Differentiation Processes in Icy Moons

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PROMISES

Presence and Role of Organic Matter in Icy Satellites and ExtraSolar planets

Early Differentiation Stages

Accretion

Formation from icy and rocky planetesimals

Heating

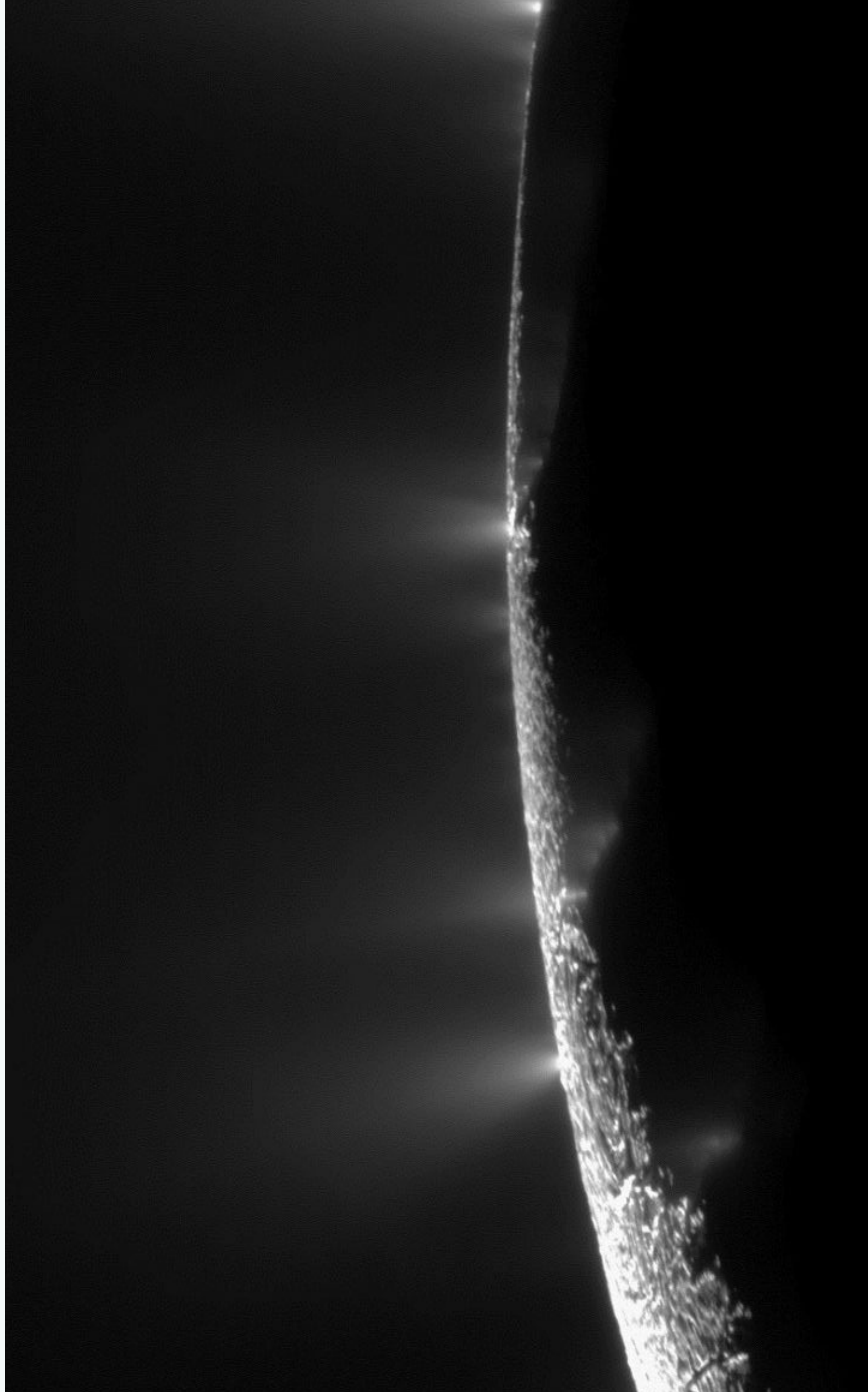
Radioactive decay and impacts increase temperature

