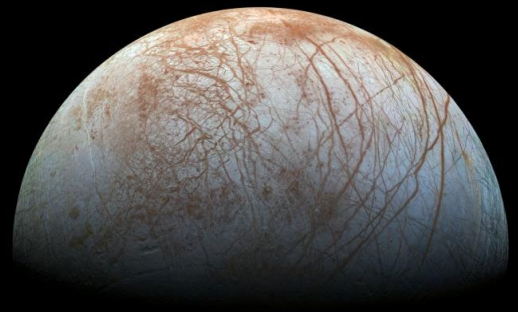
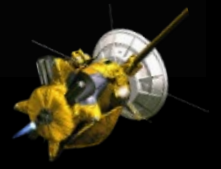


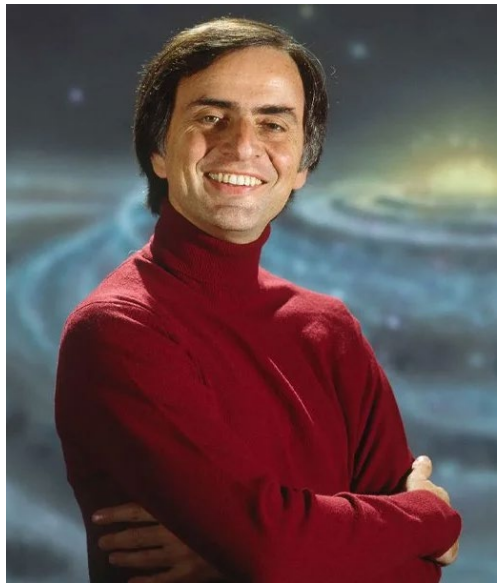
Seafaring in Space: A Personal Voyage to Enceladus

Christopher Glein
Southwest Research Institute

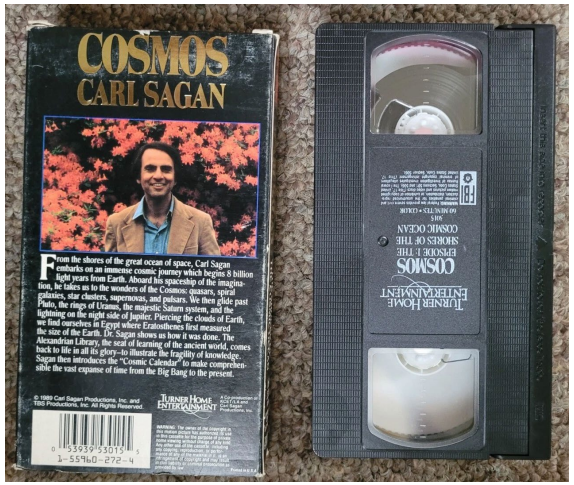
Carl Sagan Lecture
15 December 2025

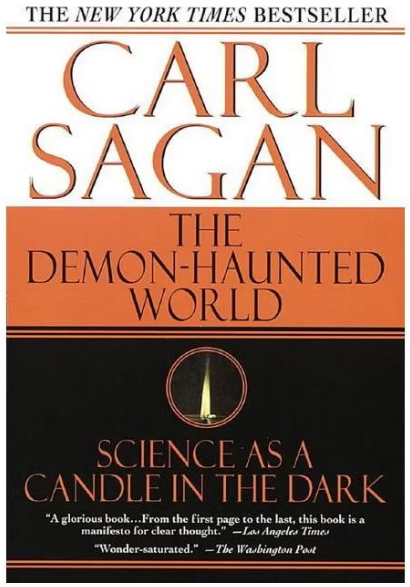


An homage to Carl Sagan by a child of the 90s



He taught us how science advances through wonder…





and skepticism

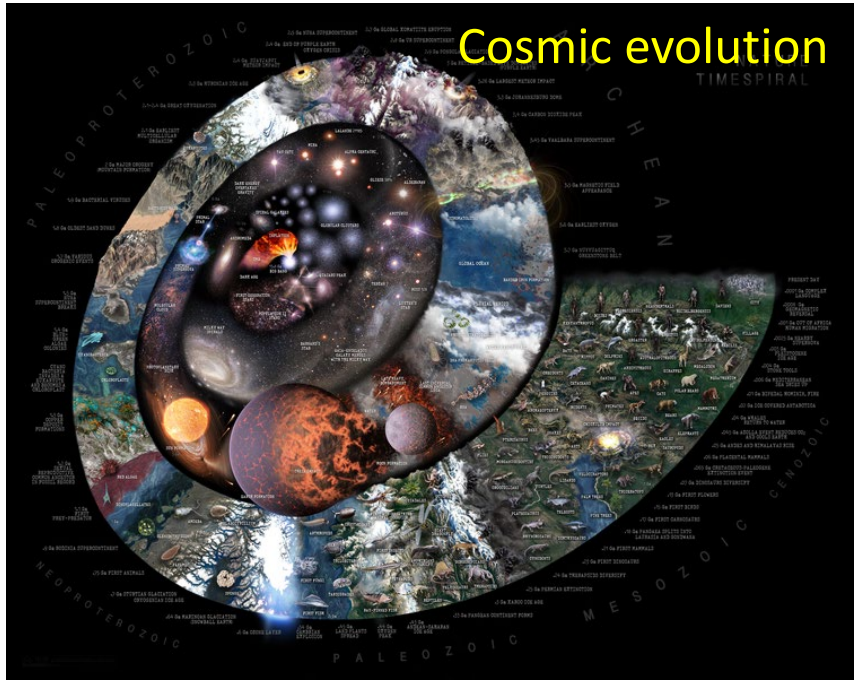
"I have a foreboding of an America…when awesome technological powers are in the hands of a very few, and no one representing the public interest can even grasp the issues; when the people have lost the ability to set their own agendas or knowledgeably question those in authority; when…our critical faculties in decline, unable to distinguish between what feels good and what's true, we slide, almost without noticing, back into superstition and darkness."

"The surface of the Earth is the shore of the cosmic ocean. On this shore, we've learned most of what we know. Recently, we've waded a little way out, maybe ankle-deep, and the water seems inviting."

Tonight, we continue Carl's grand voyage of discovery in search of ourselves to renew a time of hope

Why search for life?

- Understanding our place in the universe
- Was the origin of life a fluke?
- Are we special/alone?

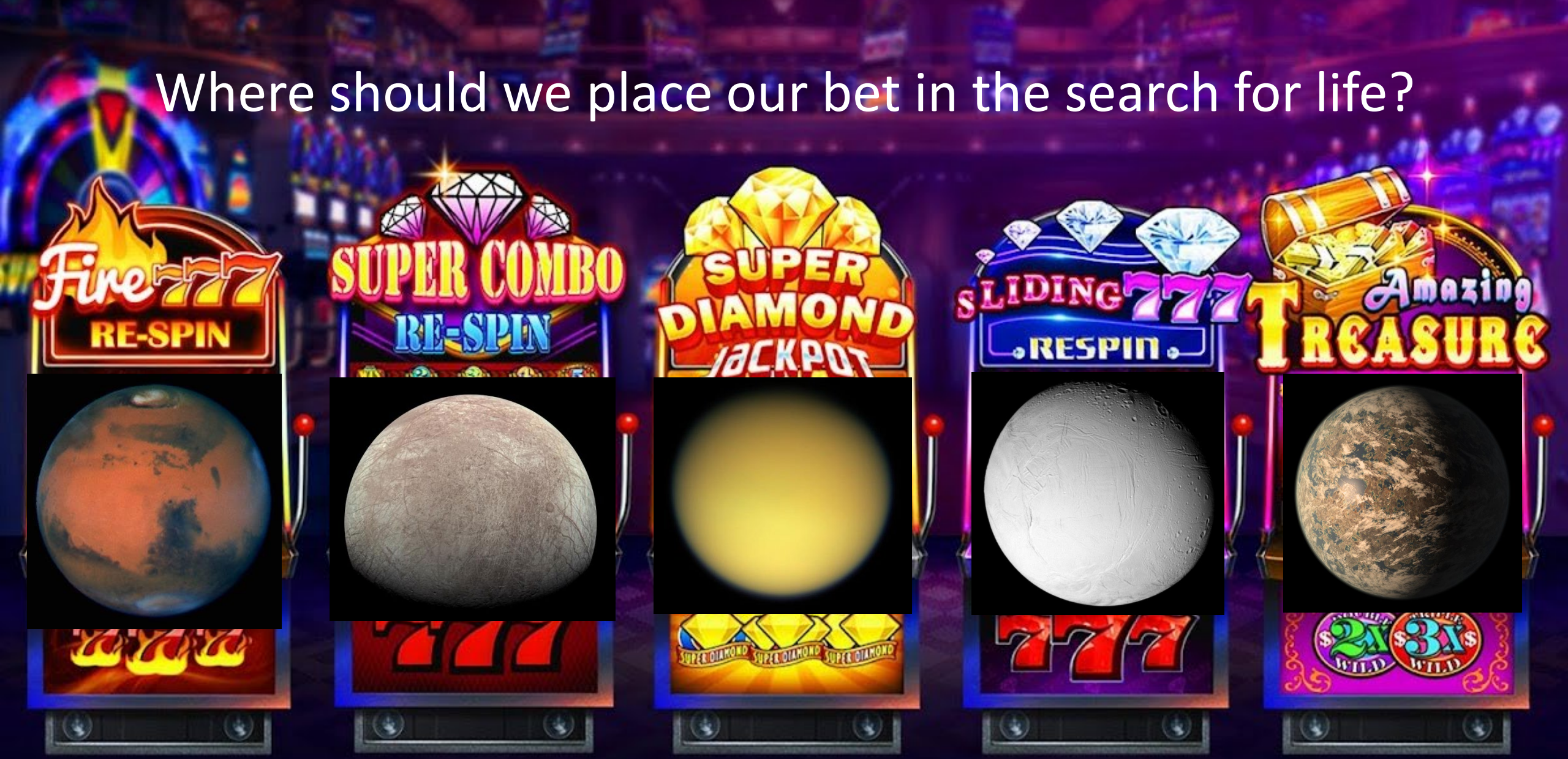


- Laws of nature
- Physics is universal
- Chemistry is universal
- Biology?

- Our legacy of contributing to humanity (for posterity!)

- The cool factor and the drive to explore
("We are living at the beginning of Star Trek" – Alan Stern

Where should we place our bet in the search for life?



Mars Europa Titan Enceladus Exoplanets

An **accessible ocean** that we can mine for insights into the chemistry and habitability of extraterrestrial oceans

Enceladus as a gateway to **astro-oceanography**

The Beginning of Enceladus Exploration

Before 1600: Five planets

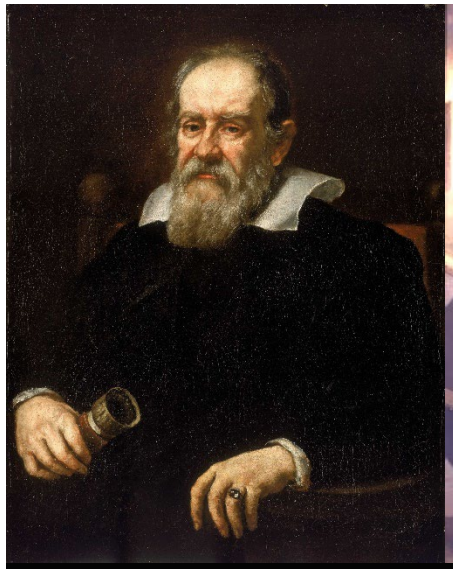
1610: Galilean satellites

1655: Titan

1671-1684: Iapetus, Rhea, Tethys, Dione

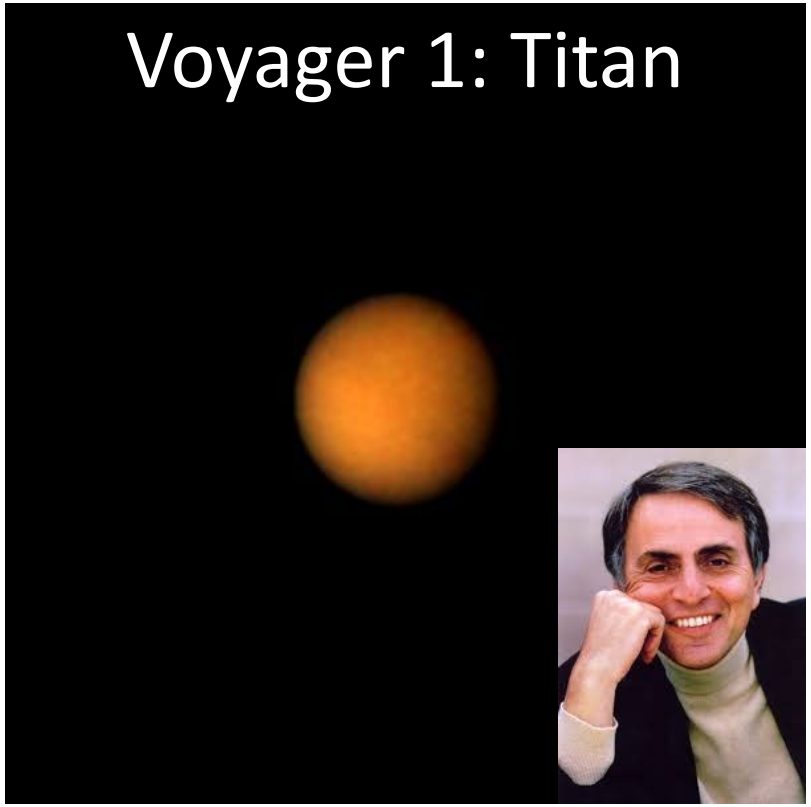
1789: Mimas, Enceladus

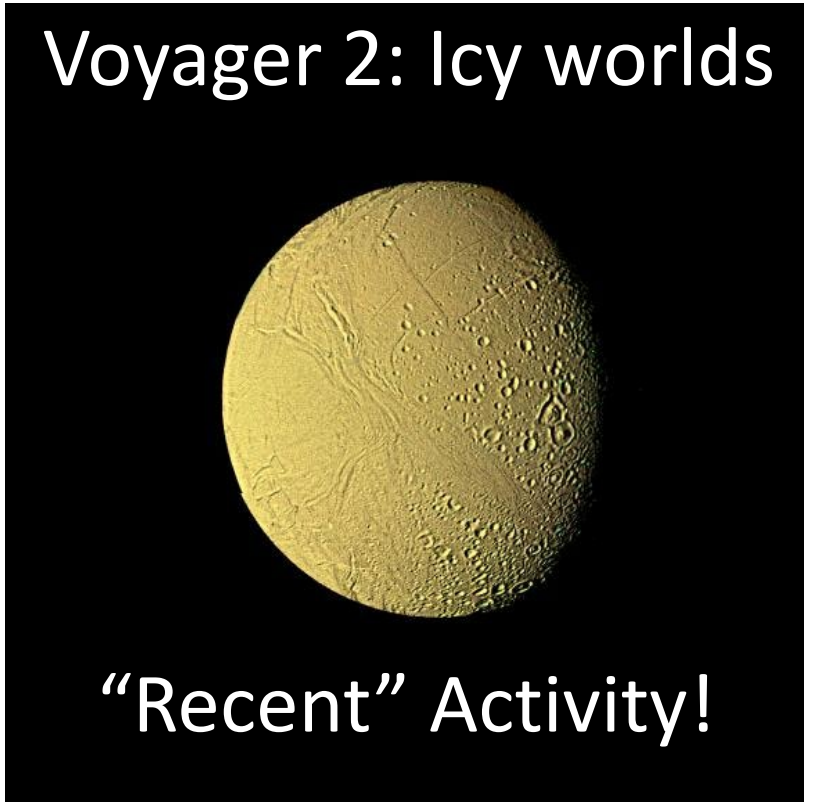
Enceladus remained a dot for the next 200 years…



