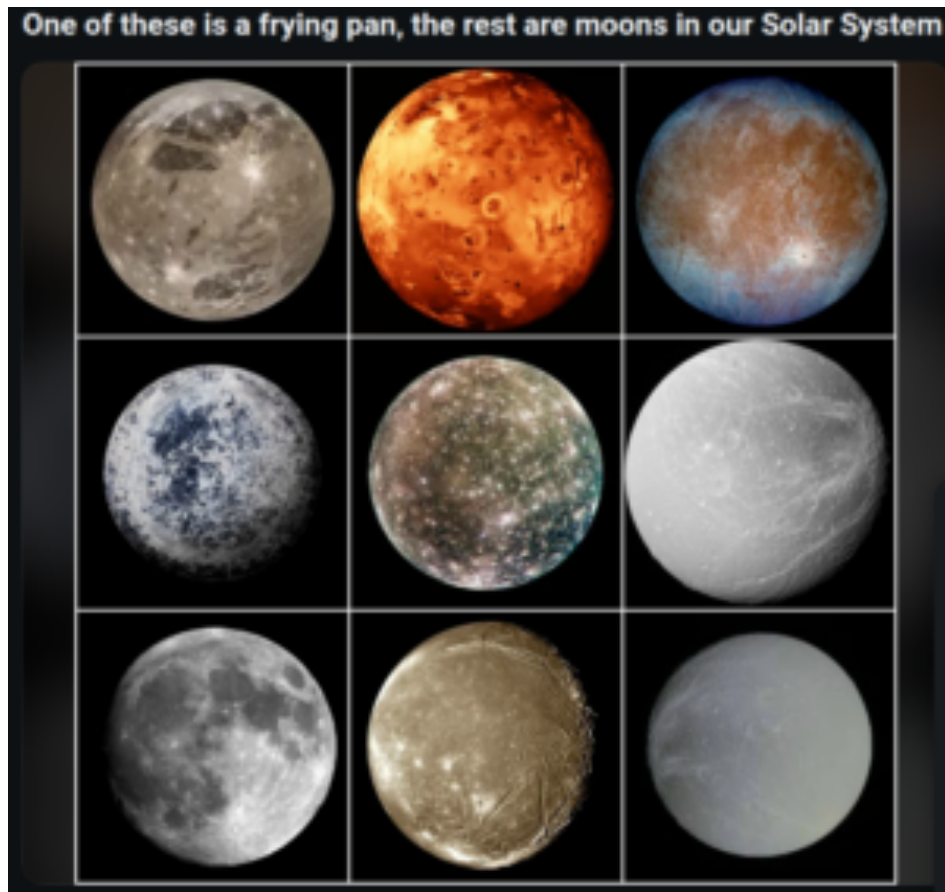




Internal evolution of tidally heated moons around giant planets

Mathilde Kervazo — LPG, Nantes Université

SF2A 2026 - Grenoble

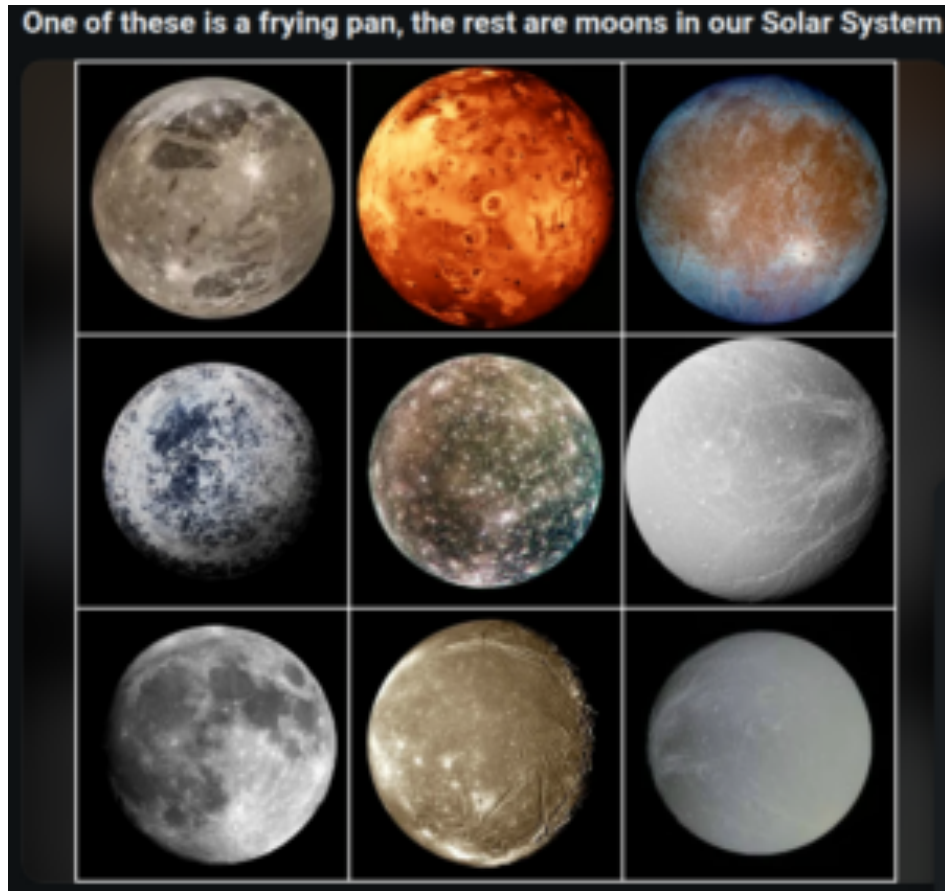




Internal evolution of tidally heated moons Galilean moons around giant planets Jupiter

Mathilde Kervazo — LPG, Nantes Université

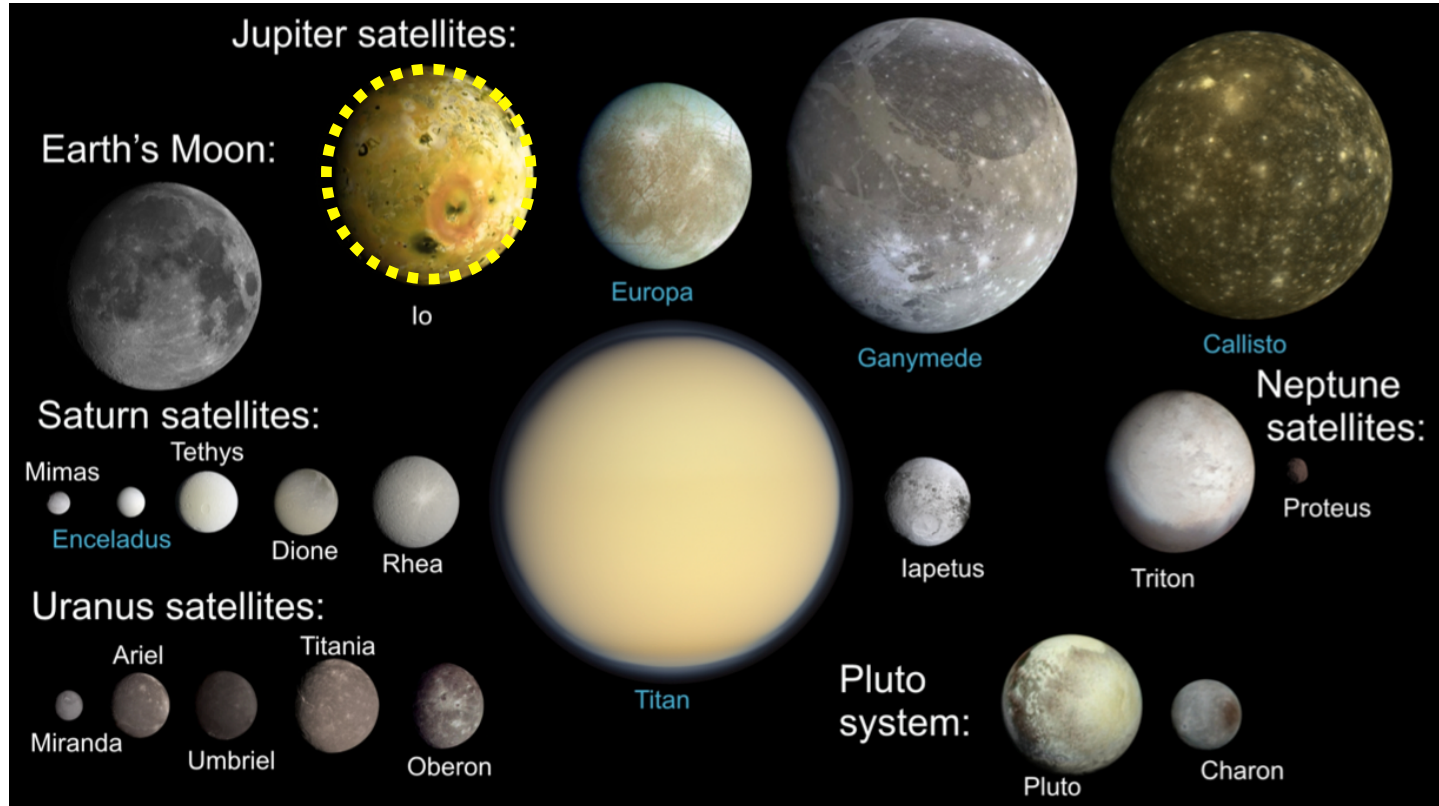
SF2A 2026 - Grenoble



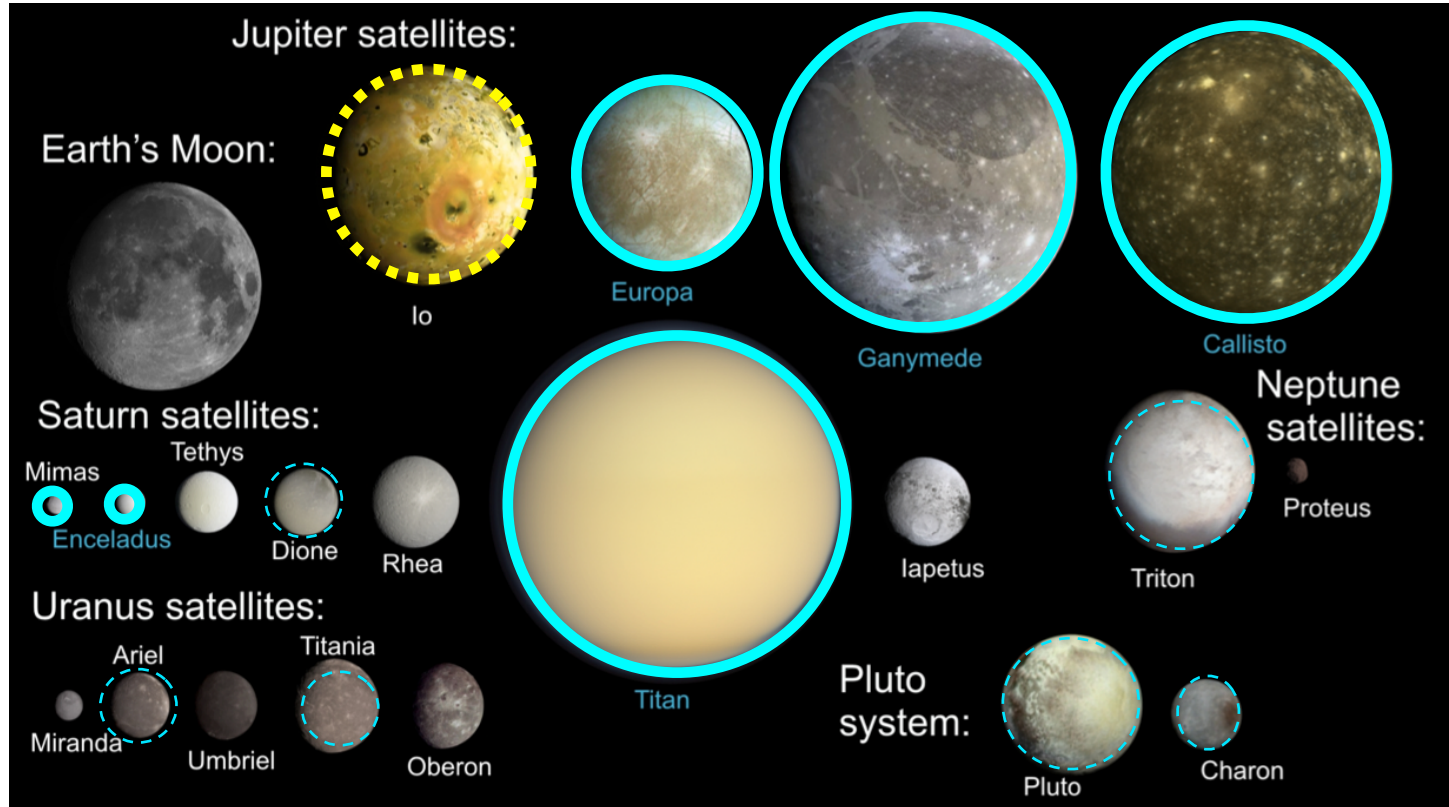
The diversity of outer Solar System moons around giant planets



