
Water during planet formation and evolution
University of Zurich, 12–16 February 2018
Confirmed Speakers
Til Birnstiel (LMU Munich)
Ilsedore Cleeves (CfA Harvard)
Jay Farihi (University College London)
Keiko Hamano (ELSI, Tokyo Tech.)
Alessandro Morbidelli (Nice Observatory)
Lena Noack (FU Berlin)
Chris Ormel (University of Amsterdam)
Laura Schaefer (Arizona State University)
Alice Stephant (Open University)
Scientific Advisory Board
Yann Alibert (University of Bern)
Ravit Helled (University of Zurich)
Anders Johansen (Lund University)
Martin Jutzi (University of Bern)
Alessandro Morbidelli (Nice Observatory)
Sascha Quanz (ETH Zurich)
Maria Schönbächler (ETH Zurich)
Ewine van Dishoeck (Leiden University)
Meeting Organisers
Joanna Drążkowska (University of Zurich)
Tim Lichtenberg (ETH Zurich)
Caroline Dorn (University of Bern)
Julia Venturini (University of Zurich)
Universität Zürich UZH
waterzurich.github.io
waterzurich@gmail.com

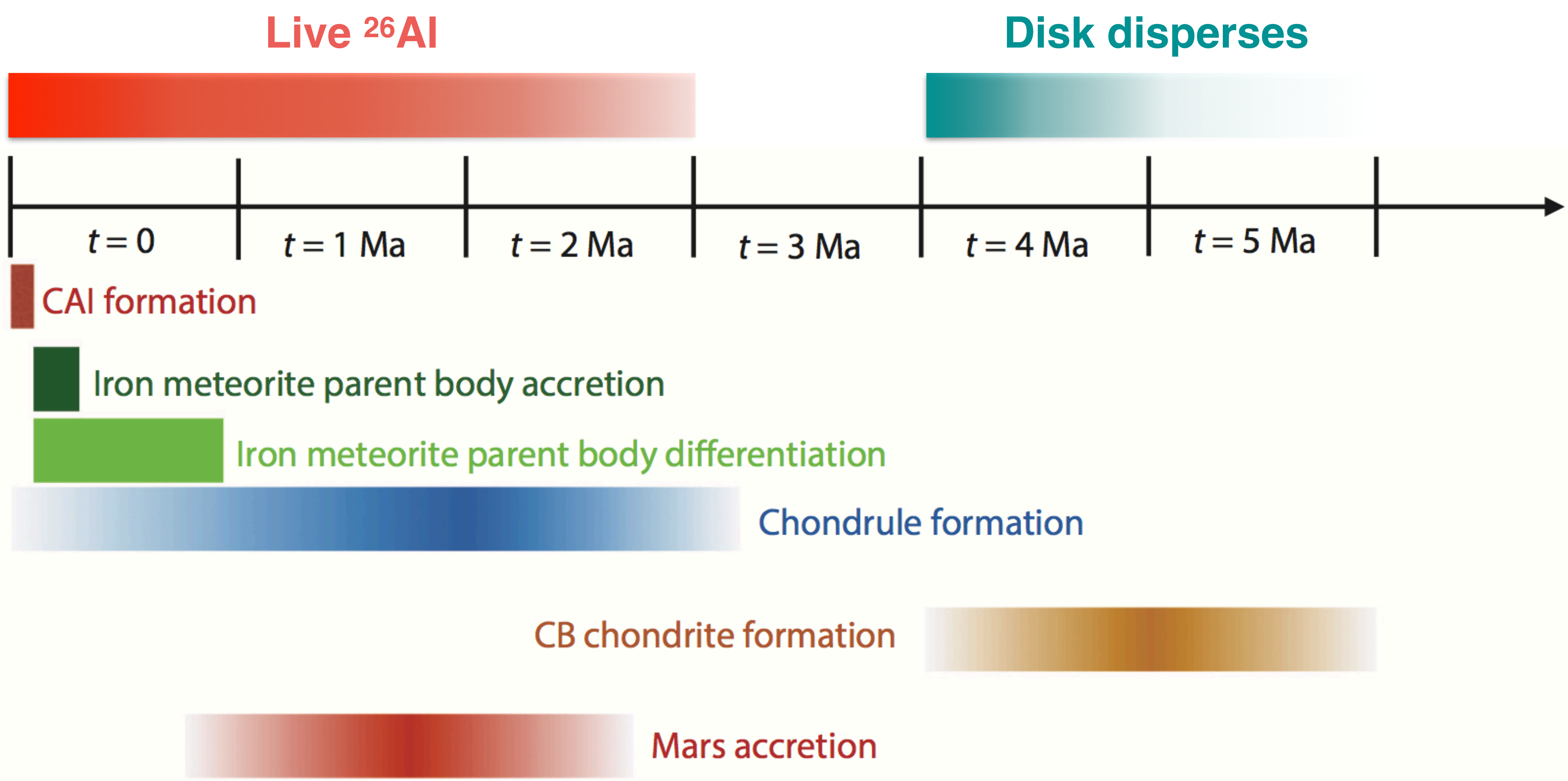
Magma dynamics and devolatilization of planetesimals during planet formation

Gregor J. Golabek (BGI Bayreuth)

BGI Geodynamics

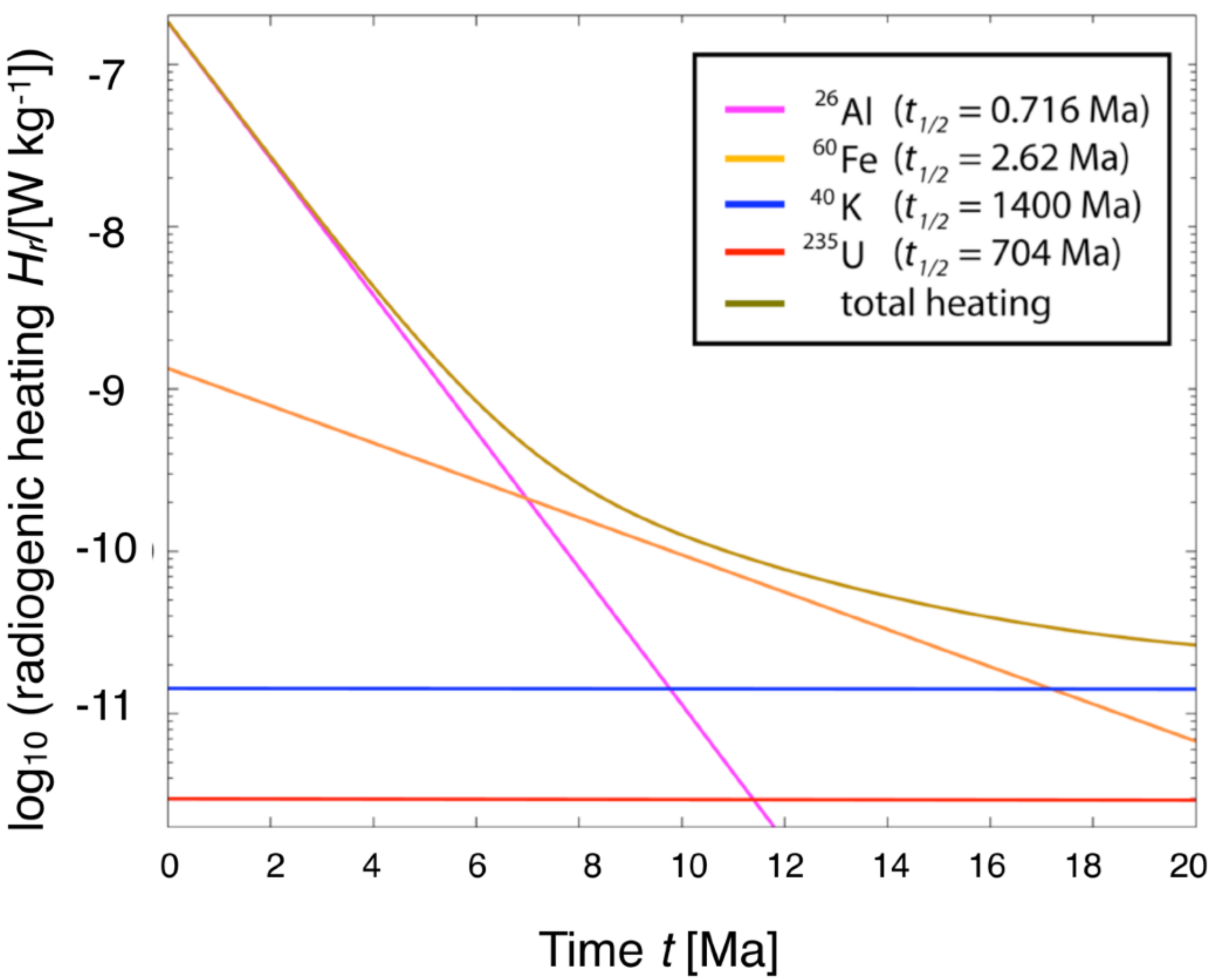
Tim Lichtenberg (ETH Zürich), Michael R. Meyer (U Michigan),
Taras V. Gerya (ETH Zürich), Tobias Keller (Stanford),
Richard F. Katz (Oxford), Yann Alibert (CSH Bern)

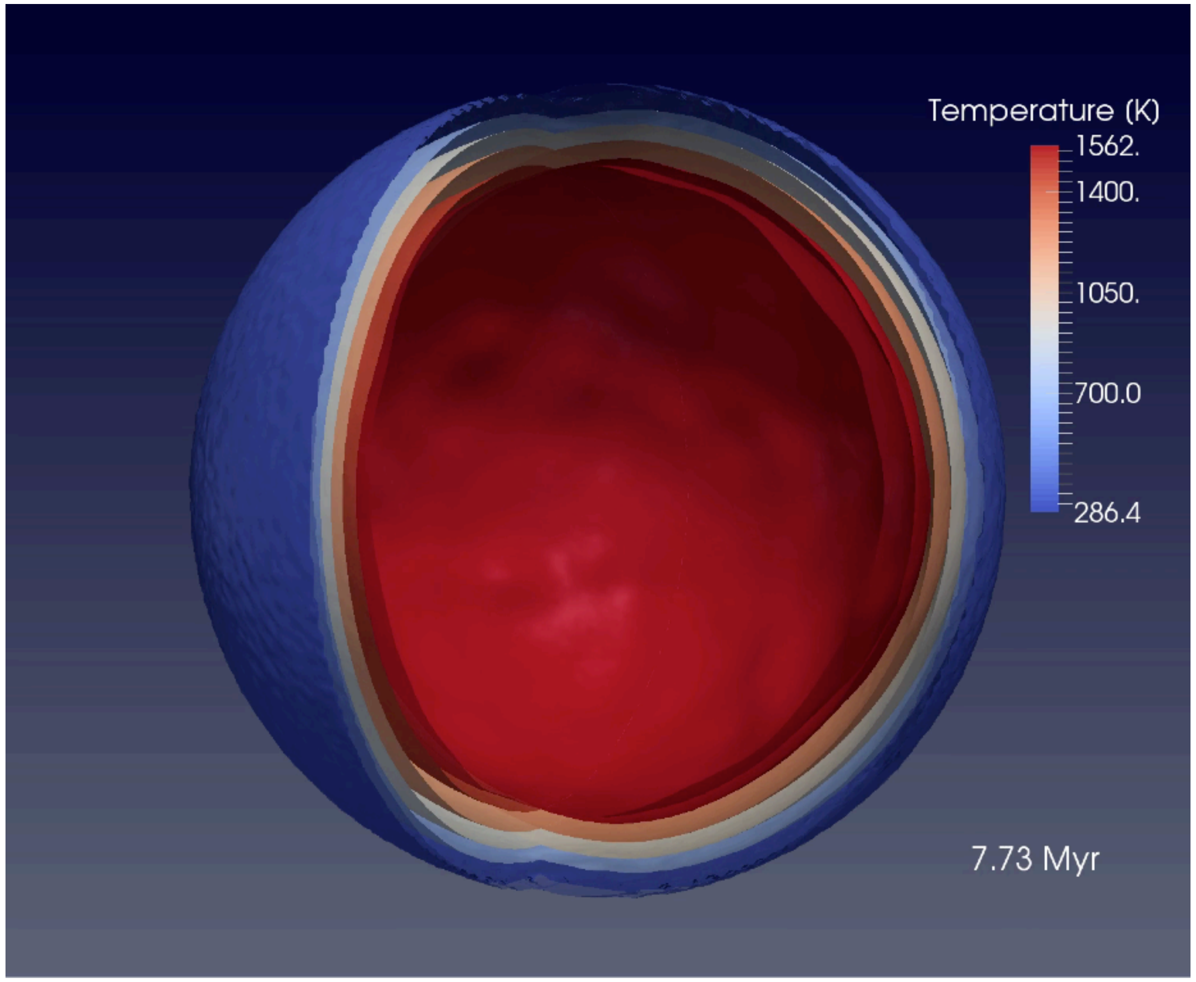
Planet formation: solar system materials



