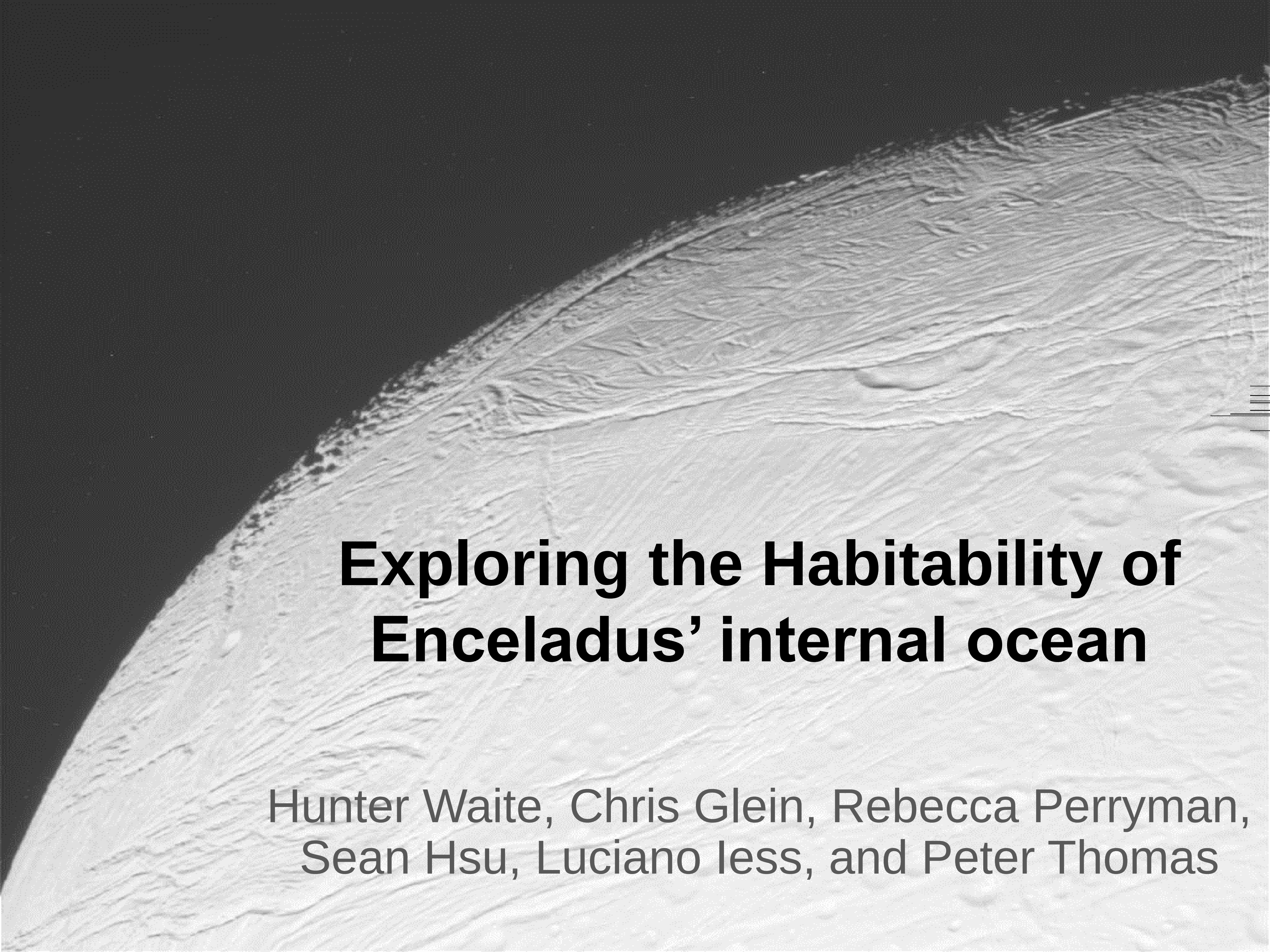
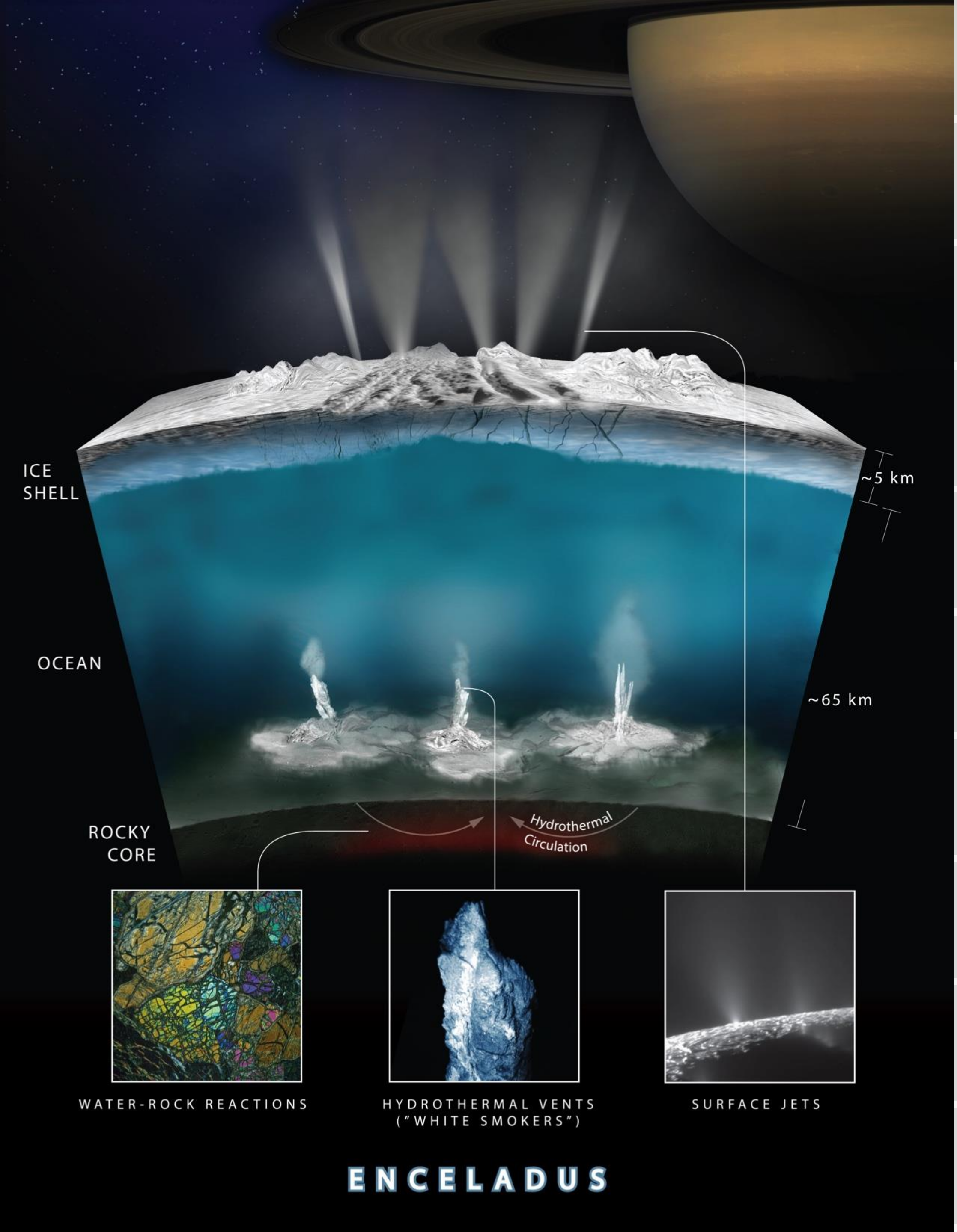


Exploring the Habitability of Enceladus' internal ocean

Hunter Waite, Chris Glein, Rebecca Perryman, Sean Hsu, Luciano Iess, and Peter Thomas



HABITABILITY

Past Observations of Enceladus

Salts

Complex Organics

Recent Observations of Enceladus

Global Oceans: Geysers

Global Oceans: Internal Structure

Hydrothermal Systems: Silica

Hydrothermal Systems: H_2

Summary

What Defines Habitability?

NASA's Astrobiology Roadmap:

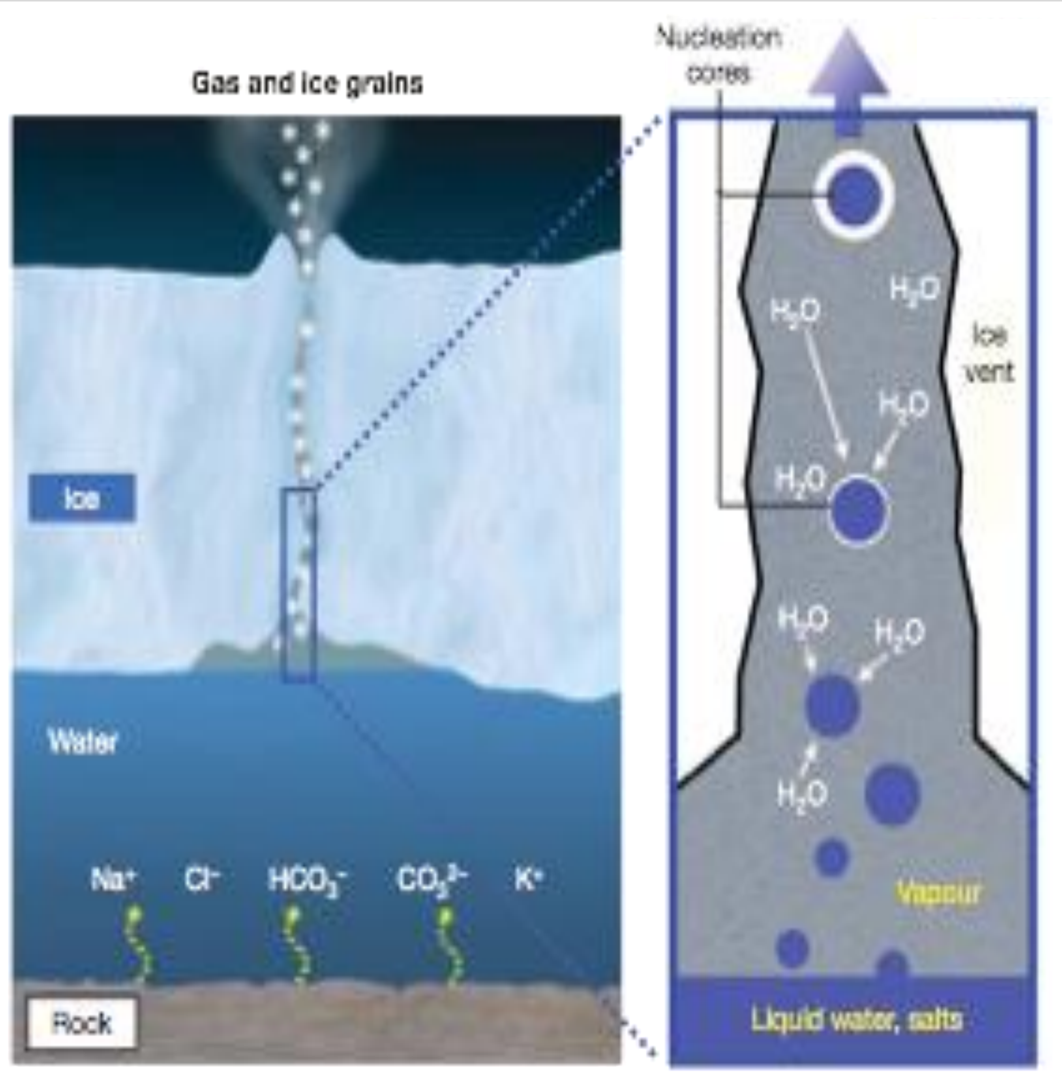
1. Extended regions of liquid WATER
2. Conditions favorable to the assembly of complex ORGANIC MOLECULES
3. ENERGY SOURCES to sustain metabolism

What we knew about Enceladus Habitability at the time of the Decadal

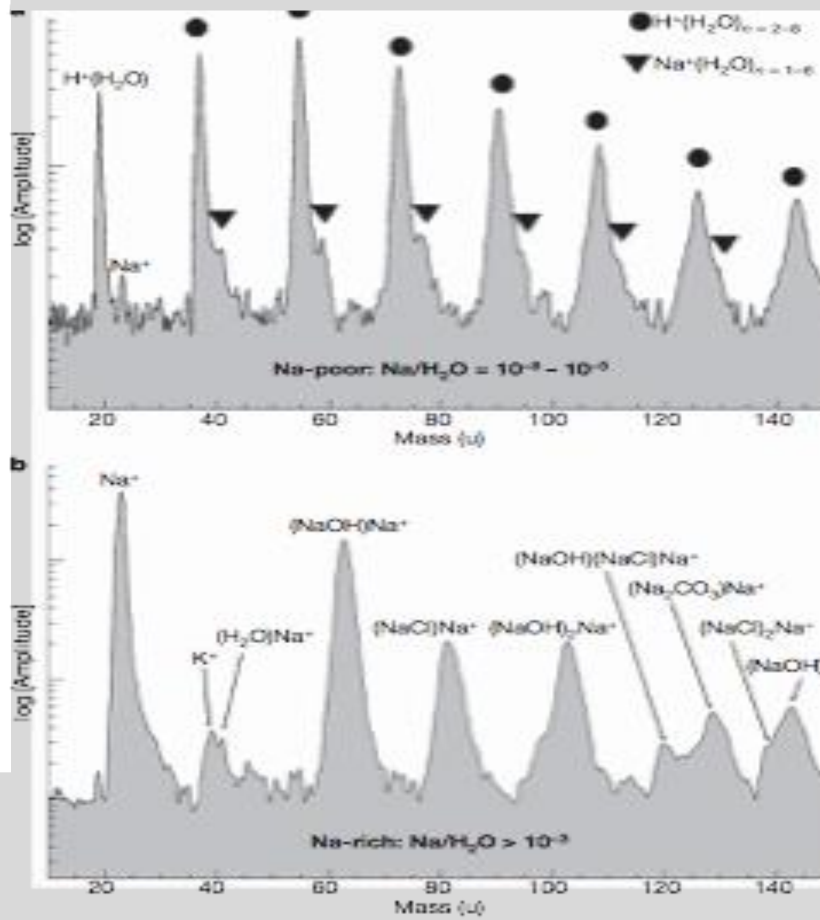
Salts as an indication of INTERIOR WATER

The existence of COMPLEX ORGANICS

A subsurface ocean in contact with the rocky core



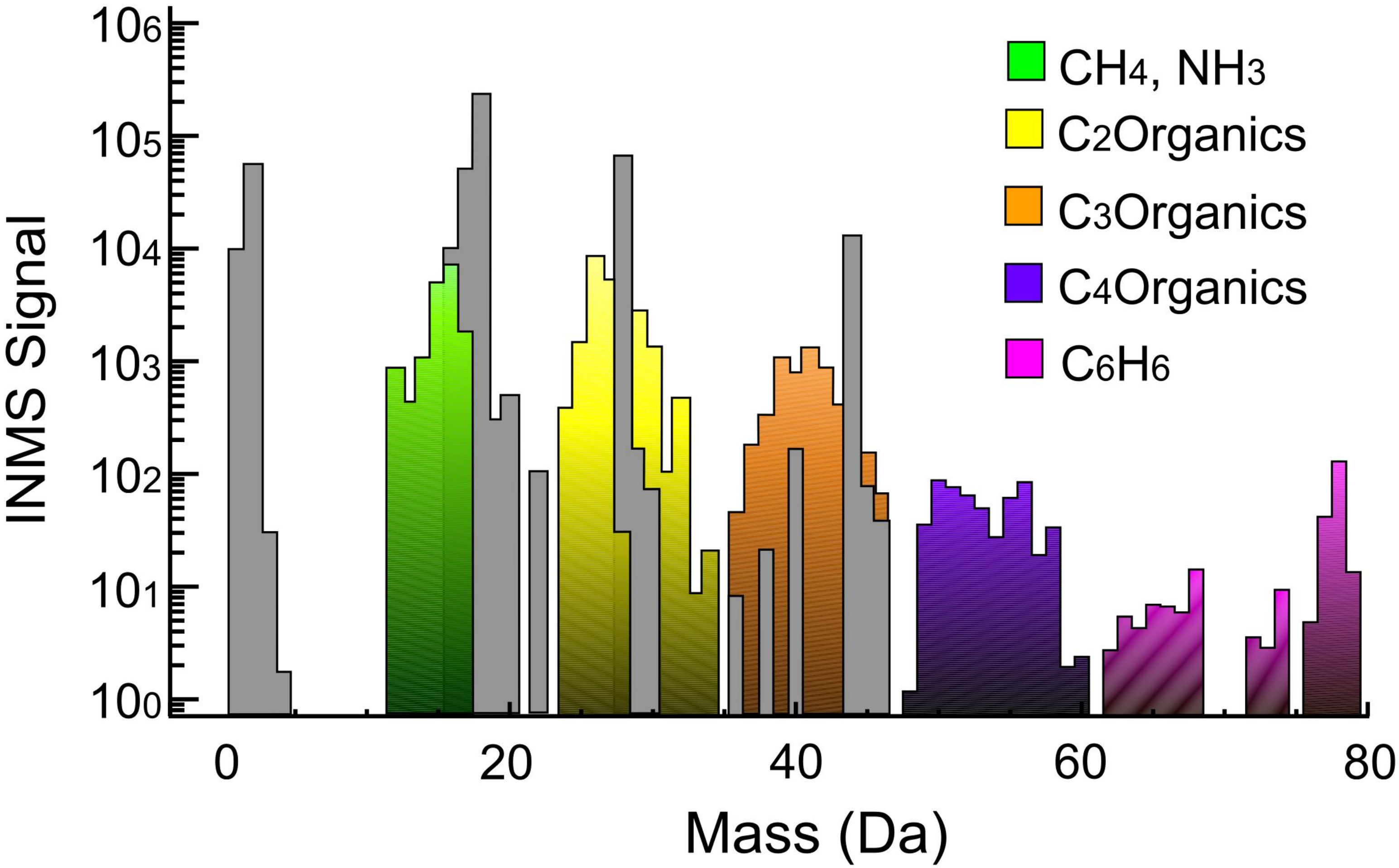
NaCl	~ 0.5 – 1.0%
NaHCO3	~ 0.2 – 0.5%
pH	~ 8.5 – 9



