

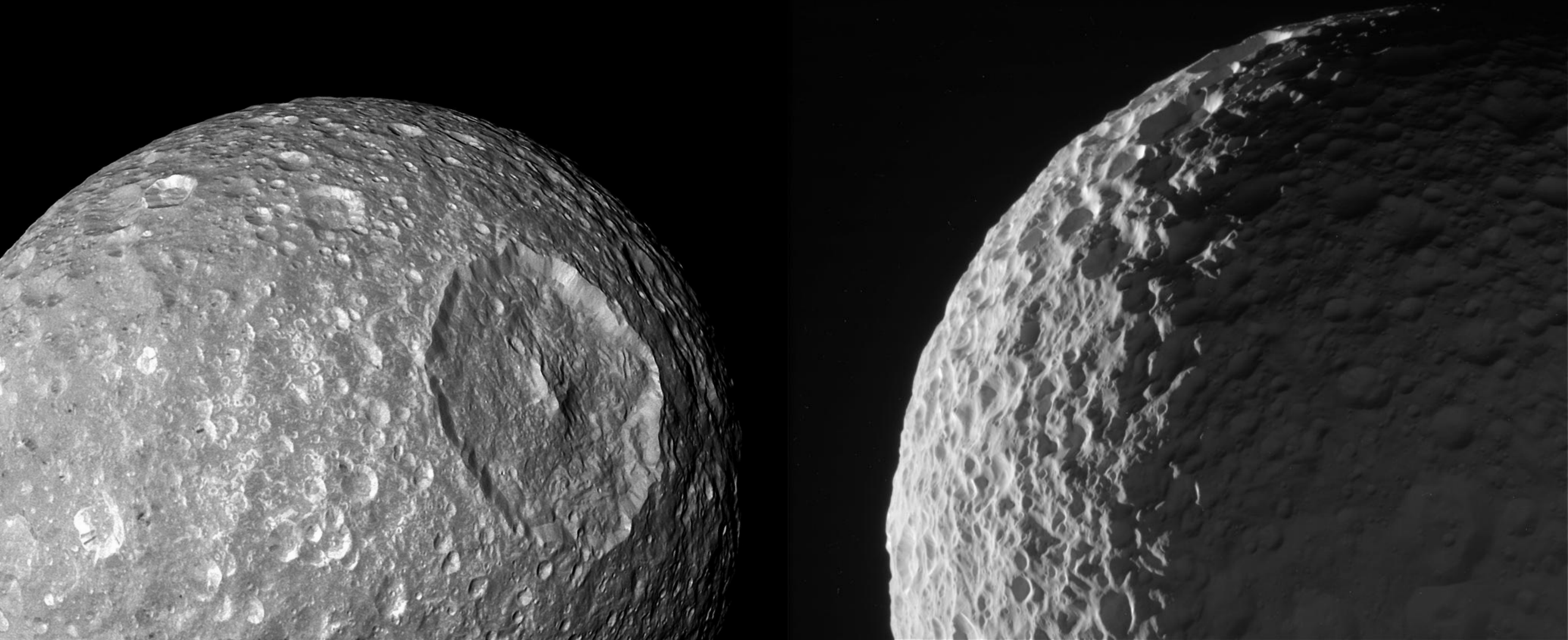
Partial Differentiation of Mimas by Tidal Heating preserves its Geologically Inert Surface



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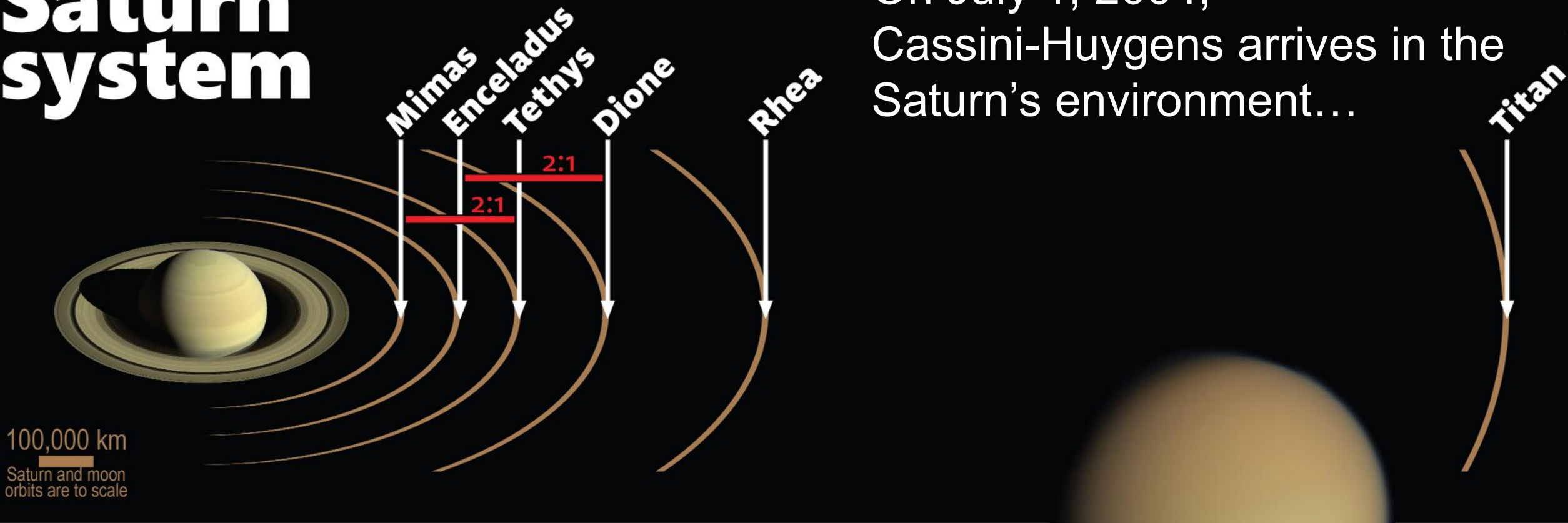
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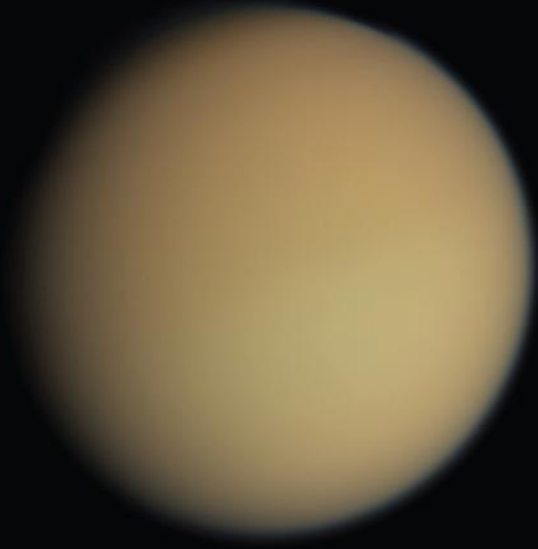
Saturn system

On July 1, 2004,
Cassini-Huygens arrives in the
Saturn's environment...

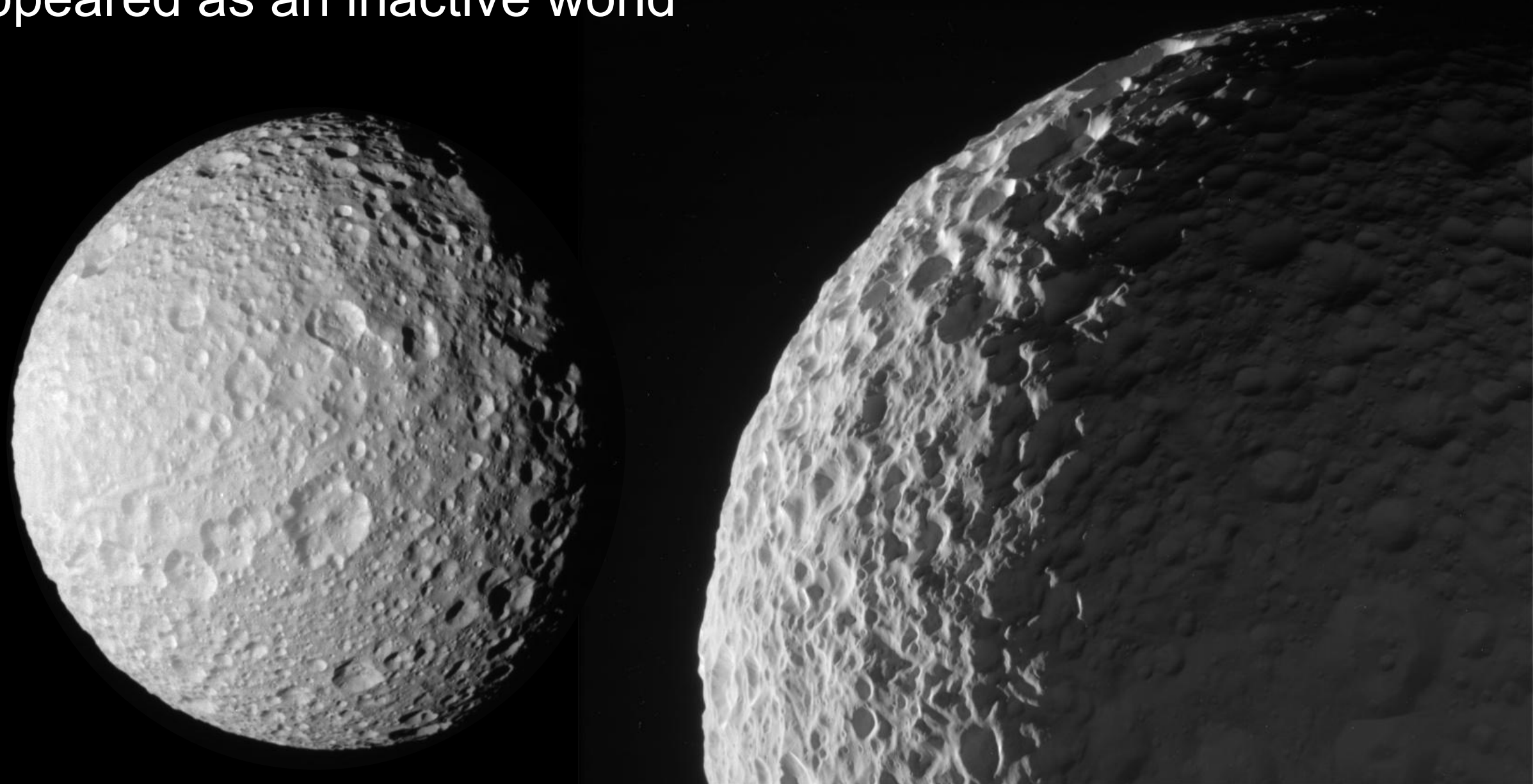


100,000 km
Saturn and moon
orbits are to scale

1,000 km
moons are to scale

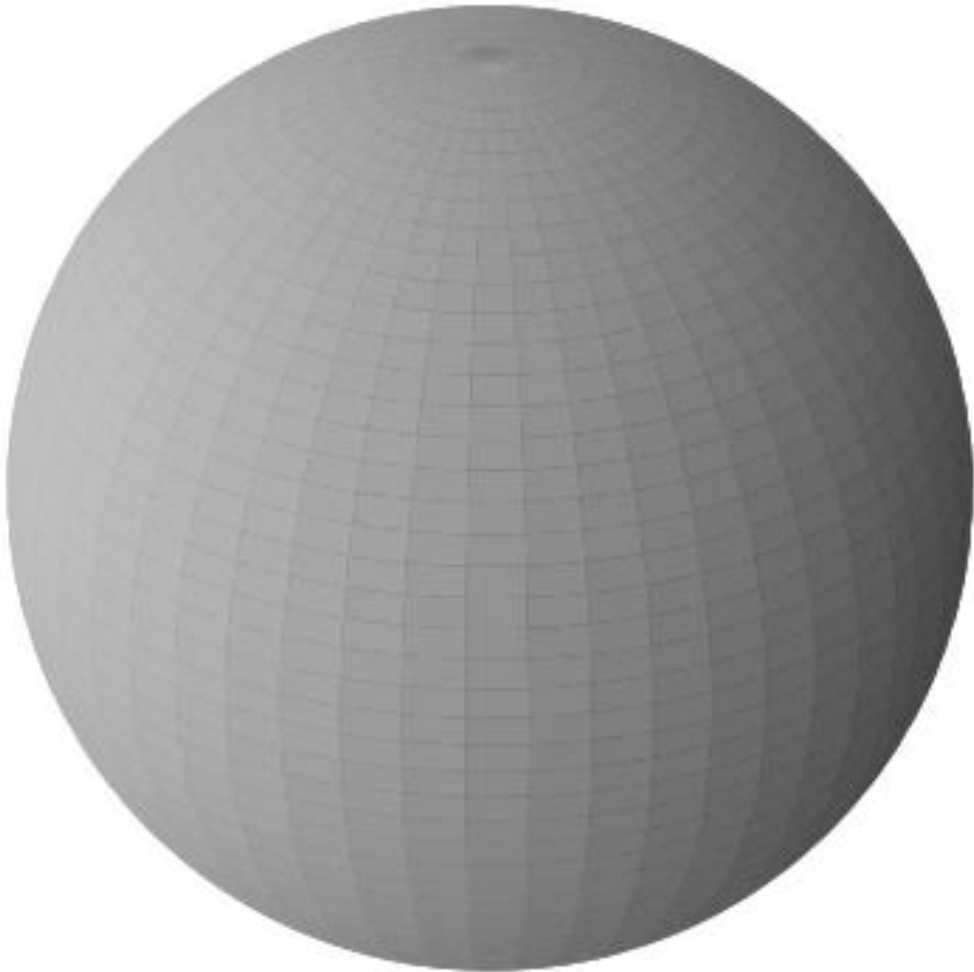


Mimas, the closest Saturn's mid-sized moon
Appeared as an inactive world

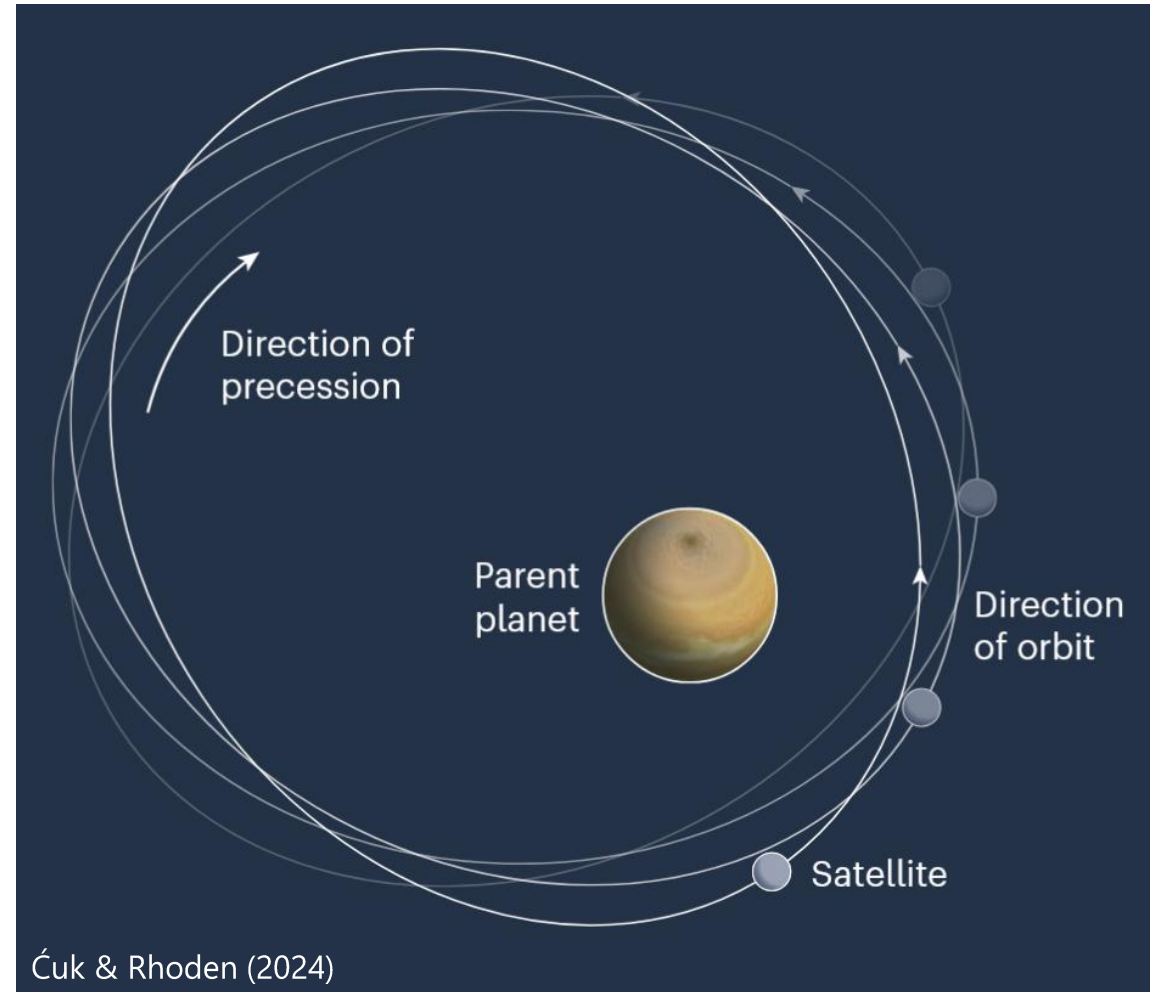


An ocean in Mimas?