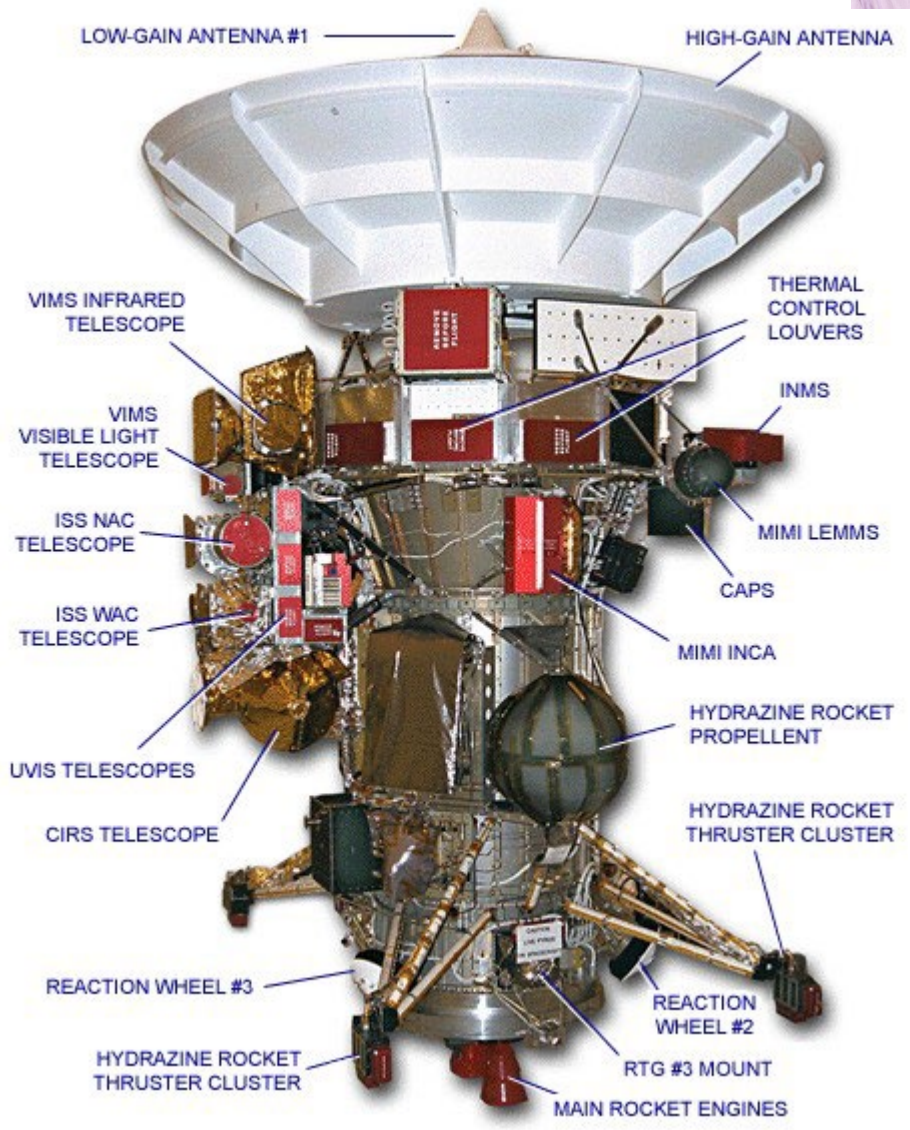
1980s: The Grand Tour

The transition from astronomy to planetary science (geology, geophysics, geochemistry) in the outer solar system





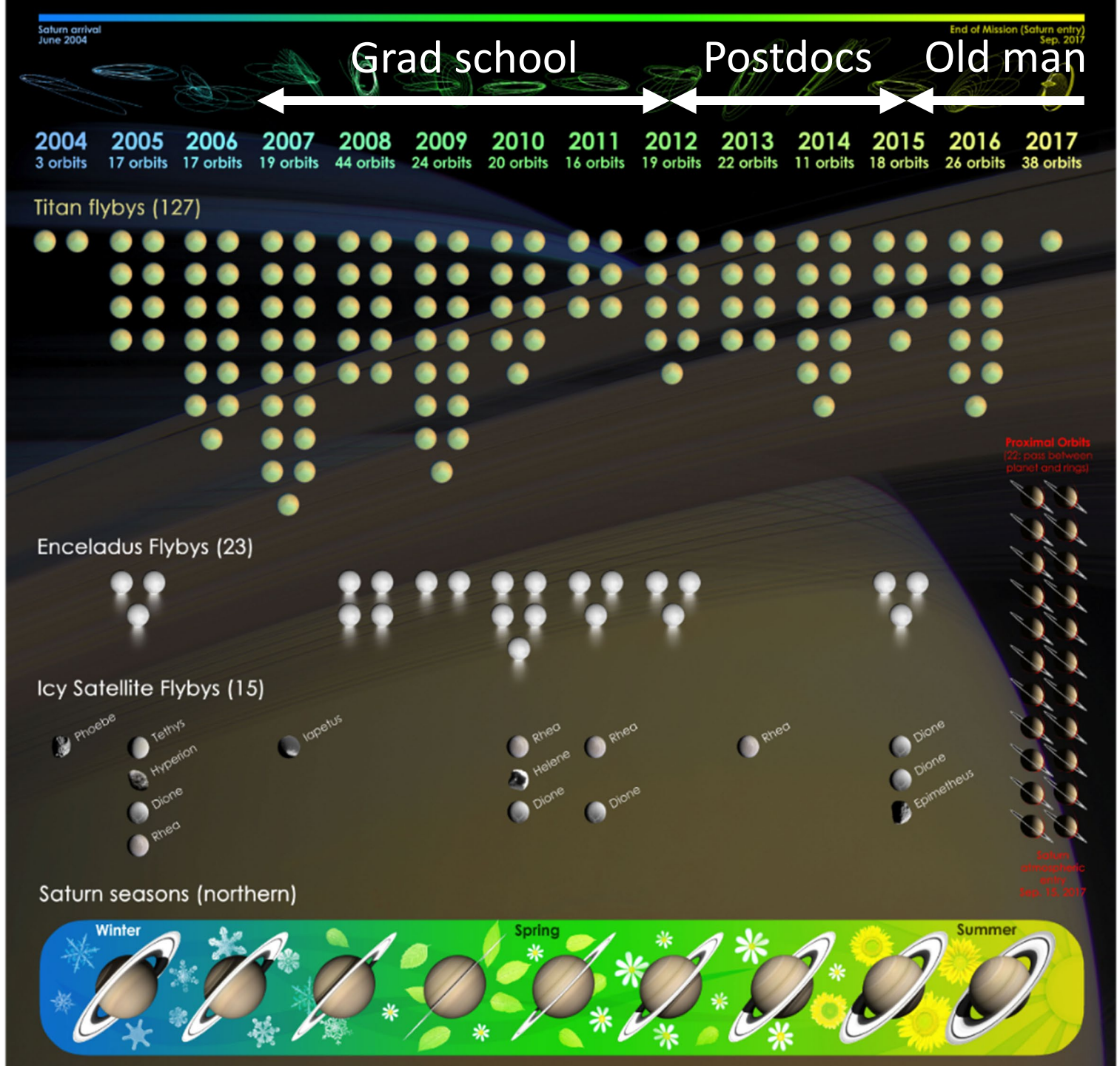
Cassini-Huygens



1997

2004

Saturn at last!

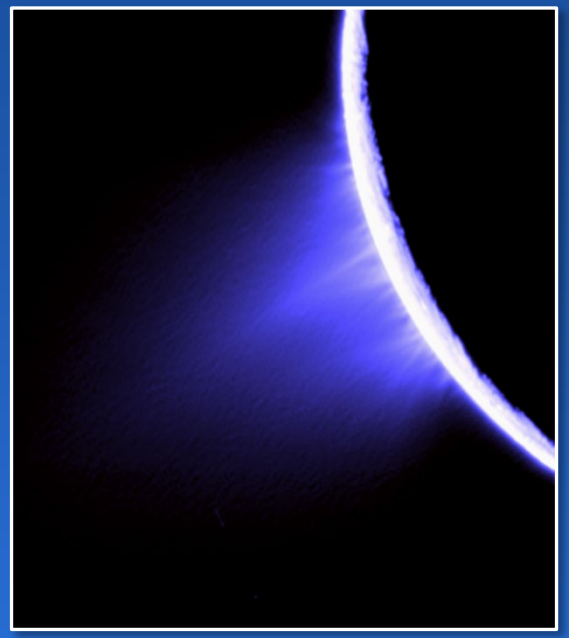

Saturn arrival
June 2004
End of Mission (Saturn entry)
Sep. 2017
Grad school
Postdocs
Old man
2004
3 orbits
2005
17 orbits
2006
17 orbits
2007
19 orbits
2008
44 orbits
2009
24 orbits
2010
20 orbits
2011
16 orbits
2012
19 orbits
2013
22 orbits
2014
11 orbits
2015
18 orbits
2016
26 orbits
2017
38 orbits
Titan flybys (127)
Proximal Orbits
(22; pass between planet and rings)
Enceladus Flybys (23)
Icy Satellite Flybys (15)
Phoebe
Tethys
Hyperion
Dione
Rhea
Iapetus
Rhea
Helene
Dione
Rhea
Dione
Rhea
Diane
Diane
Epimetheus
Saturn atmospheric entry
Sep. 15, 2017
Saturn seasons (northern)
Winter
Spring
Summer

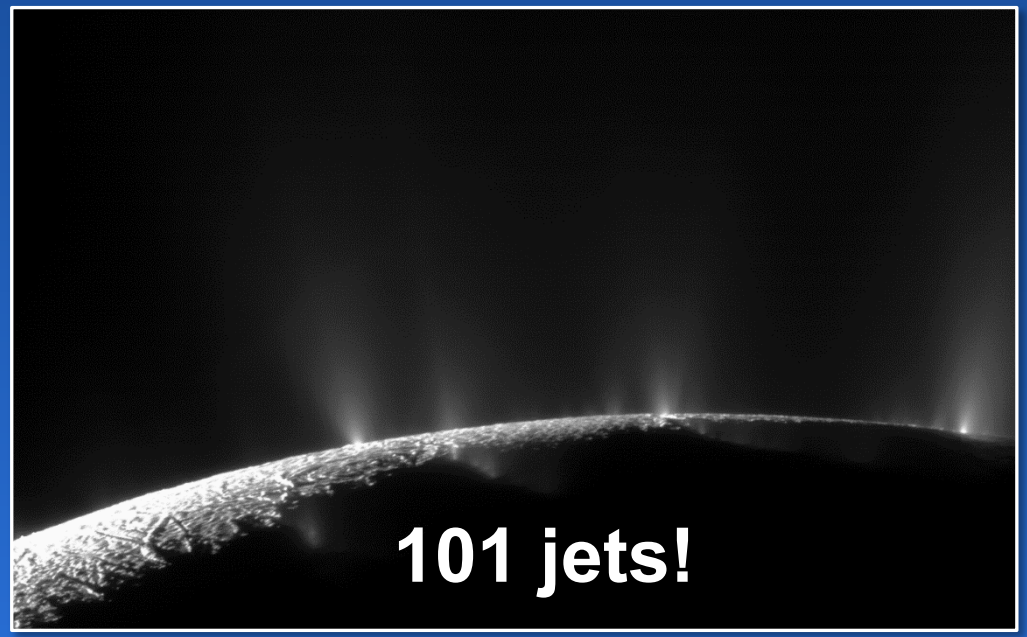
Enceladus

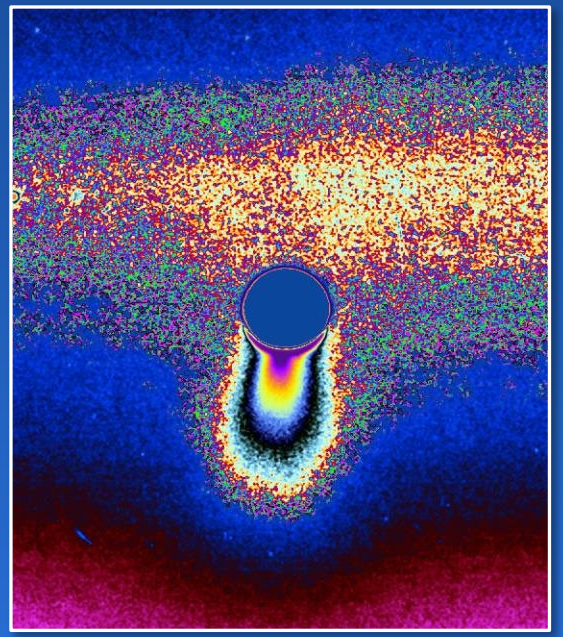
- Diameter: 500 km
- Gravity: 1% × *g*
- Albedo: 76%
- Mean surface: 75 K temperature