Separation

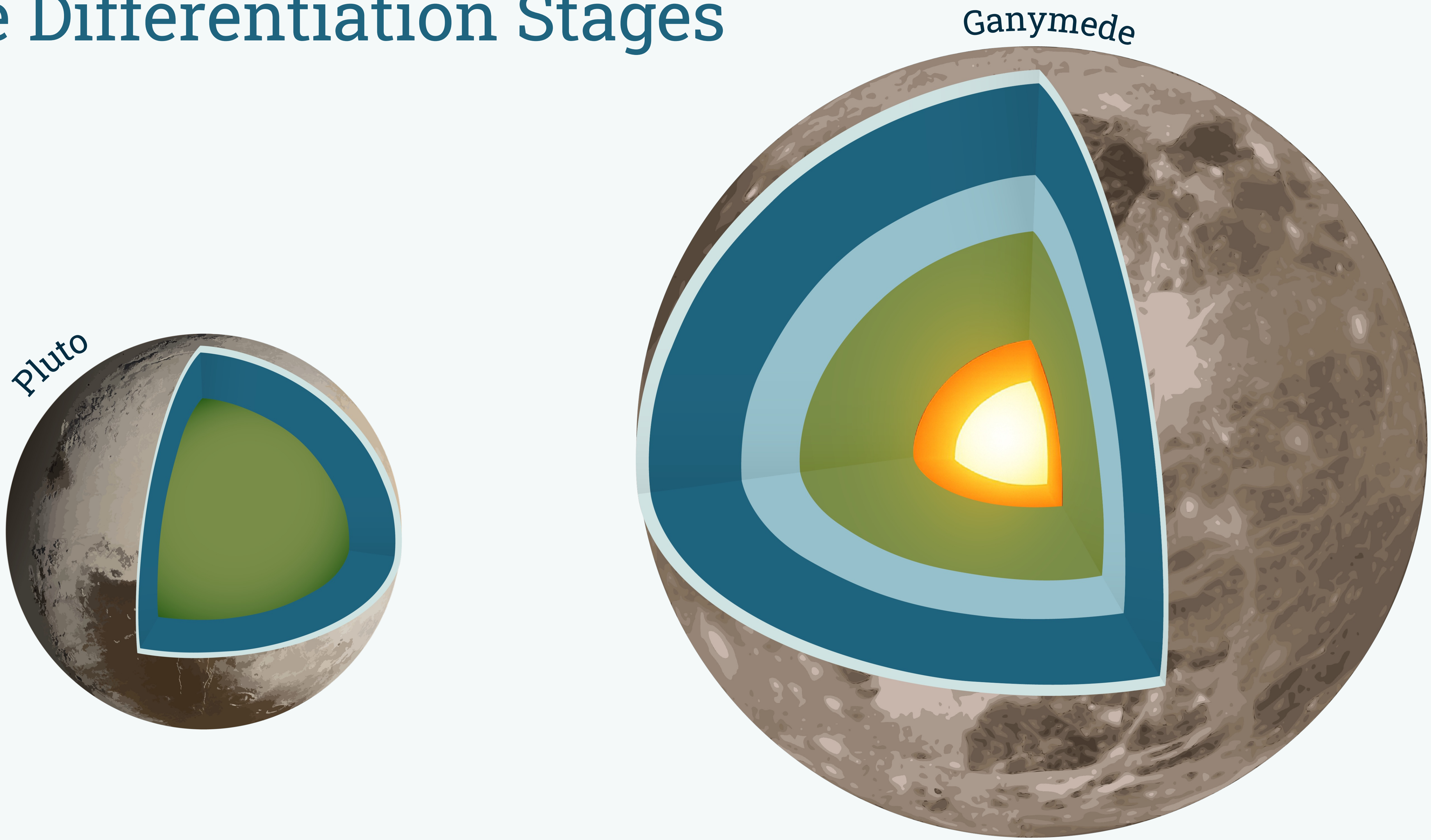
Ice melts, rocks sink, water migrates outward

