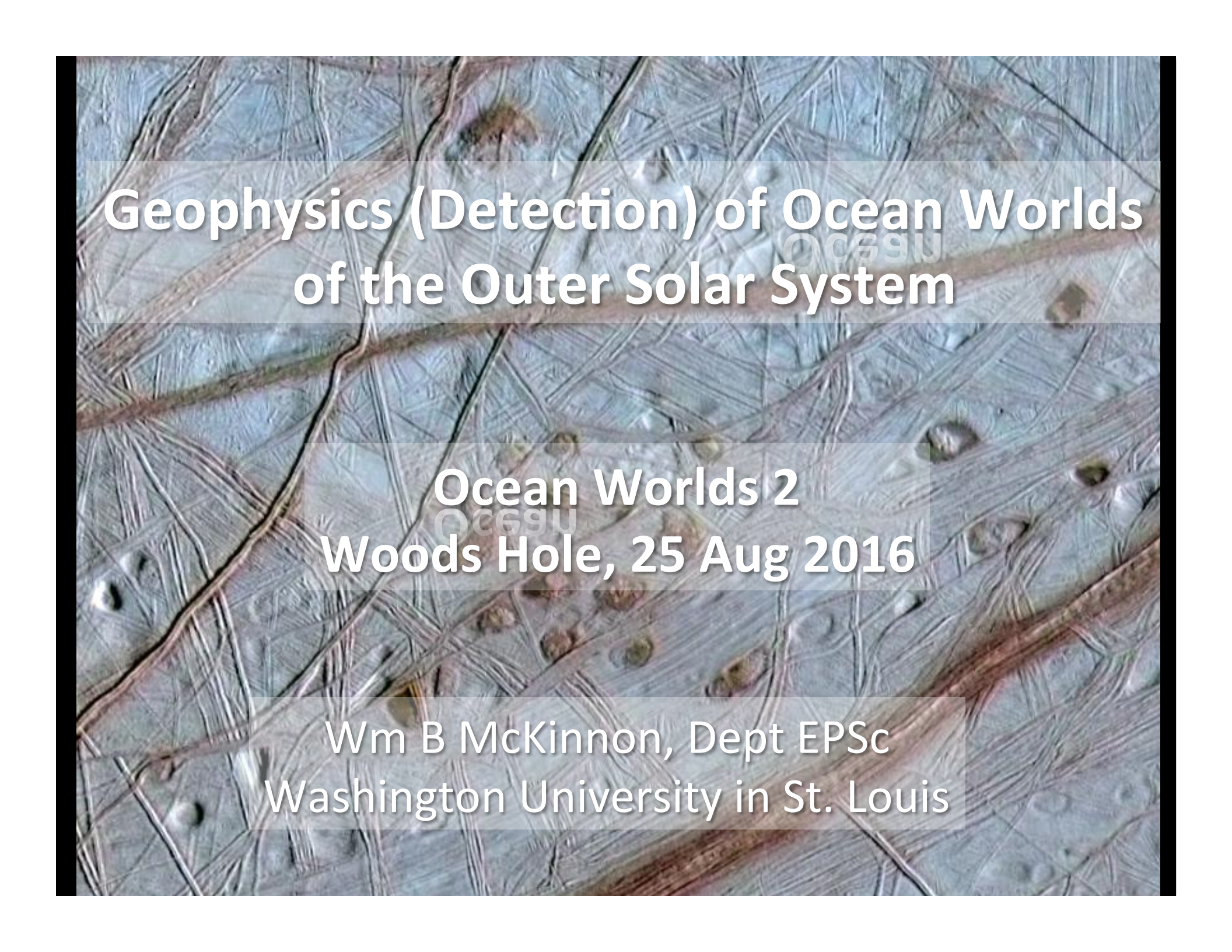


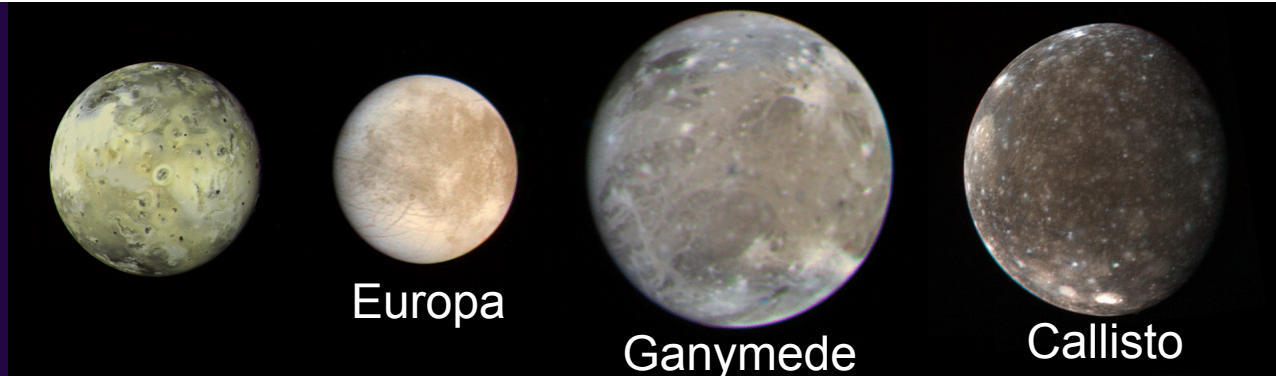


Geophysics (Detection) of Ocean Worlds of the Outer Solar System

Ocean Worlds 2
Woods Hole, 25 Aug 2016

Wm B McKinnon, Dept EPSc
Washington University in St. Louis

Dramatis Personae



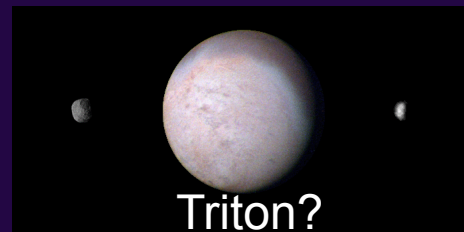
Jupiter



Saturn



Uranus



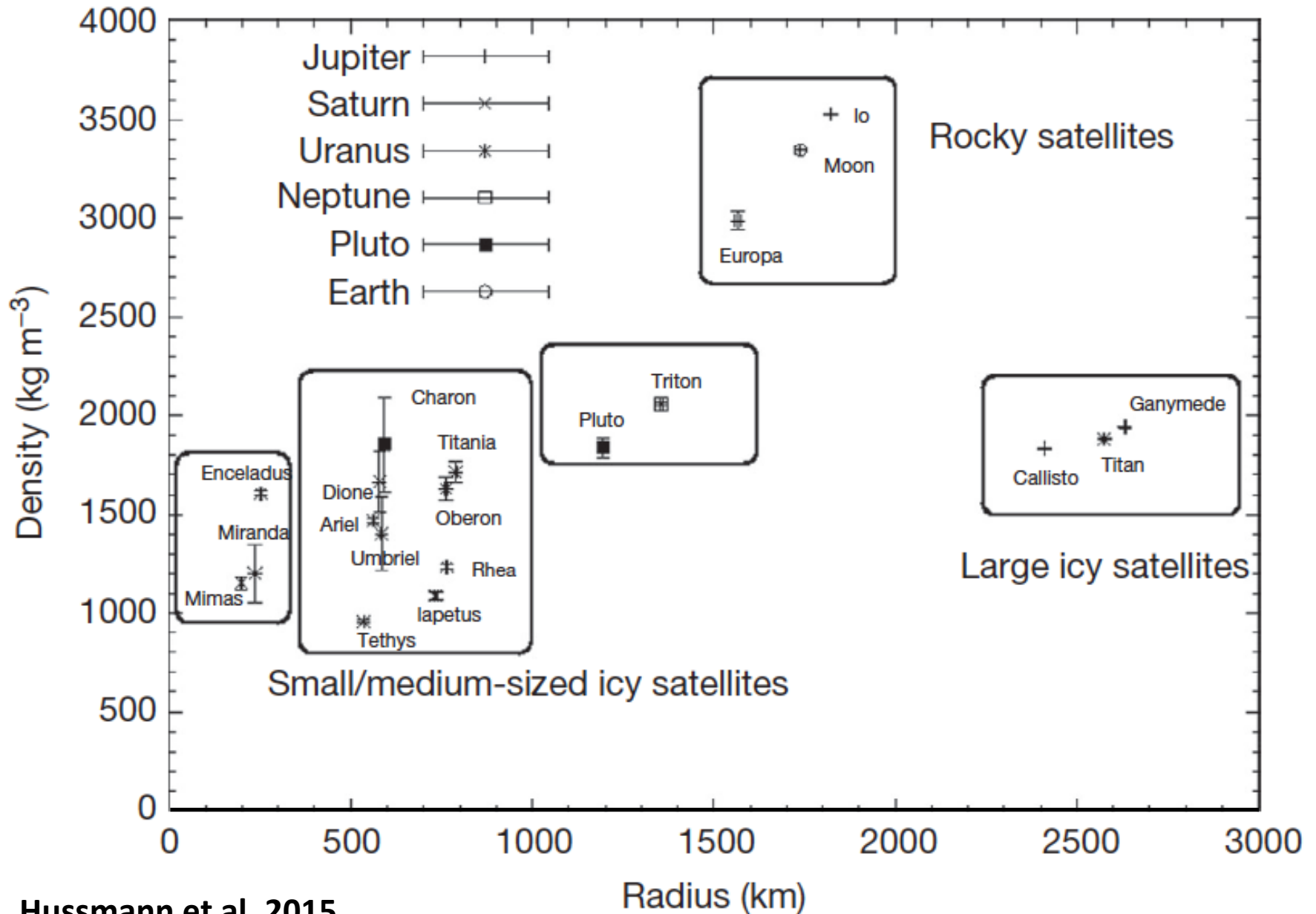
Neptune



Pluto

**How do we know
there are icy ocean worlds?
and
How do we take their measure?**

Density vs. Radius: Ice/Rock ~40/60 for largest satellites



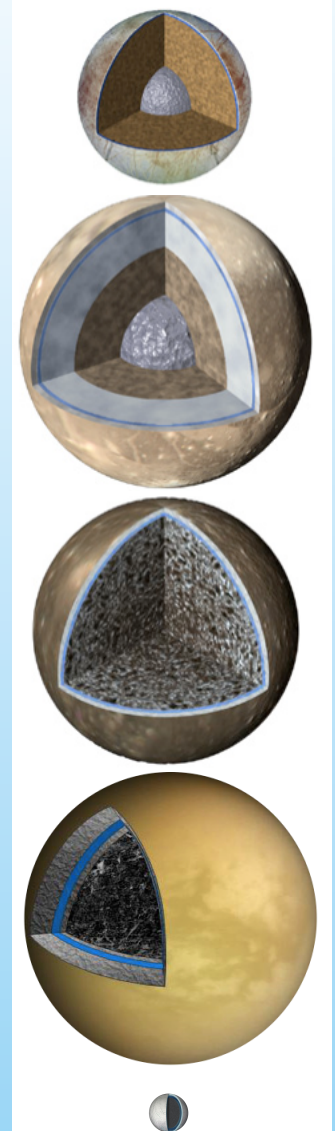
Europa Ocean Conference, San Juan Capistrano, CA, 12-14 Nov 1996

Ocean Worlds "0"



