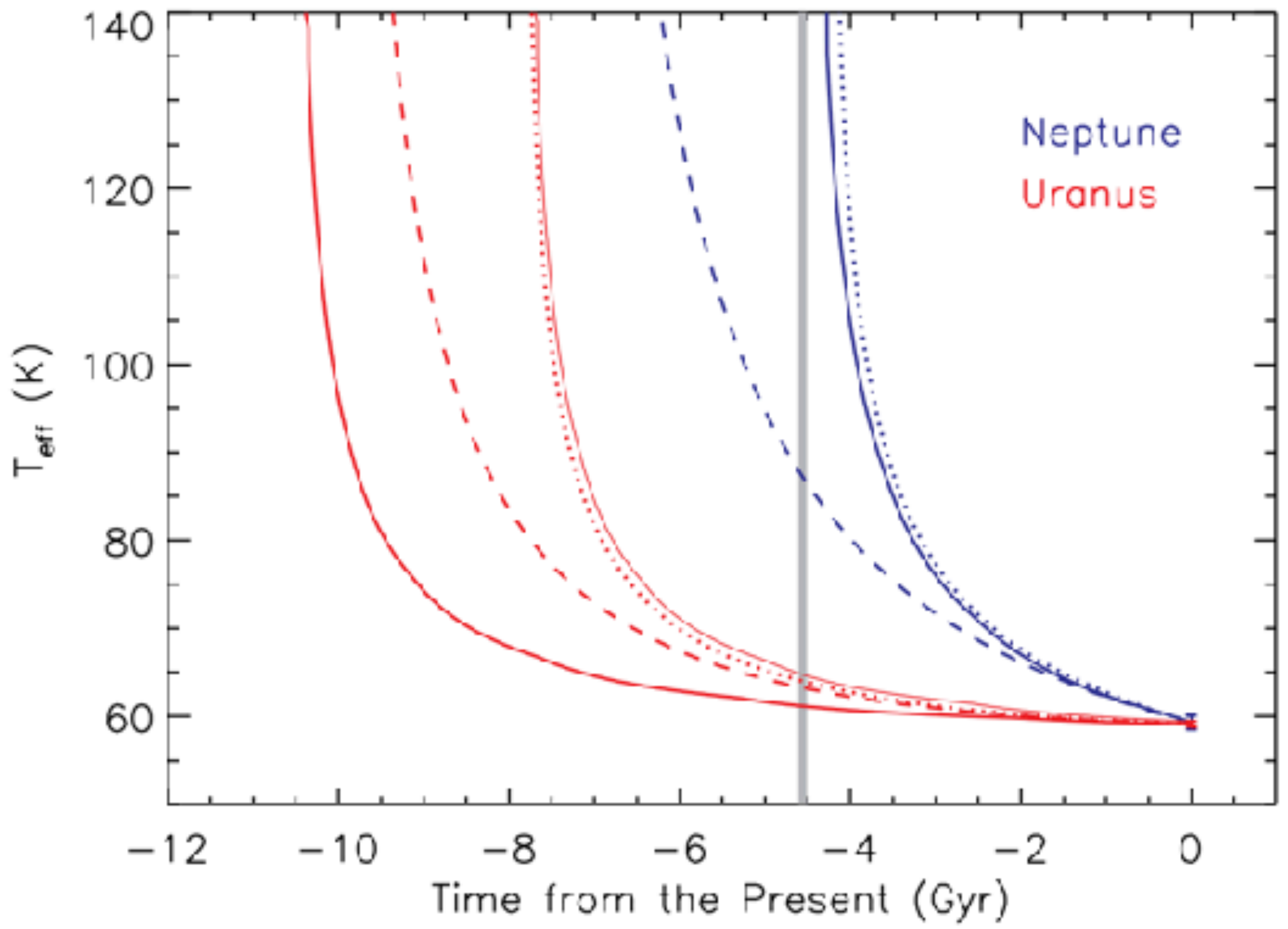
Simple layers (adiabatic) interior model is not consistent with the luminosity of Uranus (Fortney et al. 2011, Nettelmann et al. 2013) and Neptune (Shceibe et al. 2019)

Alternative?

Non-uniform composition distributions (non-adiabatic cooling)

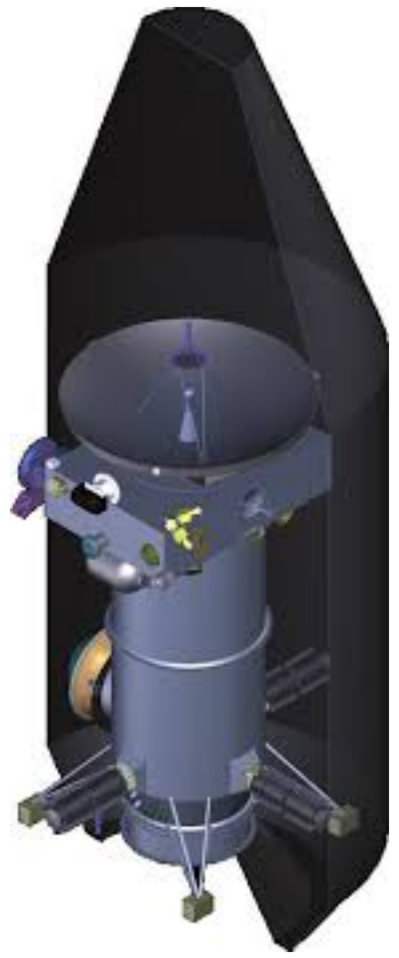
Ledoux convection criterion:

$$\nabla_R > \nabla_A + \nabla_{Ledoux}$$

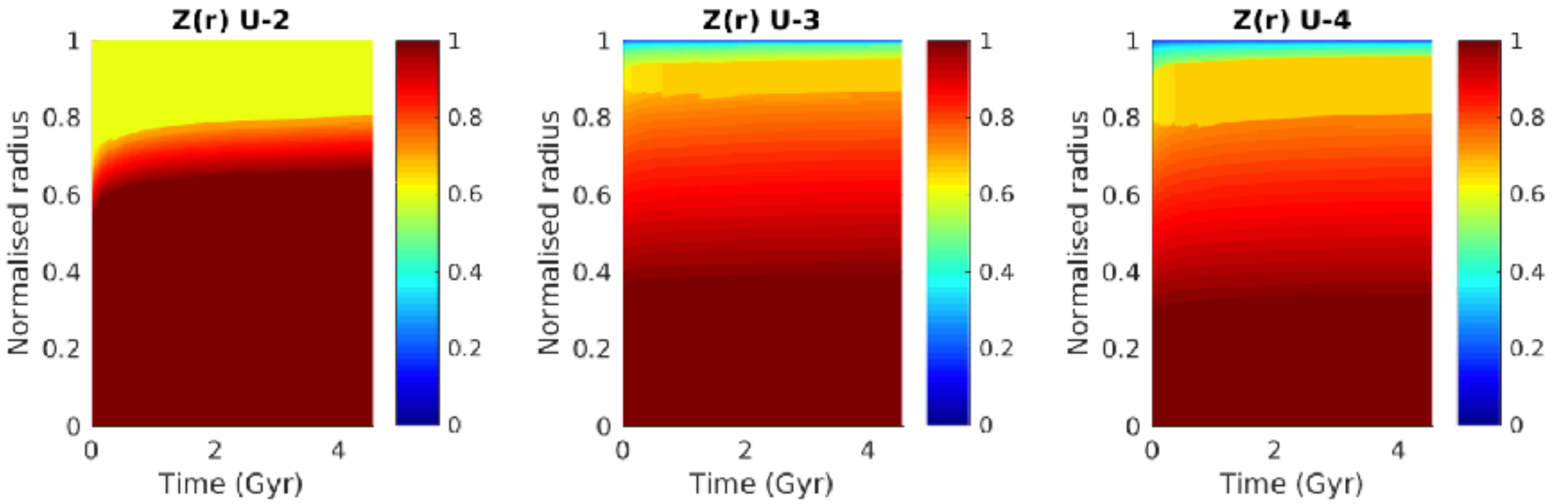


Fortney et al. 2011

Stable composition gradients explain all U&N measurements



UOP
Launch ~ 2032
Arrival ~ 2045

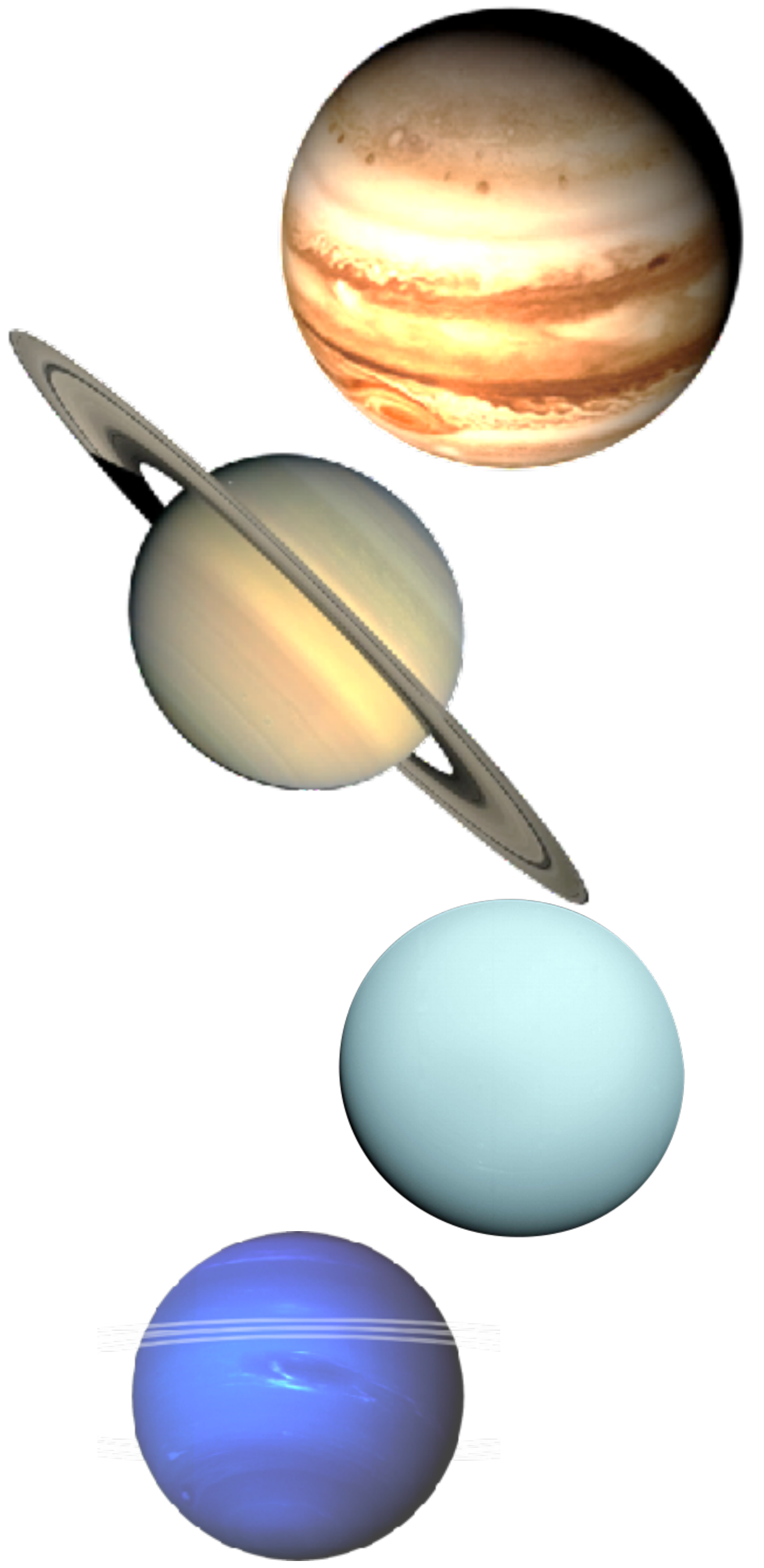


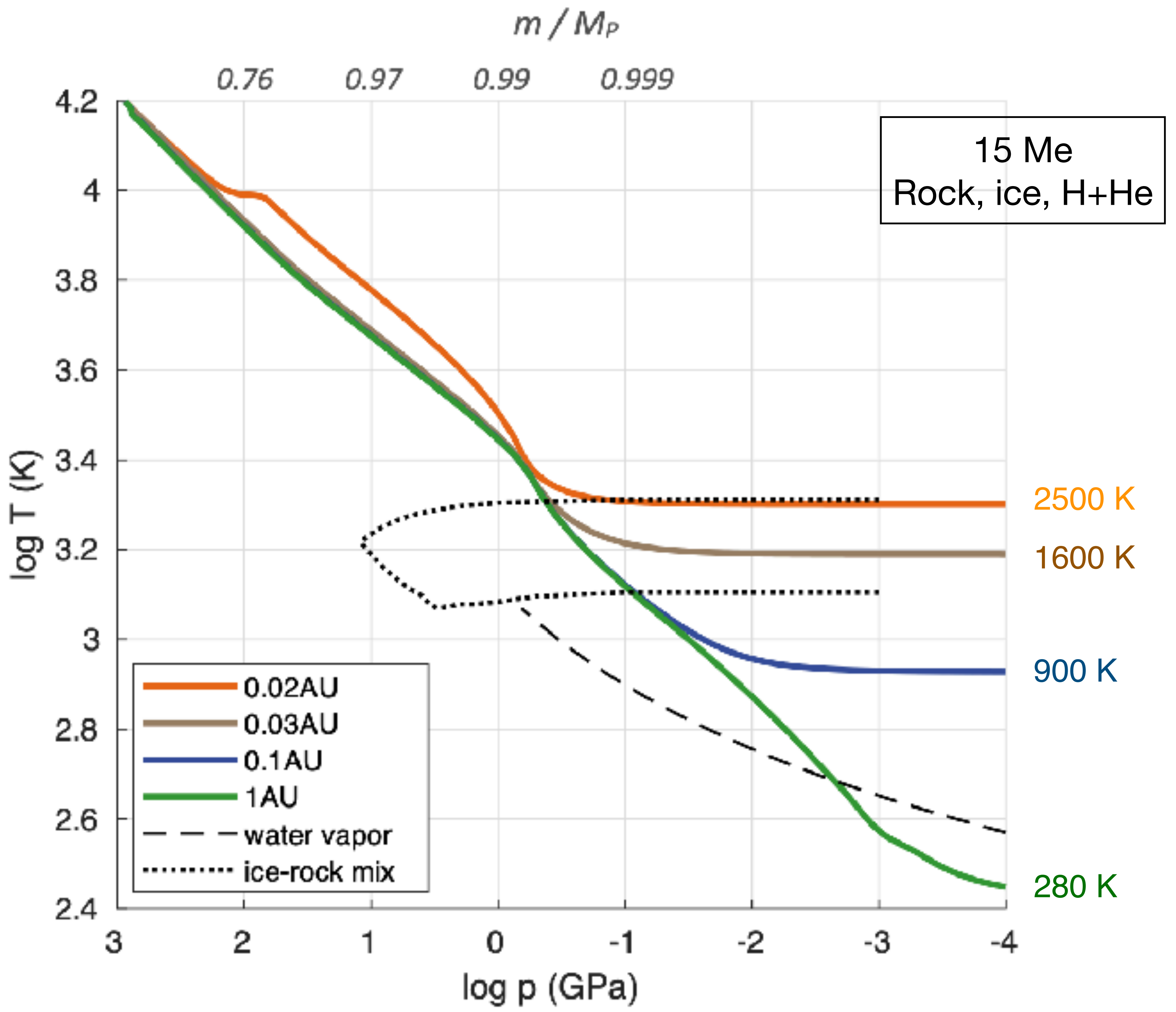
Vazan & Helled 2020

Solar system <-> exoplanets

How the interiors of far-out planets change at close-in orbits?

not much!

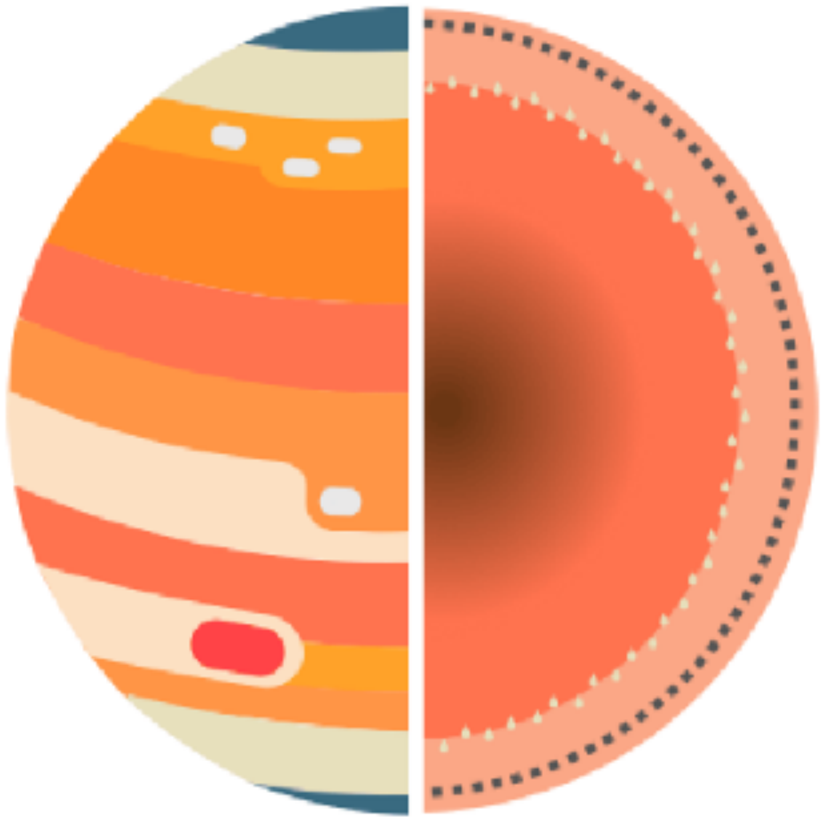




Vazan, Sari, Kessel 2022

Planet interior structure

Simple is best (if it works…)



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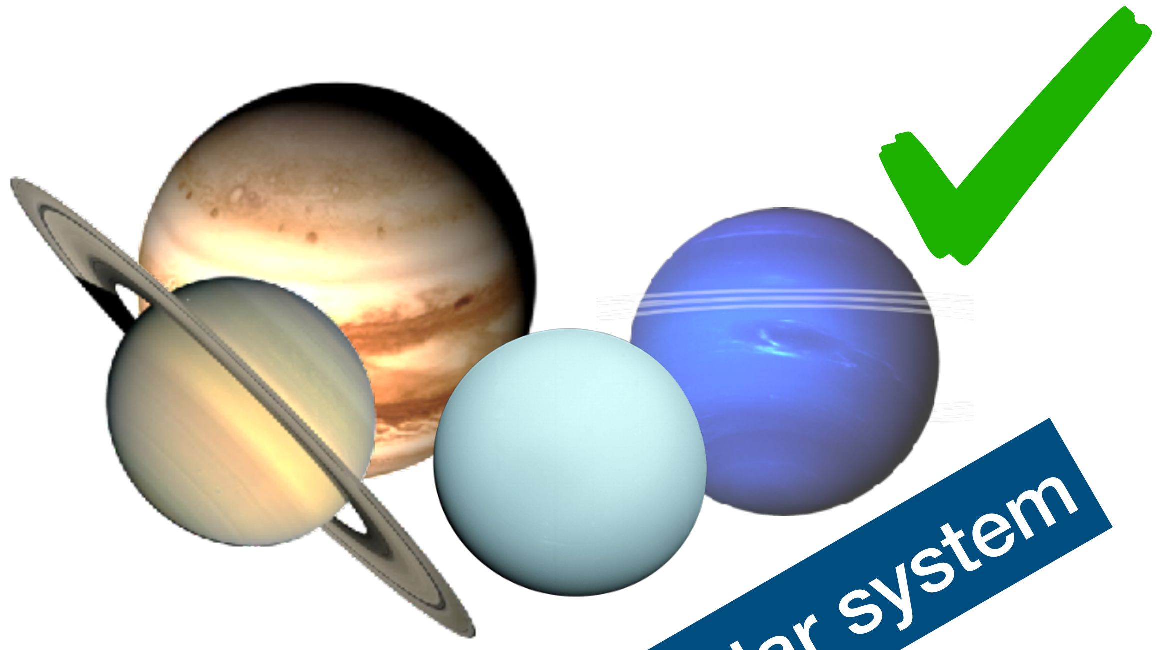
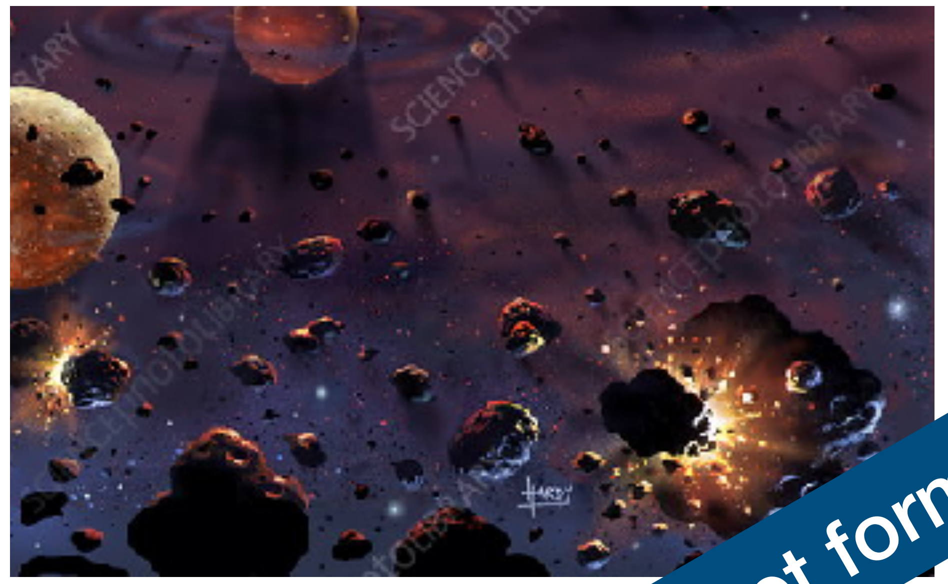