Arguably, the Biggest Discovery by Cassini

Cryovolcanic eruptions (water ice-vapor plume) on Enceladus right now

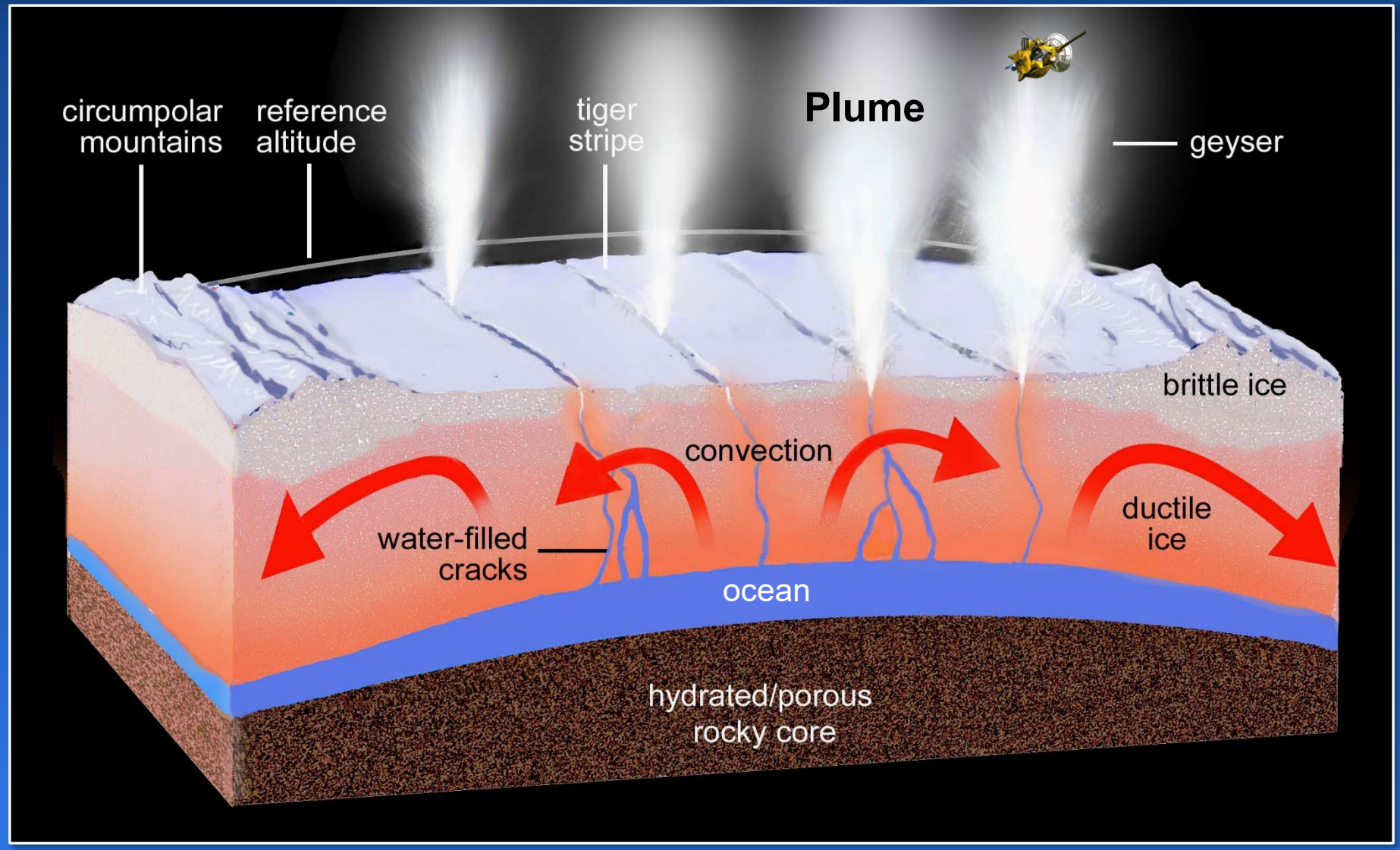




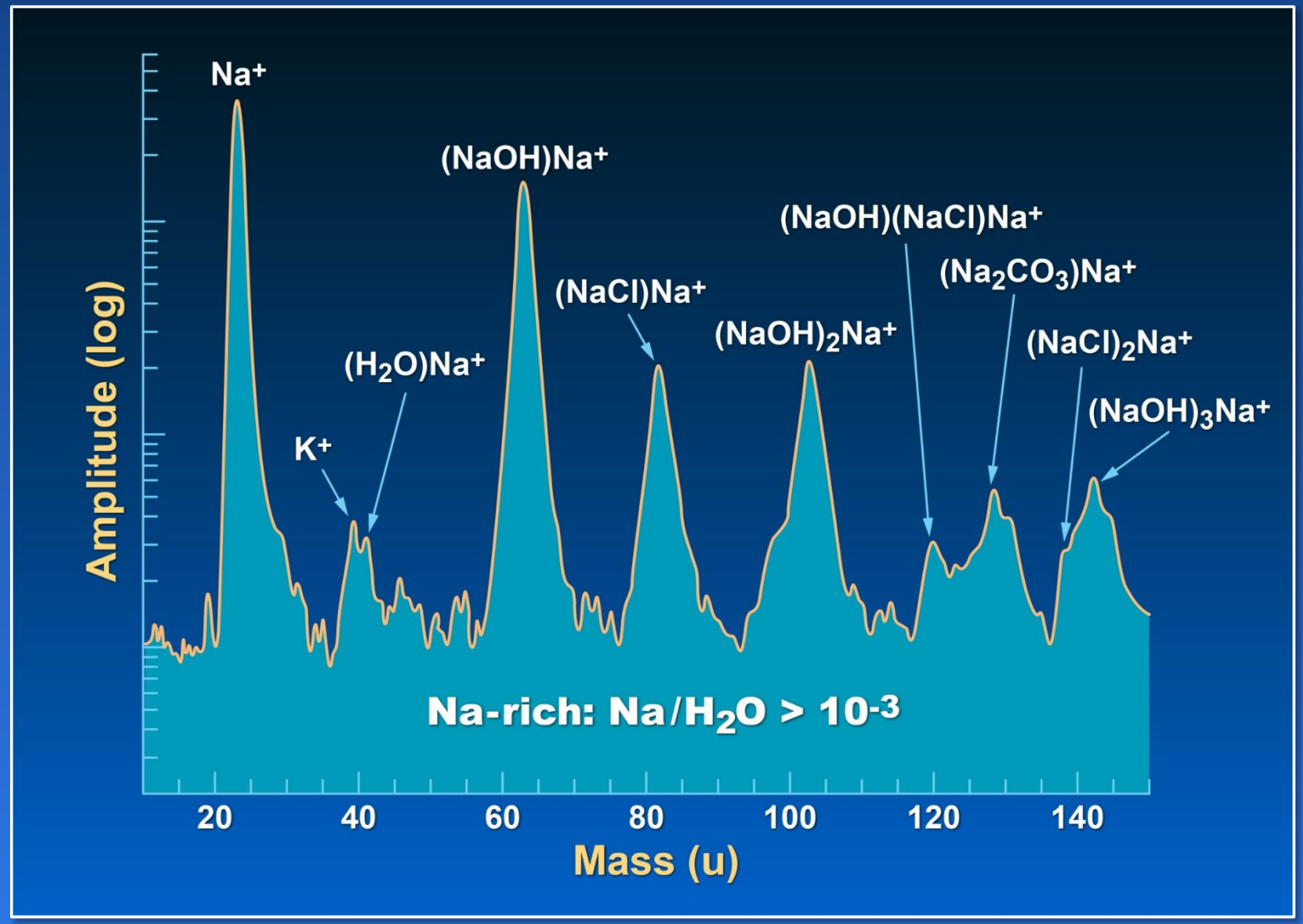


The smallest geologically active body in the solar system

Ocean Source of the Plume



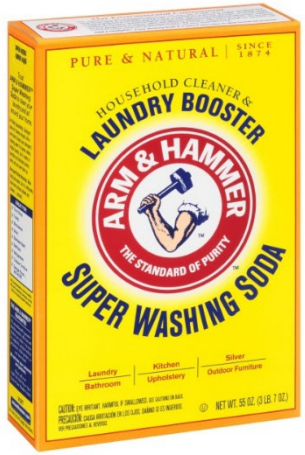
The Plume Tastes Salty…Like Seawater



Postberg et al. (2009)

Soda ocean on Enceladus

+



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(please, don't drink the water…)

Inverse model – from plume to ocean

Alkaline ocean

Chemical oceanography beyond Earth

Glein & Truong (2025)

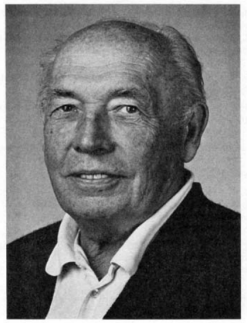


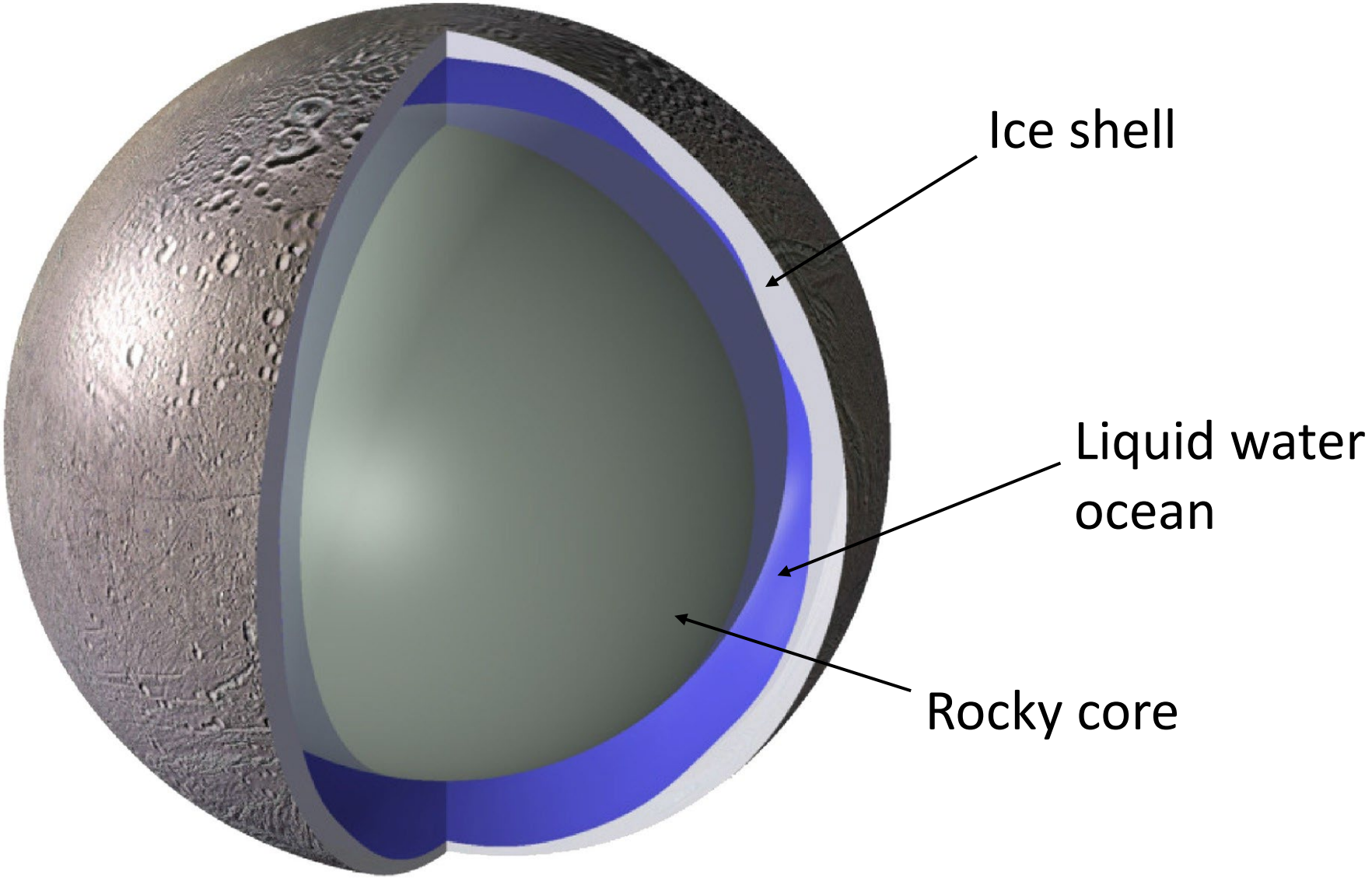
Table A1
Nominal geochemical properties of Enceladus's ocean at 0 °C and 1 bar. Brackets indicate the concentration of the enclosed species. Molal concentrations are given down to a value of 1×10^{-9}. Organic species (Khawaja et al., 2019) are not included.

Property	Value
pH	10.6
Eh (V)[a]	−0.621
$\log f_{O_2}$ (bar)[b]	−94.3
$\log f_{O_2}$ (vs. FMQ)[c]	−5.9
p_{H_2} (bar)[d]	10.2
p_{CH_4} (bar)[d]	0.4
Ionic strength (molal)	0.333
Activity of H_2O	0.994
$A_{CO_2-CH_4}$ (kJ/mol CH_4)[e]	140
$[Na^+]$	0.274
$[Cl^-]$	0.173
$[NaCO_3^-]$	0.0482
$[CO_3^{-2}]$	0.0311
$[NH_3(aq)]$[f]	0.0181
$[K^+]$	0.0179
$[HCO_3^-]$	0.0106
$[H_2(aq)]$[g]	0.0100
$[NH_4^+]$	0.00744
[NaCl(aq)]	0.00335
$[NaHCO_3(aq)]$	0.00328
$[NaHPO_4^-]$	0.00156
$[HPO_4^{-2}]$	0.00147
$[CH_4(aq)]$[f]	0.00100
$[Br^-]$	0.000402
$[Na_2HPO_4(aq)]$	0.000177
$[PO_4^{-3}]$	0.000101

(continued on next page)

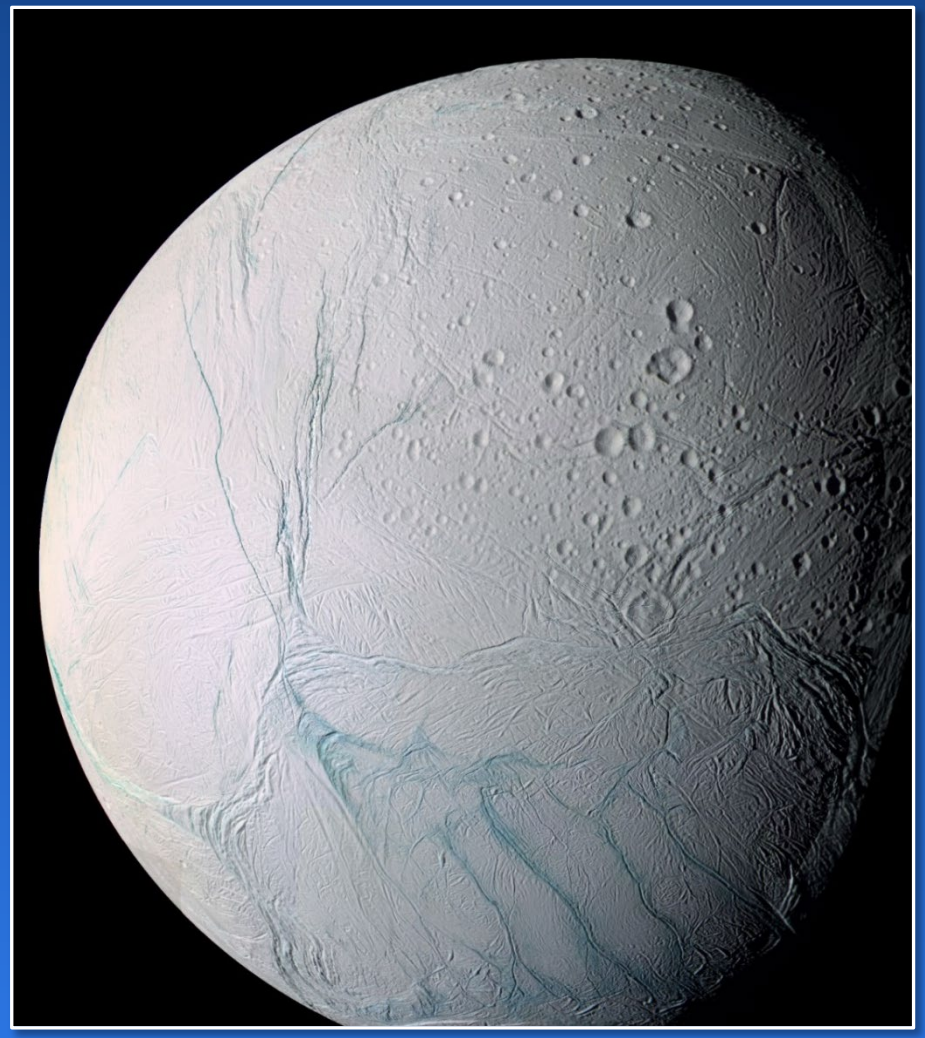
Ocean World

<u>Ocean depths</u>
Enceladus ~40 km
Earth avg. ~3.7 km,
Mariana Trench ~11 km

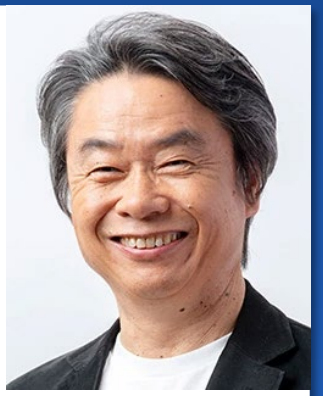


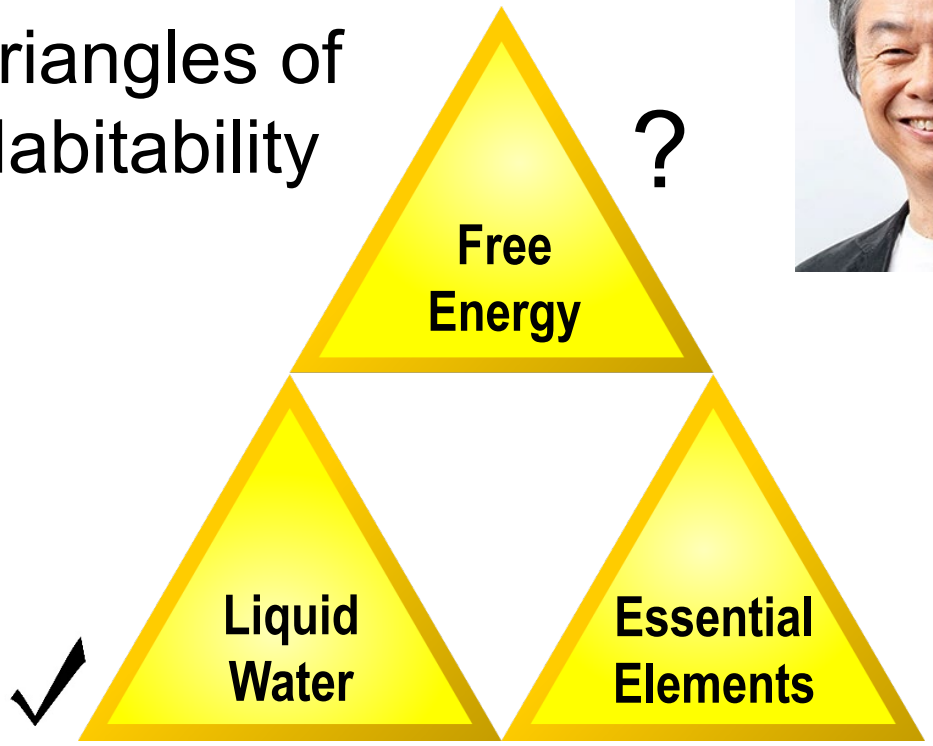
Hemingway & Mittal (2019)

2016: Saturn's moon Enceladus: Is it habitable?

