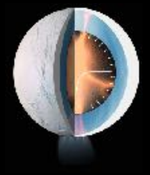
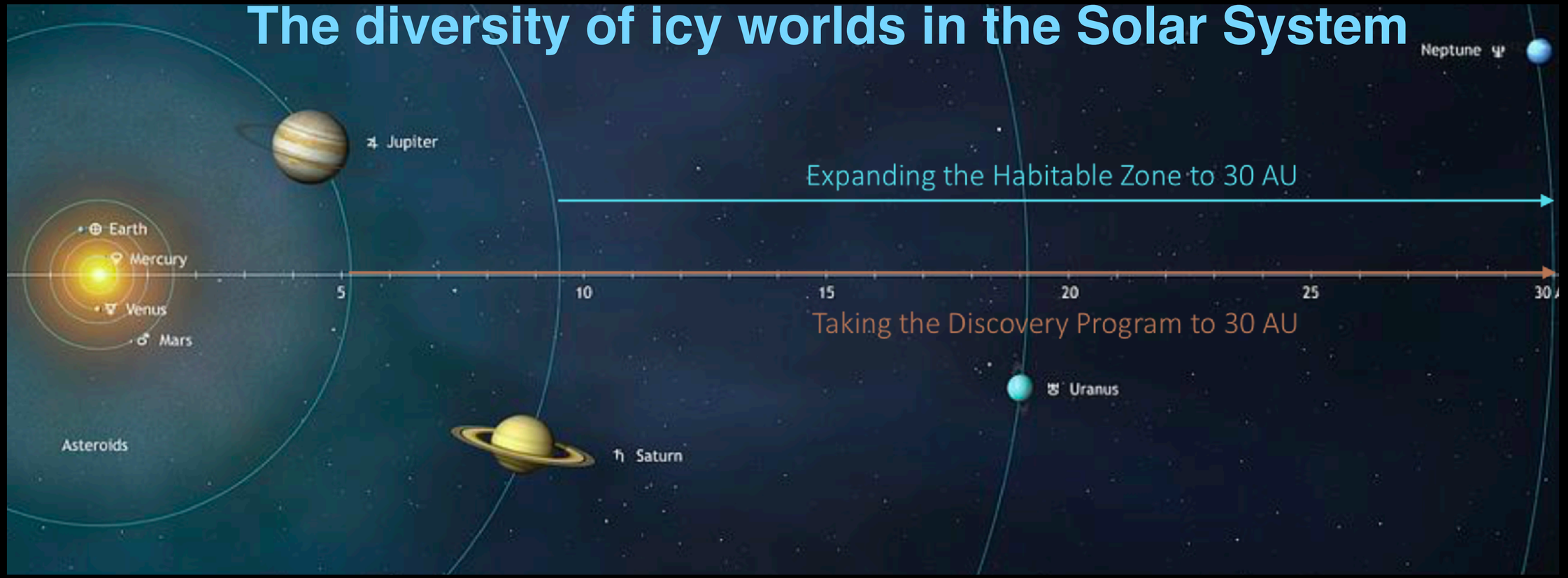
Porous media as a means of promoting exchange processes in Icy worlds of the Outer Solar System

Gabriel TOBIE

LPG cnrs Nantes Université



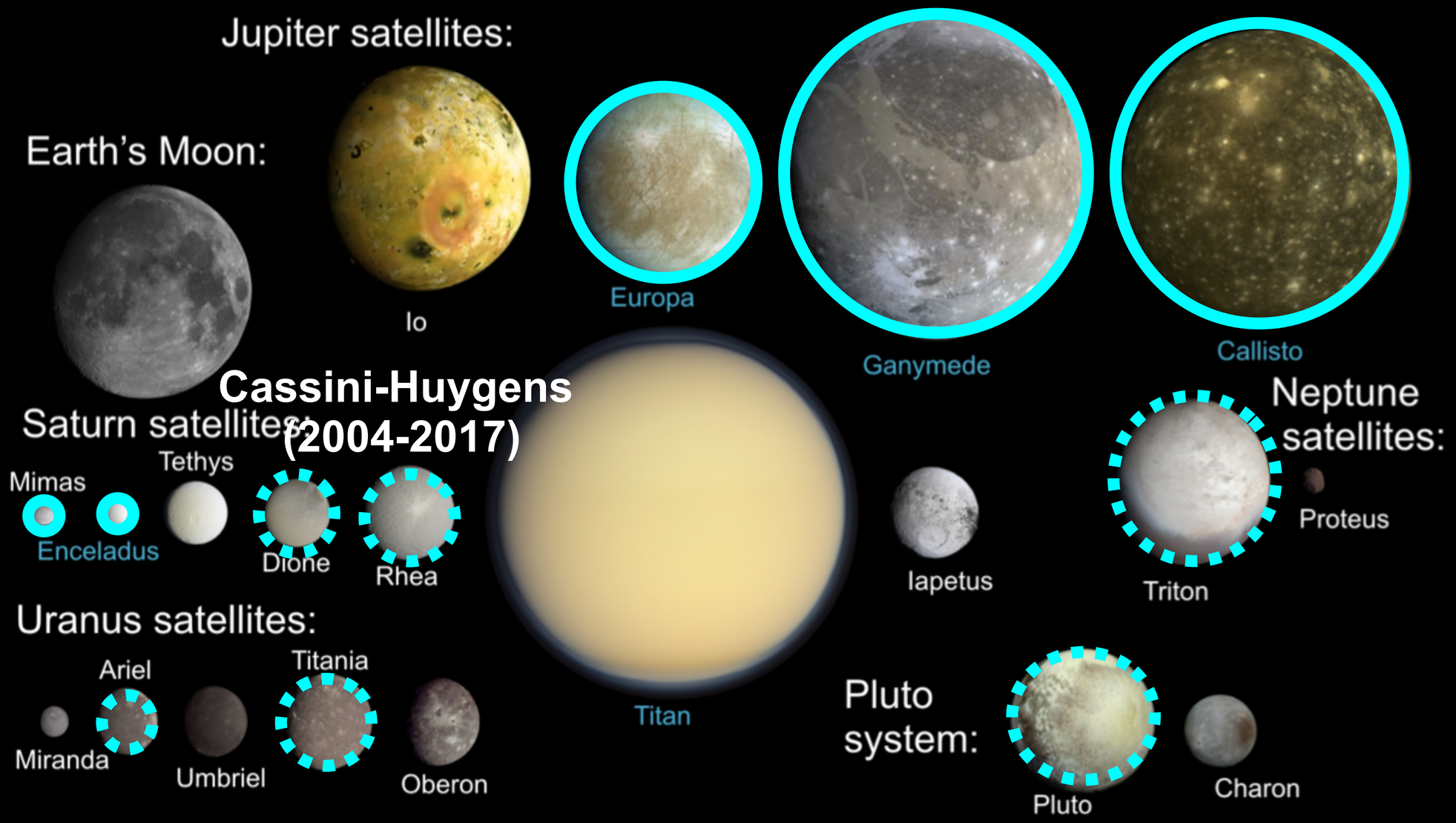
The diversity of icy worlds in the Solar System



The diversity of icy worlds in the Solar System

from Nimmo and Pappalardo (2017)

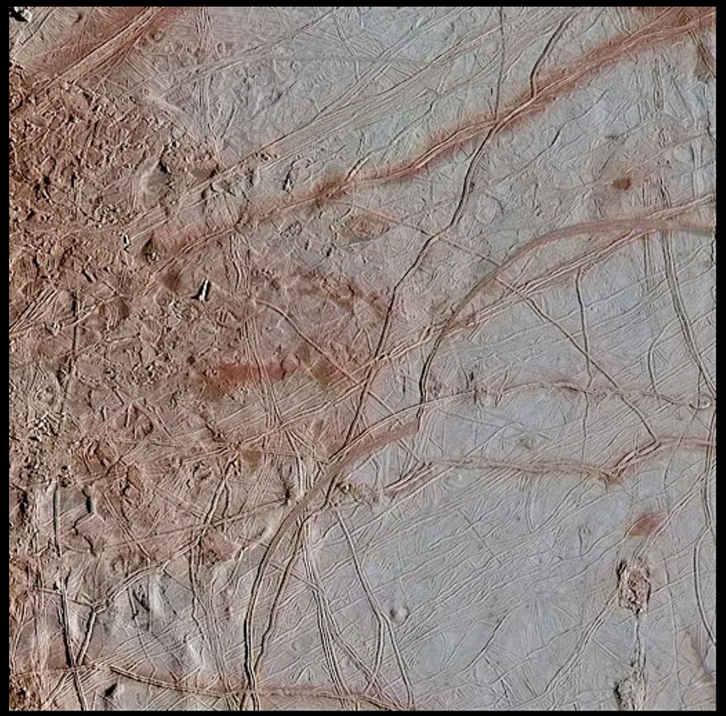
The diversity of ~~icy~~ worlds in the Solar System

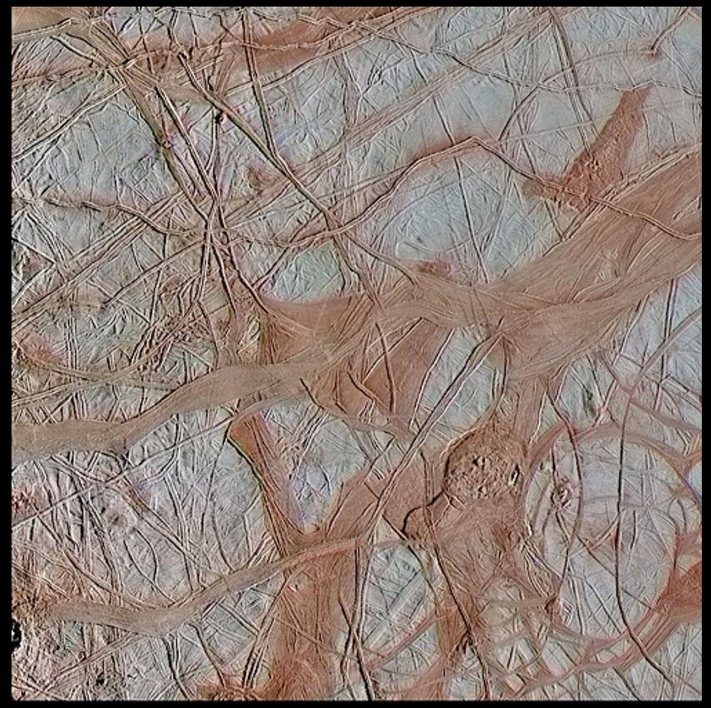


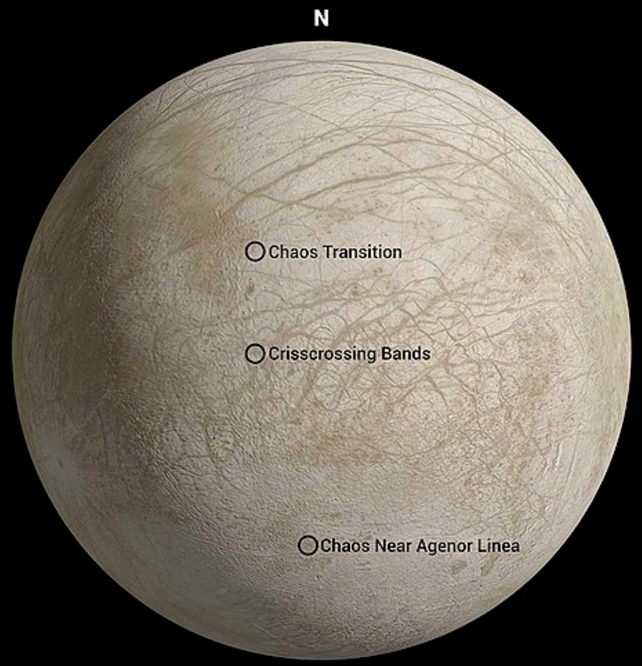
from Nimmo and Pappalardo (2017)

