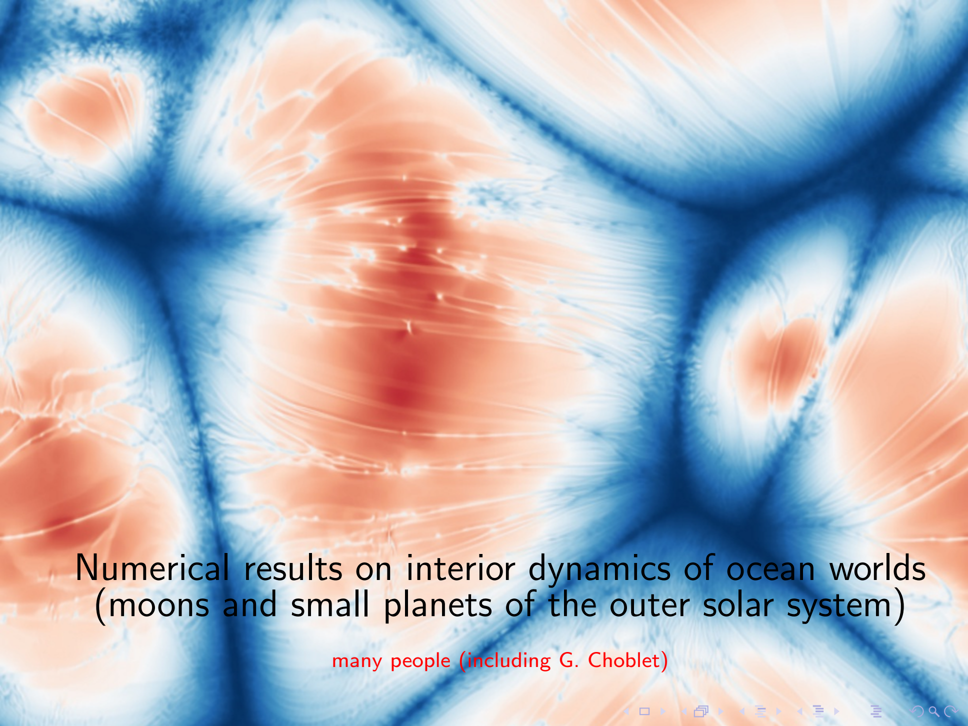
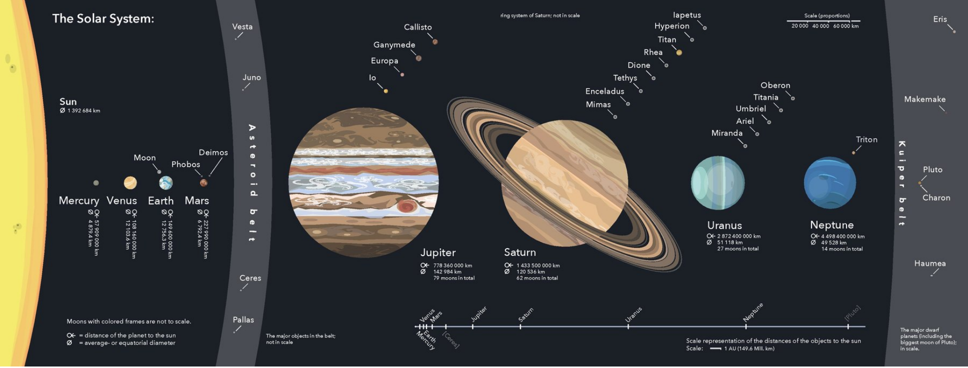


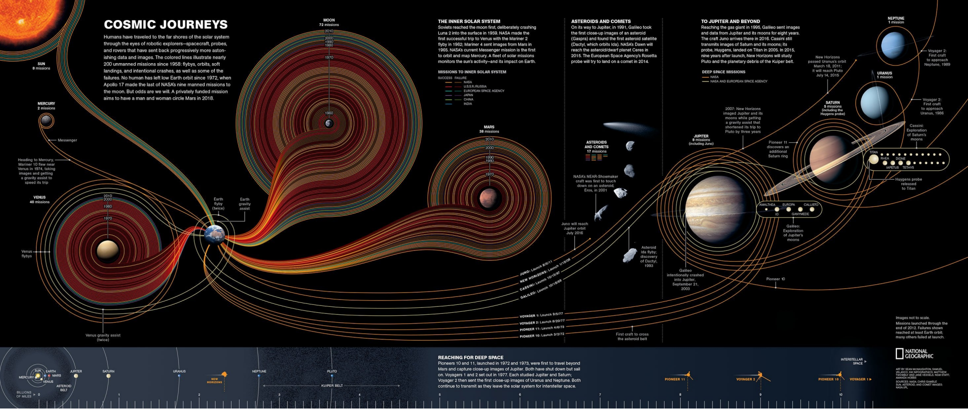
# Numerical results on interior dynamics of ocean worlds (moons and small planets of the outer solar system)

many people (including G. Choblet)

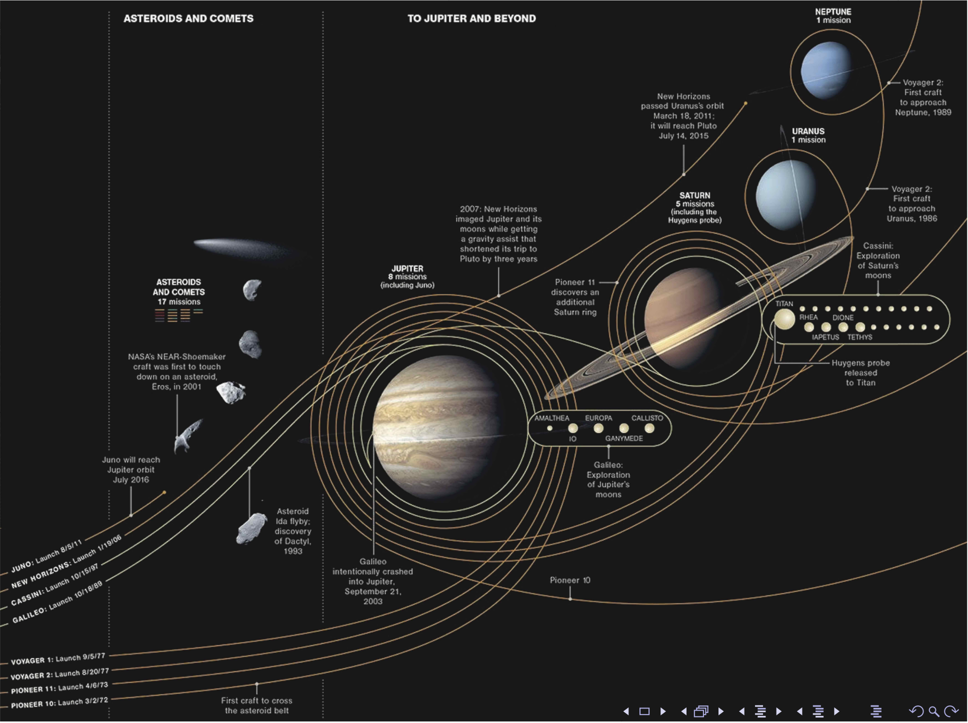
# Ocean worlds



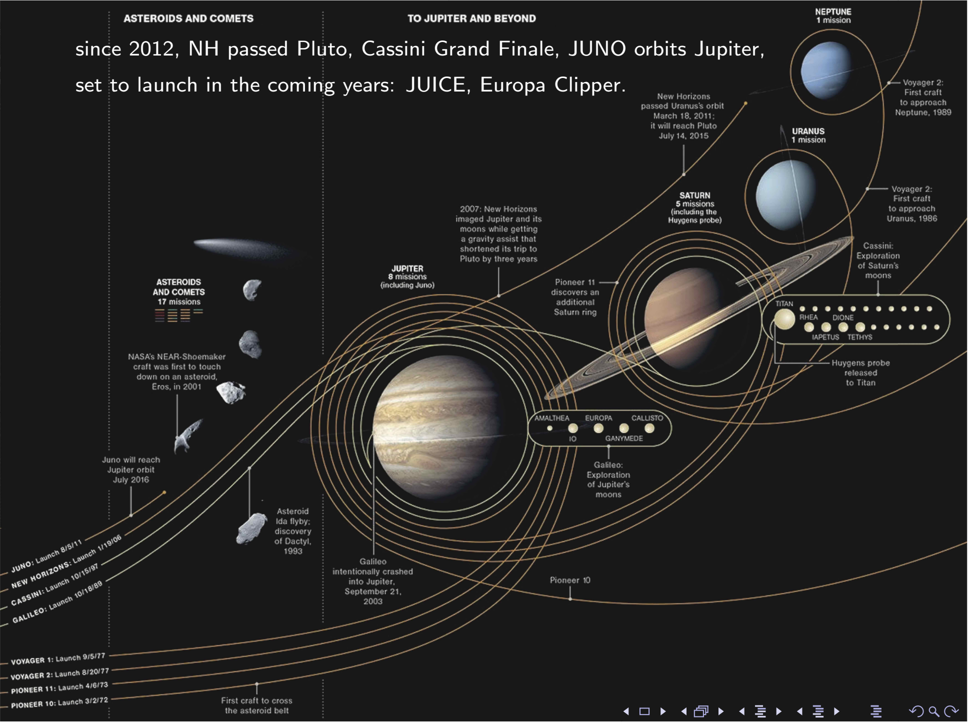

- the outer solar system: giant planets with moons, small planets/asteroids/TNOs,
- abundance of water and other volatiles beyond the snow line,
- formation history and evolution probably differ from that of terrestrial planets: slower and cooler for all planetary objects besides the giants.