Postberg et al. 2009, 2011

Species
H_2O
CO_2
CO
H_2
H_2CO
CH_3OH
C_2H_4O
C_2H_6O
H_2S
^{40}Ar
NH_3
N_2
$HCN^{\dagger}$
CH_4
C_2H_2
C_2H_4
C_2H_6
C_3H_4
C_3H_6
C_3H_8
C_4H_2
C_4H_4
C_4H_6
C_4H_8
C_4H_{10}
C_5H_6
C_5H_{12}
C_6H_6

Organics at Enceladus



What we have learned about Enceladus Habitability after the time of the Decadal

WATER: Global Oceans

ENERGY SOURCE: Hydrothermal Systems

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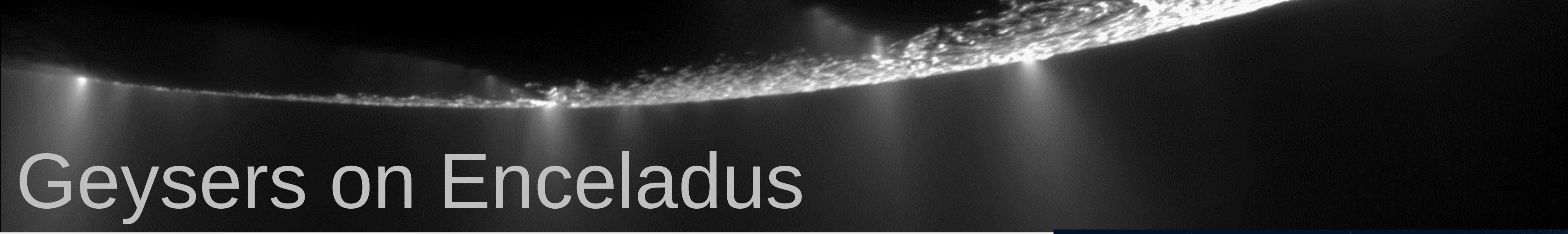
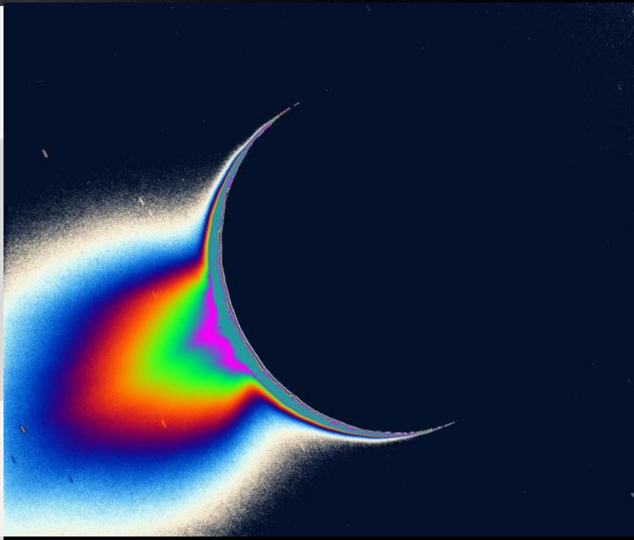
WATER: Global Oceans

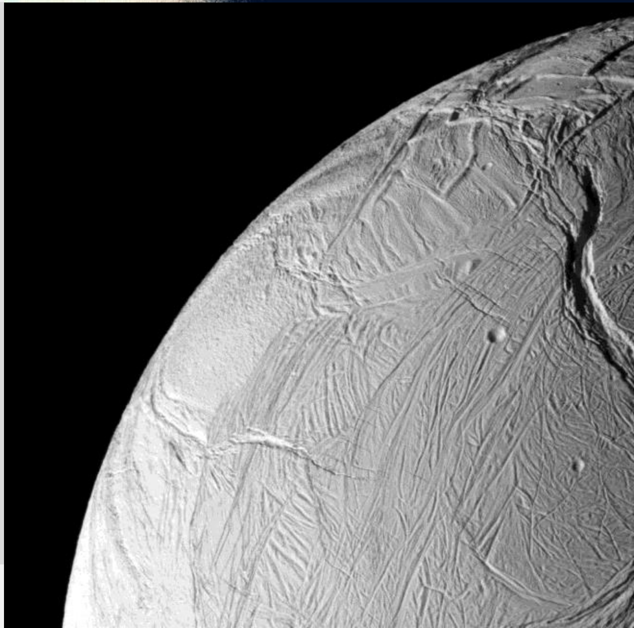
ENERGY SOURCE: Hydrothermal Systems



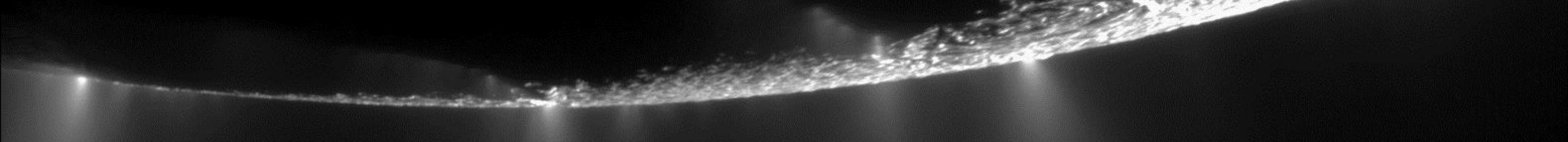
Geysers on Enceladus



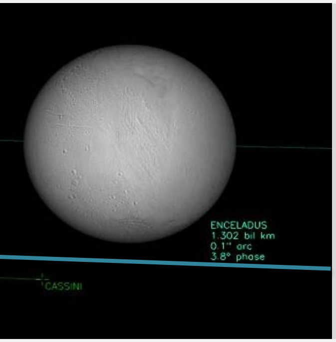
Enceladus Radius: 252 km
5 GW thermal power



Can gravity measurements help unveil the interior structure of the tiny moon?



Cassini Enceladus Observations

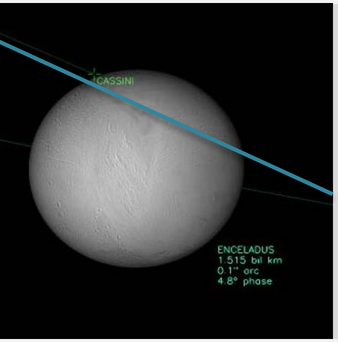


E9 Flyby

Closest Approach = 28-APR-2010 00:10:17 UTC

Altitude ≅ 100 km, Lat ≅ -89° Incl. ≅ 85°

Relative velocity ≅ 6.5 km/s, SEP angle ≅ 141°

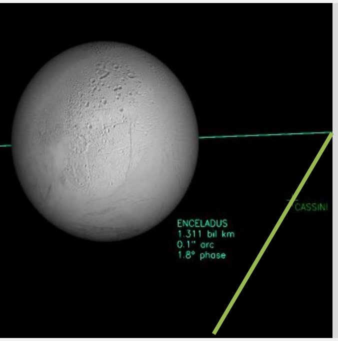


E12 Flyby

Closest Approach = 30-NOV-2010 11:53:59 UTC

Altitude ≅ 48 km, Lat ≅ 62° Incl. ≅ -62°

Relative velocity ≅ 6.3 km/s, SEP angle ≅ 54°

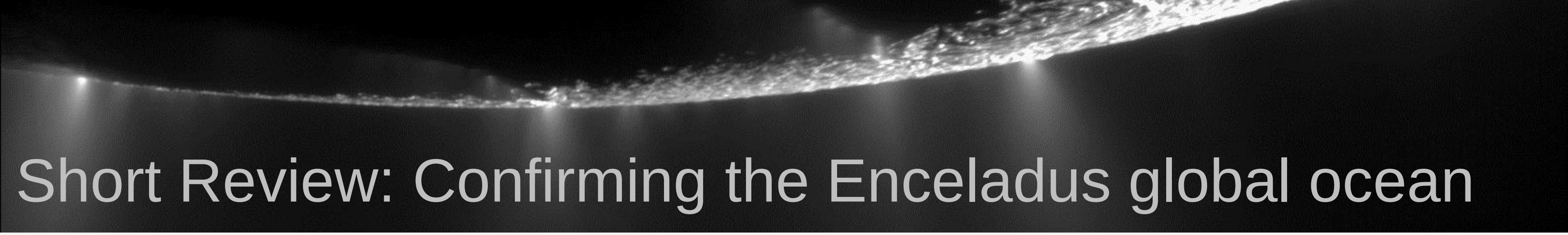


E19 Flyby

Closest Approach = 2-MAY-2012 09:32:34 UTC

Altitude ≅ 70 km, Lat ≅ -72° Incl. ≅ 108°

Relative velocity ≅ 7.5 km/s, SEP angle ≅ 162°

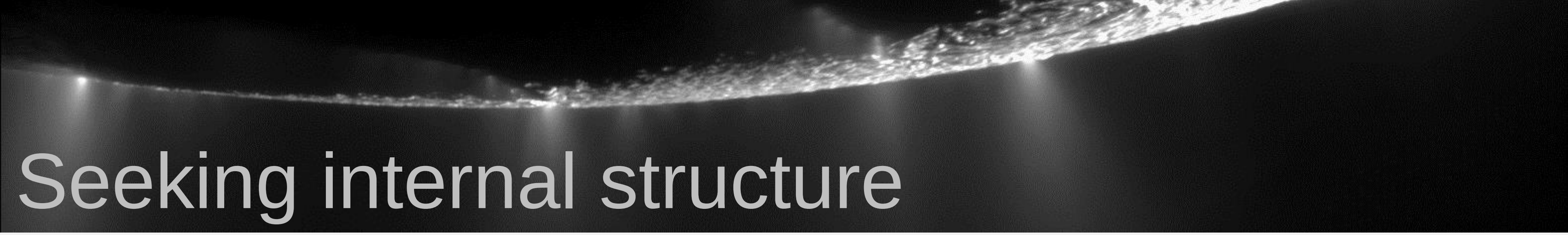


Short Review: Confirming the Enceladus global ocean

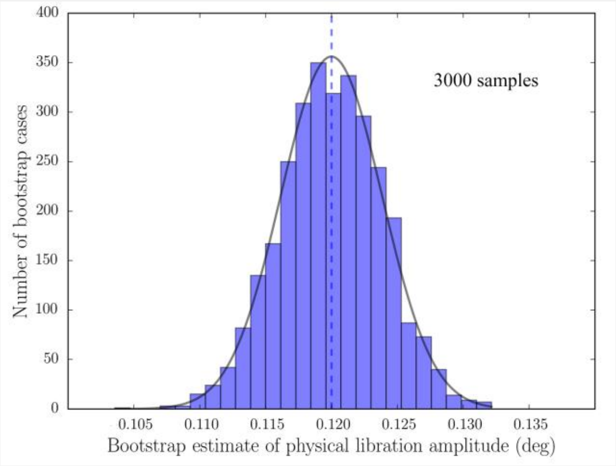
Early Cassini data showed that Enceladus had erupting material from the south polar region, and further sampling and analysis indicated a liquid water reservoir as the ultimate source.

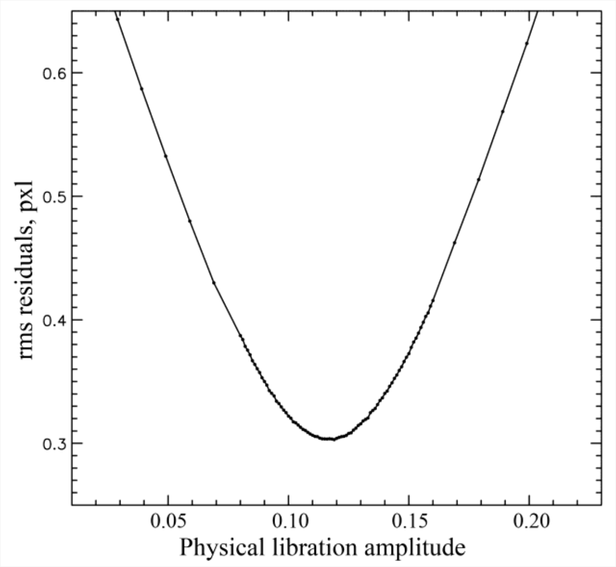
Gravity analysis is consistent with local reservoir (Iess et al., 2014) an with reinterpretation is consistent with a thin global liquid layer (McKinnon 2015).

Possible dynamical implications of maintaining an ocean on such a small object was a strong motivation to get better constraints on the interior of Enceladus, especially the extent of the liquid reservoir.



Seeking internal structure



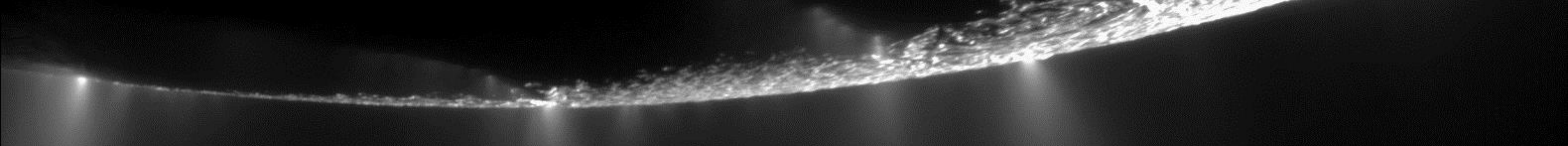


One route to interior structure is the physical libration amplitude which can indicate whether the object's surface is rigidly connected to the interior. (Van Hoolst et al., 2009 etc,)

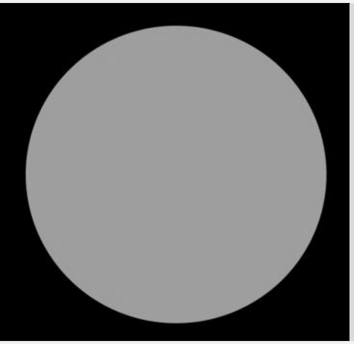
Basically, if a surface shell is not rigidly connected to the remainder, it will be subject to larger forced libration than a fully rigid object.

Cassini's long orbital tour provides multiple observations throughout Enceladus' orbit, thus allowing for accurate characterization of any forced libration.

