# Origin and evolution of Galilean satellites

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## Facts and open questions

1. The formation of Jupiter has implications for the formation of the Solar System
2. The origin of the Jovian regular satellites is linked to the conditions in the Solar Nebula and those of the accreting planet
3. The satellites in the Jovian System can track the evolution and interaction of Jupiter's System with the Solar System → collisional and capture events

**How did Jupiter form?** What is the main process leading to the formation?

- Was the core formed first, and the gas captured later or the core was formed by differentiation of an originally "quasi-uniform" self-gravitating gas sphere? → implications for Jupiter's composition and structure

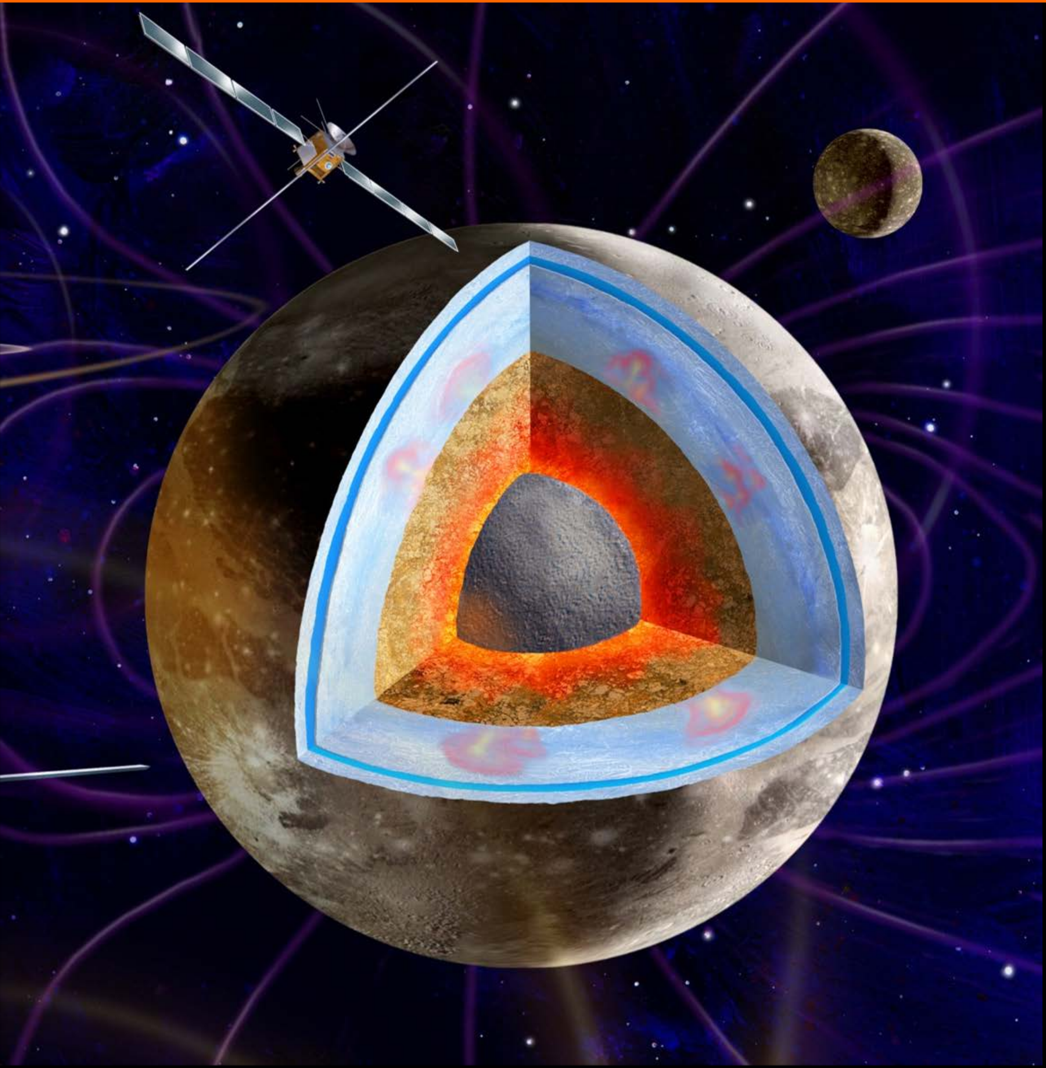
**How did the satellites form?**

- Was their formation related to the formation of the central body, or took place later? → implications for their structure and chemistry

**How different is the present Jovian system from the original system?**

- To which kind of dynamical and physical evolution the Jovian system underwent ?

## The origin of the Jovian regular satellites is not understood since:



- Compositional information still missing for determining elemental abundances in the Jovian sub-nebula and constraining those in the Solar Nebula
- Volatile abundances may allow us to evaluate the epoch and the environment of formation of the regular satellites
- The radial distribution and physical characteristics of satellites will give us clues on the nebular density profile

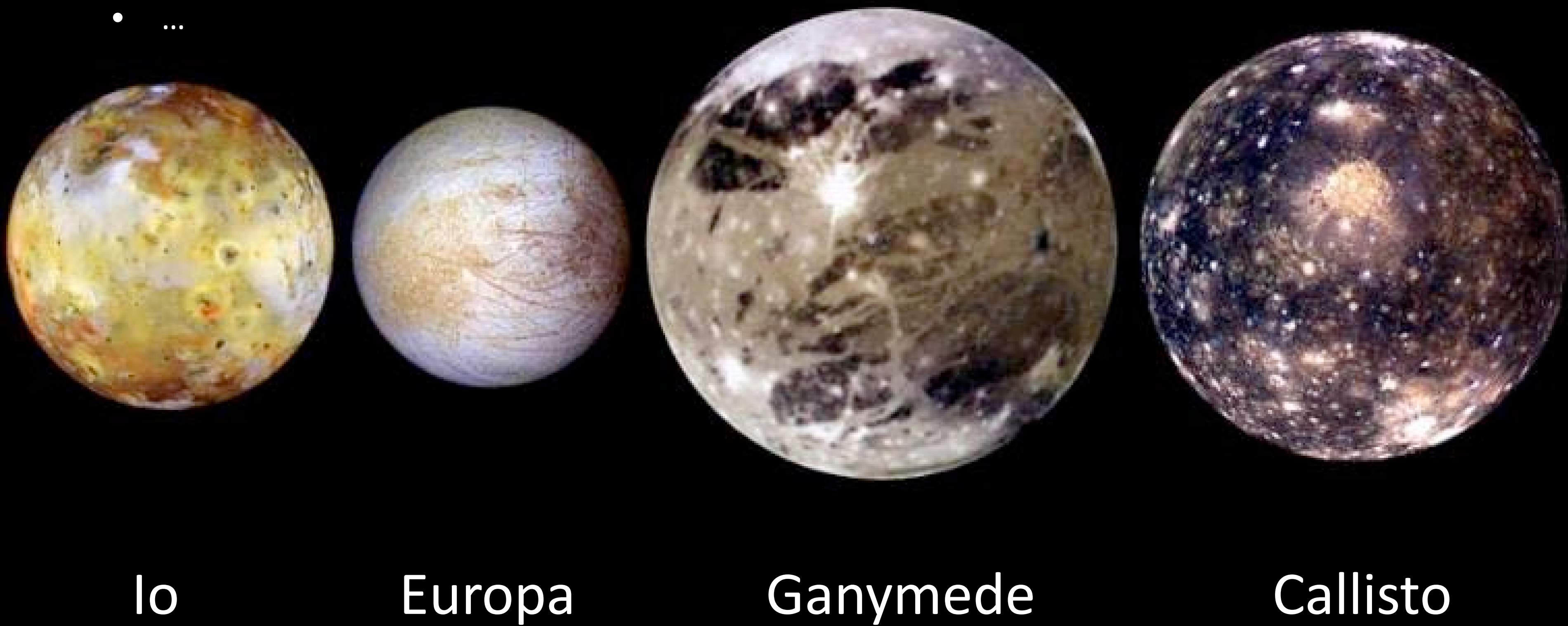
**Key observations still missing** but

Present structure and key elements responsible for the evolution are now relatively well understood – main topic of the next slides

## Surface of the moons

So many differences:

