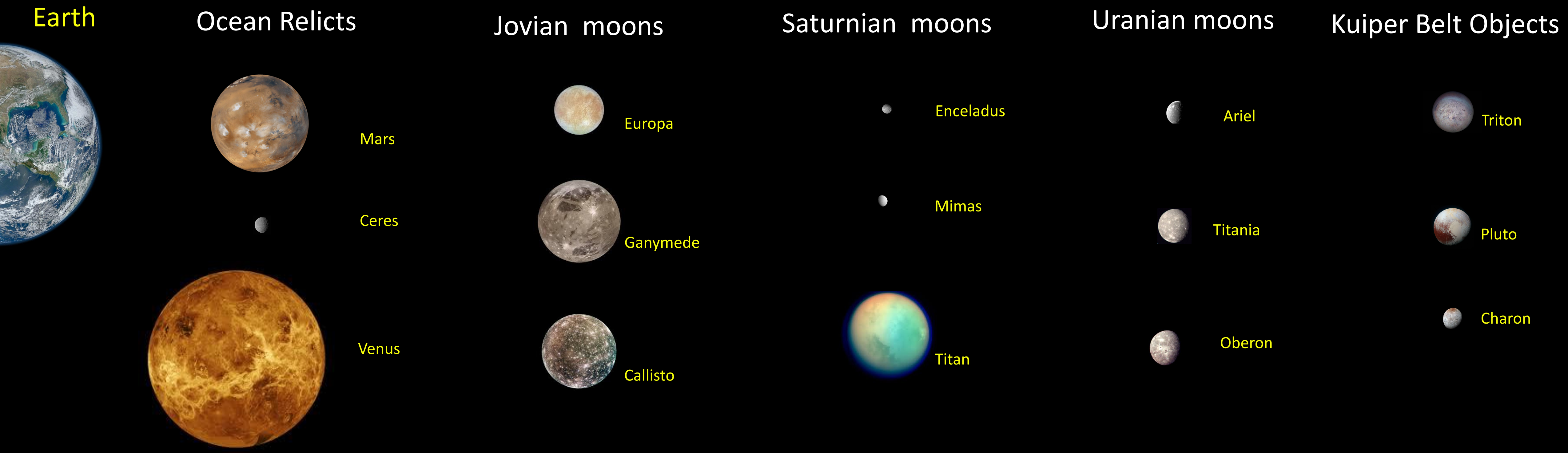
Ocean Worlds and Habitability

Jonathan I
Lunine

- The criteria for habitability, and which are particular to ocean worlds
- The key types of measurements required to establish habitability
- Results obtained at Enceladus by Cassini
- Planned Europa Clipper observations directly relevant to the habitability of Europa.
- The value of sample return for assessing the habitability of these objects.

Ocean worlds= bodies with substantial liquid water on their surfaces or within their interiors



Habitable = can sustain

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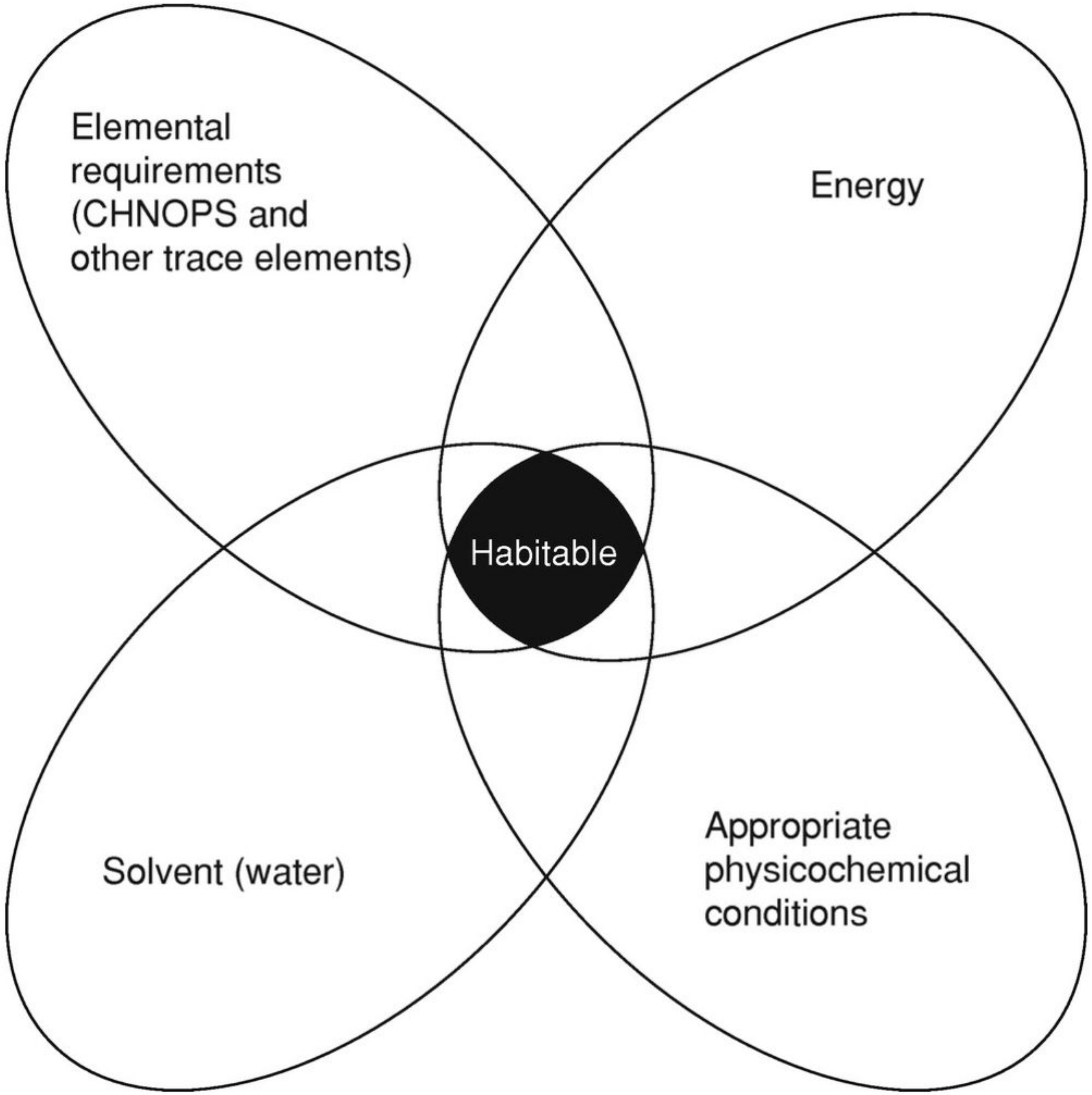
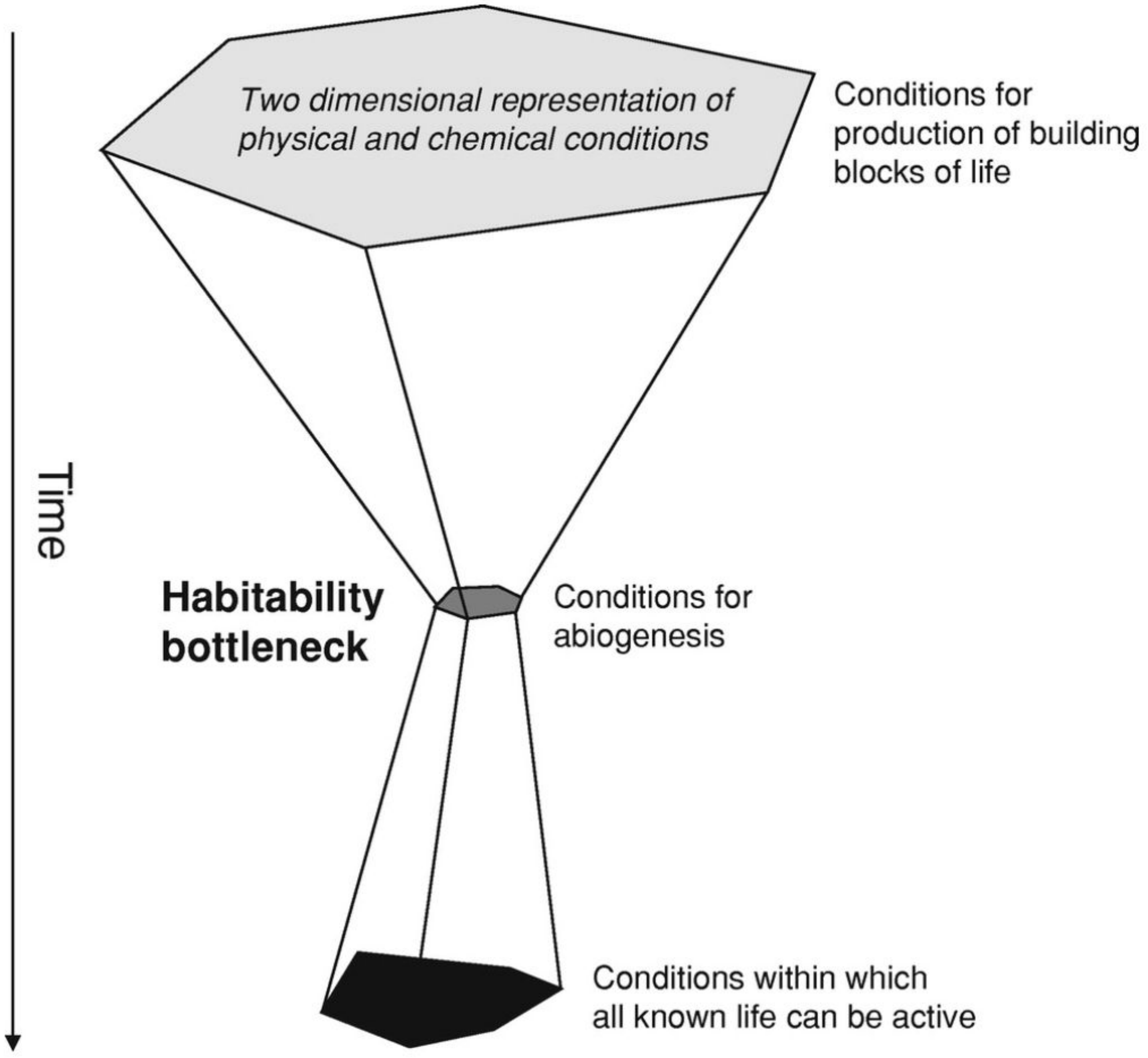
Habitability requires that three or four general conditions be met.