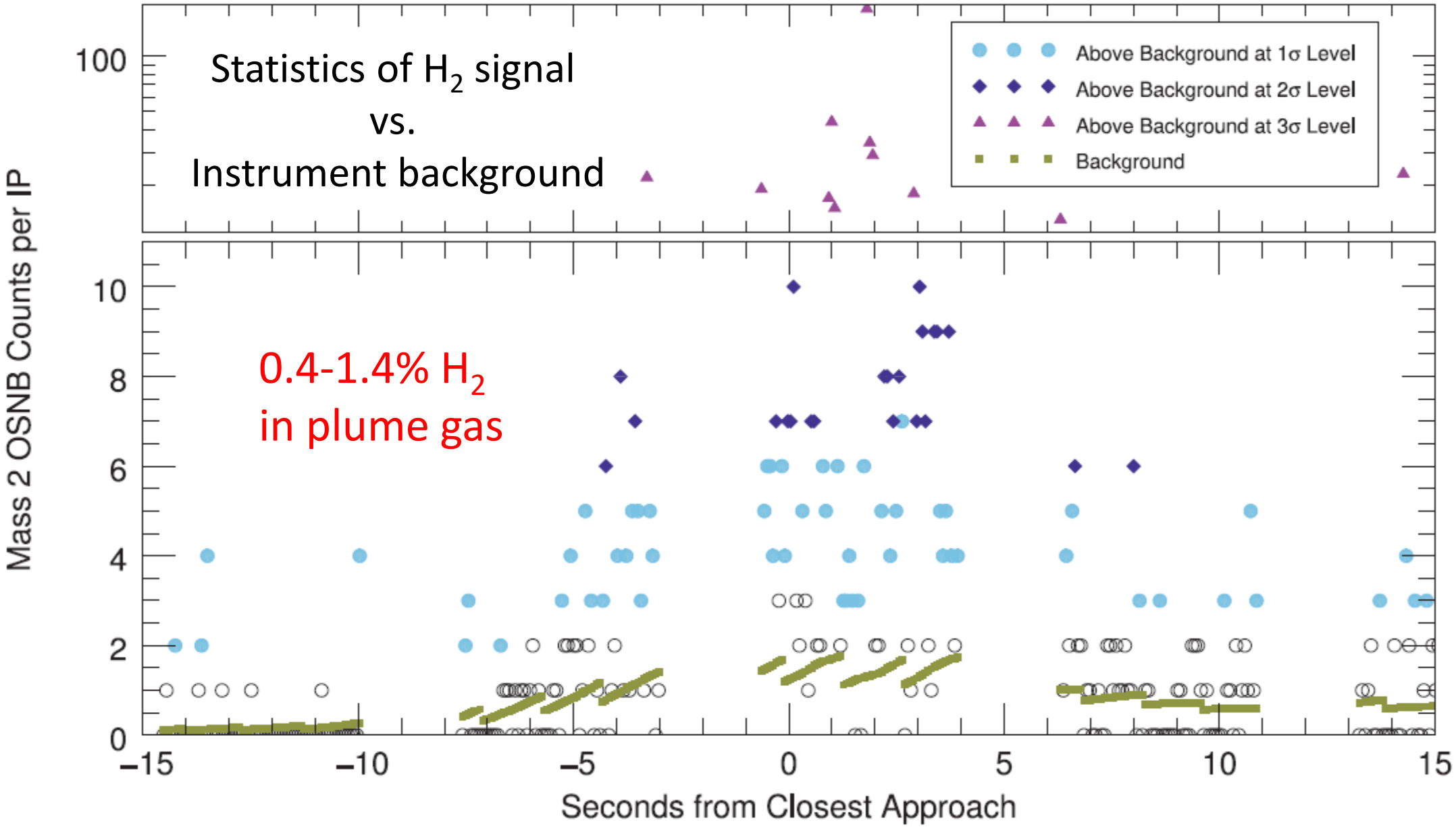


The Sacred Triangles of Habitability





INMS data from the 21st Enceladus flyby



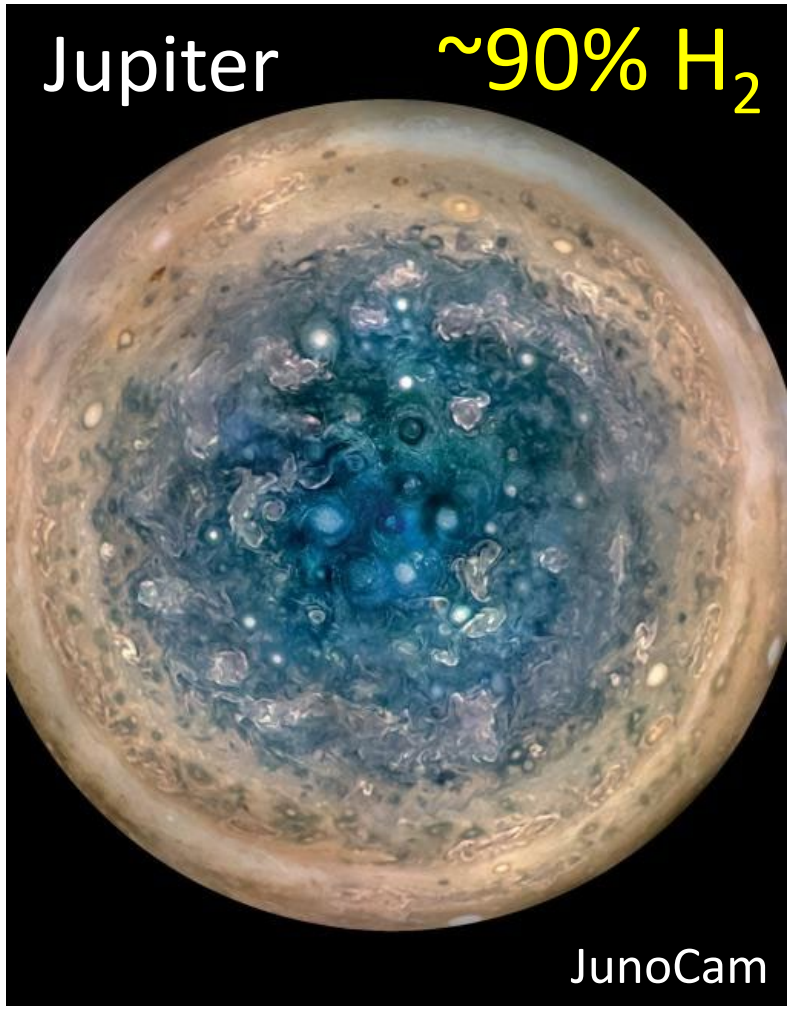
Waite, Glein et al. (2017)

Hydrogen: So what…it's everywhere!

Solar Abundances

Element	$N(El)_0$
H	2.431×10^{10}
He	2.343×10^{9}
Li	55.47
Be	0.7374
B	17.32
C	7.079×10^{6}
N	1.950×10^{6}
O	1.413×10^{7}
F	841.1
Ne	2.148×10^{6}
Na	5.751×10^{4}
Mg	1.020×10^{6}
Al	8.410×10^{4}
Si	$\equiv 1.00 \times 10^{6}$
P	8373
S	4.449×10^{5}
Cl	5237
Ar	1.025×10^{5}

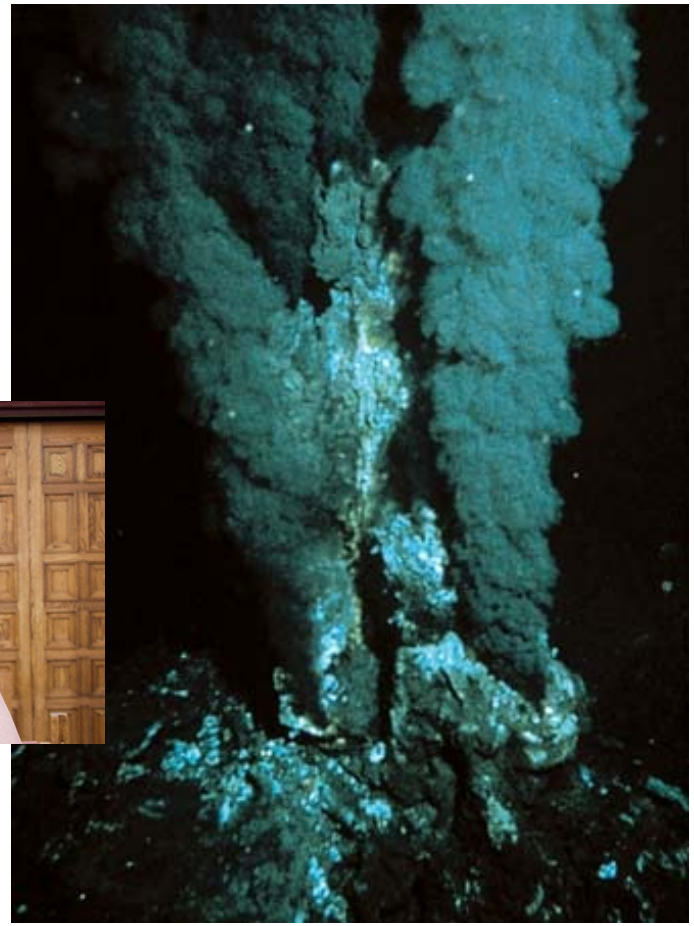
Lodders (2003)



But H_2 is relatively rare on Ocean Worlds

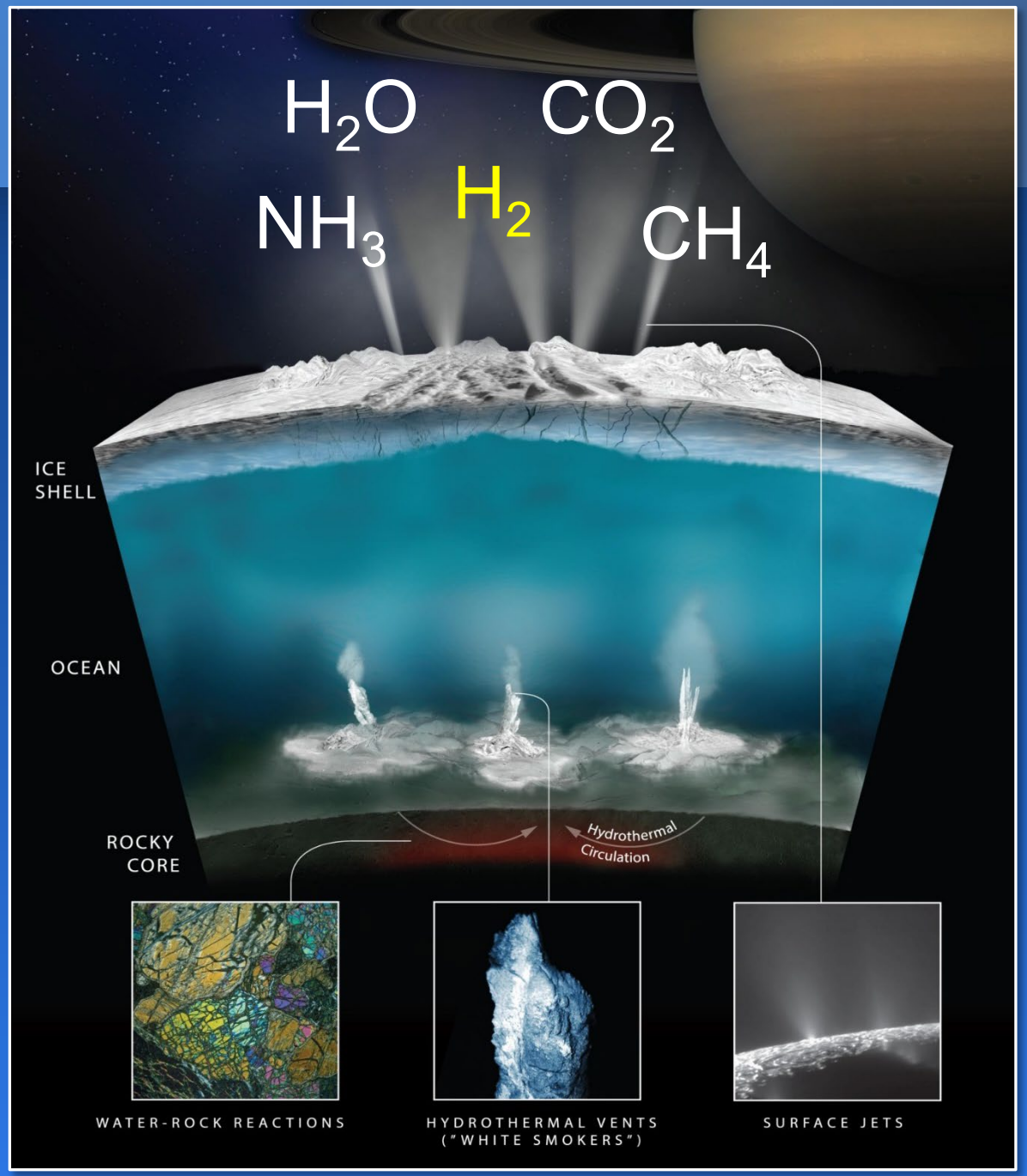
0.55 ppm H_2 in Earth's atmosphere

It's hard to hang on to H_2

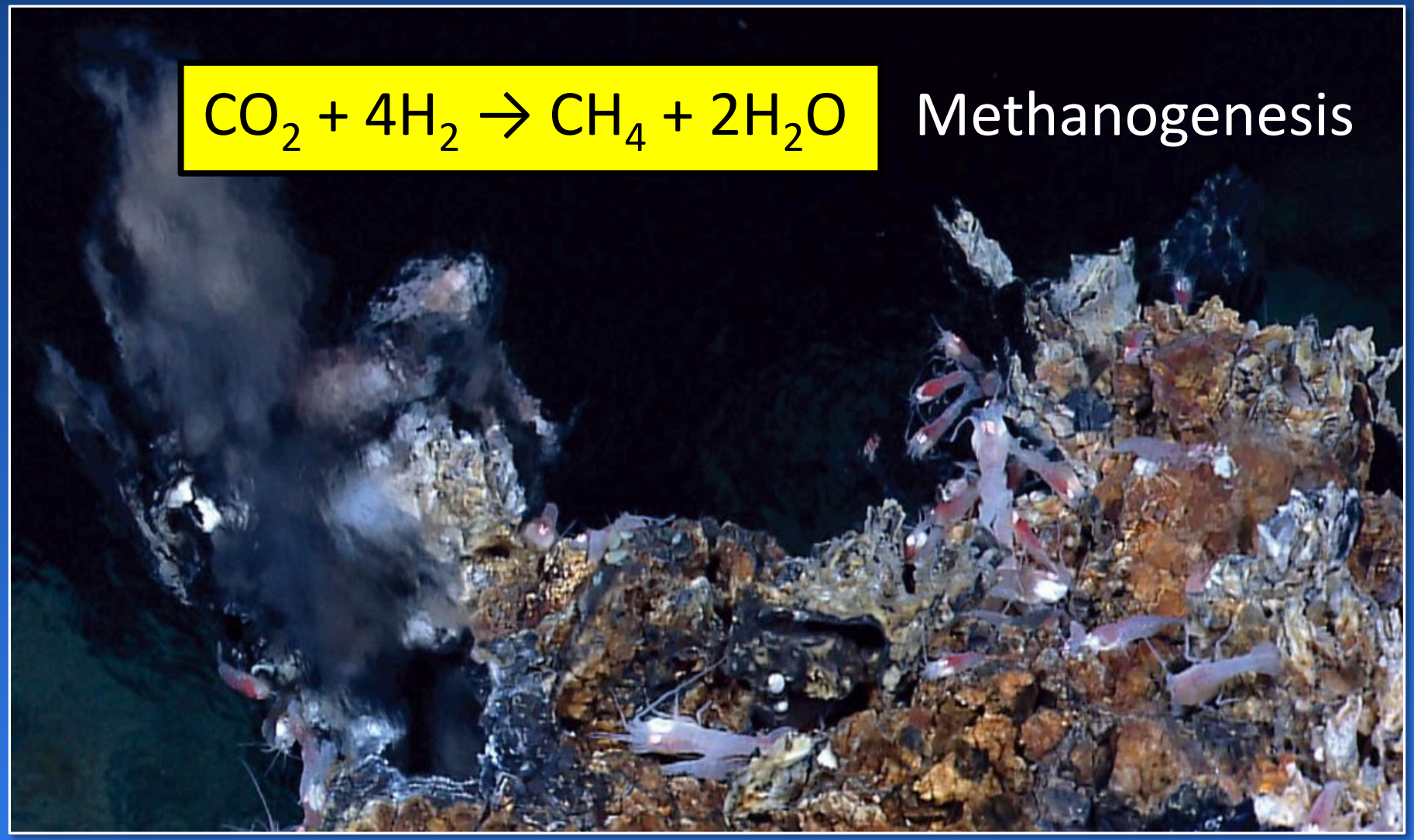


Water-rock hydrothermal processes produce of order 1 M tonnes H_2 per year (Sherwood Lollar et al., 2014)

Hydrothermal systems

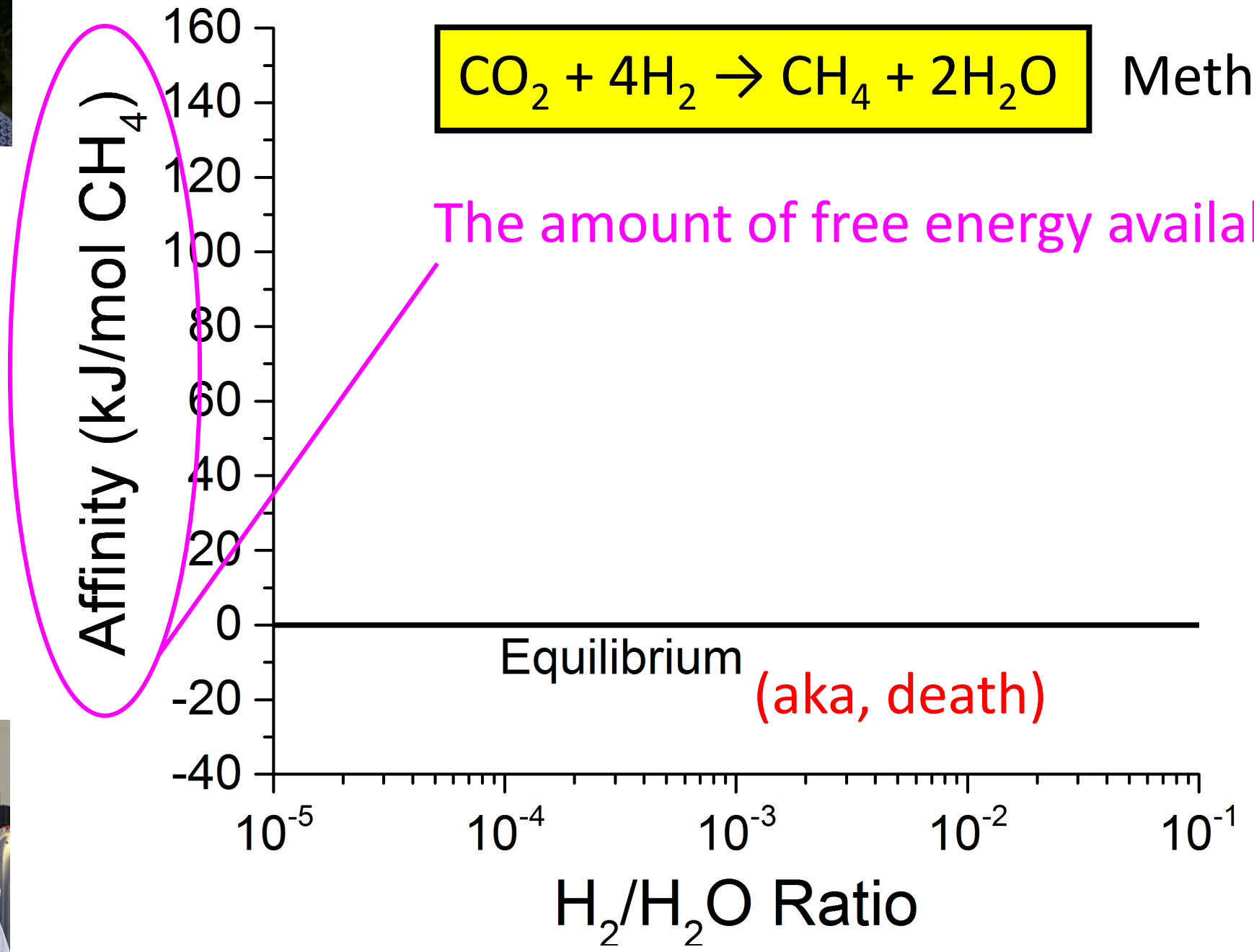


Hydrogen Gas = Food for Microbes?