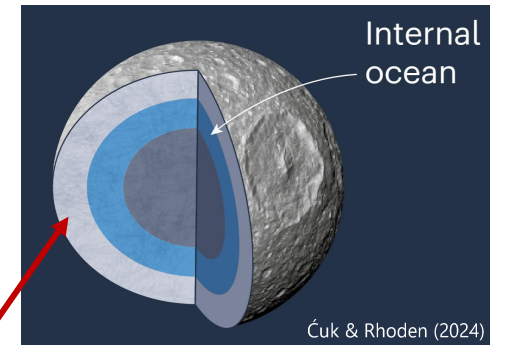
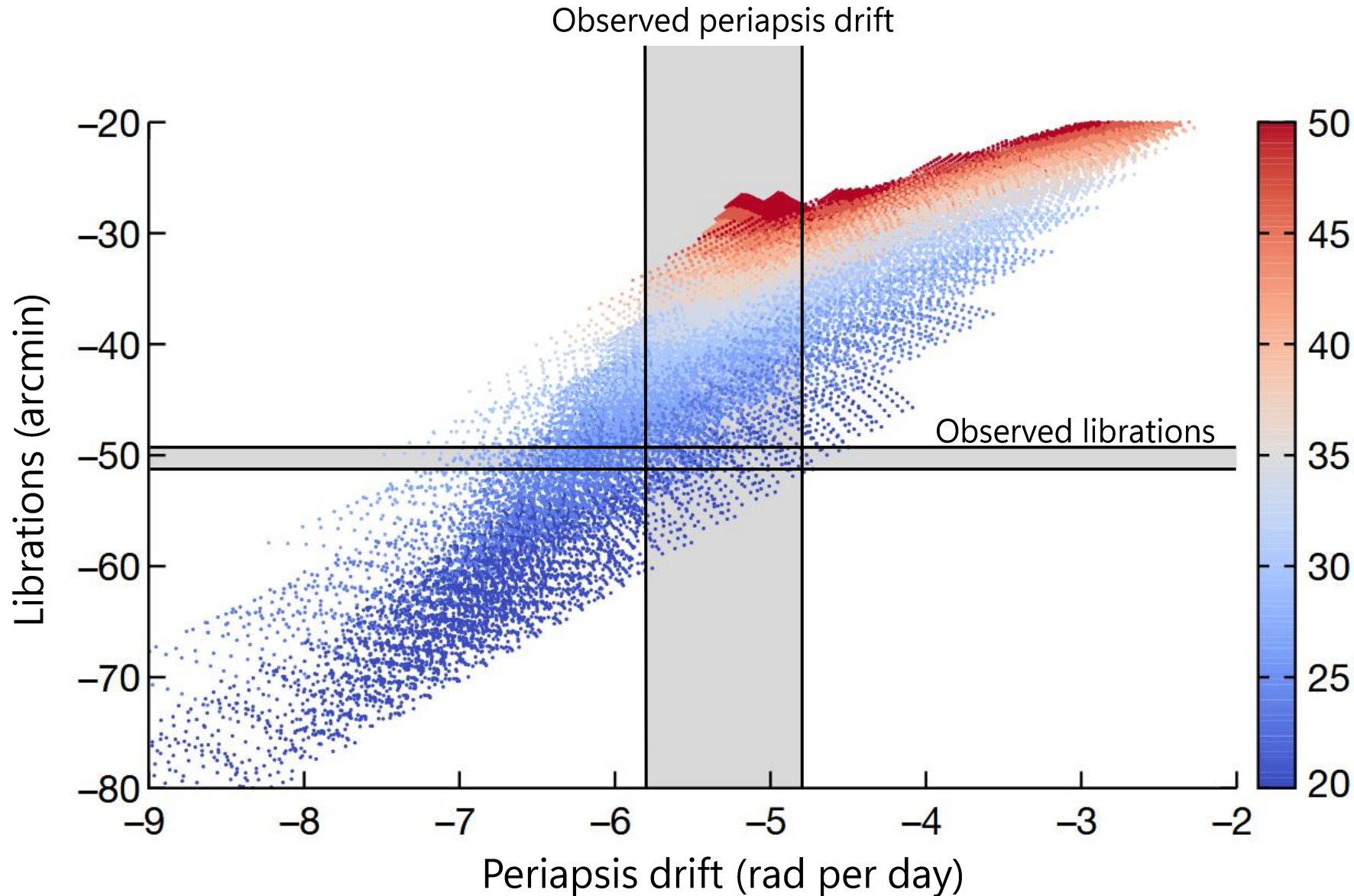
Librations
Tajeddine *et al.* (2014)



Periapsis drift
Lainey *et al.* (2024)



Evidence for an ocean in Mimas



Heat source needed to form an ocean

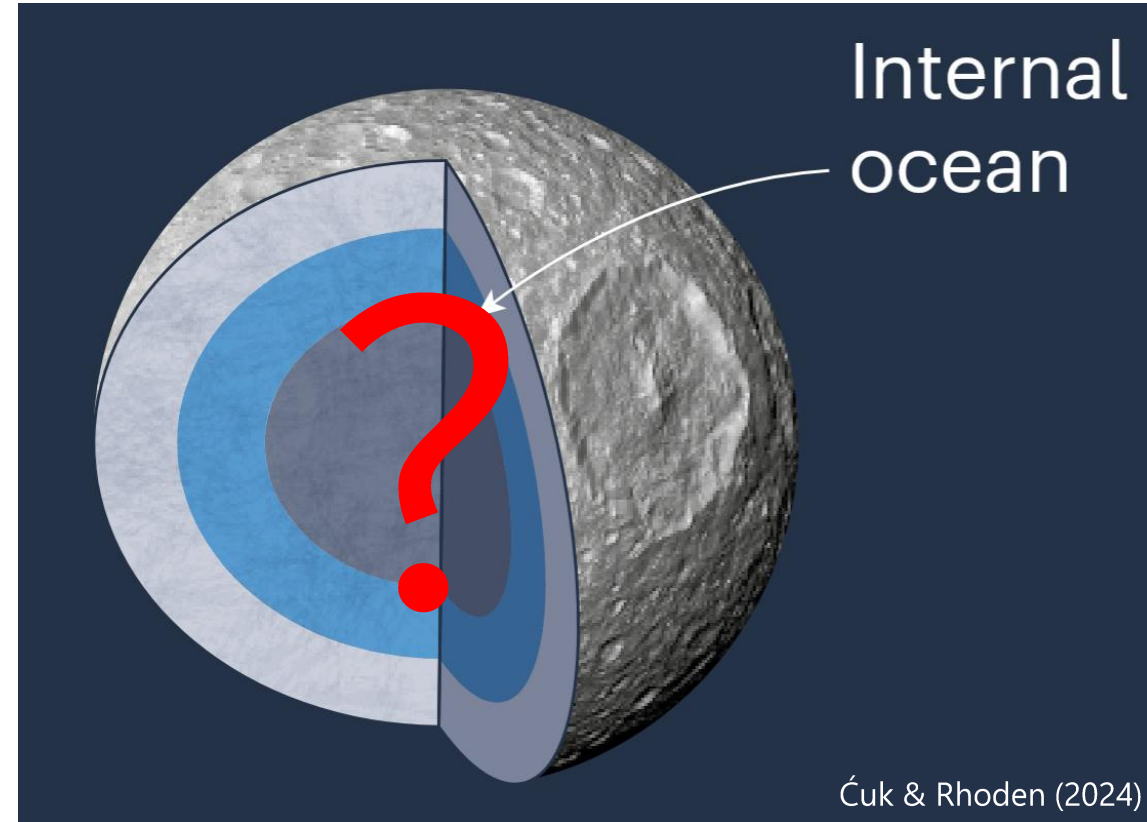
Heat released:
 $P_{\text{surf}} \sim 15 \text{ GW}$

Radiogenic power available:
 $P_{\text{rad}} \sim 0.2 \text{ GW}$

➤ **Tidal heating is needed**

What is the current structure of Mimas?

- How and when Mimas started to melt and differentiate?
- How tidal heating governs differentiation dynamics of an icy moon?
- What initial state and orbital history can explain its current state?

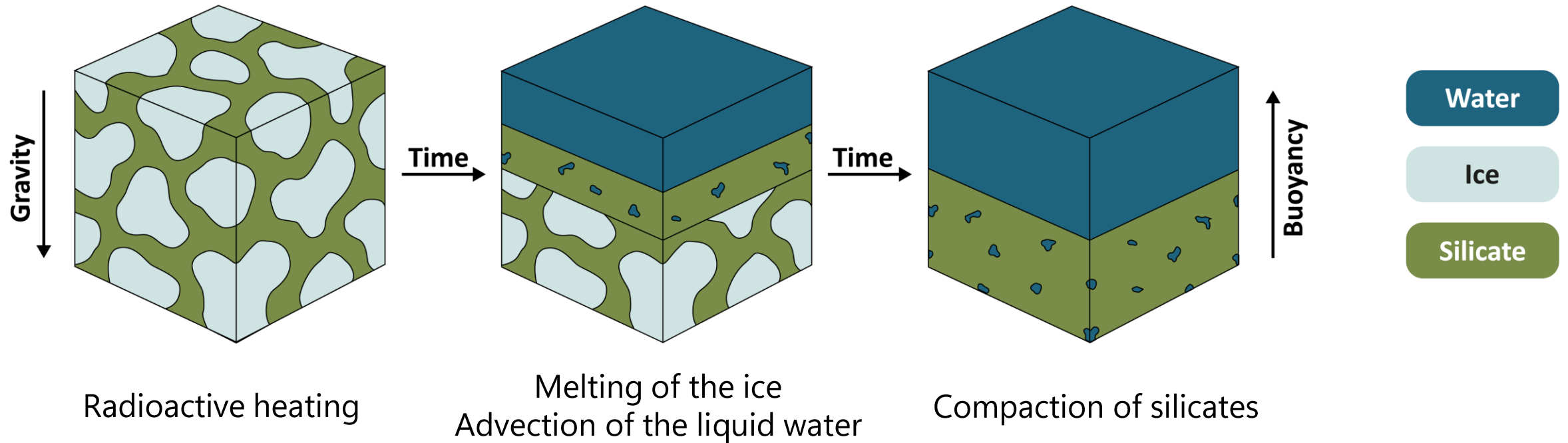


- **Need a code to compute self-consistently differentiation and tidal heating, by coupling two existing codes**

Methods

Internal structure evolution from a homogeneous interior

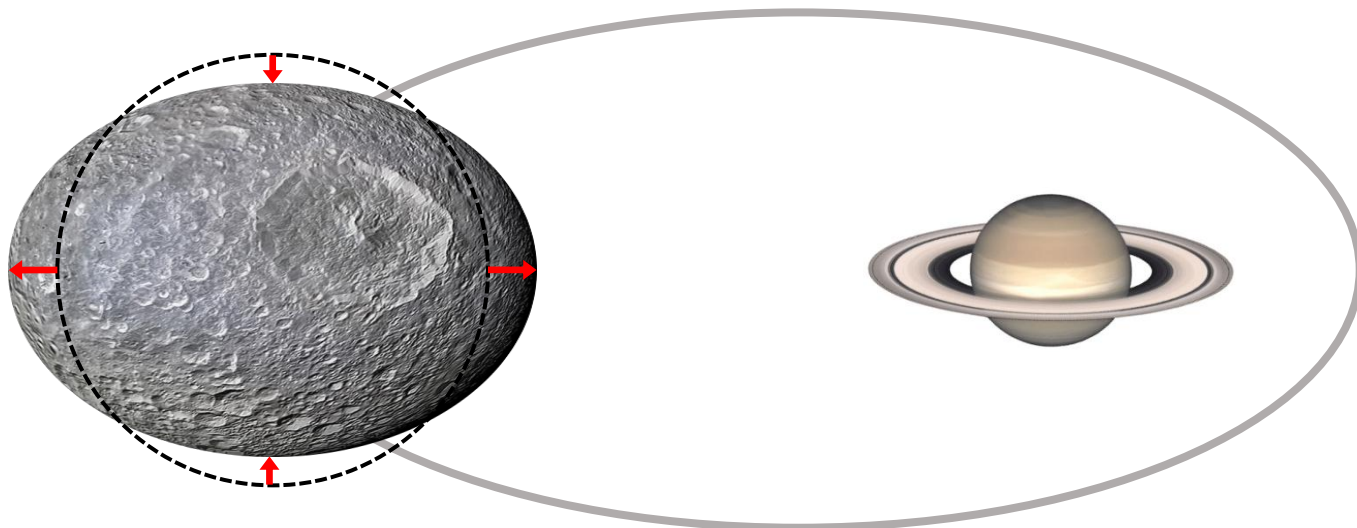
BOREAS – 1D Modeling differentiation of icy moons



➤ **Give time evolution of the structure of Mimas**

⚠ Until now, not able to compute tidal heating

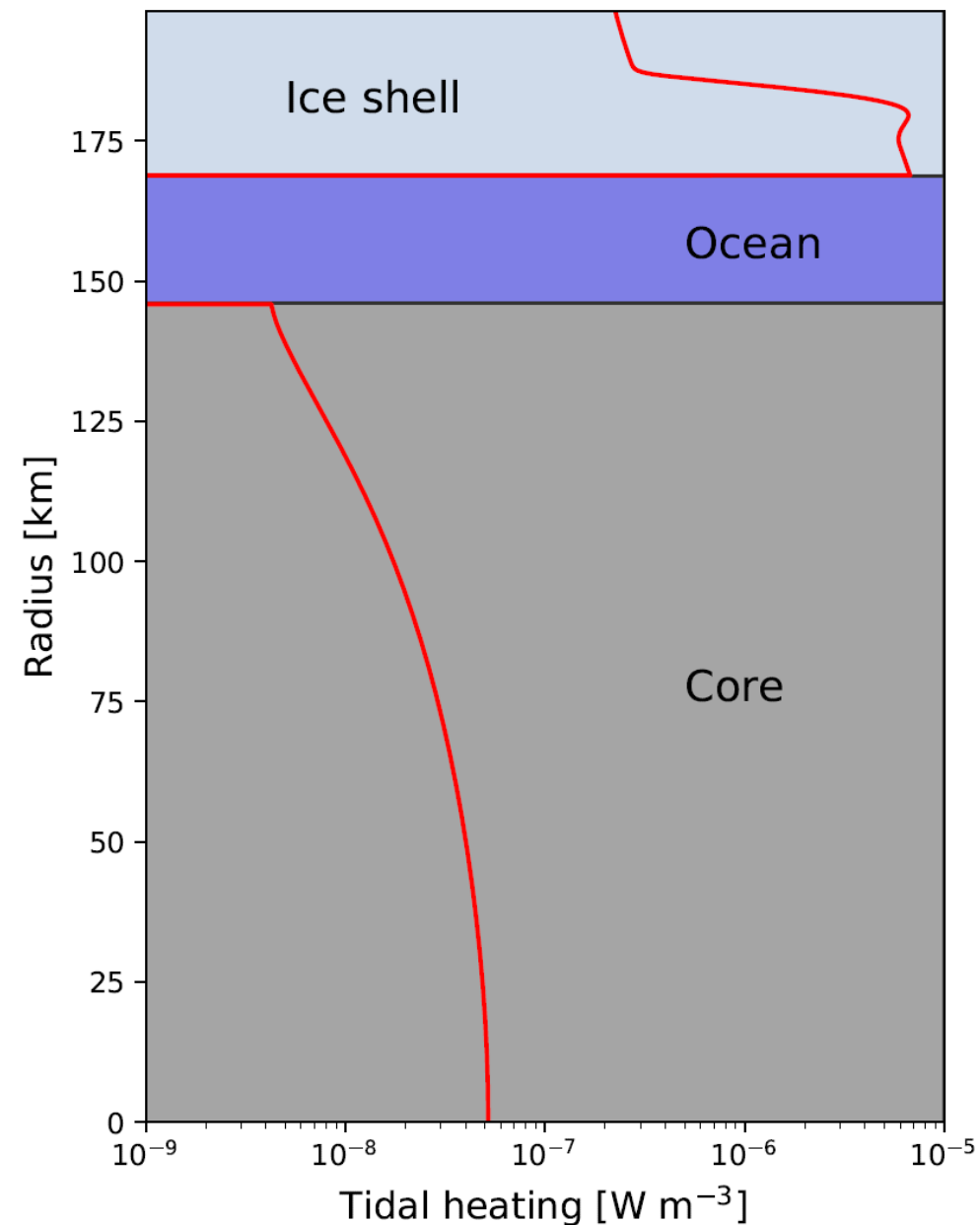
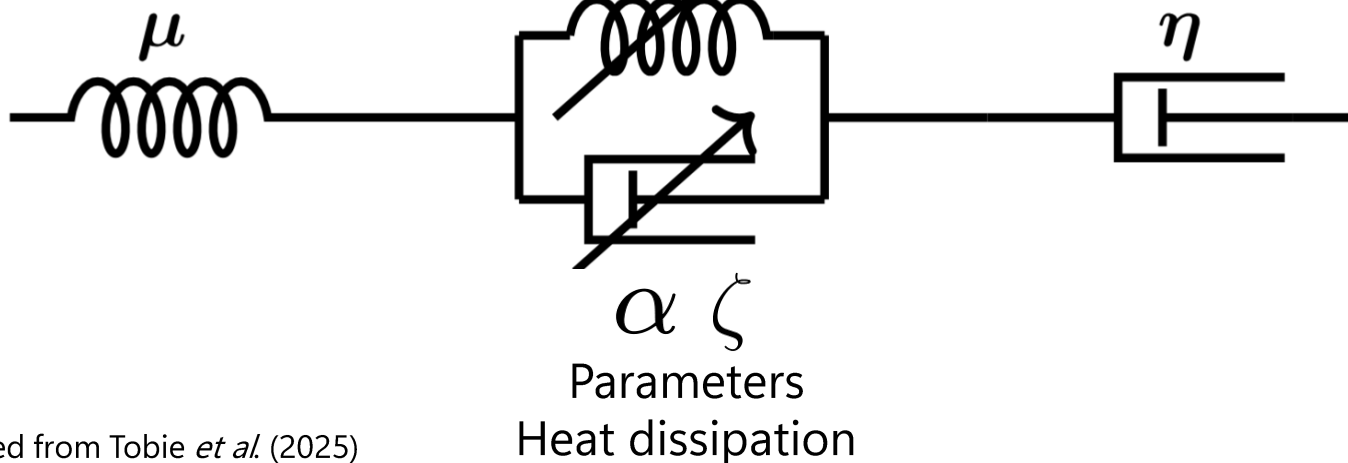
Methods – Tidal heating



Andrade law

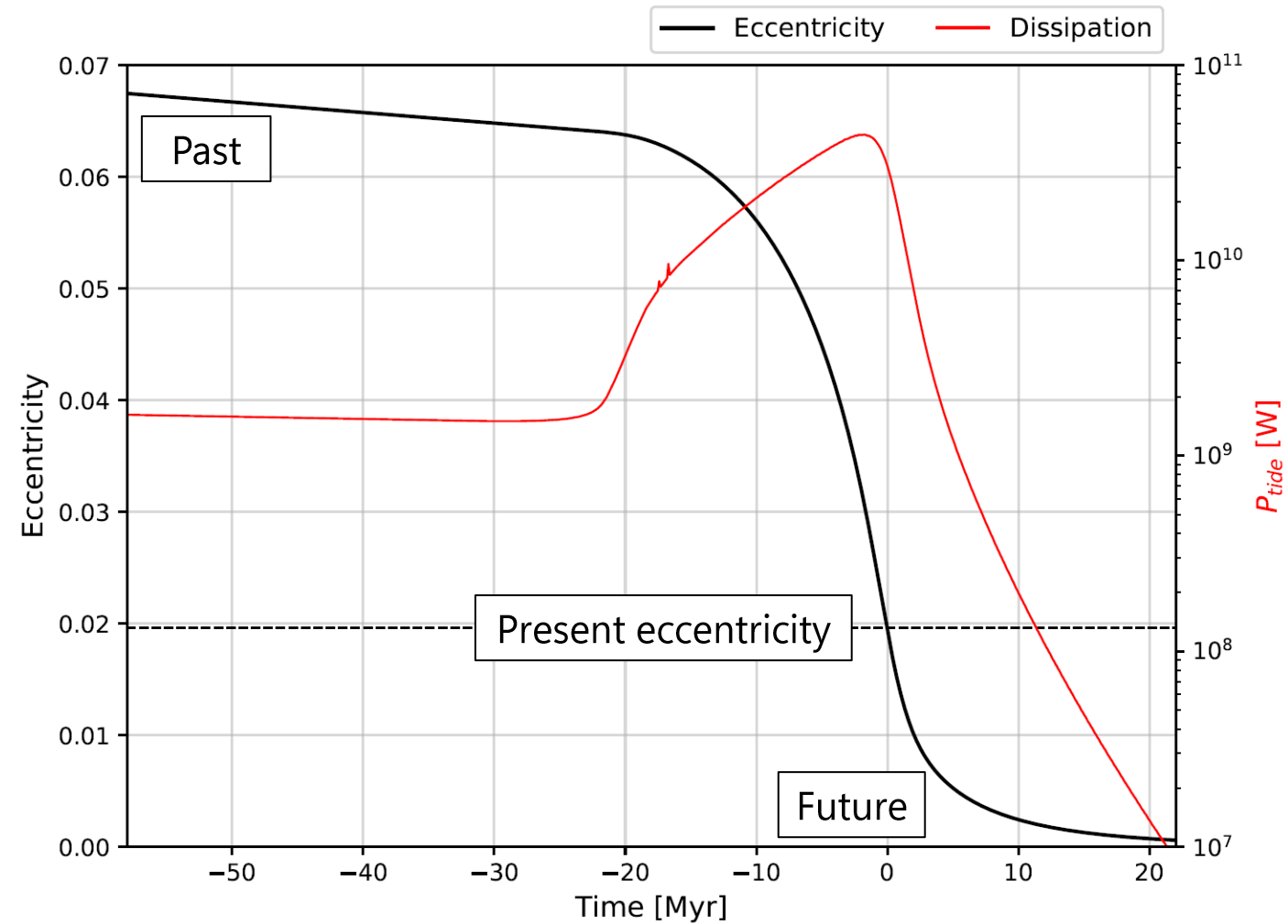
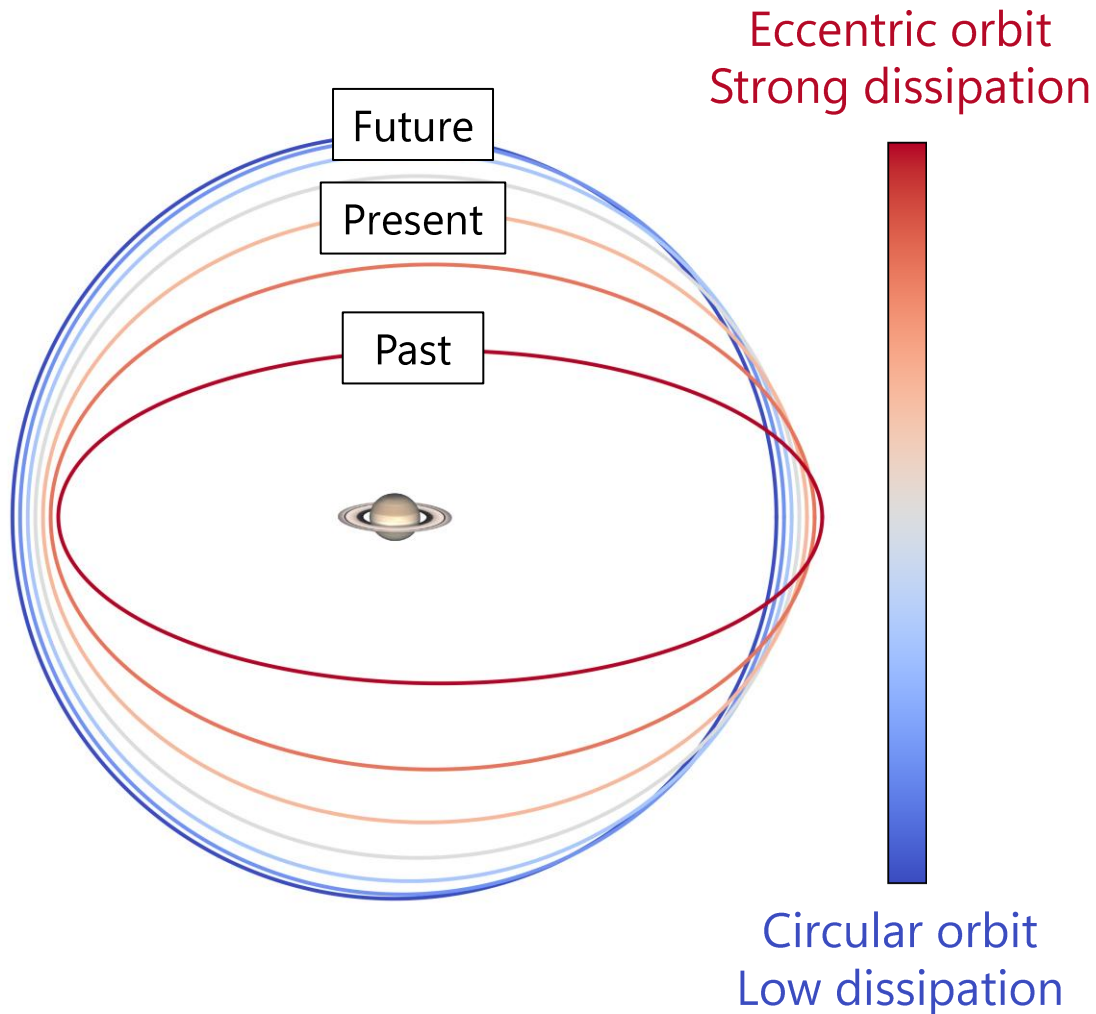
Elastic shear modulus
Shearing deformation