Cockell et al 2016, Astrobiology

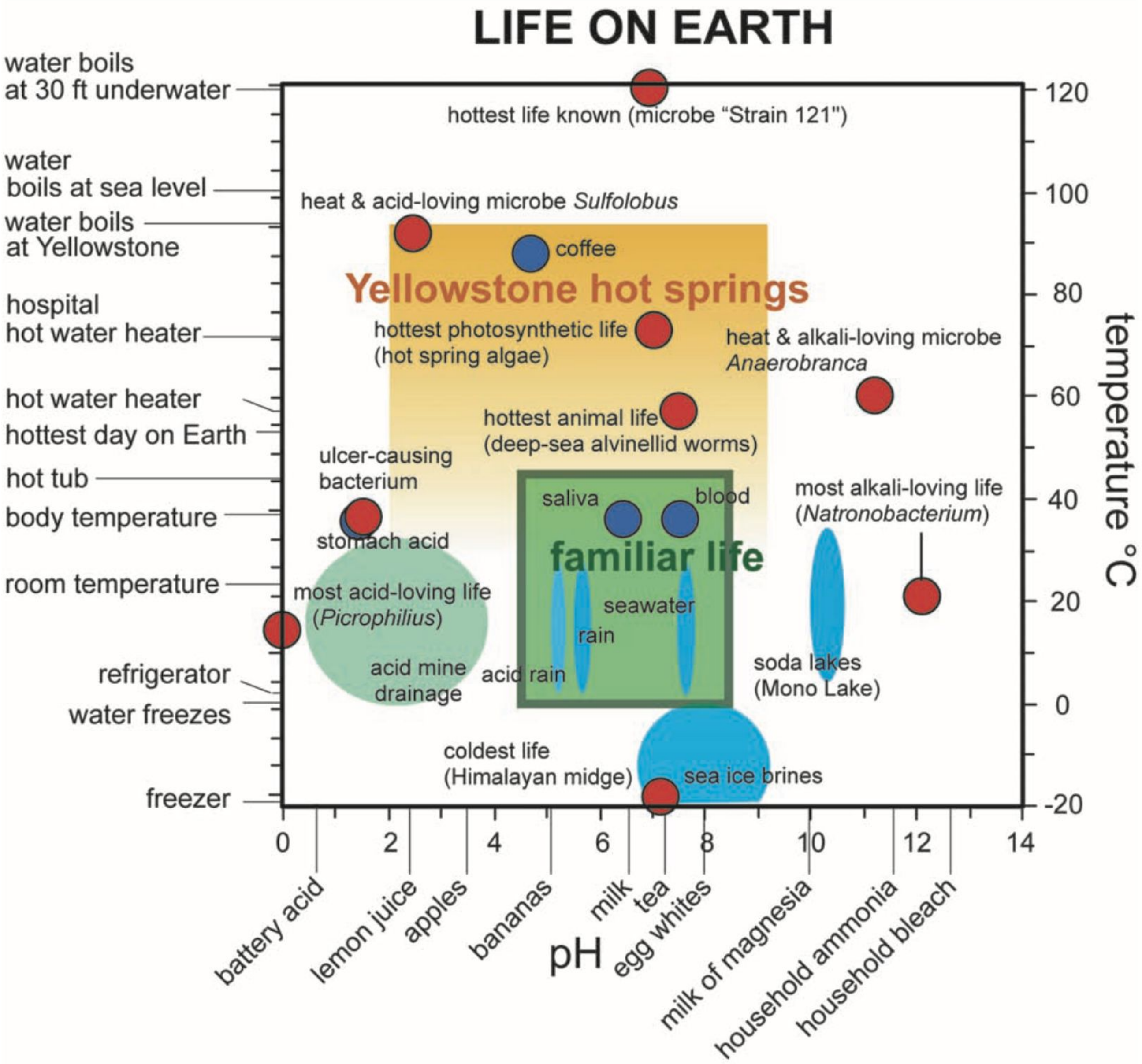
The conditions under which life is formed from non-living chemistry are likely more stringent than those for habitability…

This implies that some CPH environments may be found to be sterile (no life)



Cockell et al 2016, Astrobiology

The limits of habitability (IH and CPH) depend on the organism….



Shock and Holland, 2007
Astrobiology v. 7

TABLE 4. A PLANETARY HABITABILITY TABLE FOR ENCELADUS UPDATED FROM COCKELL ET AL, 2016

Requirement			*Comments and references*
Liquid water	Present in subsurface ocean		Numerous Cassini references
Main elements			
C	CO, CO_2, carbonic acid, methane, organics		Waite *et al.*, 2009 Postberg et al 2016
H	H_2, ^2H, H_2O, organics		Waite *et al.*, 2009, 2017
N	N_2, ammonia, HCN (hydrogen cyanide)		Waite *et al.*, 2009
O	H_2O, CO, CO_2, CH_3OH, C_2H_4O, C_2H_6O		Waite *et al.*, 2009
P	$[PO_4^{3-}] + [HPO_4^{2-}] + [H_2PO_4^{-}]$		Postberg et al 2023
S	H_2S?		Waite *et al.*, 2009
Other elements	Na, K		Postberg *et al.*, 2009
Energy—full redox couples	***Electron donor***	***Electron acceptor***	
Chemolithotrophy			
Methanogenesis, acetogenesis	H_2	CO_2	
Chemoorganotrophy			
Sulfate reduction	Organics	SO_4^{2-}	Organics expected from meteoritic input
Other forms of energy	Photosynthesis unlikely in ocean as ice layer expected to block all light. Fermentation with organics may be possible. The presence of hydrogen and organics raises the possibility of sulfate and iron reduction if these ions are available.		

Inventory of requirements for habitability in Enceladus (note that this table does not indicate whether the requirements for life are colocalized in any given environment for life). For energy sources, redox couple only shown if there is unequivocal evidence for both half reactions or for one half reaction and strong evidence or likelihood of the other.

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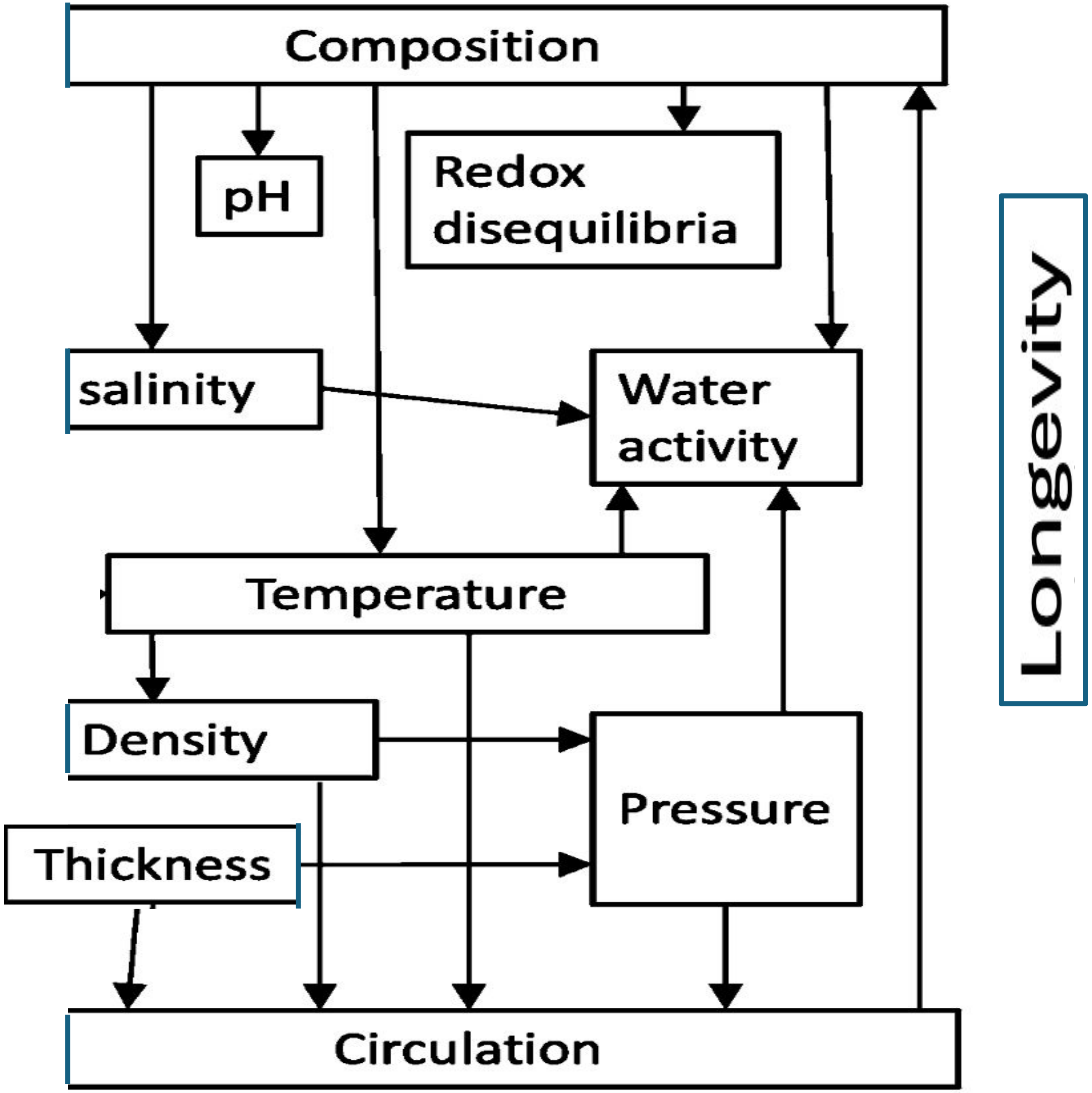
Types of measurements:

Geophysical

Chemical

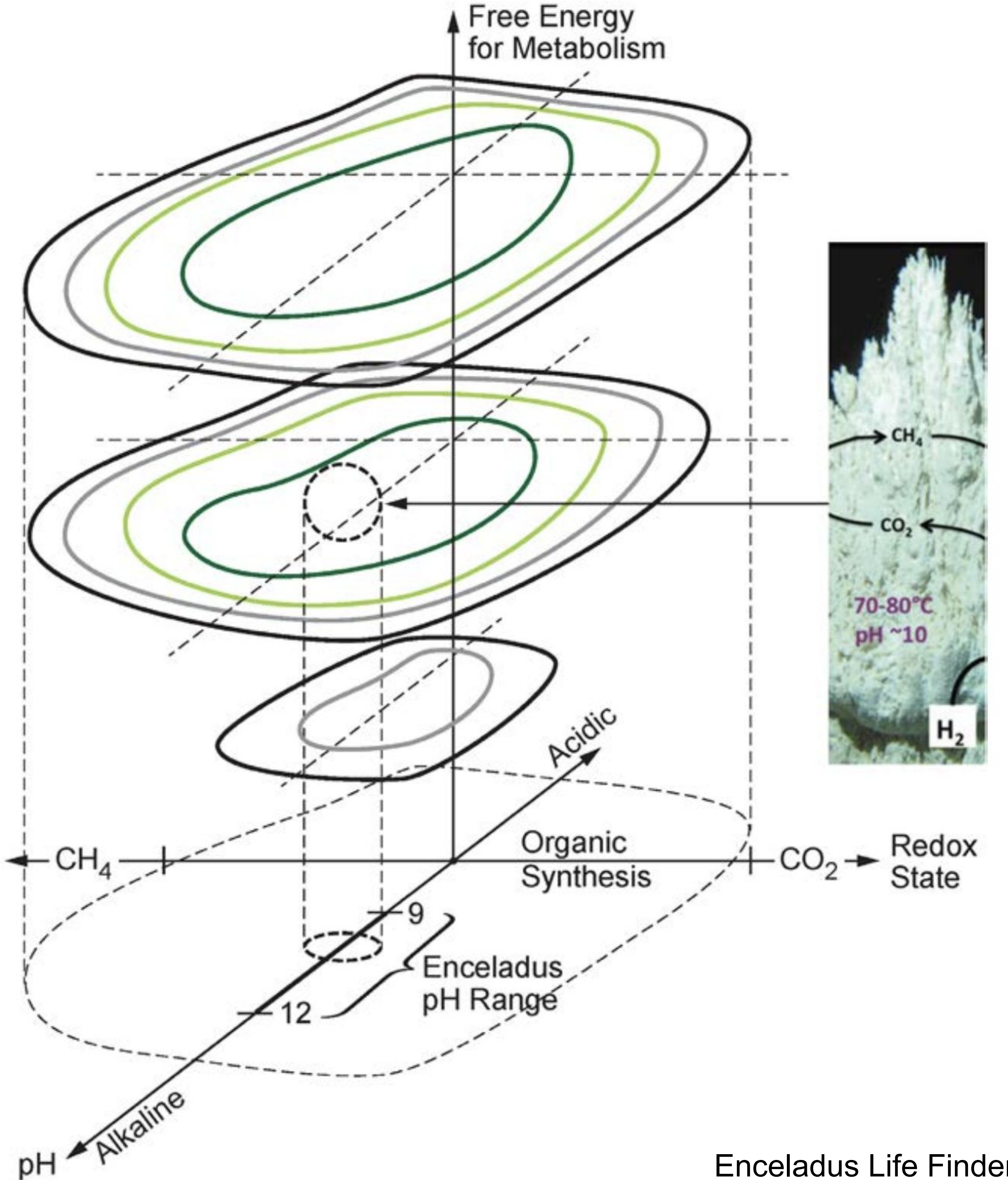
Isotopic

Electromagnetic



Modified from Vance et al

A slice of multi-dimensional habitability space, for Enceladus



Enceladus Life Finder Disco

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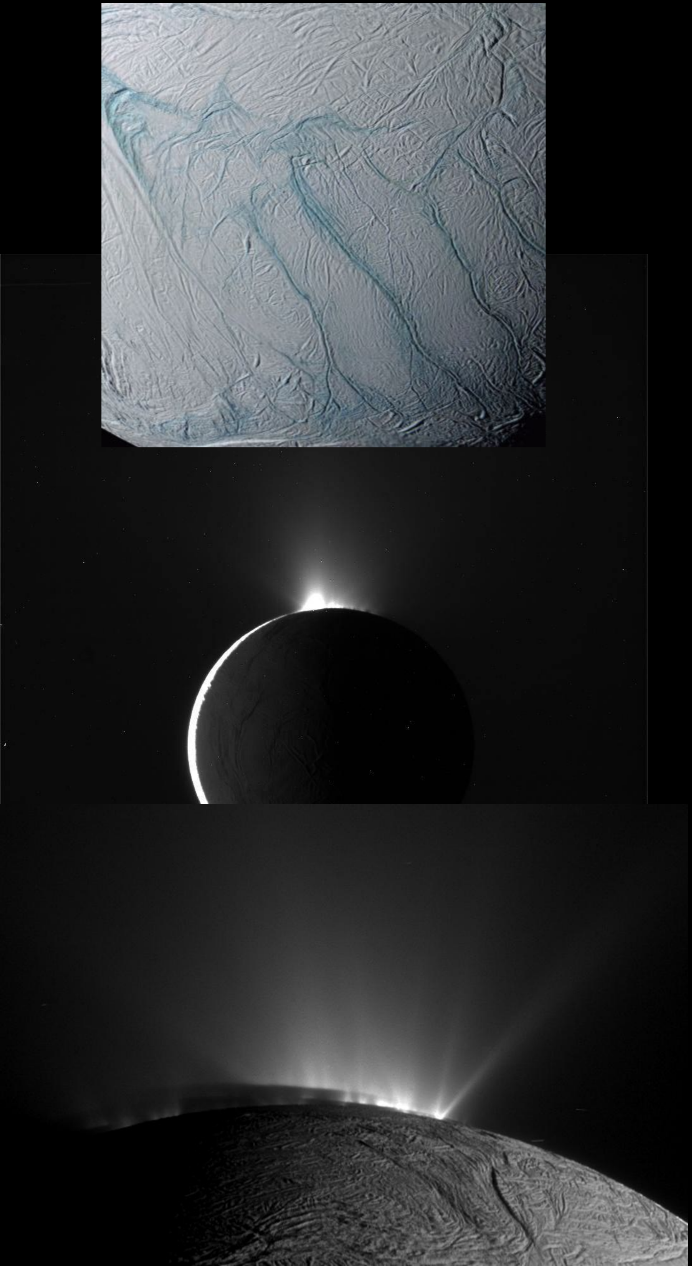
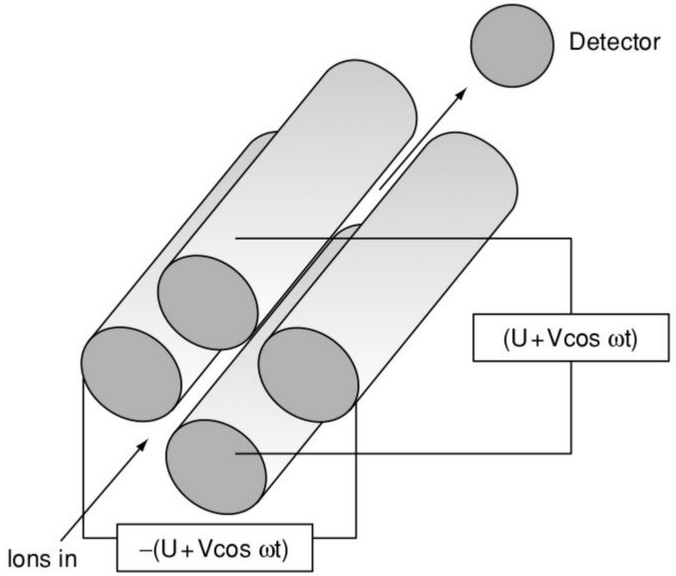
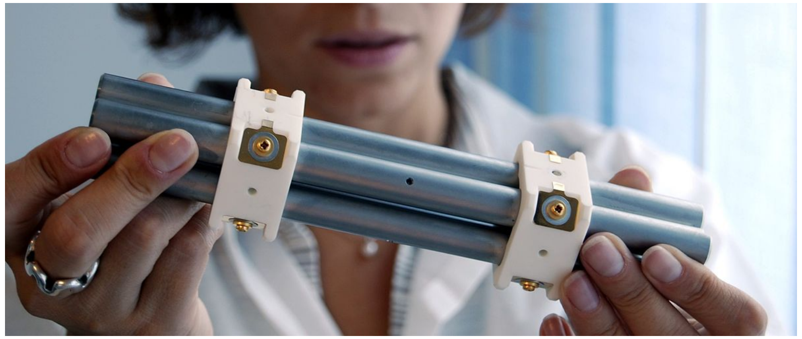
Saturn’s moon Enceladus: easiest to explore; most known about the ocean



Mass spectrometers separate species by mass

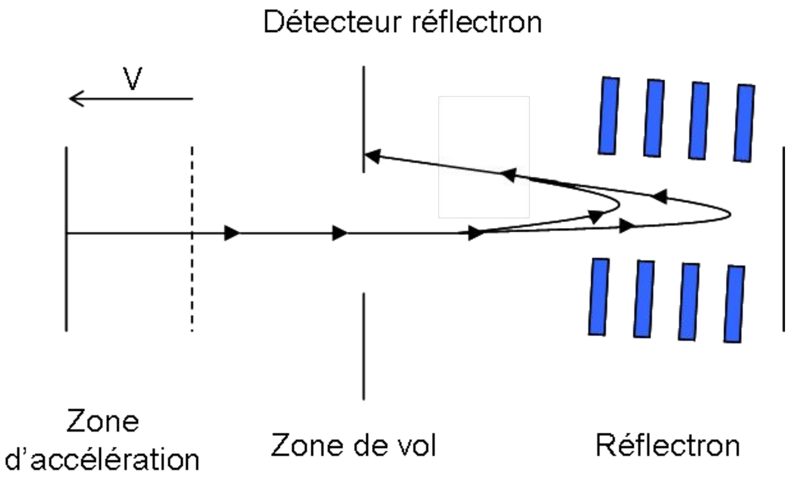
Quadrupole mass spectrometer





"The quadrupole mass analyzer acts as a mass filter, allowing one mass channel at a time to reach the detector as the mass range is scanned. " Mellon, 2003