1. Solar system



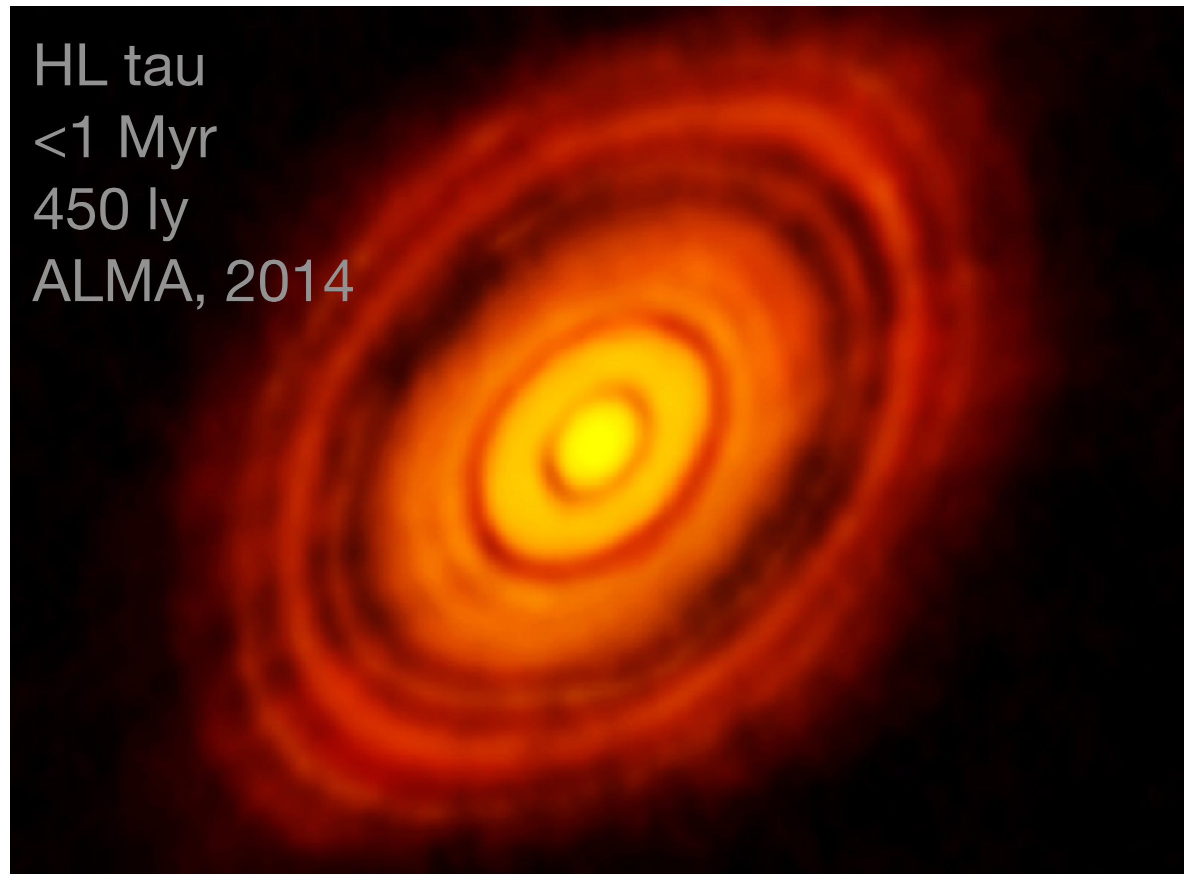
2. Planet formation

3. Material interaction

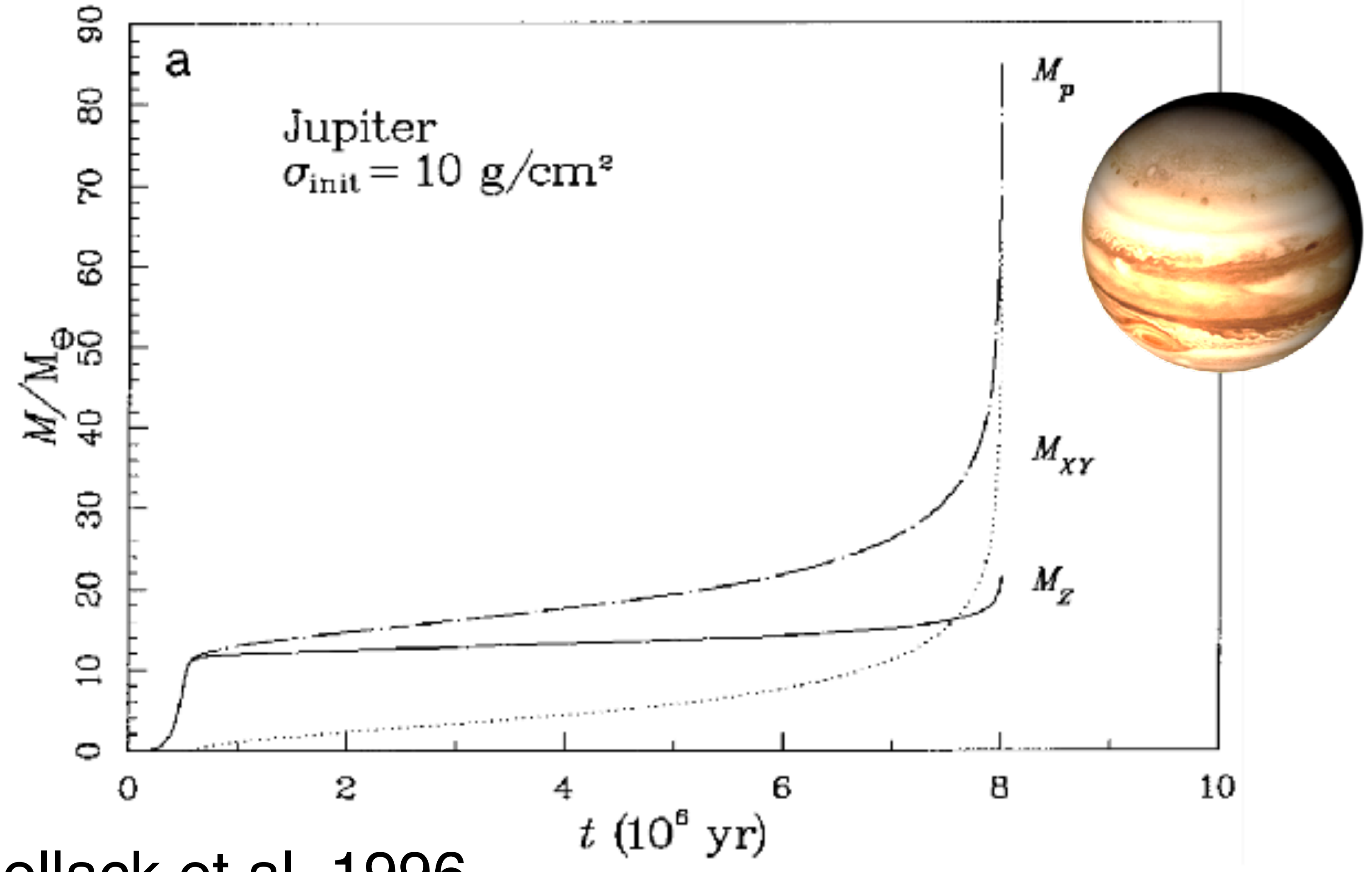
2. Planet formation

Planet Formation

How to make a planet - simple vs. realistic models



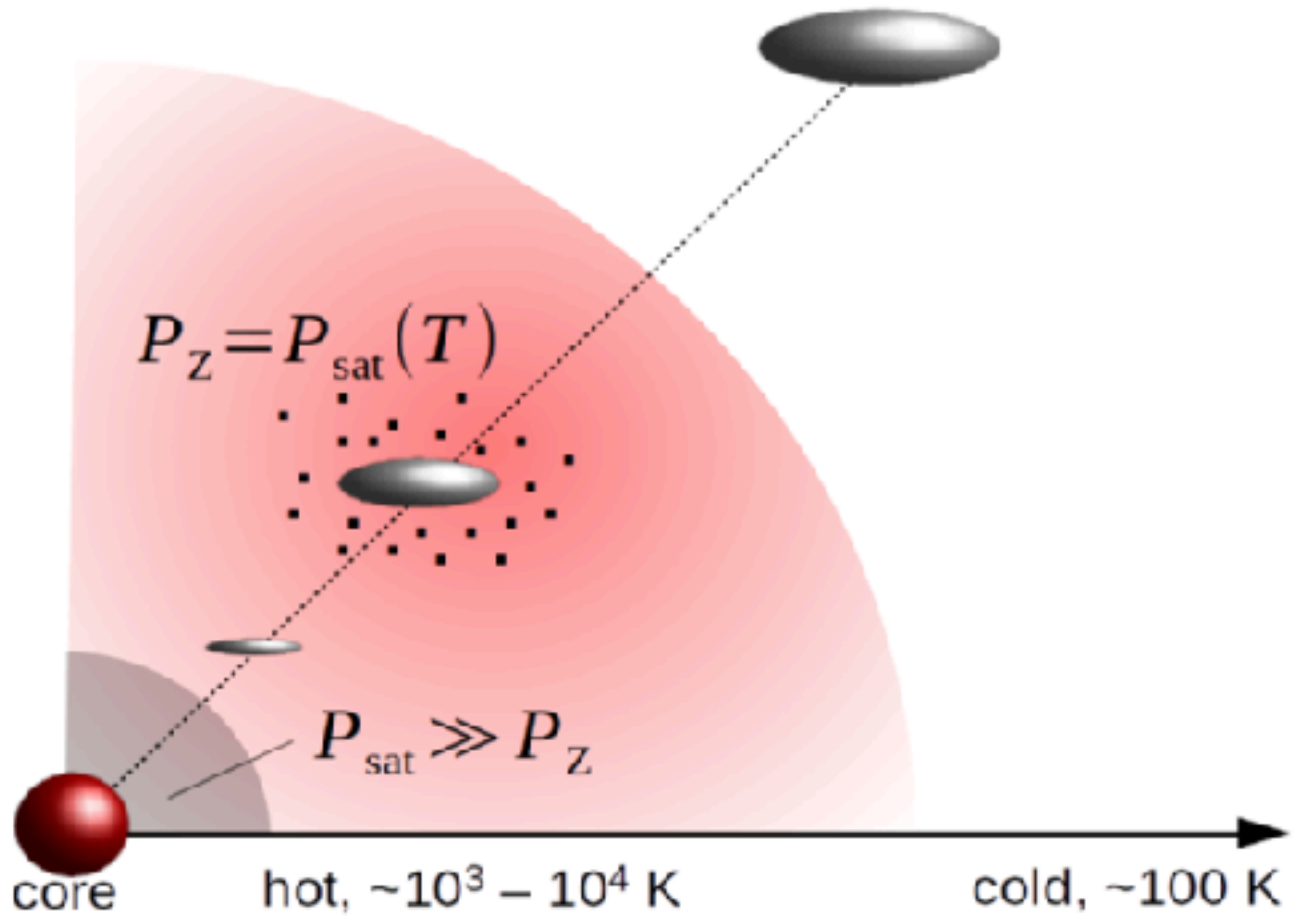
* Gas drag
* Heating
* Breaking



Pollack et al. 1996

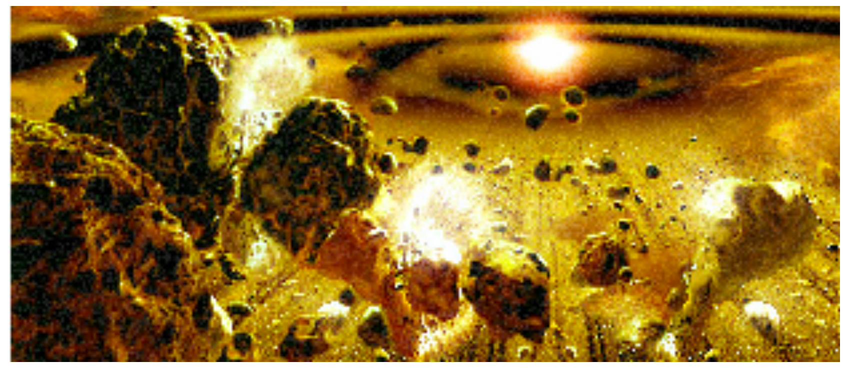
Core Accretion

Ablation of metals (ices & rocks) in the growing envelope



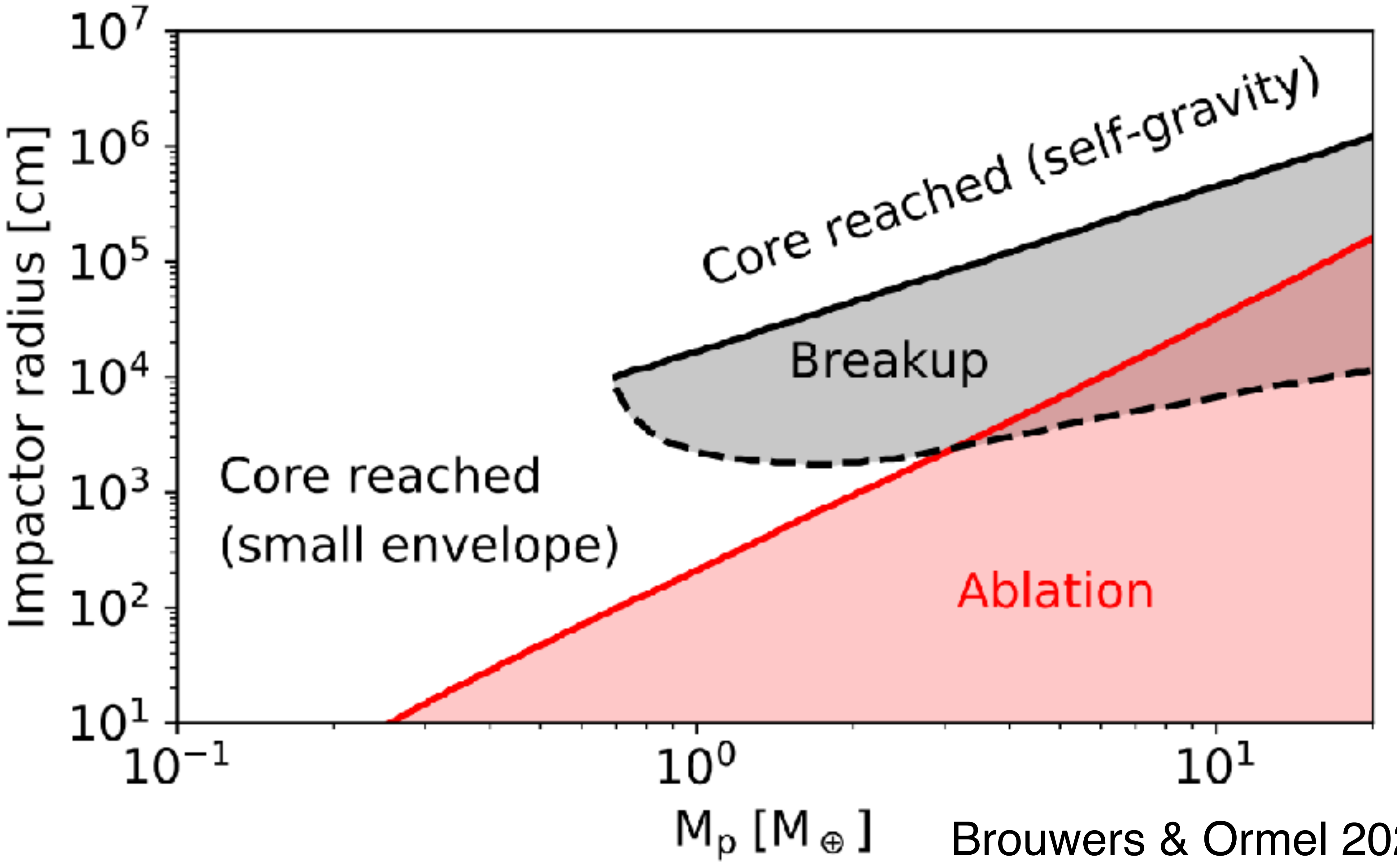
Brouwers, Vazan, Ormel 2018

Podolak et al. 1988
Mordasini et al. 2006
Iaroslavitz & Podolak 2007
Mordasini et al. 2015
Pinhas et al. 2016
Bodenheimer et al. 2018
Valletta & Helled 2019
Valletta & Helled 2020
Steinmeyer et al. 2023



Planetesimals = km solids

Pebbles = mm-cm solids



Brouwers & Ormel 2020

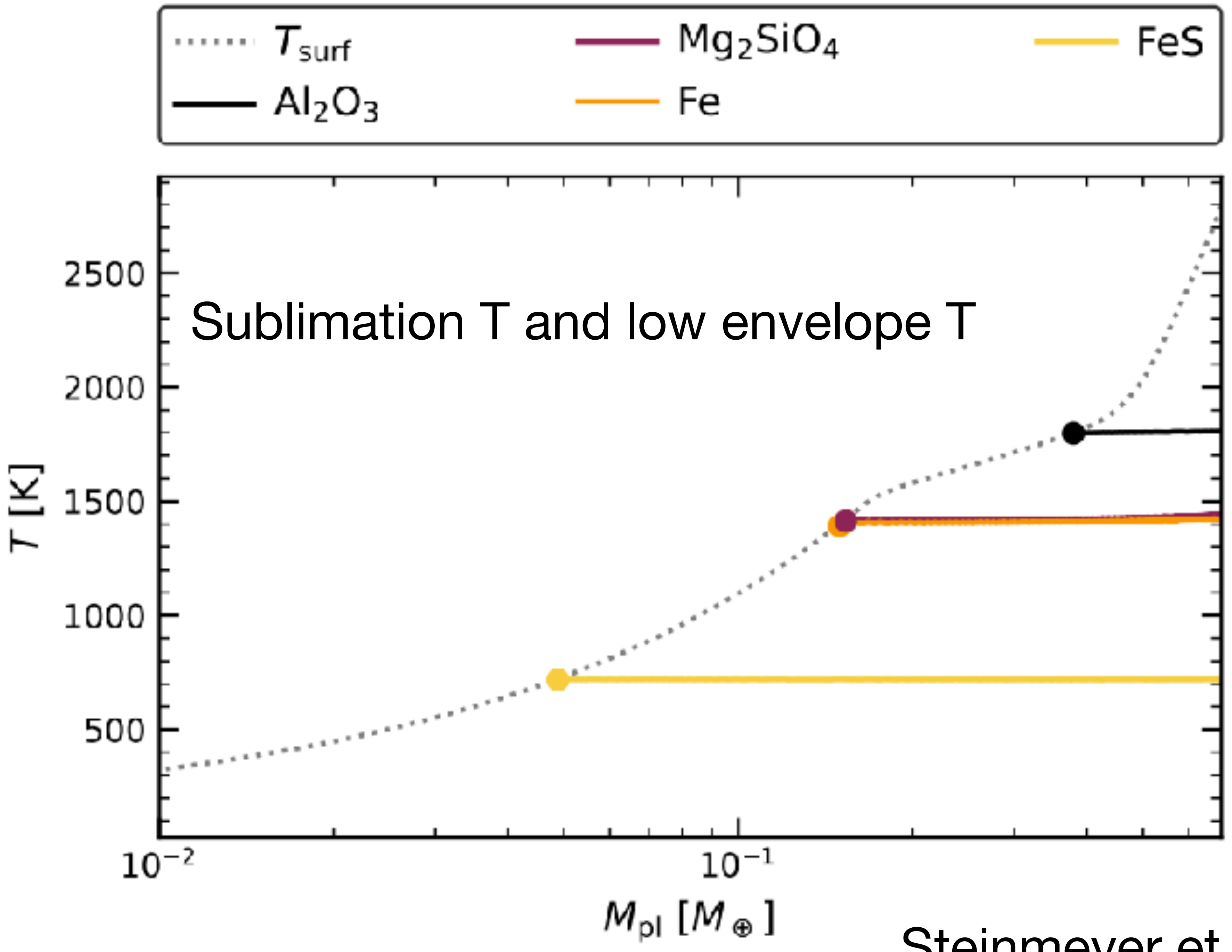
Most of the rocky pebbles end up in the envelope in the form of silicate vapor