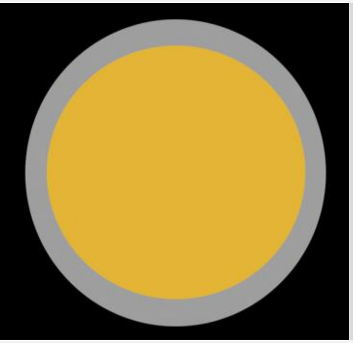
Physical libration = $0.12 \pm 0.014^\circ$ (3σ)



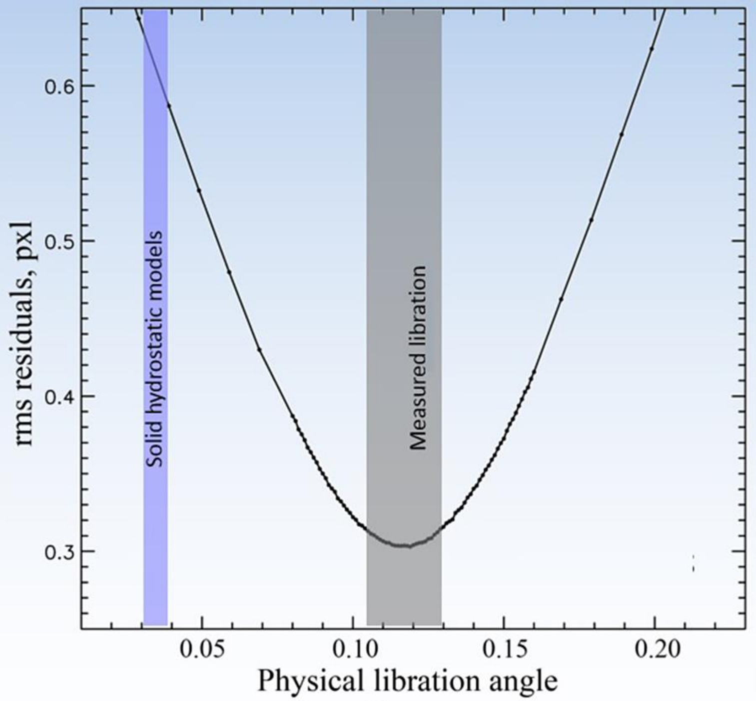
Meaning of libration amplitude: Solid Models



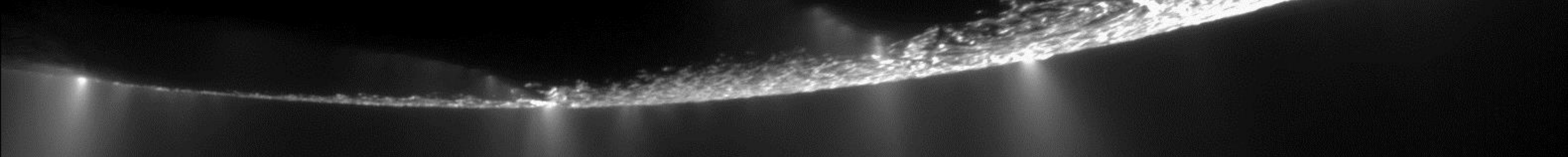
Homogeneous distribution of mass, depends only on the satellite’s measured shape:
$\gamma = 0.032°$



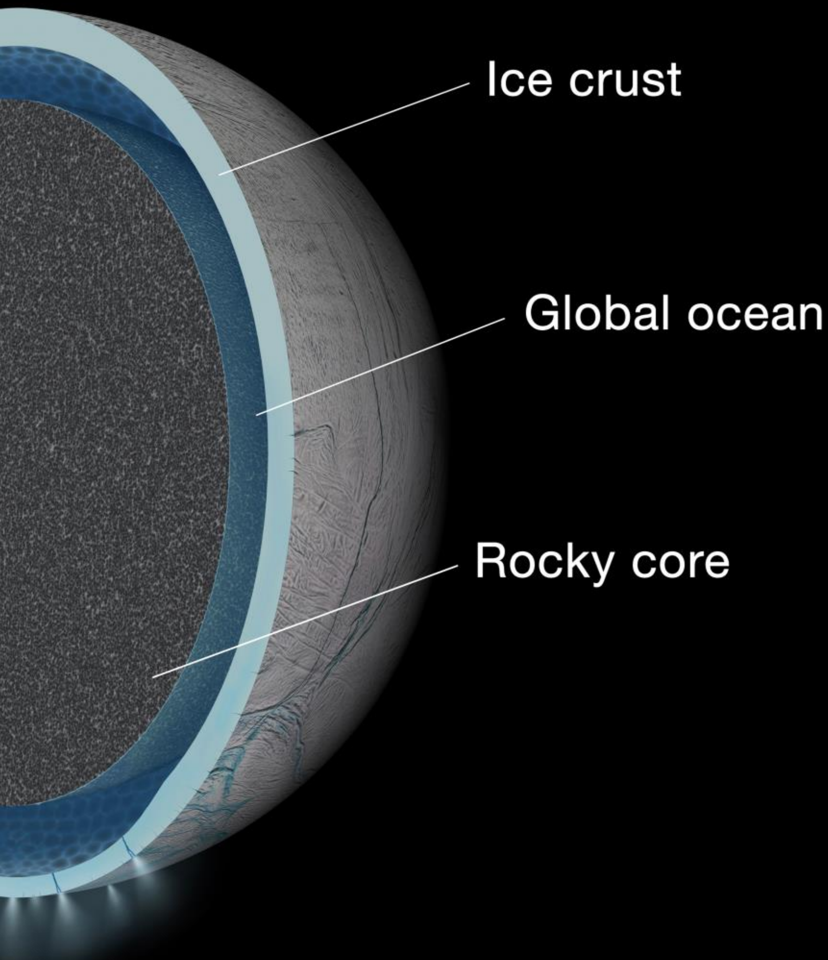
Two-layer in hydrostatic equilibrium:
$\gamma = 0.032° - 0.034°$
(Shell density: 700-930 kg/m^3
Core density: 2000-3300 kg/m^3)



None of the solid models tested were consistent with observed libration.



Global ocean model fits the measurements



Thickness of layers is not to scale.

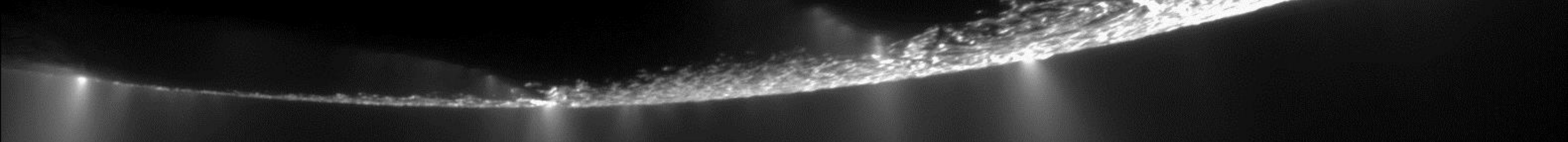
Interior Model	Amplitude of forced libration
Homogenous ellipsoid	0.032°
2-layer hydrostatic	0.032° - 0.034°
2-layer hydrostatic, including “polar sea” and depression	0.032° - 0.034°
Ellipsoidal core, global ocean, ellipsoidal shell (23 km) (2300, 1000, 850 kg/m³)	0.120°
Measured Value	**0.120° ± 0.014°(3σ)**

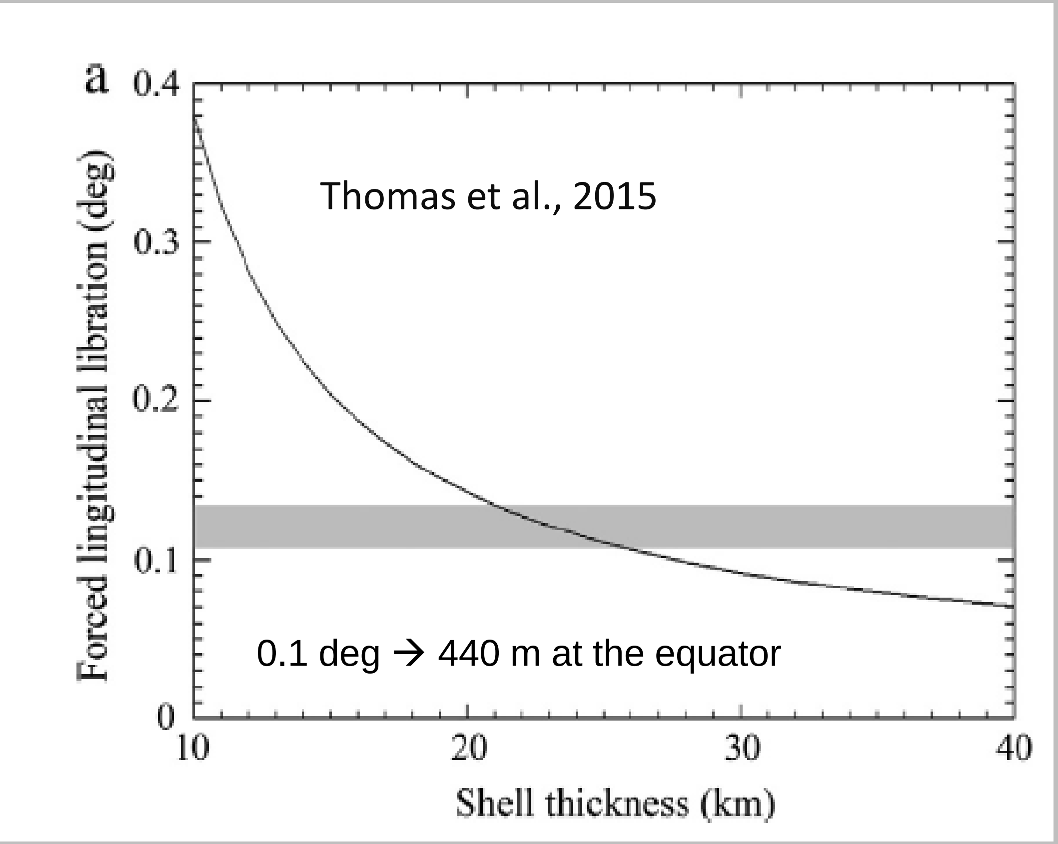
Ellipsoidal shape: 256.2, 251.4, 248.6 km

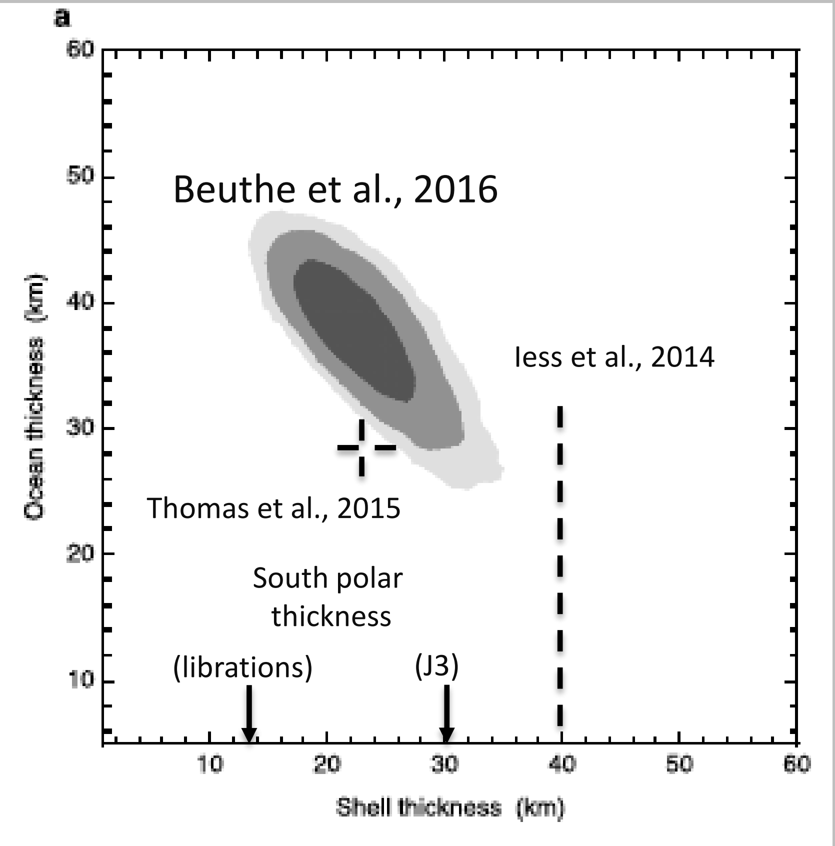
Thomas et al., 2016, Icarus 264, 27-47.

Libration measurements using ISS data confirmed suspicions that the liquid reservoir on Enceladus is global.

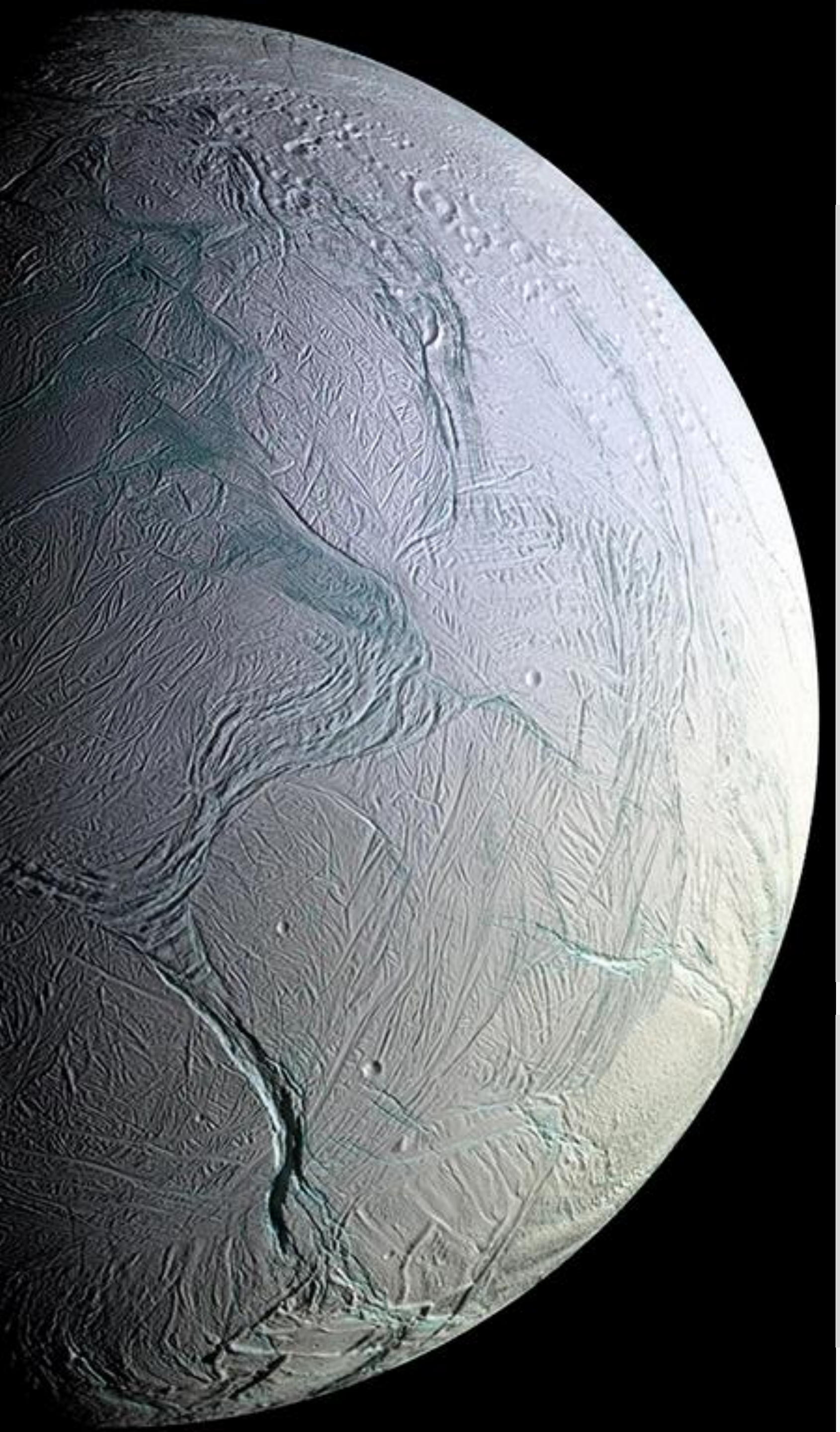
The tomography of Enceladus







Beuthe et al. reinterpreted the gravity and shape data using minimum stress isostasy and second order figure of equilibrium, showing that gravity and libration measurements can be reconciled.
Core density is in the range 2300-2500 kg/m3. Core radius is about 190 km.



In summary…

A coherent picture of the interior structure of Enceladus emerges from the combination of gravity, topography and rotation measurements:

- Core density: 2300-2500 kg/m^3
- Core radius: 190-200 km
- Water + ice mantle: 50-60 km thick
- Ice shell thickness: 20-25 km (from librations), thinning out to 10-15 km in the southern polar region. This is lower but still consistent with G-T estimates (30-40 km).
- Thickness of global ocean: 25-30 km (+10 km at the south pole)

It is surprising how much Cassini has be able to tell us about the interior of Enceladus.