- Size
- Surface composition
- Degree of surface activity
- Surface ages
- …



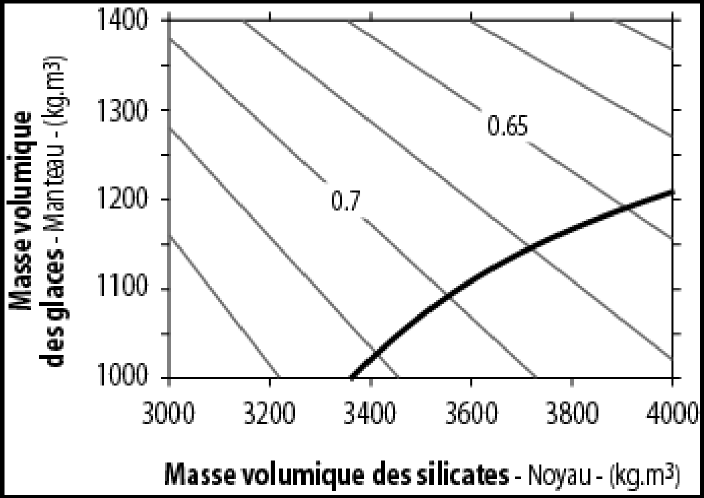
## Internal structure modeling – Not an unique solution

**Icy moons**

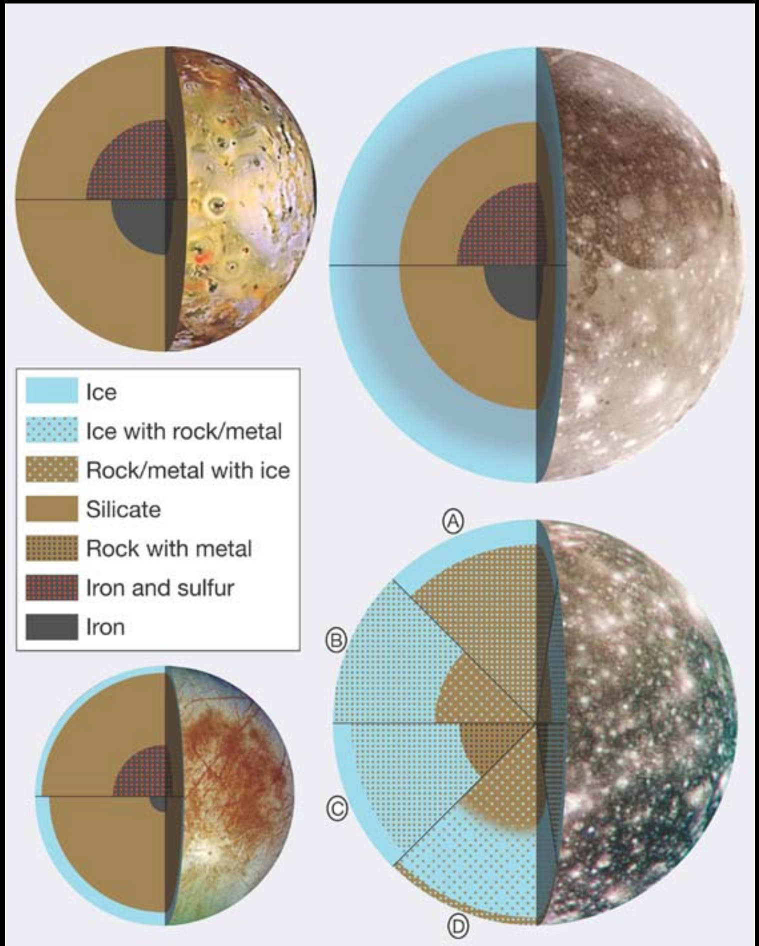
- Mass
- Radius
- $J_2$ & $C_{22}$
- Surface observations

Several structures for the same constraints…

-detailed review (F. Sohl)




Ganymede: 2 layers model

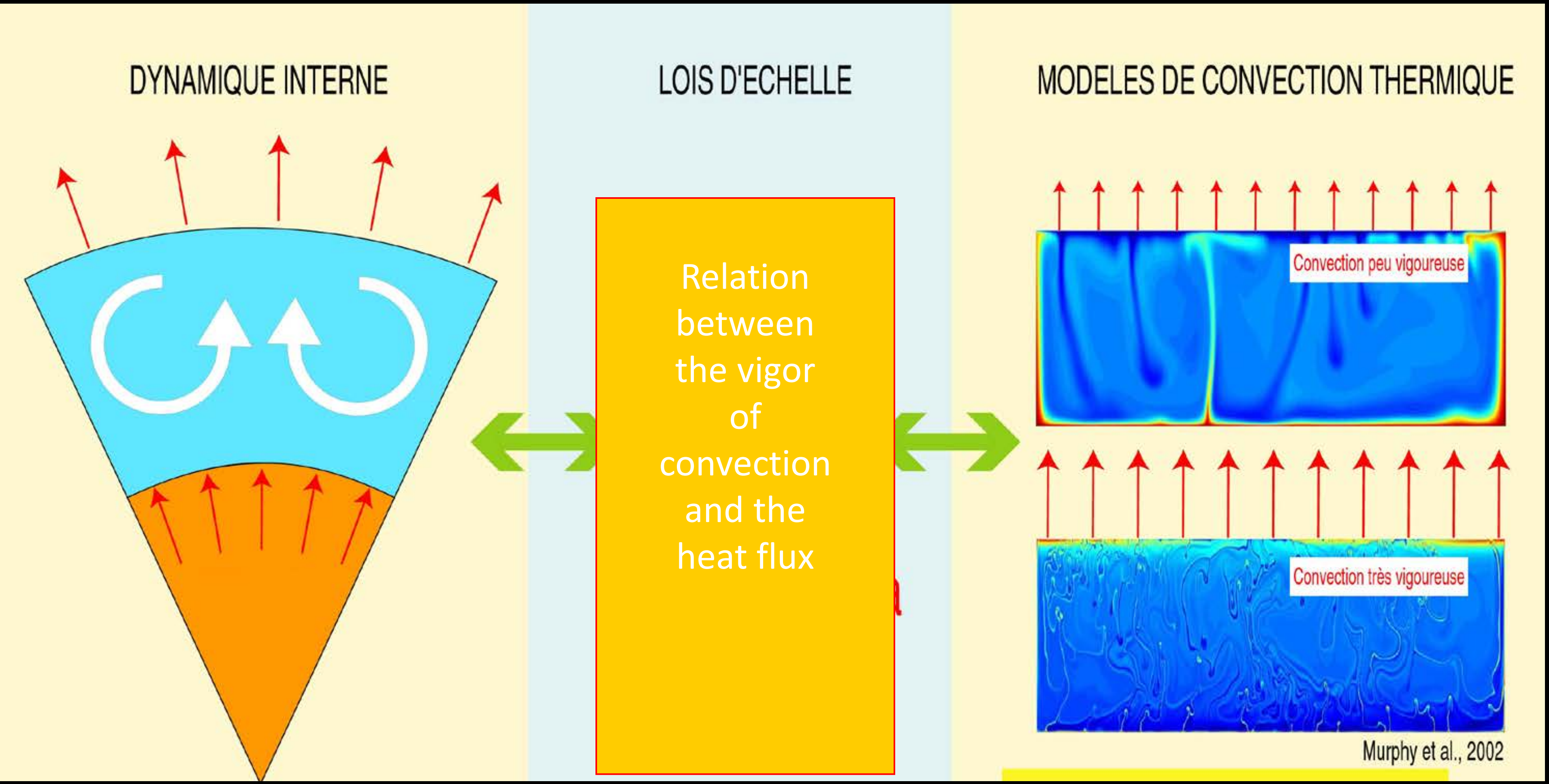



Ganymede : 3 layers model
Sohl et al., Icarus (2002)

