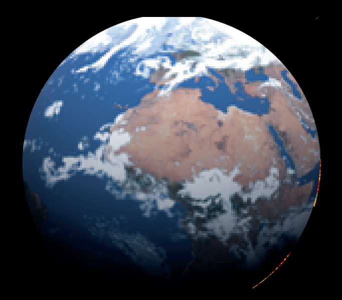
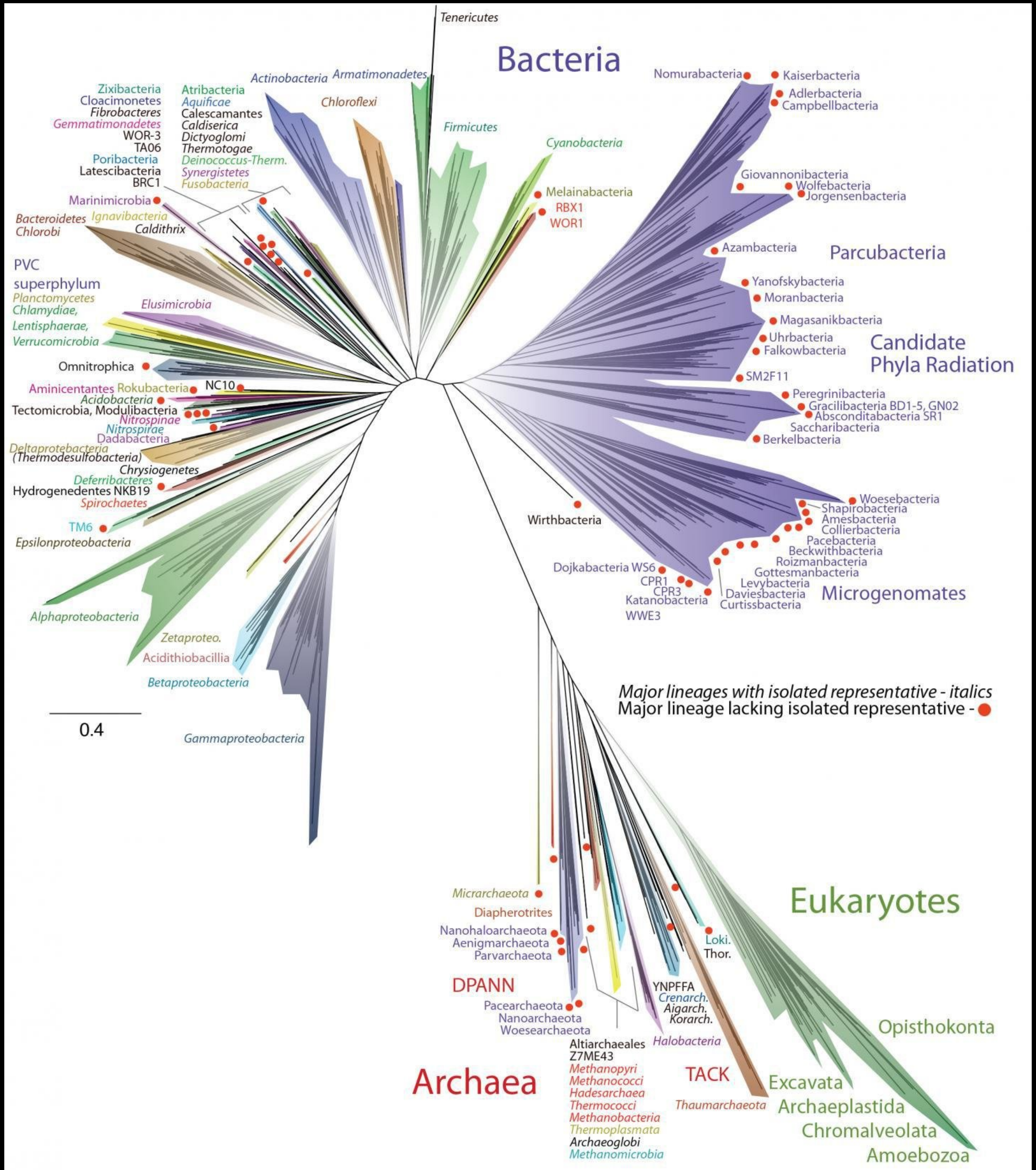
Ocean Worlds of the Outer Solar System

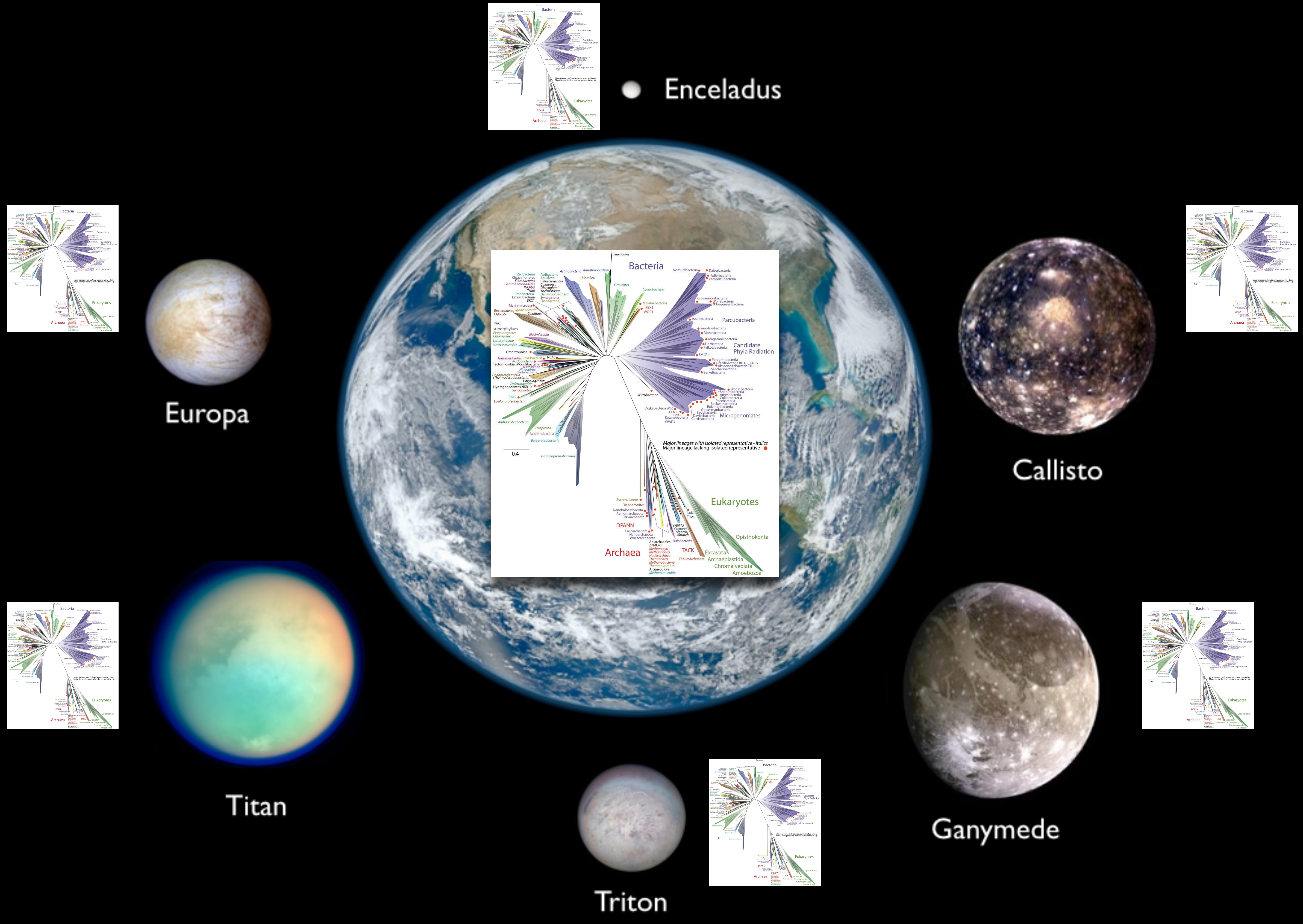
Dr. Kevin Peter Hand
NASA Jet Propulsion Laboratory, California Institute of Technology




Enceladus
Europa
Callisto
Titan
Triton
Ganymede
Shown to scale



Hug et al., 2016


Enceladus
Europa
Callisto
Titan
Ganymede
Triton
Bacteria
Parcubacteria
Candidate Phyla Radiation
Microgenomates
Eukaryotes
Opisthokonta
Excavata
Archaeplastida
Chromalveolata
Amoebozoa
Archaea
DPANN
TACK
Shown to scale

Old Goldilocks

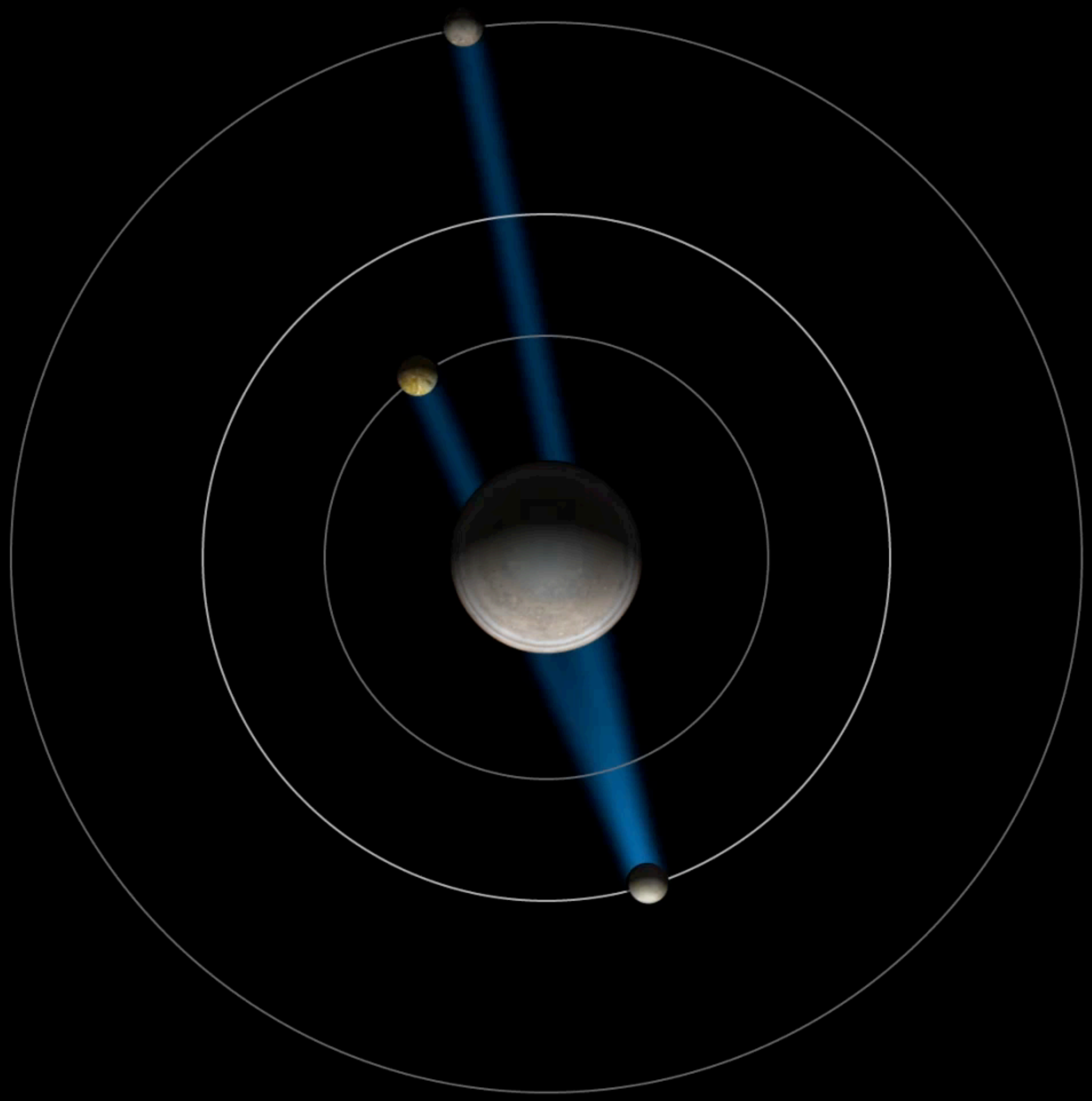
Venus

Earth

Mars

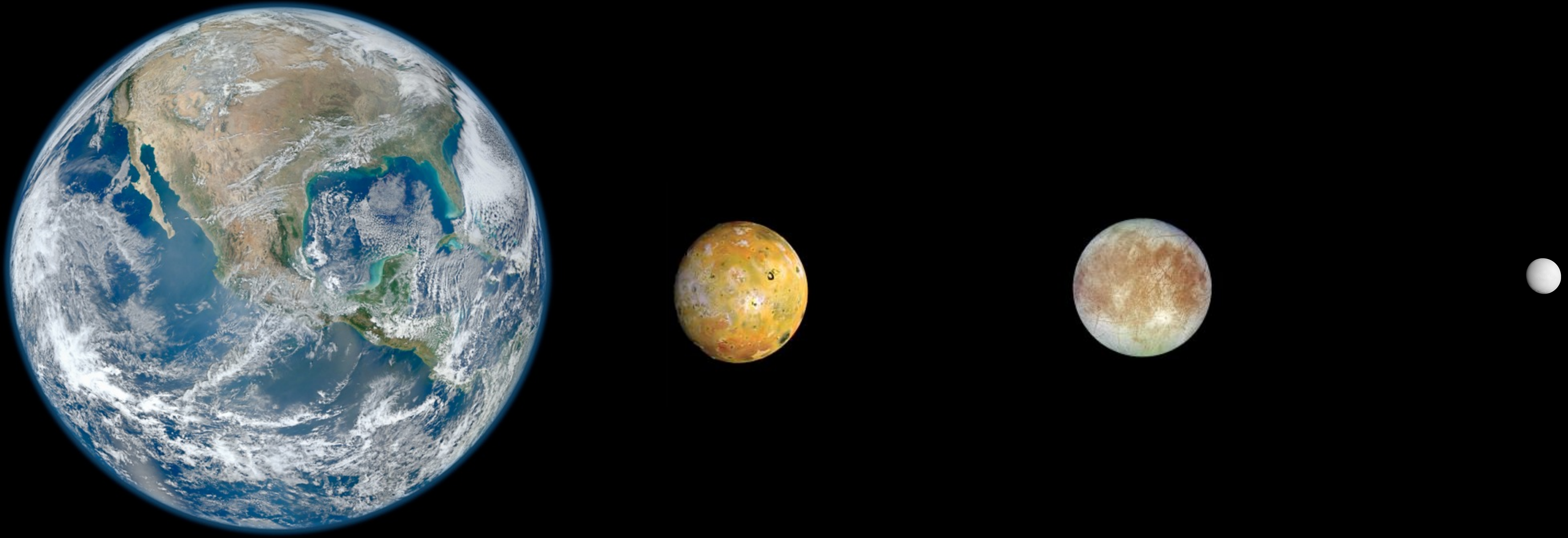
Io Europa Ganymede Callisto

New Goldilocks



National Geographic

Tidal Energy and the New Goldilocks for Habitability



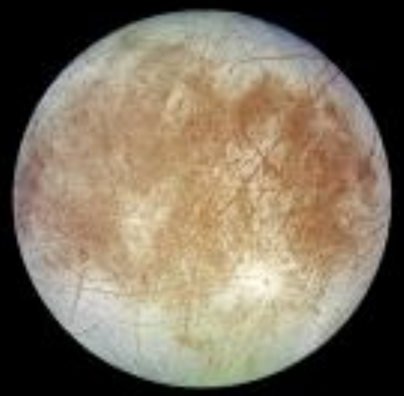
Earth
60-80 mW m^{-2}

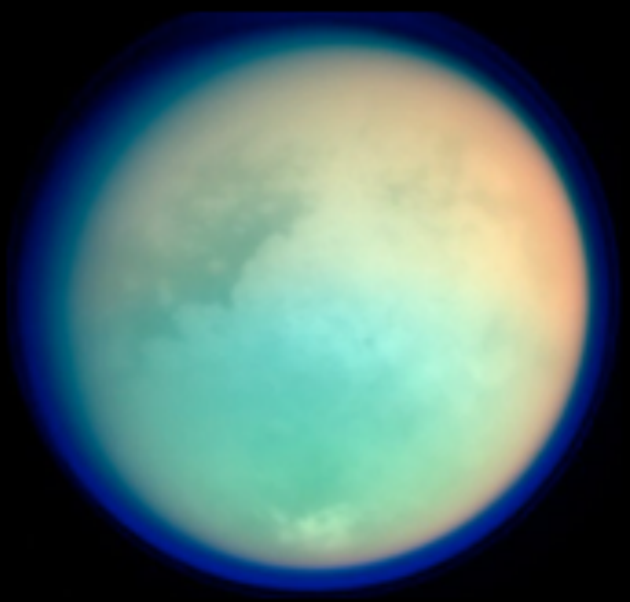
Io
2500 mW m^{-2}

Europa
10-800 mW m^{-2}

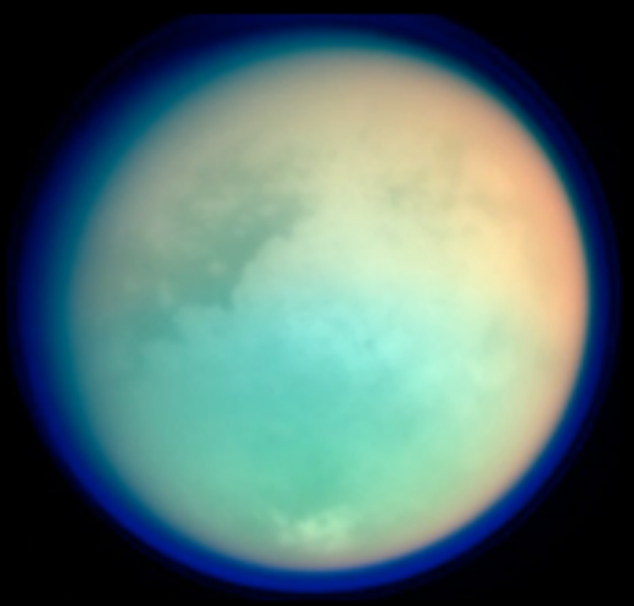
Enceladus
~16 GW
~200? mW m^{-2}

New Goldilocks

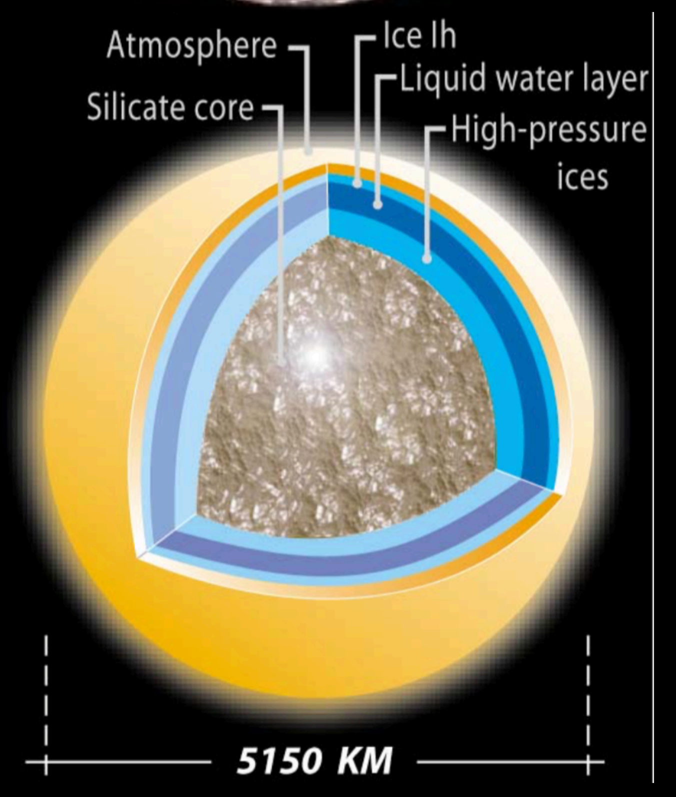




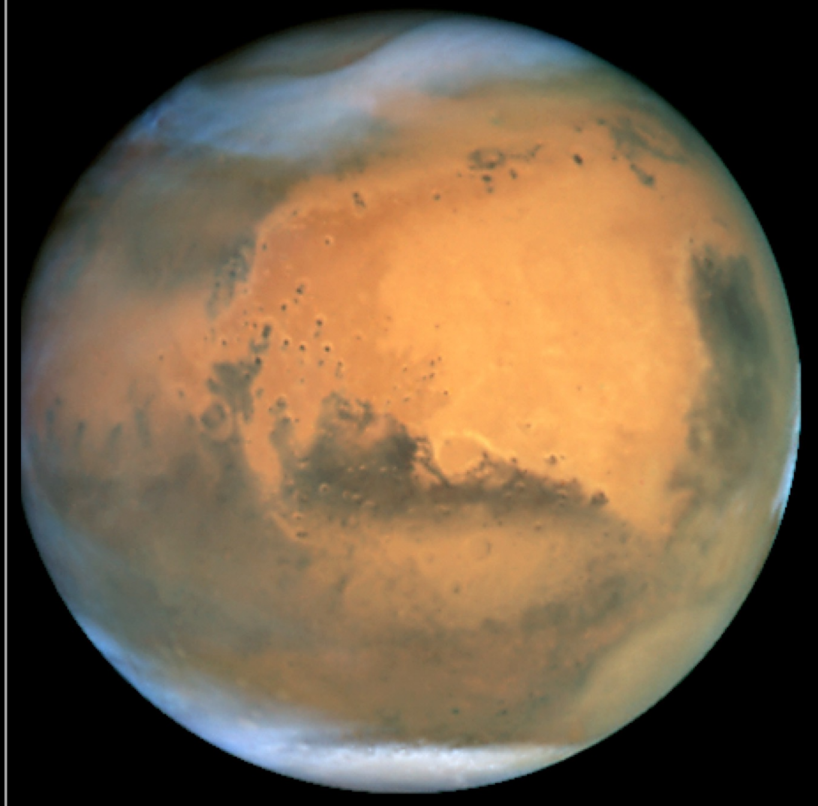
Weird Life



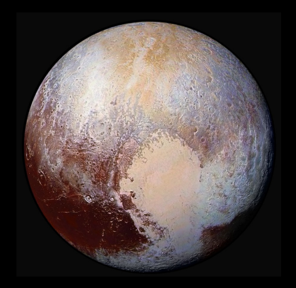
Too big? Ice too thick?



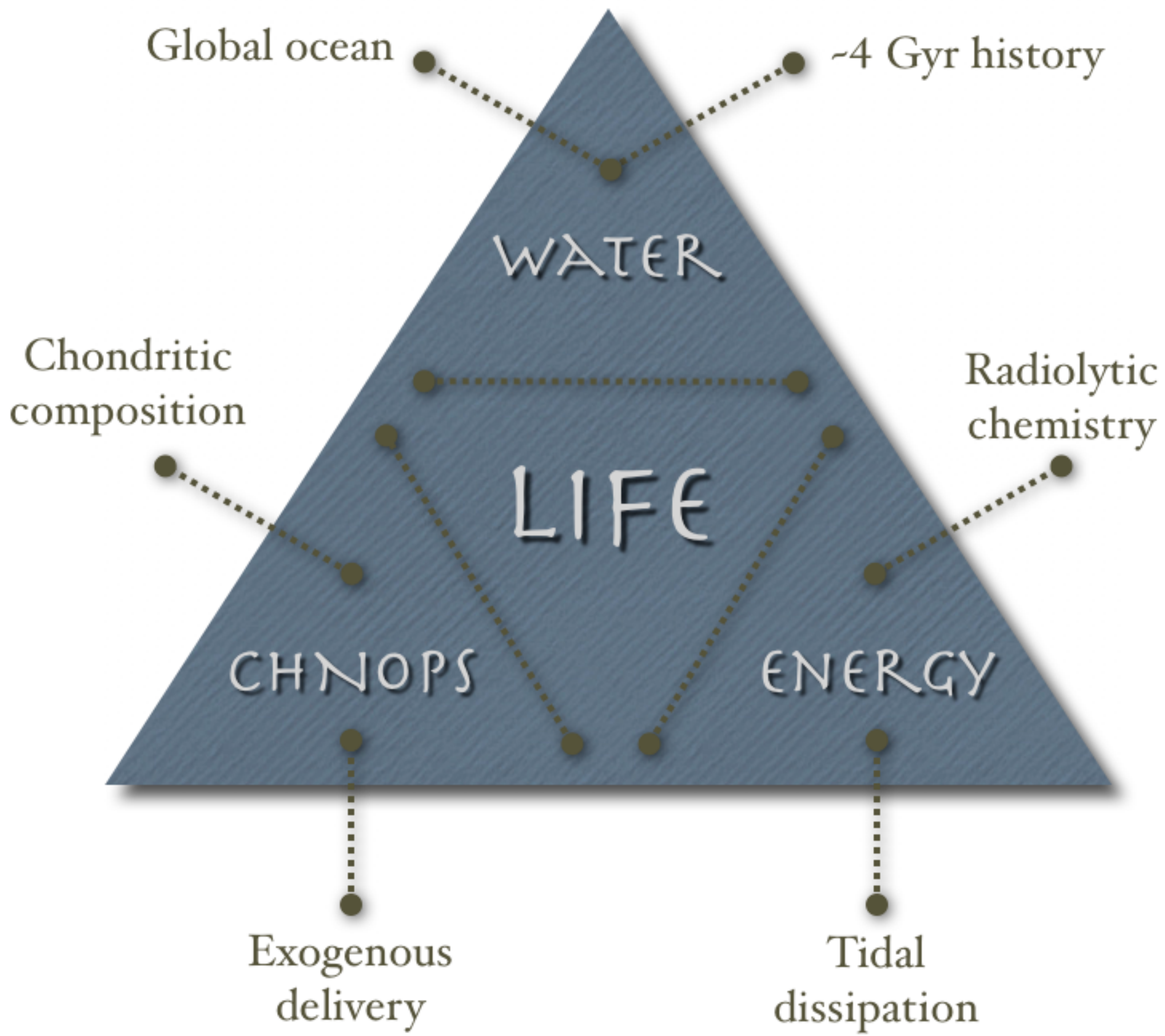
Relic oceans?