Modified from Nittler & Ciesla 16

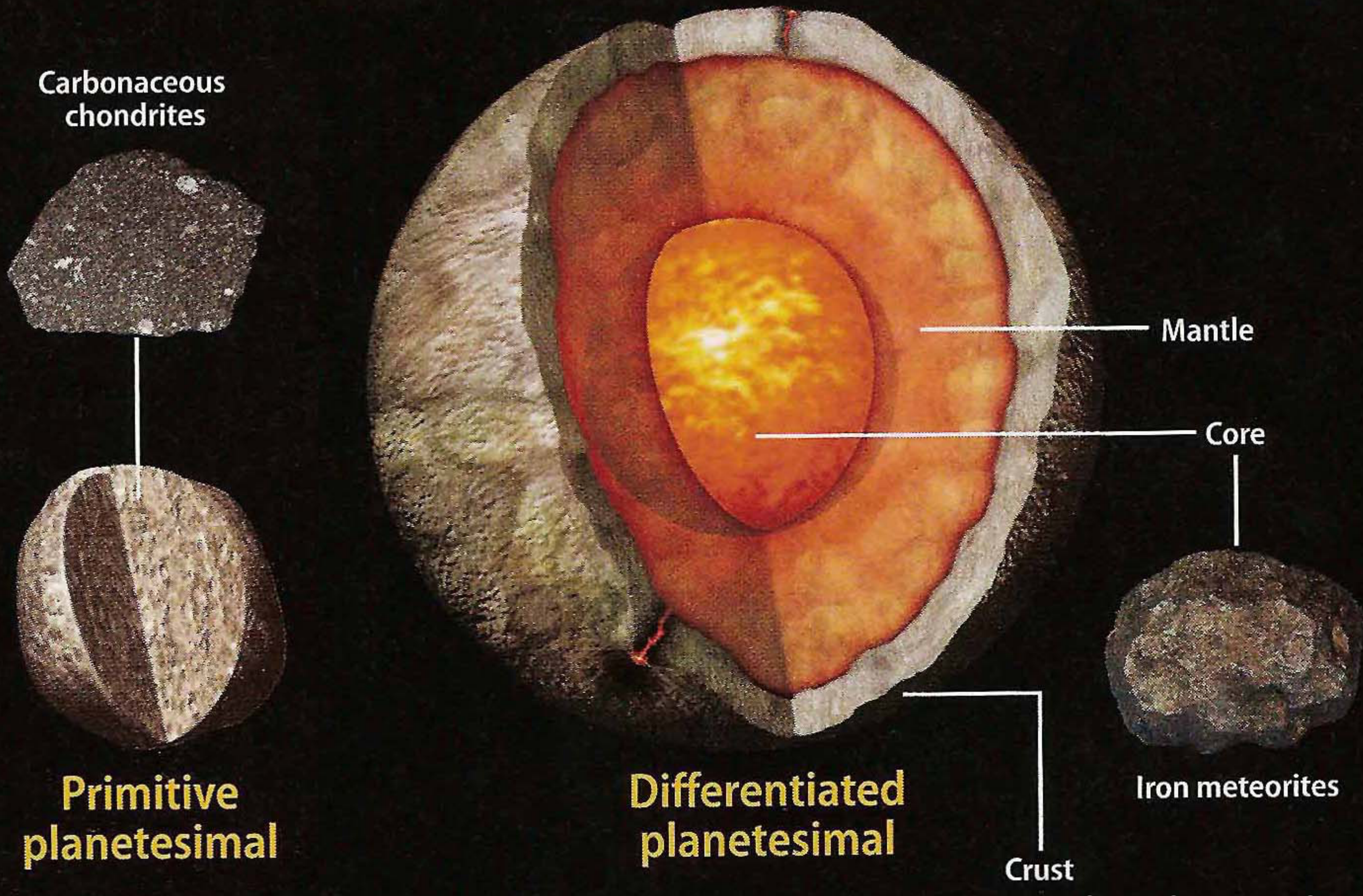
Planetesimal evolution regimes





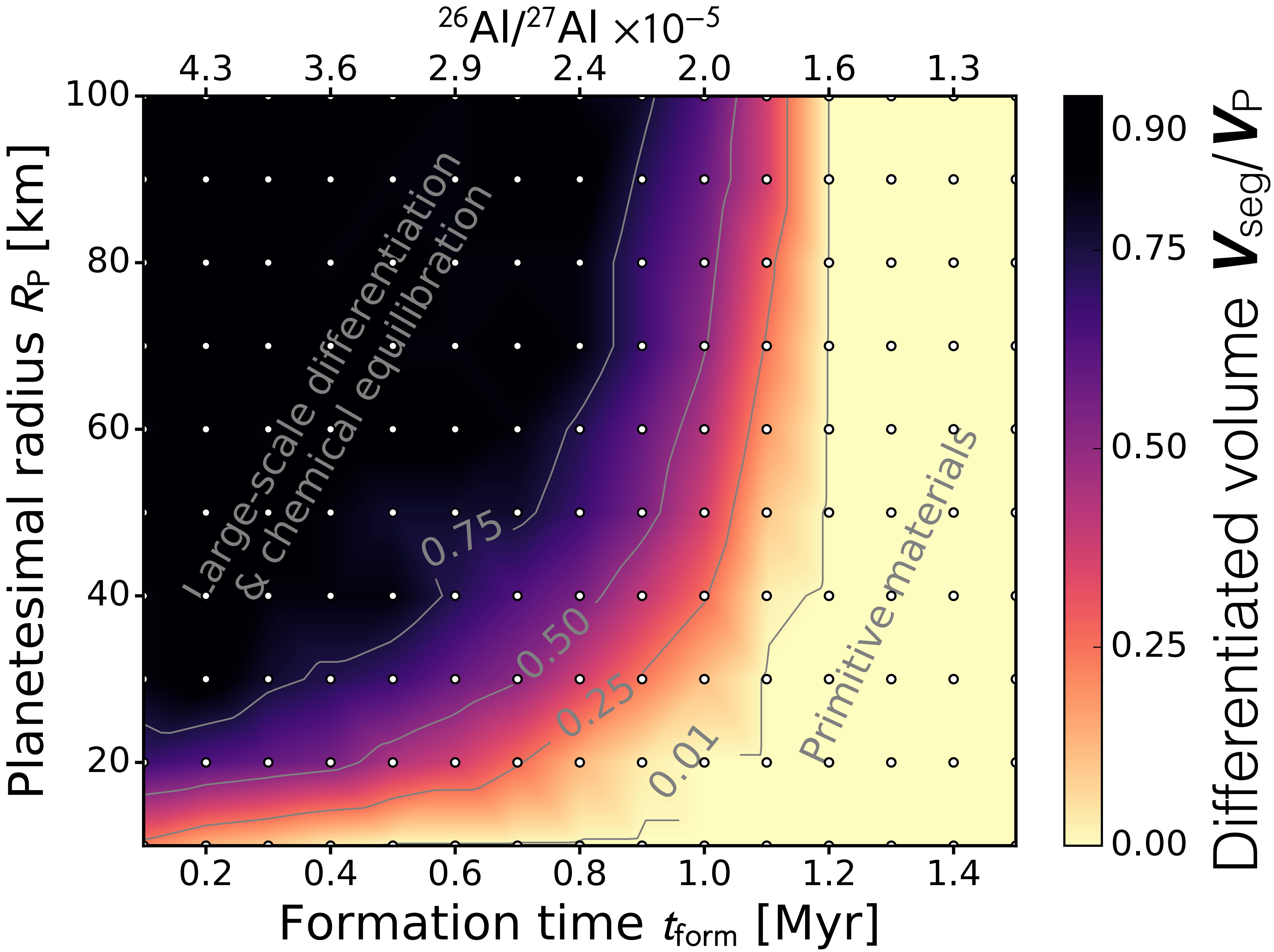
Lichtenberg, Golabek, Gerya, Meyer 16

Meteorite origins



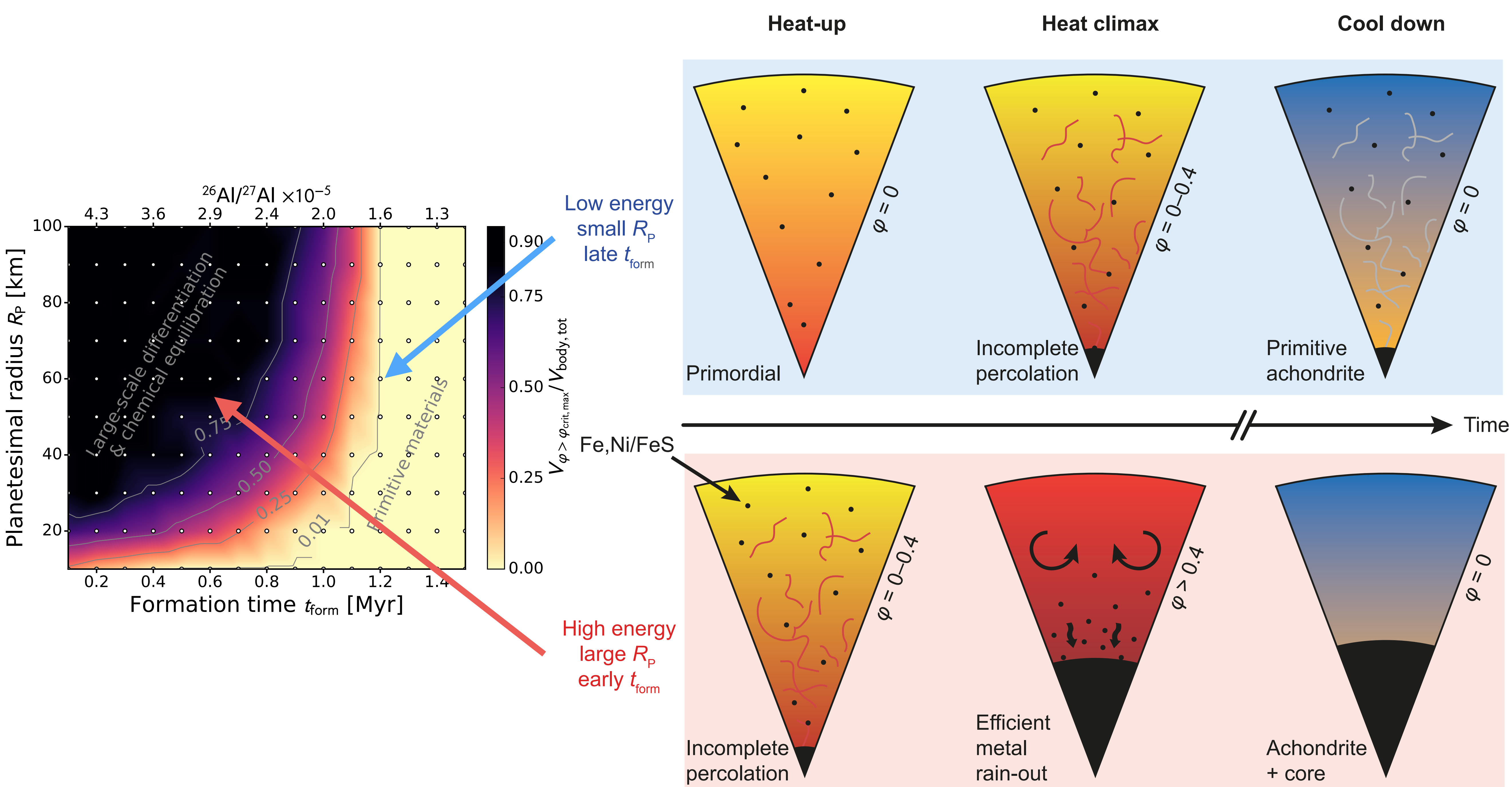
Sarah Stewart, UC Davis

Thermo-mechanical interior evolution



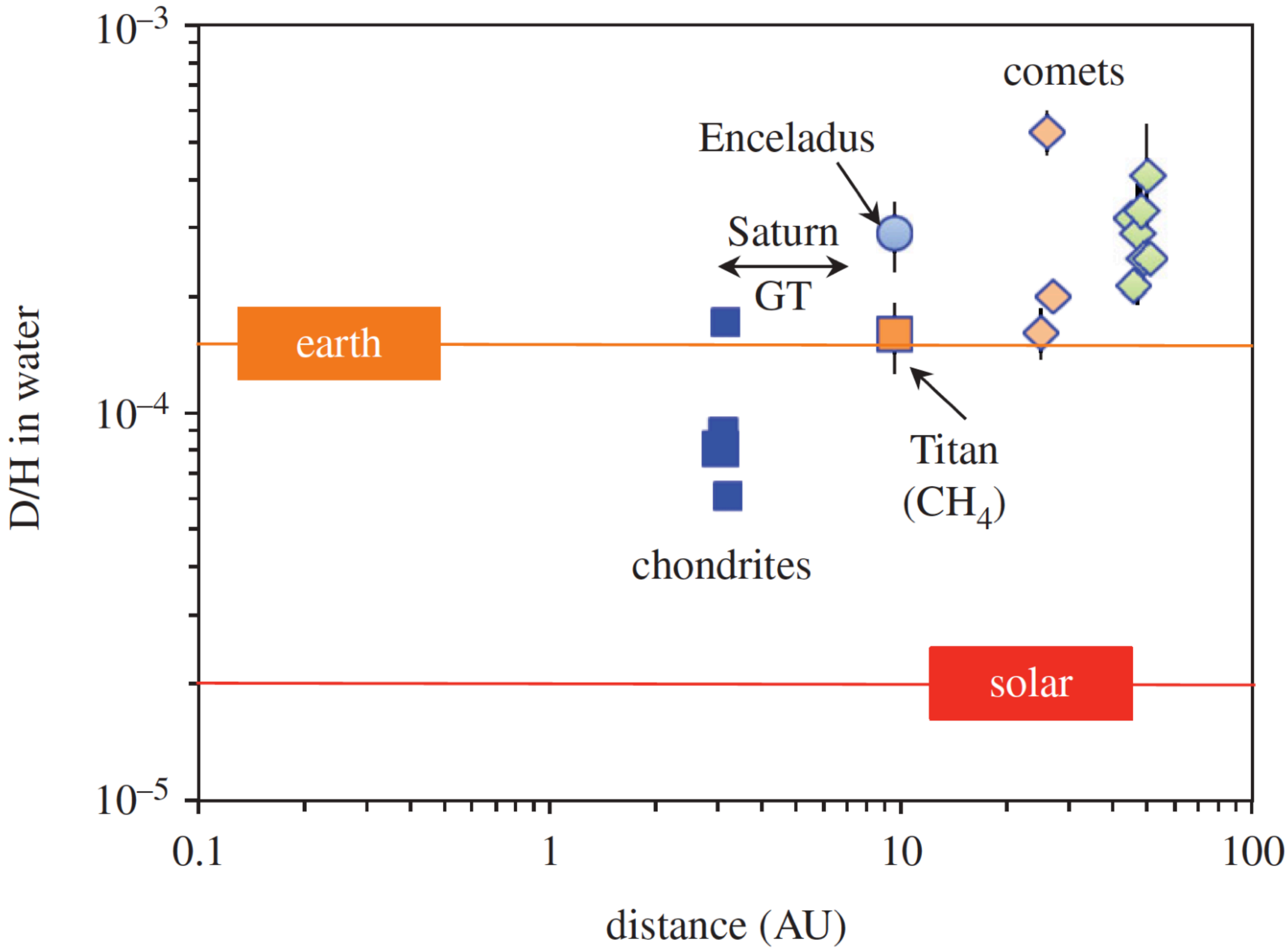
Lichtenberg, Golabek, Dullemond, Schönbächler, Gerya, Meyer (2017, in rev.)

Thermo-mechanical interior evolution



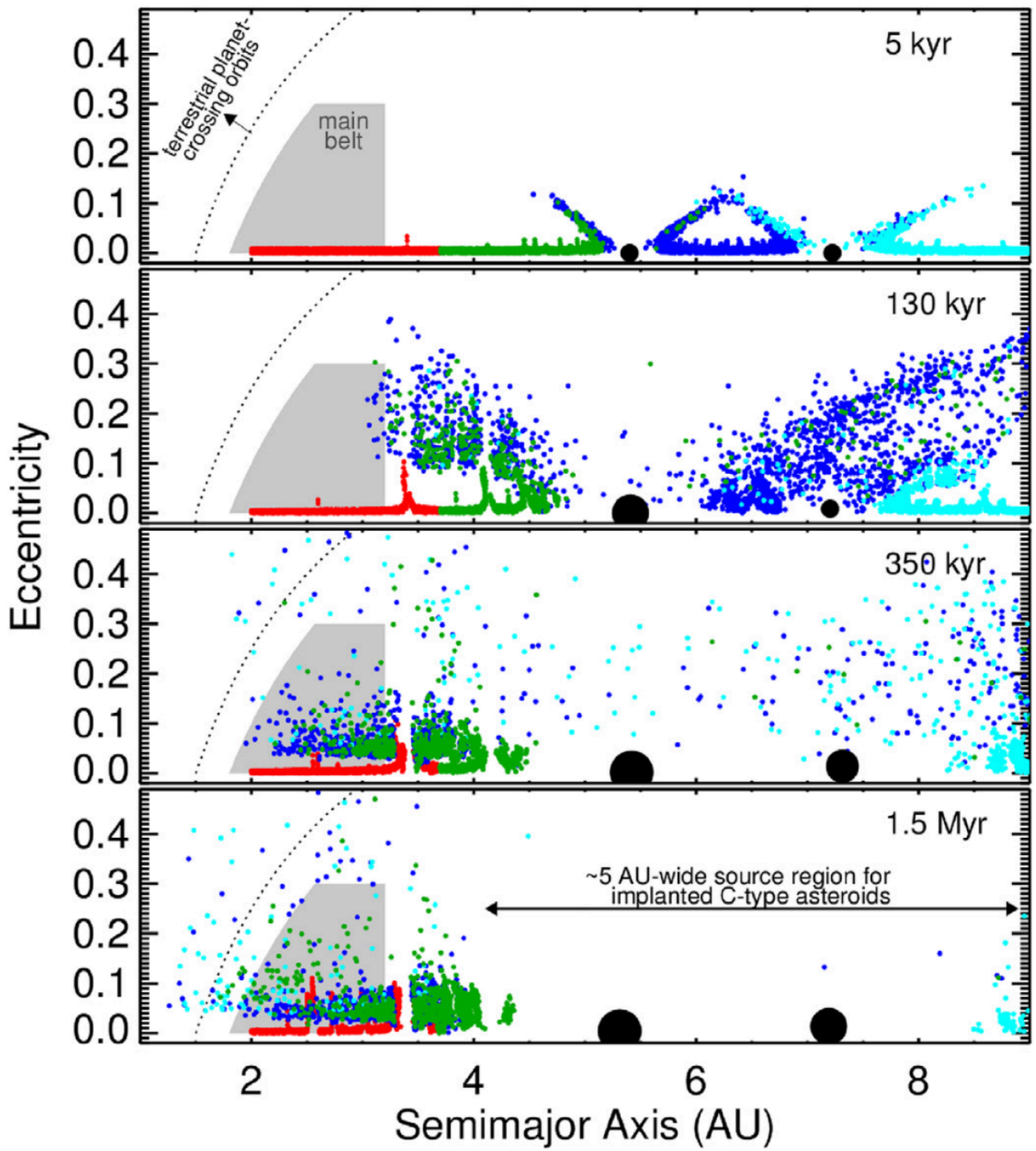
Lichtenberg, Golabek, Dullemond, Schönbächler, Gerya, Meyer (2017, in rev.)

