Ocean Worlds Roadmap

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Key references

Hand et al., 2017. Report of the Europa Lander SDT, https://solarsystem.nasa.gov/docs/Europa_Lander_SDT_Report_2016.pdf

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Lunine, J.I. 2017. Ocean worlds exploration. *Acta Astronautica* 131, 123-130.

Nimmo, F., and R. T. Pappalardo 2016. Ocean worlds in the outer solar system, *J. Geophys. Res. Planets* 121, 1378–1399,

Sherwood, B. et al. 2017. Program options to explore ocean worlds. *Acta Astronautica* 131, 123-130.

Disclosure: Op-Ed in Washington Post: https://www.washingtonpost.com/opinions/the-spacecraft-that-found-for-the-first-time-where-life-could-exist-now/2017/09/14/ad685636-9895-11e7-b569-3360011663b4_story.html

With each giant leap, the follow-ons multiply…..

Pioneer 11, Saturn 1979 flyby:

- F-ring
- Magnetic field
- Excess heat from Saturn

Voyager 1 and 2, 1980, 81 flybys:

- Dense N_2 atmosphere on Titan
- Enceladus bright and smooth
- Complex geology on Saturn's moons
- Intricate ring structure
- Shepherd moons

Cassini-Huygens, 2004-2017, orbiter and lander

- Methane hydrologic cycle on Titan with rivers, lakes, seas, dunes, subsurface water ocean
- Enceladus plume evidence of habitable/hydrothermal salty ocean
- Complex ring-moon interactions; vertical ring structure
- Saturn convective atmosphere, hurricanes, hexagon
- Slippage in Saturn magnetospheric rotation
- Ambiguous helium depletion; Z-element enrichm.

Titan mission (orbiter, balloon, UAV, boat)?

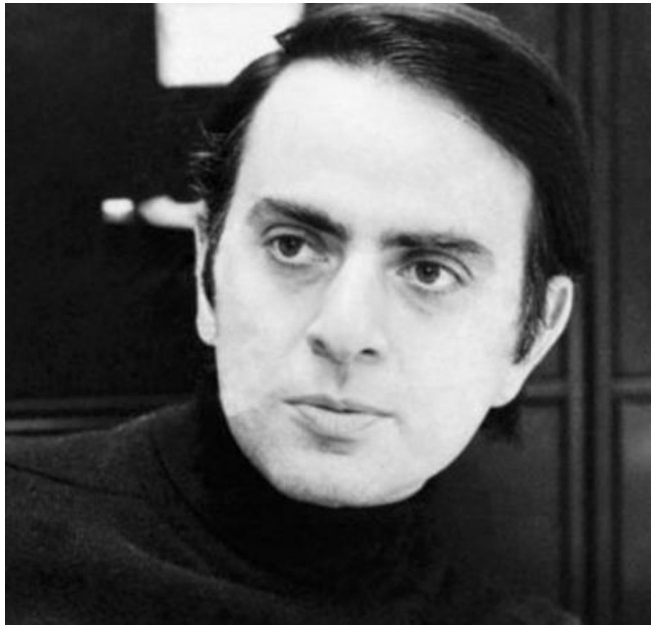
Enceladus life search?

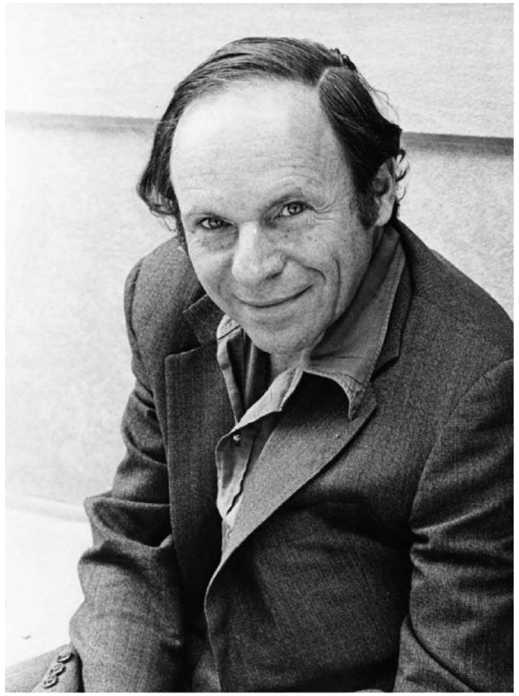
Saturn atmospheric probe?

Saturn Juno/rings?

Carl Sagan in 1966
(*Intelligent Life in the Universe*, Shklovskii and Sagan):

"The discovery of life on one other planet—e.g., Mars—can, in the words of the American physicist Philip Morrison…'transform the origin of life from a miracle to a statistic'. "

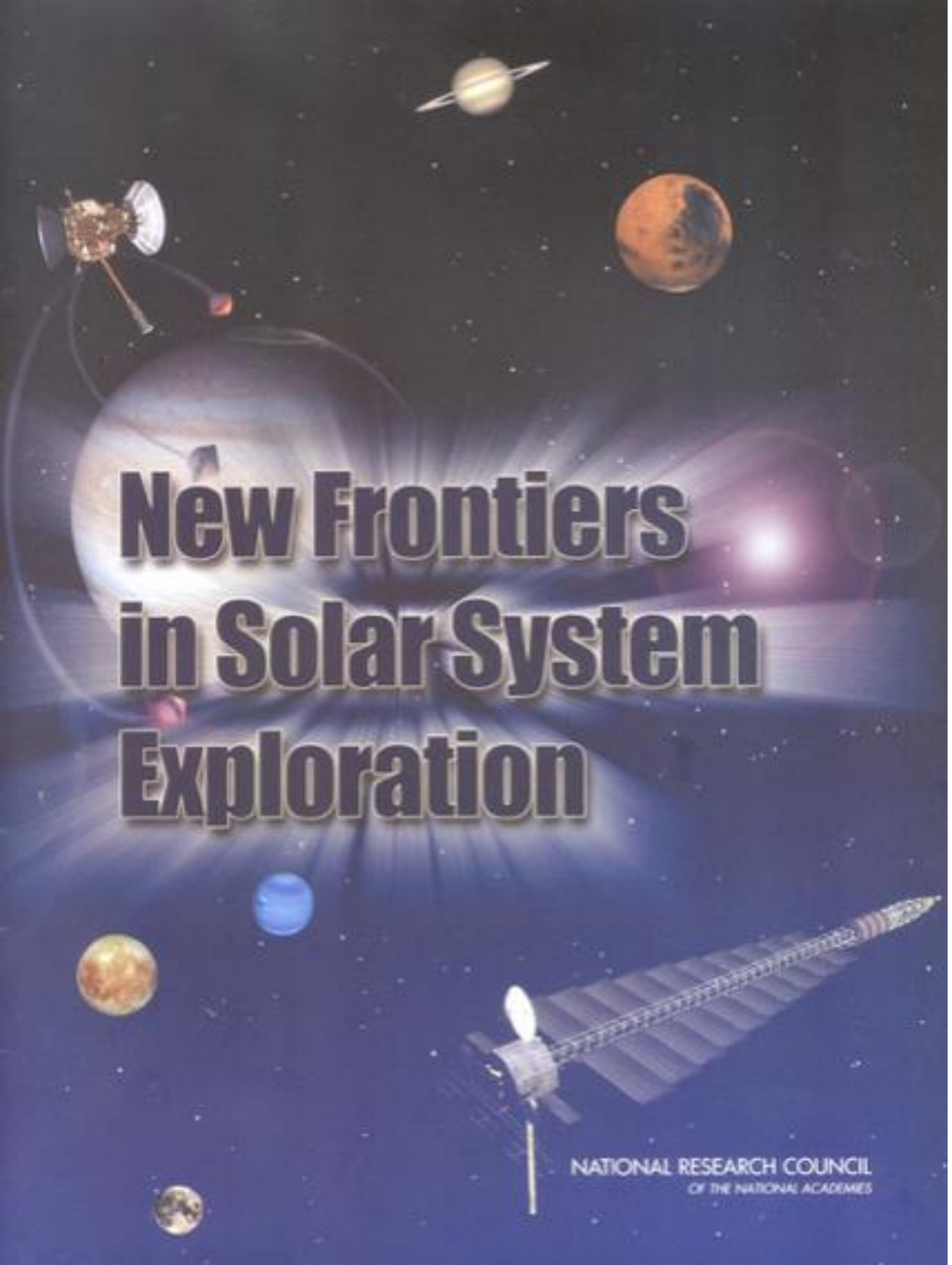




Arthur C. Clarke speaking at Caltech in 1971 (*Mars and the Mind of Man* 1973):

"I think the biological frontier may very well move past Mars out to Jupiter, which I think is where the action is."


MGM

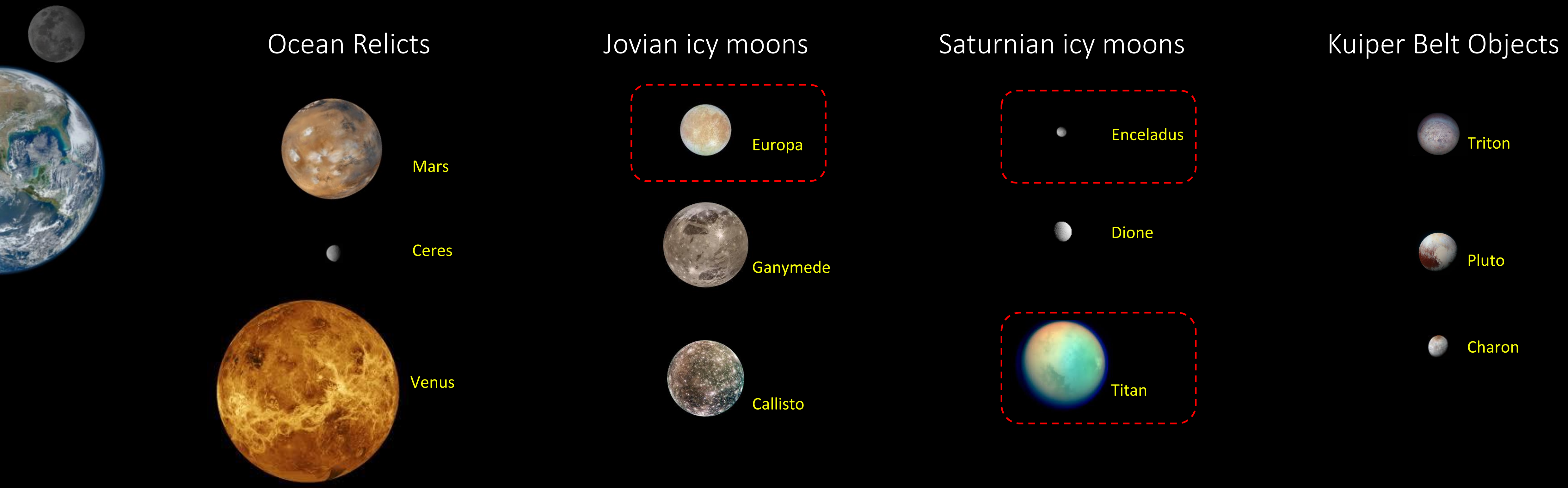


"Solar system exploration is that grand human endeavor which reaches out through interplanetary space to discover the nature and origins of the system of planets in which we live and to learn whether life exists beyond Earth. It is an international enterprise involving scientists, engineers, managers, politicians, and others, sometimes working together and sometimes in competition, to open new frontiers of knowledge. It has a proud past, a productive present, and an auspicious future.

Solar system exploration is a compelling activity. It places within our grasp answers to basic questions of profound human interest: Are we alone? Where did we come from? What is our destiny? Further, it leads to the creation of knowledge that will improve the human condition. Mars and icy satellite explorations may soon provide an answer to the first of these questions. Exploration of comets, primitive asteroids, and Kuiper Belt objects may have much to say about the second. Surveys of near-Earth objects and further exploration of planetary atmospheres will show something about the third. Finally, explorations of all planetary environments will result in a much improved understanding of the natural processes that shape the world in which we live.