The diversity of outer Solar System moons around giant planets



The diversity of outer Solar System moons around giant planets



Galilean moons

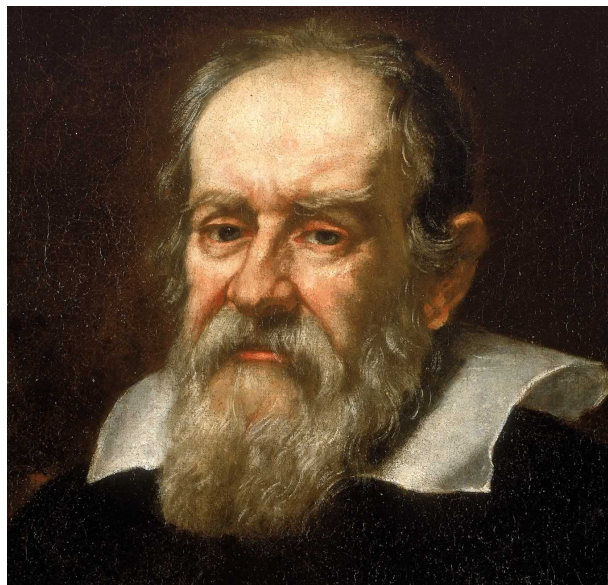
Observations made by Galileo (January 1610)



| | | | | | | | |
|-----------------|------|---|---|---|---|------|---|
| 7 janvier 1610 | Ori. | * | * | ○ | * | Occ. | |
| 8 janvier 1610 | | | | ○ | * | * | * |
| 10 janvier 1610 | | * | * | ○ | | | |
| 11 janvier 1610 | | * | * | ○ | | | |
| 12 janvier 1610 | | * | ■ | ○ | * | | |

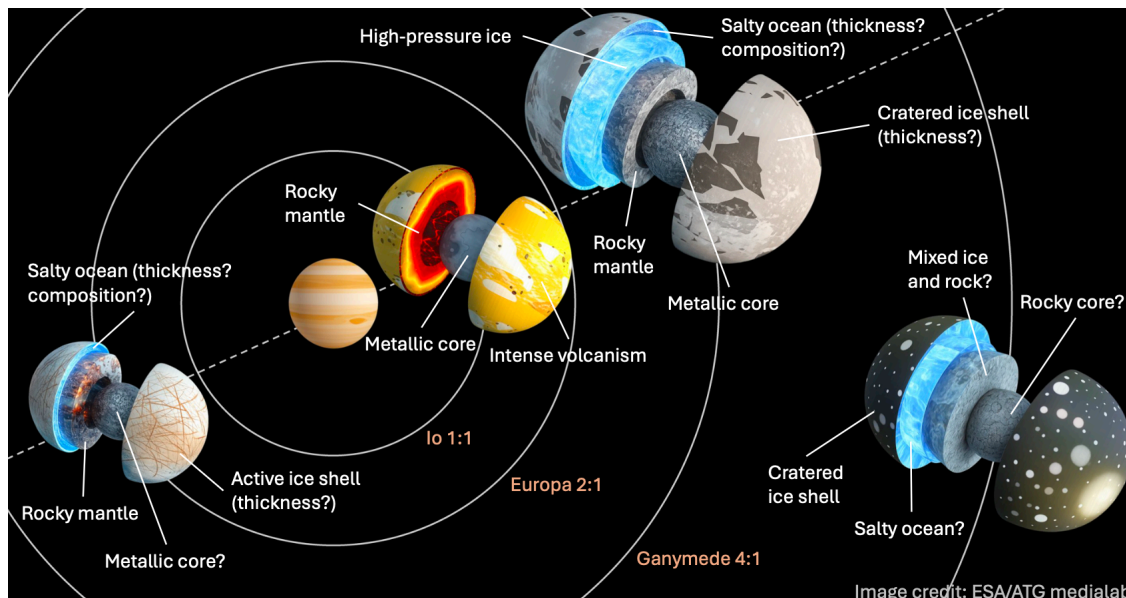
Galilean moons

Observations made by Galileo (January 1610)



| | | | | | | |
|-----------------|------|---|---|---|---|------|
| 7 janvier 1610 | Ori. | * | * | ○ | * | Occ. |
| 8 janvier 1610 | | | | ○ | * | * |
| 10 janvier 1610 | | * | * | ○ | | |
| 11 janvier 1610 | | * | * | ○ | | |
| 12 janvier 1610 | | * | ○ | * | | |

Modern view of the Galilean System
(@ S. Fayolle, Veenstra+2025)



Galilean moons: dead or alive ?

Theory

Satellites of the Outer Planets: Their Physical and Chemical Nature¹

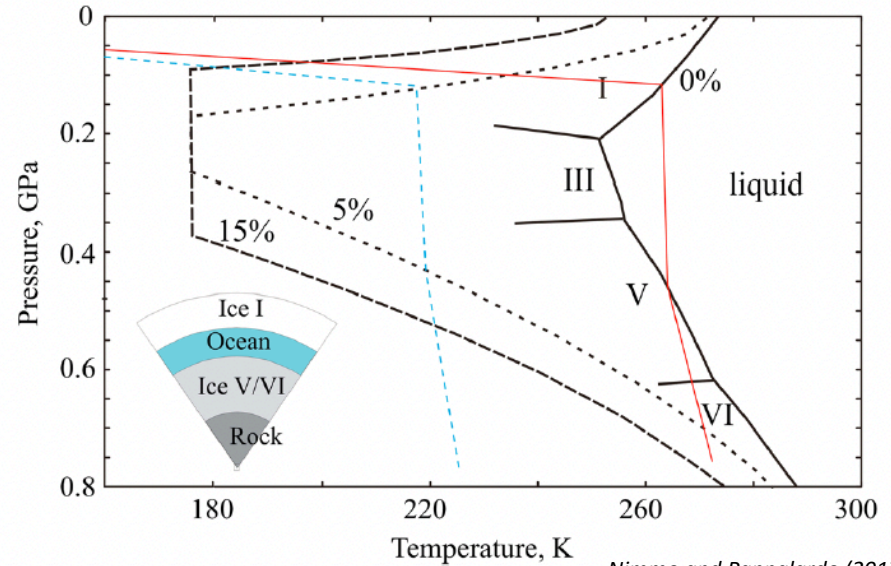
JOHN S. LEWIS

*Planetary Astronomy Laboratory, Department of Earth and Planetary Sciences
and
Department of Chemistry, Massachusetts Institute of Technology, Cambridge 02139*

Received February 16, 1971; revised April 9, 1971

Steady-state thermal models for the icy satellites are constructed in which the energy released by radioactive decay in the interiors of the satellites is exactly balanced by the net radiative loss from their surfaces. It is shown that the Galilean satellites of Jupiter and the larger satellites of Saturn, Uranus, and Neptune very likely have extensively melted interiors, and most probably contain a core of hydrous silicates, an extensive mantle of ammonia-rich liquid water, and a relatively thin crust of ices. Consequences of this model relating to the Galilean satellites and the rings of Saturn are briefly described.

The atmospheric compositions and densities of the large icy satellites and certain features of the retention of volatiles during accretion are discussed.



Nimmo and Pappalardo (2017)

1971: subsurface oceans

Galilean moons: dead or alive ?

Theory

Melting of Io by Tidal Dissipation

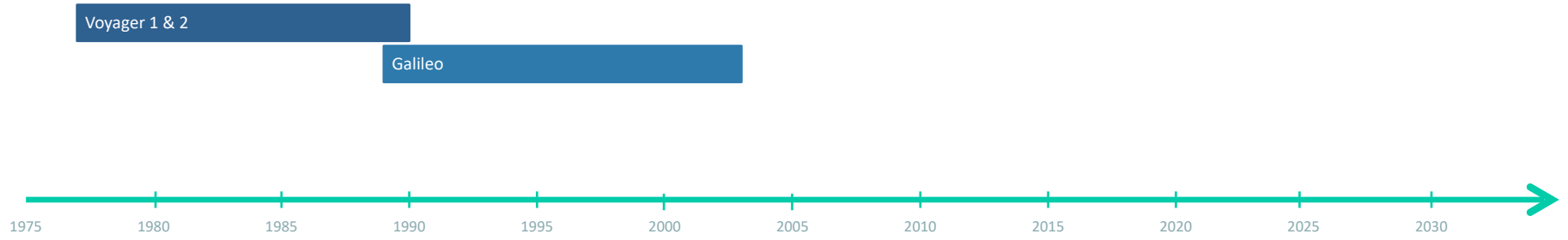
S. J. Peale; P. Cassen; R. T. Reynolds

Science, New Series, Vol. 203, No. 4383 (Mar. 2, 1979), 892-894.

Abstract. The dissipation of tidal energy in Jupiter's satellite Io is likely to have melted a major fraction of the mass. Consequences of a largely molten interior may be evident in pictures of Io's surface returned by Voyager I.

In 1979: « Io might currently be the most intensely heated terrestrial-type body in the solar system »
« Widespread and recurrent surface volcanism would occur »

Galilean moons: dead or alive ?



Galilean moons: dead or alive ?

Voyager 1 & 2

Galileo



1st extraterrestrial eruption



Voyager 1, March 8, 1979

Galilean moons: dead or alive ?

Voyager 1 & 2

Galileo

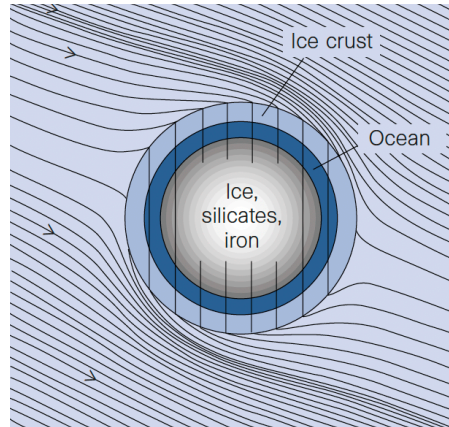


1st extraterrestrial eruption



Voyager 1, March 8, 1979

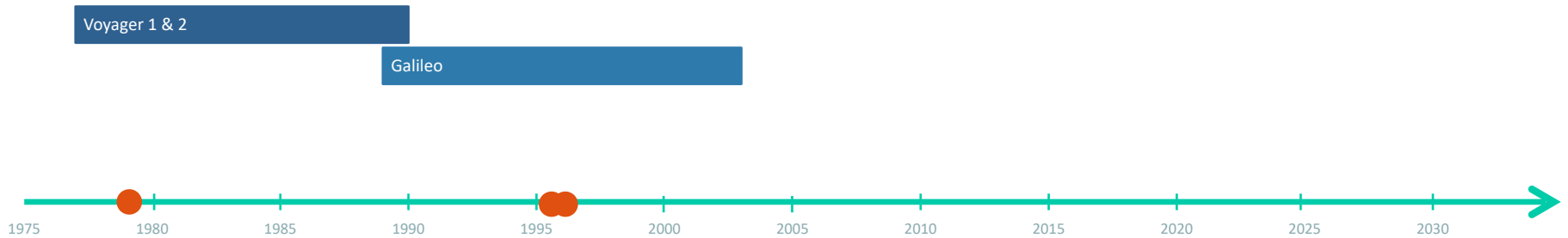
1st indirect detection of subsurface ocean



Galileo, March 1996

Zimmer+2000

Galilean moons: dead or alive ?