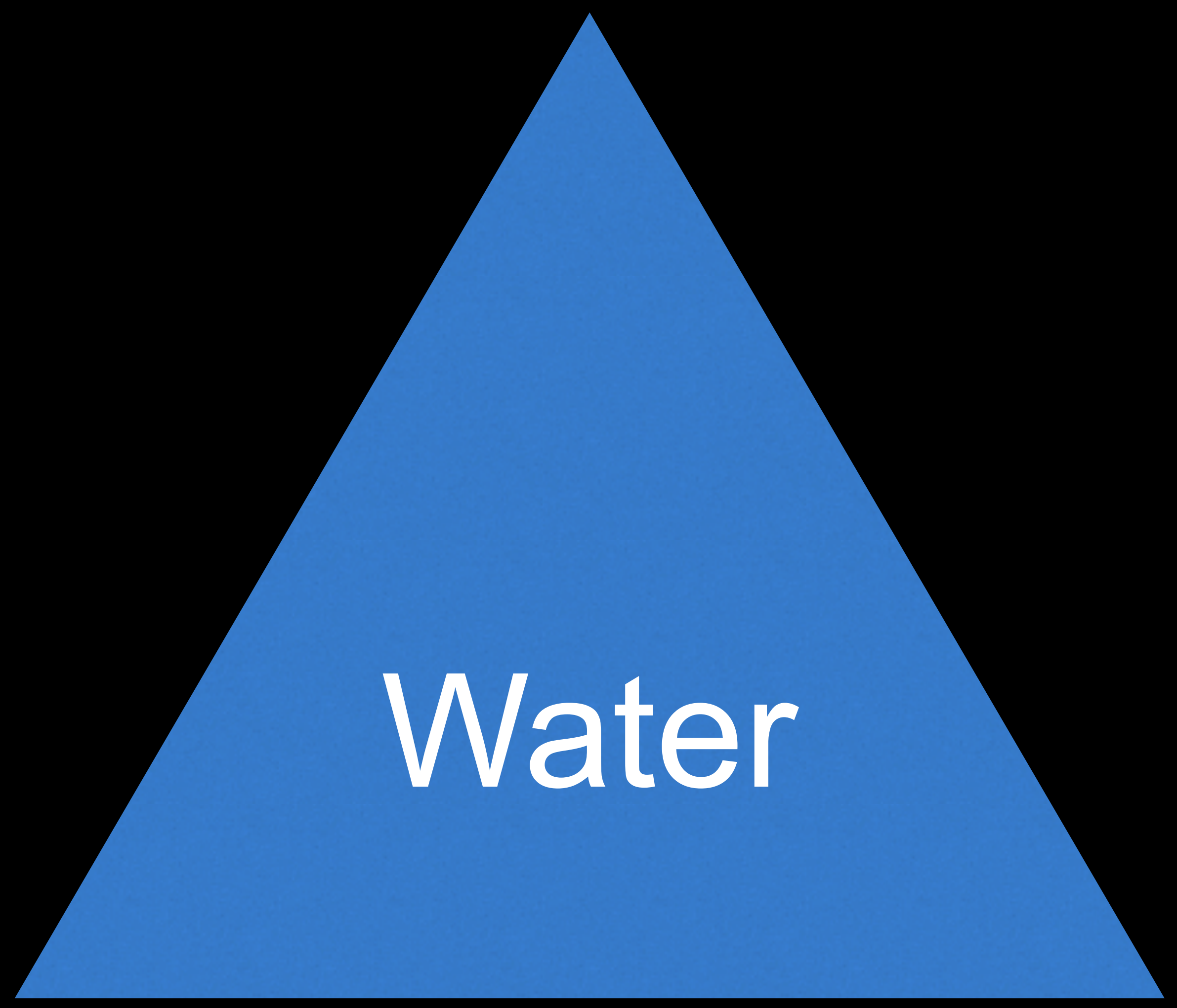
Unknown

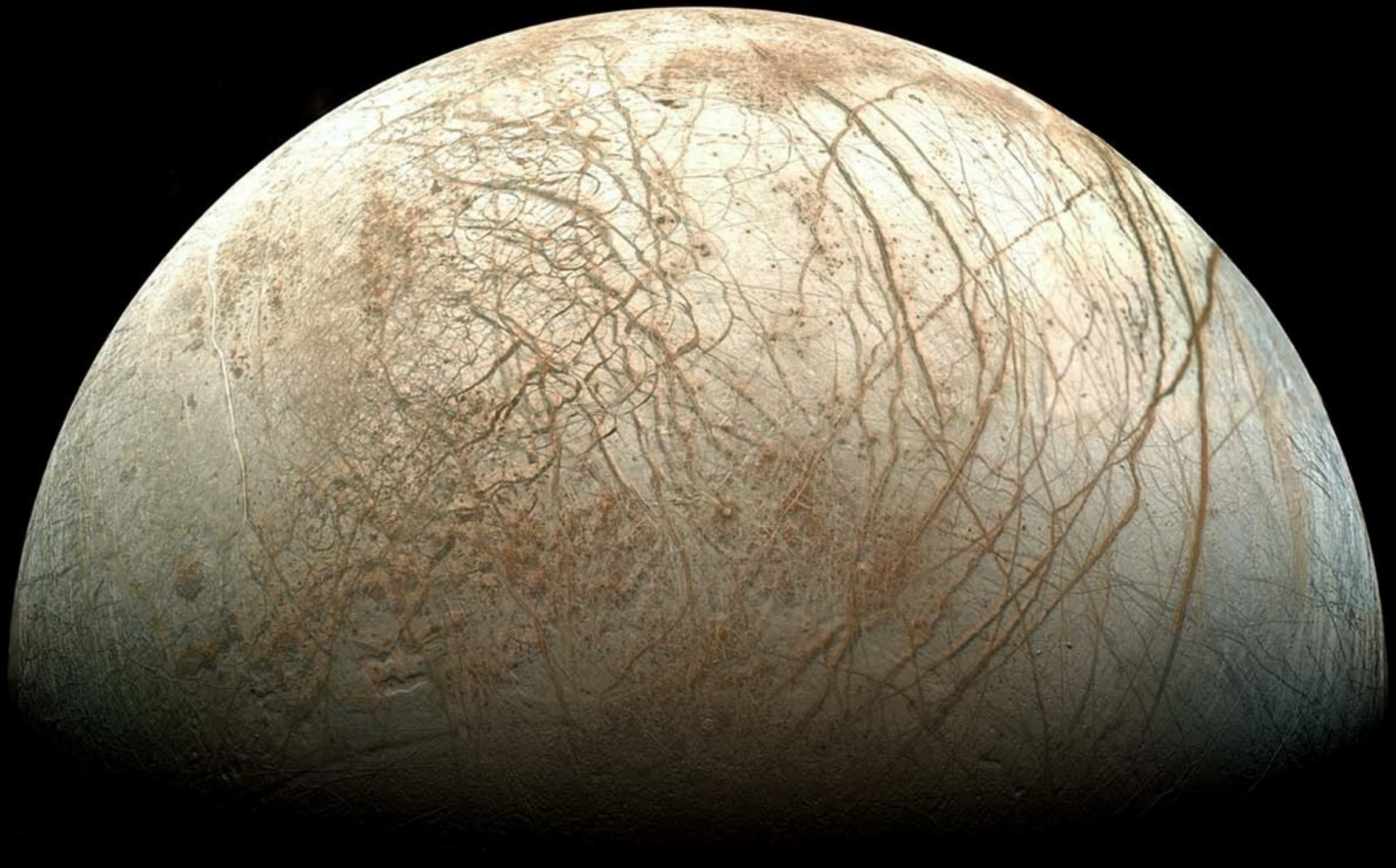


Habitability



Hand et al. 2009


Water



Discovering an Ocean in 3 Easy Pieces

Piece #1: Find a Rainbow Connection

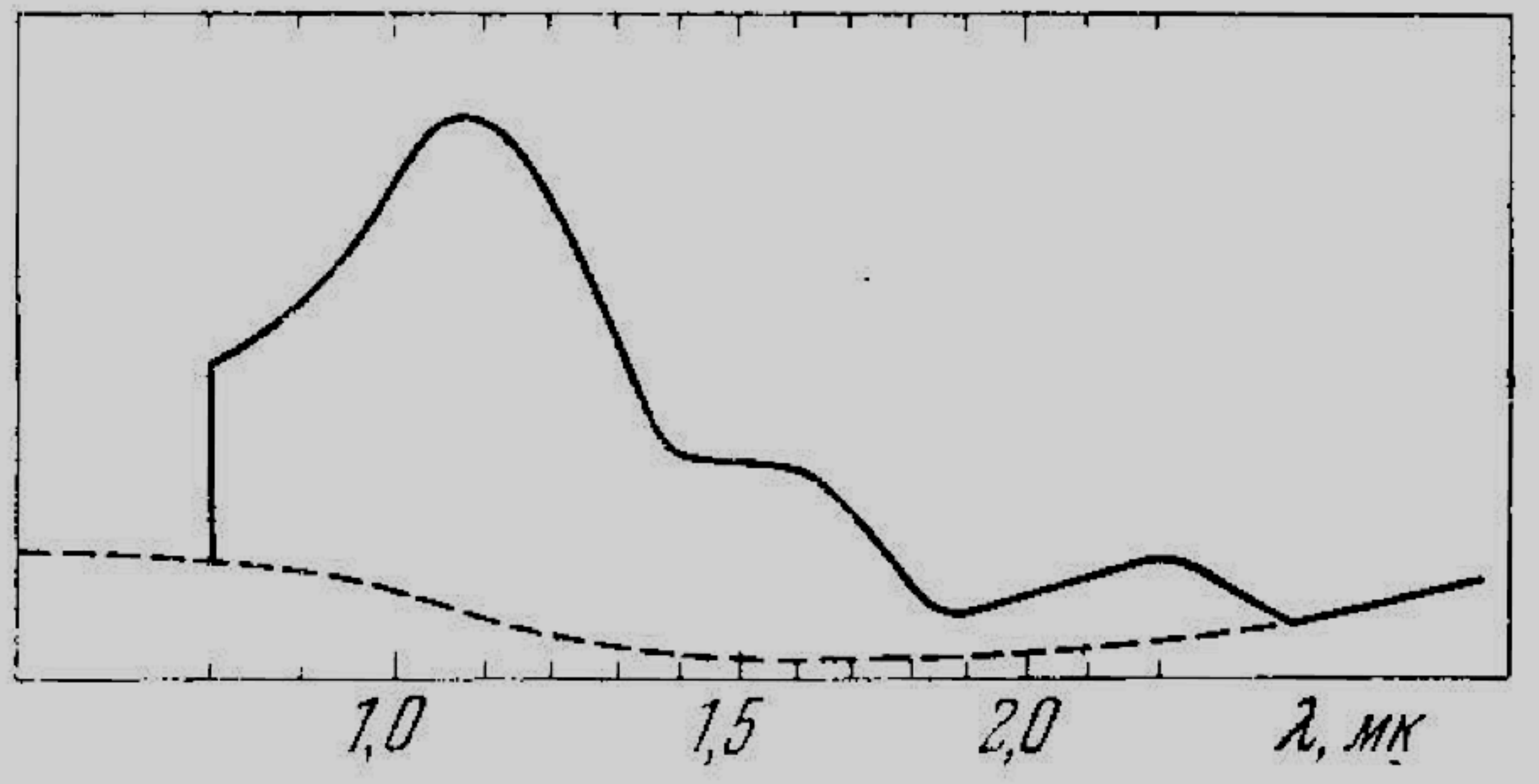
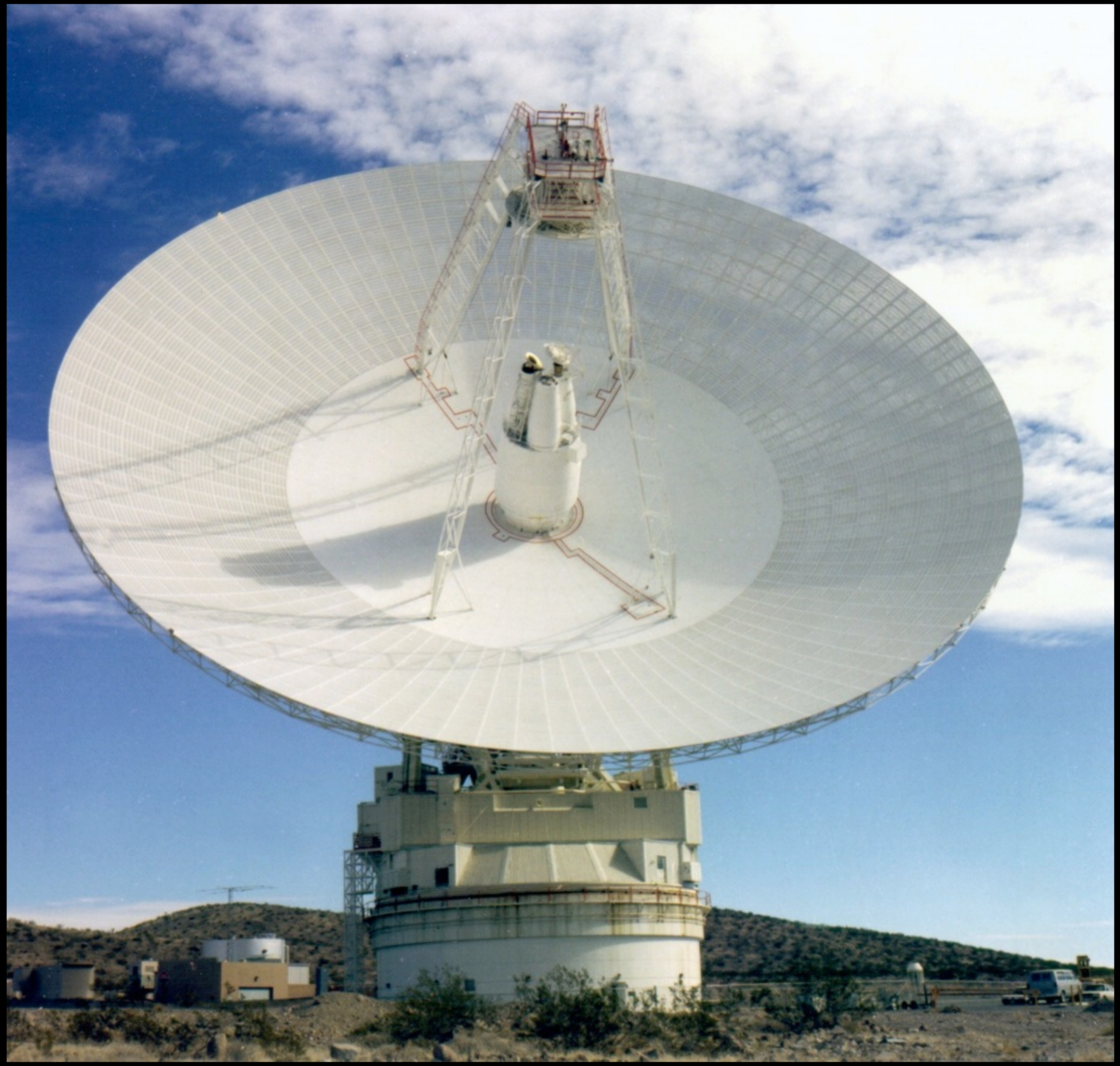


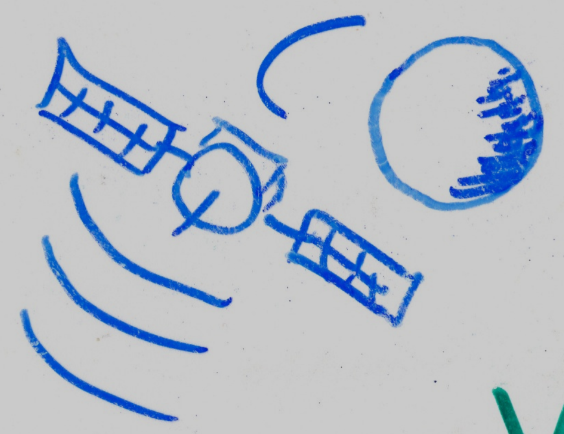
Рис. 198. Спектр Европы, среднее из четырех записей 1.10 1964 г., ЗТШ, Нуль-пункт (пунктир) зависит от длины волны вследствие слабой паразитной подсветки.

Moroz, 1964

Piece #2: Babysit a Spacecraft



EUROPA: EVIDENCE FOR AN OUTER SHELL OF WATER



$$F = \frac{G m_1 m_2}{r^2} \rightarrow V = \frac{GM}{r}\left[1 + \sum_{n=2}^{\infty}\sum_{m=0}^{n}\left(\frac{R}{r}\right)^n \left(C_{nm}\cos m\lambda + S_{nm}\sin m\lambda\right) P_{nm}(\sin\phi)\right]$$

$$V = \frac{GM}{r}\left[1 - \frac{1}{2}J_2\left(\frac{R}{r}\right)^2\left(3\sin^2\phi - 1\right) + 3C_{22}\left(\frac{R}{r}\right)^2\cos^2\phi\,\cos 2\lambda\right]$$

$$\downarrow$$

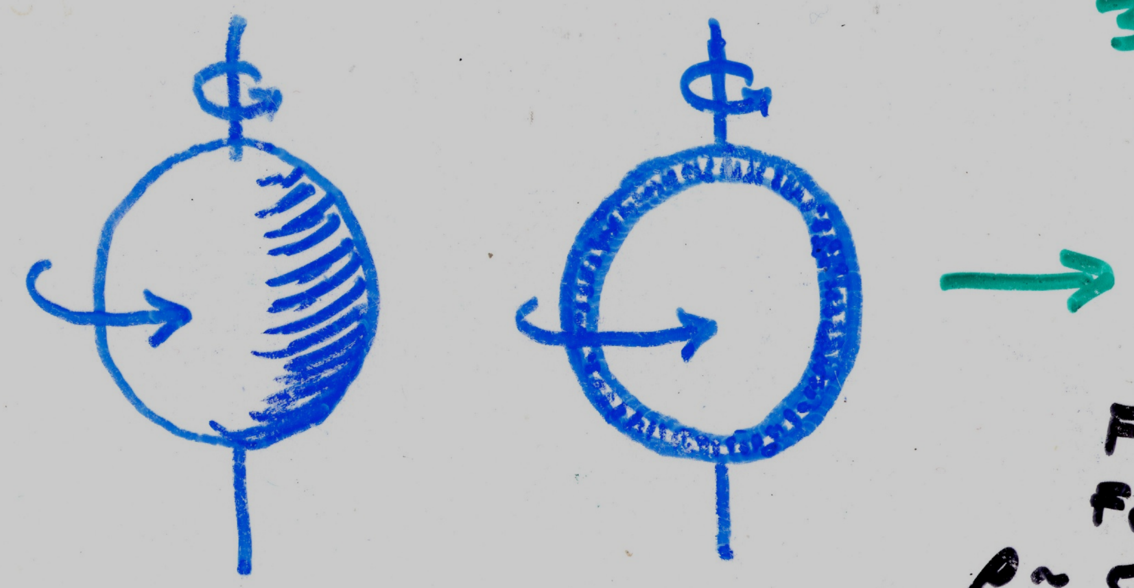
$$I = \int r^2\,dm$$

Solid sphere

$I = \frac{2}{5}MR^2$

Shell

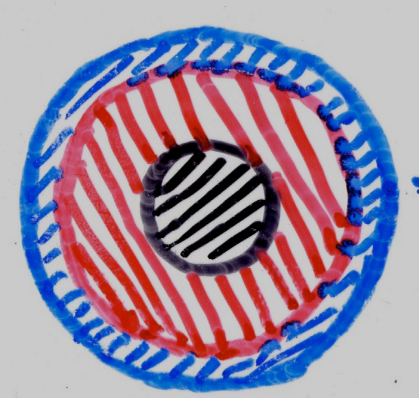
$I = \frac{2}{3}MR^2$



Galileo data for Europa:

$I = 0.346\,MR^2$

3-layer Model



$\rho = 1050$ kg m^{-3}

H_2O layer of ~80-170 km

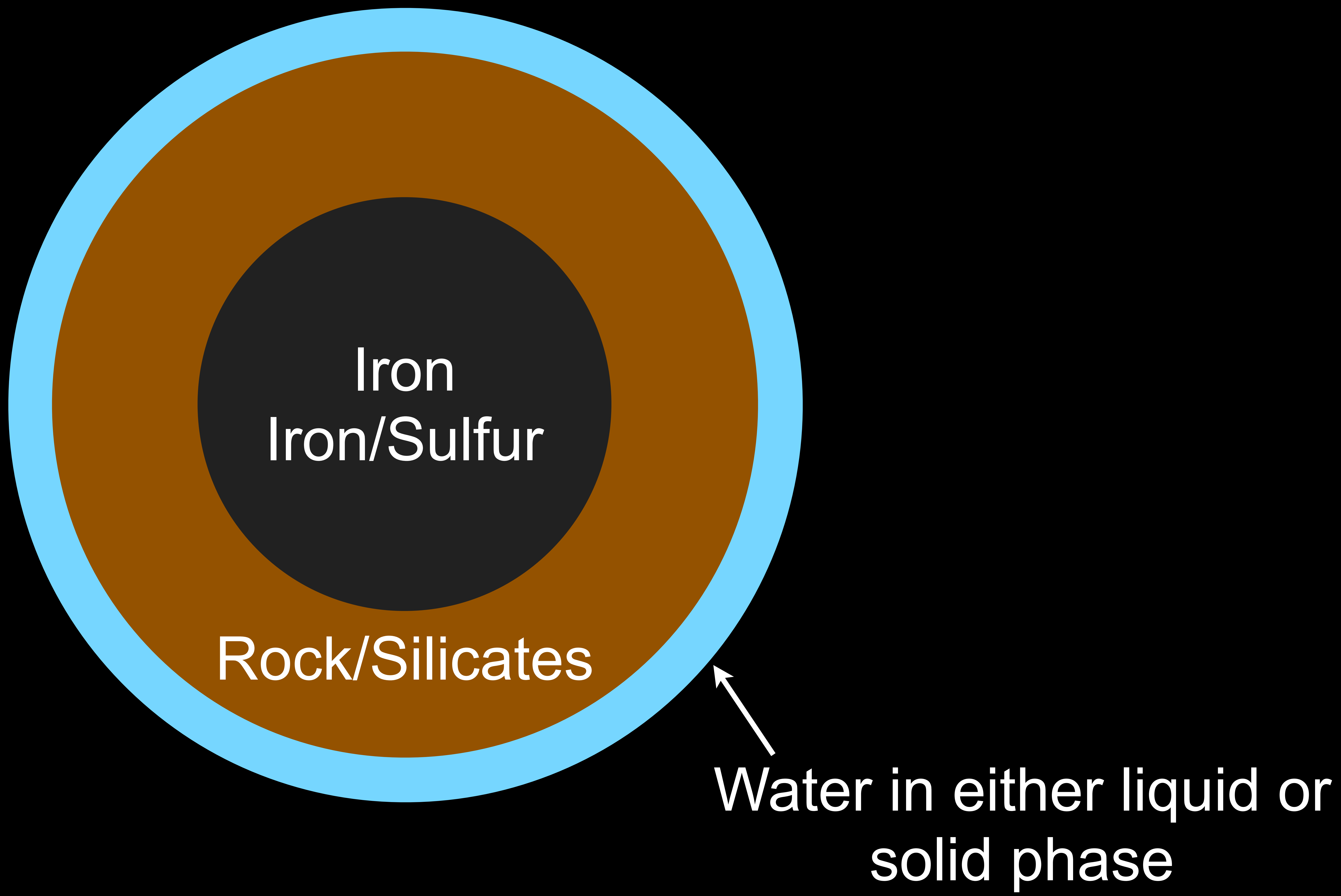
Fe, Fe-S

$\rho \sim 5000-8000$ kg m^{-3}

Silicates $\rho \sim 3000+$ kg m^{-3}

Anderson et al. (1998)