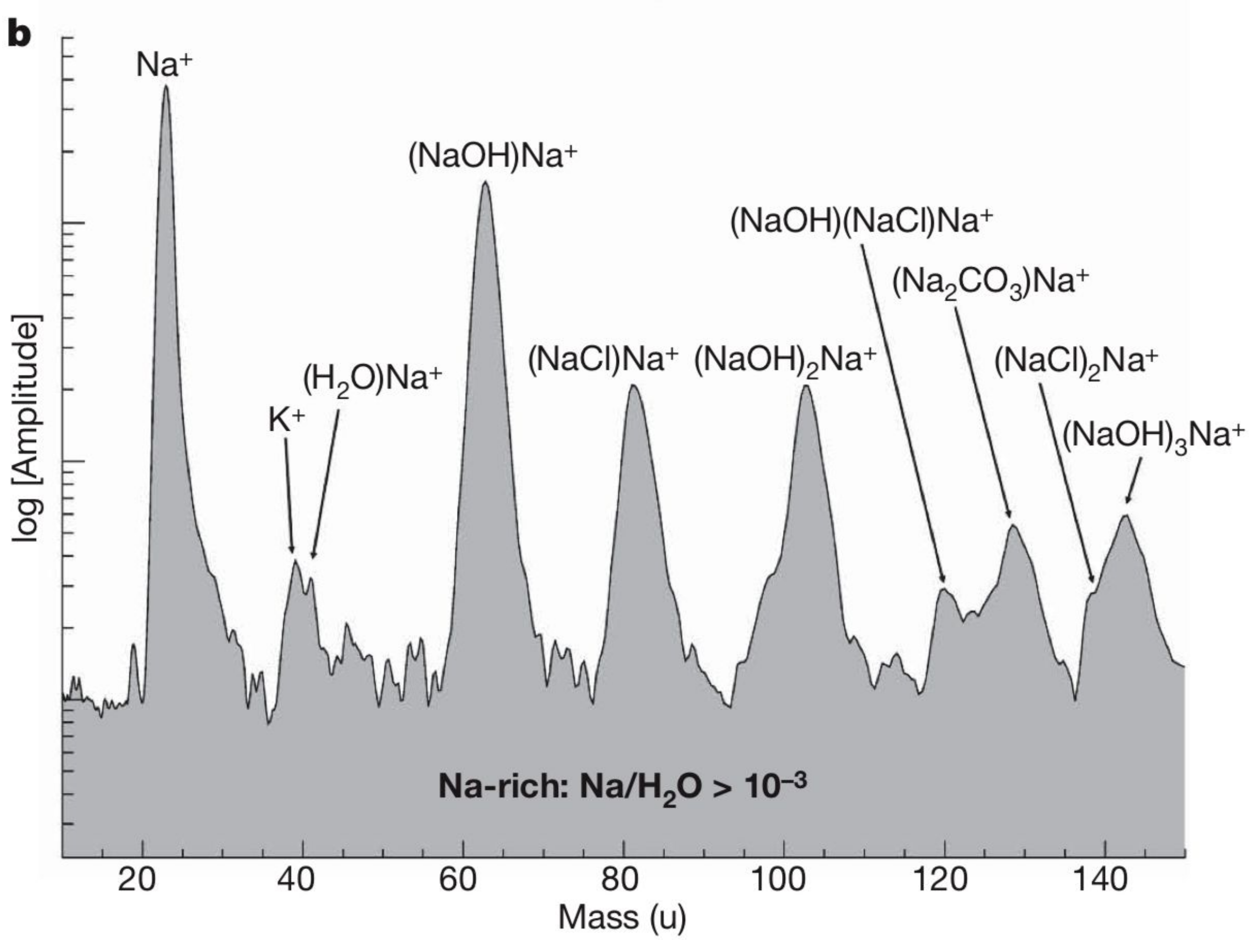
Time of flight mass spectrometer



Enceladu
s

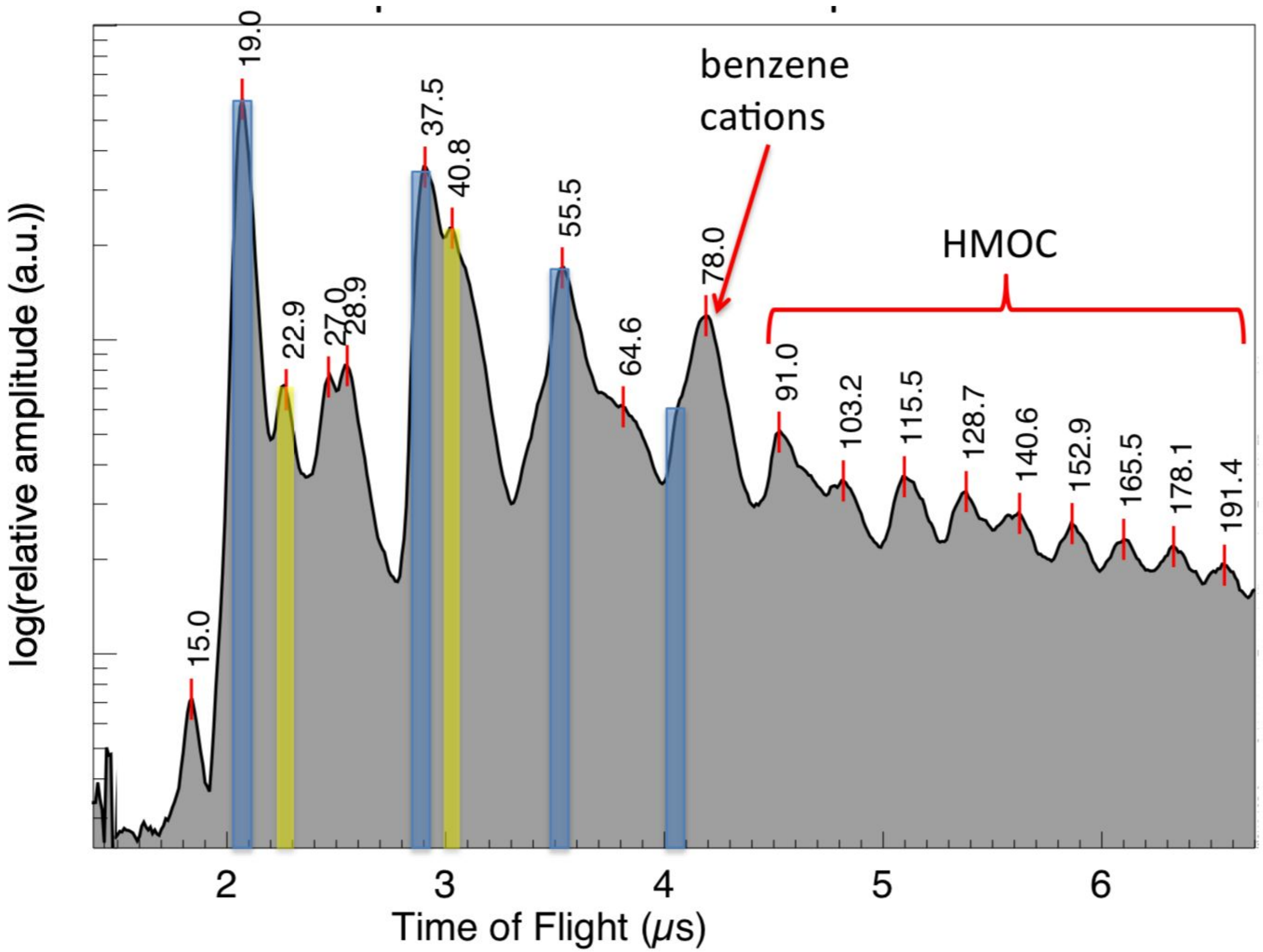
<u>Evidence for an ocean beneath the ice crust</u>

- Large ice grains (CDA) are salty and hence are flash-frozen liquid water (Postberg et al 2011).
- Fitting the mass distribution provided by gravity data (+ structure models + hydrostatic eq. + rotation) global ocean (McKinnon, 2015, GRL)
- Imaging (ISS of a rocking (libration) of Enceladus seem to requires that the crust slides back and forth over a frictionless layer (Thomas et al, 2015)
- Fractures (CIRS) are much hotter than the surface