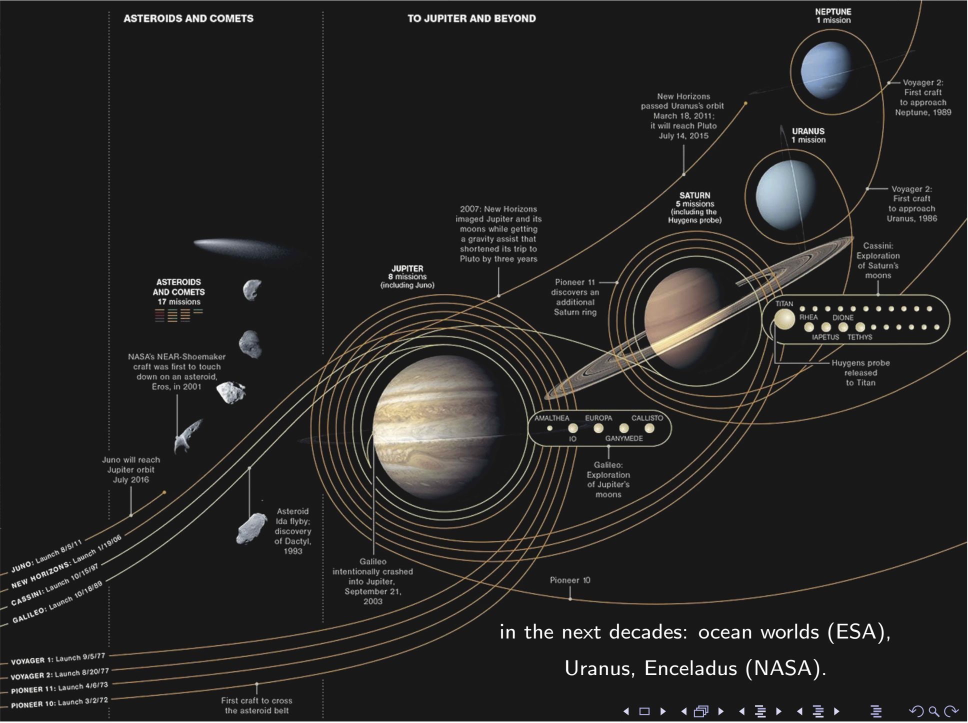



- very much a data driven science (nothing was really added to the knowledge of Galilean satellites after their discovery until the 1980s),
- opportunity driven exploration: first the Moon and Mars, then other terrestrial planets,
- outer solar system first visited through flybys by the Pioneer 10 & 11 and Voyager 1 & 2 probes (also see New Horizons).

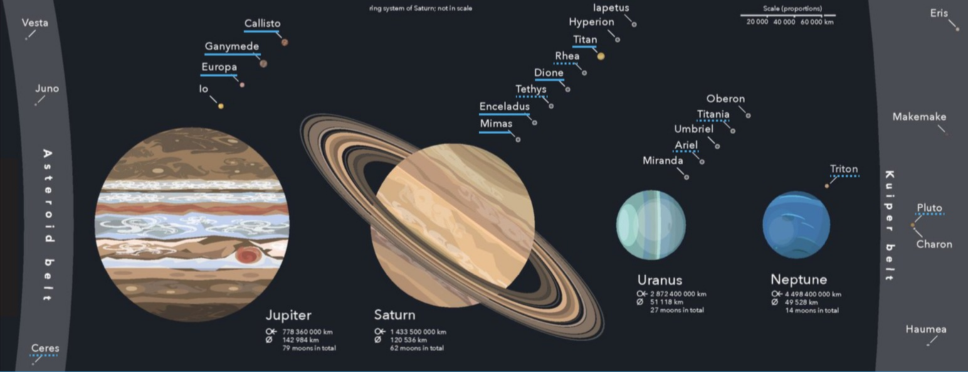

ASTEROIDS AND COMETS
TO JUPITER AND BEYOND
NEPTUNE
1 mission
Voyager 2: First craft to approach Neptune, 1989
New Horizons passed Uranus's orbit March 18, 2011; it will reach Pluto July 14, 2015
URANUS
1 mission
Voyager 2: First craft to approach Uranus, 1986
SATURN
5 missions (including the Huygens probe)
2007: New Horizons imaged Jupiter and its moons while getting a gravity assist that shortened its trip to Pluto by three years
Cassini: Exploration of Saturn's moons
ASTEROIDS AND COMETS
17 missions
JUPITER
8 missions (including Juno)
Pioneer 11 discovers an additional Saturn ring
TITAN
RHEA
DIONE
IAPETUS
TETHYS
NASA's NEAR-Shoemaker craft was first to touch down on an asteroid, Eros, in 2001
Huygens probe released to Titan
AMALTHEA
EUROPA
CALLISTO
IO
GANYMEDE
Juno will reach Jupiter orbit July 2016
Galileo: Exploration of Jupiter's moons
Asteroid Ida flyby; discovery of Dactyl, 1993
JUNO: Launch 8/5/11
NEW HORIZONS: Launch 1/19/06
CASSINI: Launch 10/15/97
GALILEO: Launch 10/18/89
Galileo intentionally crashed into Jupiter, September 21, 2003
Pioneer 10
VOYAGER 1: Launch 9/5/77
VOYAGER 2: Launch 8/20/77
PIONEER 11: Launch 4/6/73
PIONEER 10: Launch 3/2/72
First craft to cross the asteroid belt

since 2012, NH passed Pluto, Cassini Grand Finale, JUNO orbits Jupiter, set to launch in the coming years: JUICE, Europa Clipper.



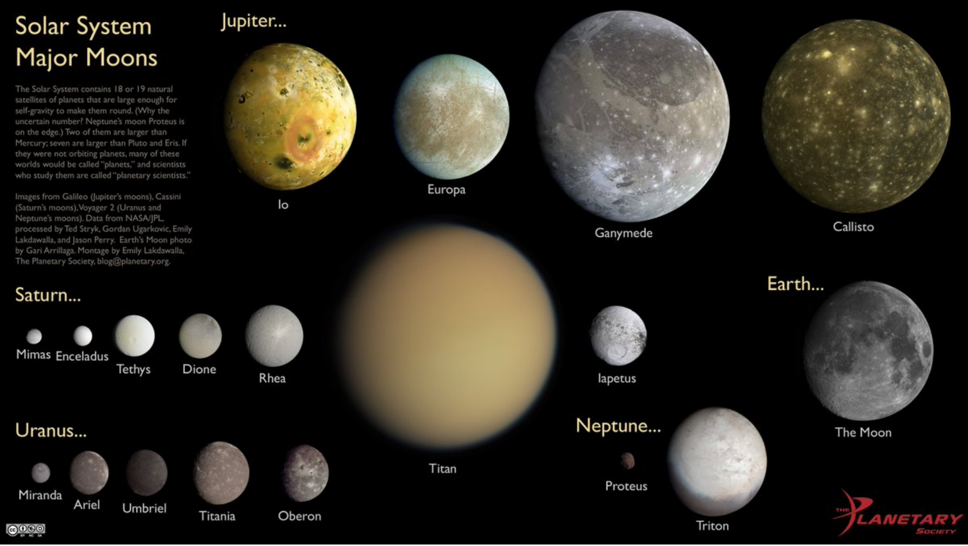



in the next decades: ocean worlds (ESA), Uranus, Enceladus (NASA).

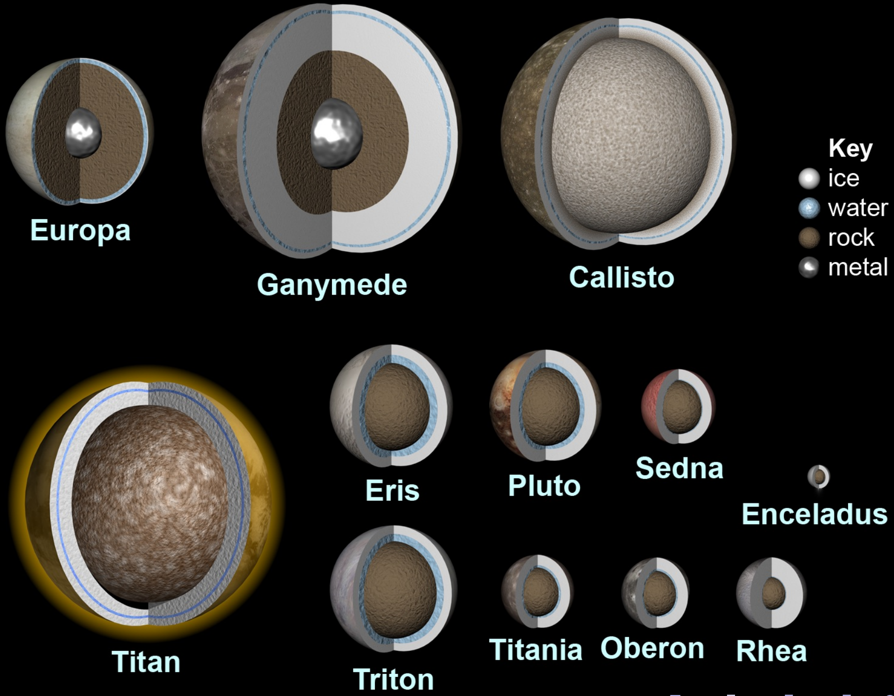


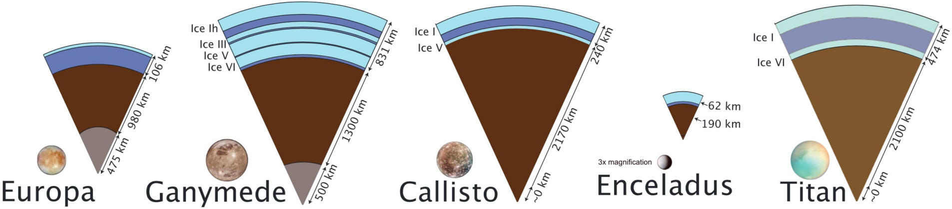

ocean worlds in the outer solar system:

- from the asteroid belt to the Kuiper belt (moons, asteroids, mini-planets),
- from planet-size moons to much smaller objects,
- hydrospheres: several tens of Earth oceans for large objects, water/rock fraction 100s of times Earth's even for smallest bodies,
- ocean worlds might be the rule rather than the exception.