Delivery of Earth’s water



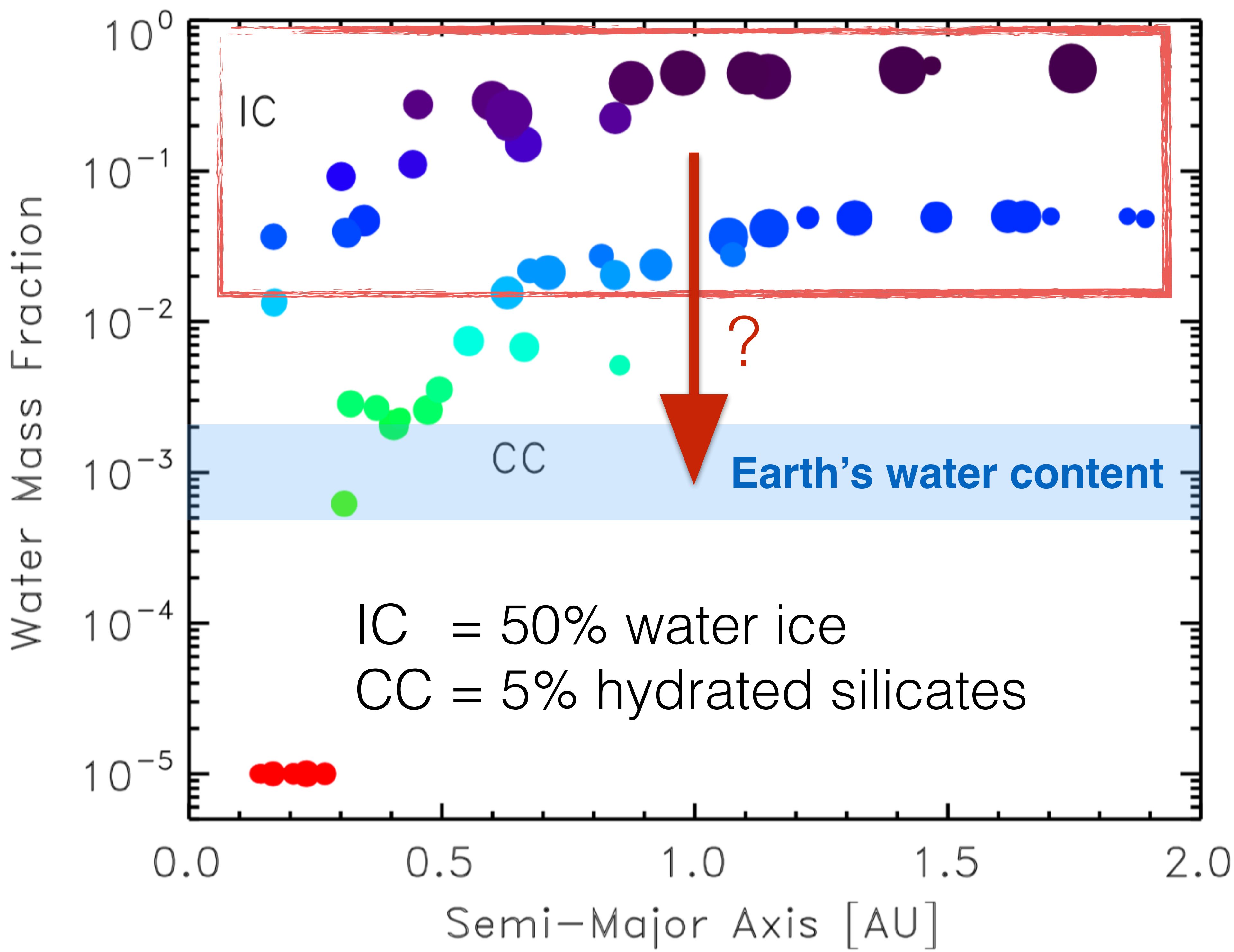
Alexander 17

Water delivery during accretion



Raymond & Izidoro 17a

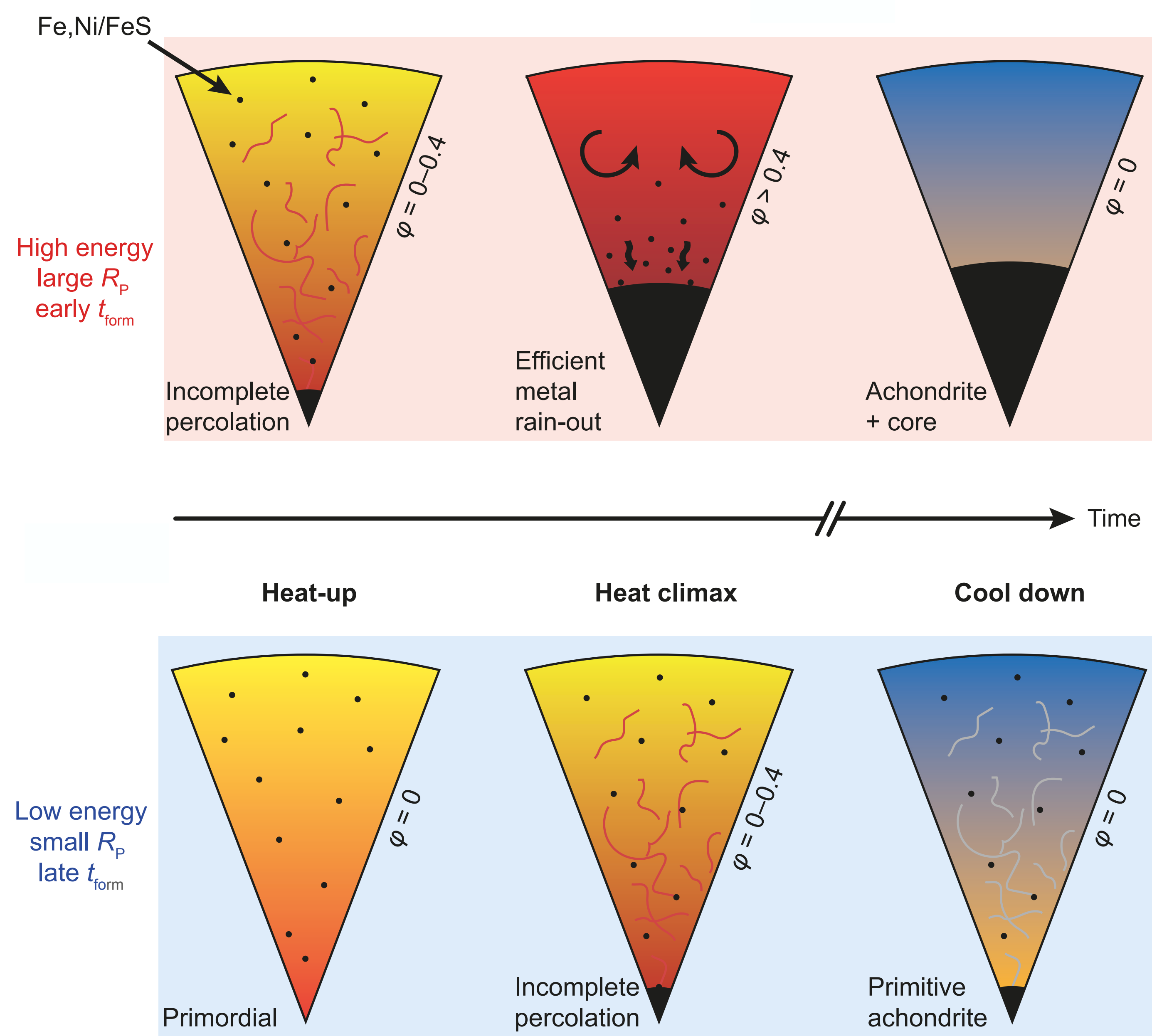
Fine-tuning Earth-like water abundances



Ciesla+ 15, Mulders+ 15

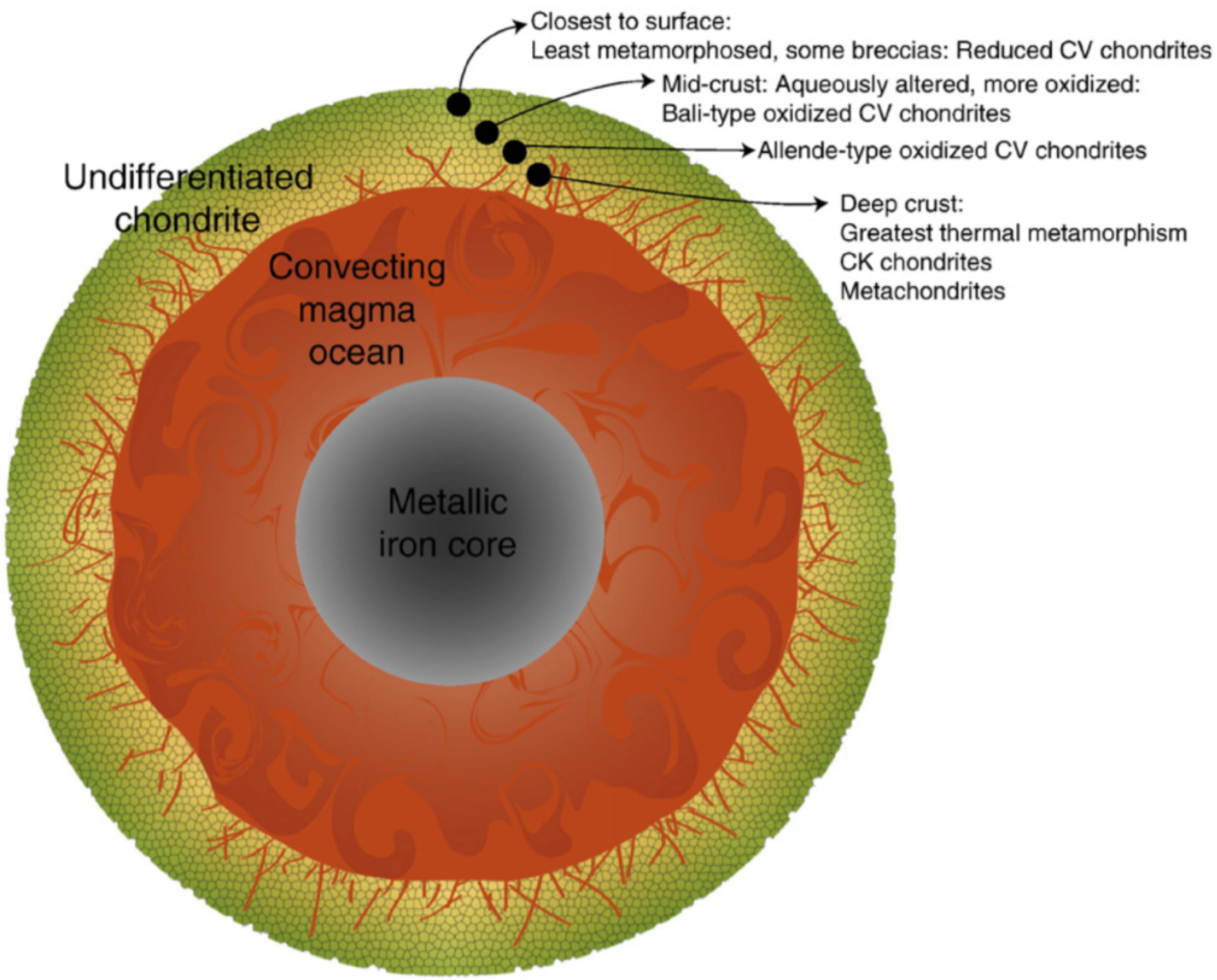
Consequences?

1. **High energy: silicate melting & differentiation**
   - Radiogenic heating, connection to meteorites
   - Magma-rock overturn?
2. **Low energy: fluid flow and volatile outgassing**
   - Dehydration of planetary materials?
   - Water delivery to terrestrial planets?



Lichtenberg, Golabek, Dullemond, Schönbächler, Gerya, Meyer (2017, in rev.)

Part I: Not so ‘onion’ after all?



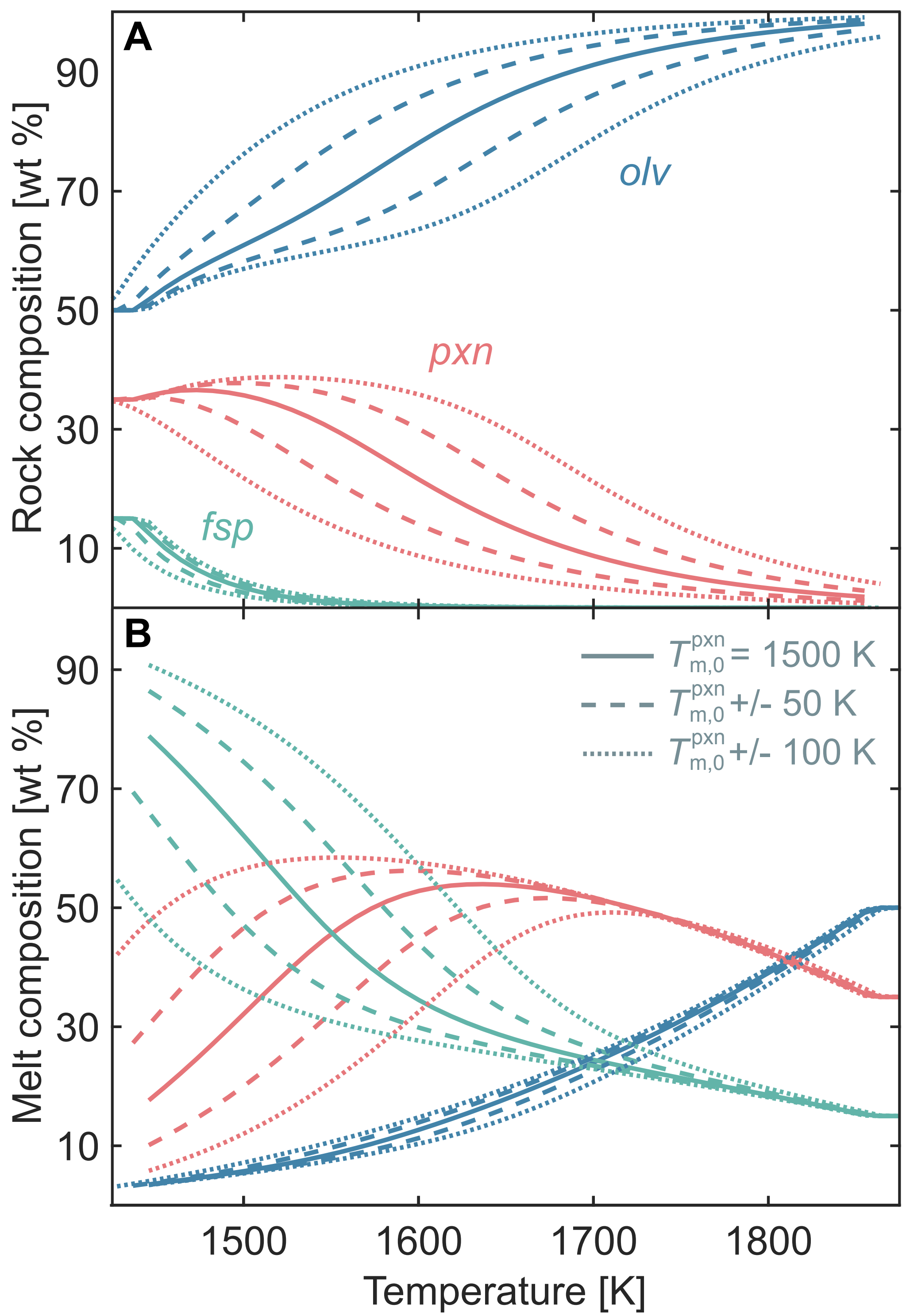
The ‘onion shell’ model

- Thermal evolution usually assume that melt and solid **do not separate**
- However: **Silicate melt** may be **buoyant** relative to planetesimal mantle
  - Planetesimals stripped of their heat source? Magma oceans at all?
  - Primordial crust preserved? Internally differentiated objects among C-complex-like asteroids? —> (21) Lutetia

Elkins-Tanton+ 11

Wilson & Keil 12, 16, 17; Sierks+ 11; Pätzold+ 11; Weiss+ 12; DeMeo+ 16

Thermo-chemical two-phase model



Lichtenberg, Keller, Katz, Golabek, Gerya (in prep.)