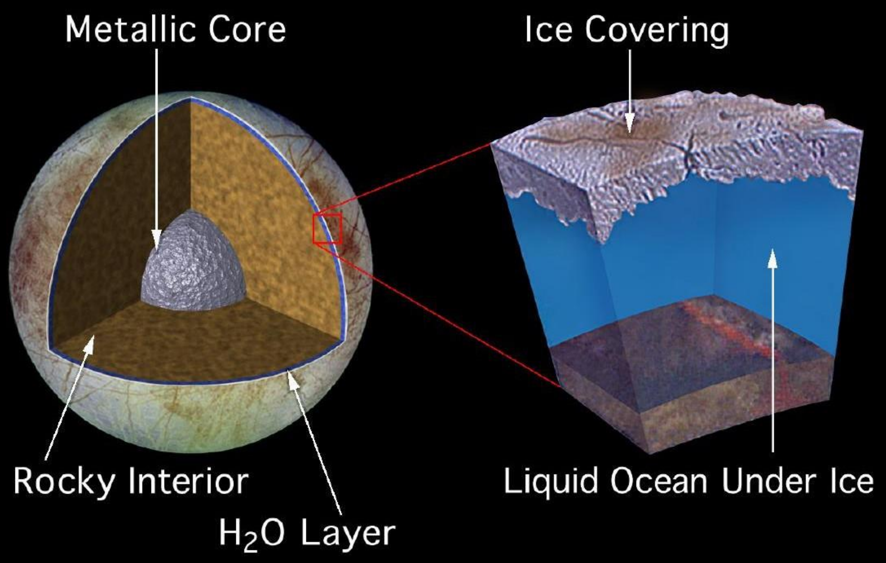
Executive Summary, 2003

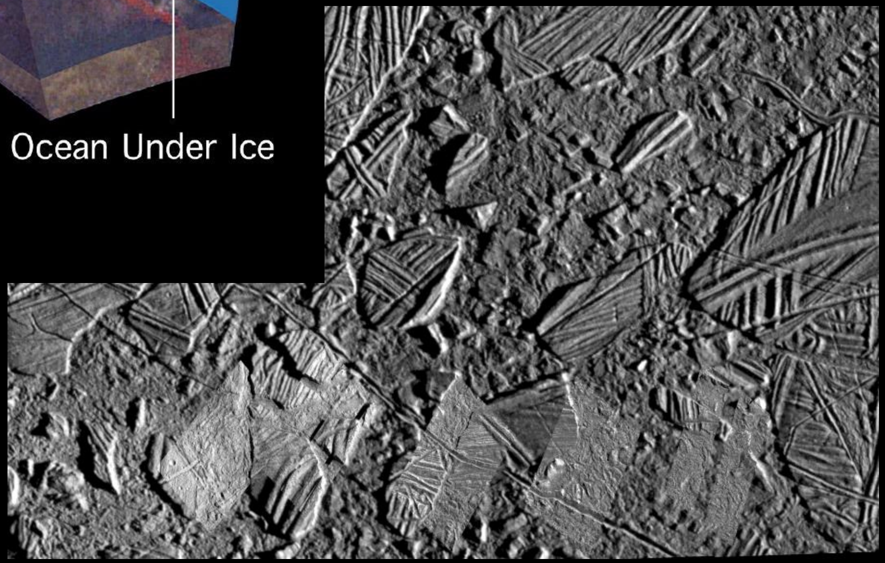
A dozen ocean worlds are within reach



Europa: best place for conventional life?

- Almost as large as Earth's Moon
- Ocean twice the volume of Earth's in contact with silicate rock
- Possible mechanism to sustain redox disequilibrium via radiolysis of surface ice





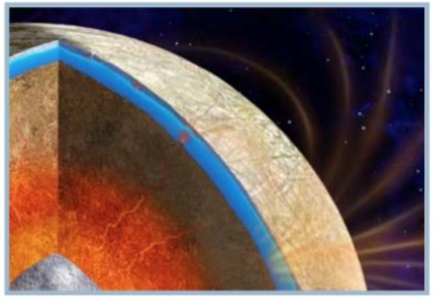
Some outstanding post-Galileo questions on Europa relevant to astrobiology

- Are there organic molecules in Europa's ocean?
- What is the saltiness of the ocean?
- What is the redox state and what are the energy sources in the ocean?
- How thick is the Europan crust and how variable is that thickness?
- Where and how frequently does the ocean communicate with the surface?
- Are there plumes and do they communicate with the ocean?
- What other dynamical processes occur between surface and the subsurface crust/ocean?
- What is the composition and provenance of the non-water-ice material at the surface?
- What indicators of past or present life (organic/inorganic) are accessible on the surface?
- Is there life in the ocean or crustal waters of Europa?

- (See also list in Hendrix et al 2017 ROW presentation)

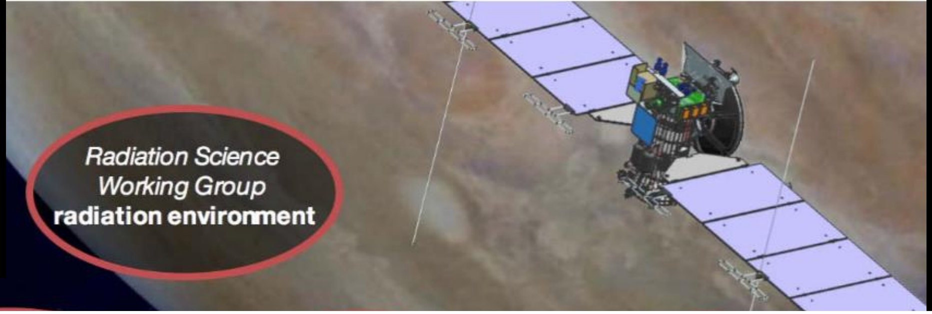
Europa Mission Science Goal & Objectives

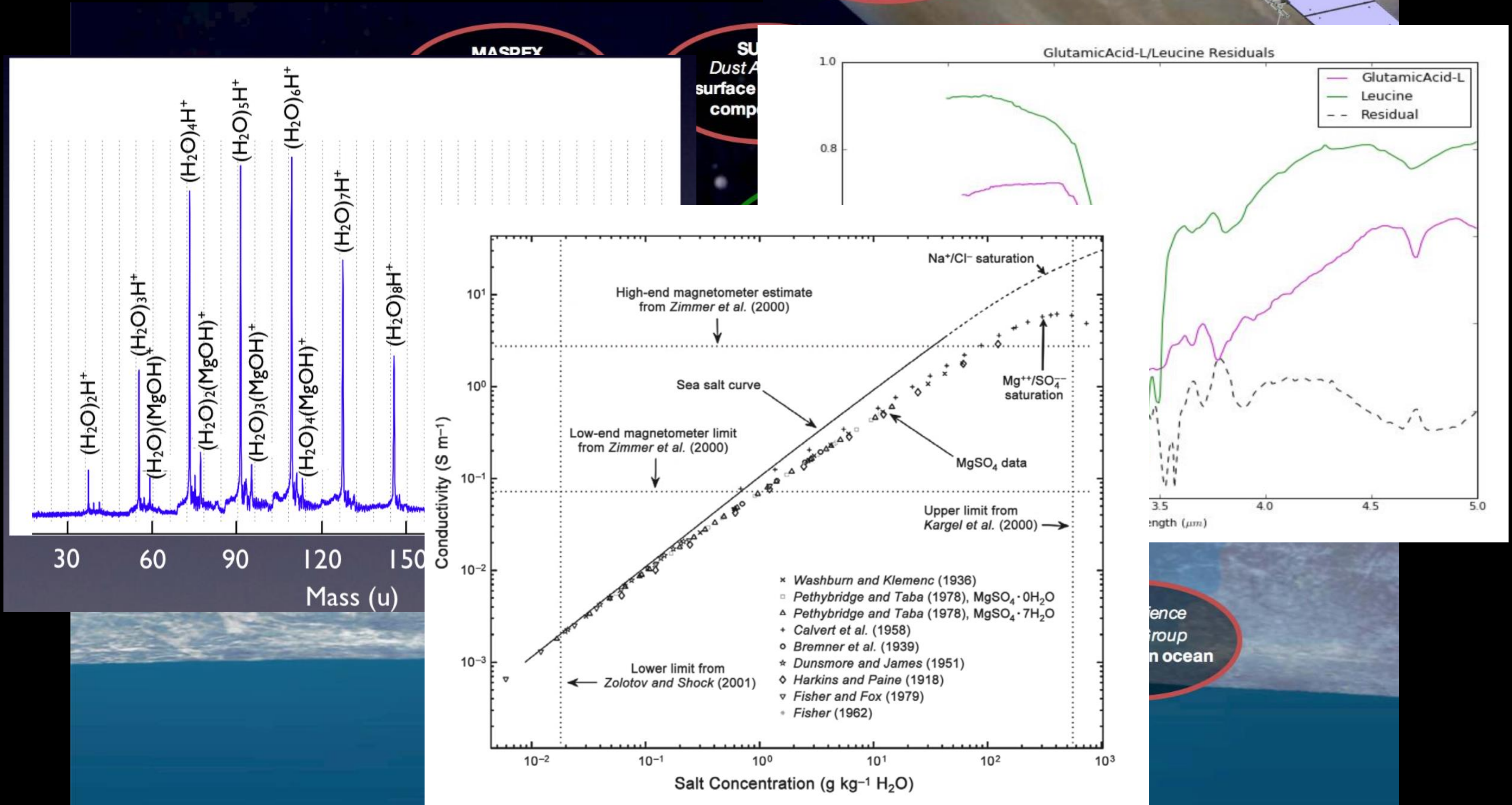
- *Goal:* **Explore Europa to investigate its habitability**
- *Objectives:*
  - **Ice Shell & Ocean:** Characterize the ice shell and any subsurface water, including their heterogeneity, ocean properties, and the nature of surface-ice-ocean exchange
  - **Composition:** Understand the habitability of Europa's ocean through composition and chemistry
  - **Geology:** Understand the formation of surface features, including sites of recent or current activity, and characterize high science interest localities*



**Note: Science Definition Team's "Reconnaissance" goal has been folded into the Geology objective*

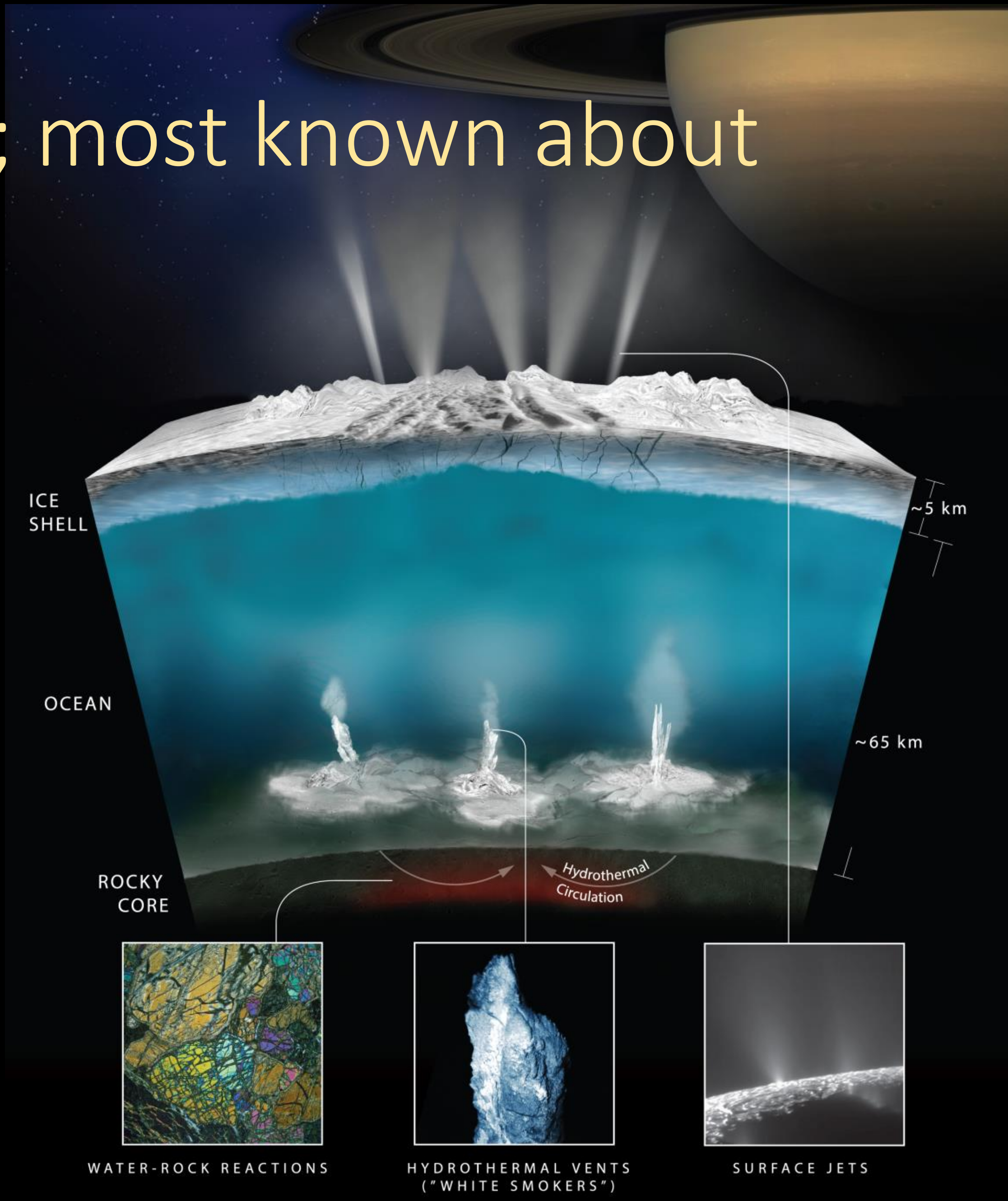
Europa Clipper superbly instrumented to determine the habitability of Europa's interior