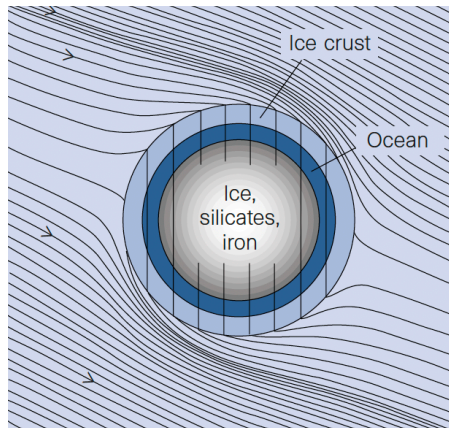


1st extraterrestrial eruption



Voyager 1, March 8, 1979

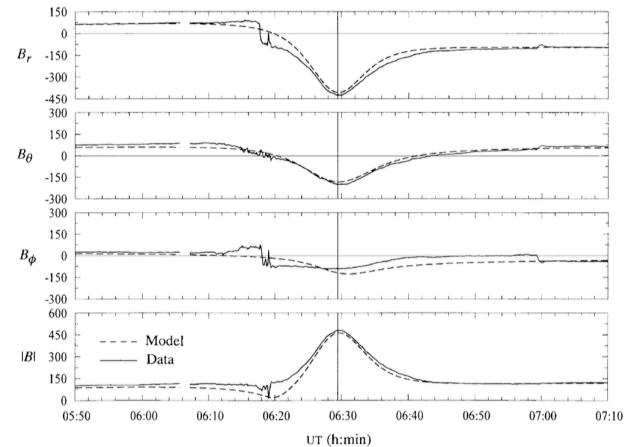
1st indirect detection of subsurface ocean



Galileo, March 1996

Zimmer+2000

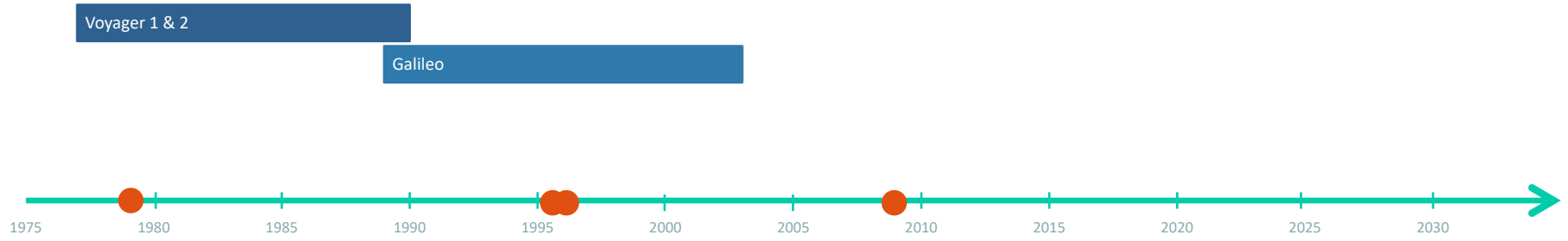
Ganymede magnetic field



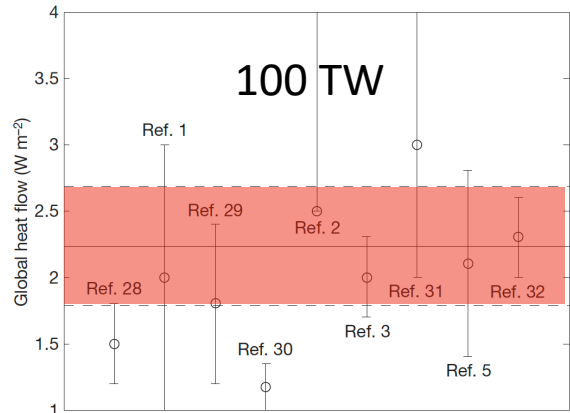
Galileo, June 1996

Kivelson+1996

Galilean moons: dead or alive ?



1st direct measurement of tidal dissipation



Lainey et al. 2009

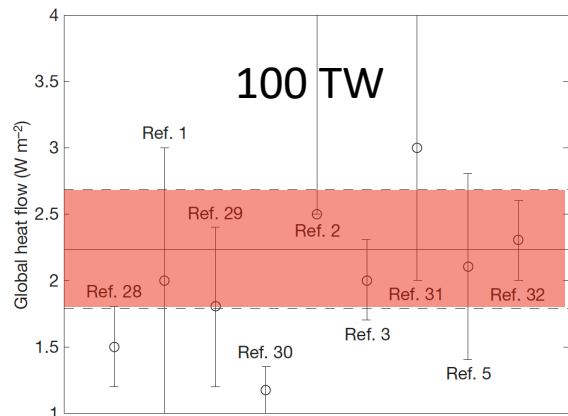
Galilean moons: dead or alive ?

Voyager 1 & 2

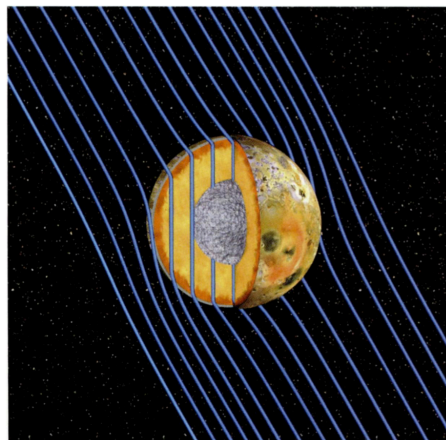
Galileo



1st direct measurement of tidal dissipation **Io induced magnetic field: molten interior?**

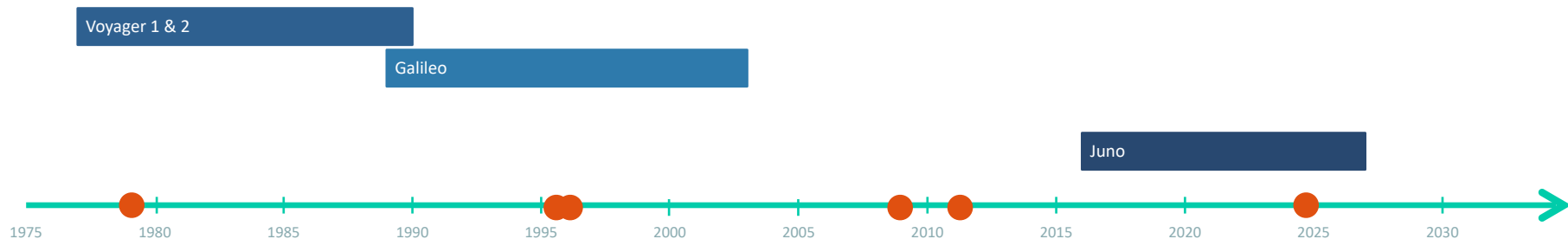


Lainey et al. 2009



Galileo, Khurana et al. 2011

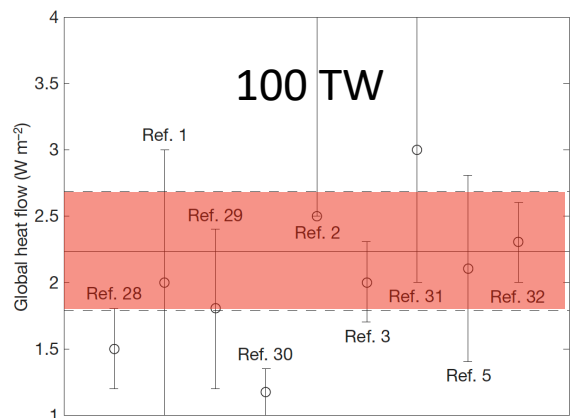
Galilean moons: dead or alive ?



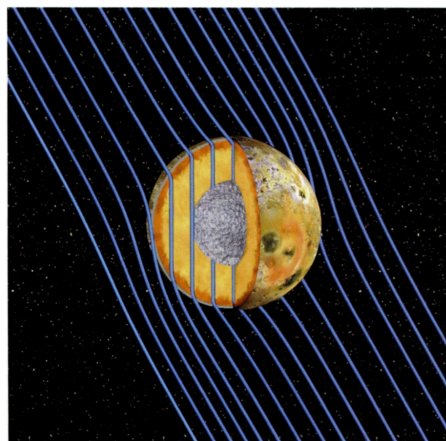
1st direct measurement of tidal dissipation

Io induced magnetic field: molten interior?

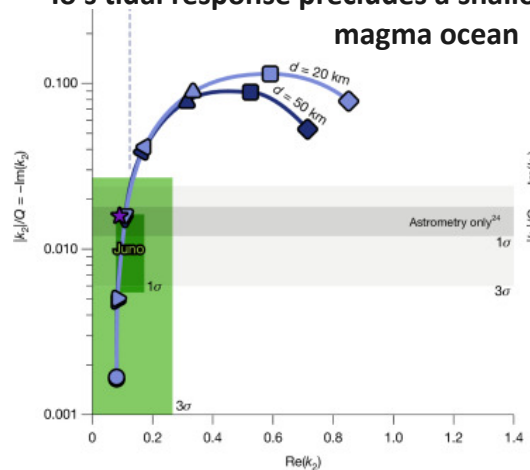
Io's tidal response precludes a shallow magma ocean



Lainey et al. 2009

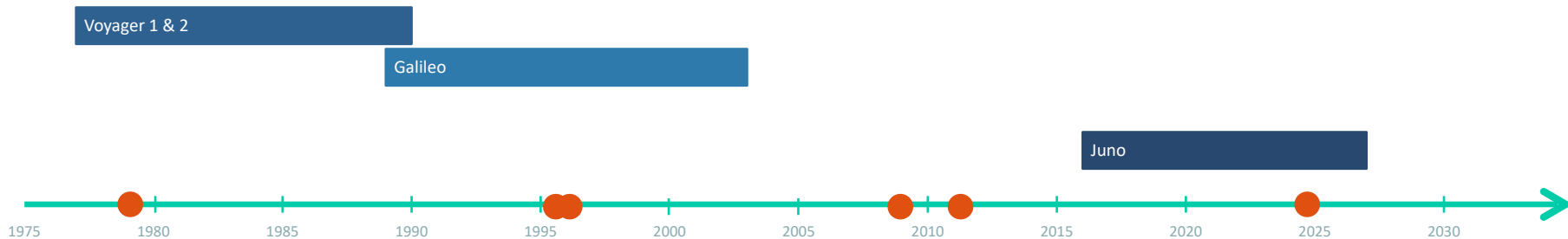


Galileo, Khurana et al. 2011



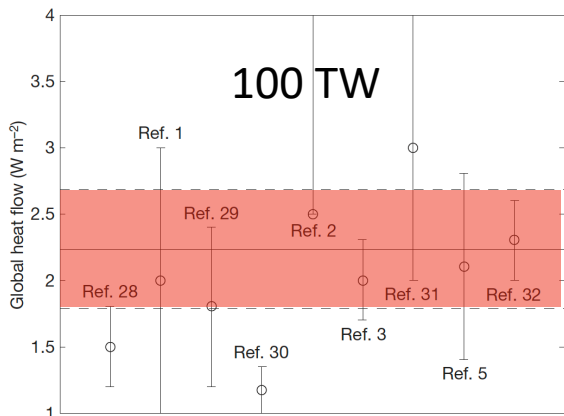
JUNO, Park et al. 2025

Galilean moons: dead or alive ?

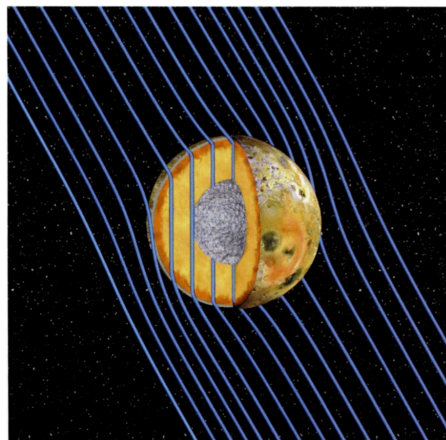


1st direct measurement of tidal dissipation Io induced magnetic field: molten interior?

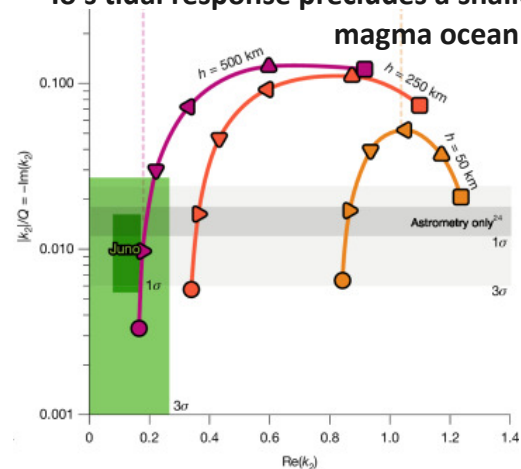
Io's tidal response precludes a shallow magma ocean