Viscosity
Irreversible flow

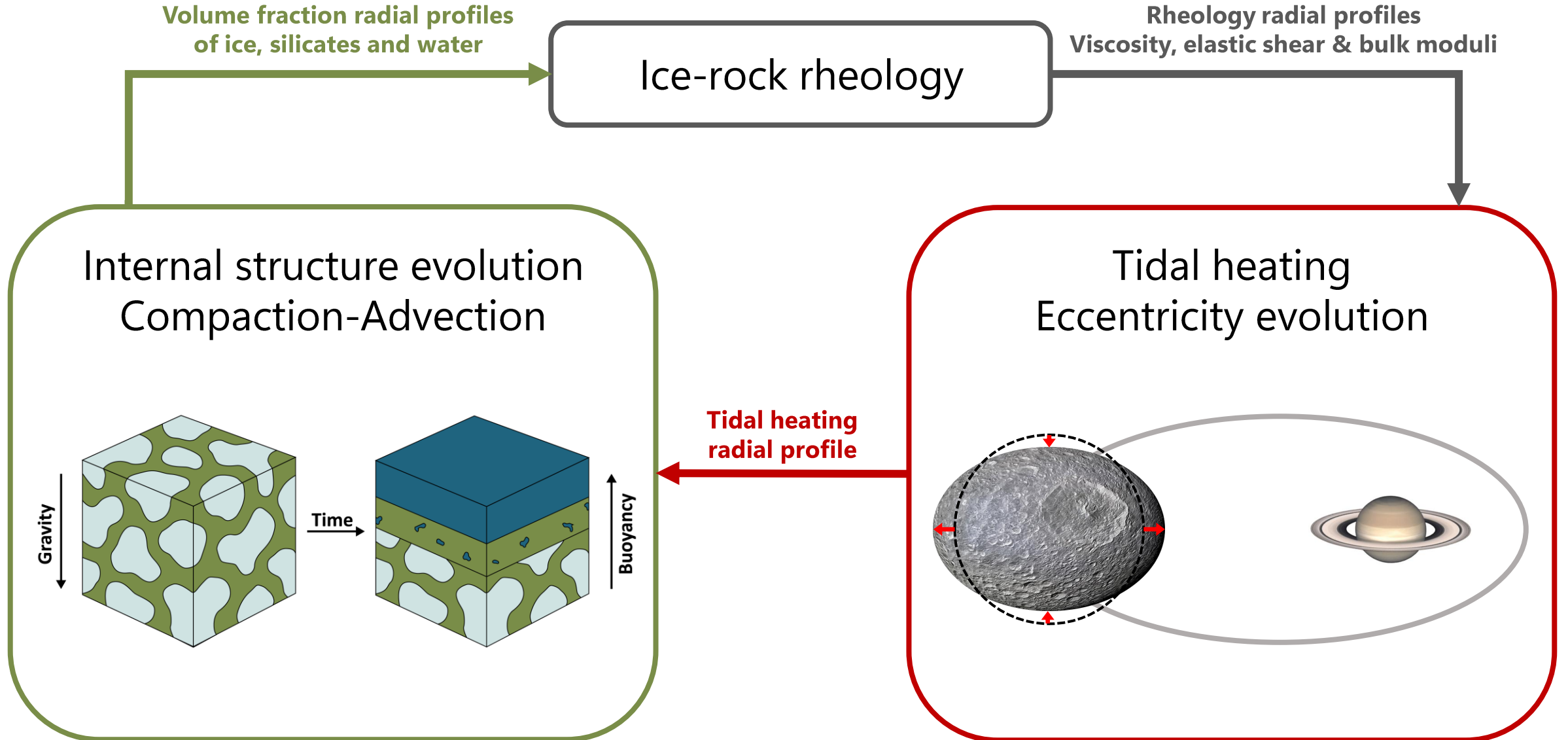


Methods – Orbital evolution

- Tidal dissipation depends on the structure and the eccentricity
- Feedback Eccentricity-Dissipation

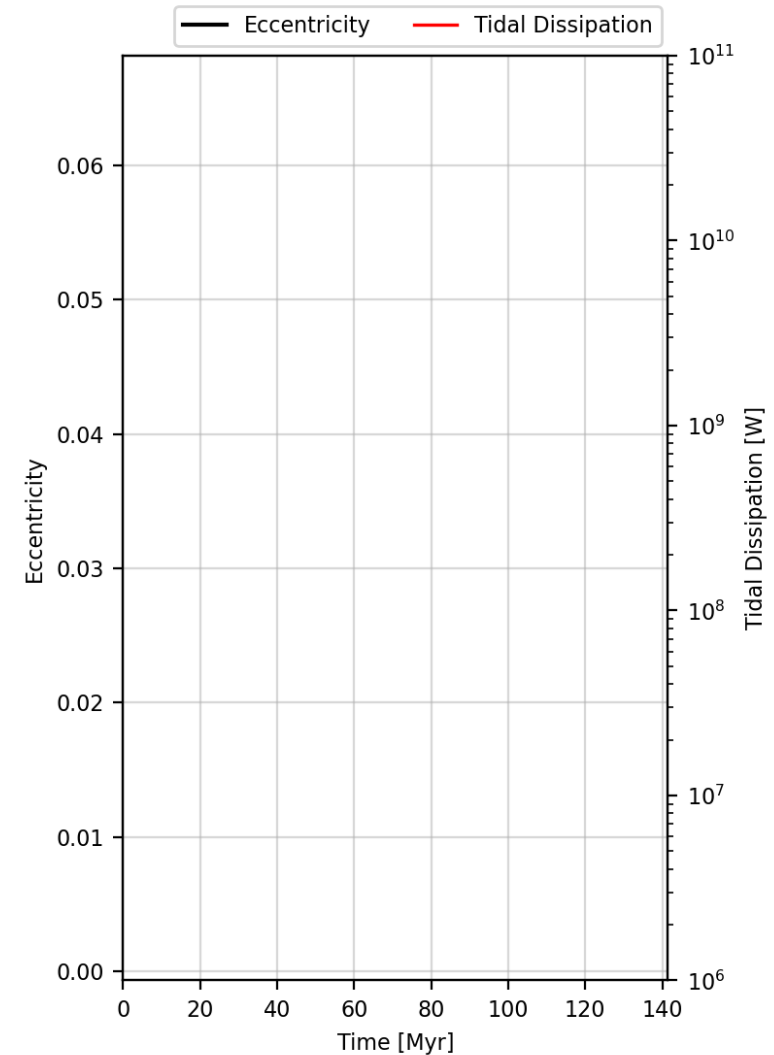
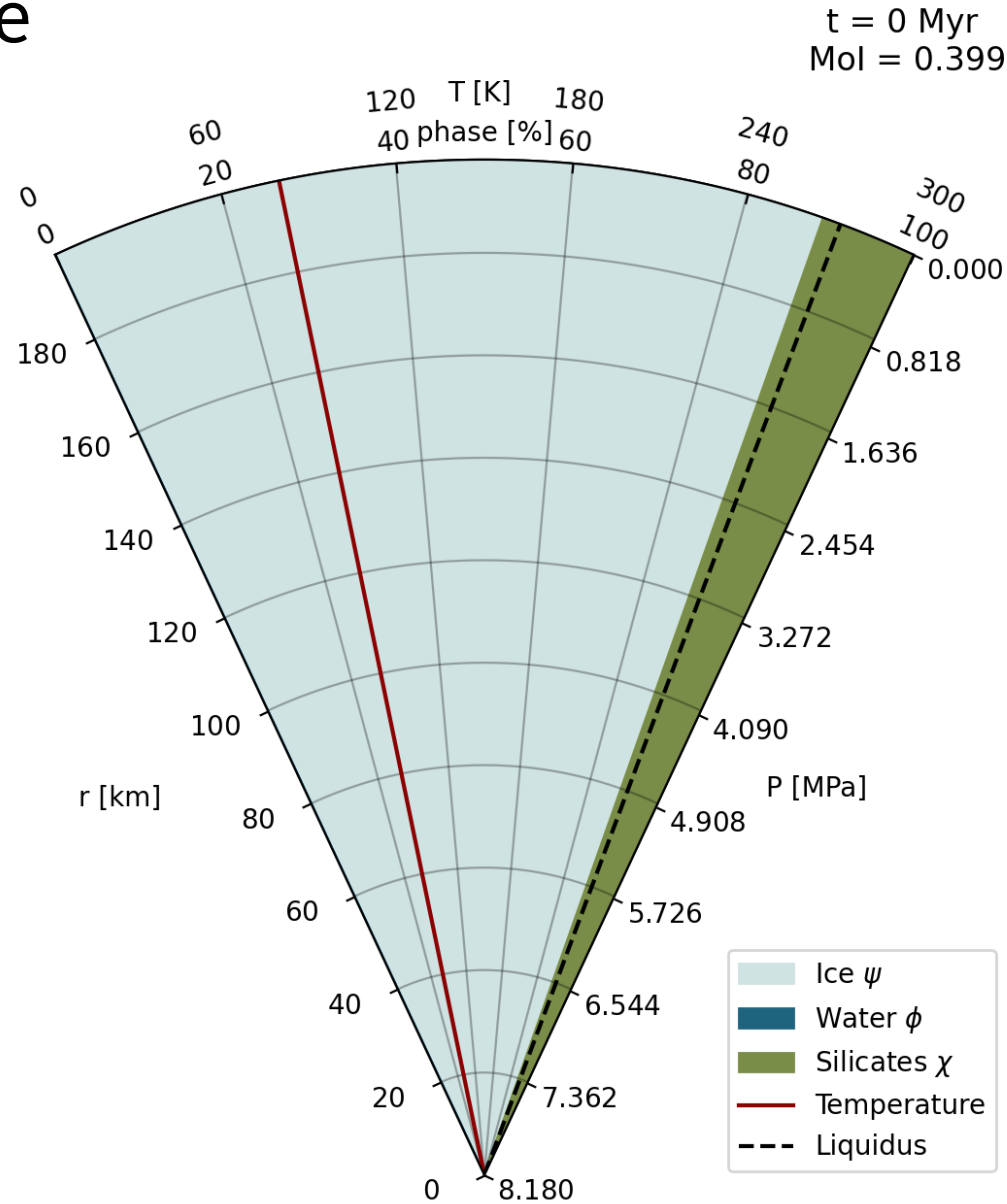


Methods – Differentiation/Tidal heating Coupling



Differentiation dynamics governed by tidal heating

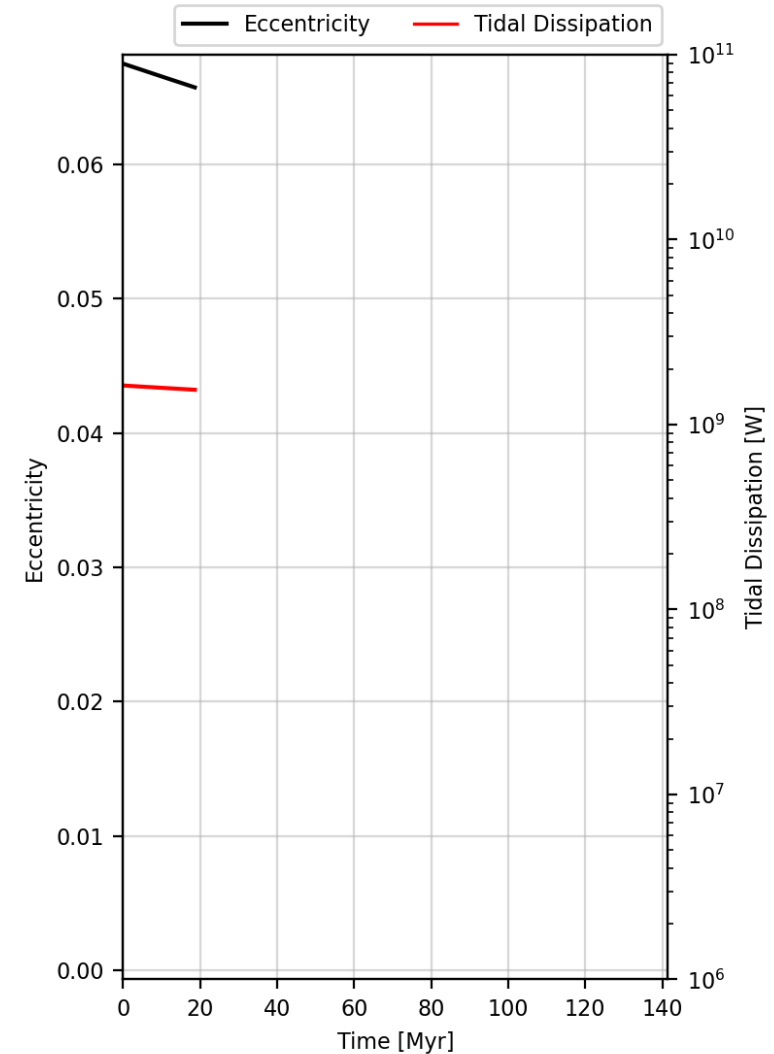
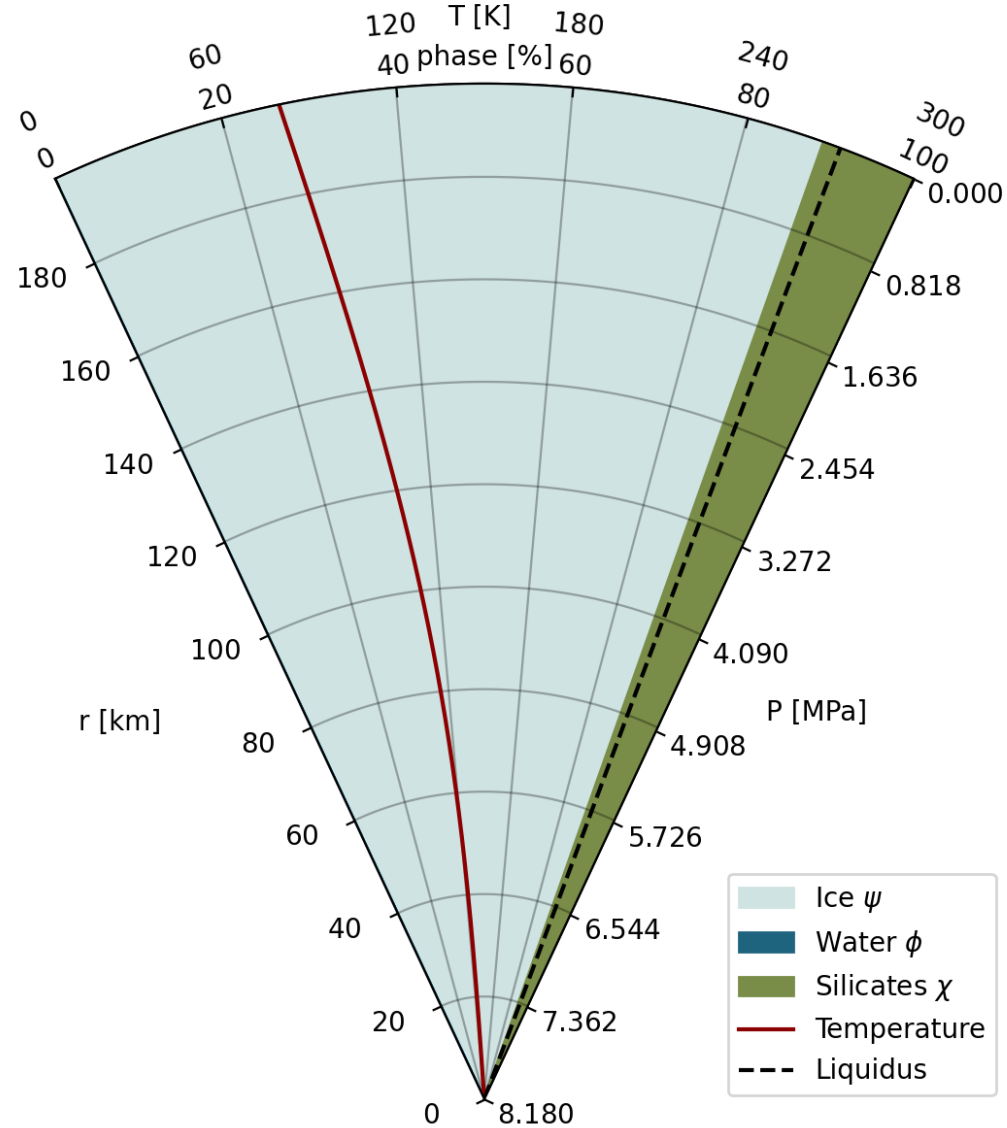
Initial state



