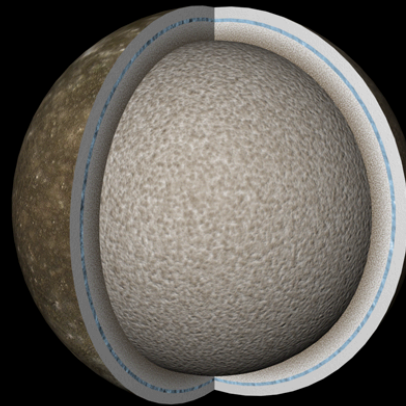
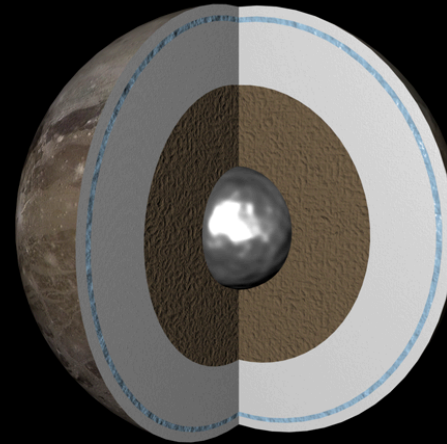


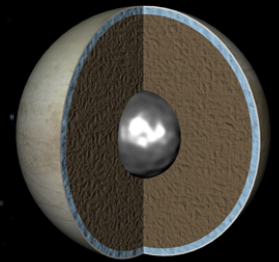
Characterizing Ganymede and the other icy moons with the ESA JUICE mission



Callisto



Ganymede



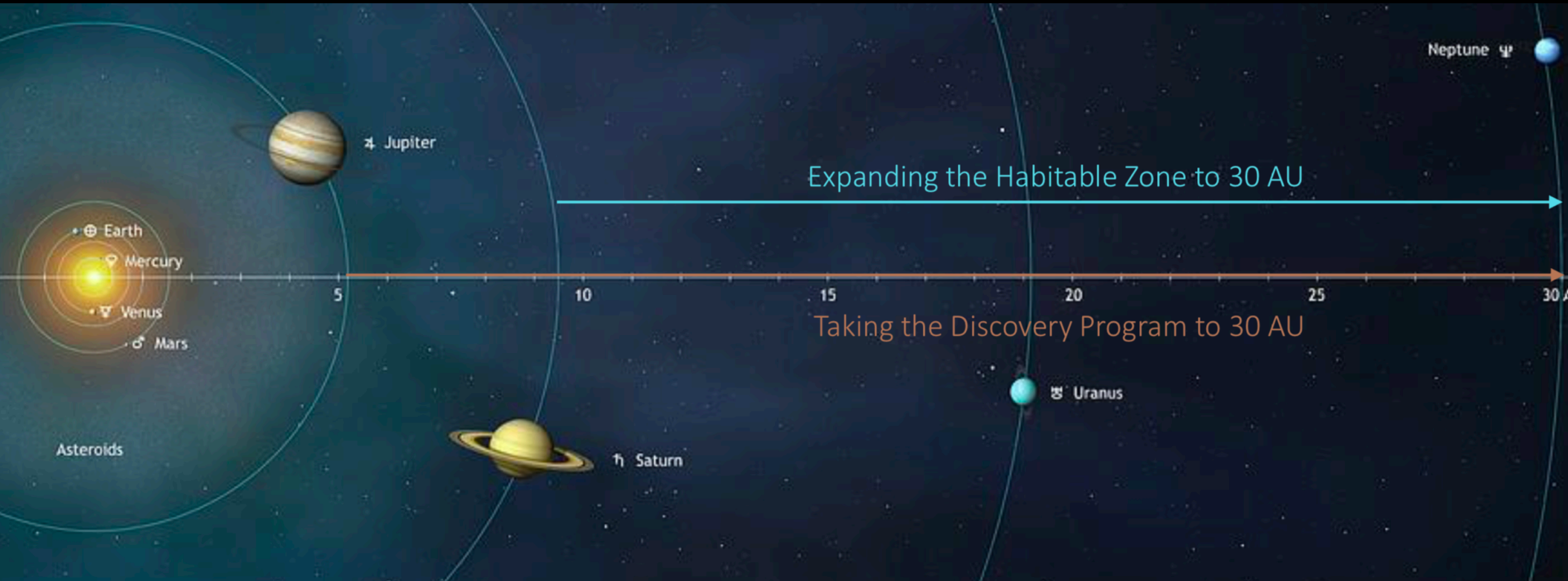
Europa

Gabriel TOBIE

*Laboratoire de Planétologie et Géosciences,
CNRS/ Université de Nantes*



The diversity of icy worlds in the Solar System

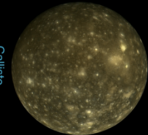
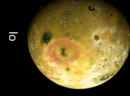


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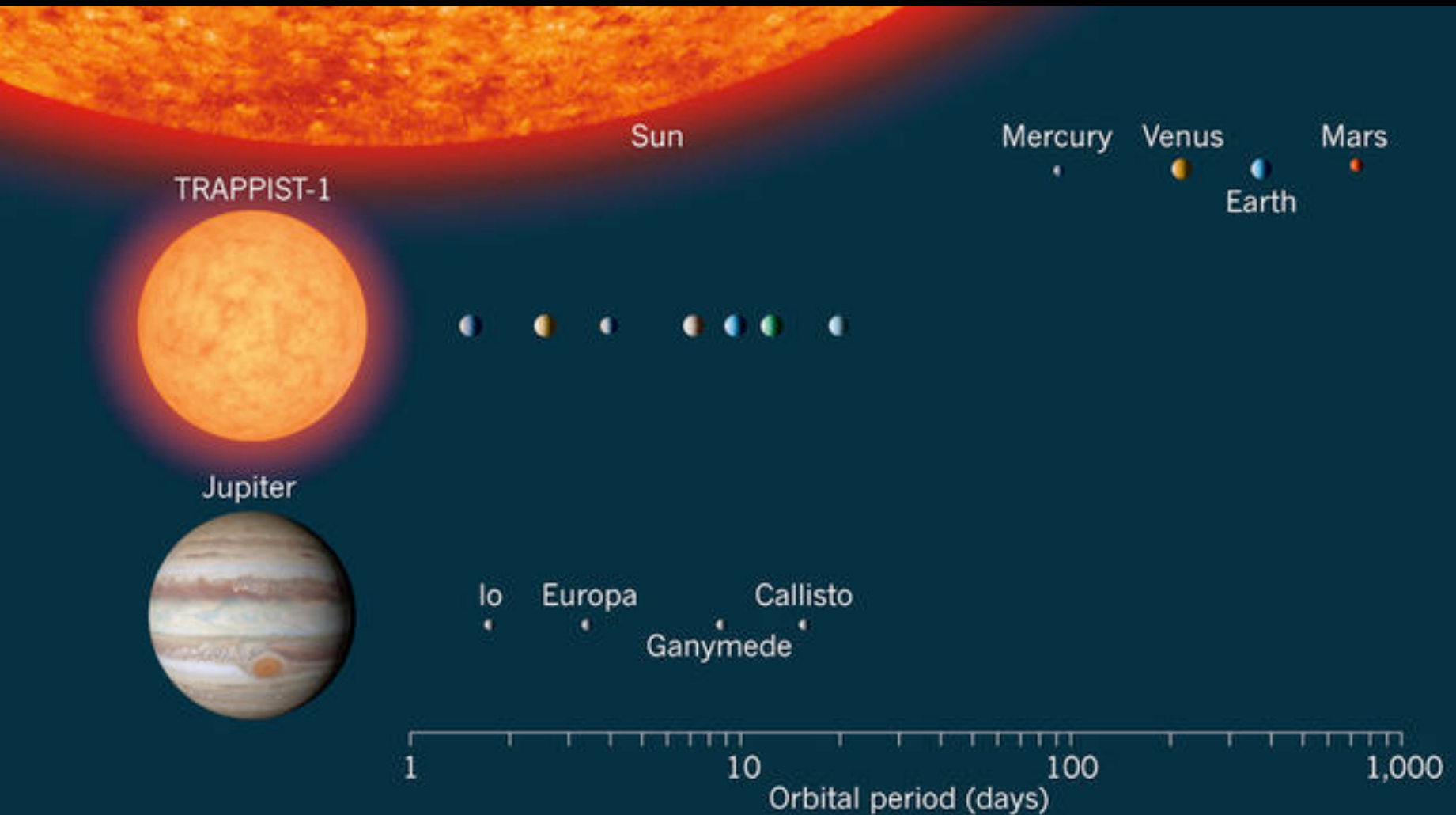
NEPTUNE



PLUTO
CHARON



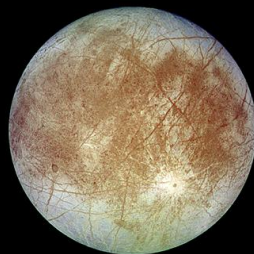
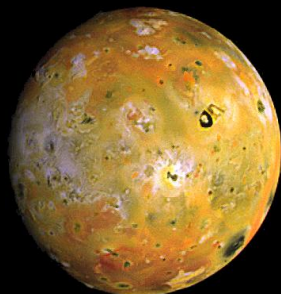
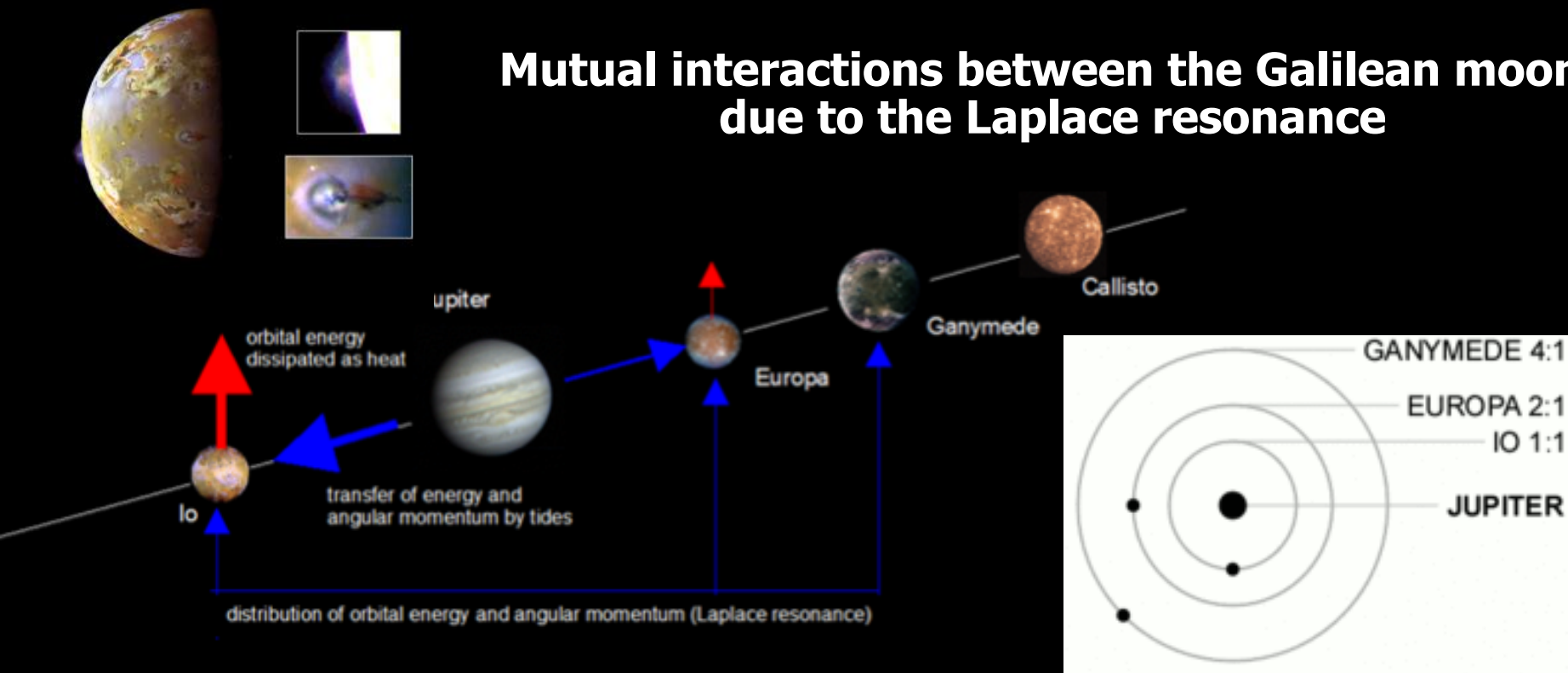
Jupiter's system as a mini-planetary system



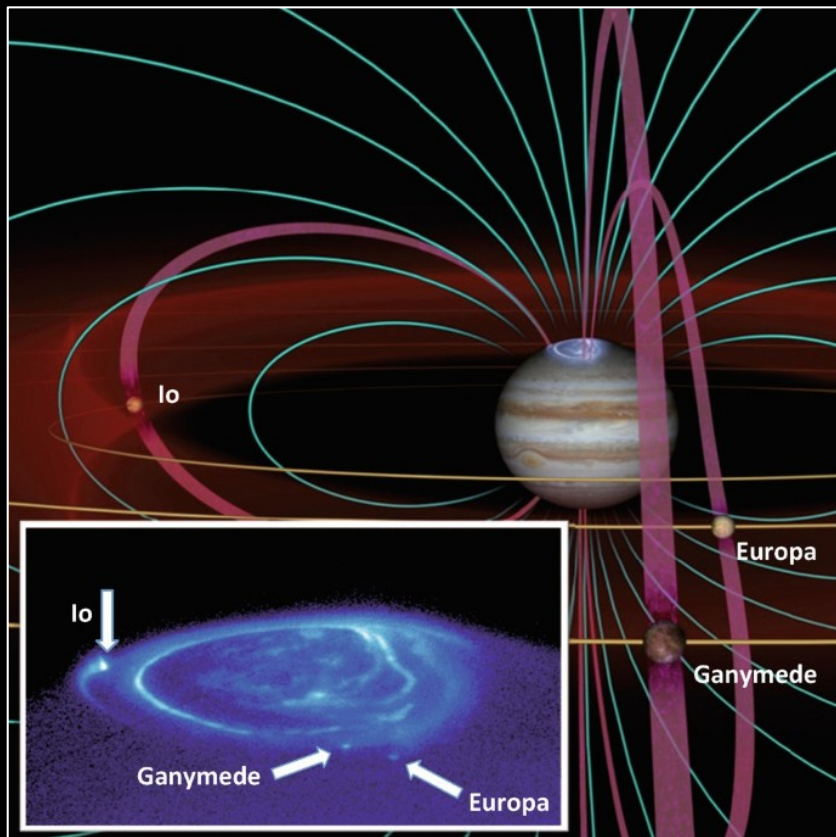
Clues on how planetary systems (including ours) may form and evolve

Jupiter's system : a strongly coupled system

Mutual interactions between the Galilean moons due to the Laplace resonance

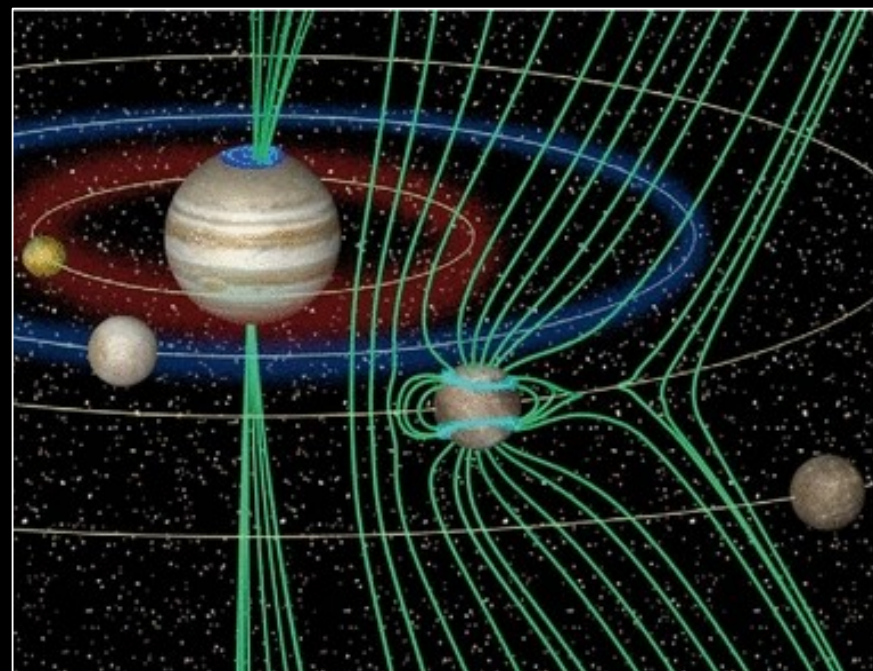
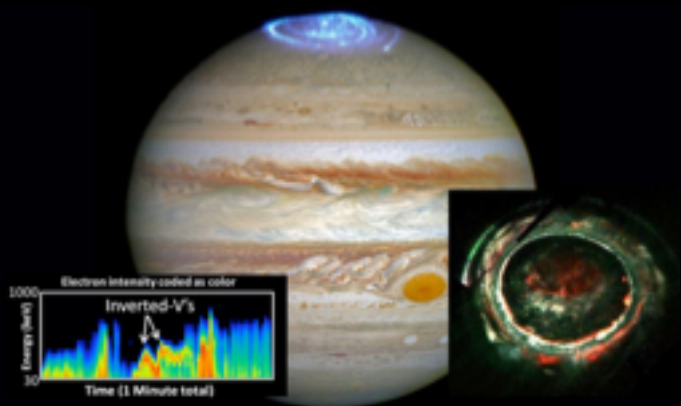


Jupiter's system : a strongly coupled system



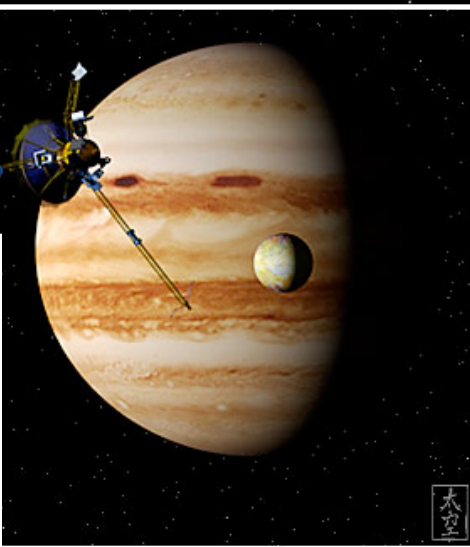
**Strong interactions between
Jupiter magnetic
environnements
and the Galilean moons**

**Two interacting magnetospheres
to explore**



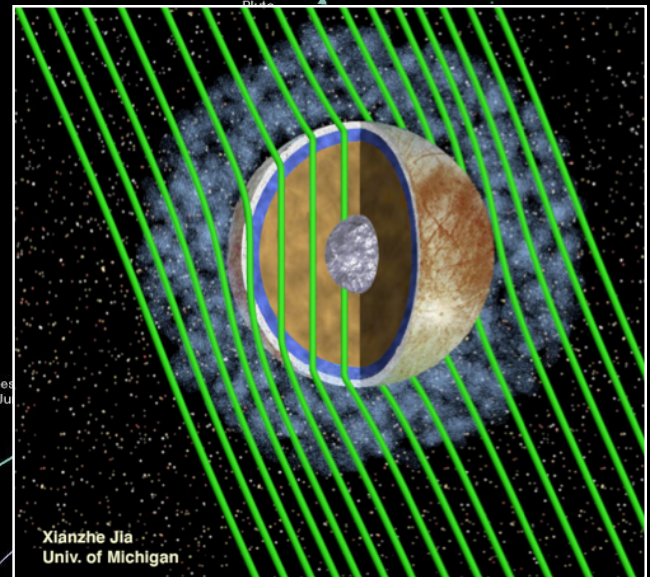
Subsurface oceans possibly habitables

NASA Galileo
1995-2003



JUPITER
9 missions

Discovers
additional
Saturn ring



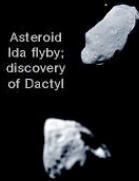
Passed
orbit Ju

Xiánzhe Jia
Univ. of Michigan

NEAR Shoemaker
becomes first probe
to orbit and touch
down on an
asteroid, 443 Eros,
February 12, 2001.



