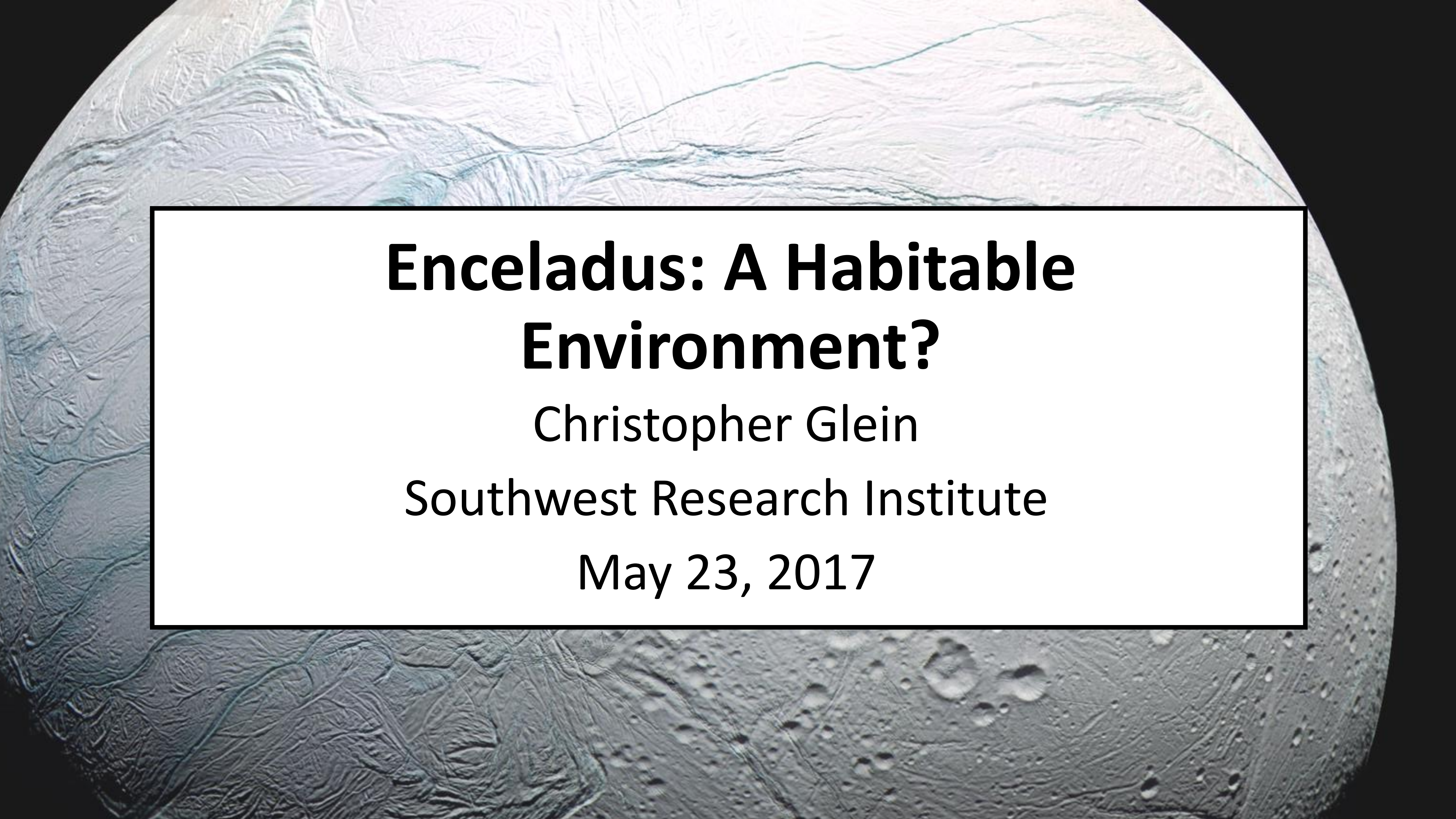


Enceladus: A Habitable Environment?

Christopher Glein

Southwest Research Institute

May 23, 2017

Hydrogen: So what…it's everywhere!