Solar System
Major Moons
The Solar System contains 18 or 19 natural satellites of planets that are large enough for self-gravity to make them round. (Why the uncertain number? Neptune's moon Proteus is on the edge.) Two of them are larger than Mercury; seven are larger than Pluto and Eris. If they were not orbiting planets, many of these worlds would be called "planets," and scientists who study them are called "planetary scientists."
Images from Galileo (Jupiter's moons), Cassini (Saturn's moons), Voyager 2 (Uranus and Neptune's moons). Data from NASA/JPL, processed by Ted Stryk, Gordan Ugarkovic, Emily Lakdawalla, and Jason Perry. Earth's Moon photo by Gari Arrillaga. Montage by Emily Lakdawalla, The Planetary Society, blog@planetary.org.
Jupiter...
Io
Europa
Ganymede
Callisto
Saturn...
Mimas
Enceladus
Tethys
Dione
Rhea
Titan
Iapetus
Earth...
The Moon
Uranus...
Miranda
Ariel
Umbriel
Titania
Oberon
Neptune...
Proteus
Triton
THE PLANETARY SOCIETY

the Moon Ganymede


Europa
Ganymede
Callisto
Key
ice
water
rock
metal
Titan
Eris
Pluto
Sedna
Enceladus
Triton
Titania
Oberon
Rhea

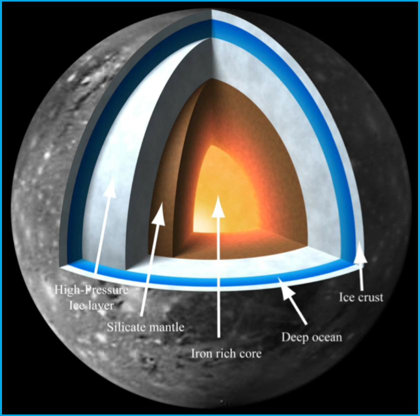



why are ocean worlds interesting?

- small terrestrial planets (rock mantle, sometimes metallic core), surrounded by an hydrosphere (liquid water and ices?),
- as such, may involve magmatism, dynamo action (Ganymede) and pertain to the comparative study of terrestrial planets, constituting a relatively numerous sample,
- as these bodies harbor liquid water together with energy sources, most promising targets in terms of habitability in the solar system which motivates space exploration.
- much less observational constraints on the interior (e.g. no seismology) $\oplus$ a larger sample: while governing equations are identical, the status of numerical models differ.

# Interior dynamics

# Interior dynamics: liquid versus solid layers




- solid (ice/rocks) and liquid (water/molten metal alloy), often two-phase
- time scale strongly differs (viscosity) from that of Earth's oceans for liquid layers to that of tectonic plates,
- in the case of liquid layers: turbulence, appropriate regimes may be hard to reach numerically,
- in the case of solid layers: much simpler dynamics but the fluid is much more complex (rheology, various phases).

# Conservation equations for a liquid layer (anelastic approx.)

- continuity:

$$\nabla \cdot (\rho_r \mathbf{u}) = 0,$$

- Navier-Stokes:

$$\rho_r \left( \frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u} + 2\boldsymbol{\Omega} \times \mathbf{u} \right) = -\nabla p' + \rho' \mathbf{g} + \mathbf{j} \times \mathbf{B} + \nabla \cdot \mathbf{S},$$

- induction:

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times \left( \mathbf{u} \times \mathbf{B} - \lambda \nabla \times \mathbf{B} \right), \nabla \cdot \mathbf{B} = 0,$$

- energy:

$$\rho_r c_p \left( \frac{\partial T'}{\partial t} + \mathbf{u} \cdot \nabla T' \right) - \alpha T_r \left( \frac{\partial p'}{\partial t} + \mathbf{u} \cdot \nabla p' \right) = -\nabla \mathbf{F} + H_\eta + H_\lambda + H_r$$

- composition:

$$\frac{\partial \xi}{\partial t} + \mathbf{u} \cdot \nabla \xi = \nabla \cdot \left( \kappa_\xi \rho_r \nabla \xi \right) + H_\xi$$

Conservation equations for a liquid layer (anelastic approx.): no magnetic field

- continuity:

$$\nabla \cdot (\rho_r \mathbf{u}) = 0,$$

- Navier-Stokes:

$$\rho_r \left( \frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u} + 2\boldsymbol{\Omega} \times \mathbf{u} \right) = -\nabla p' + \rho' \mathbf{g} + \mathbf{j} \times \mathbf{B} + \nabla \cdot \mathbf{S},$$

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- composition:

$$\frac{\partial \xi}{\partial t} + \mathbf{u} \cdot \nabla \xi = \nabla \cdot (\kappa_\xi \rho_r \nabla \xi) + H_\xi$$

Conservation equations for a solid layer (anelastic approx.): no rotation

- continuity:

$$\nabla \cdot (\rho_r \mathbf{u}) = 0,$$

- Navier-Stokes:

$$\rho_r \left( \frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u} + 2\boldsymbol{\Omega} \times \mathbf{u} \right) = -\nabla p' + \rho' \mathbf{g} + \nabla \cdot \mathbf{S},$$

- energy:

$$\rho_r c_p \left( \frac{\partial T'}{\partial t} + \mathbf{u} \cdot \nabla T' \right) - \alpha T_r \left( \frac{\partial p'}{\partial t} + \mathbf{u} \cdot \nabla p' \right) = -\nabla \mathbf{F} + H_\eta + H_r$$

- composition:

$$\frac{\partial \xi}{\partial t} + \mathbf{u} \cdot \nabla \xi = \nabla \cdot \left( \kappa_\xi \rho_r \nabla \xi \right) + H_\xi$$

Conservation equations for a solid layer (anelastic approx.): no inertia

- continuity:

$$\nabla \cdot (\rho_r \mathbf{u}) = 0,$$

- Navier-Stokes:

$$\rho_r \left( \frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u} \right) = -\nabla p' + \rho' \mathbf{g} + \nabla \cdot \mathbf{S},$$

- energy:

$$\rho_r c_p \left( \frac{\partial T'}{\partial t} + \mathbf{u} \cdot \nabla T' \right) - \alpha T_r \left( \frac{\partial p'}{\partial t} + \mathbf{u} \cdot \nabla p' \right) = -\nabla \mathbf{F} + H_\eta + H_r$$

- composition:

$$\frac{\partial \xi}{\partial t} + \mathbf{u} \cdot \nabla \xi = \nabla \cdot \left( \kappa_\xi \rho_r \nabla \xi \right) + H_\xi$$

Conservation equations for a solid layer (anelastic approx.): rheology

- continuity:

$$\nabla \cdot (\rho_r \mathbf{u}) = 0,$$

- Navier-Stokes:

$$0 = -\nabla p' + \rho' \mathbf{g} + \nabla \cdot \mathbf{S},$$

with

$$S_{ij} = 2\eta \left( e_{ij} - \frac{1}{3} \frac{\partial u_i}{\partial x_i} \right), e_{ij} = \frac{1}{2} \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right),$$

- energy:

$$\rho_r c_p \left( \frac{\partial T'}{\partial t} + \mathbf{u} \cdot \nabla T' \right) - \alpha T_r \left( \frac{\partial p'}{\partial t} + \mathbf{u} \cdot \nabla p' \right) = -\nabla \mathbf{F} + H_\eta + H_r$$

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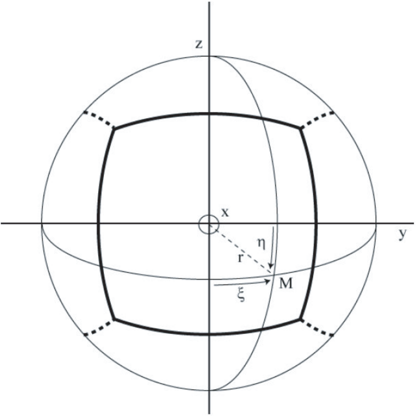
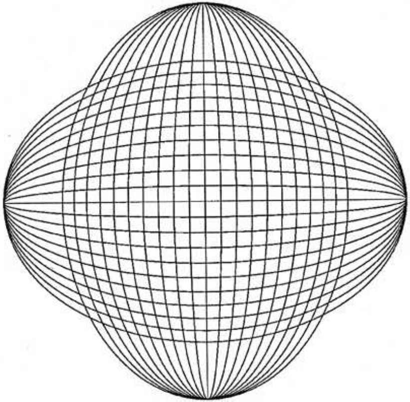
# OEDIPUS

# The cubed sphere mesh



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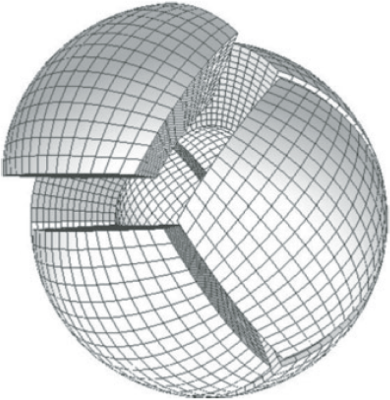
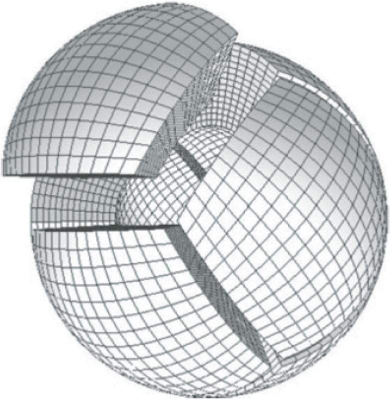
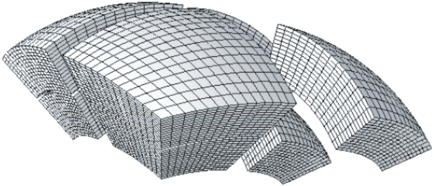