- Split up planetesimal rock body into multiple components, follow individually
- **Two-phase, thermo-chemical** evolution in 1D-column models (*R_DMC* method)
- 'Dry' compositional setup:
  - Olivine (~50%, refractory)
  - Pyroxene (~35%, fertile)
  - Feldspar (~15%, **^{26}Al**)
- Varying solid-melt density contrast, grain sizes (permeability), planetesimal radius, formation time, …

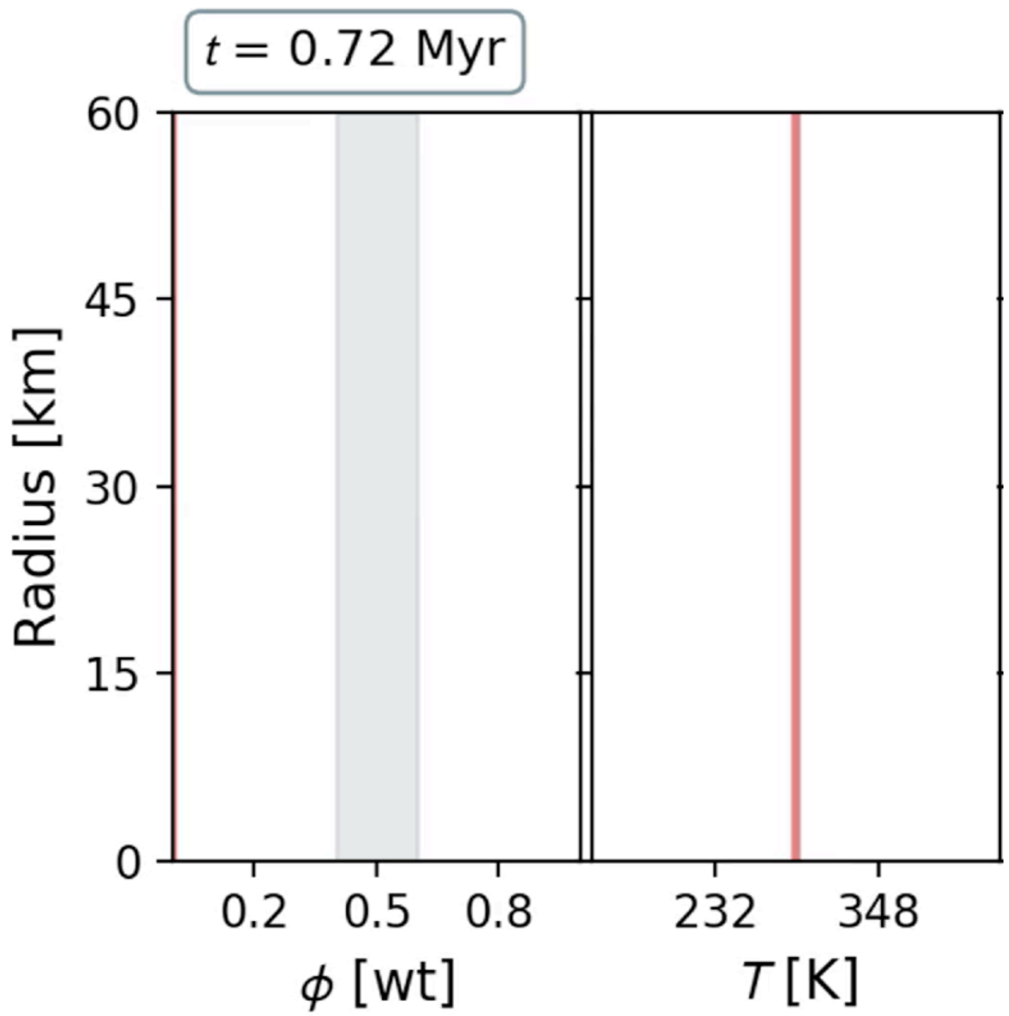
Keller & Katz 16; Keller, Katz & Hirschmann 17

Large-scale melting

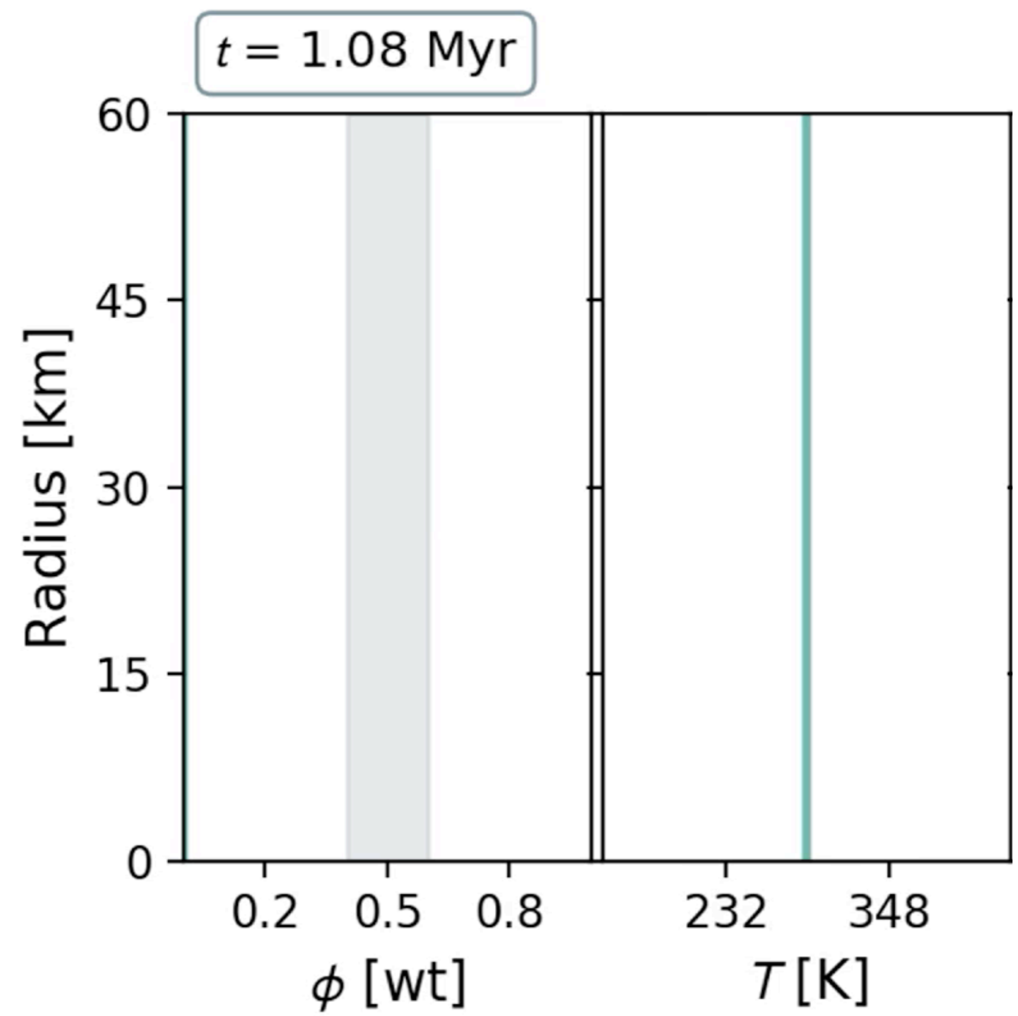
‘Magma ocean’

‘Magma sill’

RP = 60 km



t_{form} = 0.72 Myr, grain size ***a*** = 0.1 mm



t_{form} = 1.08 Myr, grain size ***a*** = 10 mm

Lichtenberg, Keller, Katz, Golabek, Gerya (in prep.)

Melt segregation efficiency

Melt segregation

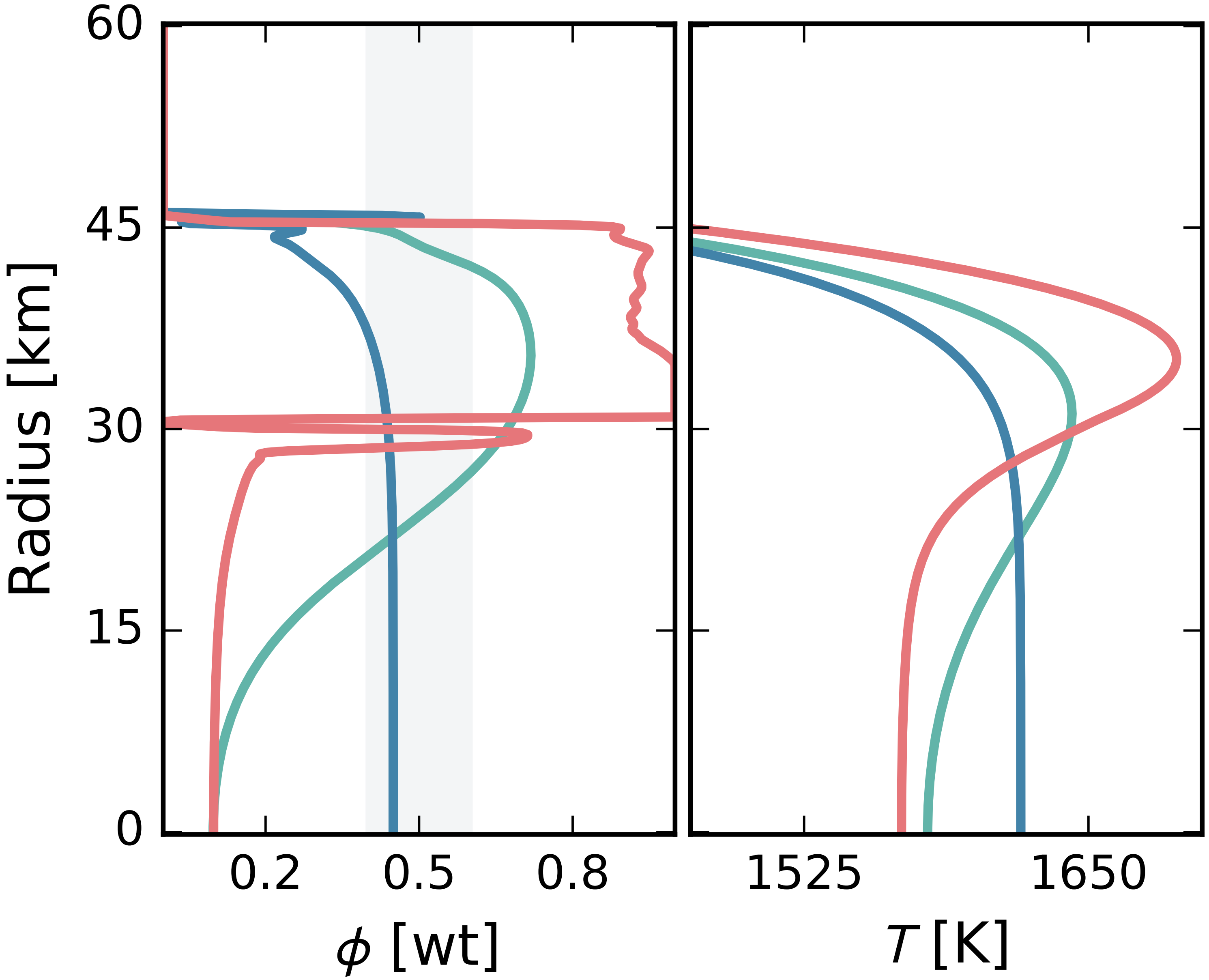
$\Delta\phi = \phi_{max} - \phi_{center}$

Temperature anomaly

$\Delta T = T_{max} - T_{center}$

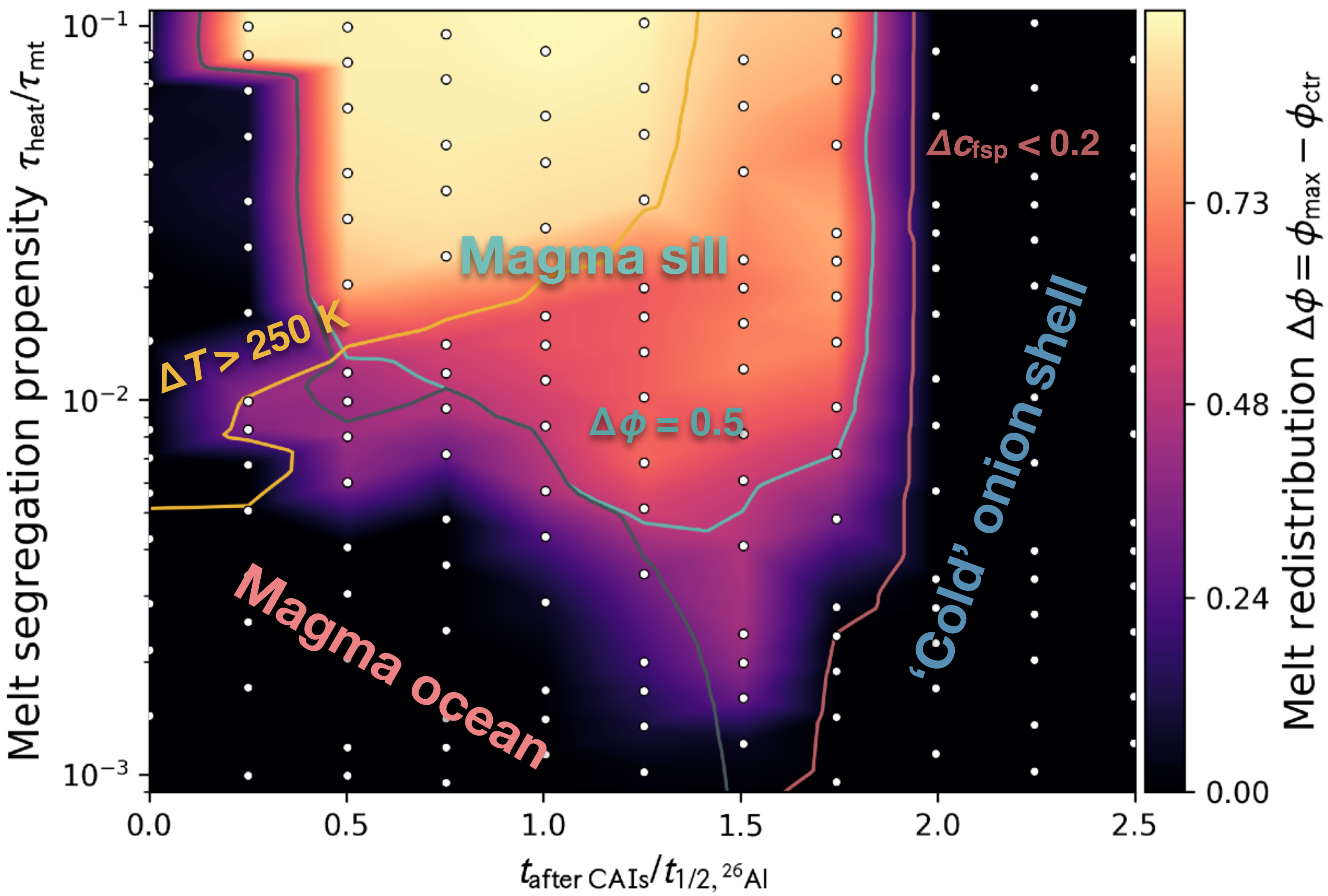
^{26}Al redistribution

$\Delta c_{fsp} = c_{fsp,max} - c_{fsp,center}$



Lichtenberg, Keller, Katz, Golabek, Gerya (in prep.)