Enceladus: easiest to explore; most known about the ocean

- Salt-water ocean with established hydrothermal activity
- Ocean reliably expressed into space by a big plume, ability to sample demonstrated by Cassini
- By today's standard, the most habitable place known off Earth

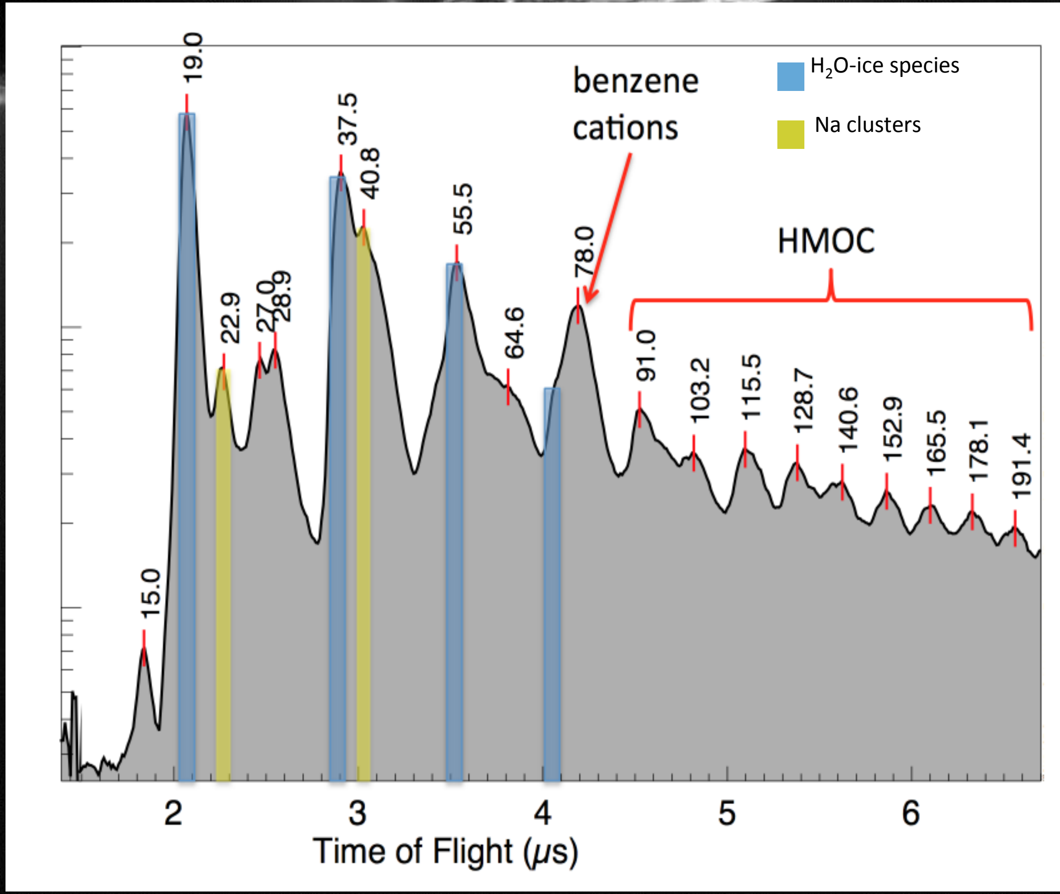


2010-2011:

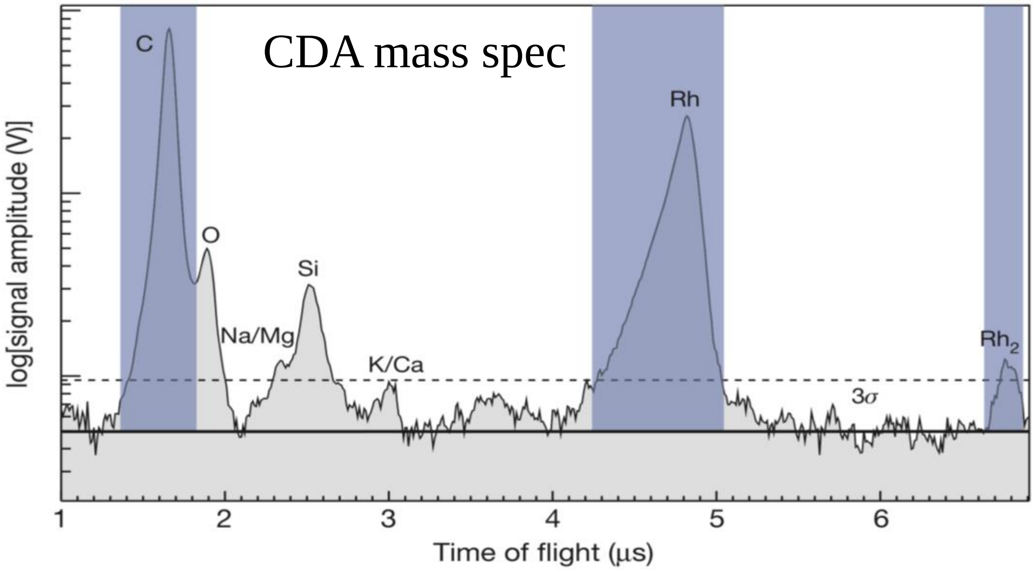
- Cassini CDA finds sodium and potassium in the plume material

The sodium and potassium are concentrated in the largest ice grains in the plume, at a concentration comparable to Earth's ocean water. Simplest interpretation is that the largest ice grains are frozen seawater.

(Postberg et al., 2009, 2011)

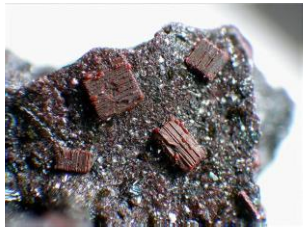


Nanometer-sized silica (SiO_2) grains (Hsu et al 2015) and molecular hydrogen (Waite et al. (2017) found by Cassini argue for active water-rock chemistry at ocean base.

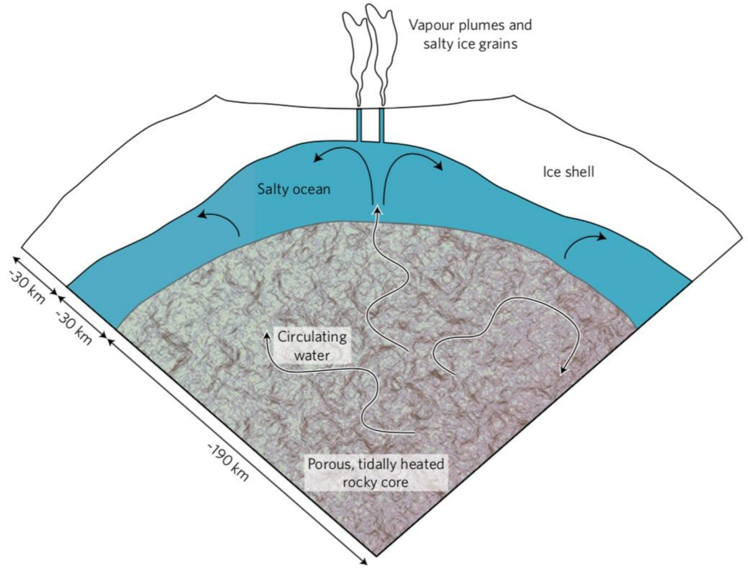


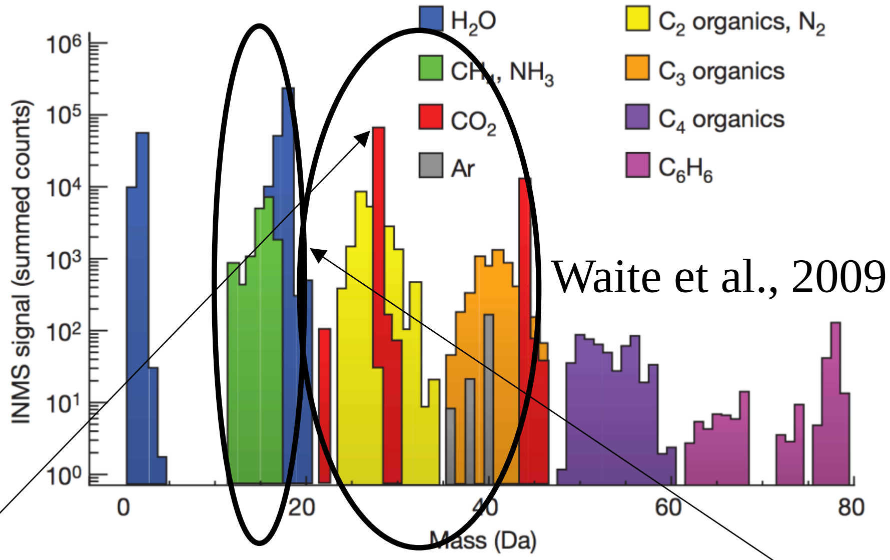
Fayalite | water | magnetite | aqueous silica | hydrogen

$$3\,Fe_2SiO_4 + 2\,H_2O \rightarrow 2\,Fe_3O_4 + 3\,SiO_2 + 2\,H_2$$



Active hydrothermal processing of rock leads to fractures and hence enhanced tidal heating (Choblet et al., Nature, 2017), and production of simple organics (CH_4; Waite et al., 2009):