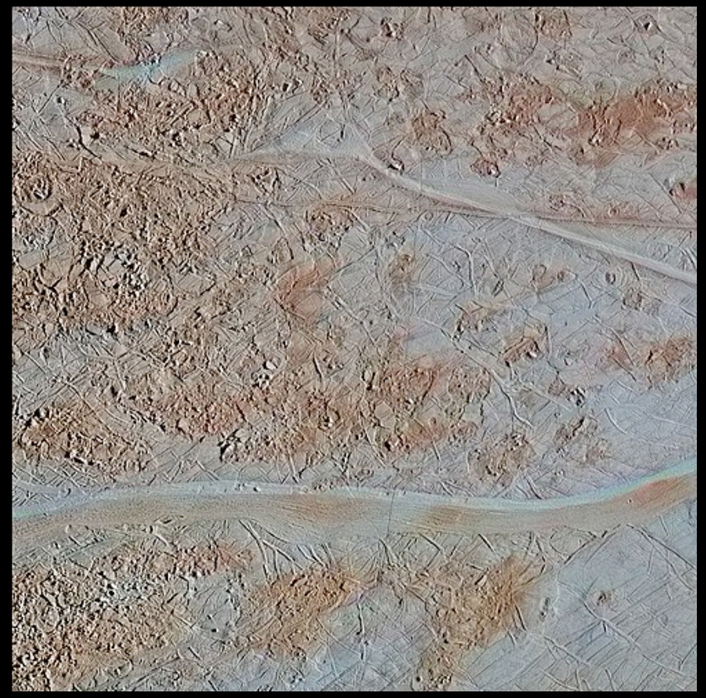
Galileo
1995-2003

EUROPA









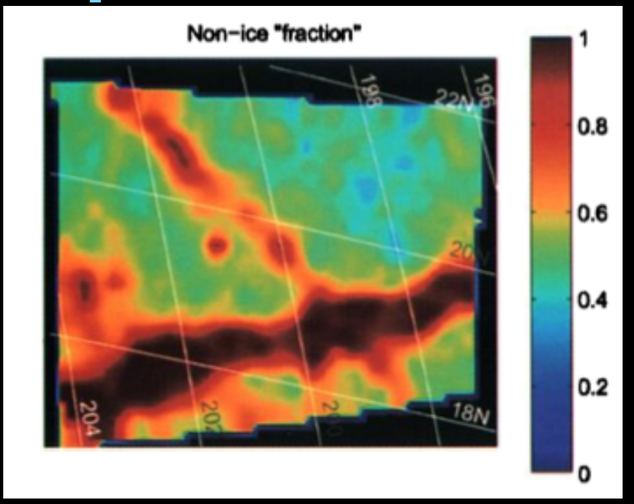
Galileo
1995-2003

NASA/JPL-Caltech/SETI Institute

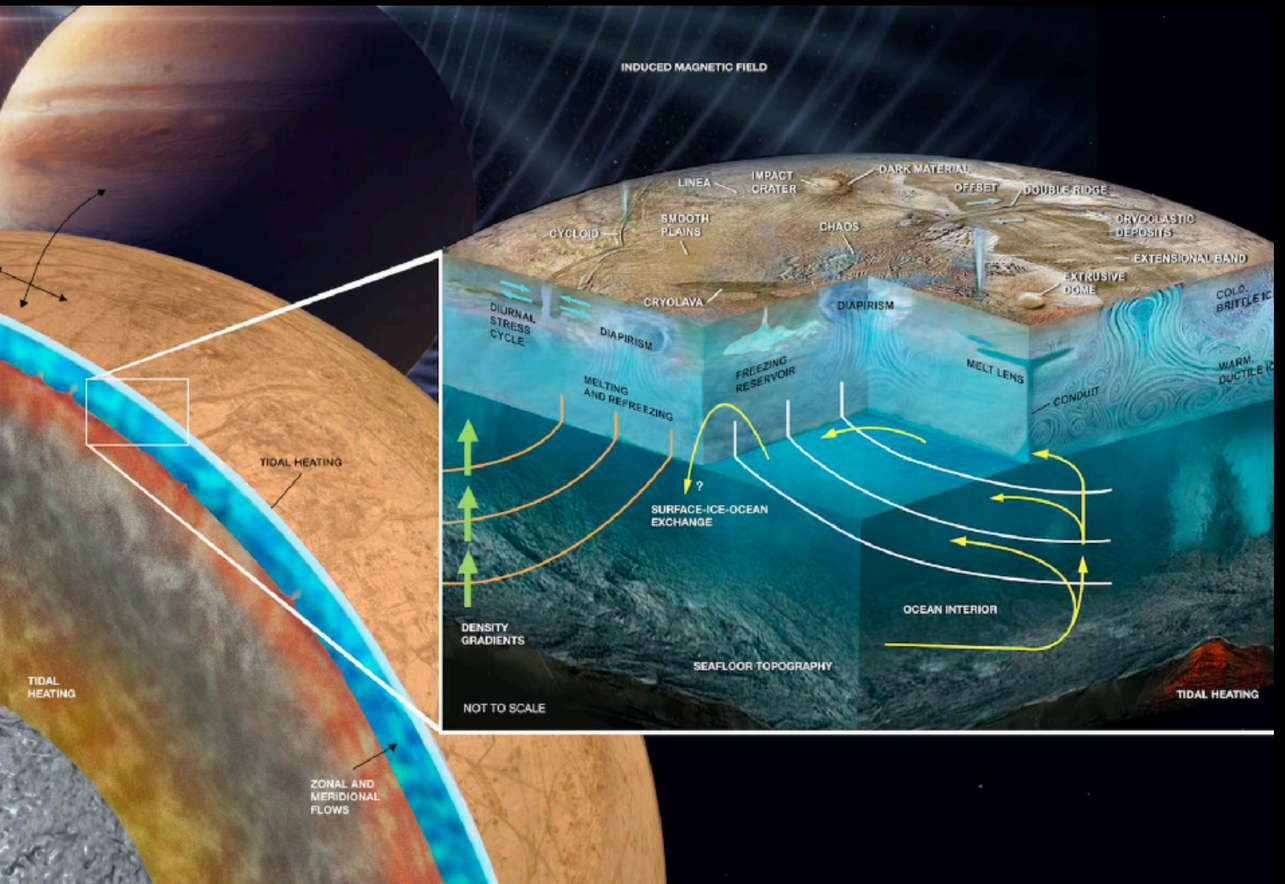
EUROPA

Identification of salt-rich regions correlated with tectonic and chaotic features on Europa

Detection of salts along tectonic and chaotic terrains, suggesting active exchange with a salty subsurface ocean

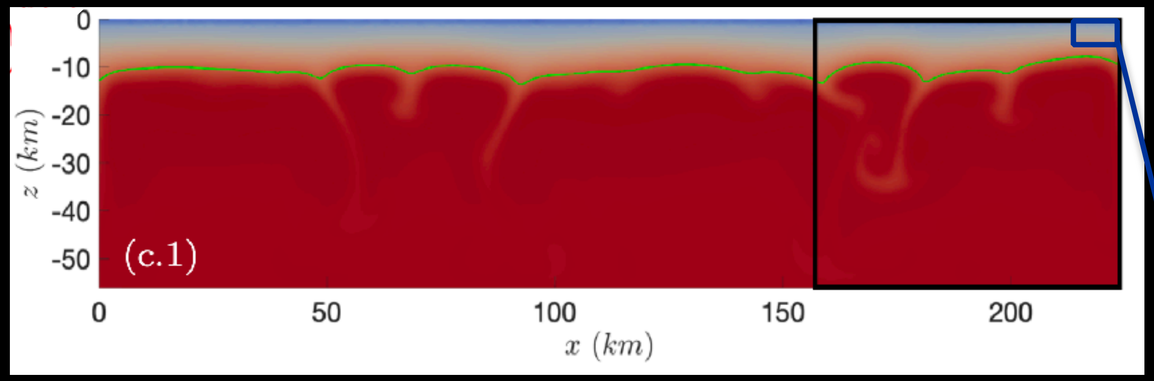


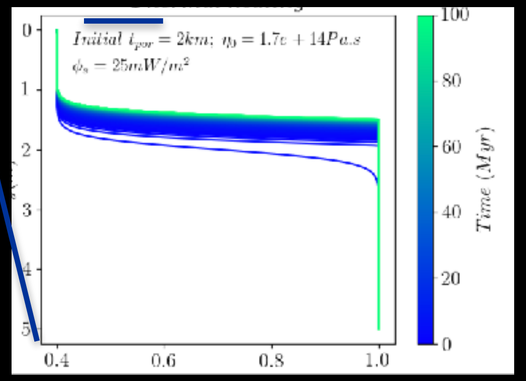
McCord et al. (1998,1999)



Role of porosity in promoting the eruption of salted liquid water ?

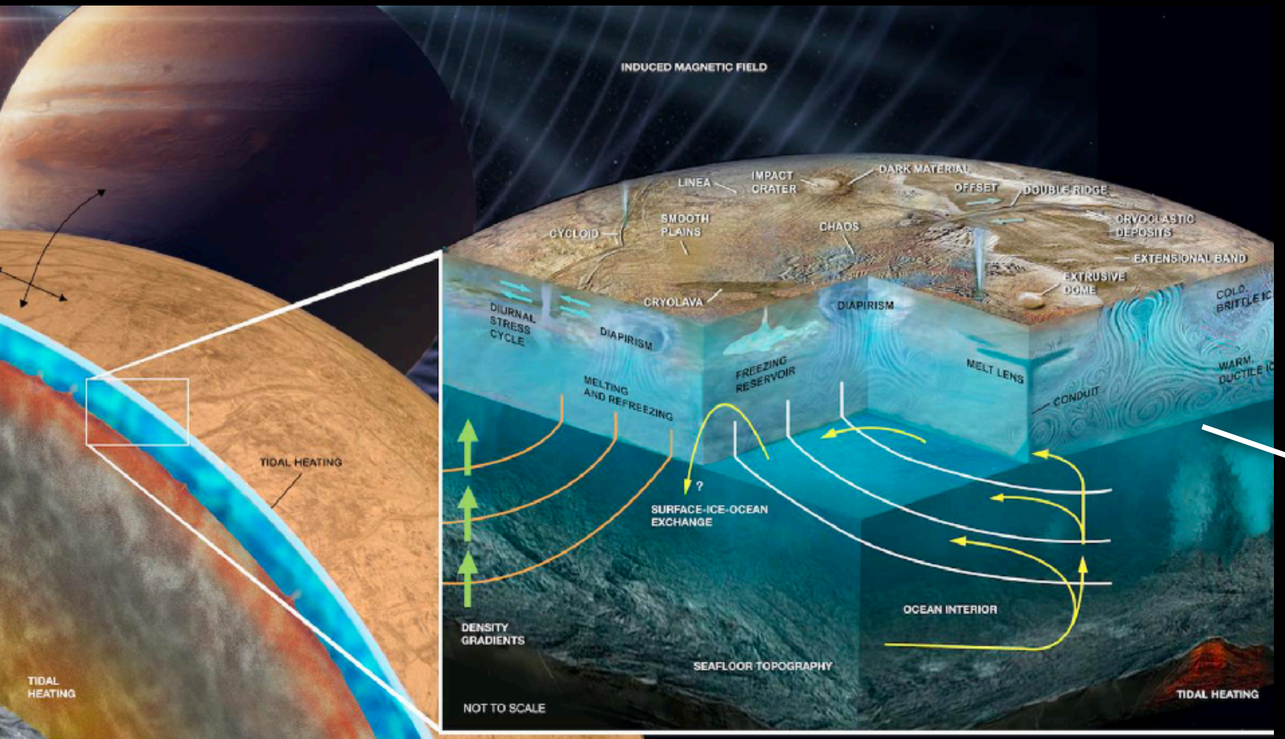
Role of porous media on the exchange processes from the ocean to the surface of Europa





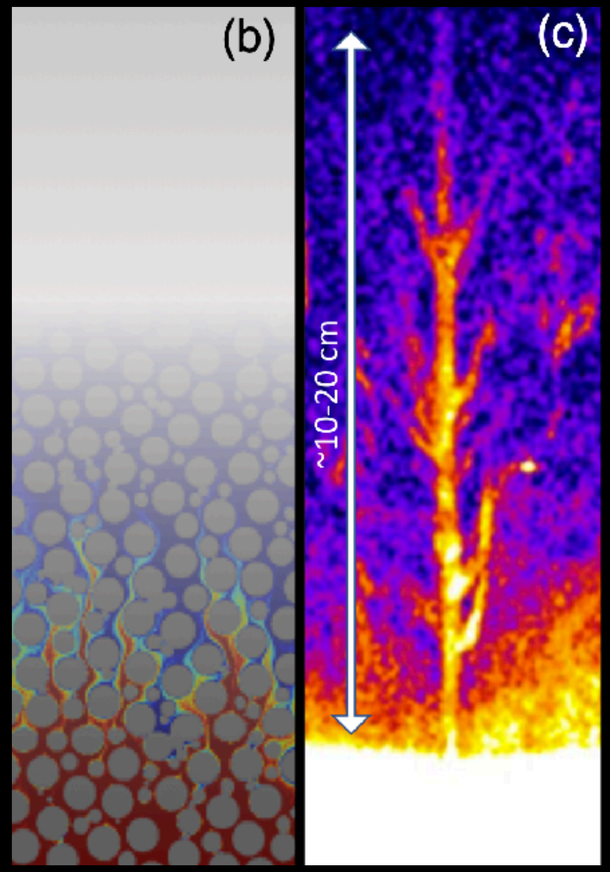
Effect of porous layer on the heat transfer through the ice shell

Himo et al. (2026)



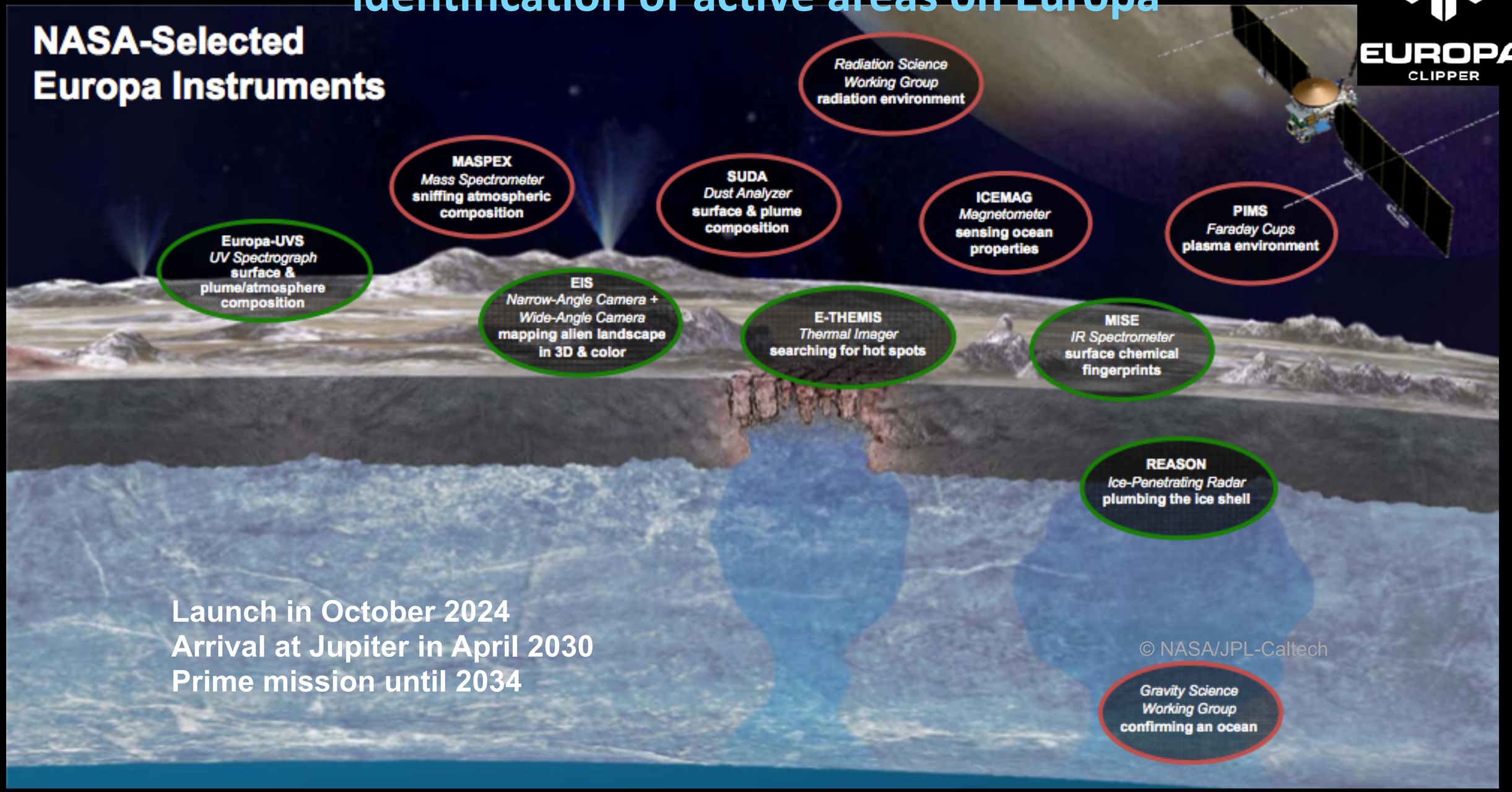
Roberts et al. (2023)