Asteroid
Ida flyby;
discovery
of Dactyl



Mission
ends upon
impact
September 21,
2003



Exploration
of Jupiter's
moons

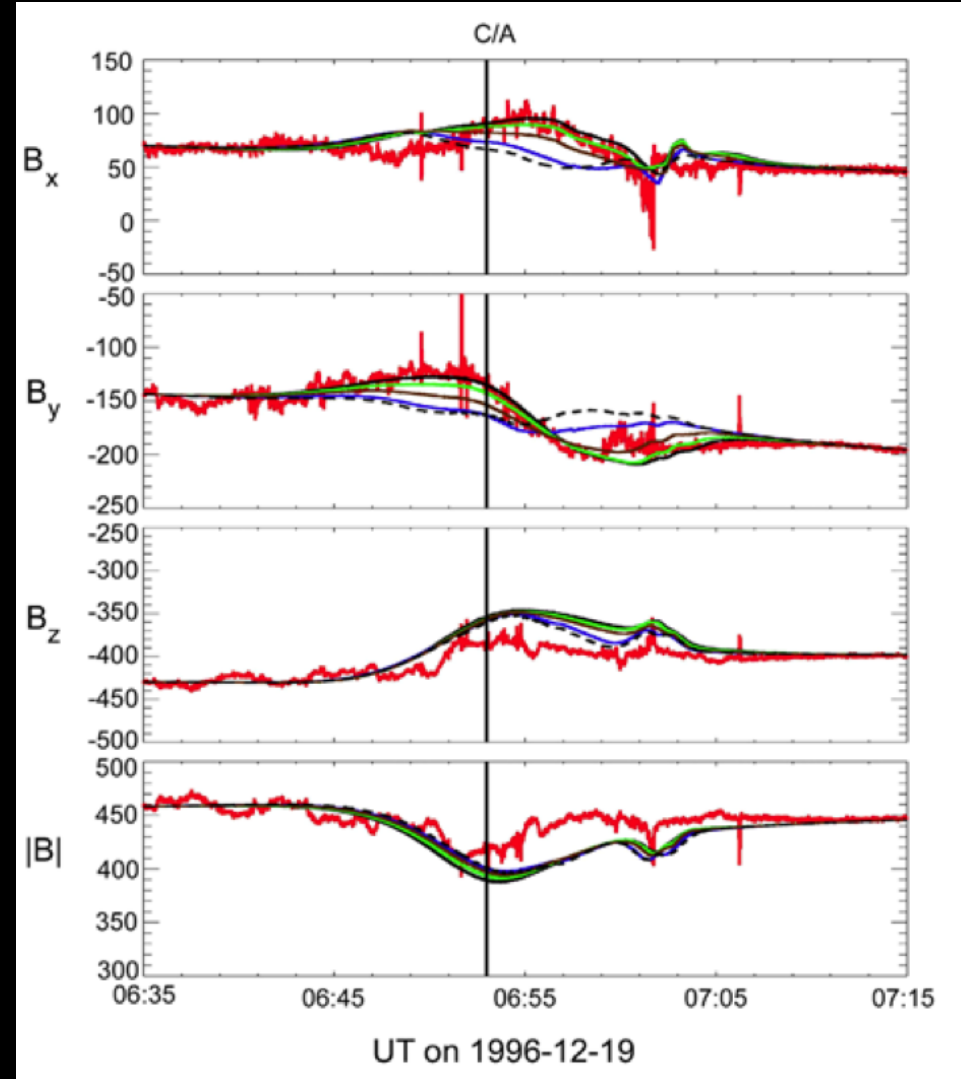
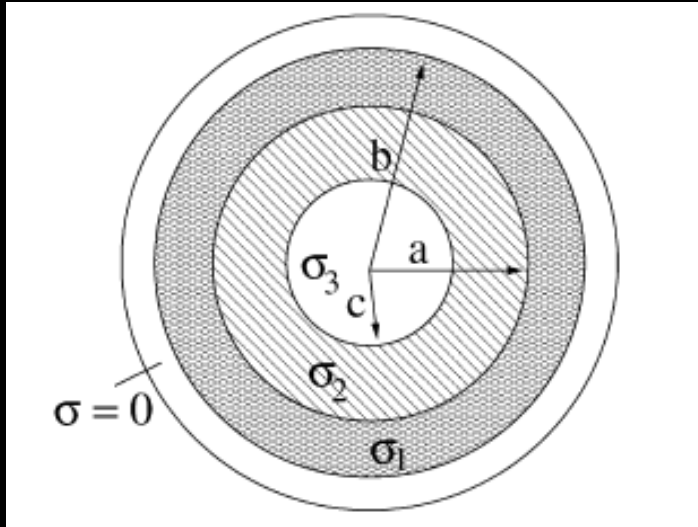


Evidence for subsurface oceans and salt-rich deposits on Europa's surface

NEW HORIZONS: Launch 1/19/06
CASSINI: Launch 10/15/97
GALILEO: Launch 10/18/89

EUROPA: Geophysical evidence for an internal ocean

Europa: observation of an induced magnetic moment during close flybys (~ 120 nT)

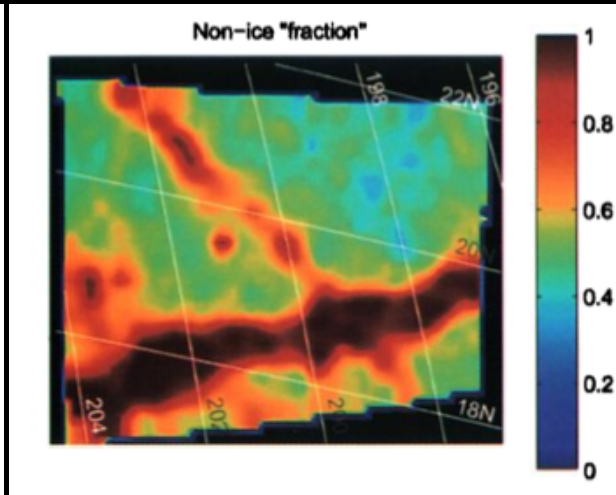
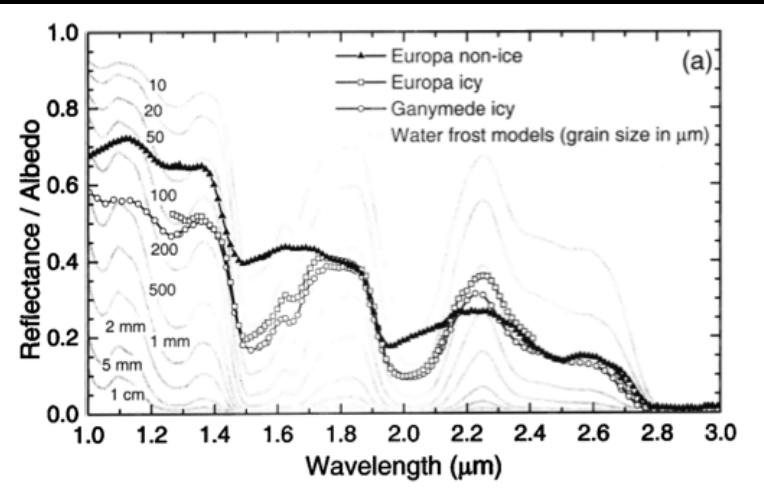


➤ Interaction of a highly electrically conductive layer in the moon's interior with the time-varying part of the Jovian magnetic field.

➤ Best candidate material: a subsurface ocean of liquid salt water. [

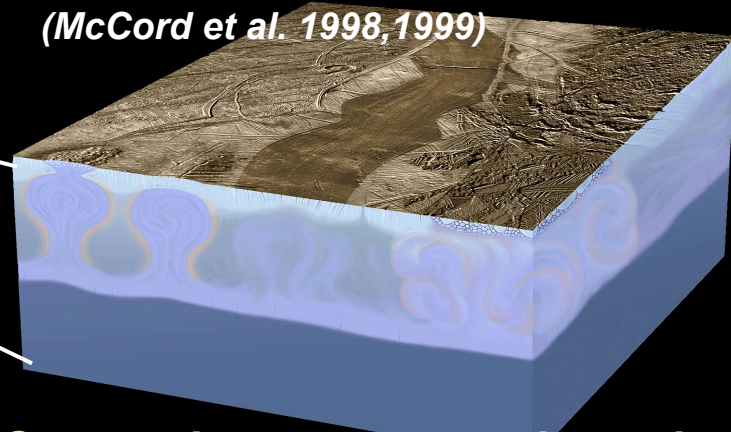
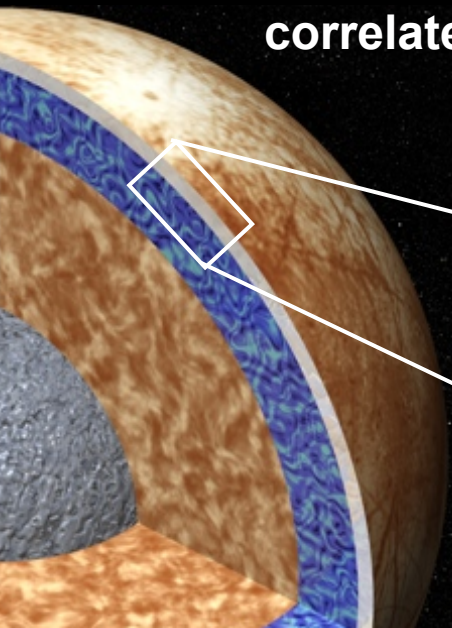
(Kivelson *et al.* 1997, Schilling *et al.* 2007)

EUROPA: Evidence for chemical exchange with a salted water ocean

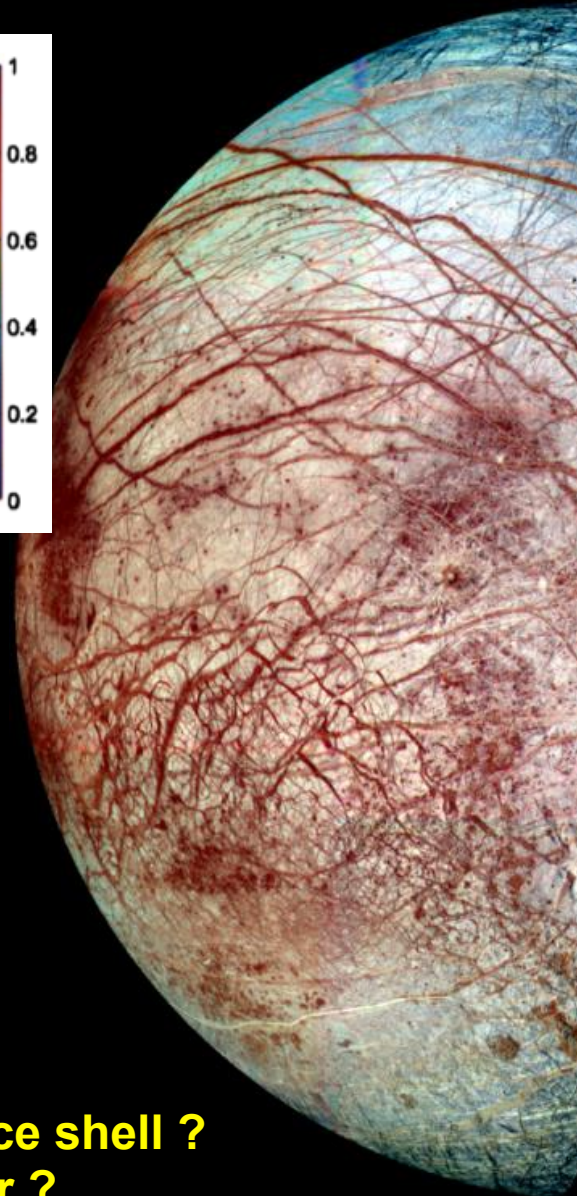


Observations of salt-rich reddish terrains correlated with tectonic and chaotic features

(McCord et al. 1998,1999)

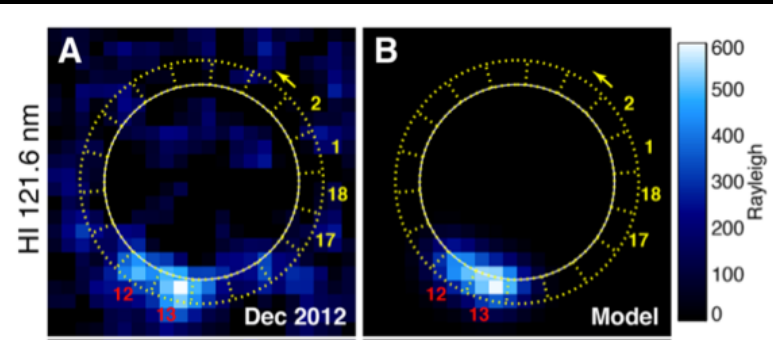


Convective processes through the ice shell ?
Eruption of salted liquid water ?

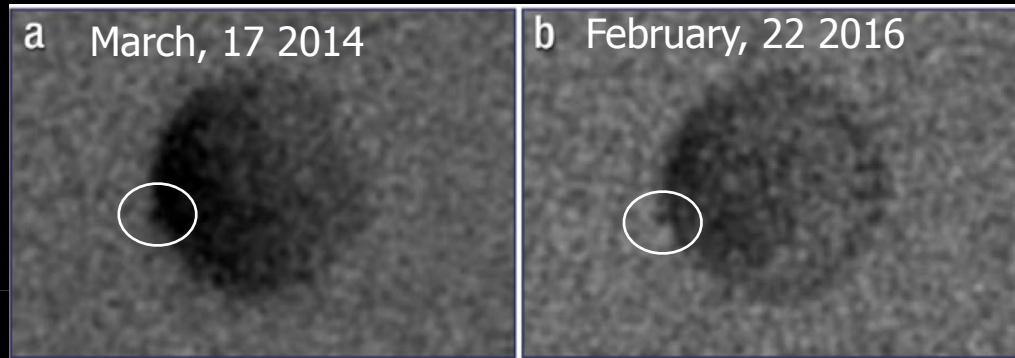


EUROPA: Evidence for active water eruption ?

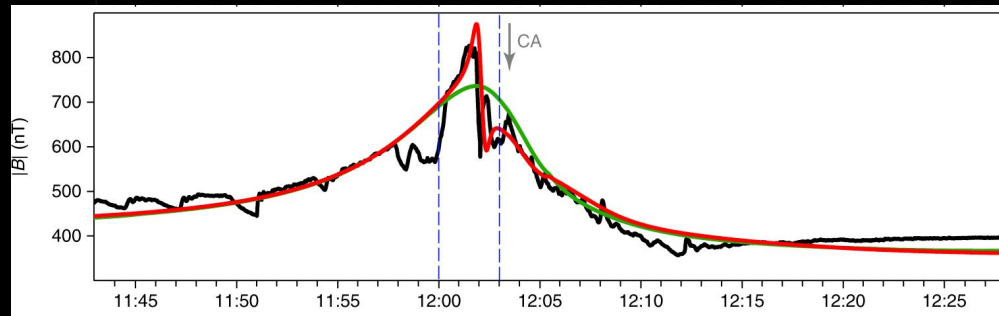
Detection of transient vapor plume above Europa from HST observations and Galileo data reprocessing



Roth et al. (2013)

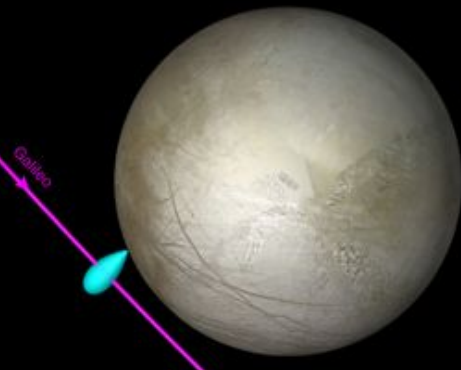


Sparks et al. (2016, 2017)

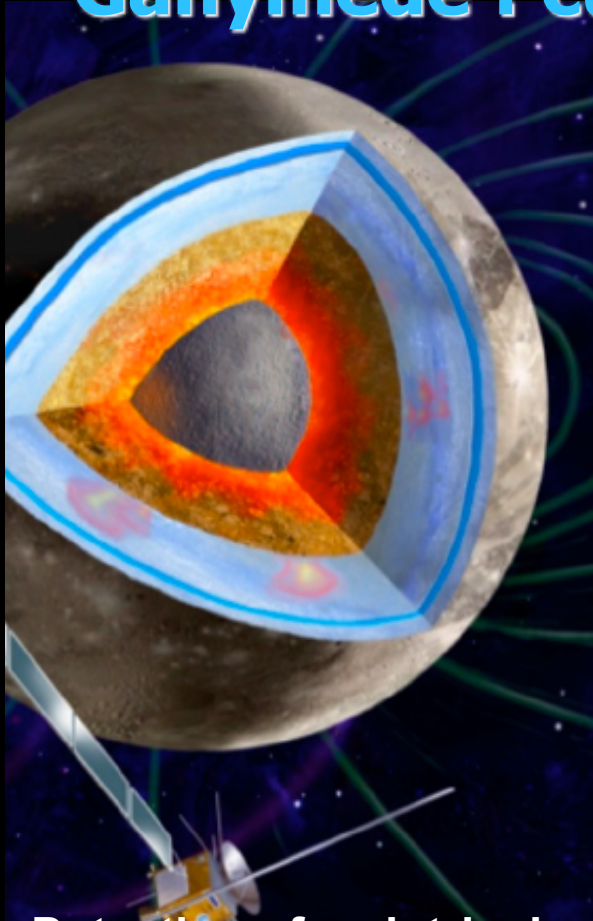


Jia et al. (2018)

Jupiter
Flow

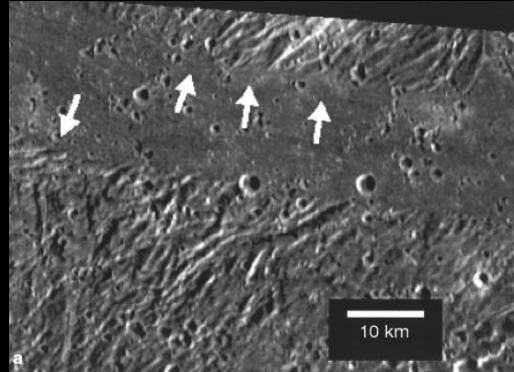


Ganymede : current and past internal activity

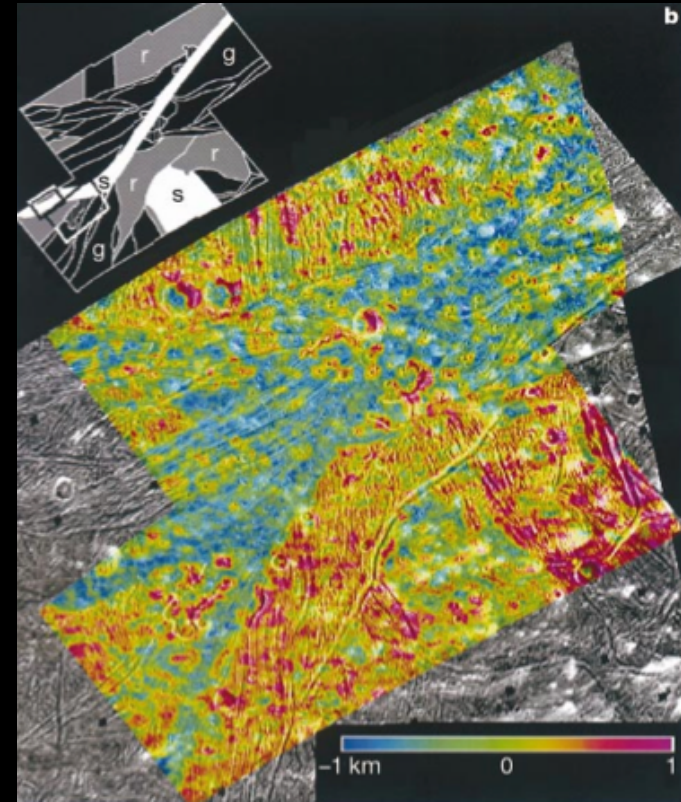


Detection of an intrinsic magnetic field indicating active dynamo in a liquid metallic core.