Melt segregation regimes



Melting timescale

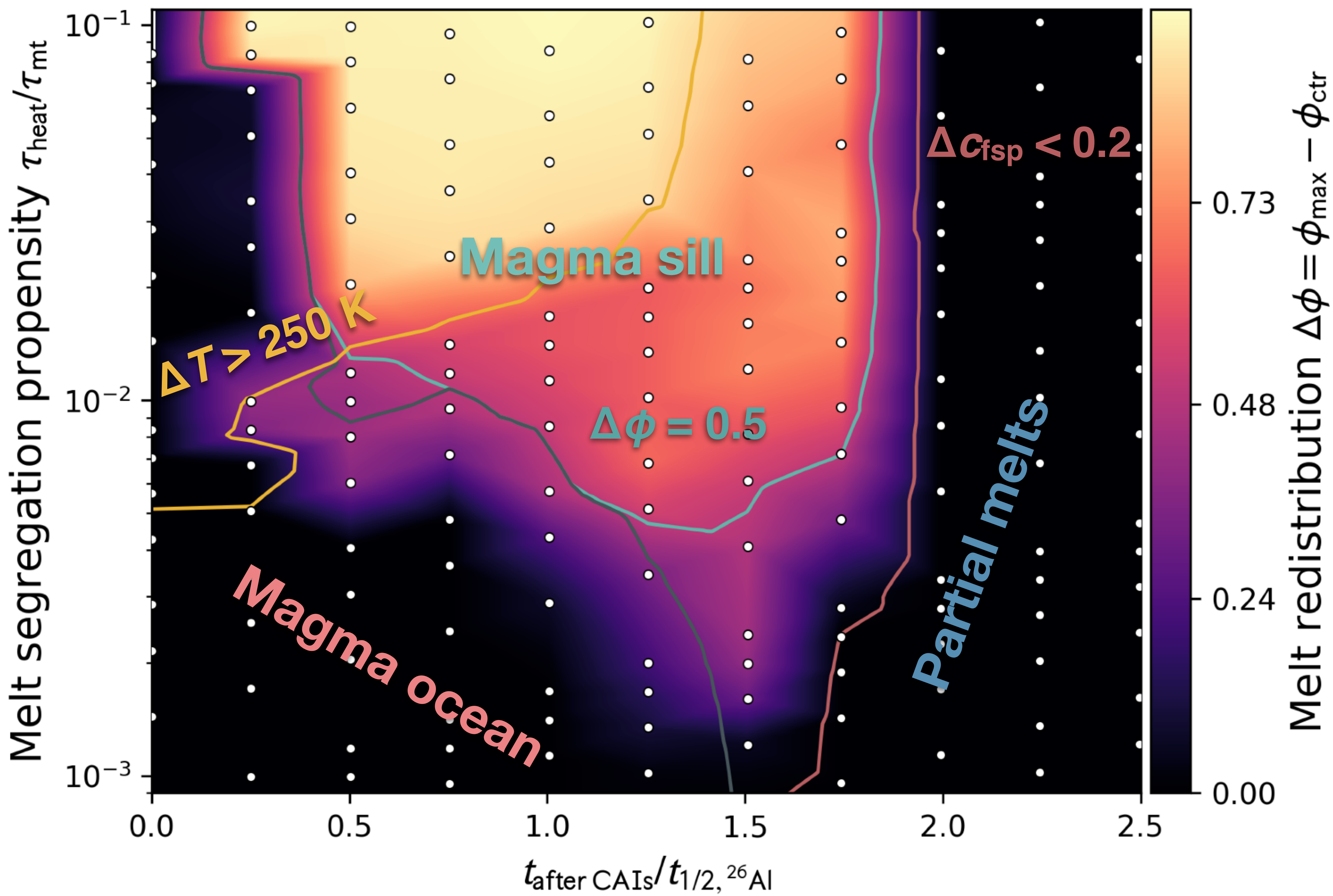
$$\tau_{heat} = c_p \cdot \Delta T \, / \, H_{Al}(t)$$

Melt transport timescale

$$\tau_{mt} = \frac{R_P}{2} \, / \, w_s$$

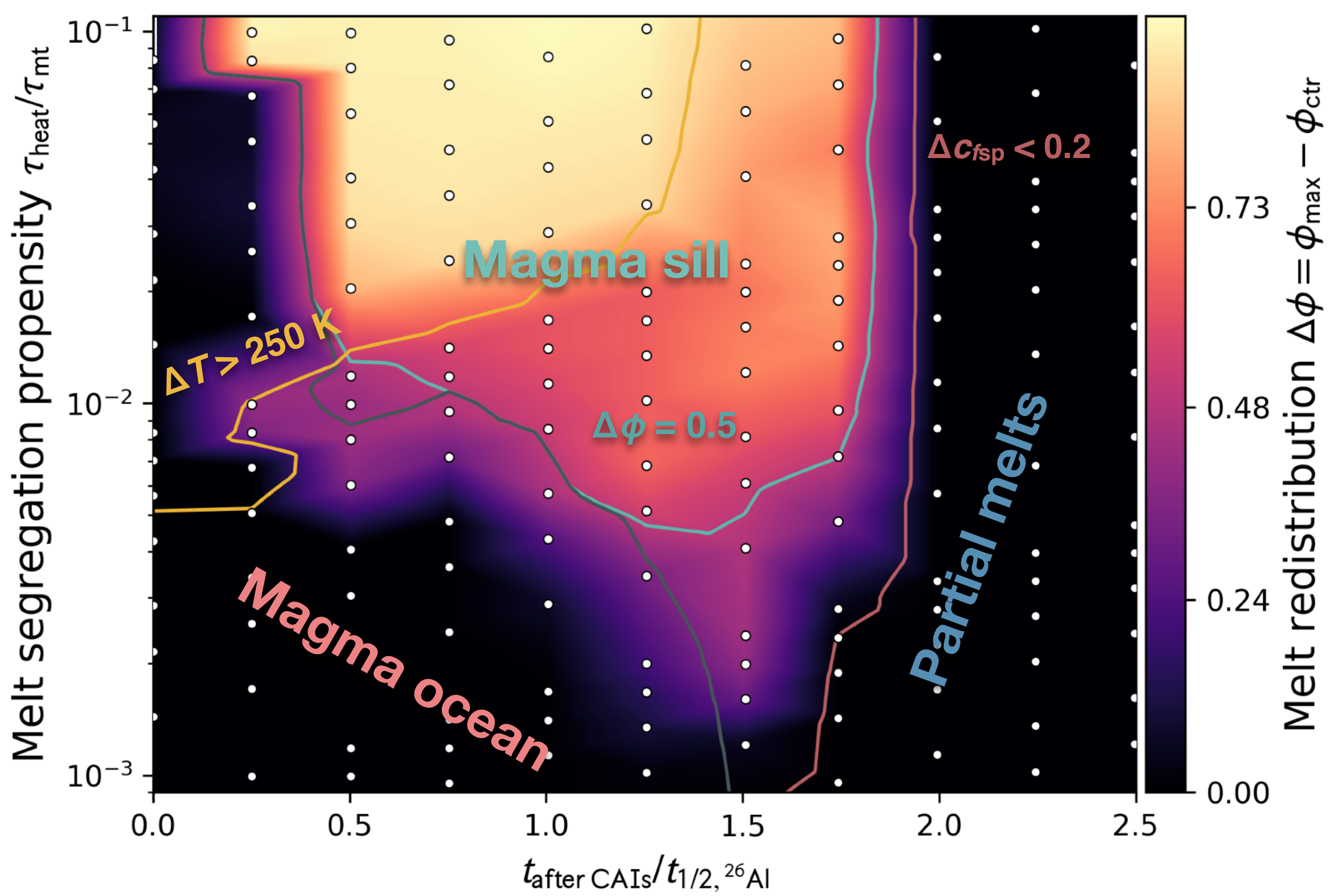
Lichtenberg, Keller, Katz, Golabek, Gerya (in prep.)

Melt segregation regimes

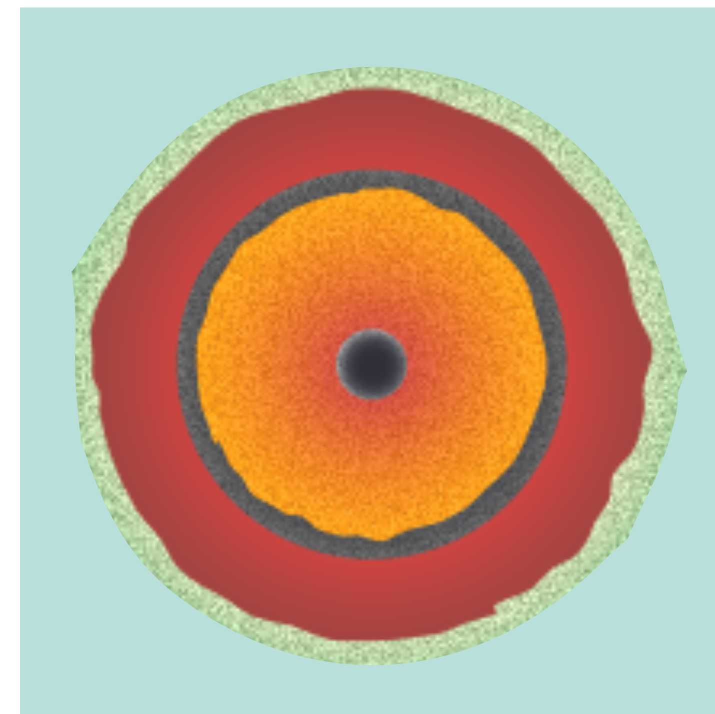


Lichtenberg, Keller, Katz, Golabek, Gerya (in prep.)

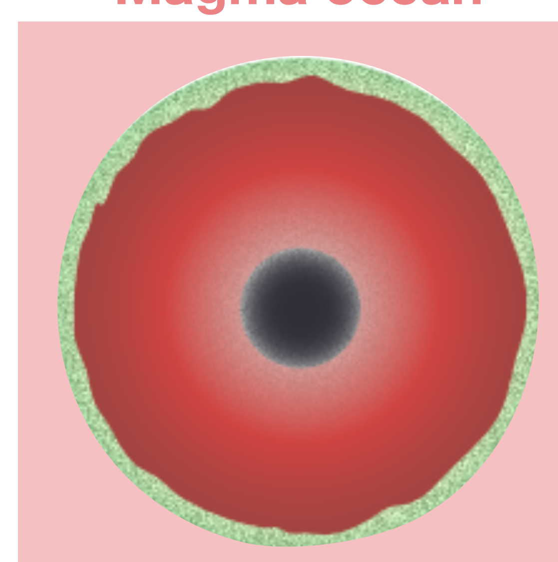
Summary I – Silicate melt ascension



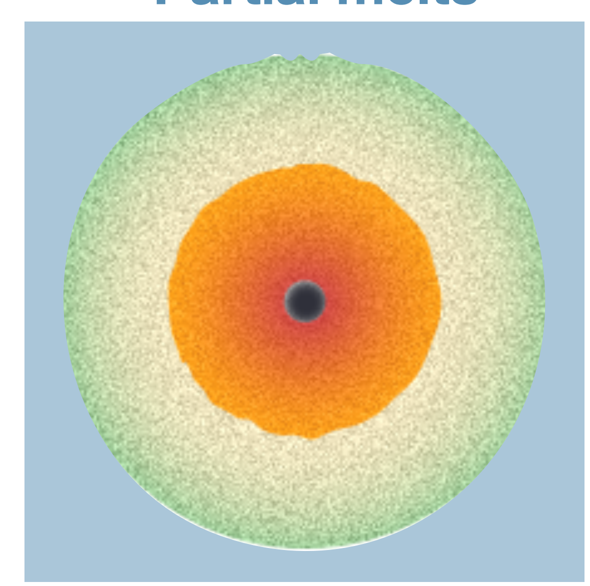
Magma sill



Magma ocean

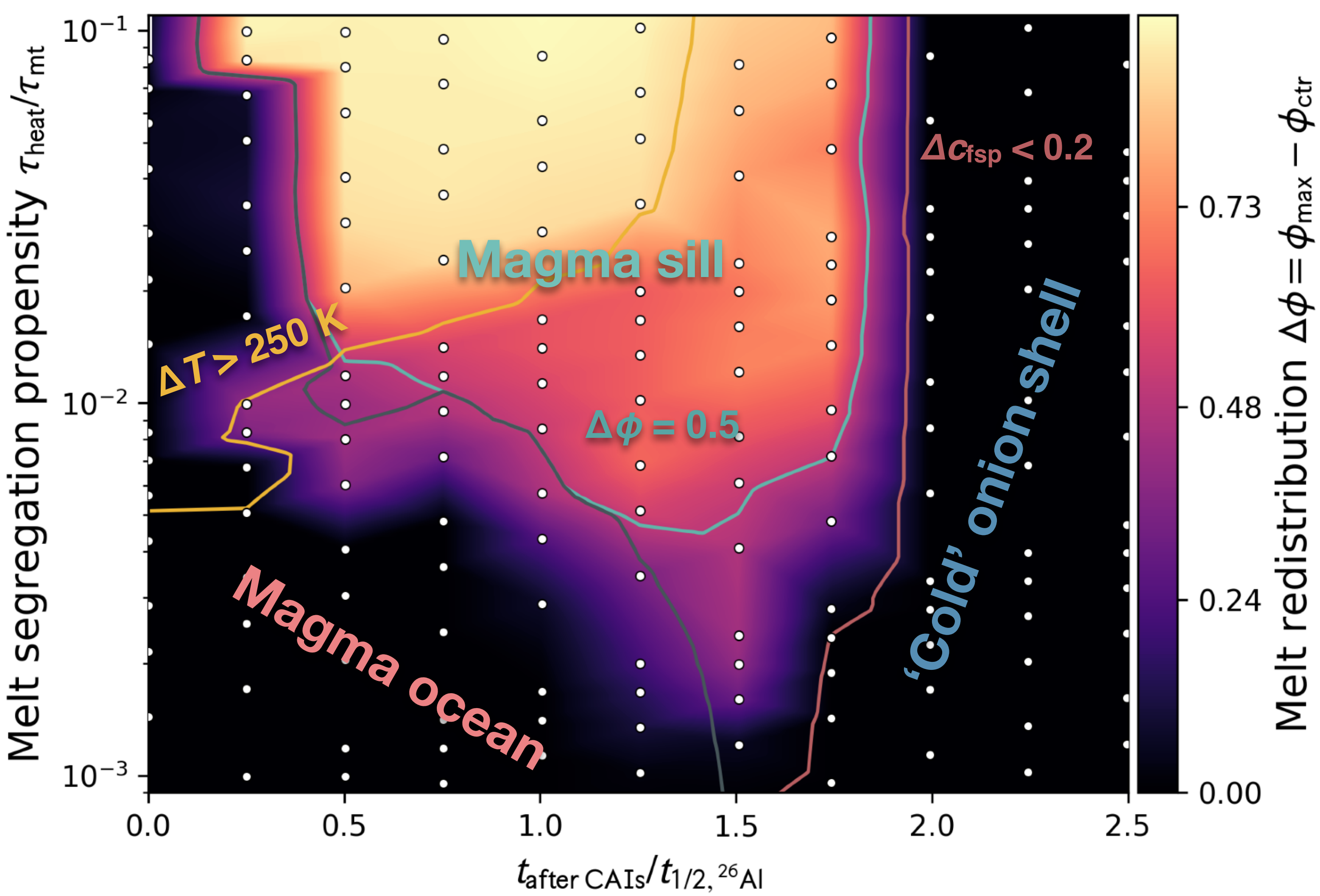


Partial melts



Lichtenberg, Keller, Katz, Golabek, Gerya (in prep.)