Although Cassini has essentially completed its observation of the moon, we may still expect a more refined tomography from theoretical work.

What we have learned about Enceladus Habitability after the time of the Decadal

WATER: Global Oceans

ENERGY SOURCE: Hydrothermal Systems

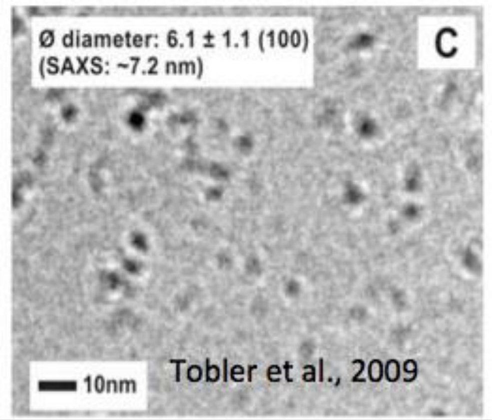
Hydrothermal activities within Enceladus

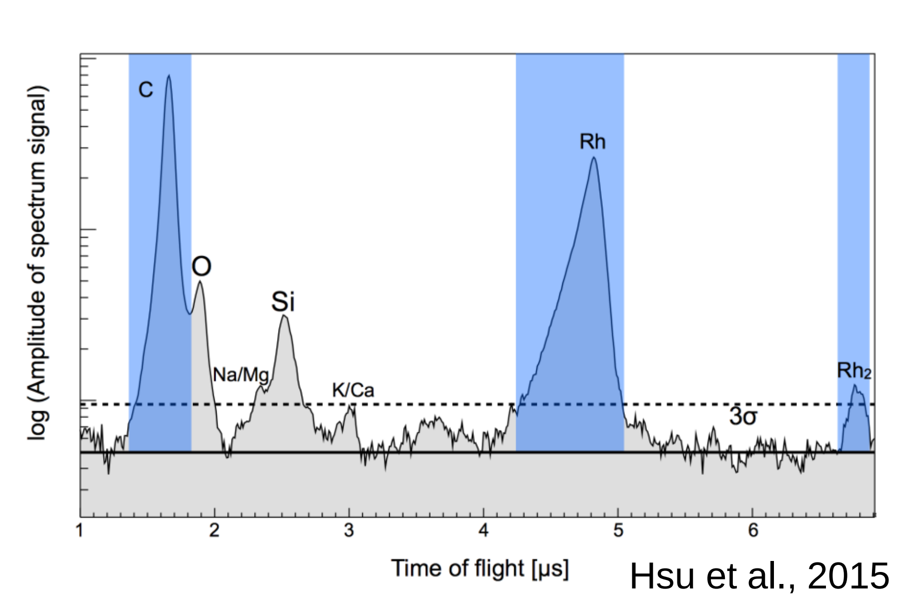
- CDA observation of fast (>100 km/s), tiny (a few nm) silica particles originating from Enceladus.
- Spontaneous, homogenous nucleation of nano-phase silica colloids occurs when the super-saturation is achieved by the pH and/or temperature changes.

$$SiO_{2(mono)} \xrightarrow{k_1} SiO_{2(cn)} \xrightarrow{k_{fast}} SiO_{2(nano)} \xrightarrow{k_2} SiO_{2(ppt)}$$

- SiO_2 is an indicator of hydrothermal reactions on Earth & Mars.

Laboratory experiments





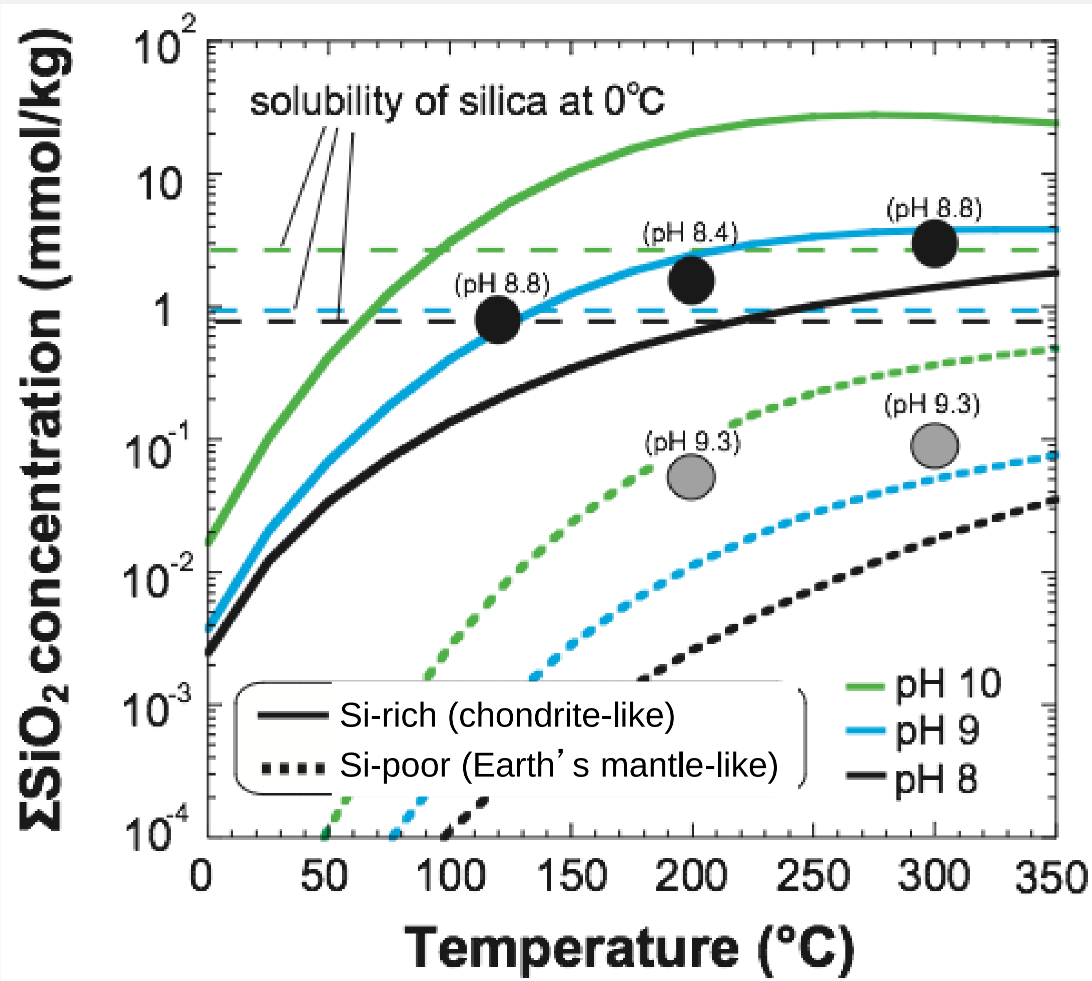
Hsu et al., 2015

hydrothermal silica deposits & colloids

Blue Lagoon, Iceland

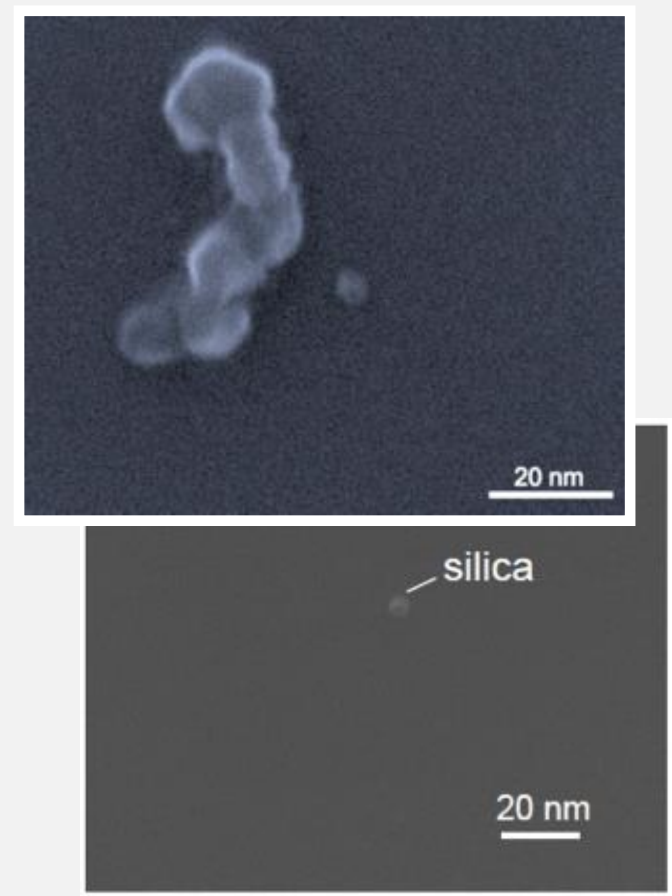
Nano-Silica

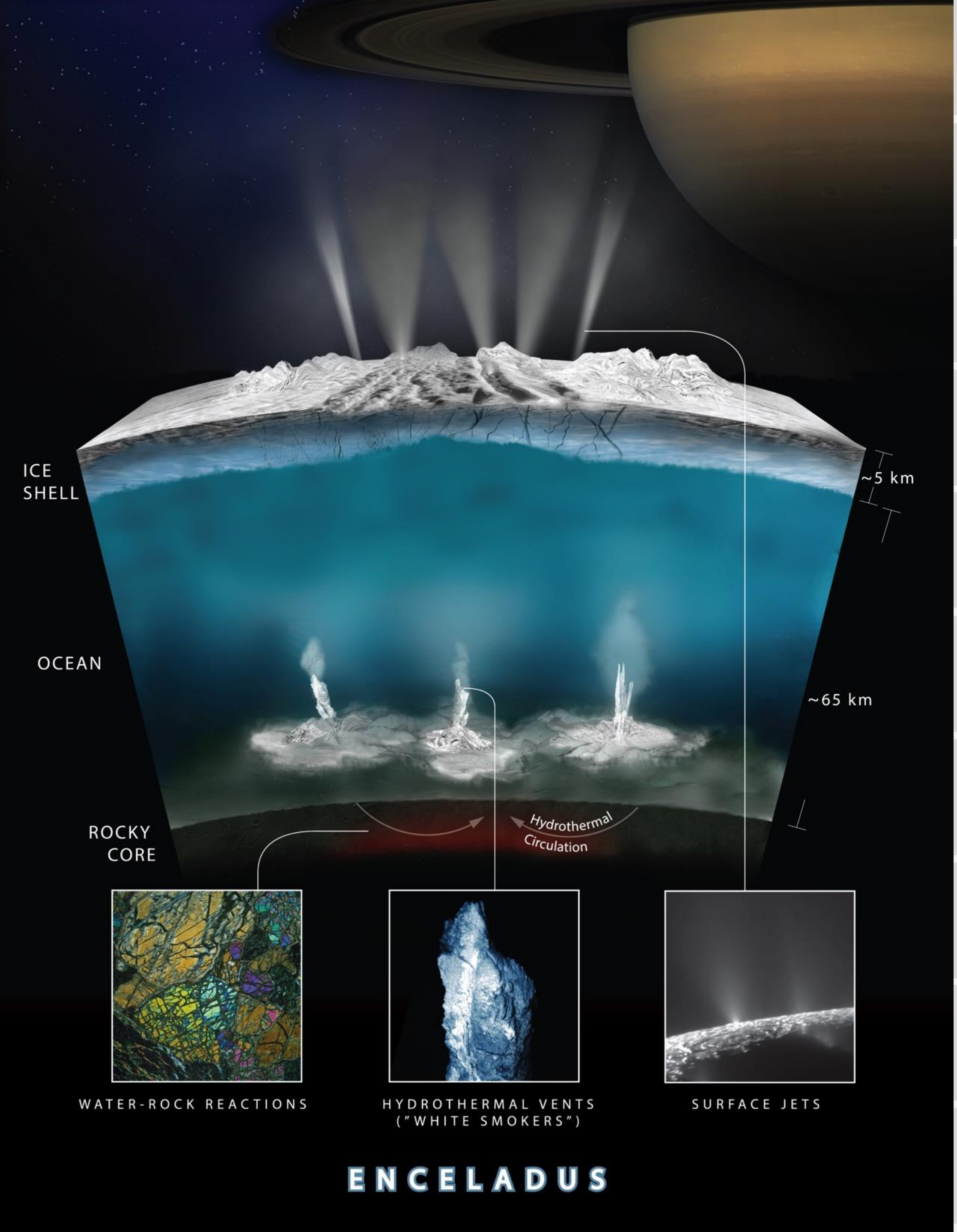
Formation vs. Rock Composition



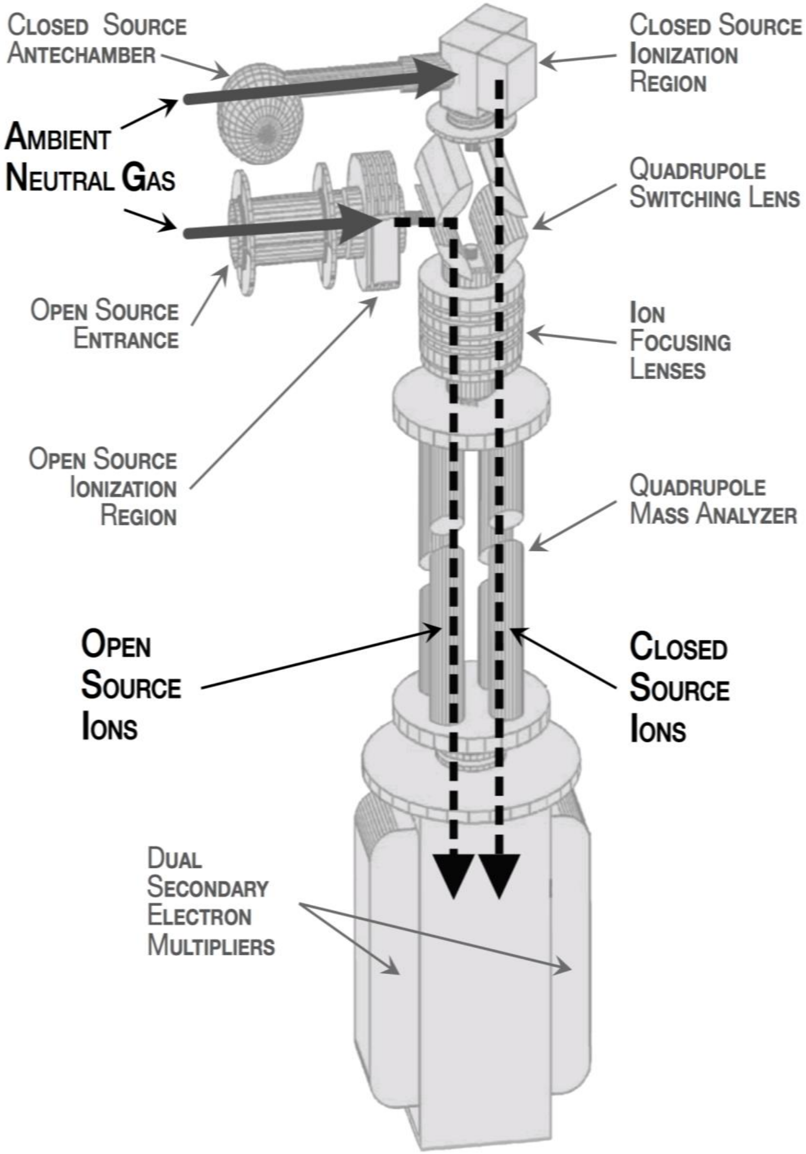
Hsu et al, 2015

Image of nano-silica formed in hydrothermal experiments.