# The cubed sphere mesh and simple block parallelism





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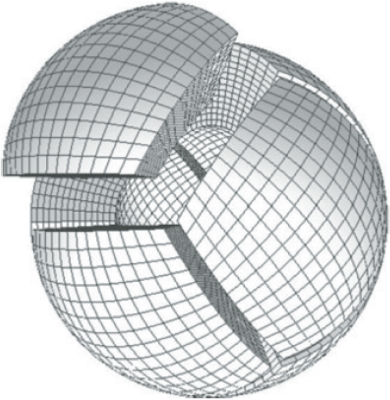

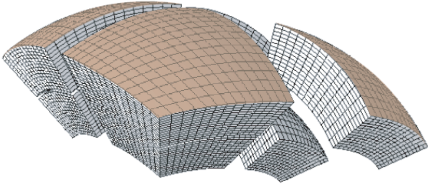

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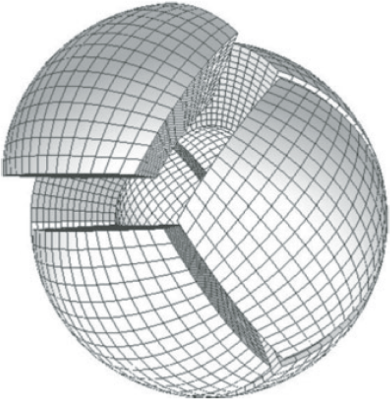

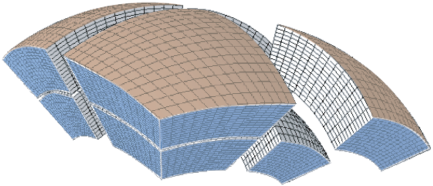

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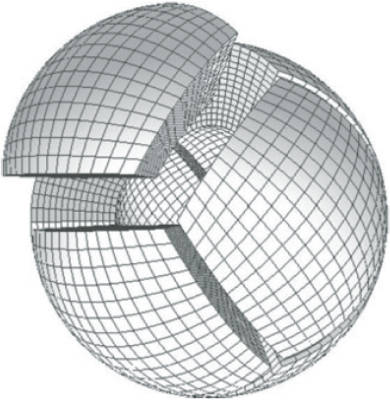

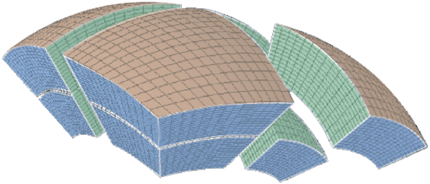

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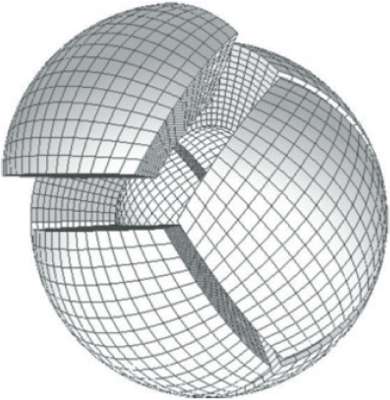
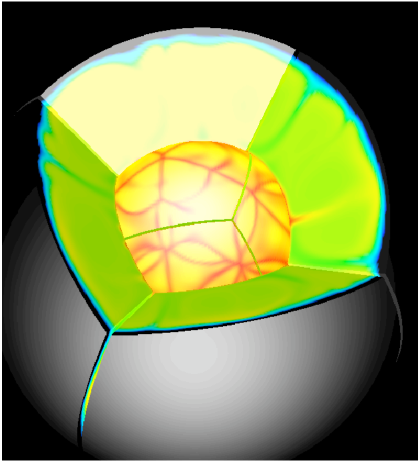
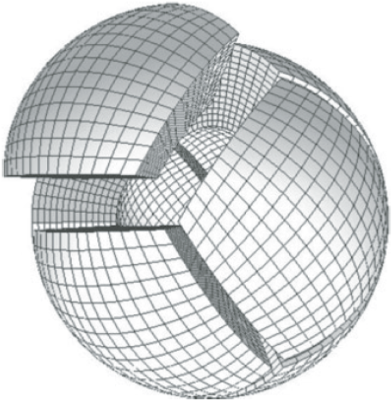
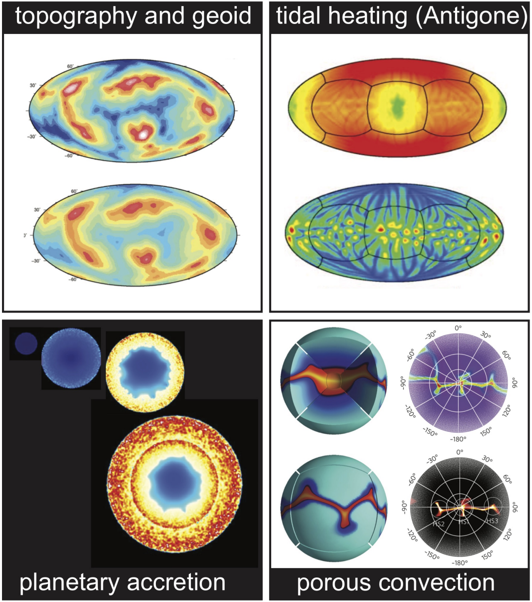


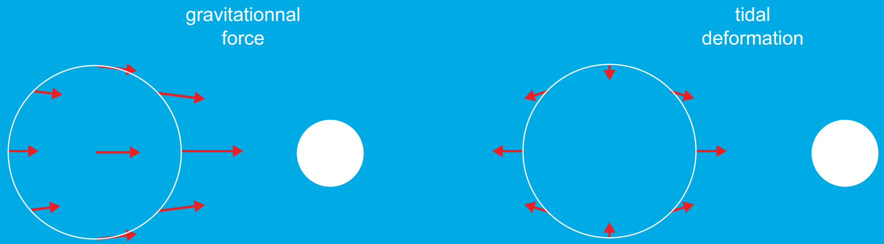


# OEDIPUS




topography and geoid
tidal heating (Antigone)
planetary accretion
porous convection

# Tidal deformation



# Tidal heating

- tidal deformation is maximal for the less rigid material layers : oceans and atmosphere for the Earth, partially molten rocks for Io, “warm” ice (close to the melting point) for Europa,
- part of the deformation (non elastic) is not reversible and the associated energy converted into heat,
- for Jupiter and Saturn’s moons, the proximity of the giant planet raises larger tides and eccentricity maintained by orbital resonances with other moons induces a varying tidal potential that warrants efficient tidal dissipation,
- while other hat sources (radioactive, primordial) decay with the planet’s age, tidal dissipation is linked to orbital evolution and may induce less monotonous evolutions.

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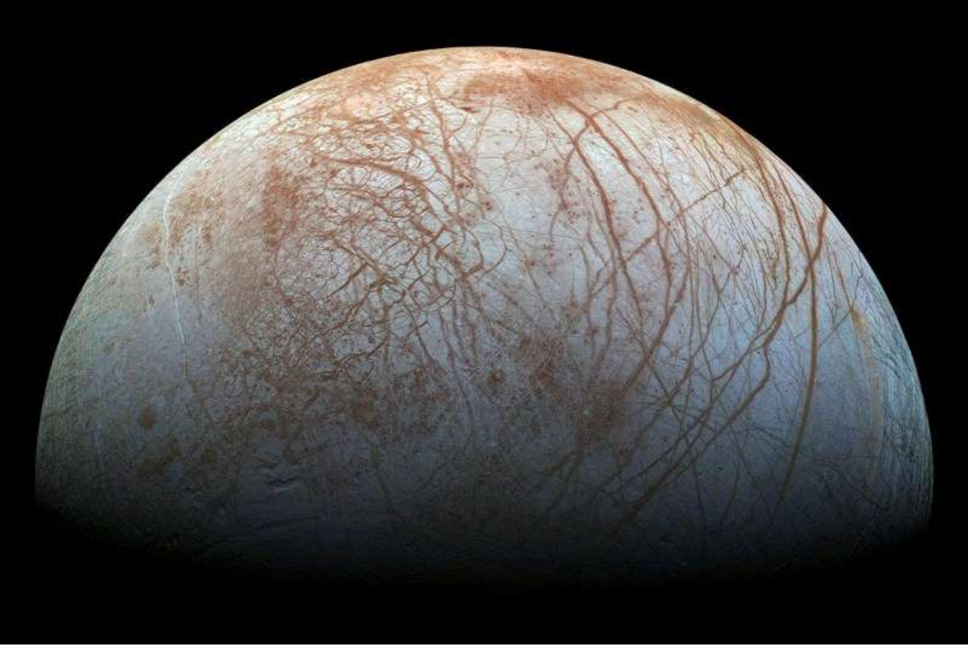
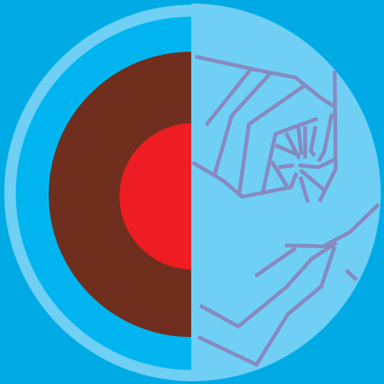


# Magmatism on Europa's seafloor

# What are the conditions for present-day magmatism on Europa?

Běhounková et al., *Geophys. Res. Lett.*, 2021.