Summary I – Silicate melt ascension

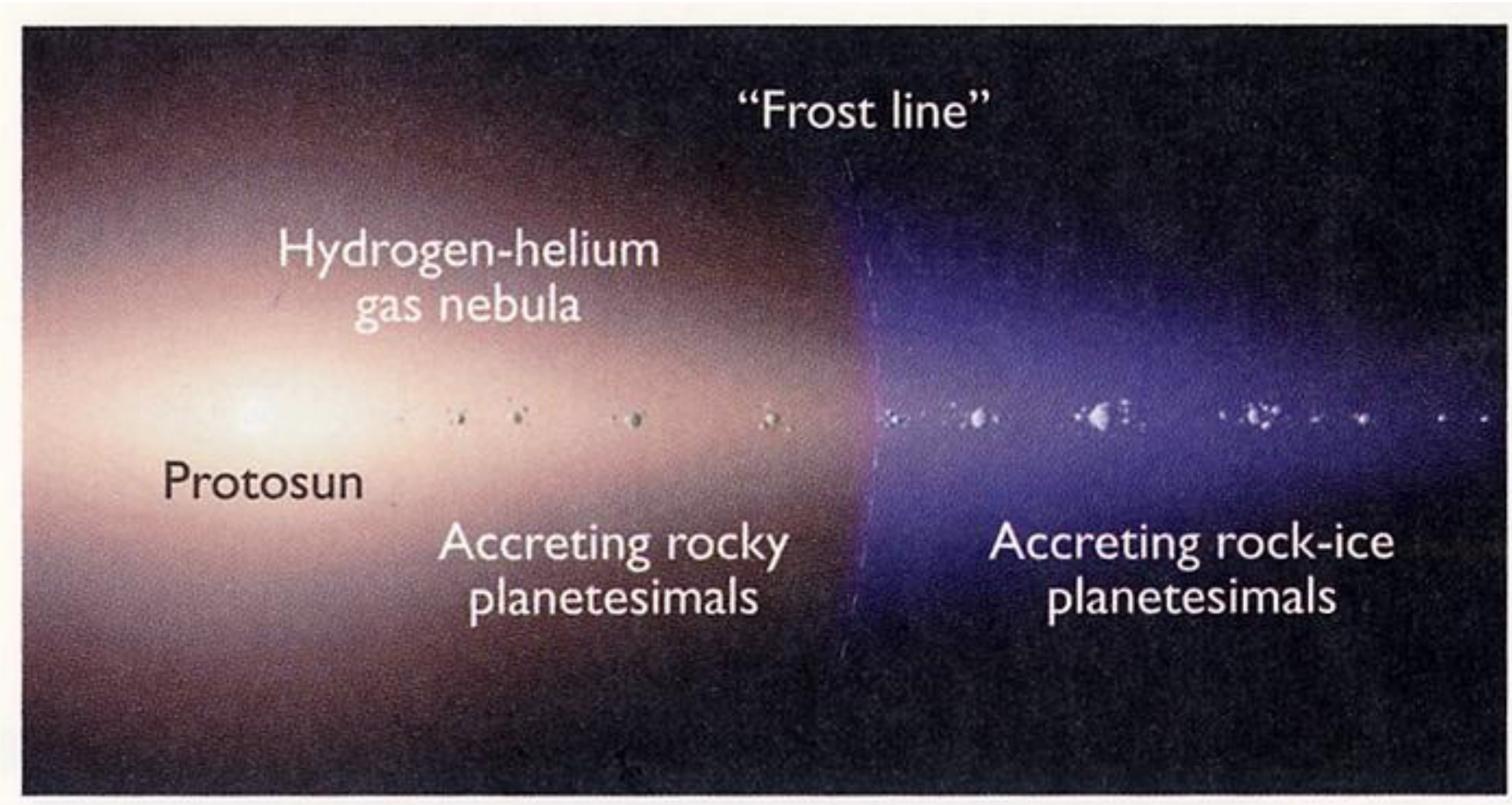


- Melt ascension **crucially dependent on grain size**
- Al partitioning does not generally deplete heat source

➡ Structural & compositional state can be related to **evolutionary tracks**

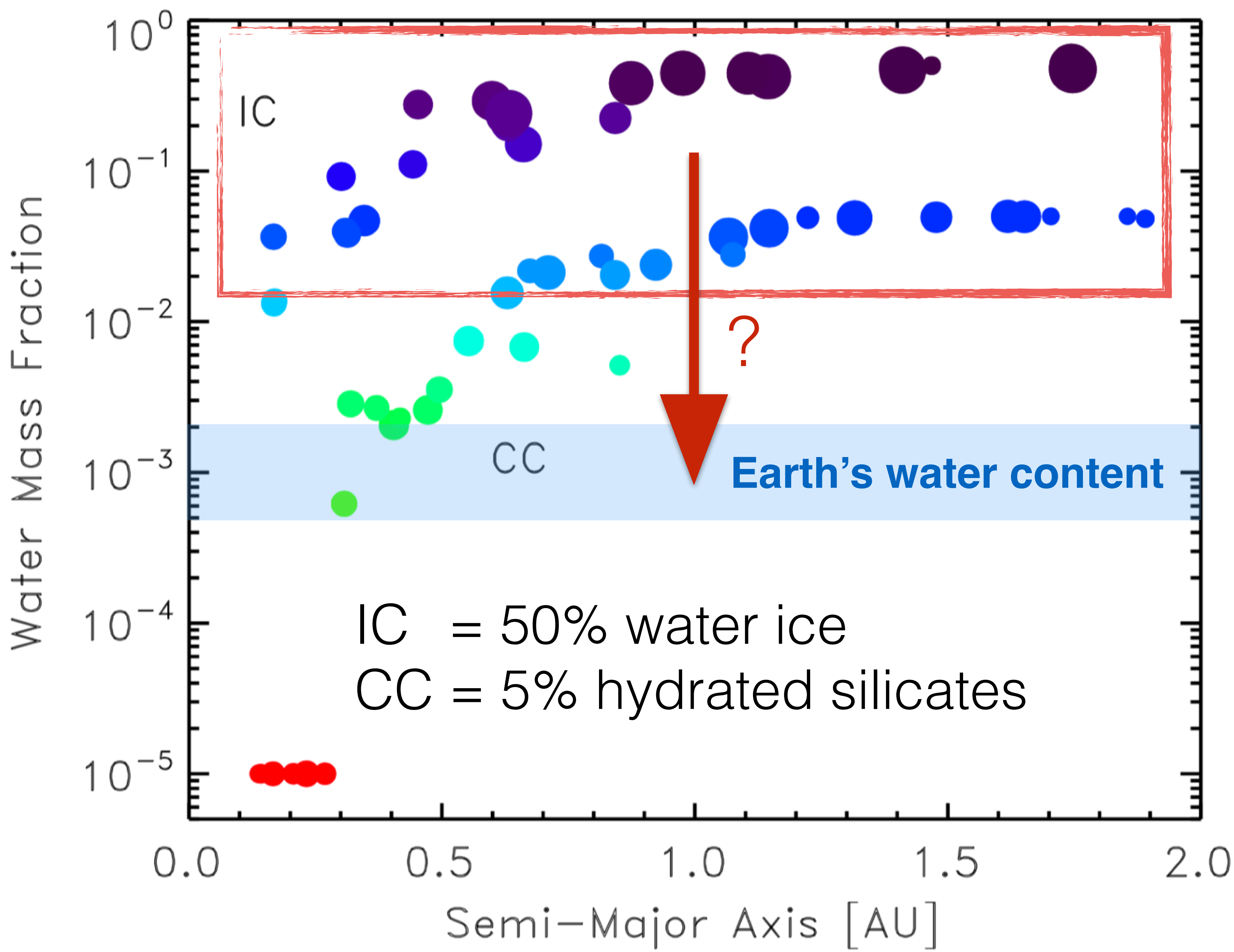
Lichtenberg, Keller, Katz, Golabek, Gerya (in prep.)

Part II: Dehydration of planetesimals



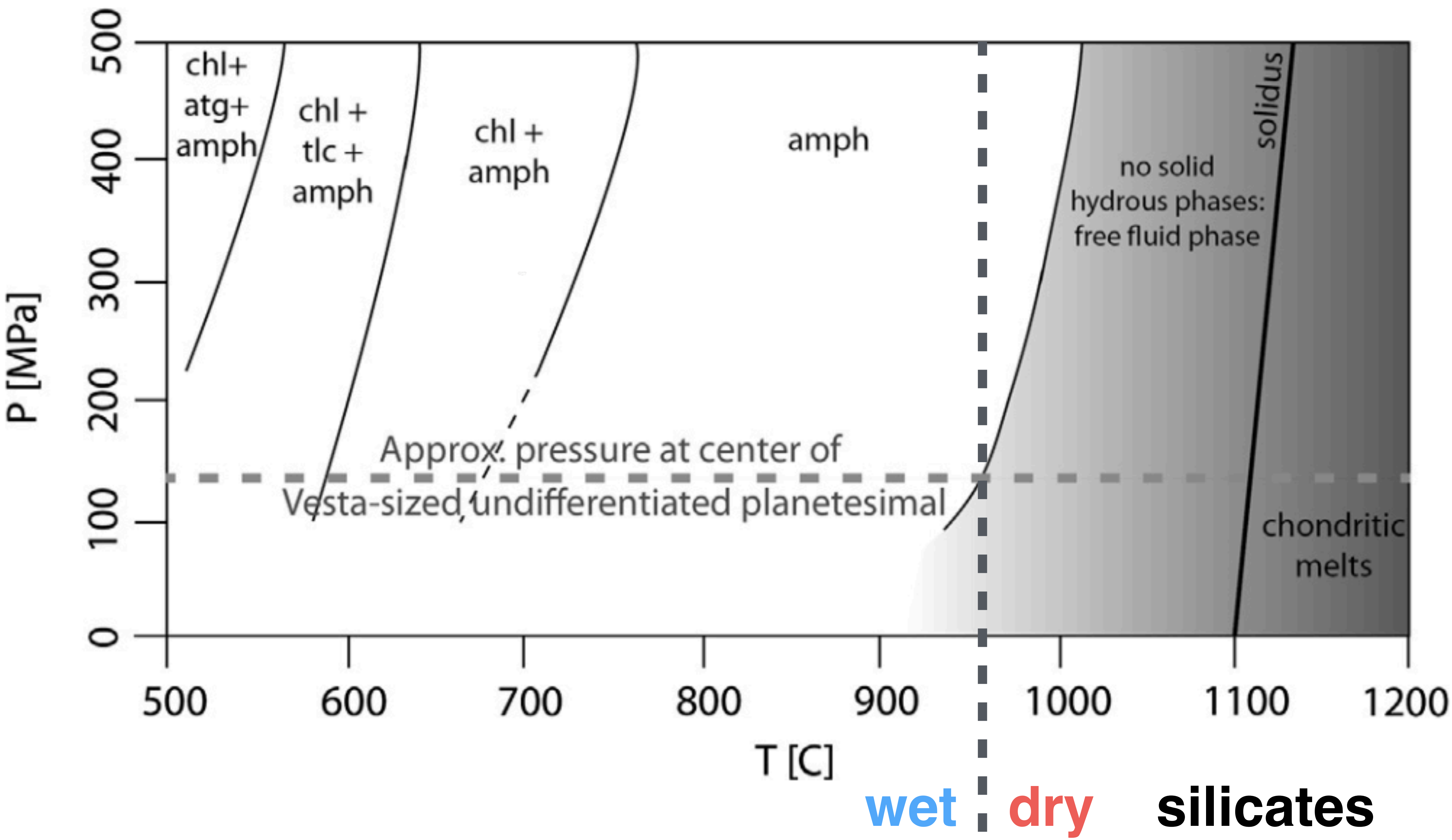
Credit: University of Hawai'i, Institute for Astronomy

Fine-tuning Earth-like water abundances



Ciesla+ 15, Mulders+ 15

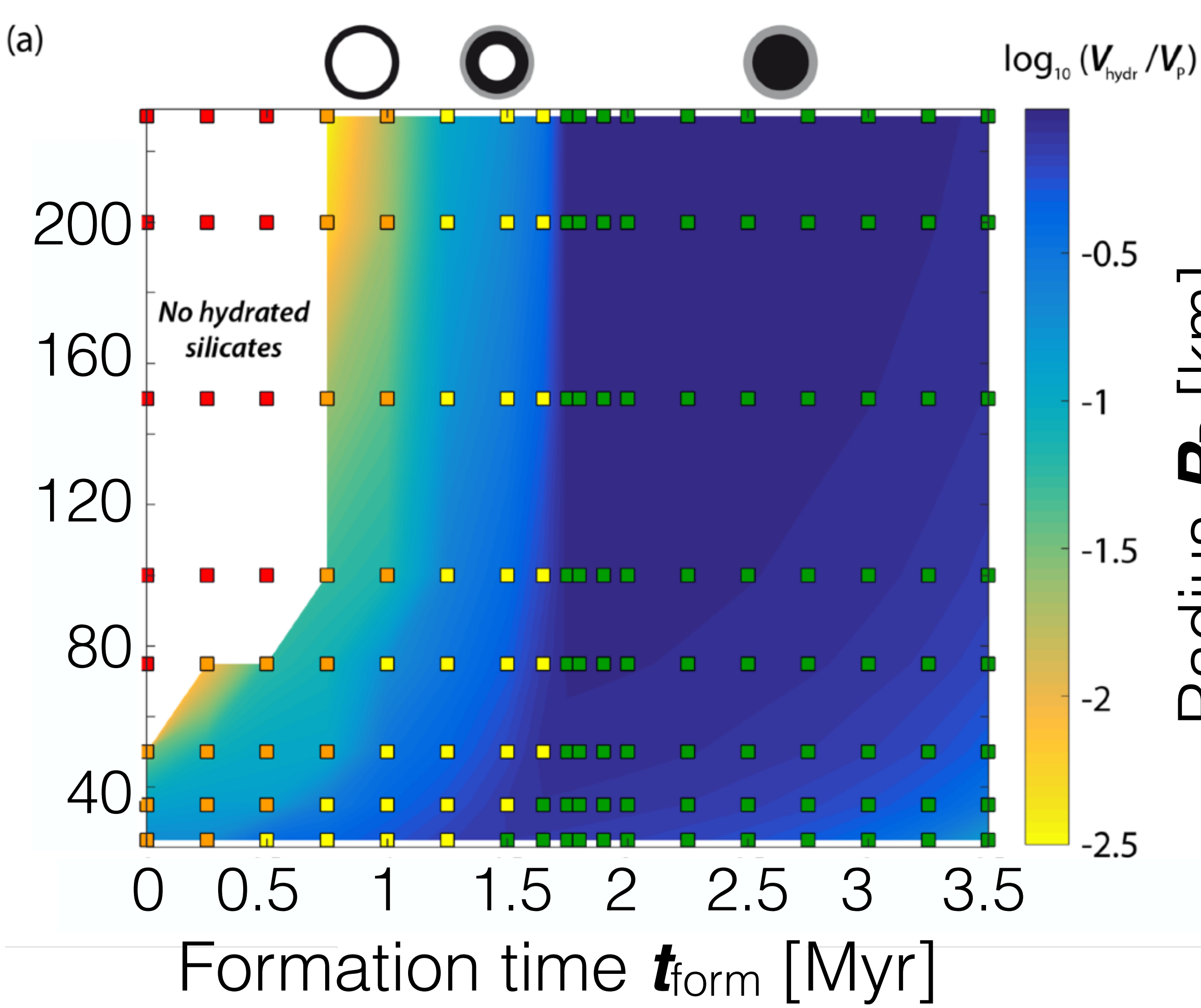
Planetesimal 'hydrology'