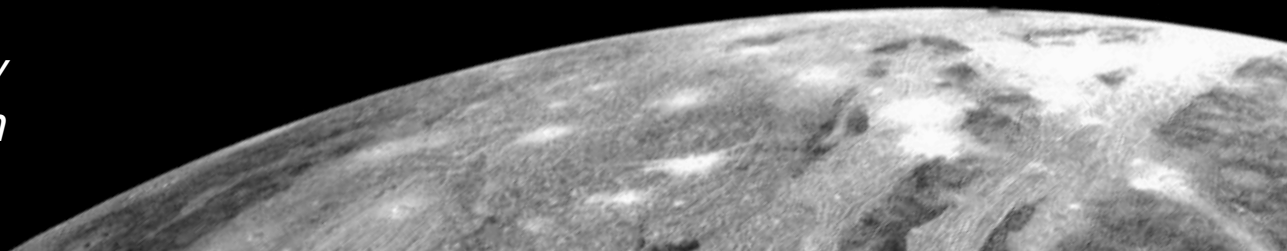
Prime target of JUpiter Icy Explorer (JUICE) mission (ESA L-class mission)



Flooding of bright terrains by low-viscosity water-ice lavas (Schenk et al. 2001)

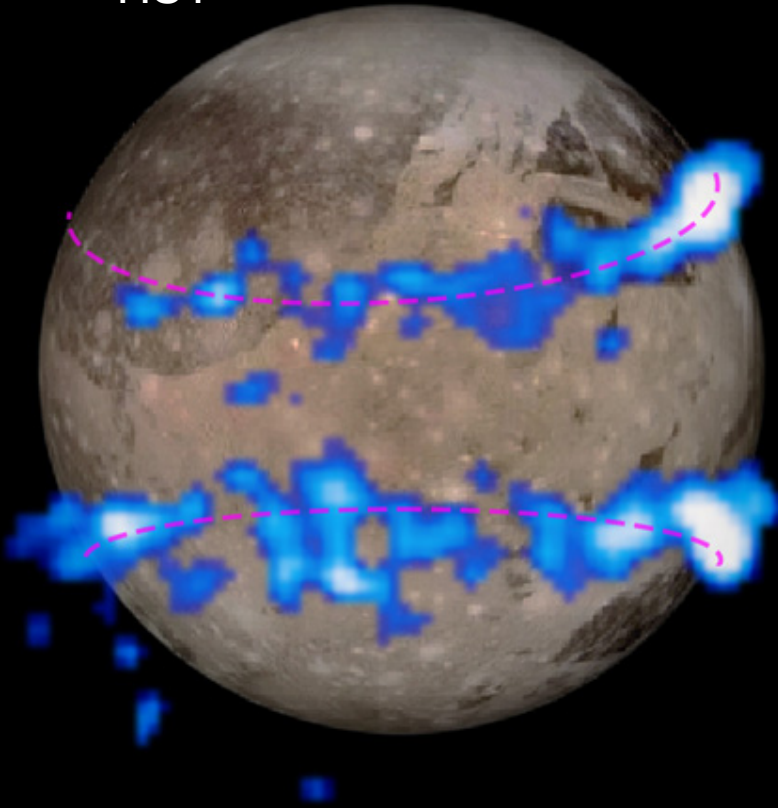


Geological evidences for past tectonic and cryovolcanic activity on Ganymede

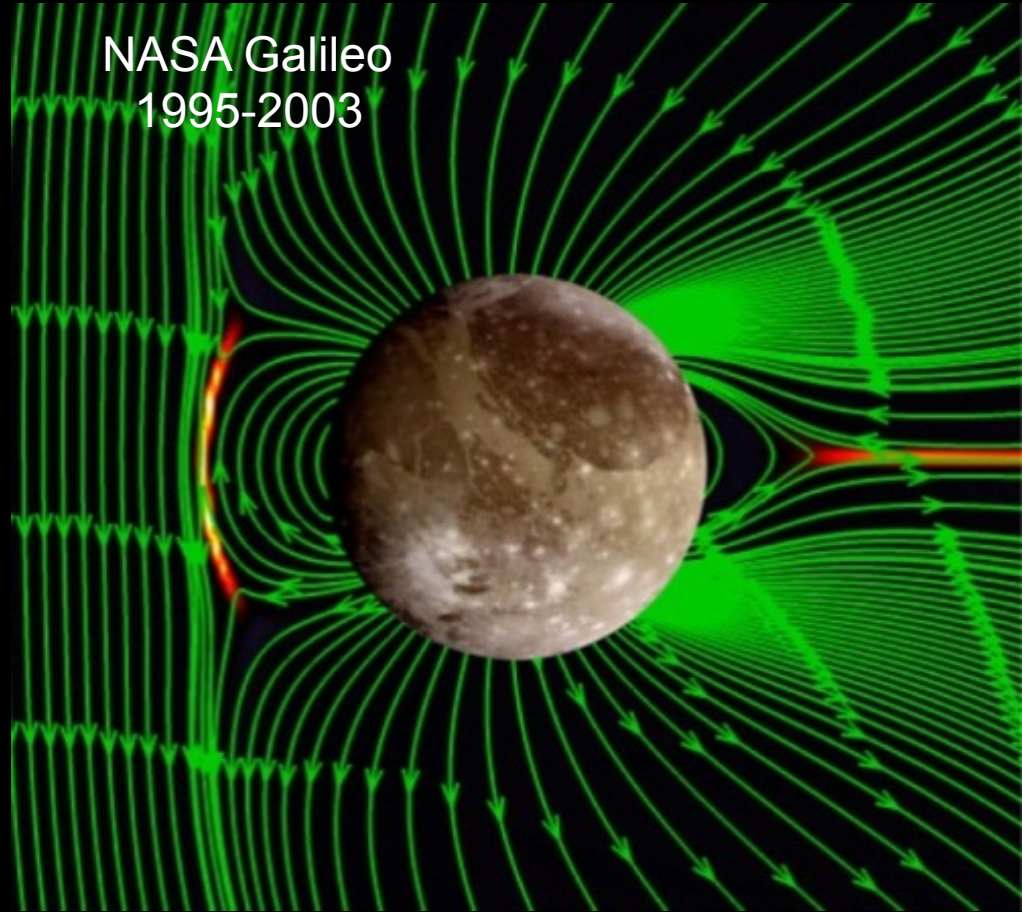


Ganymede : evidence for a subsurface ocean

HST



NASA Galileo
1995-2003



Ambiguous detection of magnetic induction due to internal magnetic field generated in the metallic core (Zimmer et al. 2000), but confirmed by HST observations of time-varying auroral ovals (Saur et al. 2015).

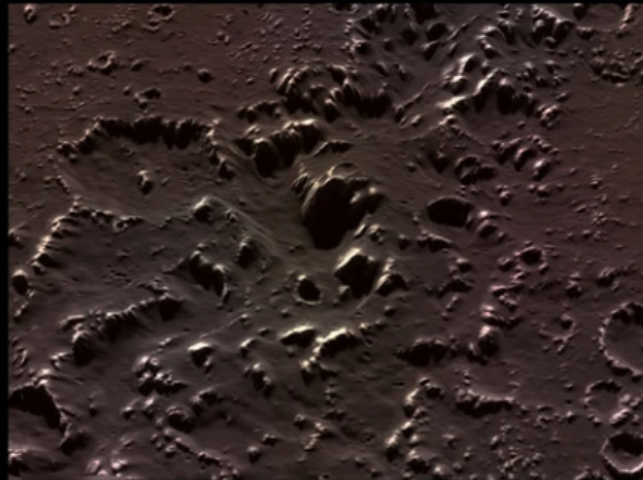
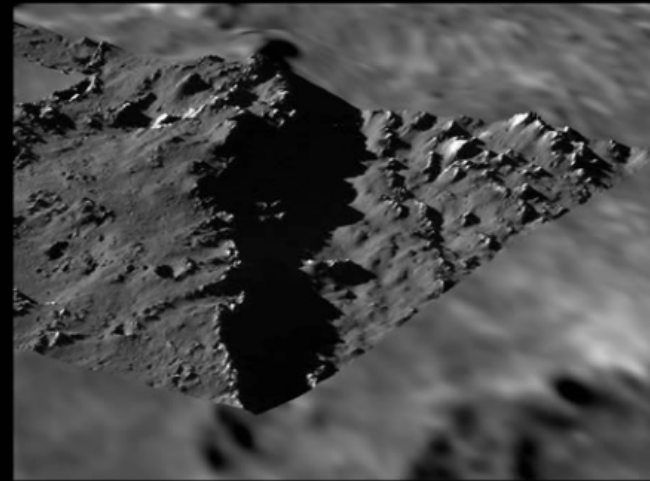
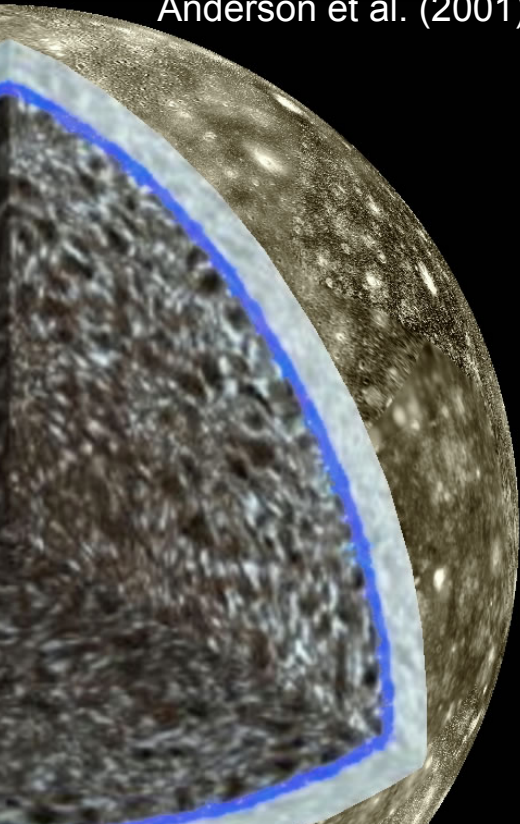
Callisto as a remnant of the early Jovian system

Possible detection of a subsurface water ocean from magnetic induction ?

Kivelson et al. (1999);
Hartkorn & Saur (2017)

Partial differentiation of the interior

Anderson et al. (2001)



Schenk (2010)

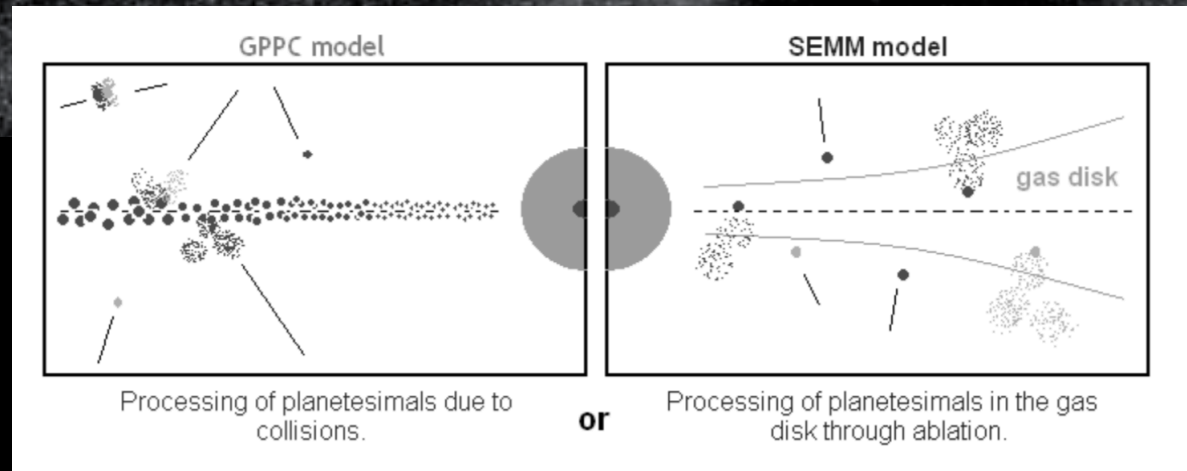
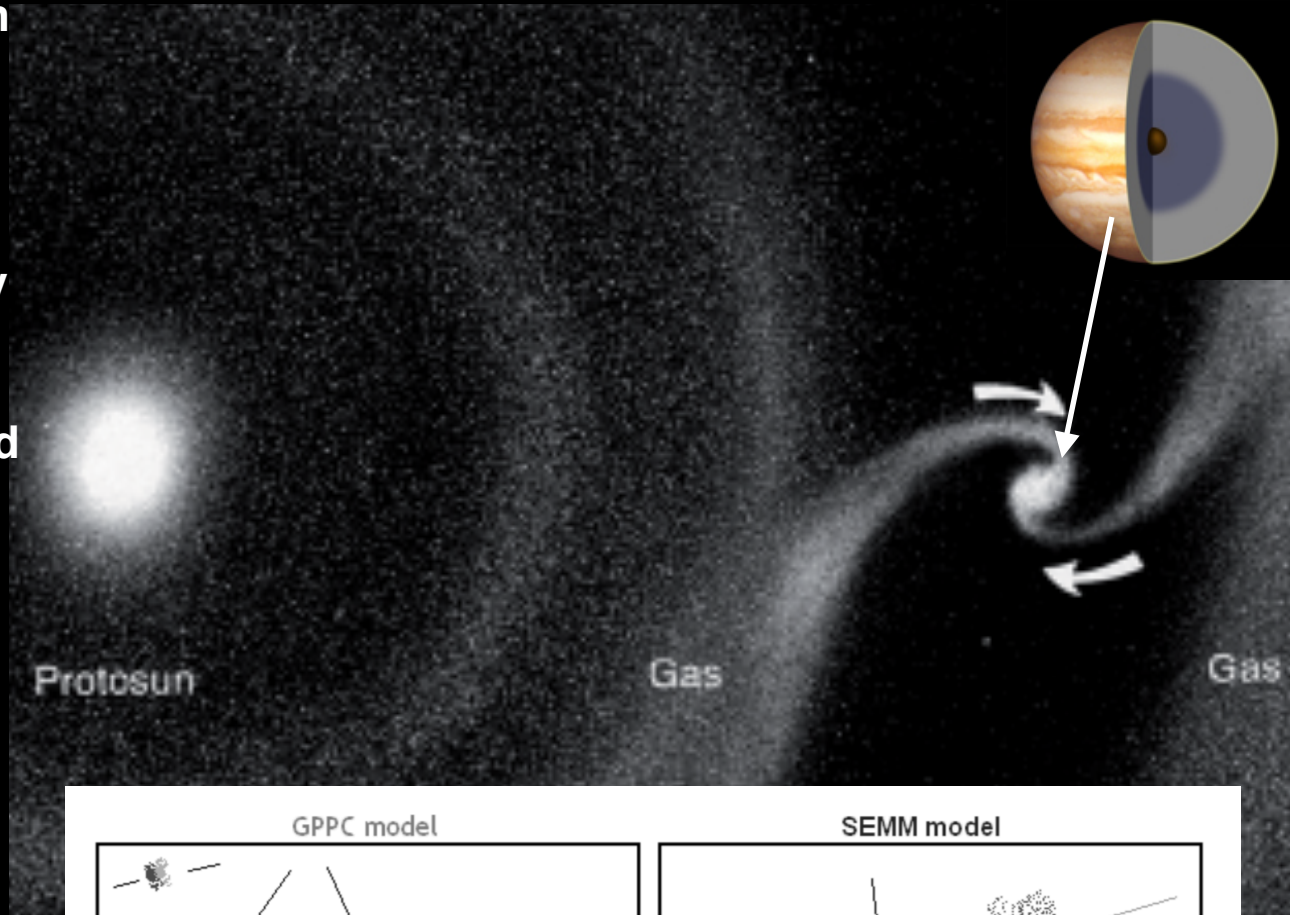
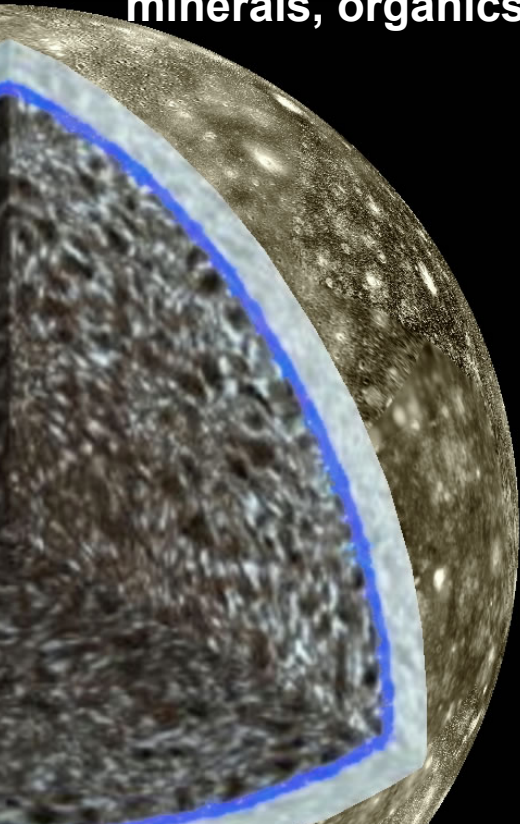
Highly cratered and degraded icy surface

Callisto as a remnant of the early Jovian system

Constraints on the accretion process in Jupiter's sub nebula

Link with the solar nebula and the chondritic-cometary reservoir

Contribution of ice, hydrated minerals, organics



Icy moons with contrasting histories

Why did they evolve so differently ?