Characteristics of the galilean moons

## Three of the galilean moons should possess a liquid water ocean


**Why do we put liquid layers ? Magnetic field evidences from Galileo.**
**Chemistry and dynamics considerations…**




**Heat transfer depends mostly on:**

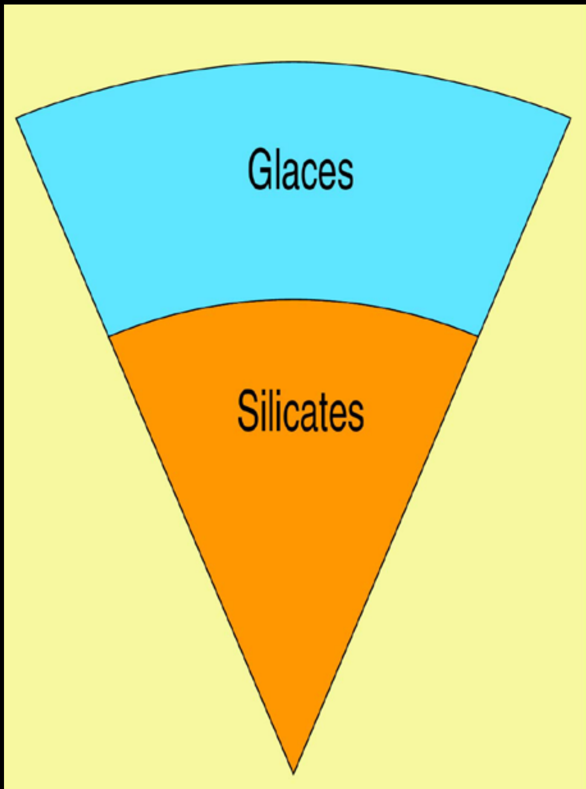
The nature of the « mantle » - Liquid/Solid – compositions -> Phase diagrams

The heating sources

The viscosity of the fluids -> experiments needed

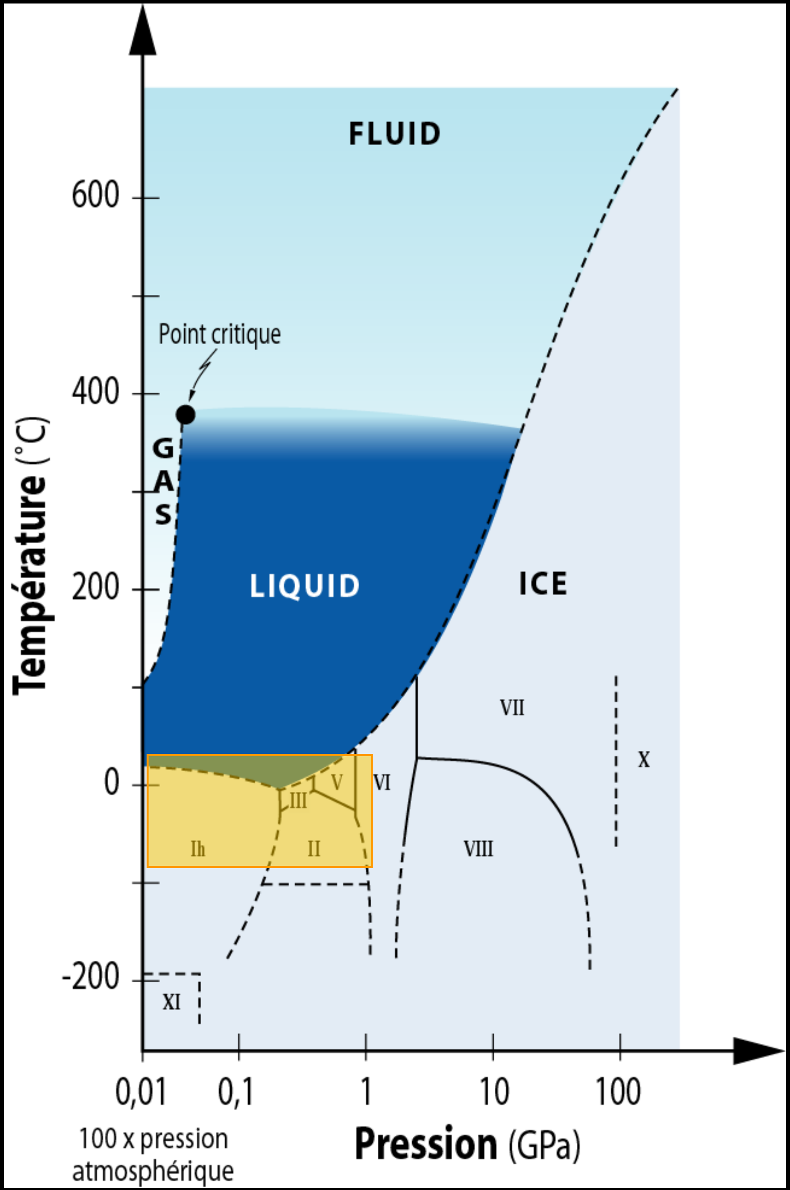
## Models in the 80's

| | |
|---|---|
| Ice composition | **PURE WATER** |
| Ice viscosity | **CONSTANT** |
| Heating sources | **SILICATES** |




**Heat from within was easily expelled**
**Icy satellites were made (of iron,) of silicates, and solid ices !**

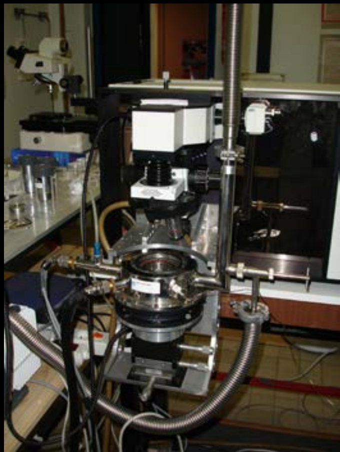
## Experimental constraints – phase diagrams



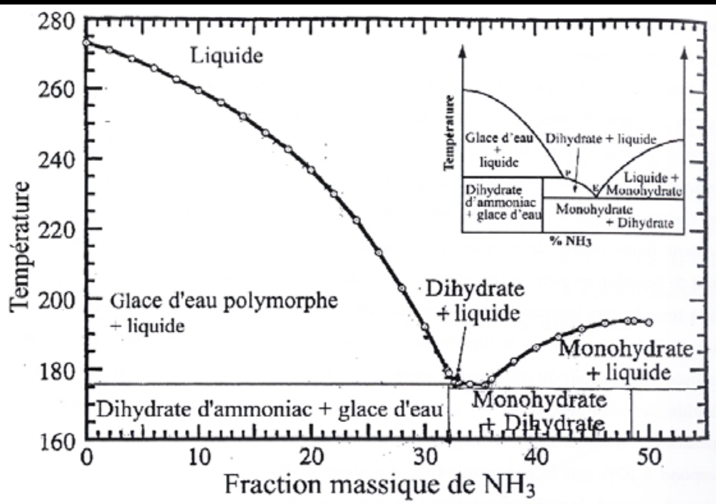

H2O Well-known since 1912 (Bridgman)

Modern experiments (for planetology) devoted to complex mixtures:

- Rheological properties (B. Durham, Kirby and Kolhstedt, …)
- Stability of amorphous and metastable ices
- New compounds (hydrates, clathrates, …)
- Thermodynamic constraints (Cp, k, Solid transitions, …)
- Densities under very high pressure (EOS and melting curves)



## Experimental constraints – phase diagrams




### The ammonia water system: main characteristics

- **Ammonia decreases strongly the melting temperature of ices**
- **Two critical points must be noticed:a peritectic and an eutectic**
- **Main phases in the water rich domain are:**
  - **- Ices of low and high pressure**
  - **- Ammonia dihydrate**
  - **- Ammonia monohydrate**