Differentiation dynamics governed by tidal heating

Heating at the center

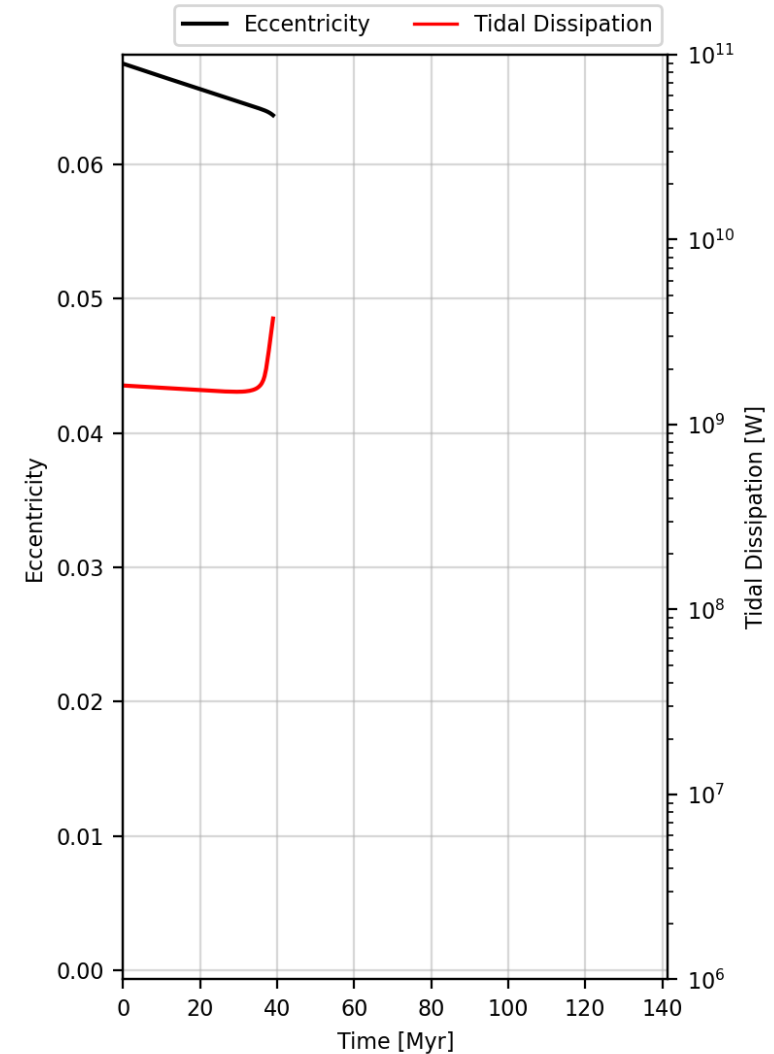
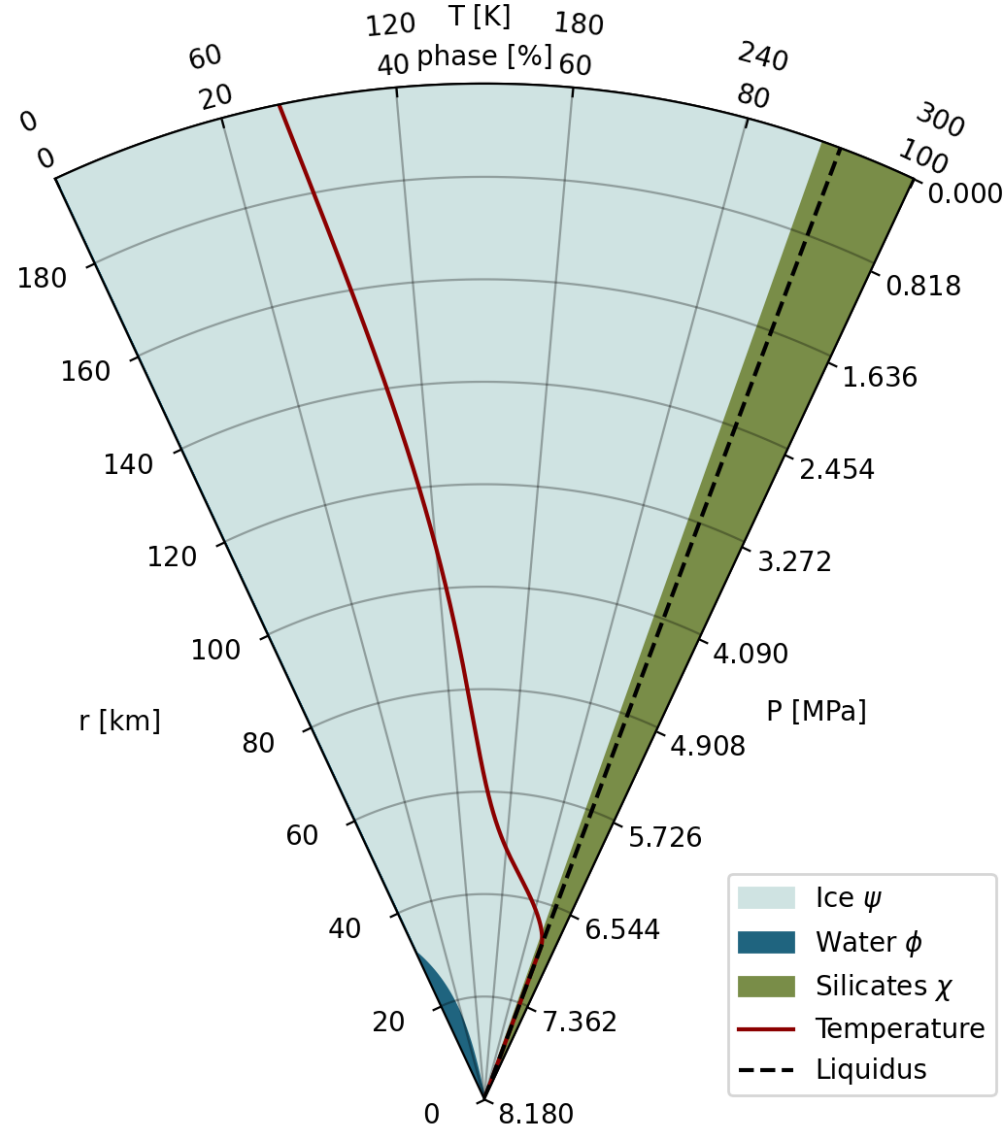
$t = 19 \text{ Myr}$
 $Mol = 0.399$



Differentiation dynamics governed by tidal heating

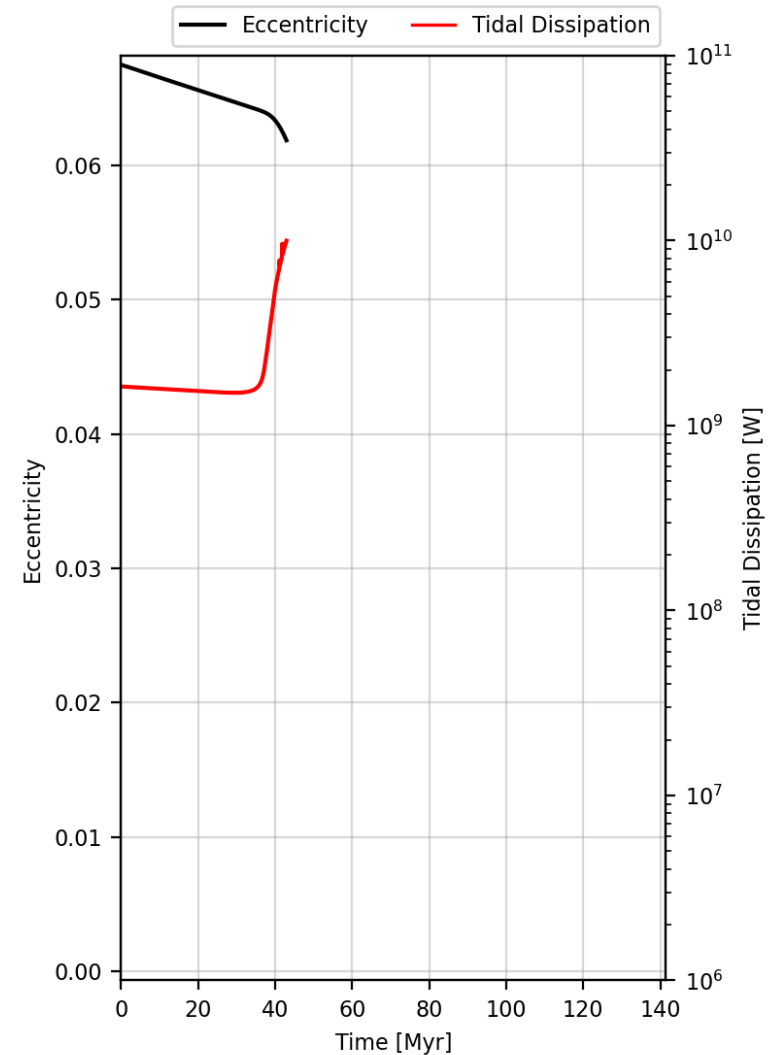
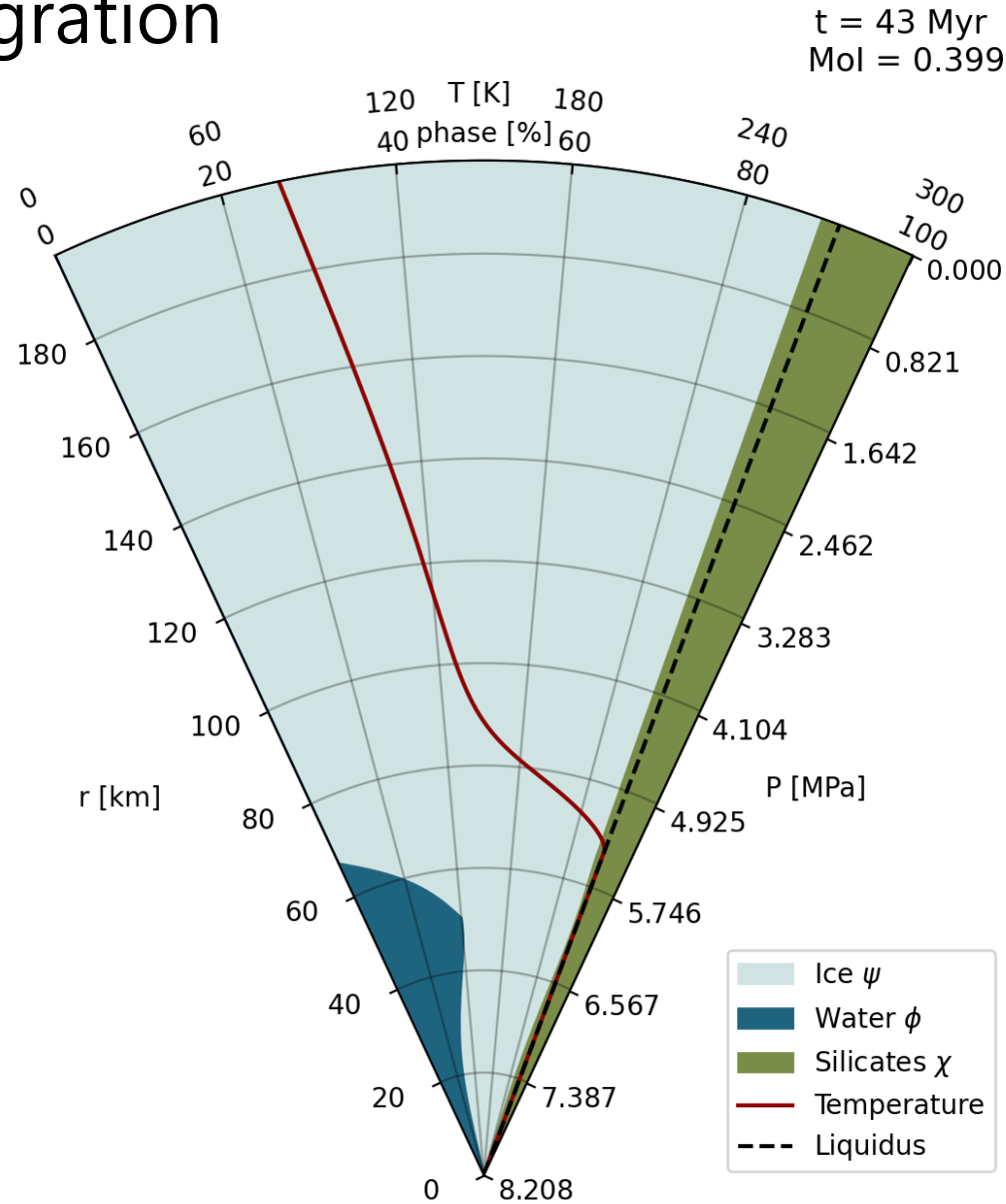
Ocean formation

$t = 39 \text{ Myr}$
 $Mol = 0.399$



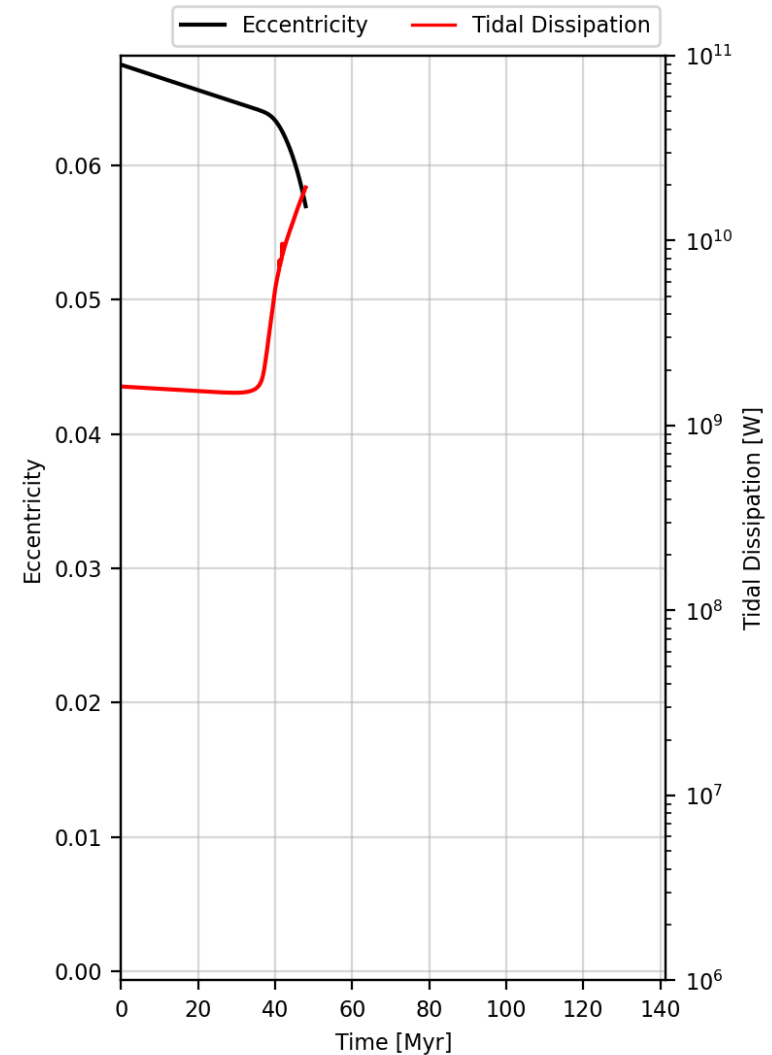
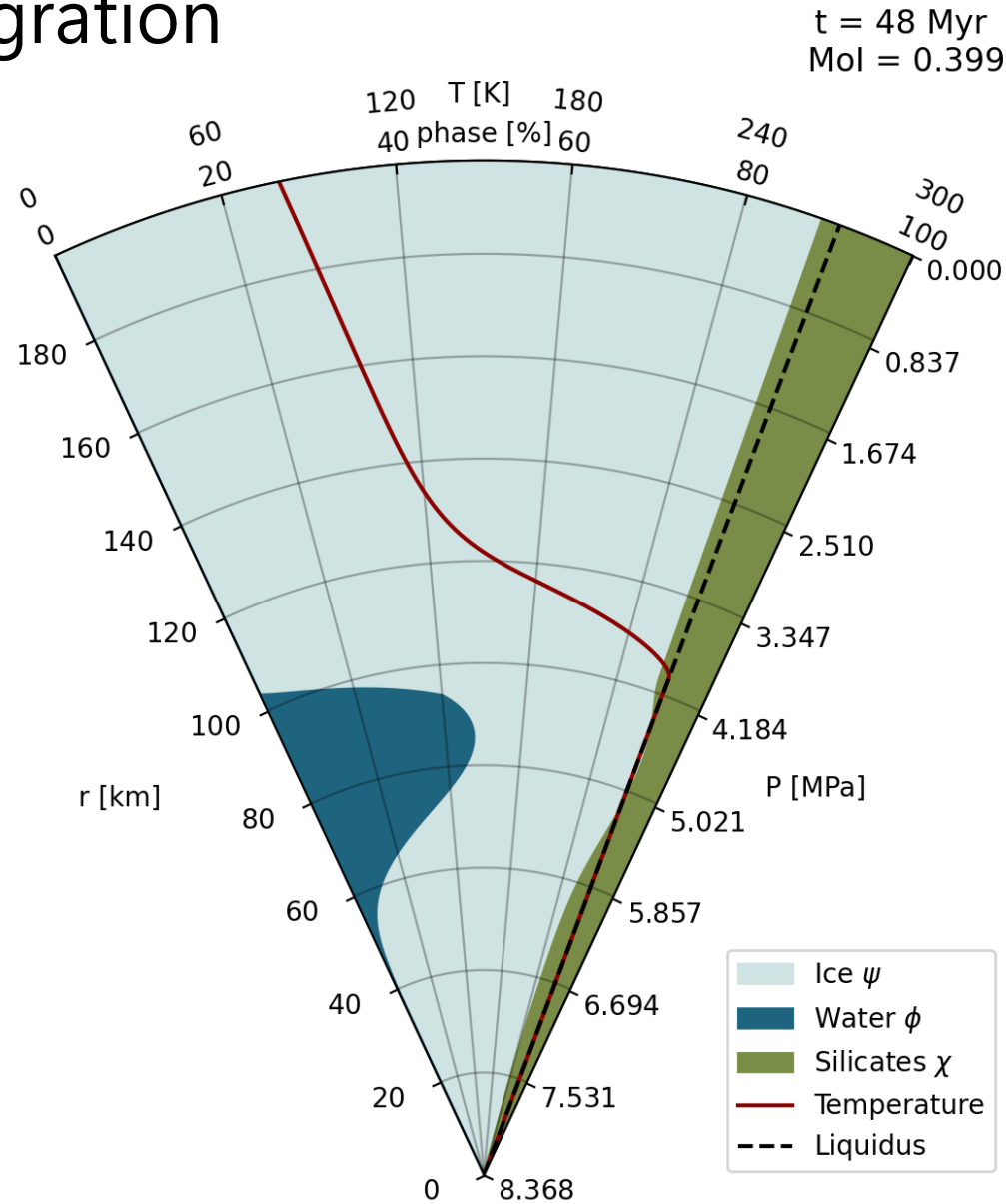
Differentiation dynamics governed by tidal heating