- tectonically active ice shell (e.g. Kattenhorn and Procter, 2014), a salty ocean (Kivelson et al., 2000) interacting with possibly active rocky interior (Moore and Hussmann, 2009),
- chemical evolution of Europa's ocean and its habitability conditioned by the interaction with the rocky seafloor (Vance et al., 2016),
- the habitability potential influenced by the heat released to seafloor (Altair et al., 2018).

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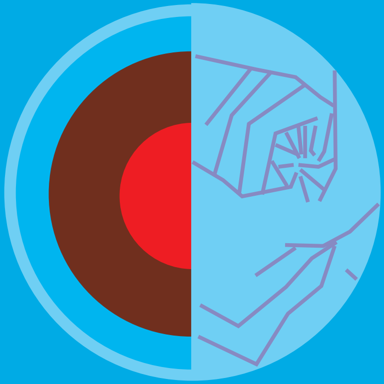
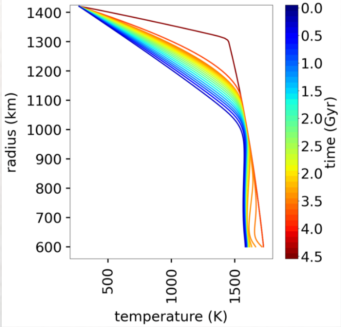


- thermal state of Europa's mantle depending on heat sources available and heat extraction,
- what are the requirements for sustainability of melting in Europa's mantle?
- which measurements can indicate a recent volcanic activity?

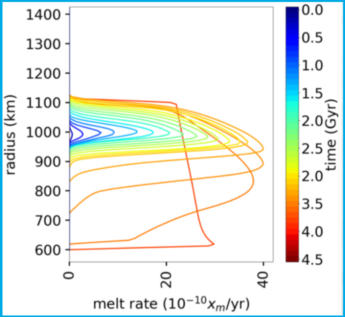
What are the conditions for present-day magmatism on Europa?

Běhounková et al., *Geophys. Res. Lett.*, 2021.

temperature profile



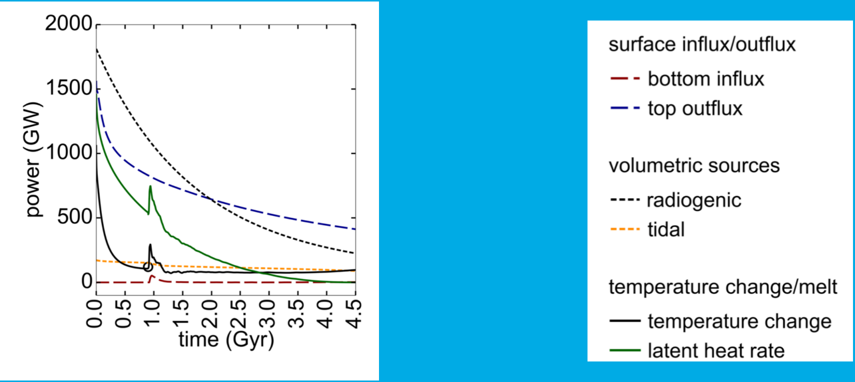

melting profile




- initial conditions: temperature profile follows the solidus temperature except in the upper part,
- huge melting at the beginning of evolution,
- melt production at the base of the conductive lid.

What are the conditions for present-day magmatism on Europa?

Běhounková et al., *Geophys. Res. Lett.*, 2021.



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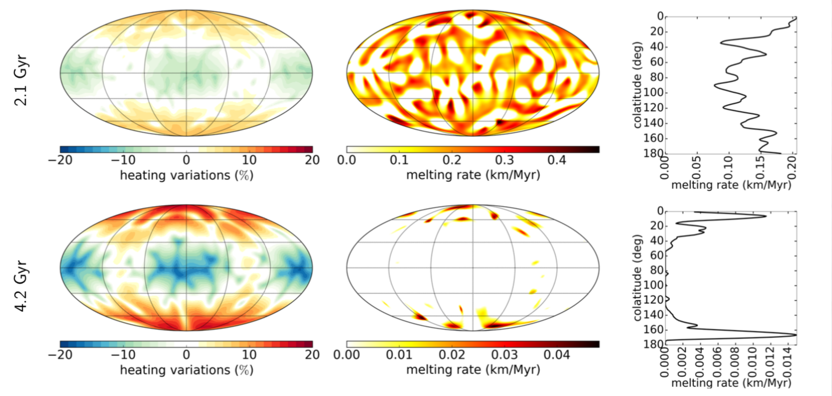
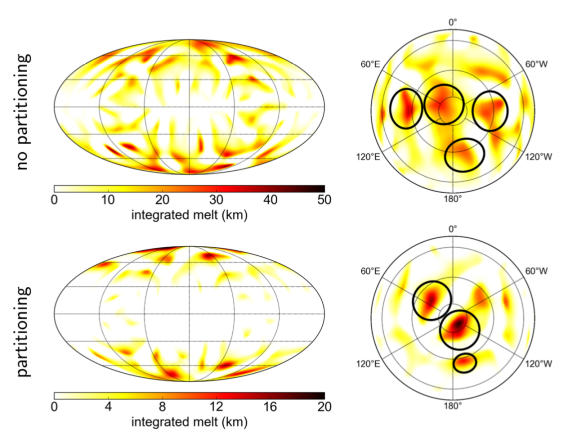



- concentration of melting zones at high latitudes due to tidal dissipation.

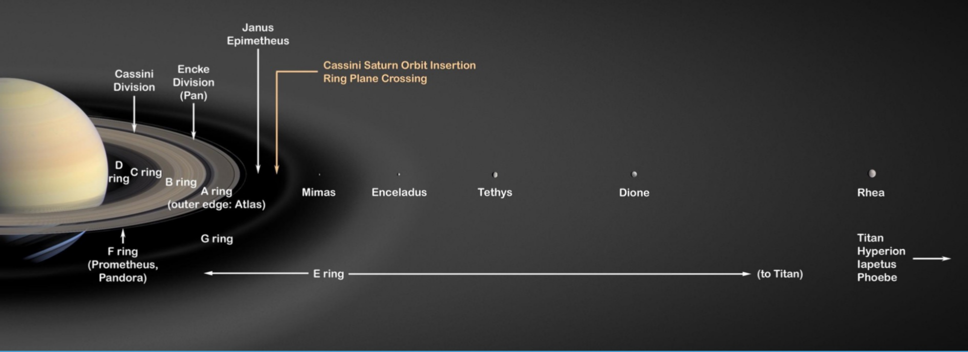
# What are the conditions for present-day magmatism on Europa?

Běhounková et al., *Geophys. Res. Lett.*, 2021.



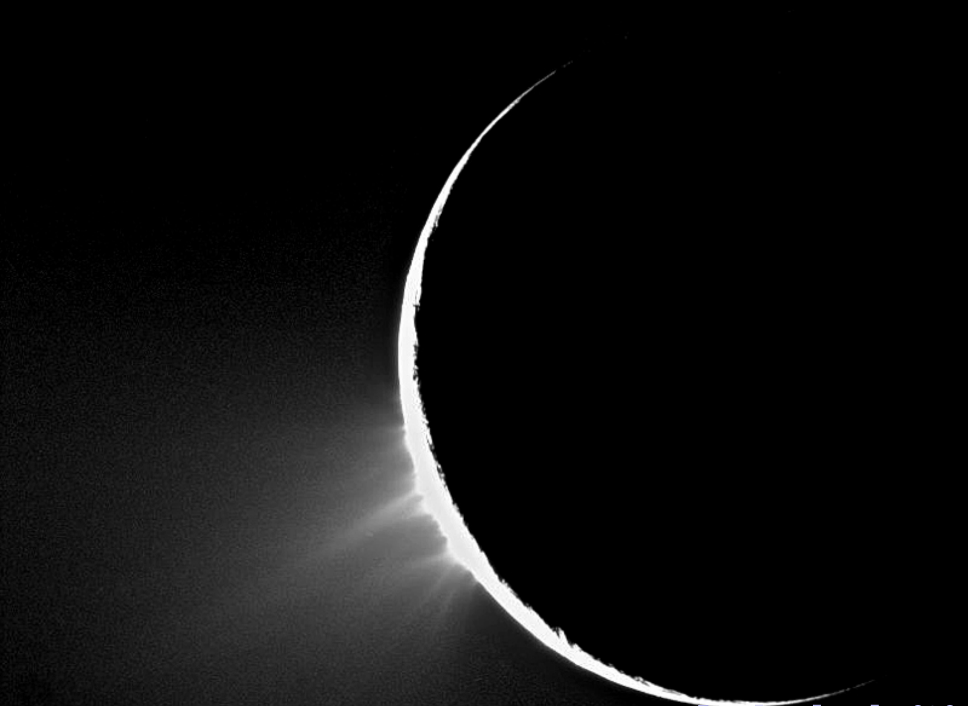

- generated melt volumes during last pulse 0.25 Gyr: $10^7$ $km^3$ in each area, comparable to Large Igneous Provinces on Earth (Ernst et al., 2005; Ross et al., 2005; Sobolev et al., 2011).