The Ocean Worlds from Gravity and Induced $\vec{B}$ Fields

_____	Radius (km)	Density (kg/m ³)	MOI	Induced $\vec{B}$
Europa	1561	3014	0.348	✓
Ganymede	2631	1942	0.3115	✓
Callisto	2410	1834	0.355	✓
Titan	2576	1880	0.34	~✓
Enceladus	252	1609	0.33	



Magnetic Induction: Conductive (salty) Subsurface Oceans

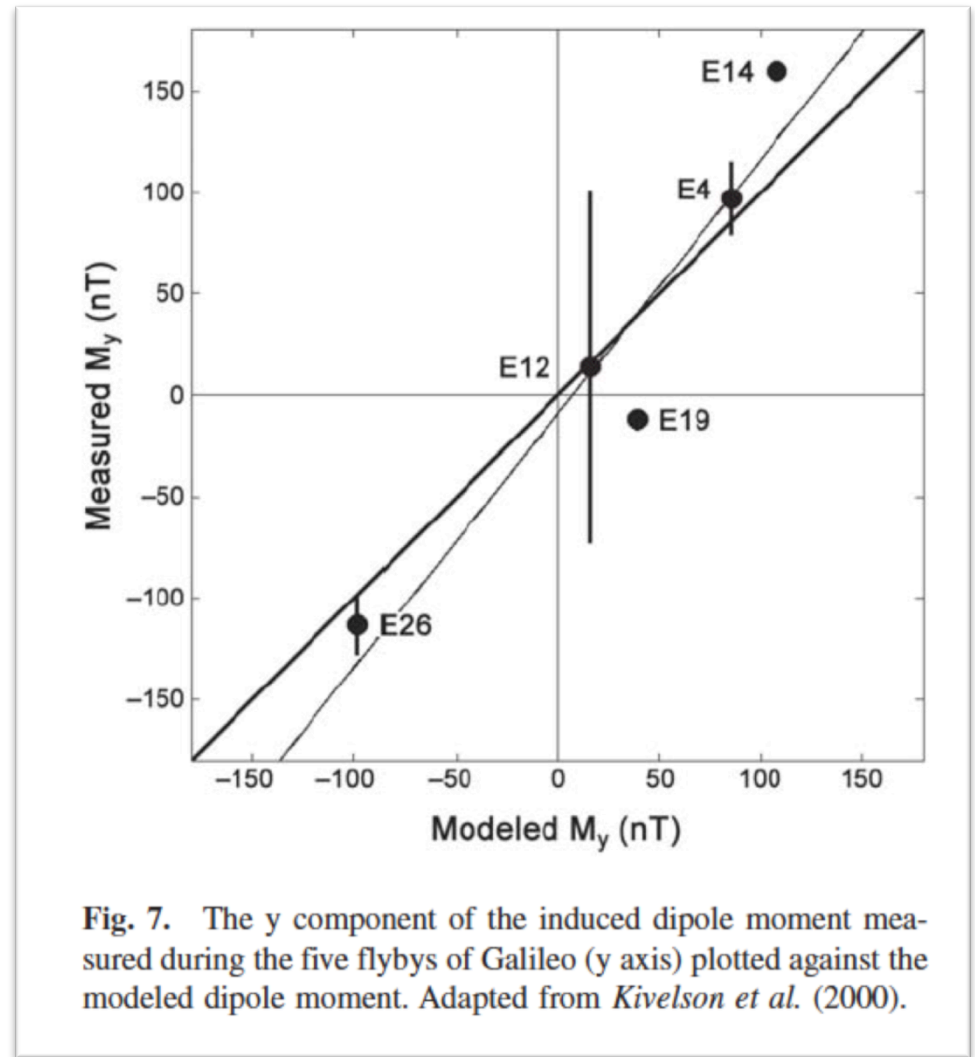
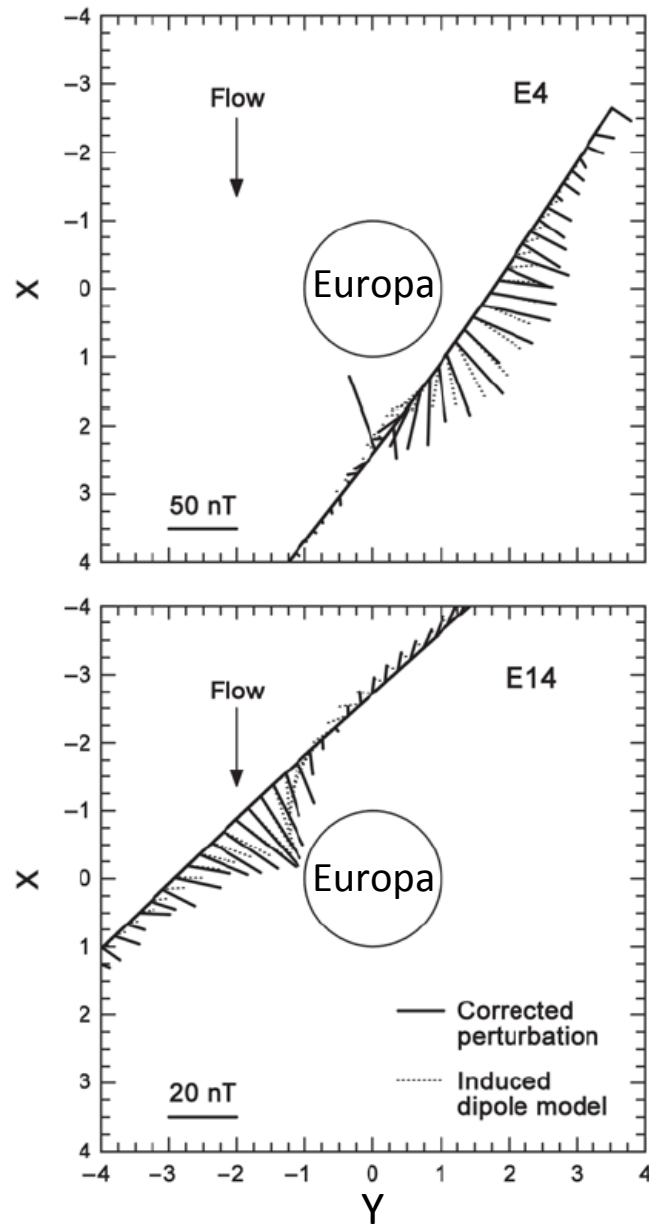


Fig. 7. The y component of the induced dipole moment measured during the five flybys of Galileo (y axis) plotted against the modeled dipole moment. Adapted from Kivelson *et al.* (2000).

Khurana *et al.* 2009, in **Europa**

Ganymede's Internal Dipole Magnetic Field

Aurora Ganymedealis!