Ocean migration



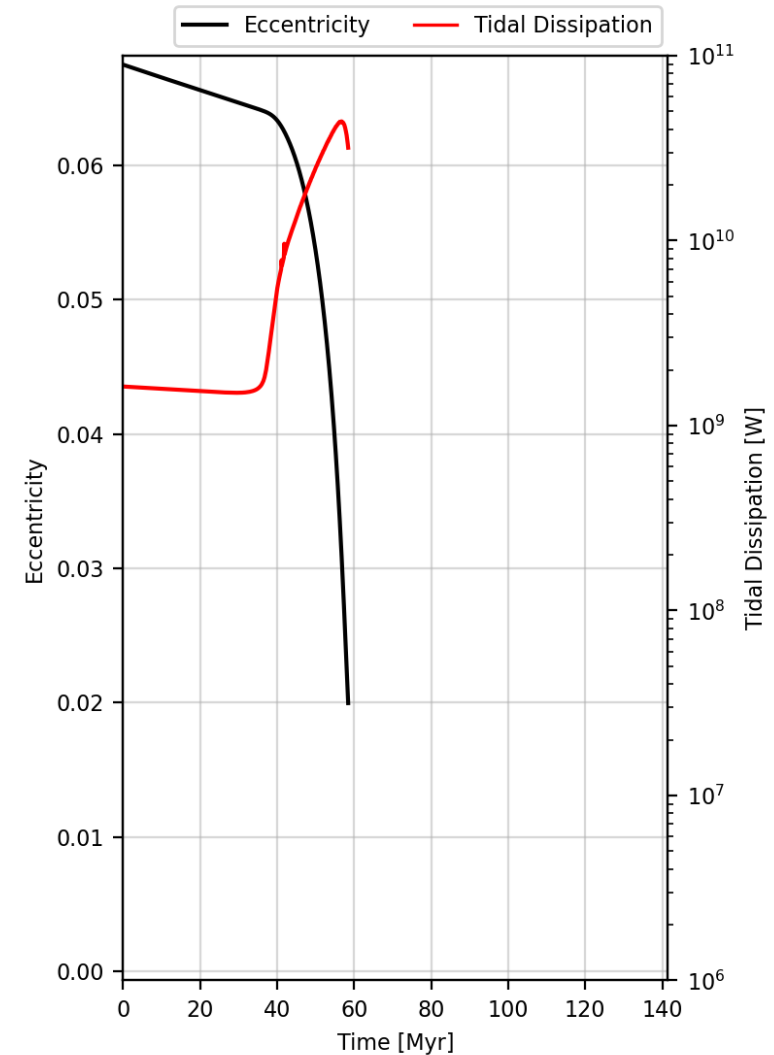
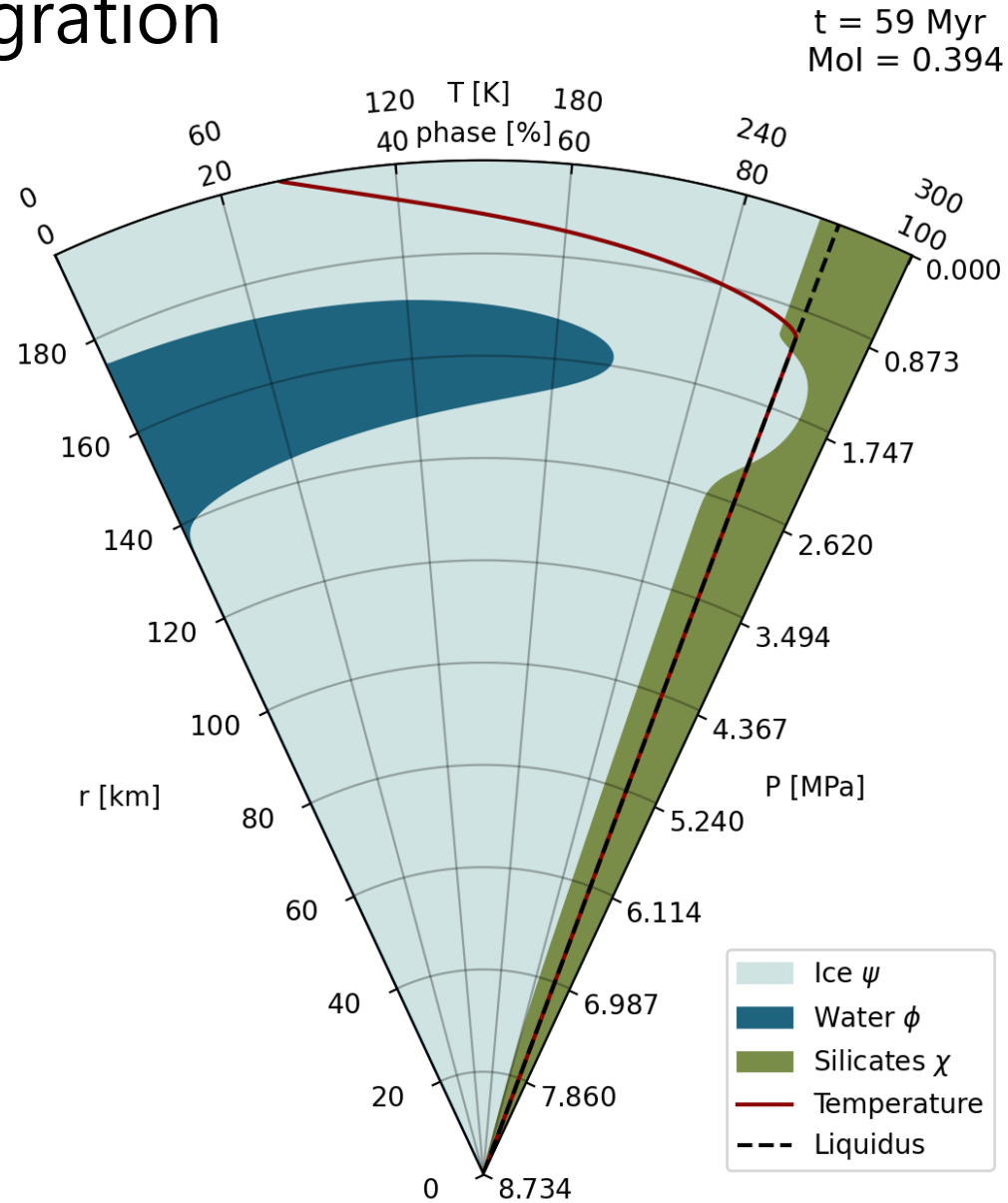
Differentiation dynamics governed by tidal heating

Ocean migration



Differentiation dynamics governed by tidal heating

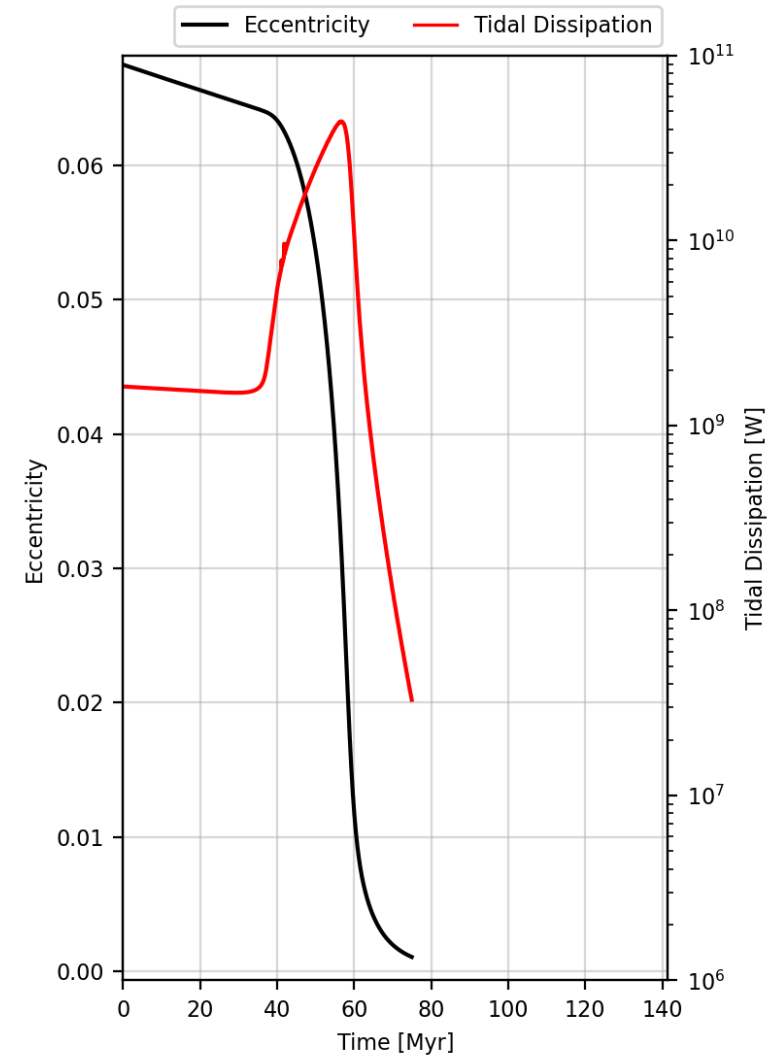
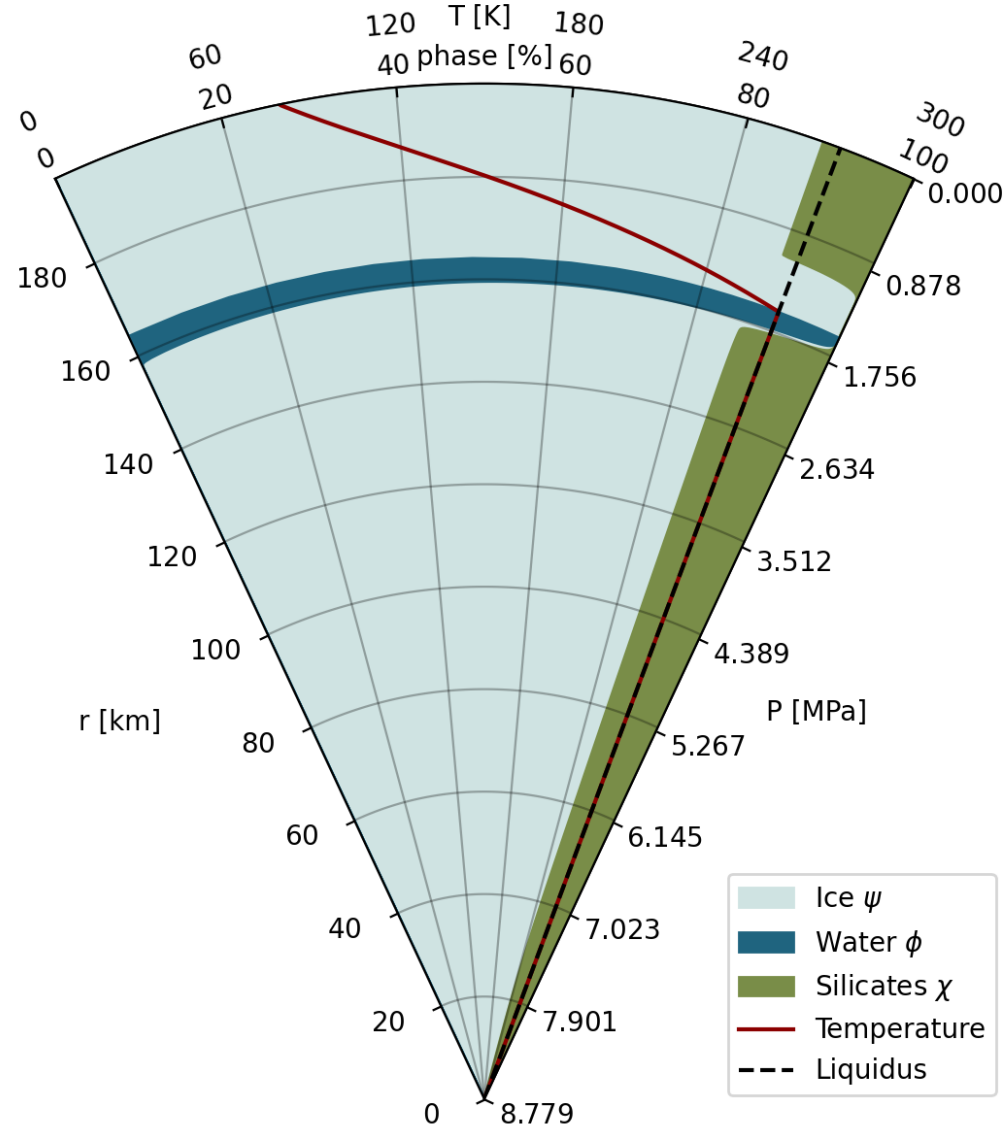
Ocean migration



Differentiation dynamics governed by tidal heating

Ocean recrystallization

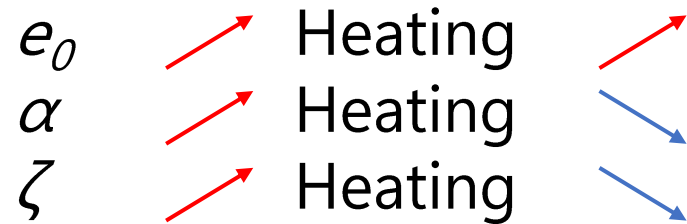
$t = 75 \text{ Myr}$
 $Mol = 0.392$



Effects of tidal heating on ocean formation timescales

Parameters exploration

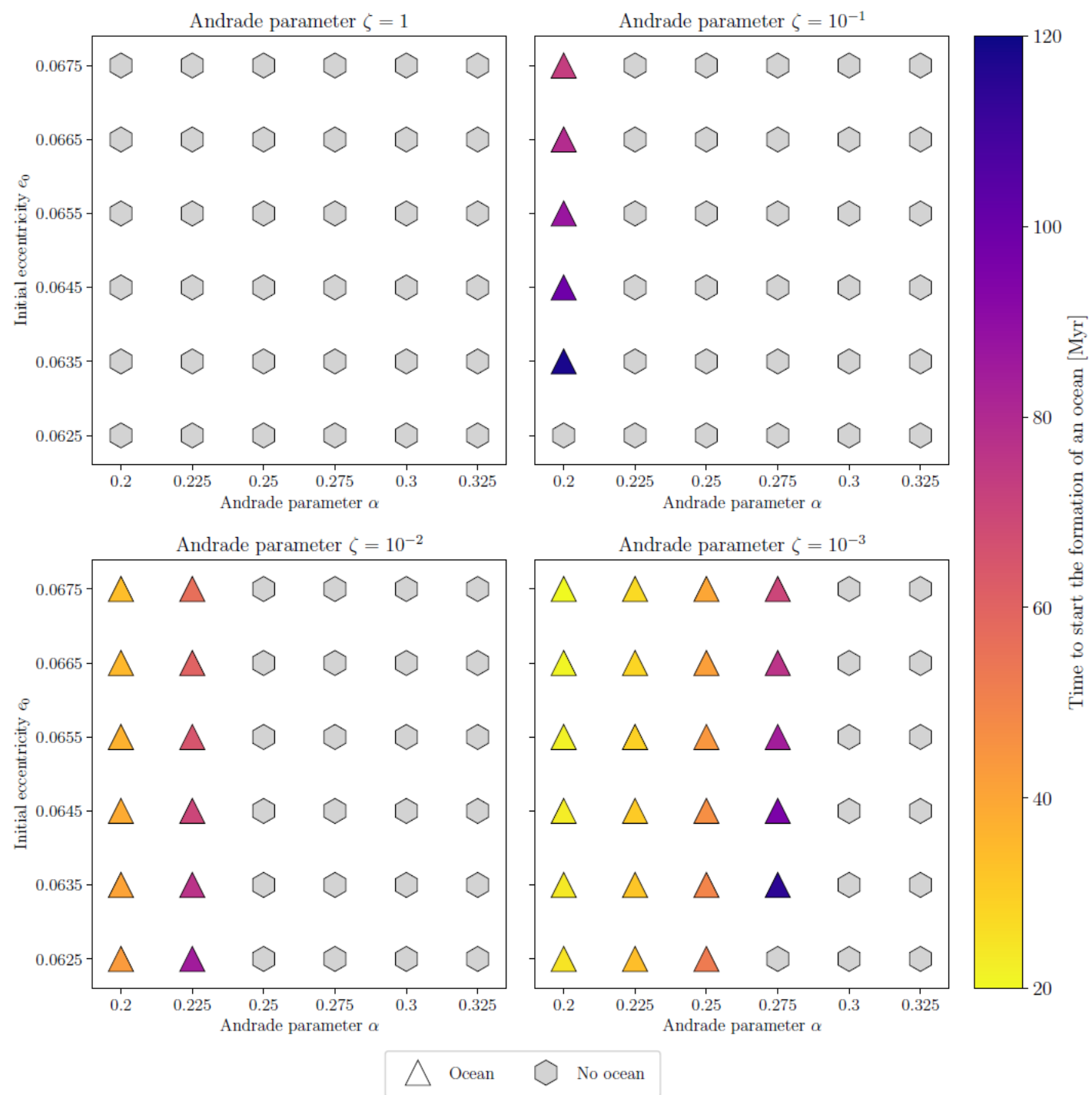
- Initial eccentricity e_0
- Andrade visco-elastic parameter α
- Andrade visco-elastic parameter ζ



➤ Competition heat produced/loss

➤ Conditions for ocean formation

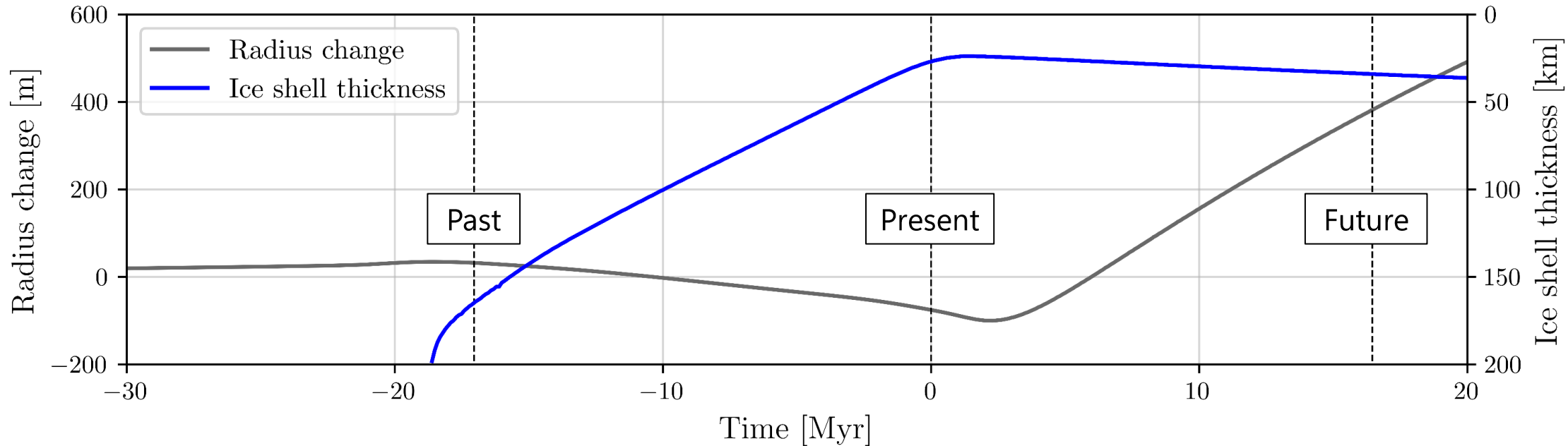
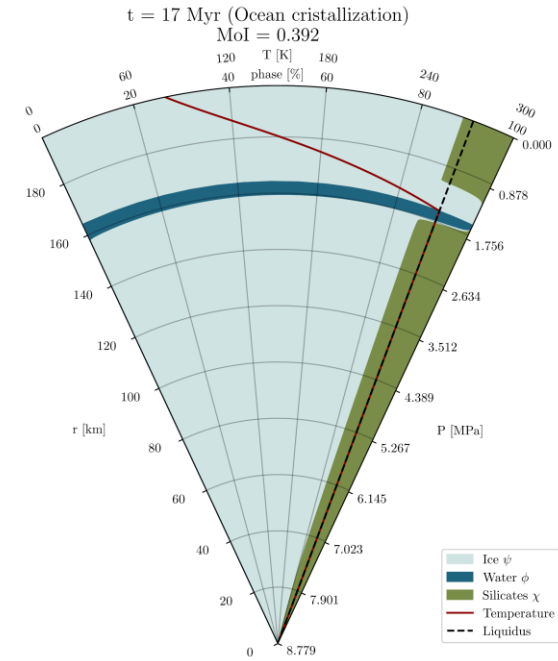
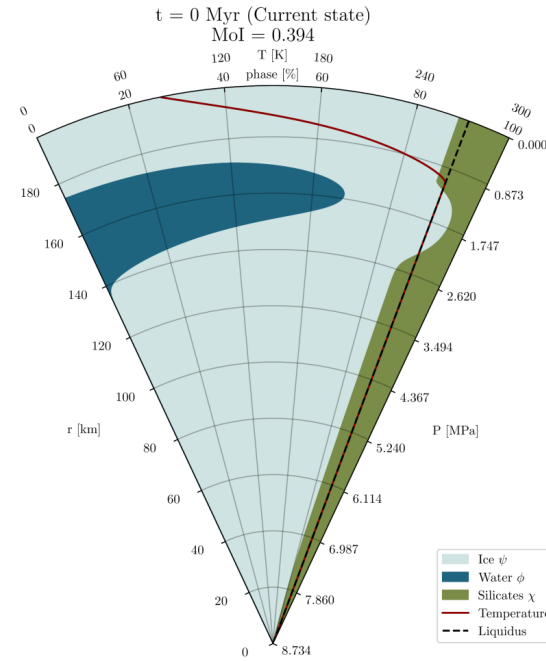
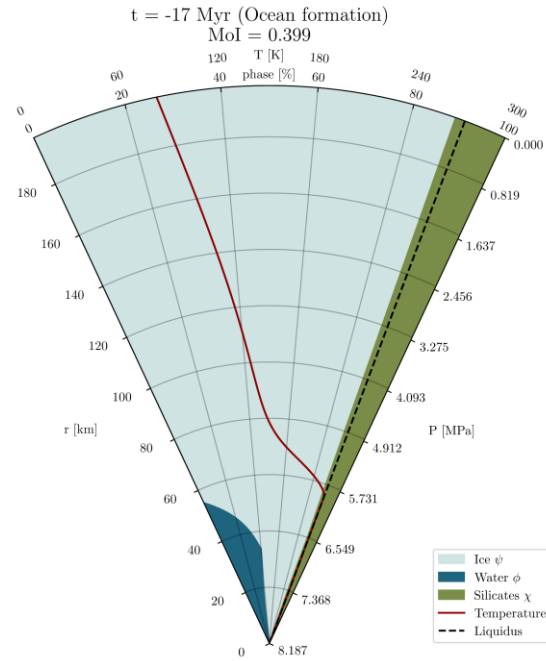
- $e_0 \sim 0.06-0.07$
- $\alpha < 0.3$
- $\zeta < 1$