Lainey et al. 2009



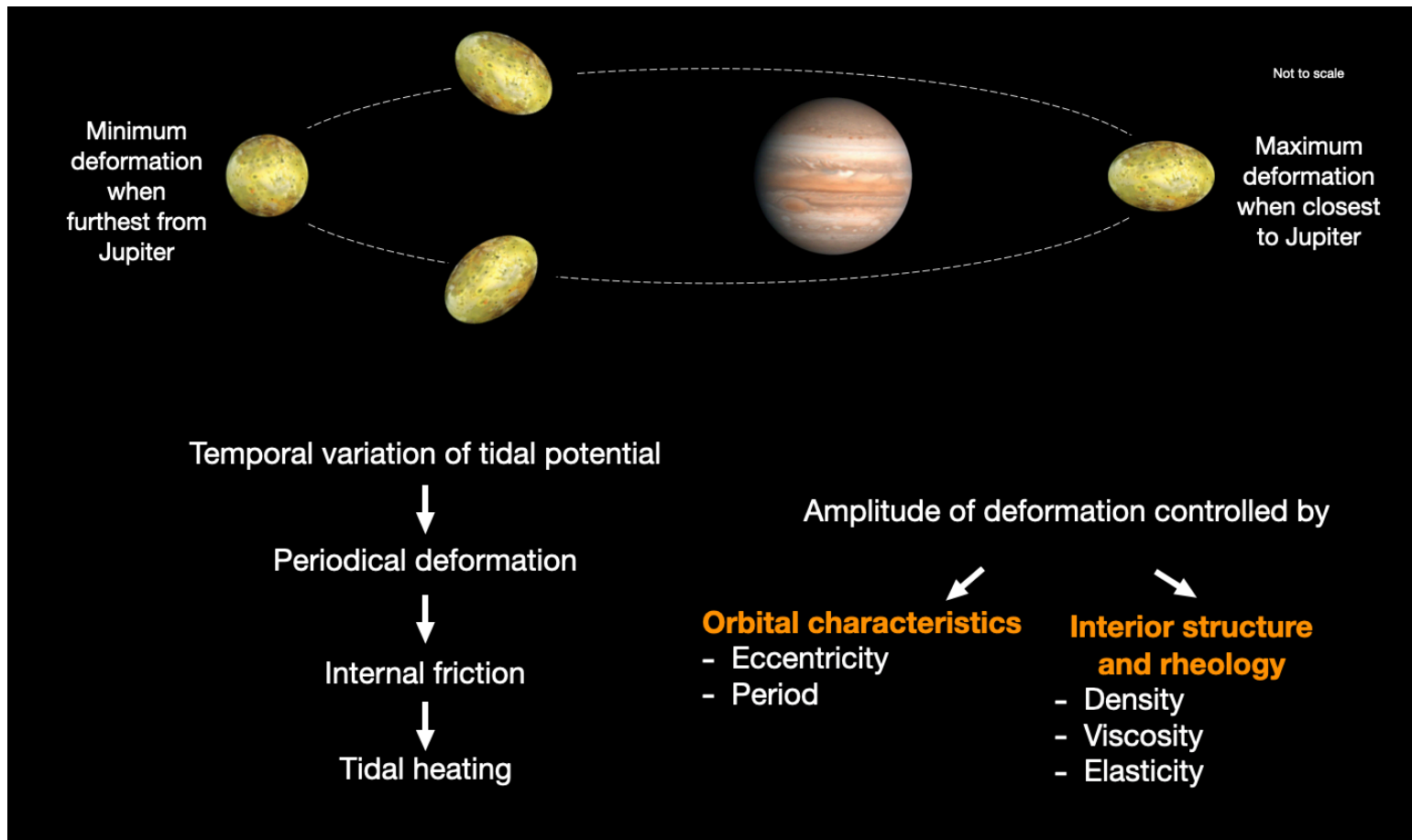
Galileo, Khurana et al. 2011



JUNO, Park et al. 2025

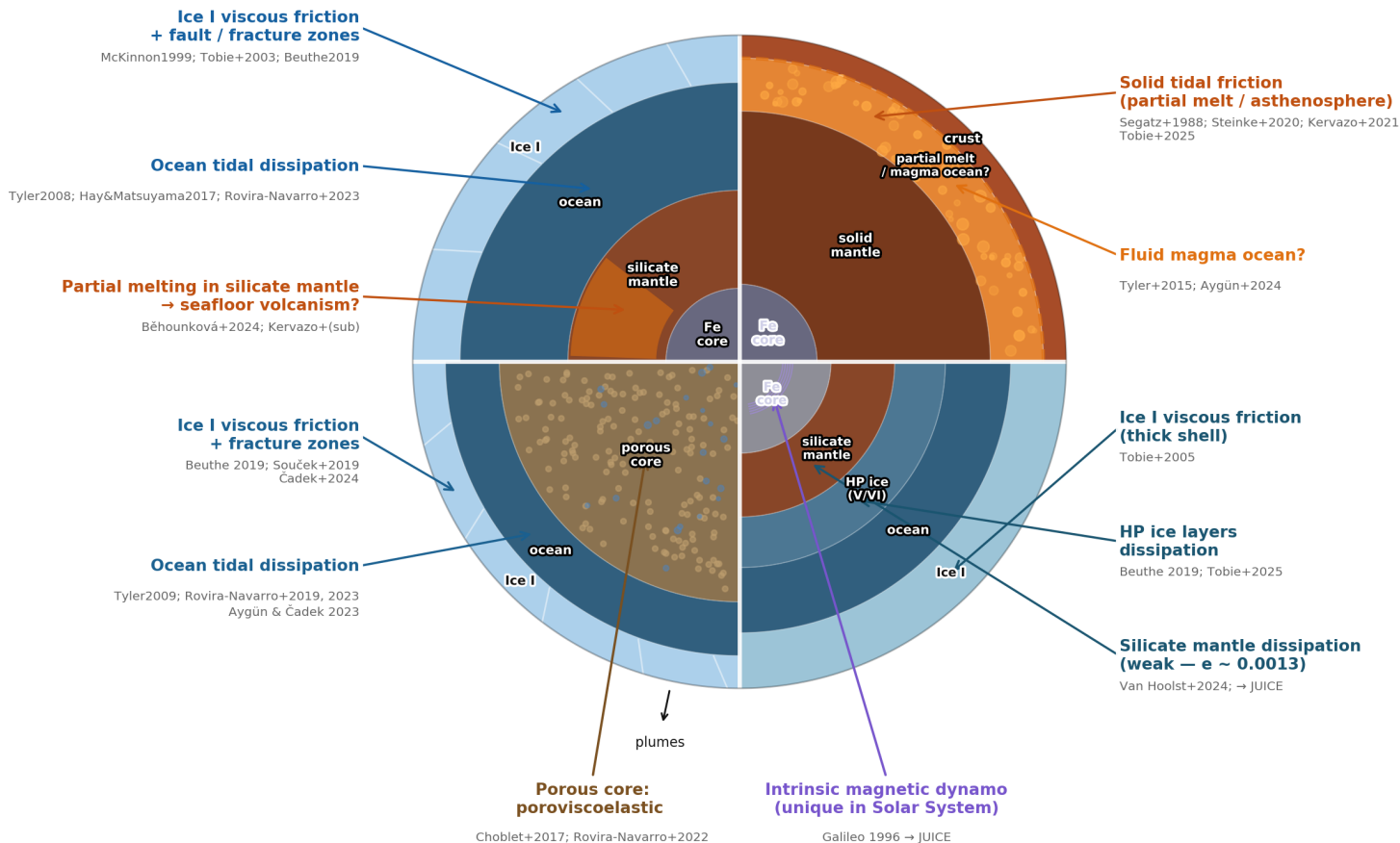
Tidal dissipation as a heat engine

Tidal dissipation as a heat engine



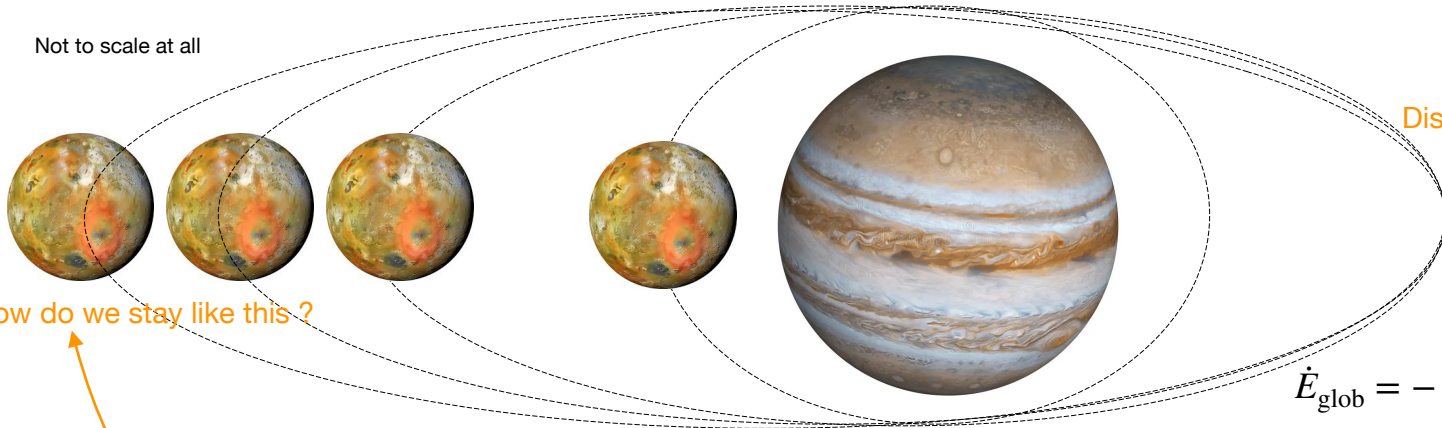
Tidal dissipation as a heat engine: rheology

Where heat is dissipated ?



Tidal dissipation as a heat engine: orbital characteristics

Not to scale at all



Dissipation of the interior, depends on rheology

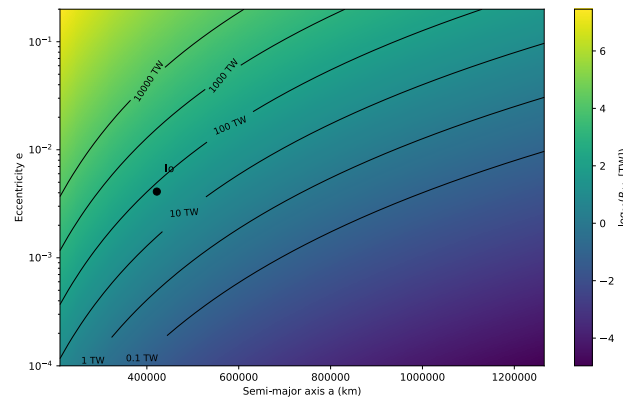
$$\dot{E}_{\text{glob}} = -\frac{21}{2} \mathfrak{F}(k_2) \frac{(\omega R_s)^5}{G} e^2.$$