ICE SHELL
~5 km
OCEAN
~65 km
ROCKY CORE
Hydrothermal Circulation
WATER-ROCK REACTIONS
HYDROTHERMAL VENTS ("WHITE SMOKERS")
SURFACE JETS
ENCELADUS

Cassini Ion and Neutral Mass Spectrometer (INMS)



INMS utilized two operating modes during the E21 Enceladus Flyby:

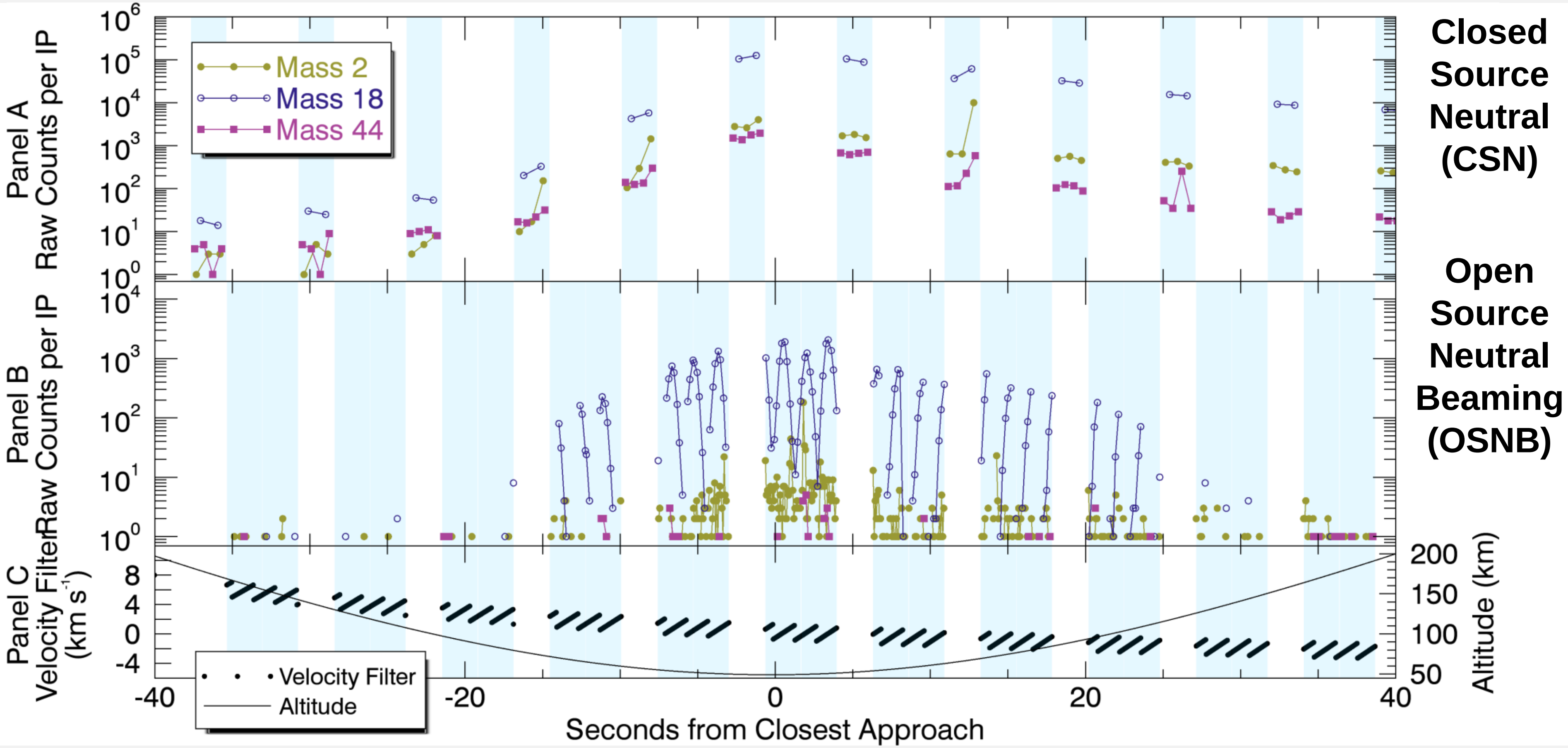
<u>Closed Source Neutral (CSN)</u>

- Measures non-reactive species only
- Subject to wall reactions, such as titanium reacting with H_2O to form H_2

<u>Open Source Neutral Beaming (OSNB)</u>

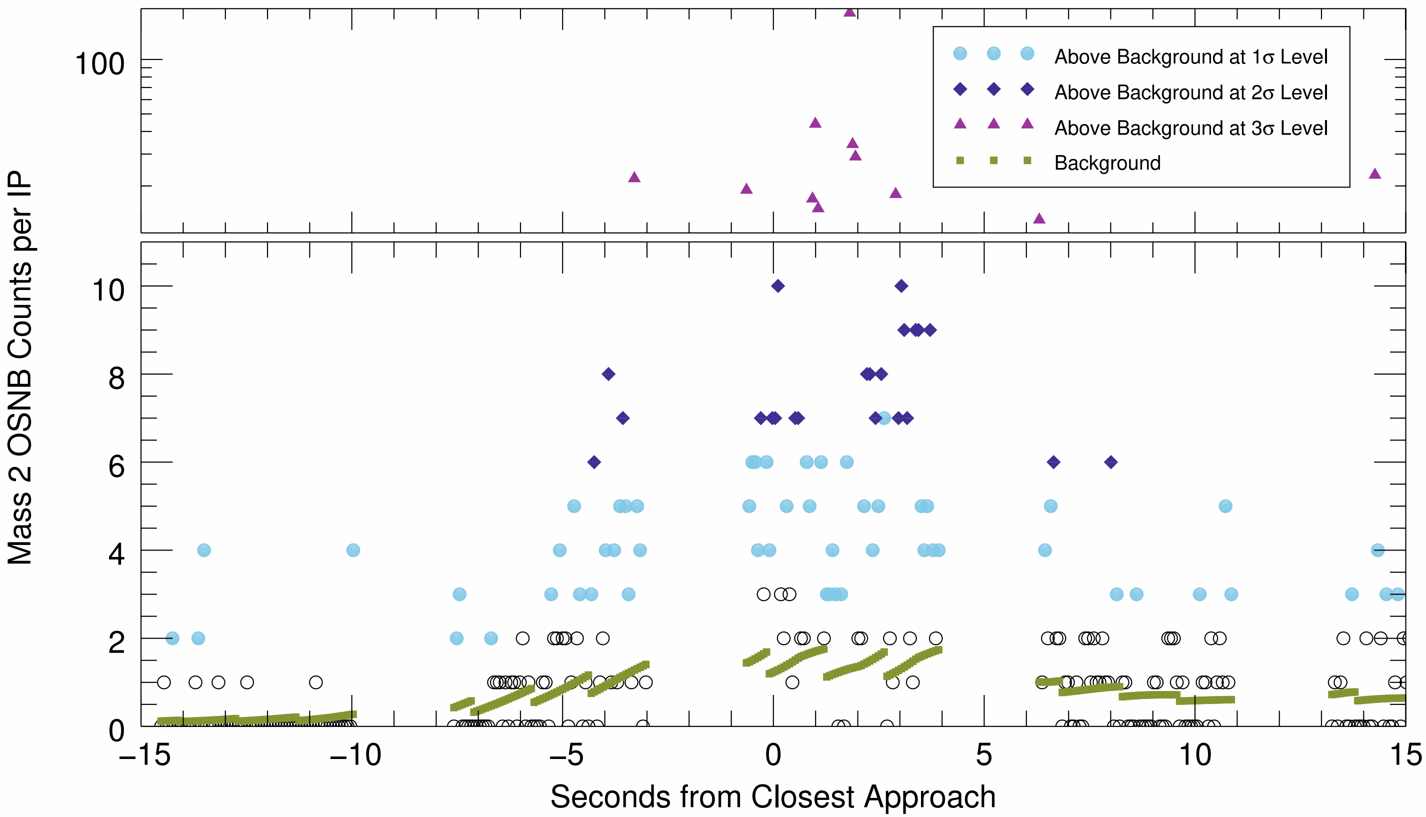
- Sensitivity 1/400 of closed source
- Material entering the open source does not directly interact with the walls

Observations of H_2, H_2O, and CO_2 by INMS during the E21 flyby



Velocity range sampled (Panel C, black points) corresponds to the field of view of the sampled region and affects both the speed and angle of the measured molecules.

OSNB measurements of mass 2 (H_2) compared to the estimated total mass 2 instrumental background



Open black circles:

No distinguishable separation from the background signal

Light blue circles:

At least one sigma separation from background signal

Dark blue diamonds:

Two sigma separation from background signal.

Purple triangles:

Three sigma separation from background signal.

The detected count rates and estimated background rates are plotted as a function of time from closest approach to Enceladus (2015-301T15:22:42).

Data show a low-level H_2 population together with several extreme H_2 signal spikes reaching intensities of tens to hundreds of counts. The low-level H_2 population was used in the calculation of H_2 to H_2O ratio.

What is the Source of the Observed H_2?

Possible <u>primordial</u> source	**Suggested inconsistency** **Theoretical**, **Observational**

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Gravitational capture of nebular H_2 e.g., Pollack et al. (1996)	Enceladus too small ($>10M_E$), He not detected in plume

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Radiolysis of water ice on surface e.g., Cooper et al. (2009)	Would not concentrate H_2 in plume, low radiation fluxes at Enceladus, O_2 not detected in plume

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Radiolysis of water ice on surface e.g., Cooper et al. (2009)	Would not concentrate H_2 in plume, low radiation fluxes at Enceladus, O_2 not detected in plume
Radiolysis of liquid water in interior e.g., Chyba & Hand (2001)	Low CI chondritic radionuclide abundances, predicts low H_2/CH_4 ratio in plume

Serpentinizing hydrothermal systems on Earth produce large quantities of H_2

Lost City as a geochemical analogue

Parameter	Value
Temperature	90°C
pH	9-11
H_2 conc.	10 mM
CH_4 conc.	1 mM

mM = mmol per kg of H_2O

Kelley et al. (2001; 2005), Proskurowski et al. (2006), Reeves et al. (2014)

A Bottom-Up Test of the Hydrothermal Model

H_2 production from H_2O
is coupled to Fe oxidation

As in hydrothermal systems on Earth because of the high abundance of Fe

Key geochemical reactions in the Fe-Si-O-H system:

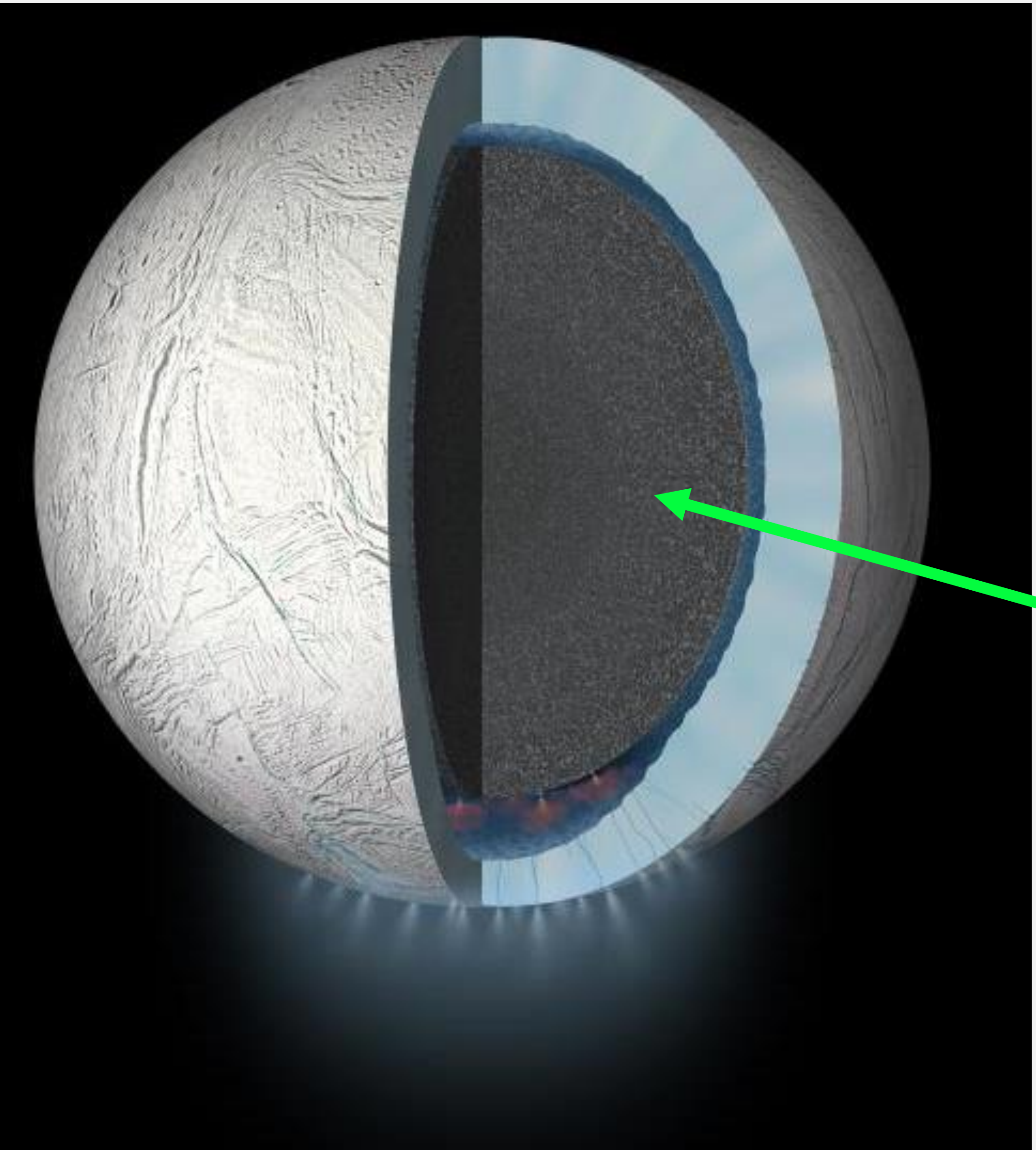
a. $3Fe^0 + 5H_2O + 2SiO_2 \rightarrow$ Fe-serpentine $+ 3H_2$

b. 3Fe-olivine $+ 2H_2O \rightarrow 2Fe_3O_4 + 3SiO_2 + 2H_2$

c. Fe-serpentine $\rightarrow Fe_3O_4 + H_2O + 2SiO_2 + H_2$

Approach: Estimate H_2 yield from amounts of Fe minerals on Enceladus

A Bottom-Up Test of the Hydrothermal Model



Mass of rock from the internal structure model of McKinnon (2015)

Rock = Source of electrons to make H_2 from H_2O

A Bottom-Up Test of the Hydrothermal Model

Mass of rock from the internal structure model of McKinnon (2015).

Mineralogy of rock based on solar elemental abundances (Lodders, 2003) and alteration phases in carbonaceous chondrites (Brearley, 2006).

Example: 1% anhydrous accreted rock in the core can sustain ~1% H_2 in the plume at today's outgassing rate (Hansen et al., 2011) for ~500 Myr.

The presence of appreciable H_2 in the plume does not require a large amount of anhydrous rock. Less if outgassing is only episodic.

Compatible with a low density core (McKinnon, 2015) that may be dominated by hydrated silicates containing some pore water.