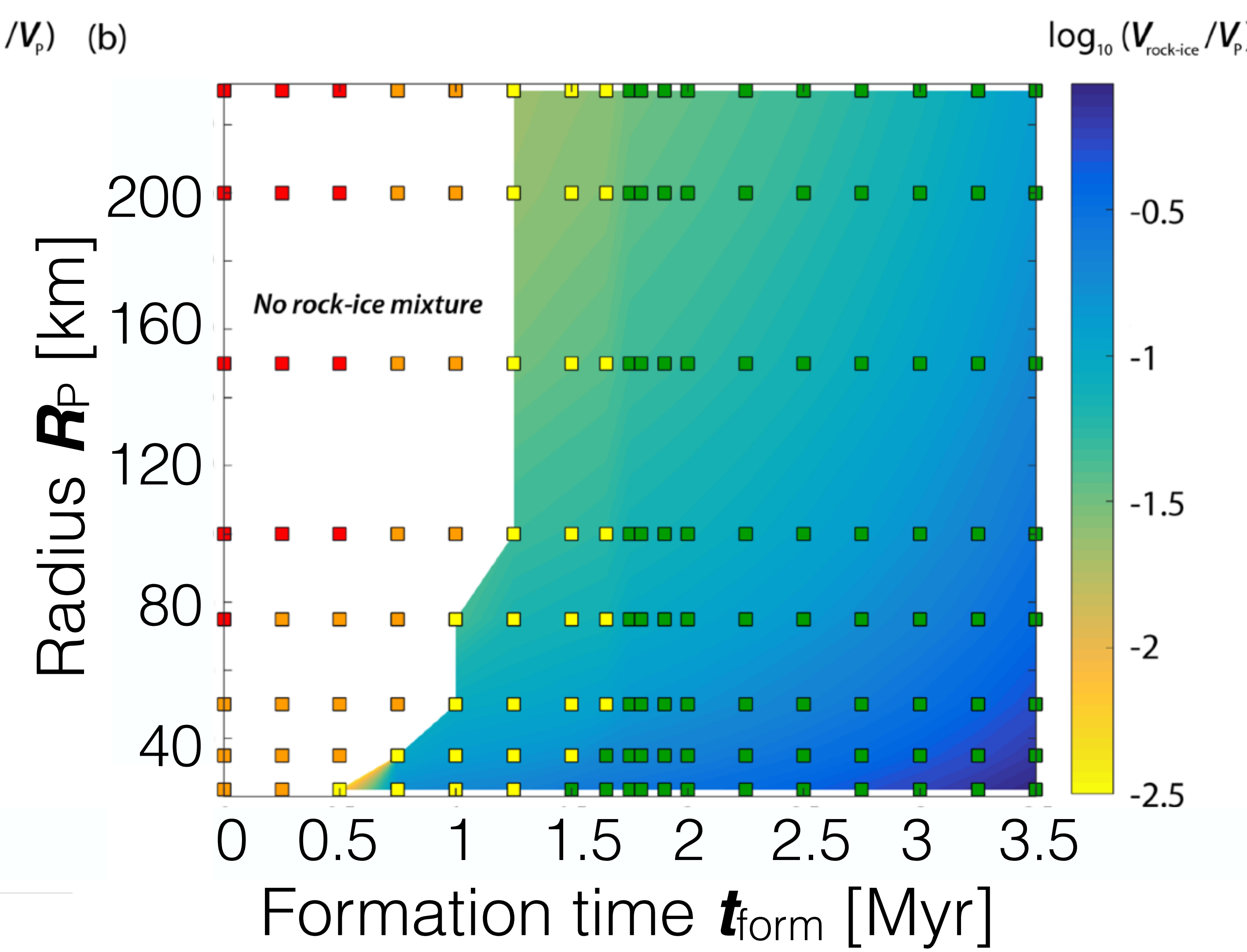


Fu & Elkins-Tanton 14

Planetesimal dehydration via outgassing

rock-ice mixture | hydrated silicates



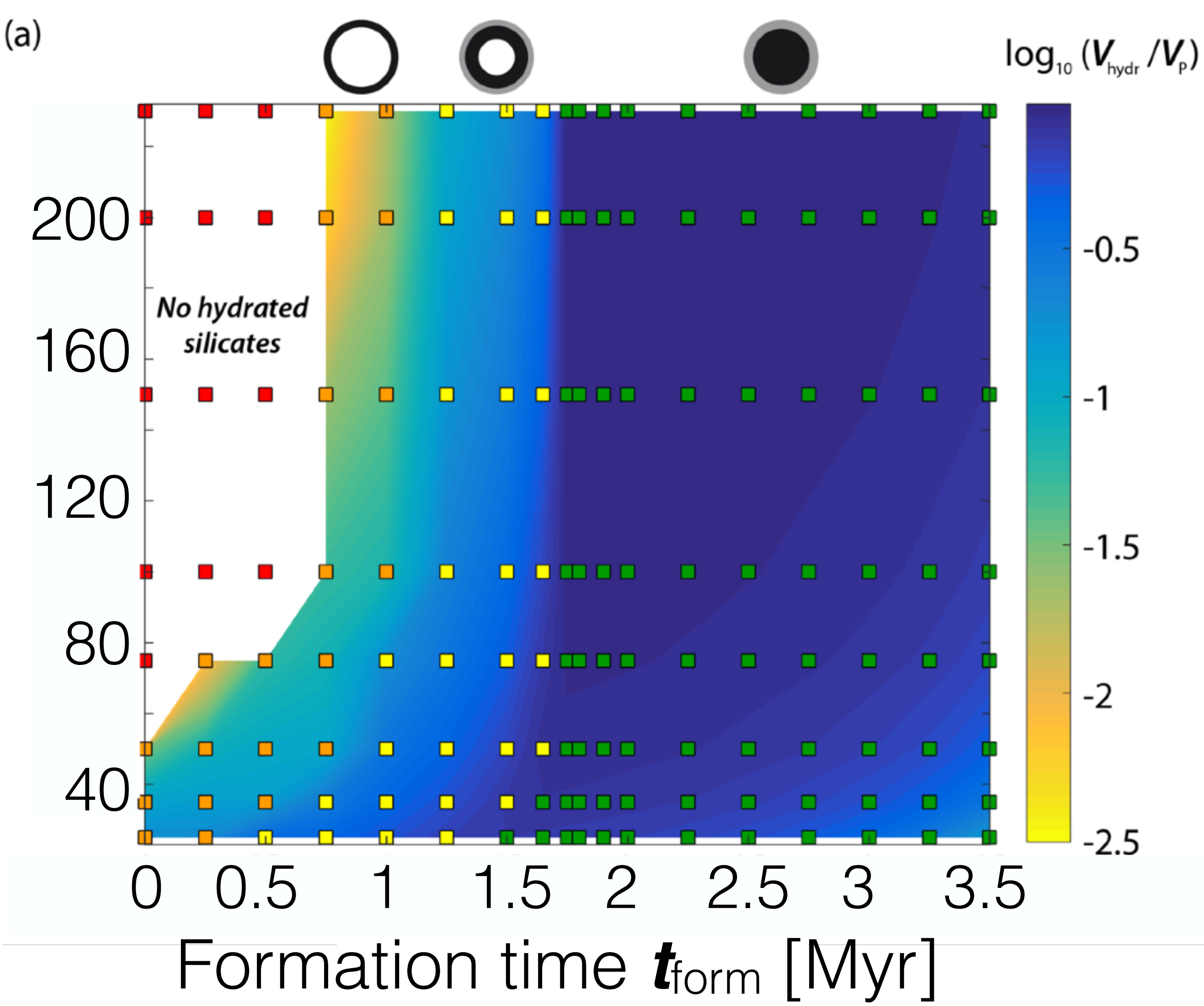


Monteux, Golabek, Rubie, Tobie, Young (in press, Space Sci. Rev.)

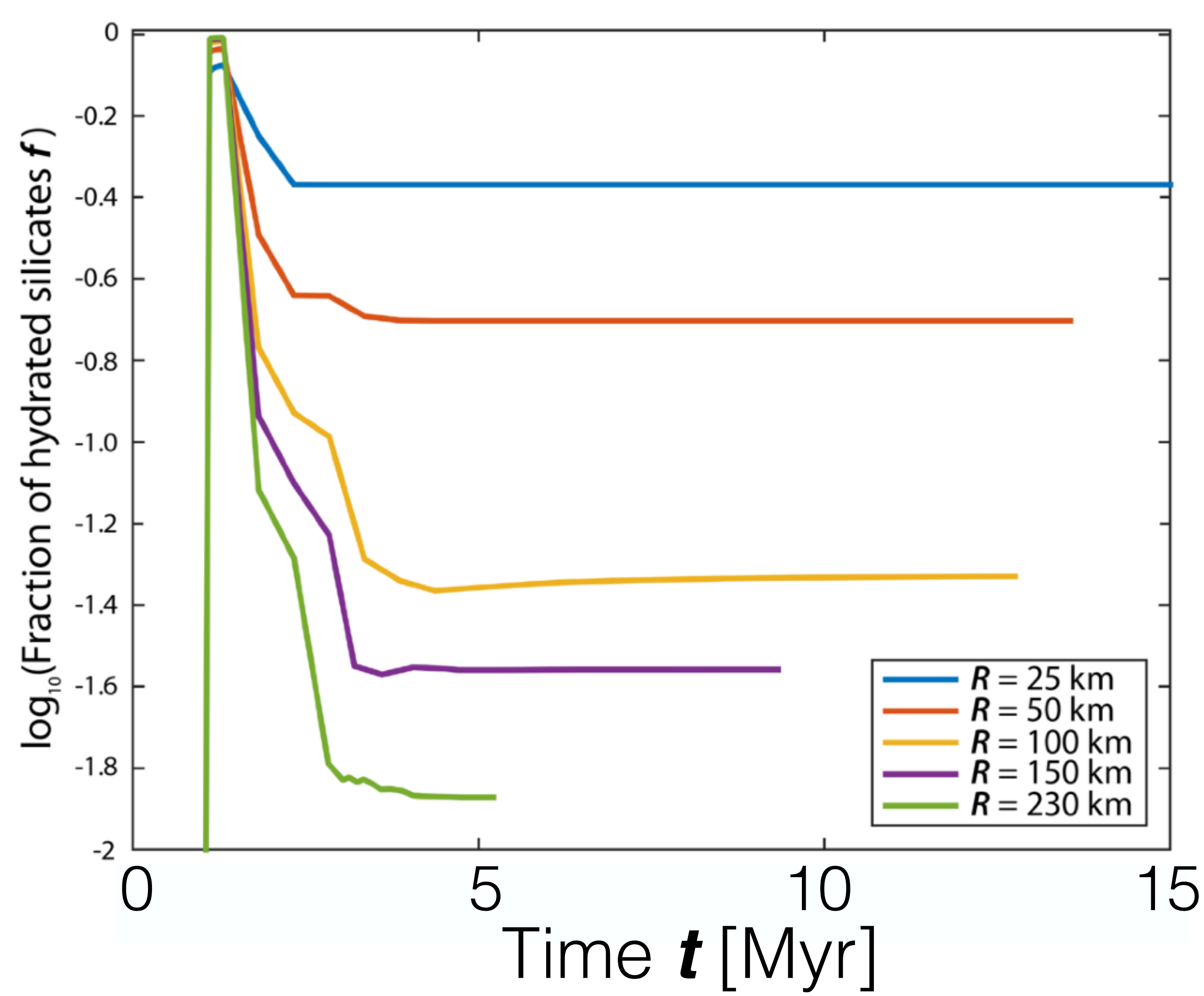
Planetesimal dehydration via outgassing

rock-ice mixture | hydrated silicates

Final volume of hydrated silicates

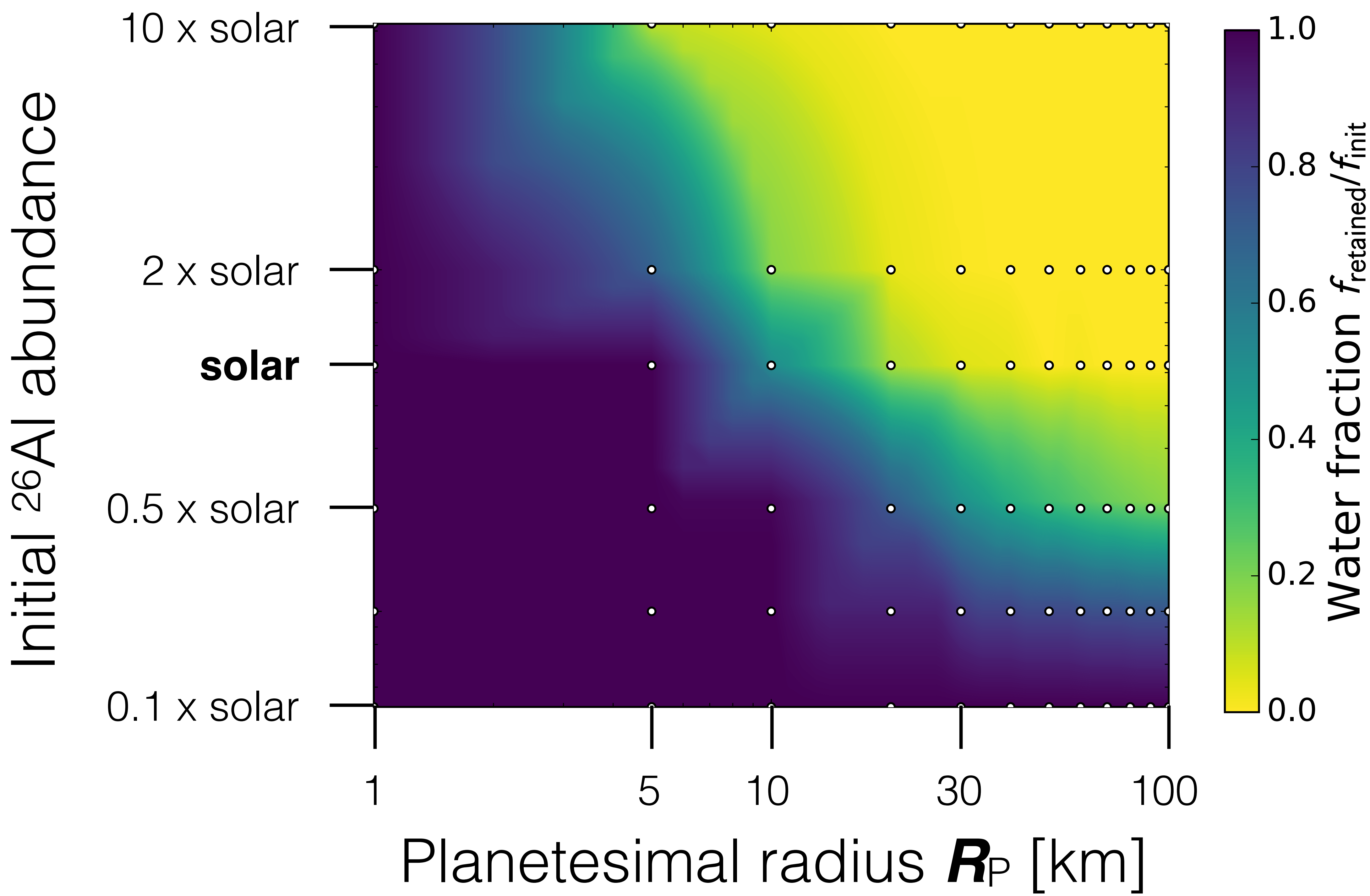


Time evolution



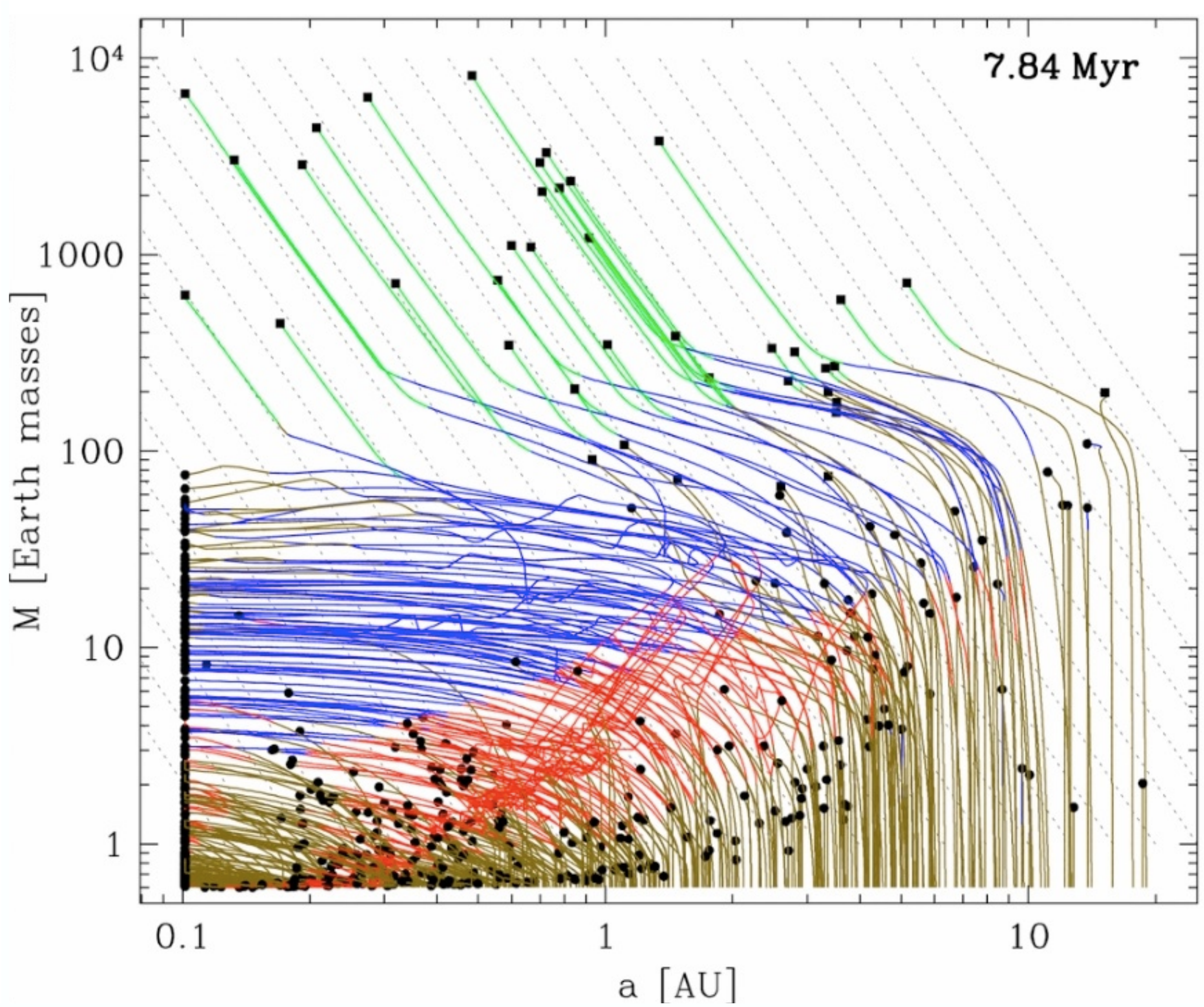
Monteux, Golabek, Rubie, Tobie, Young (in press, Space Sci. Rev.)

Extrapolation to (exo-)planetary population?