Strongly dissipating

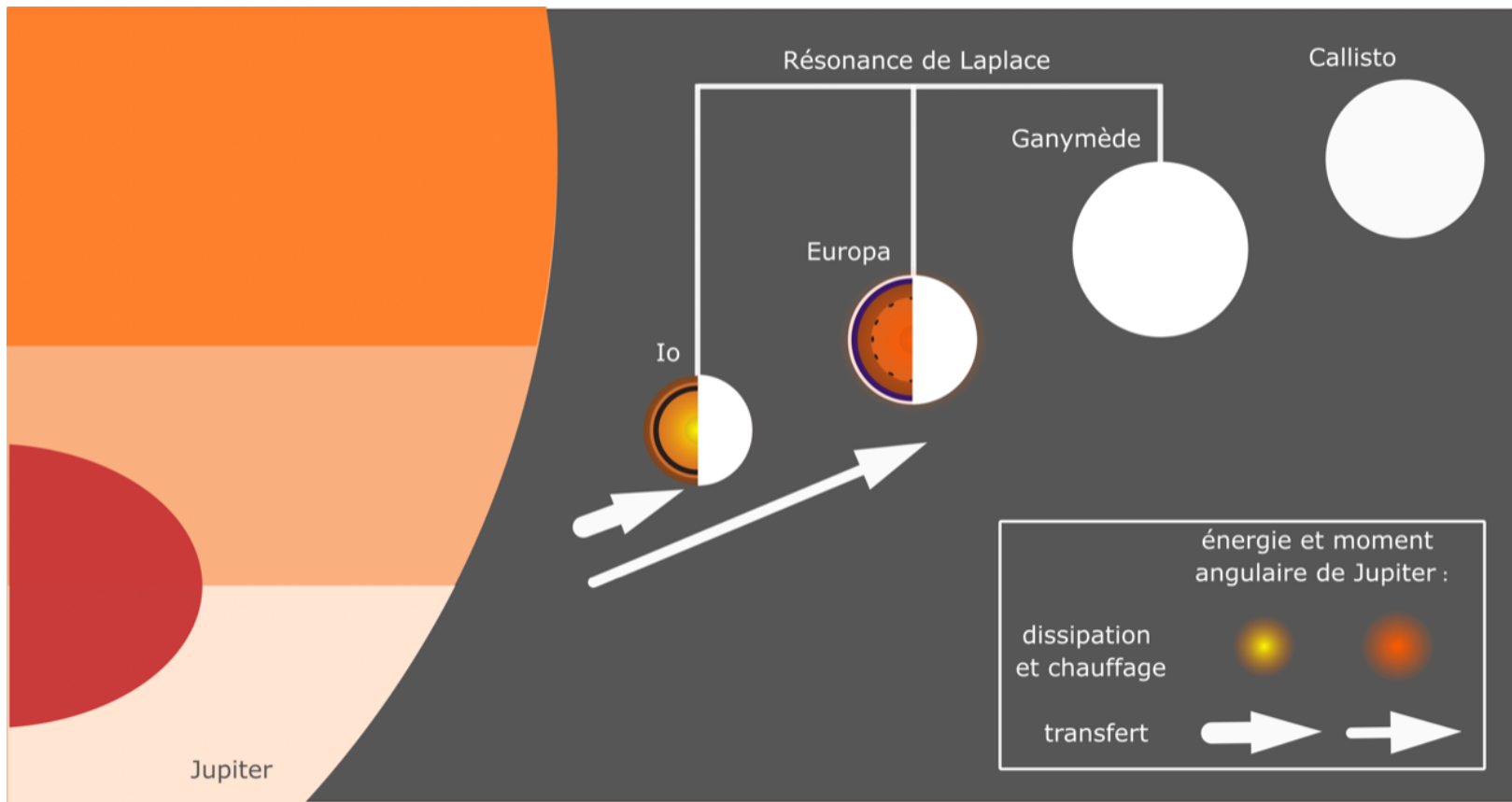
No dissipation anymore

Orbital evolution and synchronisation of the orbit

Cf Sam and Alex's talk

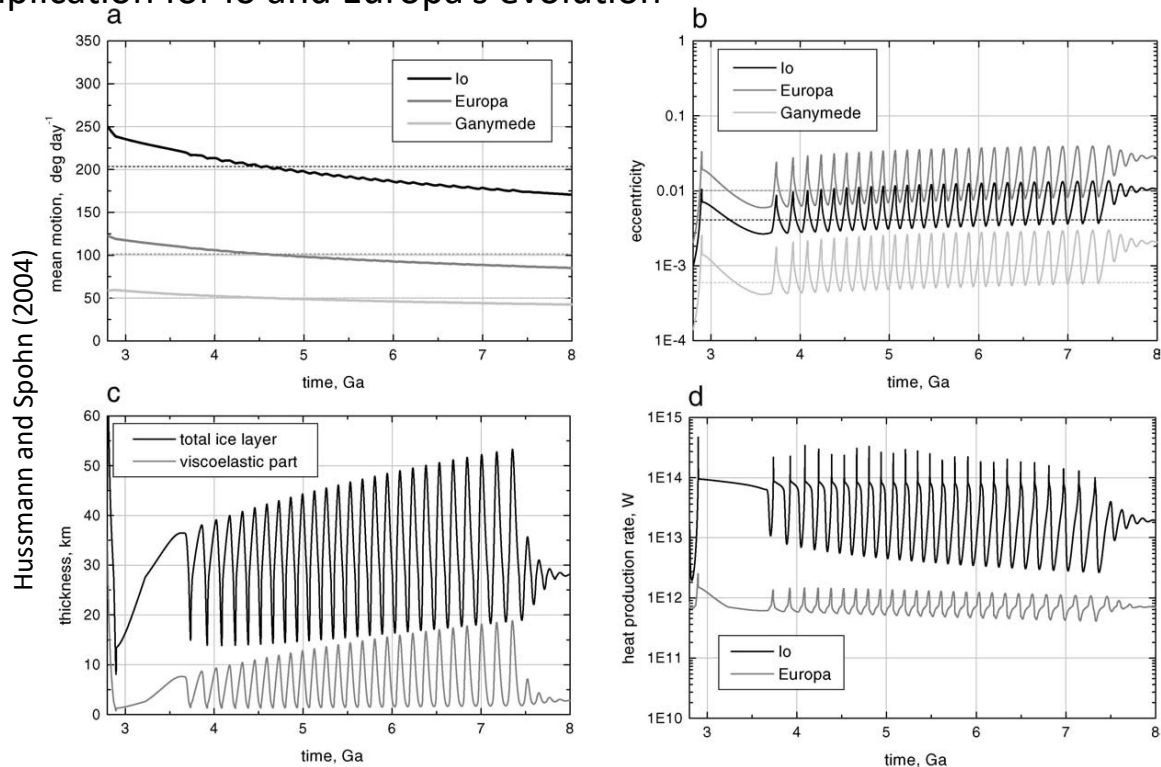


Laplace resonance: a coupled evolution

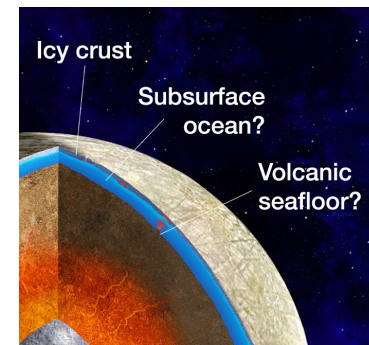
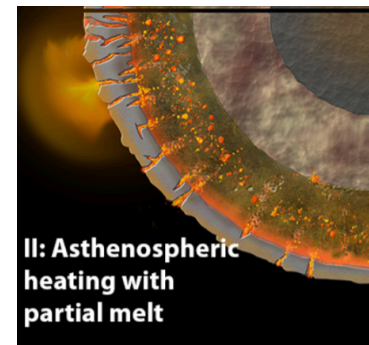


Laplace resonance: a coupled evolution

Implication for Io and Europa's evolution



Cf Sam's talk

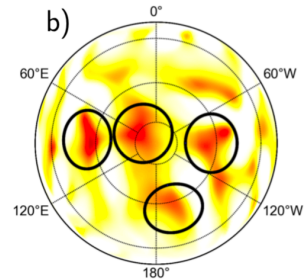
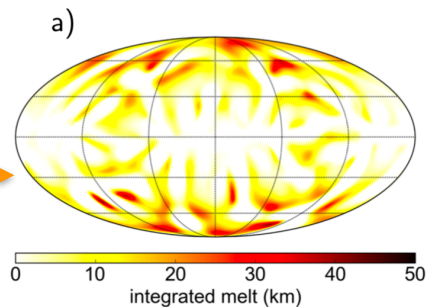
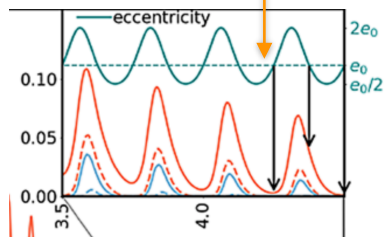
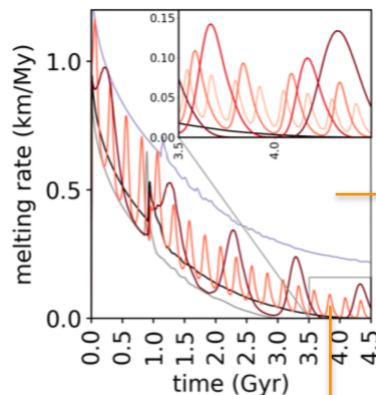
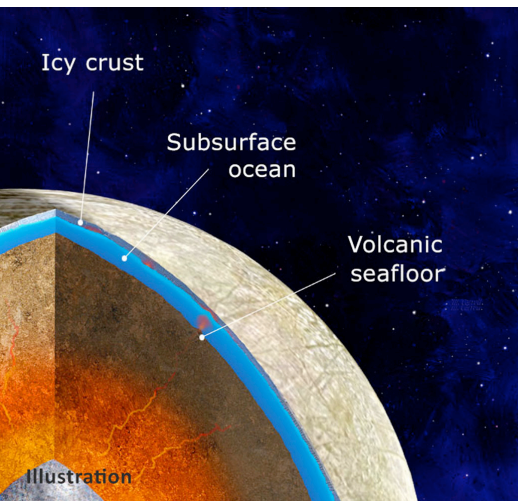


Periodical changes in eccentricity result in a modulation in heat production and hence in thermal state of the rocky mantle and thickness of the ice shell.

Laplace resonance: a coupled evolution

Implication for Io and Europa's evolution

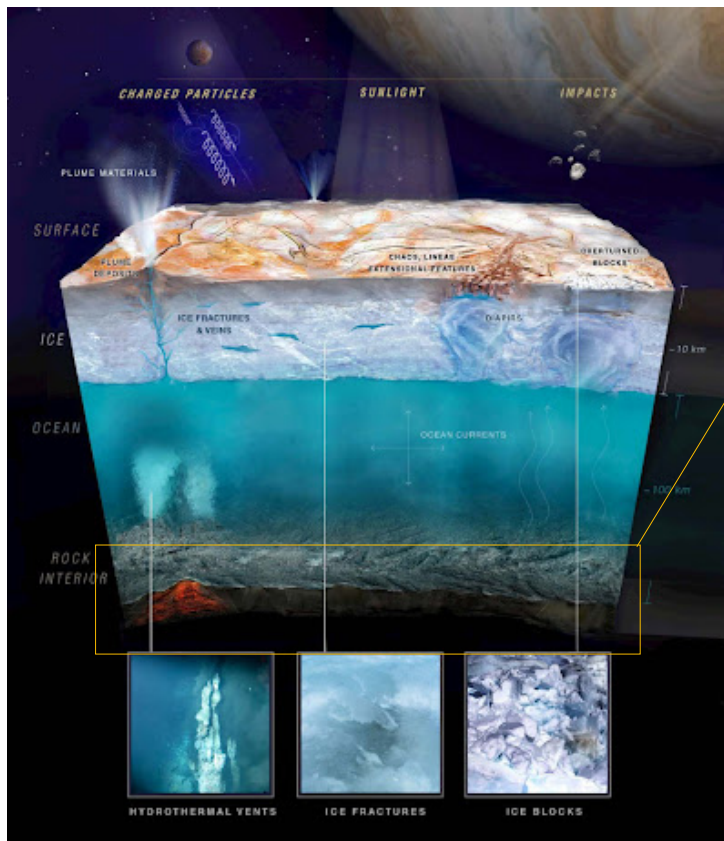
3D simulations of convective heat transfer and tidal heat production
(Běhounková et al. 2021)



- Modulation of melt production by the Laplace resonance.
- Mantle melting and magmatic activity on Europa seafloor during periods of enhanced eccentricity on Europa.

Laplace resonance: a coupled evolution

Implication for Europa's seafloor volcanism



- How much tidal heat can be generated in Europa's rocky mantle?
- Can we envision partial melting?
- Is there magmatism at the seafloor?

nature astronomy

Article

<https://doi.org/10.1038/s41550-025-02508-8>

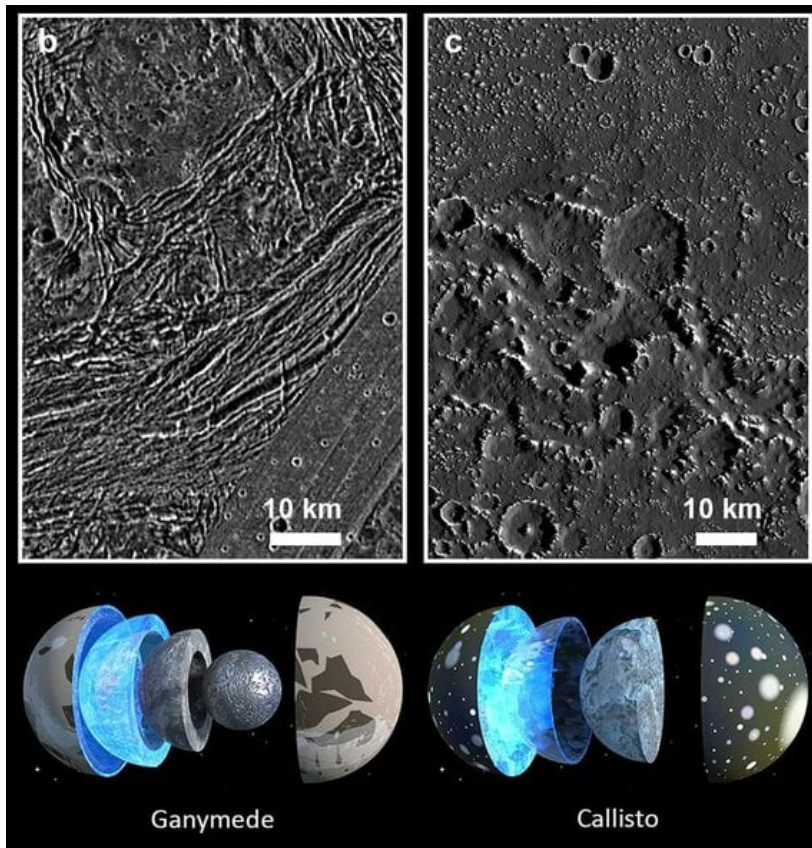
No magmatic driving force for European sea-floor volcanism

Received: 26 March 2024

A. P. Green¹✉, C. M. Elder¹, M. T. Bland², P. J. Tackley³ & P. K. Byrne⁴

Laplace resonance: a coupled evolution

Ganymede and Callisto puzzle

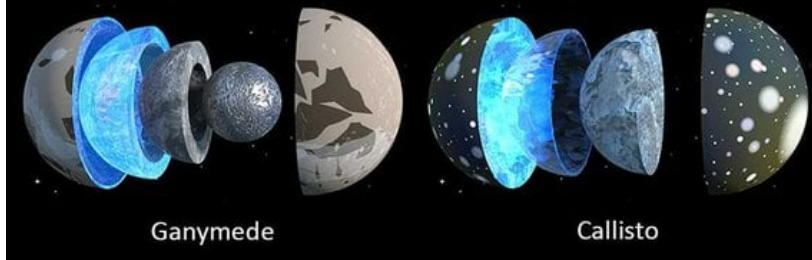
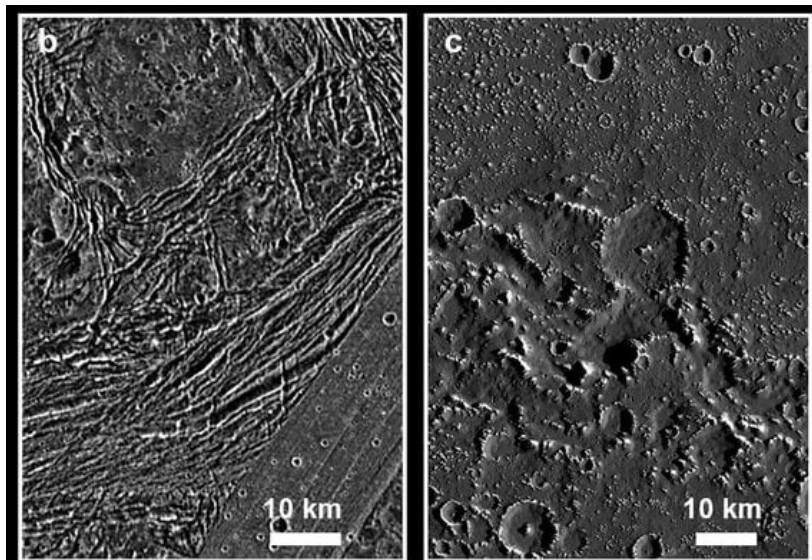


Tosi et al. 2025

- Did tidal heating trigger Ganymede's differentiation? (Showman et al. 1997+ Mathis Pinceloup!)
- Was the dichotomy set at formation — rate, temperature, or accretion mechanism? (Barr & Canup 2008; Bennacer et al. 2025; Shibaïke 2025)
- Is Callisto even undifferentiated?