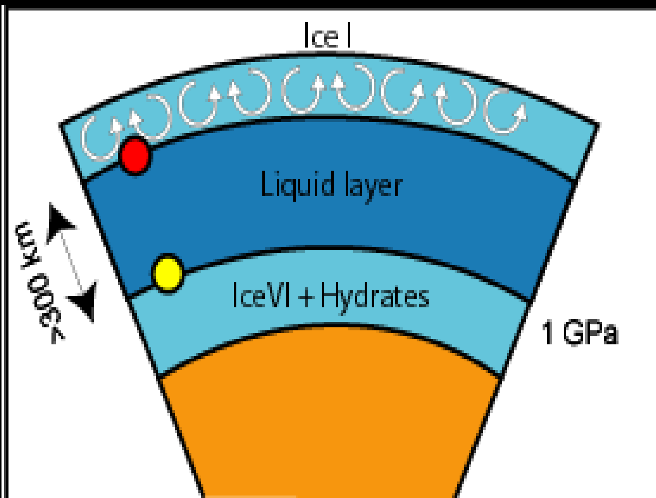



Figure 1: Internal structure of large icy satellites

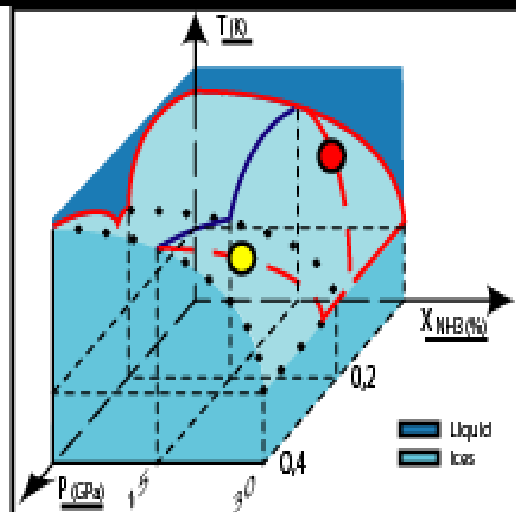
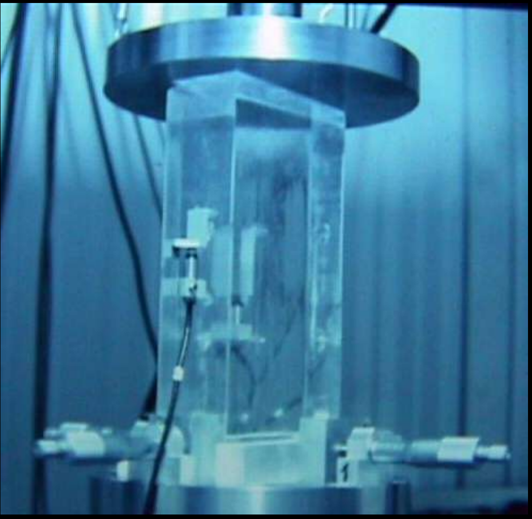



Figure 2: The ammonia-water phase diagram

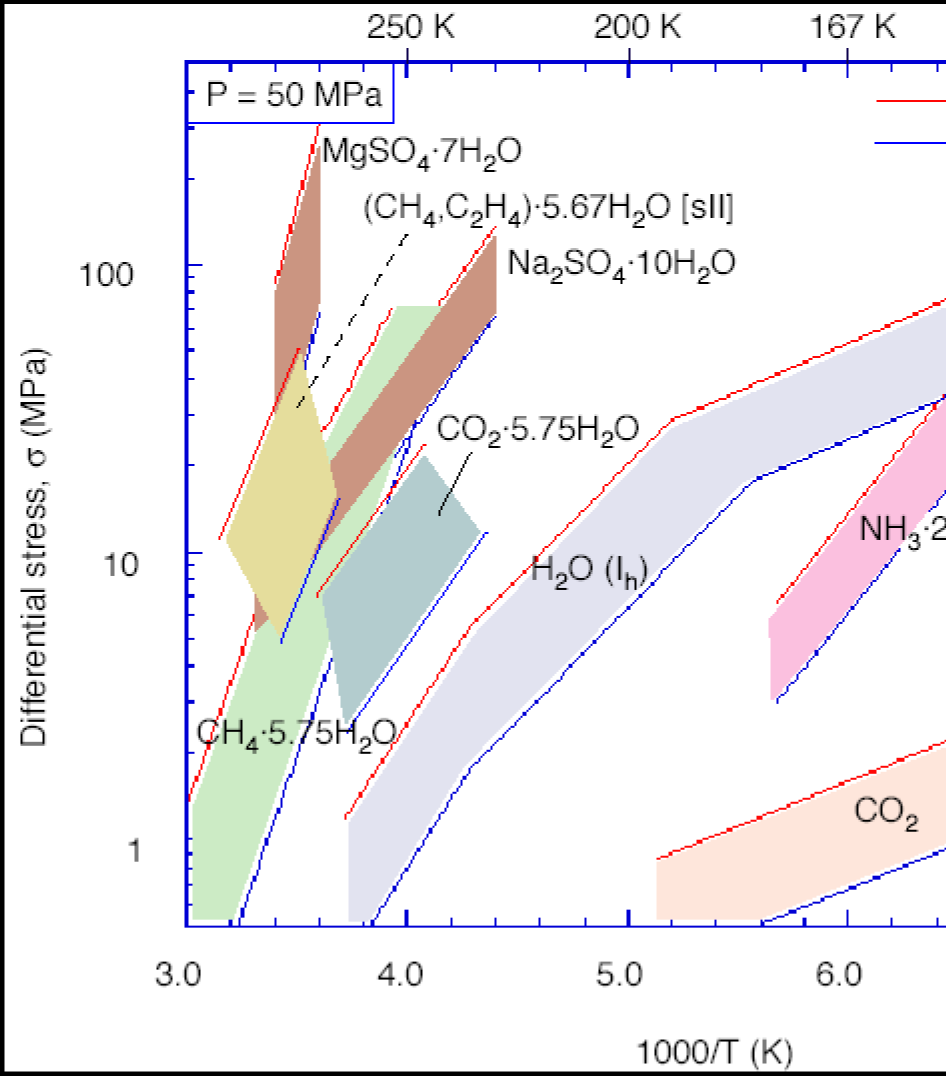
P-T-X phase diagram is required for describing the deep interior

## Rheology of the icy materials

### Rheological properties: **Dynamics**



Crystal deformation under pressure




Durham et al., 2009

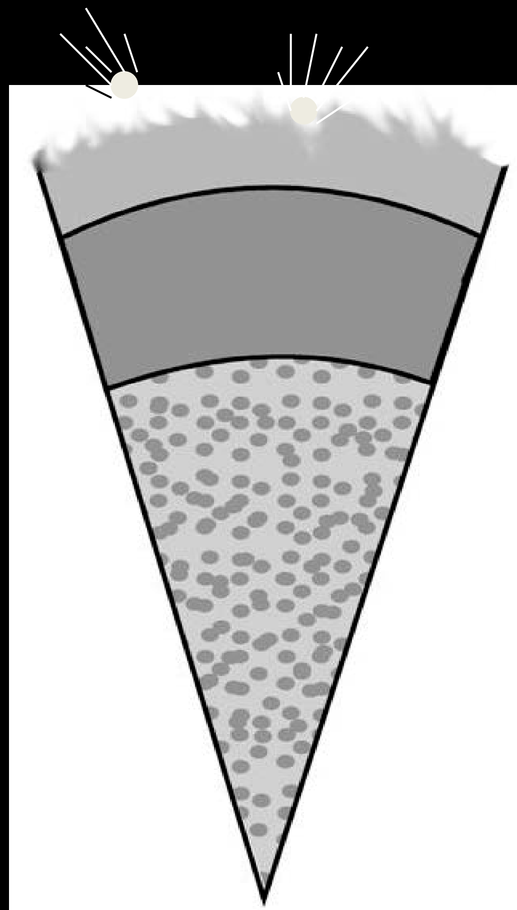
**The icy mantles are T-dependent viscosity fluids**