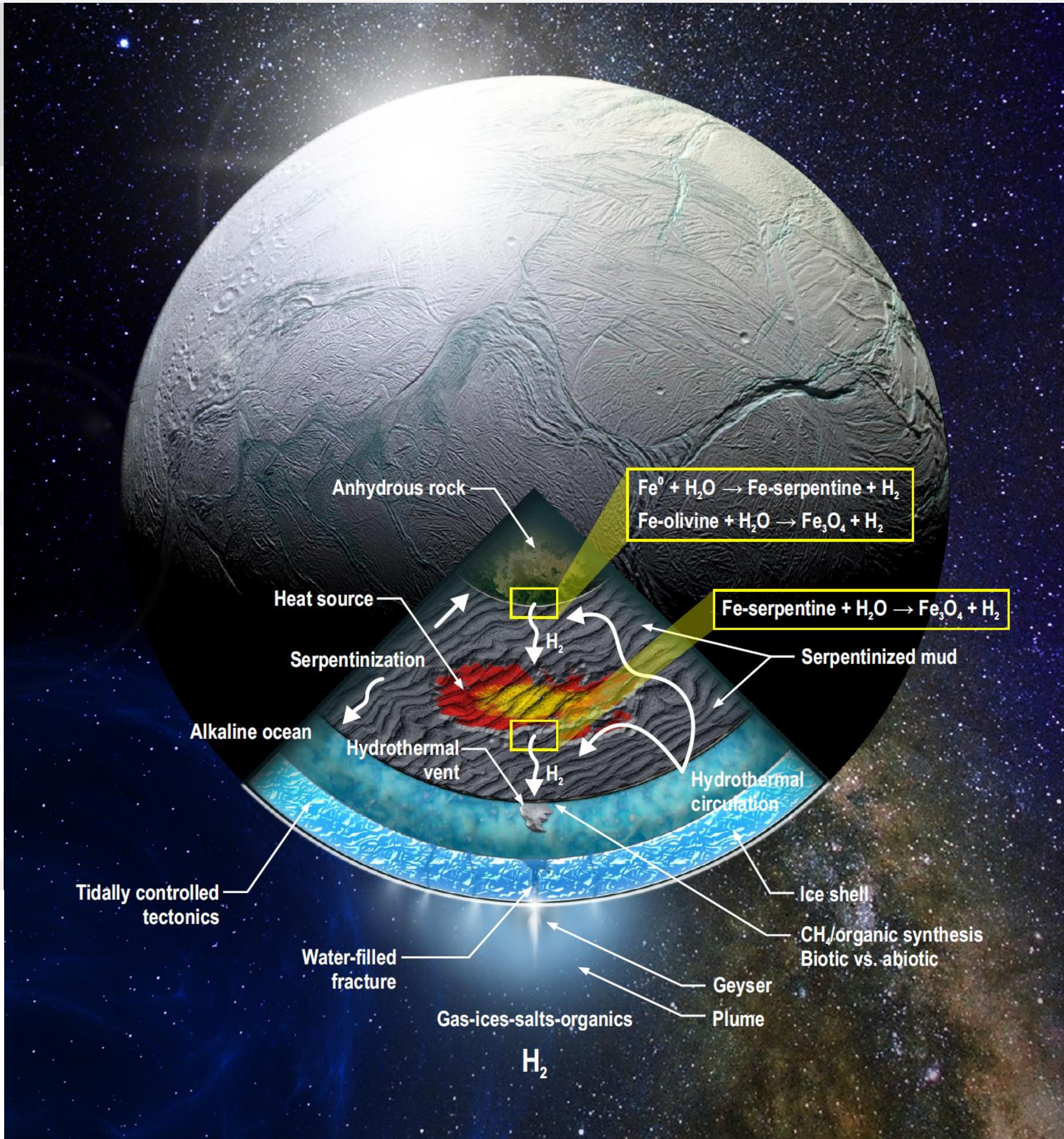
Hydrothermal Mineral Alteration as a Source of H_2

H_2 production from H_2O is coupled to Fe oxidation

Similar to hydrothermal systems on Earth because of the high abundance of Fe

This geochemical model was used to estimate the H_2 yield (≤20×10^{19} moles) of Enceladus' core (Waite et al., 2017)

Steady-state plume requires ~1×10^{19} moles H_2 over 4.56 Gyr

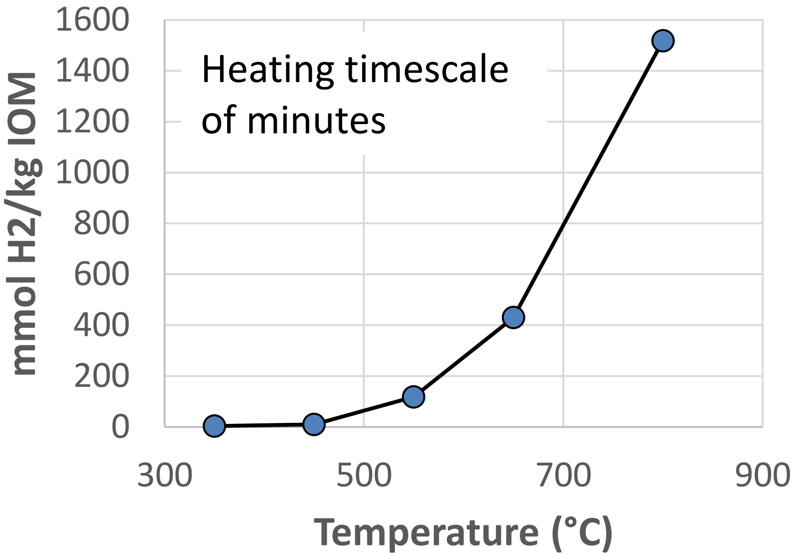


Thermogenesis as a Complementary Source of H_2

Accreted rocks on Enceladus could be rich in organic matter

Those organics would contain H.
Comet Halley: $C_{100}H_{80}N_4O_{20}S_2$ (Kissel & Krueger, 1987)

Heating organic matter from the Murchison meteorite generates H_2 (Okumura & Mimura, 2011)



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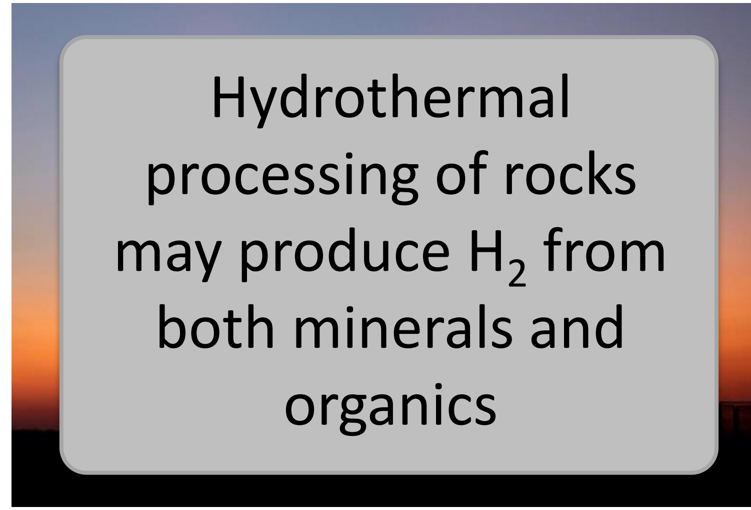
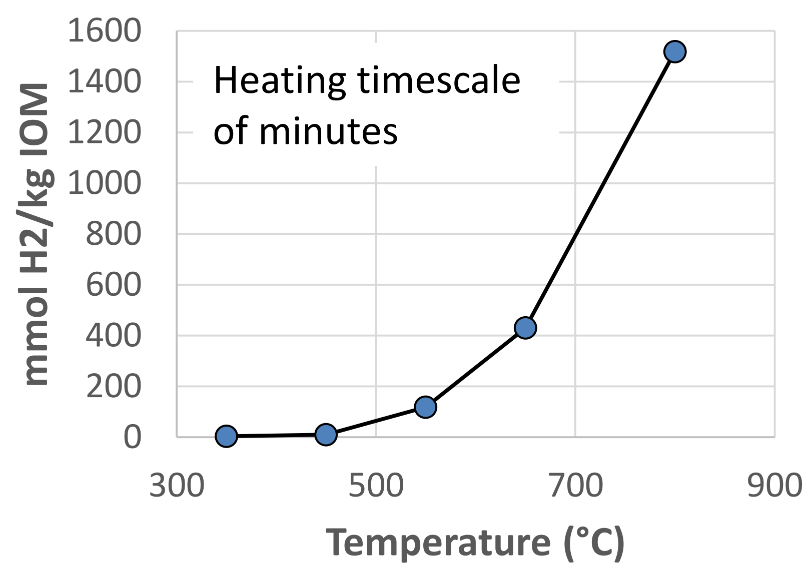
Thermogenesis ≤3.5×10^{19} moles H_2
Mineral Alteration ≤20×10^{19} moles H_2
Steady-state plume requires ~1×10^{19} moles H_2 over 4.56 Gyr





H_2 links the inorganic and organic/living worlds

Organic synthesis

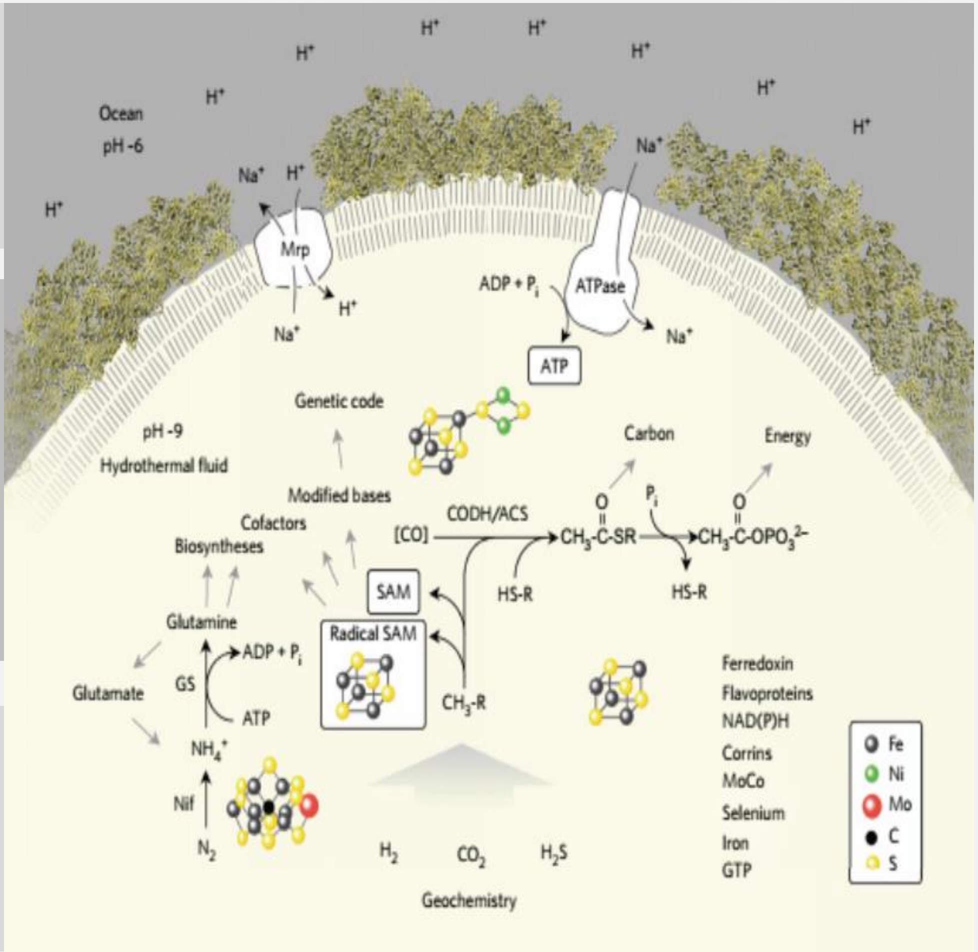
$CO_2 + H_2 \rightarrow$ Organics + H_2O

Prebiotic chemistry

Current model: Life began at *alkaline* hydrothermal vent (shout out to Mike Russell!)

Chemical energy for life

H_2/CH_4-based metabolisms



Weiss et al. (2016, Nat. Microbiol. 1, 16116)

Enceladus Plume Composition

-Major plume constituents-

Ice Grains (CDA)

Component	Concentration (mol/kg H_2O)
NaCl	0.05-0.2
$NaHCO_3$+Na_2CO_3	0.01-0.1
KCl	~0.001

Postberg et al. (2009)

Gas Phase (INMS)

Species	Molar Percentage
H_2O	~98
CO_2	0.3-0.8
CH_4	0.1-0.3
NH_3	0.4-1.3
H_2	0.4-1.4

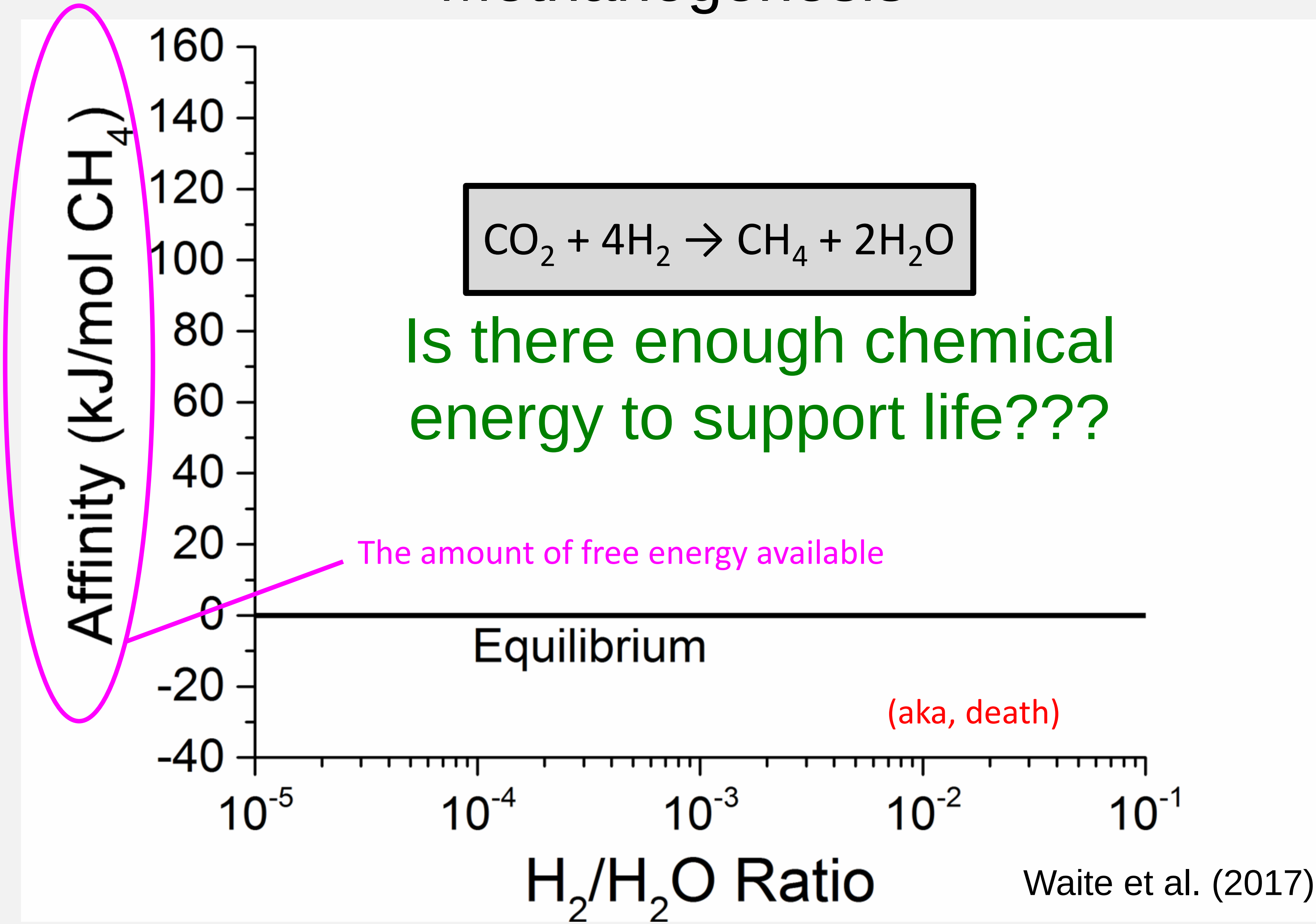
Waite et al. (2017)

Terrestrial seawater:

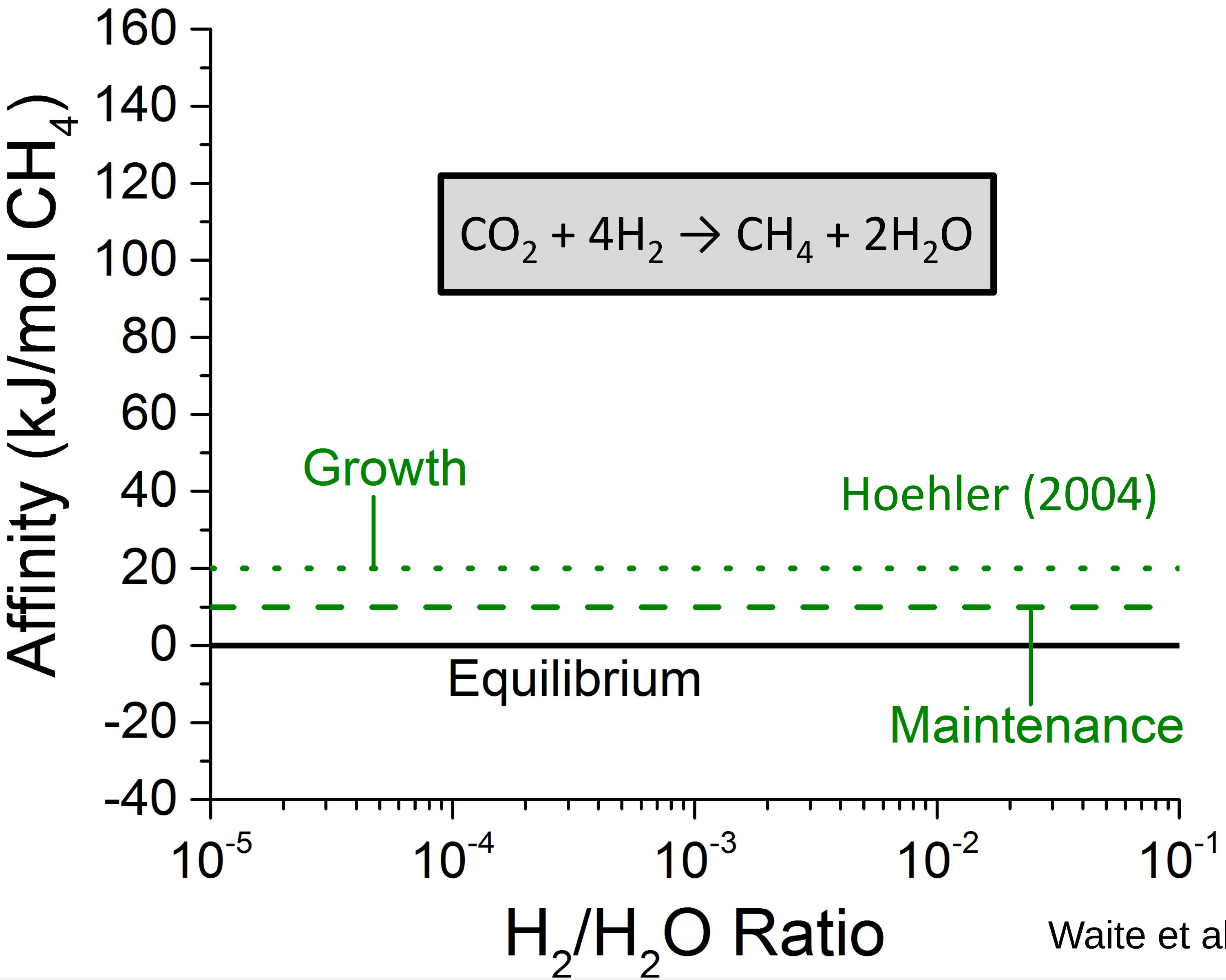
0.5 *m* NaCl 0.03 *m* SO_4^{-2}
0.01 *m* KCl 0.002 *m* HCO_3^-