Laplace resonance: a coupled evolution

Ganymede and Callisto puzzle



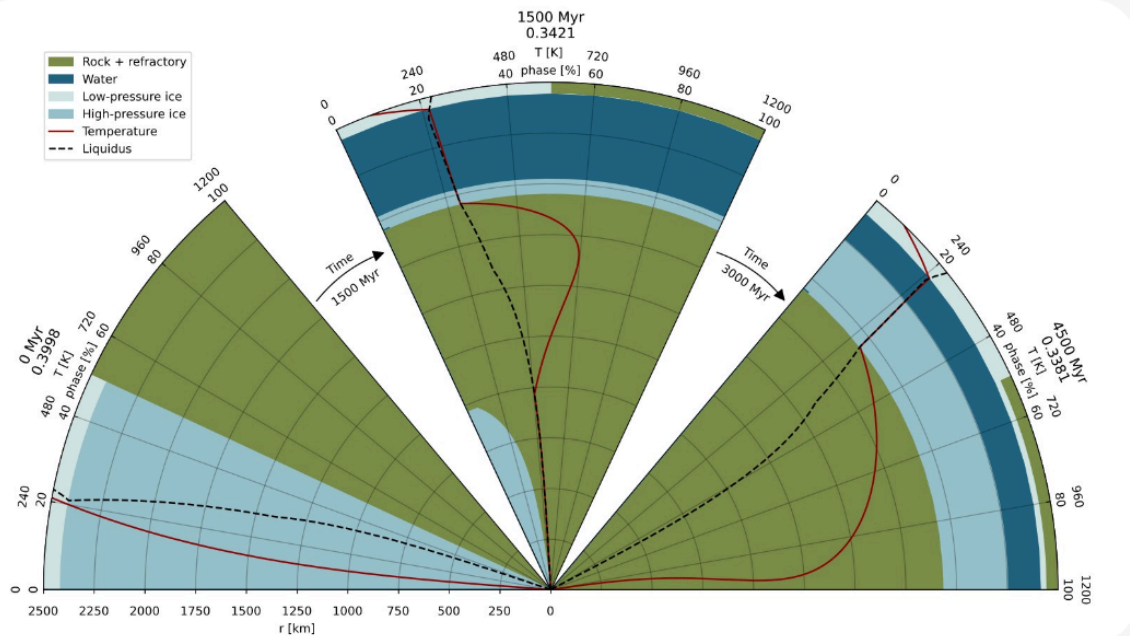
• Did tidal heating trigger Ganymede's differentiation? (Showman et al. 1997+ Mathis Pinceloup!)

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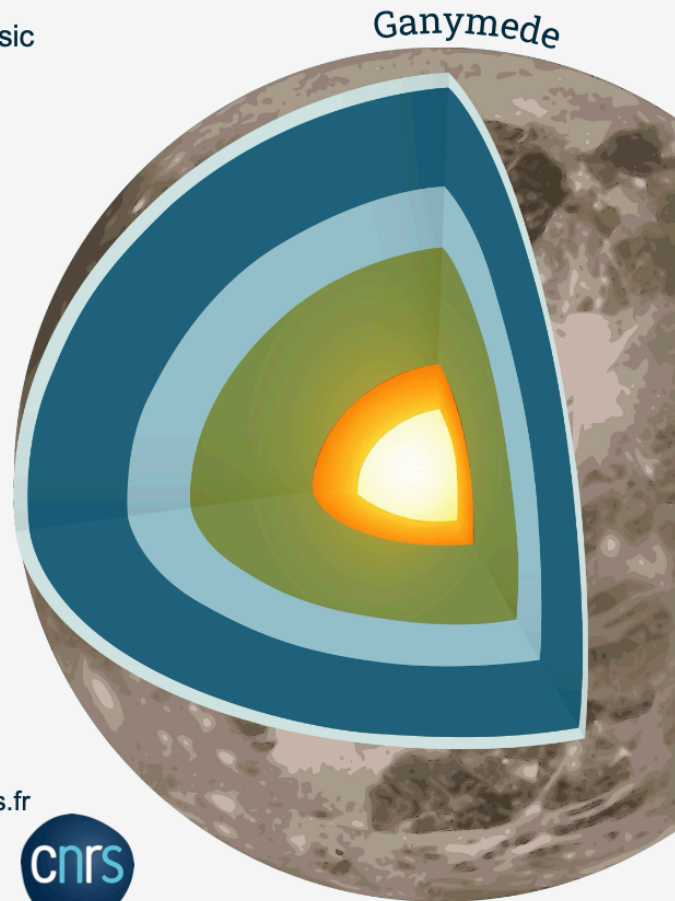
• Is Callisto even undifferentiated?

Differentiation processed in icy moons - Mathis Pinceloup and Tristan Babilin's talk!

BOREAS: A new Python code designed for multiphase temporal evolution using biphasic physic



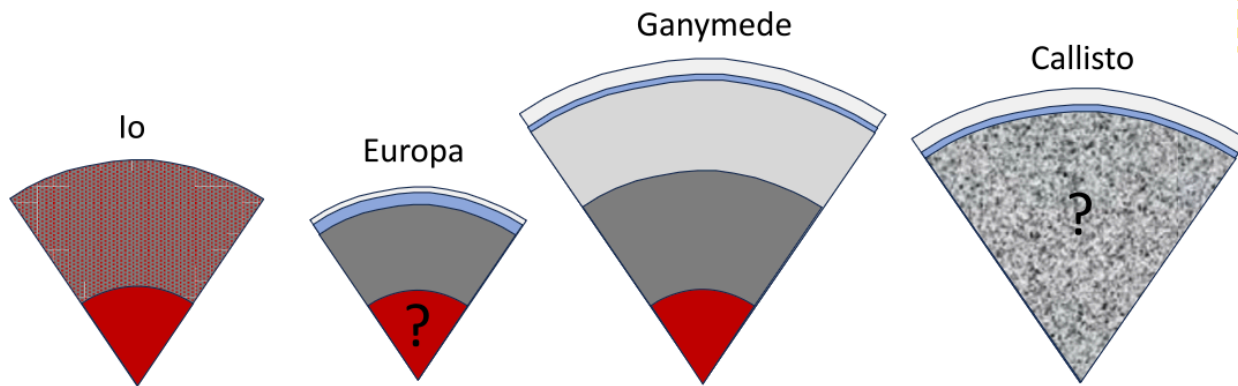
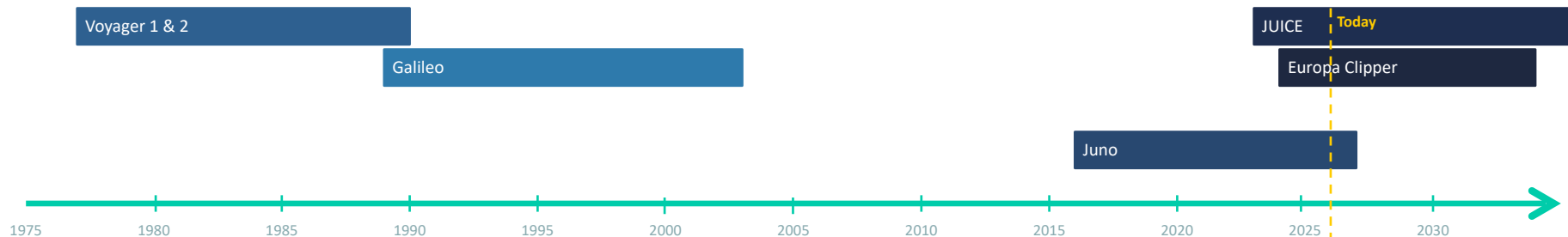
Icy moons differentiation is slow and organics can easily be brought to the ocean



Pinceloup Mathis, 3rd year PhD student at LPG, Nantes

mathis.pinceloup@univ-nantes.fr

Galilean moons's view from today



Nimmo+2026

Gravity

Magnetic induction

Tides

Surface observation

Mol, iron core size

≥20% melt fraction

$k_2 = 0.125$

heat flux 2.5 W/m^2

Mol, core ?

subsurface ocean

-

ice shell >20 km

Mol, differentiated

subsurface ocean

-

ice shell ≤150 km

active dynamo

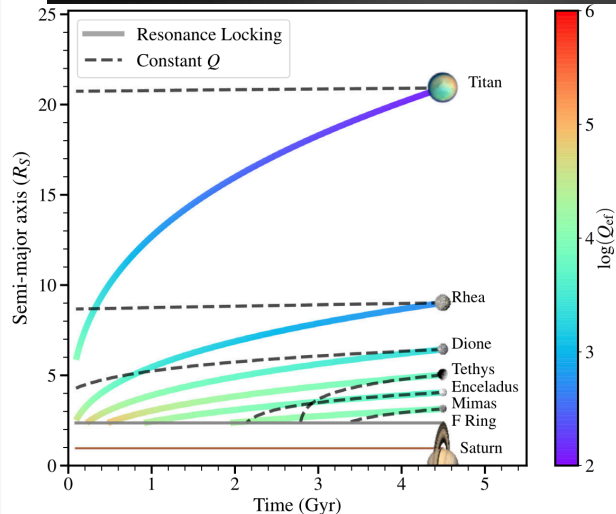
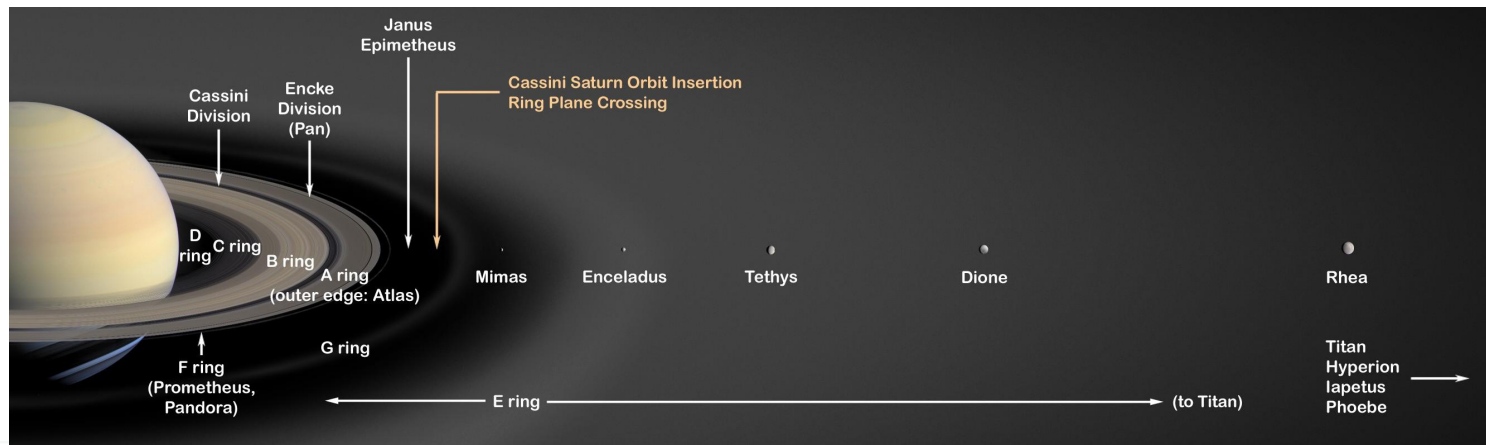
Mol, undifferentiated?