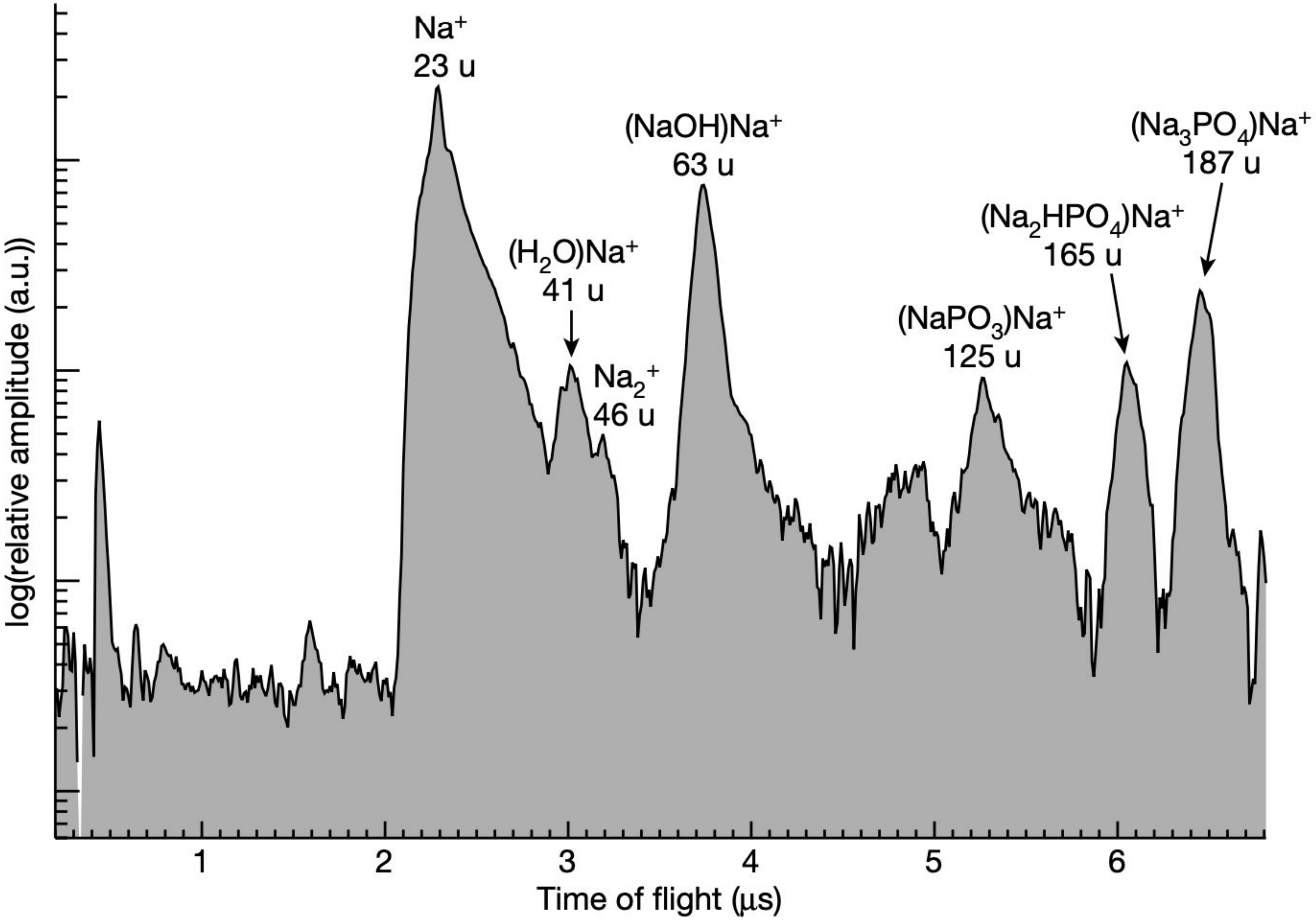


Cassini CDA spectra Postberg et al 2011

There are organics in the Enceladus ocean, but their identity is not known

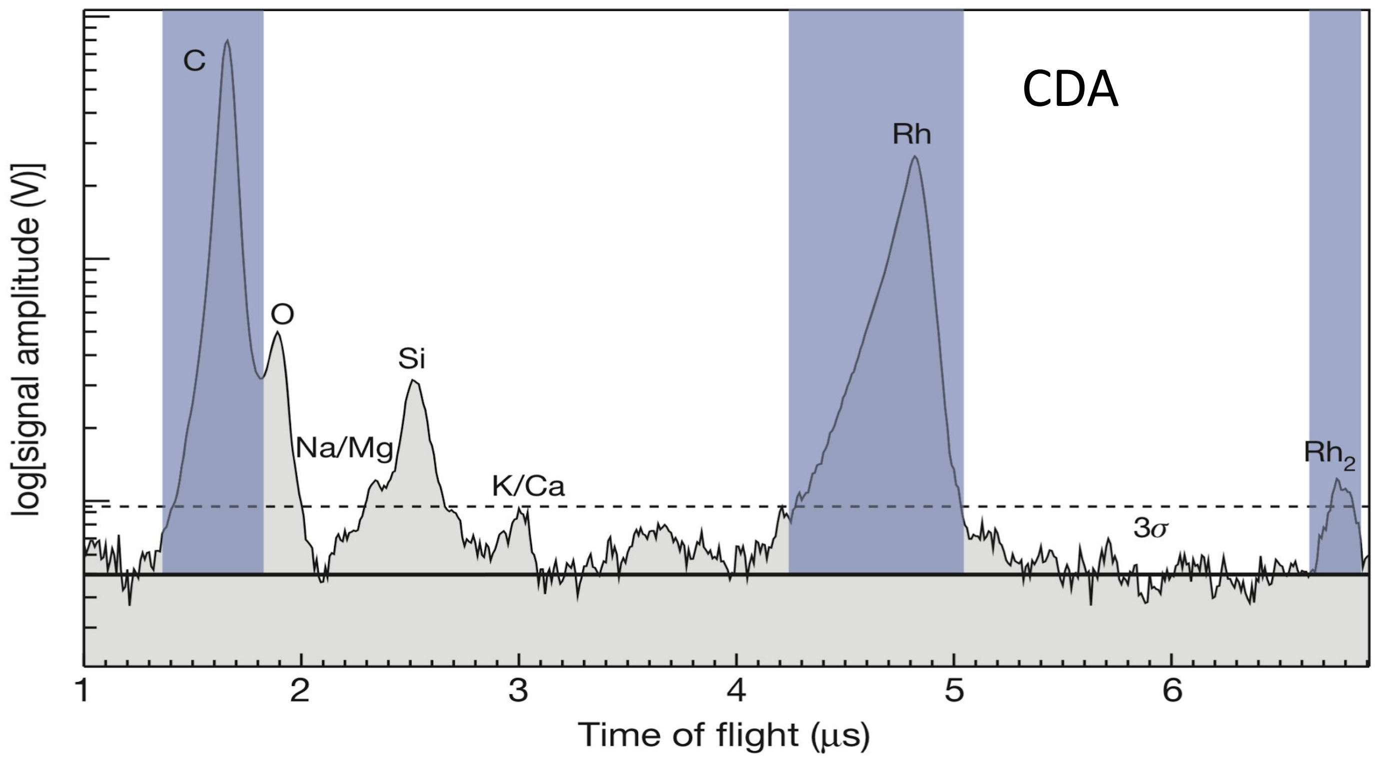


A small number of grains analyzed by CDA mass spectrometer contain phosphates



Postberg et al 2023

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.



$$\underset{\text{Fayalite}}{3\ Fe_2SiO_4} + \underset{\text{water}}{2\ H_2O} \rightarrow \underset{\text{magnetite}}{2\ Fe_3O_4} + \underset{\text{aqueous silica}}{3\ SiO_2} + \underset{\text{hydrogen}}{2\ H_2}$$

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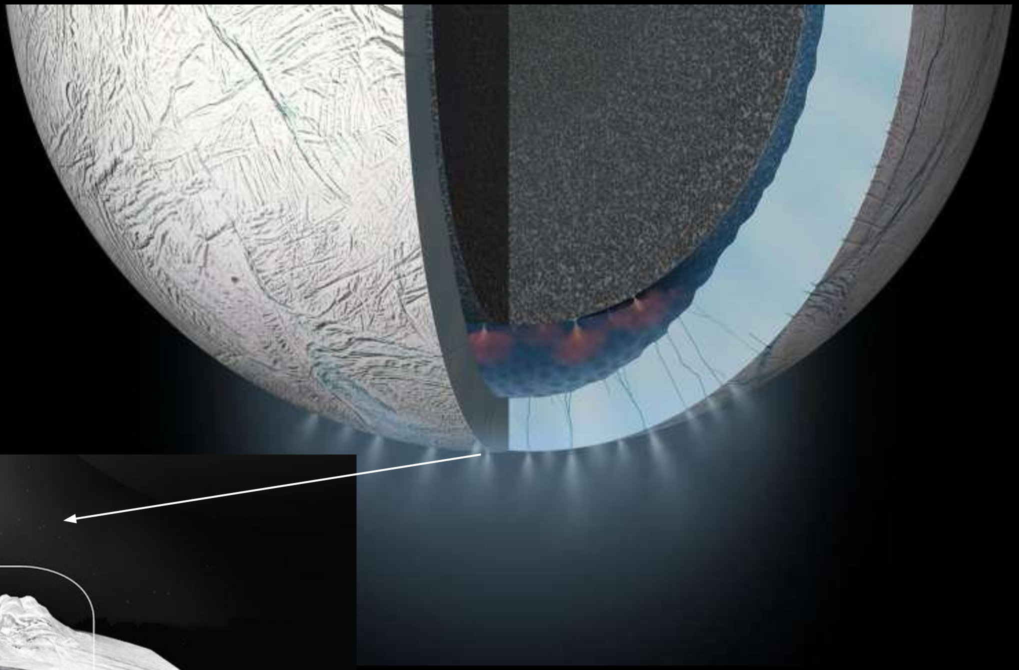
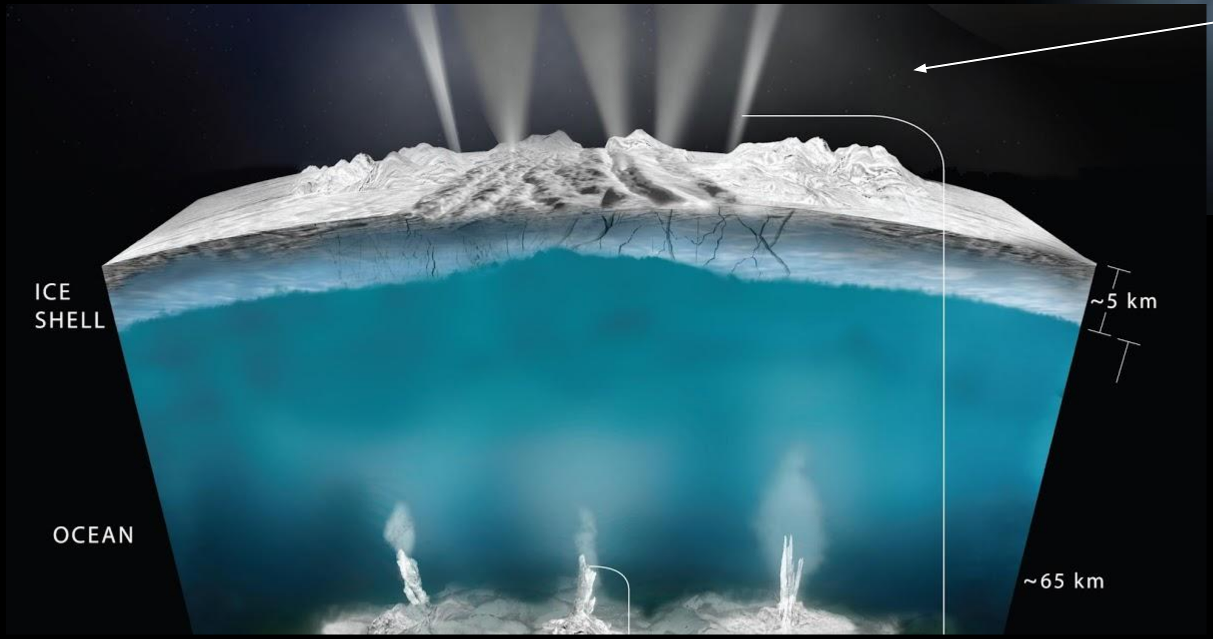