Lichtenberg, Alibert, Golabek, Thiabaud, Meyer (in prep.)

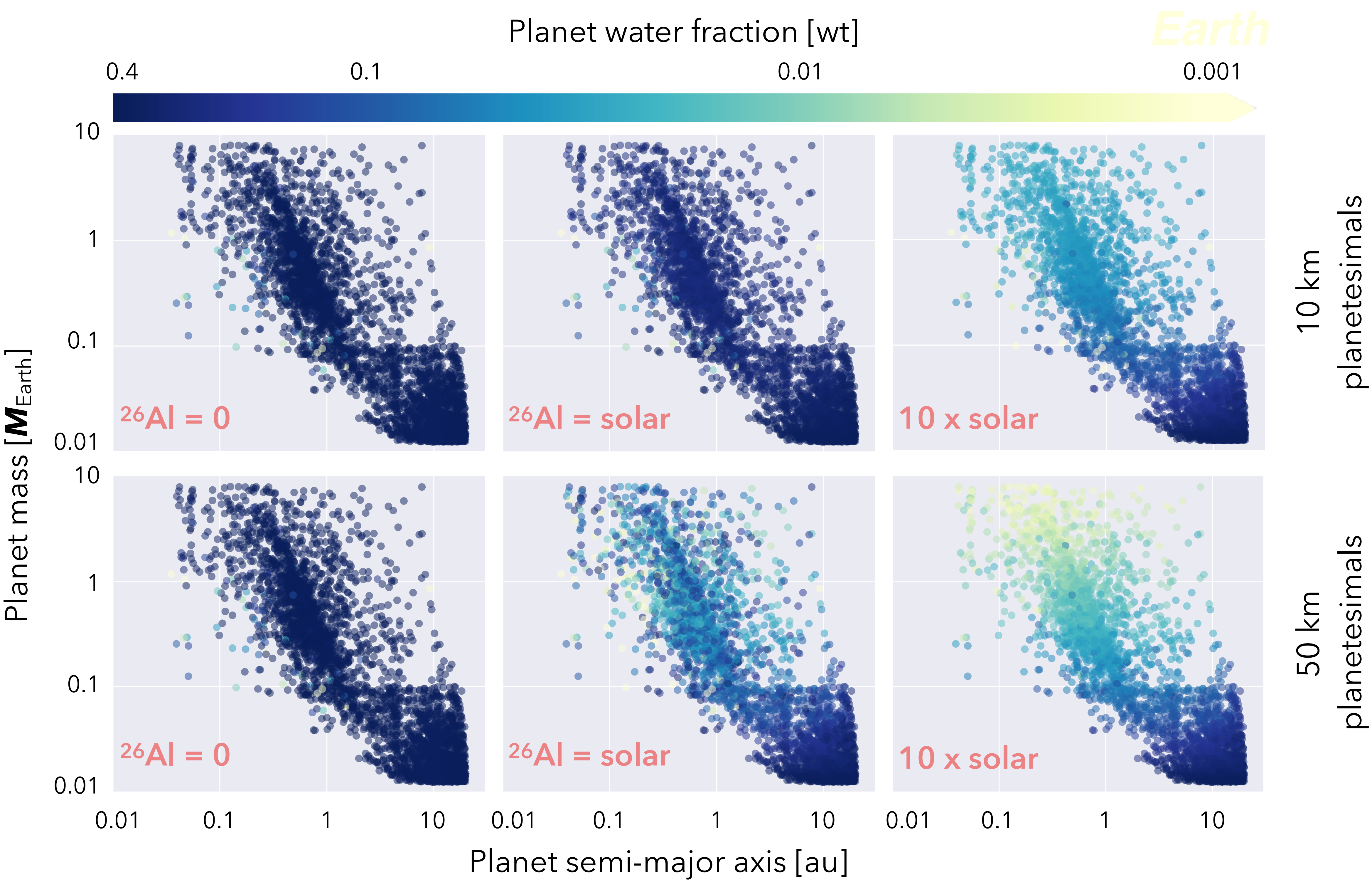
‘Degassing’ planet population synthesis



- Planet population synthesis calculations (‘Bern model’)
- Planetary embryos migrate through ‘sea’ of planetesimals
- Follow planetary built-up and major silicate + volatile phases
- **Add degassing/dehydration from planetesimal models**

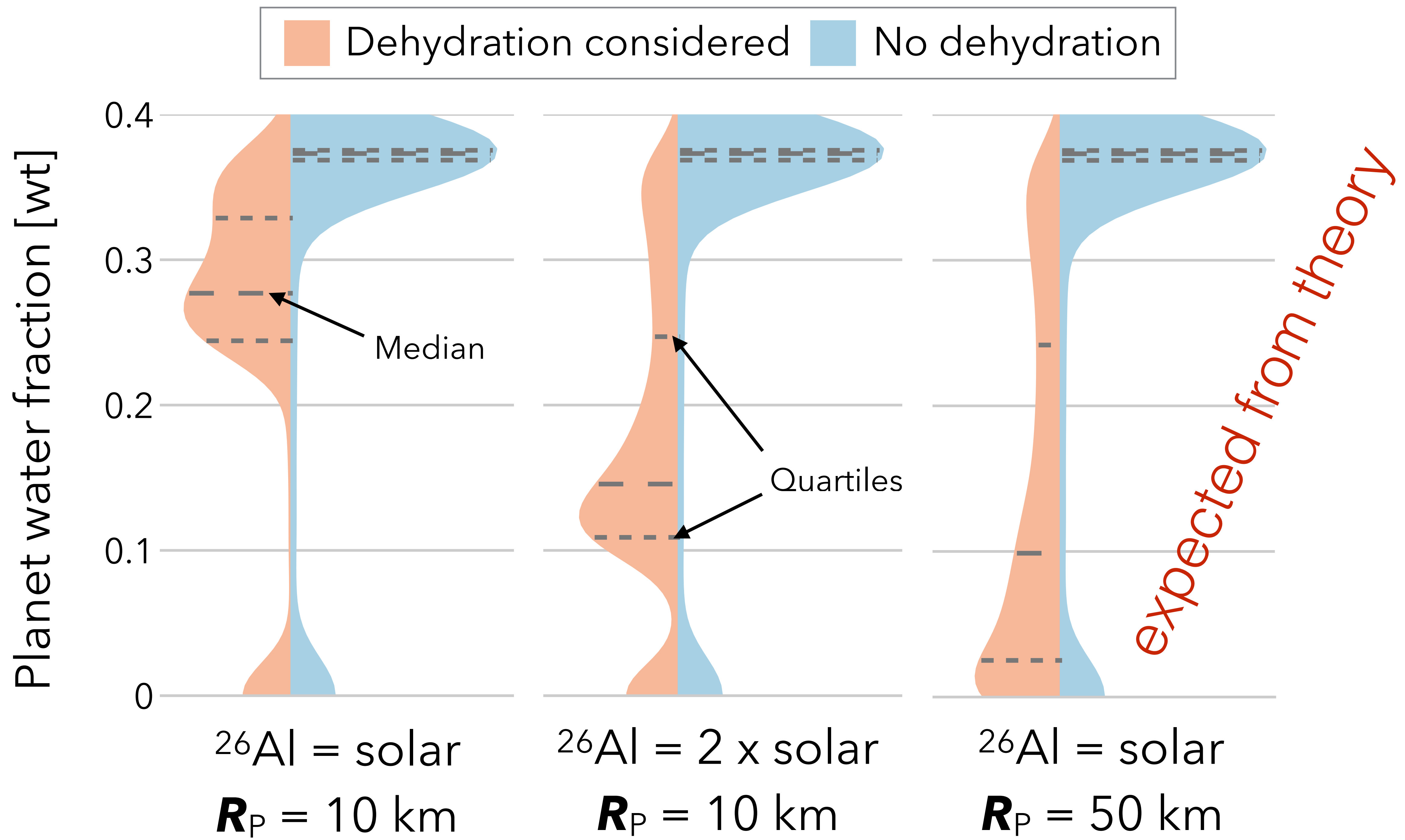
Credit: Christoph Mordasini, Univ. Bern

‘Degassing’ planet population synthesis



Lichtenberg, Alibert, Golabek, Thiabaud, Meyer (in prep.)

‘Degassing’ planet population synthesis



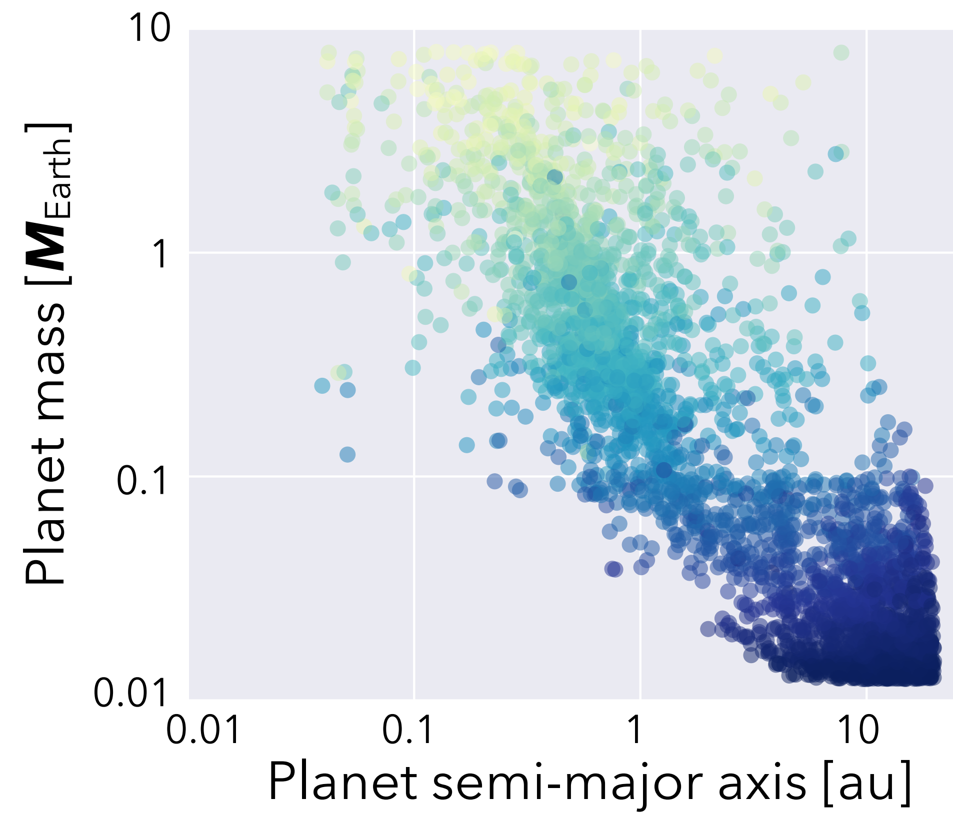
Lichtenberg, Alibert, Golabek, Thiabaud, Meyer (in prep.)

Summary II – Planetesimal devolatilisation

- **Degassing planetesimals** with low ^{26}Al, low-water fraction may be important **contributor of Earth's water**

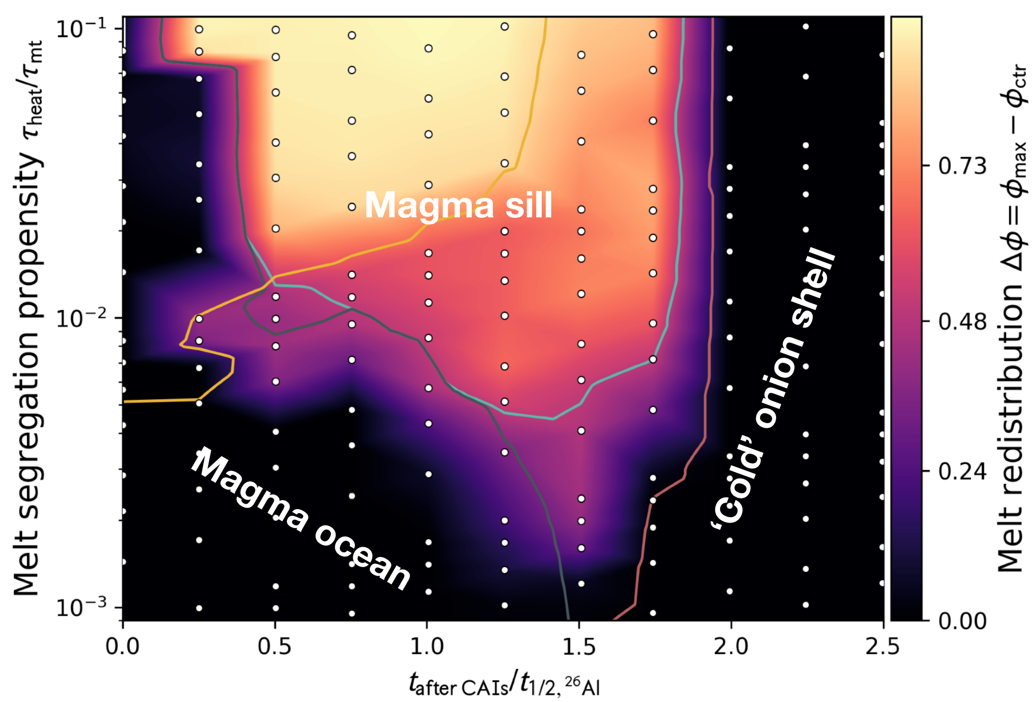
- **Degassing** processes on planetesimals alter volatile abundances **before accretion, flatten distribution**

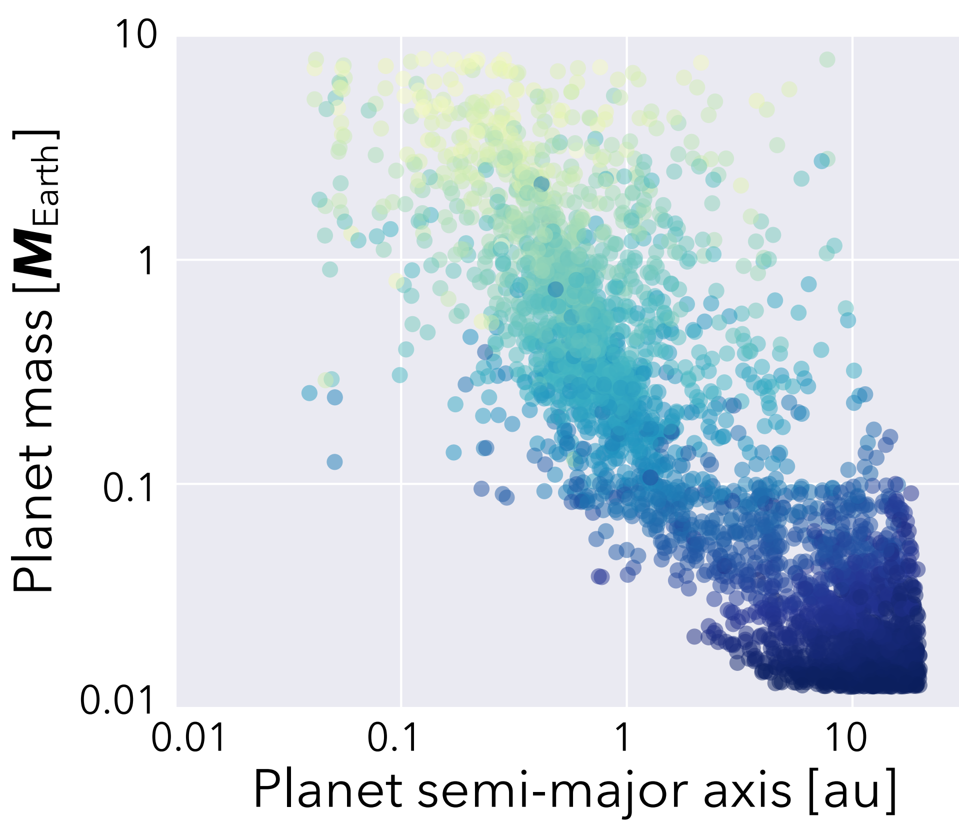
- Does ^{26}Al heating imprint **traceable signature** in planetary **volatile abundances**?



Monteux, Golabek, Rubie, Tobie, Young (in rev., Space Sci. Rev.)

Conclusions





1. Interior magma oceans likely existed, **melt segregation only partly effective**

2. Can we identify **primordial planetesimals** left-over from accretion and **assign evolutionary pathways** related to **silicate melt migration**?

3. **Degassing can deplete volatile abundances in terrestrial planets**

    - Signature may be traceable in **exoplanet** census?