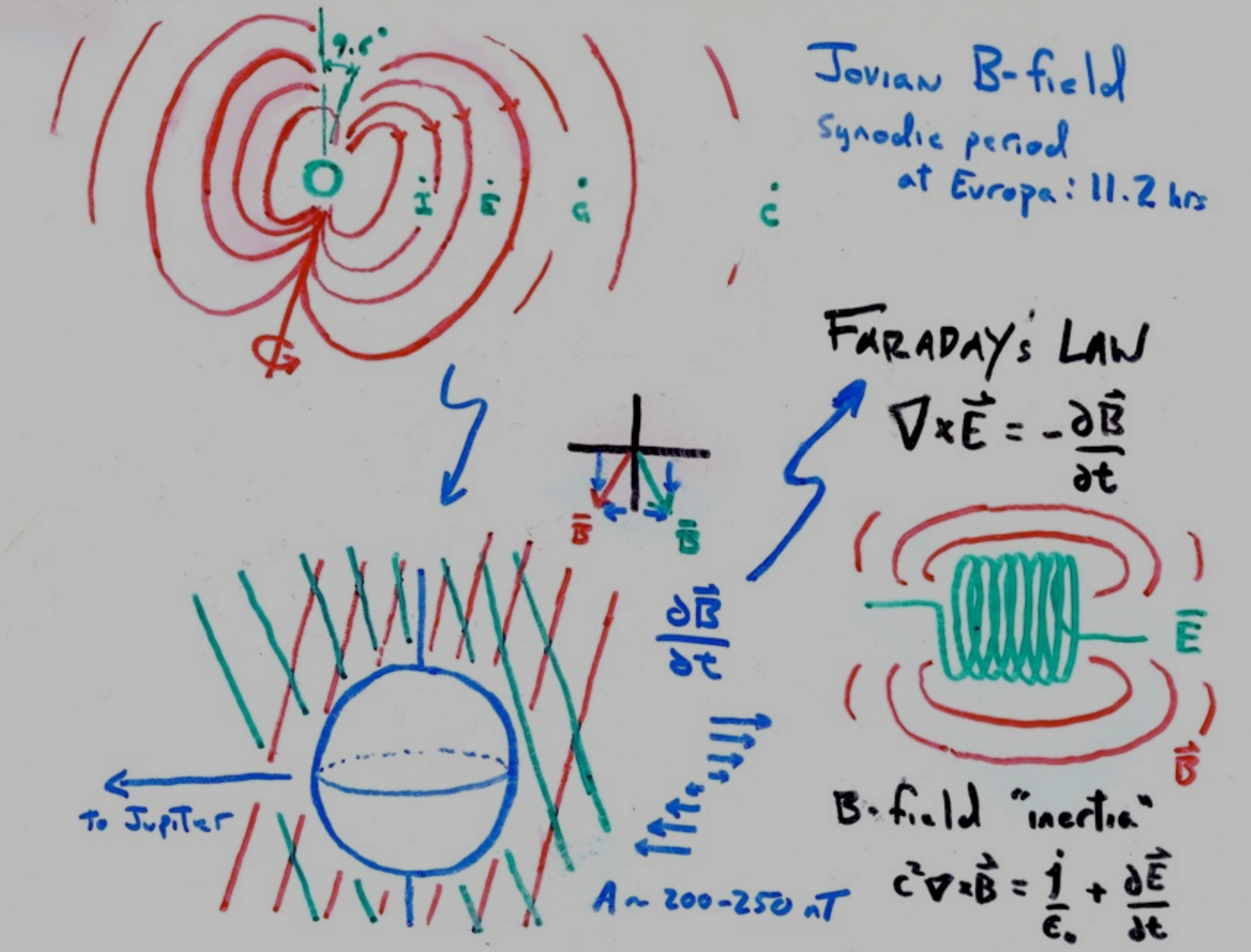
Europa Cross Section

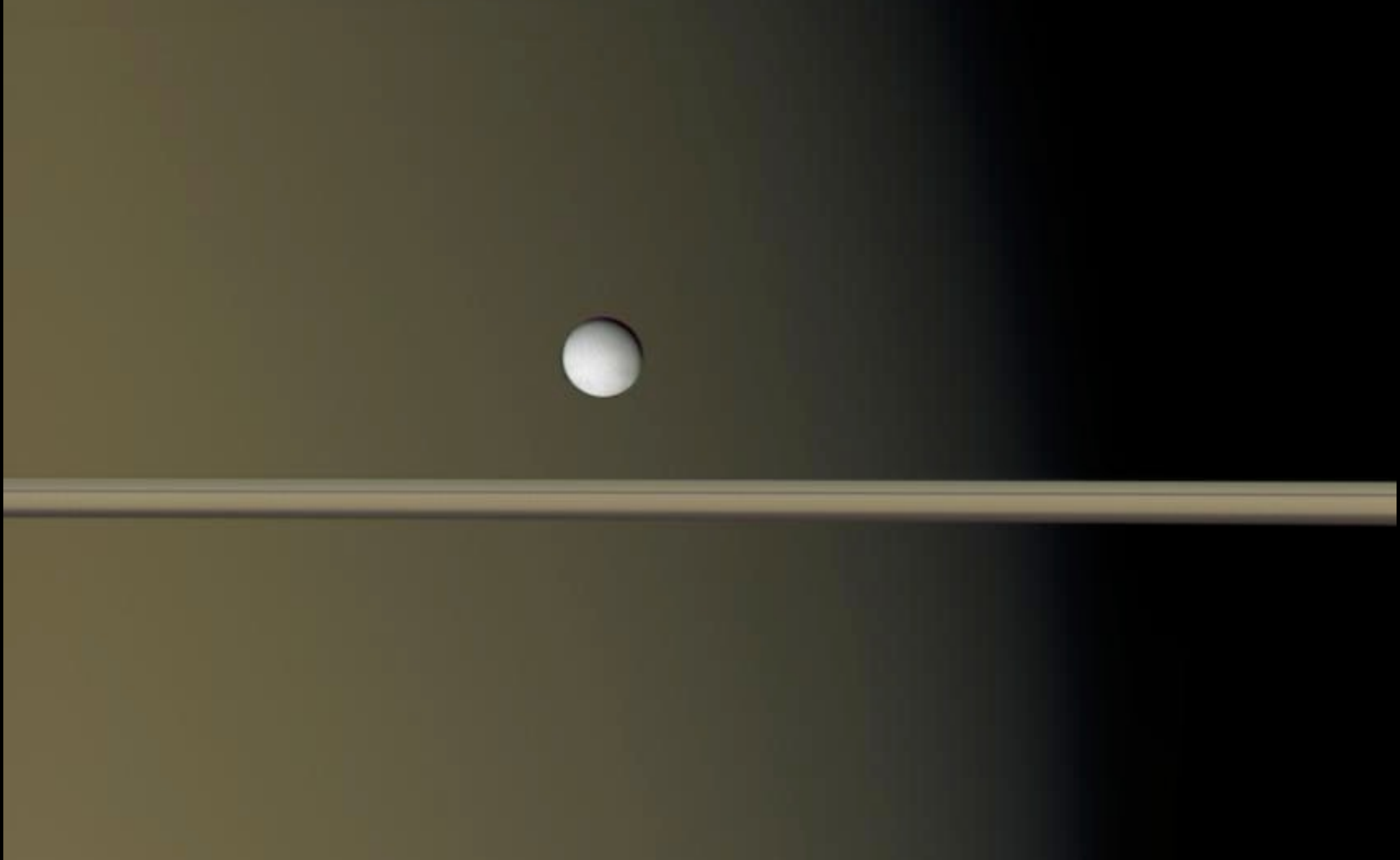


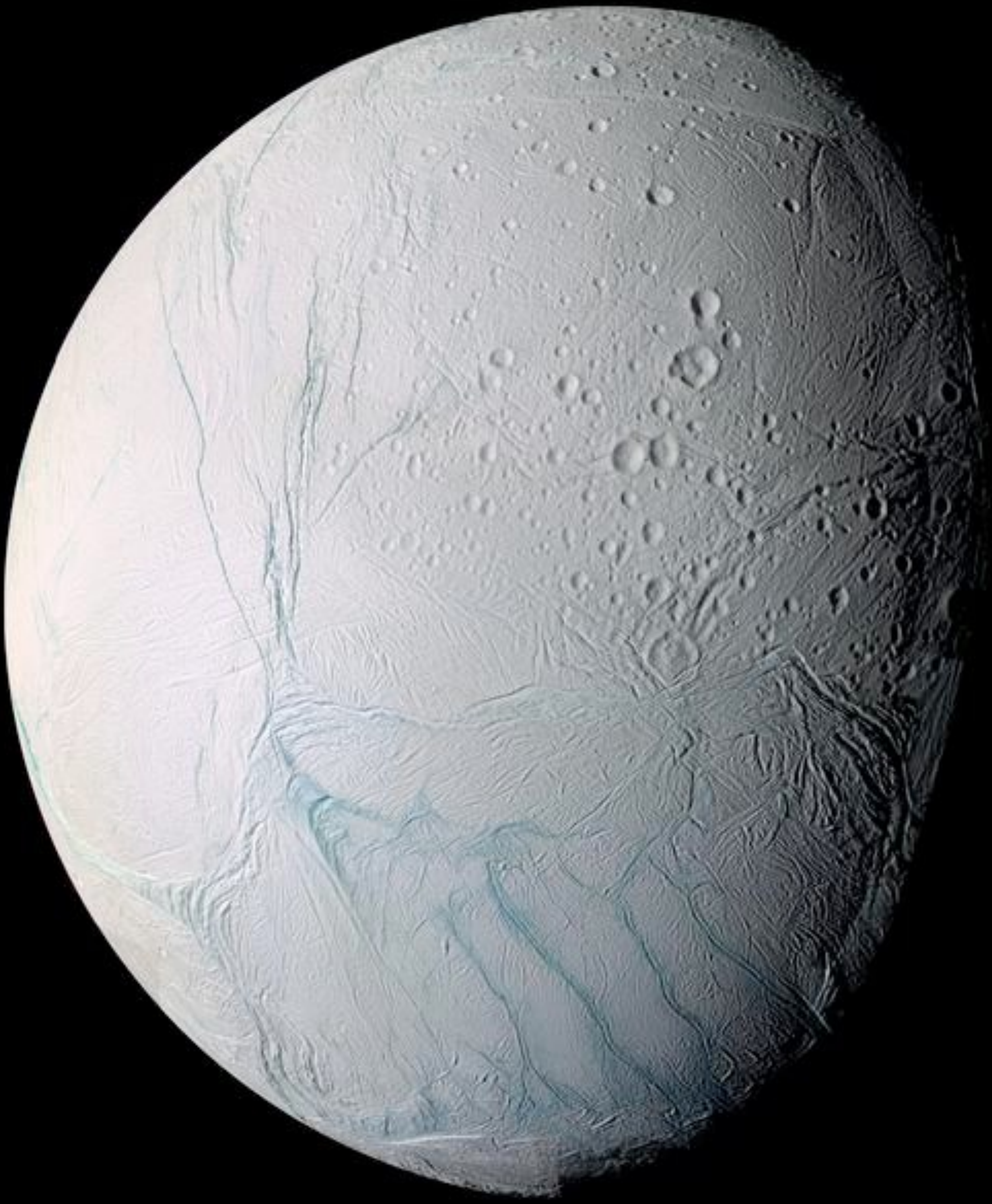
Piece #3: Adhere to Airport Security


View to Jupiter
Date: 12/18/96 18:55 UTC
Range to Jupiter: 755,421 km
Range to Europa: 212,569 km

Europa: Evidence for a Shell of Liquid Water



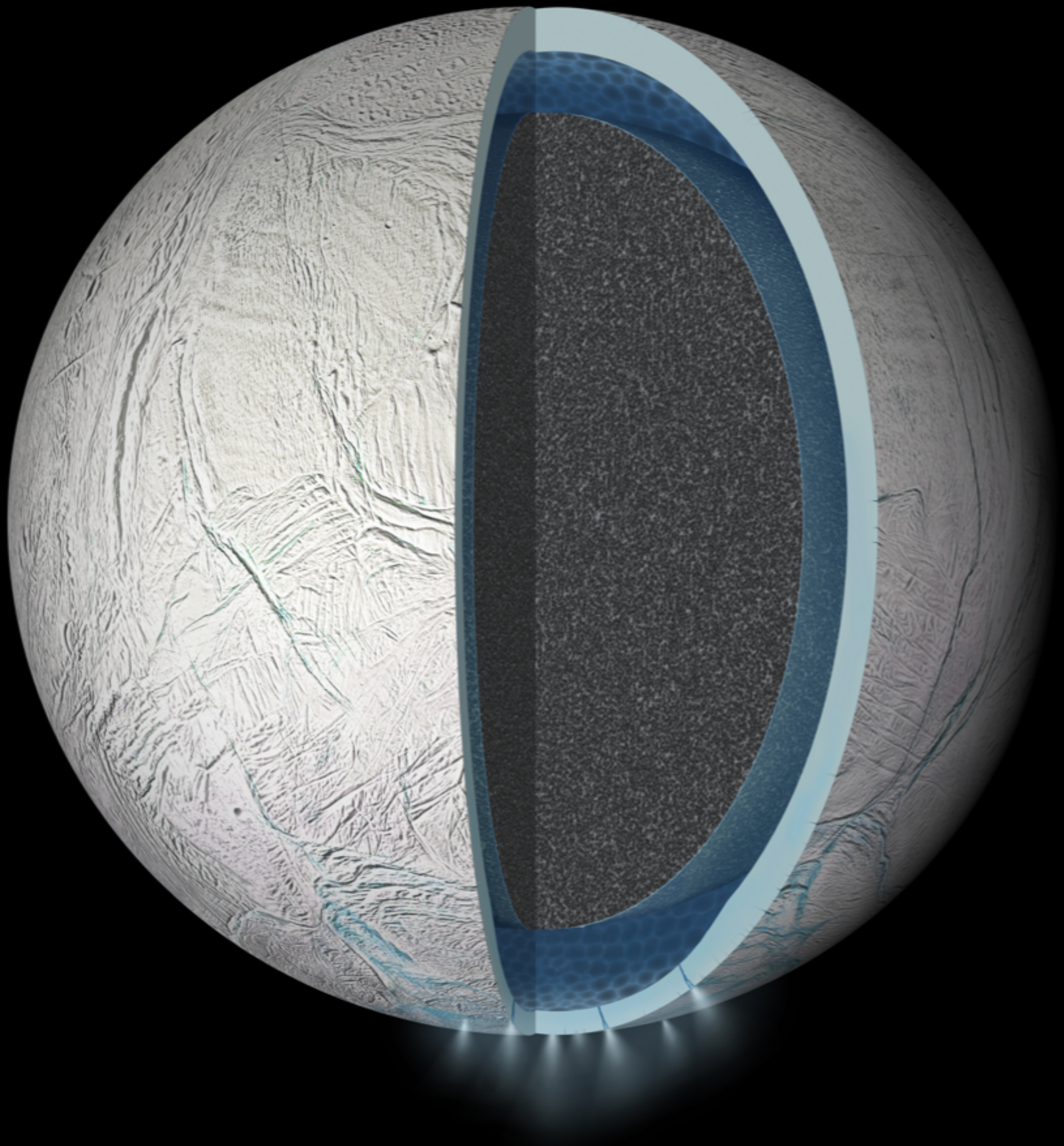




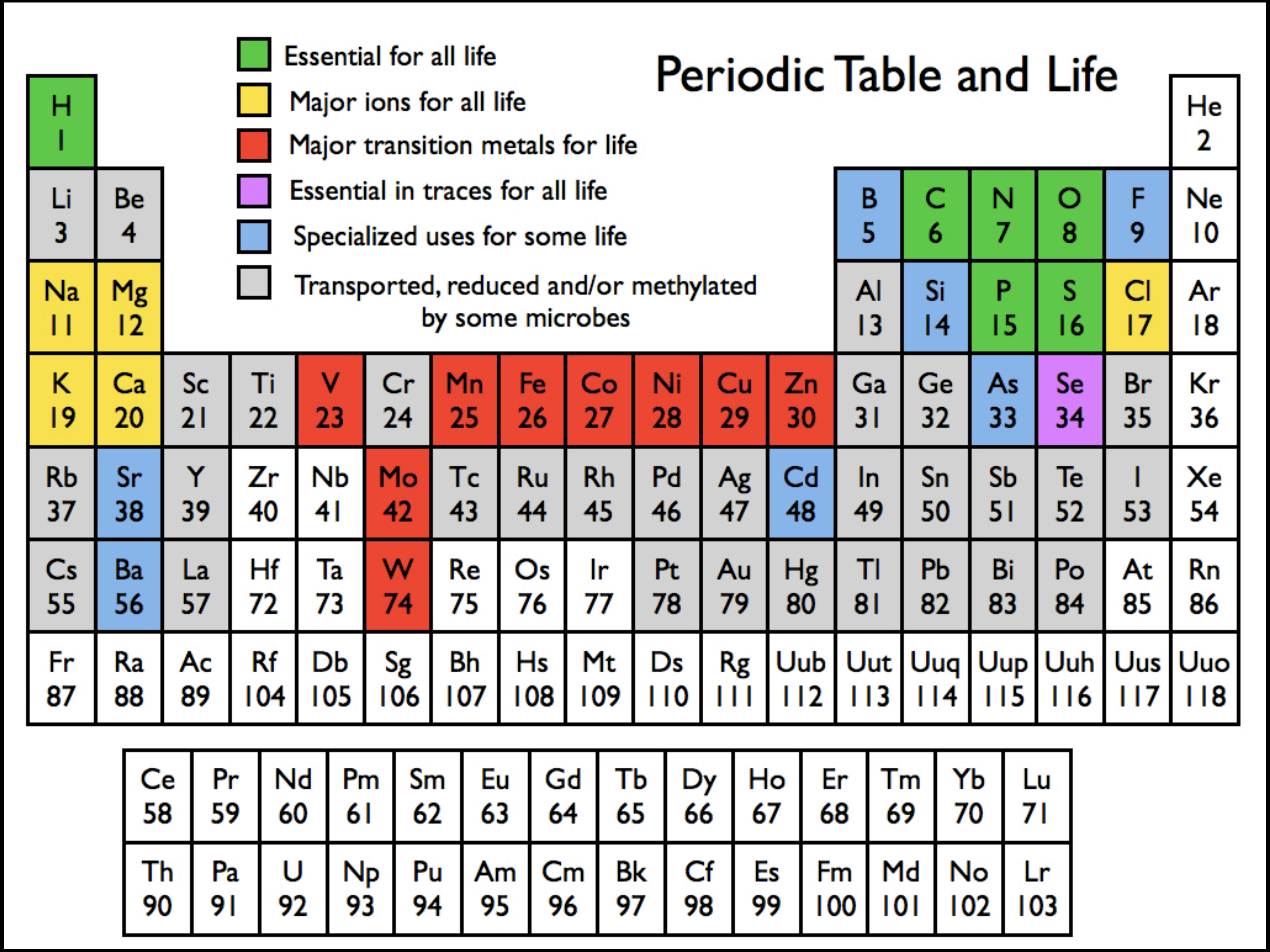
Enceladus

NASA/JPL/SSI

NASA/JPL/SSI

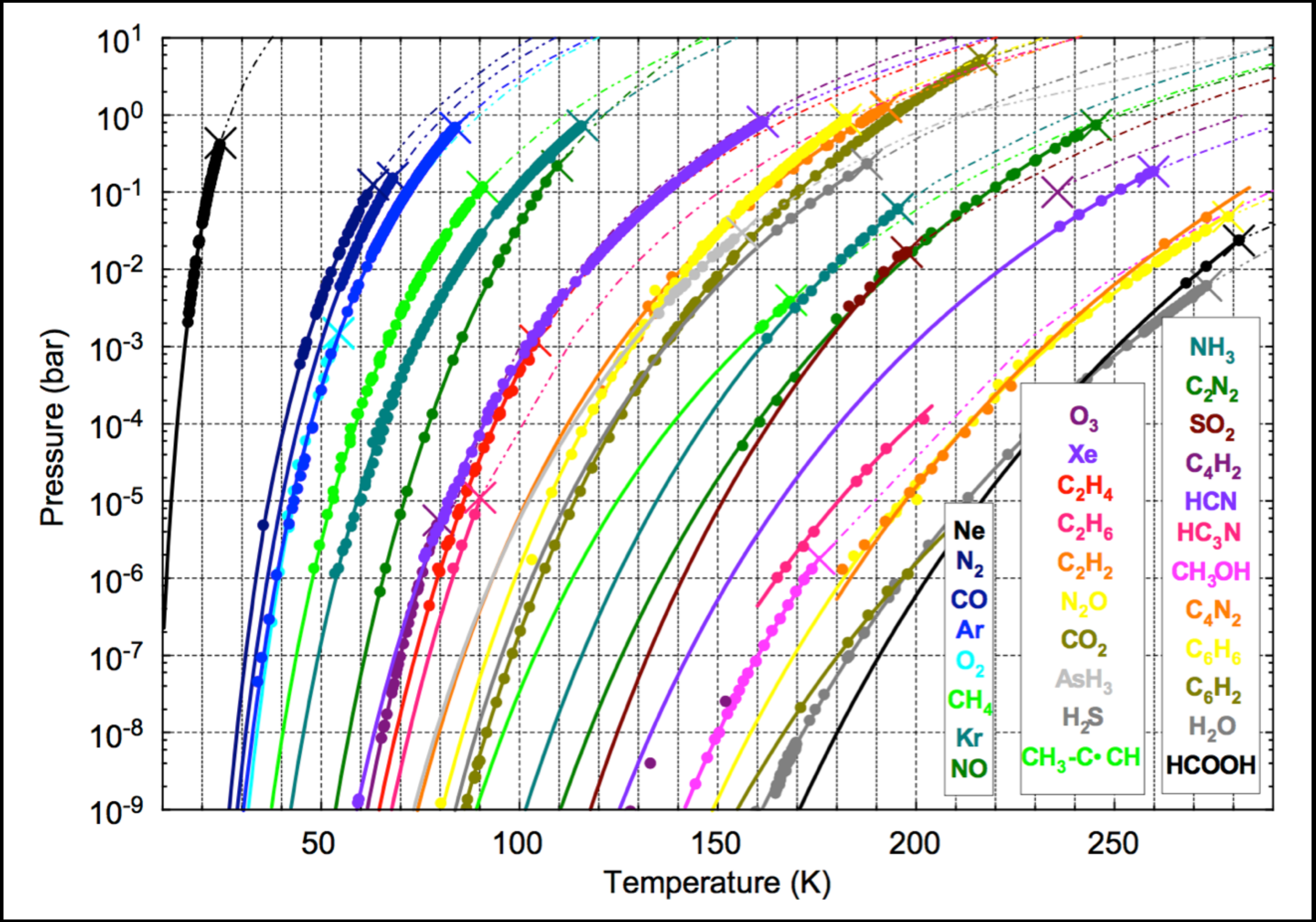


Elements

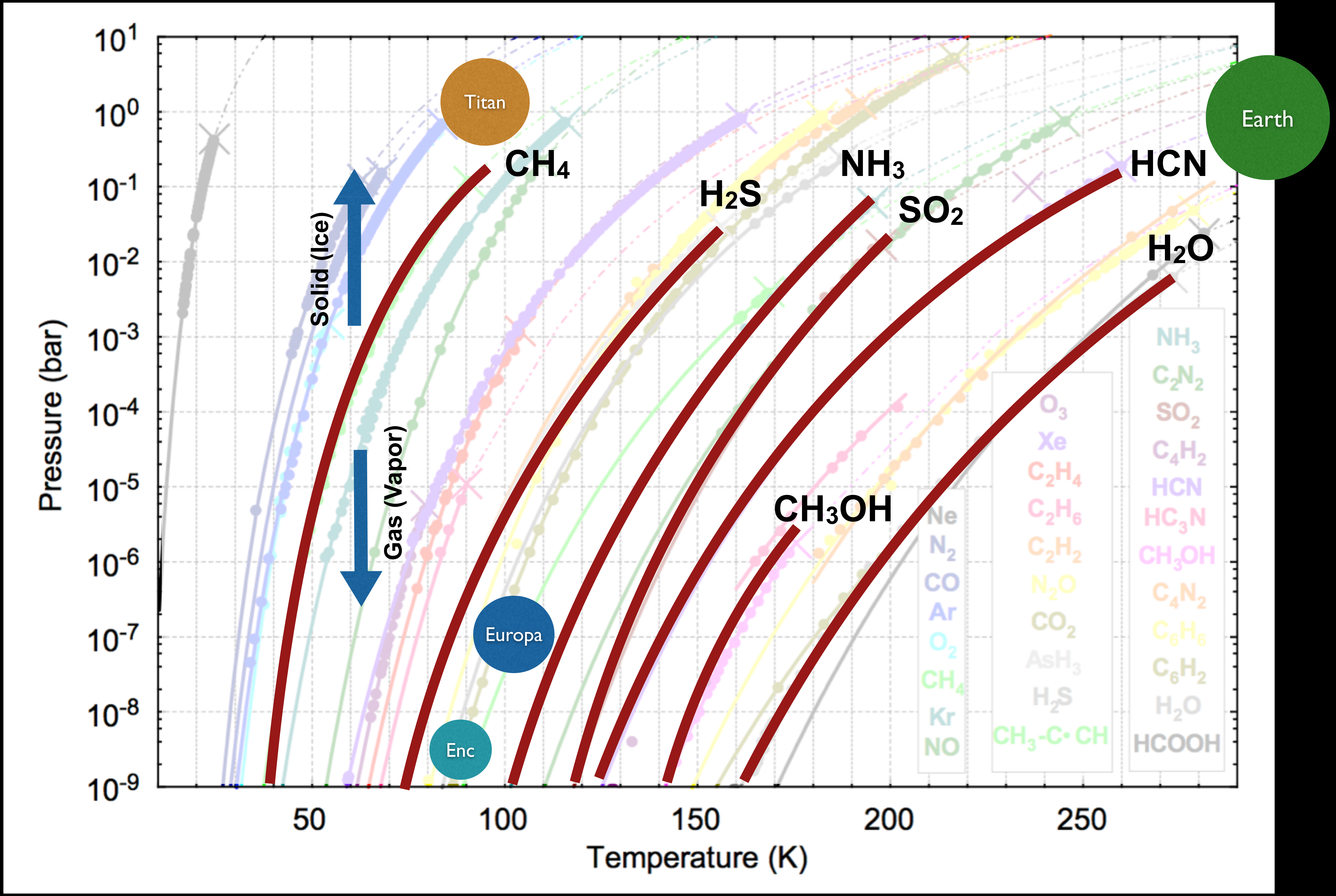


Raulin et al., (2010) Adapted from Wackett et al. (2004)

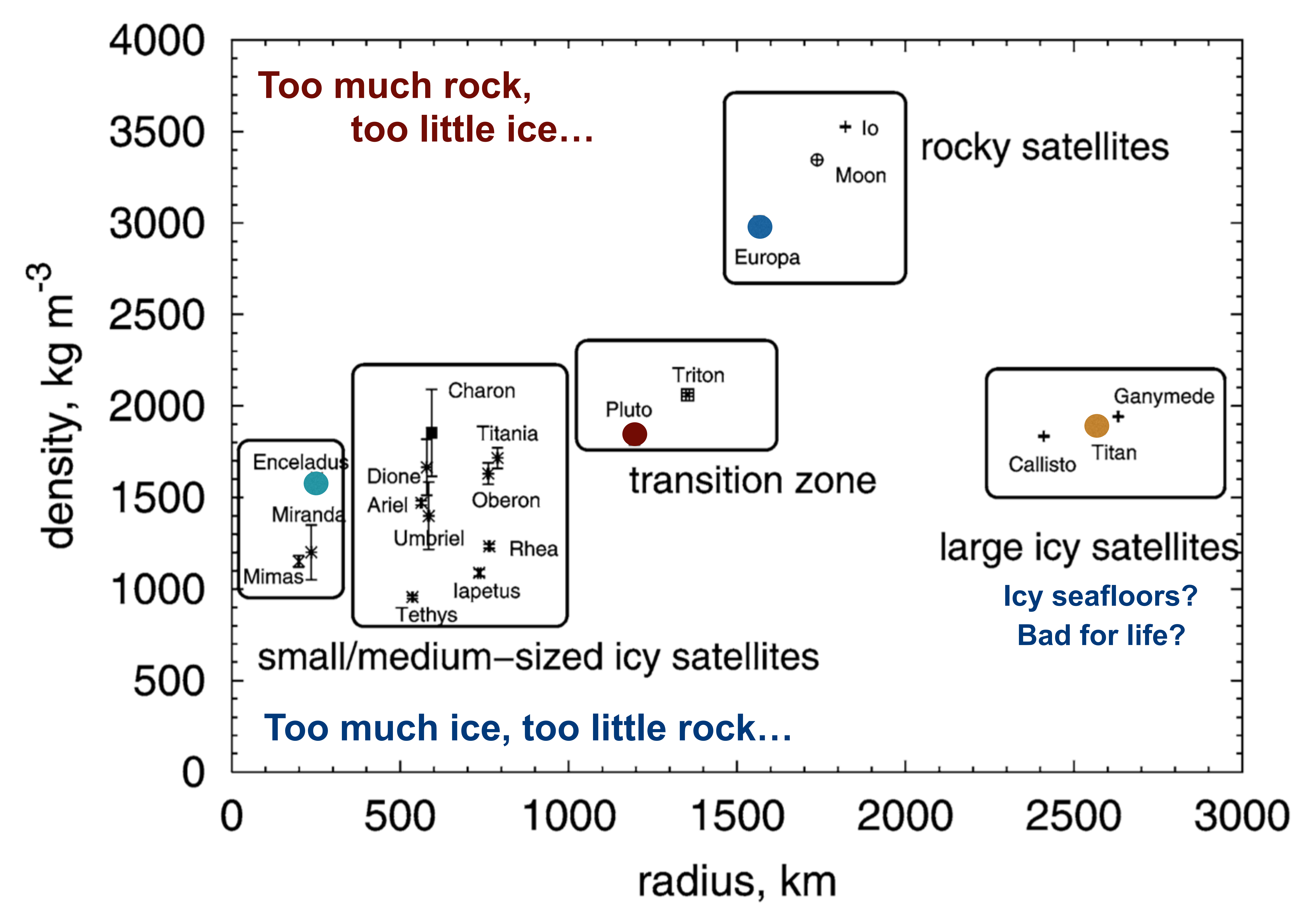
Dana Barry/National Geographic



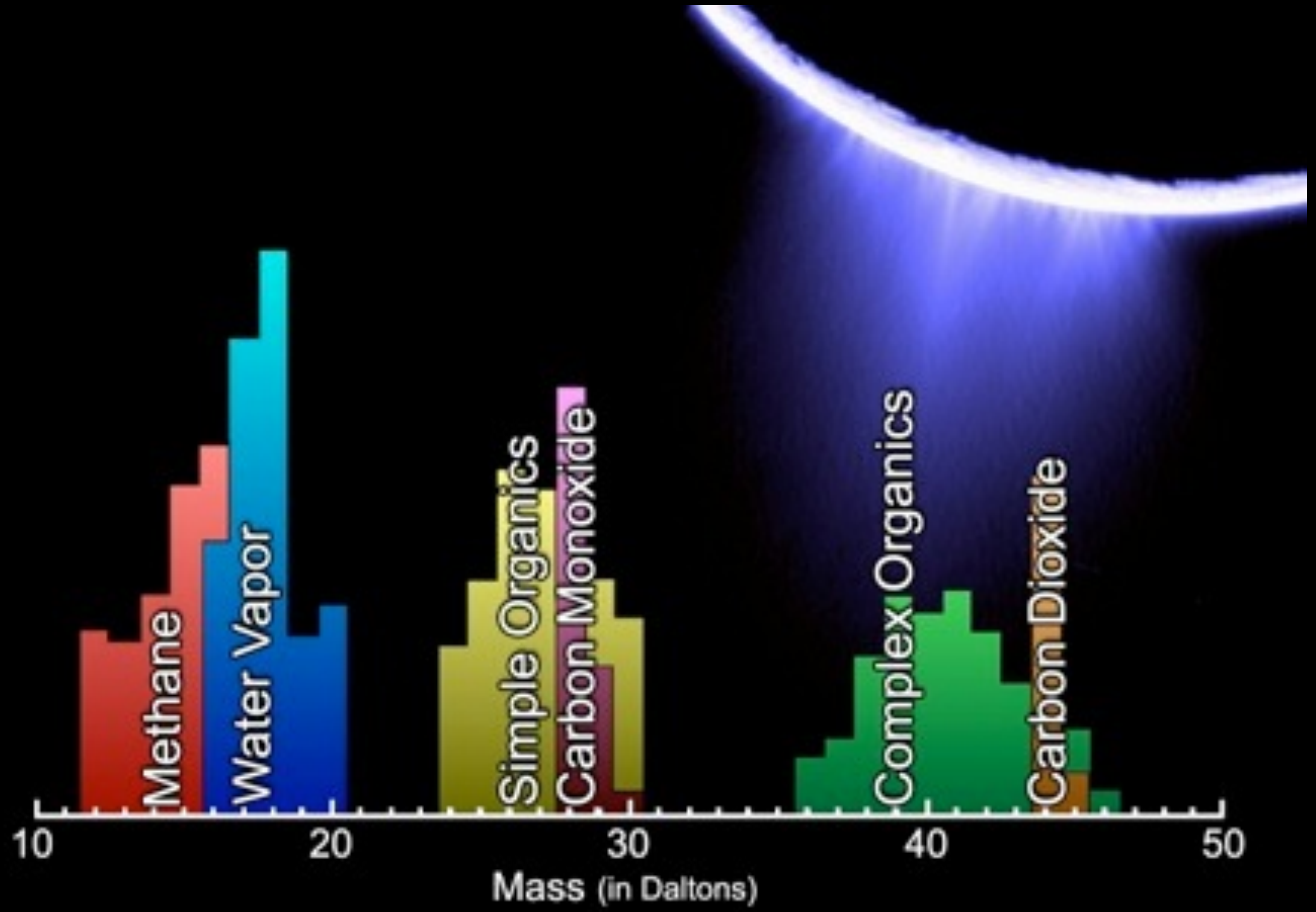
Fray & Schmitt (2009)