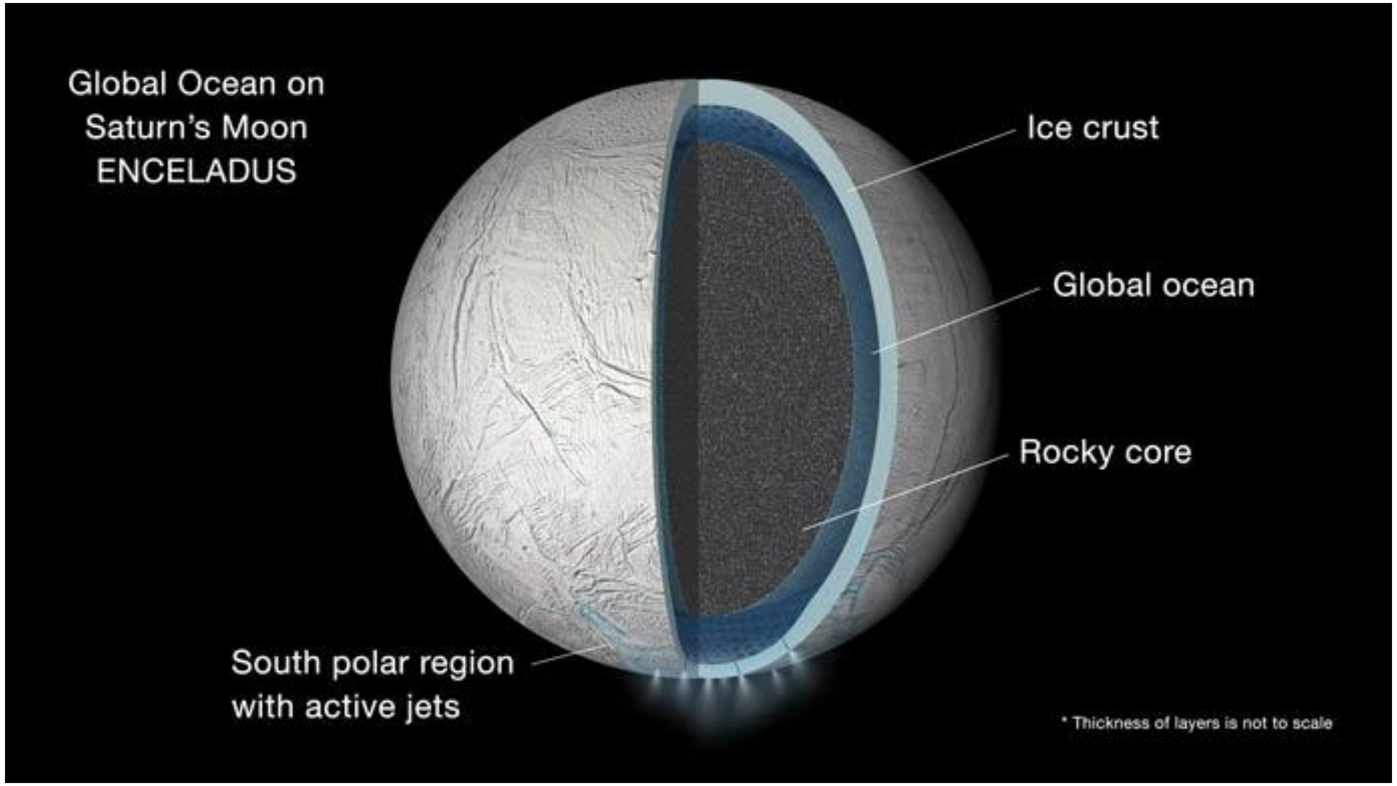


Waite et al., 2009

$$\underset{\text{Olivine}}{(Fe,Mg)_2SiO_4} + \underset{\text{water}}{n\cdot H_2O} + \underset{\text{carbon dioxide}}{CO_2} \rightarrow \underset{\text{serpentine}}{Mg_3Si_2O_5(OH)_4} + \underset{\text{magnetite}}{Fe_3O_4} + \underset{\text{methane}}{CH_4}$$

"An important lesson from Enceladus is that even small amounts of chemical information can be extremely useful" (Nimmo, Nature, 1^{st} December).

2014-5: Global ocean under the Ice

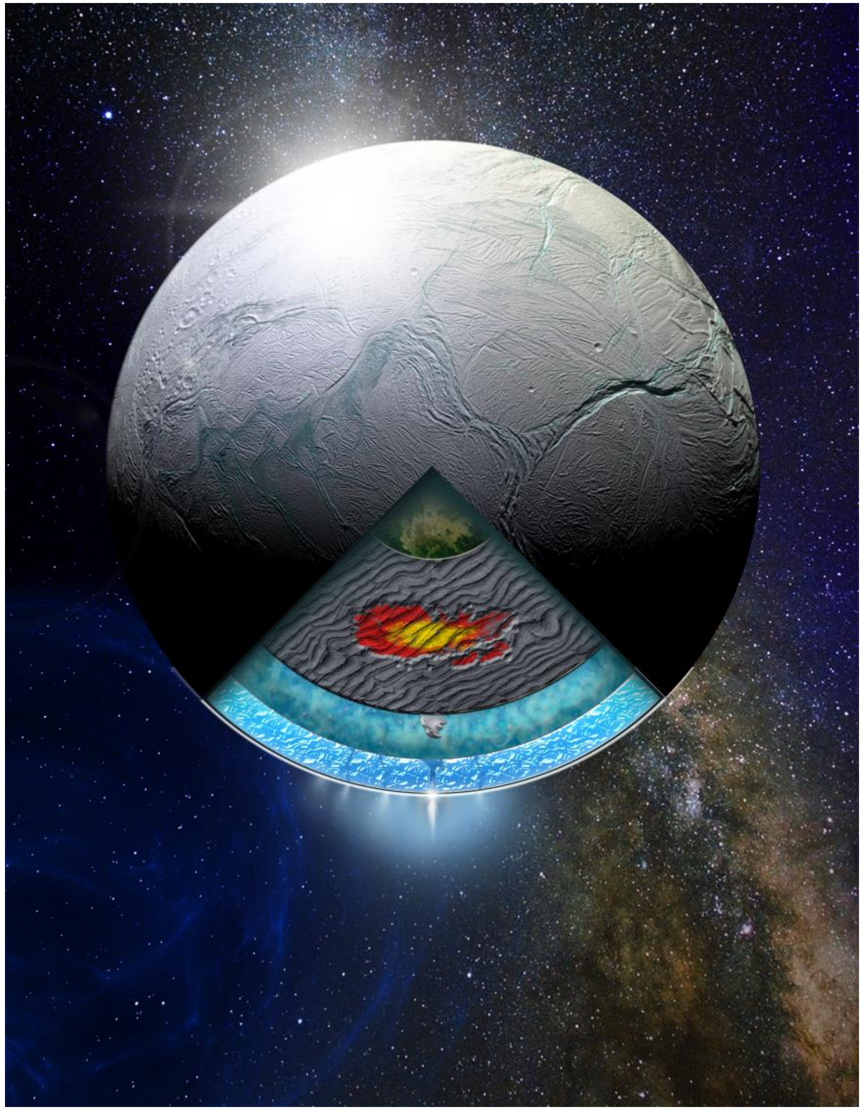


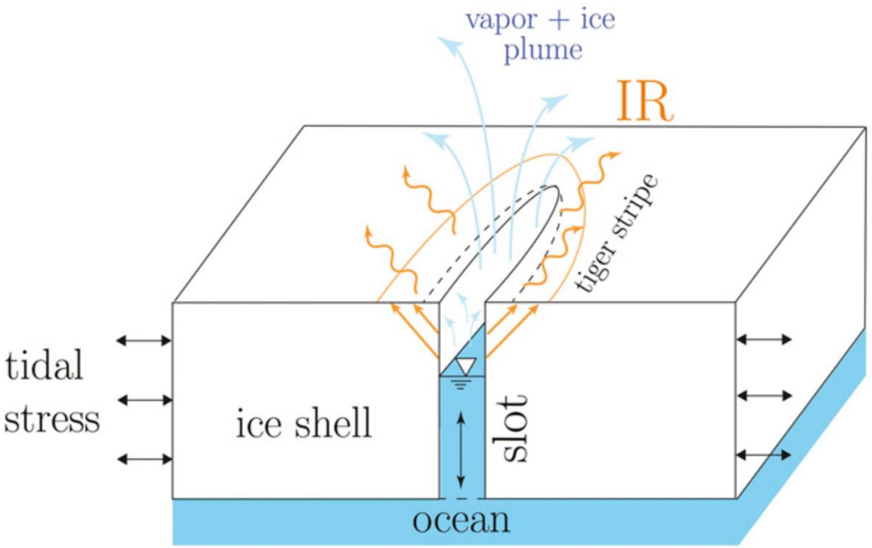
Cassini radio science combined with topography and rotational data discovers a global ocean, perhaps thicker at the south pole: the smoking gun that beneath the jets is a region of liquid water, stable for very long time periods.

Iess et al., 2014.; McKinnon 2015; Thomas et al. 2016

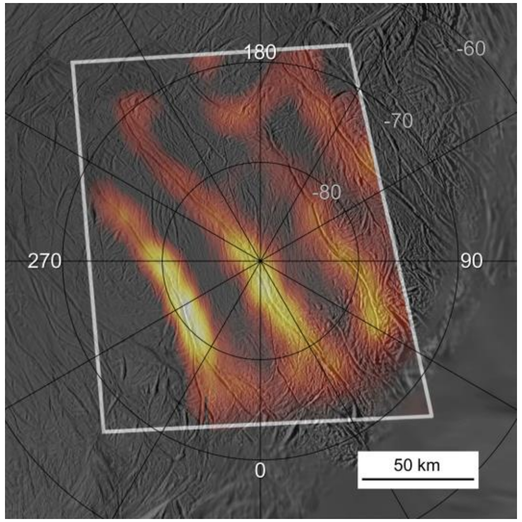
Tidal heating as the source

Choblet et al 2017: Fractured core (Painting by Chris Glein, SWRI)





Kite and Rubin, 2016: Fractures in ice



Cassini CIRS

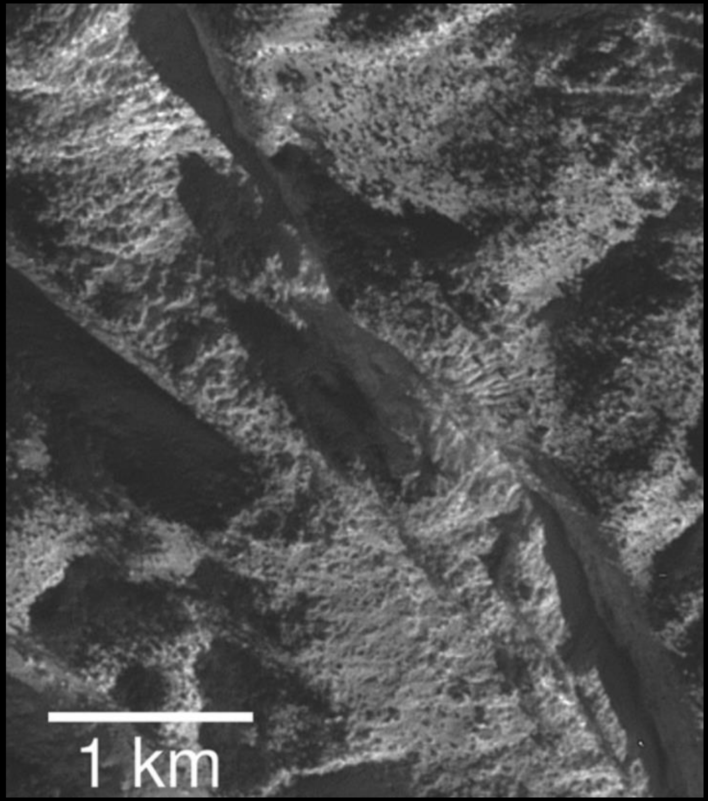
Outstanding post-Cassini questions on Enceladus relevant to astrobiology

- Where and in what form is the P,S in the ocean?
- What is the identity of the heavy organics?
- What is the redox state of the ocean and departure from equilibrium?
- How long has the ocean been an ocean? How is the tidal heating sustained?
- What is the detailed nature of the hydrothermal circulation in the ocean?
- What are the transport processes and timescales involved in getting material from the ocean to the plume?
- How closely does the plume material resemble the ocean, vs crustal, composition?
- Is the hydrothermal system located only under the south pole, or distributed?
- Is there life in the ocean of Enceladus?