Minor organic compounds also

Methanogenesis



The energy demands of Earth microbes…



Waite et al. (2017)

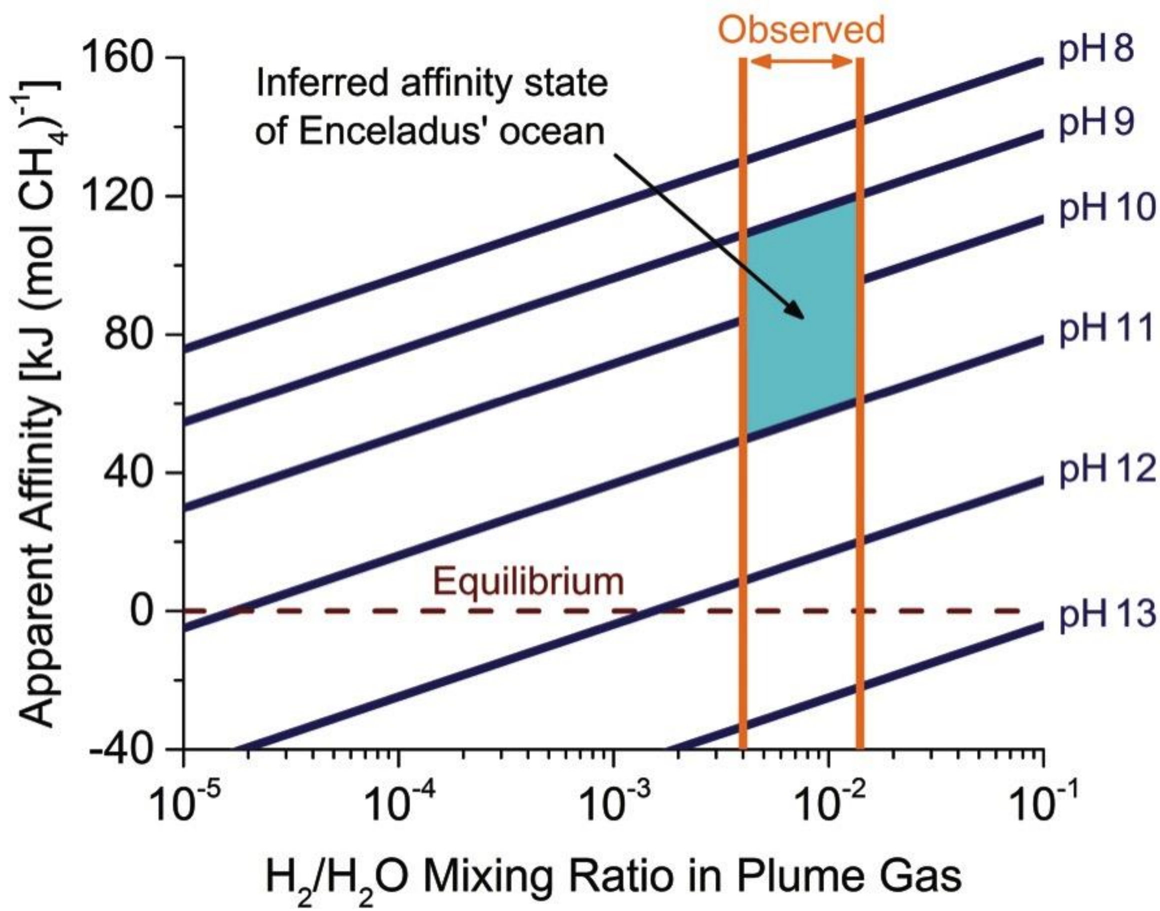
Apparent chemical affinity for hydrogenotrophic methanogenesis in the ocean of Enceladus (273 K, 1 bar)

The major species composition of Enceladus' plume gas (Waite et al., 2017)

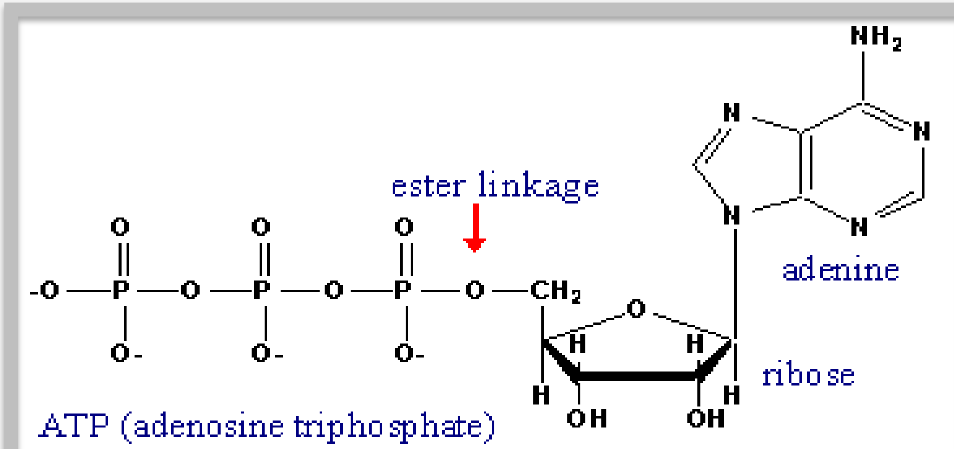
Constituent	Mixing ratio (%)
H_2O	96 to 99
CO_2	0.3 to 0.8
CH_4	0.1 to 0.3
NH_3	0.4 to 1.3
H_2	0.4 to 1.4

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

Enceladus H_2 Affinity: 40 to 130 kJ/(Mol CH_4)



These nominal model results are based on $CH_4/CO_2 = 0.4$, a chlorinity of 0.1 molal, and 0.03 molal total dissolved carbonate (*Hansen, et al., 2011*). Reported ranges in these parameters propagate to give an uncertainty in the computed affinities of ~10 kJ (mol CH_4)$^{-1}$.



Compound	DG^{01} of phosphate hydrolysis (kJ/mol)
ATP (to ADP)	**-30.5**
Methanogenic system	$-\Delta G$ (kJ mol^{-1} CH_4)
Sewage sludge	28–32
Lake Mendota; Knaack Lake	27–35
Wetwood	42
Canal with detritus and leaves	8–18
Alder swamp	12–19
Littoral sediment, Lake Constance	33–39
Profundal sediment, Lake Constance	23–34
Upland soils turned methanogenic	25–50
Italian rice field soil	24–38
Methanobacterium bryantii	29–37
Other methanogenic archaea	29–50

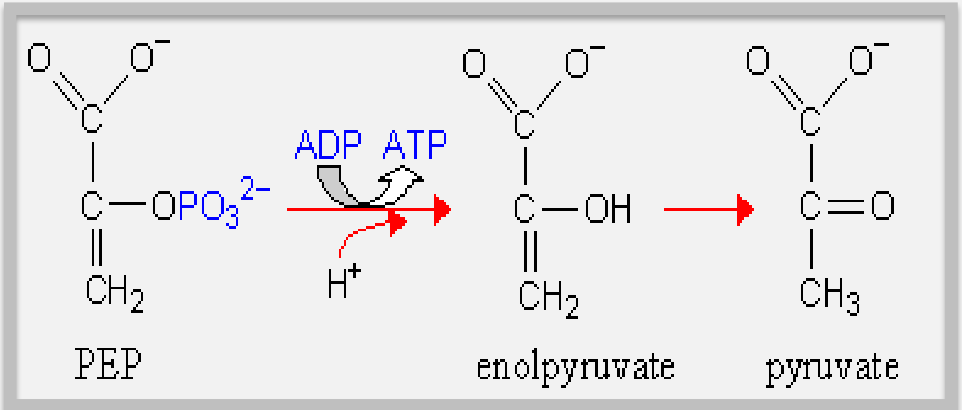
Enceladus H_2 Affinity: 40 to 130 kJ/(Mol CH_4)

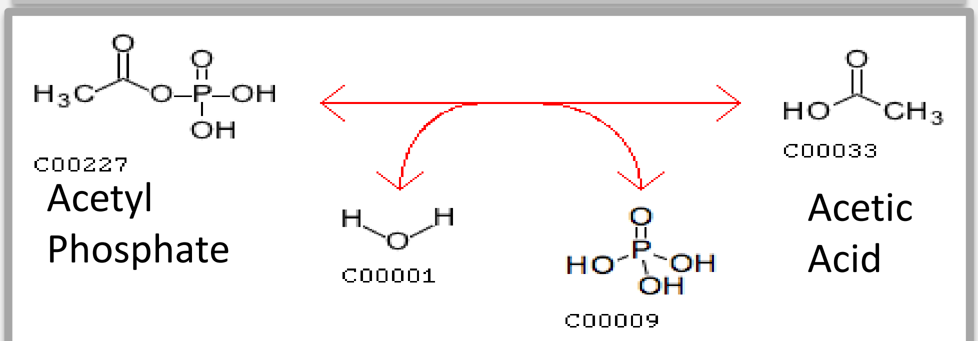
Does "Abundant H_2" = "No Life"?

The paper adopts an agnostic position on whether the result indicates or negates the presence of life – the argument against life asks if there is so much H_2 why wouldn’t microbes have eaten it.

H_2 utilization in Earth microbial systems stops at a value that maintains a small negative Gibbs free energy (vGc). This critical value is explained by the coupling to the energy-generating system of the cell that has a threshold of about 1/3 ATP or approximately -23 kJ/mol of the energy-generating reaction *R. Conrad/FEMS Microbiology Ecology 28 (1999) 193-202.*

Alternative H_2 Affinity Interpretation





Compound	DG[01] of phosphate hydrolysis (kJ/mol)
Phosphoenolpyruvate	**-61.9**
Acetylphosphate	**-41**
ATP (to ADP)	**-30.5**

Measured Enceladus
H_2 Affinity: 40 to 130 kJ/(Mol CH_4)
[best guess: 100 kJ/(Mol CH_4)]

Life on Enceladus may not rely on ATP as an energy transfer molecule, which would imply the H_2 affinity threshold for microbial growth may be different.

Primitive life in the ocean of Enceladus may choose a simpler organic molecule for phosphate to bind to such as acetic acid or enolpyruvate – the simplest alpha ketone – or it may choose a completely different energy transfer mechanism.

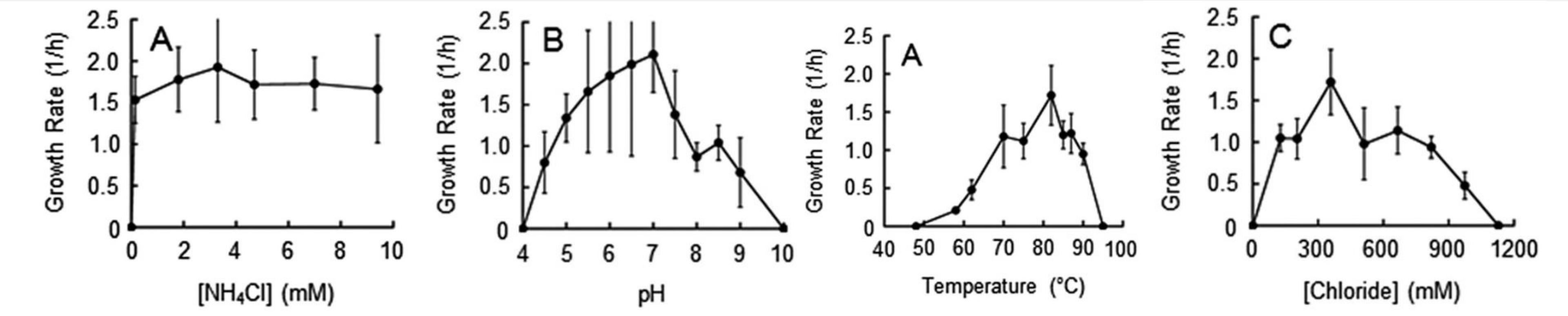
This cannot be determined apriori. Therefore we cannot know the critical Gibbs free energy threshold for microbes in the ocean of Enceladus.

Effect of Growth Factors on H_2 Consumption

Several factors affect the microbial growth rate in Earth based methanogens:

1. H_2 must not fall below the level of 17-23 ❍M [H.C.Ver Ecke et al., PNAS, August 21, 2012, vol.109(34),13674-13679] for methanogenesis to take place in Earth microbes. Our inferred ocean level ranged from 100 ❍M (pH9) to 0.1 ❍M (pH11). Note also that the concentrations of H_2 produced in the hydrothermal system would double if we assume that the observed CH_4 is biogenic in origin.

2. H.C. Ver Ecke et al., Environmental Microbiology Reports, doi:10.1111/1758-2229.12065, 2013 also studied growth rate for methanonogens as a function of temperature, pH, chloride content, and NH_4^+ availability.



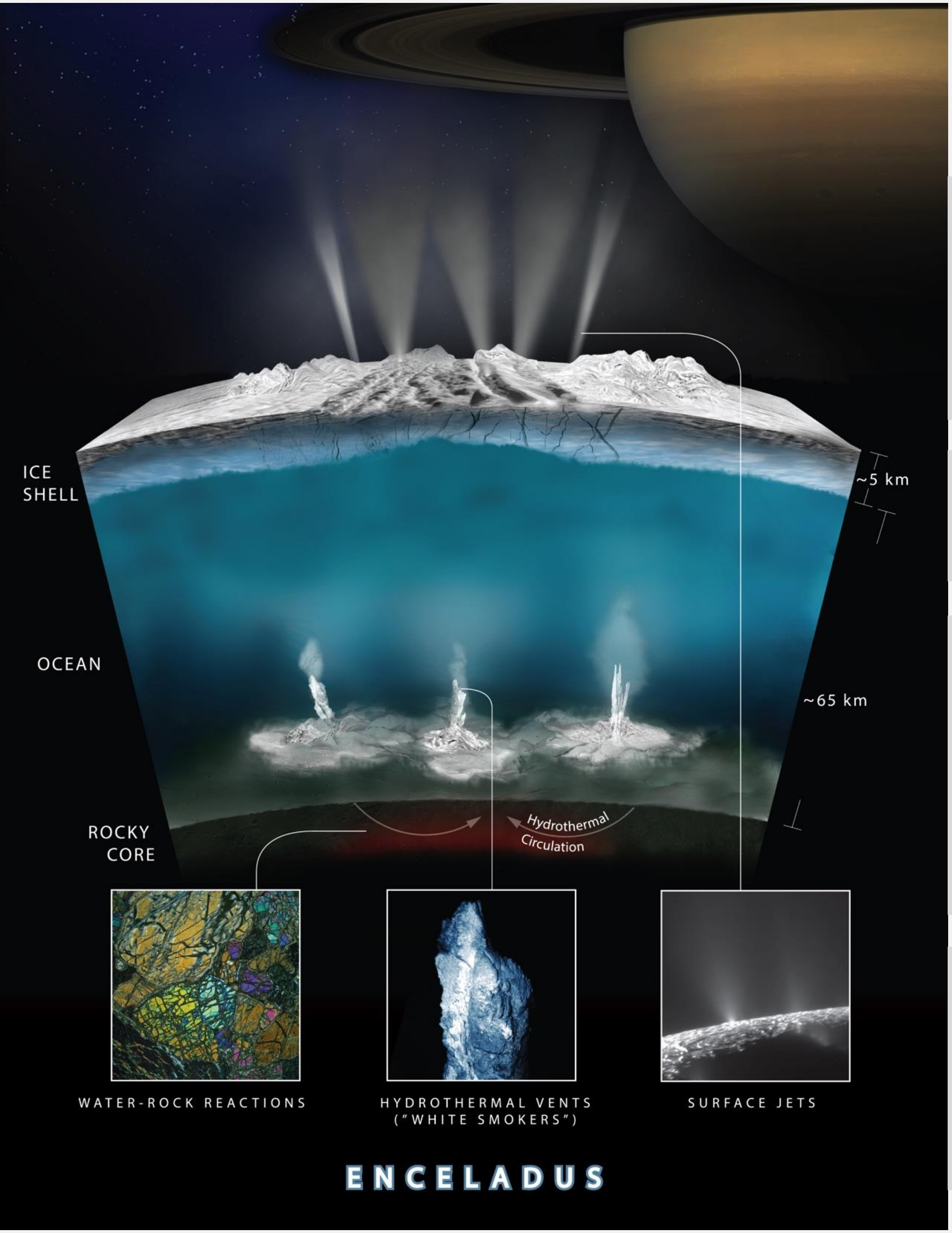
One of the most likely scenarios is that microbial growth is limited by environmental growth factors.