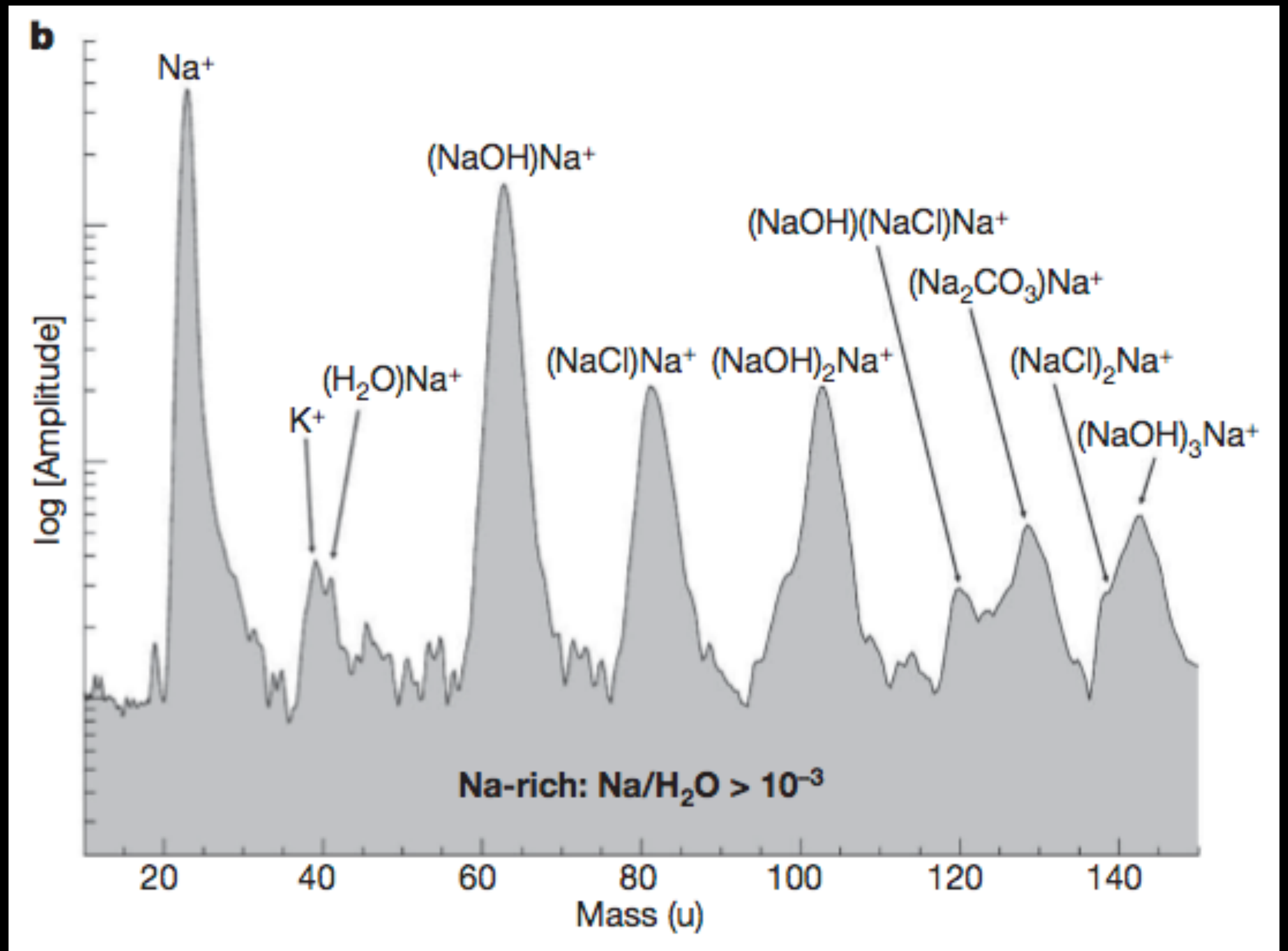
Fray & Schmitt (2009)



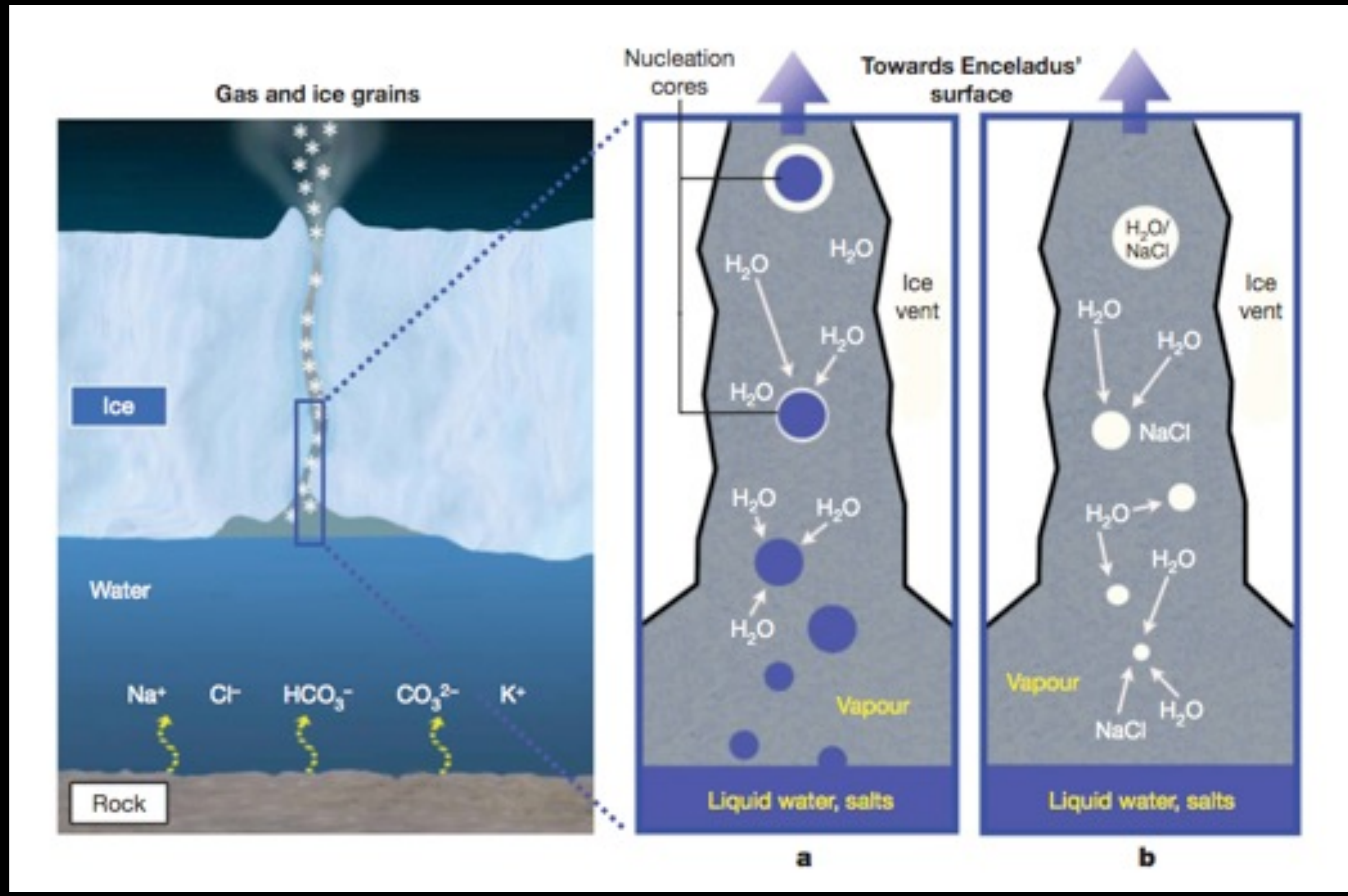
Hussmann et al. (2006)



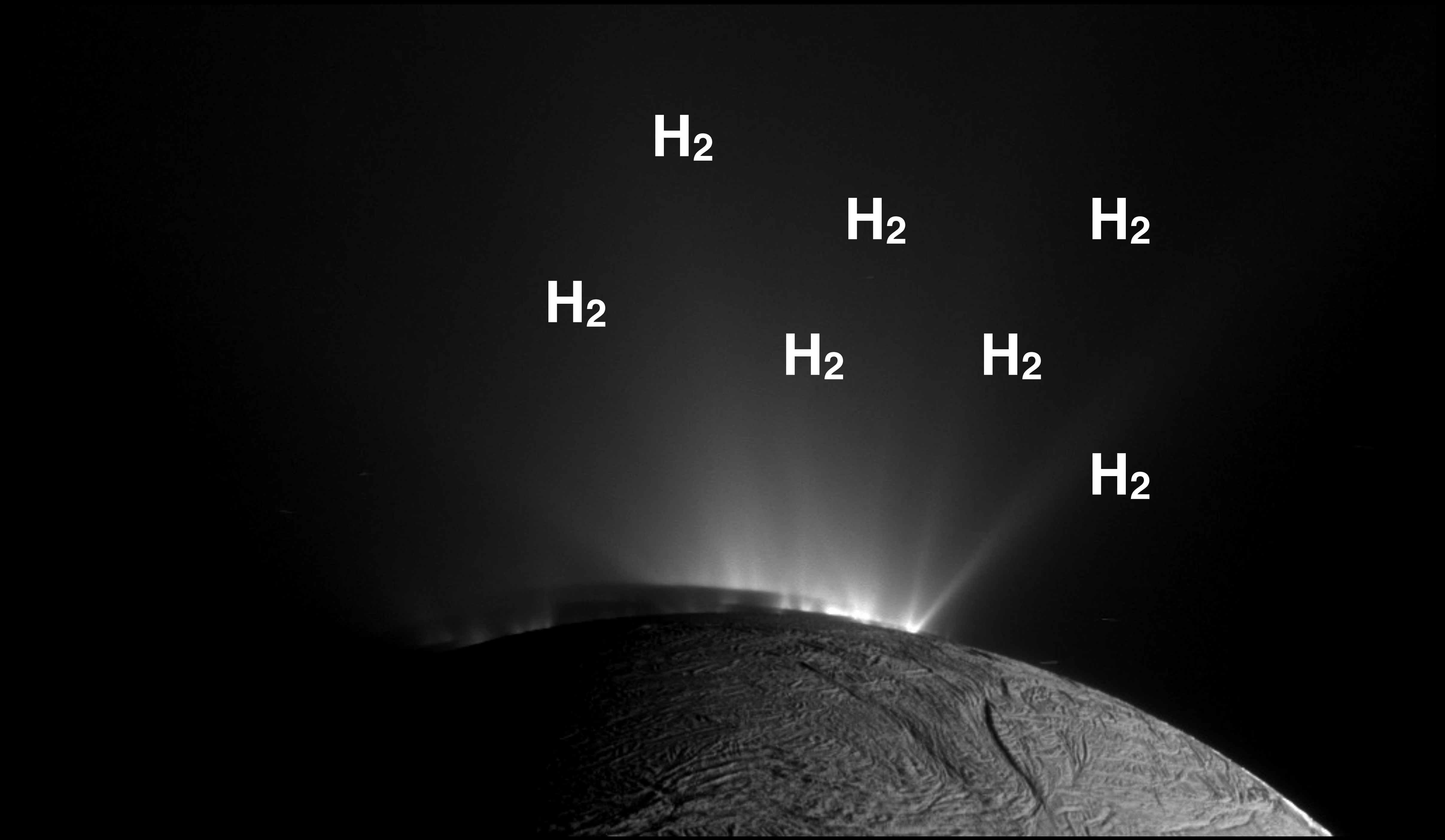
Waite et al. 2006; 2009

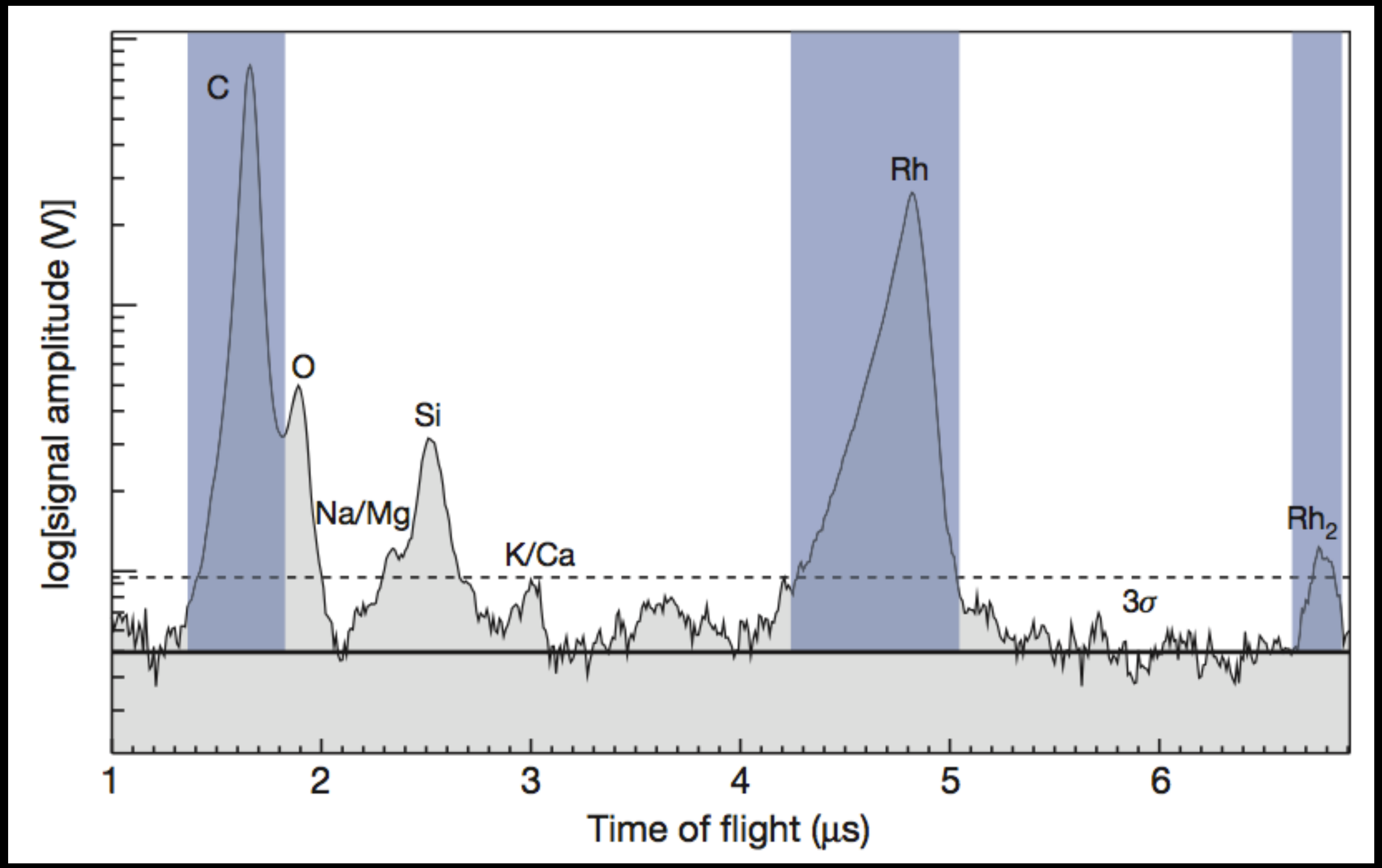


Postberg et al. 2009



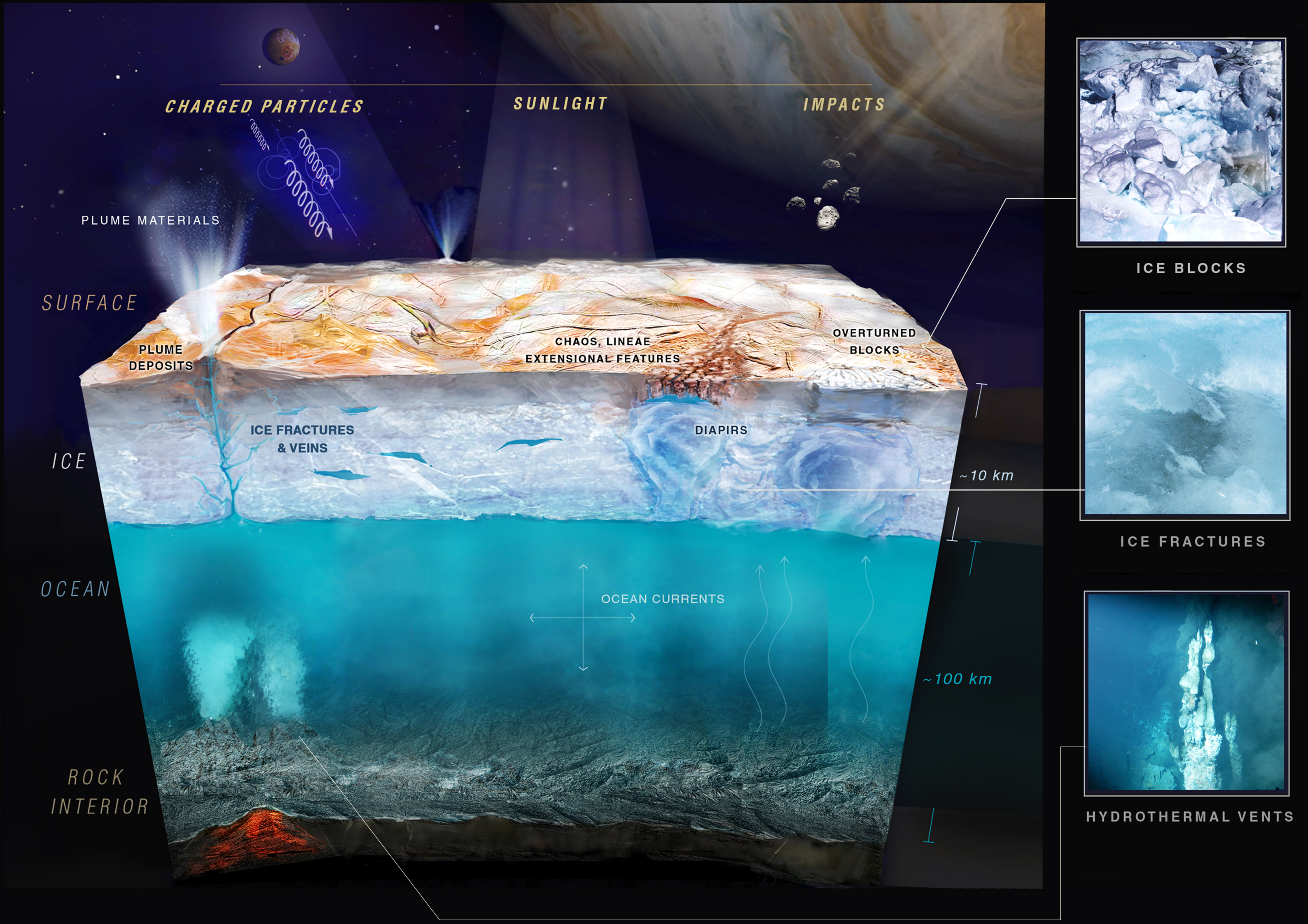
Postberg et al. 2009





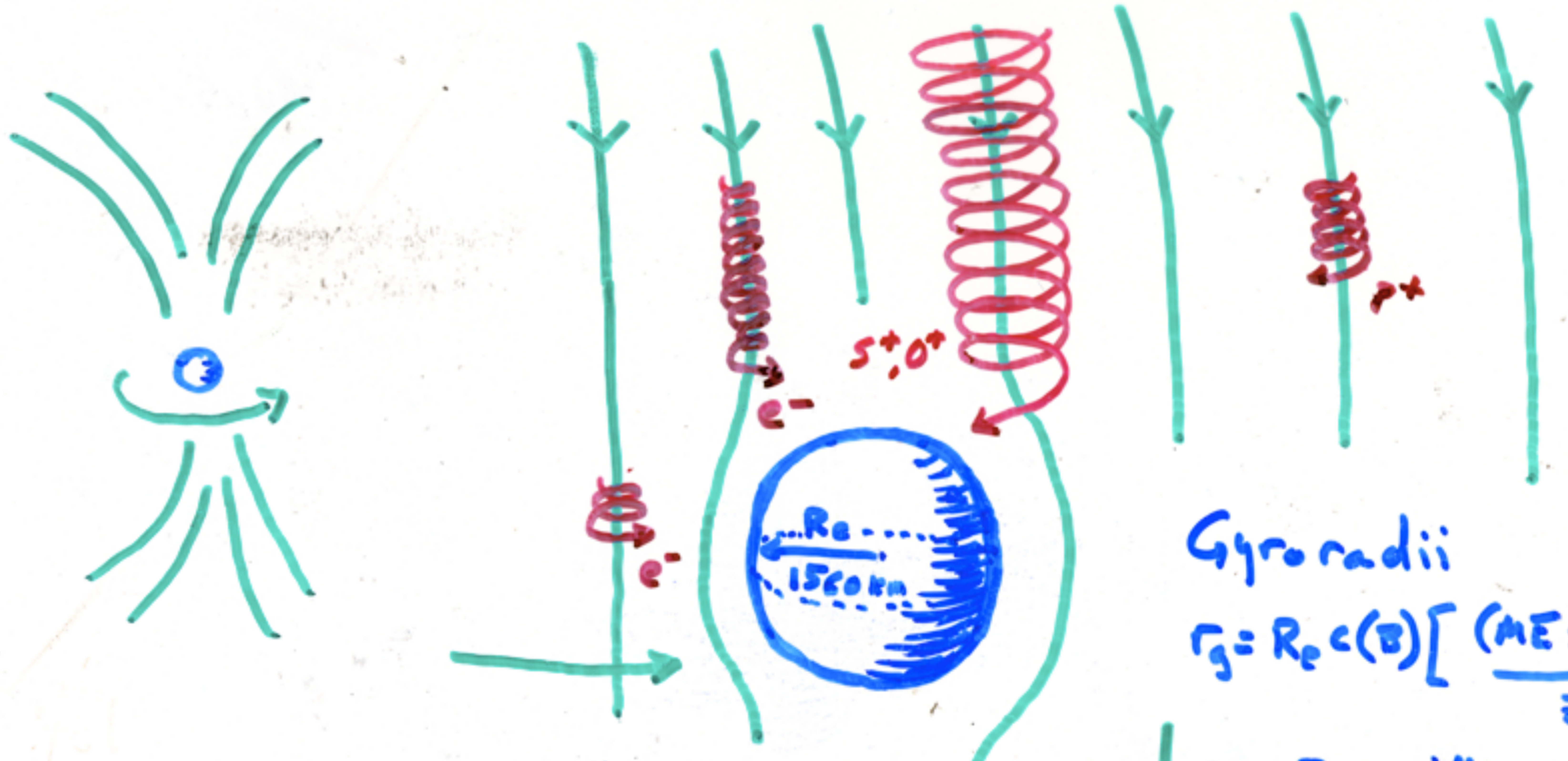
Hsu et al., 2015

EUROPA



CHARGED PARTICLES
SUNLIGHT
IMPACTS
PLUME MATERIALS
SURFACE
PLUME DEPOSITS
CHAOS, LINEAE
EXTENSIONAL FEATURES
OVERTURNED BLOCKS
ICE
ICE FRACTURES & VEINS
DIAPIRS
~10 km
OCEAN
OCEAN CURRENTS
~100 km
ROCK INTERIOR
ICE BLOCKS
ICE FRACTURES
HYDROTHERMAL VENTS

Europa: Radiation Environment



Electrons with energy in 10 keV – 10 MeV range have r_g of ~1–30 km for $\Theta = 90°$