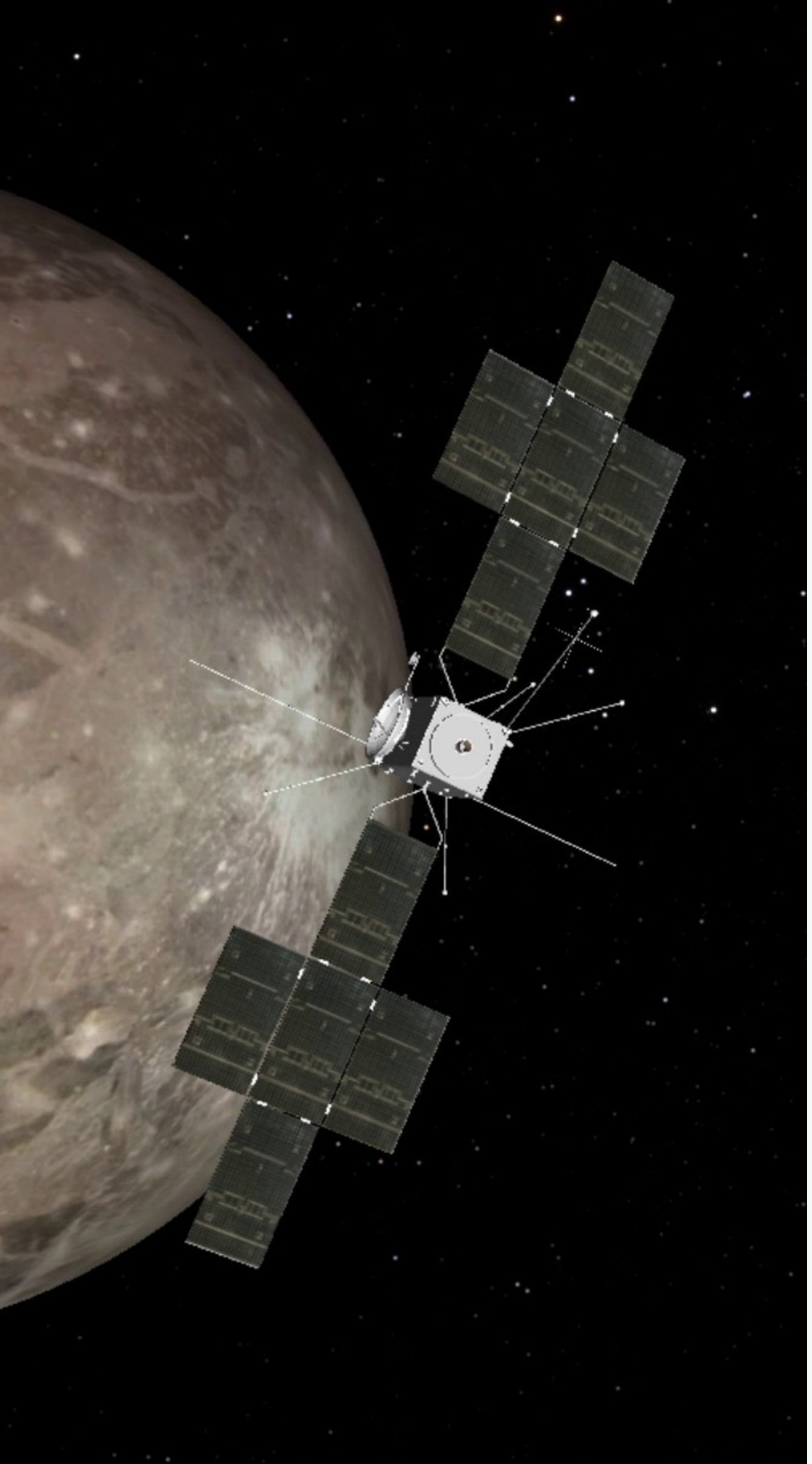
Stratification

Primordial ocean forms beneath icy crust



Late Differentiation Stages





From Missions to Models

Space Missions

ESA JUICE and NASA Europa Clipper

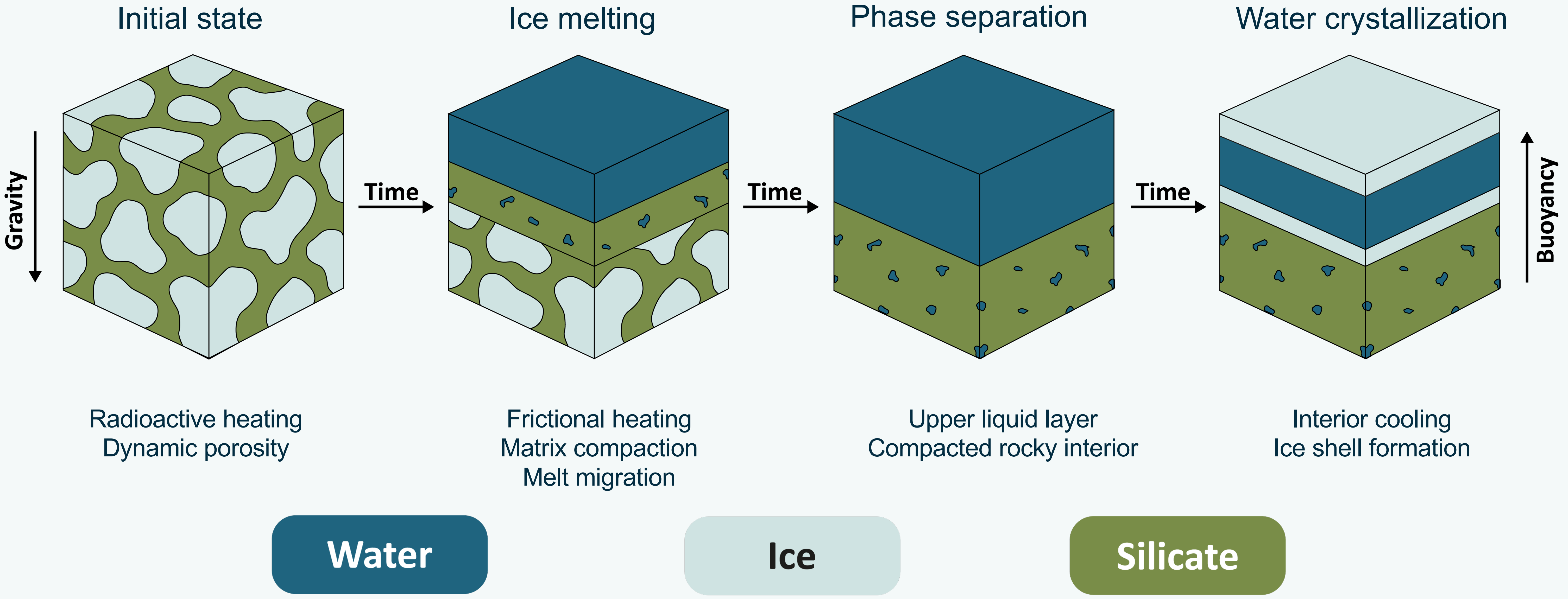
Laboratory Experiments

Ices and COM properties under extreme conditions

Numerical Models

Developing biphasic differentiation models

Biphasic physic: Multiphasic porous flow



BOREAS: Model Framework

Biphasic flows in Ocean moons: Role in Evolution And Segregation

Conservation Equations

- Mass conservation:

$$\frac{\partial \phi}{\partial t} + \nabla \cdot \left(v_f \phi\right) - \Gamma = 0 \qquad \frac{\partial \psi}{\partial t} + \nabla \cdot (v_m \psi) + \Gamma = 0 \qquad \frac{\partial \chi}{\partial t} + \nabla \cdot (v_m \chi) = 0$$

- Momentum conservation:

$$0 = -\phi[1-\phi][\nabla(\Delta P) - \boldsymbol{g}\Delta\rho] + \phi\nabla \cdot \left([1-\phi]\underline{\boldsymbol{\tau_m}}\right) - c\boldsymbol{\Delta v} + \phi\Delta P\nabla\phi$$