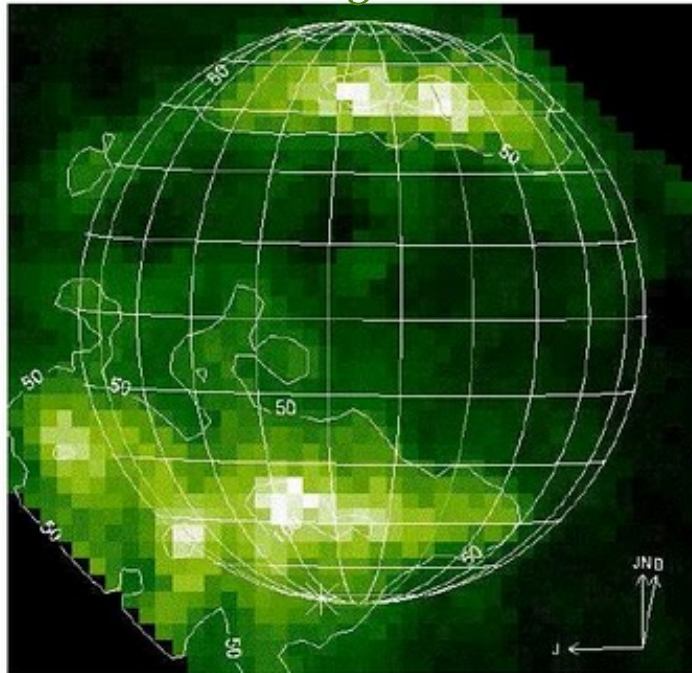
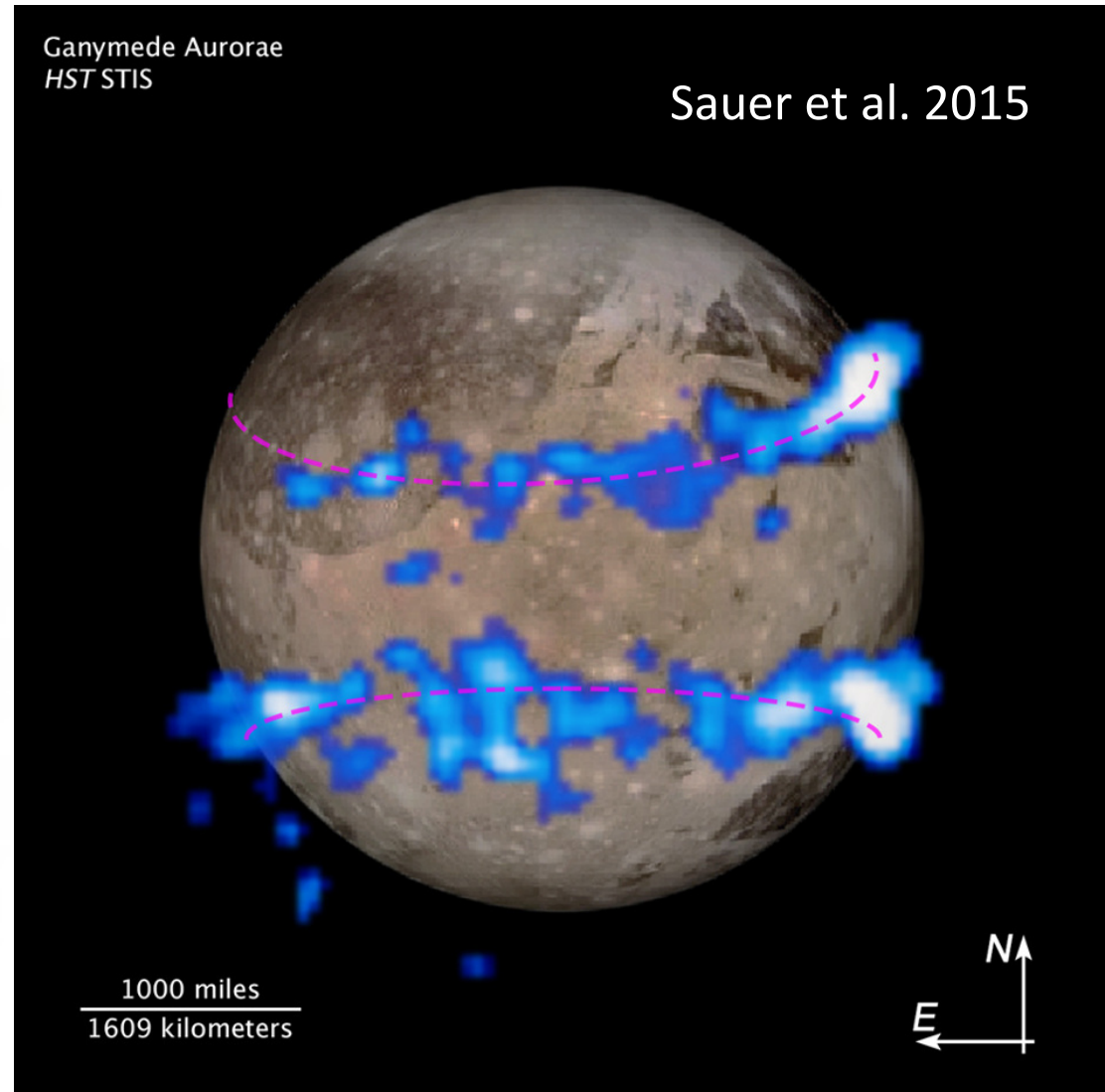


Figure 19.12. Ganymede auroral emission from oxygen (OI 1356 Å) observed with HST. Contours illustrate the observed brightness in Rayleighs. McGrath et al. 2004



⊗ Almost certainly a dynamo

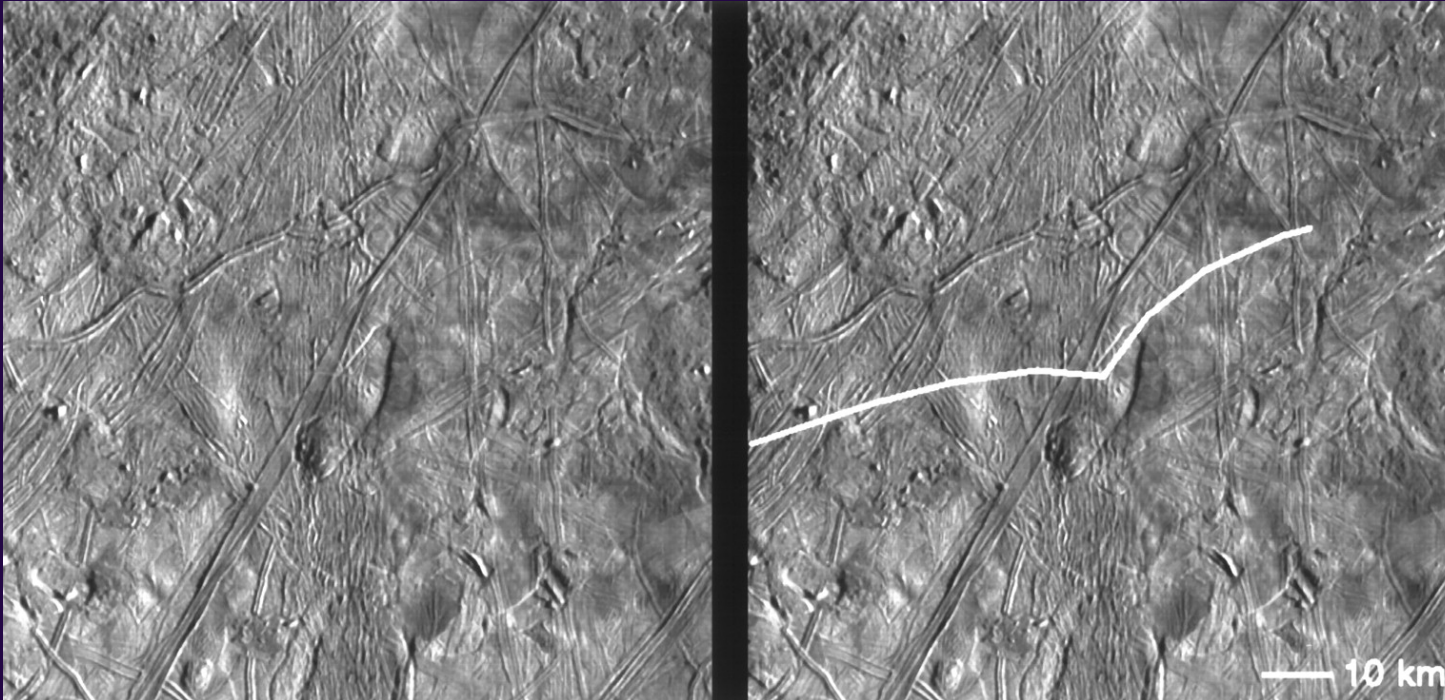
⊗ But is there truly an induced, oscillating component?

YES!