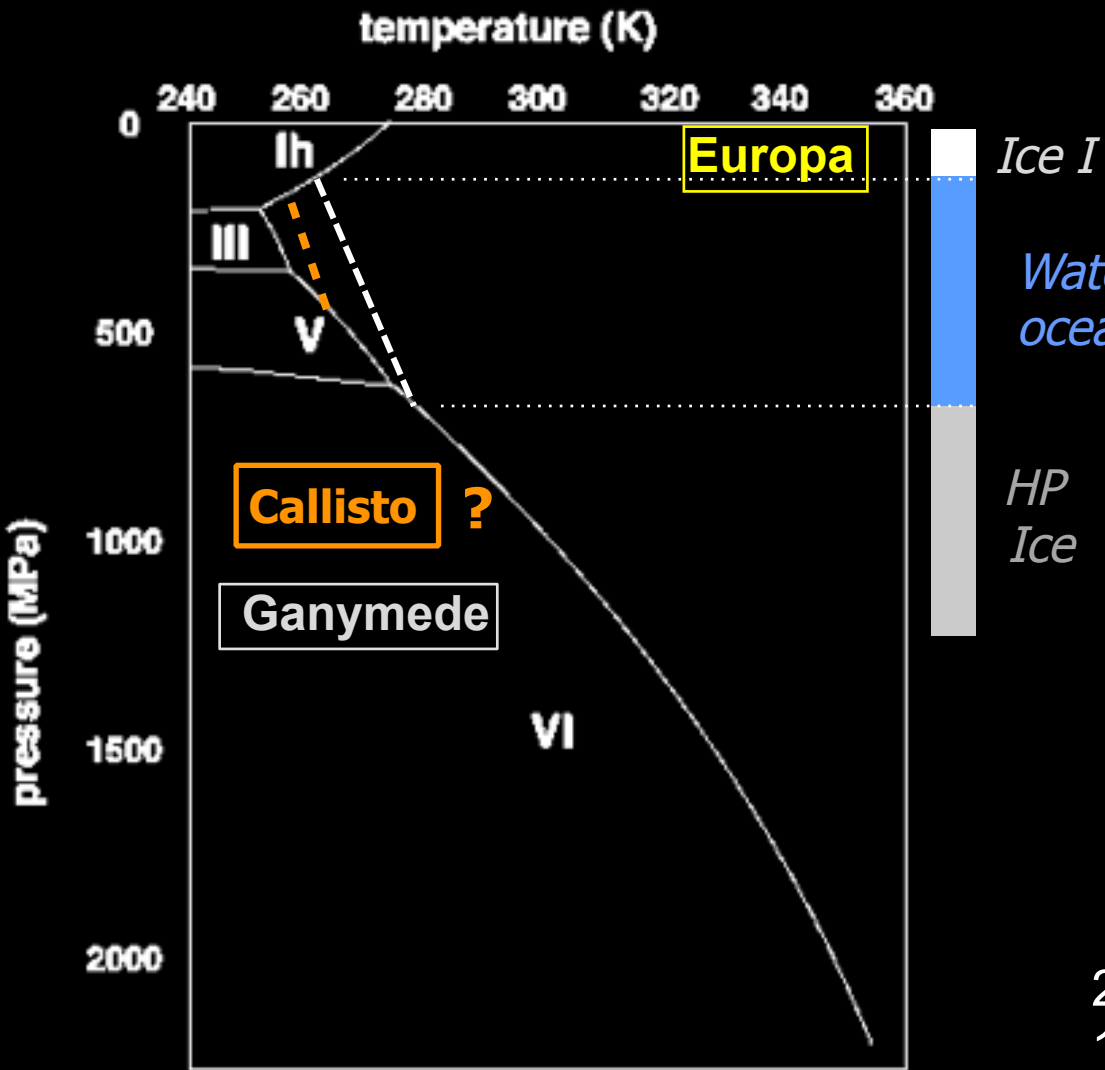
What processes are at the origin of surface activity on Europa at present and on Ganymede in the past ?

Why does Callisto lack evidence of endogenic activity ?

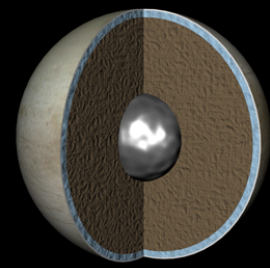


Crater images: UTM / P. Schenk

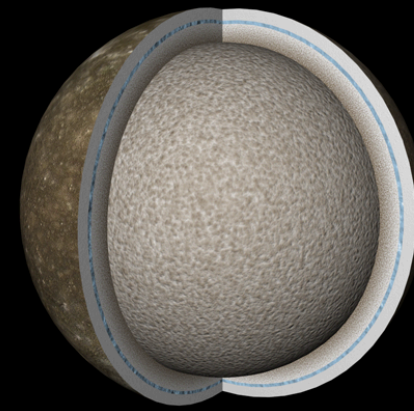
Possible internal structure of the Galilean moons



1561 km
 2970 kg.m⁻³
 C/MR²=0.347



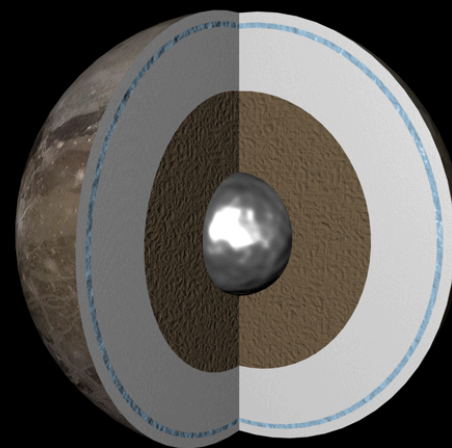
Europa



Callisto

2403 km
 1851 kg.m⁻³
 C/MR²=0.358

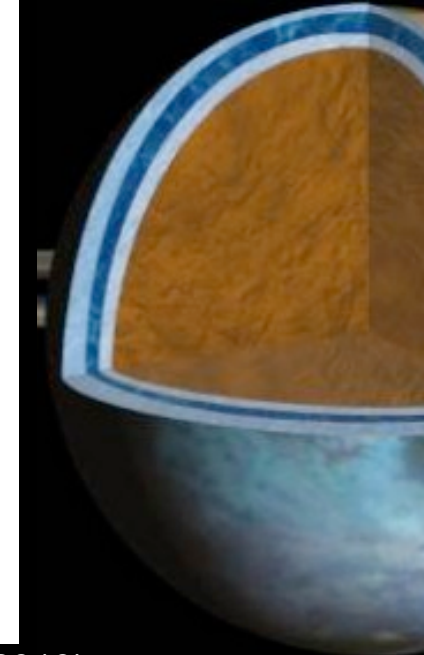
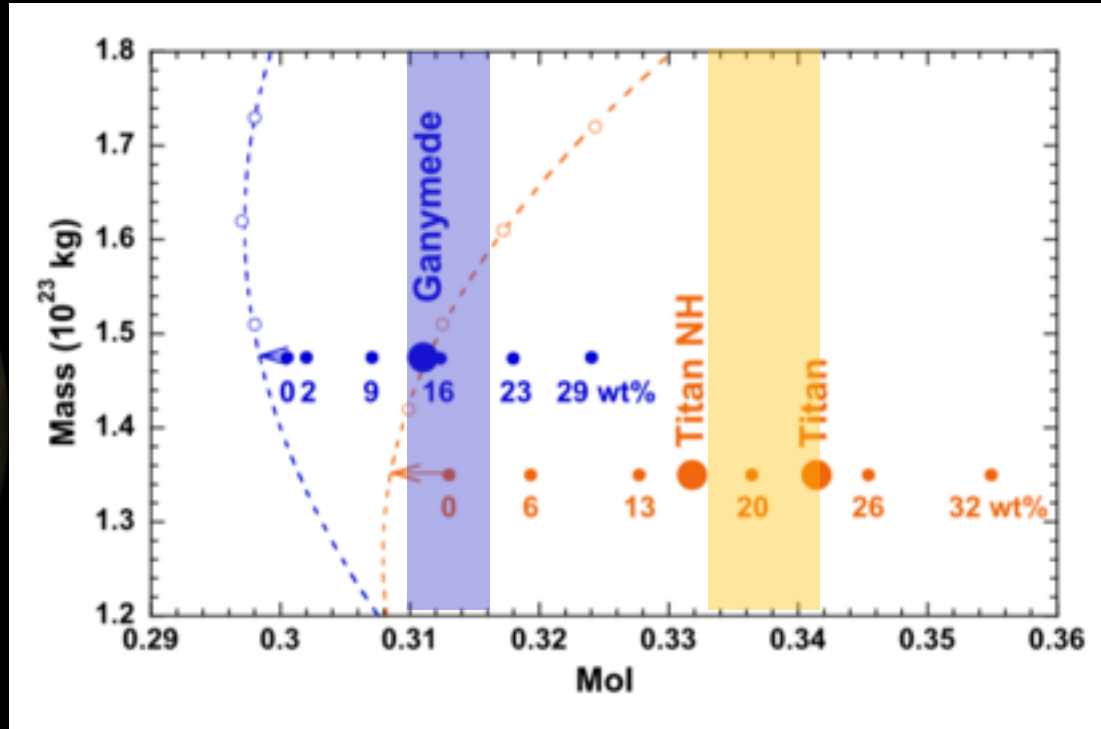
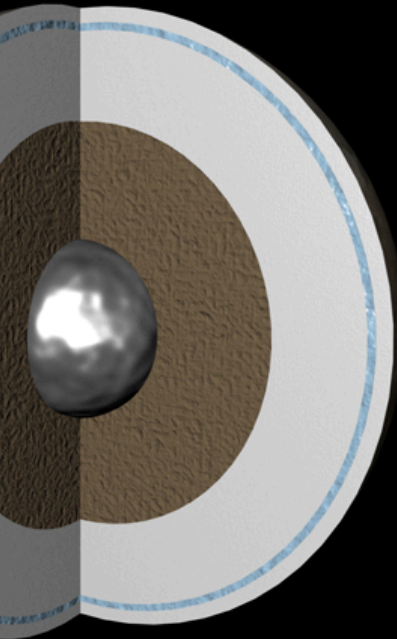
2634 km,
 1940 kg.m⁻³
 C/MR²=0.311



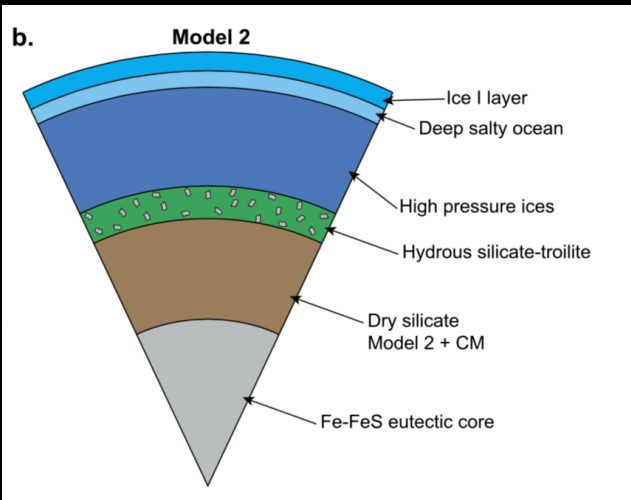
Ganymede

Depth and composition of the subsurface ocean ?
 Deep structure and water-organics-rock interaction ?

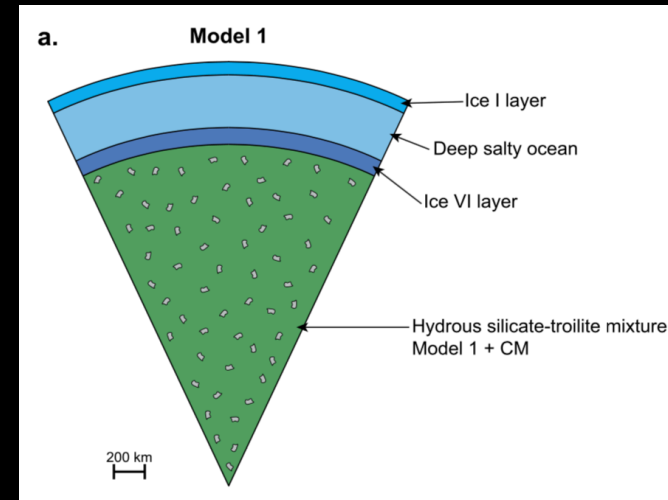
Potential role of organic matter in the interior evolution



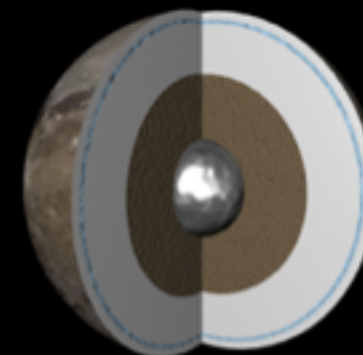
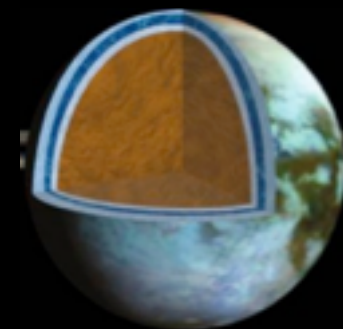
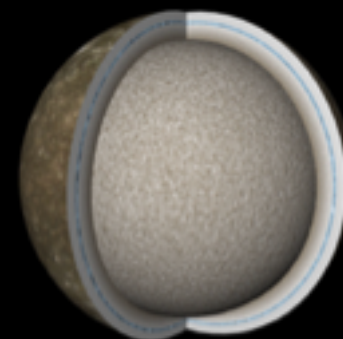
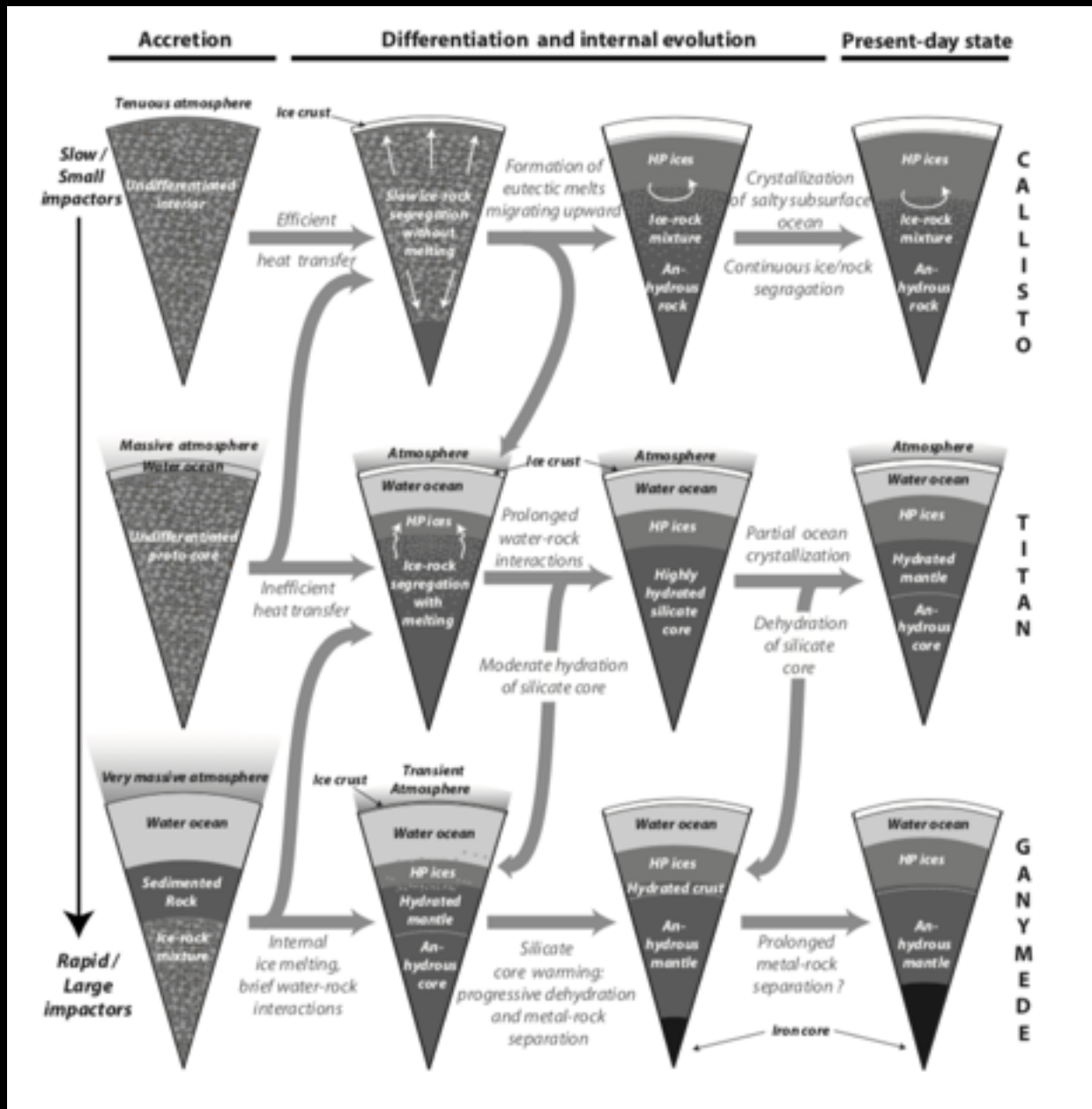
Neri et al. (2019)



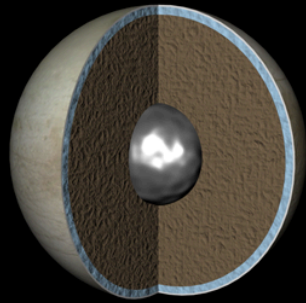
The refractory core of Ganymede and Titan should contain 10-20 % of organic matter in order to explain their moment of inertia.