subsurface ocean

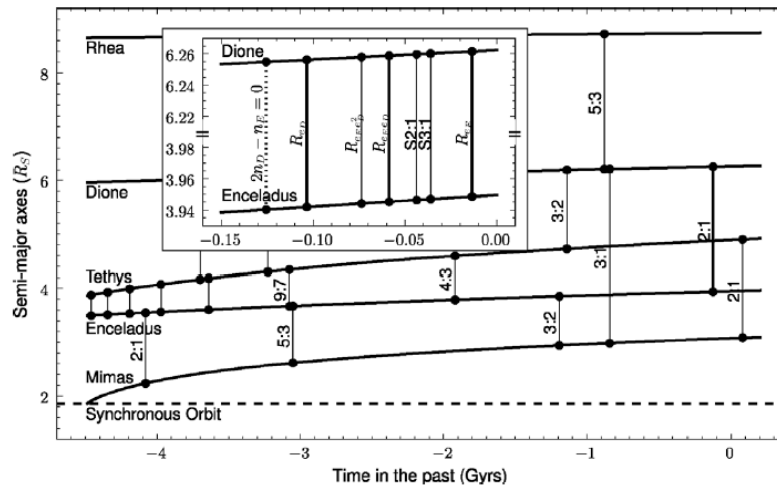
-

geologically quiescent

Saturnian system: dynamical history with many possible resonances

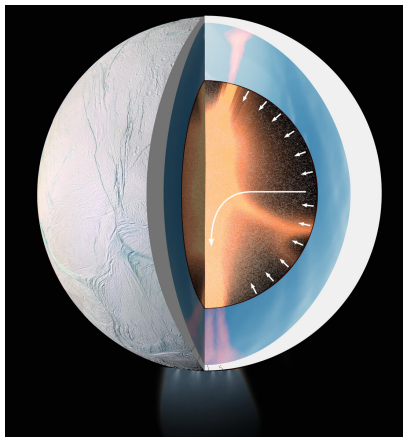
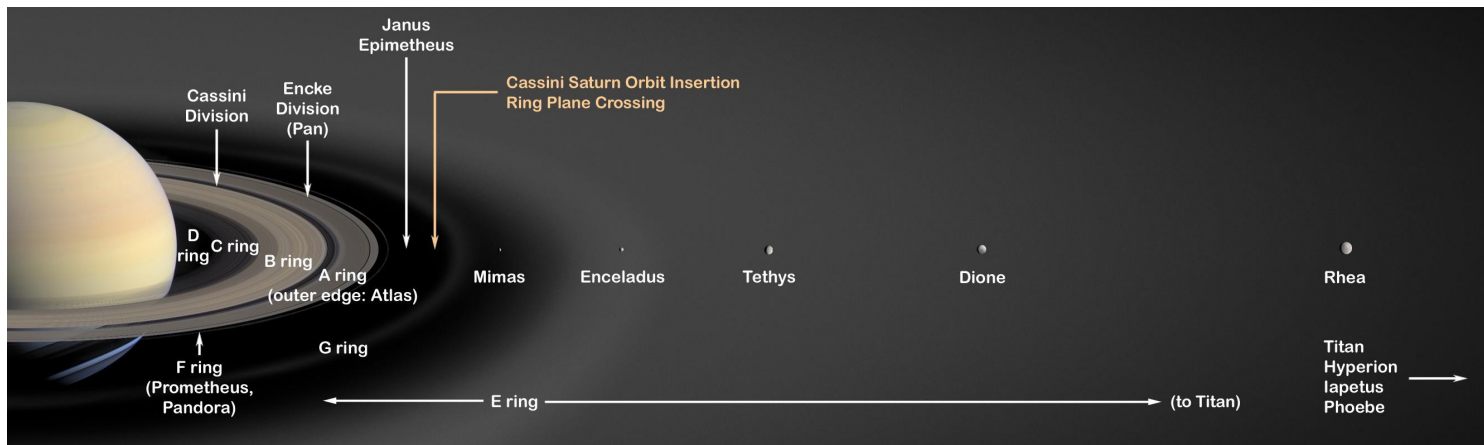


Fuller+2024 after Lainey+2020



Zhang and Nimmo 2009

Saturnian system: active mid-sized moons



Cf Tristan's talk

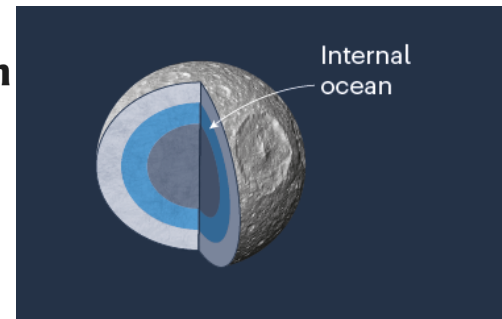
Article | Published: 07 February 2024

A recently formed ocean inside Saturn's moon Mimas

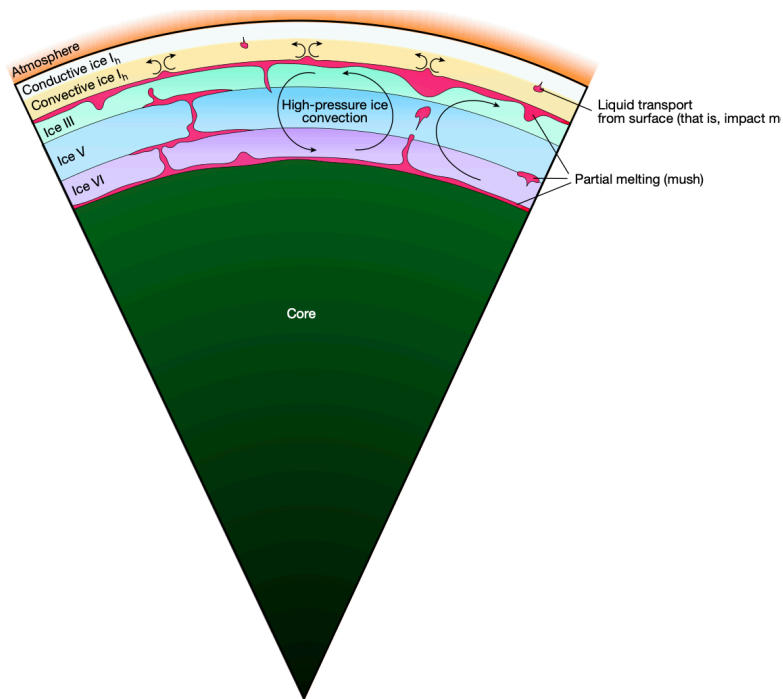
[V. Lainey](#) , [N. Rambaux](#), [G. Tobie](#), [N. Cooper](#), [Q. Zhang](#), [B. Noyelles](#) & [K. Baillié](#)

[Nature](#) **626**, 280–282 (2024) | [Cite this article](#)

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Saturnian system: reconcile Titan orbital state, tidal dissipation and interior



Article

Titan's strong tidal dissipation precludes a subsurface ocean

<https://doi.org/10.1038/s41586-025-09818-x>

Received: 5 May 2025

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Flavio Petricca¹, Steven D. Vance¹, Marzia Parisi¹, Dustin Buccino¹, Gaël Cascioli^{2,3}, Julie Castillo-Rogez¹, Brynna G. Downey⁴, Francis Nimmo⁵, Gabriel Tobie⁶, Baptiste Journaux⁷, Andrea Magnanini⁸, Ula Jones⁷, Mark Panning¹, Amirhossein Bagheri⁹, Antonio Genova¹⁰ & Jonathan I. Lunine¹

Matters Arising | Published: 11 June 2026

On the tidal response of Titan inferred from Cassini data

[Daniele Durante](#) ✉, [Luciano Iess](#) & [Valery Lainey](#)

Nature Astronomy **10**, 788–790 (2026) | [Cite this article](#)

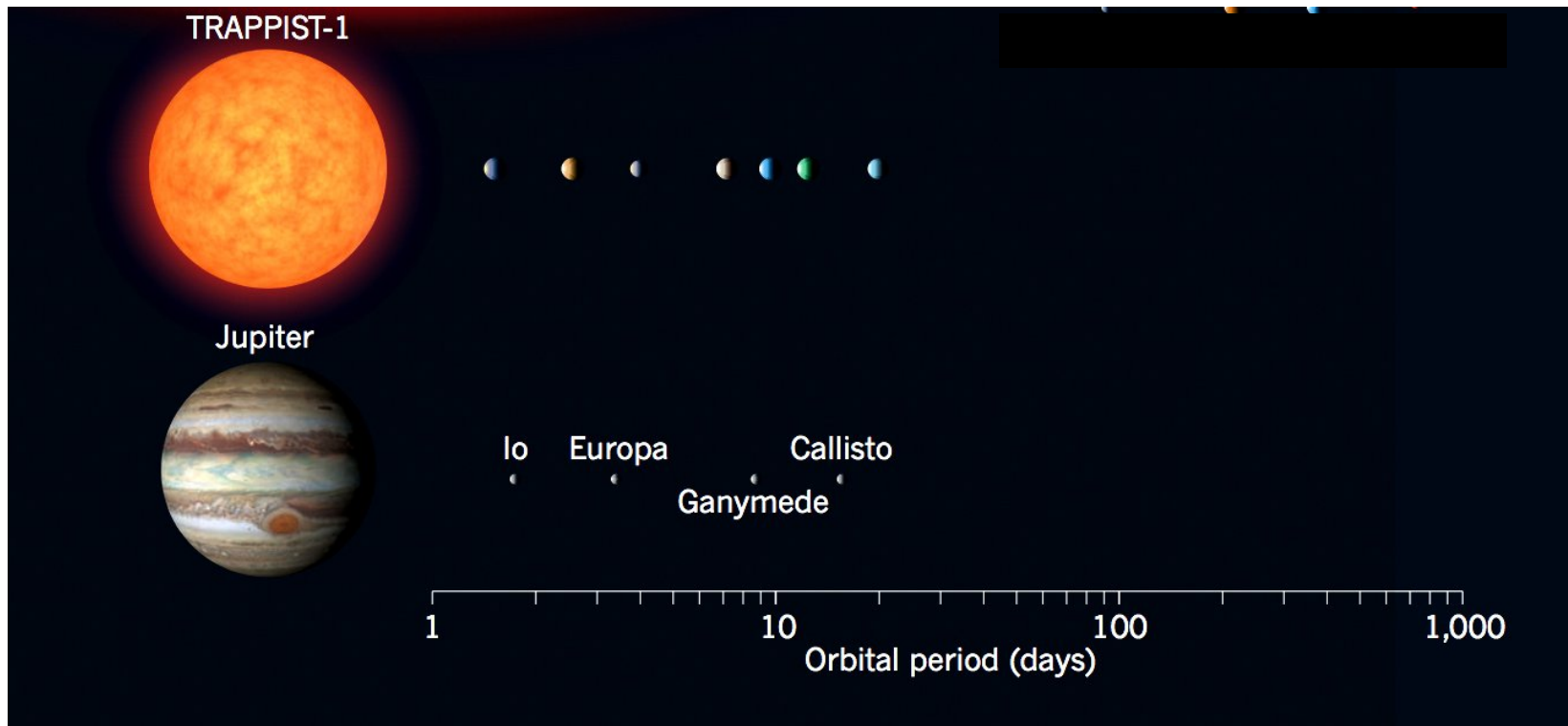
Matters Arising | Published: 11 June 2026

Reply to: On the tidal response of Titan inferred from Cassini data

[Sander Goossens](#) ✉, [Bob van Noort](#), [Alfonso Mateo](#), [Erwan Mazarico](#) & [Wouter van der Wal](#)

Exoplanetary resonant systems ?

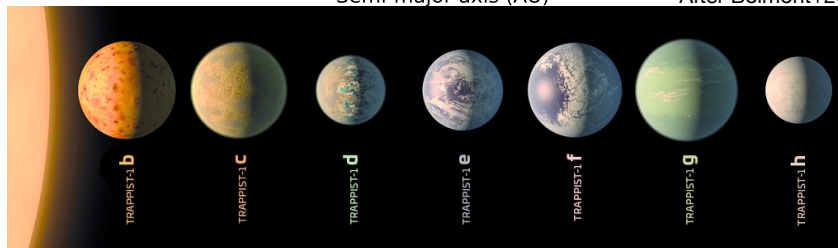
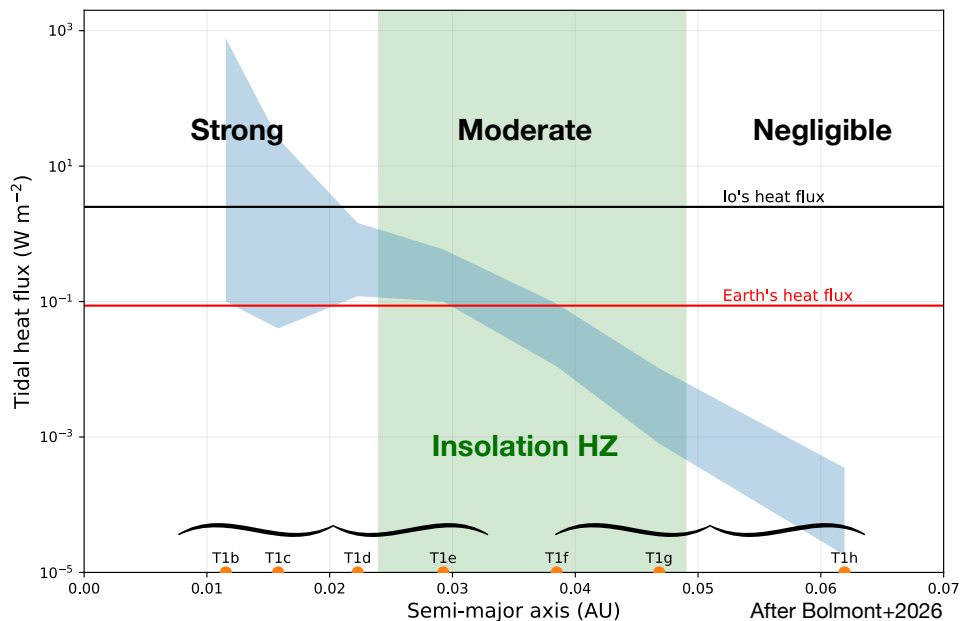
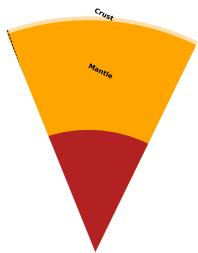
TRAPPIST-1 system: terrestrial (?!) Earth-sized planets subjected to tidal heating



Exoplanetary resonant systems ?