How and when Mimas differentiate

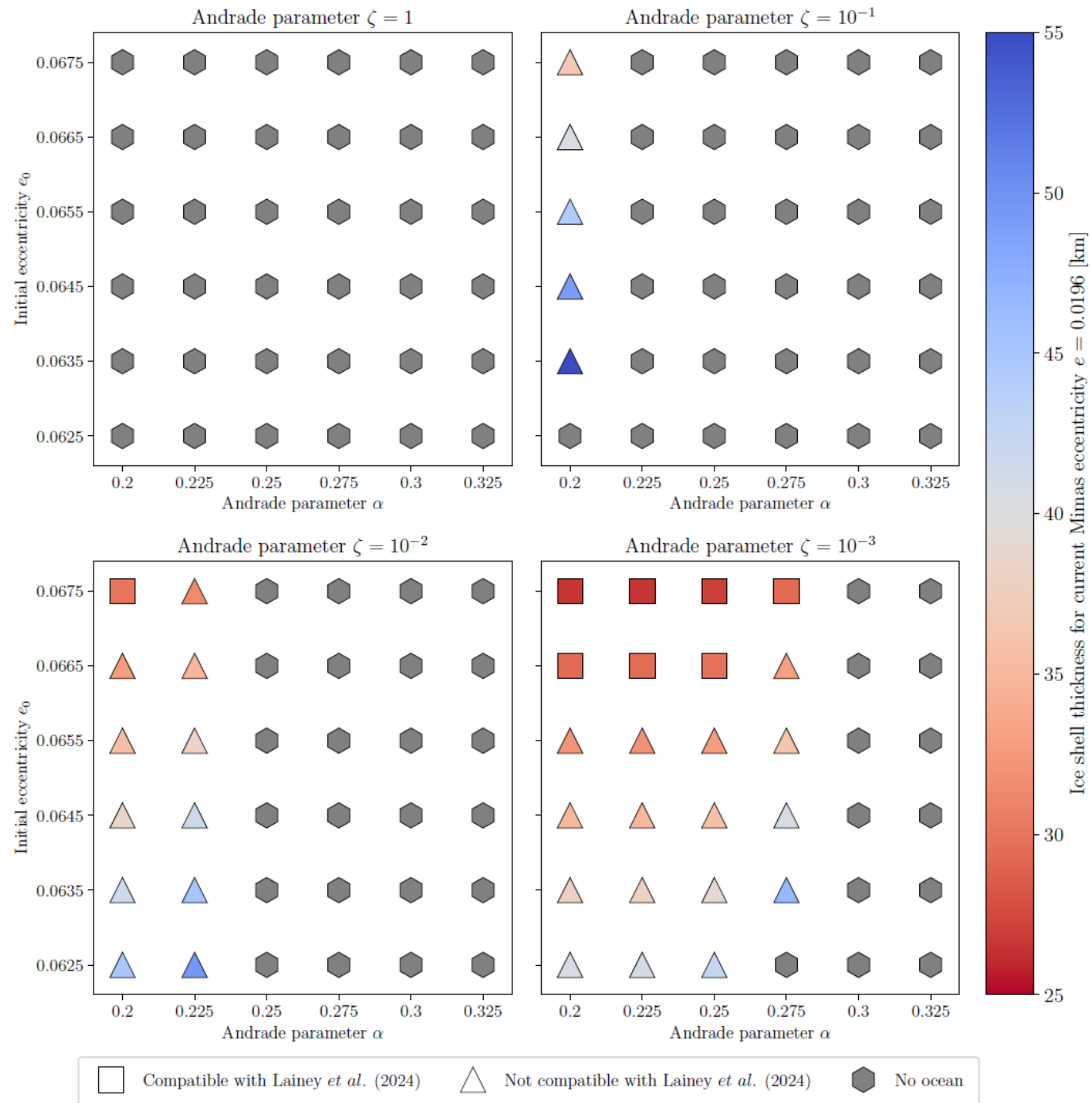
Timescales of ocean formation change with e_0 , α and ζ

➤ But ocean evolution timescales are similar whatever the parameters



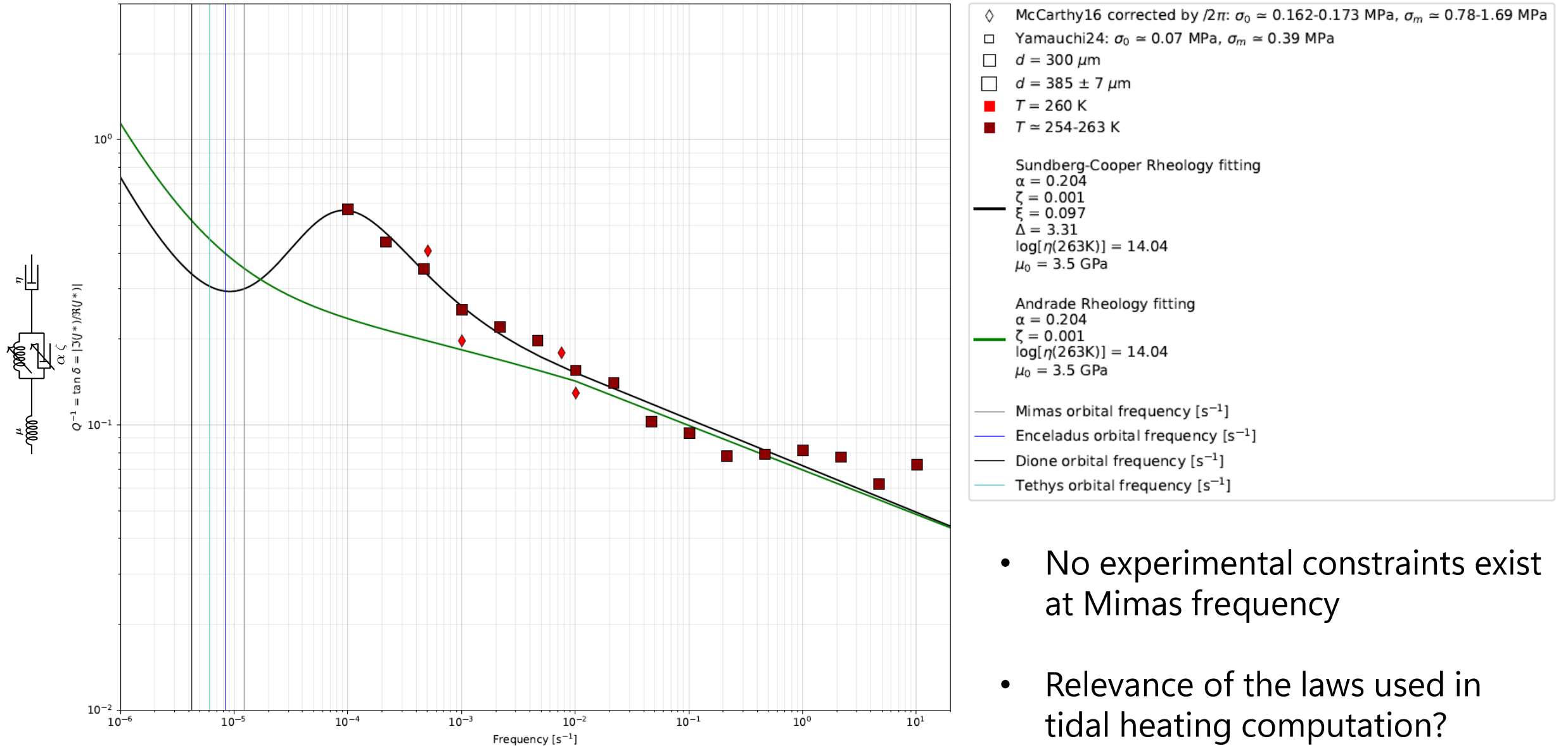
Compatibility with Mimas current state

- Lainey *et al.* (2024) constrained an ocean under an ice shell 20-30 km thick
- 8 scenarios verify the constraints
 - Ice shell 20-30 km thick
 - Eccentricity $e = 0.0196$
- Short-term perspective: Compute librations and periapsis drift of our models



Discussion – Relevance of the Andrade law?

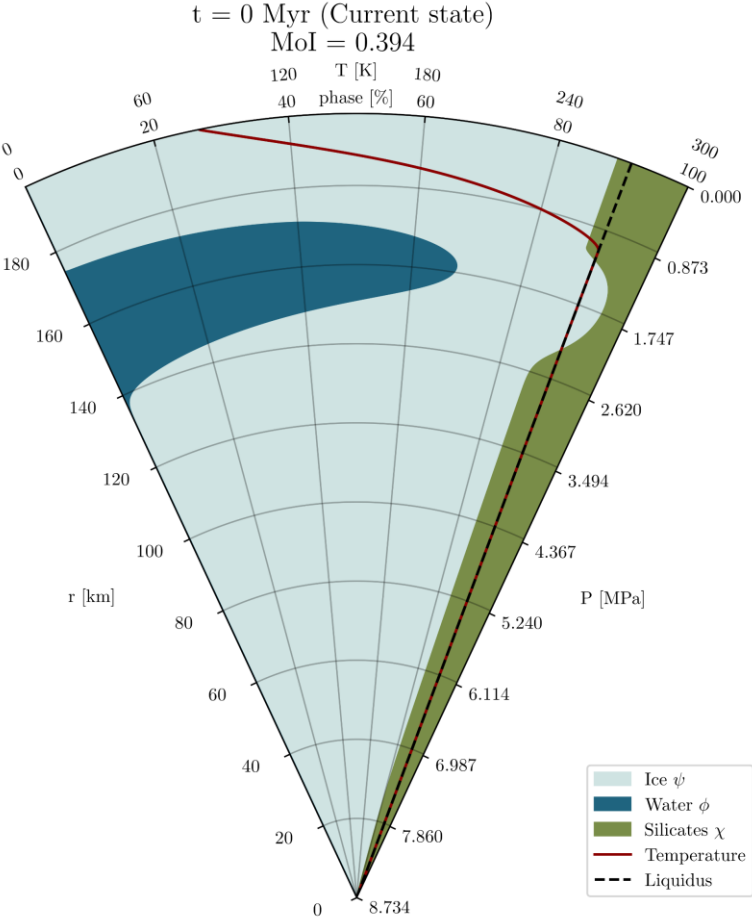
Only $T > 260$ K and $d > 300$ μm from McCarty16 and Yamauchi24



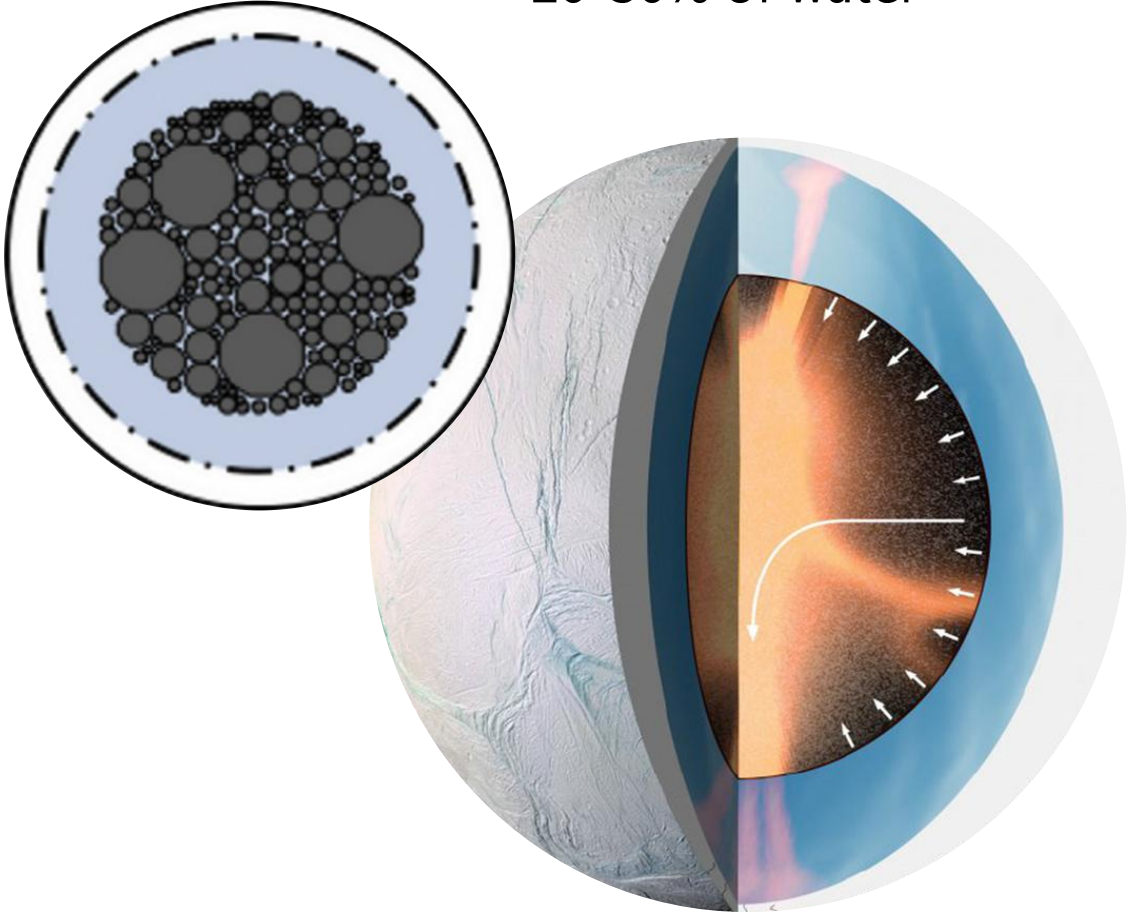
- No experimental constraints exist at Mimas frequency
- Relevance of the laws used in tidal heating computation?

Discussion – Implications of an ice-rich core in Mimas for core dissipation in Enceladus?

Mimas could have an ice-rich core



Enceladus should have a silicated porous core with 20-30% of water

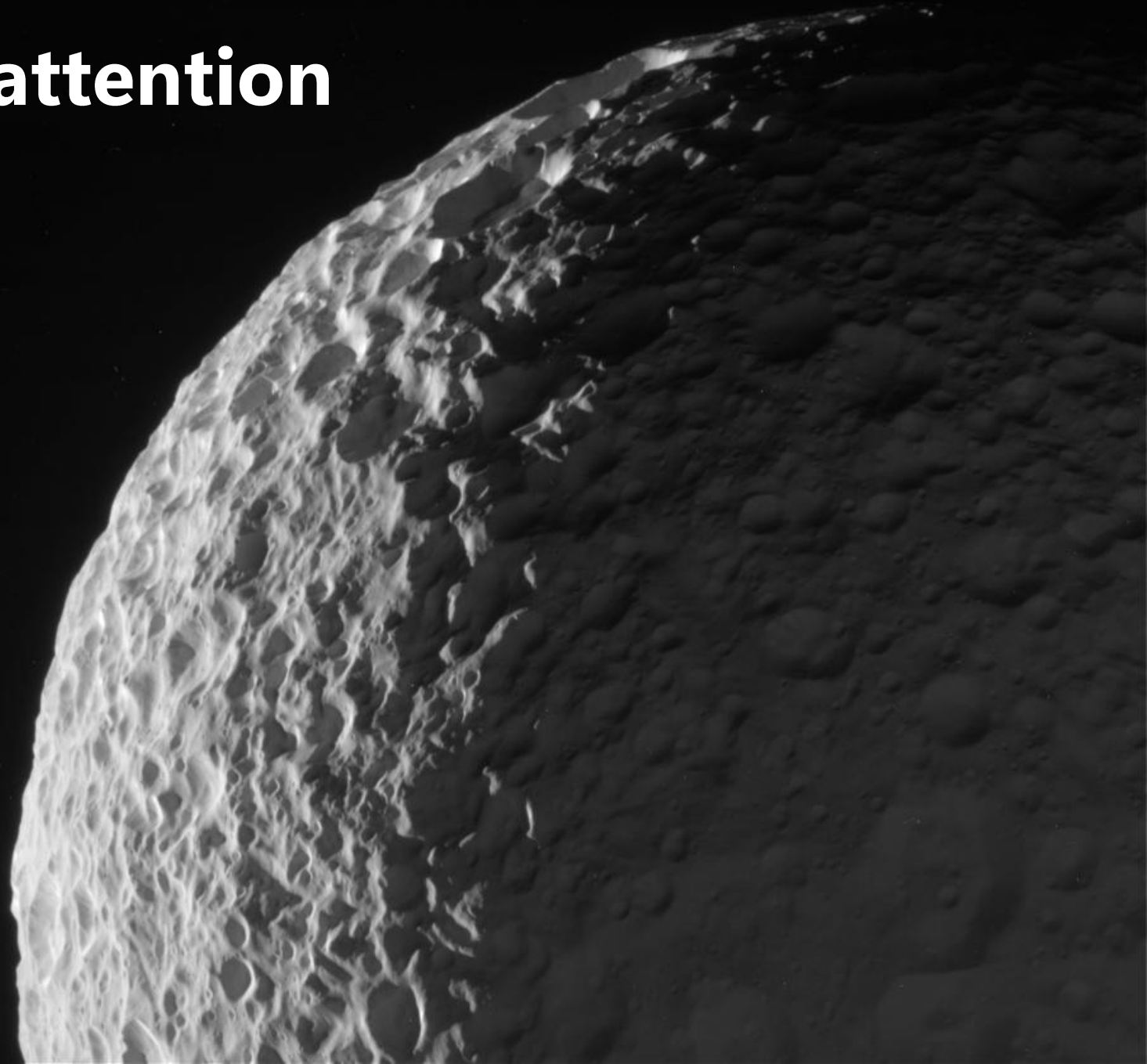


Conclusion

- A paradox exists between evidence for an ocean in Mimas and its lack of surface tectonic activity
- By coupling a code of differentiation and a code of tidal heating, and implementing orbital evolution, we investigate a scenario where Mimas is currently differentiating by tidal heating
- We find that Mimas could have currently an ice-rich core and a mushy ocean recently formed in the last 20 Myr, consistent with its inactive surface
- The model developed during this internship can be applied to all icy moons, as Ganymede, Dione or Enceladus for example