Arcuate Ridges on Europa

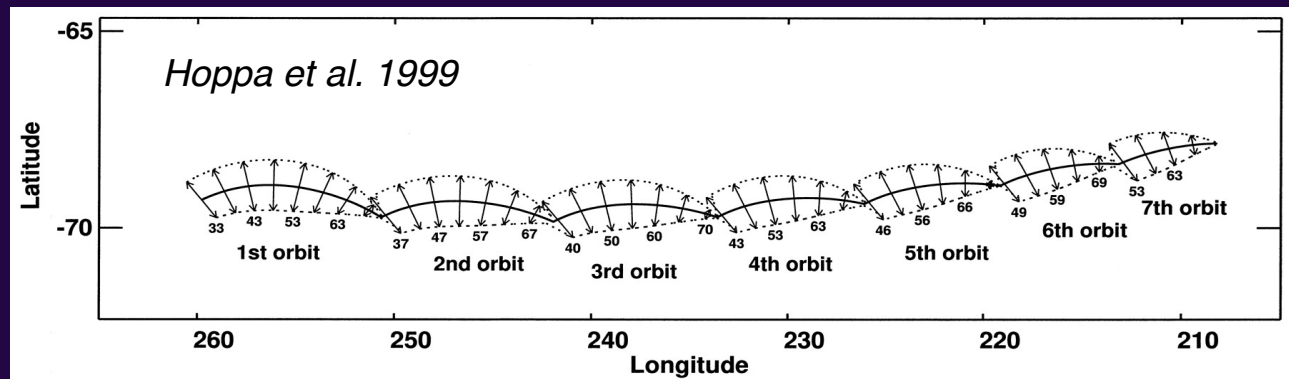


Tectonics of Cycloid Ridges requires an Ocean

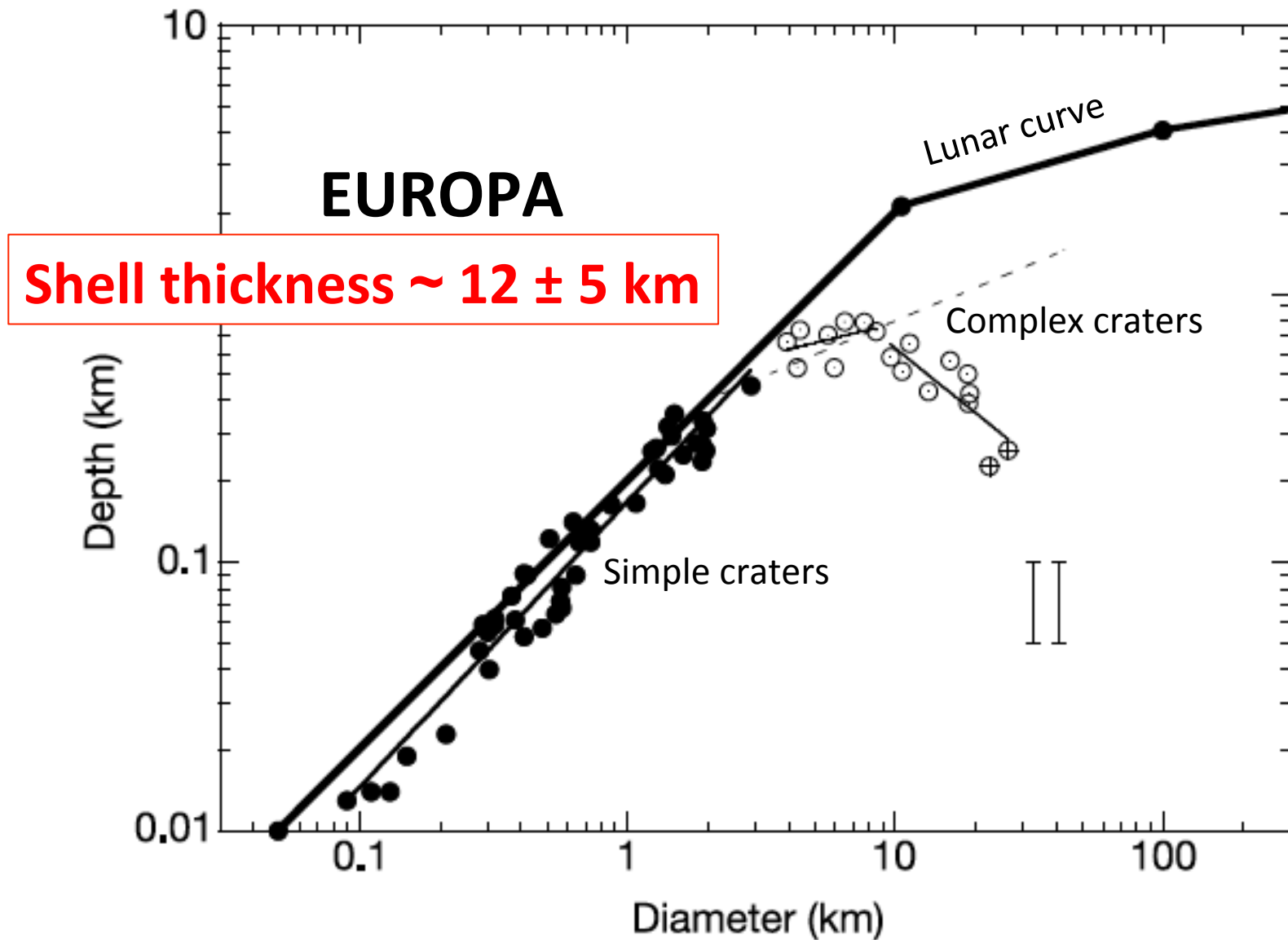


Arcuate ridges begin as arcuate cracks

Kinematic model
depends critically on
variation and magnitude
of diurnal tide



Sensing the ocean the old fashioned way: Impact craters!

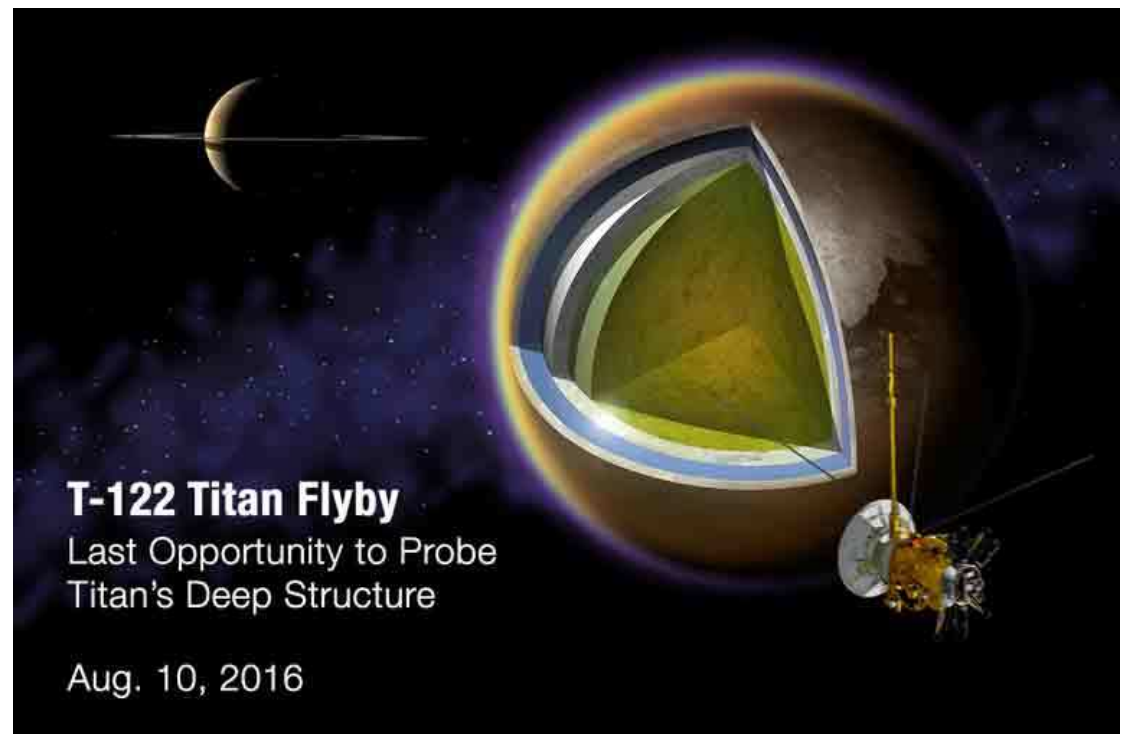


Schenk 2002

Saturn's Magnetic Field Does not Oscillate (from a satellite's perspective) in the Manner of the Jovian Field

But TITAN's orbit is eccentric (0.03), leading to variations in tidal gravity and corotating plasma flow