NASA/JPL-Caltech/SWRI

Is methane a metabolic product? $CO_2 + 4H_2 <\square\ CH_4 + 2H_2O$

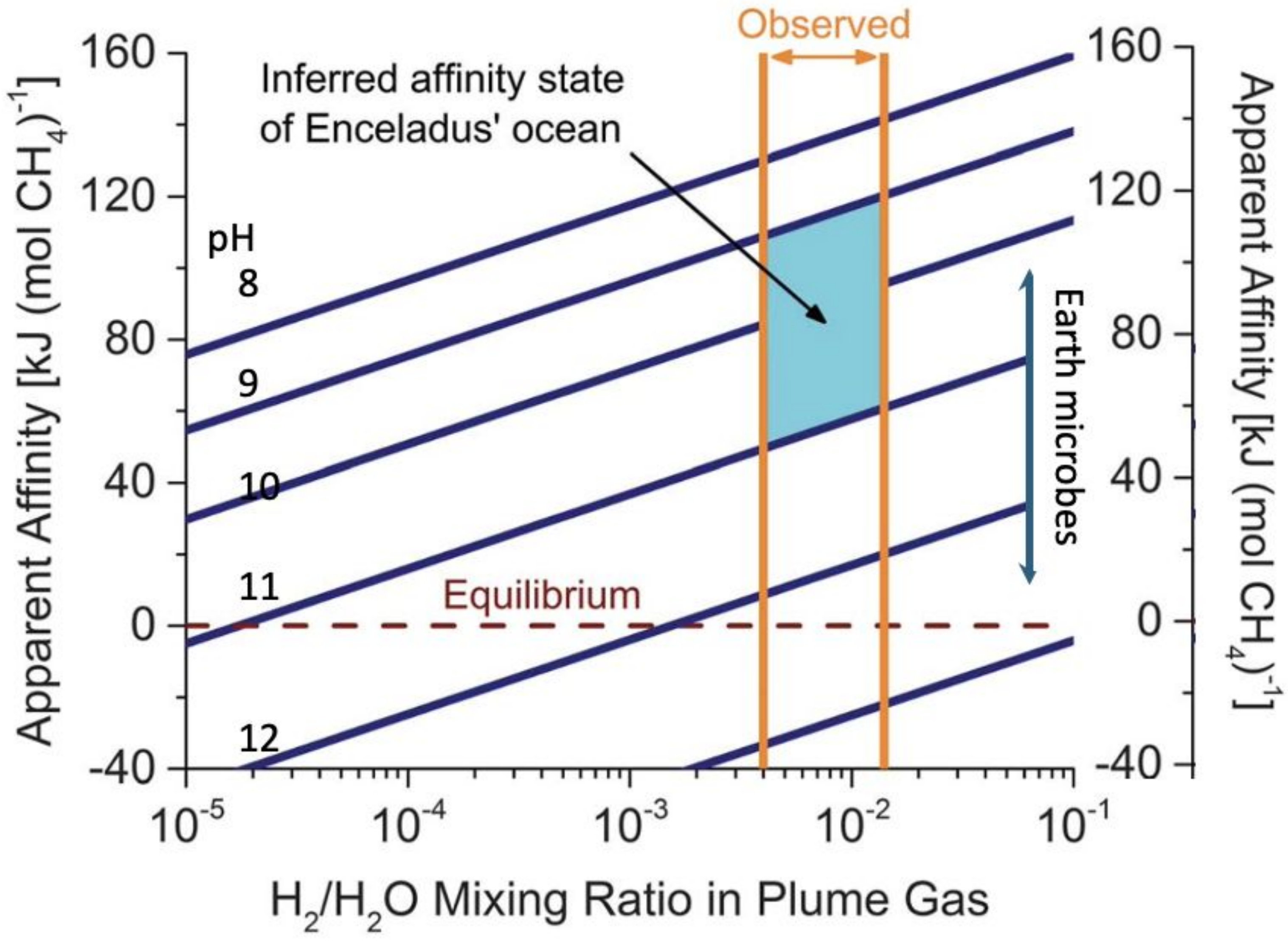


Fig by Chris Glein, SWRi , from Waite et al 2017; Earth microbes from T.M. Hoehler, 2022 Nature

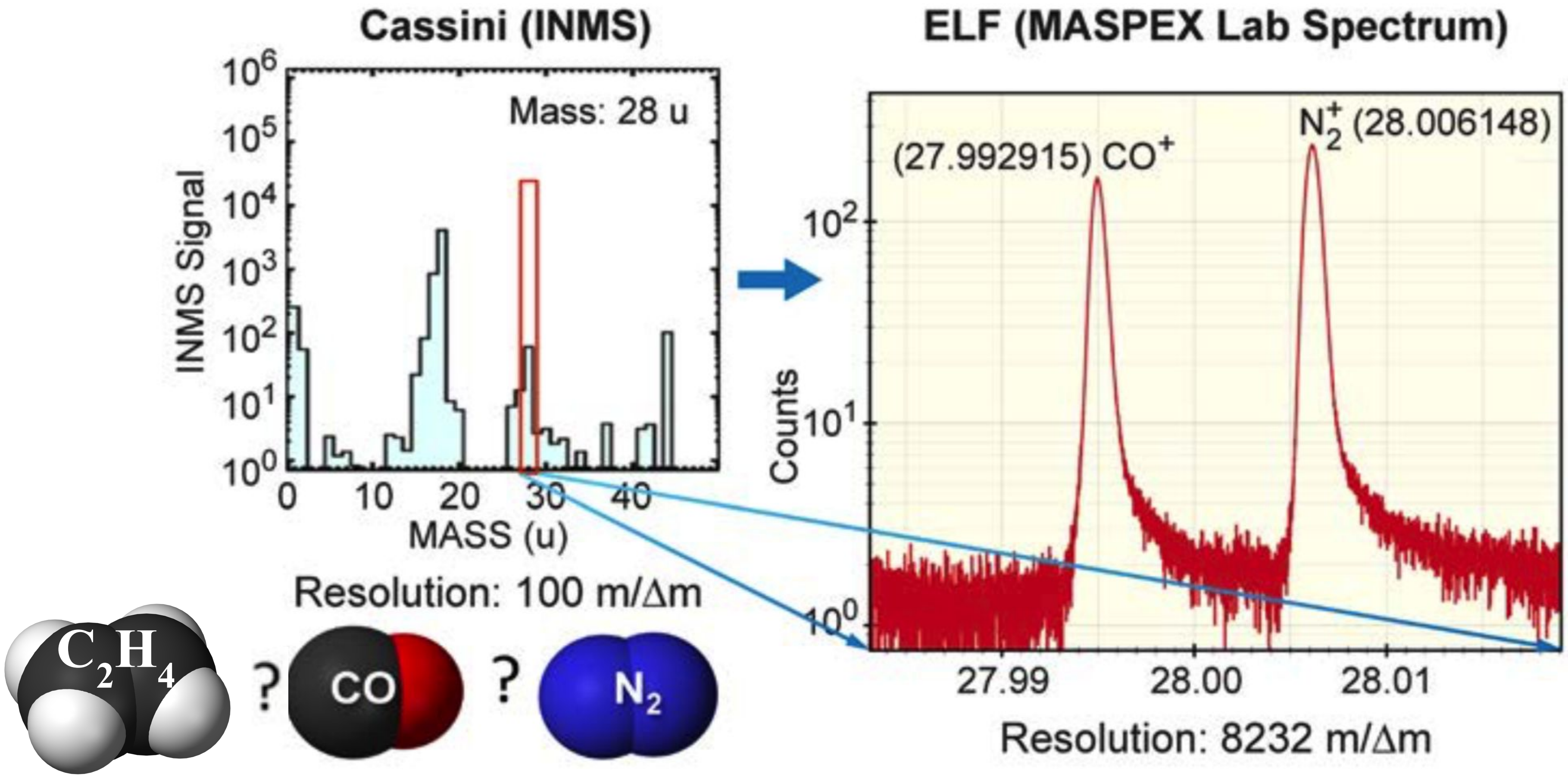
Next step: a mission to search for biosignatures in the Enceladus ocean

Low resolution of Cassini mass spectrometers resulted in species ambiguities

Mass (u)	Potential ly ambiguous species	Notes
26	C_2H_2, C_2H_4	Degree of saturation of hydrocarbons – primordial versus hydrothermally produced
27	C_2H_4, HCN	How much N on Enceladus?
28	CO, N_2, C_2H_4	
30	C_2H_6, CH_2O, $C_2H_5NO_2$, NO	How much does O dominate?
31	CH_4O, $C_2H_4O_2$, C_3H_8O, $C_4H_{10}O$, $C_2H_6O_2$, CH_5N	
34	H_2S, H_3P	Is reduced sulfur present?
40	C_3H_4, C_2H_3N, Ar	Amount of radiogenic argon.
41	C_3H_6, C_2H_3N	Are the nitrogen-substituted organics nitriles, amines, or amides?
42	C_3H_6, C_5H_{10}, C_2H_2O, C_4H_9N, $C_4H_8N_2$	CH vs. CHO vs. CHN vs. CHON?
43	C_3H_8, C_4H_{10}, C_5H_{12}, C_8H_{18}, C_2H_4O, C_3H_6O, $C_4H_{10}O$, C_4H_9N, $C_2H_6N_2$, $C_3H_7NO_2$, C_2H_7N	
58	C_4H_{10}, C_6H_6O, $C_2H_6N_2$, $C_2H_3NaO_2$	Amino acids present?

Enceladus Life Finder Disco prop.

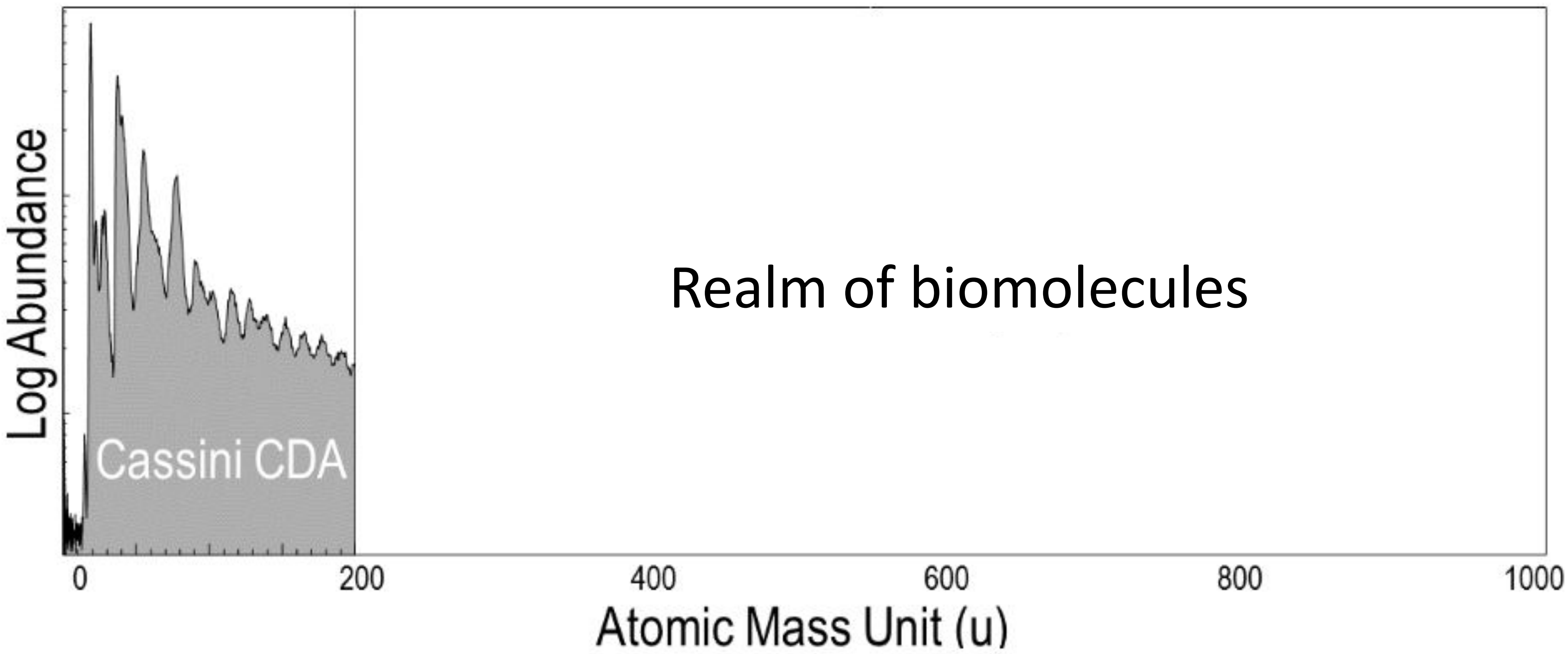
Key tool is high resolution mass spectrometry



C_2H_4
28.05

Current generation mass spectrometers have much higher mass resolution than Cassini carried.