Possible entrainement of oceanic impurities in the ice shell involving two-phase flow in porous ice



Buffo et al. (2020)

Characterization of its subsurface ocean and identification of active areas on Europa

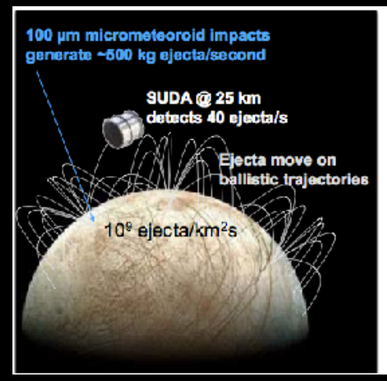


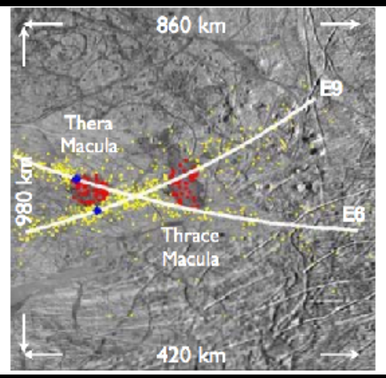
EUROPA CLIPPER

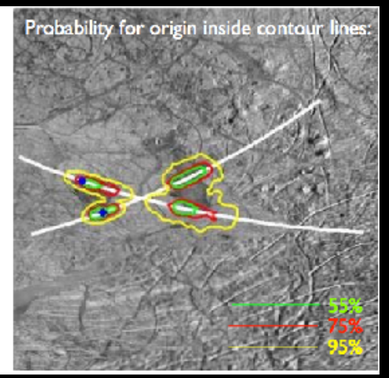
Characterization of its subsurface ocean and identification of active areas on Europa

EUROPA CLIPPER

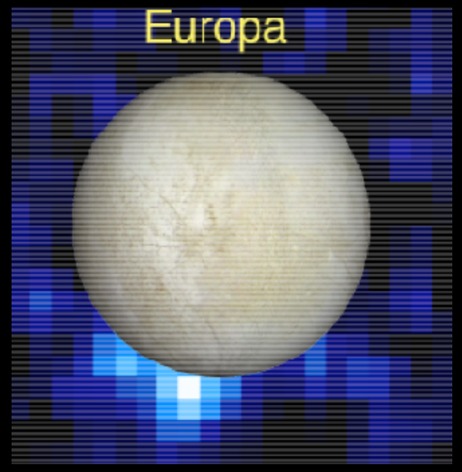
MISE



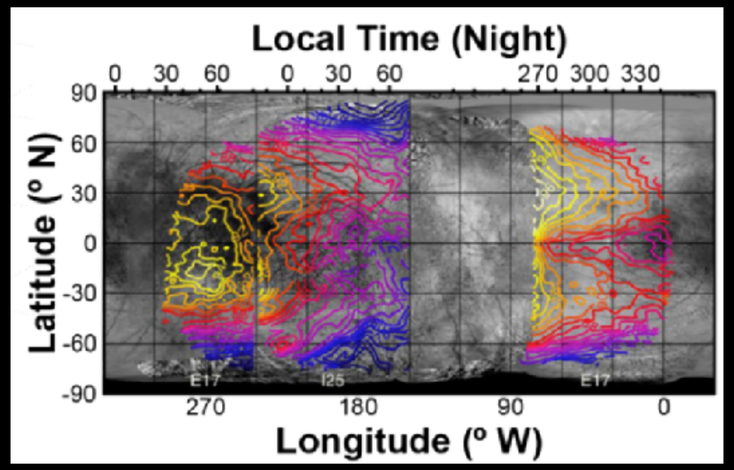




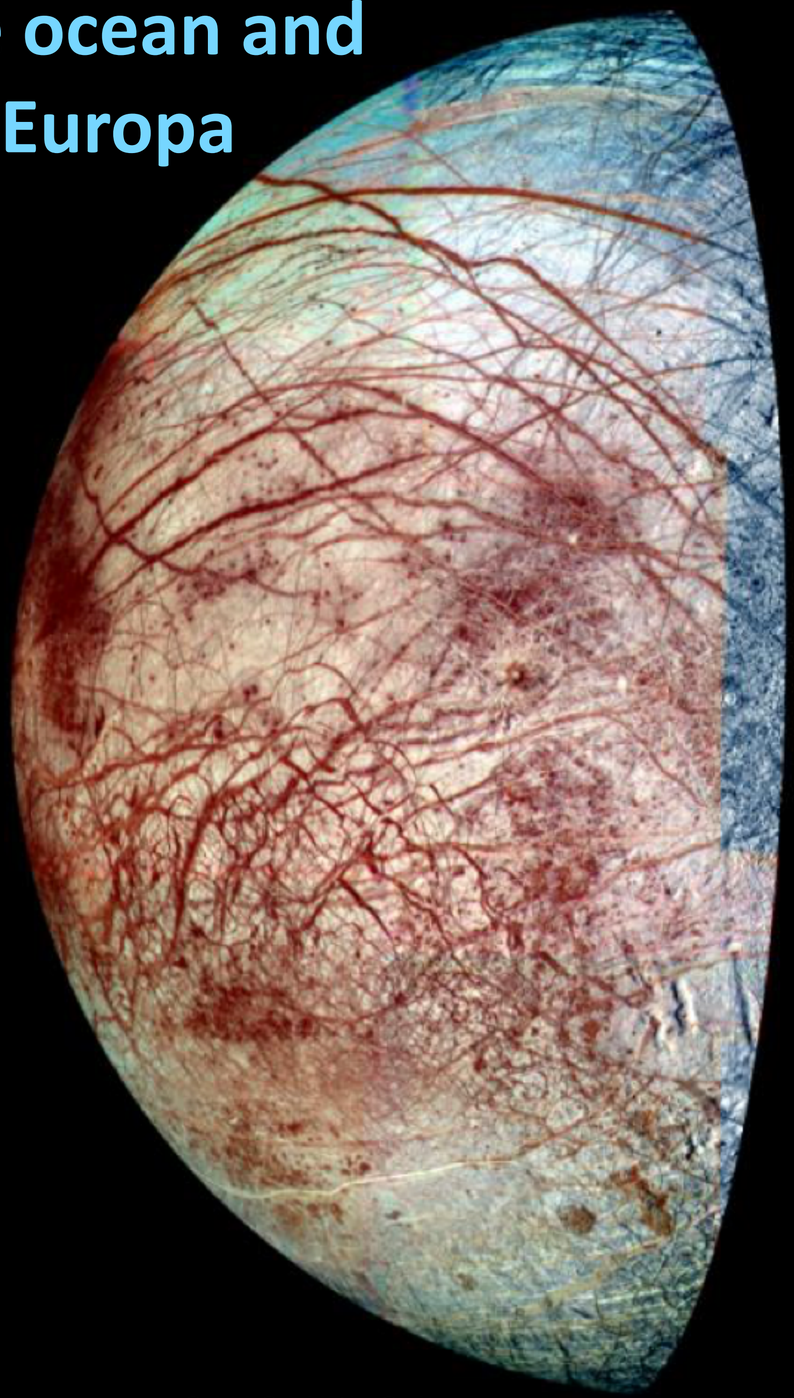
SUDA



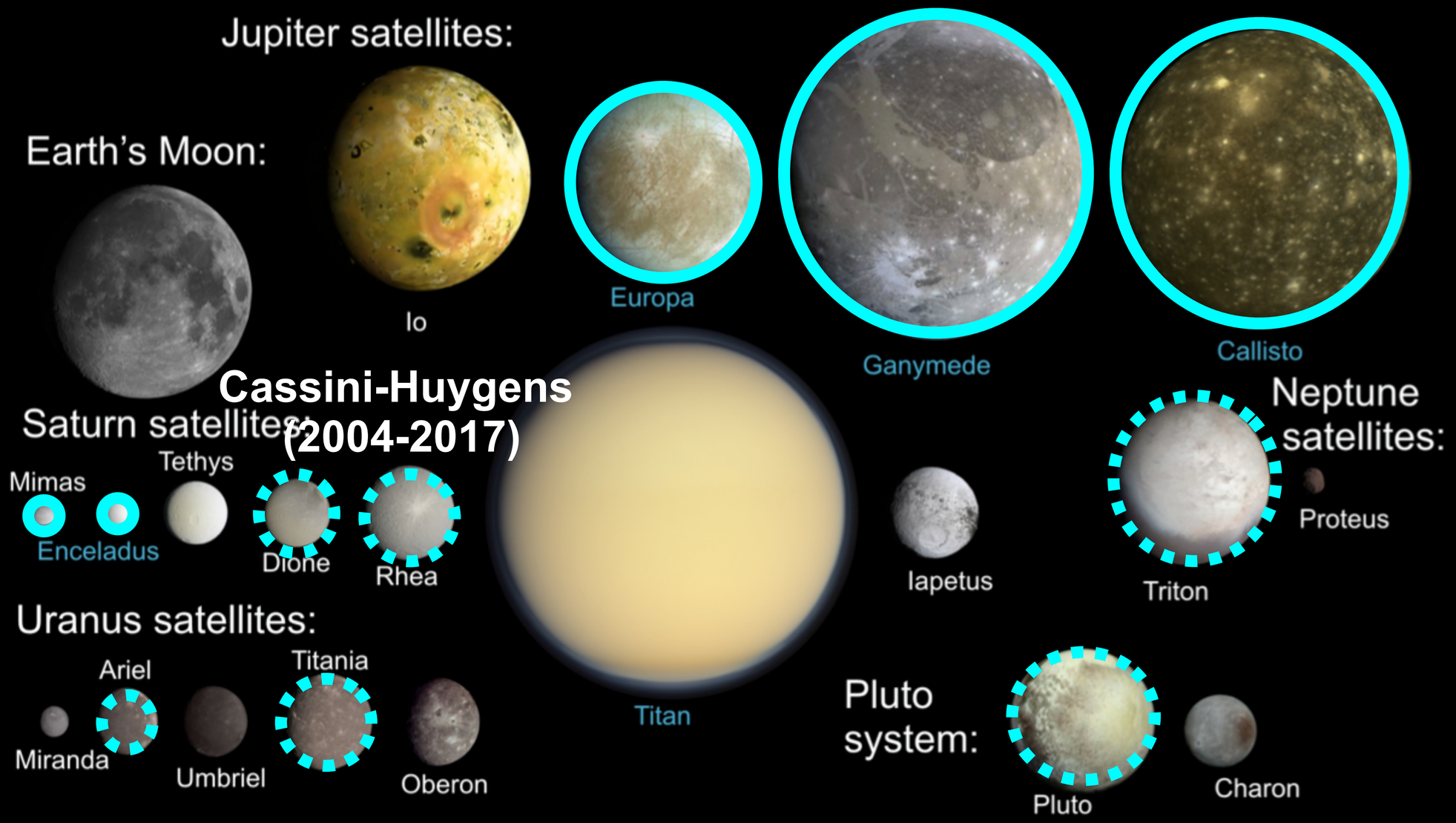
E-UVS



E-THEMIS



The diversity of ~~icy~~ worlds in the Solar System



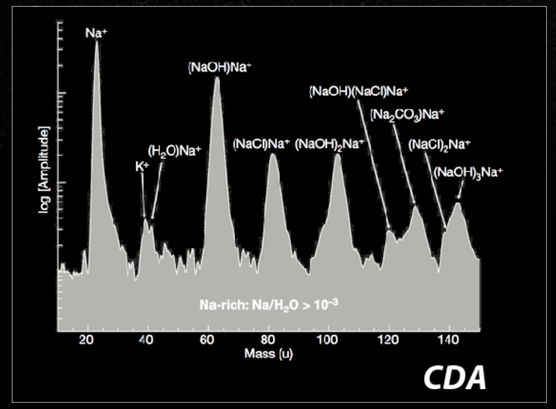
from Nimmo and Pappalardo (2017)