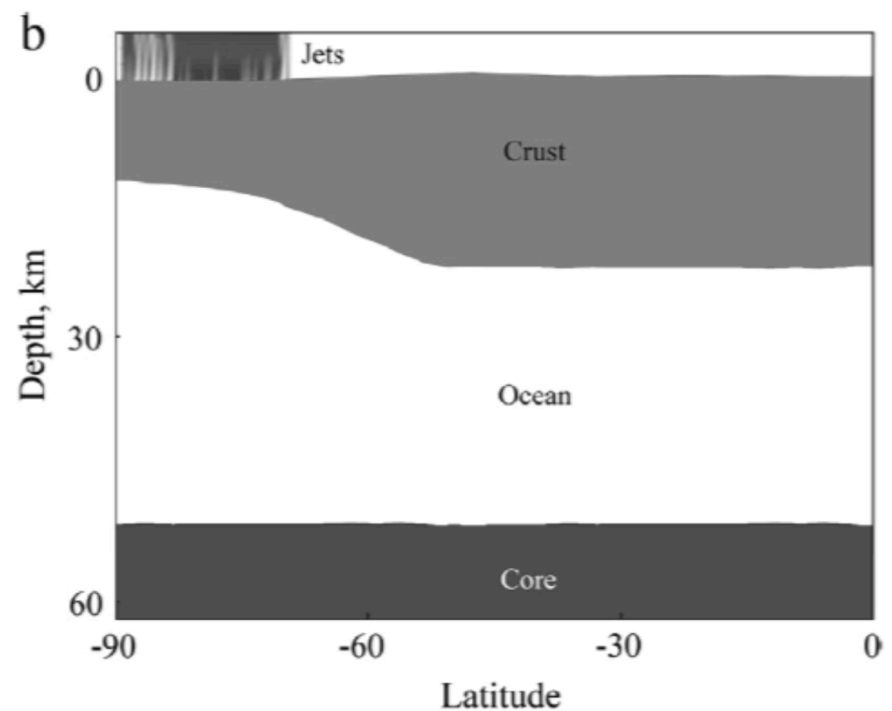
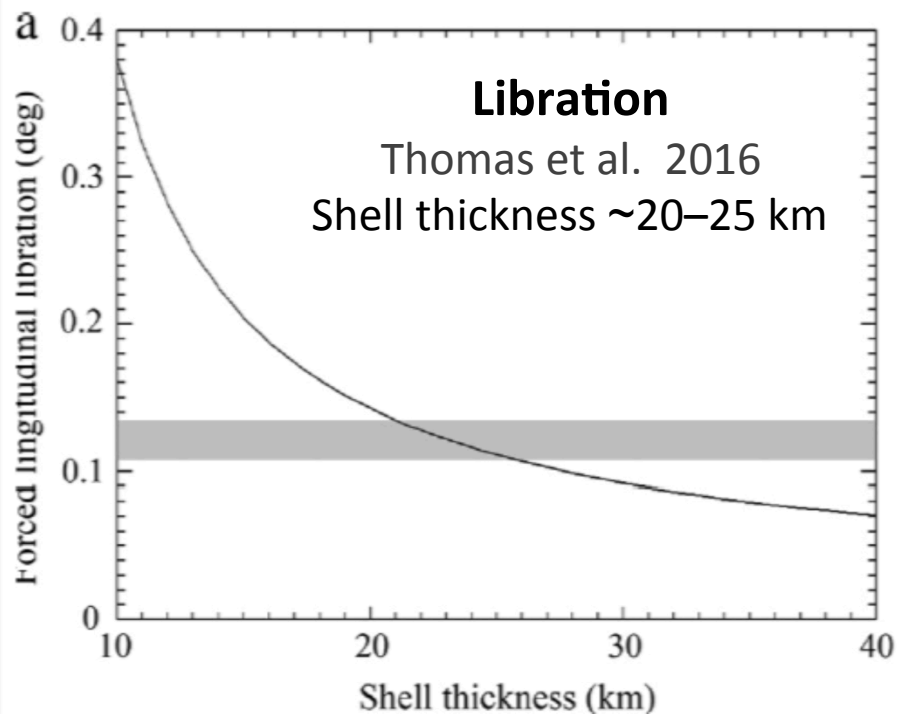
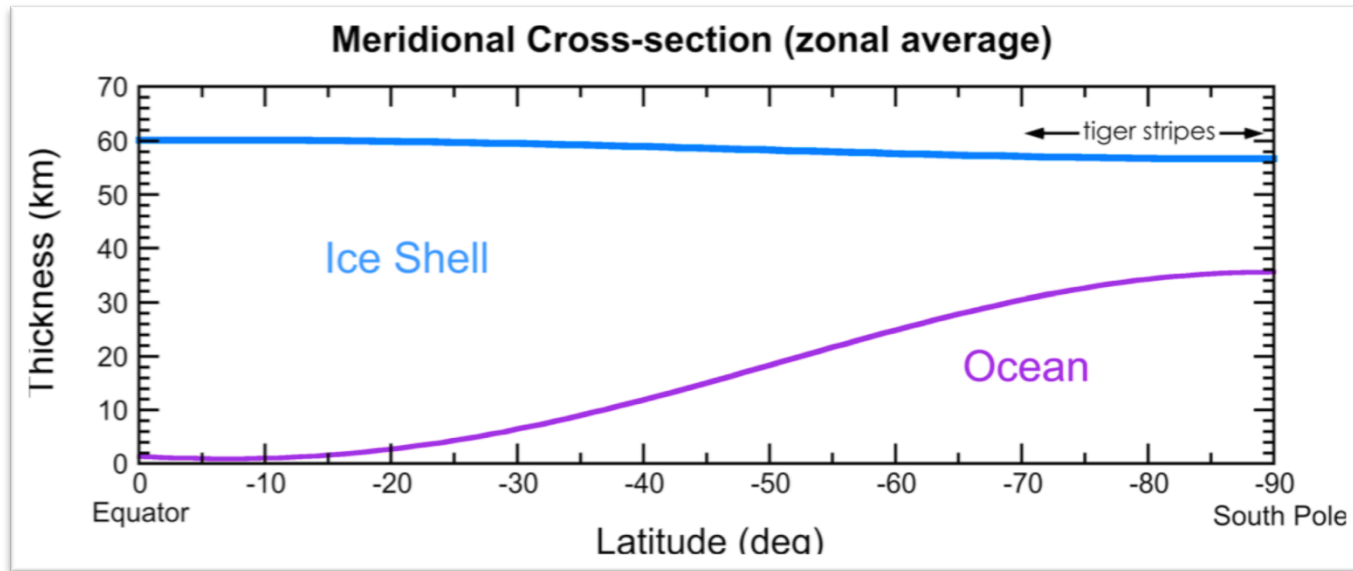
- 1) Schumann EM resonance, detected by Huygens probe (Beghin et al. 2012)**
- 2) Oscillating tidal gravity
 $k_2 \sim 0.6$ (less et al. 2014)
Unexpectedly large!**



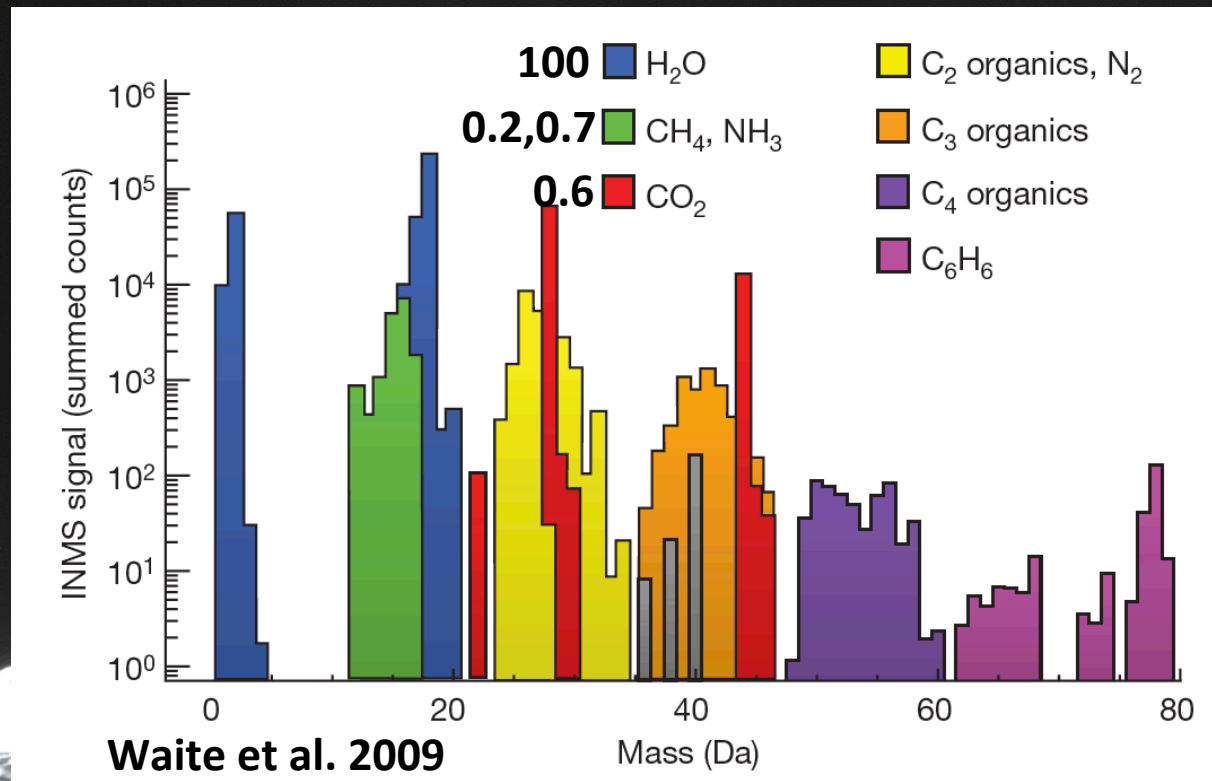
ENCELADUS Ice Shell Gravity & Topography Model

e.g., McKinnon 2015
Compensation (shell)
depth ~50 km

vs.