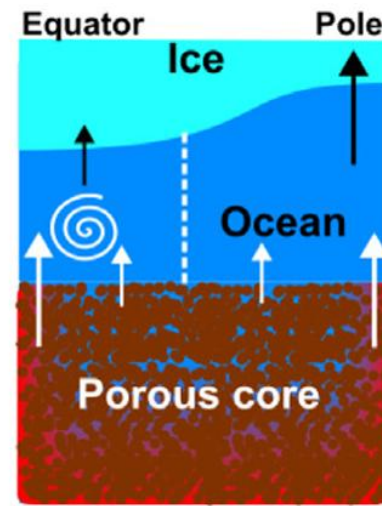
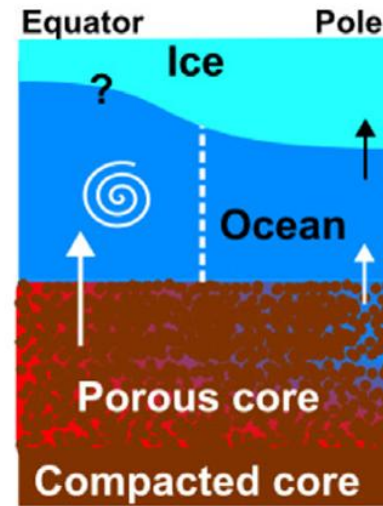


Thank you for your attention



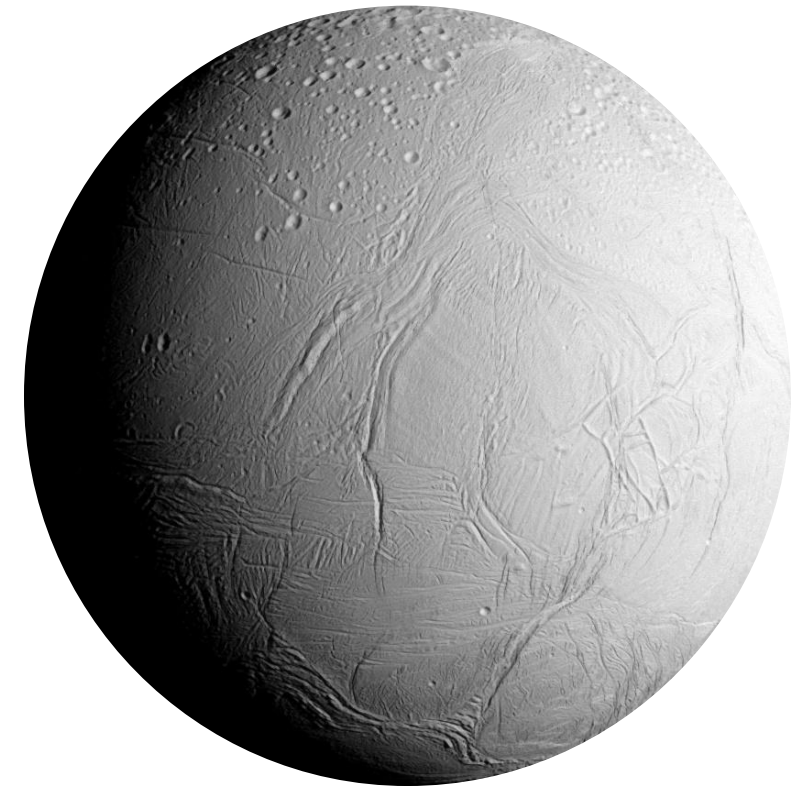
Differentiation of icy mid-sized moons and ocean dynamics

Dione

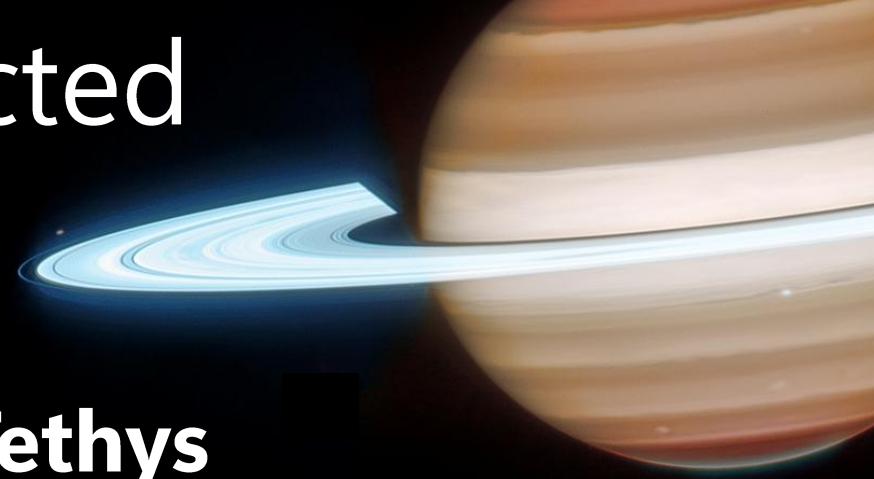


Terra-Nova *et al.* (2026)

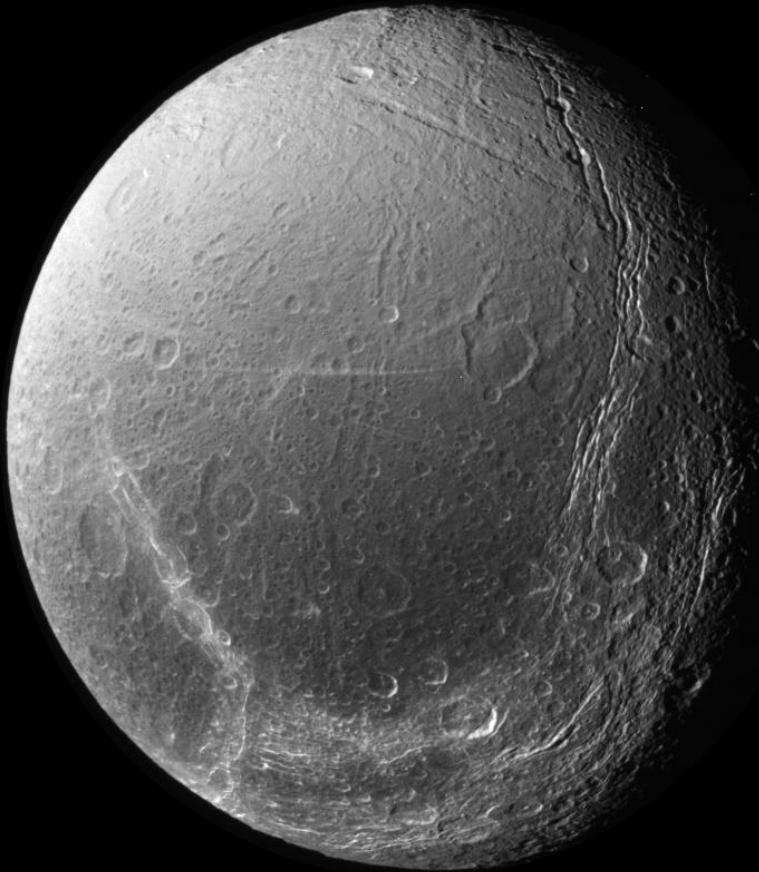
Enceladus



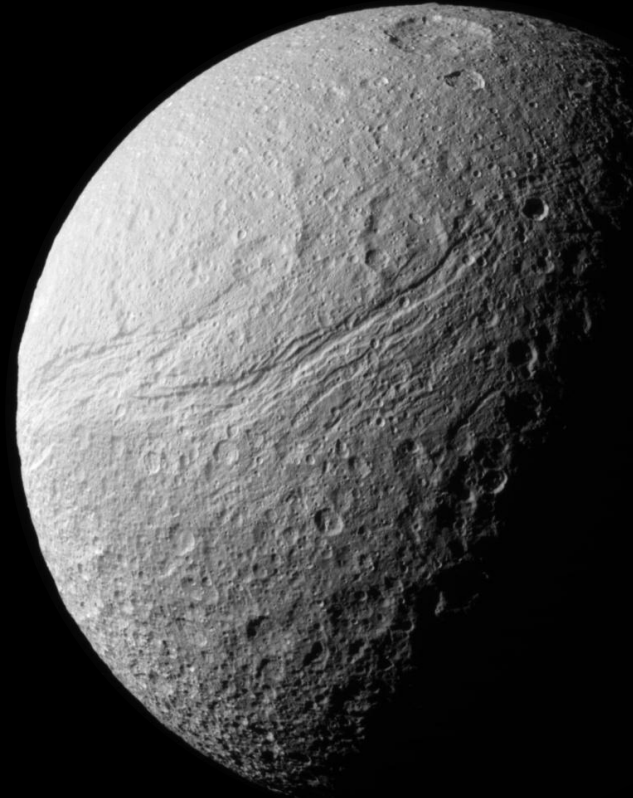
Dione and Tethys show unexpected evidence of (past?) activity



Dione



Tethys



Momentum conservation in fluid

$$\mathbf{0} = -\nabla (P_f \phi) + \nabla \cdot (\underline{\boldsymbol{\tau}}_f \phi) + \rho_\phi \mathbf{g} \phi + \mathbf{h}_f,$$

Momentum conservation in the matrix

$$\mathbf{0} = -\nabla [P_m(\chi + \psi)] + \nabla \cdot [\underline{\boldsymbol{\tau}}_m(\chi + \psi)] + \rho_m \mathbf{g}(\chi + \psi) + \mathbf{h}_m,$$

Action-reaction equation

$$\mathbf{0} = -(\chi + \psi) [\nabla (\Delta P) - \mathbf{g} \Delta \rho] + \nabla \cdot [(\chi + \psi) \underline{\boldsymbol{\tau}}_m] - \frac{1}{\phi} c \Delta \mathbf{v} + \Delta P \nabla \phi,$$

$$\frac{\partial \chi}{\partial t} + \nabla \cdot (\mathbf{v}_m \chi) = 0,$$

Silicates mass conservation

$$\frac{\partial \psi}{\partial t} + \nabla \cdot (\mathbf{v}_m \psi) = -\frac{F}{\rho_\psi},$$

Ice mass conservation

$$\frac{\partial \phi}{\partial t} + \nabla \cdot (\mathbf{v}_f \phi) = \frac{F}{\rho_\phi},$$

Liquid water mass conservation

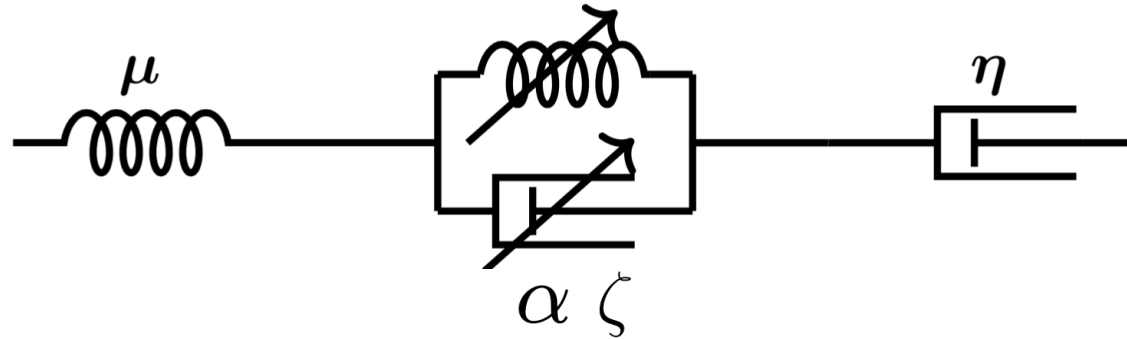
Energy conservation

$$\frac{\partial \overline{\rho C_P T}}{\partial t} = \nabla \cdot (\overline{k} \nabla T) + H_\chi + H_{\text{tide}} - T \Delta S_\phi \rho_\phi F$$

$$- \rho_\phi C_{P\phi} \nabla \cdot (\phi \mathbf{v}_f T) - \rho_\psi C_{P\psi} \nabla \cdot (\psi \mathbf{v}_m T) - \rho_\chi C_{P\chi} \nabla \cdot (\chi \mathbf{v}_m T),$$

Visco-elastic shear modulus

$$\mu(\omega) = \mu_0 \left[1 - i (\omega\tau_M)^{-1} + (i\omega\zeta\tau_M)^{-\alpha} \Gamma(1 + \alpha) \right]^{-1},$$



Tidal heating radial profile

$$H_{\text{tide}} = \frac{21}{10} \frac{\omega^5 R_M^4 e^2}{r^2} \left[H_\mu \Im(\mu) \right],$$

Elastic shear and bulk moduli

$$\mu_0(\chi) = 65.73\chi^3 - 15.84\chi^2 + 6.11\chi + 4.0,$$

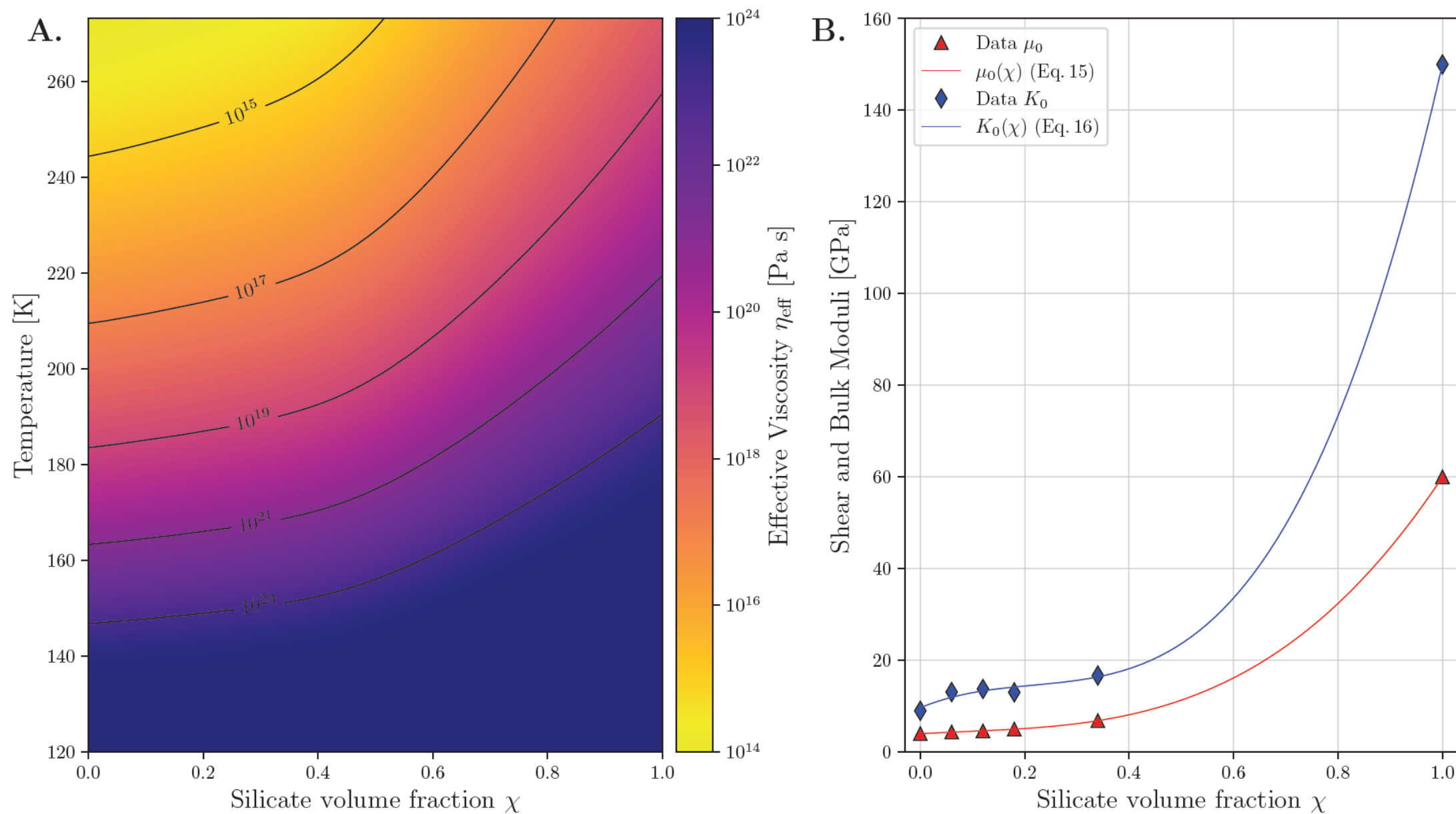
$$K_0(\chi) = 263.38\chi^3 - 170.27\chi^2 + 47.23\chi + 9.67,$$

Viscosity

$$\eta(T, \chi) = \nu_0 \eta_r(\chi) \exp \left[A \left(\frac{T_m}{T} - 1 \right) \right],$$

$$\eta_{\text{eff}} = \eta_{\text{min}} + \left(\frac{1}{\eta(T, \chi)} + \frac{1}{\eta_{\text{max}}} \right)^{-1}.$$