Polluted envelopes as a natural outcome of planet formation for planets > 2 Me

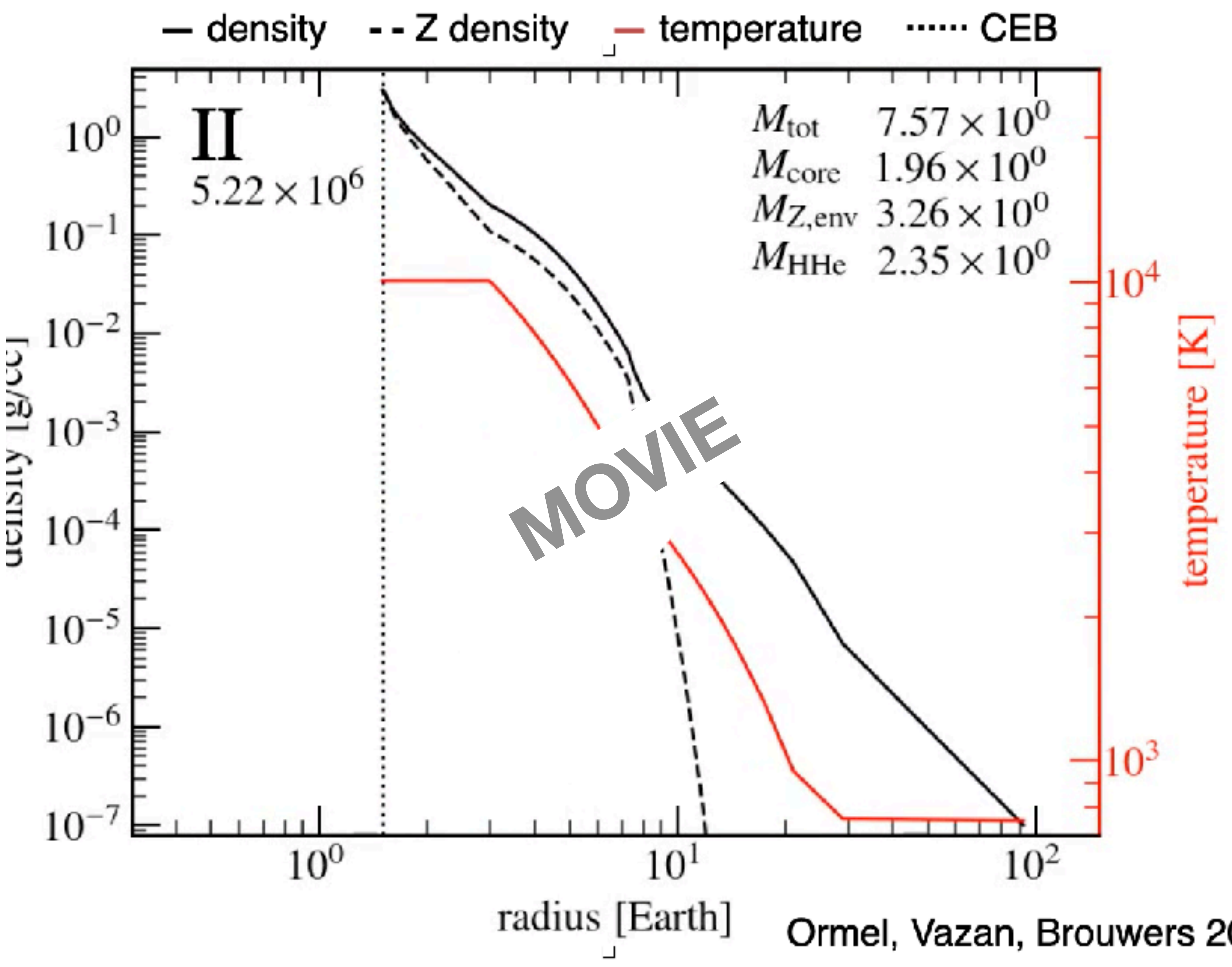
Planet formation - interior perspective

Pebble Accretion

$$P_{\rm vap}^{\rm SiO_2} = \exp\left[a_0 - \frac{a_1}{T + a_2}\right],$$



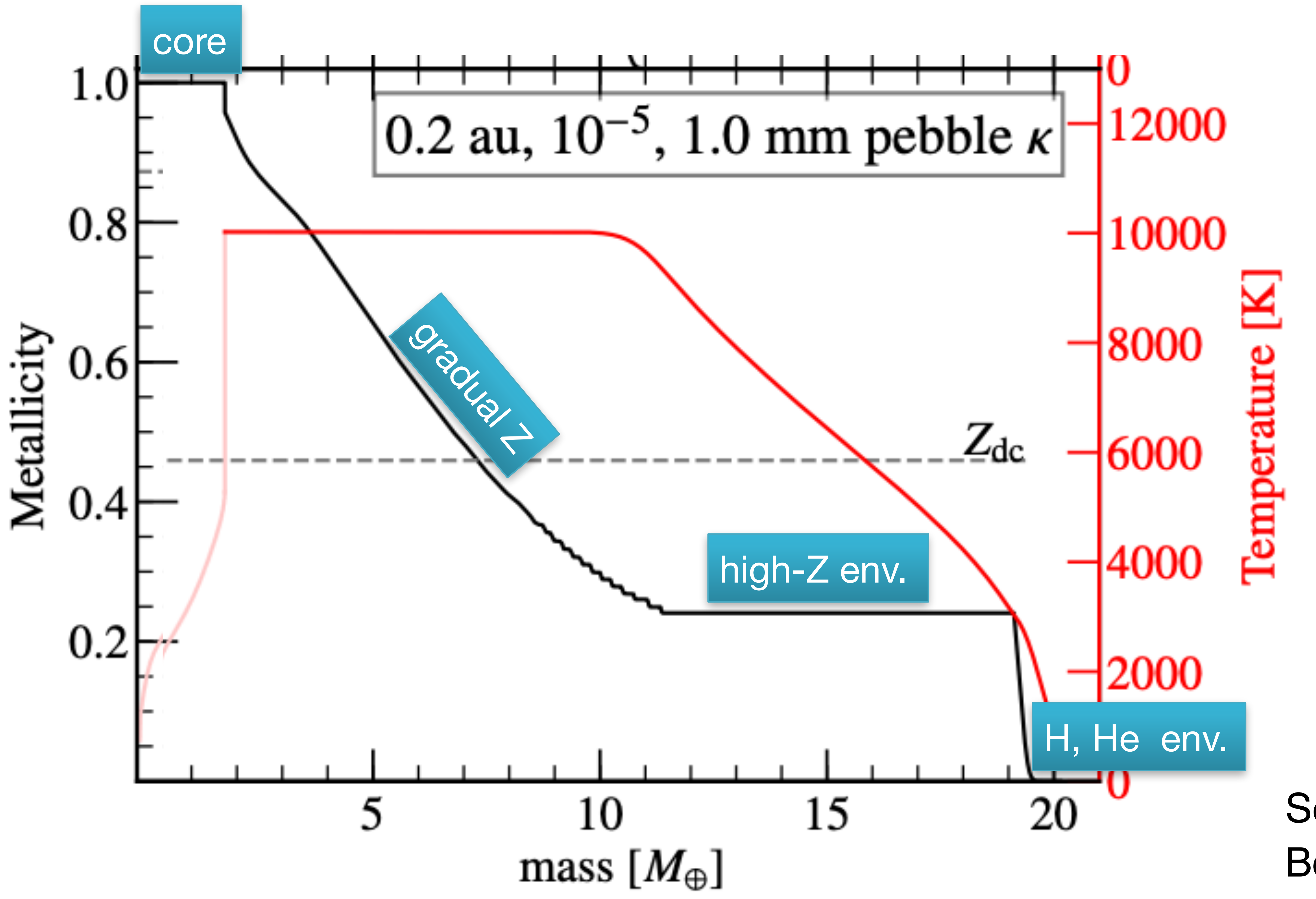
Steinmeyer et al. 2023



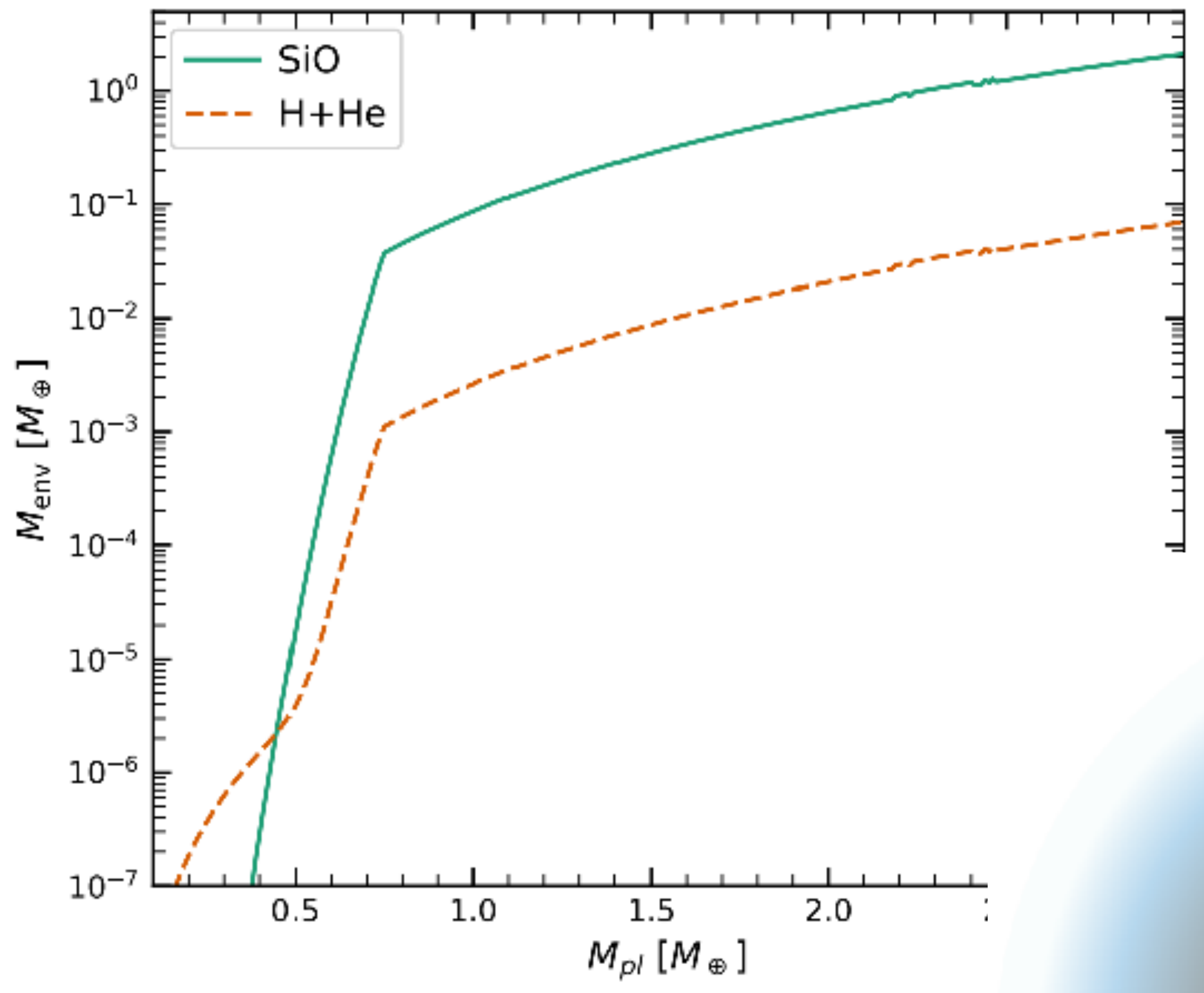
Ormel, Vazan, Brouwers 2021

Core Accretion

Composition gradients as a natural outcome of planet formation

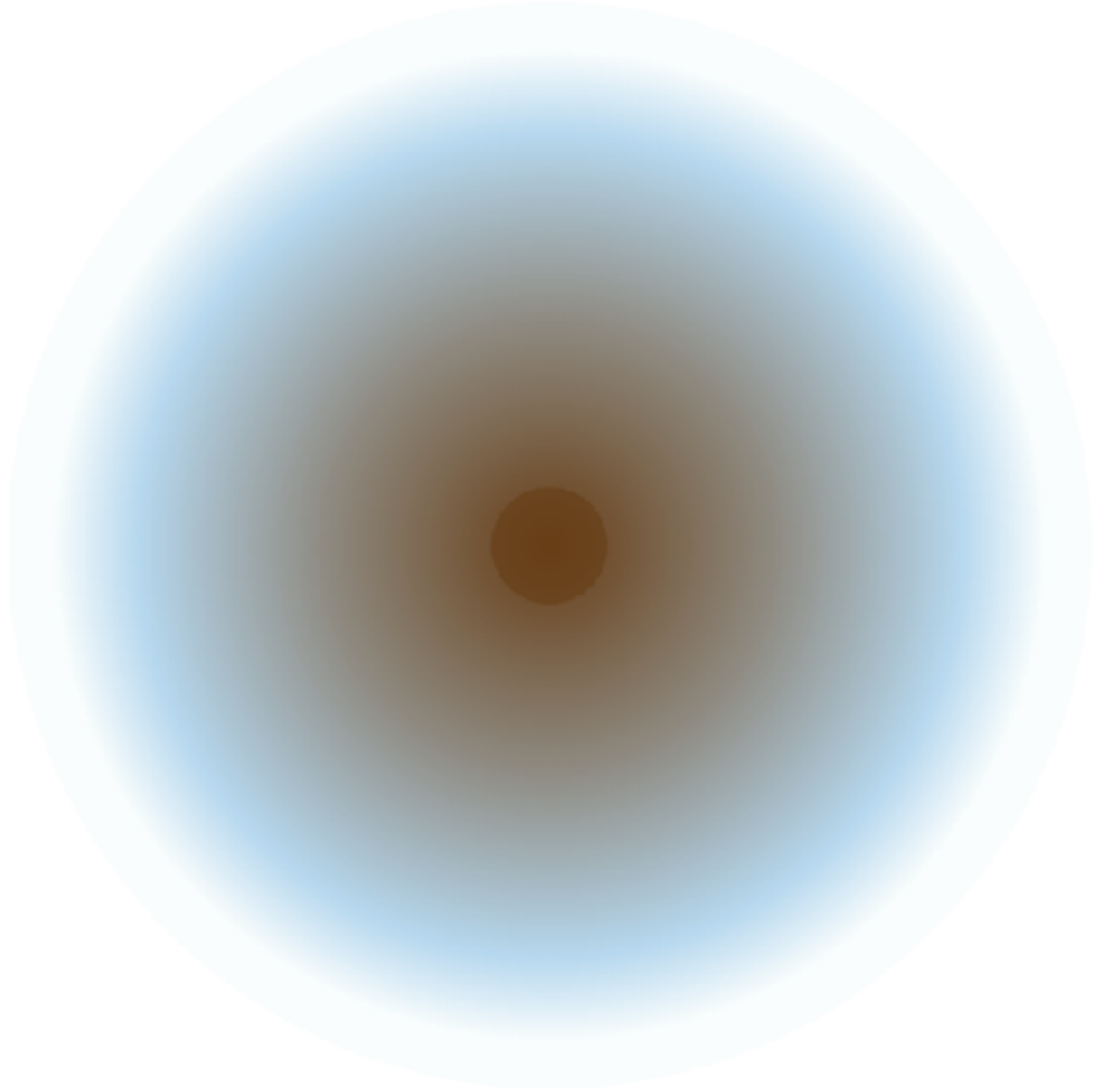


Ormel, Vazan, Brouwers 2021



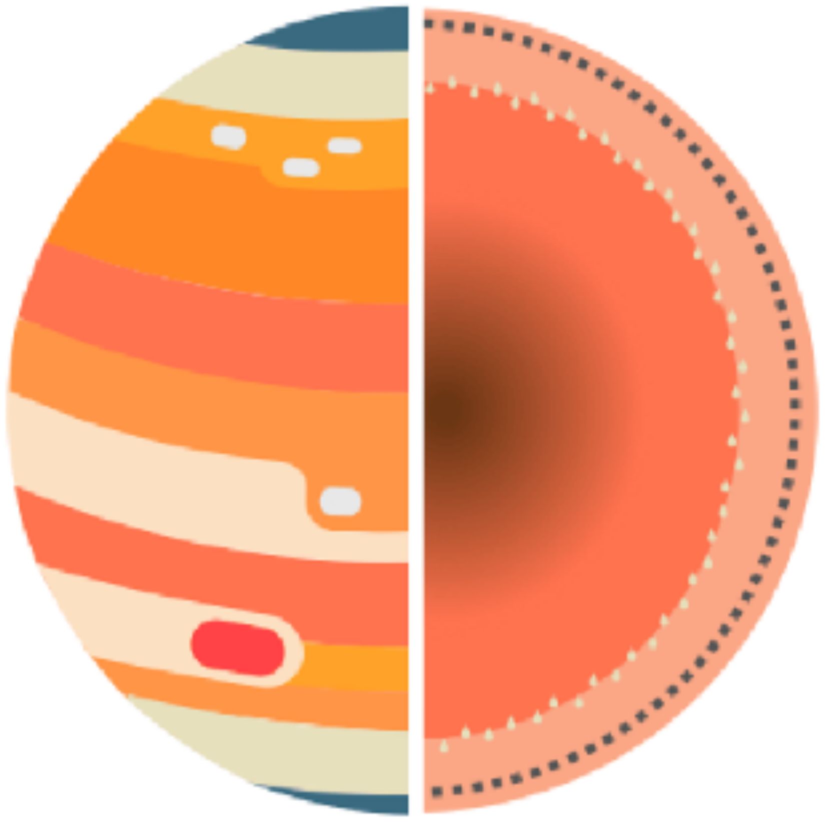
Steinmeyer & Johansen 2024

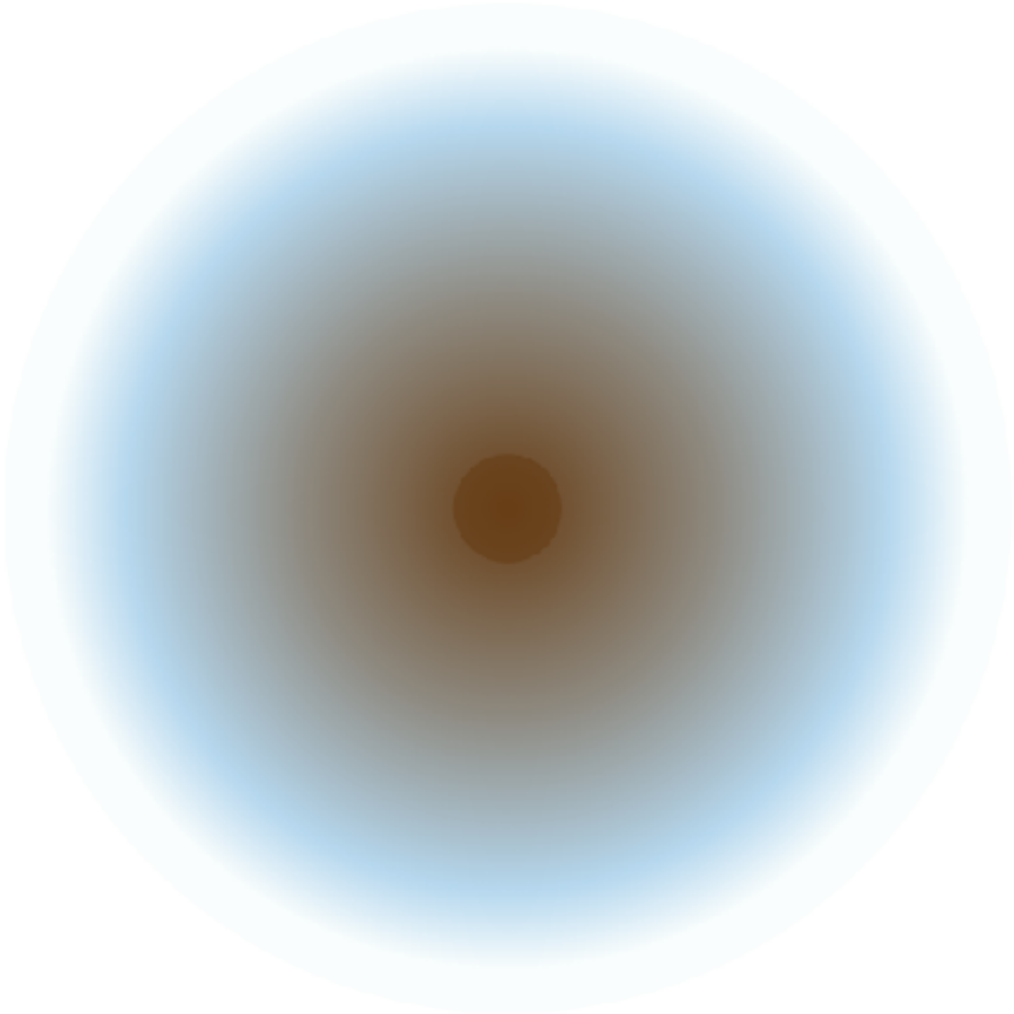
See also:
Bodenheimer et al. 2018
Valletta & Helled 2020
Meisner et al. 2024



Planet interior structure

Simple is best (if it works…)





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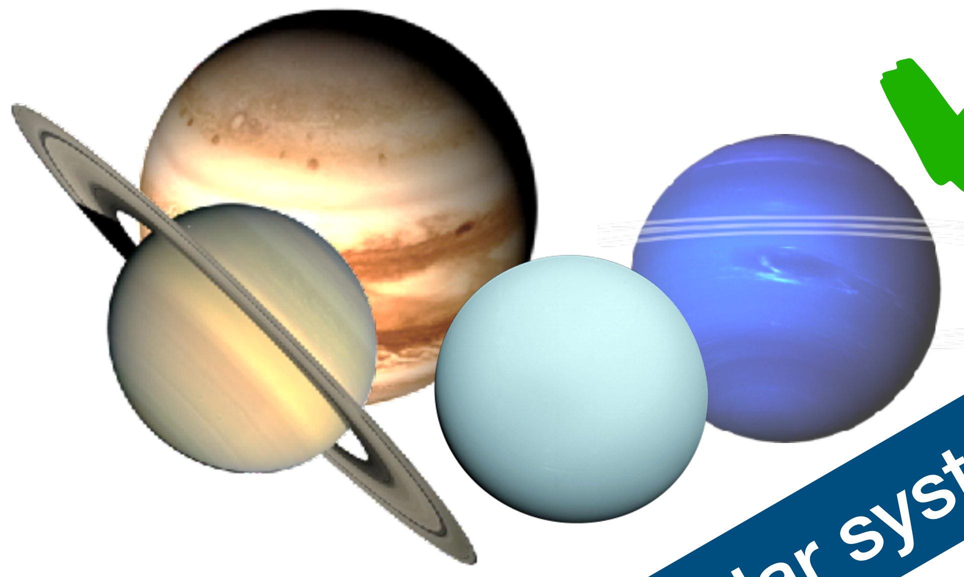

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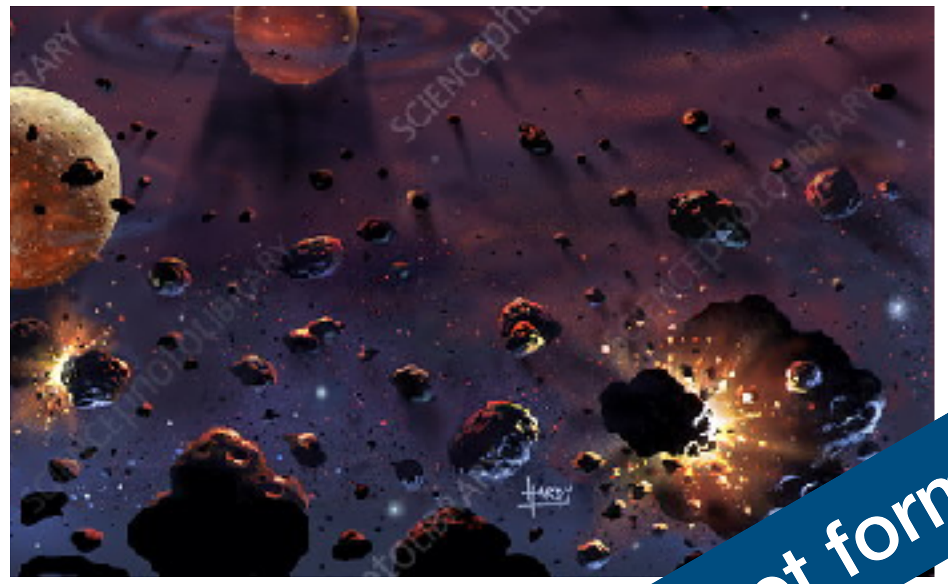


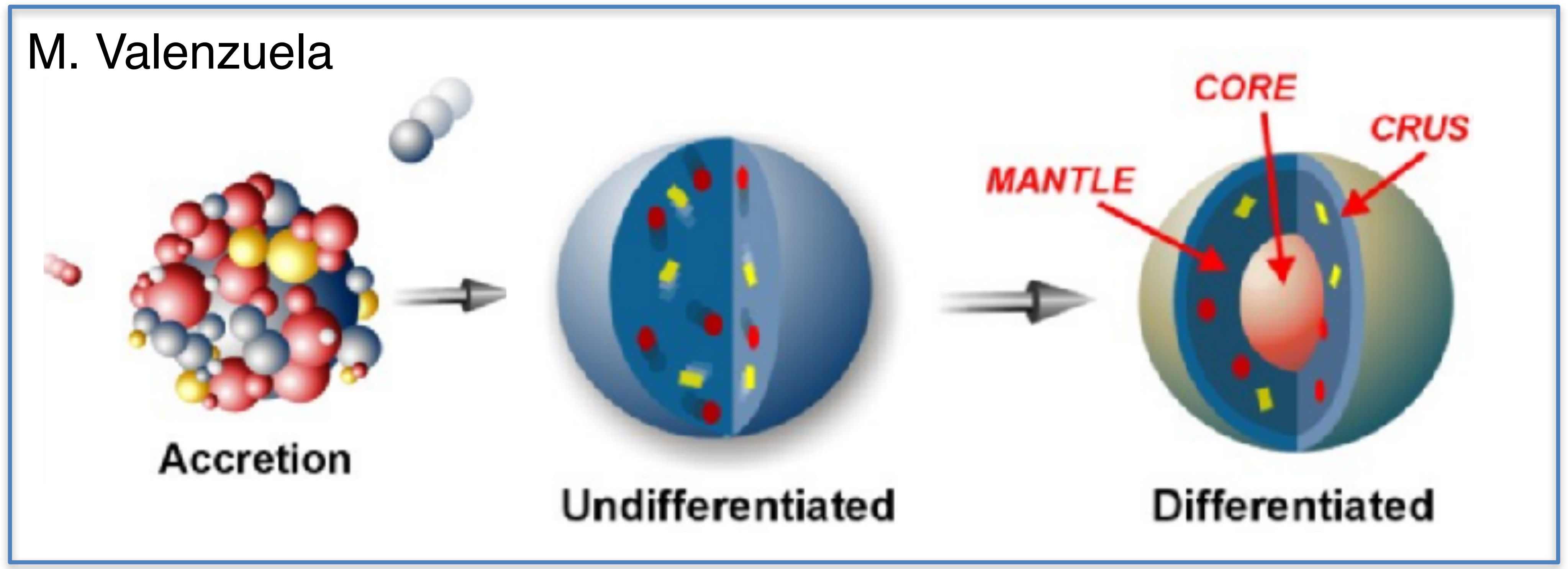
2. Planet formation

3. Material interaction

3. material interaction

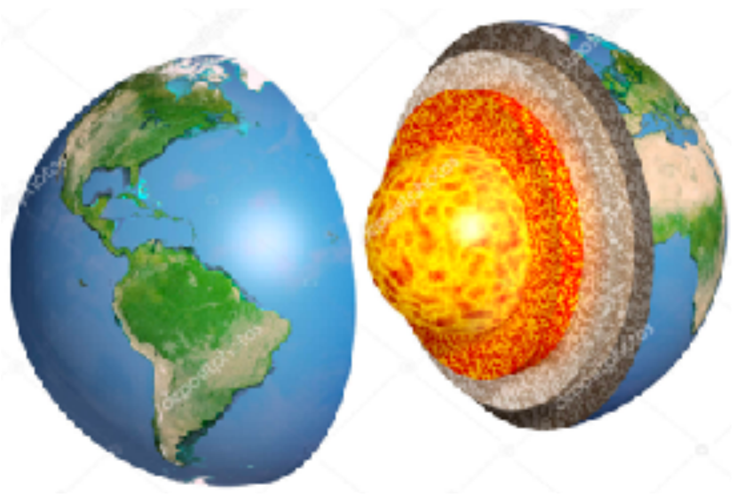
Interior evolution

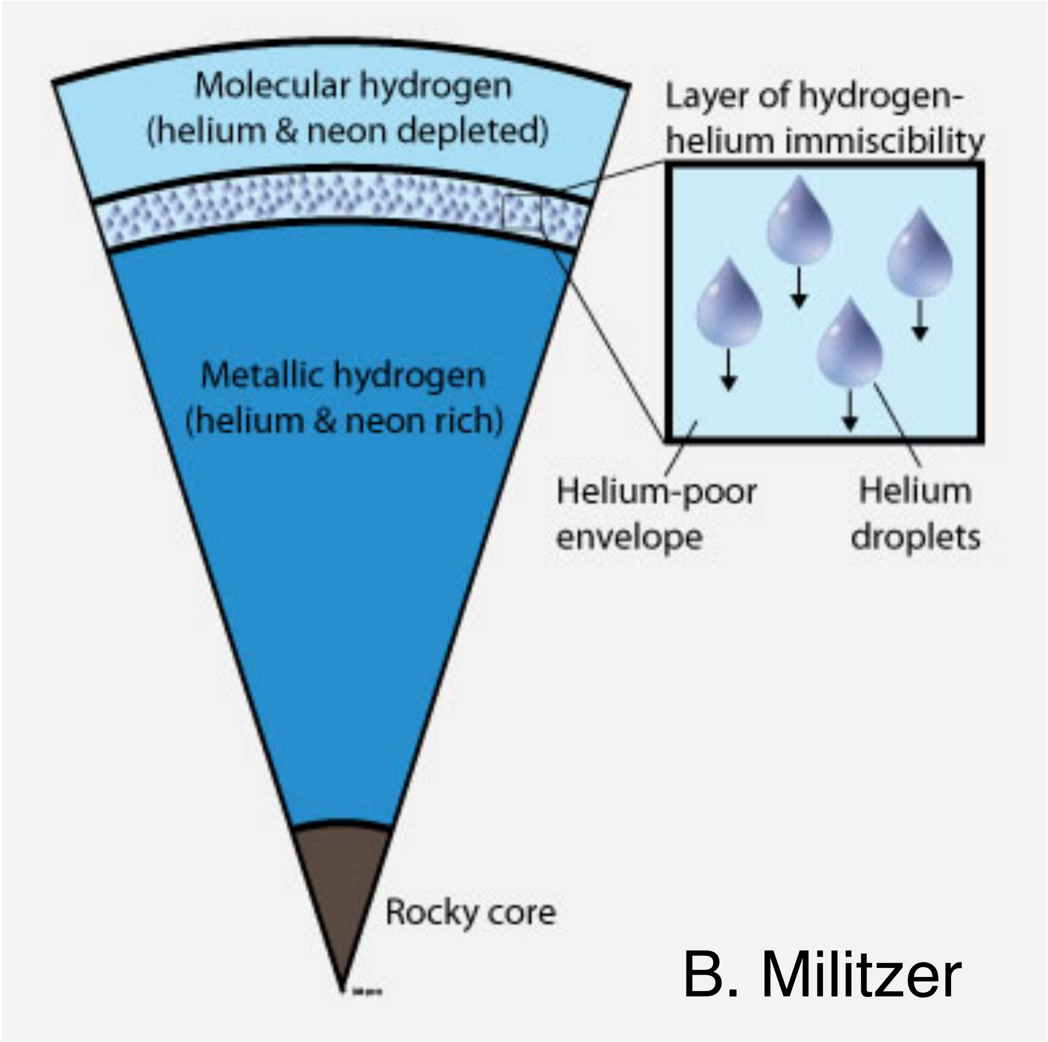
Differentiation



Phases:

1.accretion
2.cooling
3.material demixing
4.density difference
5.differentiation (low viscosity)

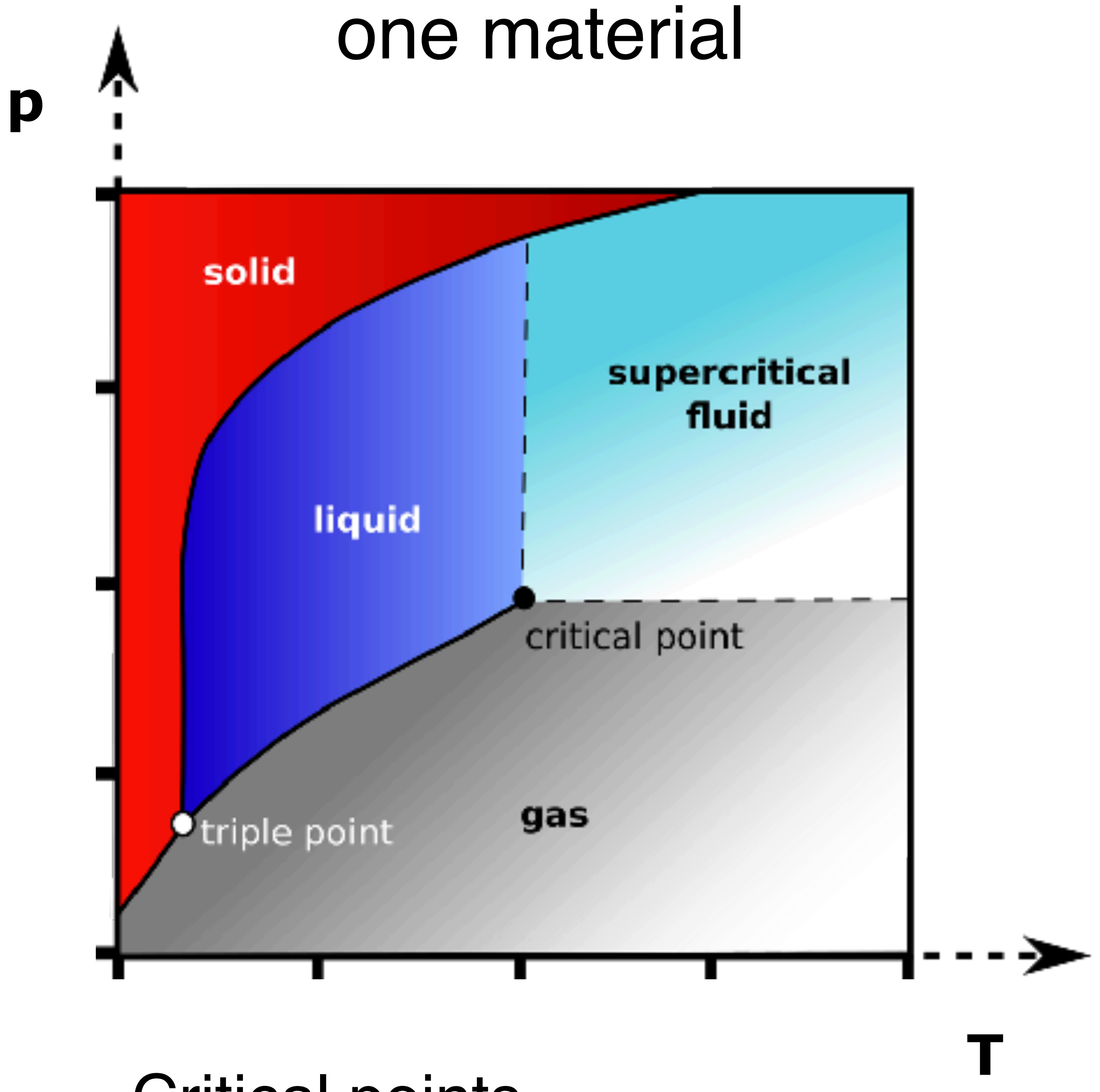




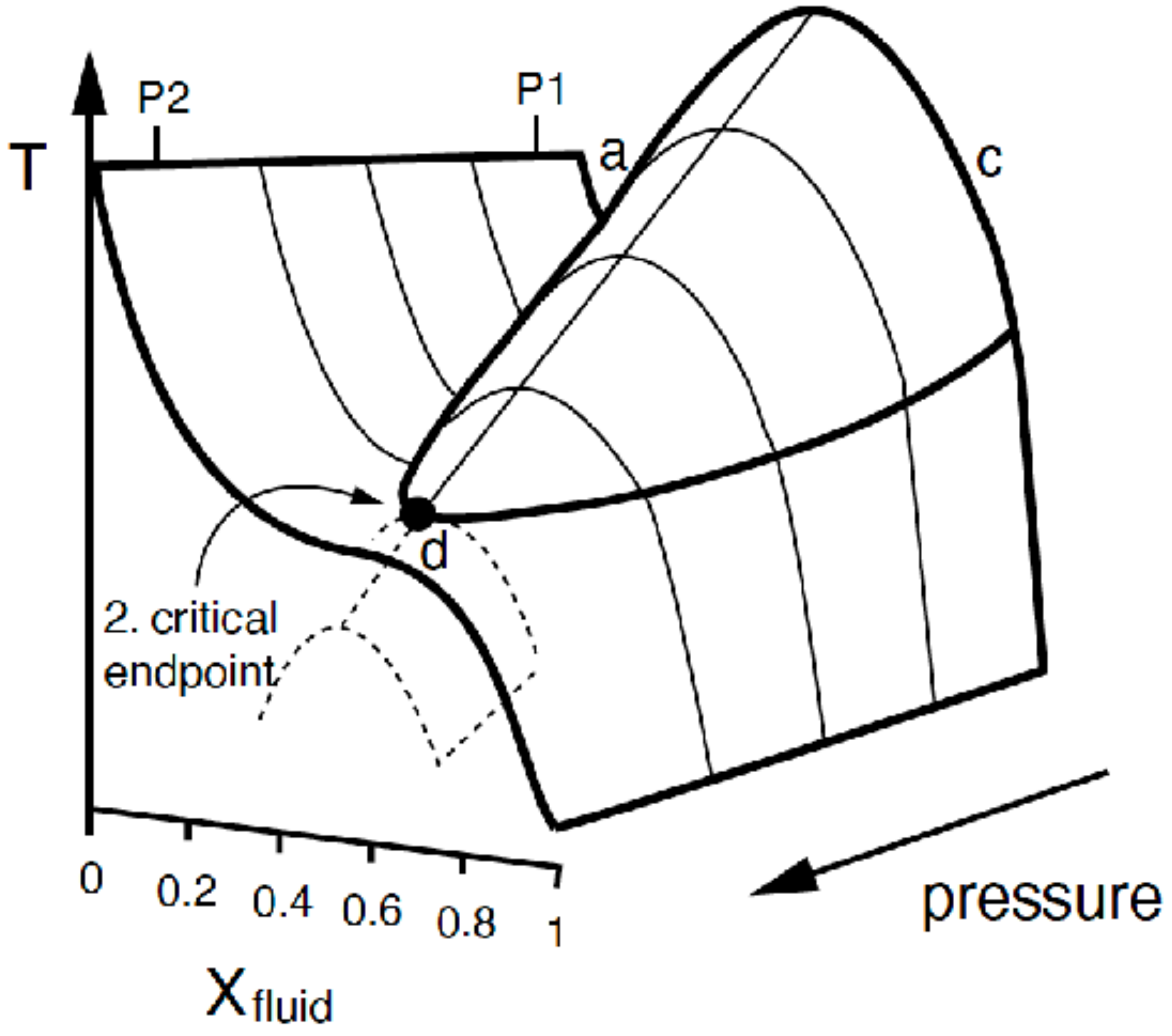
Interior differentiation depends on material tendency to demix (thermodynamically)