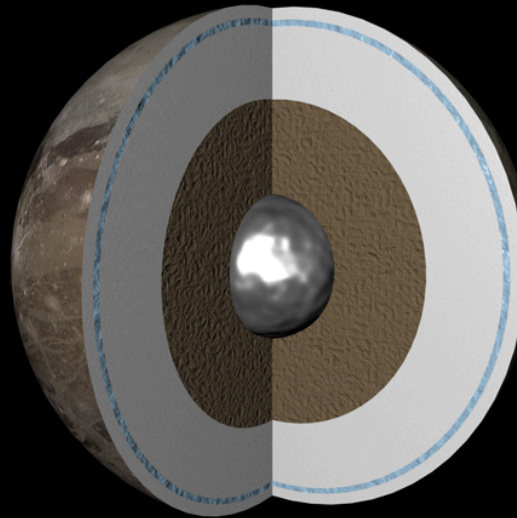
Possible evolution scenario for large icy moons



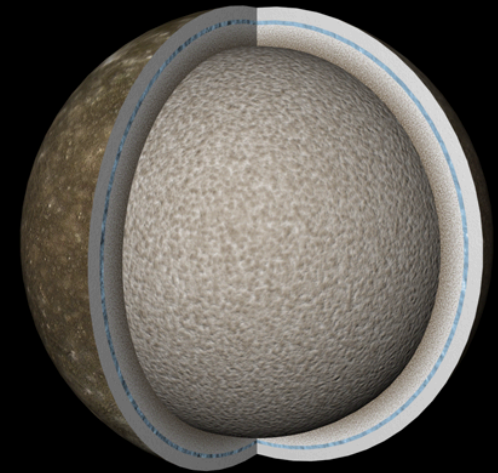
Core-ocean-ice interactions in the Galilean moons



Europa



Ganymede



Callisto

Direct contact between the rocky core and the ocean.

Seafloor volcanism
& hydrothermal
vents ?

No direct contact between the rocky core and the ocean

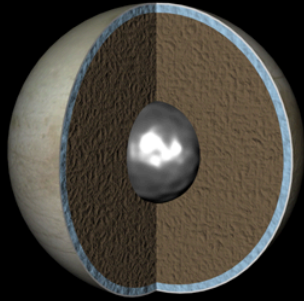
Water-organics-rock interactions
during differentiation ?

Efficiency of chemical
transport through
HP-ice mantle ?

Why does differentiation
abort ?

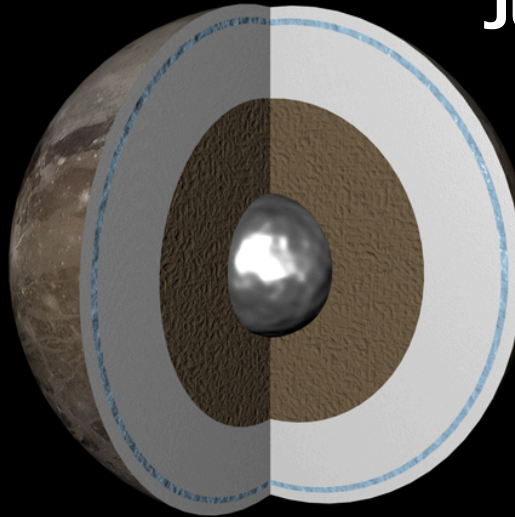
Core-ocean-ice interactions in the Galilean moons

EUROPA CLIPPER

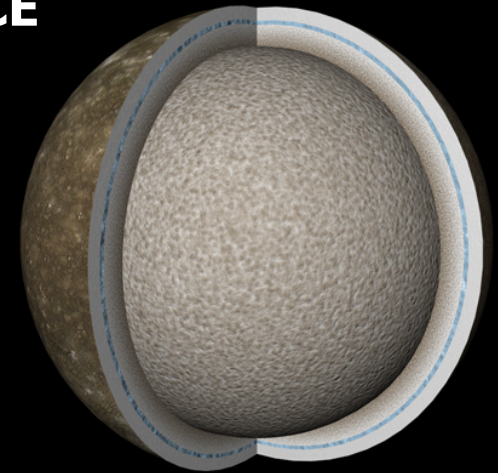


Europa

JUICE



Ganymede



Callisto

Direct contact between the rocky core and the ocean.

Seafloor volcanism & hydrothermal vents ?

No direct contact between the rocky core and the ocean

Water-organics-rock interactions during differentiation ?

Efficiency of chemical transport through HP-ice mantle ?

Why does differentiation abort ?

JUICE - JUPITER ICY moon Explorer

Exploring the emergence of habitable worlds around gas giants

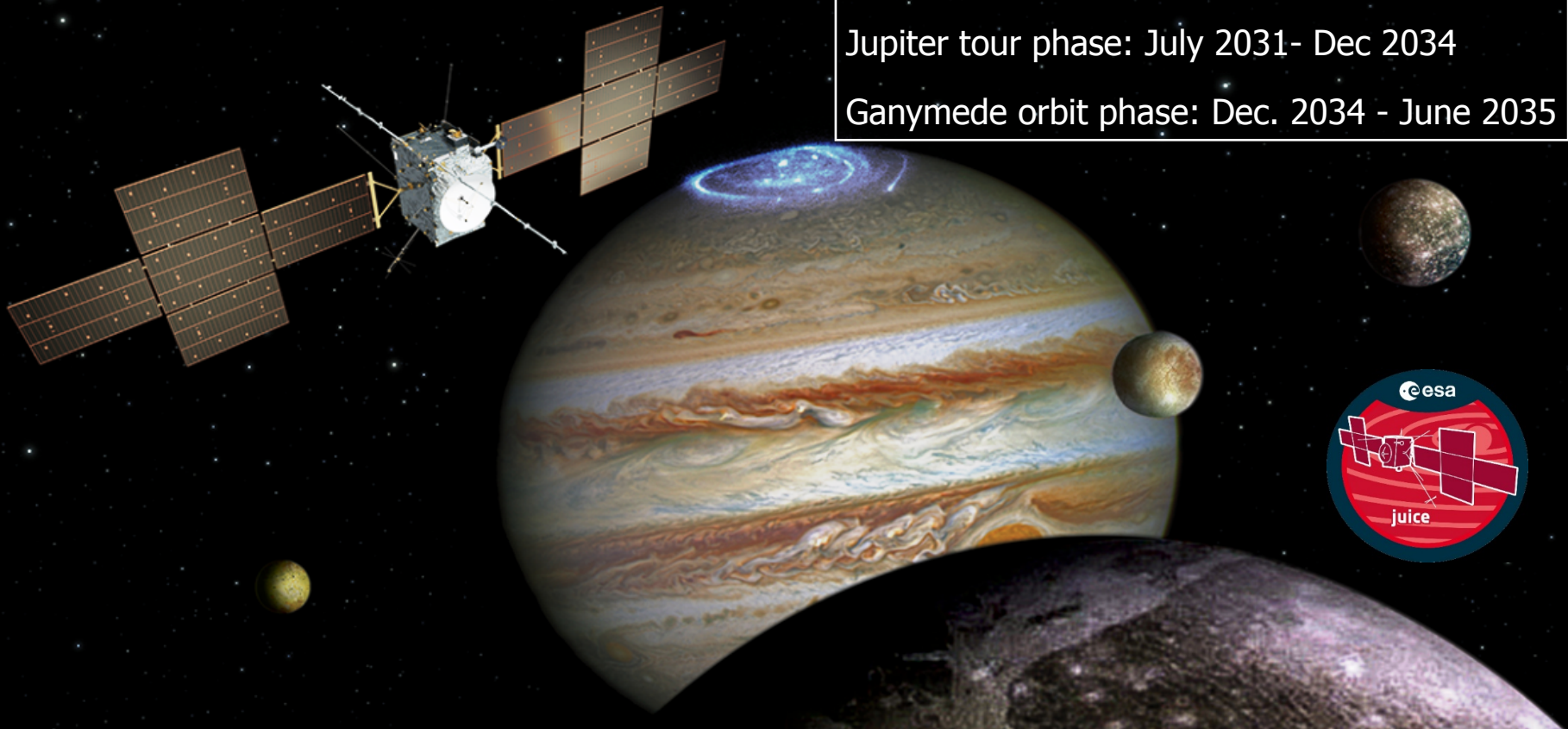
- Characterize Ganymede, Europa and Callisto as planetary objects and potential habitats
- Explore the Jupiter system as an archetype for gas giants

10 instruments

Launch: 13 April 2023

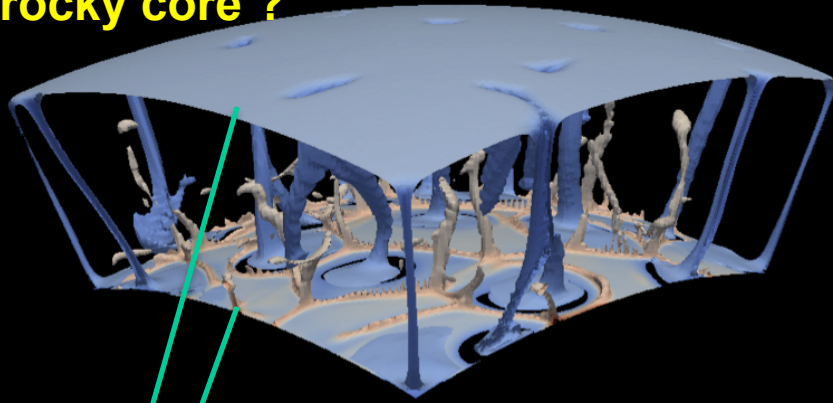
Jupiter tour phase: July 2031- Dec 2034

Ganymede orbit phase: Dec. 2034 - June 2035

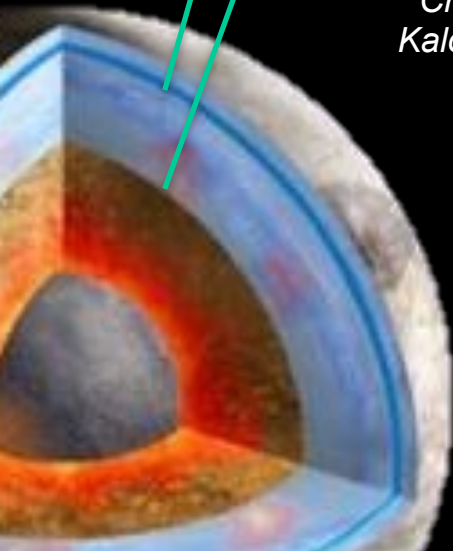


GANYMEDE: Characterization of an ocean world

Is the thick high-pressure mantle a barrier to rock/ocean exchanges ?
Efficiency of water-rock interactions at the surface of the rocky core ?

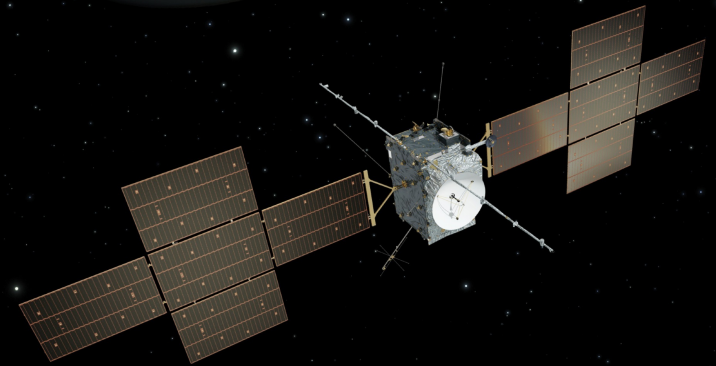
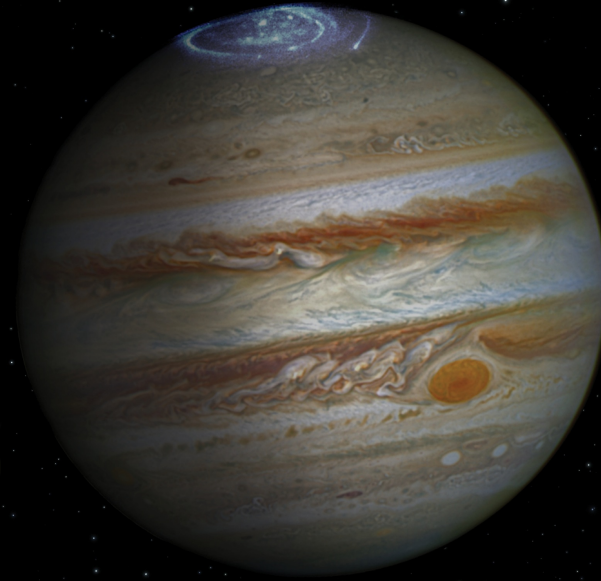


Choblet et al. (2017)
Kalousova et al. (2018)



ESA JUper ICy moon Explorer (JUICE)

Launch planned in April 2023
Operation around Jupiter: 2031-2034
Orbit insertion around Ganymede: 2034








JUICE - JUpiter ICy moon Explorer



JUICE'S SCIENCE INSTRUMENTS

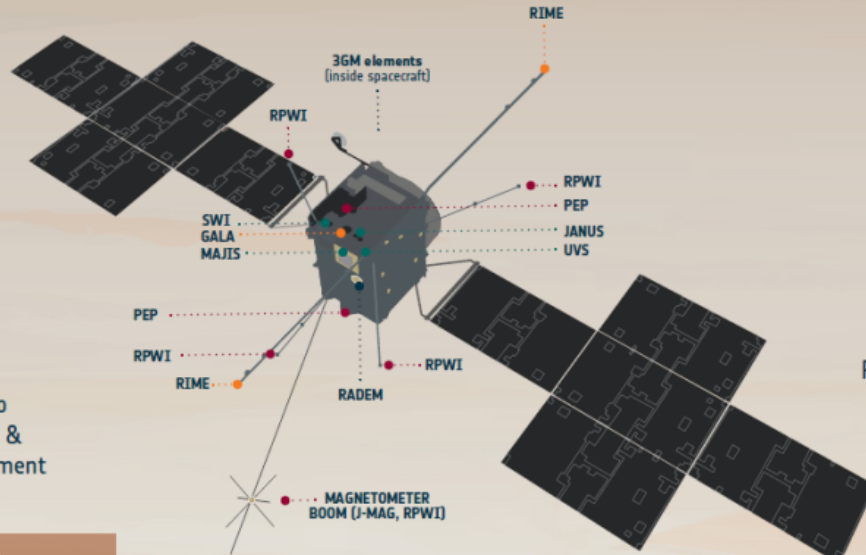
Juice will carry ten state-of-the-art instruments, including the most powerful remote sensing, geophysical and in situ payloads ever flown to the outer Solar System. Nine of the instruments are led by European partners, and one by NASA. Juice also includes an experiment called PRIDE, which will perform precise measurements using radio telescopes on Earth.



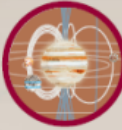
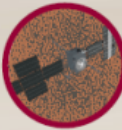

● In situ instruments ● Remote sensing instruments ● Geophysical instruments ● Experiment

-  Optical camera system (JANUS)
-  Visible and infrared imaging spectrometer (MAJIS)
-  UV imaging spectrograph (UVS)
-  Sub-millimetre wave instrument (SWI)
-  Radar sounder (RIME)

 Planetary Radio Interferometer & Doppler Experiment (PRIDE)

Juice will also carry a radiation monitor (RADEM)



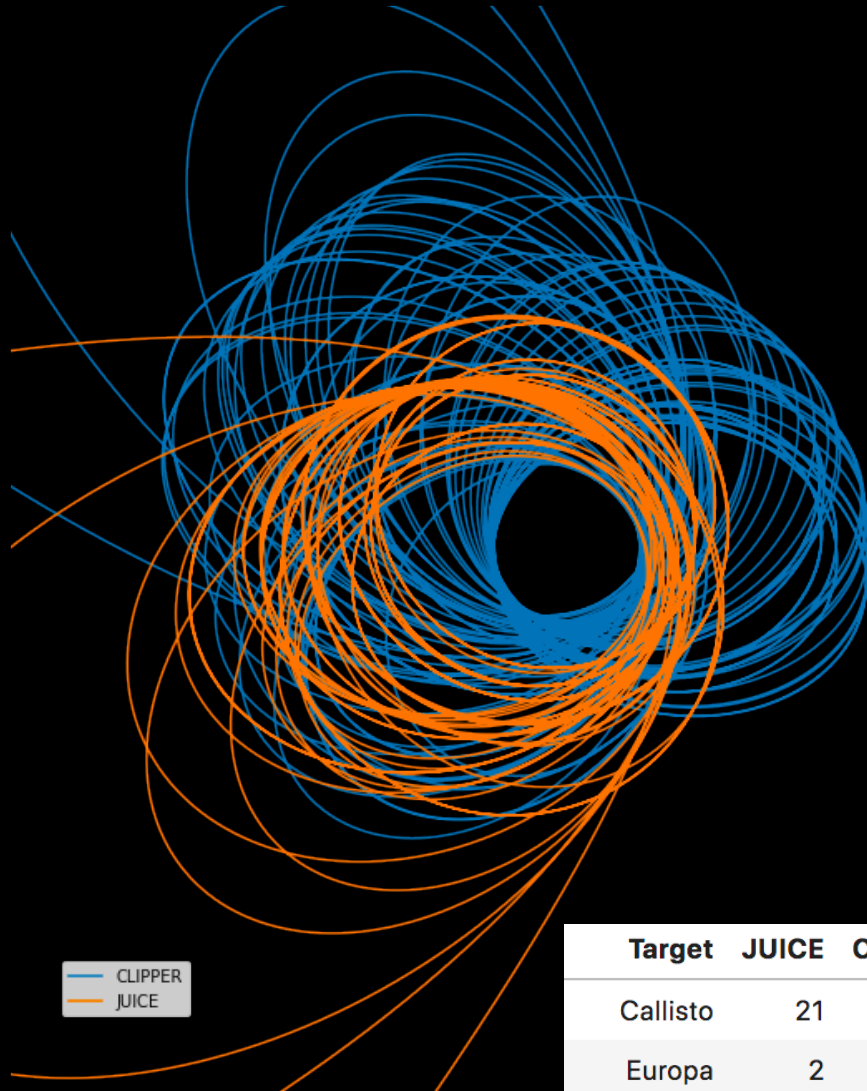
-  Laser altimeter (GALA)
-  Radio science experiment (3GM)
-  Magnetometer (J-MAG)
-  Particle environment package (PEP)
-  Radio and plasma wave instrument (RPWI)



Complementary payload to address science objectives on the interior and surface of the moons, exosphere/magnetosphere, and Jupiter's atmosphere