The discovery space with modern mass spectrometers is huge



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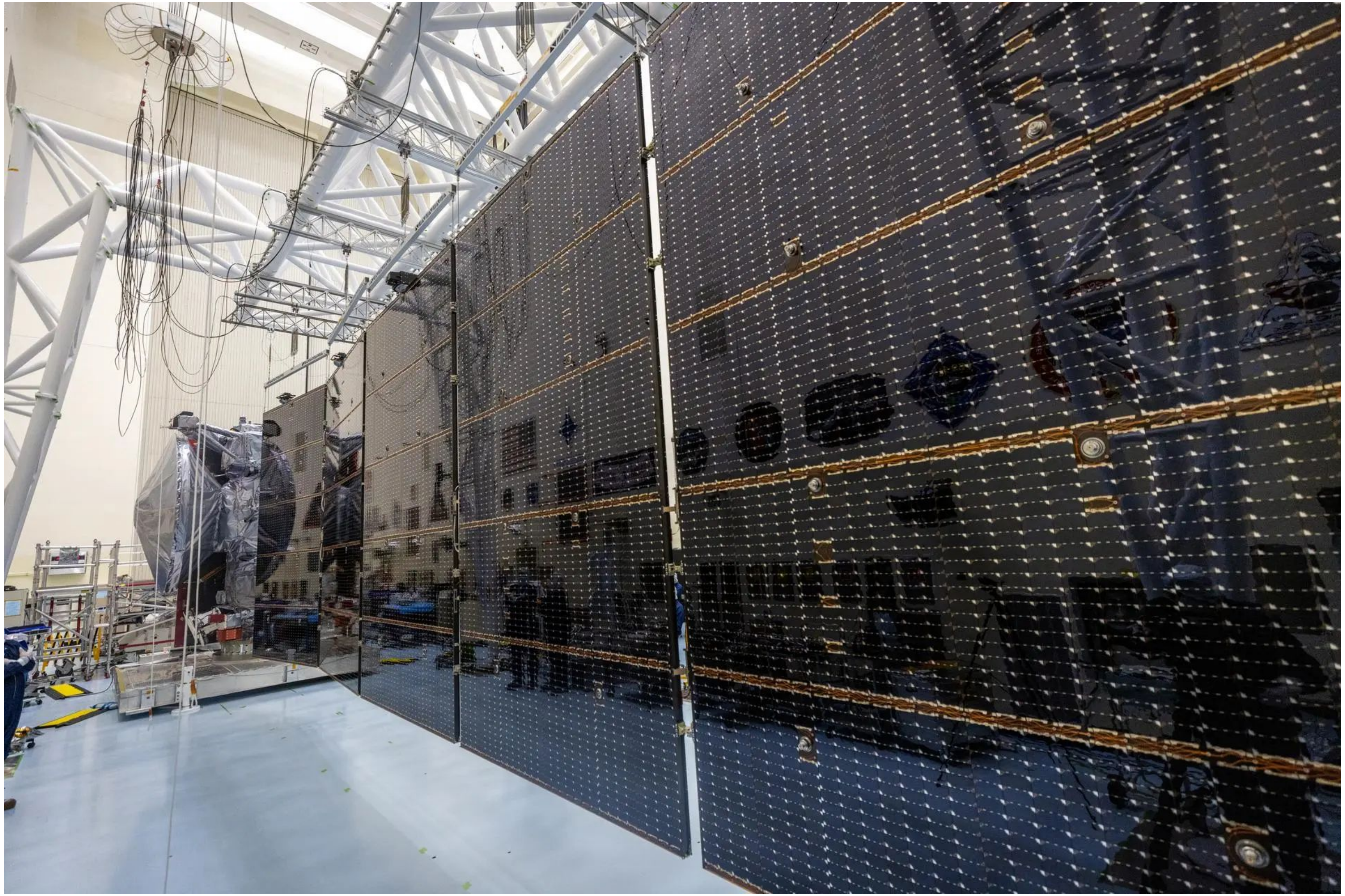
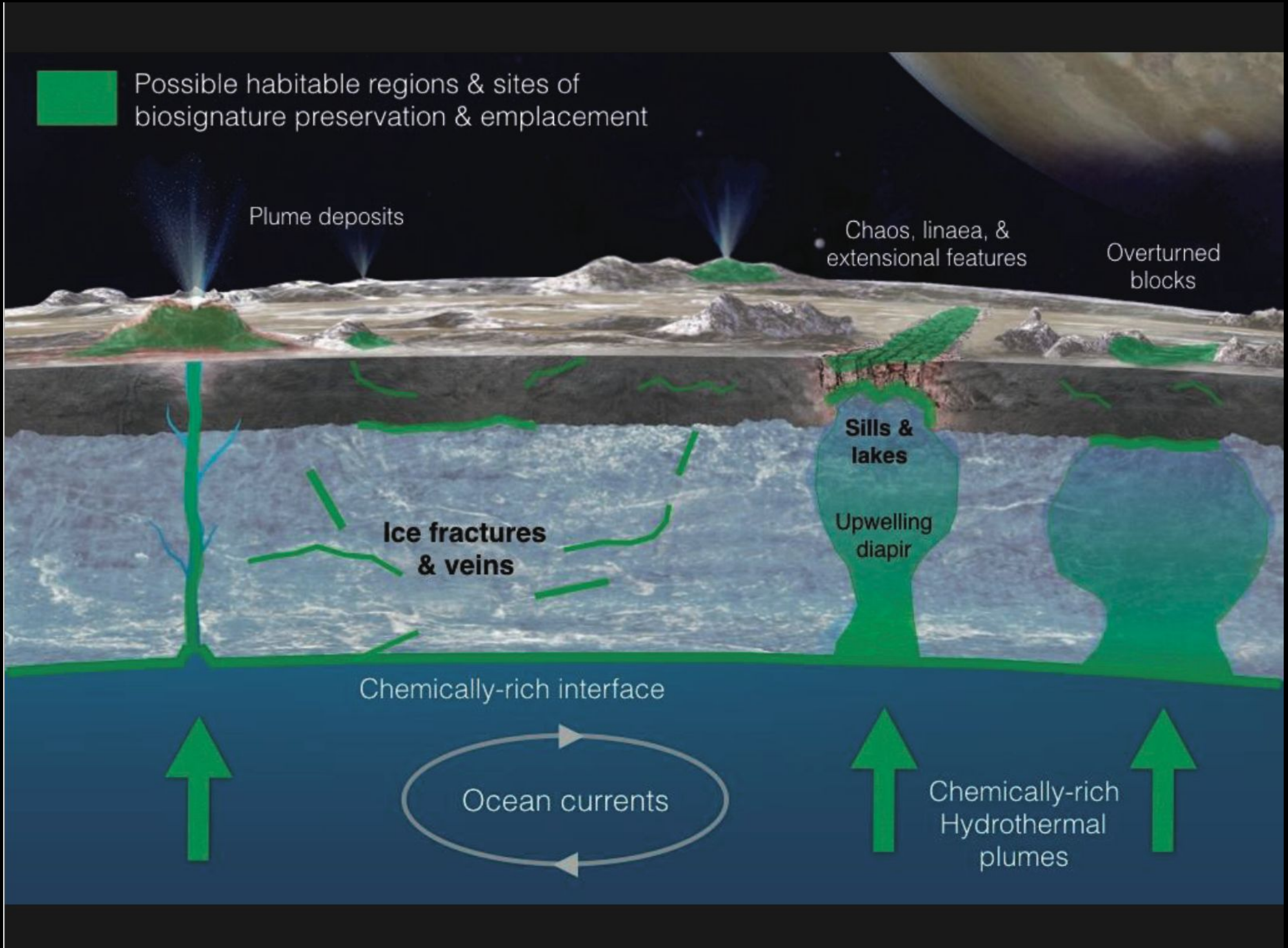
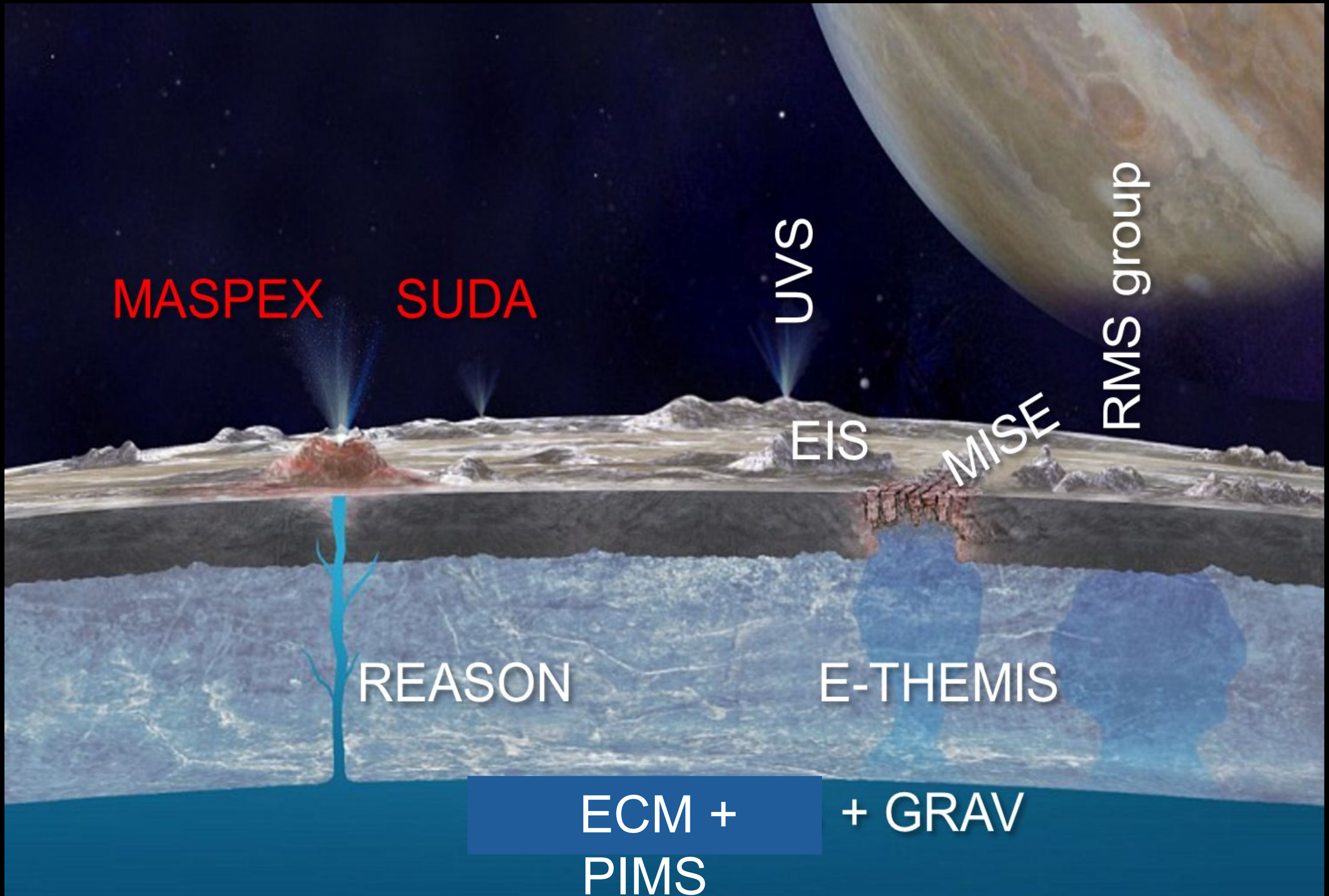
Europa Clipper