Material interaction in lab

one material

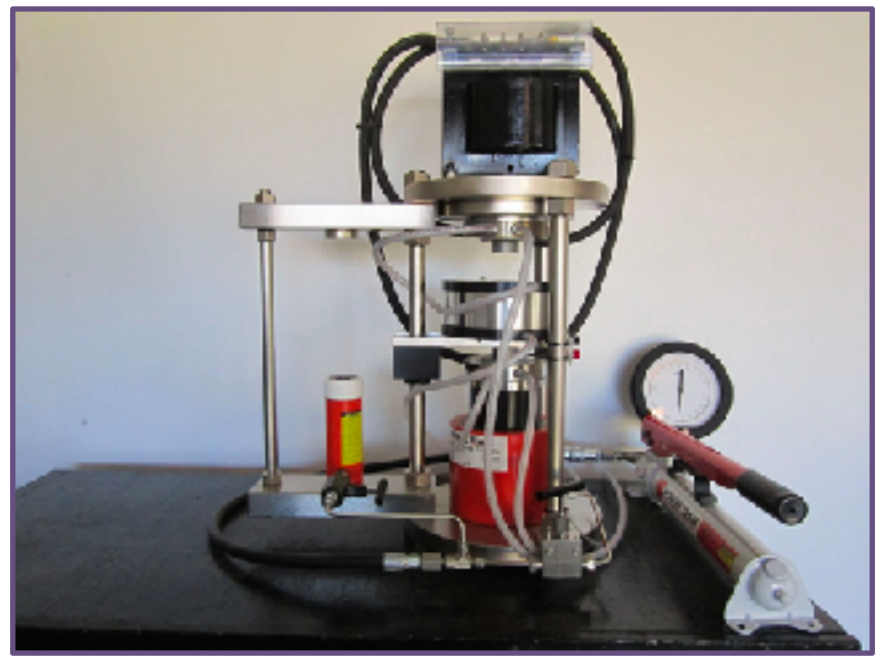


Mixture

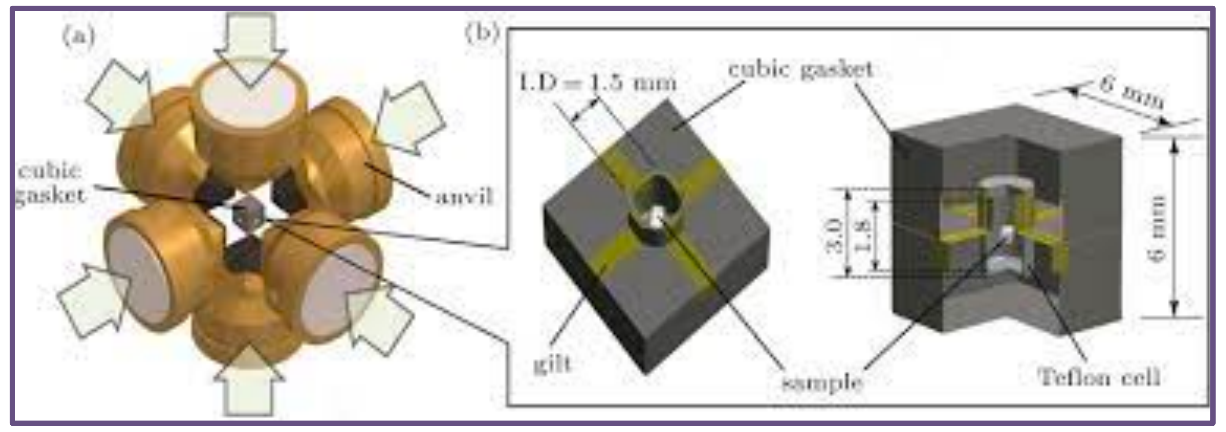


Stalder et al. 2000

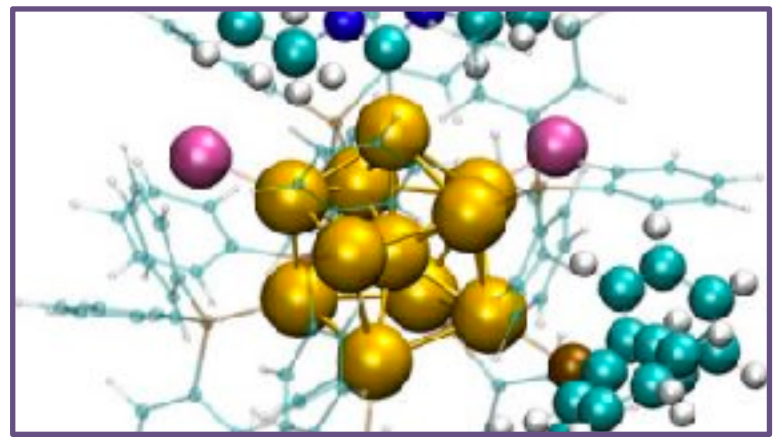
Piston-cylinder apparatus <10 GPa



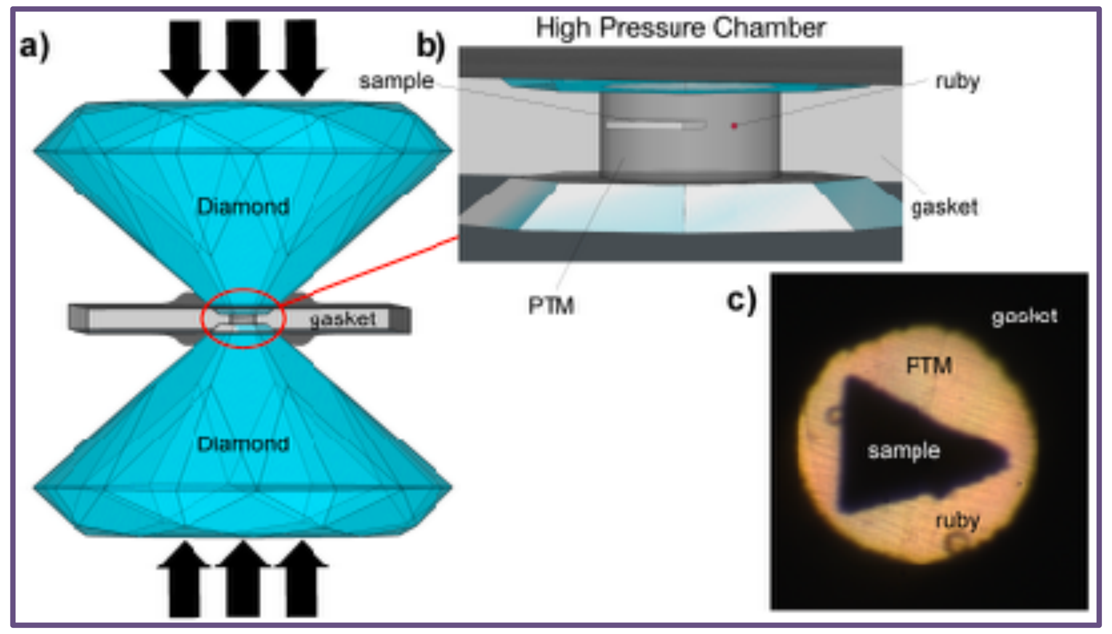
Multi anvil press 10s GPa



Molecular dynamics simulations



Diamond anvil cell 100s GPa



Critical points

H_2O: 647K, 22MPa

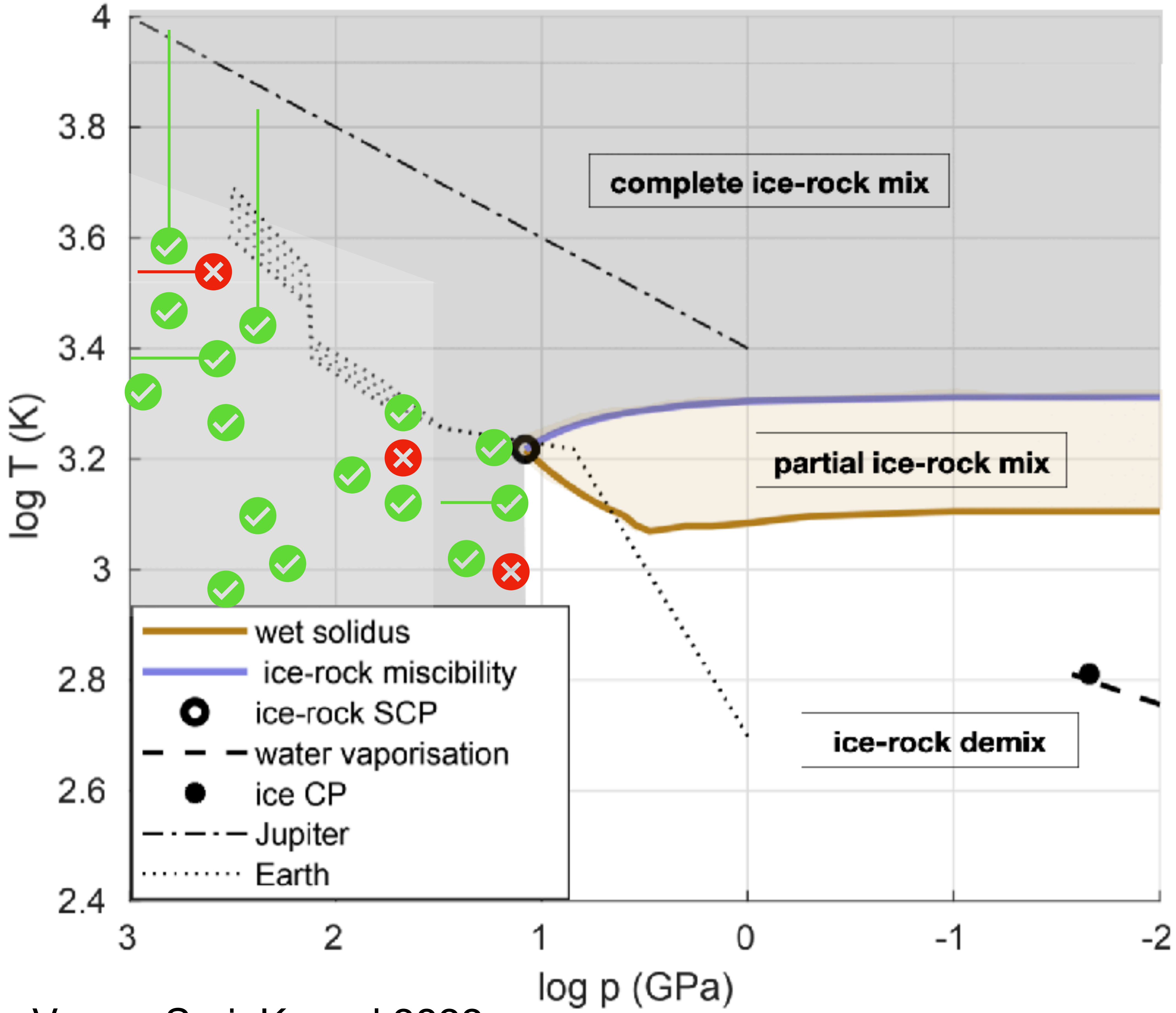
SiO_2: ~5400K, 0.2 GPa

Fe: ~8500K, 0.5 GPa

Supercritical fluids are miscible in each other

Material interaction P-T space

Miscibility of water and rock

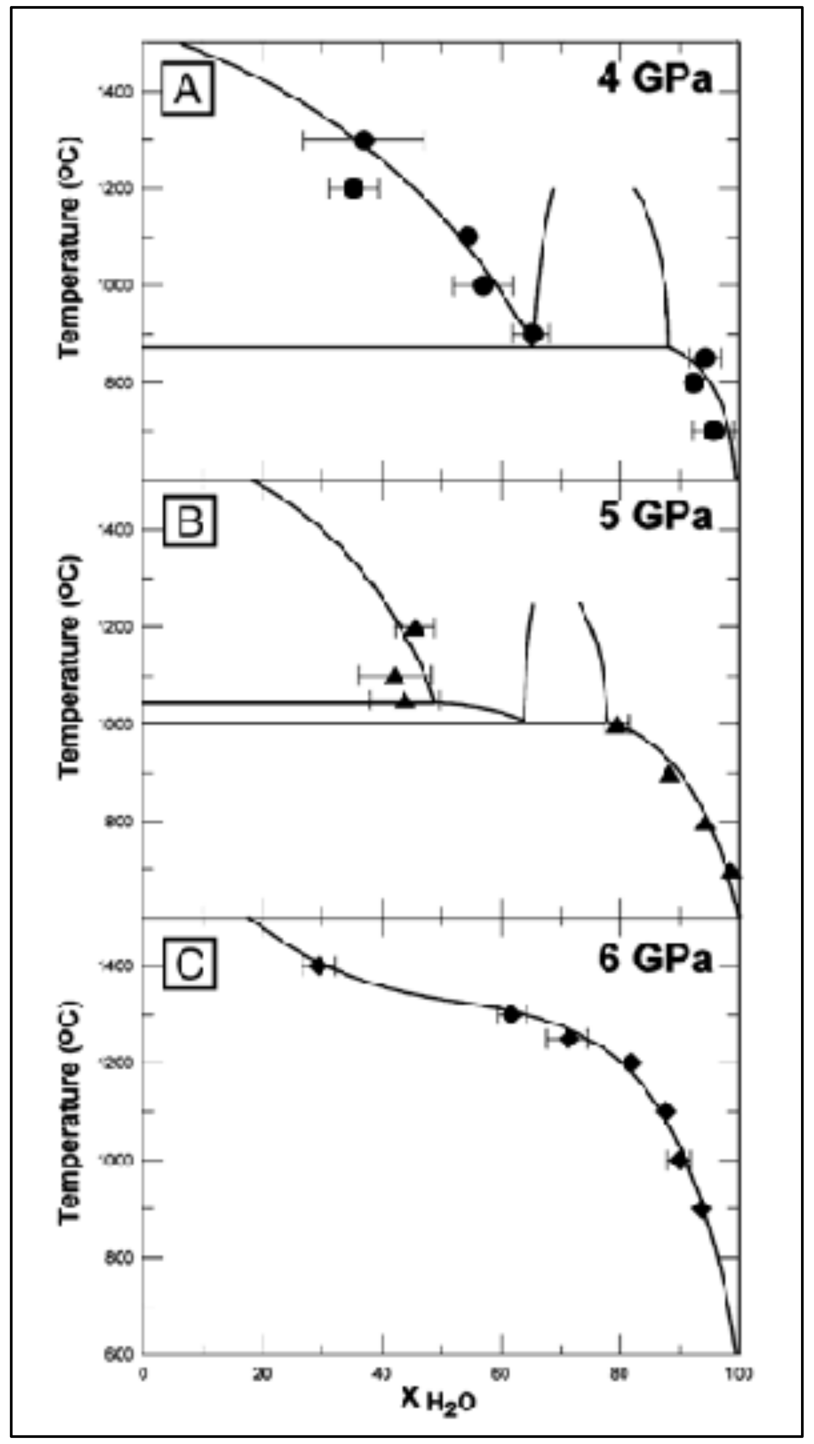


Vazan, Sari, Kessel 2022

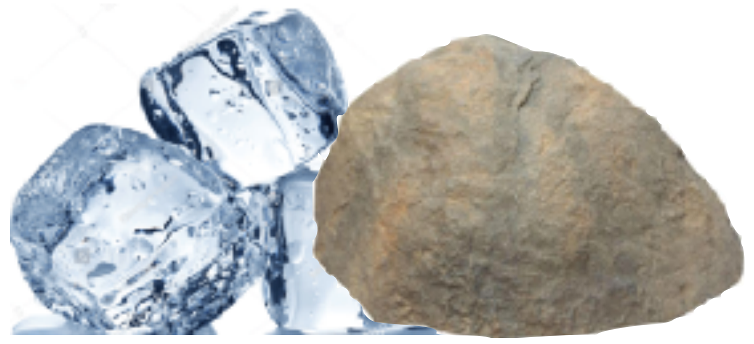
<u>Experimental water-rock data:</u>

Nisr et al. 2020 (lab.)
Kim et al. 2021 (lab.)
Gao et al. 2022 (calc.)
Li et al. 2022 (calc.)
Kovacevic et al. 2022 (calc.)

Ice-rock mixture

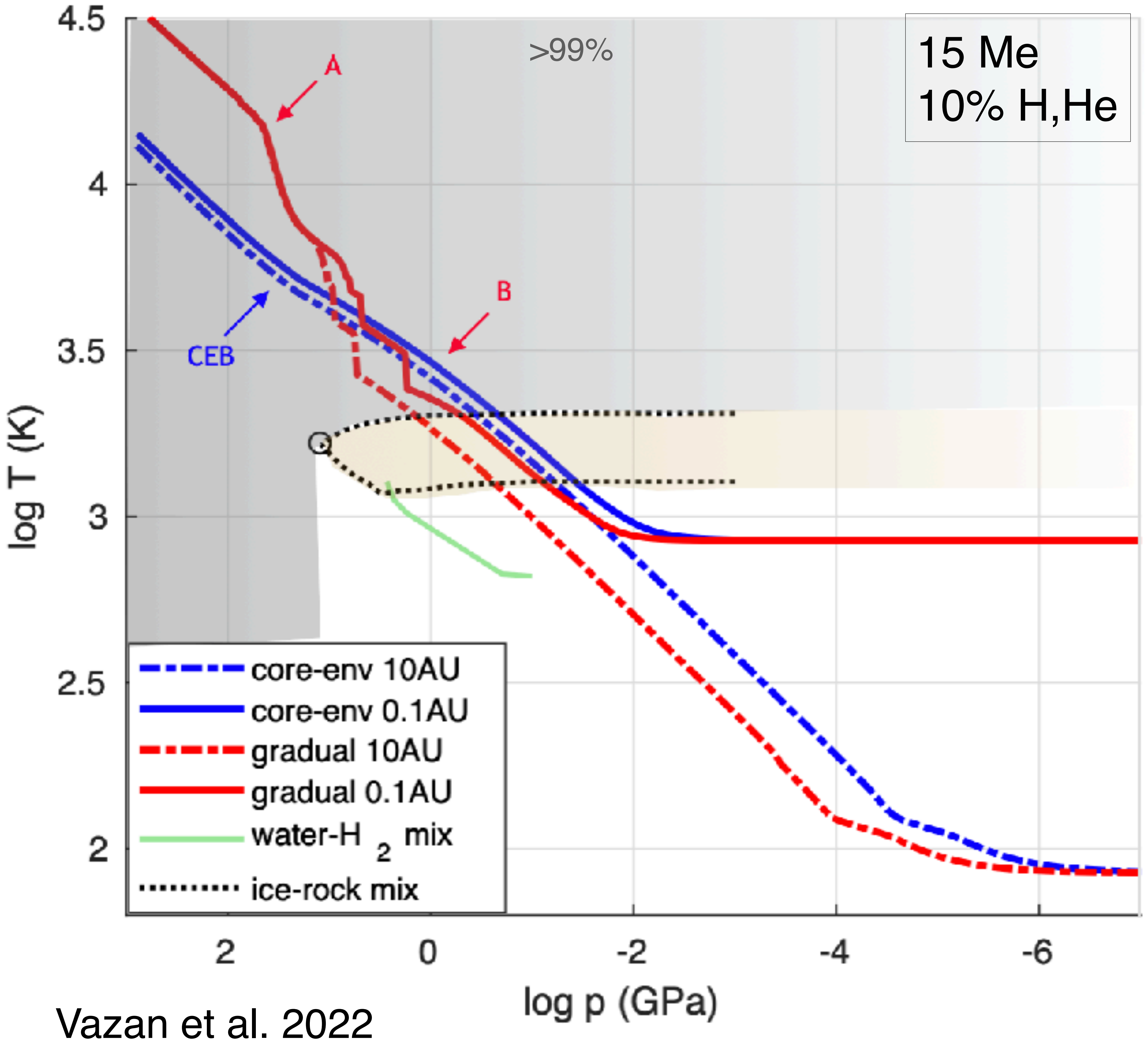


Kessel et al. 2005

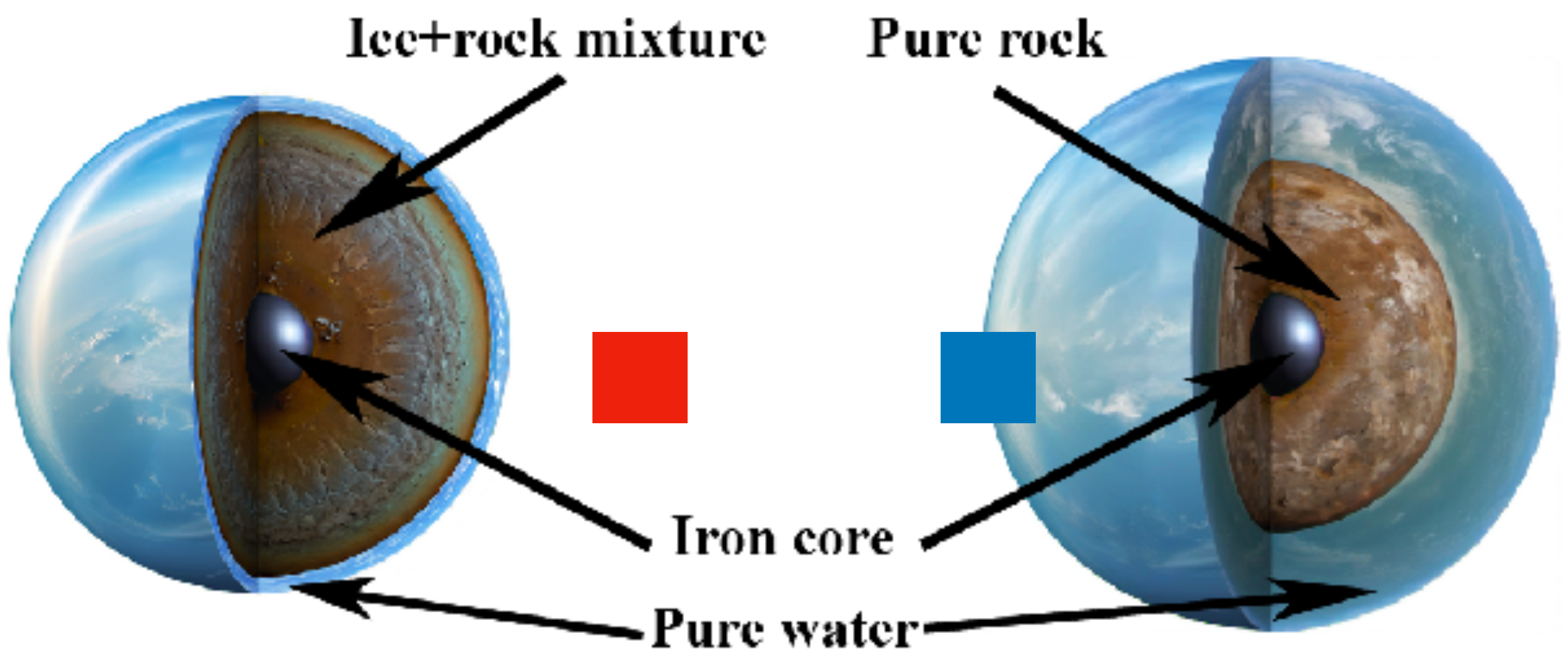


Interiors of wet worlds

Water-rock miscibility in Neptunes

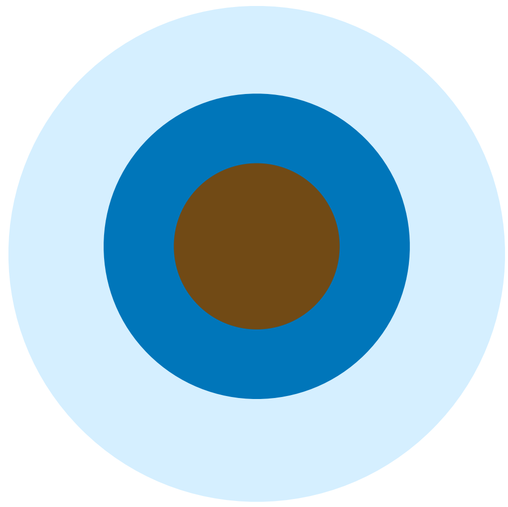


Vazan et al. 2022



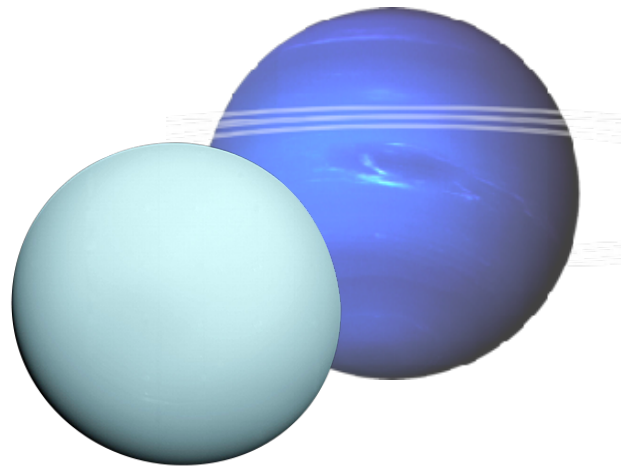
Lozovsky & Vazan - under review

Traditional picture of wet planets:



Water and rock are mixed in ~99% of the planet's mass

Water - hydrogen miscibility in the envelope

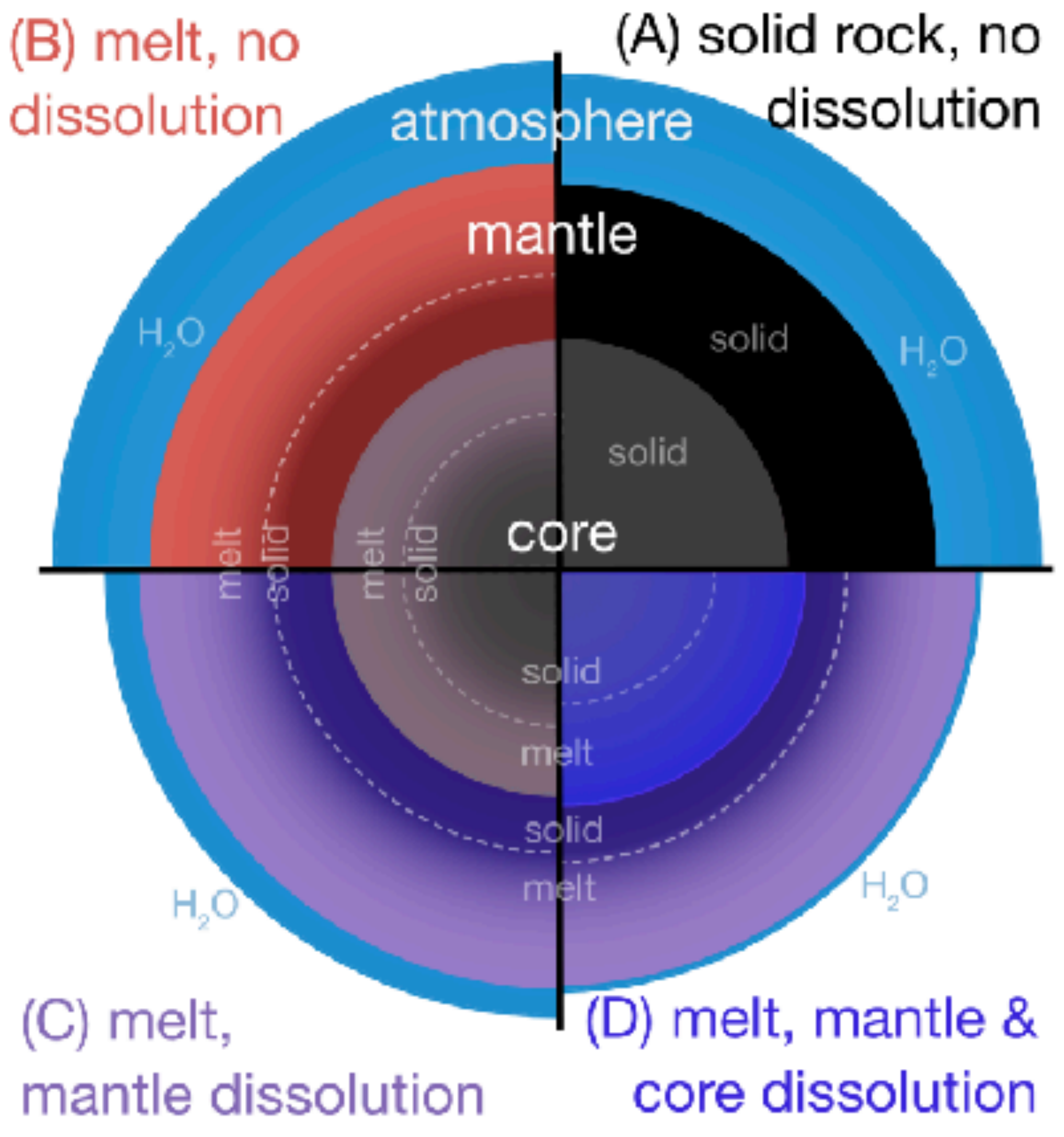


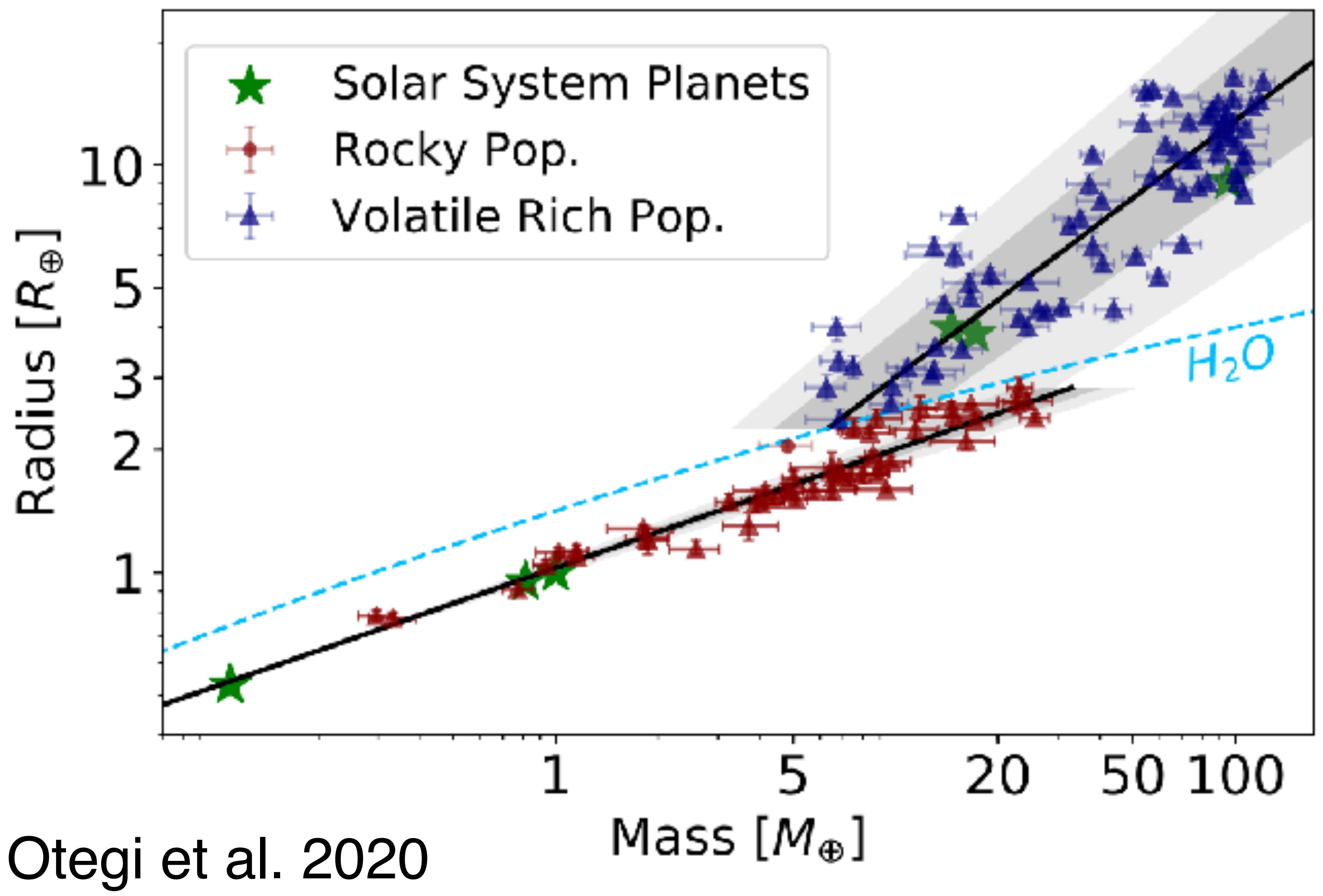
Solubility and miscibility of other materials:

H - water (Bali et al. 2013, Soubiran & Militzer 2015, Bailey & Stevenson 2022)
H- carbon (Kraus et al. 2017)
H - rock (Hirschmann et al. 2012)
H - He (Bergermann et al. 2021)
Fe - water - rock (Tronnes et al. 2019)
water - volatiles (Bethkenhagen et al. 2017, Naden Robinson et al. 2018, …)
…

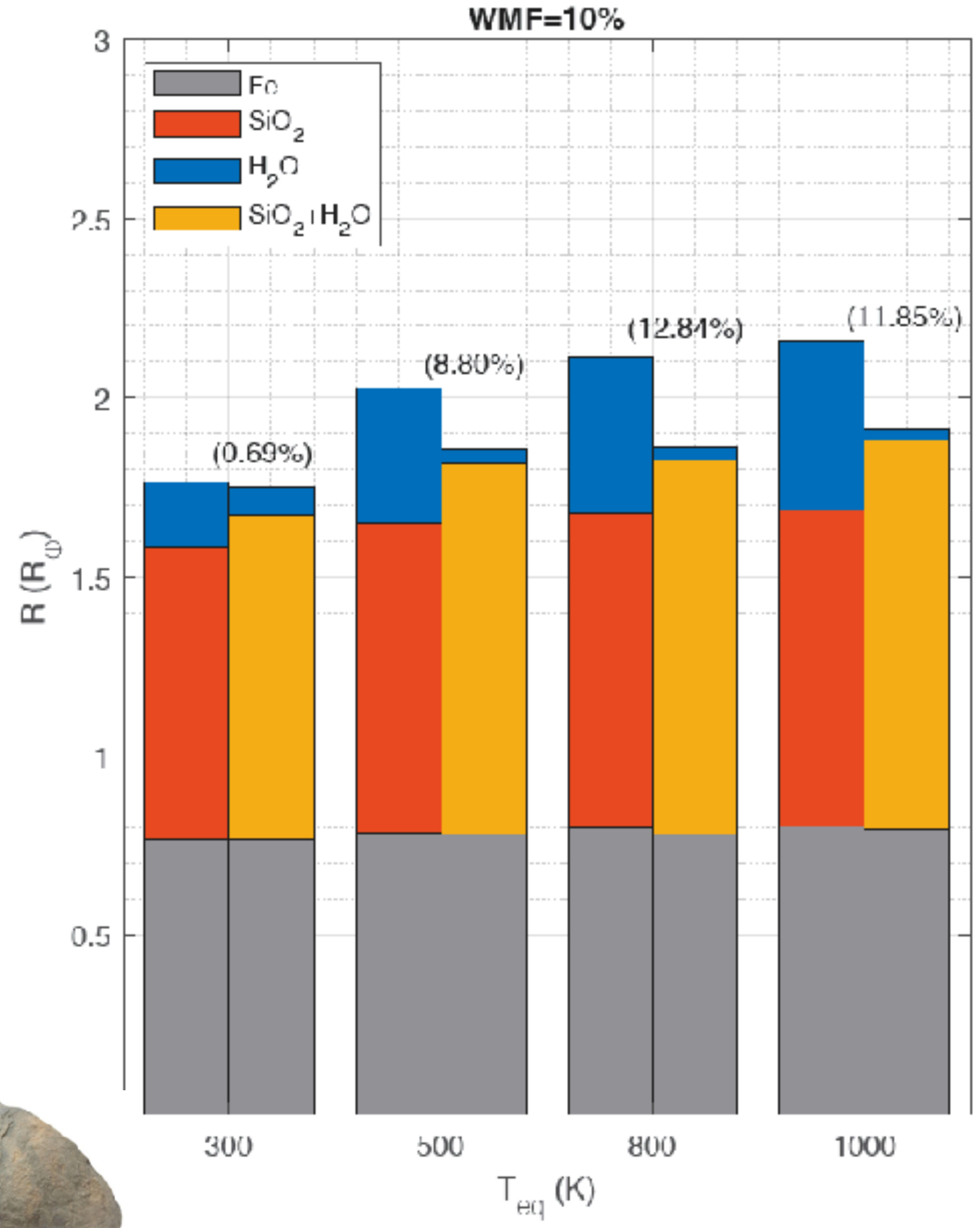
Interiors of wet worlds

Water-rock miscibility in gas-less planets





Otegi et al. 2020



Luo et al. 2024

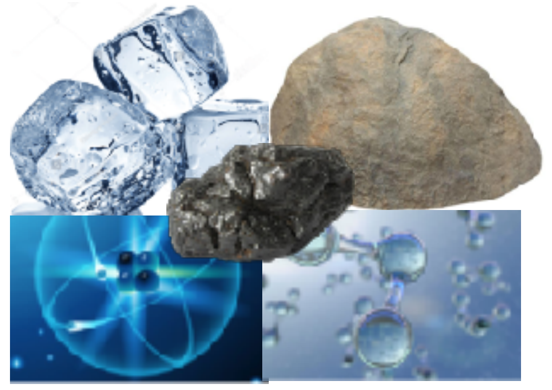
Dorn & Lichtenberg 2021

Lozovsky & Vazan - under review

Material interaction determines **mass-radius** relation

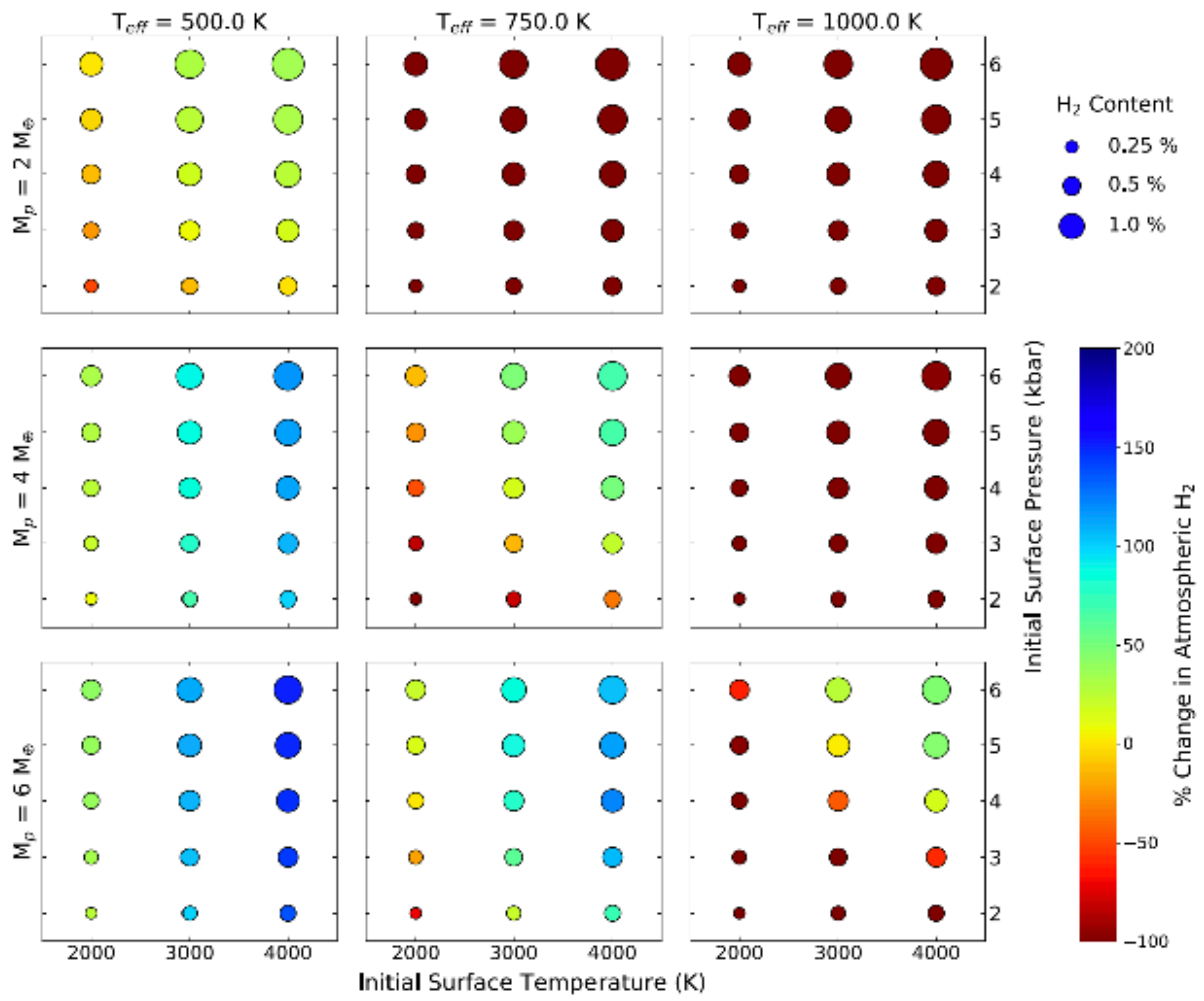
Interior-atmosphere link

JWST and ARIEL observations



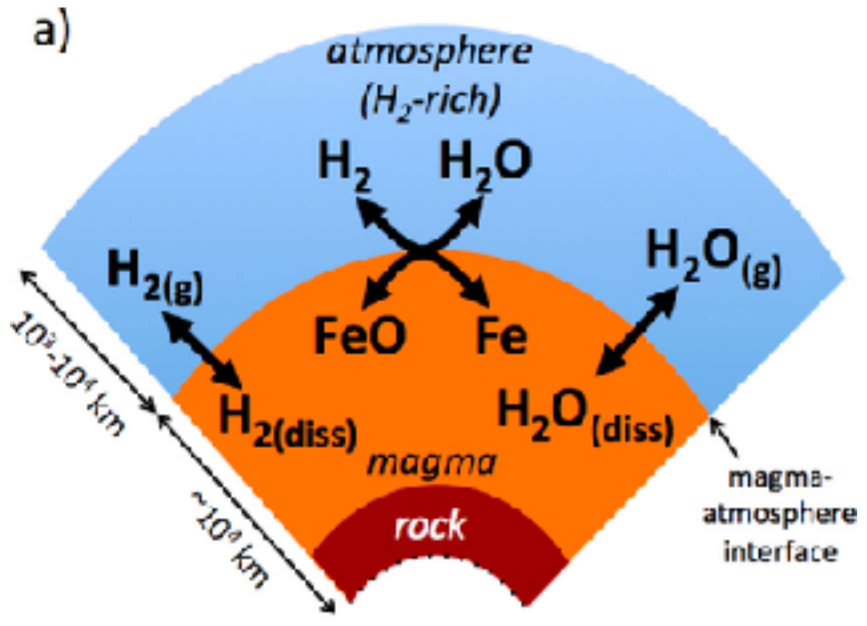
@ 2029

hydrogen atmospheres

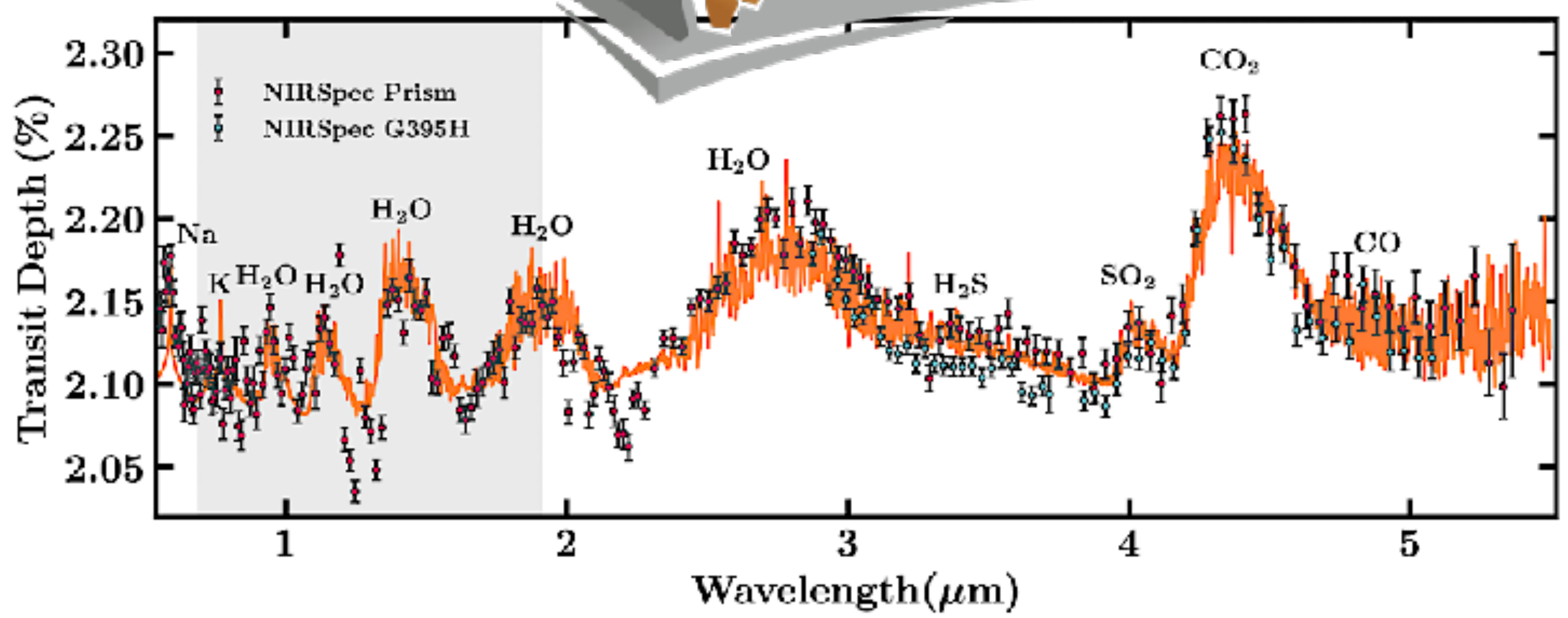


Chachan & Stevenson 2018

steam atmospheres



Kite et al. 2020



Sarkar et al. 2024

Atmospheric composition is tightly linked to deep interior thermal evolution and material interaction

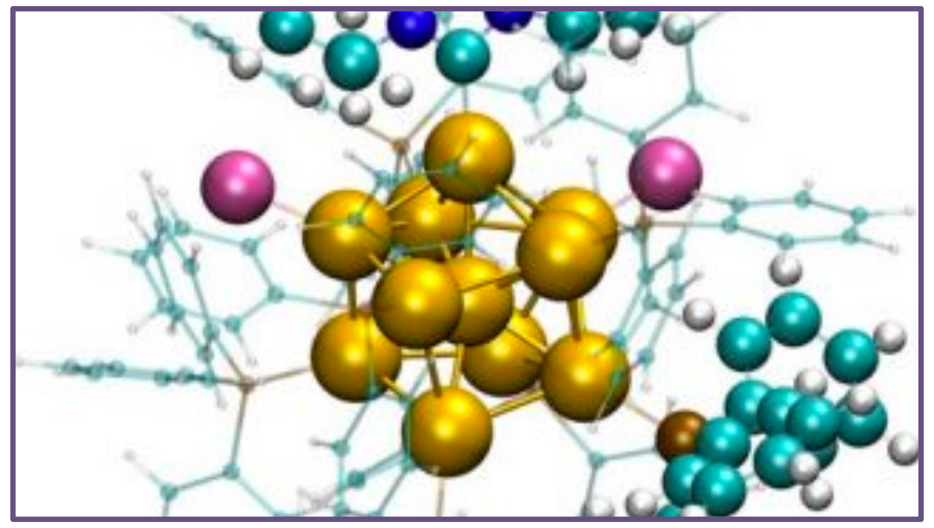
Planetary composition

Where we are

The new planet formation scheme requires knowledge on mixtures at high pressure:

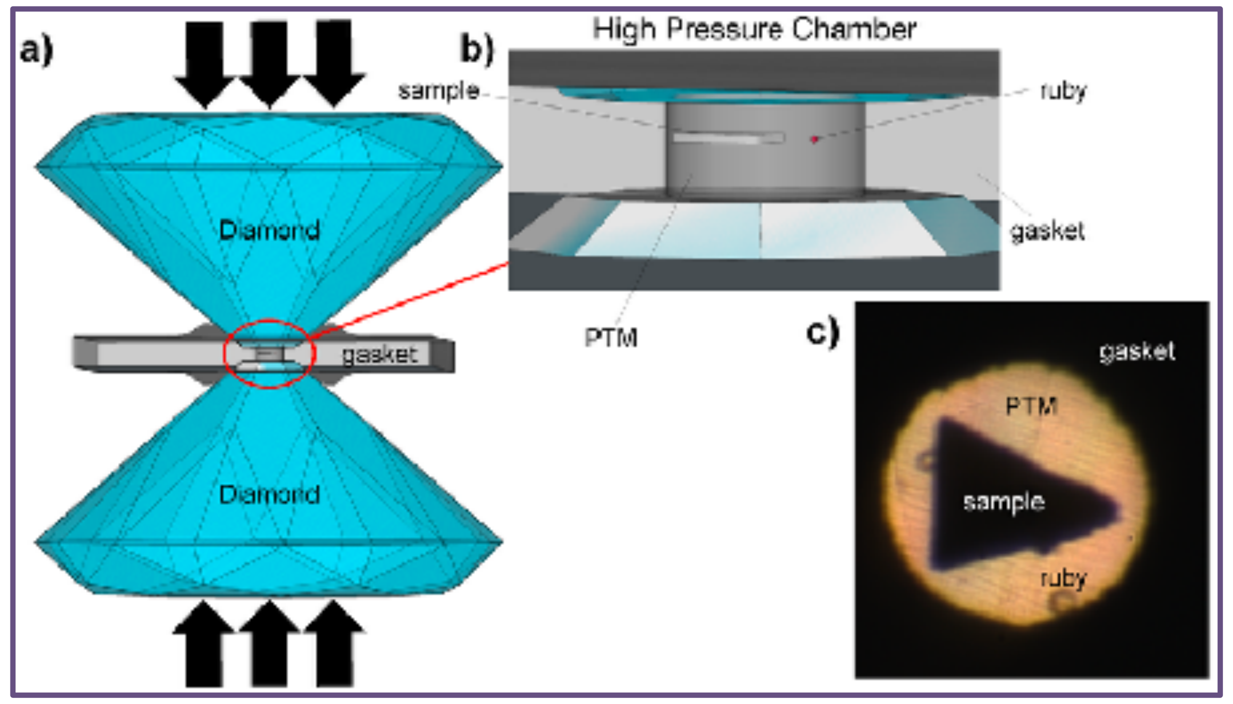
- Equation(s) of state + phase transitions
- Higher temperature data (10-10,000K)
- Material chemical interaction:
    - Miscibility of various species
    - Equilibrium chemistry
- Physical properties of mixtures:
    - Thermal conductivity
    - Electrical conductivity
    - Viscosity