Gyroradii

$$r_g = R_e\, c(B) \left[\frac{(M E \sin^2\theta)^{1/2}}{Z} \right]$$

$r_g \simeq R_e$ with $\Theta = 90°$

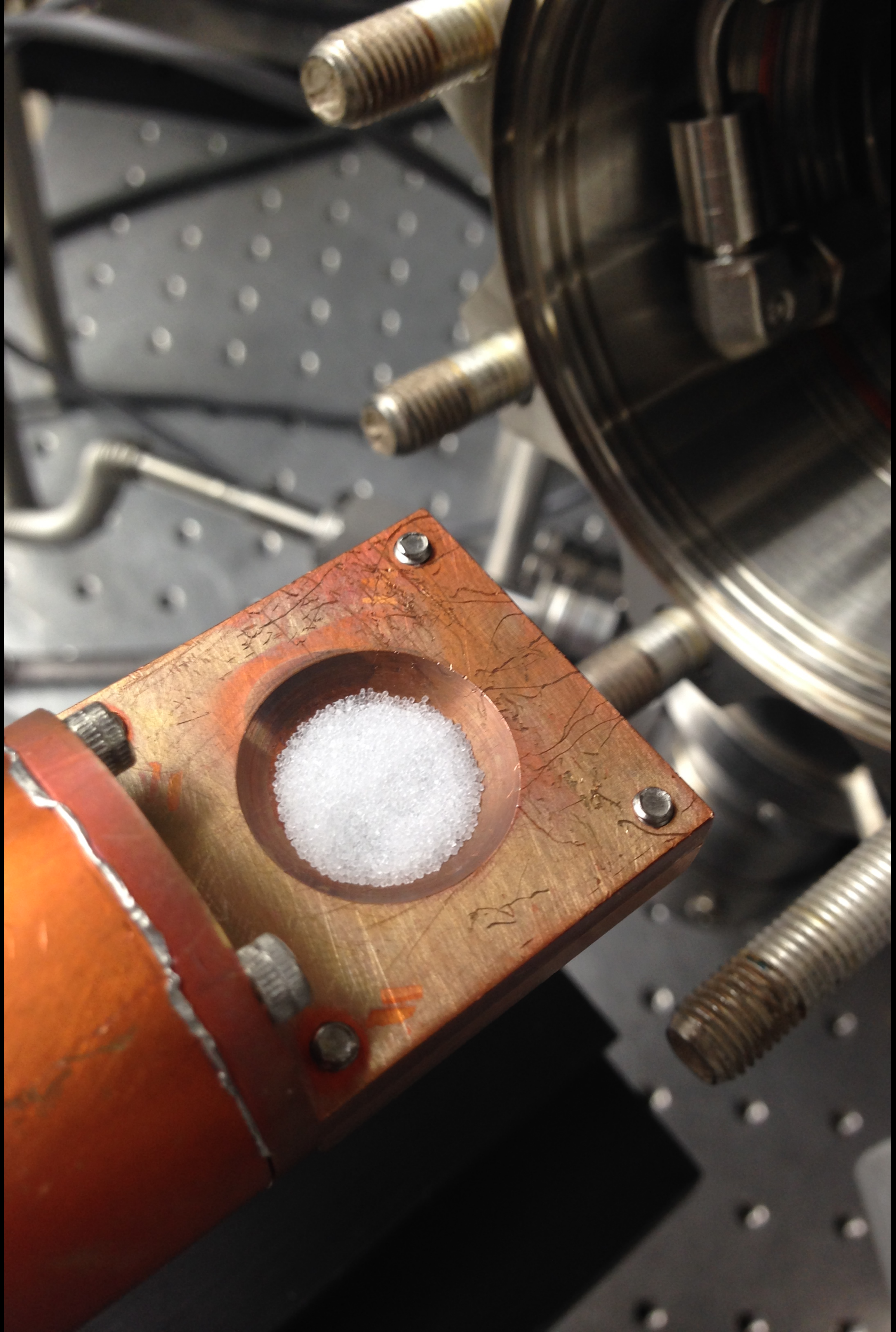
→ 18 MeV p^+

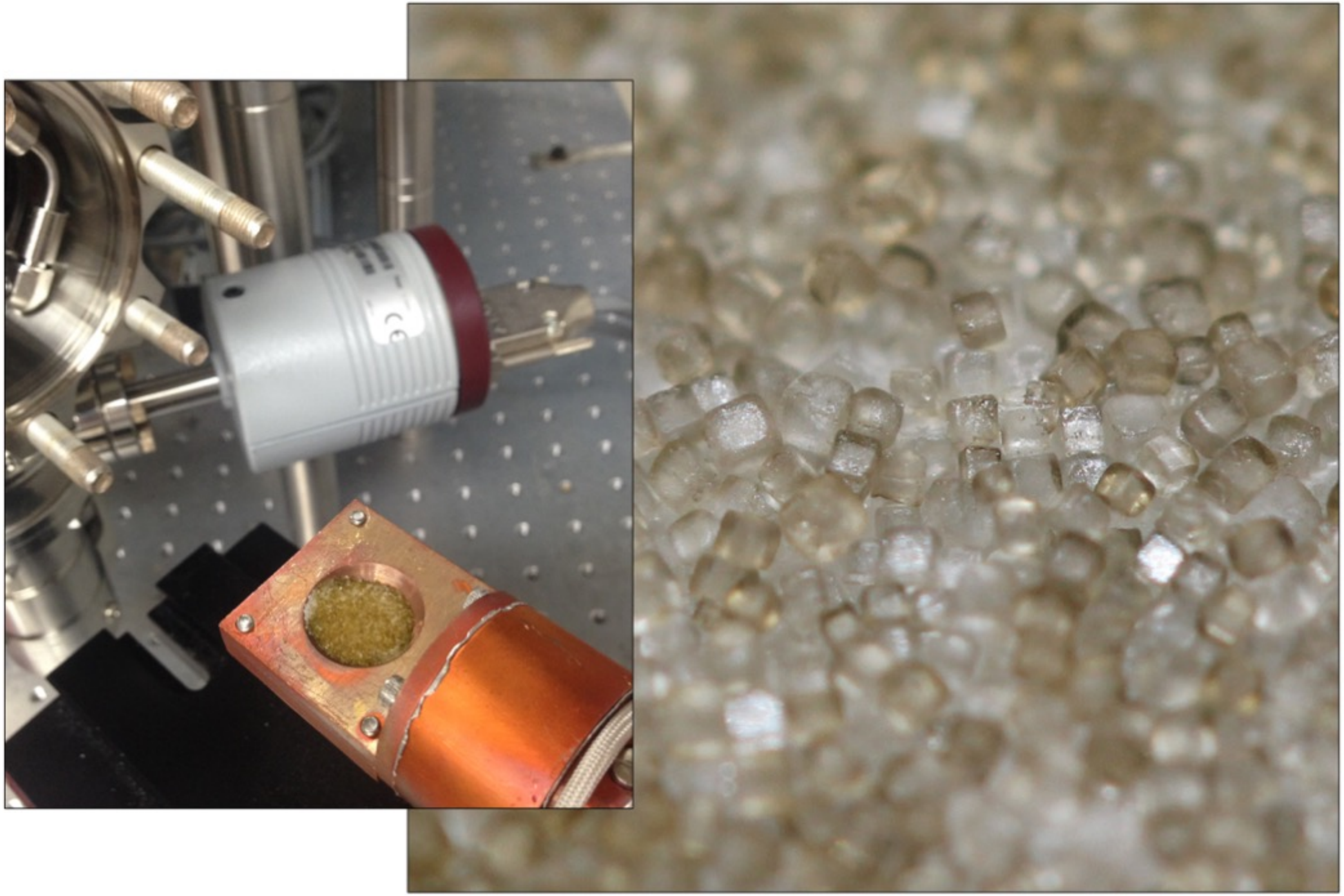
→ 1.1 MeV O^+

→ 0.6 MeV S^+

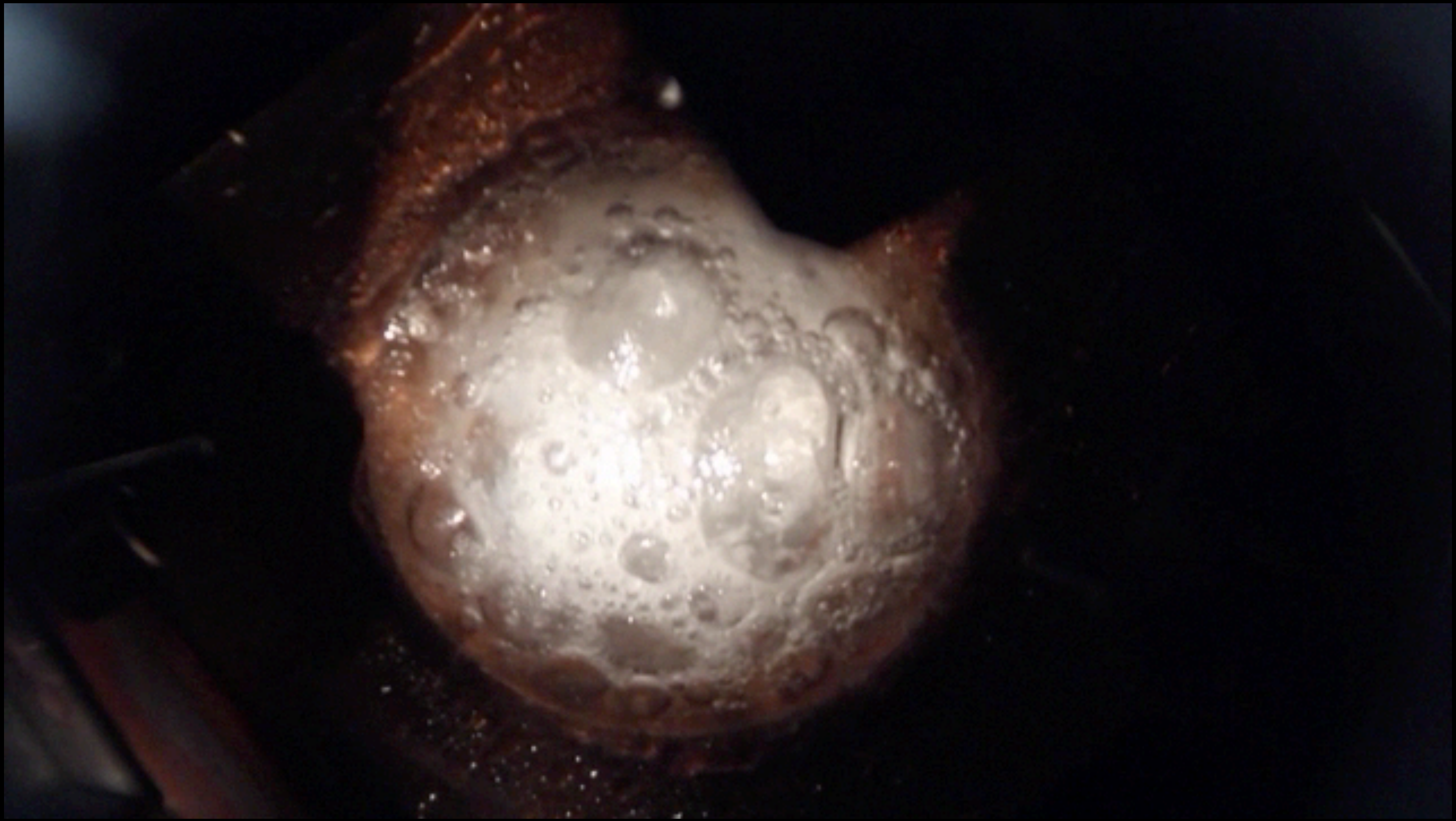
Johnson et al. (2004)

oceanworldslab.jpl.nasa.gov





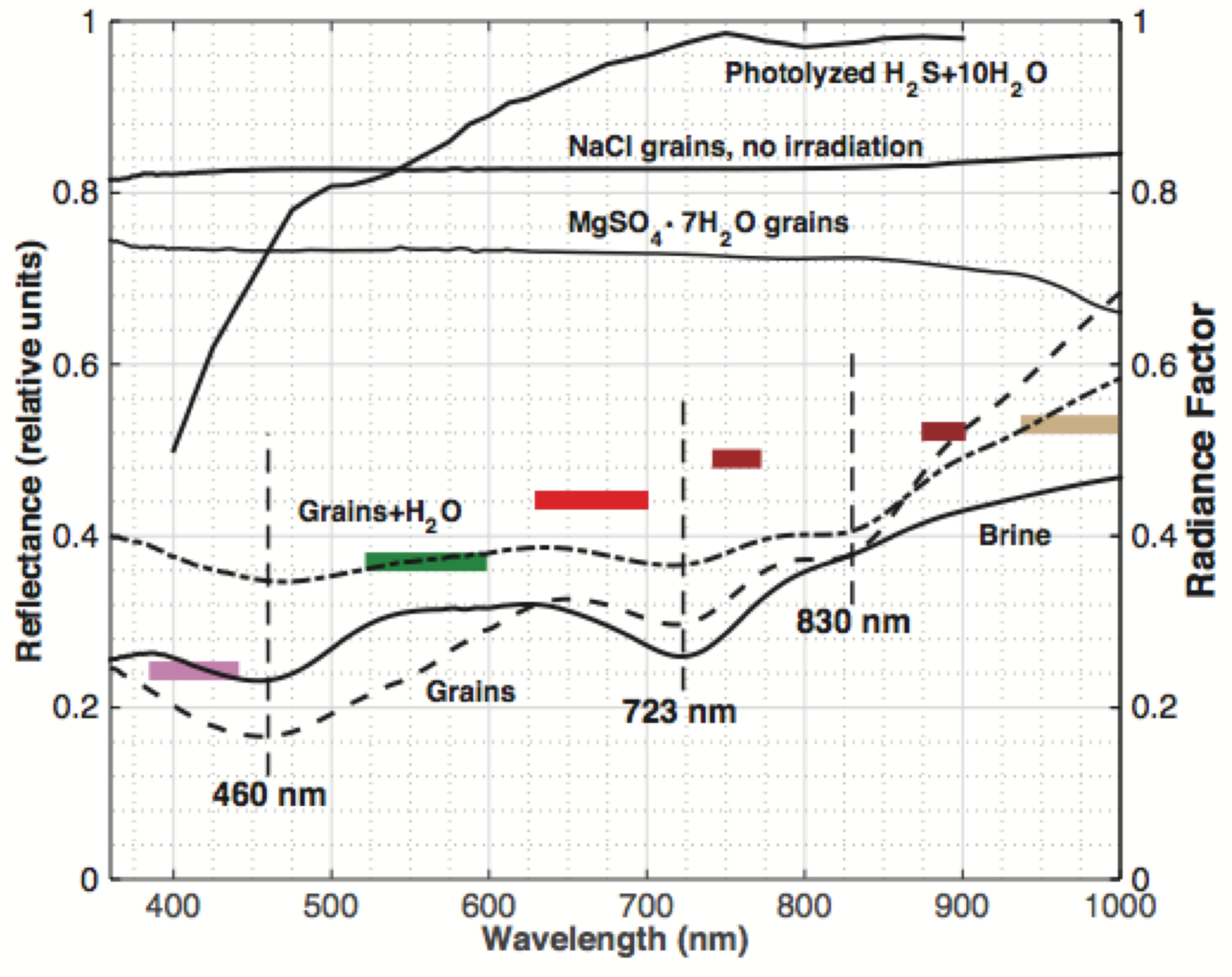
Sodium chloride grains post-irradiation



NaCl saturated brine. T = 290 K, P ~ 1e-6 Torr

NaCl evaporite. T = 100 K, P = 1e-9 Torr, 10 keV electrons

Sodium chloride brine evaporite post-irradiation

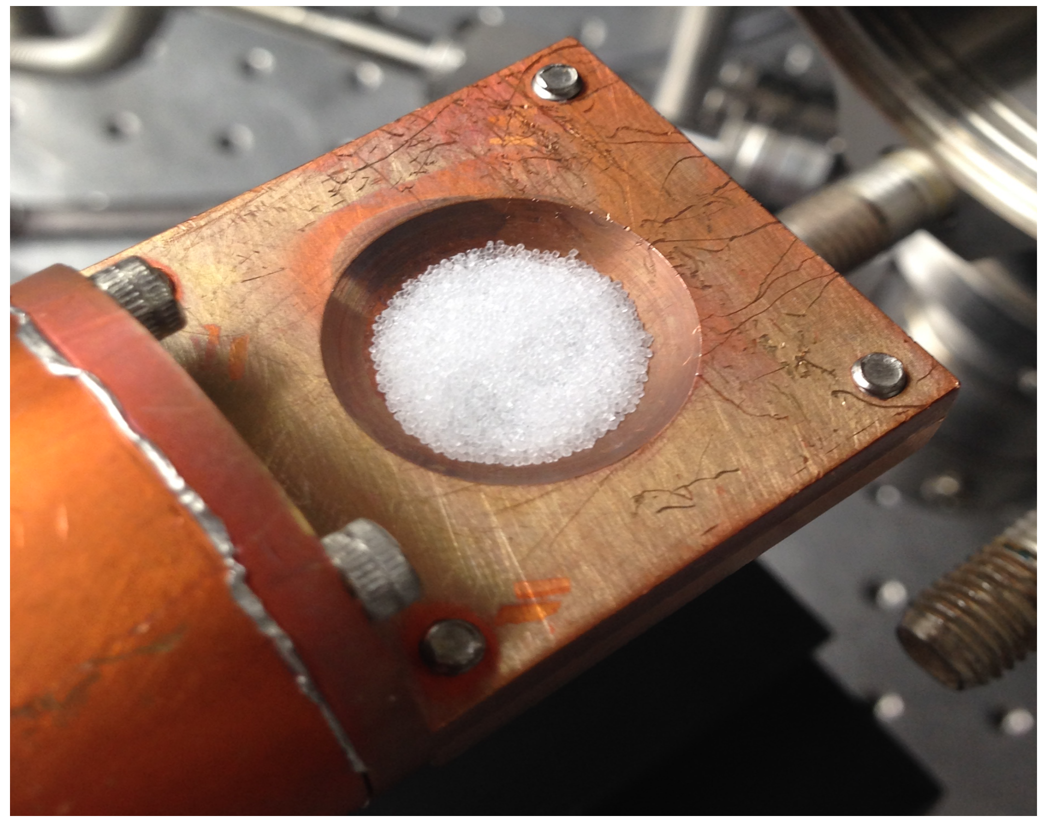


Hand & Carlson, 2015

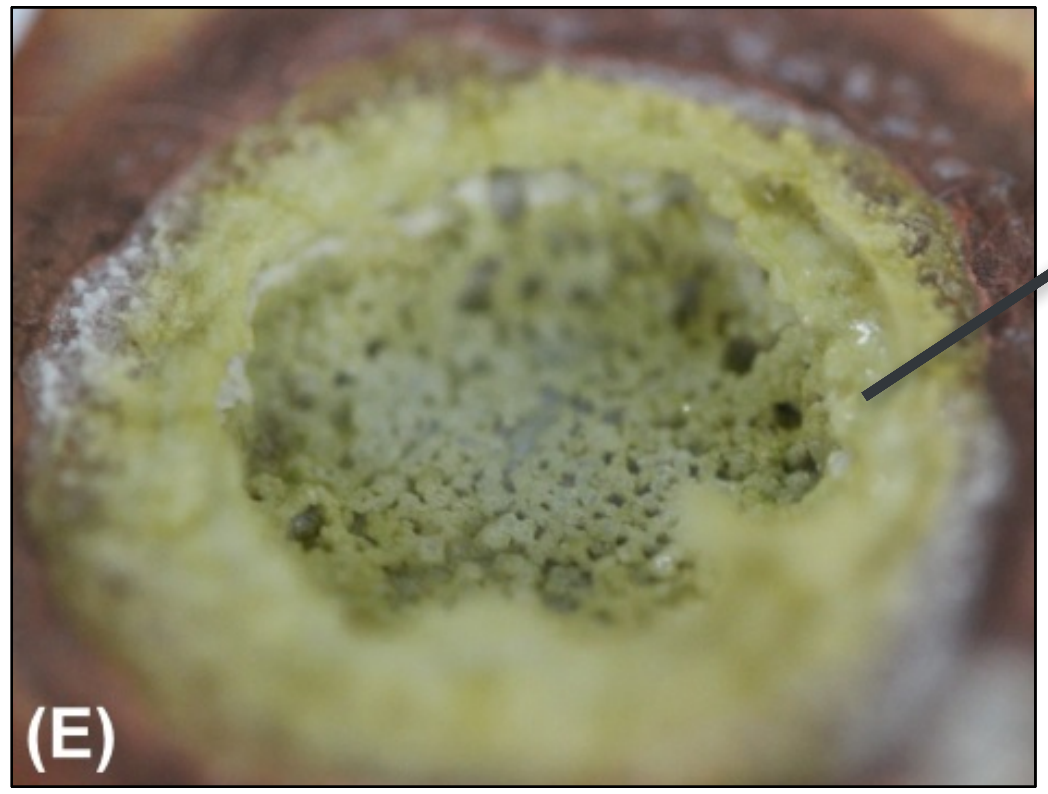
Sea salt (NaCl) found on Europa

Hubble Space Telescope follows up on lab experiments and finds the fingerprint of irradiated salt from the ocean below.

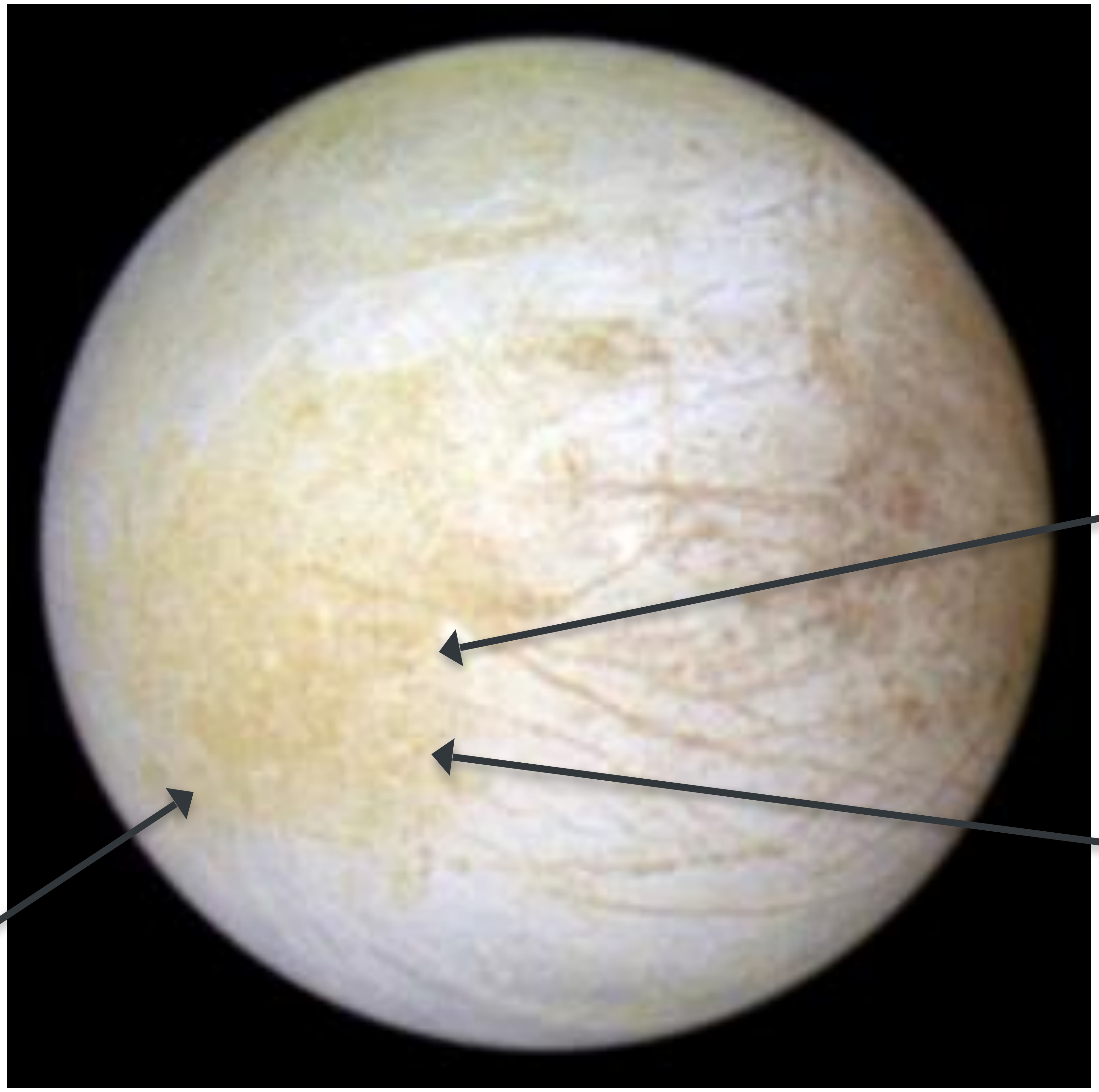
Lab sodium chloride ***before*** irradiation with electrons.



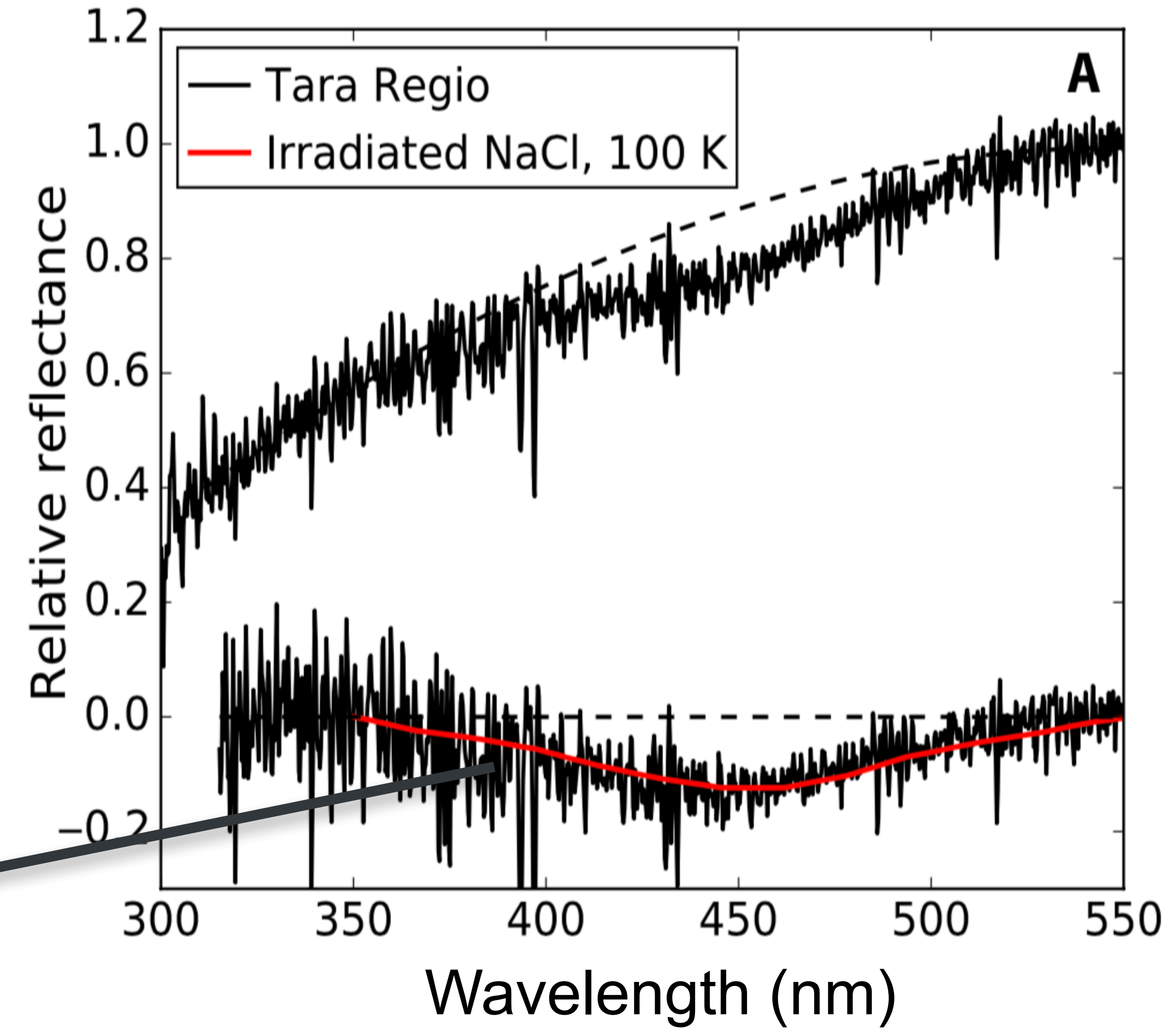
Lab sodium chloride ***after*** irradiation with electrons.



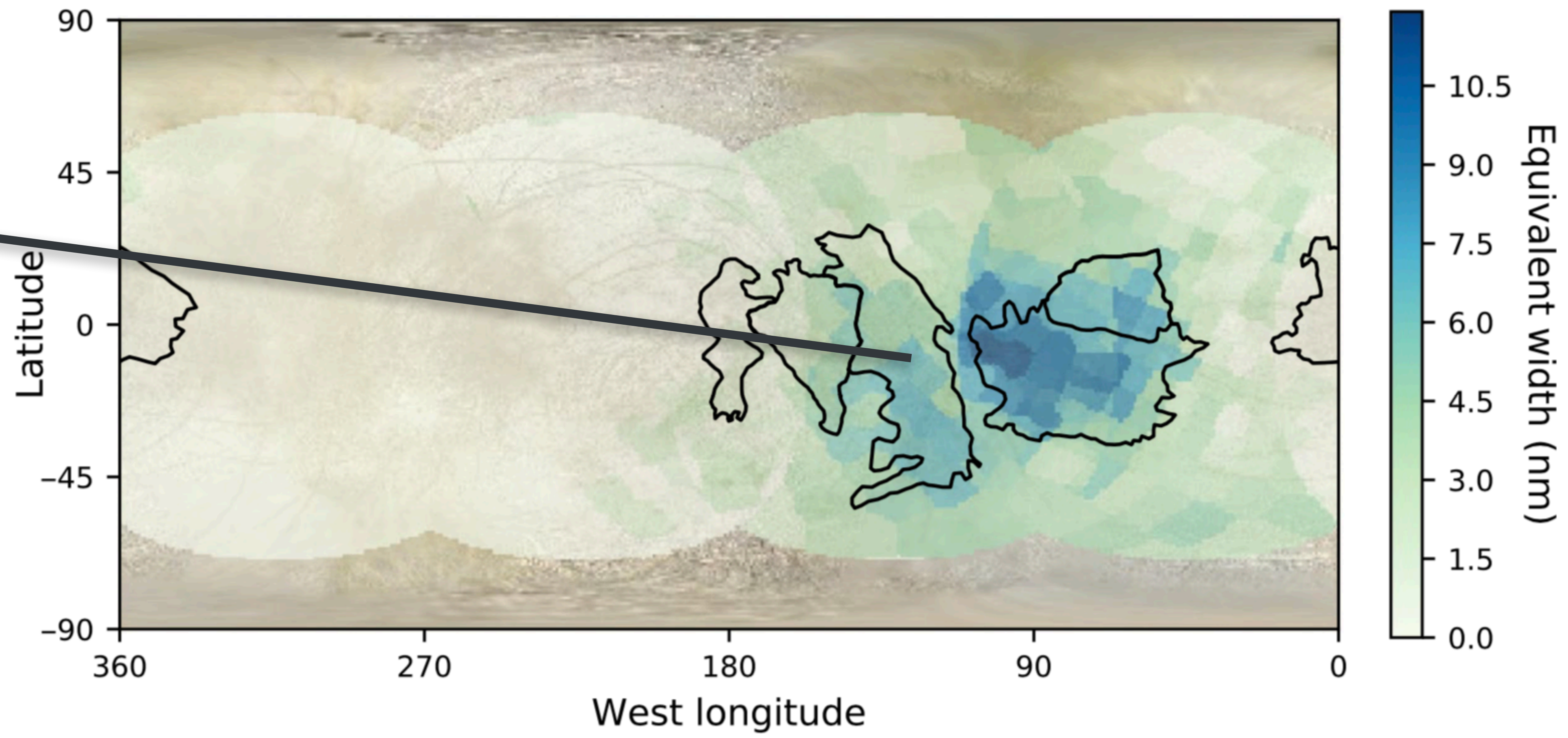
Hand and Carlson (2015)



Yellow region on Europa matches irradiated NaCl both visually and spectroscopically.