Methods – Ice-rock mixture rheology

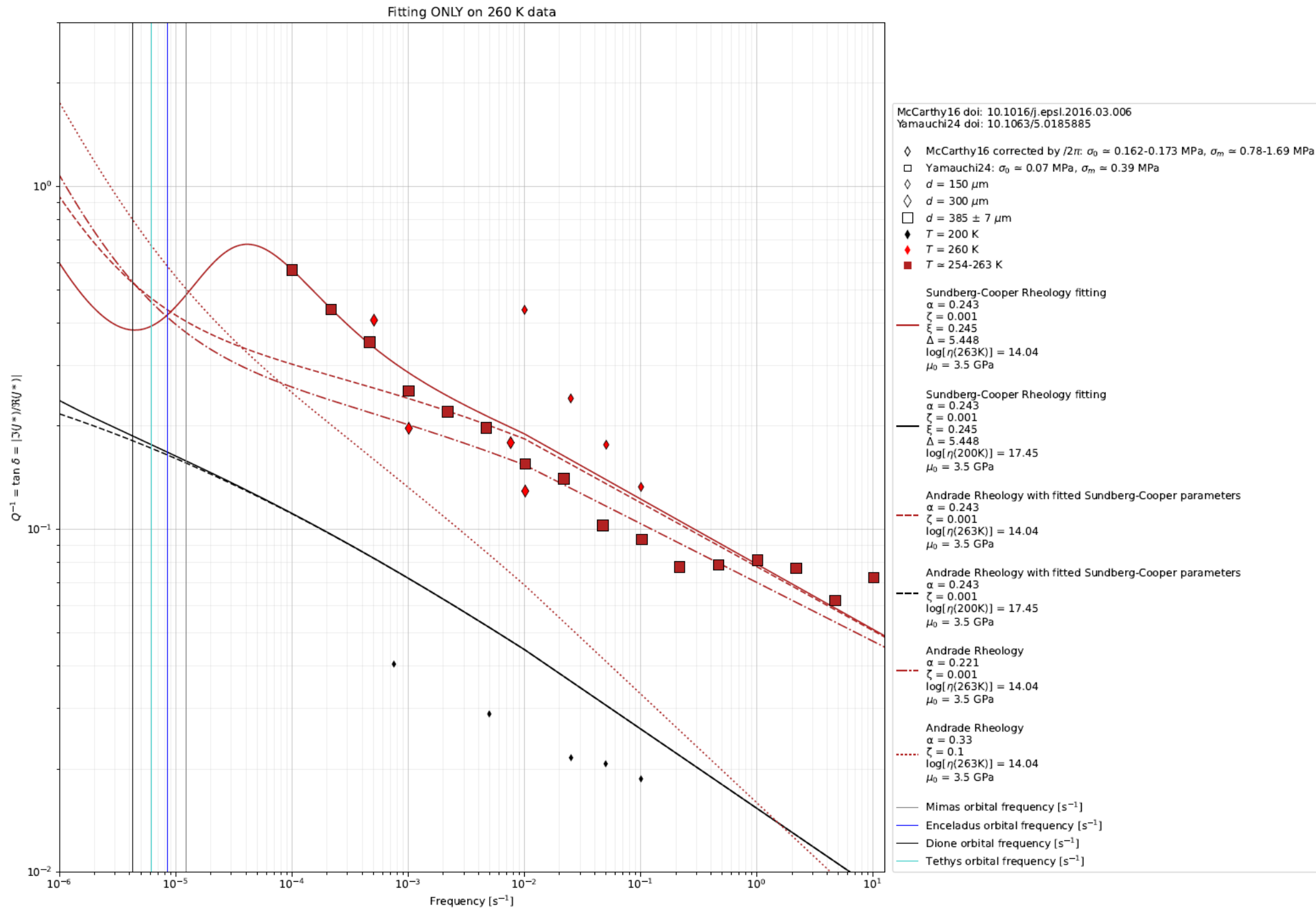


Eccentricity and angular frequency time variation

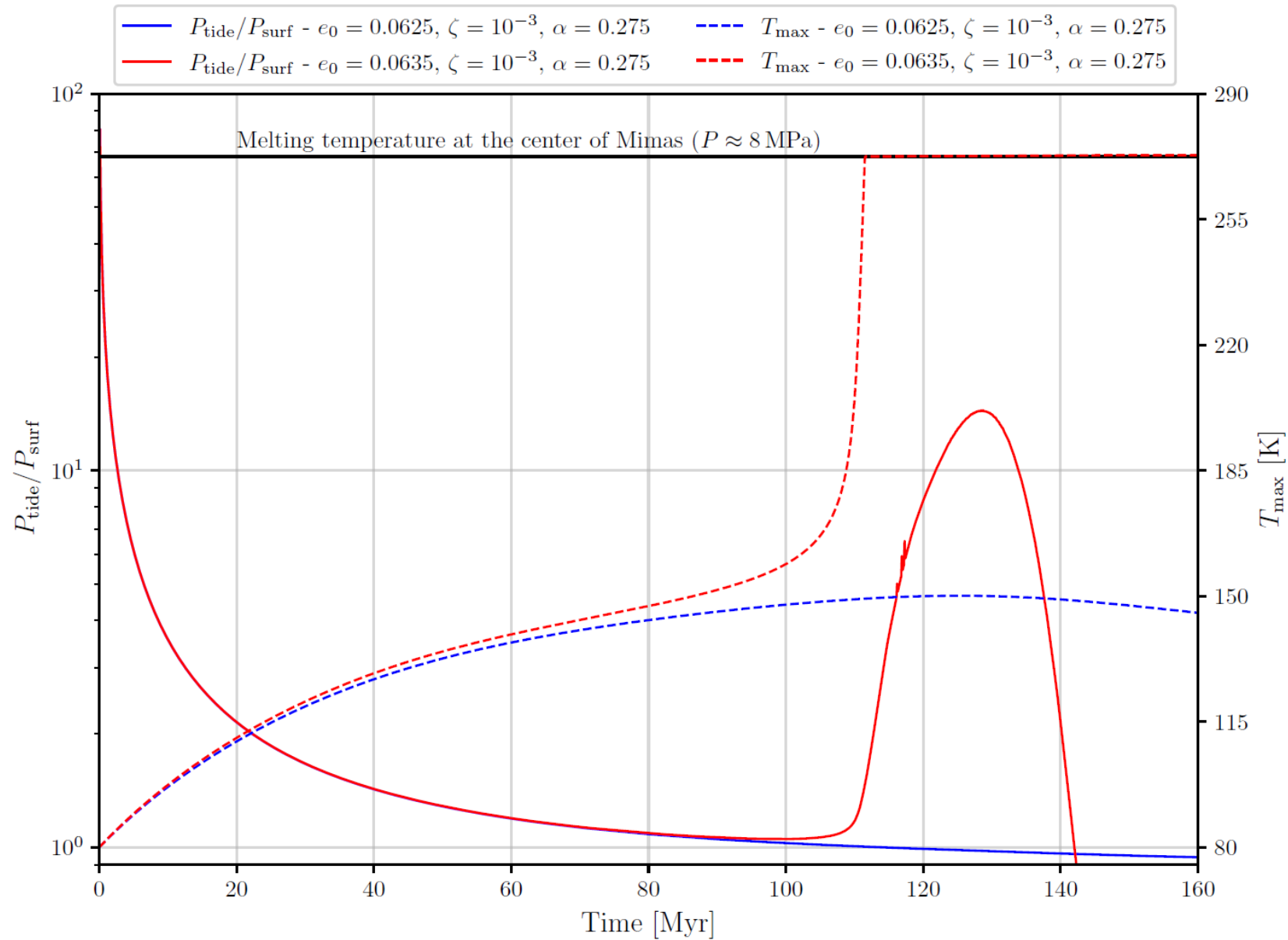
$$\frac{de}{dt} = \frac{57}{8} \left(\frac{k_2}{Q} \right)_S \omega \frac{M_M}{M_S} \left(\frac{R_S}{a} \right)^5 e - \frac{21}{2} \left(\frac{k_2}{Q} \right)_M \omega \frac{M_S}{M_M} \left(\frac{R_M}{a} \right)^5 e,$$

$$\frac{d\omega}{dt} = -\frac{9}{2} \left(\frac{k_2}{Q} \right)_S \omega^2 \frac{M_M}{M_S} \left(\frac{R_S}{a} \right)^5 \left(1 + \frac{51}{4} e^2 \right) + \frac{63}{2} \left(\frac{k_2}{Q} \right)_M \omega^2 \frac{M_S}{M_M} \left(\frac{R_M}{a} \right)^5 e^2,$$

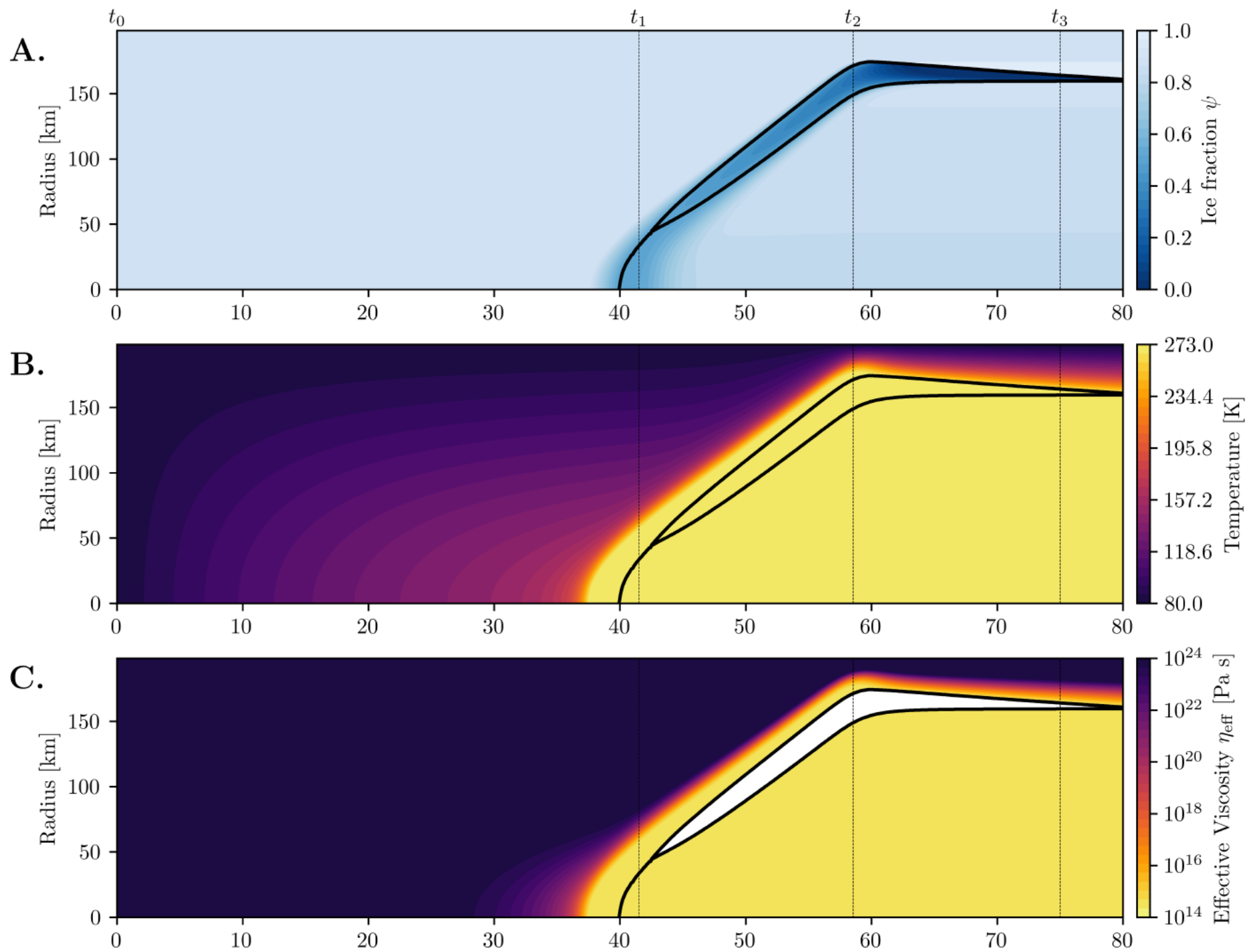
Experimental constraints



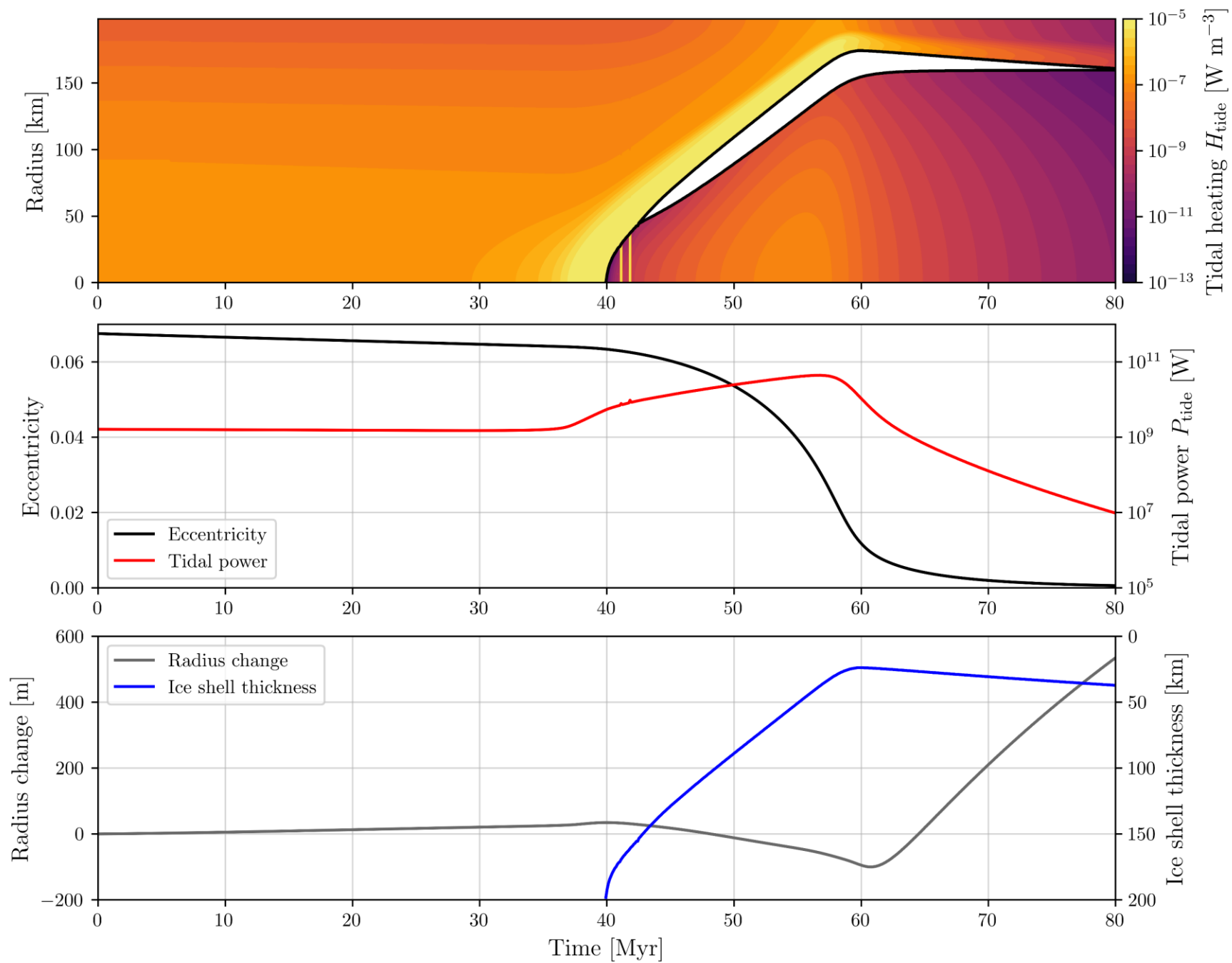
Results – Competition heat source/transfer



Results

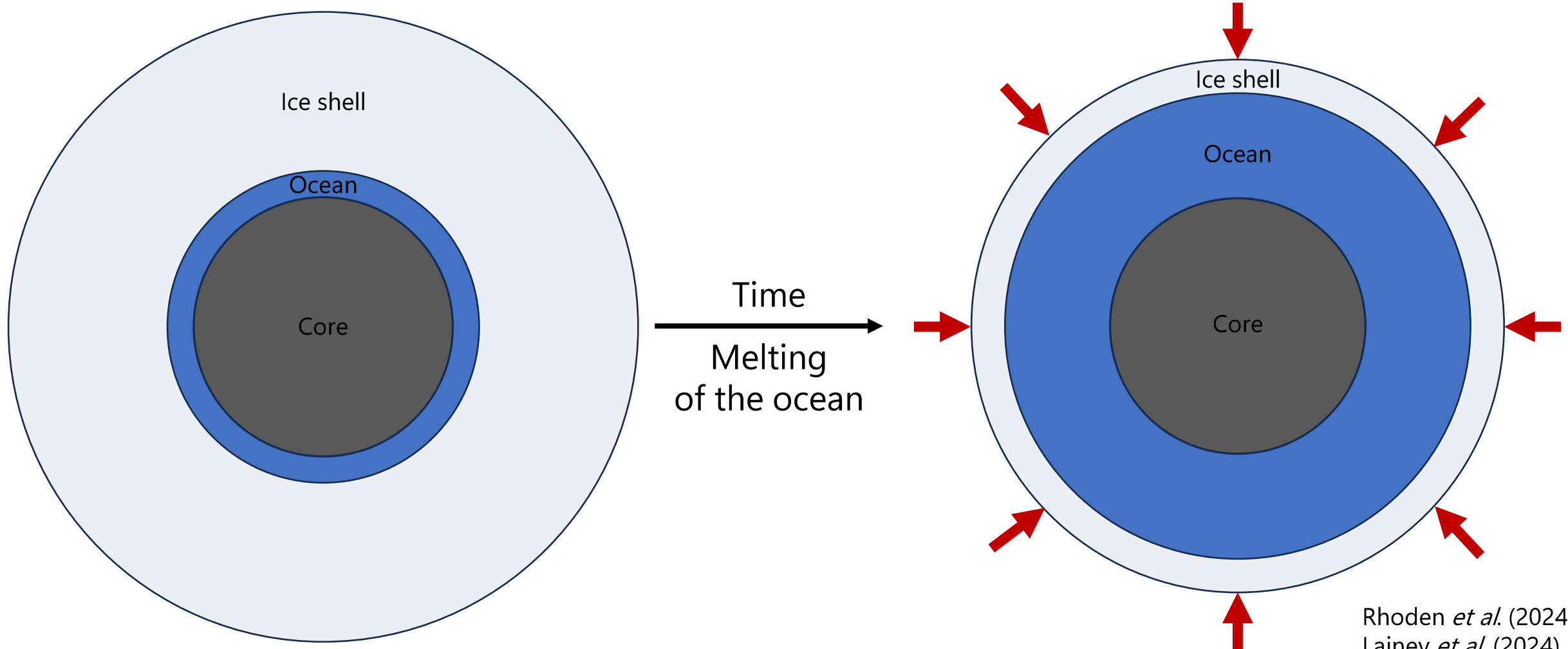


Results



Mimas' internal structure in literature

Melting of an ocean in this structure could imply a global contraction and compressive stresses in the ice shell leading potentially to its breaking

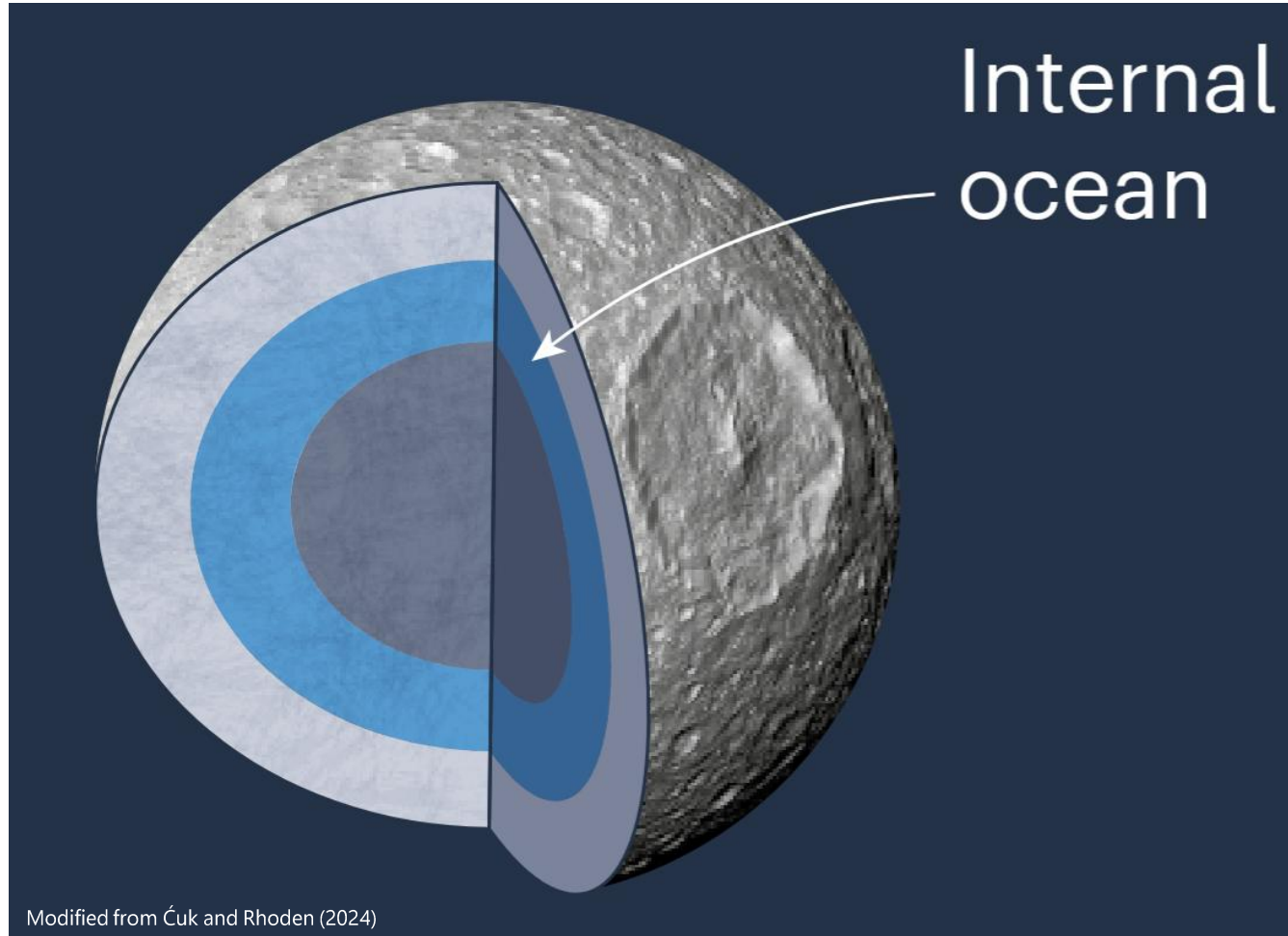


Rhoden *et al.* (2024)
Lainey *et al.* (2024)
Rudolph *et al.* (2025)

Mimas' internal structure

Mimas' structure is usually assumed as Enceladus...

Mimas



Enceladus