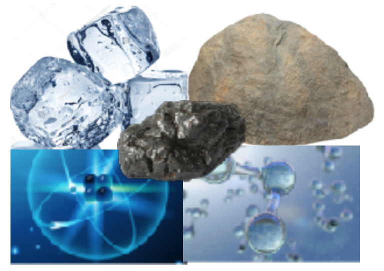
Molecular dynamics simulations



Diamond anvil cell

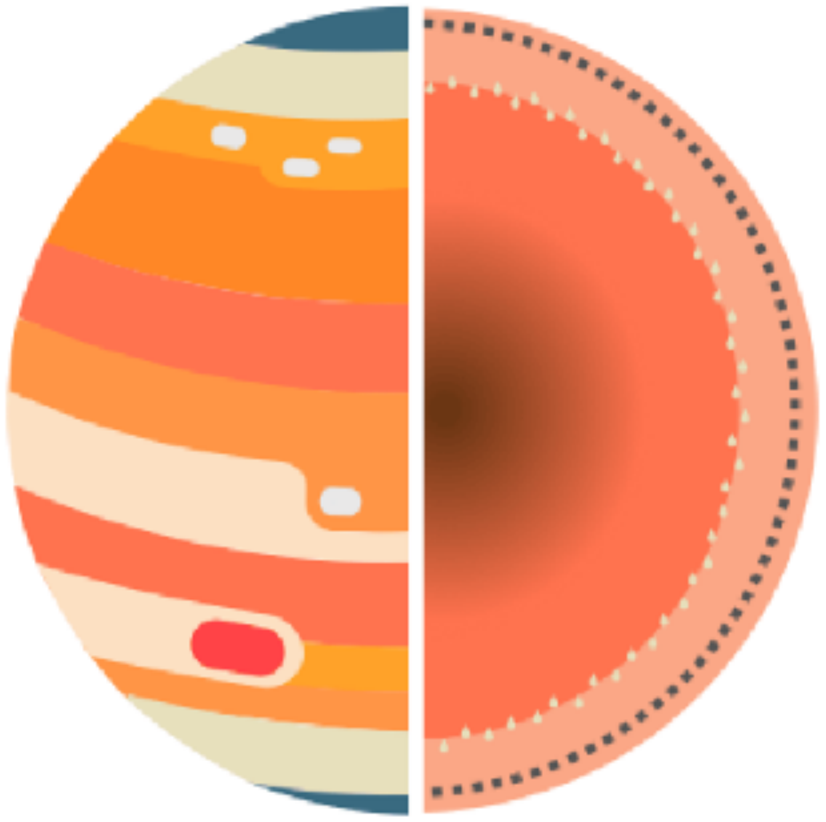
100s GPa

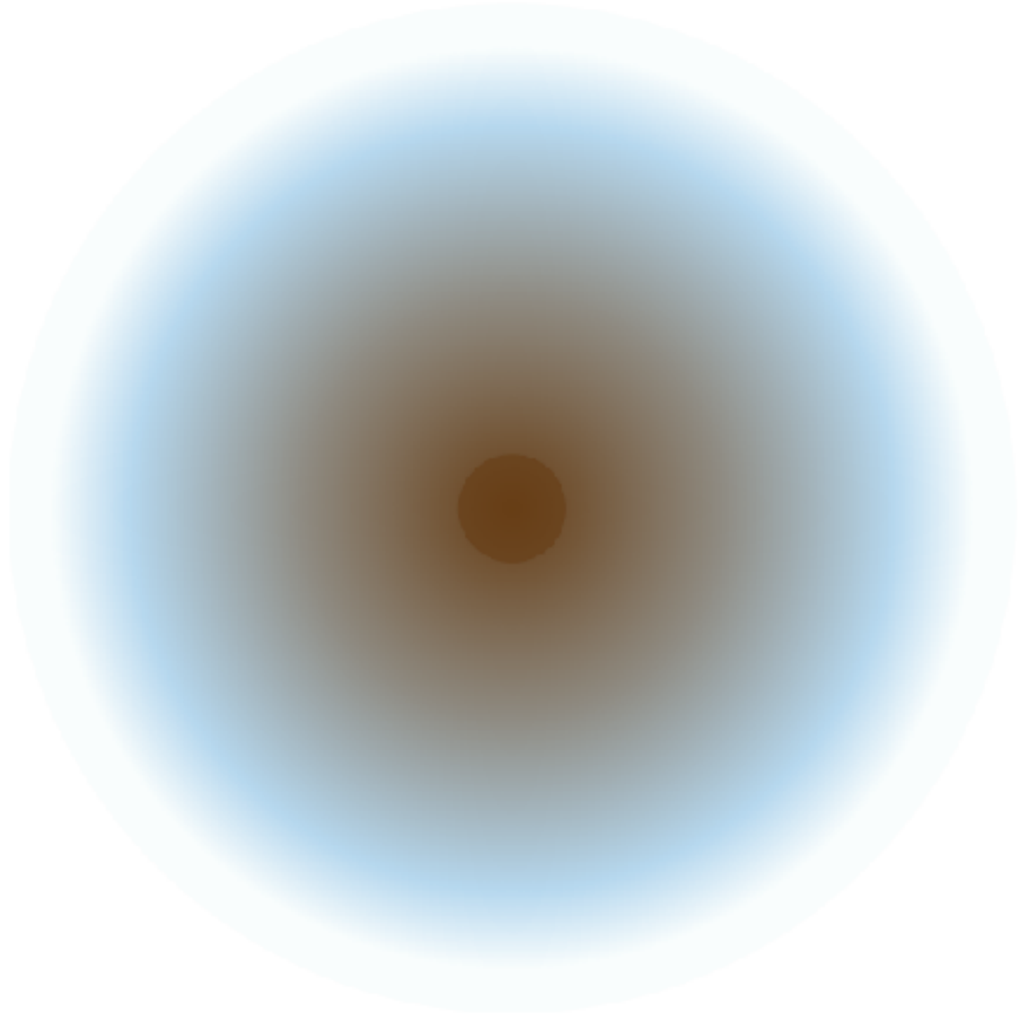




Planet interior structure

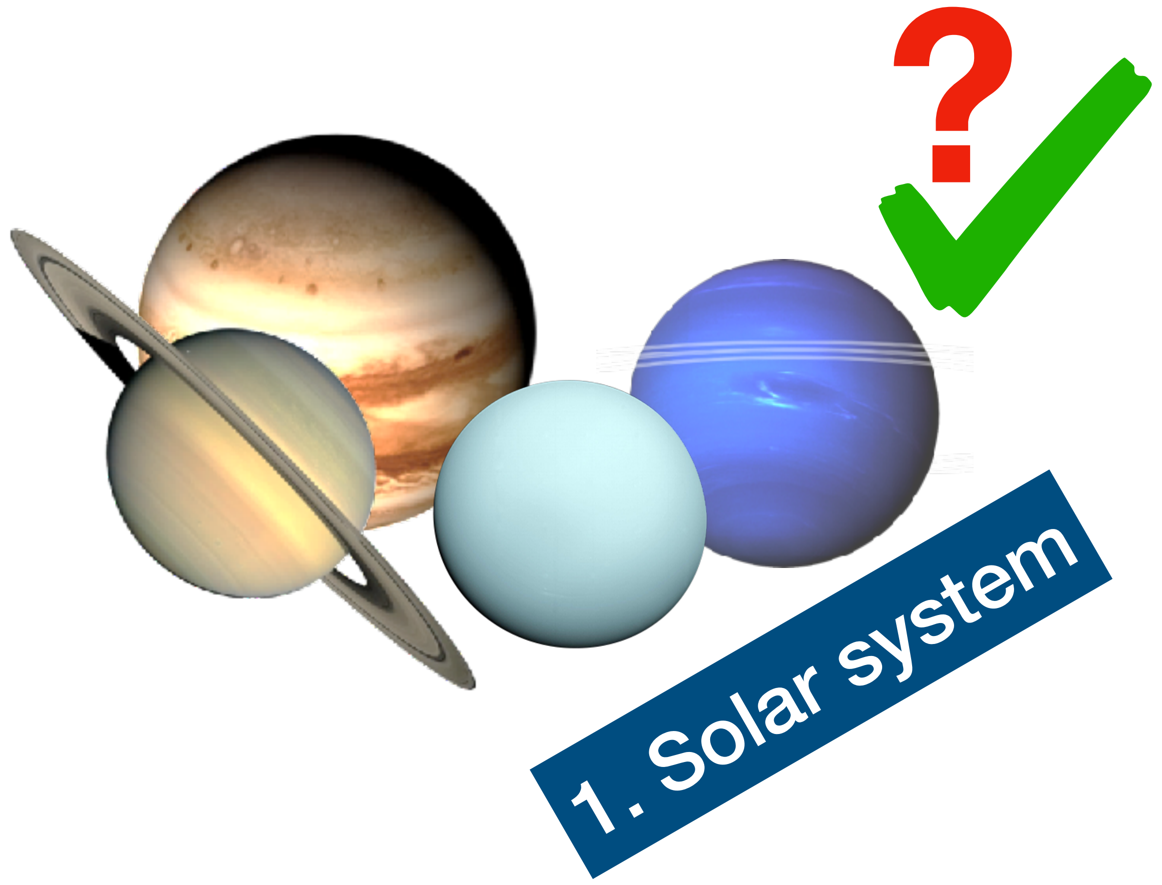
Simple is best (if it works…)





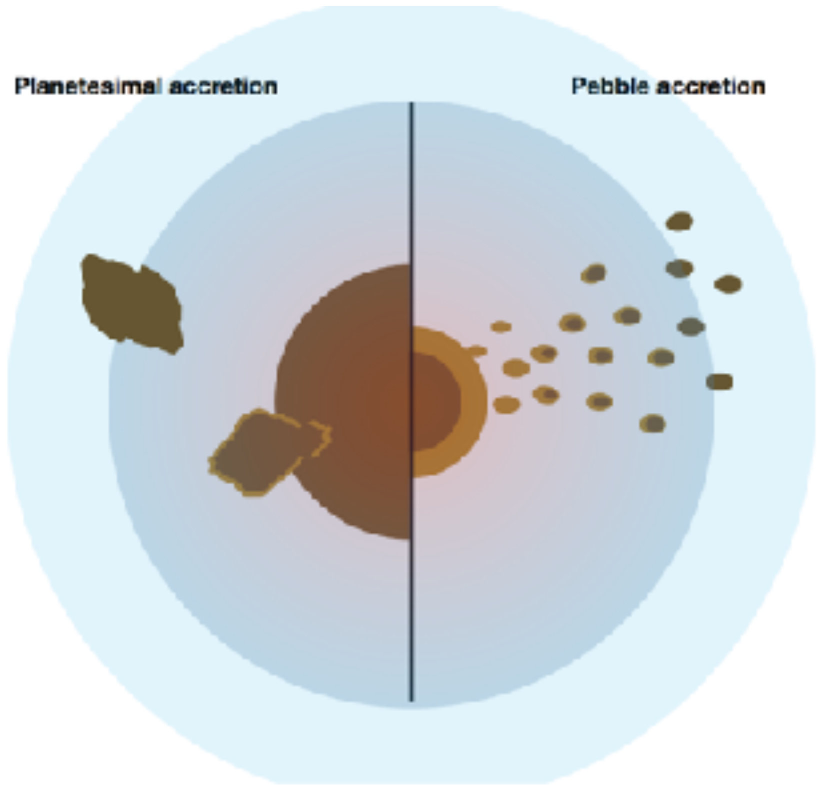
Then why not?

New findings challenge traditional theory:

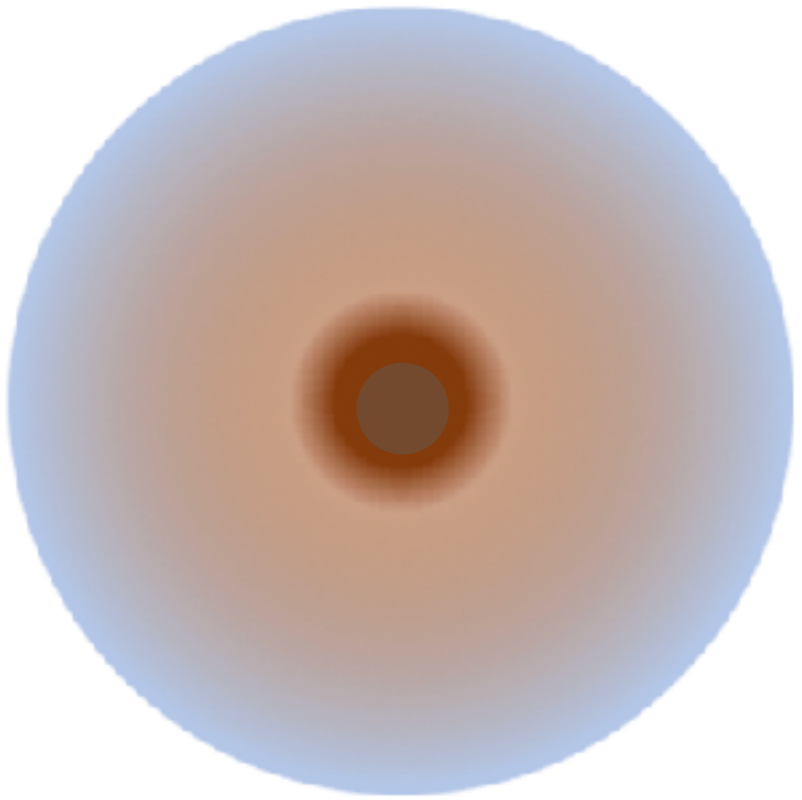


The link to observations

The fate of the interior - long term evolution

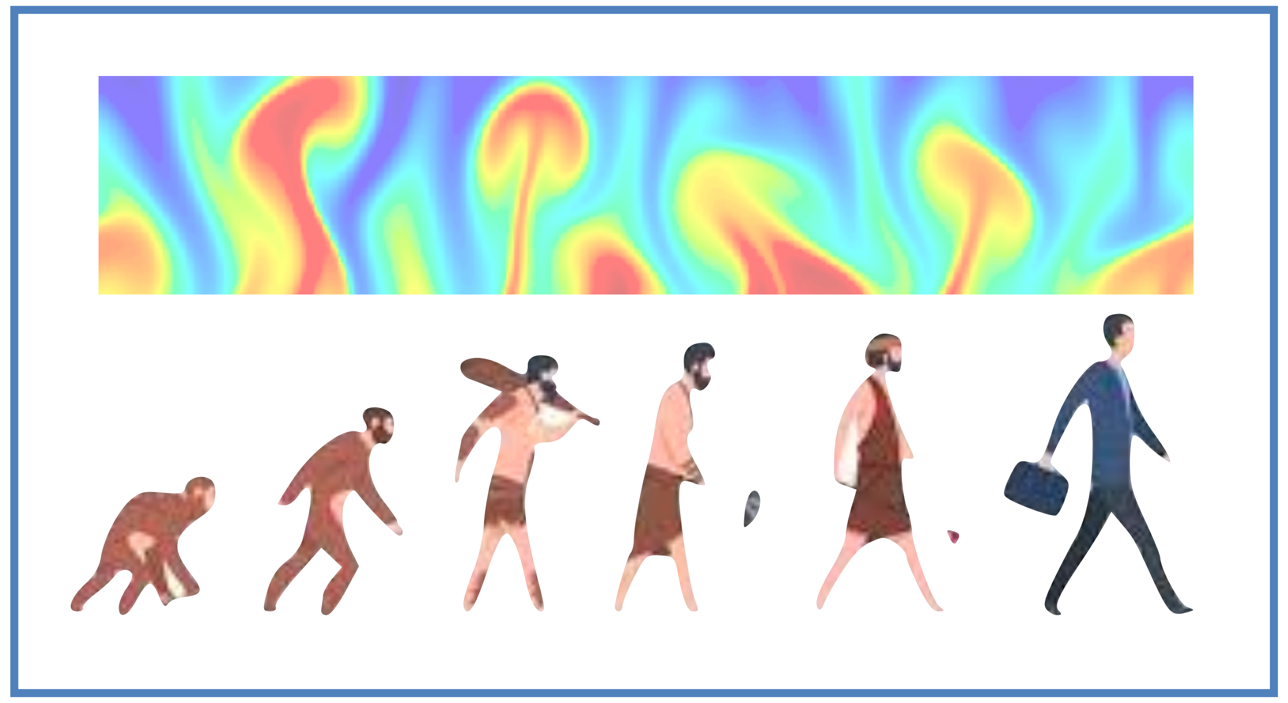


Myr

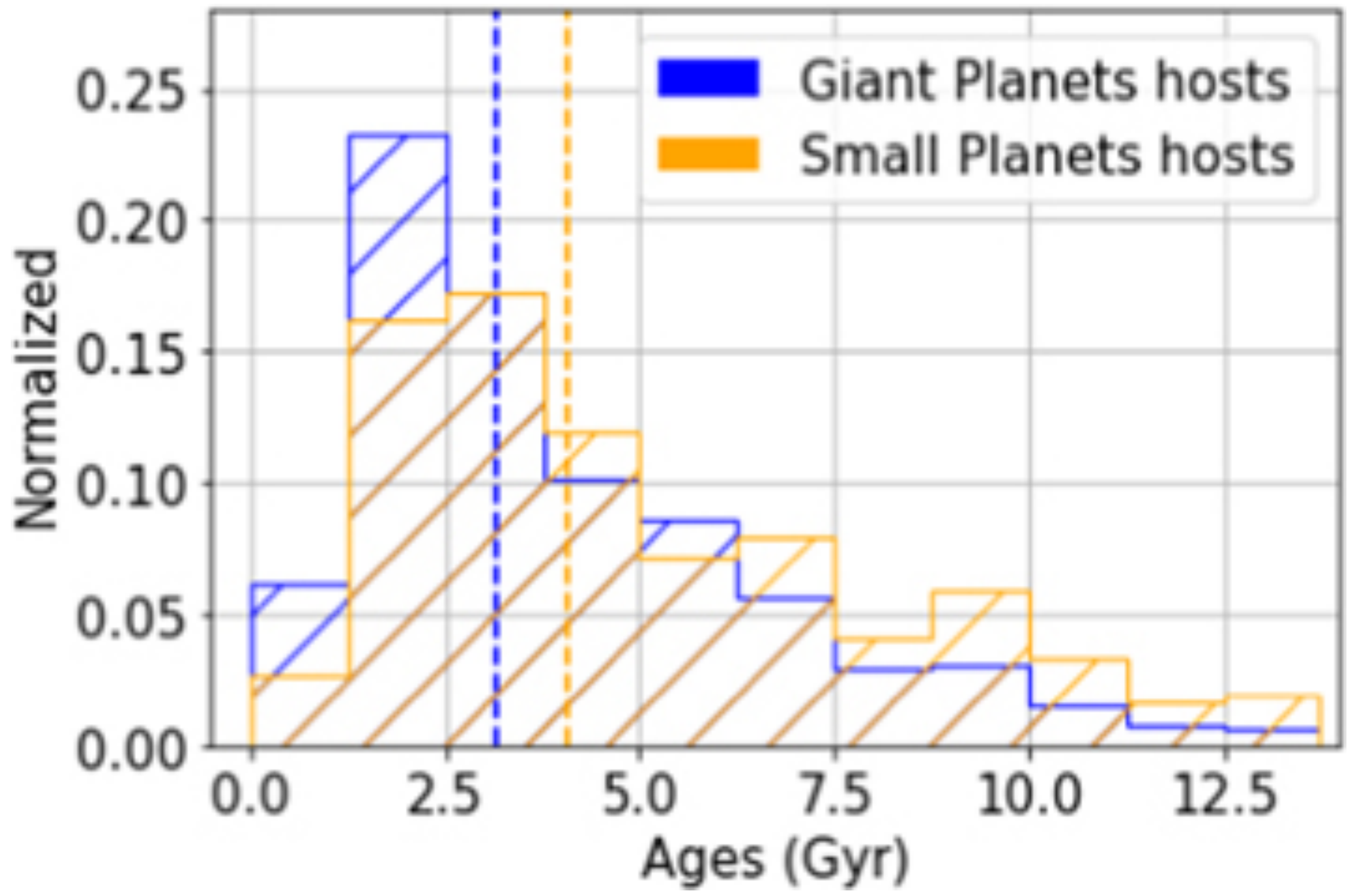


Gyr

?



Most observed exoplanets are Gyrs old

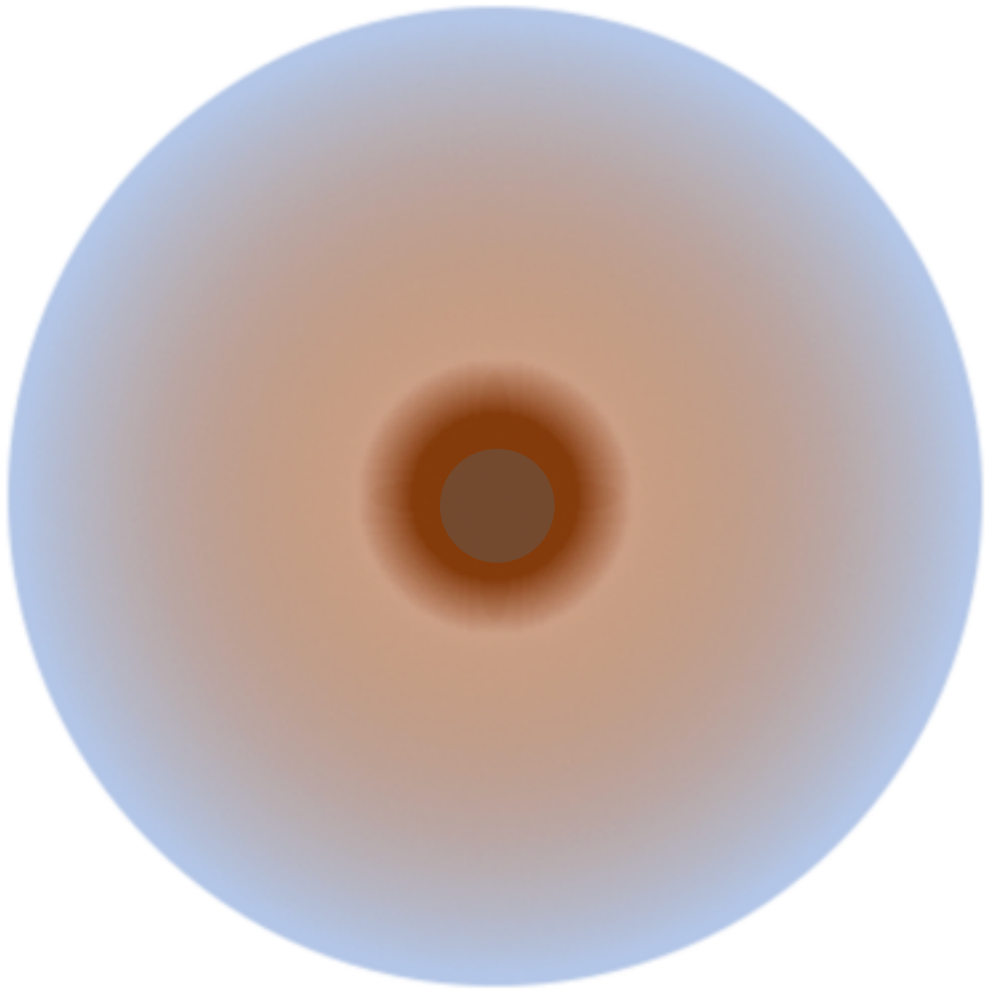


Swastik et al. 2023

Interior after formation

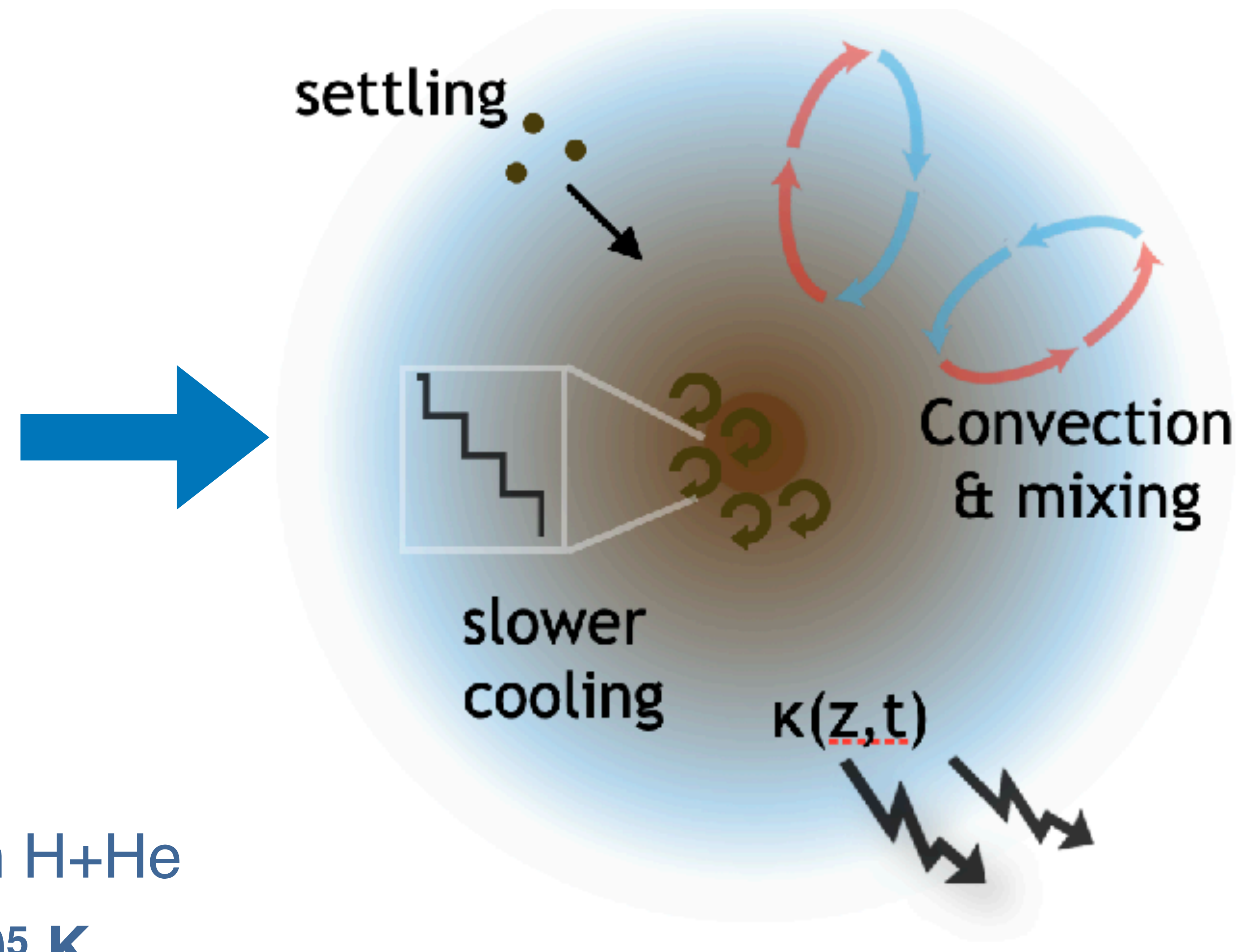
Thermal evolution of hot polluted envelopes

After formation

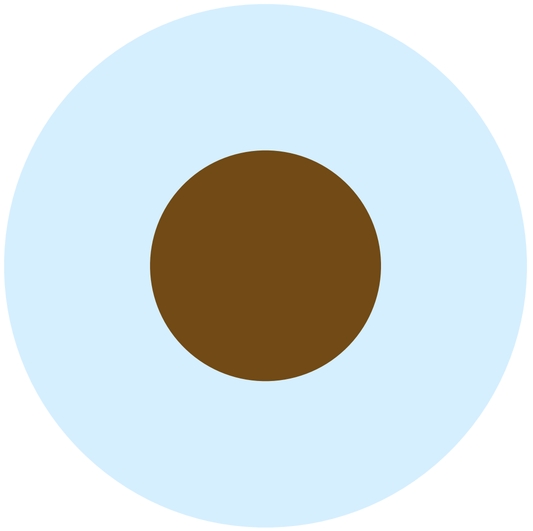


Gradual distribution of metals in H+He

Deep interior is initially **~ 10^4-10^5 K**



1) Much more physics is involved
2) Initial conditions matter



Simple model:
- Adiabatic structure
- Fixed Z(r)
- Opacity depends on P,T

Physics-based model:
- Not necessarily adiabatic
  - Conduction / radiation
  - Layered convection
- Evolving Z(r,t):
  - Convective-mixing
  - Rainout (condensation + settling)
- Evolving opacity of Z,P,T