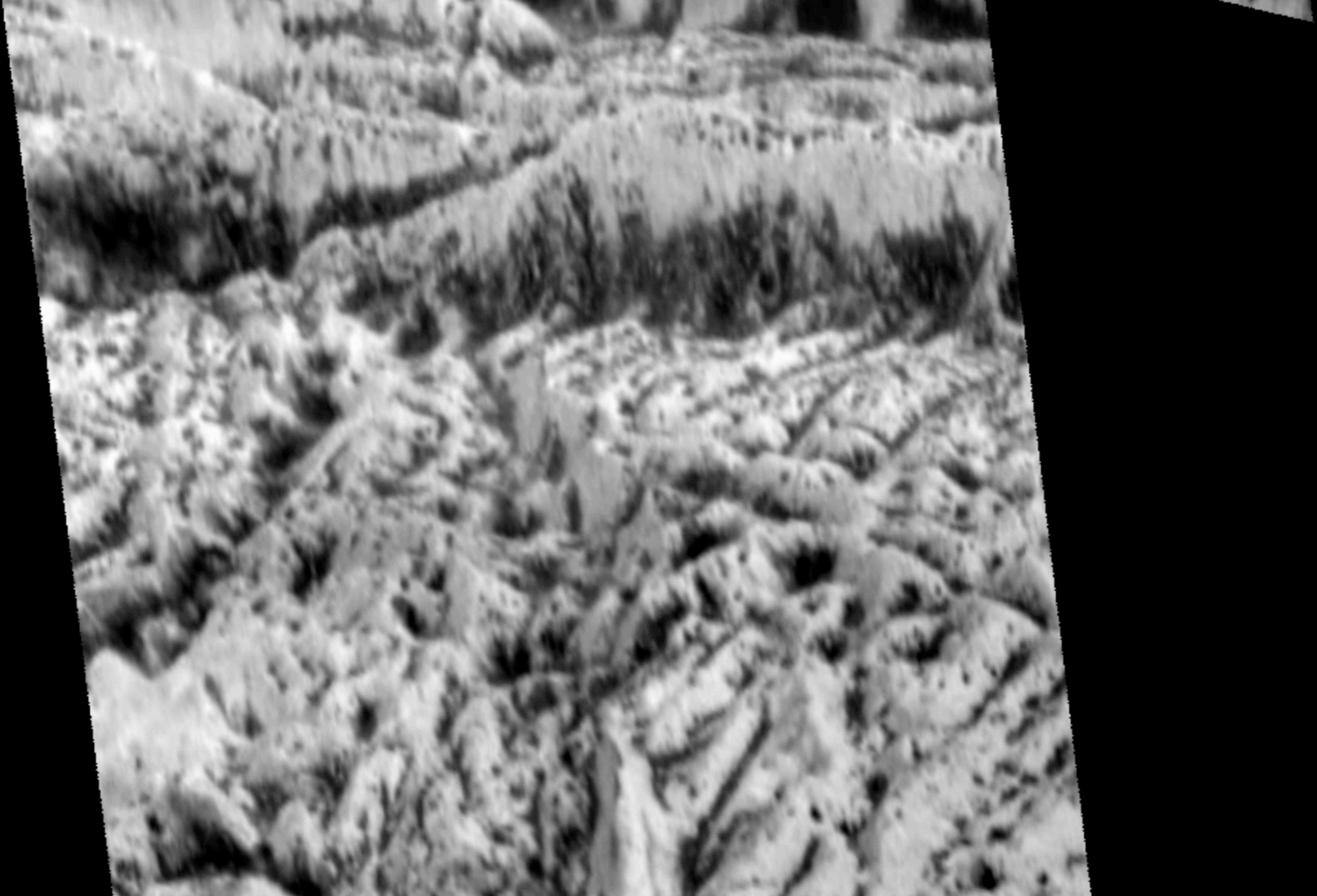


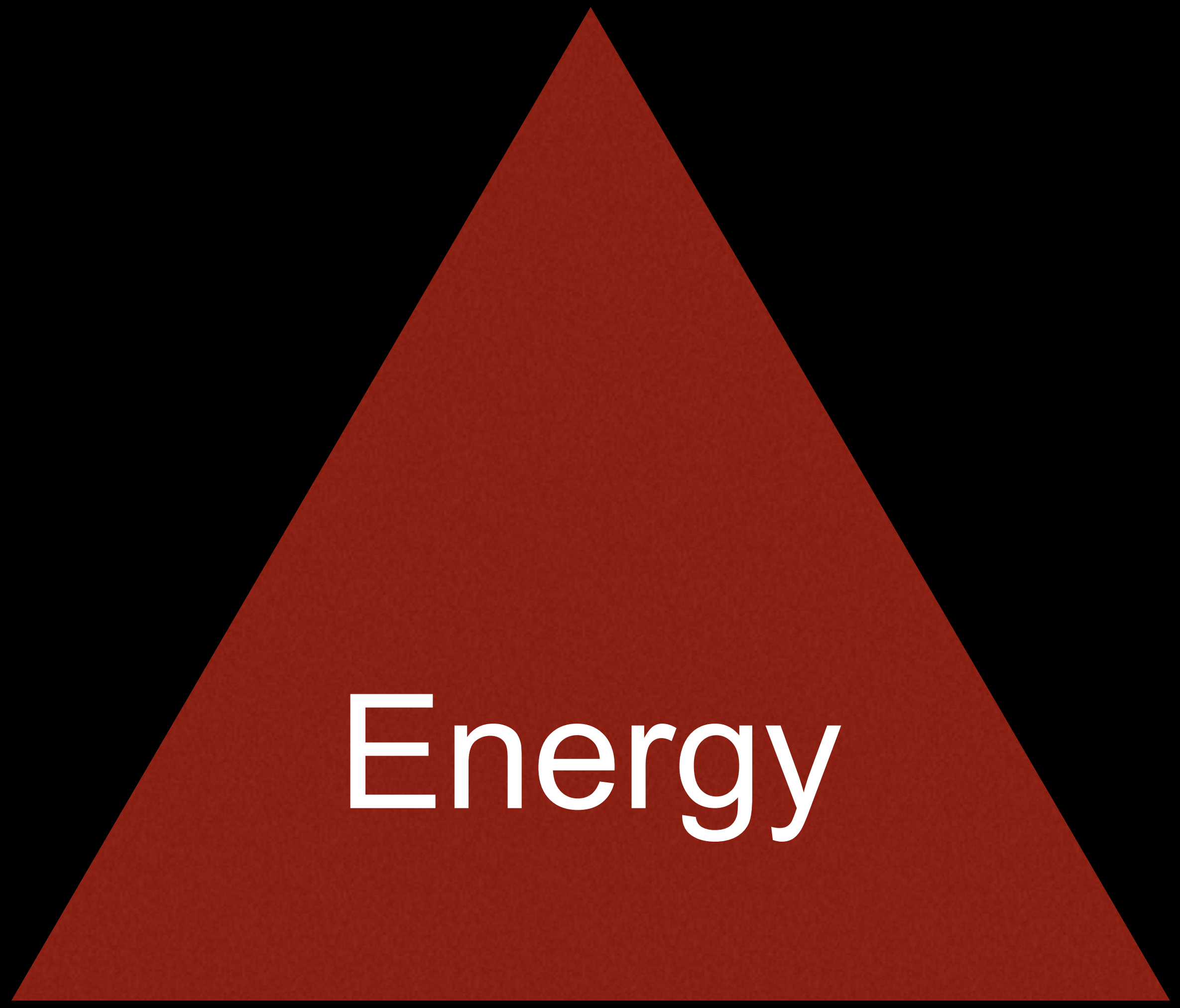
Hubble spectra (black) compared to lab spectrum of irradiated NaCl (red).



Oceanworldslab.jpl.nasa.gov

Trumbo, Brown, and Hand (2019)




Energy

Life alleviates chemical disequilibrium in the environment

+

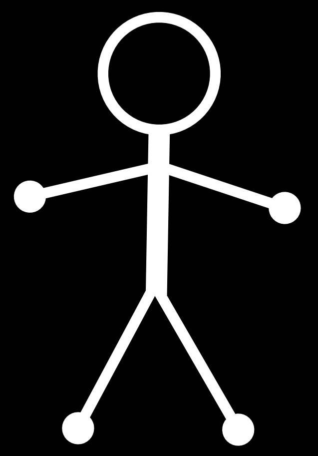
-

Flashlight

Oxygen

Wood

Oxygen



Food

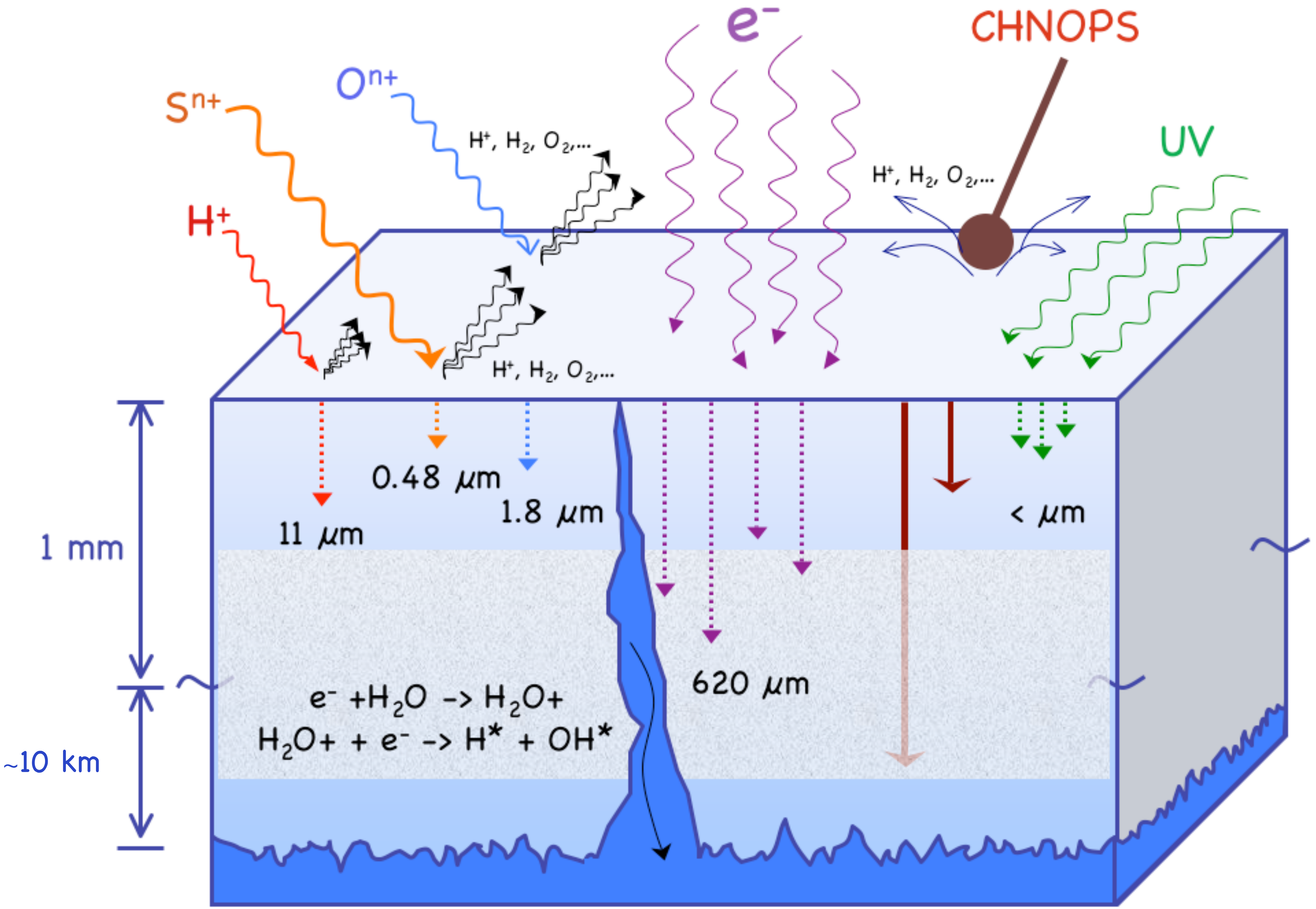
Oxidant

Microbe

Reductant

Earth is a dynamic planet with many niches of chemical disequilibrium

The Surface Radiation Environment of Europa



Solid-state radiolytic-photolytic oxidant cycle

(1) $H_2O \xrightarrow{h\nu,\, e^-,\, ion} OH + H$

(2) $OH + OH \longrightarrow H_2O_2$

(3) $H_2O_2 \xrightarrow{h\nu,\, e^-,\, ion} OH + OH \longrightarrow H_2O{\bullet}O$

(4) $H_2O_2{\bullet}H_2O_2 \xrightarrow{h\nu,\, e^-,\, ion} (OH+OH) + (OH+OH) \ldots$

$\longrightarrow H_2O{\bullet}O + H_2O{\bullet}O \longrightarrow H_2O{\bullet} H_2O + O_2$

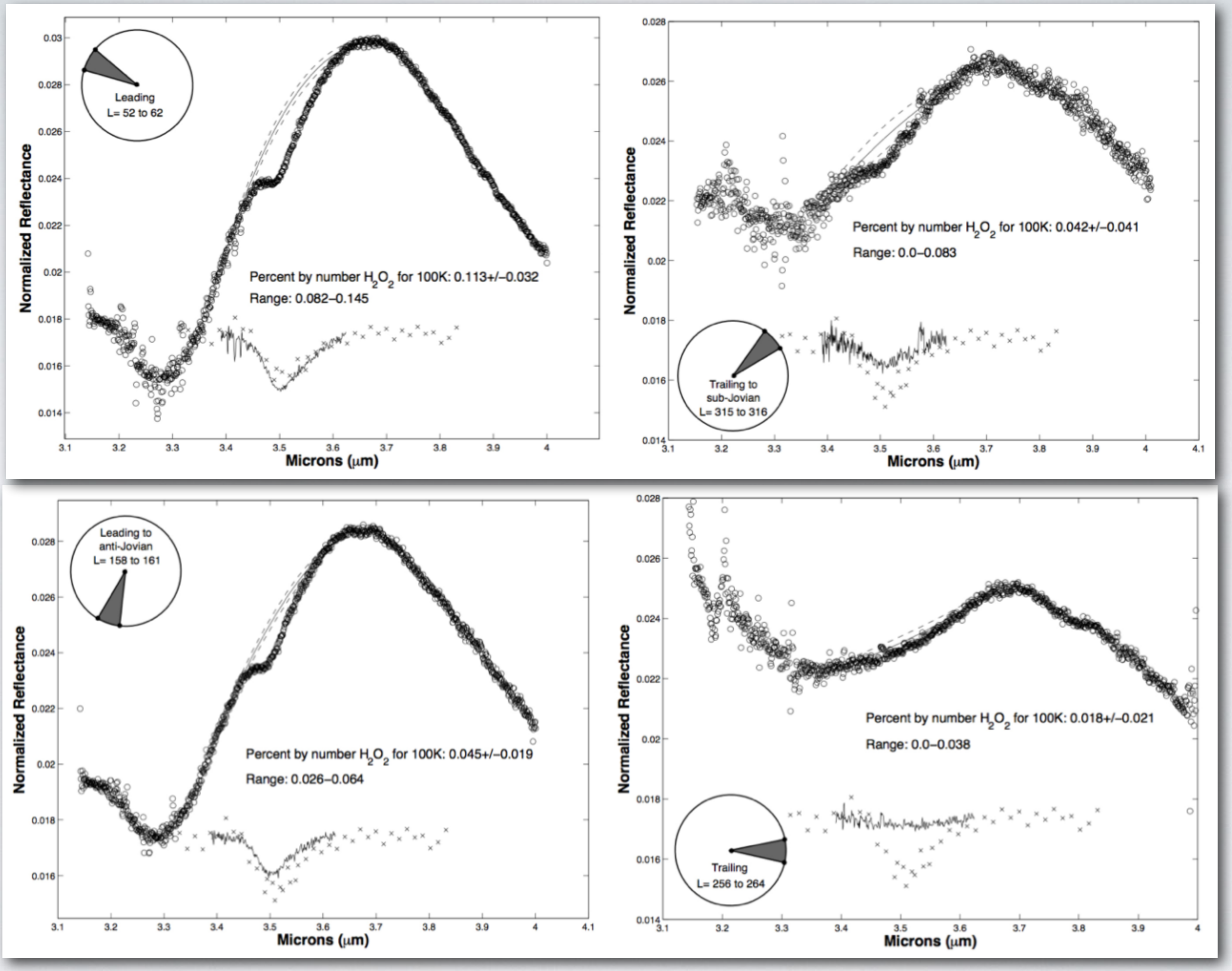
(1)

(5) $H_2O_2 + OH \longrightarrow H_2O + HO_2$

$HO_2 + HO_2 \longrightarrow H_2O_2 + O_2$

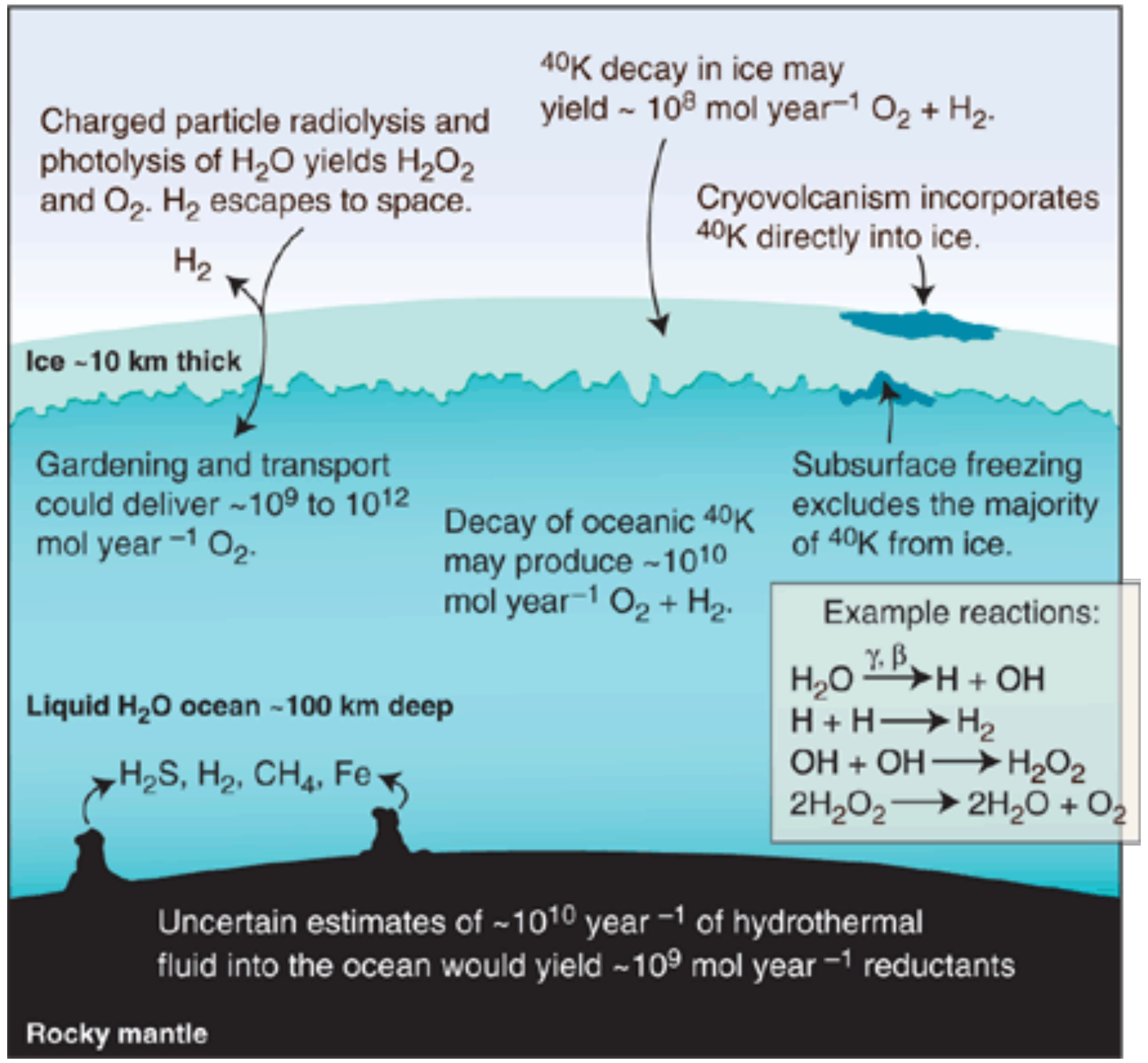
(3,4,5)

Trapped O_2

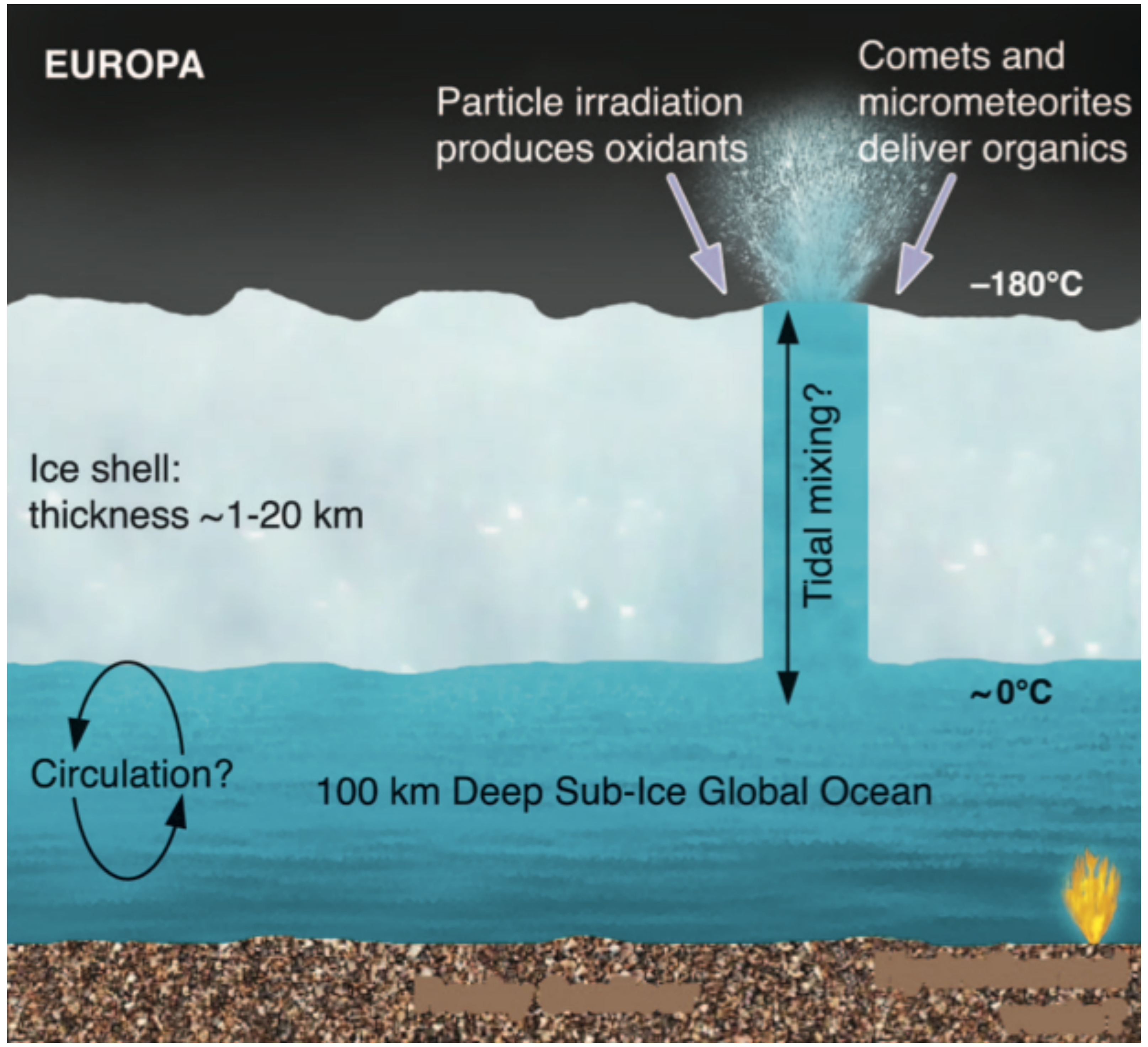


Hand & Brown, 2013

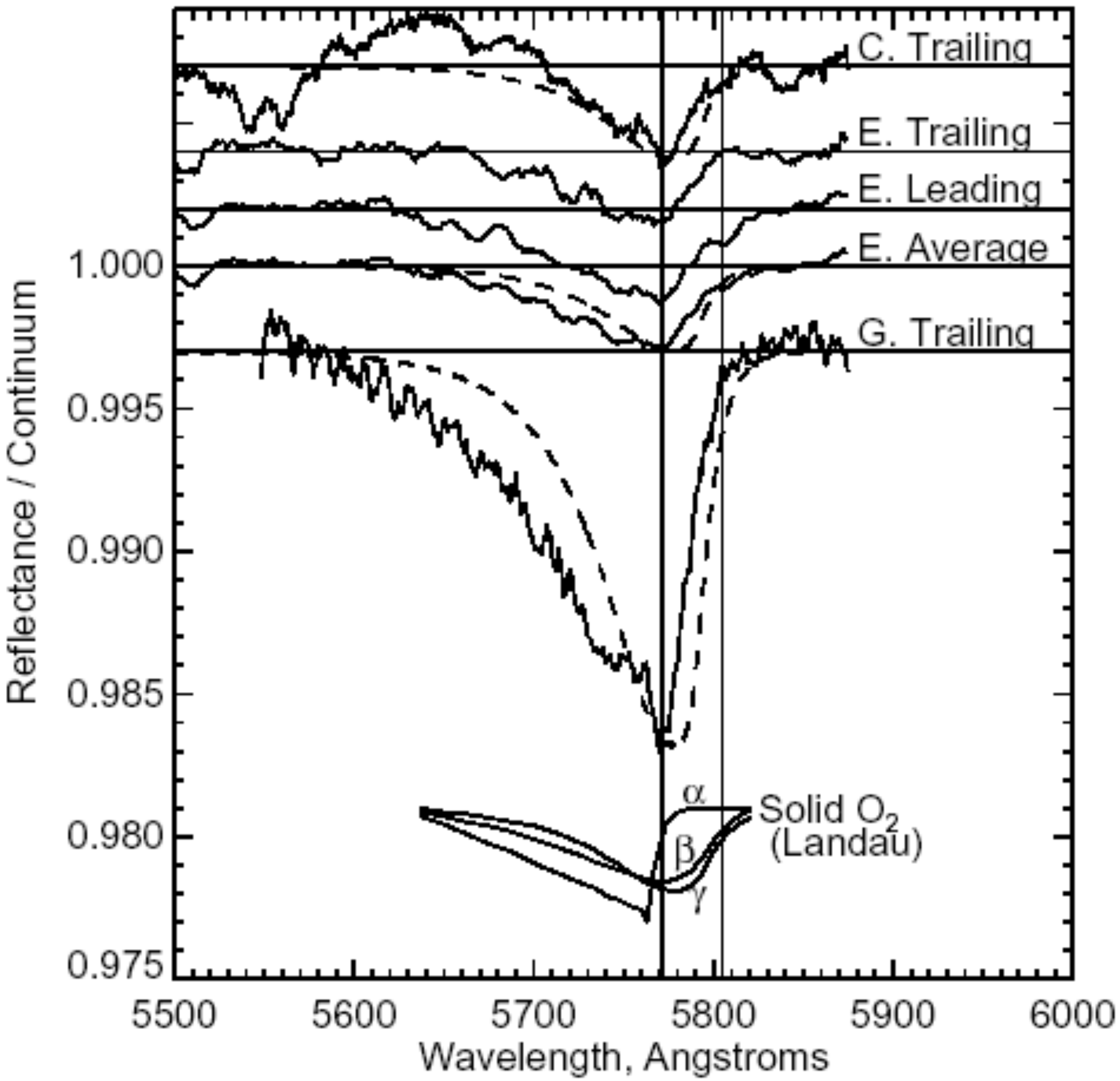
Radiolytic Hydrogen peroxide = Energy for Life?