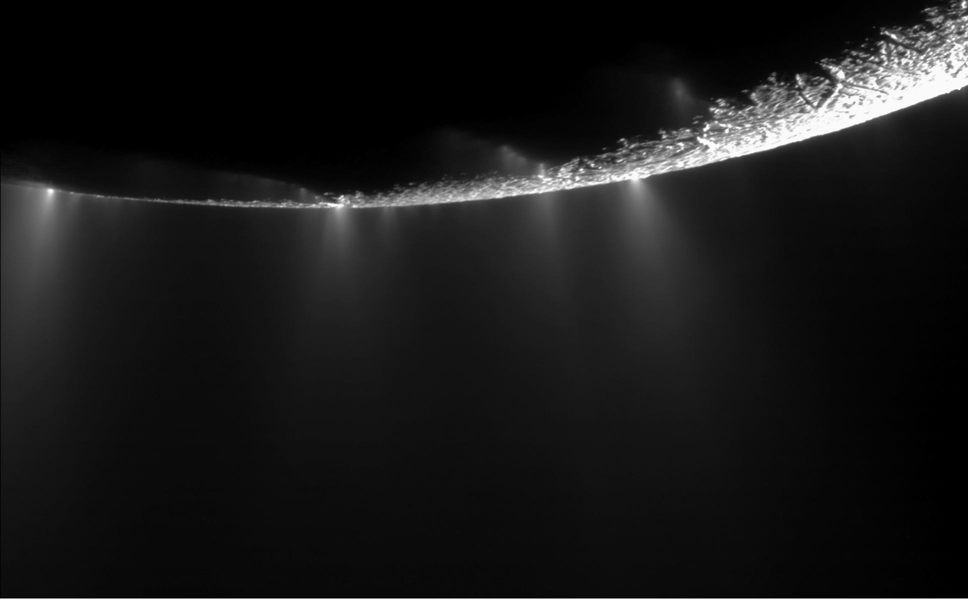
the enigmatic activity at Enceladus' south pole

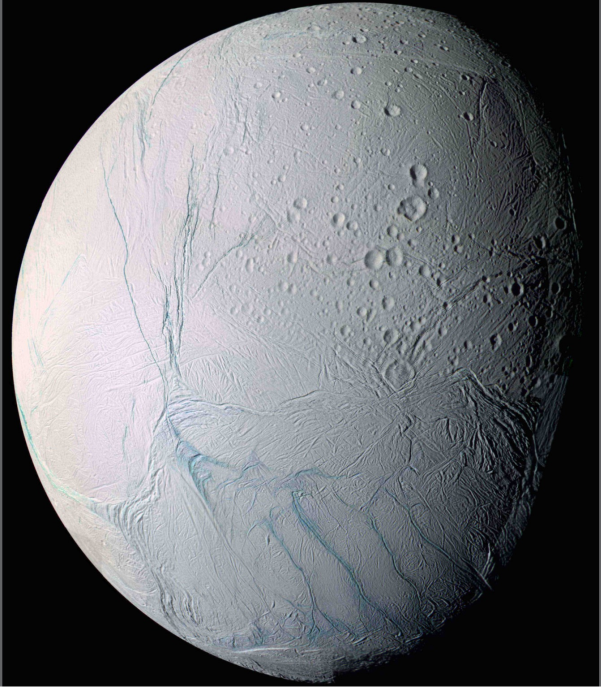


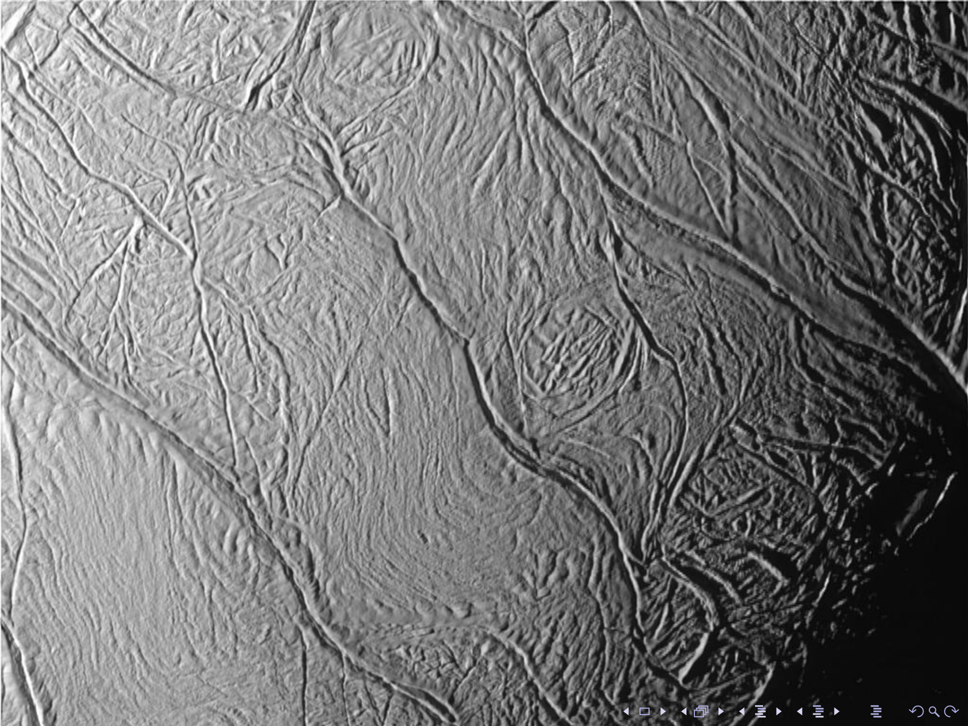

- Saturn's (♄) sixth moon, $R_s = 252$ km, $T \simeq 33$ h, $e \simeq 5 \times 10^{-3}$
- embedded in the densest part of Saturn's diffuse E-ring,
- *Voyager 2*: contrast between relatively young regions near equator and older, high latitude regions, very much unlike Mimas' ancient cratered surface,

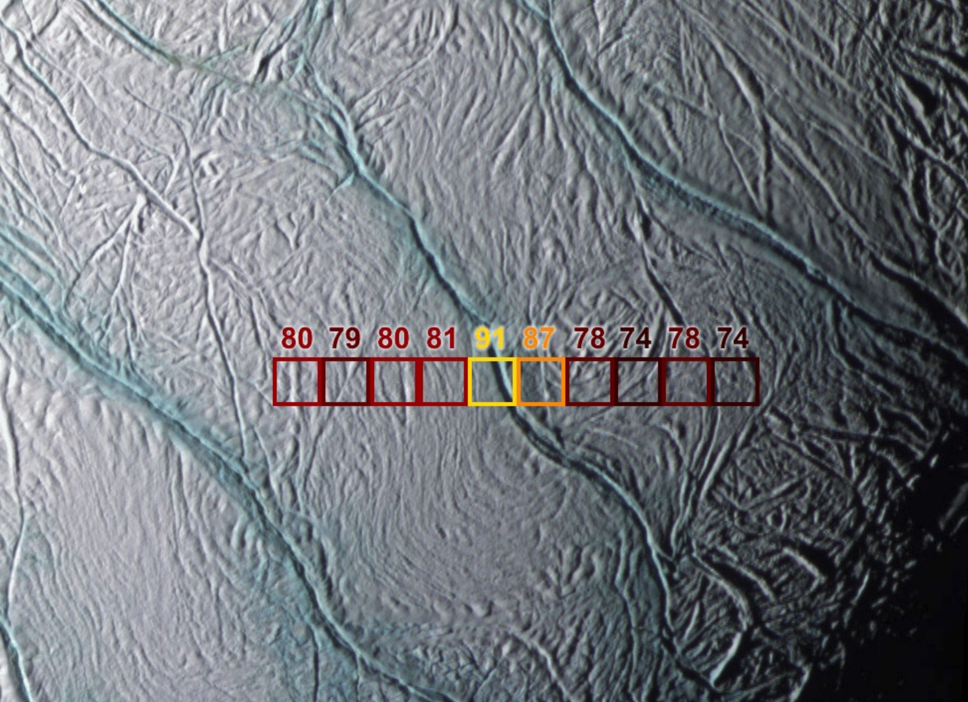
$\Rightarrow$ is Enceladus the source of E-ring's material ? (Terrile and Cook, 1981)







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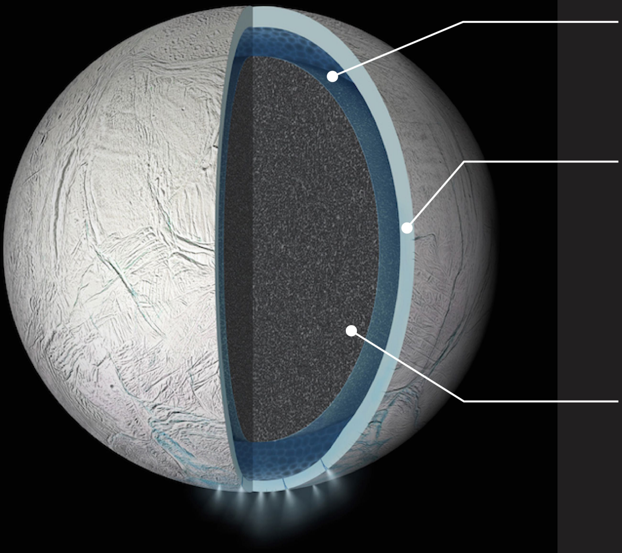


buried global ocean

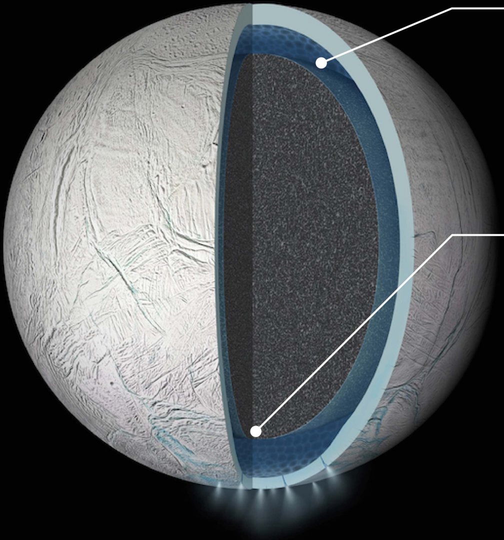
30-40 km thick
(Thomas et al., 2016)

very uneven ice shell

25-30 km thick in average
up to 35 km at equator
less than 5 km at south pole
(Čadek et al., 2016 ;
Beuthe et al., 2016)

porous rock core

filled with 20-30 % water
(e.g. Roberts, 2015 ;
Waite et al., 2017)



ocean is salty

Na (and K) salts in E-ring
(Postberg et al., 2009)

salts and organics in plume
(Postberg et al., 2011)