$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$ Methanogenesis

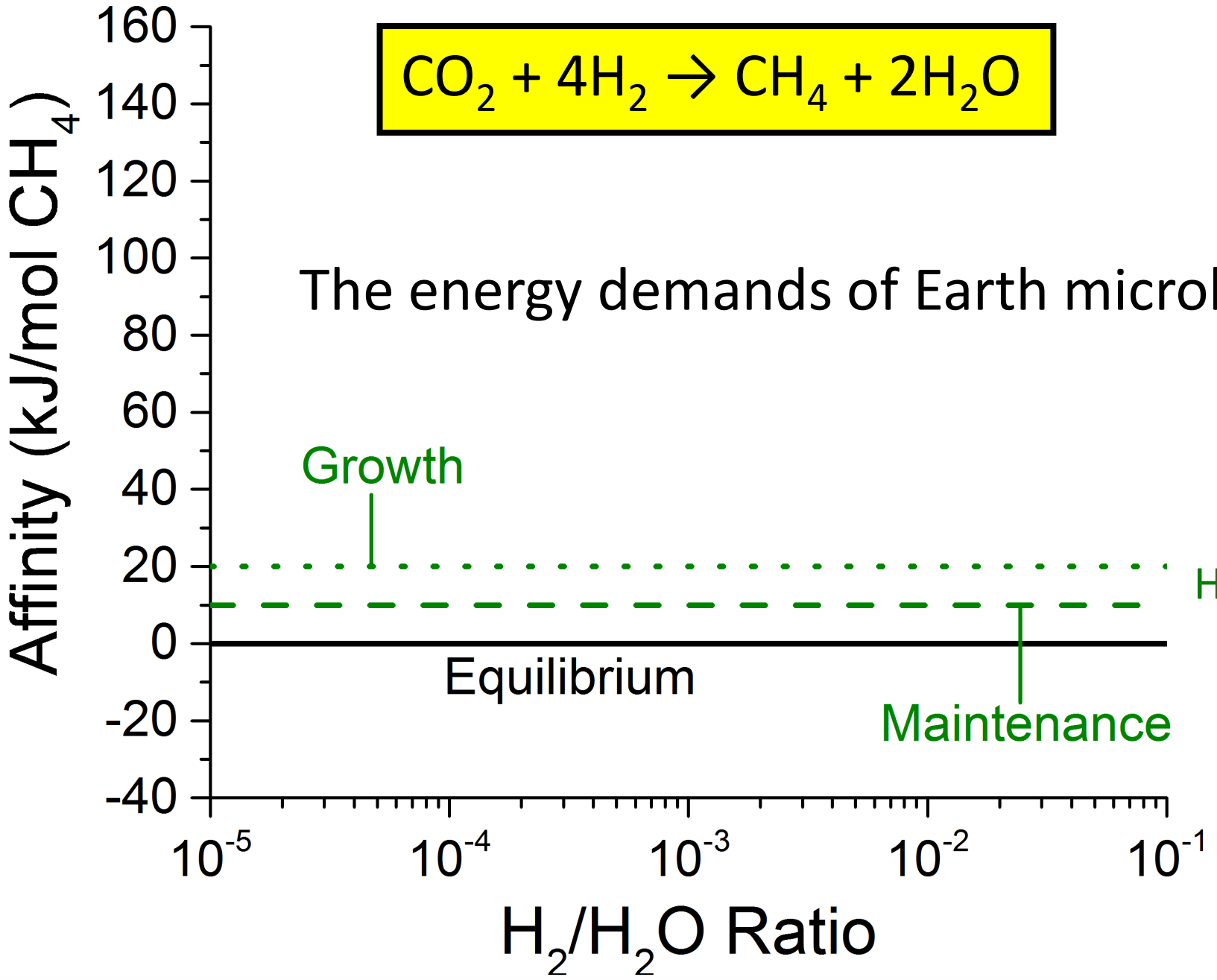
The amount of free energy available



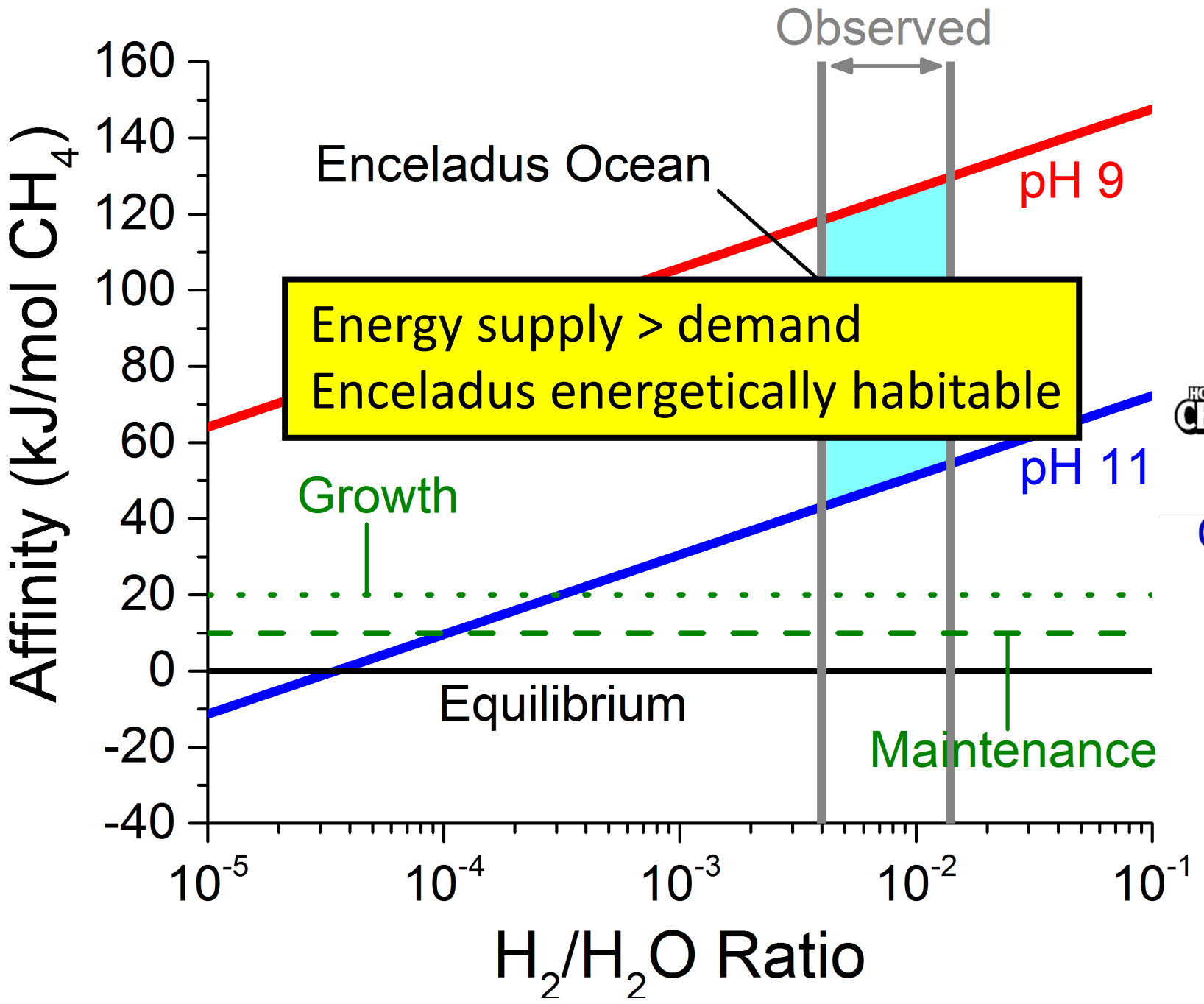
Waite, Glein et al. (2017)

$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$

The energy demands of Earth microbes…



Waite, Glein et al. (2017)

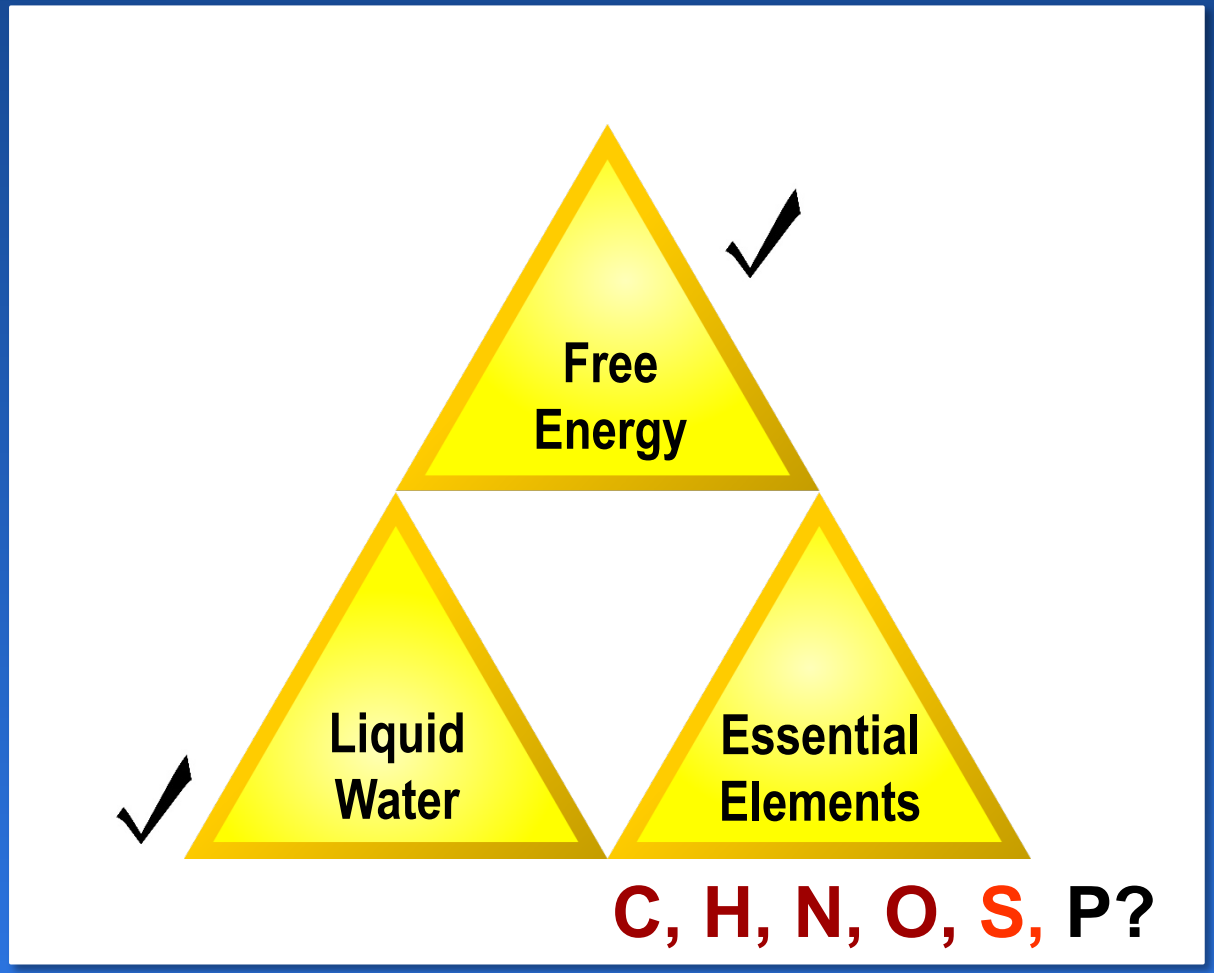


Putting all the pieces together from Cassini

Caloric equivalent of ~300 pizzas every hour!

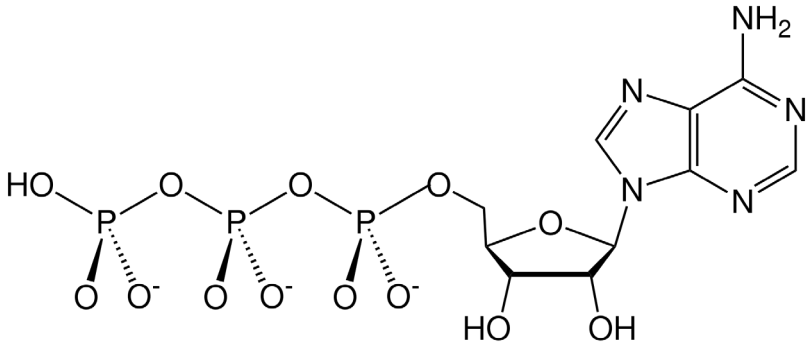
Waite, Glein et al. (2017)

View of Enceladus Habitability circa 2020



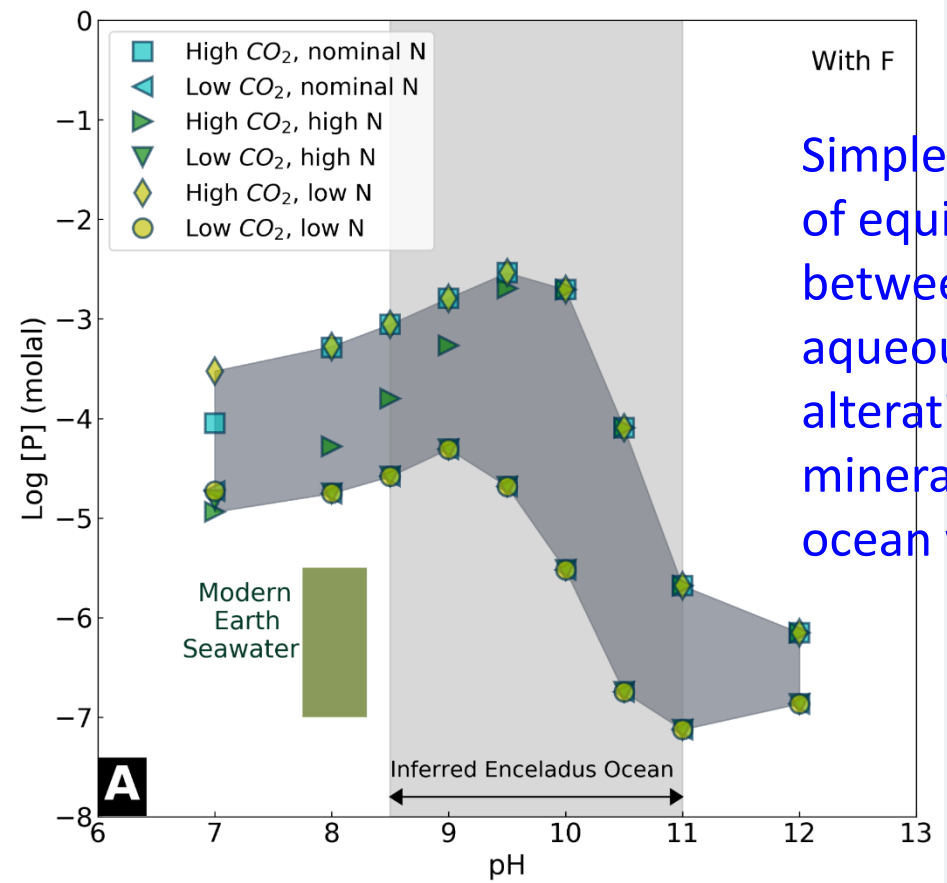
Is there P in Enceladus's ocean?