- Energy conservation:

$$\frac{\partial \overline{\rho c_P} T}{\partial t} = \boldsymbol{\nabla} \cdot [k\boldsymbol{\nabla}T + k_a(\boldsymbol{\nabla}T - \boldsymbol{\nabla}T_s)]$$
$$+Q\chi + c(\boldsymbol{\Delta v})^2 - L\rho_\phi\Gamma$$
$$-\rho_\phi c_{P\phi}\boldsymbol{\nabla} \cdot \left(\phi\boldsymbol{v_f}T\right) - \rho_\psi c_{P\psi}\boldsymbol{\nabla} \cdot (\psi\boldsymbol{v_m}T) - \rho_\chi c_{P\chi}\boldsymbol{\nabla} \cdot (\chi\boldsymbol{v_m}T)$$

BOREAS: Model Framework

Biphasic flows in Ocean moons: Role in Evolution And Segregation

Numerical Scheme

Velocity profile

Pressure, gravity, melting temperature

Temperature profile

Advection, conduction, radioactivity, friction and convection

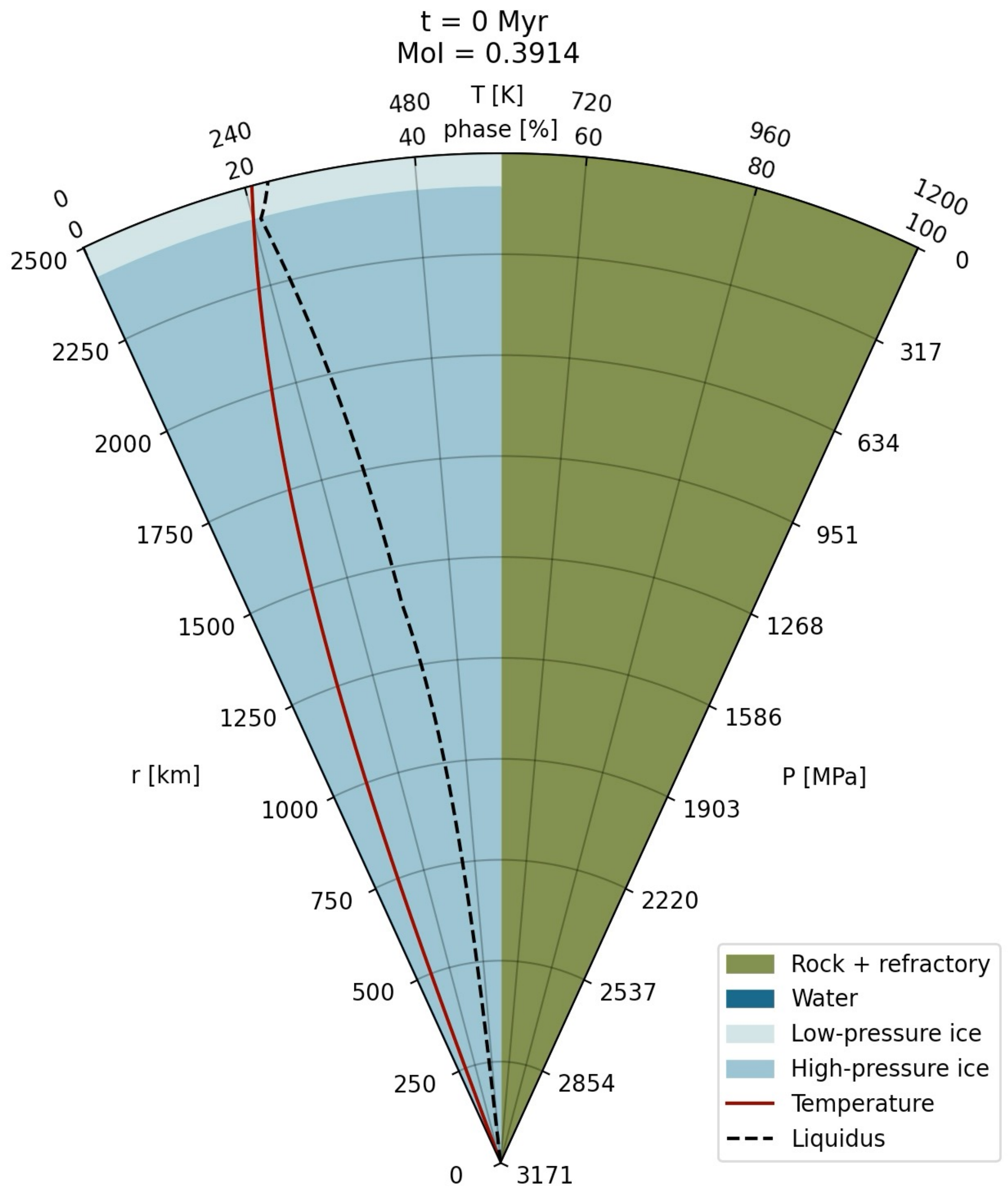
Phases advection

Liquid, meltable solid and silicate matrix

Melting and crystallization

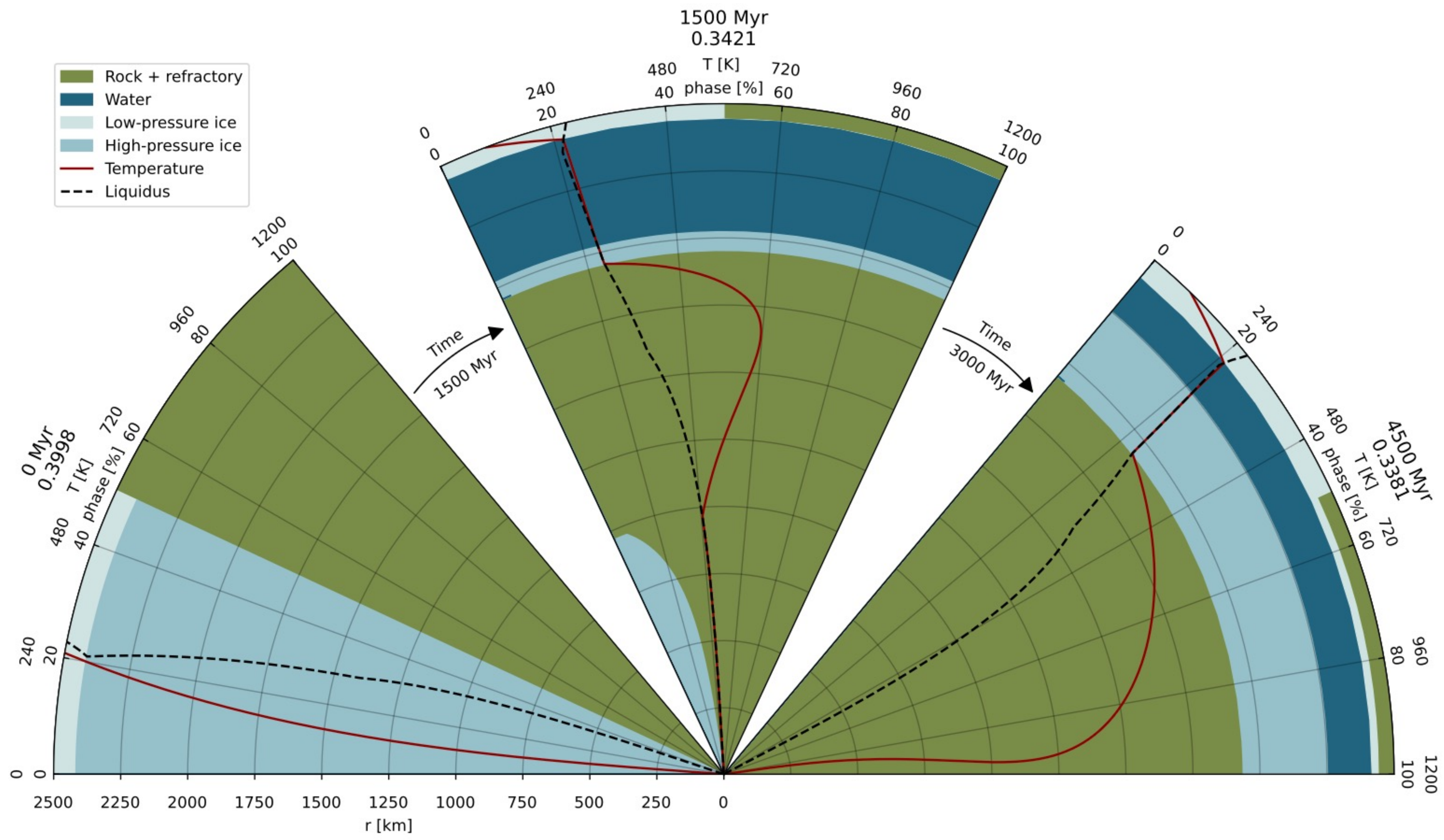
Water/ice phase changes

BOREAS: Water Segregation and Ocean Formation



BOREAS: Water Segregation and Ocean Formation

Internal evolution



- **Organic delivery pathway**: Migrating water through hot outer core layers creates an active leaching zone that may supply organics to the ocean and support potential habitability.