- Migration
- Mass loss

A. Vazan

Thermal evolution

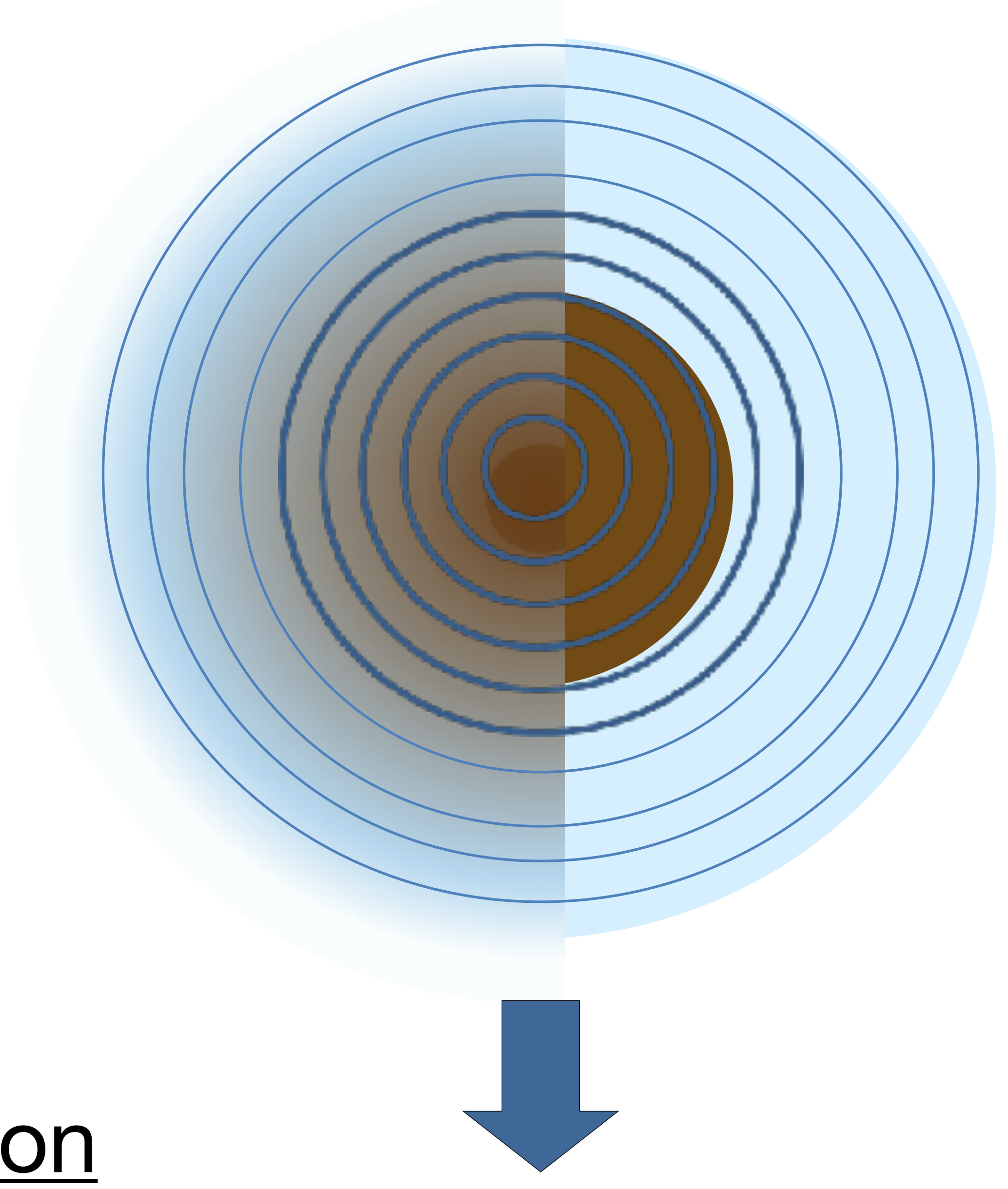
Model (Vazan et al. 2013,15,18c,22,24)

From formation to current stage:
interior thermal evolution

- Stellar evolution based (Kovetz et al. 2009)
- Mass loss / accretion scheme
- Disk migration, stellar irradiation
- Tabular EoS for H, He, water, rock, iron, …
- Heat transport: convection, radiation, conduction
- Material transport: advection, rainout
- Self-consistent (adaptive Z) radiative opacity

$\nabla_R > \nabla_A + \nabla_{Ledoux}$ + Mixing Length Theory

$$L_{\rm core} = M_c \left(c_v \frac{dT_c}{dt} + \frac{E_{\rm radio}}{\tau_r} e^{(-t/\tau_r)} + \frac{E_{\rm solid}}{\Delta t} \delta\left(T - T_{\rm solid}\right) \right)$$



Radius
Temperature
Luminosity
Density
Pressure
Composition

$$\frac{\partial}{\partial m} \frac{4\pi}{3} r^3 = \frac{1}{\rho}$$

$$\frac{\partial p}{\partial m} = -\frac{Gm}{4\pi r^4}$$

$$\frac{\partial \ln T}{\partial m} = \nabla \frac{\partial \ln p}{\partial m}$$

$$\frac{\partial u}{\partial t} + p \frac{\partial}{\partial t} \frac{1}{\rho} = q - \frac{\partial L}{\partial m}$$

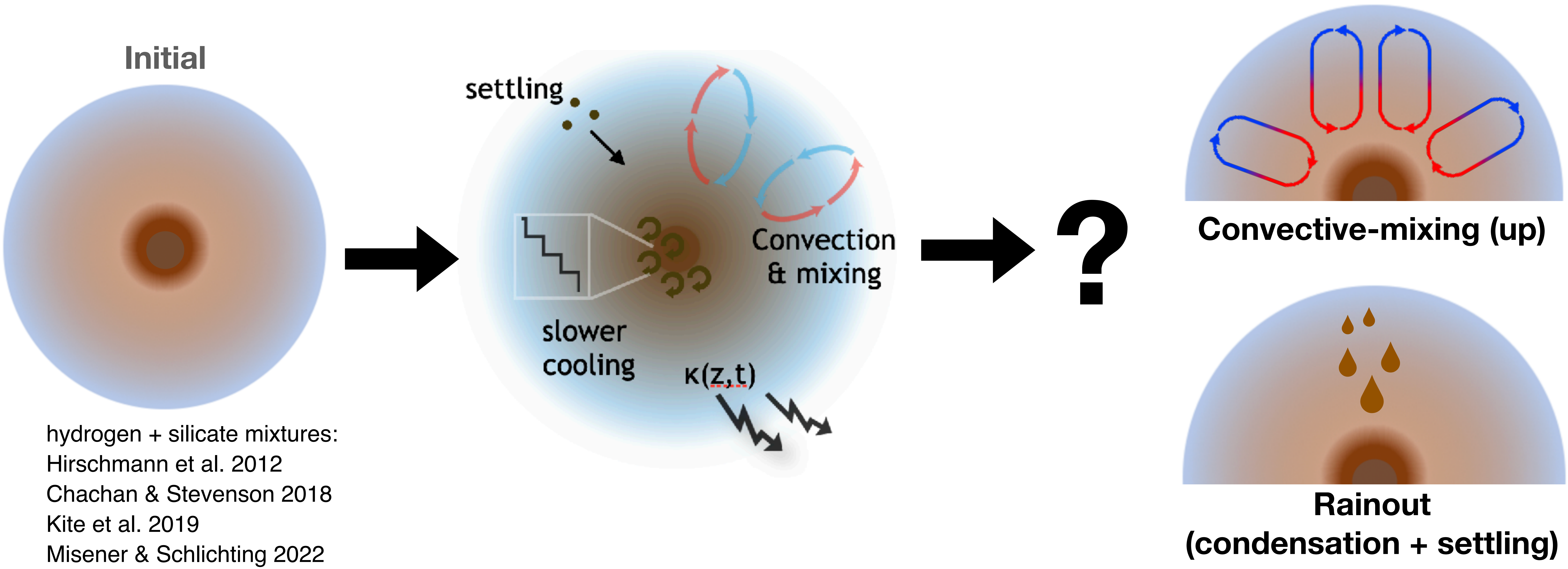
$$\frac{\partial Y_j}{\partial t} = R_j - \frac{\partial F_j}{\partial m}; \qquad F_j = -\sigma_j \frac{\partial Y_j}{\partial m}$$

Opacity: $\frac{1}{\kappa} = \frac{1}{\kappa_{rad}} + \frac{1}{\kappa_{cond}}$

EoS for a mixture: $\frac{1}{\rho(P,T)} = \sum_{i=1}^{n} \frac{Xi}{\rho_{Xi}(P,T)}$

Interior evolution

Long-term evolution of young polluted interiors - material transport

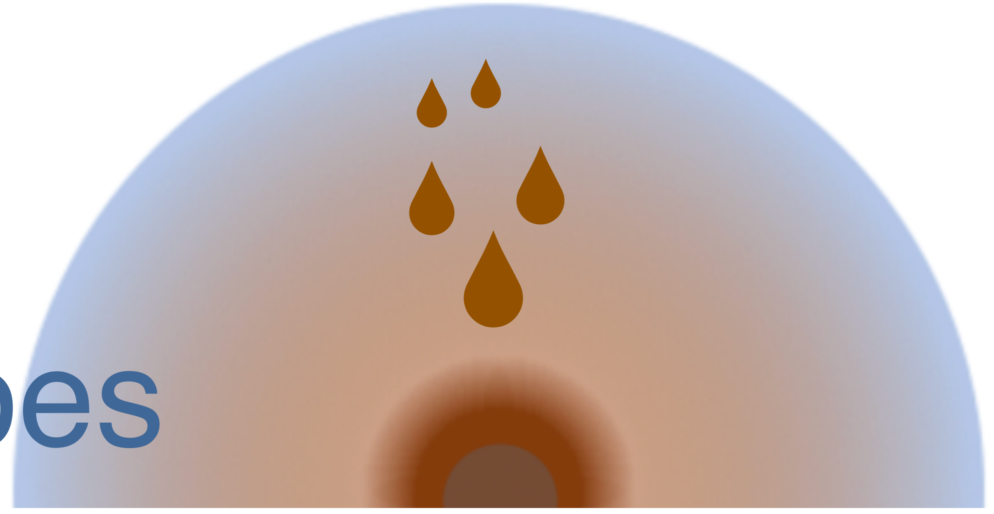


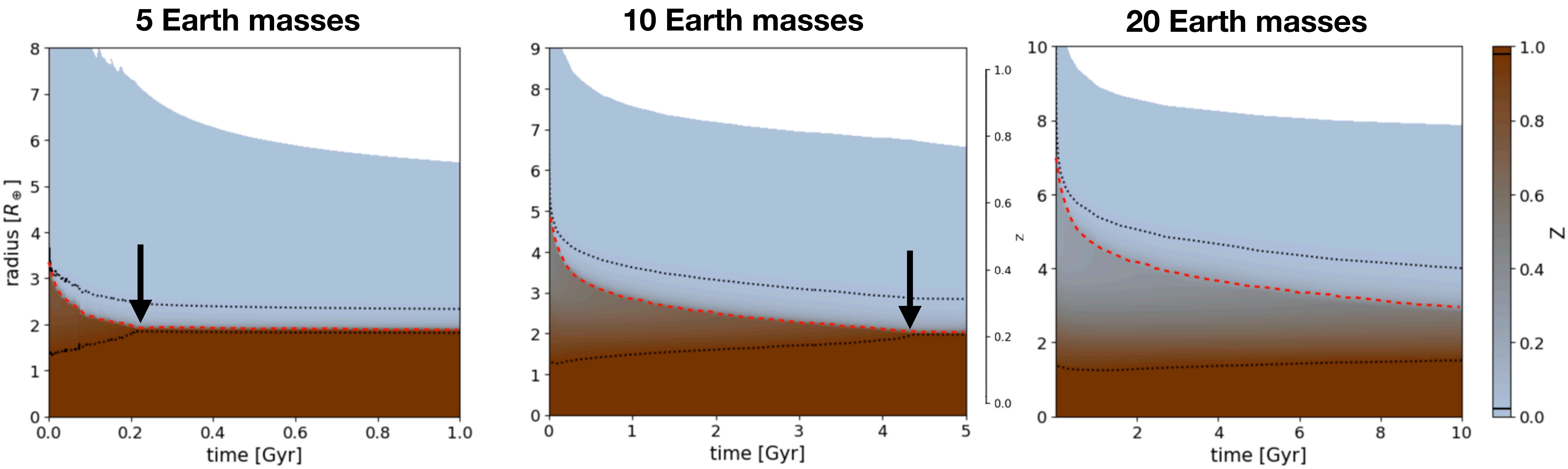
hydrogen + silicate mixtures:
Hirschmann et al. 2012
Chachan & Stevenson 2018
Kite et al. 2019
Misener & Schlichting 2022

Rainout is fundamental in interior evolution of **super-Earth and sub-Neptune** planets

Interior evolution

Silicate rainout in planets born with polluted envelopes



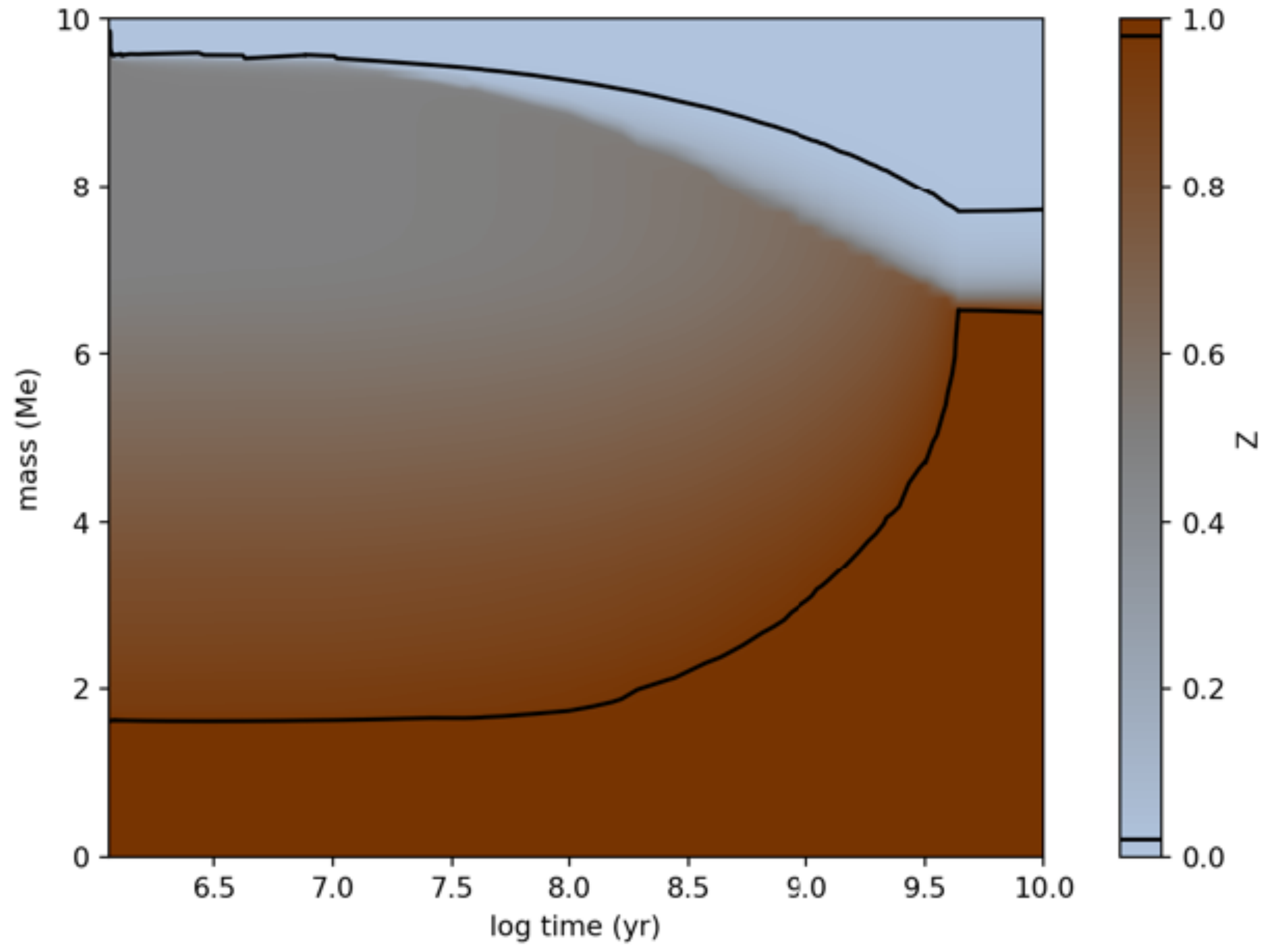


Vazan, Ormel, Brouwers 2024

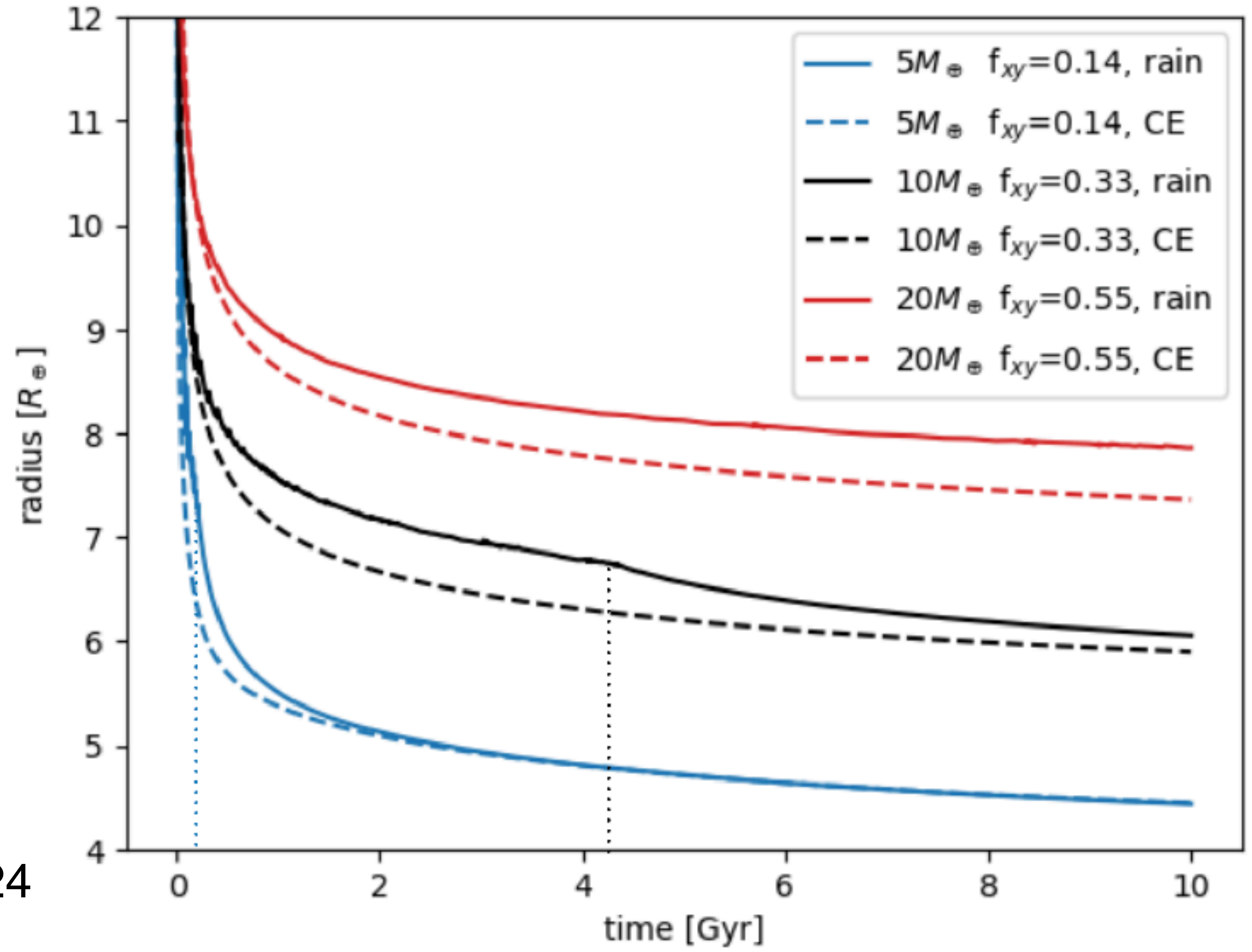
Late growth of the rocky core in sub-Neptunes by silicate rainout, on ~ 1Gyr time

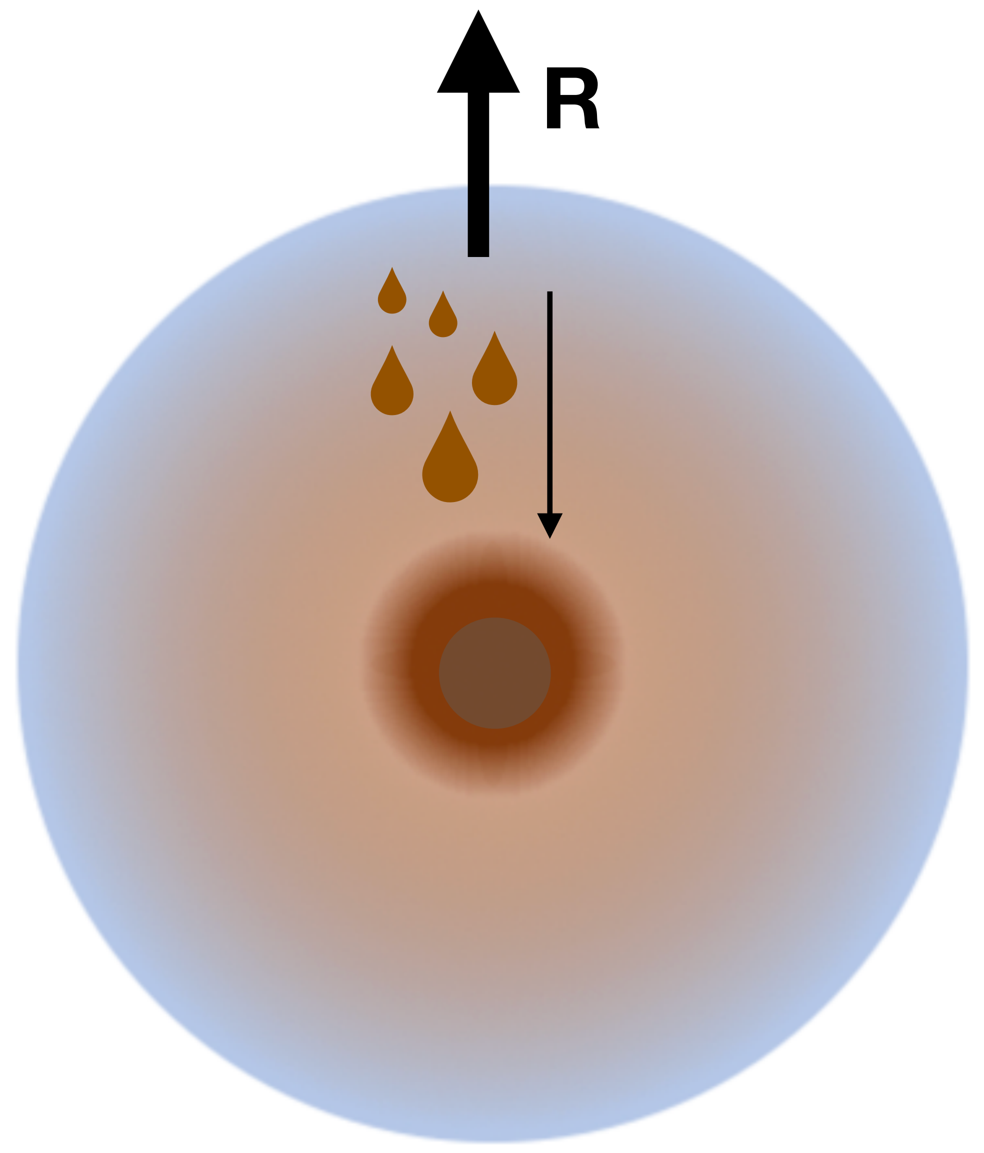
Radius evolution

Radius inflation by rainout energy release



Vazan, Ormel, Brouwers 2024





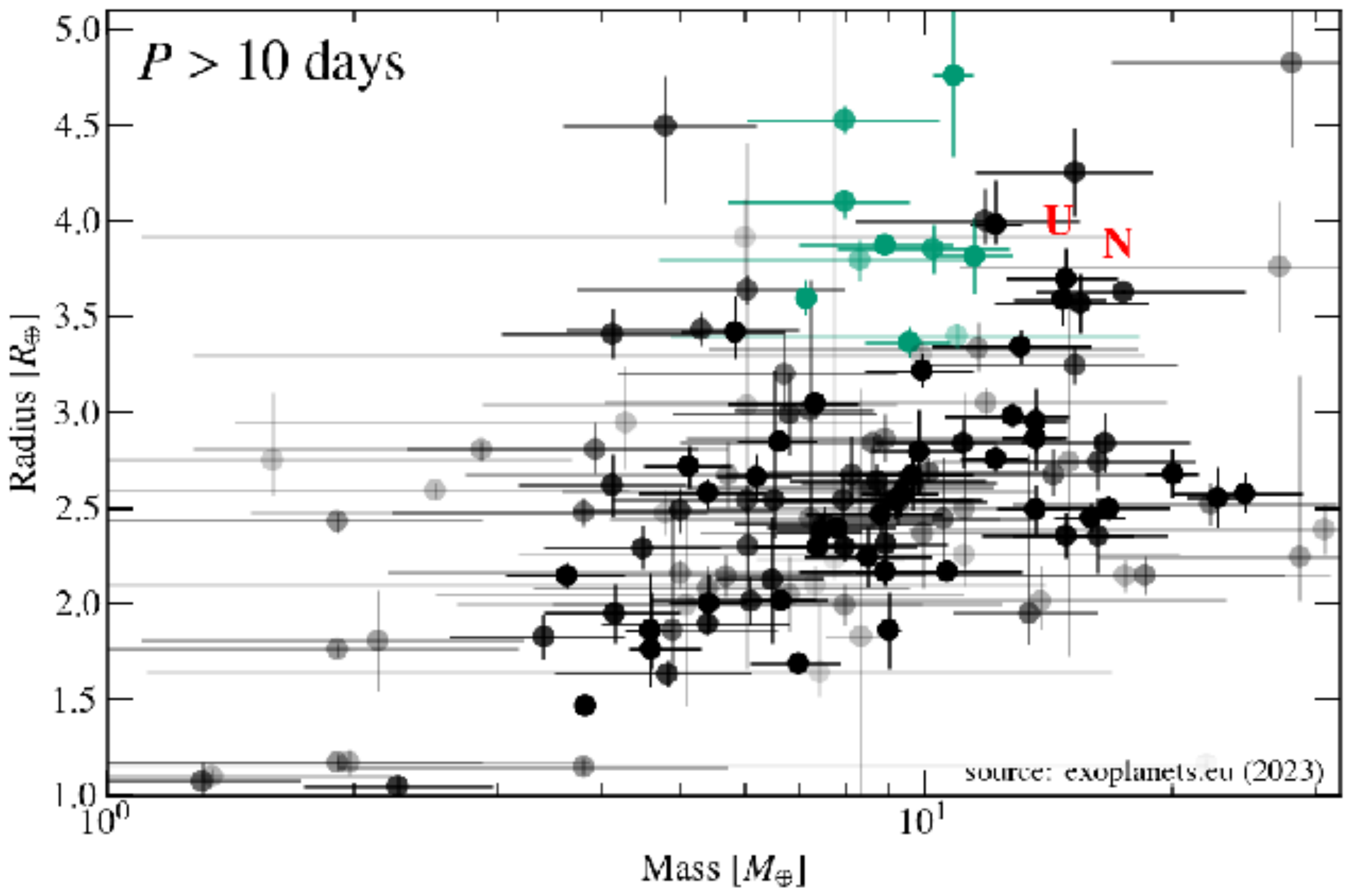
Energy release:
* Potential (gravity)
* Latent (condensation)
* Locked (formation)