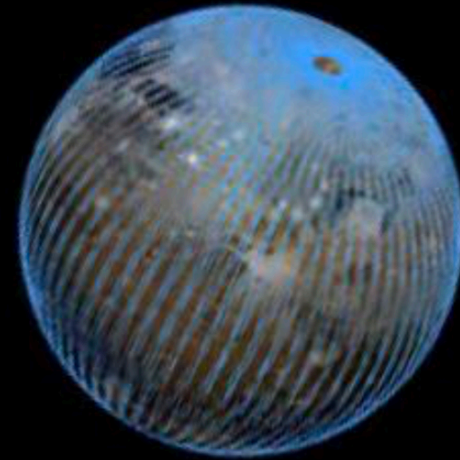
JUICE - JUpiter ICy moon Explorer

Jupiter tour phase



Target	JUICE	Clipper
Callisto	21	9
Europa	2	53
Ganymede	8	8

Ganymede orbital phase



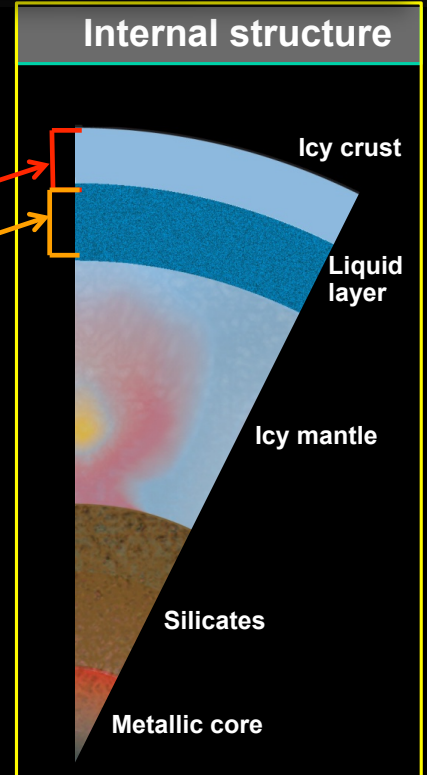
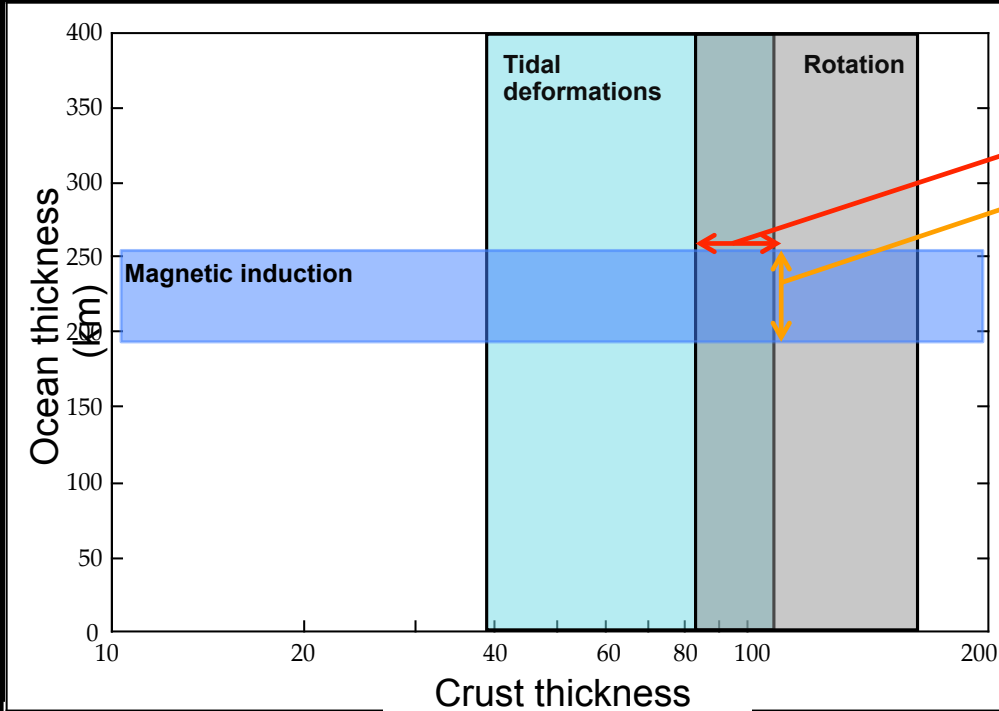
GEO, GCO5000, GCO500

284 days

GANYMEDE: Characterization of an ocean world

Characterise Ganymede as a planetary object and possible habitat

1. Extent of the ocean and its relation to the deeper interior

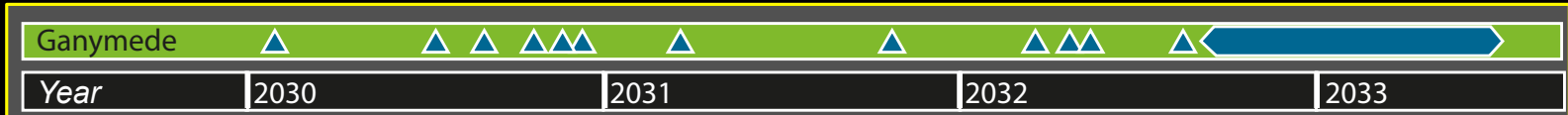


JUICE measurements

- Tidal deformations
- Rotation
- Magnetic induction

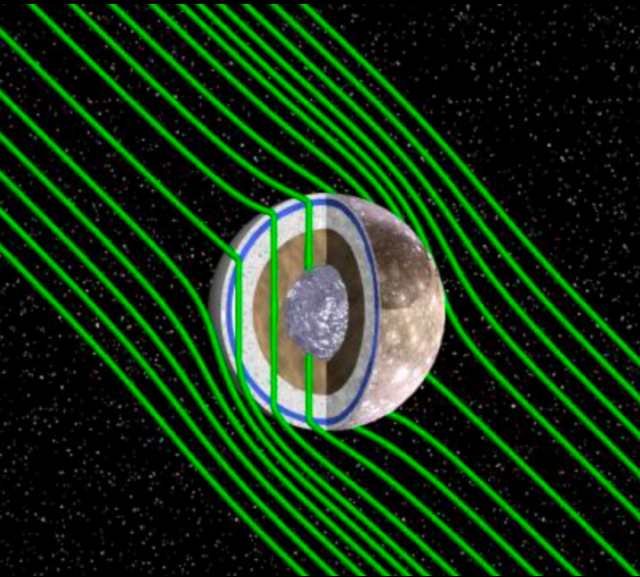
Instrument Packages

- In situ Fields and Particles
- Imaging
- Sounders and Radio Science



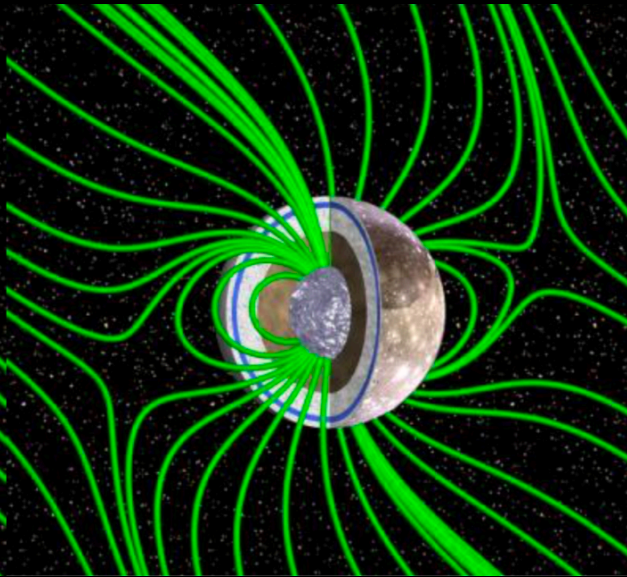
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Induced magnetic field



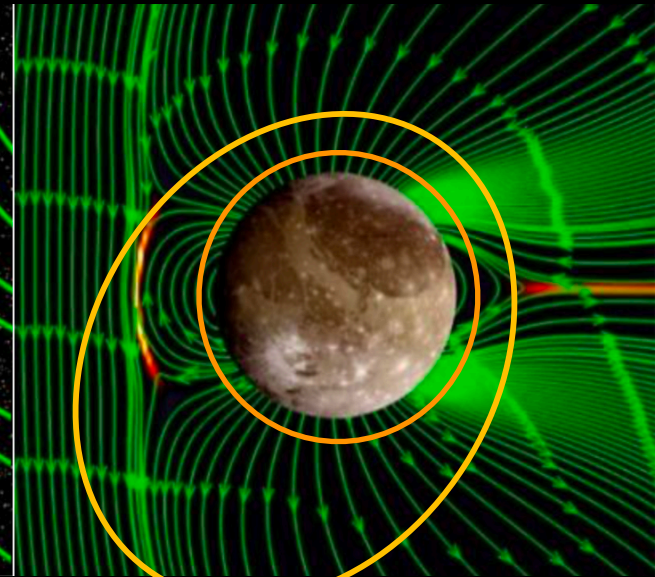
Variable (10h, 171h, 27 days)

Permanent magnetic field

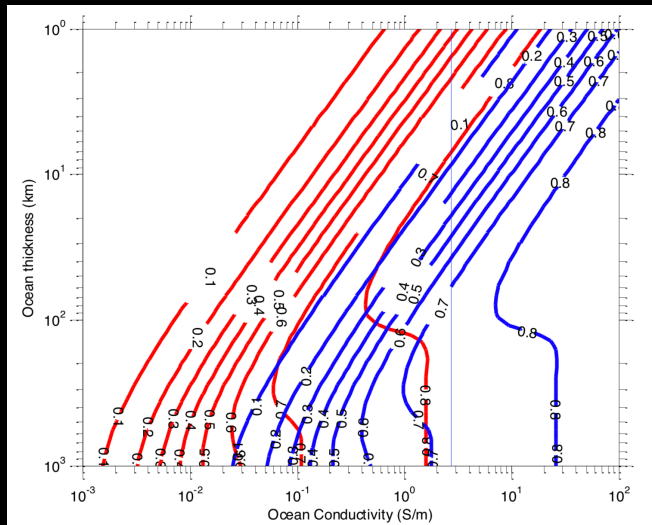


Static + secular variations

Interconnected magnetic field



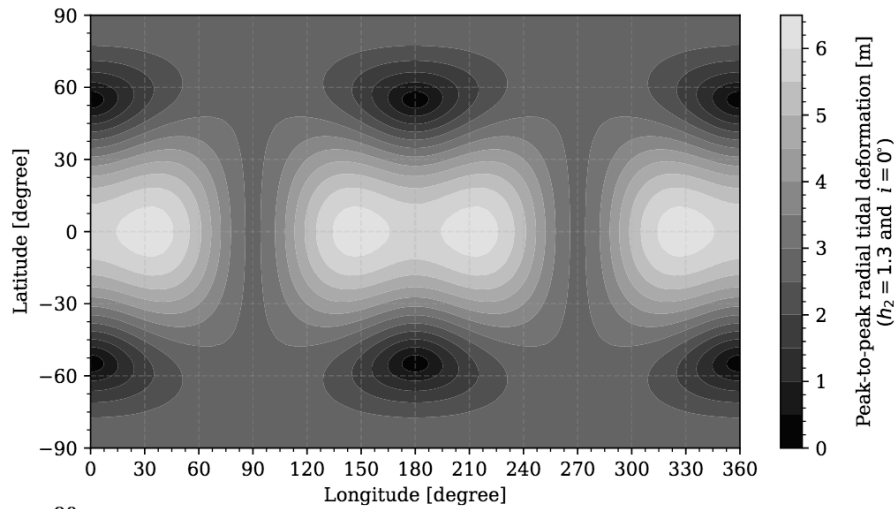
Variable (<10 min, 10h)



JUICE will measure precisely the magnetic field during the Ganymede orbital allowing a separation of the different components of the complex magnetic field.

Multi-frequency induced signals will give constraints on the ocean conductivity and thickness

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Steinbrügge et al. (in rev)

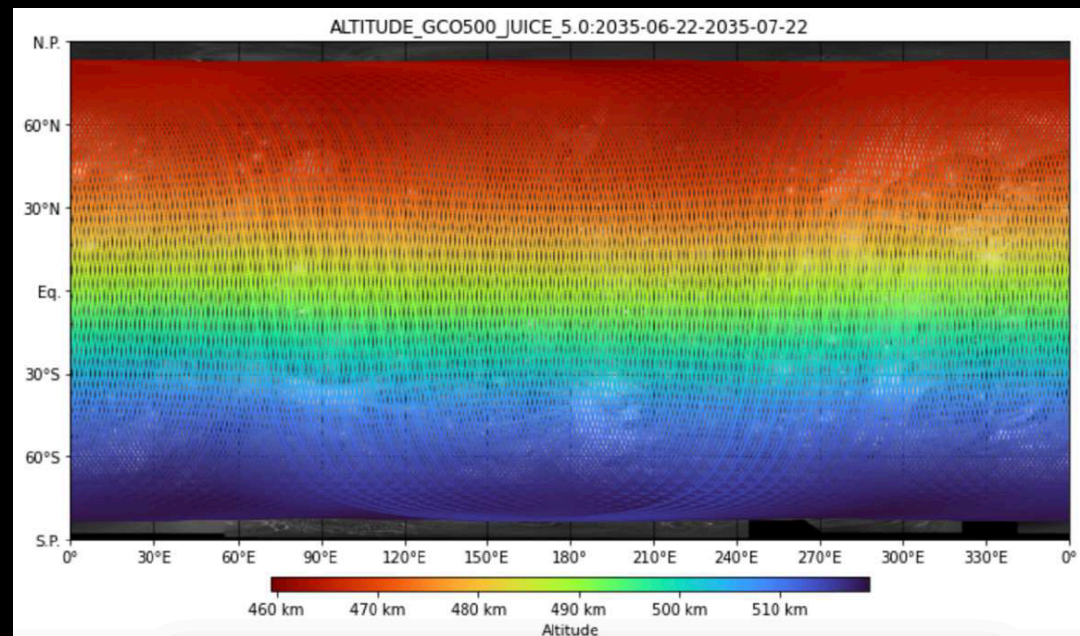
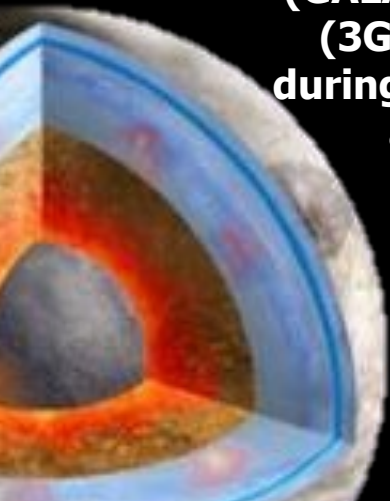
Expected accuracy:

Re(k_2): 0.0001, Im(k_2): 0.000068
(Cappuccio et al. 2020)

h_2 : <0.02
(Steinbrügge et al. 2015)

Constraining on the hydrosphere structure and thermal state from tidal monitoring

Precise tidal monitoring by the JUICE spacecraft using both altimetric (GALA) and gravimetric (3GM) measurements during the orbital phase around Ganymede (GC0500)



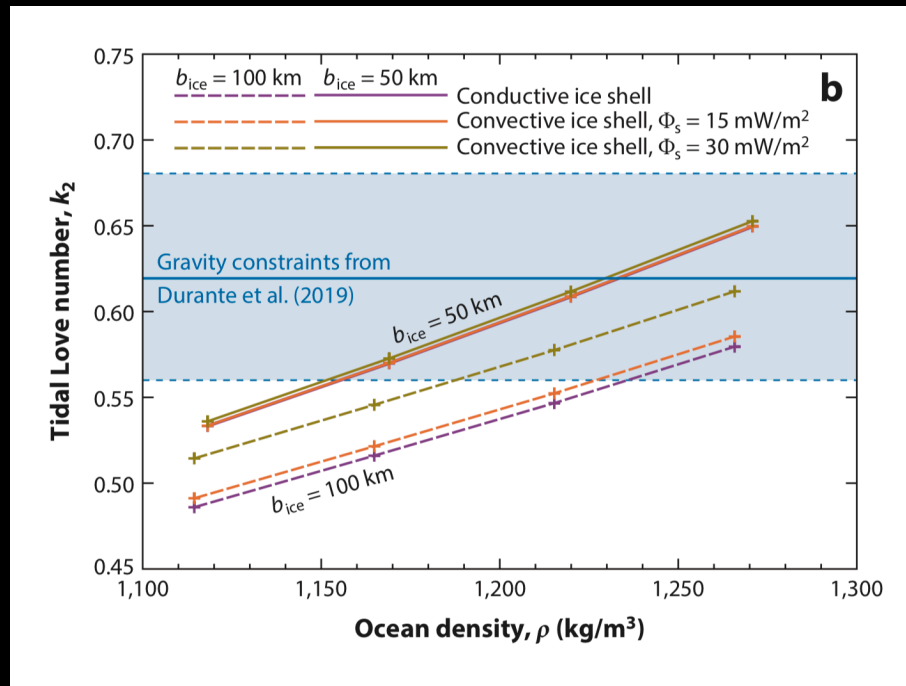
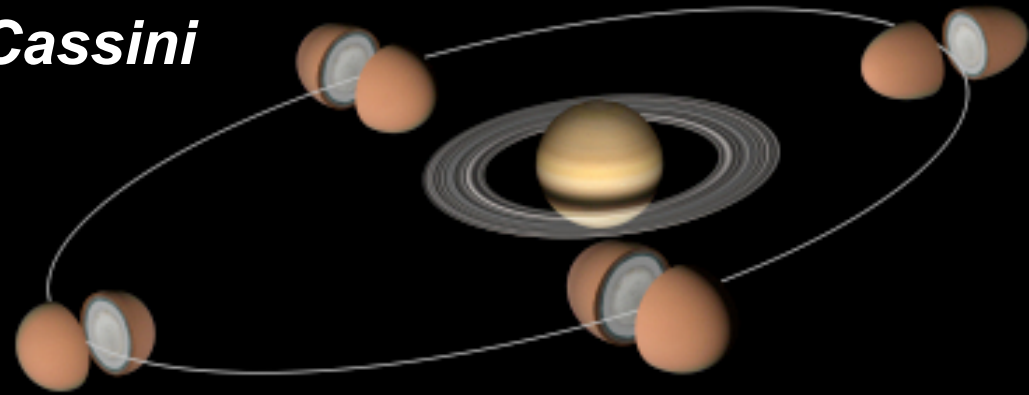
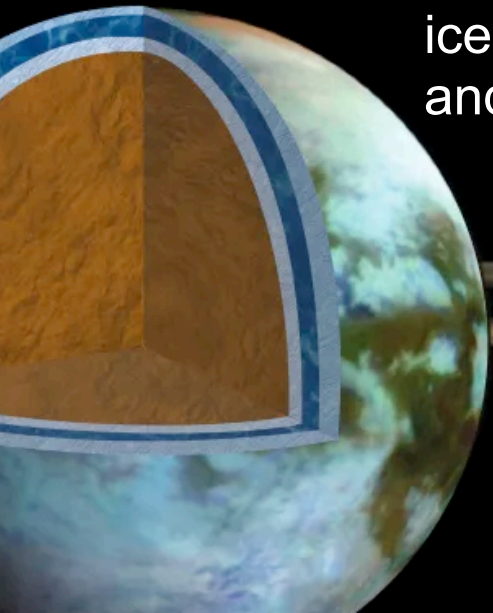
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The example of Titan with *Cassini*