BOREAS: Parameters space exploration

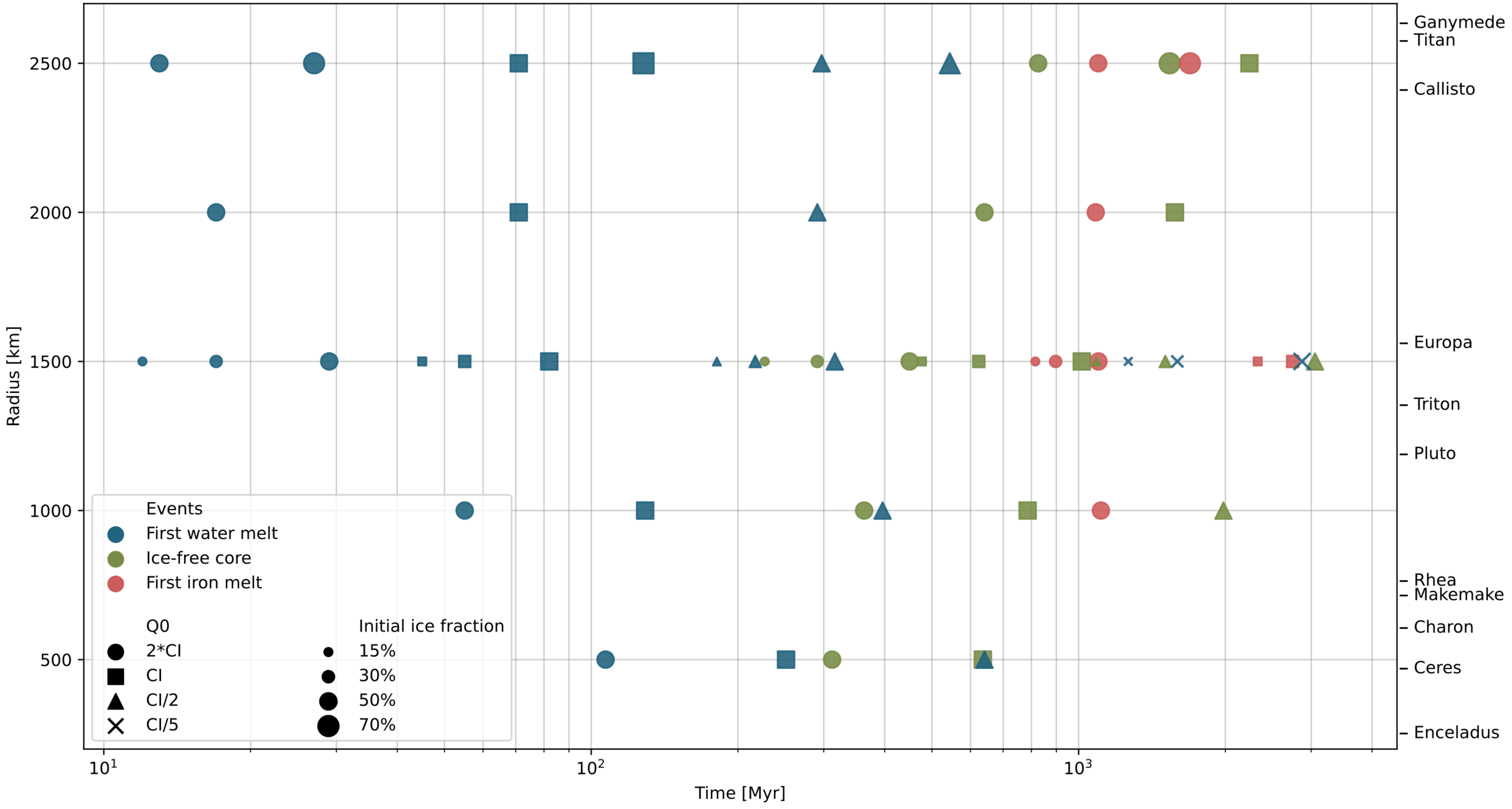
Influence of Initial Conditions on Icy Moons Differentiation

Initial Parameter Space Exploration		Q0 (W/kg)			
		6E-11 (2*CI)	3E-11 (CI)	1.5E-11 (CI/2)	6E-12 (CI/5)
Radius (km)	2500 (Ganymede)	ox	ox	ox	ox
	2000 (Unknown)	x	x	x	x
	1500 (Triton)	x▲■	x▲■	x▲■	x▲■
	1000 (Pluto)	x	x	x	x
	500 (Ceres)	x	x	x	x
Ice fraction (%)		o = 70%	x = 50%	▲= 30%	■= 15%

- Radius (2500 – Ganymede-like, 2000 – no moon in the solar system, 1500 – Triton/Europa-like , 1000 – Pluto-like, 500 – Ceres-like)
- Initial ice to rock ratio (15/85 – Europa-like, 30/70 – Triton-like, 50/50 - Reference, 70/30 – Callisto-like)
- Initial radioactive heating (2*CI – Tidal heating-like, CI - Reference, CI/2 and CI/5 – Silicates with COM)