Solar Abundances

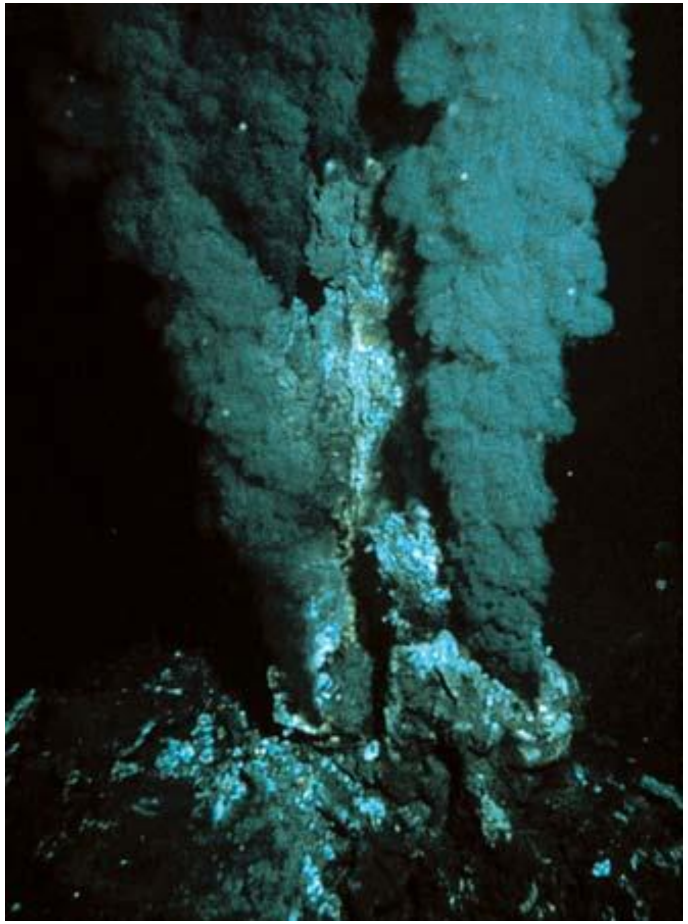
Element	$N(\mathrm{El})_0$
H	2.431×10^{10}
He	2.343×10^{9}
Li	55.47
Be	0.7374
B	17.32
C	7.079×10^{6}
N	1.950×10^{6}
O	1.413×10^{7}
F	841.1
Ne	2.148×10^{6}
Na	5.751×10^{4}
Mg	1.020×10^{6}
Al	8.410×10^{4}
Si	$\equiv 1.00 \times 10^{6}$
P	8373
S	4.449×10^{5}
Cl	5237
Ar	1.025×10^{5}

Lodders (2003)