Estimate of the Love number from time variations of the gravity field (less et al. 2012, Durante et al. 2019)

$$k_2 = 0.616 \pm 0.067$$

Evidence for a subsurface ocean
Constraints on the ice shell thickness and ocean density



Sotin et al. (2021) adapted from Mitri et al. (2014)

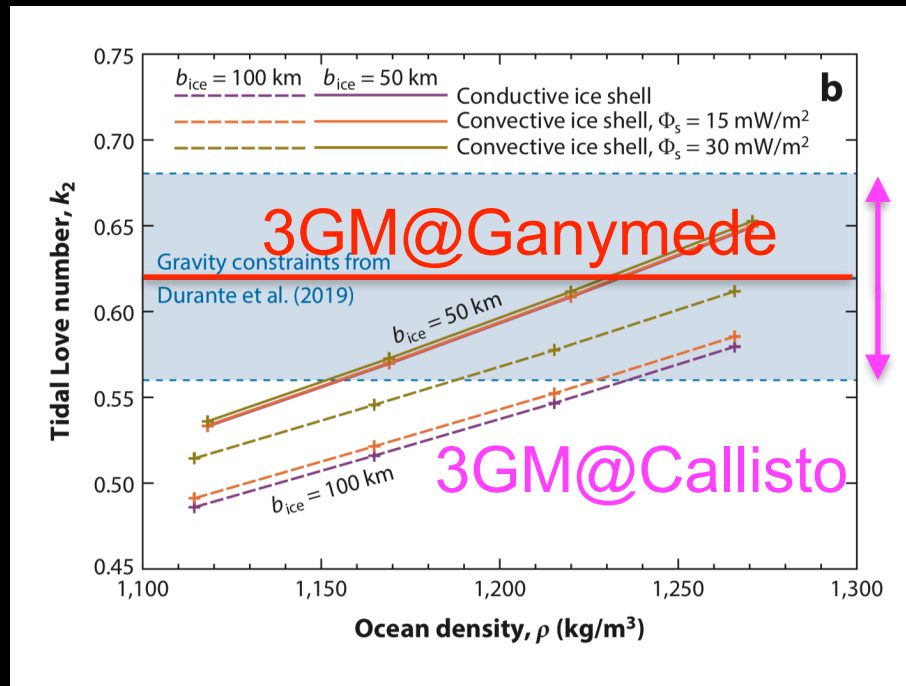
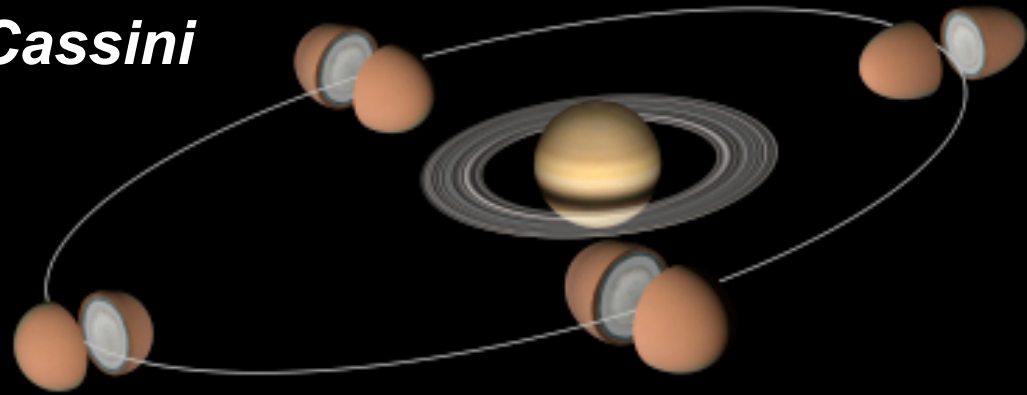
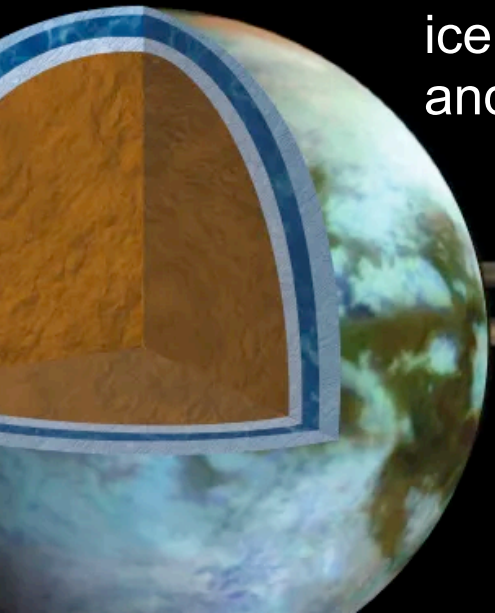
GANYMEDE: Characterization of an ocean world

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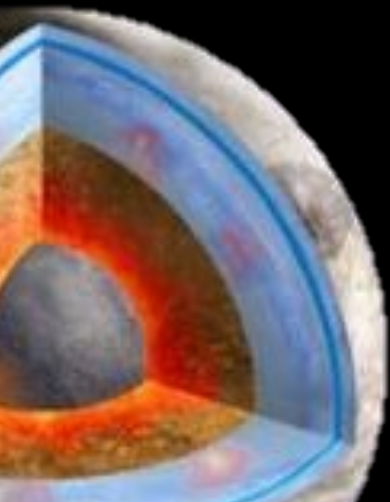
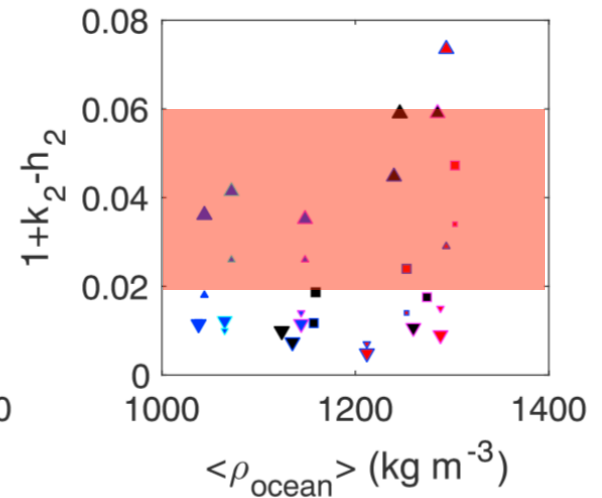
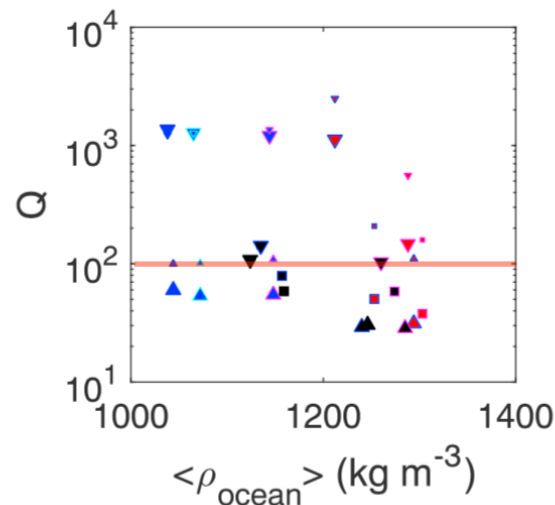
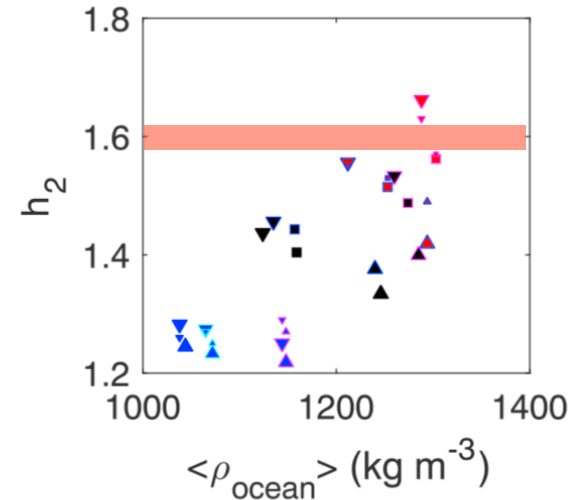
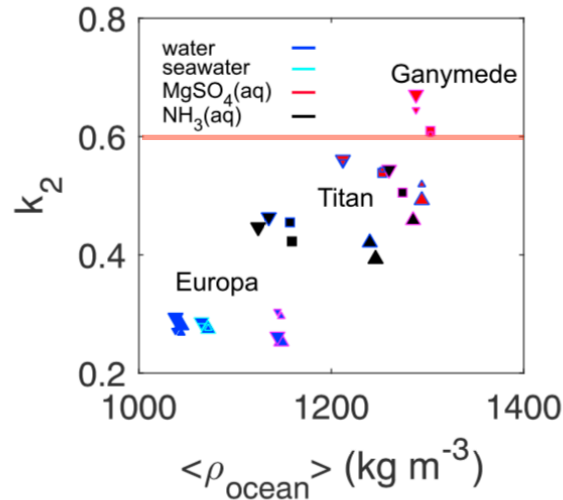
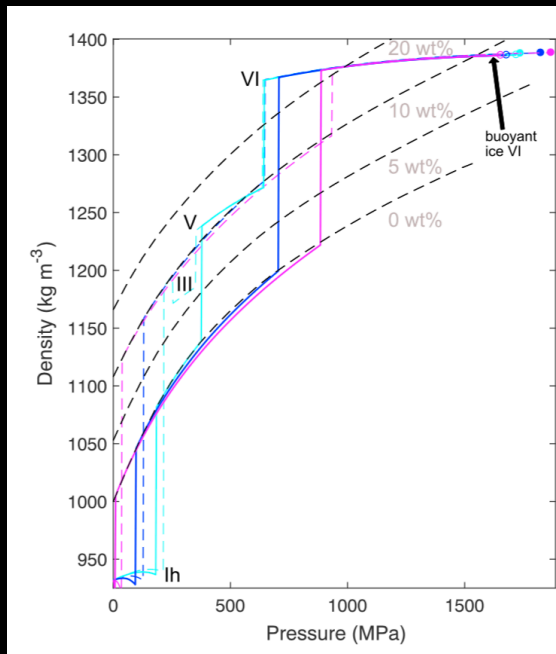
Evidence for a subsurface ocean
Constraints on the ice shell thickness and ocean density



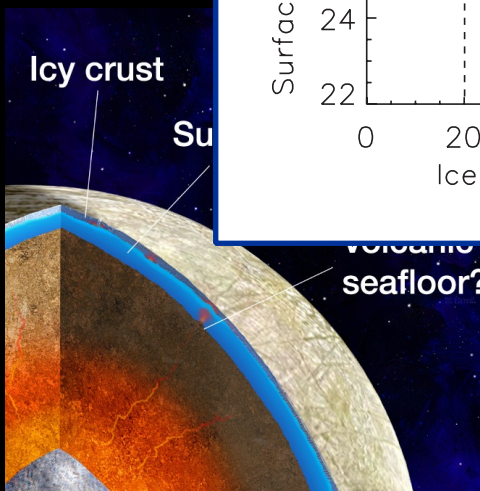
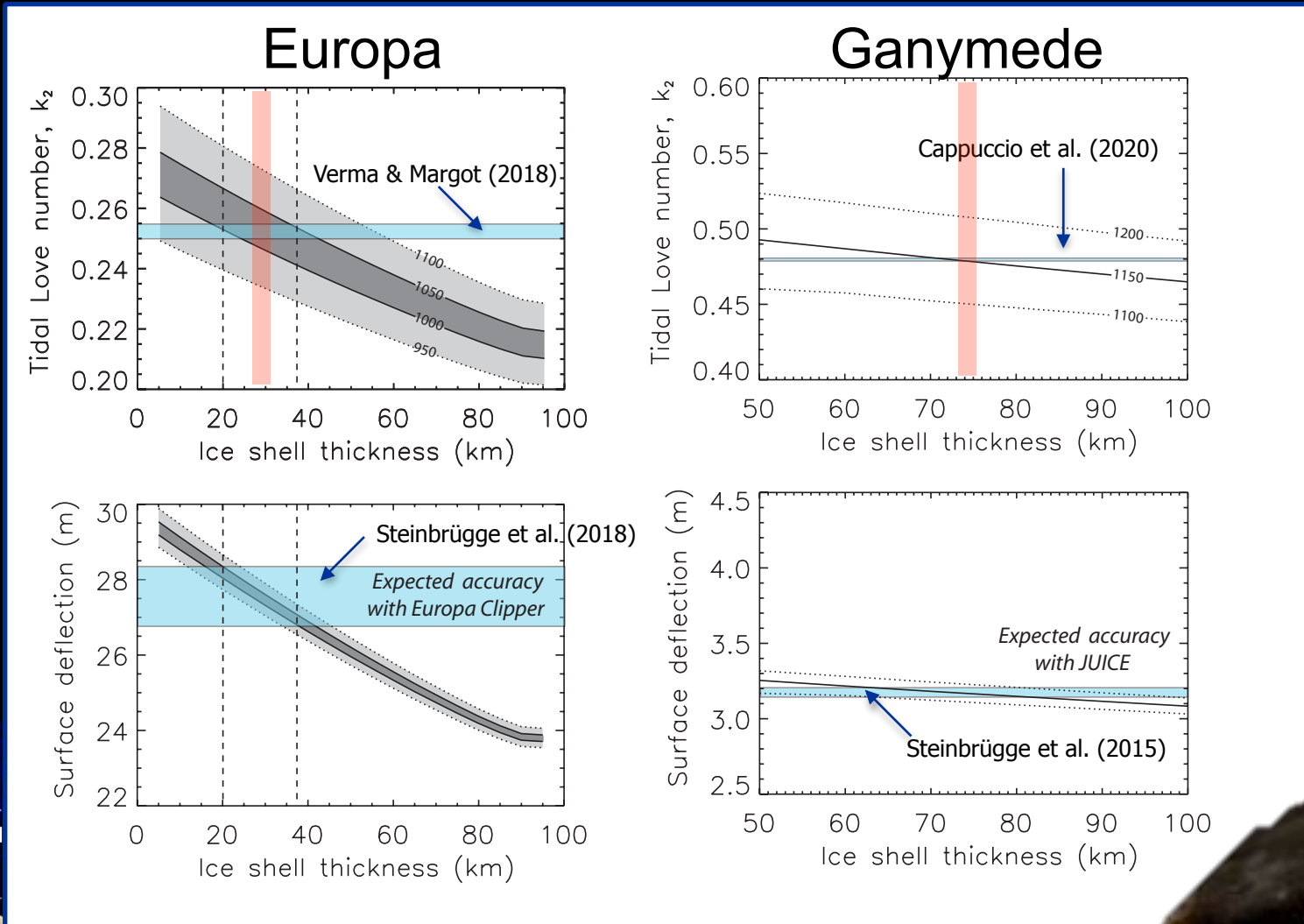
Sotin et al. (2021) adapted from Mitri et al. (2014)

GANYMEDE: Characterization of an ocean world

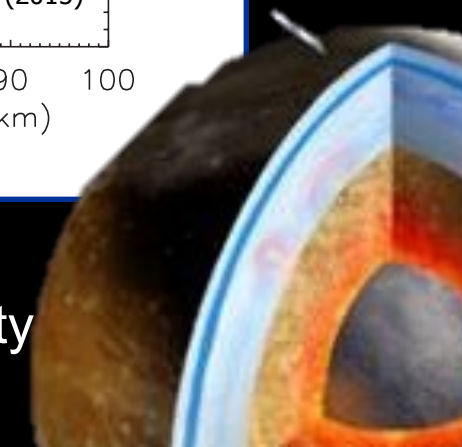
Constraints on the ocean density and ice shell structure from tidal monitoring



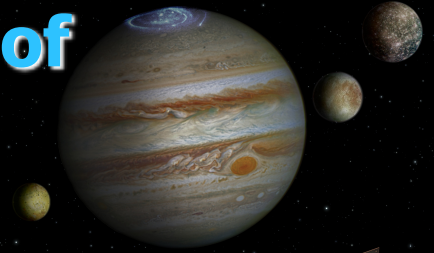
GANYMEDE: Characterization of an ocean world



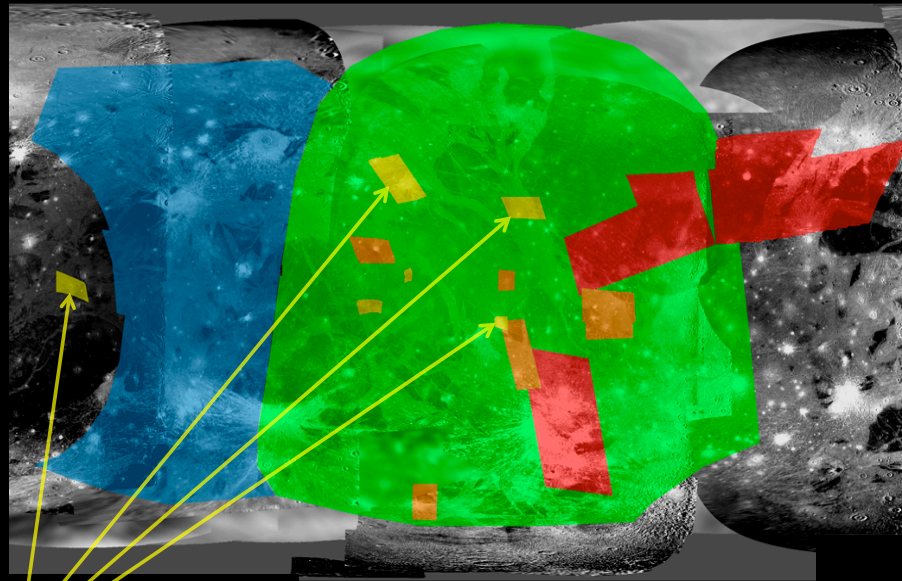
By combining k_2 and h_2 measurements, both ice shell thickness and ocean density may be constrained.



GANYMEDE: Characterization of an ocean world



What are the surface chemical compounds ?



Galileo NIMS coverage

2 - 10 km/pix 10 - 20 km/pix 20 - 50 km/pix 50 - 100 km/pix 100 - 150 km/pix

Remote sensing

Spatial coverage

>50% at 2-3 km/px
100 m/px on a few %
10 m/px where needed

Spectral coverage

4 times better than Galileo NIMS
Close to lab data quality when needed

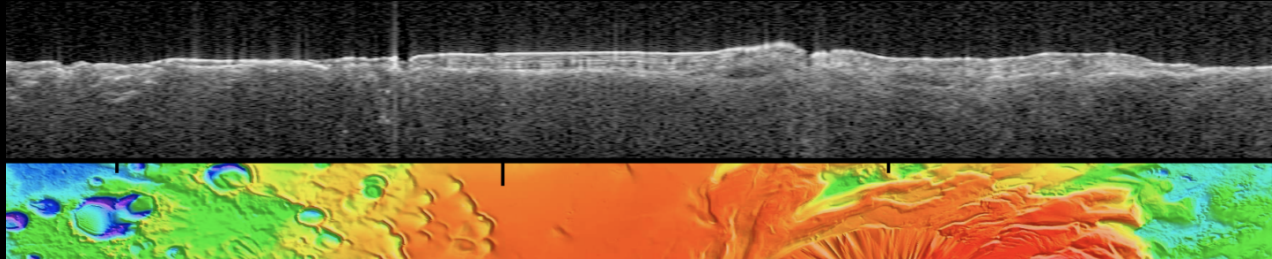
Exogeneous / endogeneous ?