Cassini
2004-2017

ENCELADUS

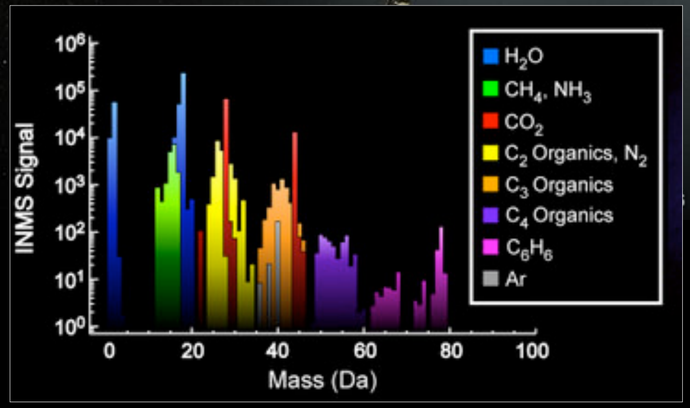
Cassini
2004-2017

Detection of salts in icy grains



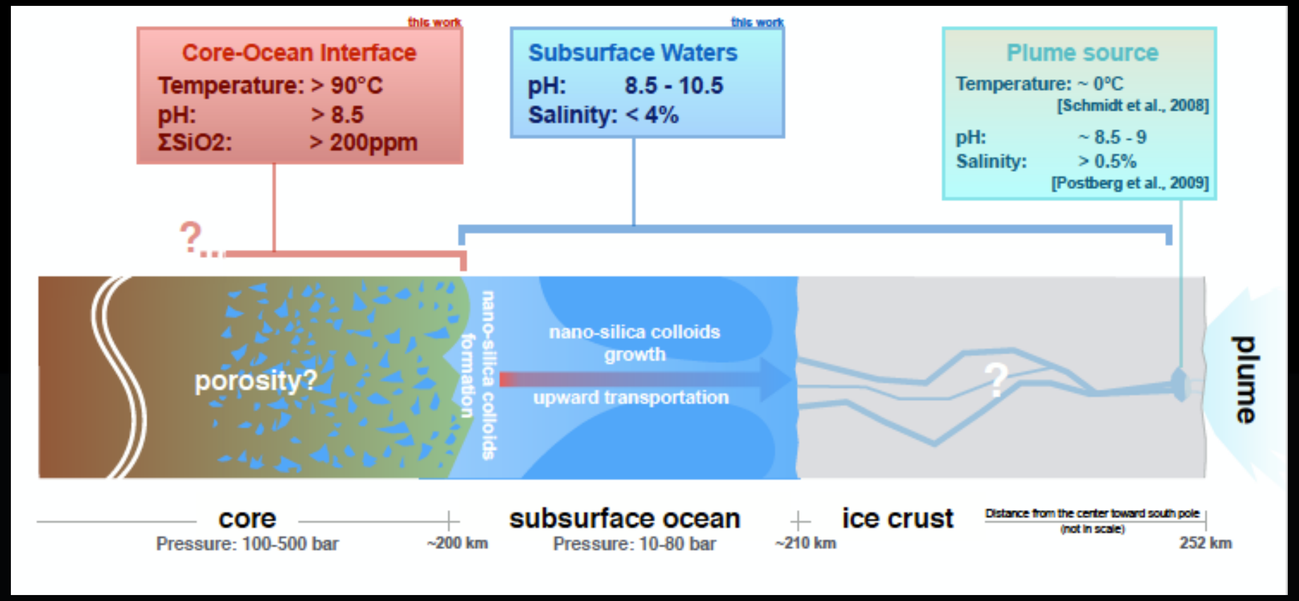
Postberg et al. (2009, 2011)

Identification of complex organics



Waite et al. (2009), Postberg et al. (2018)

First sample from an extraterrestrial ocean



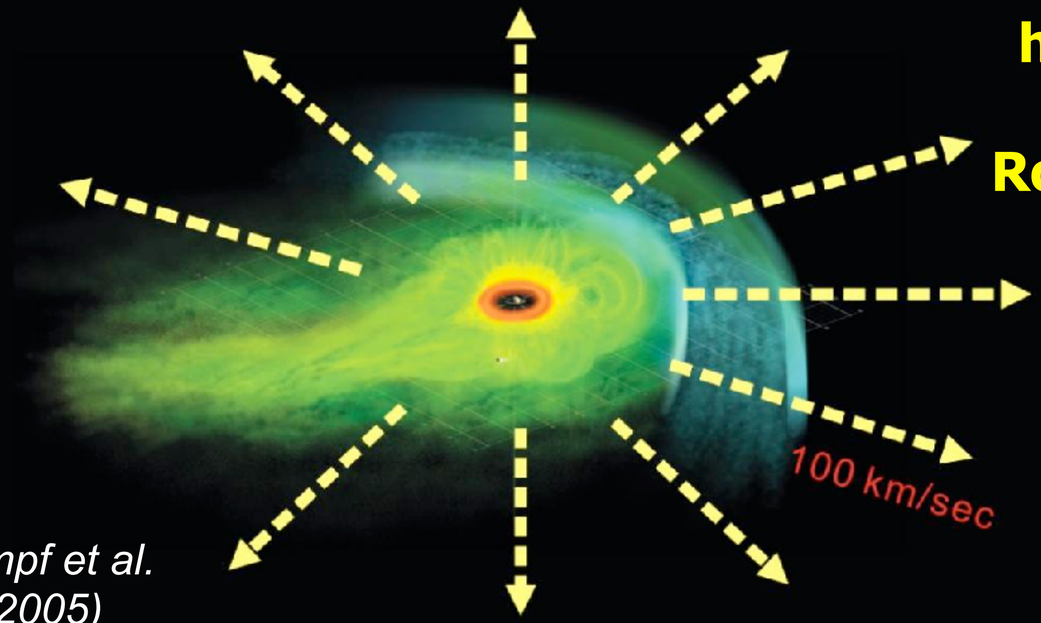
Hsu et al. (2015), Sekine et al. (2015), Waite et al. (2017)

Evidence for ongoing hydrothermal processes from detection of nano-silica ejected from Saturn's system
+ native H_2 detected in the plume

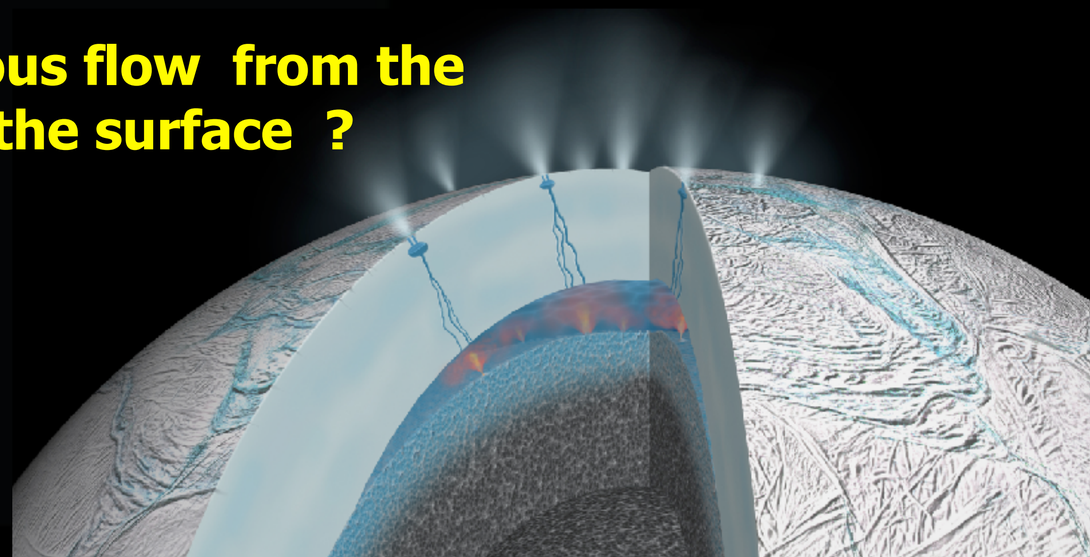
Requiring circulation of hot water (>90°C) in a porous core

Heat sources powering hydrothermal activities ???

Role of porous flow from the core to the surface ?

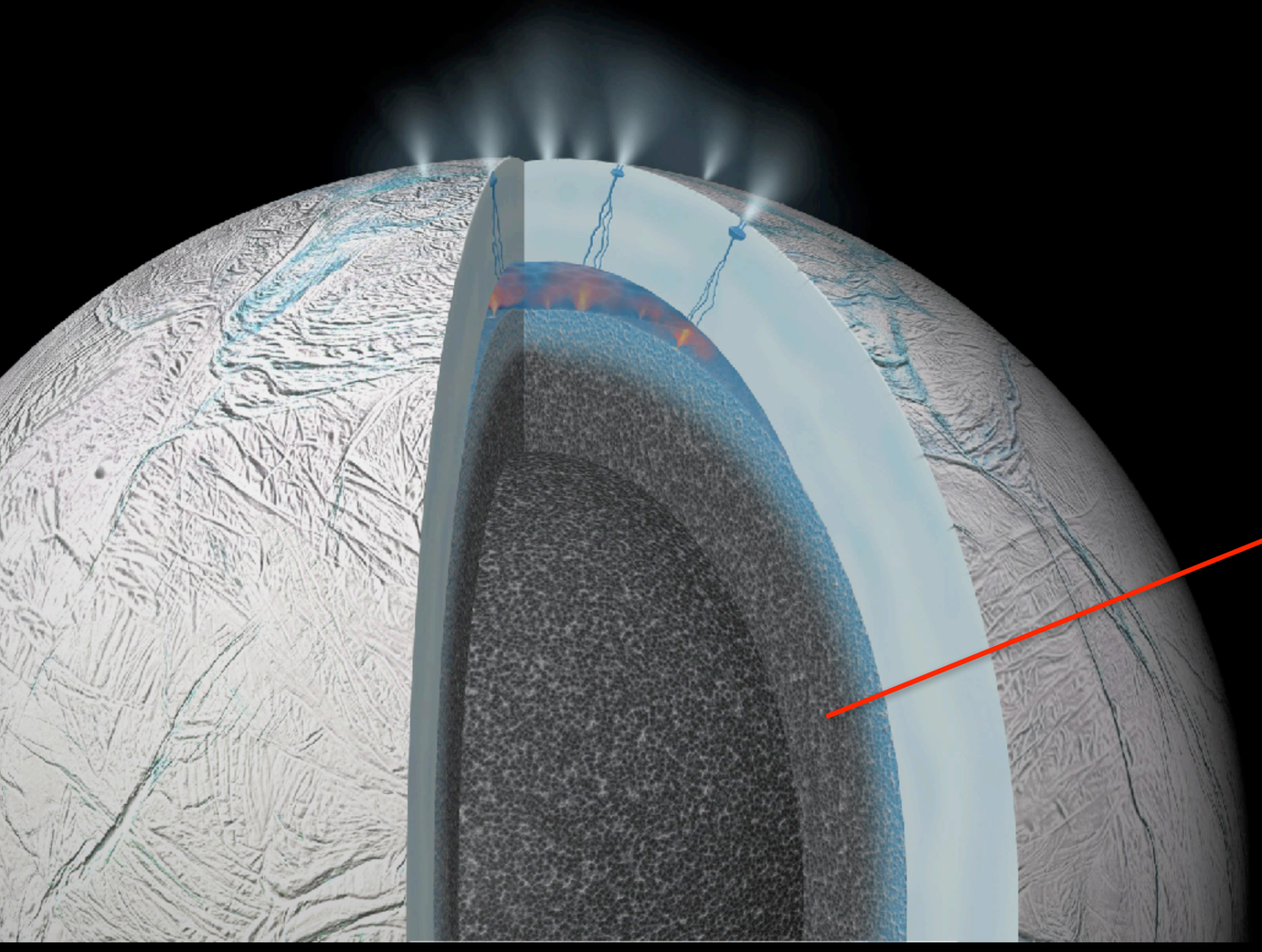


Kempf et al. (2005)

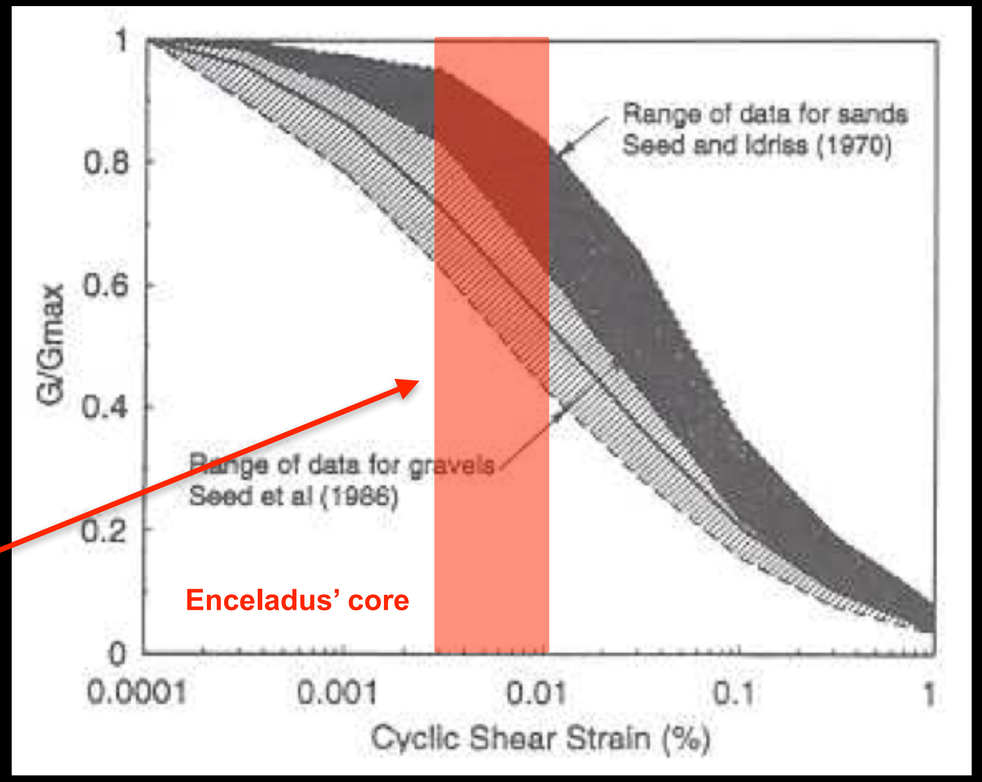


Tidal heat production in an unconsolidated water-saturated porous core

Porosity in the core estimated between 20-30% based on Cassini's gravity data *(Iess et al. 2014)*

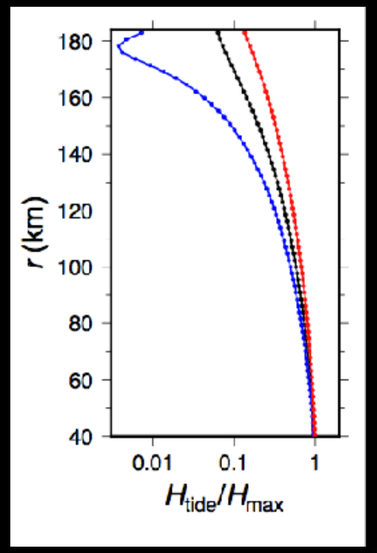


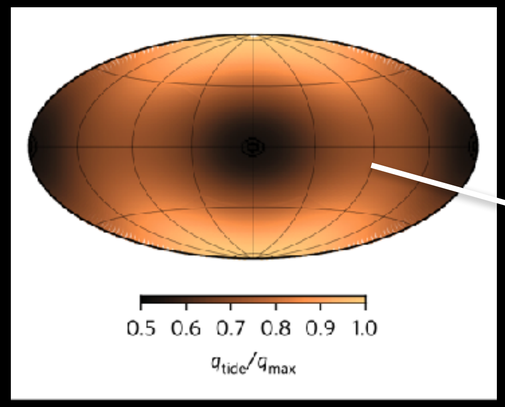
Due to low gravity, the core may consist of a mixture of unconsolidated water-saturated sands and gravels.