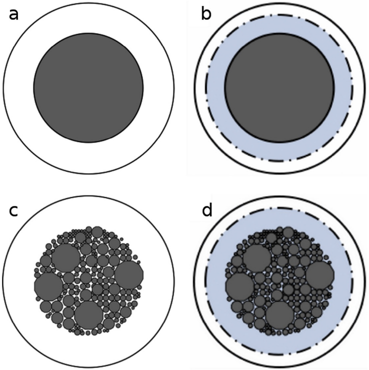
deep hydrothermalism

nano-silica particles
in Saturn's environment
⇒ 90°C, > 40 km deep
(Hsu et al., 2015)

$H_2$ in the plume
⇒ hydrothermal reactions
(Waite et al., 2017)

# Tidal heat production in Enceladus' deep interior (2): the core

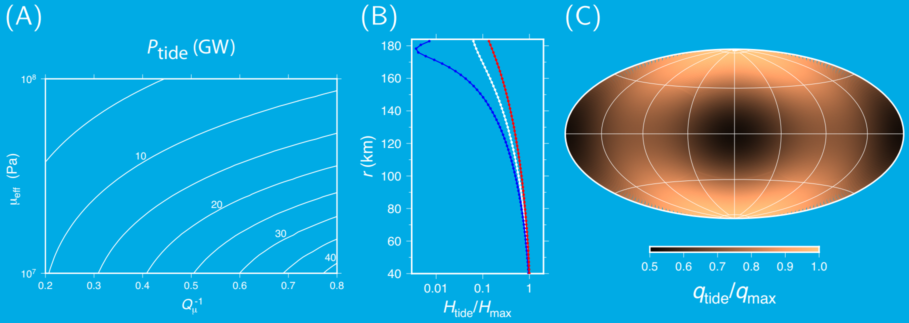
- due to low central pressure, Enceladus' core is likely unconsolidated, even if accretion involved large impacts (Monteux et al., 2016),
- first gravity measurements (Iess et al., 2014) yield $\rho_{core} \simeq 2.4$ g cm$^{-3}$ $\rightarrow$ porosity could be as large as 20-25 %,
- porosity in excess to 20, % weakens the core with ice/water controlling the deformation,
- at present, a few GW could be generated by viscous dissipation in the core filled with ice.



*Roberts (2015)*

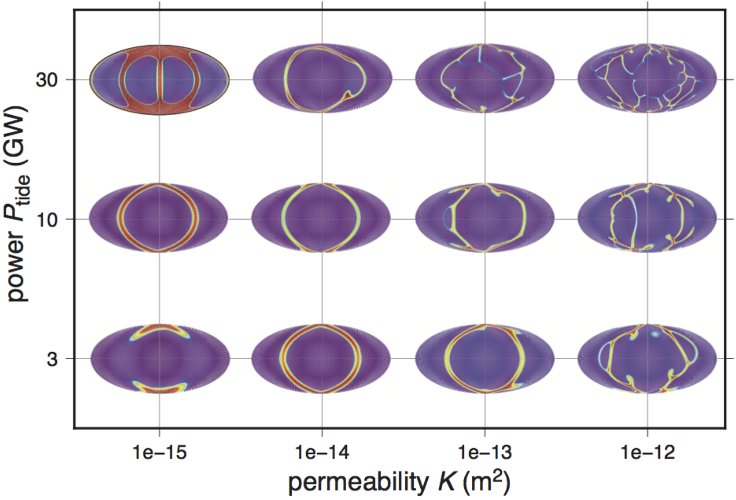
$\Rightarrow$ what power could be produced by dissipation in a core filled with liquid water ?

# Tidal dissipation in Enceladus porous core



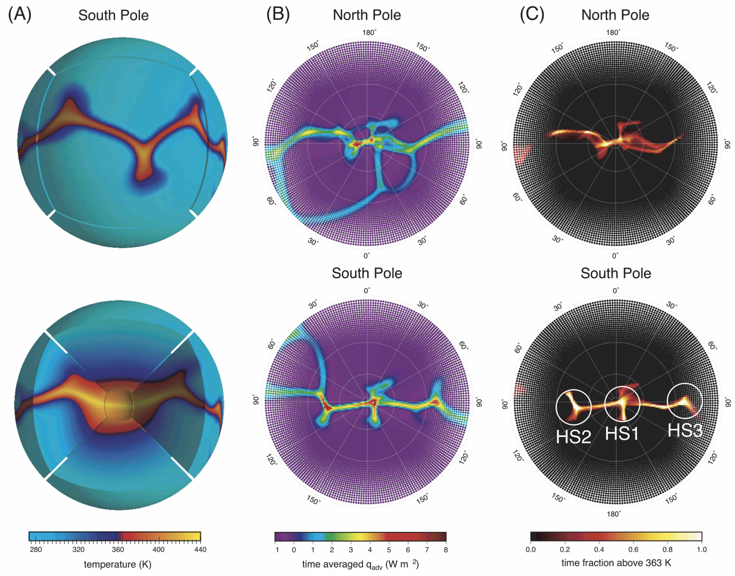

⇒ several 10s of GW can be produced with a slightly heterogeneous diffuse pattern: heating is maximal and homogeneous near the centre and decreases more slowly at the poles towards the surface

# Porous convection with heterogeneous (tidal) heating

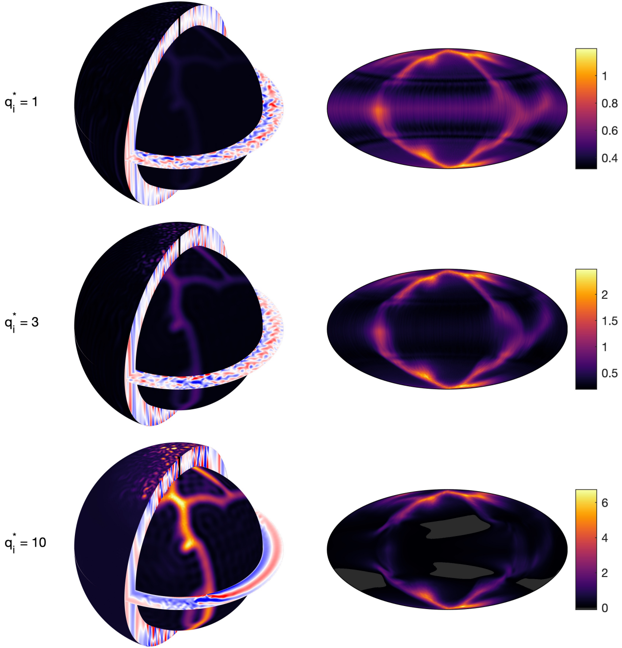



⇒ upwellings concentrated at the poles and trailing/leading meridians where maximal dissipation occurs.