Coupled Metabolic Systems

Metabolic pathways found in the Earth's oceans:

1. Methanogenesis: $4H_2+CO_2 \rightarrow CH_4+2H_2O$	Subject of the present finding
2. Anaerobic Oxidation of Methane: $CH_4+SO_4+H^+ \rightarrow CO_2+H_2S+2H_2O$ 3. Sulfate Reduction: $4H_2+SO_4+2H^+ \rightarrow H_2S+4H_2O$	Could be investigated on a future mission
4. Hydrogen Oxidation: $2H_2+O_2 \rightarrow 2H_2O$ 5. Methane Oxidation: $CH_4+2O_2 \rightarrow CO_2+2H_2O$ 6. Sulfide Oxidation: $H_2S+2O_2 \rightarrow SO_4+2H^+$	Difficult to measure directly due to the low concentrations expected for O_2 in the ocean environment

This limited set of metabolic pathways illustrates the possible effects of coupled metabolic pathways on the interpretation of the chemical affinity of H_2.



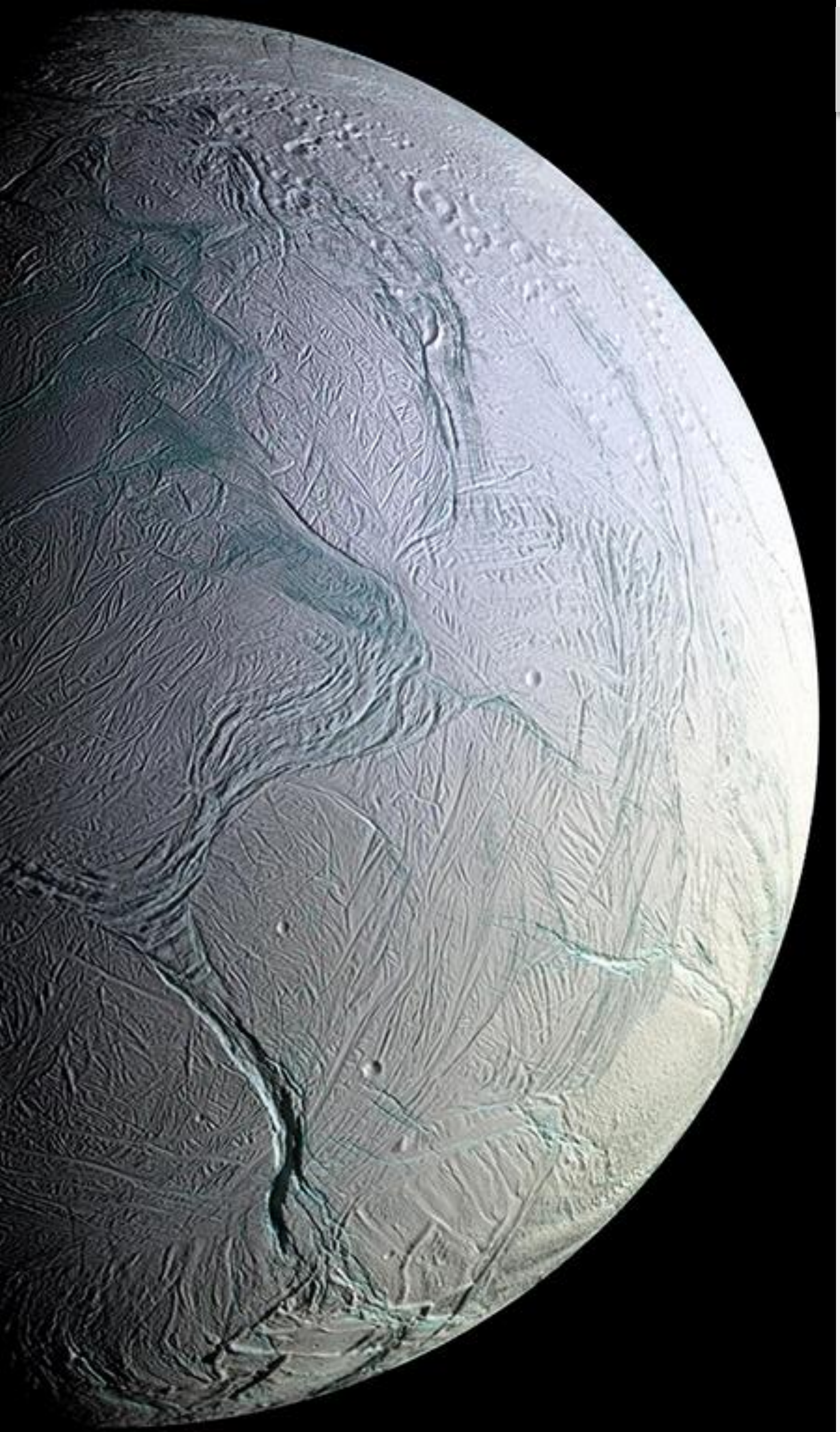
In summary…

Waite et al., Science 356, 155–159 14 April 2017: Cassini INMS has observed H_2 emanating from the plume, which is inferred to originate in the interior ocean.

The H_2 implies a hydrothermal source in the ocean of Enceladus.

The H_2 affinity interpreted in terms of the chemical equilibrium represented by the methanogenesis reaction: $4H_2 + CO_2 \rightarrow CH_4 + 2H_2O$ indicate a potential source of chemical food for microbes.

The published results are agnostic with regard to the existence of life in the ocean of Enceladus – a Search for Life must be pursued through a future mission.



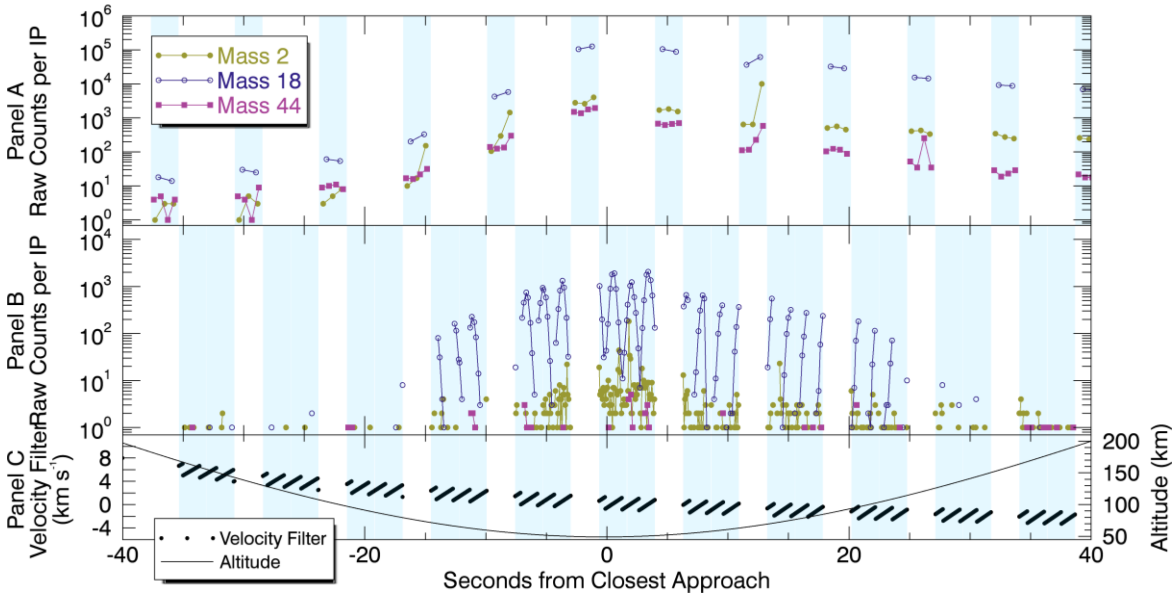
Overall Summary

1. Measurements in the last five years of internal structure firmly establish a global ocean with a thin ice crust separation near the south pole.
2. Composition of the ice grains and gas from the plume strongly indicate the existence of hydrothermal systems at the rock ocean interface that produce molecular hydrogen and provide evidence for chemical energy for methanogenic microbes.
3. Next step: SEARCH FOR LIFE

Supplementary Slides

Cassini Finds Molecular Hydrogen in the Enceladus Plume: Evidence for Hydrothermal Processes

Cassini-Huygens Mission To Saturn and Titan

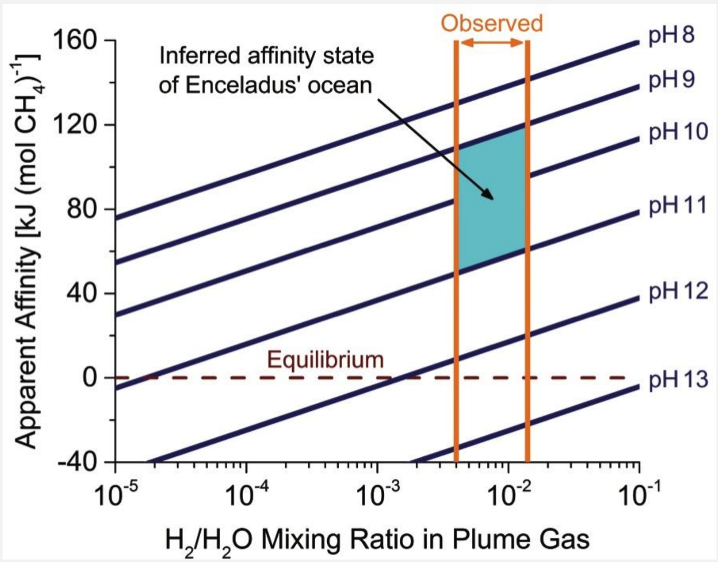


Cassini-INMS raw counts from E21 Enceladus flyby. (A) Closed Source Neutral; (B) Open Source Neutral Beaming; (C) Velocity Filter & Altitude

Hydrogen gas is discovered coming from Saturn's moon Enceladus, suggesting reaction of rock with warm water at the base of a subsurface ocean.

The major species composition of Enceladus' plume gas

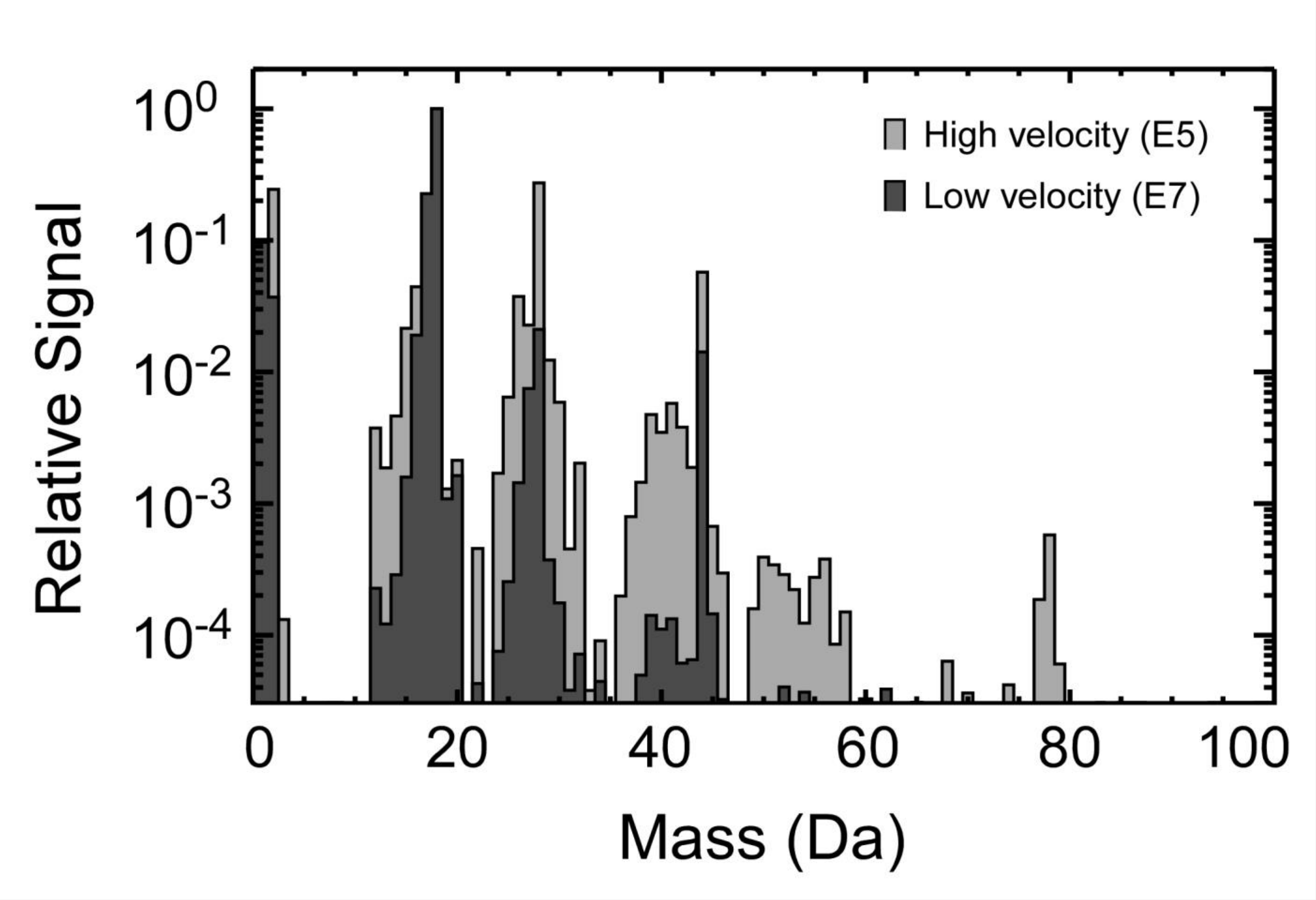
Constituent	Mixing ratio (%)
H_2O	96 to 99
CO_2	0.3 to 0.8
CH_4	0.1 to 0.3
NH_3	0.4 to 1.3
H_2	0.4 to 1.4



Apparent chemical affinity for hydrogenotrophic methanogenesis in the ocean of Enceladus (273 K, 1 bar). The orange lines bracket the observed range in the mixing ratio of H_2 in the plume gas (0.4% to 1.4%). The blue lines are contours of constant ocean pH, a key model parameter. The cyan region indicates affinities for a pH range that may provide the greatest consistency between literature results. The dashed red line designates chemical equilibrium, where no energy would be available from methanogenesis. These nominal model results are based on $CH_4/CO_2 = 0.4$, a chlorinity of 0.1 molal, and 0.03 molal total dissolved carbonate. Reported ranges in these parameters propagate to give an uncertainty in the computed affinities of ~10 kJ (mol CH_4)$^{-1}$.

Waite et al., Science 356, 155–159 14 April 2017

'Slow' versus 'Fast' spectra



The accumulated signal mass spectra for E5 and E7 representative of the high and low velocity distributions described in the text. The spectra have been normalized so that the signal in other masses can be compared to the H_2O signal at 18 Da. The lower bound of the plot window represents the noise level for both data sets. A significant velocity dependence is observed when comparing the two spectra. The E5 spectrum shows composition with complexity up to C_6H_6 (78 Da) whereas E7 complexity peaks in the C_3 group (around 40 Da).