Plumes of Enceladus: The Smoking Gun



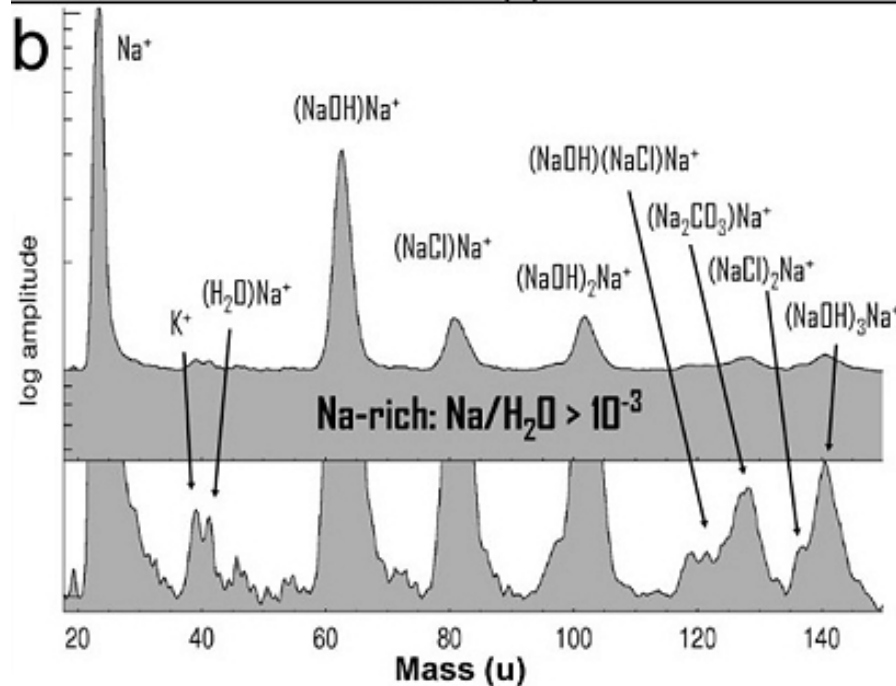
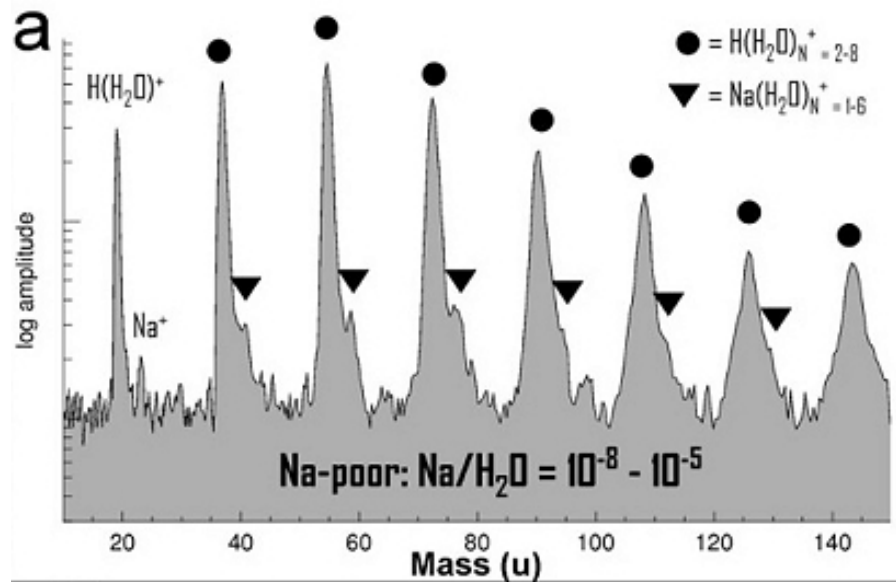
Baghdad

Damascus

Cairo

Alexandria

Cassini CDA (Cosmic Dust Analyser)