- (See also list in Hendrix et al 2017 ROW presentation)

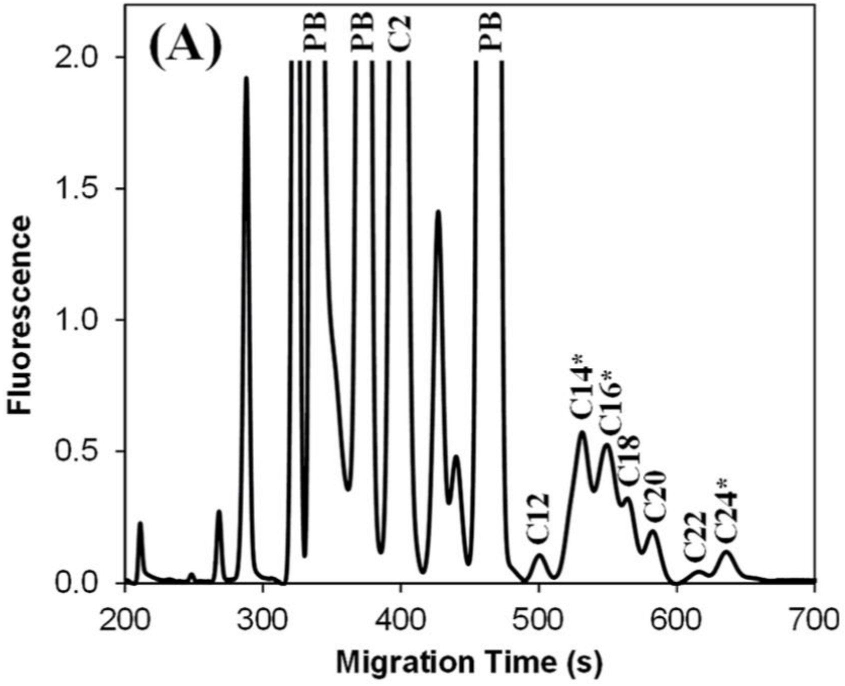
Awaiting focused missions

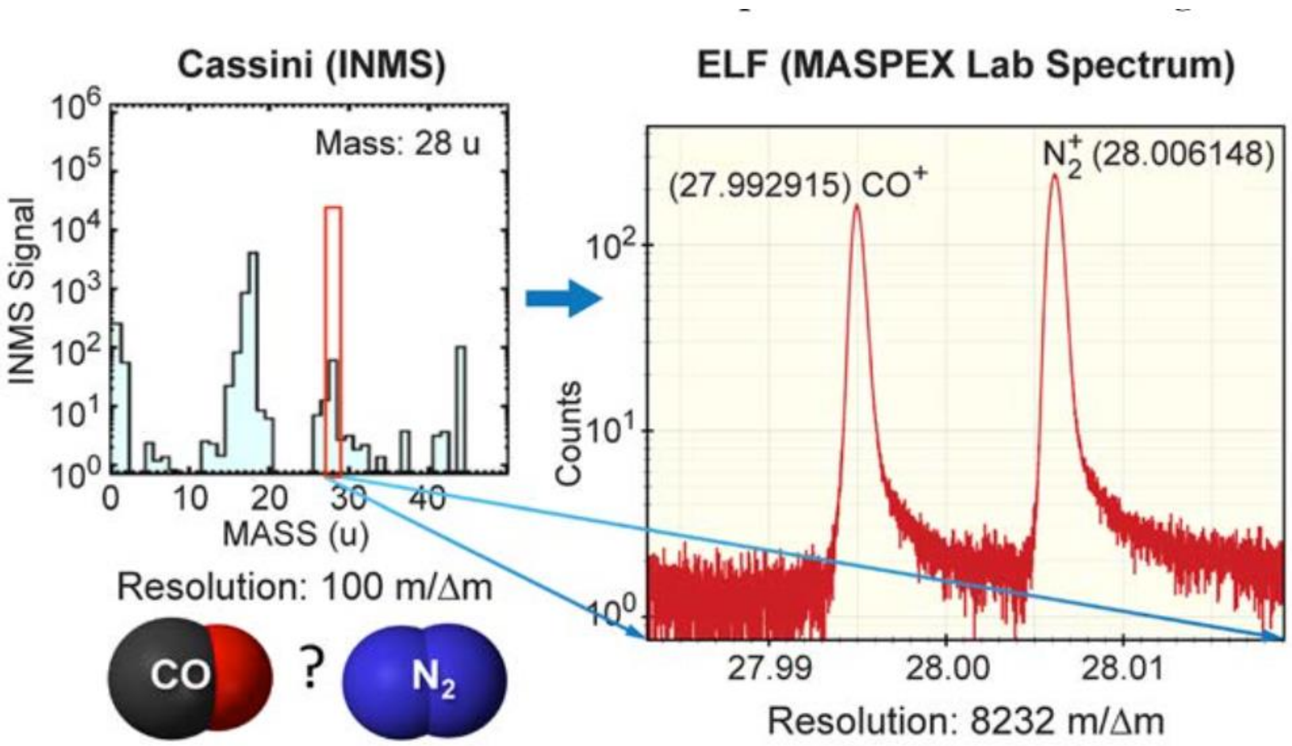
- Plume is easy to transect
- Ability to obtain composition of gas and grains proved by Cassini
- Next step is to look for signs of life



ELSAH (ARC/GSFC/APL)

Enceladus Life Finder (JPL)





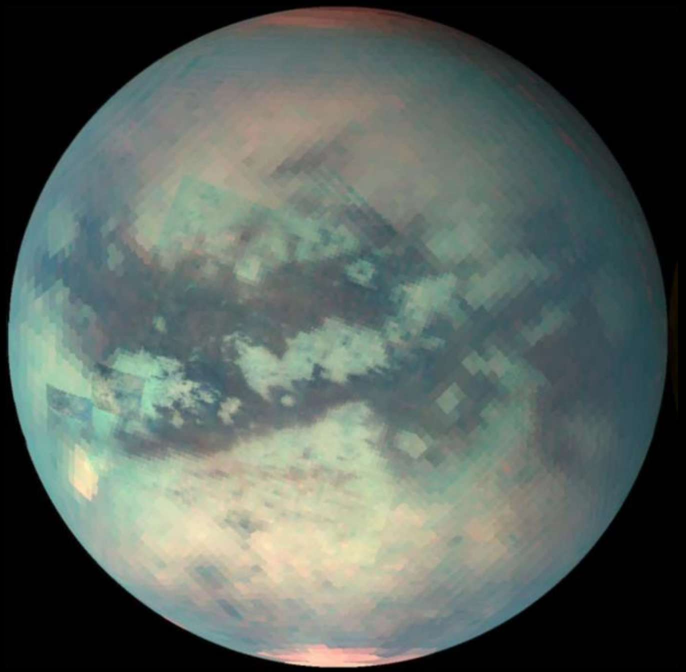
Microfluidic device (Cable et al 2014)

Lab high resolution mass spectrometry

*"I am perplexed that NASA had two Enceladus proposals in front of them and neither got … a Phase A study."

An experienced aerospace engineer/manager.

Titan: The once and future Earth

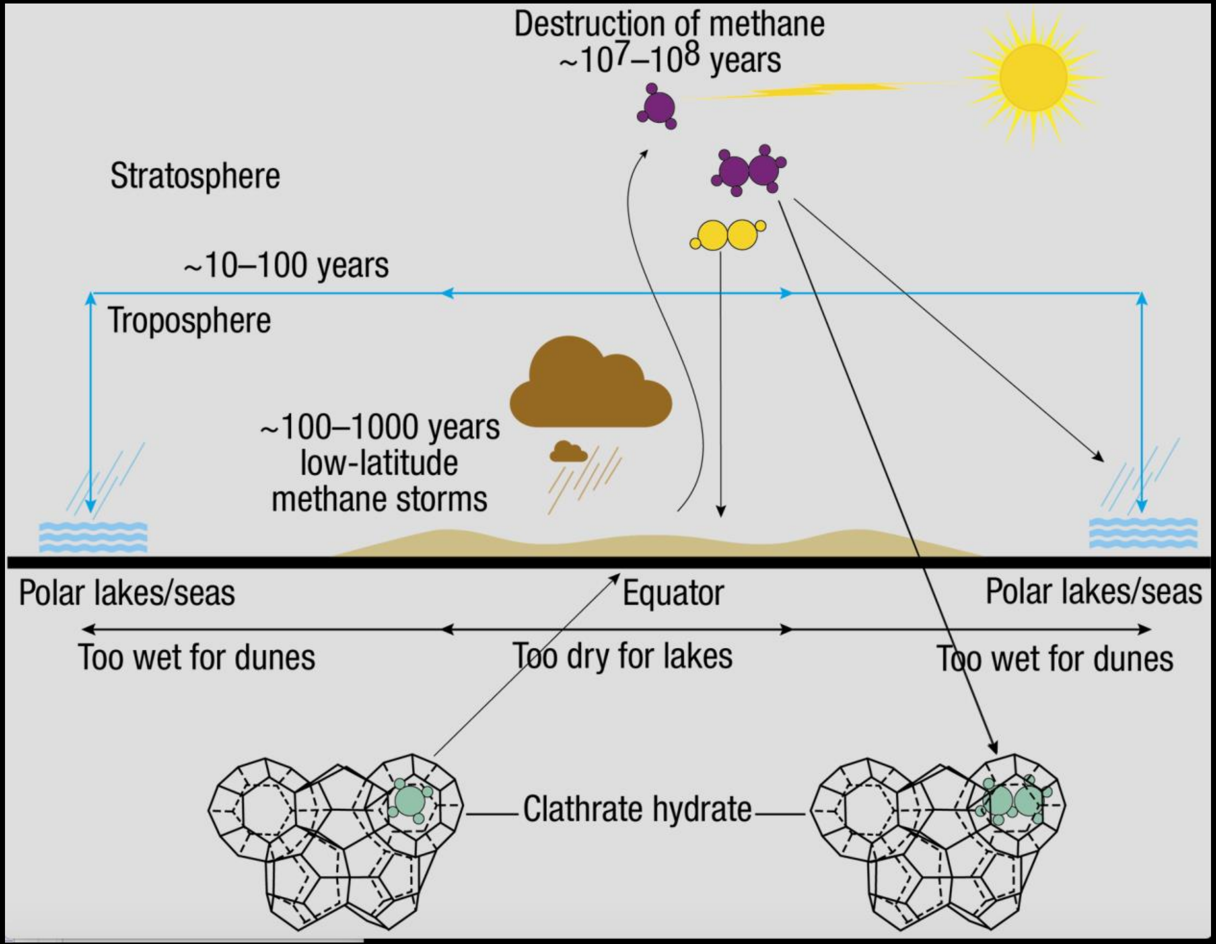


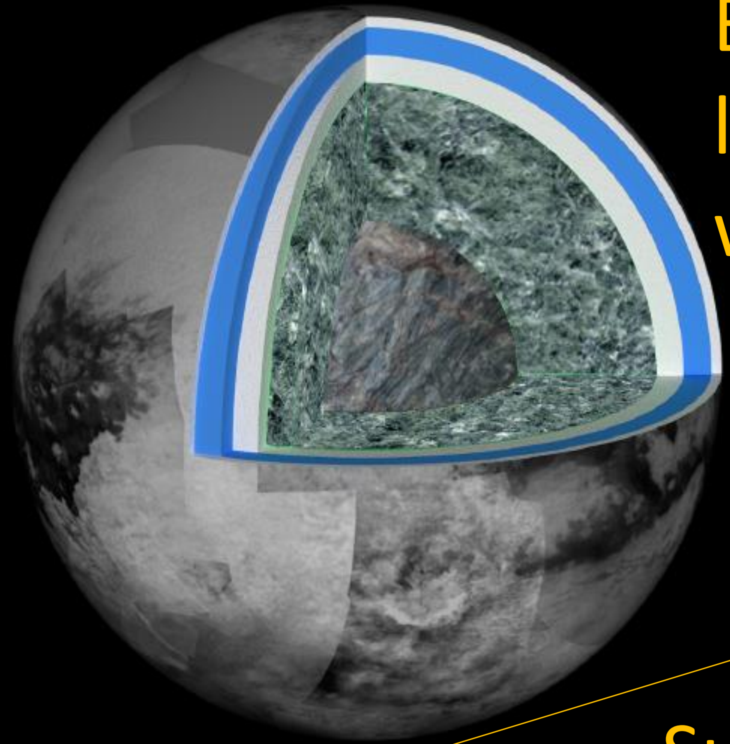
- Before Earth was a "pale blue dot" was it a pale orange dot? Early organic chemistry on the Earth's surface and in atmosphere may be playing out on Titan.
- Titan may model in methane the post-ocean hydrologic cycle of Earth's far future: Loss of methane in upper atmosphere is rapid just like water-loss on future Earth

NASA/JPL/UA

Titan's methane cycle as complex as Earth's hydrologic cycle

- Organic molecules capture energy from sunlight in upper atmosphere
- Methanogenic cycle weathers ice and organic sediment on surface
- Lakes and seas of methane, ethane…empty basins speak to a wetter past?
- Does Titan host conventional life in a water ocean and/or exotic life in the methane seas?





Beneath the surface lies an ocean of liquid water, probably salty.