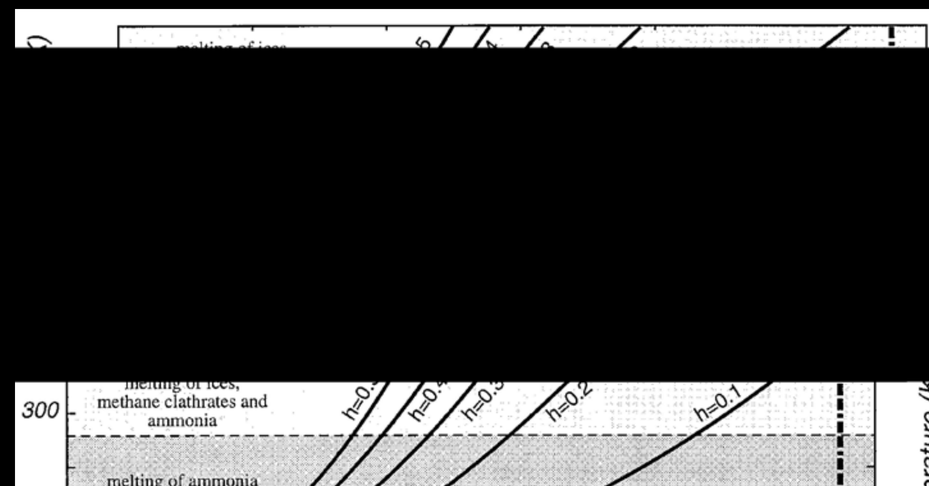
## Heat sources

Melting of ice

Silicate mantle

Homogeneous mixture






From kinetic energy to internal heat

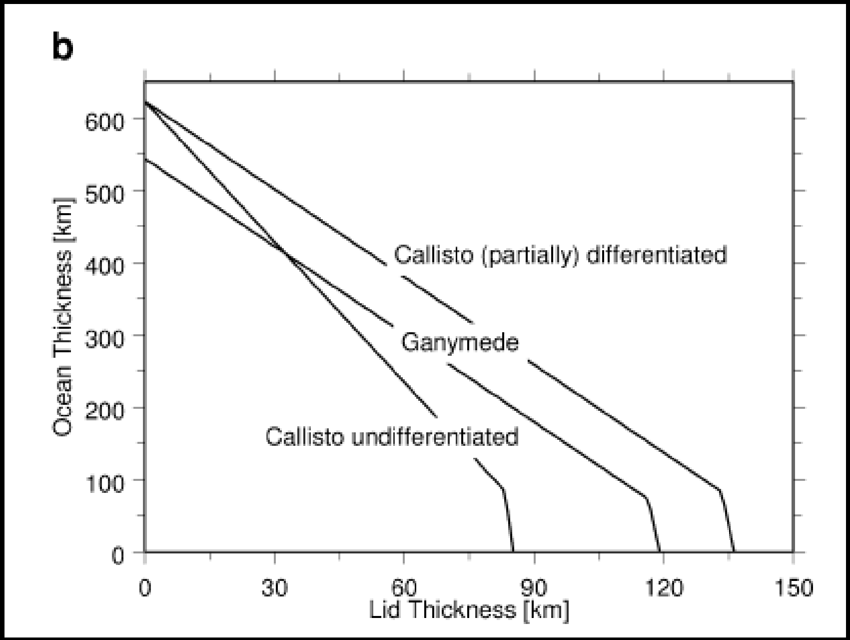
**1. Primordial heat accumulated during accretion – internal heat source**

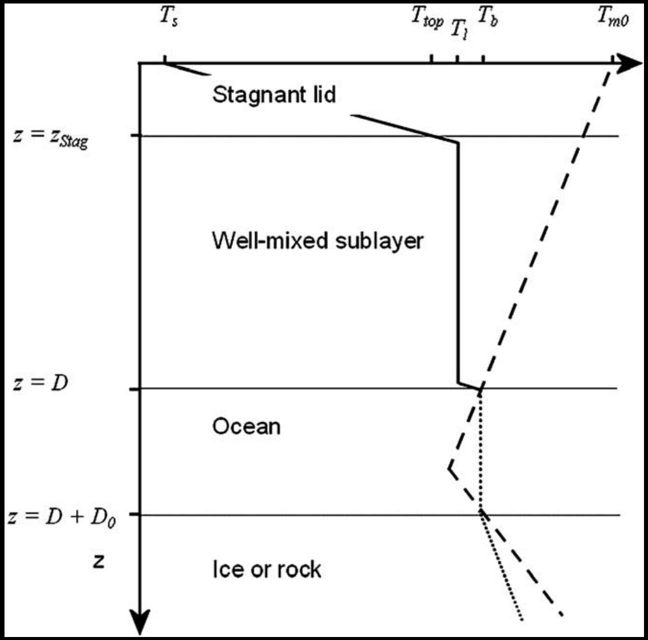
## Heat sources

$t = t_{acc}$: $E_{rad} \sim 3\text{-}4TW$
$t = 4.55Ga$: $E_{rad} \sim 0.5TW$

**2. Radiogenic heat from silicate mantles – heating from below**

## Models in the 90's




Spohn and Schubert, 2003

### Incorporation of salts and ammonia

- Decrease of the ice melting temperature
- Decrease of the Rayleigh number

### Incorporation of variable viscosities

- Increase of the upper lid thickness
- Decrease of the surface heat flux

### Tidal heating not yet well quantified

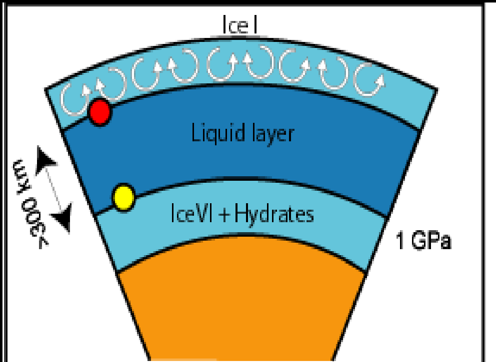



Figure 1: Internal structure of large icy satellites

**The heat is more and more difficult to expell**
**Huge liquid layers appearing…**

## Origin and evolution of the Laplace resonance

Laplace resonance: $n_1 - 2n_2 \approx 0$

$$n_2 - 2n_3 \approx 0$$

$$n_1 - 3n_2 + 2n_3 = 0$$

Origin:

•Classical scenario: expansion of the orbits of the satellites due to tidal dissipation in Jupiter, with Io's orbit expanding most rapidly, and subsequent capture in 2:1 resonances (Yoder and Peale 1981).

•Primordial origin scenario: inward migration of the satellites in the accretion disk of Jupiter, with Ganymede migrating most rapidly (Peale and Lee 2002)

## Heat sources

From the observation of the orbital evolution, the dissipation of tidal energy in Io and Jupiter has been deduced (Lainey et al. 2009):

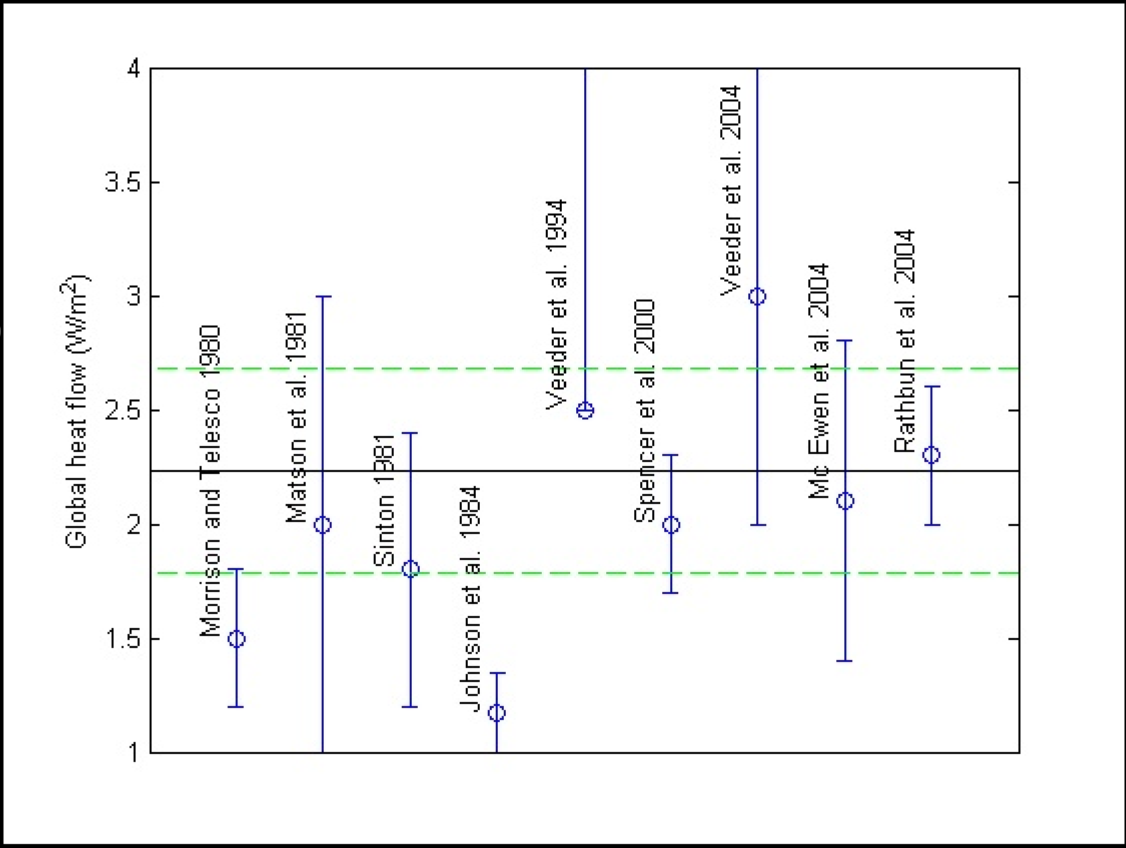
$k_2/Q = 0.015 \pm 0.003$

$dE/dt = (9.33 \pm 1.87)\ 10^{13}$ W

q= $(2.24 \pm 0.45)$ $Wm^{-2}$
(~25 times larger than the Earth's flux)