- **P as building block of life (C, H, O, N, P, S)**
  - Nucleotides, phospholipids, supporting material (bones)
- **P as metabolic currency**
  - ATP, pyrophosphate, acetyl phosphate

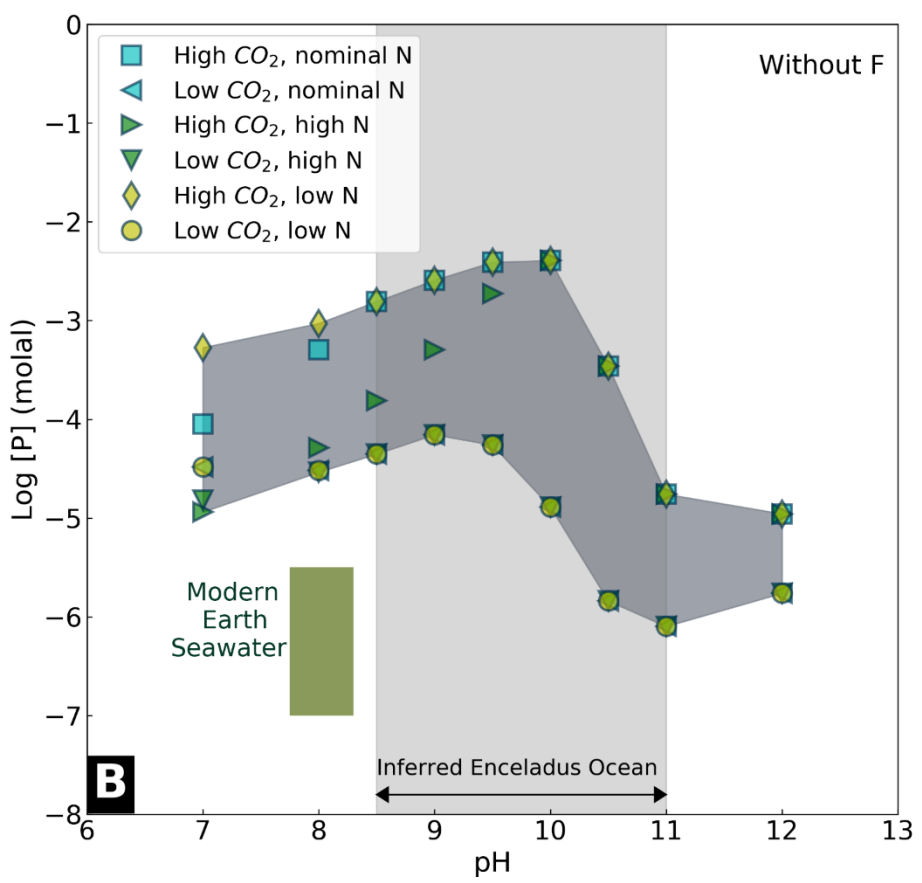


- **P as a limiting nutrient for ocean bioproductivity**

P was originally expected to be scarce, but we predicted it to be abundant in Enceladus's ocean



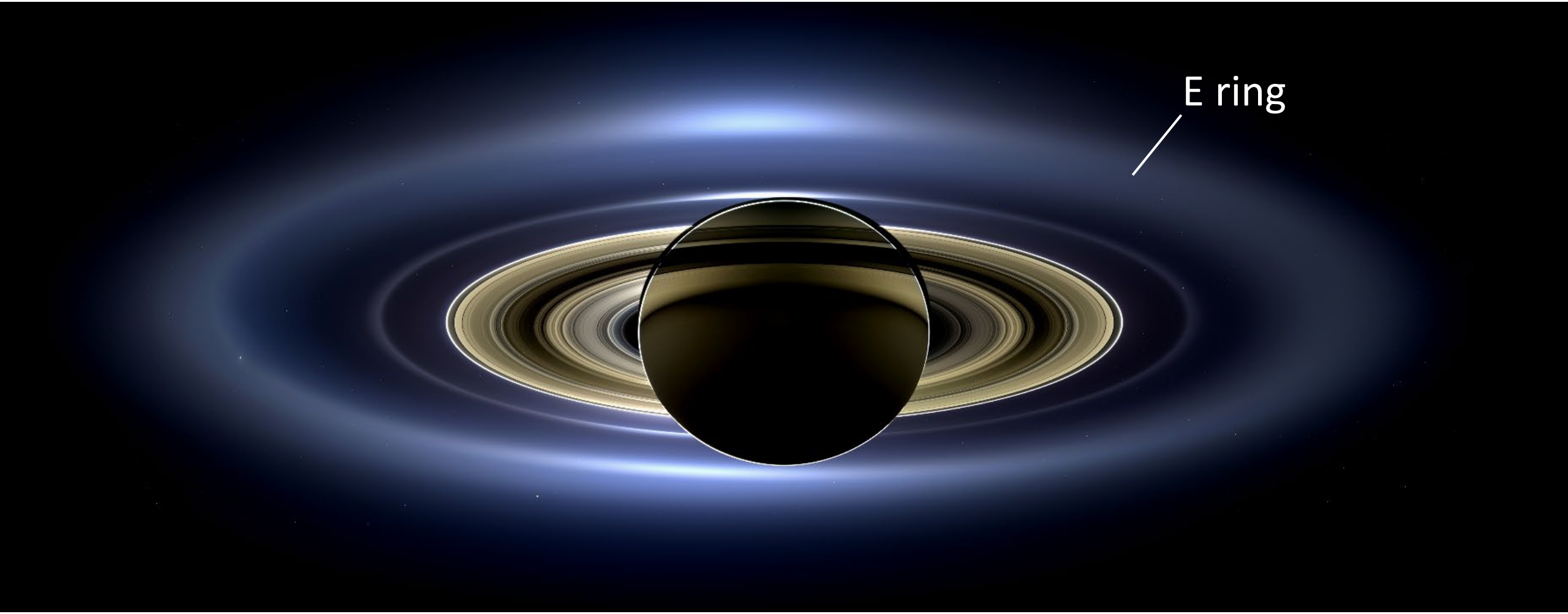
Simple models of equilibrium between aqueous alteration minerals and ocean water

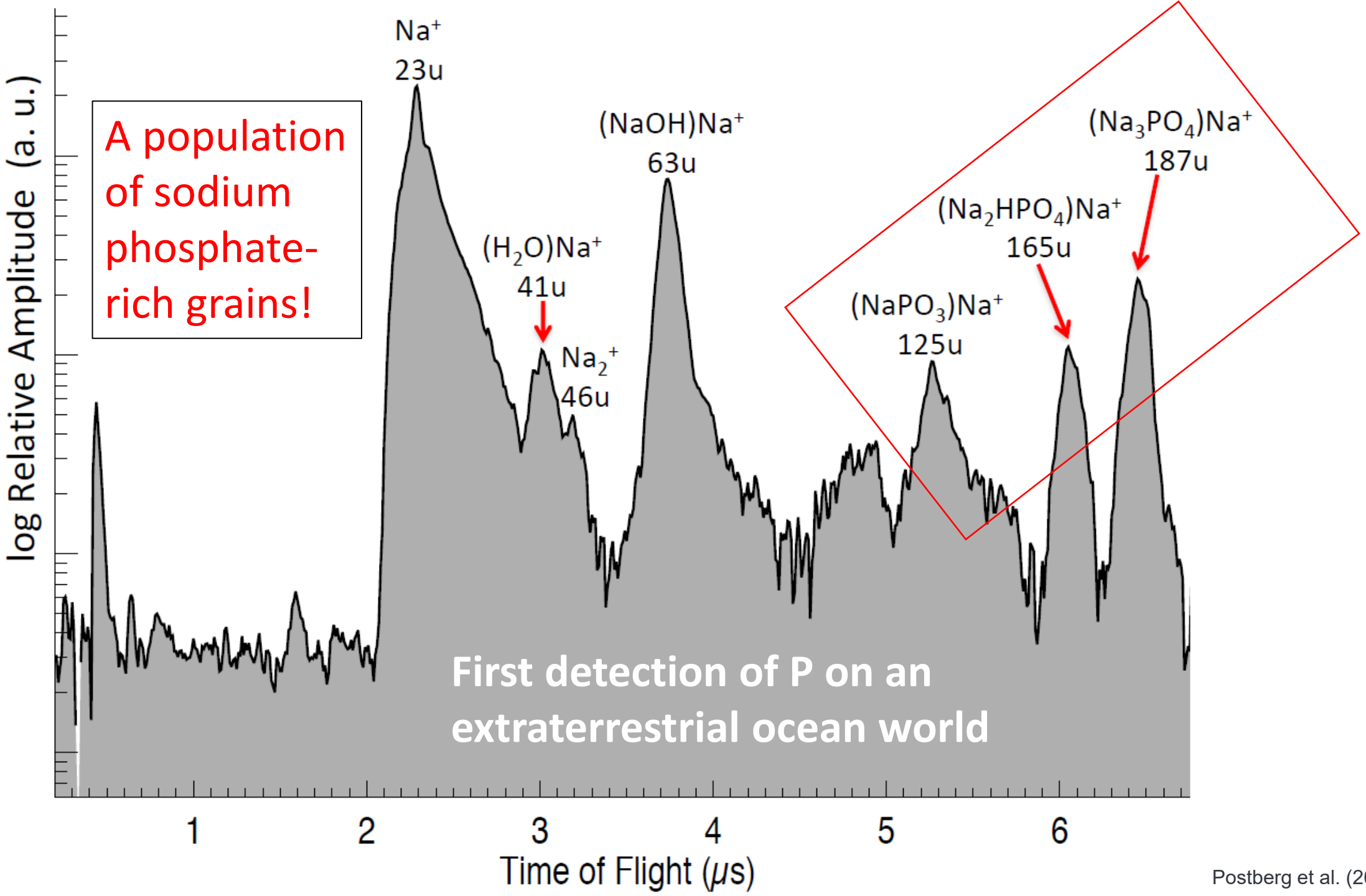


P level in Enceladus ocean water is likely higher or at least comparable to modern seawater. Seawater is known to contain enough P to support life

Hao et al. (2022)

Testing the geochemical model with observational data

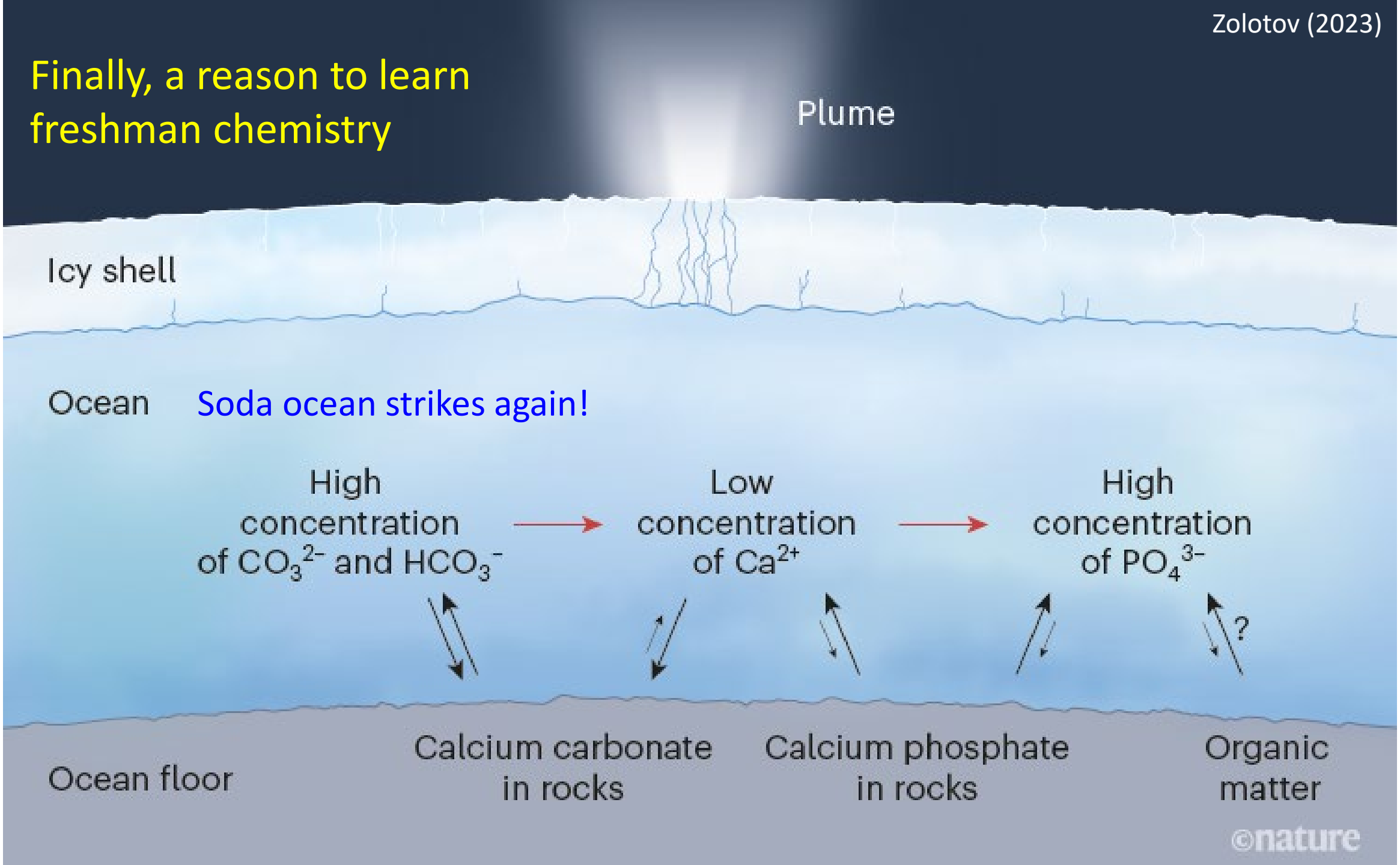




Postberg et al. (2023)

Zolotov (2023)

Finally, a reason to learn freshman chemistry

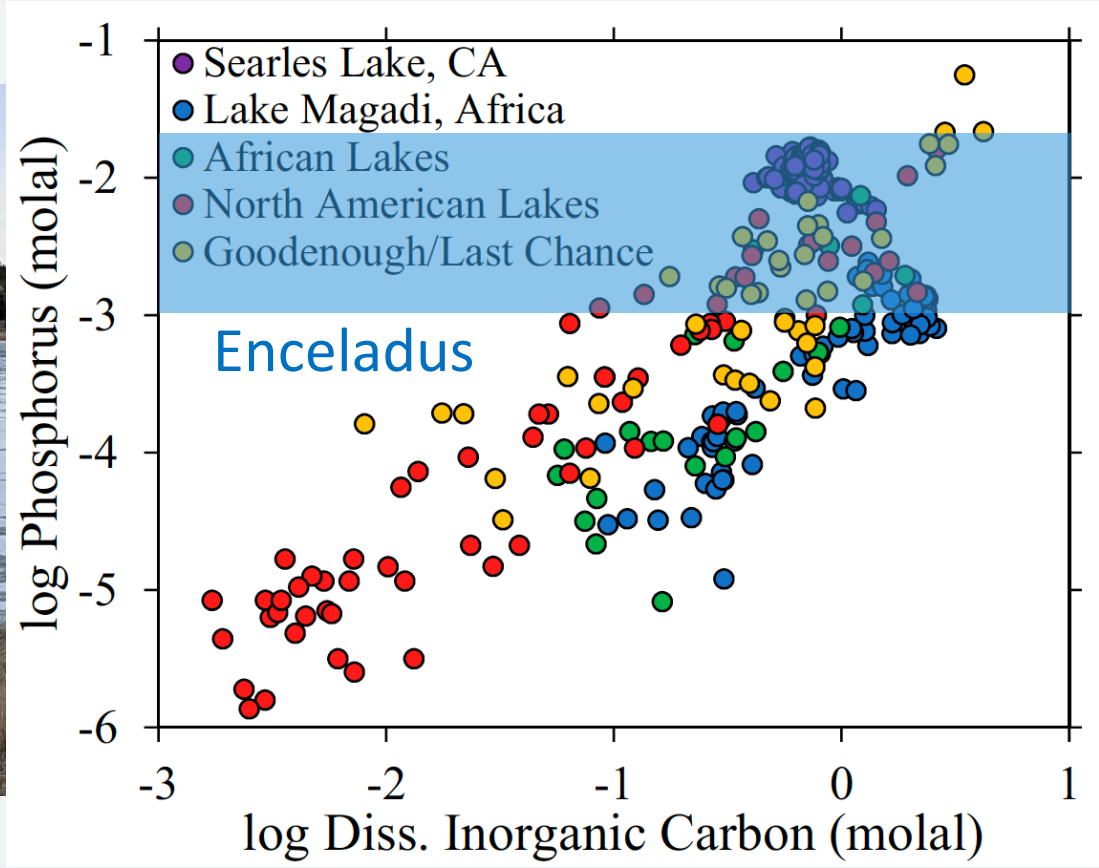


High P observed in modern Earth alkaline lakes
(potential geochemical analogues of Enceladus's ocean)