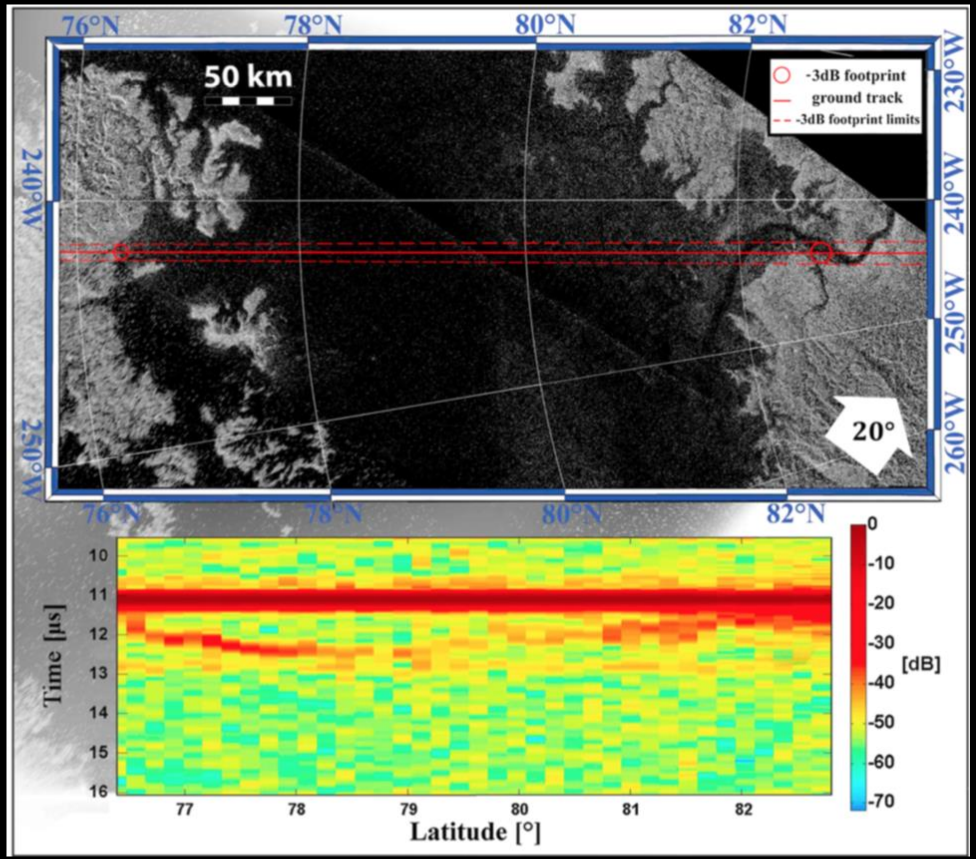
Ocean from: tidal distortion, electric field measurements.

Figure: Castillo-Rogez

Surface methane seas: we know their depth, bulk composition

Trace from nadir radar pass over Ligeia Mare.

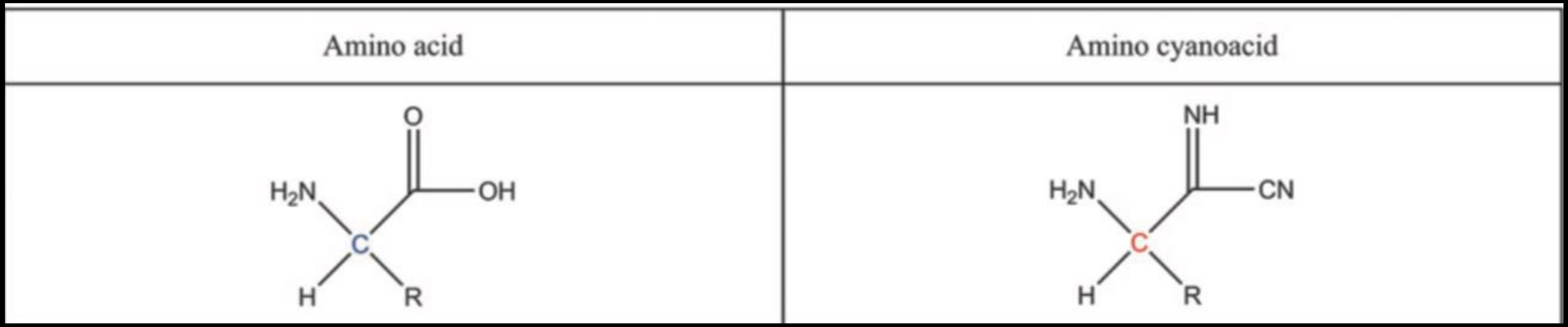
Mastrogiuseppe et al 2014



Titan: best place to look for weird biochemistry?

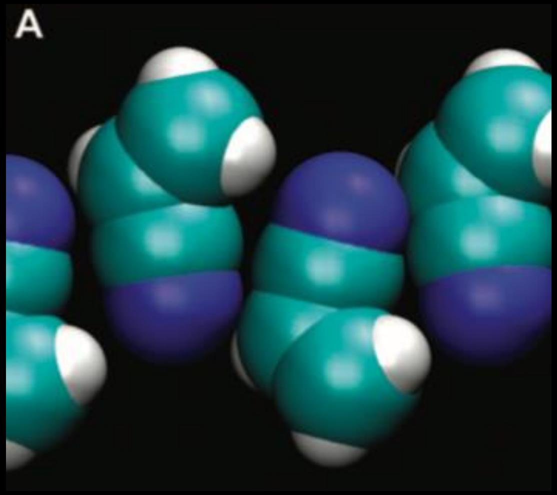
- Stable surface seas of methane etc. How far can chemical evolution proceed in such systems? Across the life “threshold”?(whatever that is)

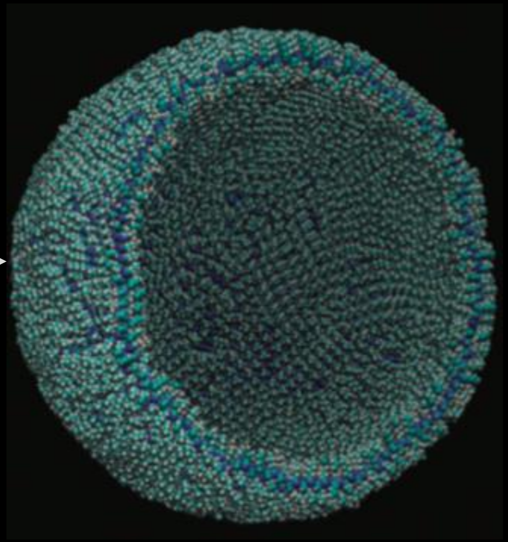
Structure/ function



Lv, Norman, and Li, 2017.

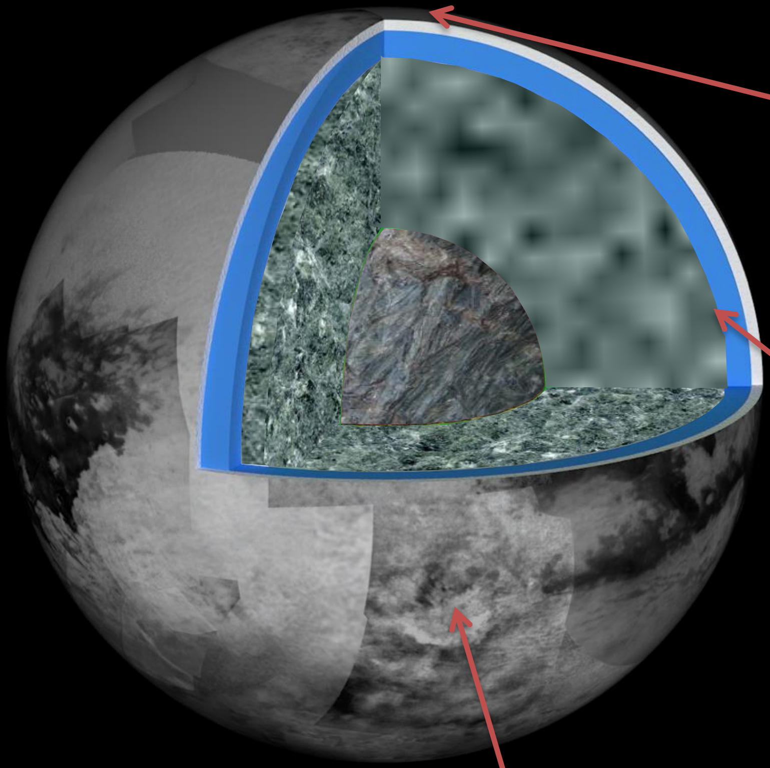
Containment

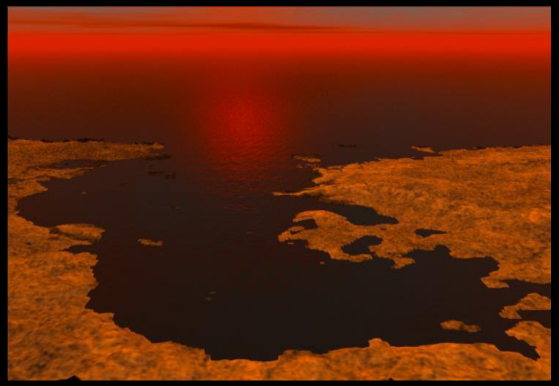




Stevenson et al, 2015.

Where to look for life on Titan?



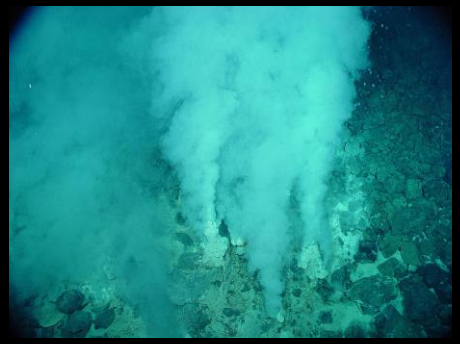


Can a form of life exist in ethane-methane instead of water?:

--totally alien biology

--strict test of life's cosmic commonality

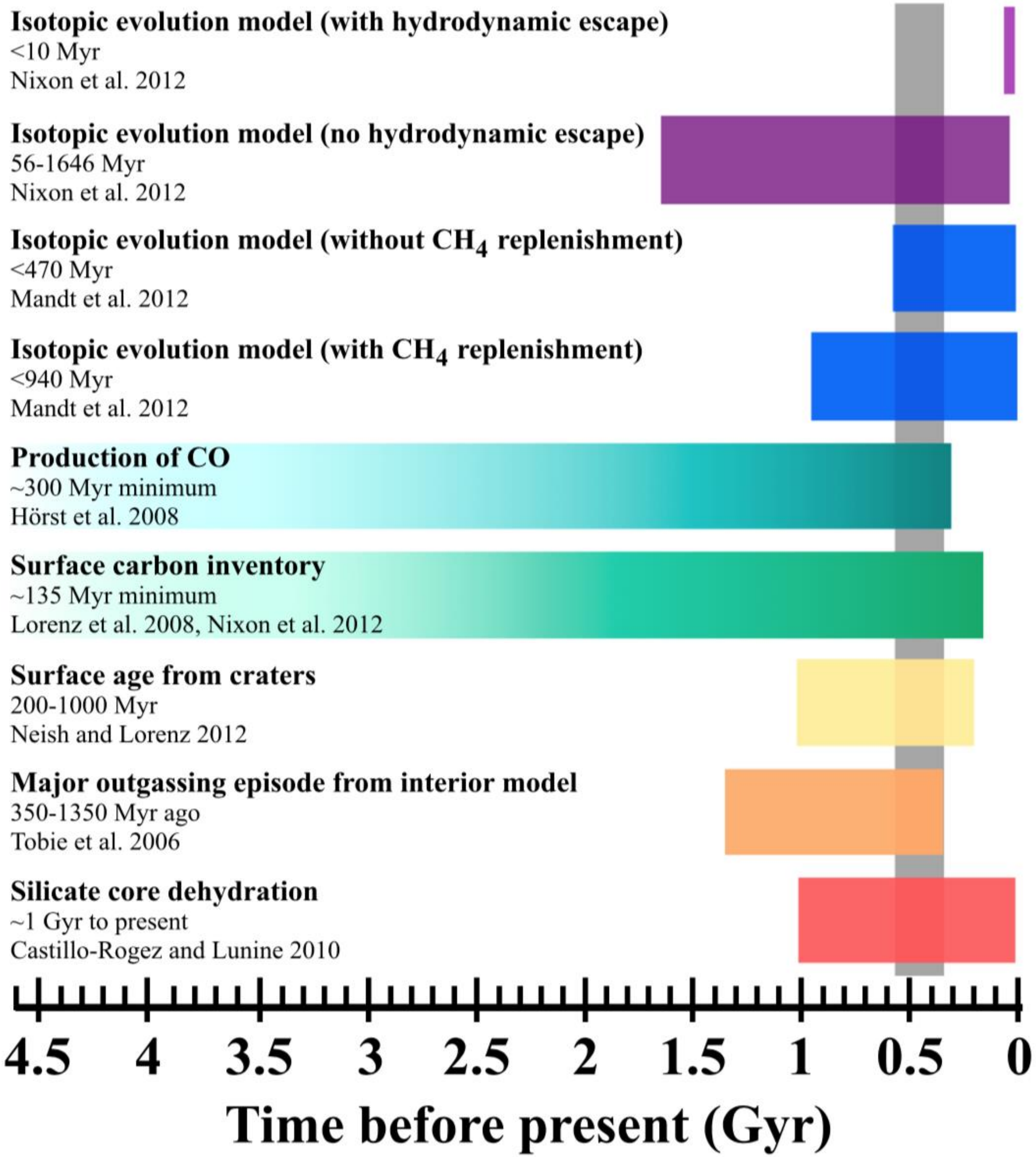
Base of the liquid water ocean: Does life as we know exist in hydrothermal vents?