BOREAS: Parameters space exploration

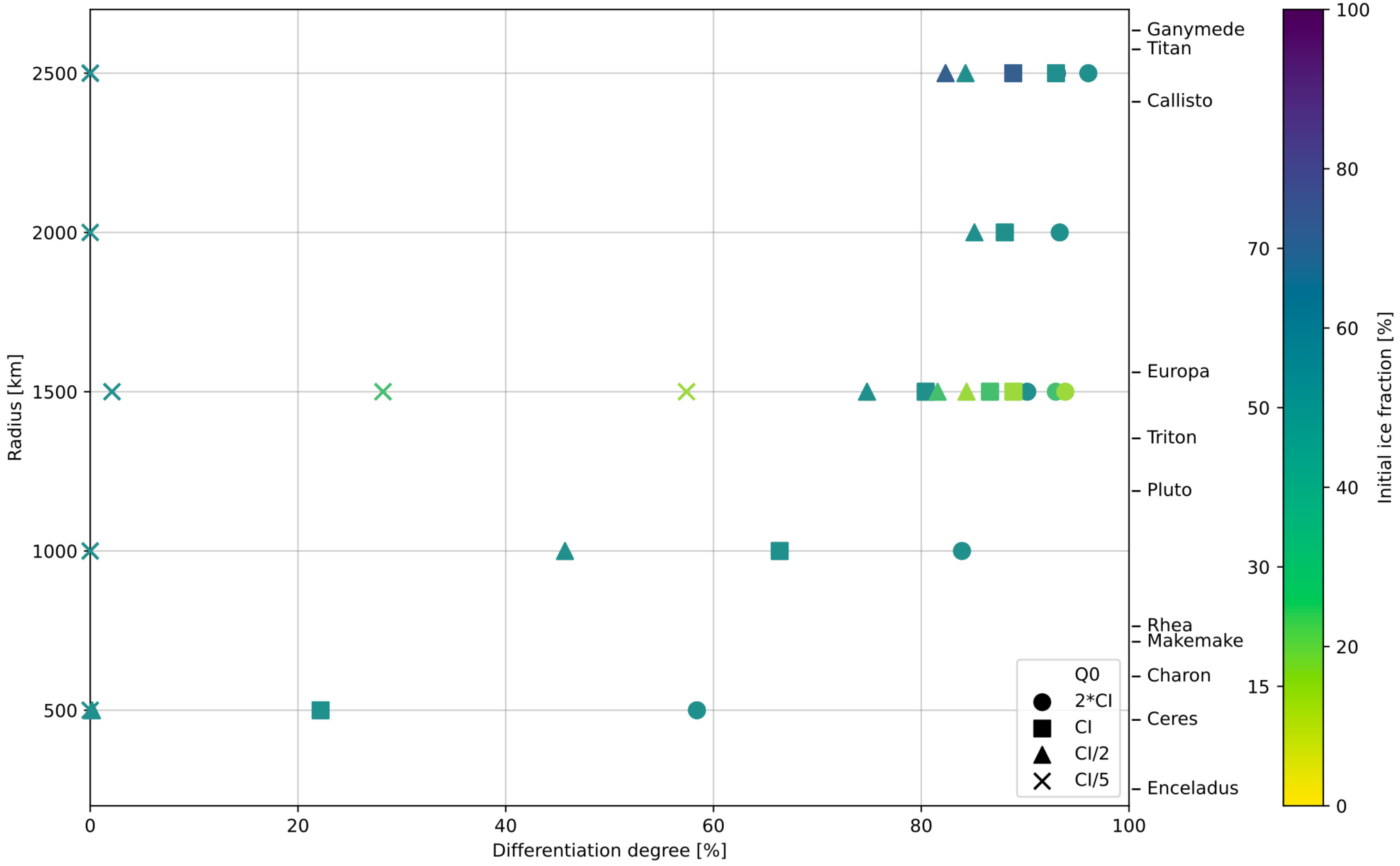
Timing of the differentiation



- **Differentiation is slow**: Icy moon interiors evolve over hundreds of millions of years before forming stable subsurface oceans.

BOREAS: Parameters space exploration

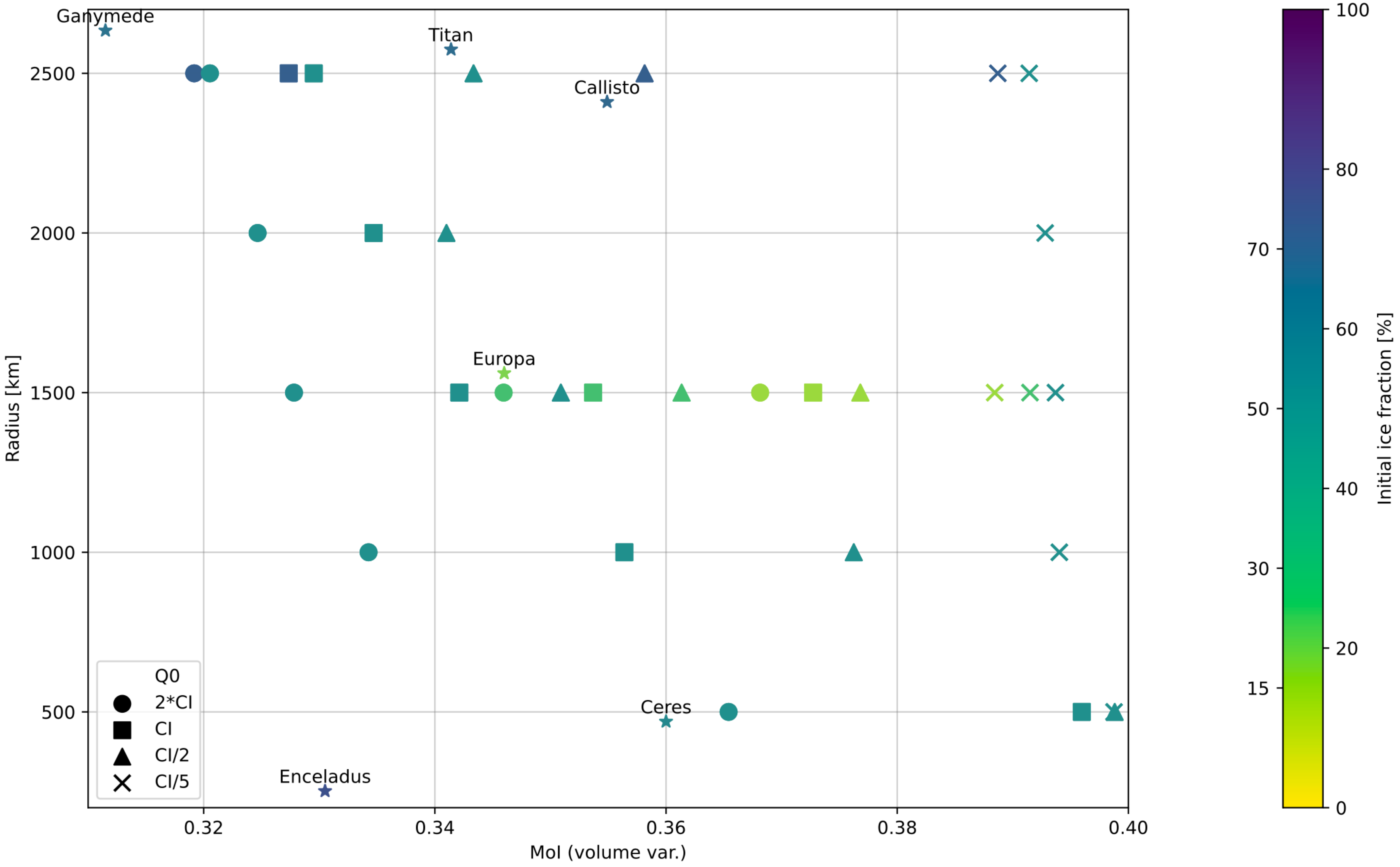
Degree of differentiation between the moons