Volatiles

Ions and Neutrals

How does the surface relate to the subsurface ?

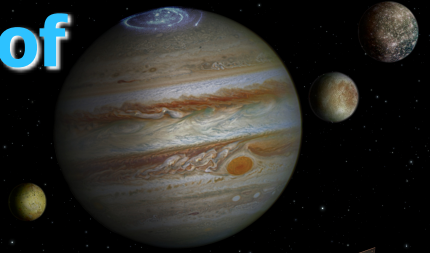


Instrument Packages

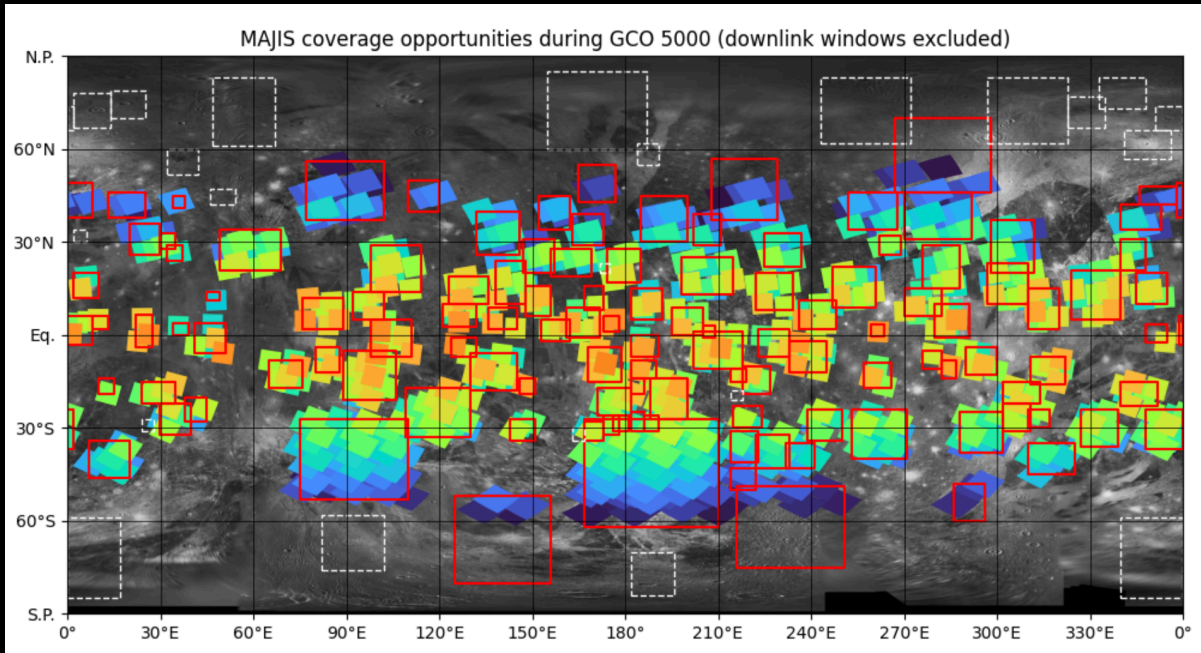
- Spectroscopy
- Imaging
- In situ
- Radar sounder



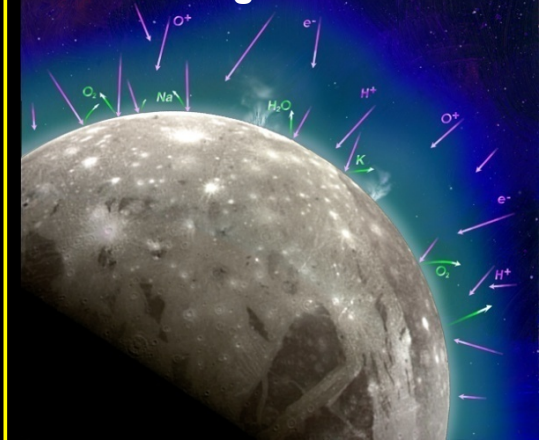
GANYMEDE: Characterization of an ocean world



What are the surface chemical compounds ?



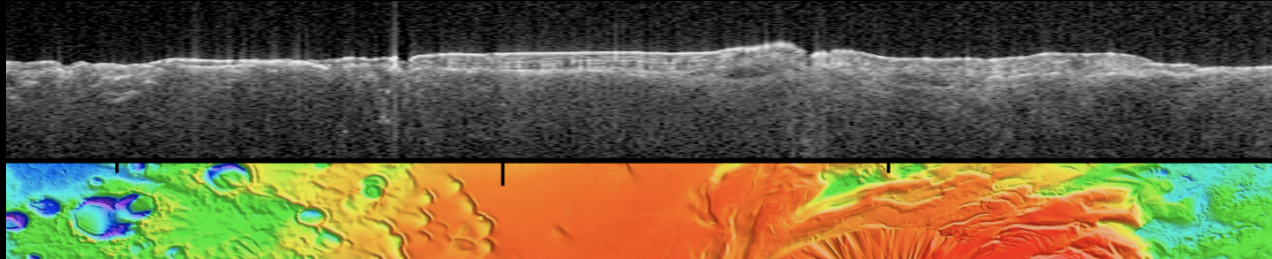
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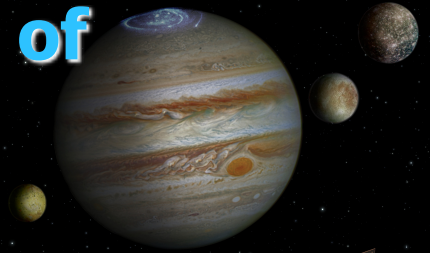
How does the surface relate to the subsurface ?



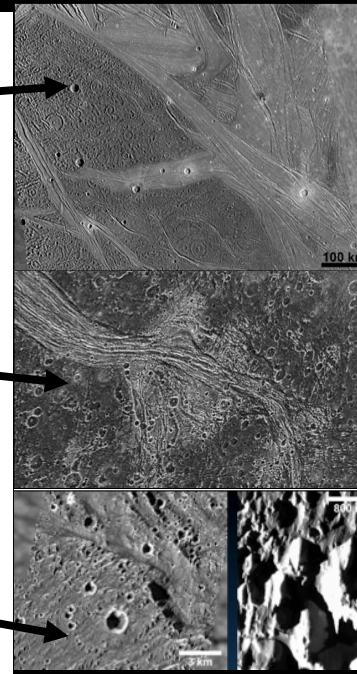
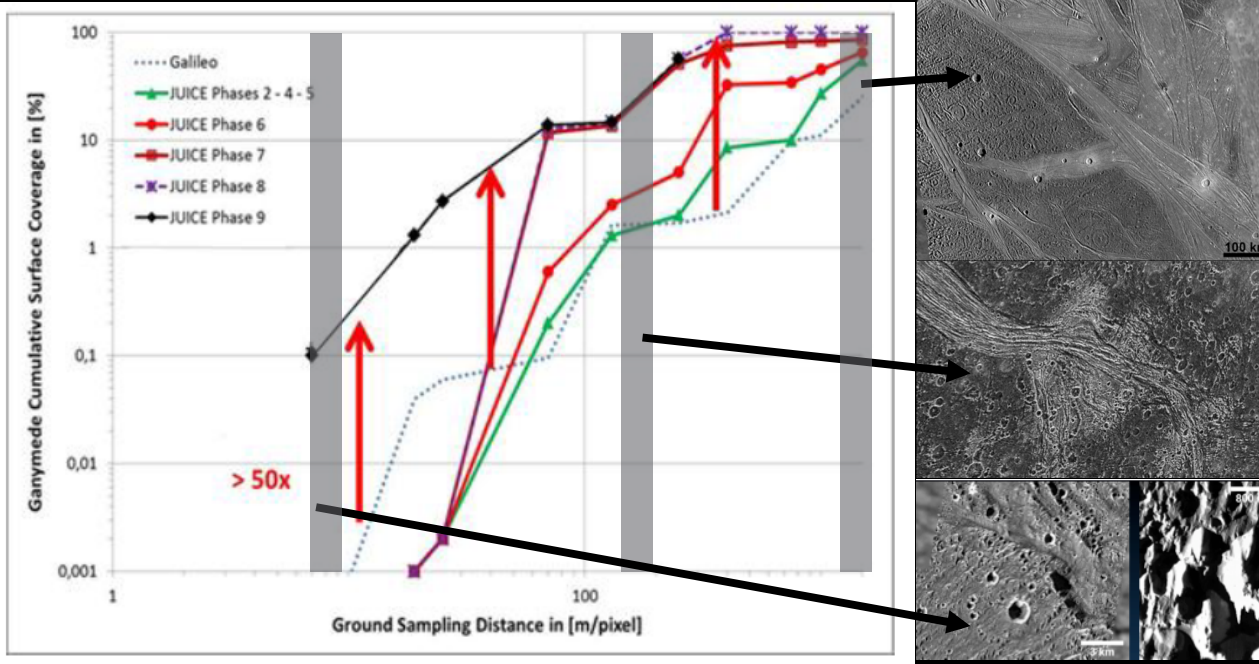
- Instrument Packages
- Spectroscopy
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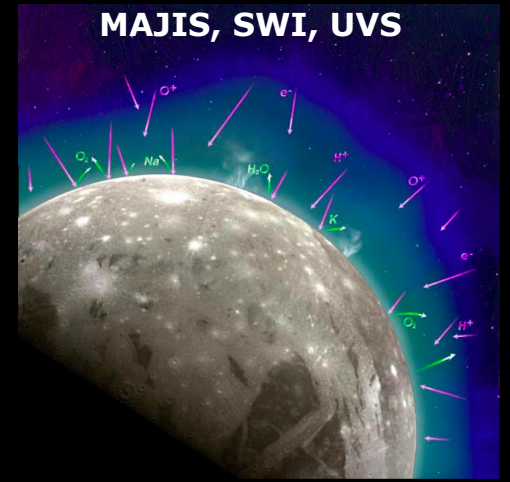
GANYMEDE: Characterization of an ocean world



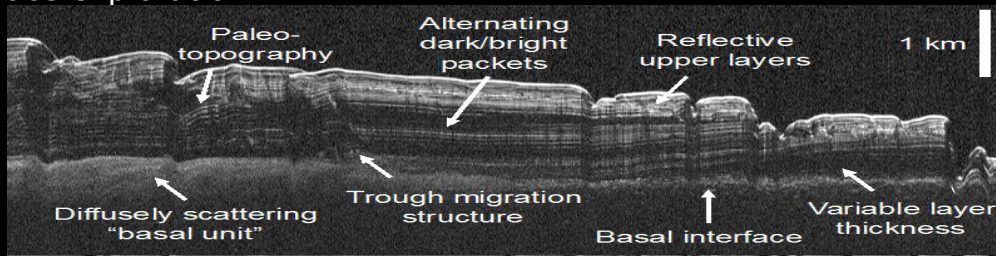
Surface mapping : JANUS



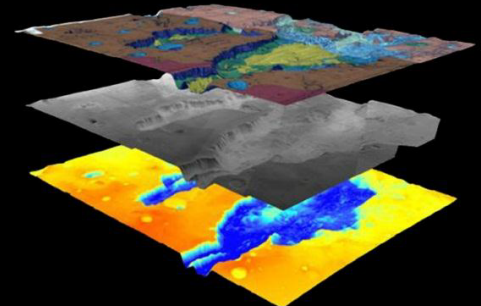
Exogeneous contribution to surface properties
JMAG, RPWI, PEP
MAJIS, SWI, UVS

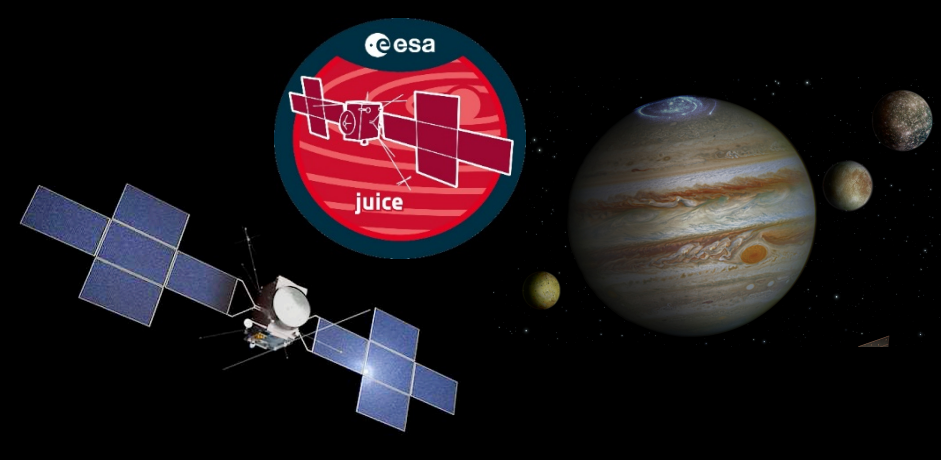
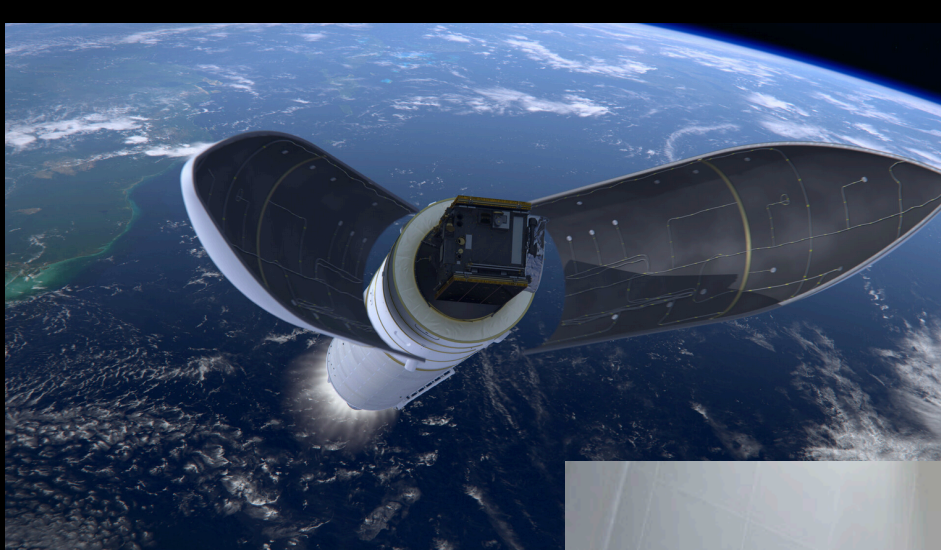


Subsurface exploration: RIME



Surface topography
GALA JANUS

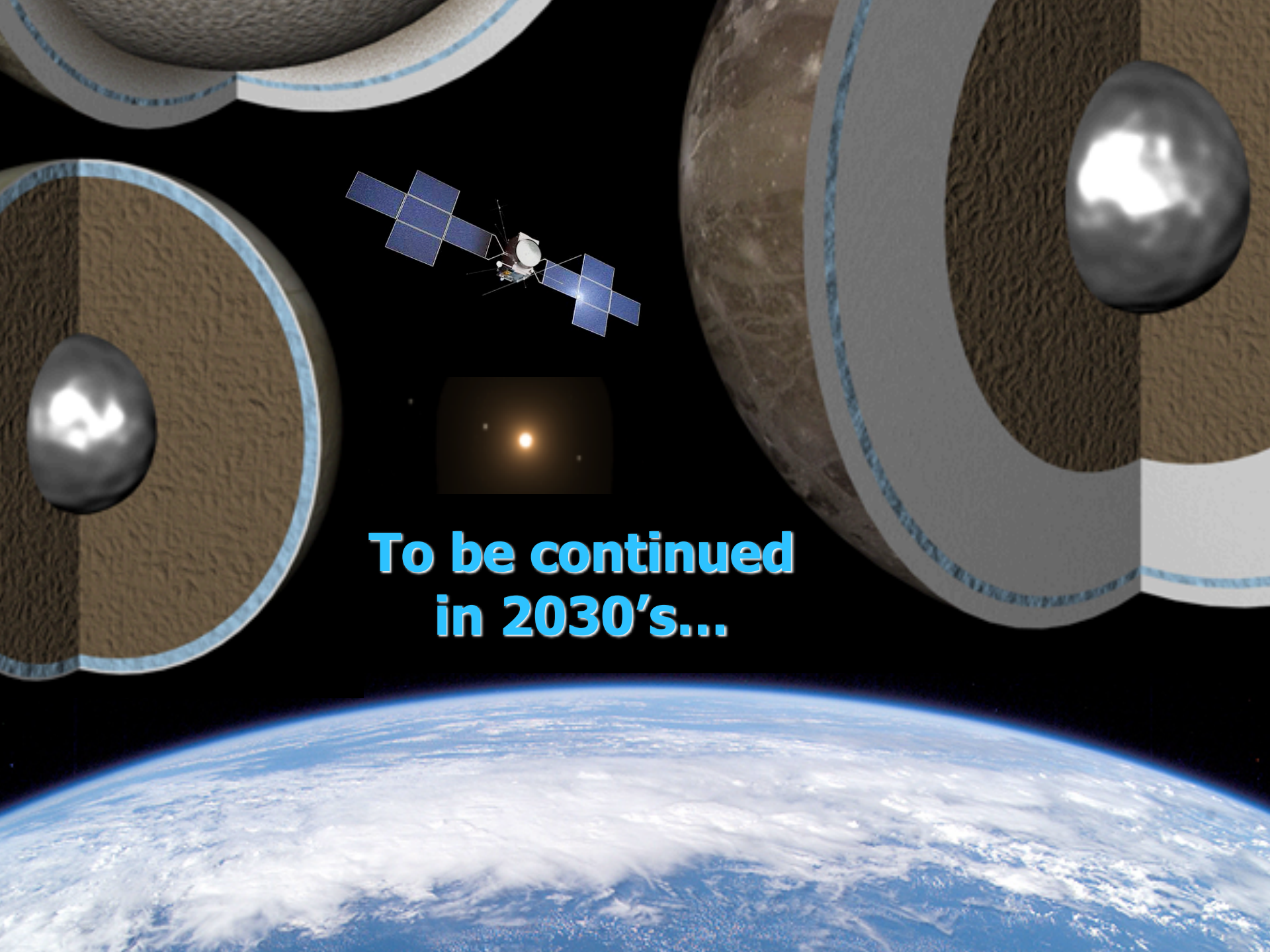




JUICE now in Kourou
ready for launch
with Ariane 5

April 13th 2023,
14:15:01 CEST





**To be continued
in 2030's...**