Traces of the chemistry leading to life: Preserved on the surface in many places?

Constraints on the age of Titan's atmosphere from Cassini-Huygens

Hörst, S. M. (2017), Titan's atmosphere and climate, *J. Geophys. Res. Planets*, *122*, 432–482, doi:10.1002/2016JE005240.



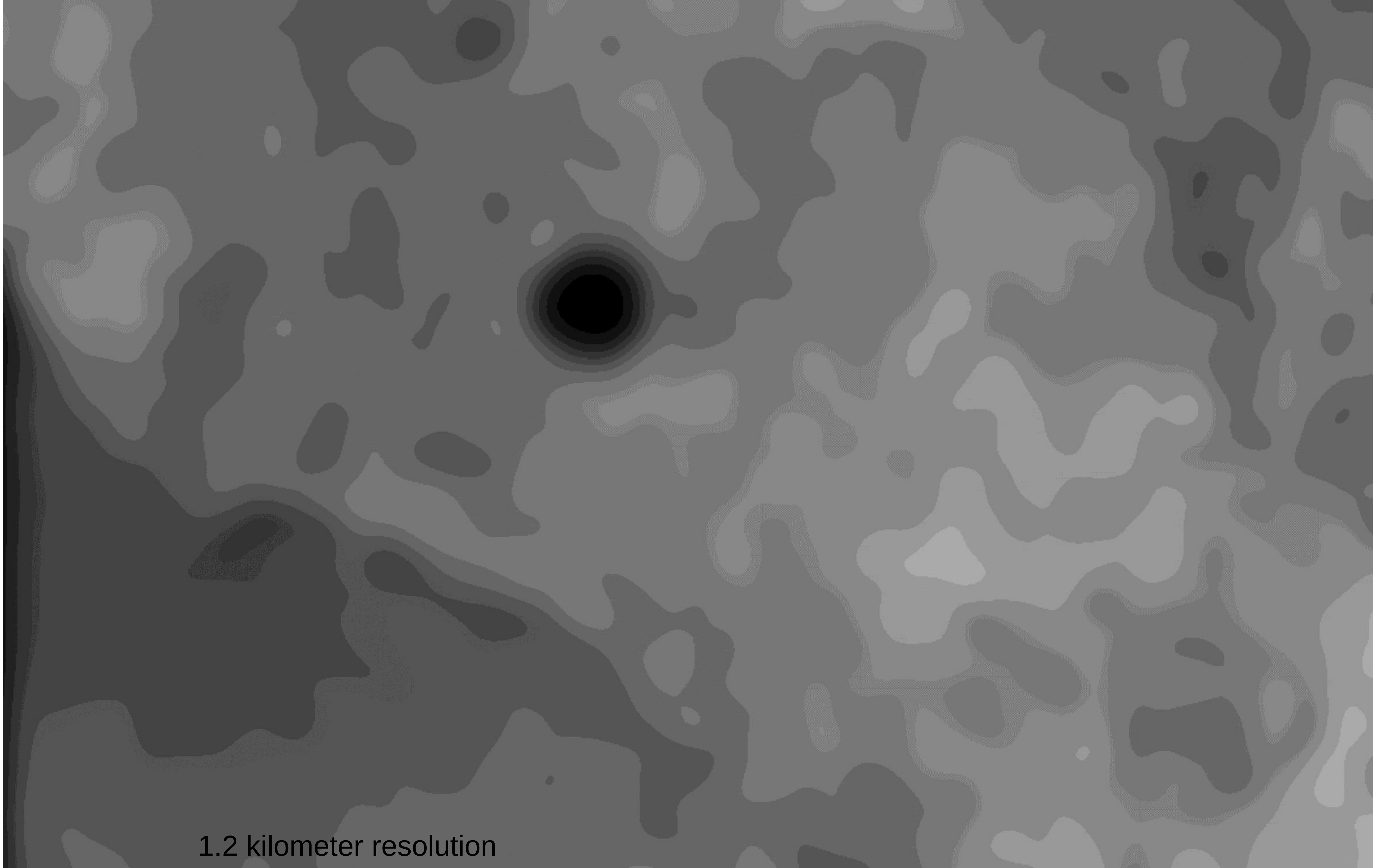
Outstanding post-Cassini questions on Titan relevant to astrobiology (adapted from Horst, 2017)

- What are the very heavy ions in the ionosphere, how do they form, and what are the implications for complexity of prebiotic chemistry?
- How do the organic compounds produced in the atmosphere evolve on the surface?
- What are the dynamics of Titan’s surface-atmosphere interactions? Fluvial erosion?
- How variable is the climate over 10^4 years and longer?
- How old is Titan’s current atmosphere and what happened on Titan 300–500 Myrs ago?
- Is Titan’s atmospheric methane episodic, and what are the implications on habitability?
- What is the origin of Titan’s methane and the fate of the photochemically produced ethane?
- What is controlling Titan’s H2 profile and potential spatial variations?
- What is the organic composition of the surface and on what scales is it spatially variable?
- What is the circulation in the lakes and seas and how is it affected by the atmosphere?
- What is the composition of the dune particles and how are they produced?
- Does cryovolcanism occur on Titan?
- What is the salinity and composition of the deep ocean and is it in contact with rock beneath?
- Is there life in the deep ocean, and some exotic “life” in the methane lakes or seas?

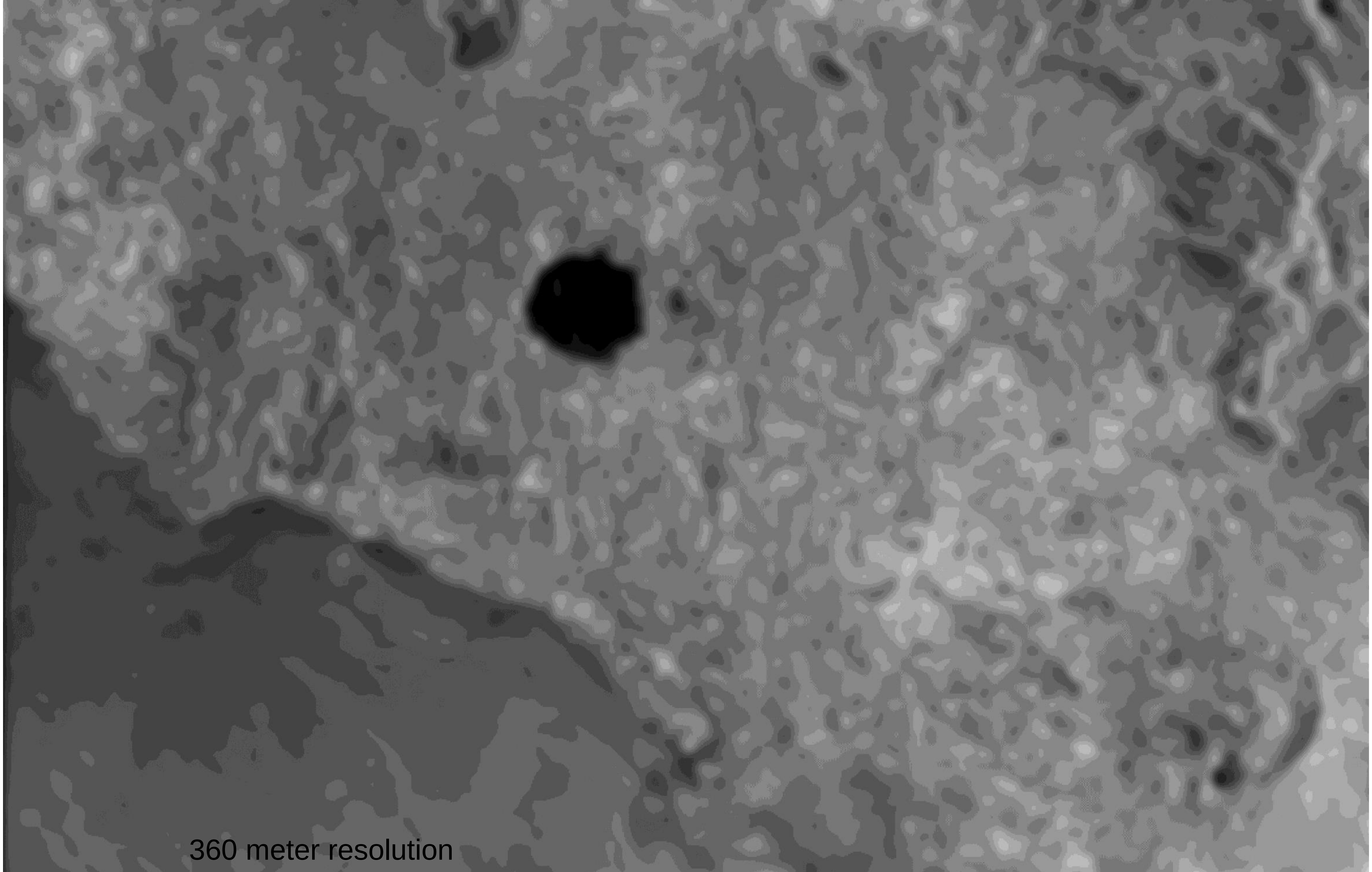
Dragonfly selected for NF Step 2

Fly a drone hundreds of km in steps to map and sample Titan's surface.

E. Turtle, PI (APL)



1.2 kilometer resolution



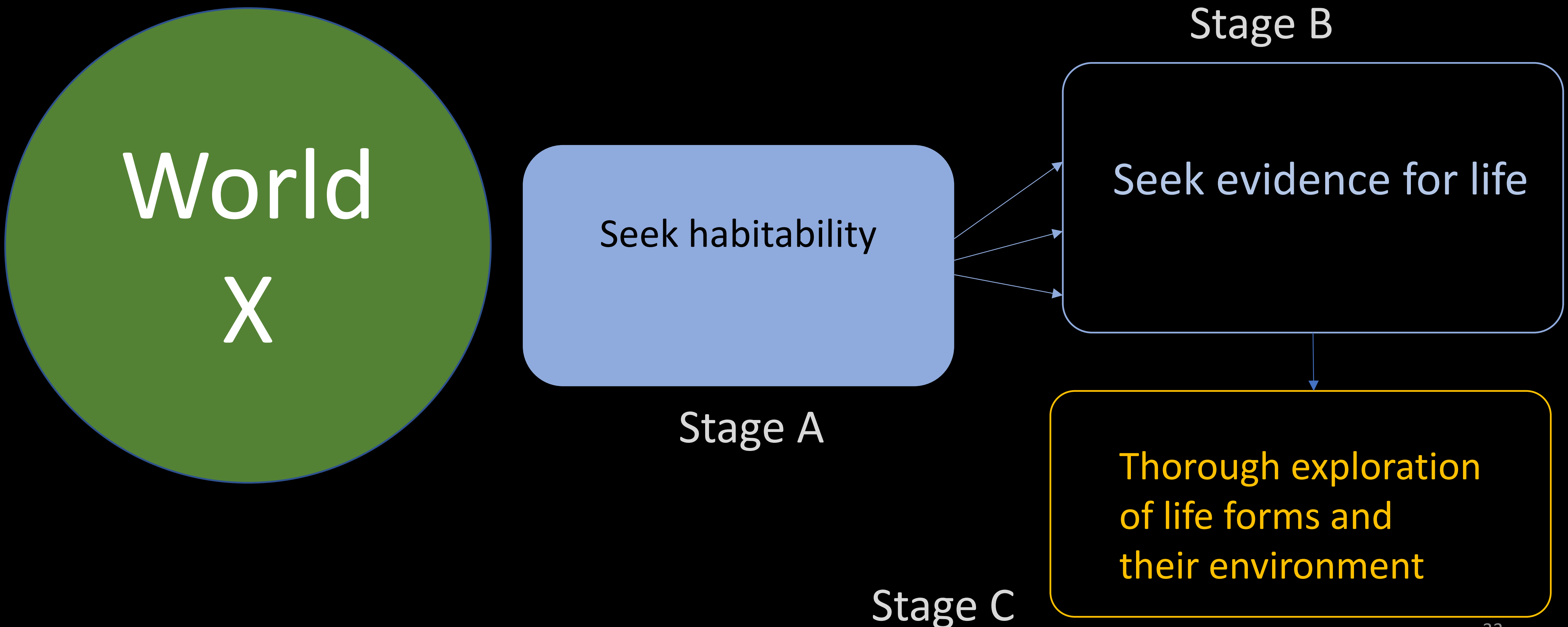
360 meter resolution

12 meter resolution

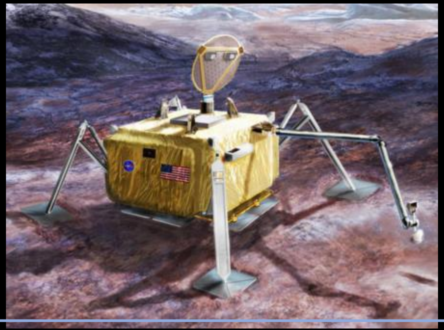
Steps to find and understand life elsewhere