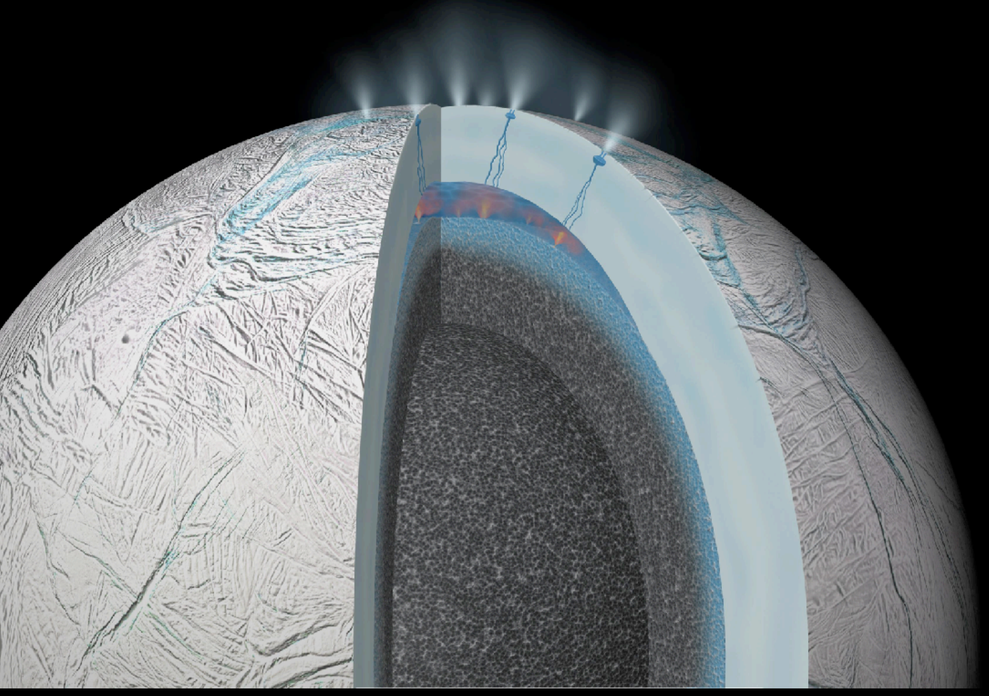
Strong decrease of effective shear modulus for cyclic strain exceeding ~ 0.01 % and increase of dissipation

Implications for hydrothermal activities inside Enceladus

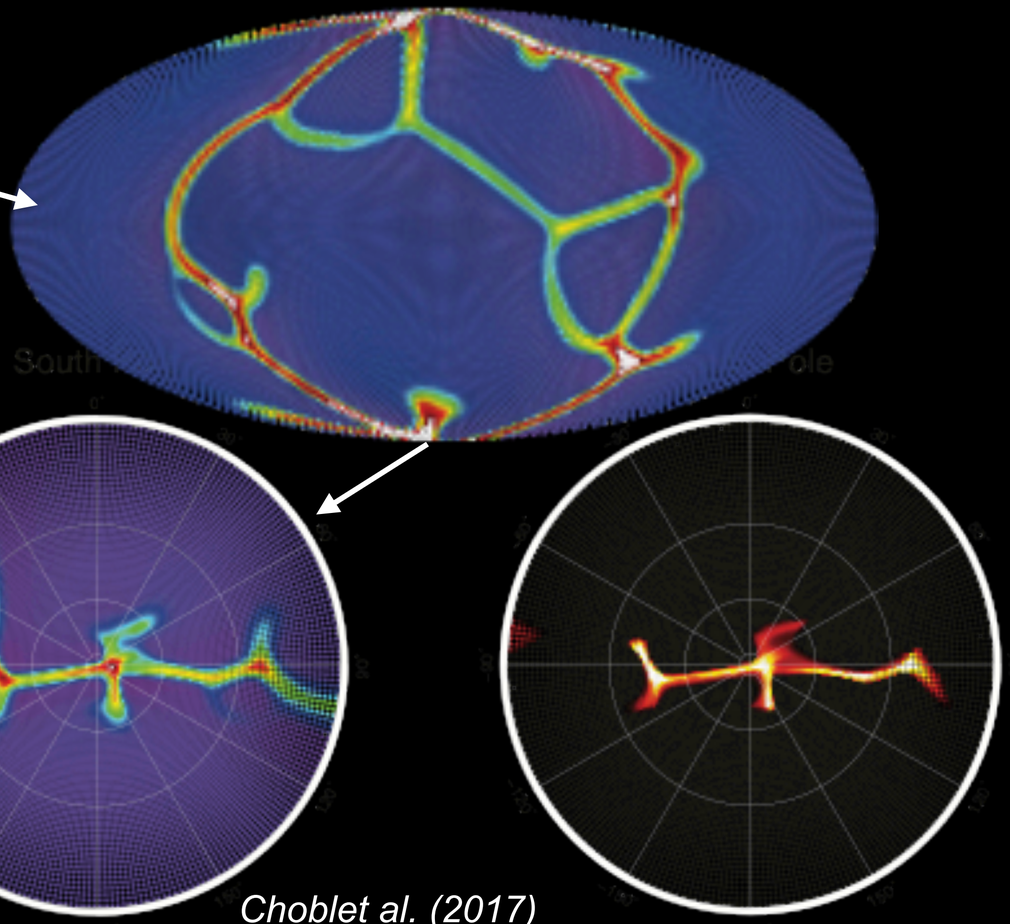




Tidal friction in an unconsolidated core

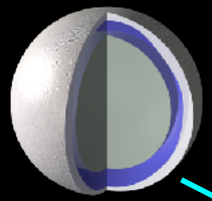


3D modelling of water flow in a tidally-heated porous core



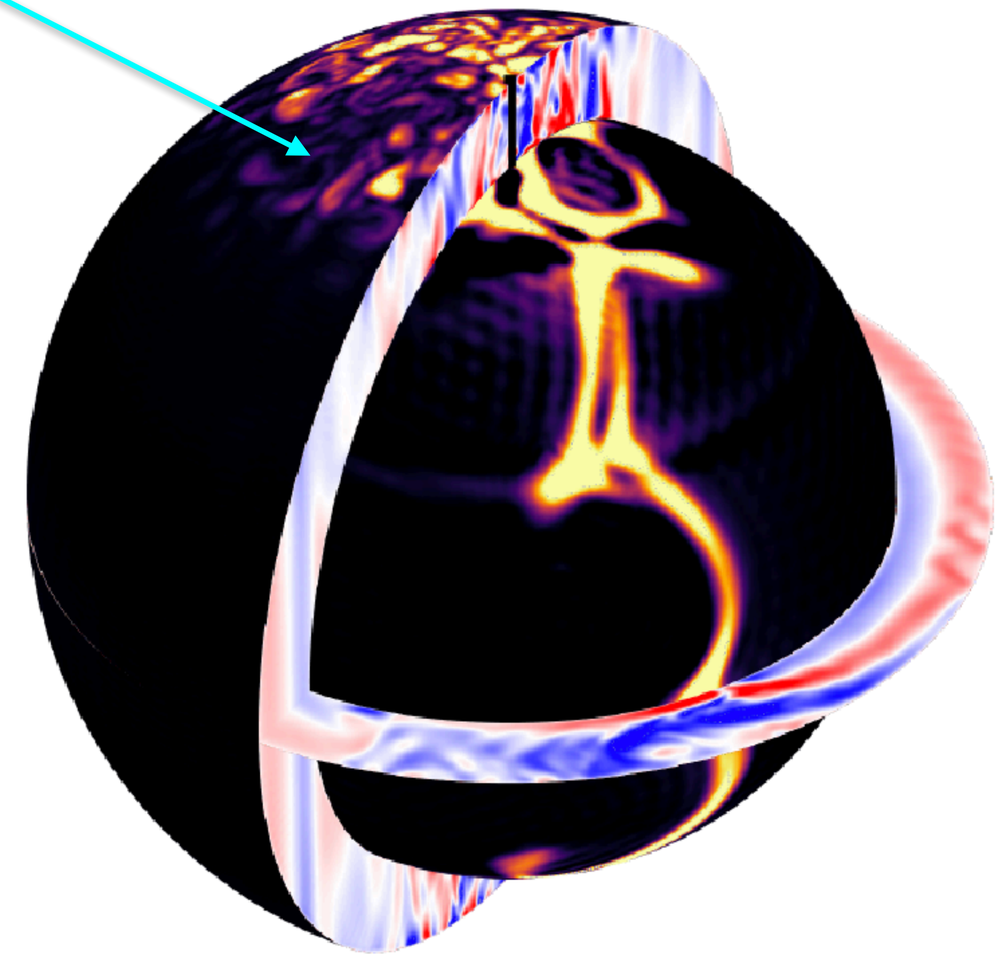
Choblet al. (2017)

Narrow upwelling of hot water (>100°C), leading to hotspots preferentially at the poles



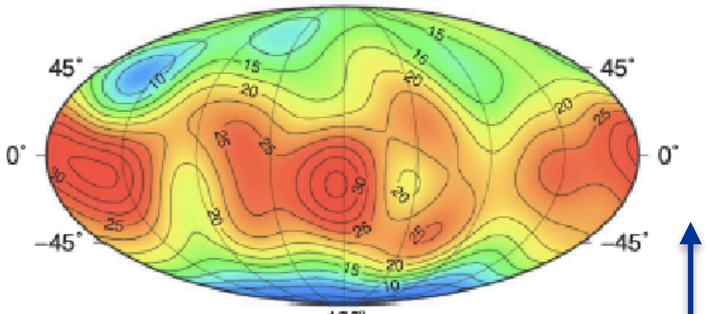
Tidal friction as an engine for hydrothermal activity

Hydrothermal control of ocean dynamics on Enceladus

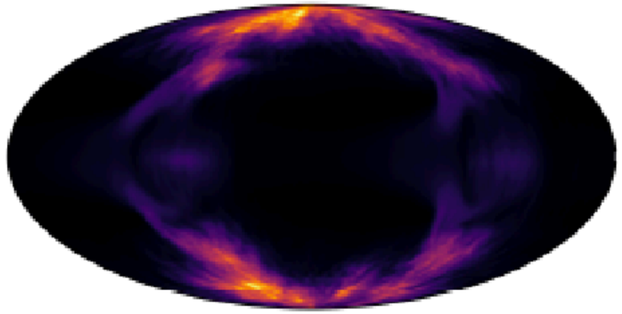


3D simulations of ocean dynamics including strongly heterogenous seafloor heat flux