High levels of dissolved carbonate allow high dissolved P

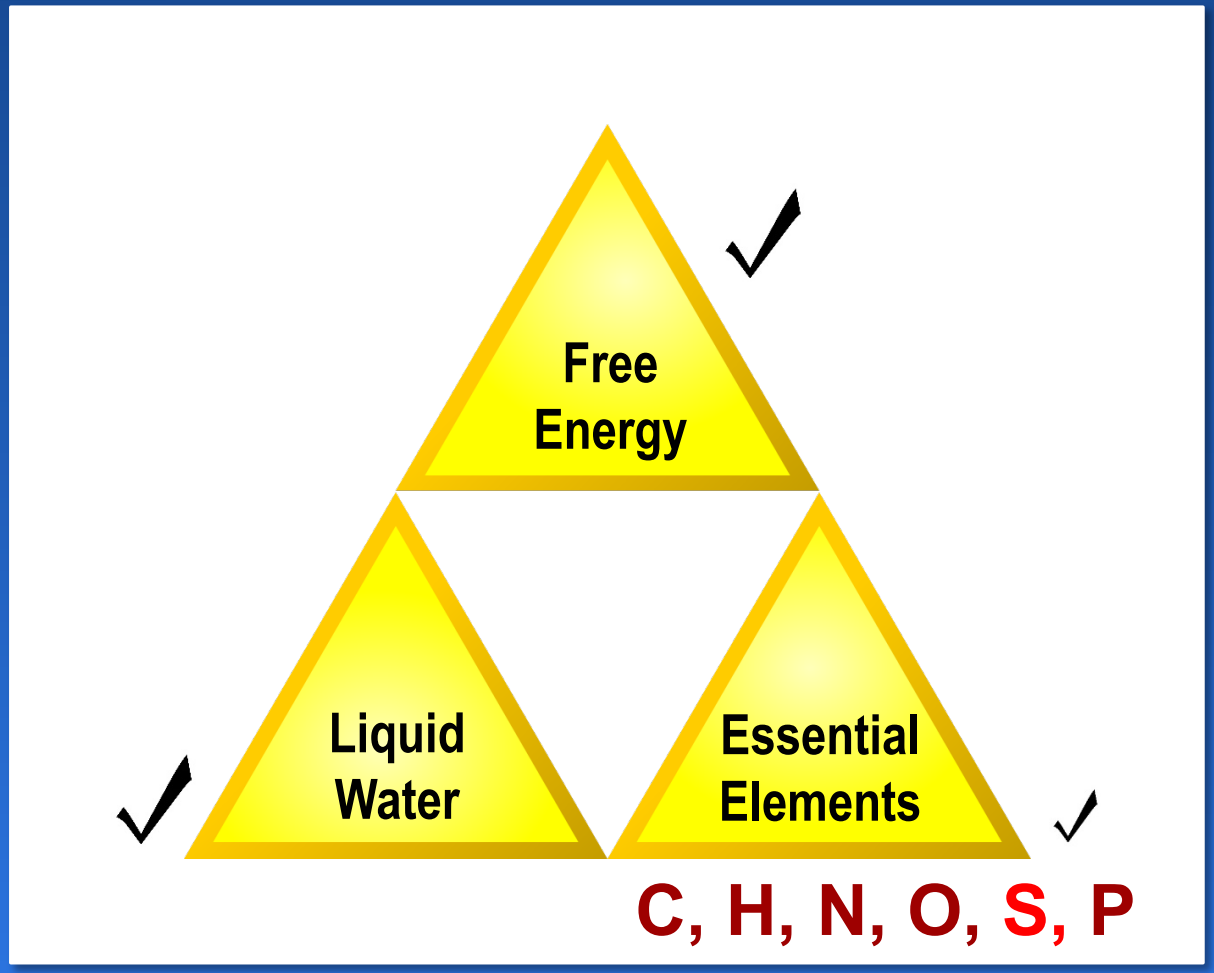
Soda ocean, meet soda lake

Haas et al. (2024)



Toner & Catling (2019)

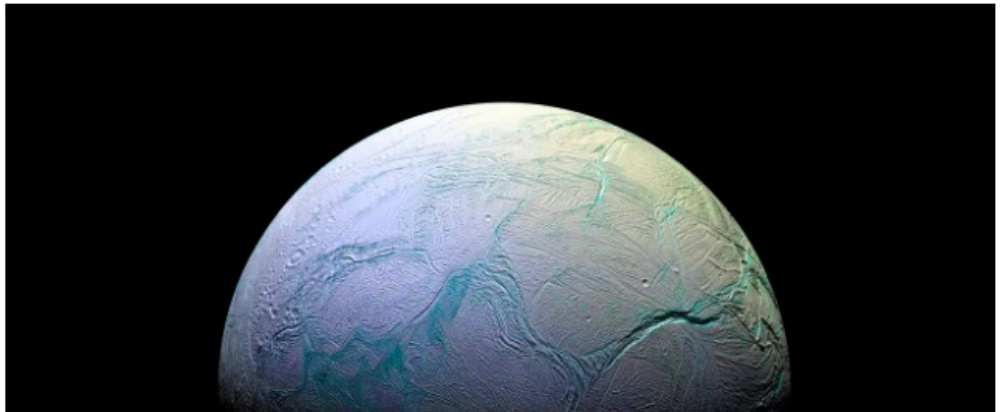
Today's View of Enceladus Habitability



BREAKING NEWS

One Of Saturn's Moons Discovered To Have All The Ingredients For Mouthwatering Enchiladas

Published June 15, 2023

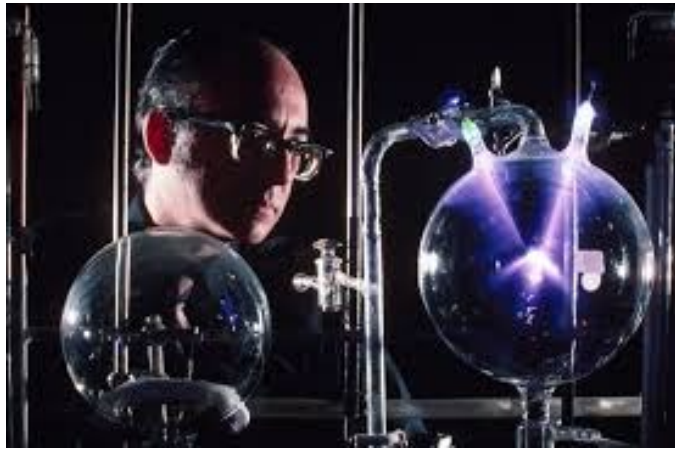


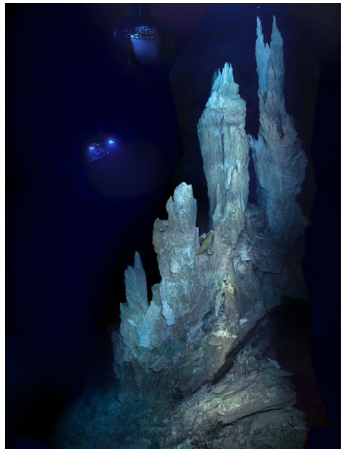
PASADENA, CA—Analyzing a baking dish with cheese crusted on the sides sent back from NASA's Cassini spacecraft, scientists confirmed Thursday that one of Saturn's 146 moons contained all the ingredients necessary for making enchiladas. "We have found legitimate proof of the basic elements that make up enchiladas here on one of Saturn's moons," said NASA analyst Lillian Parikh, pointing out satellite-captured images of a far-off crevice on Enceladus, the gas giant's sixth-largest moon, where samples came back positive for trace amounts of diced green chilies and shredded chicken. "Earlier research indicated that both red and green sauce should be scarce on extraterrestrial ocean worlds like this one, which would prevent any life from forming the recipe for enchiladas independently of Earth, but we found the opposite to be true on this particular moon, which appears to contain large deposits of masa. Planetary researchers had previously only speculated the existence of the optional garnishes sometimes paired with the classic Mexican dish in this area of outer space, like green onions, black olives, and sour cream, but it was never enough to prove definitively that it could support a full pan of enchiladas. I do feel I need to specify that, though certainly a monumental breakthrough, there are only enough of these particles in the Enceladus atmosphere to feed maybe four to six people." At press time, President Joe Biden had reportedly commented that the discovery would completely change the way Americans create easy weeknight dinners in space.

Inhabited?

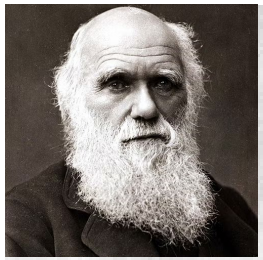
Is the origin of life hard?

- Fundamental to the Drake equation (f_l)
- We don't know how life started on Earth
- After some early successes, progress has slowed over the past ~20 years
- We need new clues!
- Exploration as an antidote to the doldrums
- If organic chemistry in water driven by hydrothermal flows of energy inevitably leads to life, then Enceladus should host life
- If more specific conditions are needed, then lack of evidence of life on Enceladus would provide clarity on what those conditions might be
- A negative result is still useful!
- Searching for life on habitable worlds will shed light on the origin of life
- Let's go look!

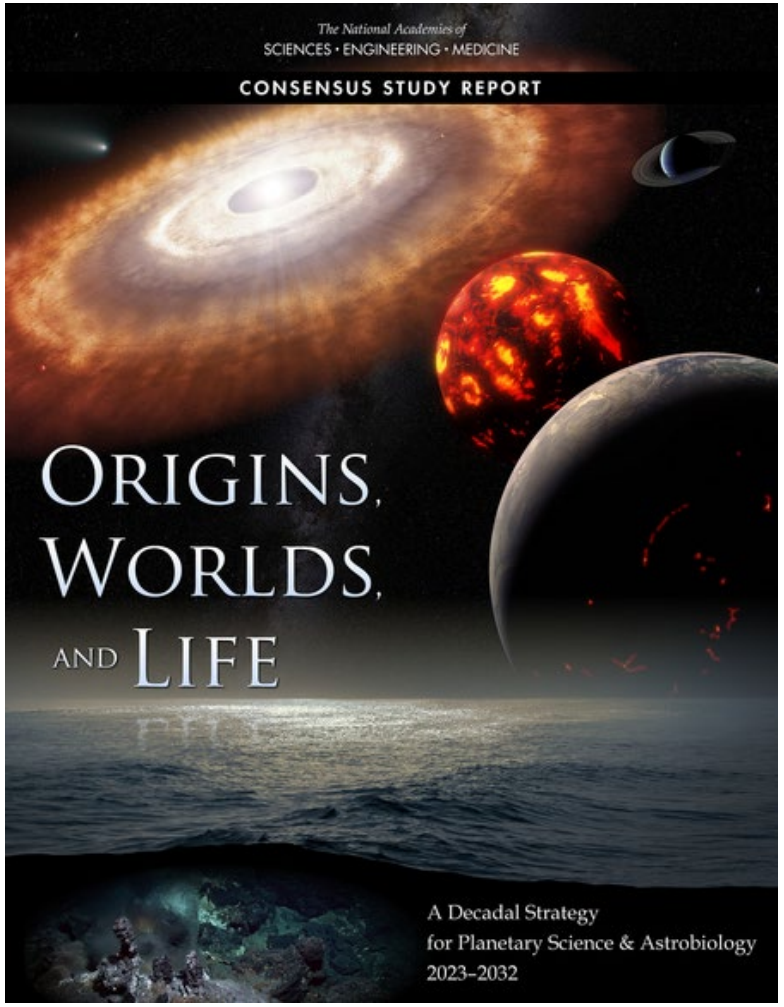




Darwin's Voyage



Getting back to Enceladus starts now



The second highest priority new Flagship mission for the decade 2023-2032 is the Enceladus Orbilander. Enceladus is a small, active ice world in which gas and particles from its subsurface ocean are being jetted into space. Conditions at Enceladus thus allow for direct investigation of the habitability of an ocean world and assessment of whether or not it is inhabited. This addresses one of the most fundamental questions in solar system science: is there life beyond Earth and if not, why not?

TABLE 22.3 Comparison of Representative Programs

Recommended Program	Level Program
Continue Mars Sample Return	Continue Mars Sample Return
Five new Discovery selections at recommended cost cap	Five new Discovery selections at recommended cost cap
Support LDEP with mid-decade start of Endurance-A	Support LDEP with mid-decade start of Endurance-A
R&A increased by $1.25 billion	R&A increased by $730 million
Continue Planetary Defense Program with NEO Surveyor and a follow-on NEO characterization mission	Continue Planetary Defense Program with NEO Surveyor and a follow-on NEO characterization mission
Gradually restore MEP to pre-MSR level with late decade start of Mars Life Explorer	radually restore MEP to pre-MSR level in late decade with no new start for Mars Life Explorer
New Frontiers 5 (1 selection) New Frontiers 6 (2 selections)	New Frontiers 5 (1 selection) New Frontiers 6 (late, or not included)
Begin Uranus Orbiter and Probe in FY24	Begin Uranus Orbiter and Probe in FY28
Begin Enceladus Orbilander in FY29	No new start for Enceladus Orbilander this decade

L4 to Enceladus

EXPLORING THE HABITABILITY OF SATURN'S ICY MOONS

- Approved by ESA and funded for development
- Detailed study now underway
- Orbiter and lander(!)

- Mission adoption ~2034
- Launch ~2042
- Saturn arrival early 2050s

- Visit Joern Helbert's poster for more info: Tue 2:15-5:45 pm

Explore ocean composition and core dynamics:
What is the composition of the subsurface ocean and how does it interact with the moon's core?

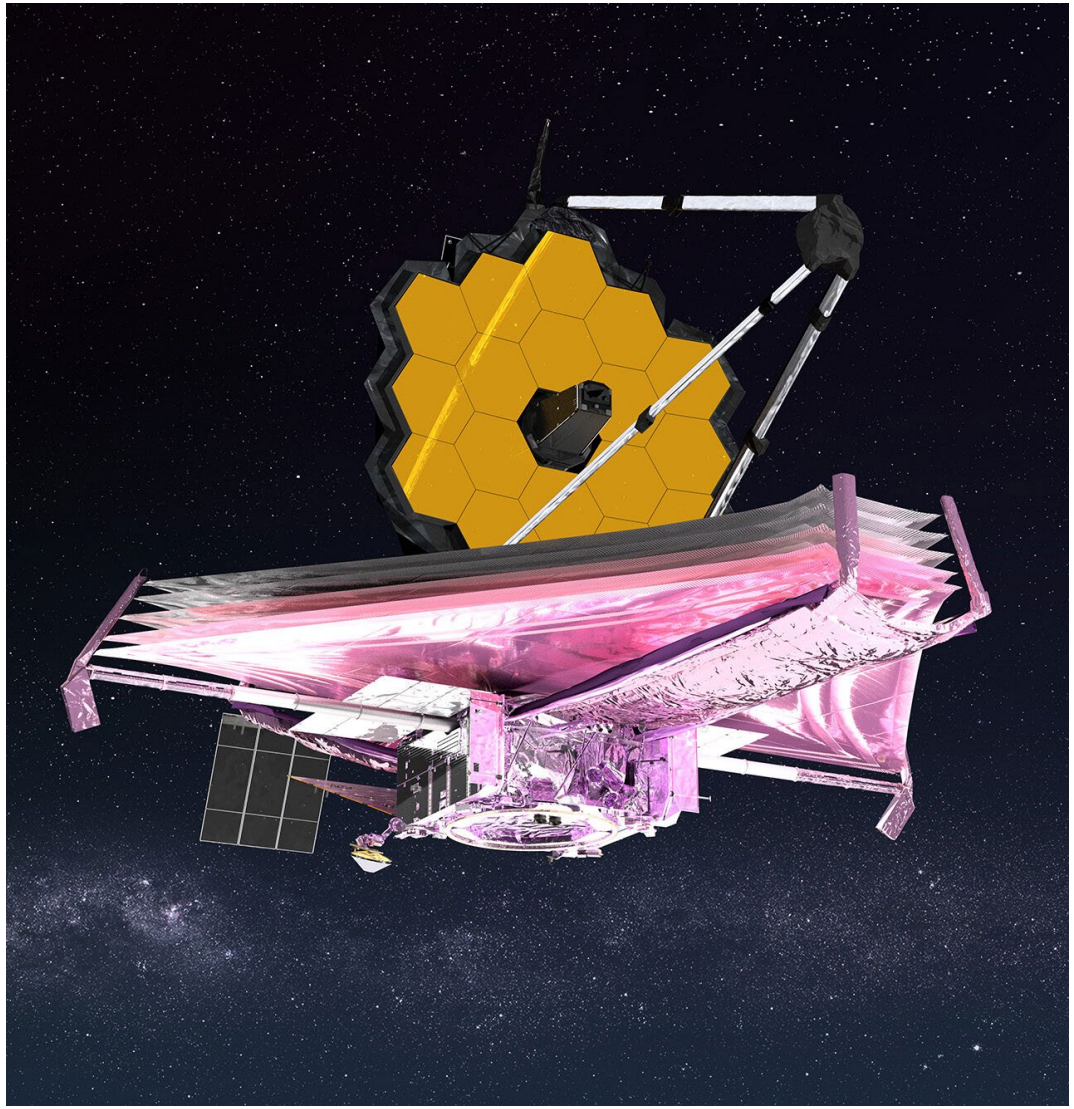
Assess external impacts on habitability:
How does the external environment, including radiation and tidal forces, affect the potential for life?