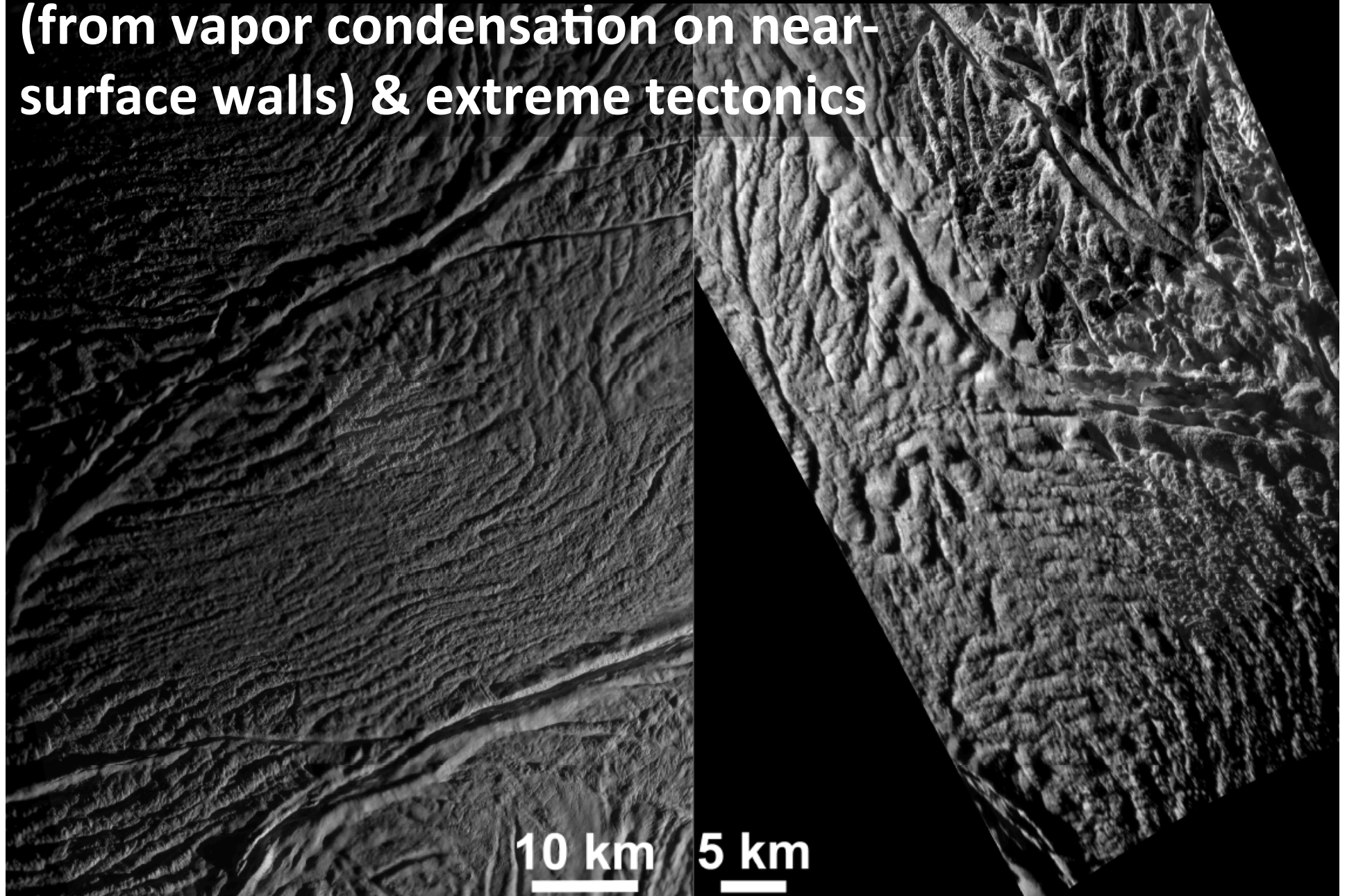
Postberg et al.
2008,2009,2011

$\text{Na}/\text{K} \gg 1$

NaCl , NaCO_3 , NaHCO_3

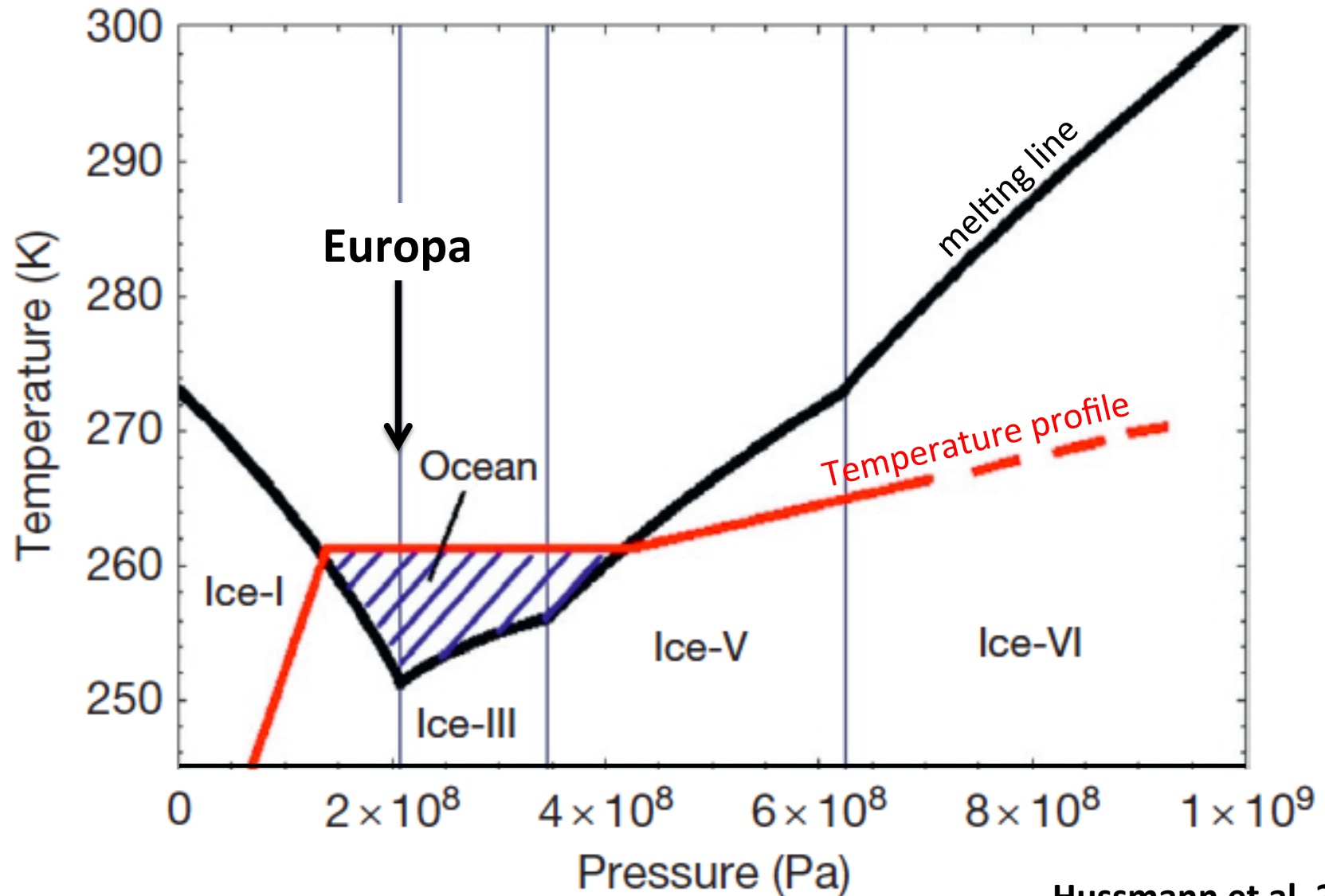
plus organic rich particles

**Plus very high heat flow measured
(from vapor condensation on near-
surface walls) & extreme tectonics**

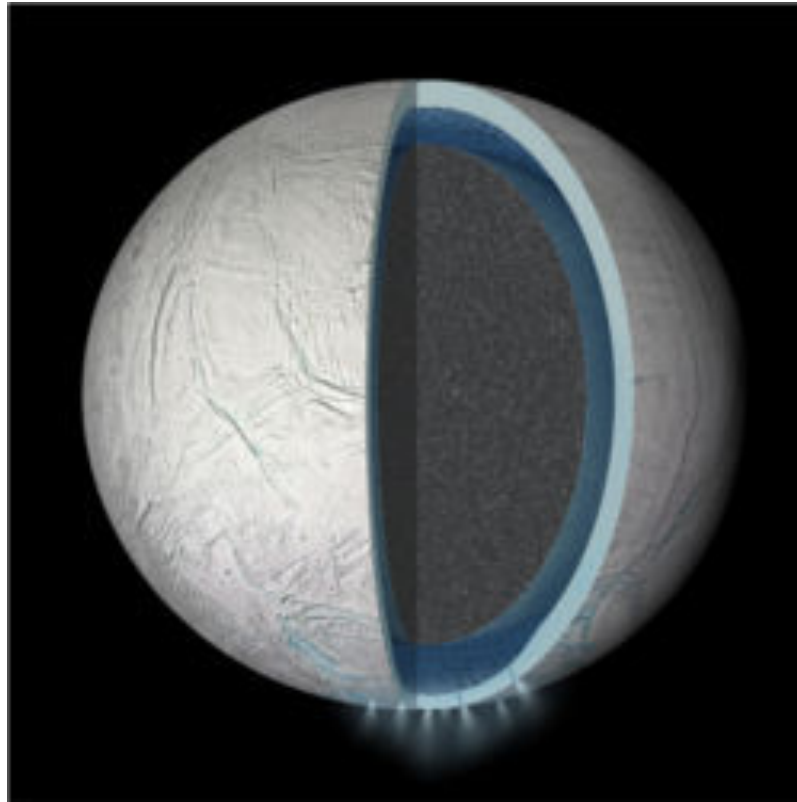


There are 2 classes of ocean worlds

Europa & Enceladus oceans have seafloors (Ganymede, Callisto, Titan are perched)



Hussmann et al. 2015



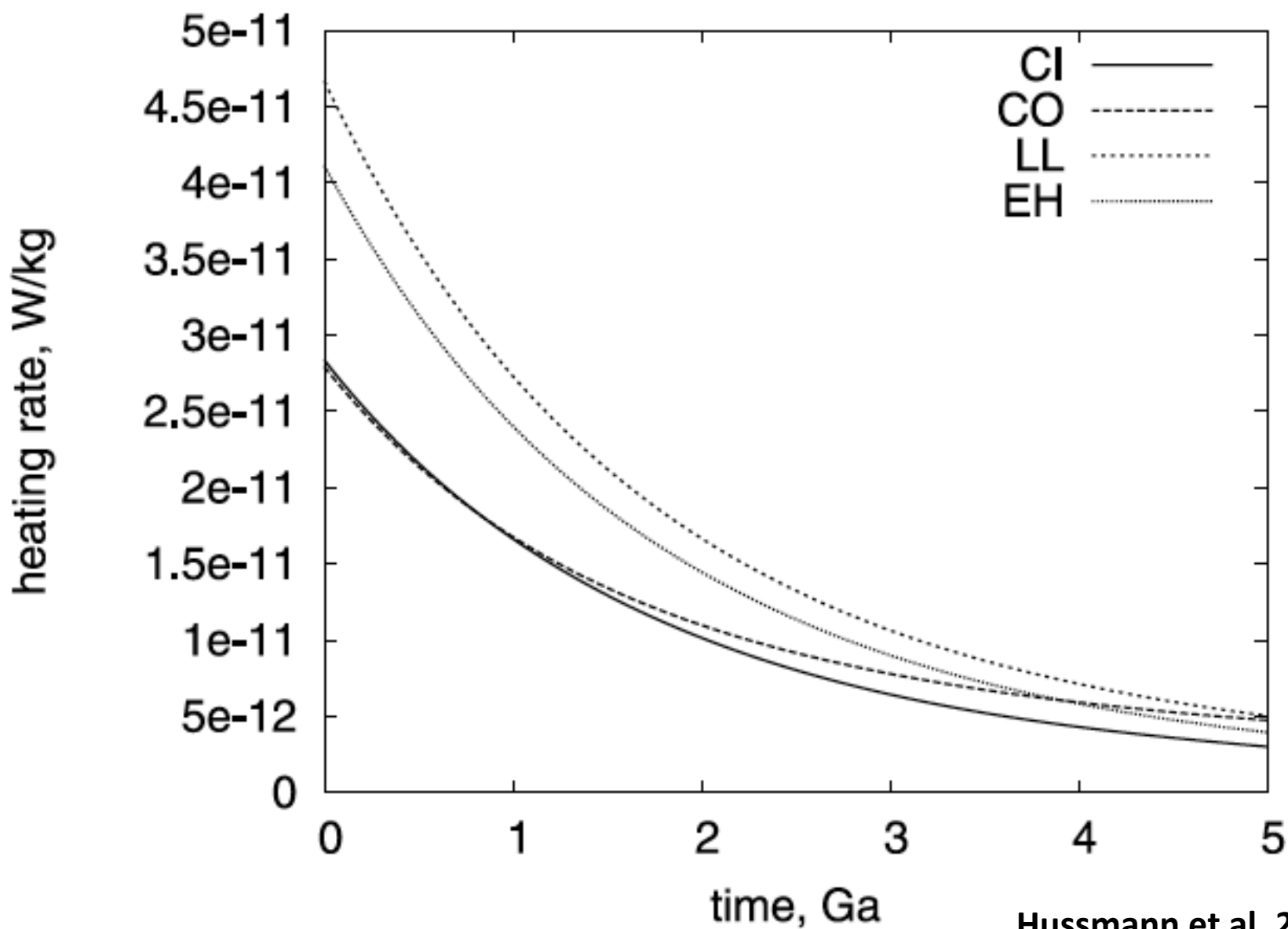
Enceladus Cross-section

Early heat sources (accretion, SLR, satellite-disk interactions) may be important for initial ocean formation