Radius inflation is stronger yet shorter duration in planets with low mass envelopes

Future observations

Rainout affects observation interpretation

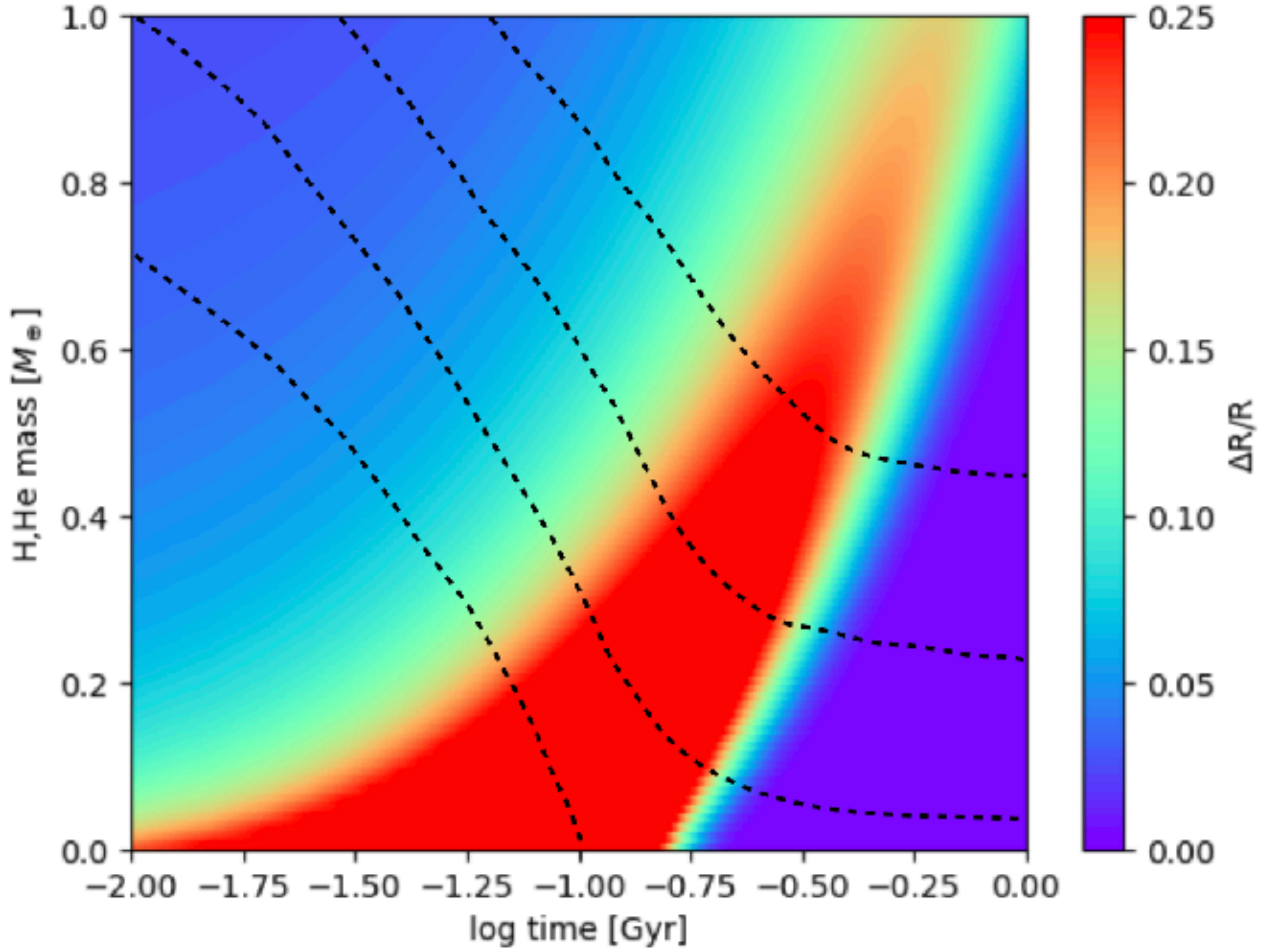
Mass-radius-age



Vazan & Ormel 2023

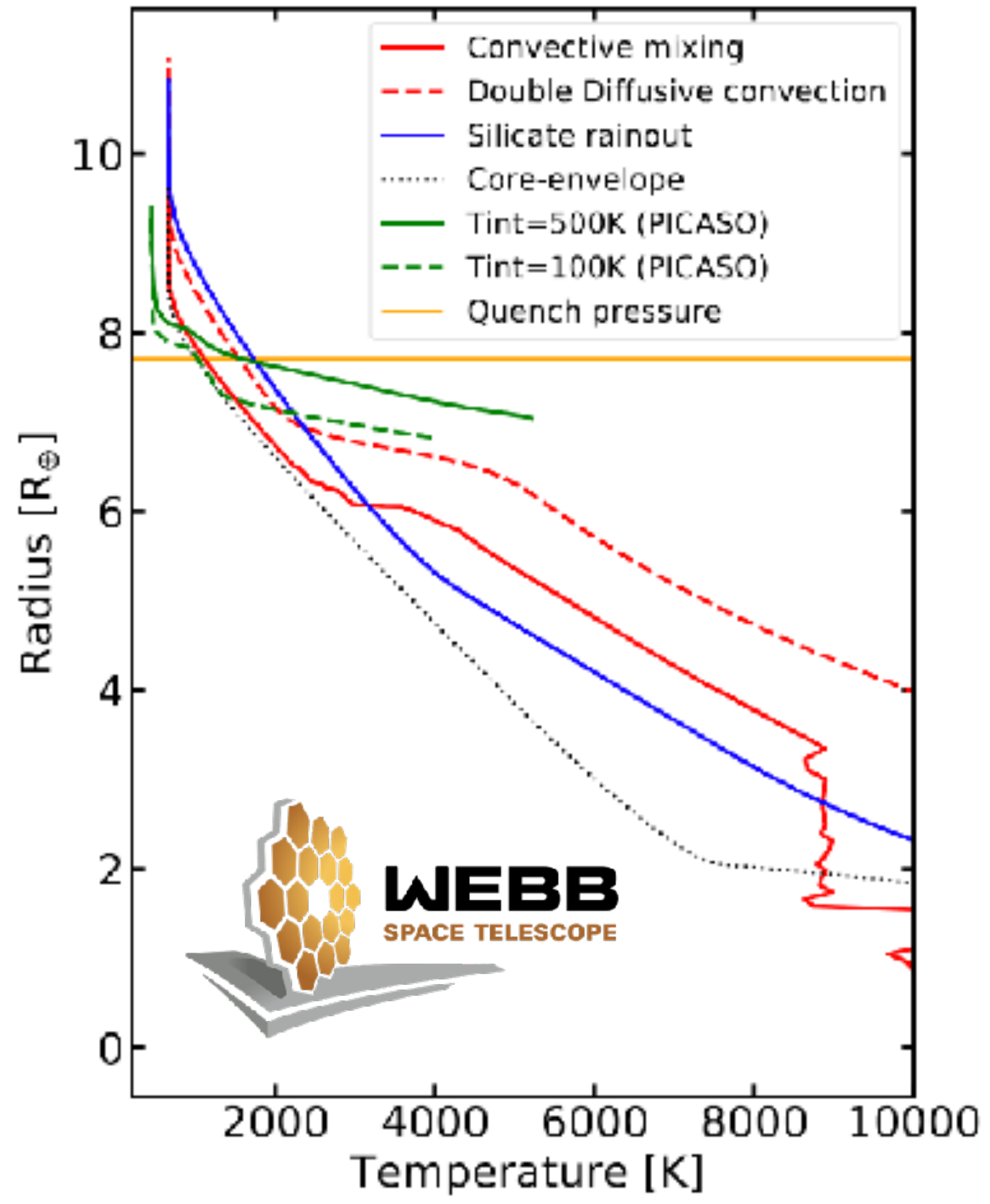
H-He mass fraction is <u>overestimated</u> when using core-envelope models

Mass loss ~ R³

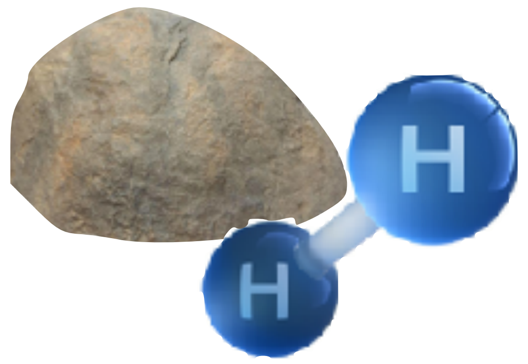


Strong radius inflation at early stages => <u>enhanced mass loss</u> by photoevaporation

V1298 b

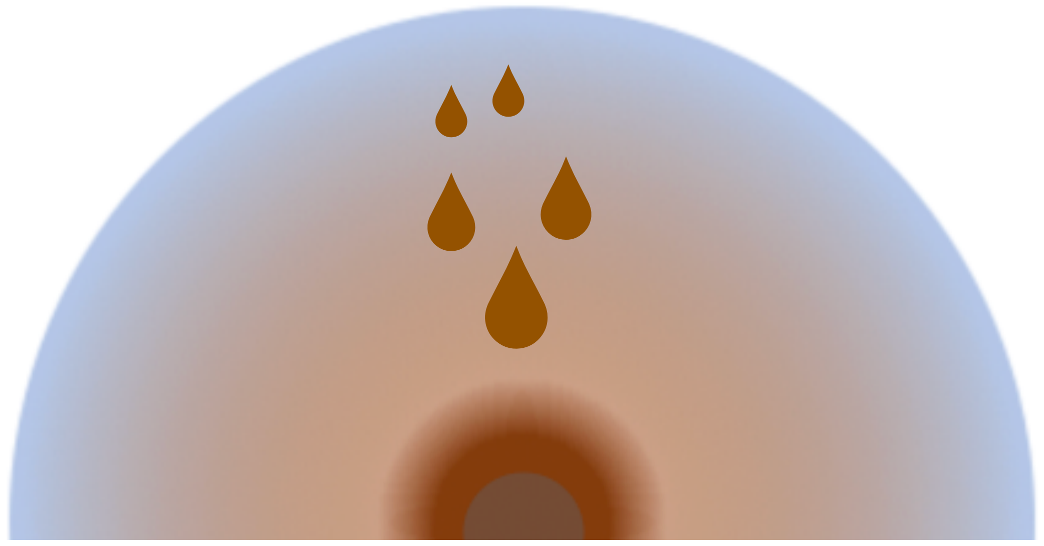


Barat et al. - in prep.



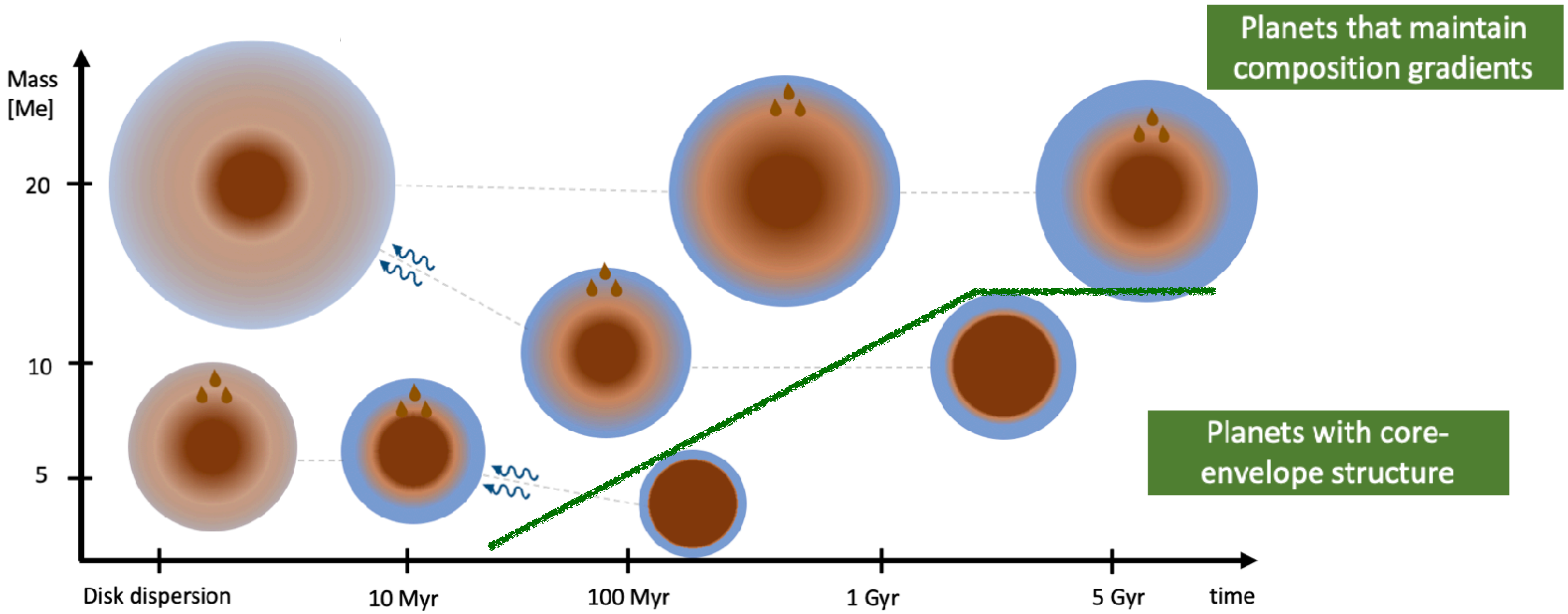
Interior evolution: silicate-rich

Silicate rainout in planets born with polluted envelopes



Rainout
(condensation + settling)

Rainout model is based on silicate saturation curve



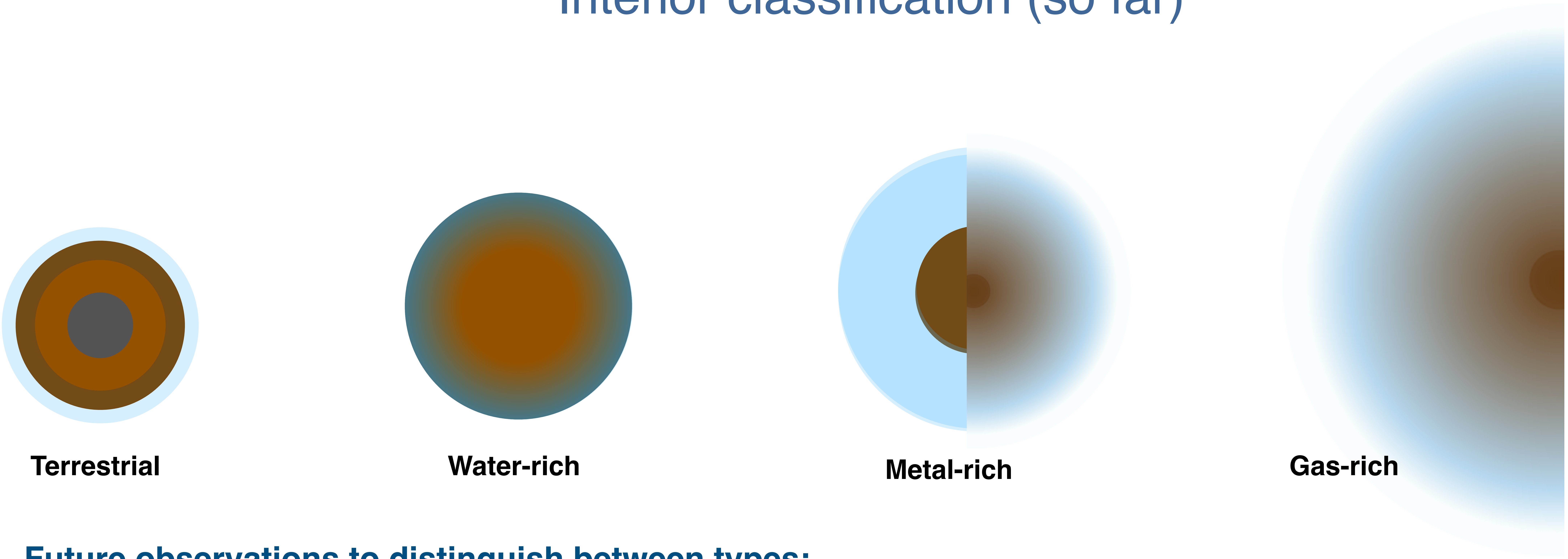
Vazan et al. 2024

Light envelopes => core-envelope structure

Massive envelopes => composition gradients

Planet interior structure

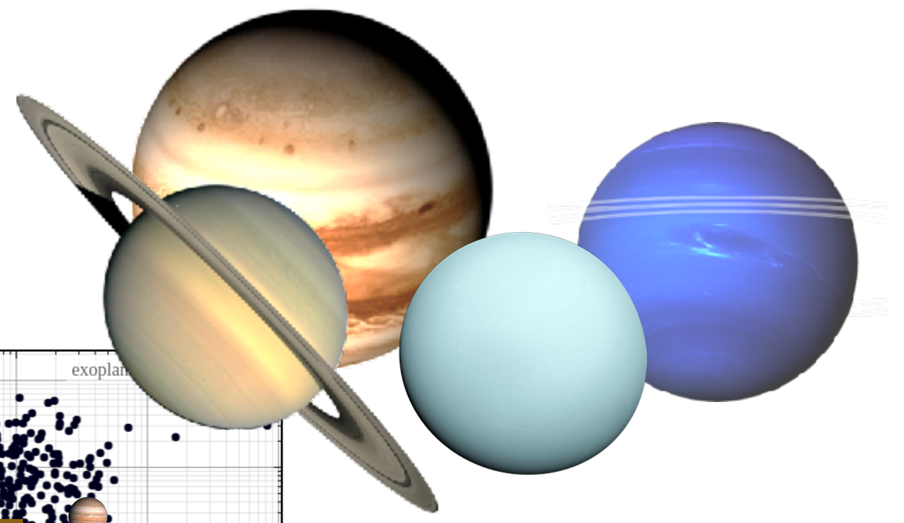
Interior classification (so far)



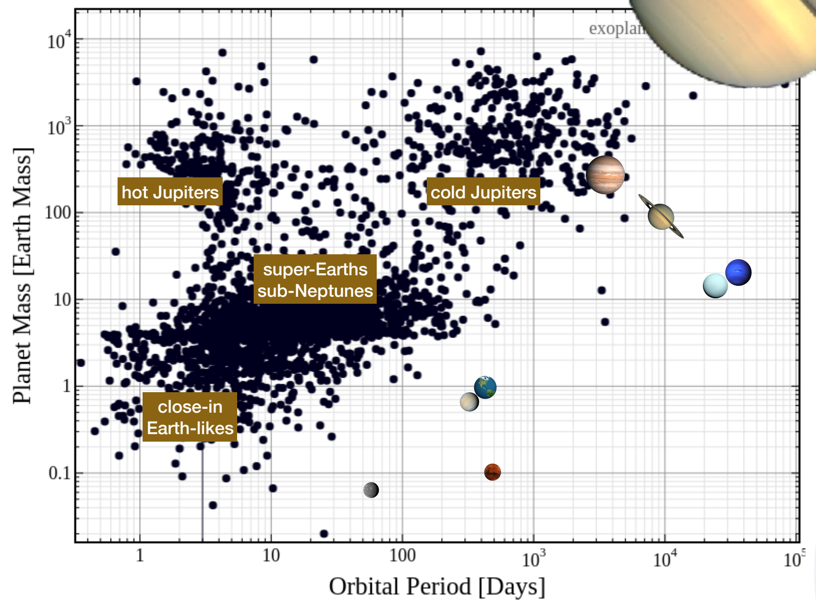
Future observations to distinguish between types:

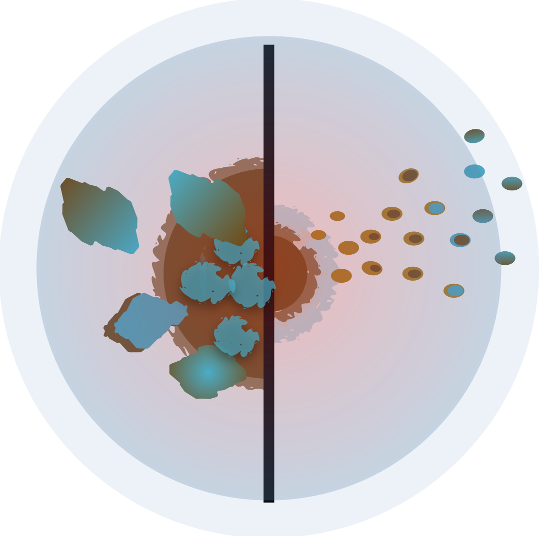
- Atmospheric abundances (JWST, ARIEL)
- Radius-mass relation at higher accuracy (all)
- Age of star (PLATO)
- Cold planets (ROMAN)

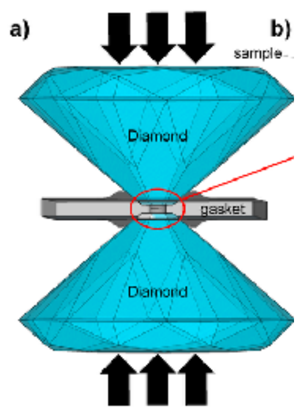
New era for planetary interiors

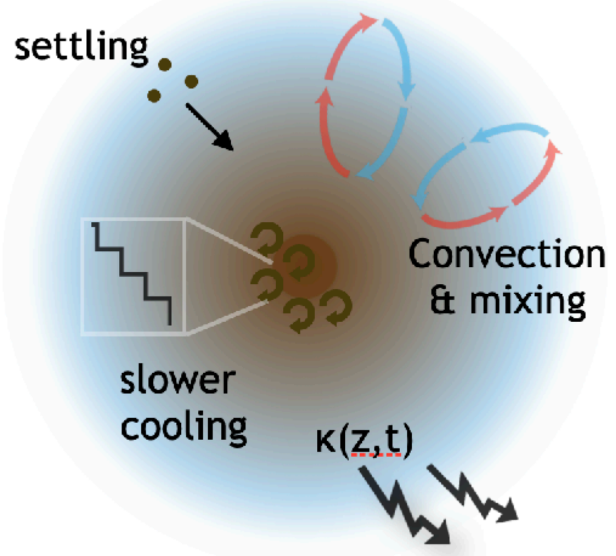


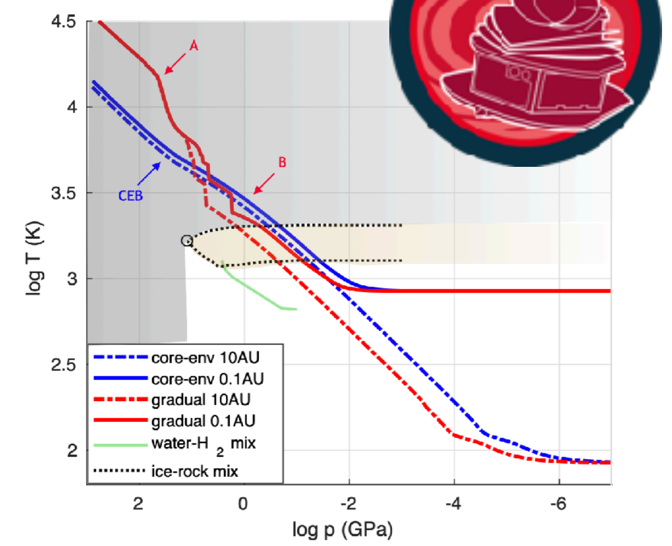
- **Planets are not necessarily structured in 2-4 layers:**
  - Initially <u>polluted envelopes</u> in planets > 2 M⊕ (solid ablation)
- **Composition thermodynamics affect the long-term structure:**
  - Distinct layers as a result of de-mixing and rainout
  - Surface water can be << total water content of a wet planet
- **Thermal evolution is linked to material distribution:**
  - Composition gradients in massive planets
  - Layer-structure in small / dry planets
- **Observation interpretation depends on mixture properties:**
  - Mass-radius relation <=> composition / miscibility / rainout
  - Atmospheric abundances <=> outgassing / rainout / convective-mixing

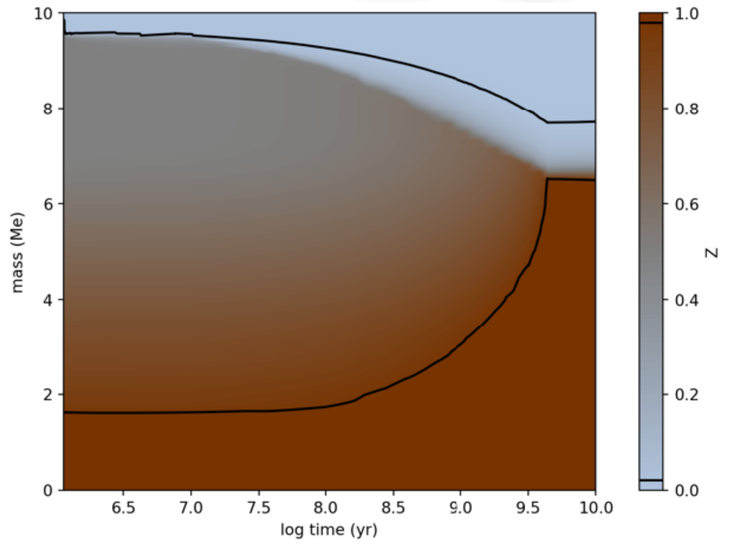












Thank you!