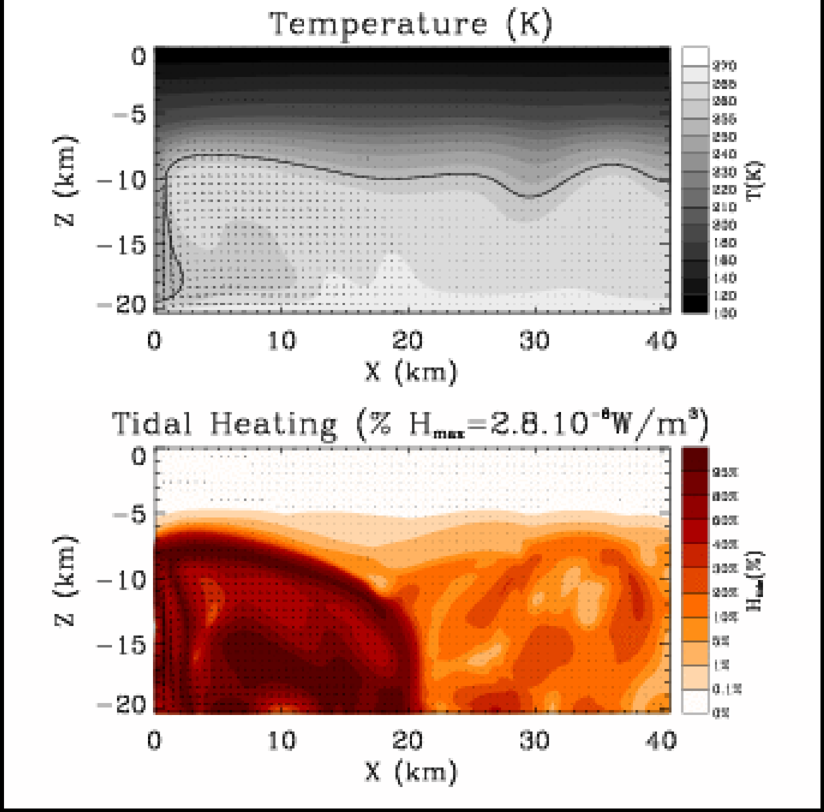
Io is close to thermal steady state.

Efficient heat transport mechanism needed (magma migration?).



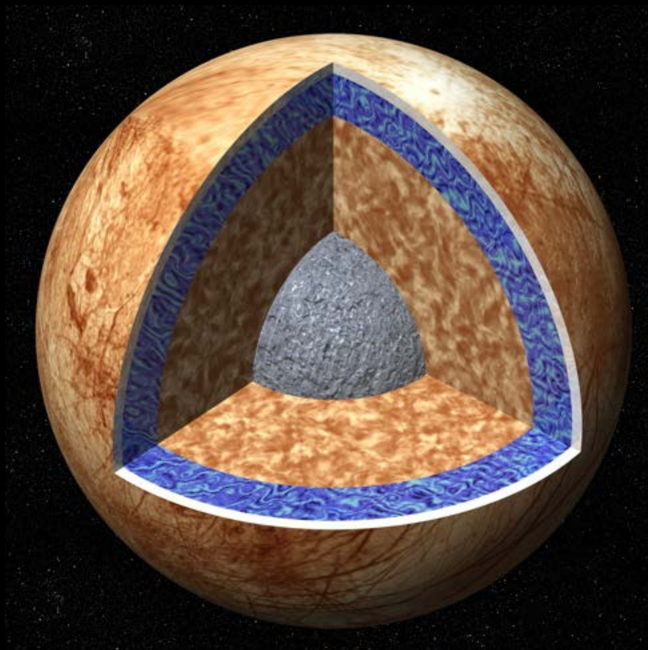

Dissipation in Jupiter is close to the upper bound of the average value expected from the long-term evolution

## Dynamic models at present (1/4)

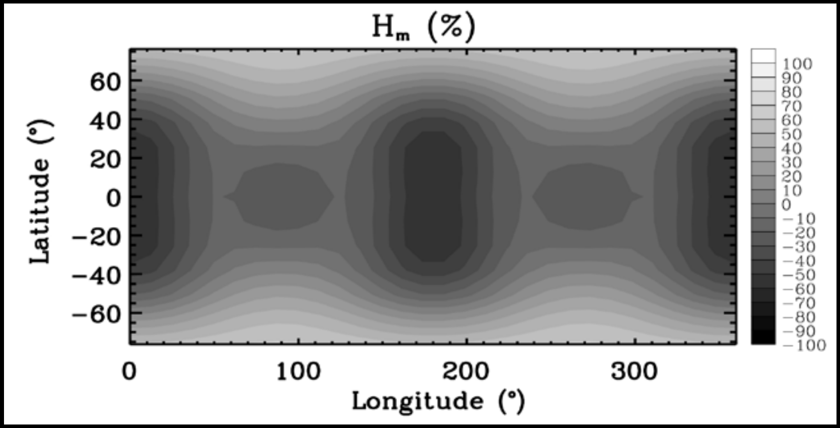



**Tidal heating is now considered and well quantified on some bodies**
**Time and space dependent heating rate…**

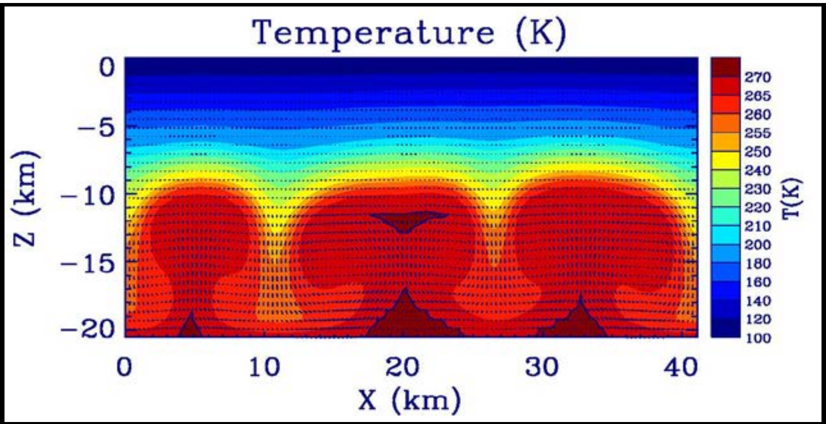
## Dynamic models at present – the Europa case