1. Find liquid water (or some other liquid) (Stage 0)
2. Quantify the habitability of the environment (Stage A)
3. Detect biosignatures (Stage B)
4. Confirm life is present and understand its biochemistry (Stage C)

Ocean world X program in three stages



A Europa program



- Europa Clipper for ocean habitability, crustal thickness and properties, site selection

Land at ocean-surface exchange zone

Subsurface access to pursue fresher material

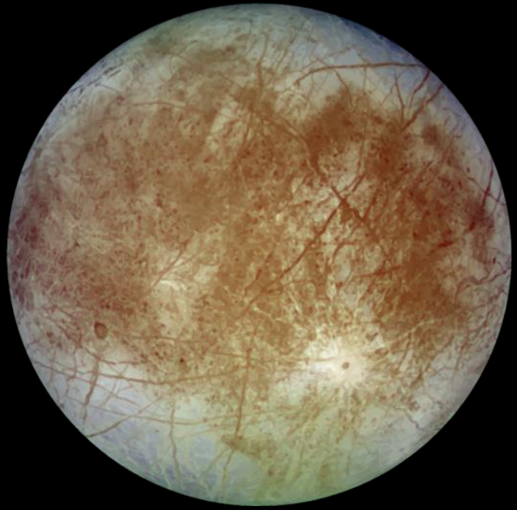
Selection of trench sites around lander

Repeat with surface mobility if necessary

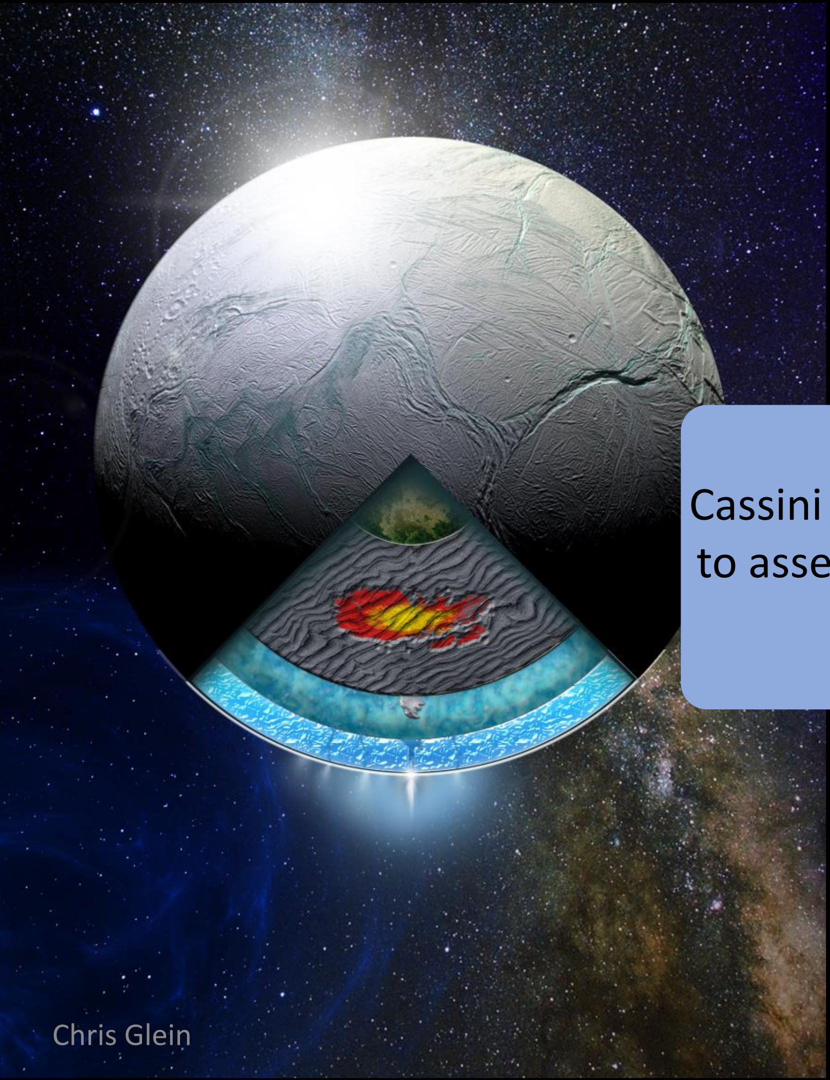
Trans-shell probe into ocean, sample return

Under-ice exploration of ocean ceiling

Open ocean exploration, including seafloor



An Enceladus program



Cassini penetrations of the plume to assess basic habitability of the ocean.

- Plume penetrations to detect molecular signatures of life and complete habitability assessment
- As above but with wet chemistry and attempted cell collection
- Collection, preservation, and return of samples

- ‘Downhole’ access to the foaming interface
- Under-ice exploration of ocean ceiling
- Open ocean exploration, including seafloor hydrothermal systems known to exist

A Titan program

Reconnaissance of a complex world

- Global hi-res surface mapping
- Remote sense subsurface
- Sample surface organic chem.

Buoyant sea exploration for biosignatures

Drilling at selected sites for biosignatures

Sampling of sites of past aqueous chemistry

Submarine exploration of methane sea bottom

Through-crust ocean access

Sample return?

Status of ocean worlds exploration

	Stage A Habitability	Stage B Biosignatures	Stage C Discover life
Europa	Europa Clipper	Europa Lander	
Enceladus	Cassini (complete)	ELSAH/ELF*	
Titan	Dragonfly	TiME	

Schedule for this NF

• Selection for Phase A	2017
• Selection for flight	2019
• Launch	2024
• Arrival at Saturn	2034
• Science complete	2036

Schedule for next NF

• Selection for Phase A	2022
• Selection for flight	2023
• Launch	2028
• Arrival at Saturn	2038
• Pump down complete	2039-2041
• Science complete	2041-2043

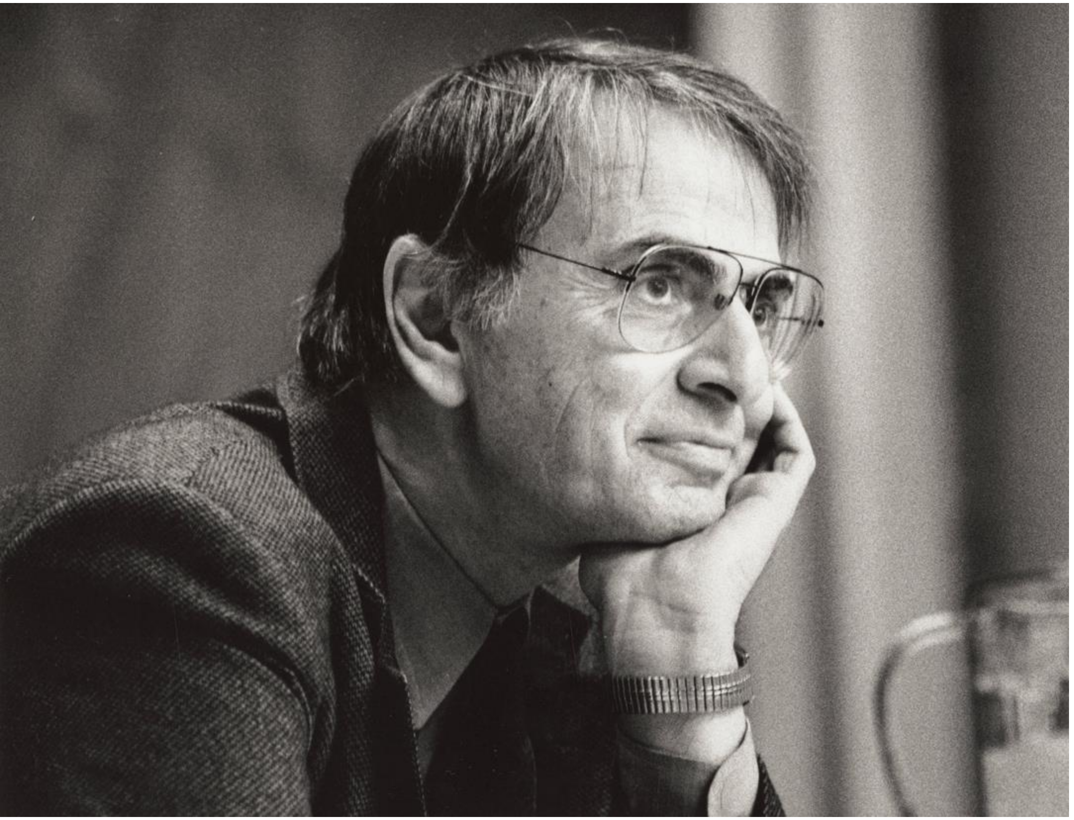
Gaps in the exploration of the ocean worlds of Jupiter and Saturn

Mission	Science years	Gap (years)
• Pioneer 10/11	1973, 1974, 1979	
• Voyagers 1&2	1979, 1980-1 (1986/89)	0
• Galileo	1995-2003	14 (6 from VN)
• Cassini	2000, 2004-2017	0-1
• Europa Clipper	2025-2028 to 2030-2033	8-13
• Europa Lander	~2032	0-4
• Dragonfly	2034-	1-6
• Enceladus plume mission	2039/2041-	6-13 (EC), 5-9 (Df/EL)

Some closing thoughts on exploring the ocean worlds

- Finding alien microbial life in the solar system will have impacts that are scientific, philosophical, economic, agricultural and medical.
- Trying to explore all ocean worlds for habitability before searching for life is not an optimal strategy given budgetary and flight time constraints. In practice, planned missions will do a good job anyway:
  - **Mars** exploration continues at a vigorous pace
  - Dawn extended mission at **Ceres**.
  - Jupiter Icy Moons Explorer being developed by ESA: **Ganymede** and **Callisto**.
  - Ice giants are a high priority in current Decadal—choose Neptune so as to explore **Triton**.
- Relying on New Frontiers and/or Discovery to carry out a strategic plan is risky because the missions are not necessarily designed to optimally address scientific objectives and there is little community participation in ensuring that they do so.
- Next Decadal Survey MUST build astrobiological goals (habitability, life-search) into the strategy in a robust and coherent fashion.
- Next decadal survey should explicitly recognize ocean worlds as a class of solar system targets, with Europa, Titan and Mars deserving of especial attention.
  - Consider a coherent strategy for Europa (Europa Clipper + Europa Lander).
  - Consider a directed mission (NF or flagship class) to Enceladus and Titan

“By and large, scientists’ minds are open when exploring new worlds. If we knew beforehand what we’d find, it would be unnecessary to go. In future missions to Mars or to the other fascinating worlds in our neck of the cosmic woods, surprises—even some of mythic proportions—are possible, maybe even likely.



But we humans have a talent for deceiving ourselves. Skepticism must be a component of the explorer’s toolkit, or we will lose our way. There are wonders enough out there without our inventing any.”

Carl Sagan, *The Demon-Haunted World*, 1996.