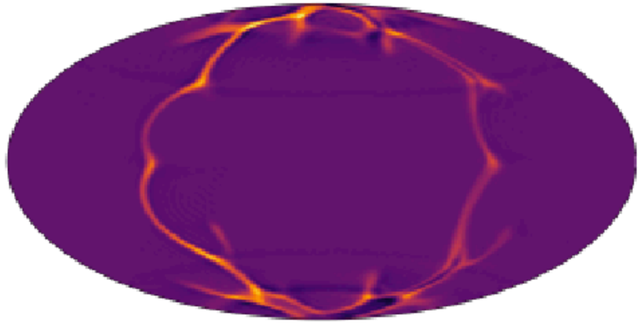
Observed ice shell variations



Modeled surface heat flux



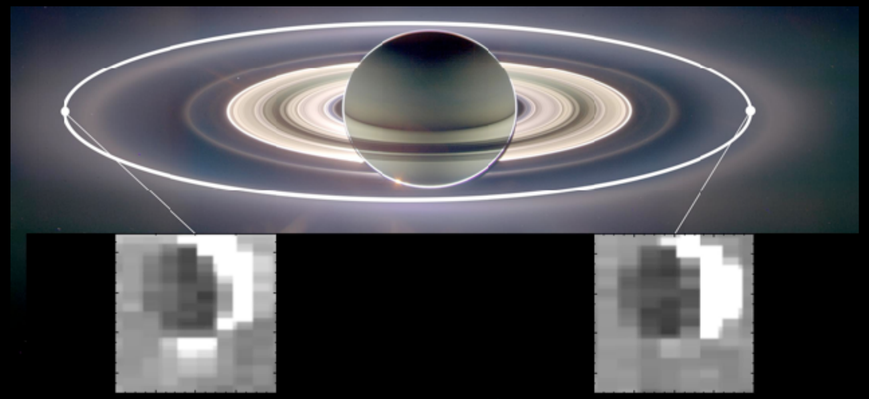
Imposed bottom heat flux

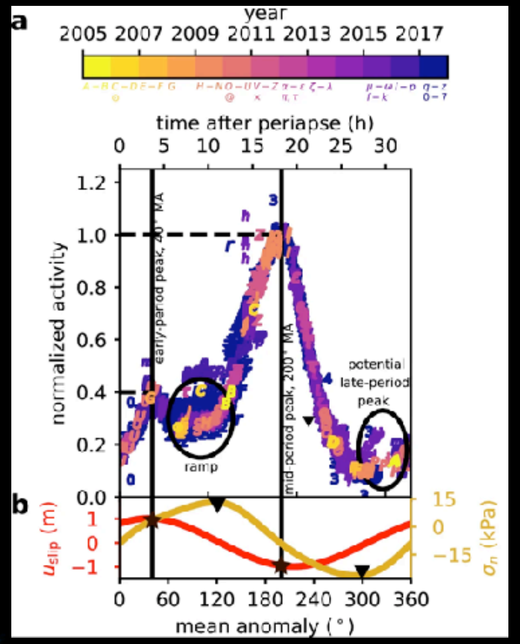


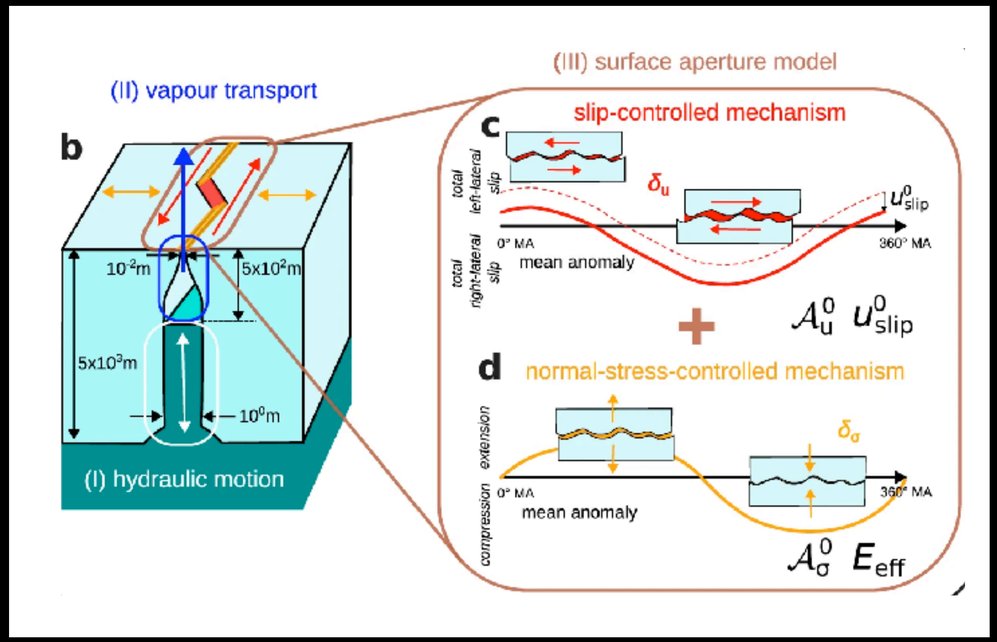
Bouffard al. (2025)

Tidally-induced variability of plume activity on Enceladus

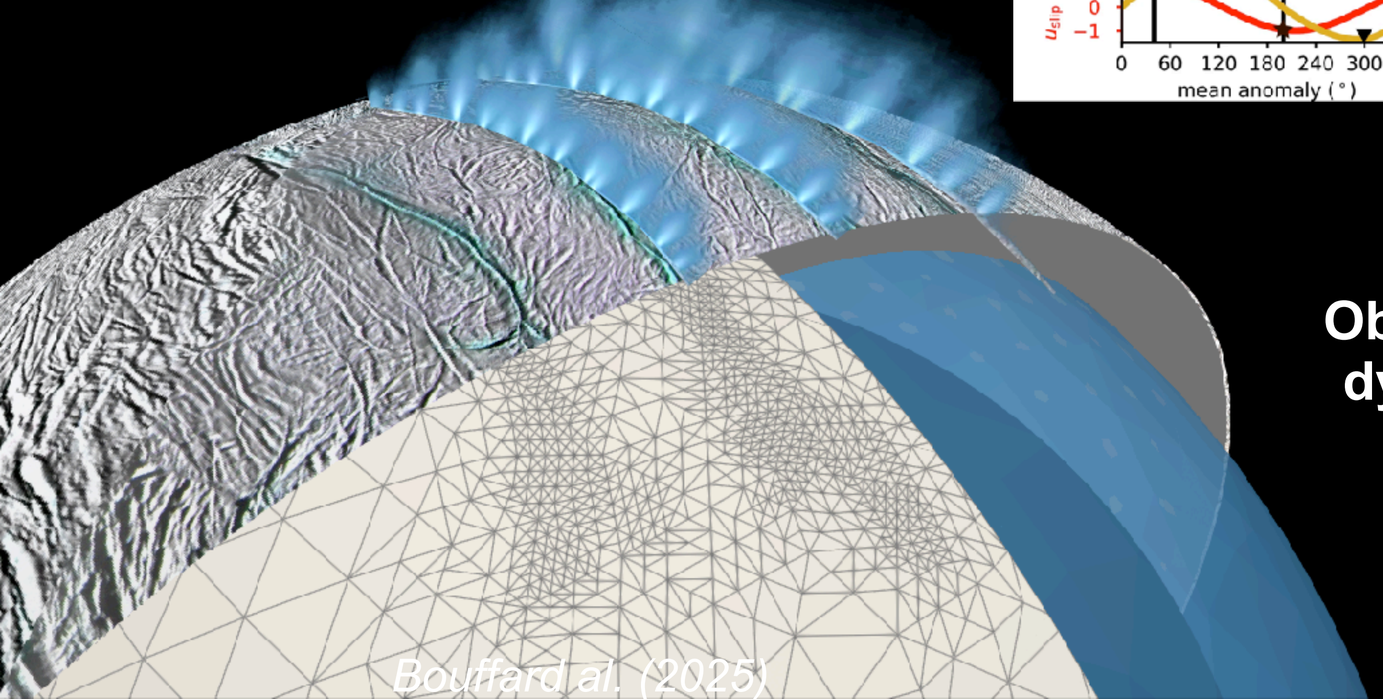
Variations of plume activity depending on Enceladus' position on its orbit







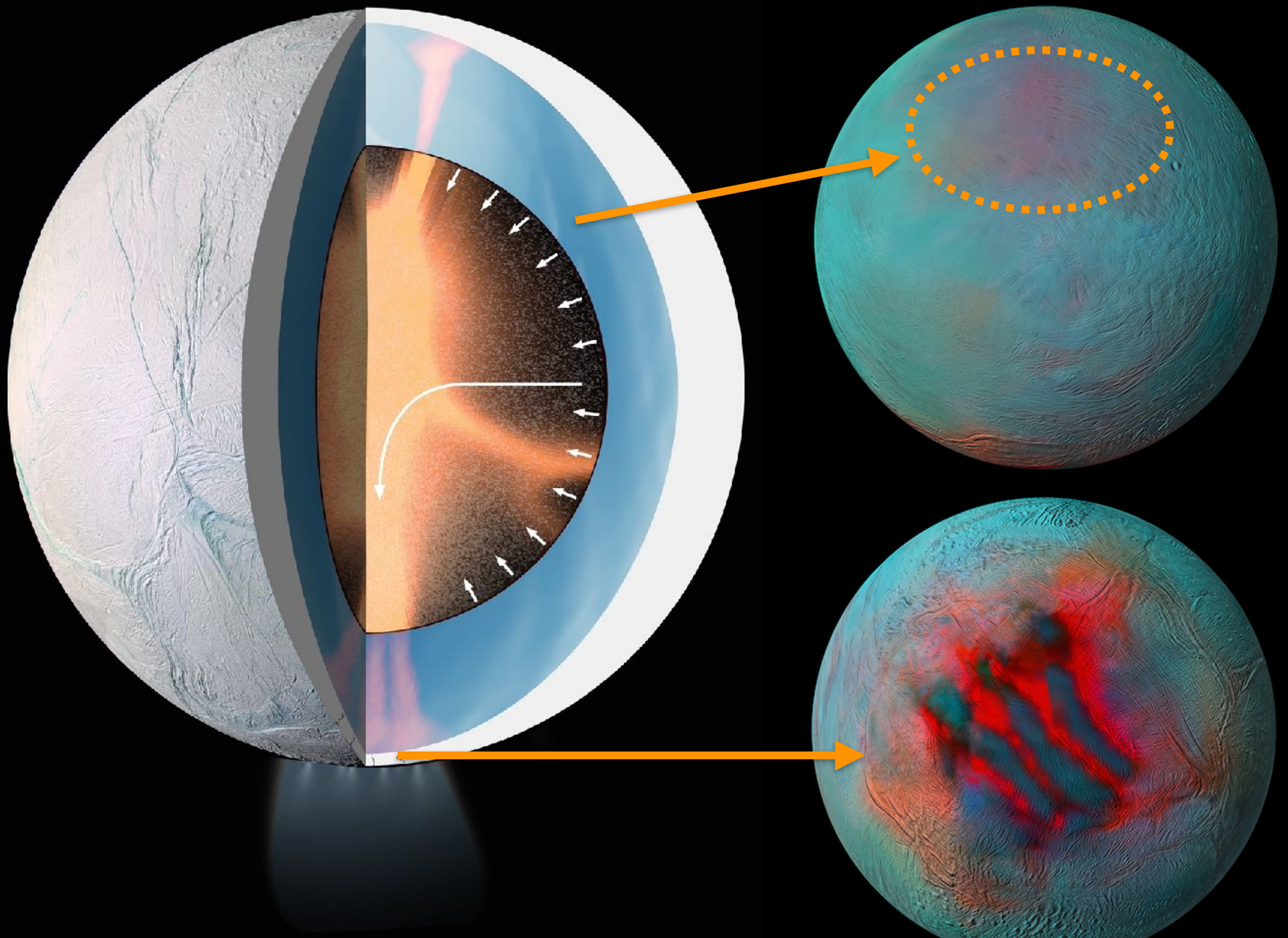
Soucek et al. (2024)



Bouffard al. (2025)

Observed plume variability explained by the dynamics of water-filled faults, involding a porous flow component for the vapour transport

Surface signatures of internal activity and plume deposits

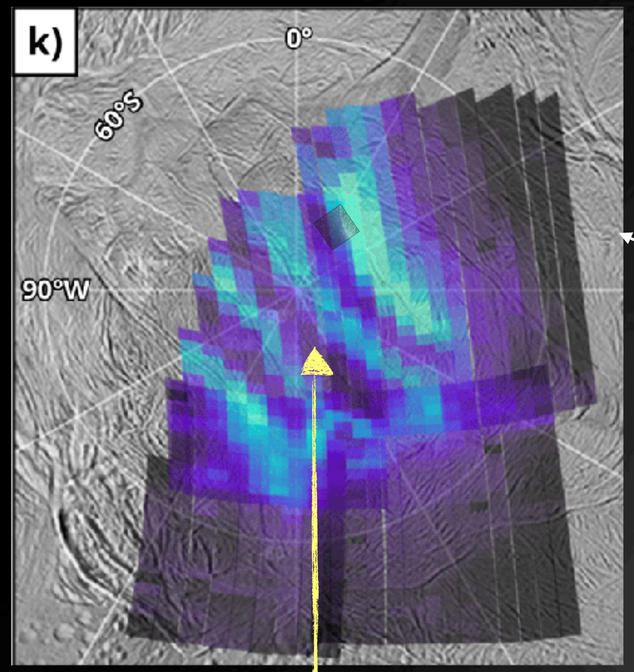


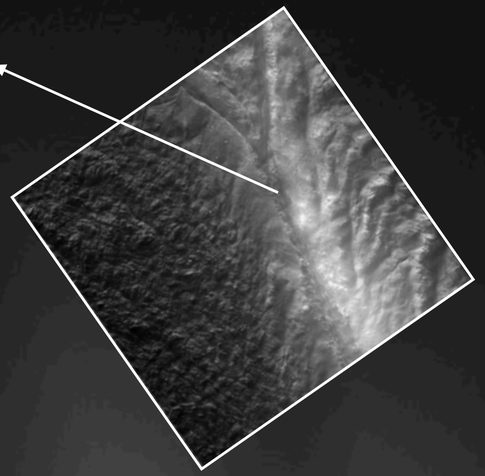
Evidence of past activity in the northern hemisphere

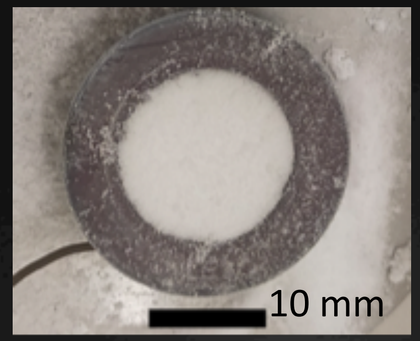
Infrared spectral observations revealed the presence of freshly deposited ice, likely porous over the south polar terrain

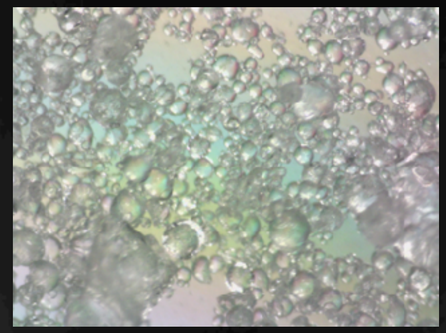
Robidel al. (2020)

Mechanical properties of porous plume deposits for future landing missions







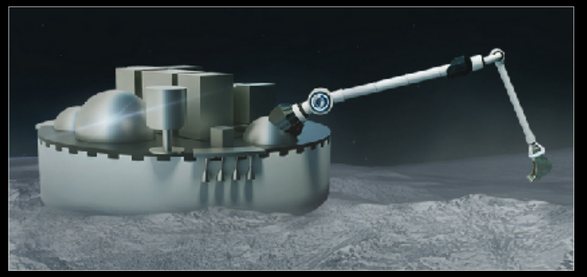


LPG

Experimental work to determine the link between spectral and mechanical properties of analogue ice samples

Porous, poorly-consolidated ice samples containing small fraction of salts and organics

Project of Landing mission to Enceladus (2050's)



esa

Porous media as drivers for exchange processes in icy worlds

What mechanisms can fuel the hydrothermal activity and explain the eruptions of water and ice observed on Enceladus?

Are there ongoing hydrothermal activities on Europa's seafloor ?

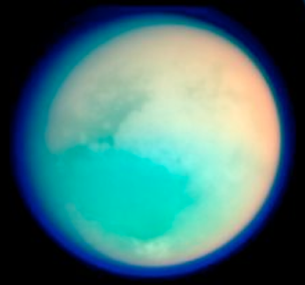
Europa

Enceladus

Callisto

What processes control the exchange between the ocean and the surface ?

Why Callisto is much less differentiated and active than Ganymede ?