TRAPPIST-1 system: terrestrial (?!) Earth-sized planets subjected to tidal heating

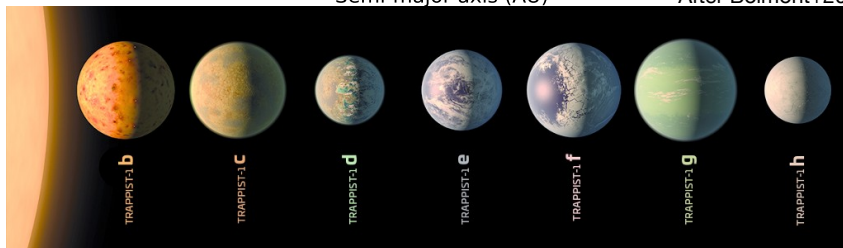
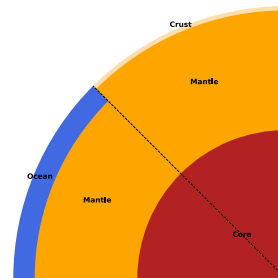
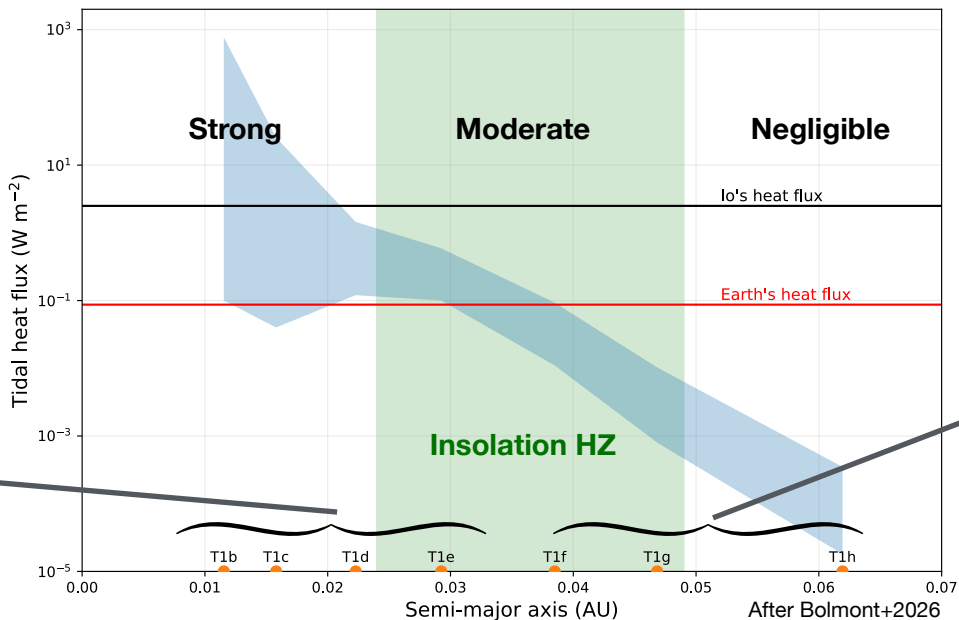
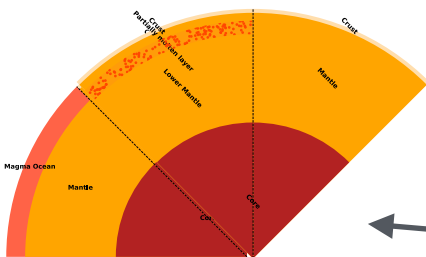
Impact of tidal heating on thermal heat budget :



Exoplanetary resonant systems ?

TRAPPIST-1 system: terrestrial (?!) Earth-sized planets subjected to tidal heating

Impact of tidal heating on thermal heat budget :

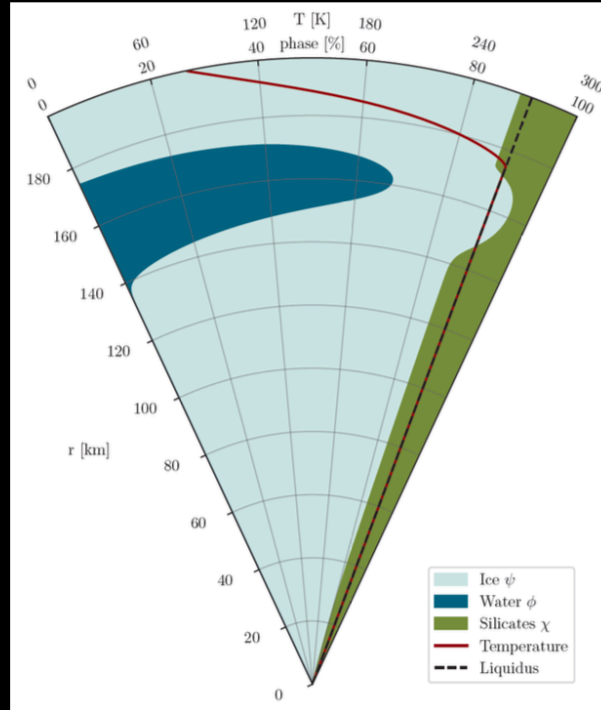
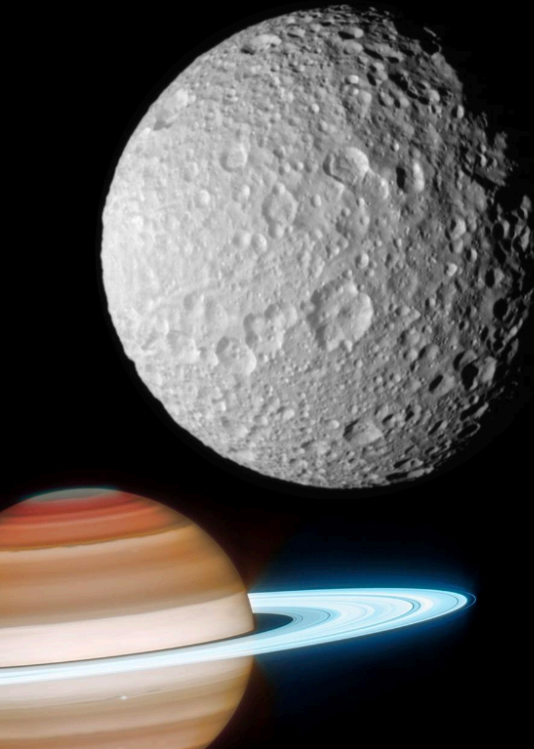


Partial Differentiation of Mimas by Tidal Heating preserves its Geologically Inert Surface

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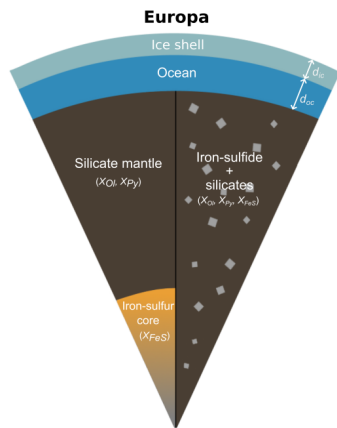
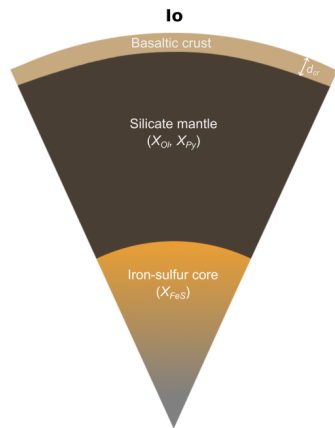
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- Mimas is a small icy moon of Saturn ($r = 198.2$ km), presenting an inactive surface heavily craterized.
- From librations and periapsis drift of Mimas, an internal ocean can be constrained under an ice shell 20-30 km thick.
- We investigate a scenario where Mimas could still differentiating.

Figure: Mimas 1D structure with phases radial distribution and temperature profile

Recent Interior models of Io and Europa - Valentin Andre et al. 2026

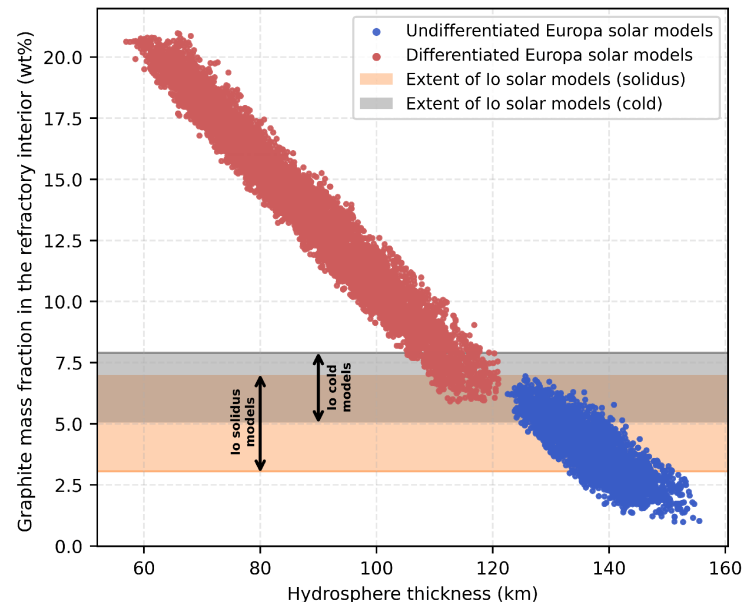
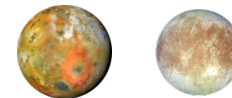


Geophysical +
Geochemical modelling

Monte-Carlo inversion to
satisfy the mass, radius and
moment-of-inertia

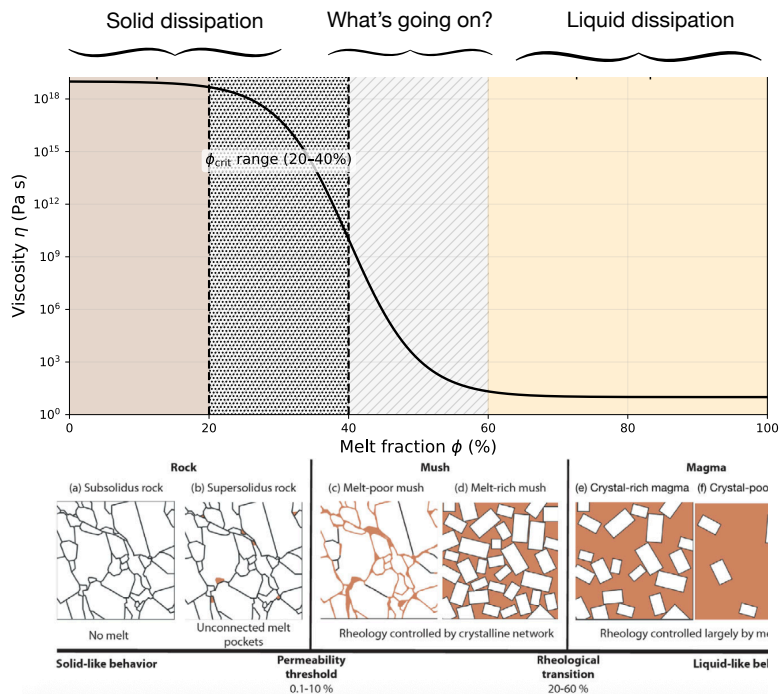
Main results of the study:

- Io and Europa must respectively incorporate **3-8 wt% and 1-22 wt% of graphite** to have a silicate-sulfide composition consistent with that of carbonaceous chondrites (potential building blocks).
- Carbon content in Europa is strongly anti-correlated with the hydrosphere thickness, which will be measured by Europa Clipper.
- A significant fraction of Europa's hydrosphere may come from thermal metamorphism of carbonaceous organic matter.



Tidal dissipation as a heat engine: rheology

Partial melting



Depending where tidal heat is dissipated:
 - increase tidal heating budget
 - modifies heat flux pattern