Persistence requires long-lived radiogenics & esp. tidal heating

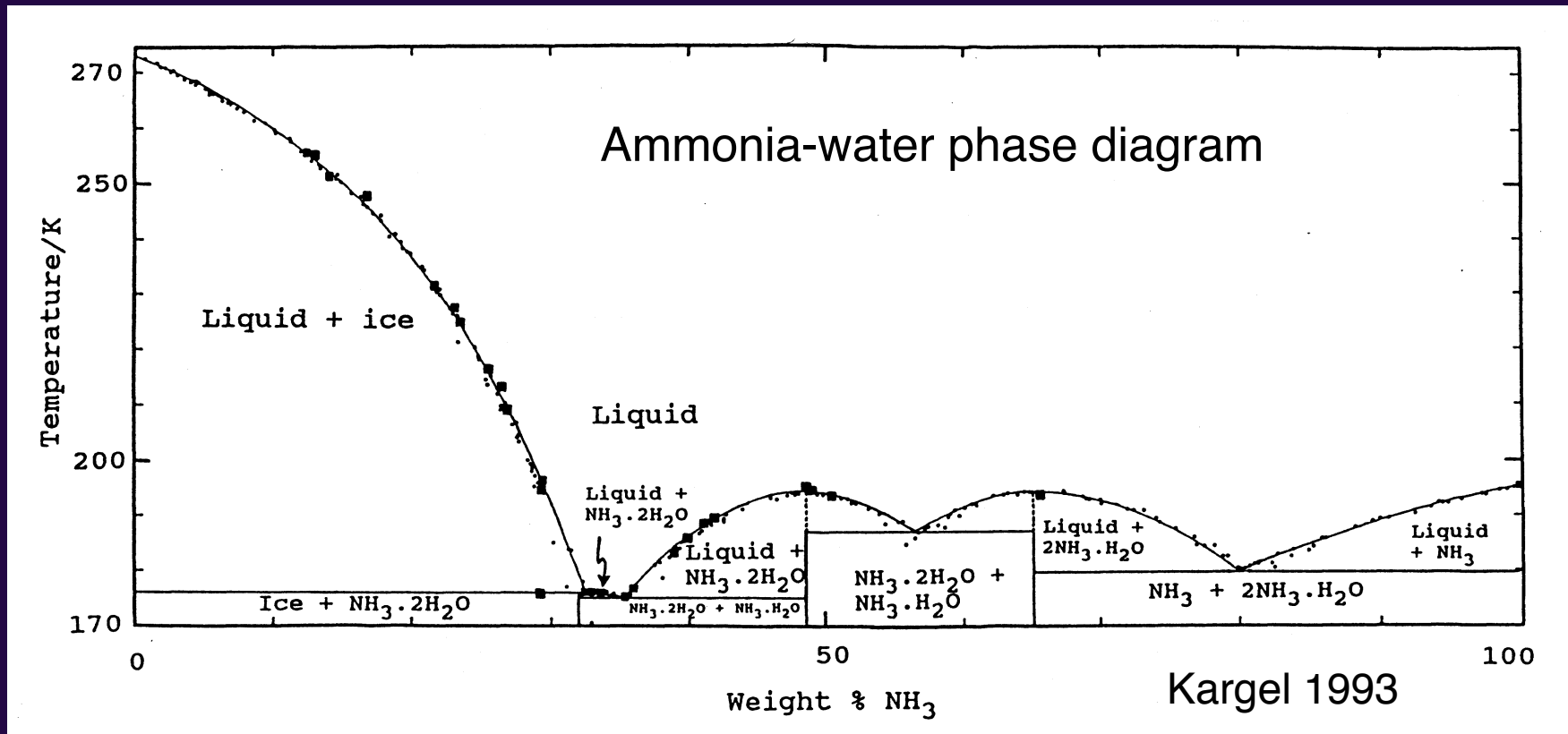
Greatly assisted by antifreezes

Radiogenic heating, based on meteorite class



Hussmann et al. 2010

Very large freezing point depressions possible: Hard to totally freeze oceans

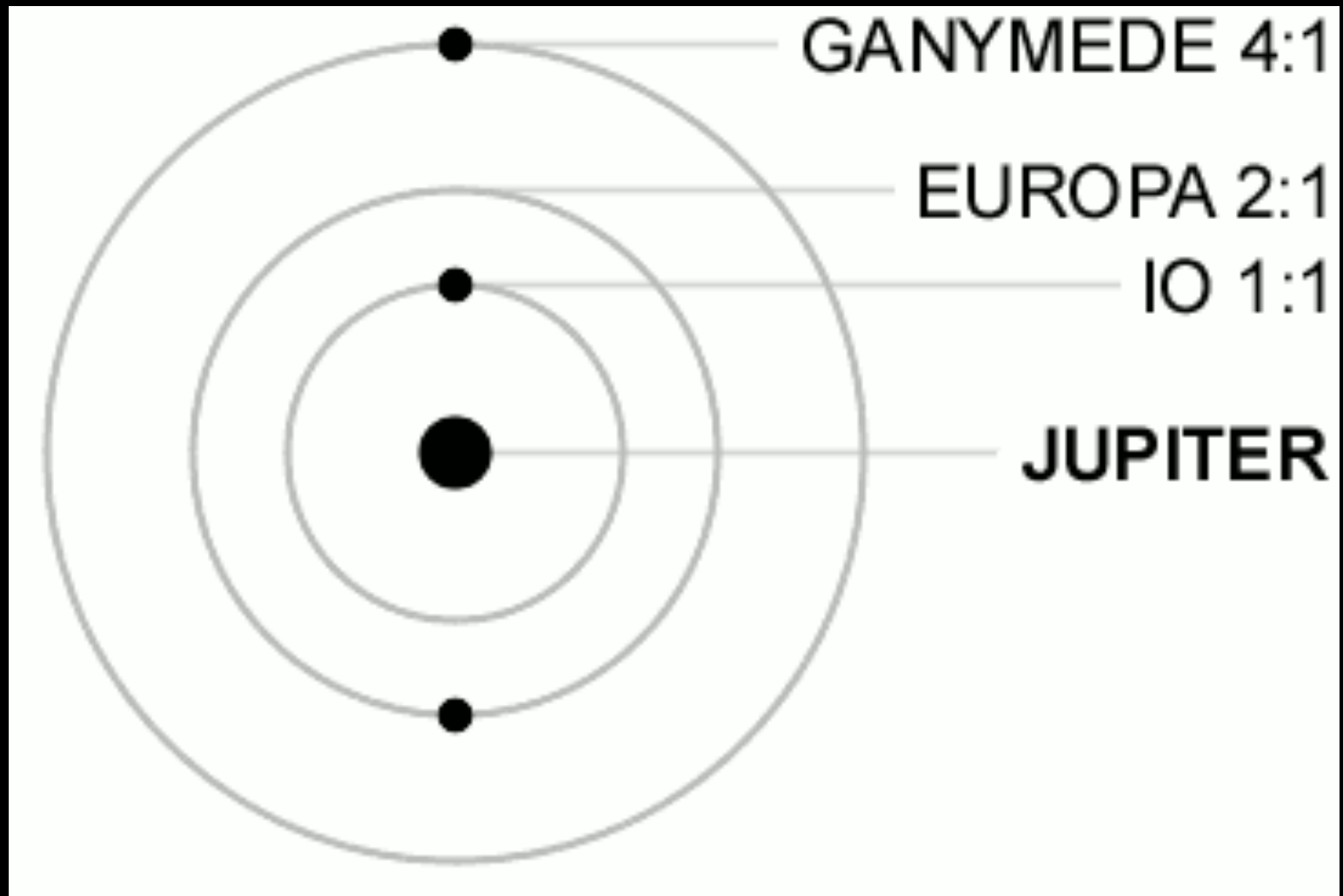


methanol

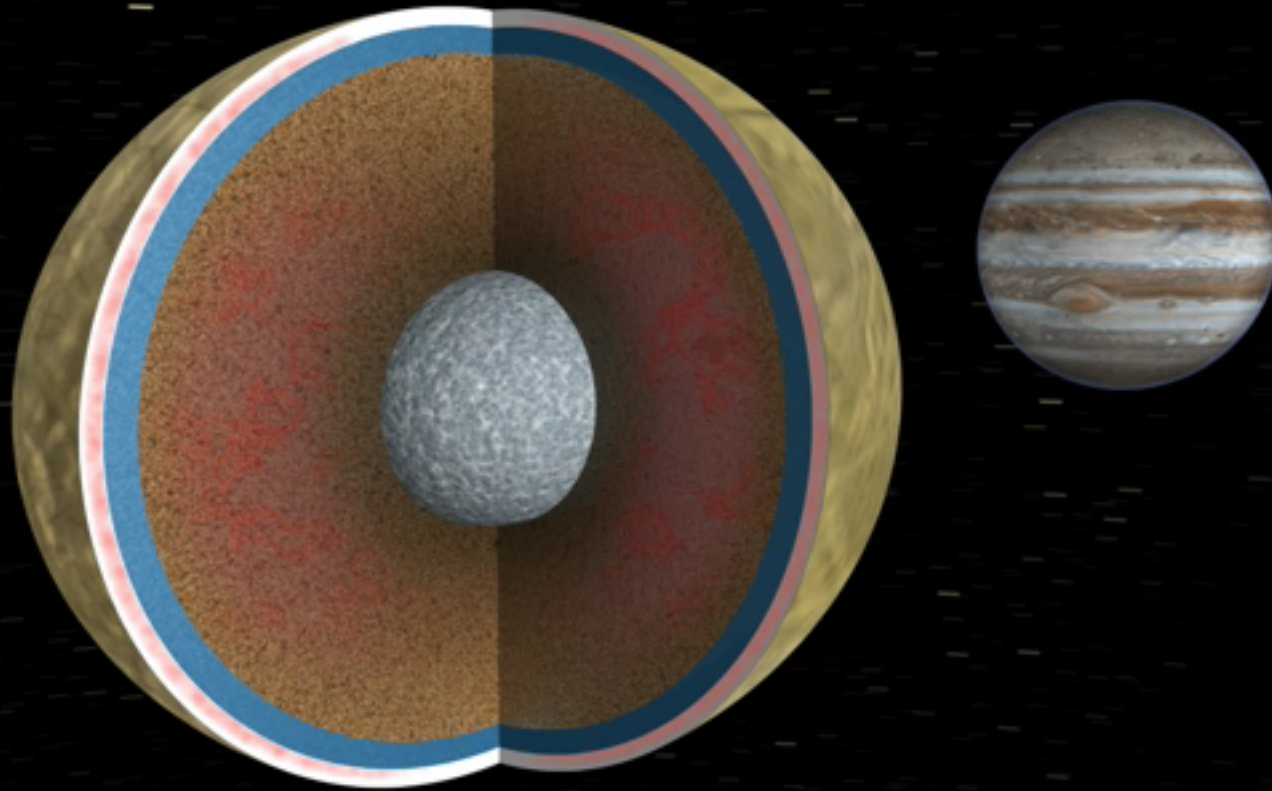
alkali halides

sulfate hydrates

Tidal heating key to ocean survival
e.g., the *Laplace Resonance*:



jovian tides on Europa



The Ocean Worlds

_____	Gravity	Induced $\vec{B}$ $\vec{E}$	Libration	Obliquity	Geology	Plumes
Europa	✓	✓		TBD	Active	?
Ganymede	✓	✓		TBD	Dormant	
Callisto	✓	✓			Dead	
Titan	✓		✓		“not dead yet”	
Enceladus	✓		✓		Hyperactive	✓✓
Triton					Active	✓

Further Background

Nimmo & Pappalardo, *Ocean Worlds in the Outer Solar System* (JGR, 2016)

Hussmann et al., *Interiors and Evolution of Icy Satellites*, (Treatise on Geophysics, 2015)

Grasset et al. (eds), *Satellites of the Outer Solar System: Exchange Processes Involving the Interiors* (Space Science Reviews, 2010)

Pappalardo et al. (eds), *Europa* (UofA Space Science Series, 2009)

Schenk et al. (eds), *Enceladus and the Icy Moons of Saturn* (UofA Space Science Series, 201x)