- **Ocean worlds can be partially differentiated**: Liquid water can form while a significant fraction of H_2O remains trapped within the rocky interior.

BOREAS: Parameters space exploration

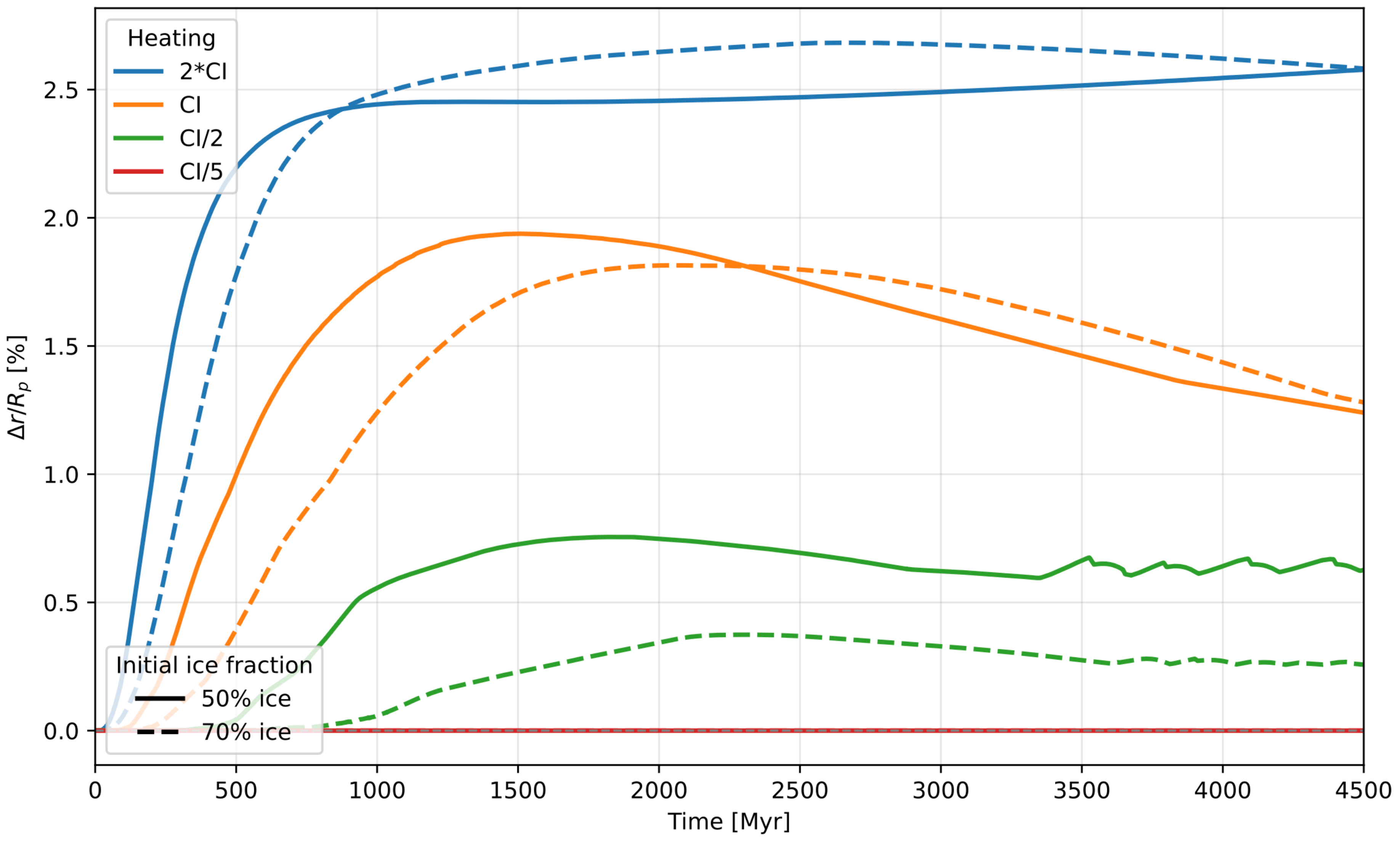
Impact of the differentiation on the Moment of Inertia



- **Moment of inertia tracks mass redistribution**: Lower MoI values reflect more efficient differentiation, but similar MoI can arise from different heating, composition, and size histories.

BOREAS: Parameters space exploration

Radius evolution of 2500km simulations



- **Internal differentiation can drive global expansion**: Ganymede-like pathways produce percent-level radius changes, potentially linking ocean formation to large-scale extensional tectonics.

BOREAS: Iron segregation and Core Formation