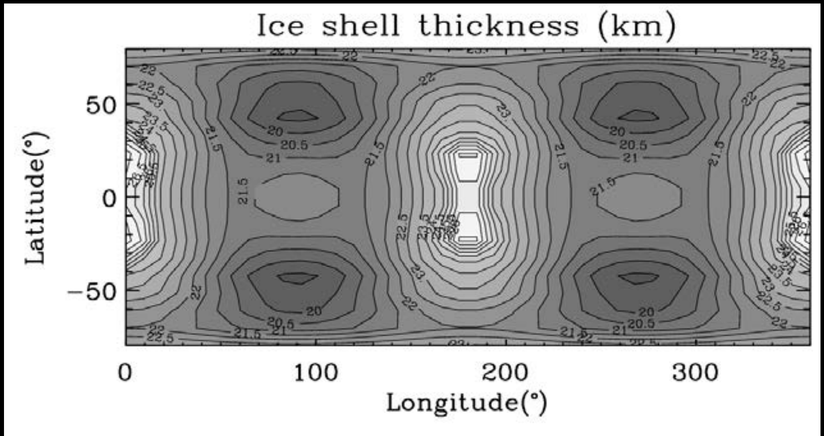
**Lateral distribution**




**Thermal transfer through ice Ih layer**




**Ocean thickness: 20-25 km**




Tobie et al., 2009

## Dynamic models at present – the Ganymede case

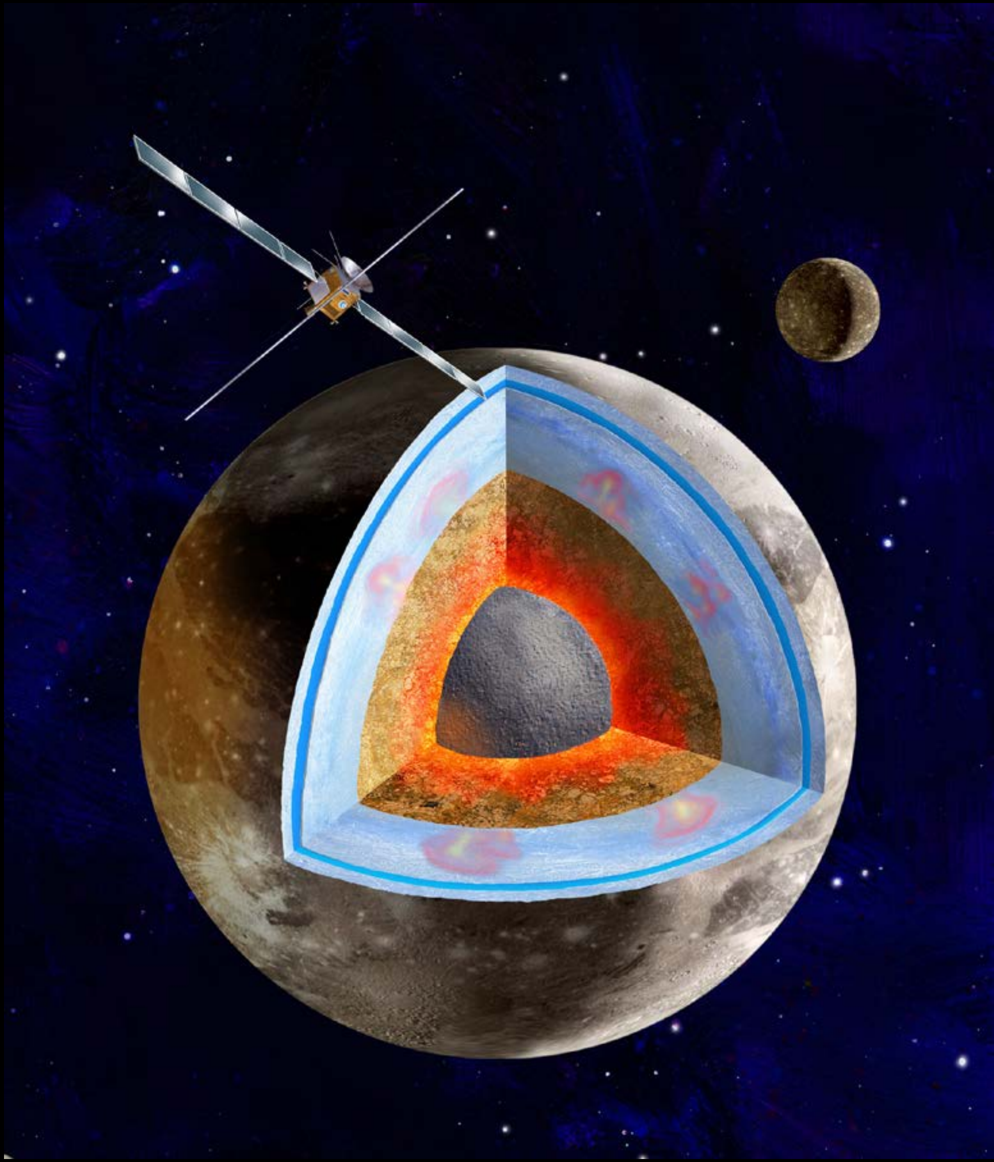
**No strong evidence of a liquid layer from numerical models**

- no significant tidal heating
- no evidence of ammonia or other anti-freezing compounds

**BUT**

The ocean must be there since an induced magnetic field which originates from shallow depth has been detected by Galileo

**Still progress to be done ...**



# Existence of deep oceans

## Dynamic models at present – the Callisto case

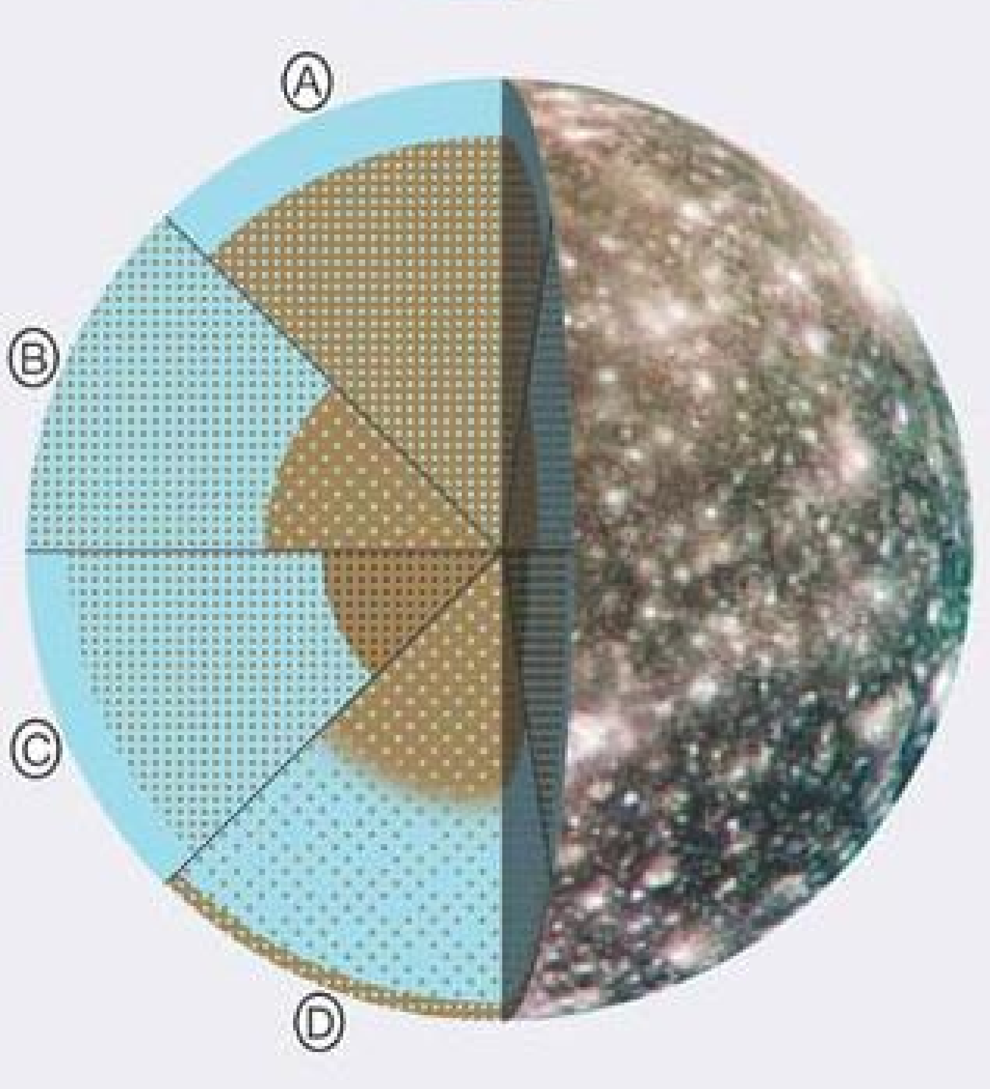
**No easy way to get a structure which is not fully differentiated after the first billion year because of:**