Chyba & Hand 2001

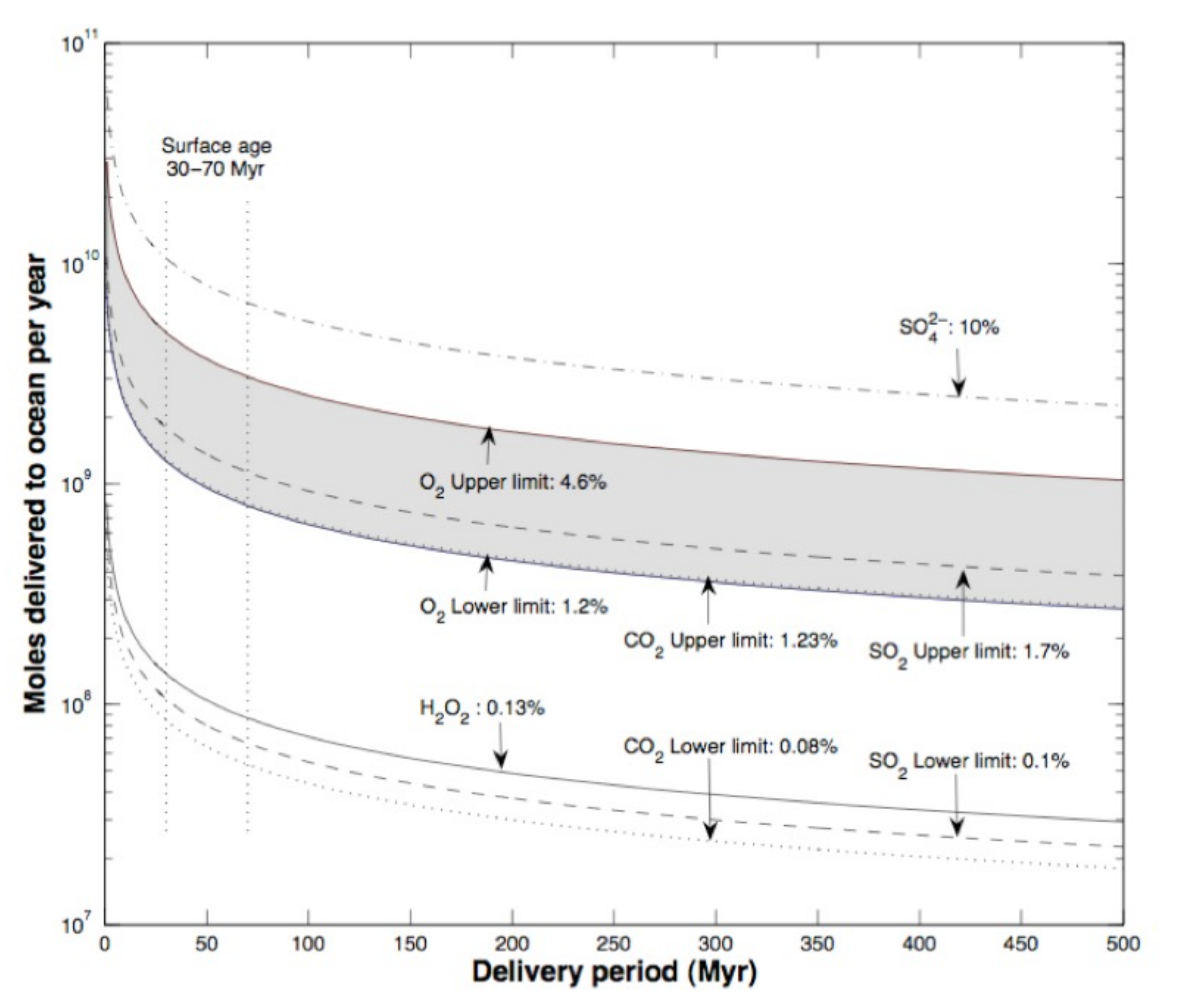


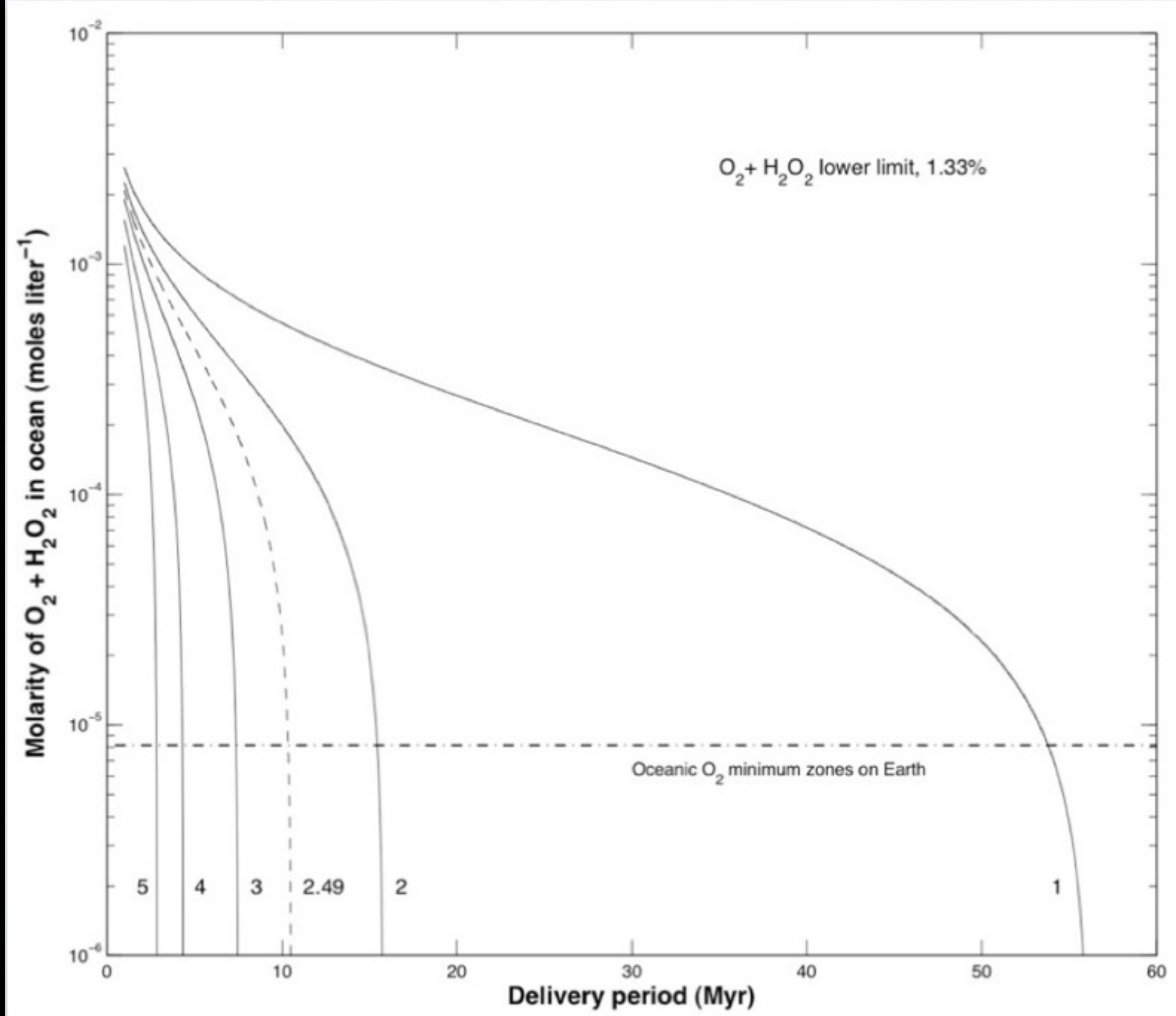
Priscu & Hand 2012



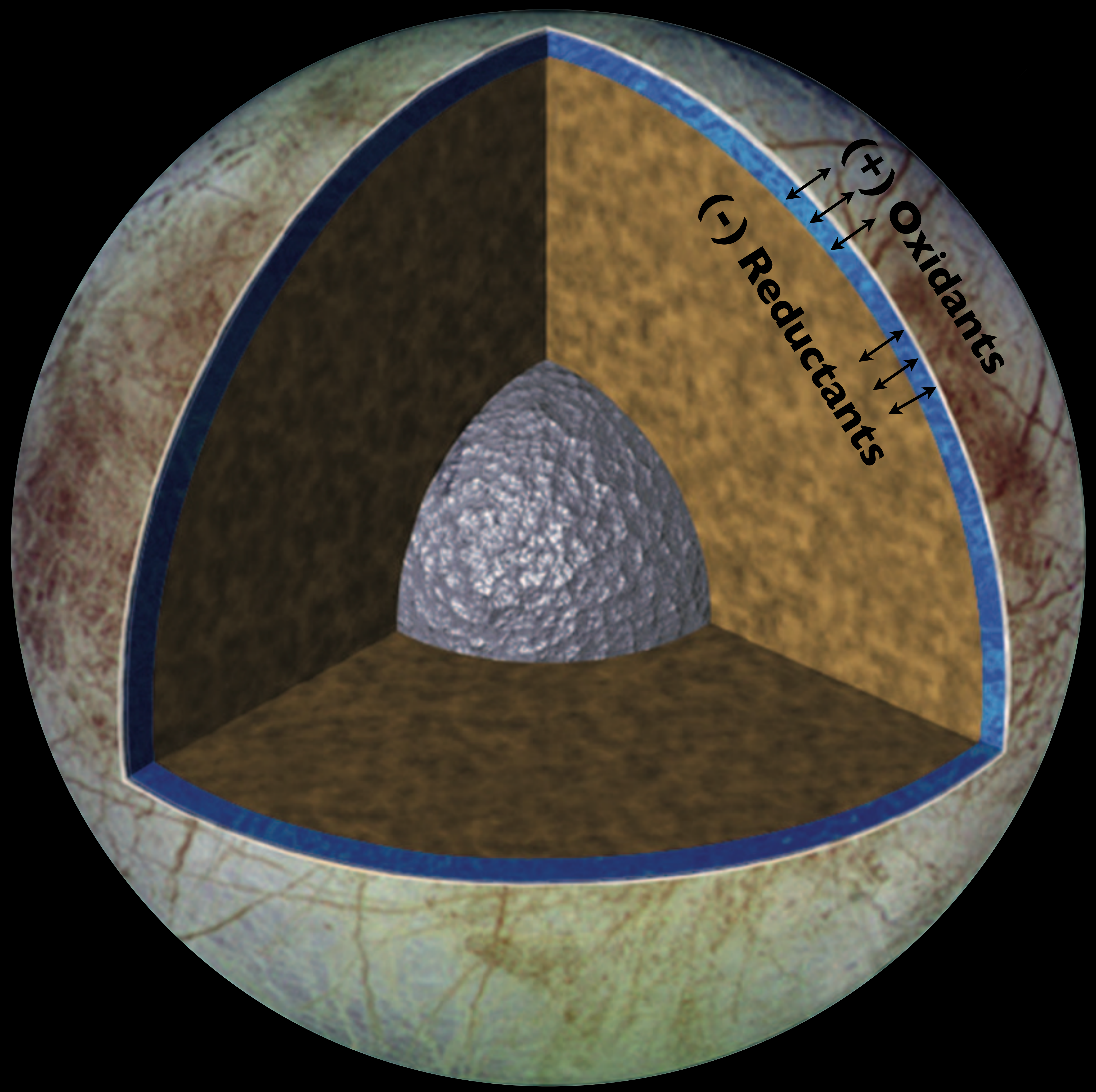
Spencer & Calvin 2002

How oxidized is Europa's ocean?

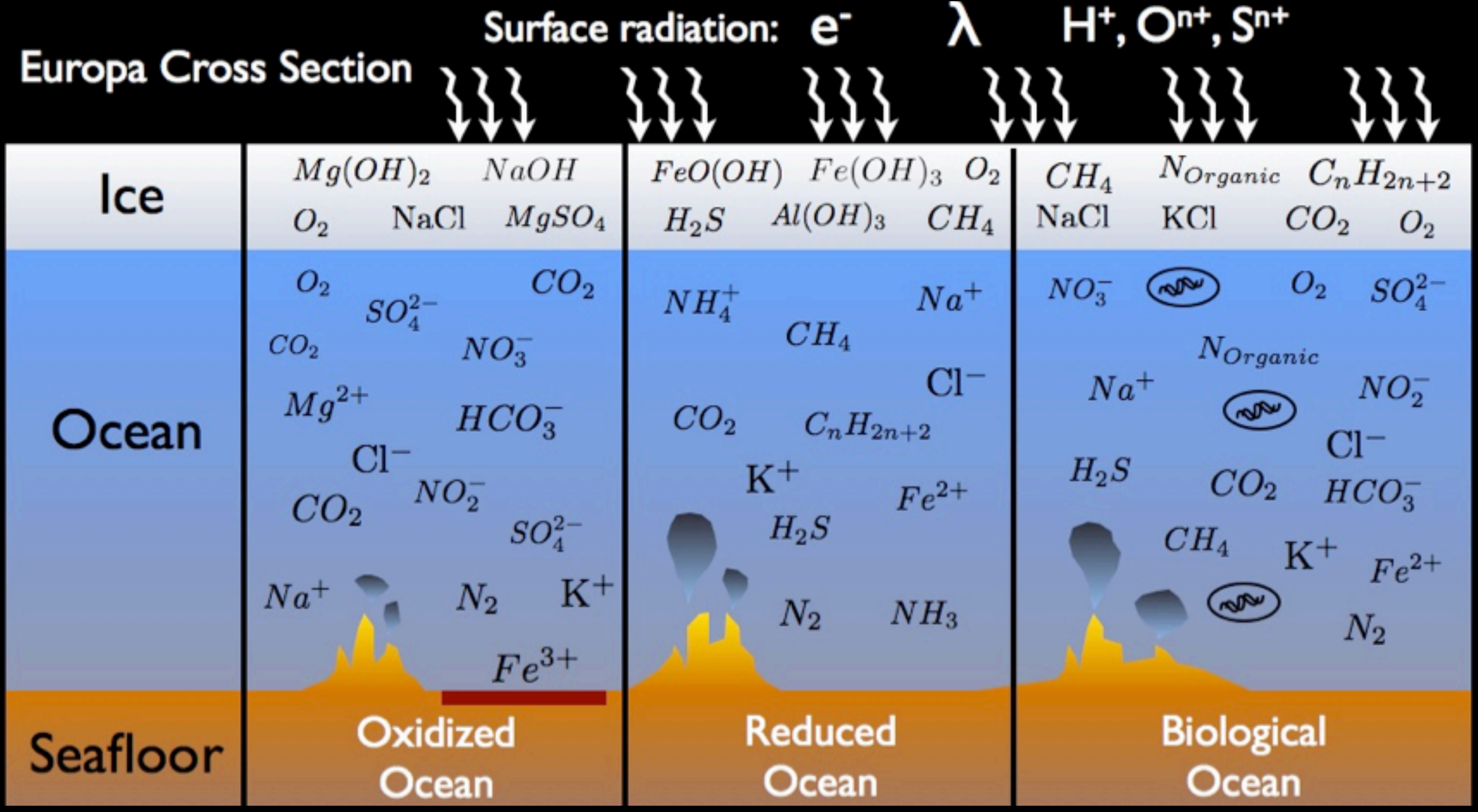




Hand et al., 2007; 2009

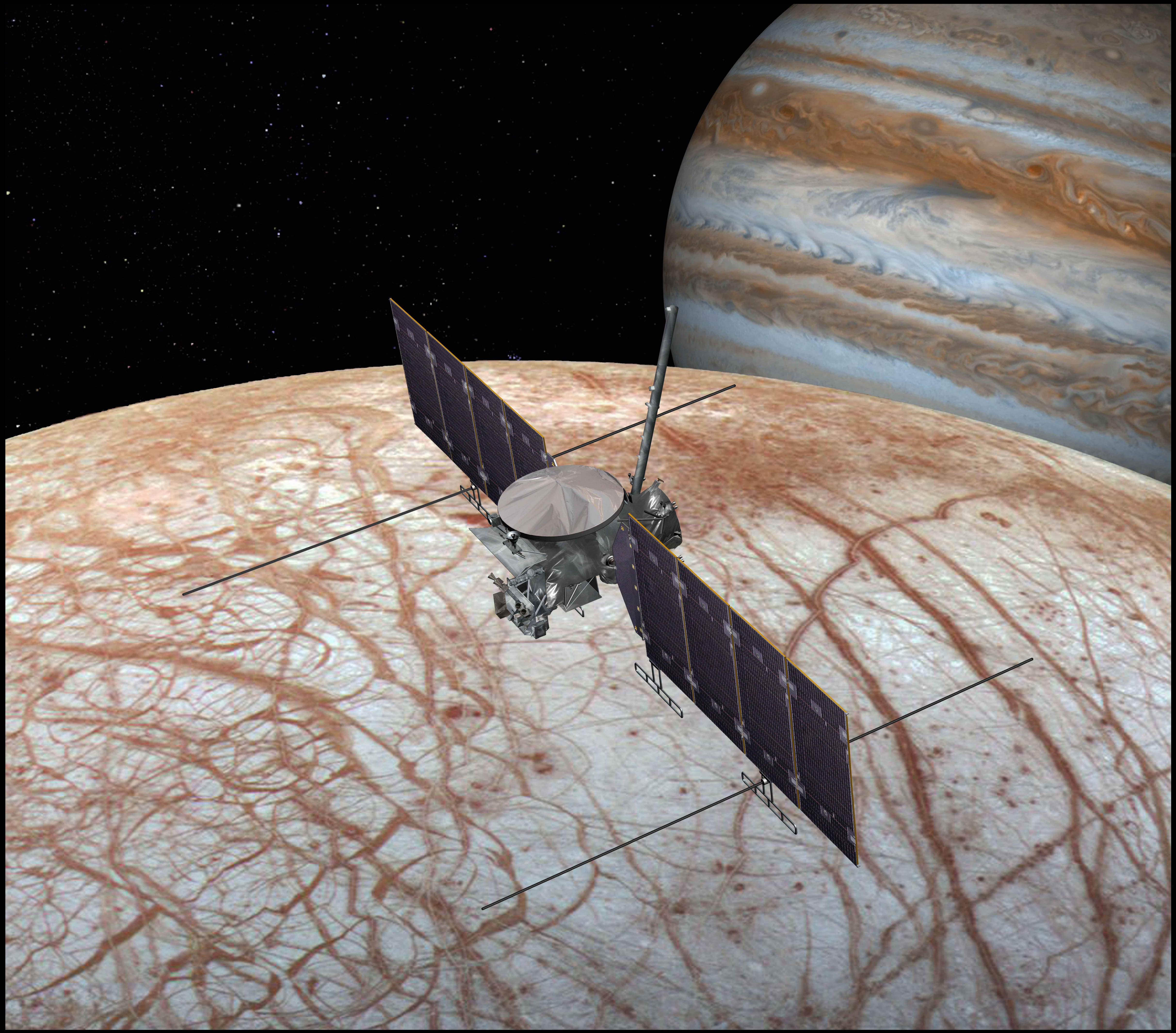


(+) Oxidants
(-) Reductants



Hand et al., 2009

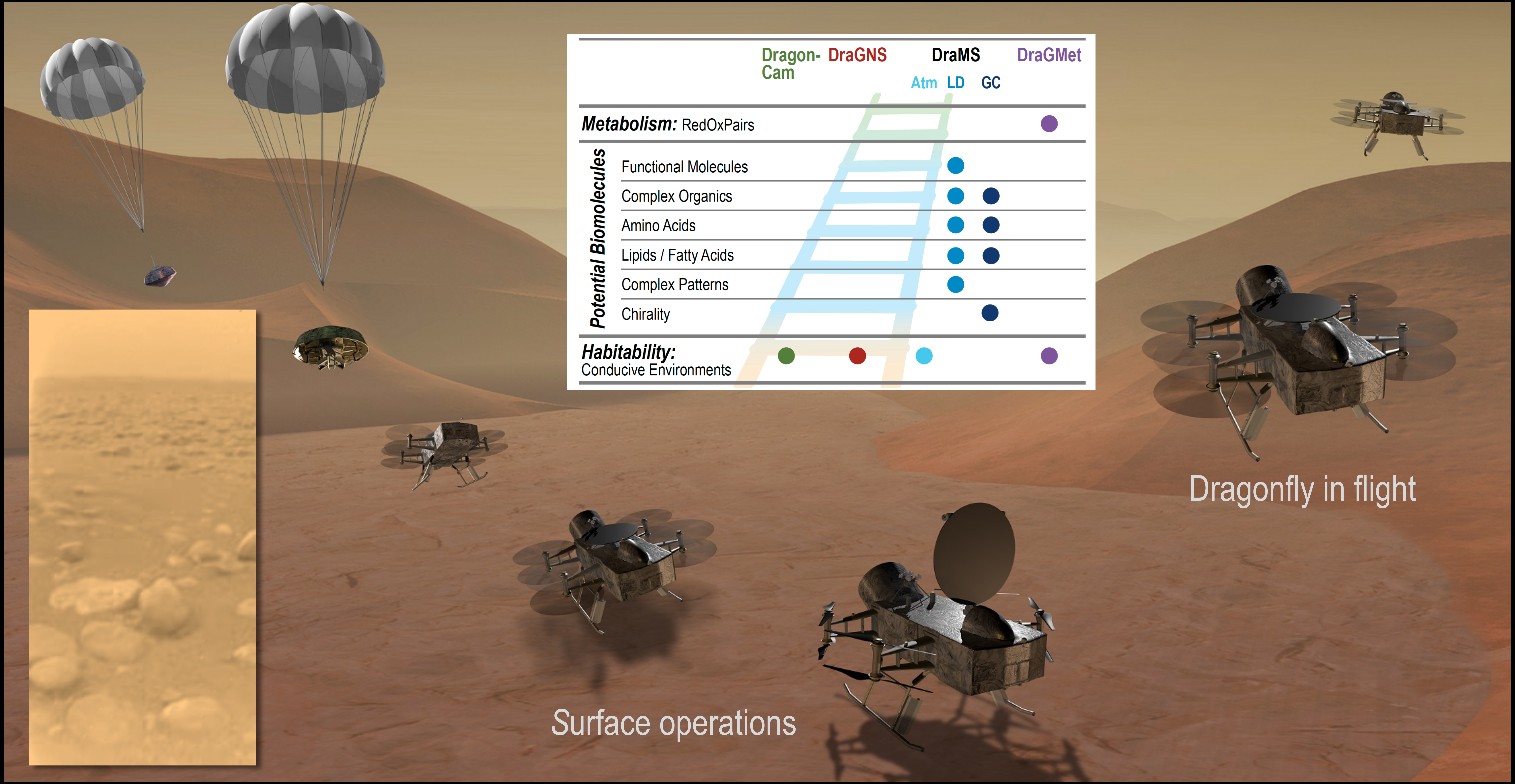
Great, so how do we *find* it?