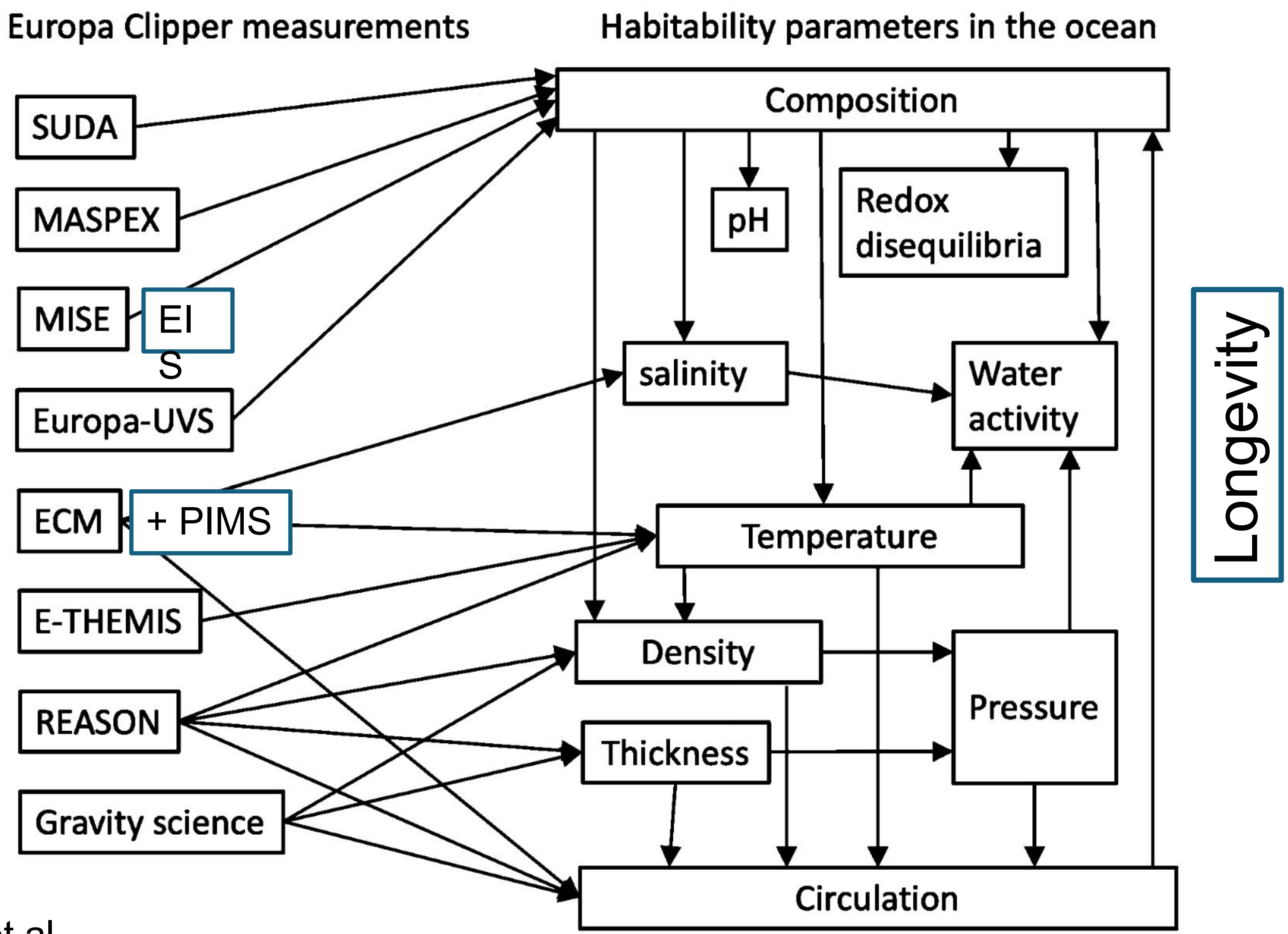
National Academies of Sciences, Engineering, and Medicine. 2019. *An Astrobiology Strategy for the Search for Life in the Universe*. Washington, DC: The National Academies Press. https://doi.org/10.17226/25252.



Europa Clipper's payload is designed to assess habitability



Europa Clipper instruments address a variety of habitability parameters



Modified from Vance et al

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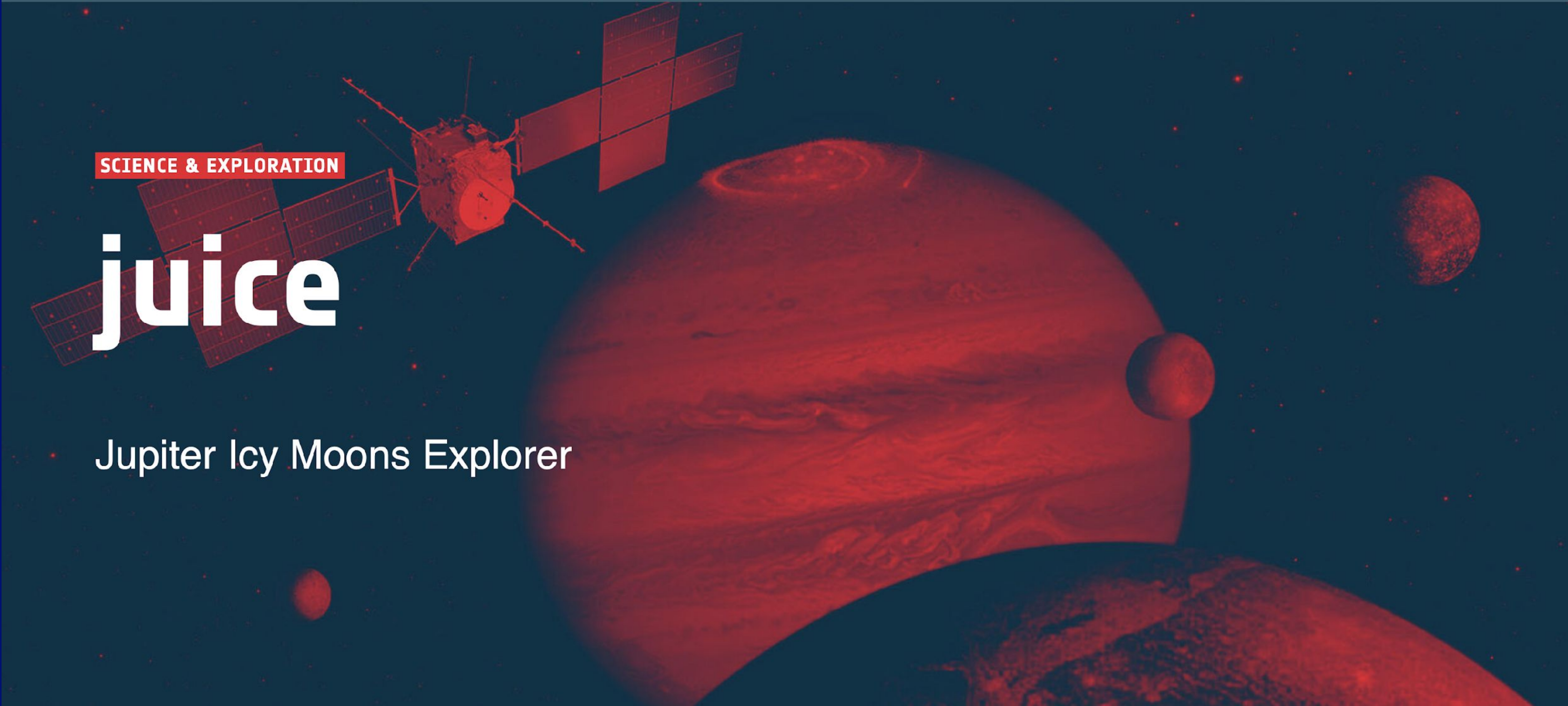

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- Determining definitively habitability of ancient Mars *requires* sample return because of the faintness of signatures and need for multiple radioisotopic pairs for precision dating of geologic events. *In situ* investigations inform but do not replace sample return.

- Neither sample return nor *in situ* analysis are possible for exoplanets. Only remote sensing can assess habitability and this is a very challenging task.

- For ocean worlds, present-day habitability can be established with *in situ* measurements; what about past habitability or ocean longevity or detecting cells?

Sample Return for Ocean Worlds

Pro

- Obtain evidence of relict habitable environments by teasing out very faint signatures; stable isotopic ratios, radioisotopic information on chronology.
- Avoids the daunting problem of large data volumes from hi-res in situ mass spectrometry
- Detect and conduct studies on few or one cells collected during flythrough, including microscopic imaging and genomic sequencing.

Con

- Collection from surface or bound orbits requires either huge delta-V for leaving giant planet system.
- Collection from a solar orbit is a high-speed plume flythrough, risking sample integrity
- Cryogenic sample preservation is challenging during long trip times and Earth reentry heating
- Challenging planetary protection requirements.