- Ratio of 3 in densities

-Silicate heating which reduces the viscosity of ices

-Convective motion within the layers

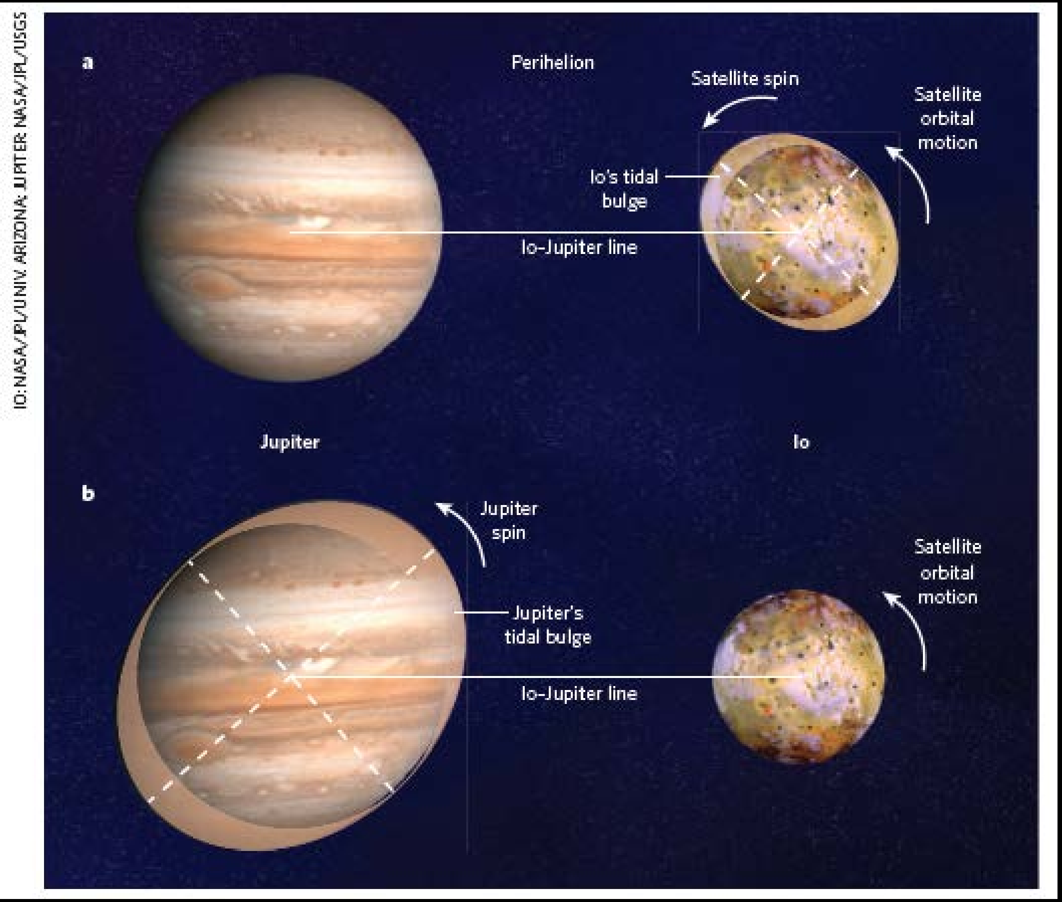
**Ocean detected – difficult to get it from numerical modelling. Question still open ...**



## Secular change in orbits due to dissipation of tidal energy

Dissipation of energy related to tides raised on Jupiter and the satellites causes the tidal bulges not to be exactly in the direction to the tide-raising body.

- Jupiter tides:
  - satellites move away from Jupiter (e.g. 2m/century for Europa)
  - satellites decelerate: change in position in orbit (e.g. Europa: 93 km/century)
- tides on synchronous satellites:
  - Satellites move inward to Jupiter and accelerate



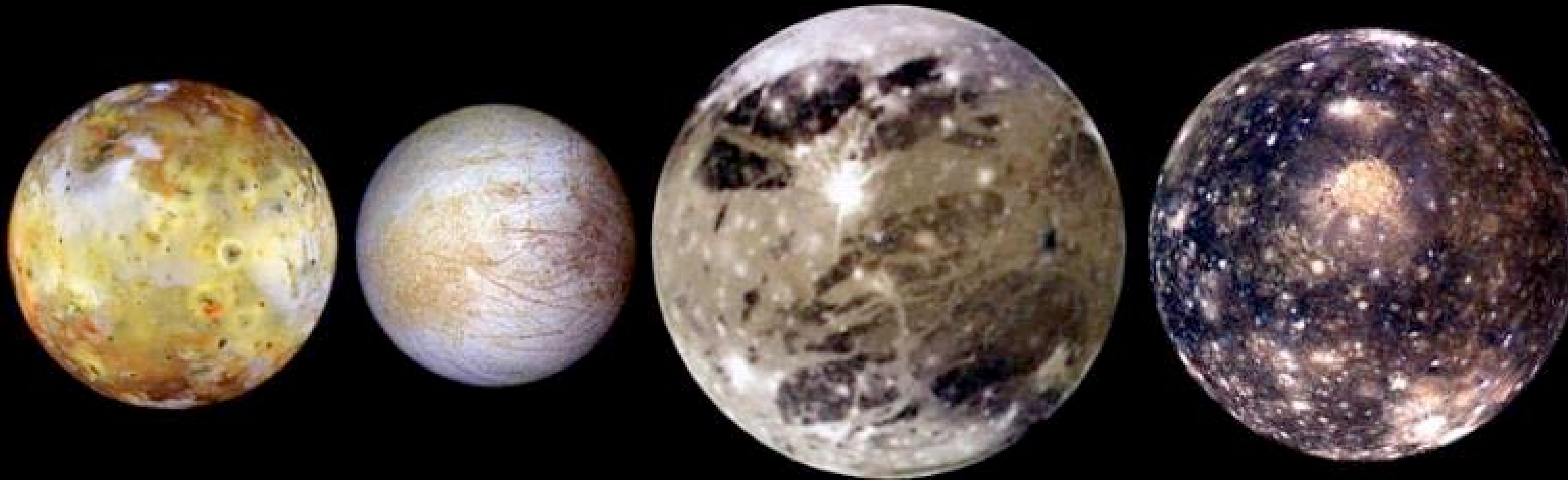
## Evolution of the Laplace resonance

Evolution of the Laplace resonance is characterized by

$$\frac{dn_1}{dt} - 2\frac{dn_2}{dt} = \frac{dn_2}{dt} - 2\frac{dn_3}{dt} = (0.74 \pm 0.24)\ 10^{-7}\ \text{rad yr}^{-2}$$

→ evolution away from exact resonance (increasing differences $n_1$-$2n_2$ and $n_2$-$2n_3$)
→ decrease in eccentricities
→ decrease in tidal heating of Io

- Evolution on long time scale (Gyr)?
  - will Laplace resonance be broken?
    → end of Io volcanism
  - cycles of tidal heating in Io associated with changes in eccentricity? (Ojakangas & Stevenson 1986, Hussmann & Spohn 2004)



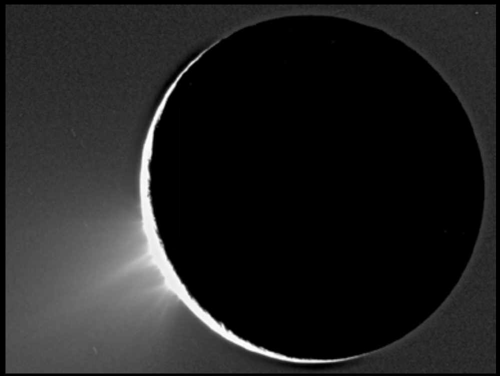
Origins -  An interesting debate, not yet solved.  Listen to the talks to come.

Evolution – mostly related to the thermal exchanges.
Many progress regarding complexity of the models
Moons are part of a system, not isolated – next models?

Still a lot of questions – but how far can we go without constraints ?
Earth’s example illustrates so well how data are important.
JUICE (Jupiter Icy moon Explorer) will help a lot…

# III. Thermal evolution – existence of deep oceans

## 2. Heat sources



**Io et Enceladus :** best examples of lunar activity induced by tidal heating

Without tidal heating,
Io would be like the Moon,
and Enceladus like Mimas.