Europa Clipper (NASA)

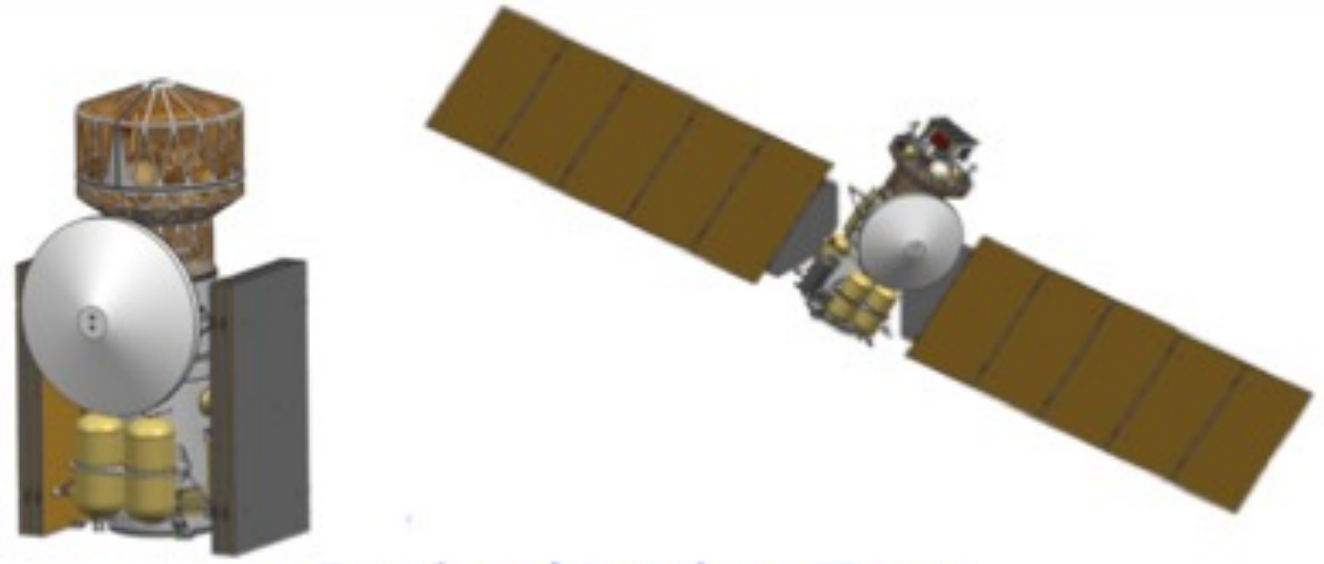
JUICE (ESA)

Dragonfly Mission Concept for Titan exploration (NASA New Frontiers, competed mission)



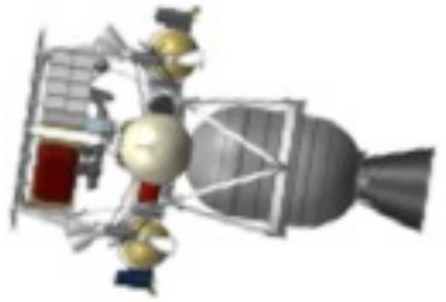
		Dragon-Cam	DraGNS	DraMS Atm	DraMS LD	DraMS GC	DraGMet
Metabolism: RedOxPairs							●
Potential Biomolecules	Functional Molecules				●		
	Complex Organics				●	●	
	Amino Acids				●	●	
	Lipids / Fatty Acids				●	●	
	Complex Patterns				●		
	Chirality					●	
Habitability: Conducive Environments		●	●	●			●

Europa Lander Mission Concept

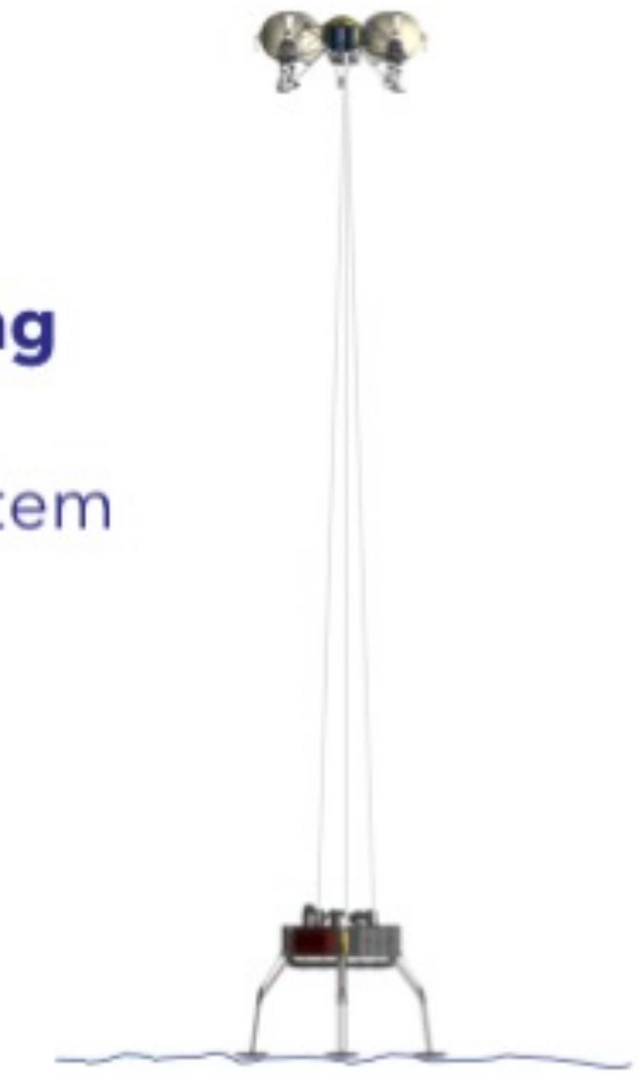


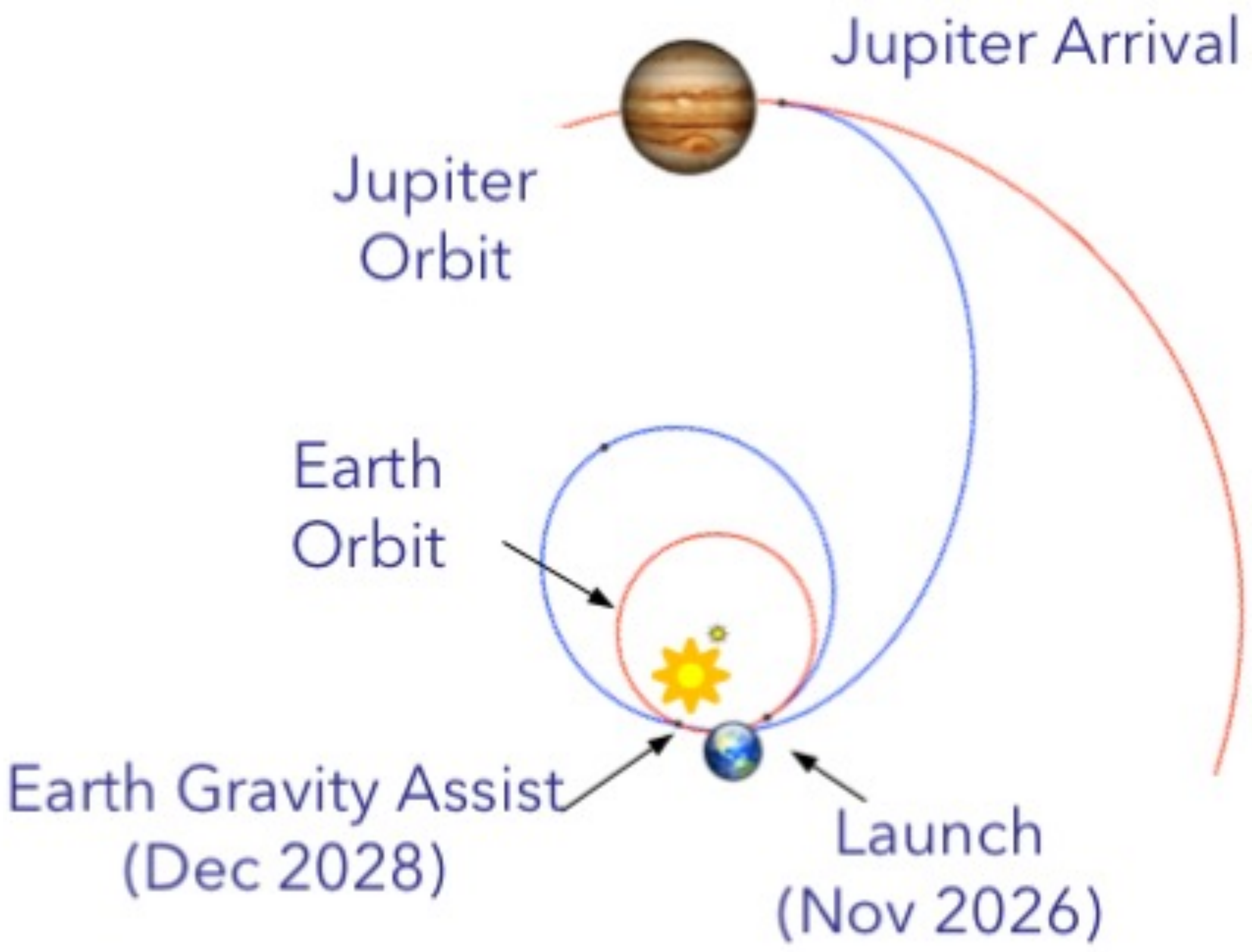
Cruise/Jovian Tour
- Jupiter Orbit Insertion: Sep 2031
- Europa Landing: 2033

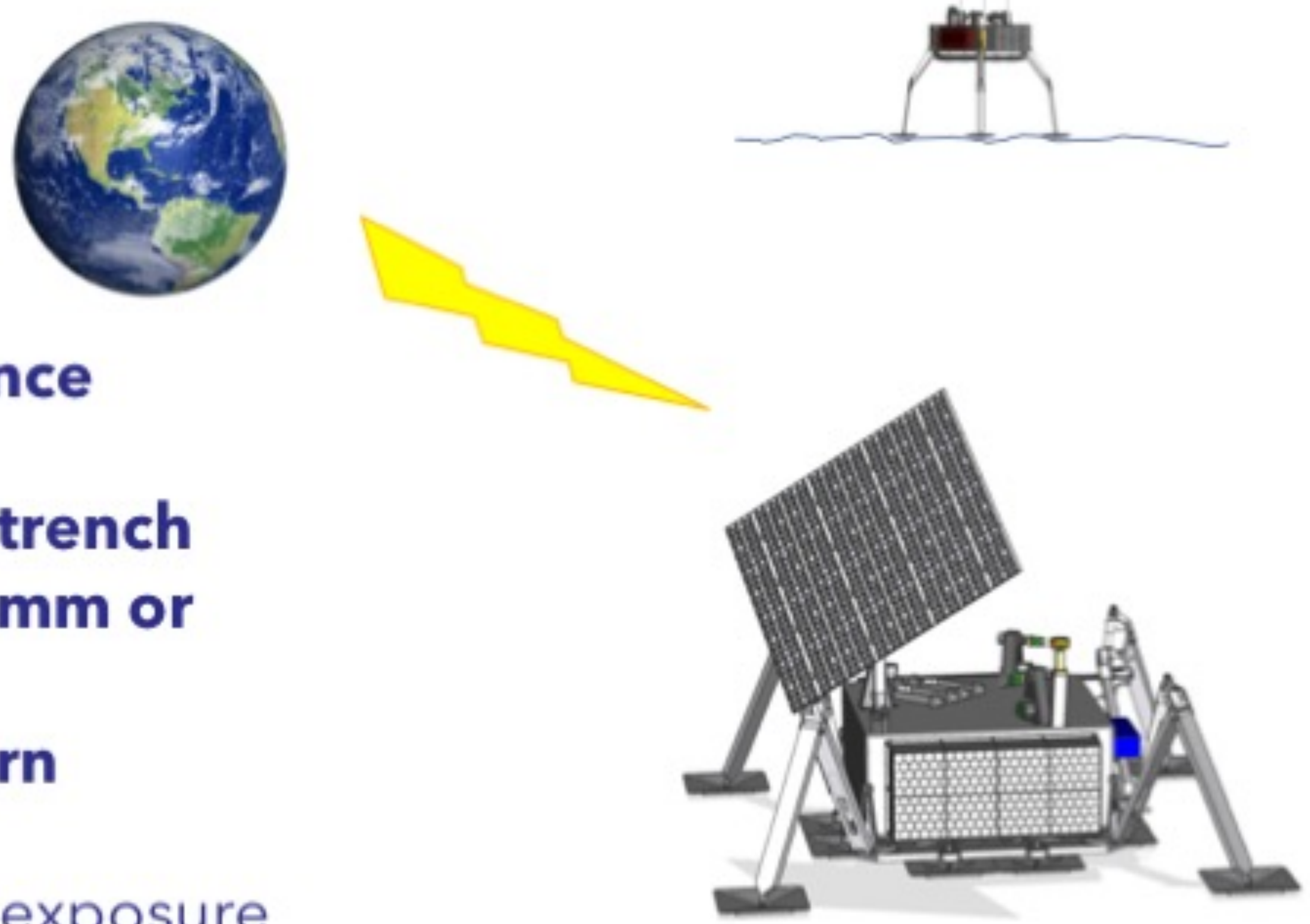
Carrier Stage
- 2.0 Mrad radiation exposure
- **Elliptical disposal orbit**



Deorbit, Decent, Landing
- Guided deorbit burn
- Sky Crane landing system
- 100-m accuracy
- **DTE tones only**





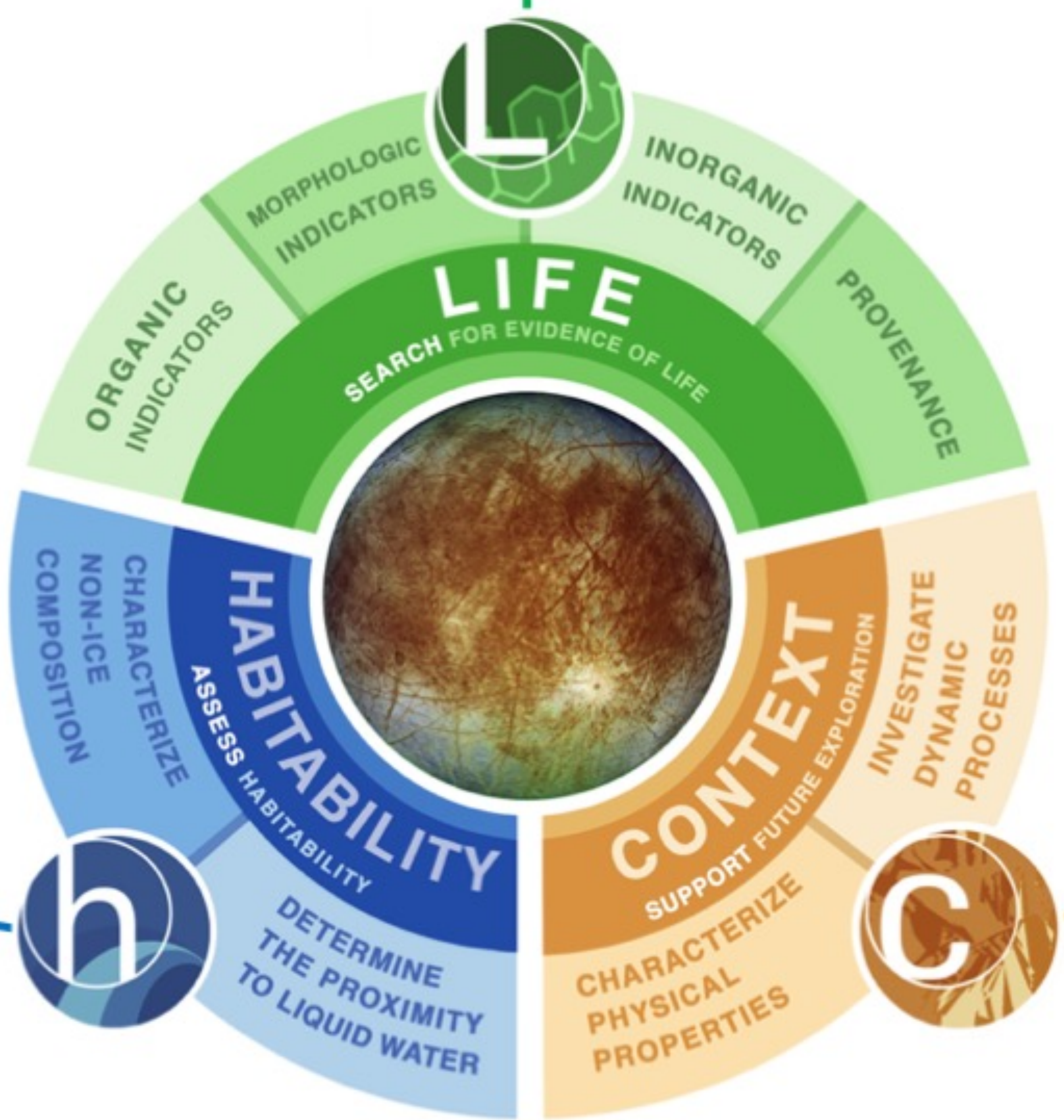


Surface Mission
- **Biosignature Science**
- 20+ days
- **3 samples from 1 trench**
- **Direct to Earth Comm or Clipper (backup)**
- **1.5 Gbit data return**
- 50 kWh battery
- 2.0 Mrad radiation exposure

Launch
- SLS Block 1B
- Nov. 2026

A Connected Set of Goals & Objectives Addressed with a Focused Model Payload

GC-MS	Microscope	Raman spectrometer	Context cameras

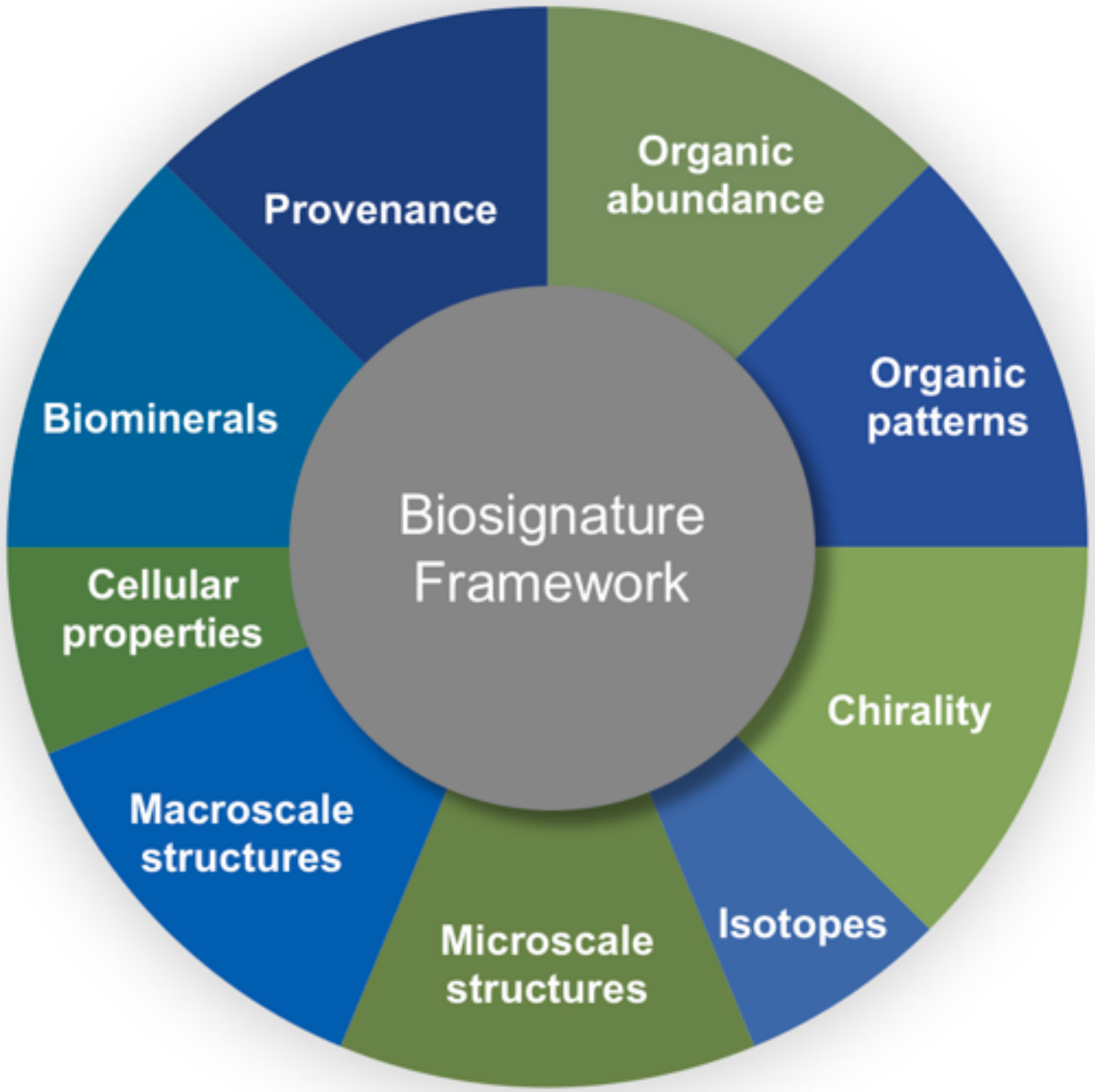


Habitability instruments:
- Raman spectrometer
- GC-MS
- Context cameras
- Geophone

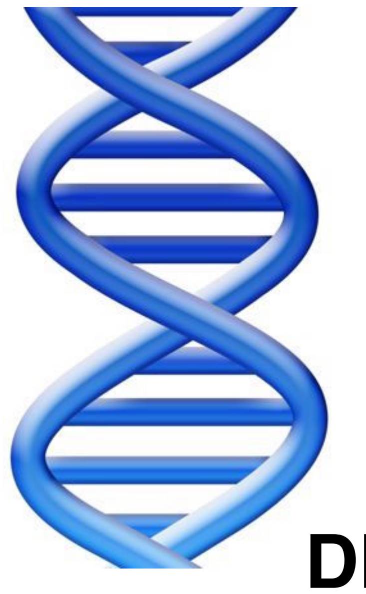
Context instruments:
- Raman spectrometer
- Microscope
- GC-MS
- Context cameras
- Geophone

Lander Provides a Robust Suite of Biosignature Measurements

- Model payload provides a minimum of **9 lines of evidence** for identifying potential biosignatures
- Biosignature Investigations are highly **complementary**
- Model payload ensures measurement **redundancy**
- **Investigations yield high value science even in the absence of any potential biosignatures.**



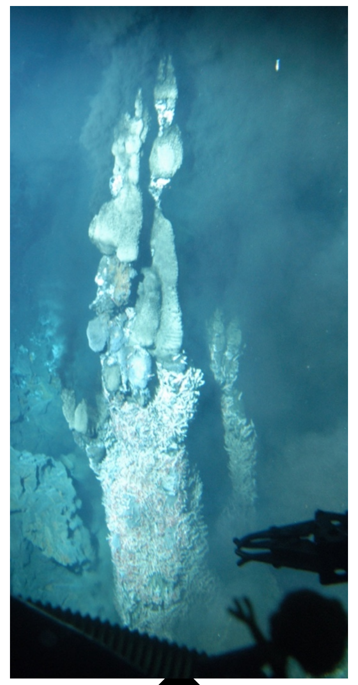
Viking Results: Then & Now



DNA discovered

1953

Hydrothermal vents discovered



1976

1977

Archaea discovered (3rd domain of life)

Cryptoendoliths in Antarctica discovered

PCR Invented

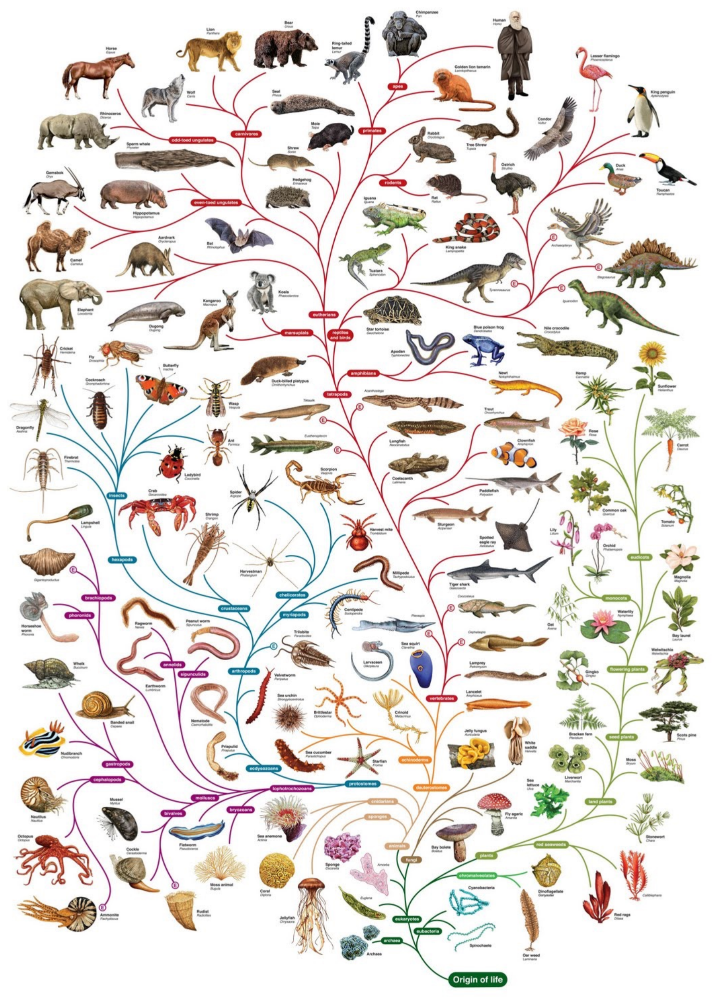
1983

2003

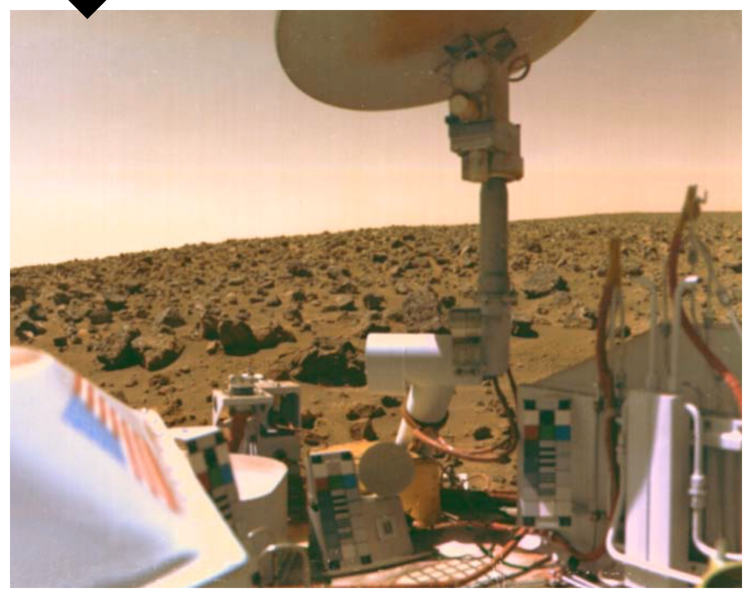
2016

Europa Lander SDT Report delivered

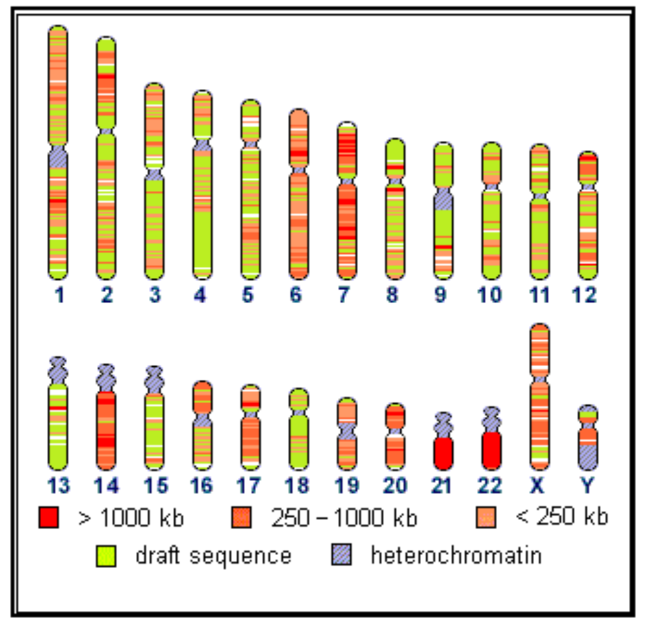
2017



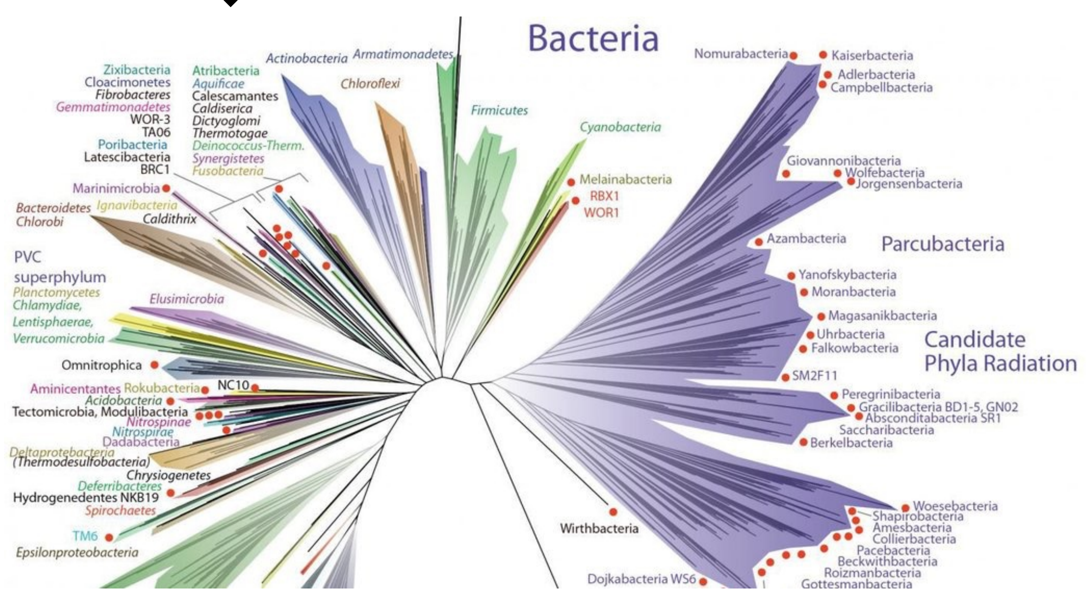
Tree of Life Then…



Viking Landers



Human genome sequenced



…Tree of Life Now.

Europa Lander

Potential Future Mission Concept