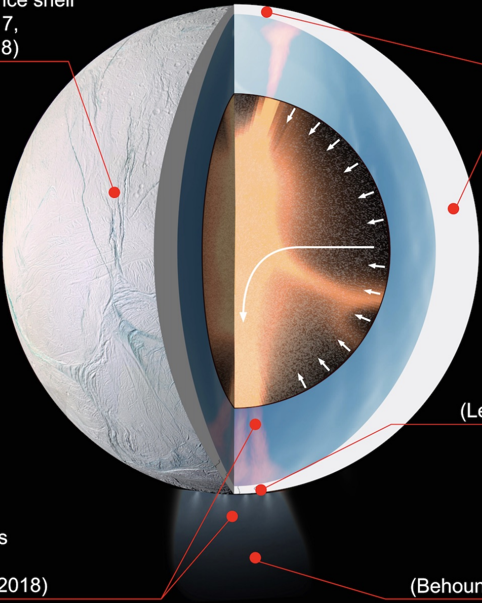
# Hot spots at the seafloor

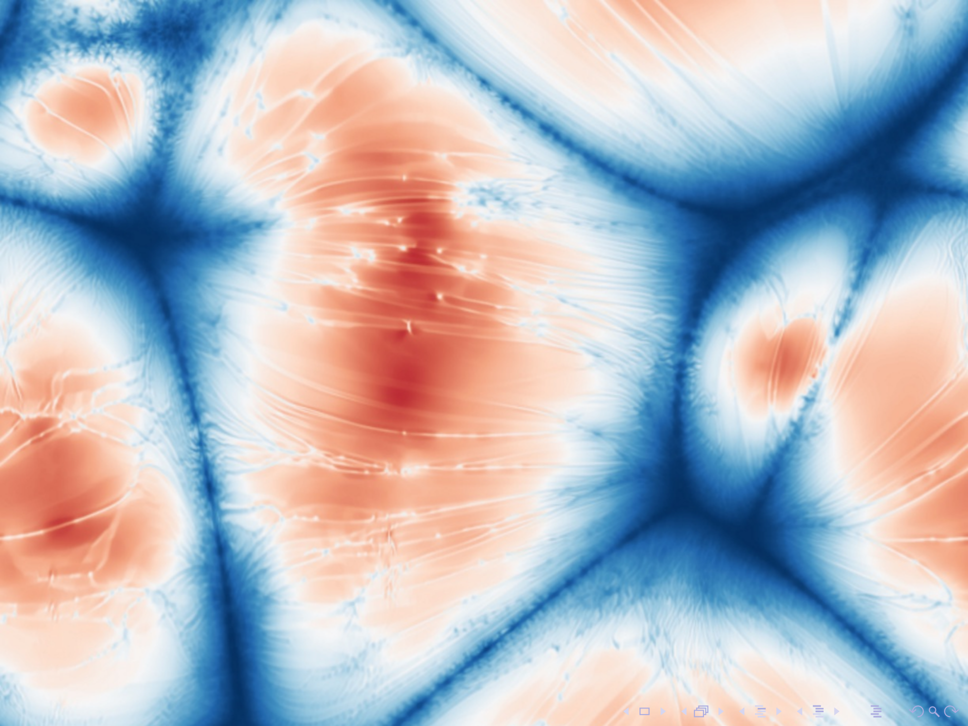


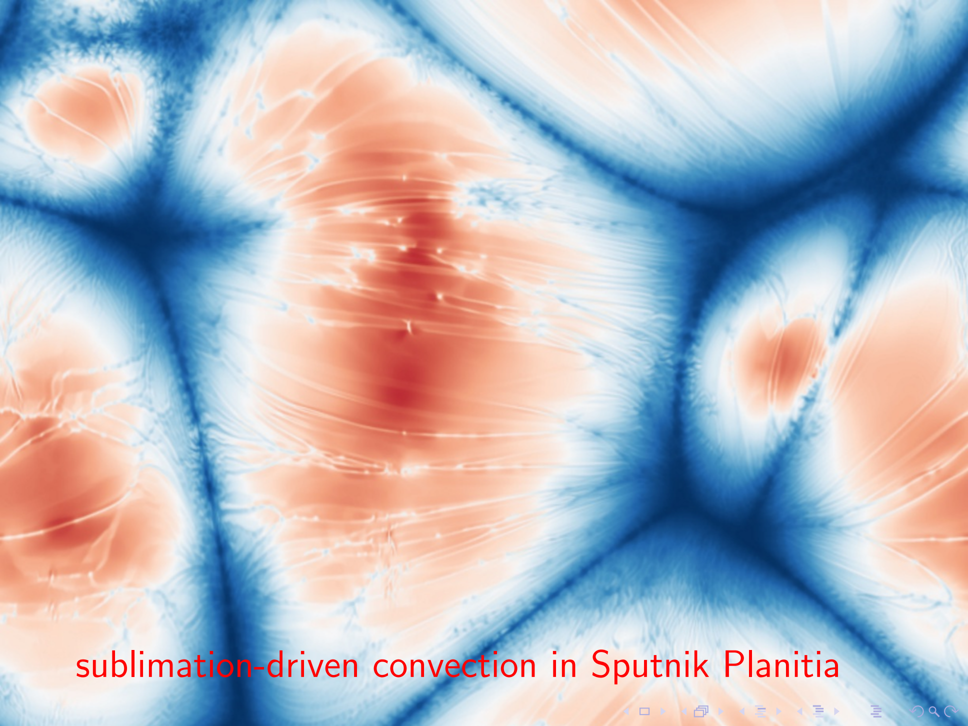
# Ocean circulation driven by seafloor heterogeneity



# hot vibrating core model (Choblet et al., Nat. Astro. 2017)

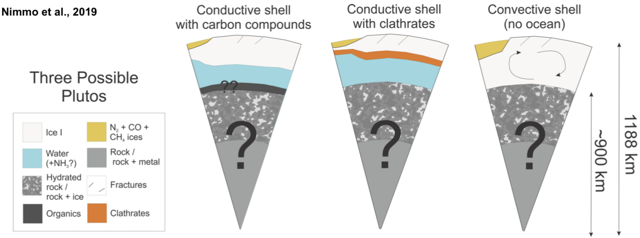





sublimation-driven convection in Sputnik Planitia

# Pluto's interior

- Pluto and Charo's masses determined from astrometry prior to New Horizons (HST, Earth-based, Brozović et al., 2015)
- after refined shape from NH's LORRI camera, Pluto's bulk density is $1854 \pm 11$ kg m$^{-3}$ (or 2/3 rock, 1/3 water),
- Pluto's differentiation is likely (icy surface, accretion and radiogenic heat models) but still uncertain, subsurface ocean is possible (several circumstantial clues but no direct evidence),
- carbon compounds could/might/should/must be present, clathrates...



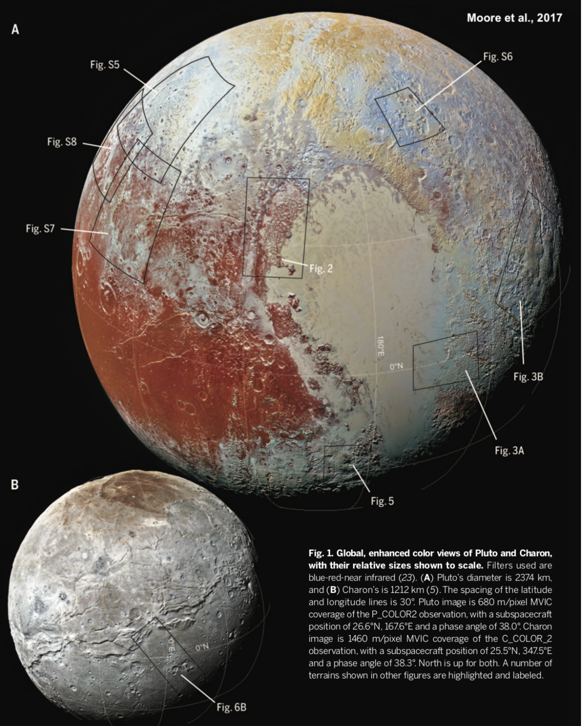
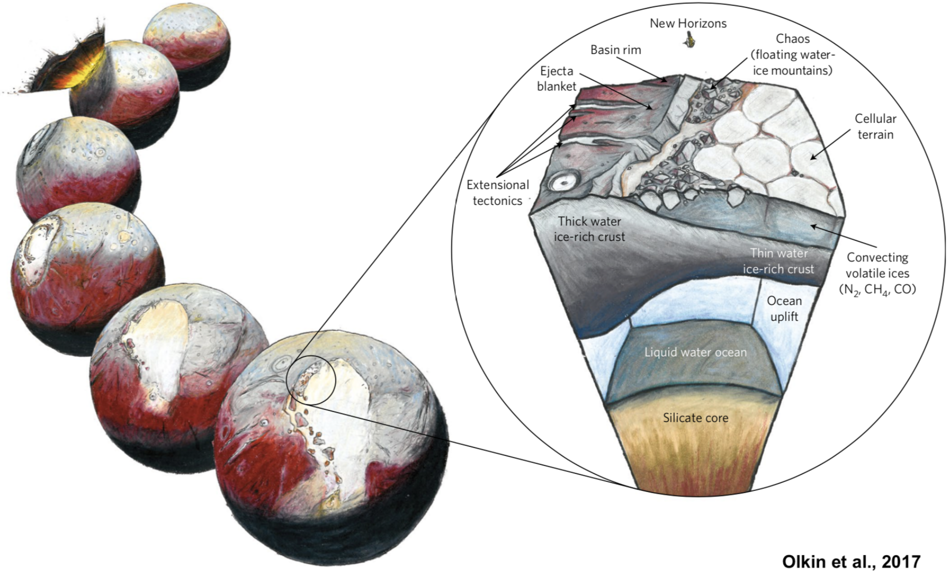



**Fig. 1. Global, enhanced color views of Pluto and Charon, with their relative sizes shown to scale.** Filters used are blue-red-near infrared (*23*). (**A**) Pluto's diameter is 2374 km, and (**B**) Charon's is 1212 km (*5*). The spacing of the latitude and longitude lines is 30°. Pluto image is 680 m/pixel MVIC coverage of the P_COLOR2 observation, with a subspacecraft position of 26.6°N, 167.6°E and a phase angle of 38.0°. Charon image is 1460 m/pixel MVIC coverage of the C_COLOR_2 observation, with a subspacecraft position of 25.5°N, 347.5°E and a phase angle of 38.3°. North is up for both. A number of terrains shown in other figures are highlighted and labeled.

# Pluto's geology

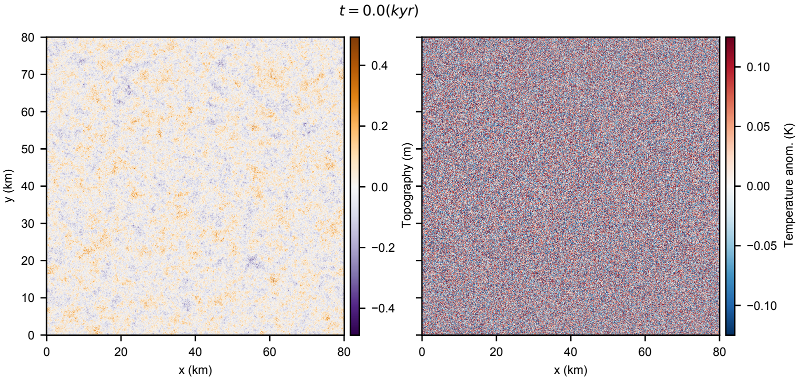
Cruikshank and Sheehan, 2018




Olkin et al., 2017

# A transient phenomenon: pattern maturation

$Ra_\infty = 10^7; R_\eta^\infty = 10^3$




- convection sets in with small scale plumes.

# Planetary scale convection as a result of climate

- the convective dynamics of SP's $N_2$ ice layer depends on Pluto's global climate,
- as such, it differs strongly from the subsolidus convection in the ice layers of Jupiter or Saturn (largely controlled by the interior heat budget), and would resemble ocean dynamics on Earth,
- on other sufficiently massive planetary bodies, a similar activity could occur if low-viscosity volatile ice ($N_2$, CO, $CO_2$ or possibly $CH_4$) is abundant - plausible candidates areTriton or Umbriel as well as large TNOs such as Eris and Makemake.