Search for prebiotic chemistry and biosignatures:
Is there evidence of prebiotic molecules or signs of life in the subsurface or surface materials?


LAUNCH WITH TWO ARIANE 6 ROCKETS
ASSEMBLE IN SPACE
JOURNEY TO SATURN
ORBIT SATURN
esa
TITAN
RHEA
DIONE
TETHYS
ENCELADUS
MIMAS
FLY BY SATURN'S ICY MOONS
SAMPLE PLUMES
ORBIT ENCELADUS
In 2058, let's remember
"Extraordinary claims require extraordinary evidence"
LAND ON THE SOUTH POLE OF ENCELADUS

That sounds great, but I really don’t want to wait until 2050 (I’ll be nearly 70, yikes!) to get new data back from Enceladus. What can we do?

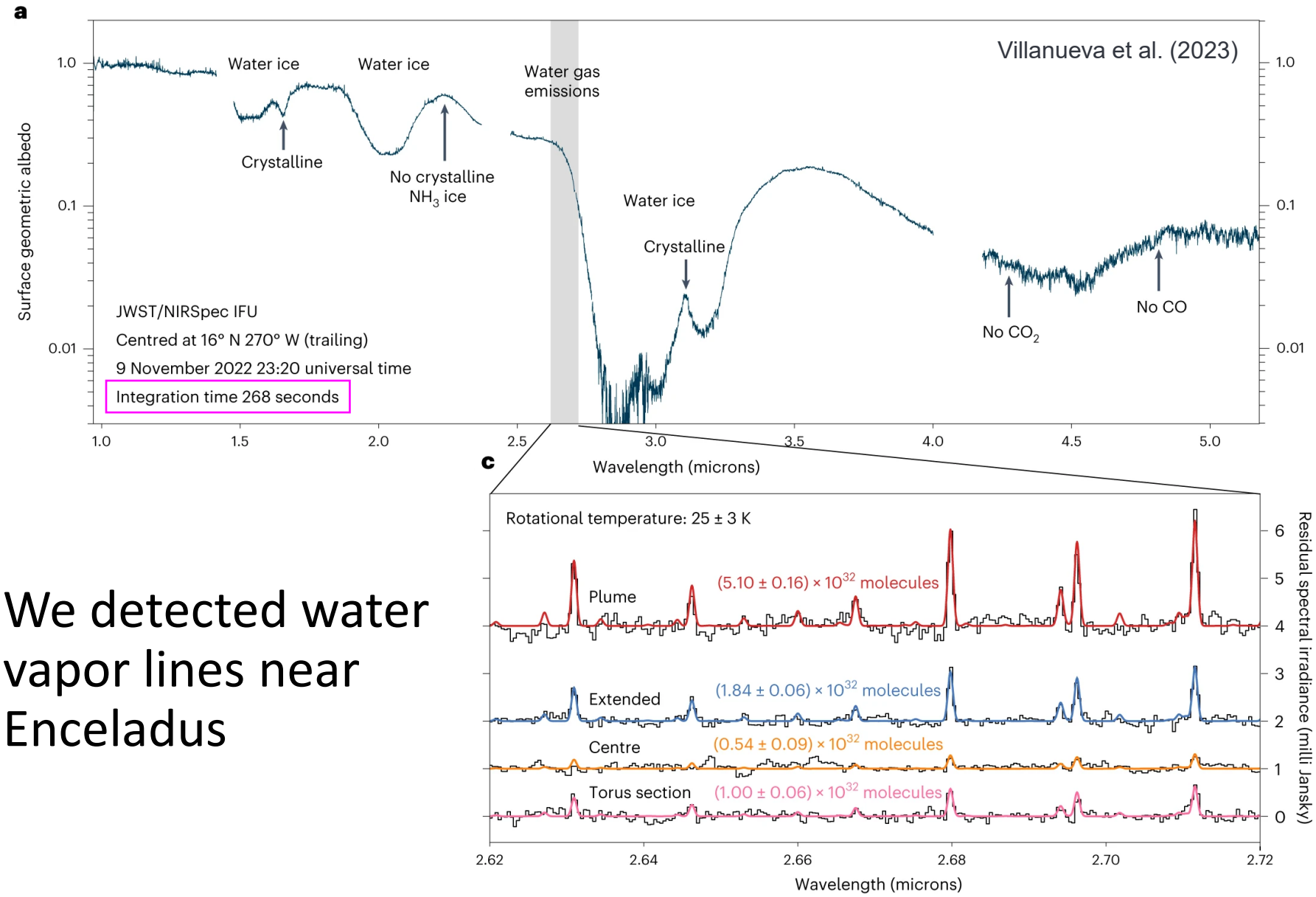
James Webb Space Telescope (JWST)



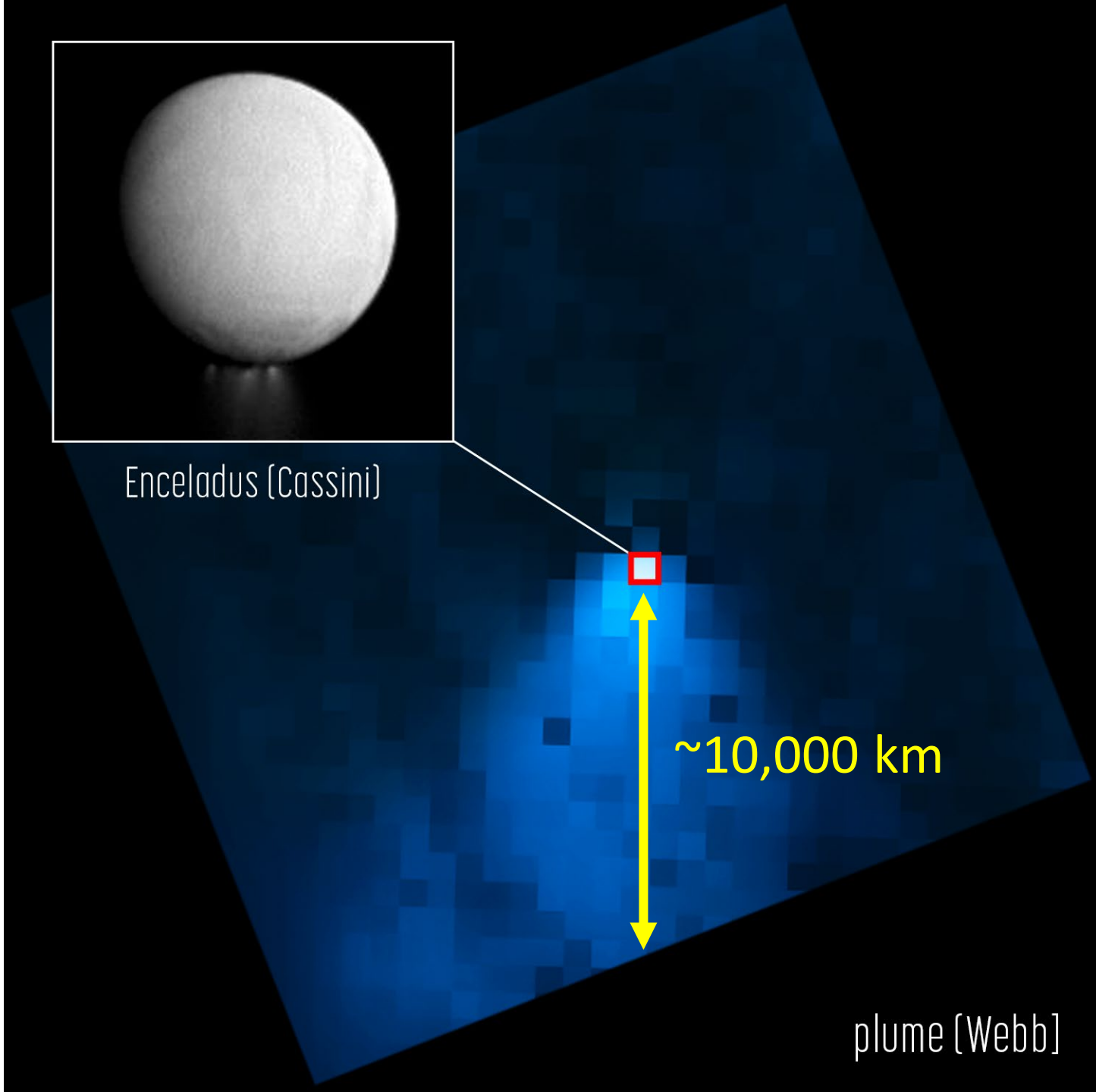
Our current “mission” to Enceladus

James Webb Space Telescope (JWST)

- A team led by Geronimo Villanueva observed Enceladus in November 2022
- We mainly focused on analyzing near-infrared (~1-5 µm) spectra
- We detected water vapor lines near Enceladus



- JWST can see the plume!
- JWST's unique view revealed that the plume is much more extensive than what Cassini could map
- We also found that the outgassing rate is remarkably consistent with determinations from the Cassini era (~300 kg/s)
- "Cold faithful" over at least 2005 – 2024

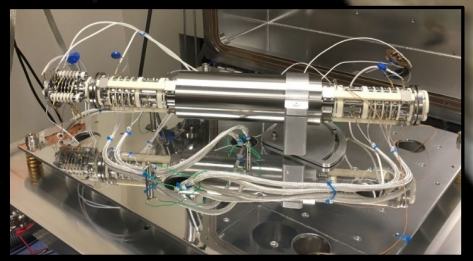


In the 2030s, another ocean world awaits

Europa Clipper
Habitability mission

What does Europa smell like?

MAss Spectrometer for Planetary EXploration (MASPEX)



Our next voyage has already begun

Come to the Europa session on Thursday afternoon to hear the latest!

On a more serious note

- "There is no way back into the past; the choice is the universe—or nothing.” – Arthur C. Clarke & H. G. Wells

On a more serious note

- "There is no way back into the past; the choice is the universe—or nothing." – Arthur C. Clarke & H. G. Wells
- We have come so far in only 400 years. A slow, self-correcting process brought us to the shore of a distant ocean. We will see many more.

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- We have come so far in only 400 years. A slow, self-correcting process brought us to the shore of a distant ocean. We will see many more.
- We are responsible for the candle of science. Keep it burning bright and ready to pass on.

On a more serious note

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- Never stop dreaming, exploring, and questioning. Aim farther than the last generation, even when it gets hard.

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- Leave a mark on this world (or another) that will make posterity proud.

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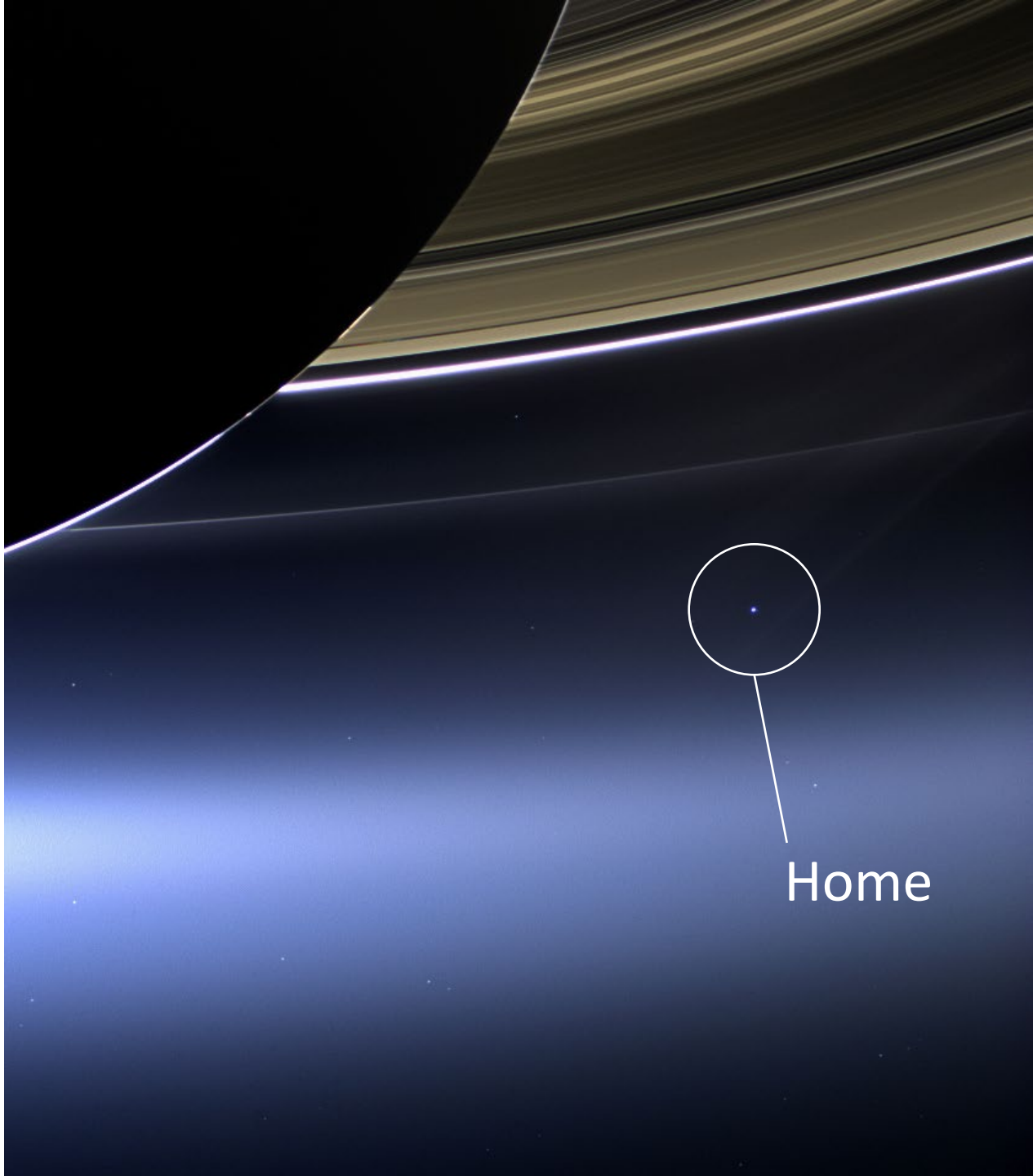
- Leave a mark on this world (or another) that will make posterity proud.
- We are one world.



- We are living in a golden age of seafaring in space, discovering oceans and characterizing their basic properties.
- Saturn's moon Enceladus can teach us about how the geochemistry of an ocean world affects its prospects to support life.
- The high abundance of H_2 coexisting with CO_2 establishes an energy source for potential microbial methanogenesis.
- Enceladus has a lot of P in its ocean, as a consequence of equilibrium chemistry between calcium carbonate and apatite in a soda ocean.
- Enceladus satisfies the general requirements for life as we know it – a global ocean of liquid water, almost all of the key chemical elements (H_2S detection is tentative), and abundant energy.
- Daring new missions are being planned to search for signs of life on Enceladus. The search will allow us to test hydrothermal hypotheses for the origin of life.
- In the meantime, we can stretch our sea legs with JWST and pursue comparative oceanography with Europa Clipper.