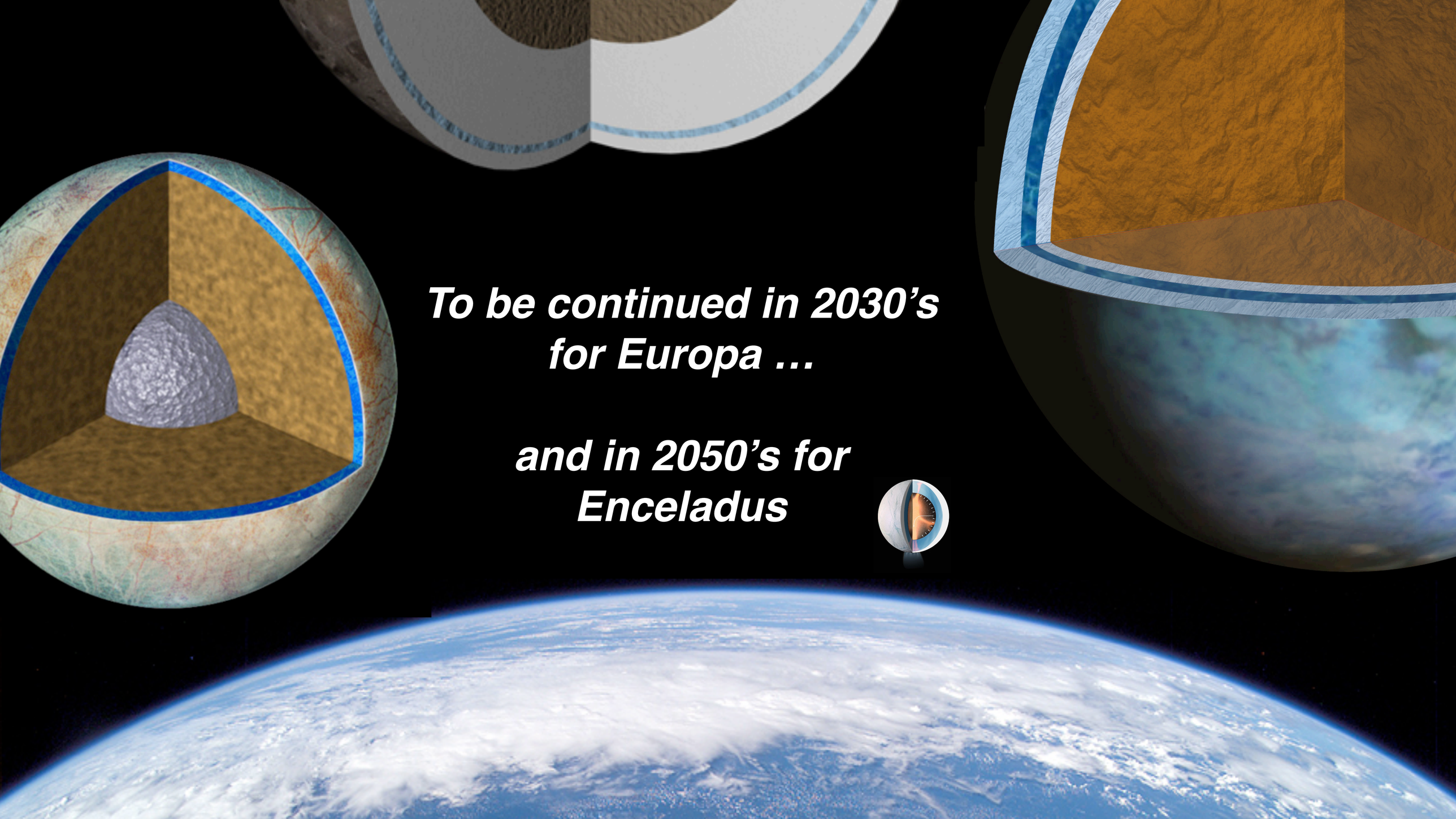
Titan

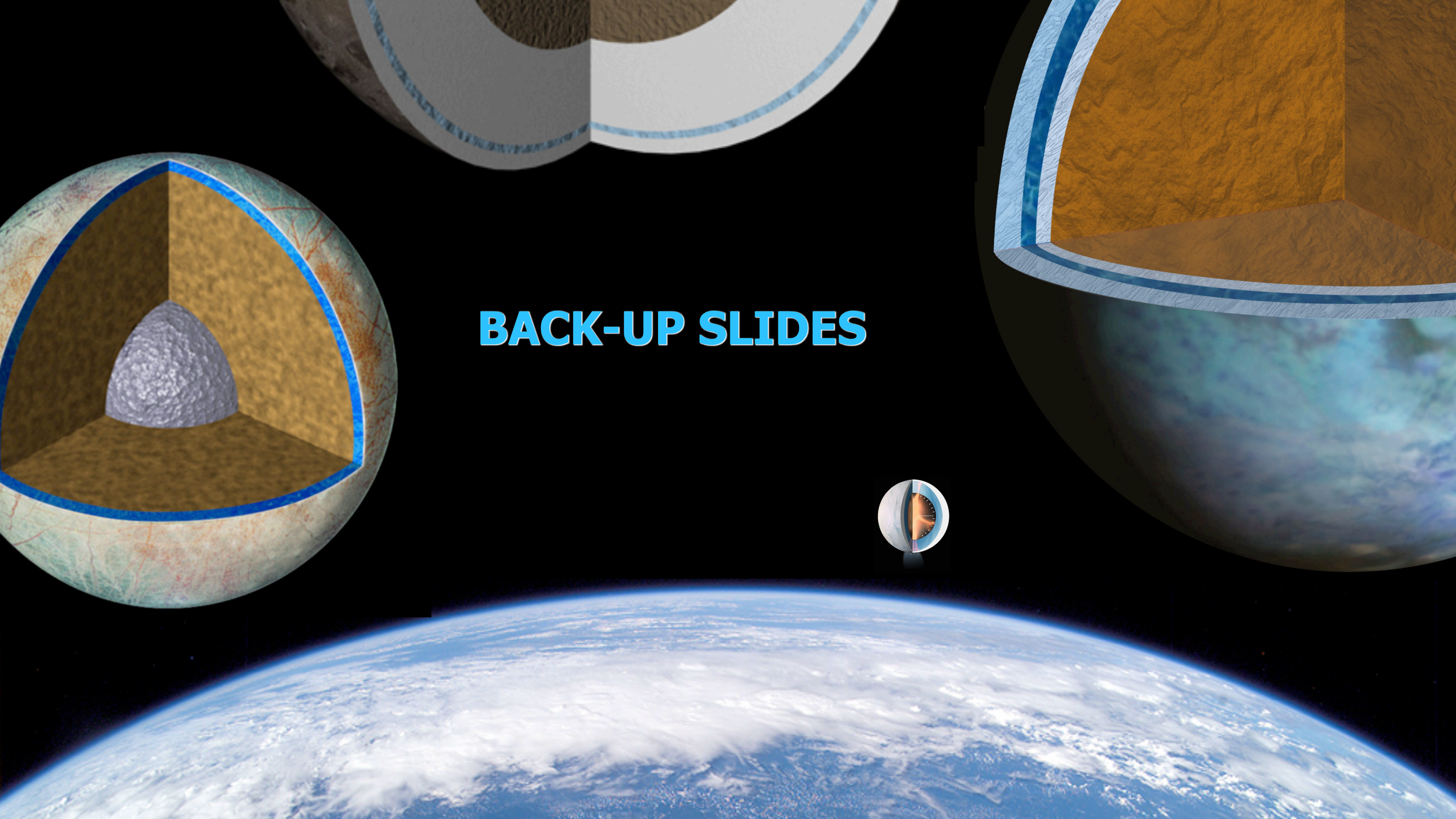
Ganymede

What control the methane cycle on Titan ?

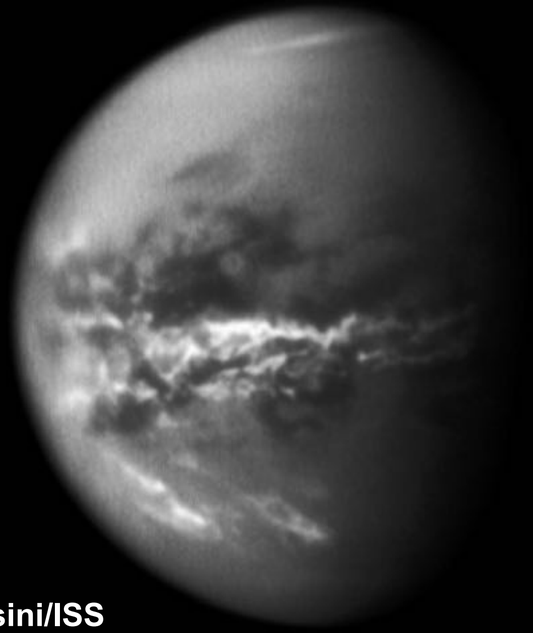
Triton

How a metallic core was formed on Ganymede ?


To be continued in 2030's
for Europa …
and in 2050's for
Enceladus


BACK-UP SLIDES

TITAN : a moon with an active methane cycle comparable to the water cycle on Earth



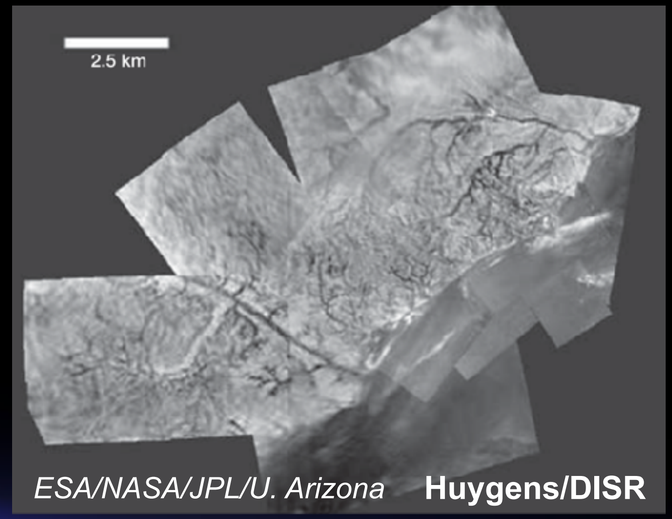
Methane clouds

Cassini/ISS

NASA/JPL/SSI

Interaction between surface liquids and porous regolith ?

River networks near the Huygens landing site



ESA/NASA/JPL/U. Arizona **Huygens/DISR**

Tomasko et al. (2005)

Cassini-Huygens
2004-2017

Cassini/RADAR

NASA/JPL/LPG/CNRS/U. Nantes

TITAN : a moon with an active methane cycle comparable to the water cycle on Earth

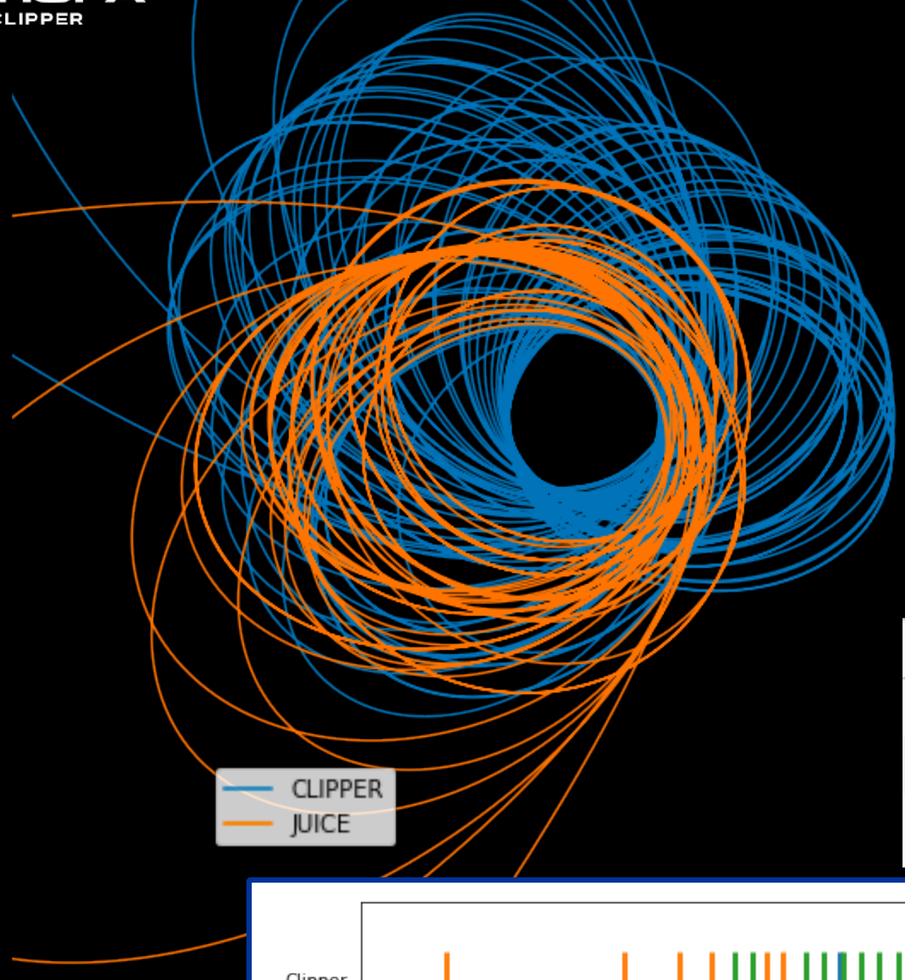
DRAGONFLY

Nasa New Frontiers Mission
Launch in 2028
Arrival in 2034

Jupiter tour phase

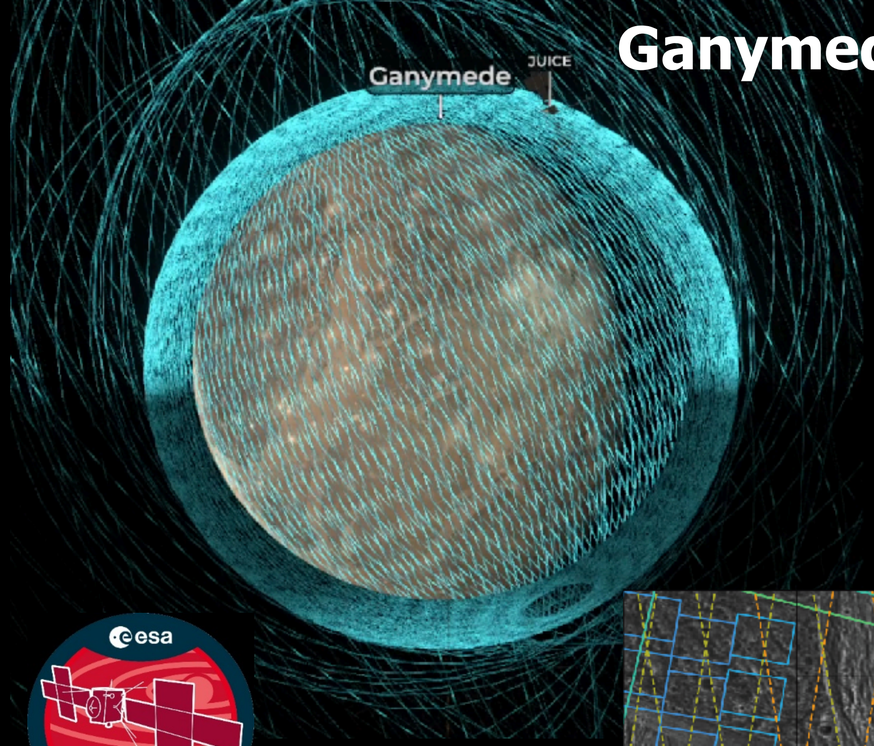
Clipper: April 2030 - July 2034

Juice: July 31- Dec 2034



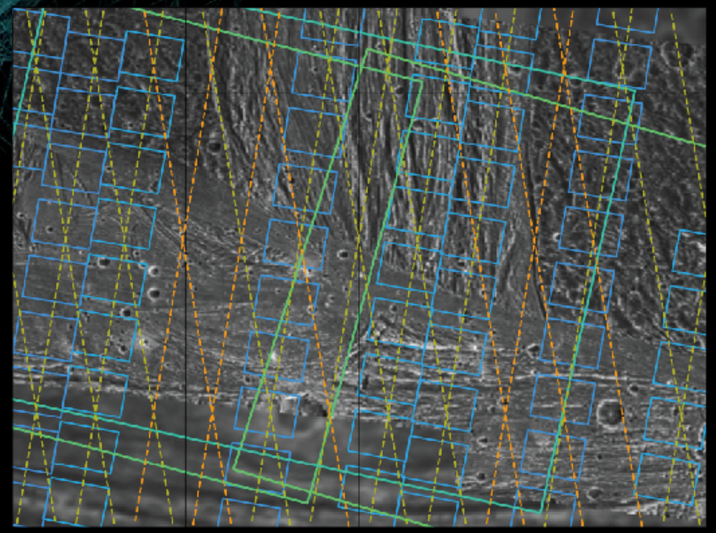
Ganymede orbital phase

Dec 2034 - Sep 2035

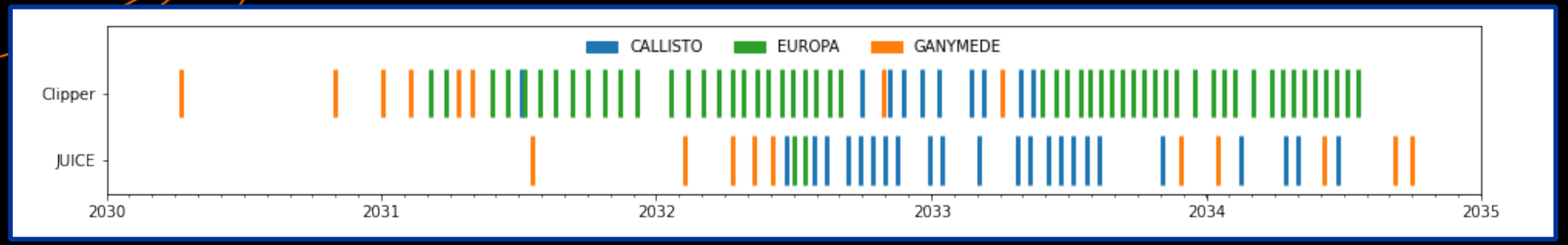


Geophysics campaign (GCO500-200)

May - Sep 2035

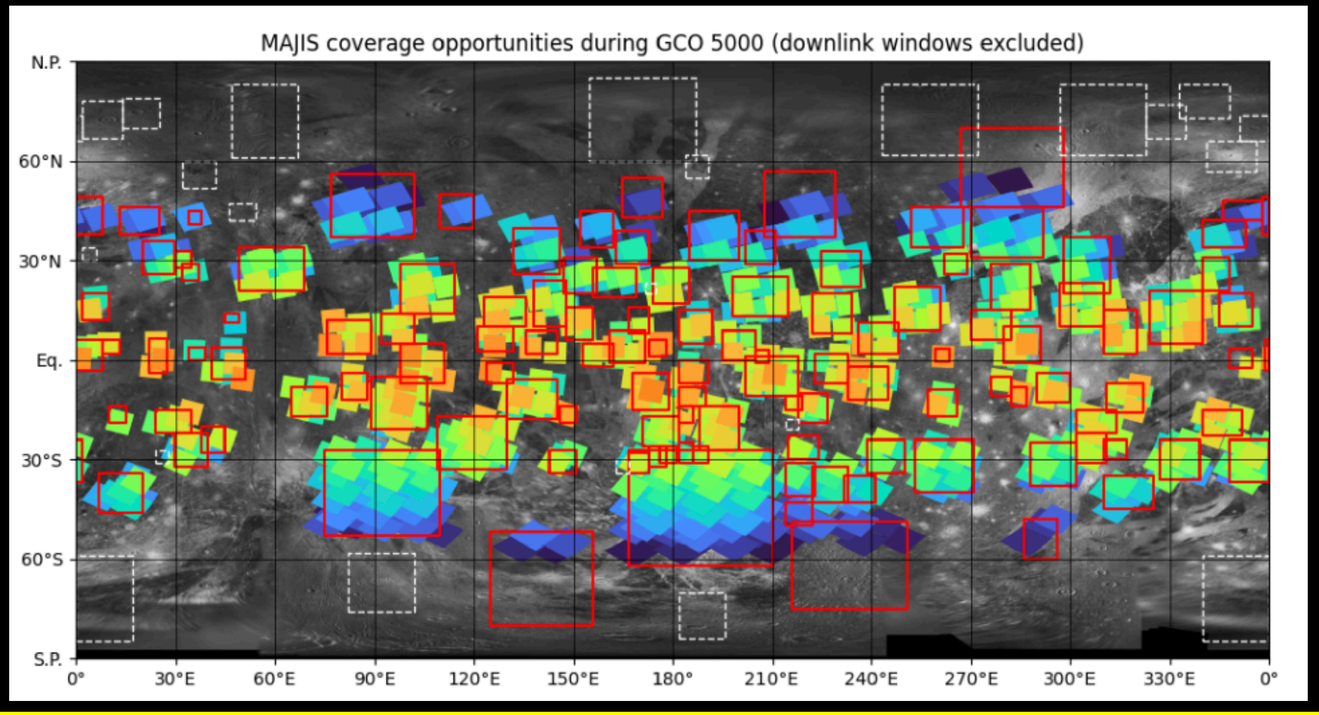


Target	JUICE	Clipper
Callisto	24	10
Europa	2	53
Ganymede	10	8



Surface composition and exchange processes at Ganymede

What are the surface chemical compounds ?

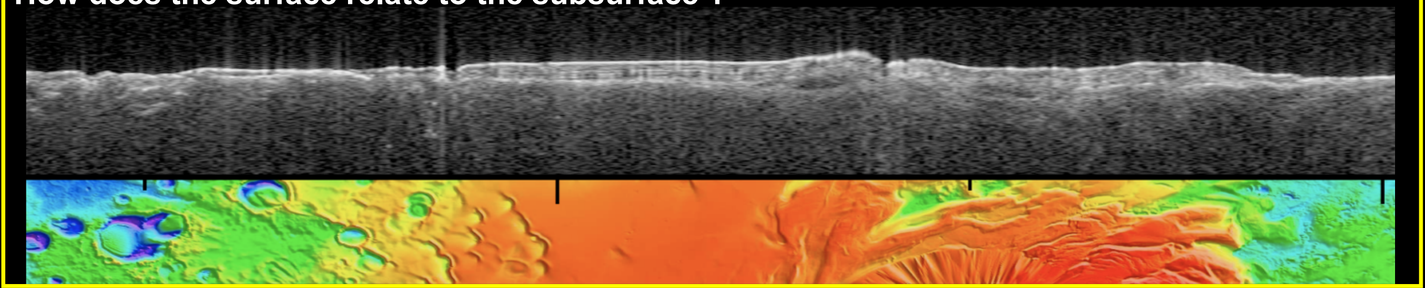


Exogeneous / endogeneous ?

Volatiles

Ions and Neutrals

How does the surface relate to the subsurface ?



Instrument Packages

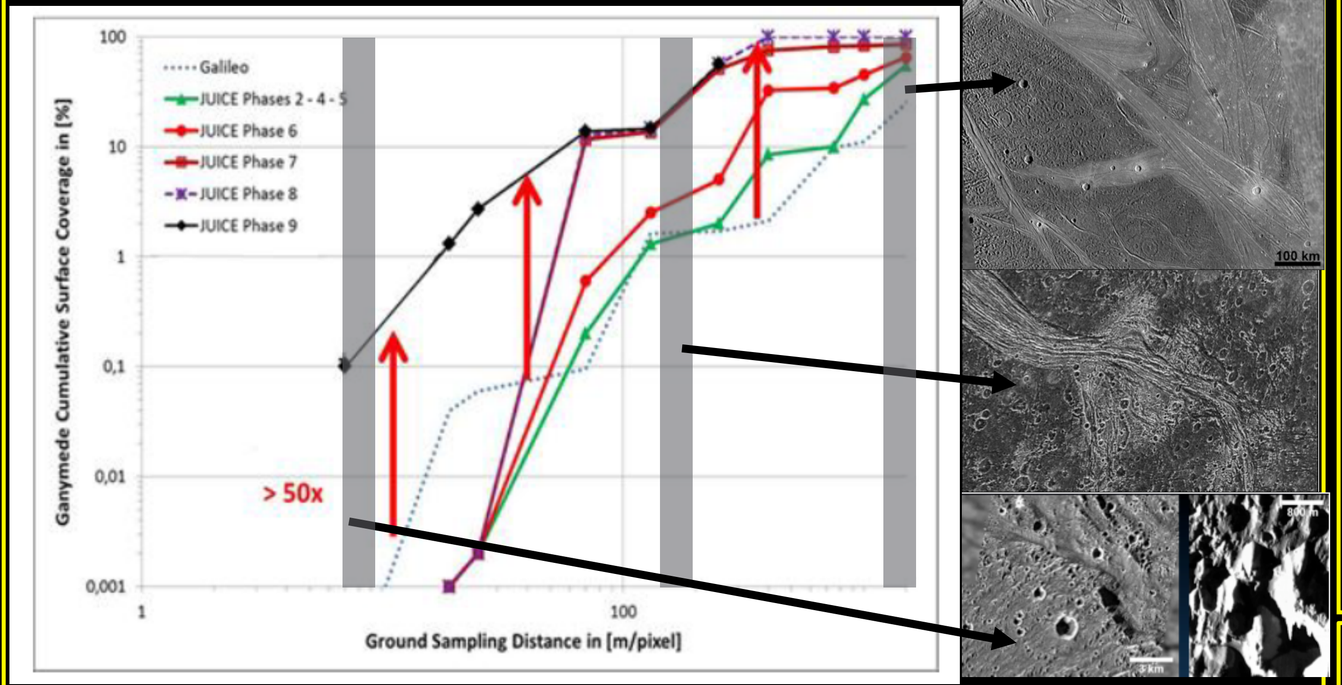
- Spectroscopy
- Imaging
- In situ
- Radar sounder

Icy shell dynamics and exchange processes at Ganymede

Topo-gravi relationship and correlation with main geological and compositional units.

Determination of subsurface structure underneath tectonic and cryovolcanic features.

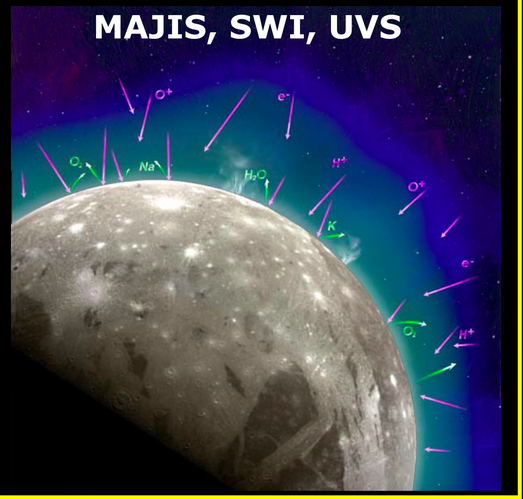
Surface mapping : **JANUS**



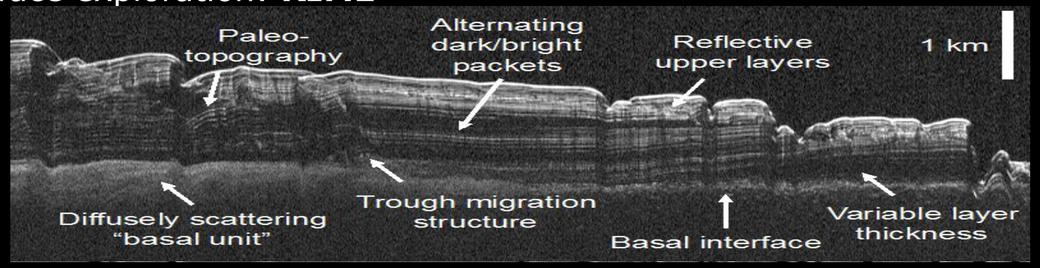
Exogeneous contribution to surface properties

JMAG, RPWI, PEP

MAJIS, SWI, UVS



Subsurface exploration: **RIME**



Surface topography

GALA JANUS