But, H_2 is relatively rare on Ocean Worlds

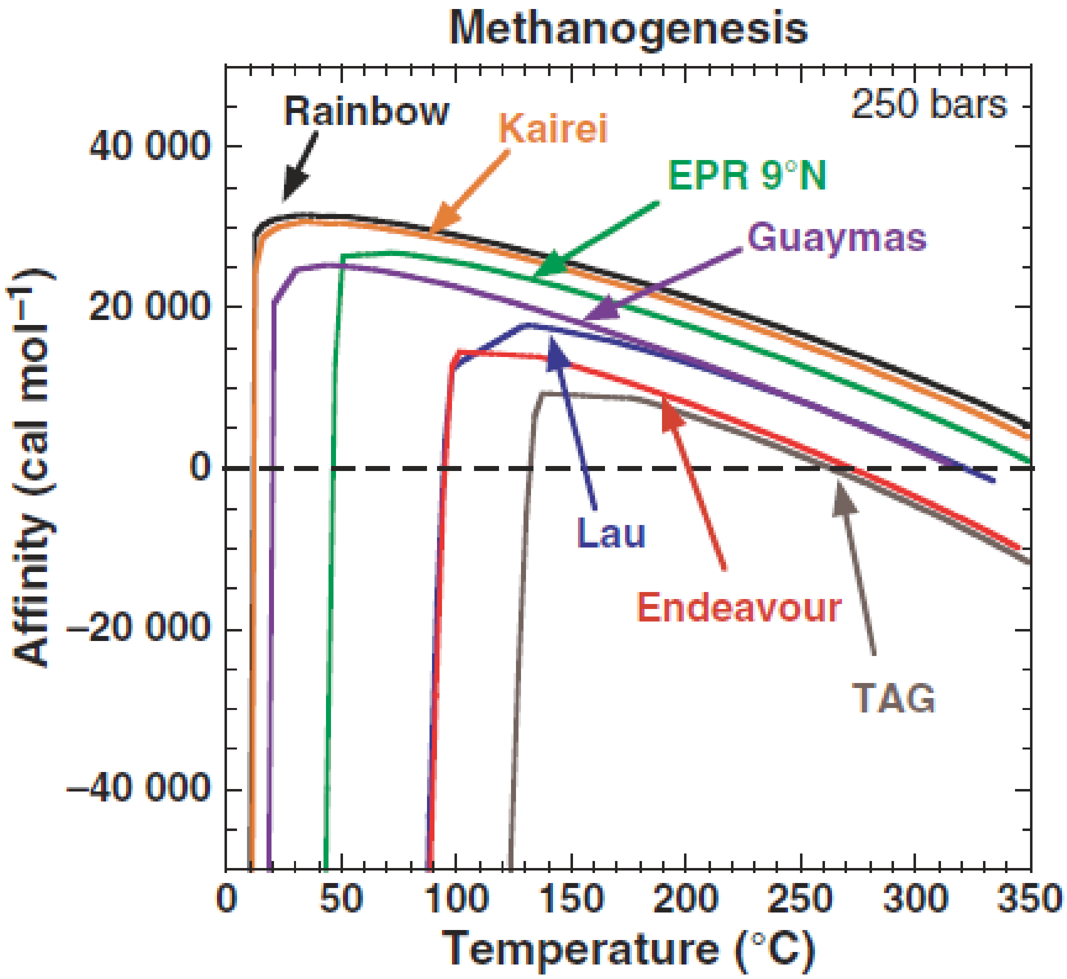
0.55 ppm H_2 in Earth's atmosphere

It's hard to hang on to H_2



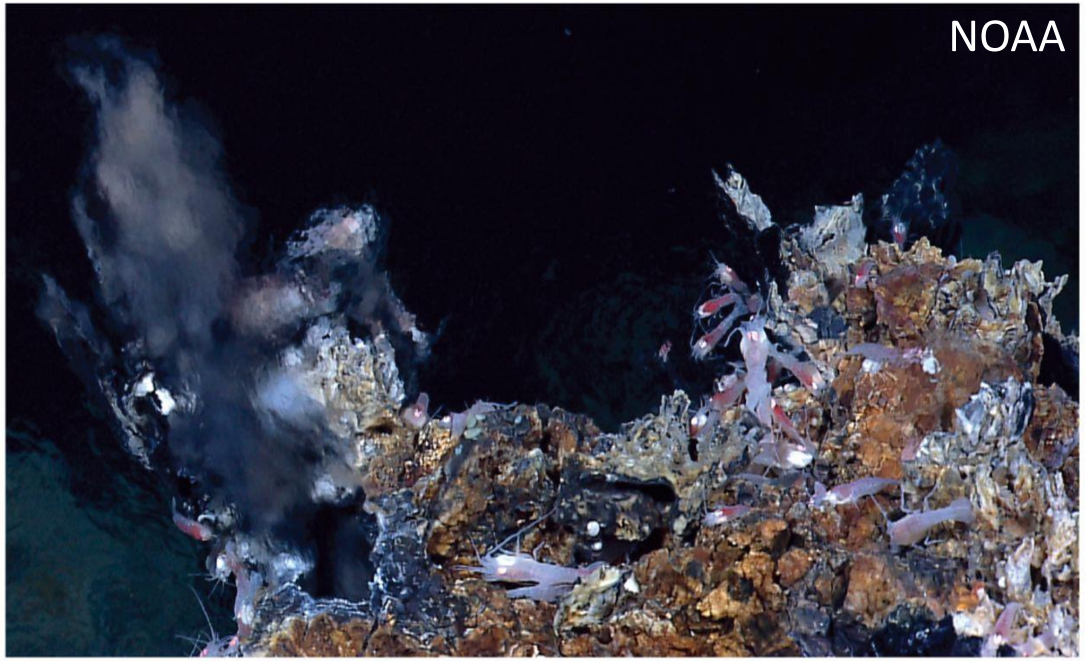
Water-rock hydrothermal processes produce of order 1 M tonnes H_2 per year (Sherwood Lollar et al., 2014)

H_2 on Ocean Worlds: An Energy Source for Life



Shock & Canovas (2010)

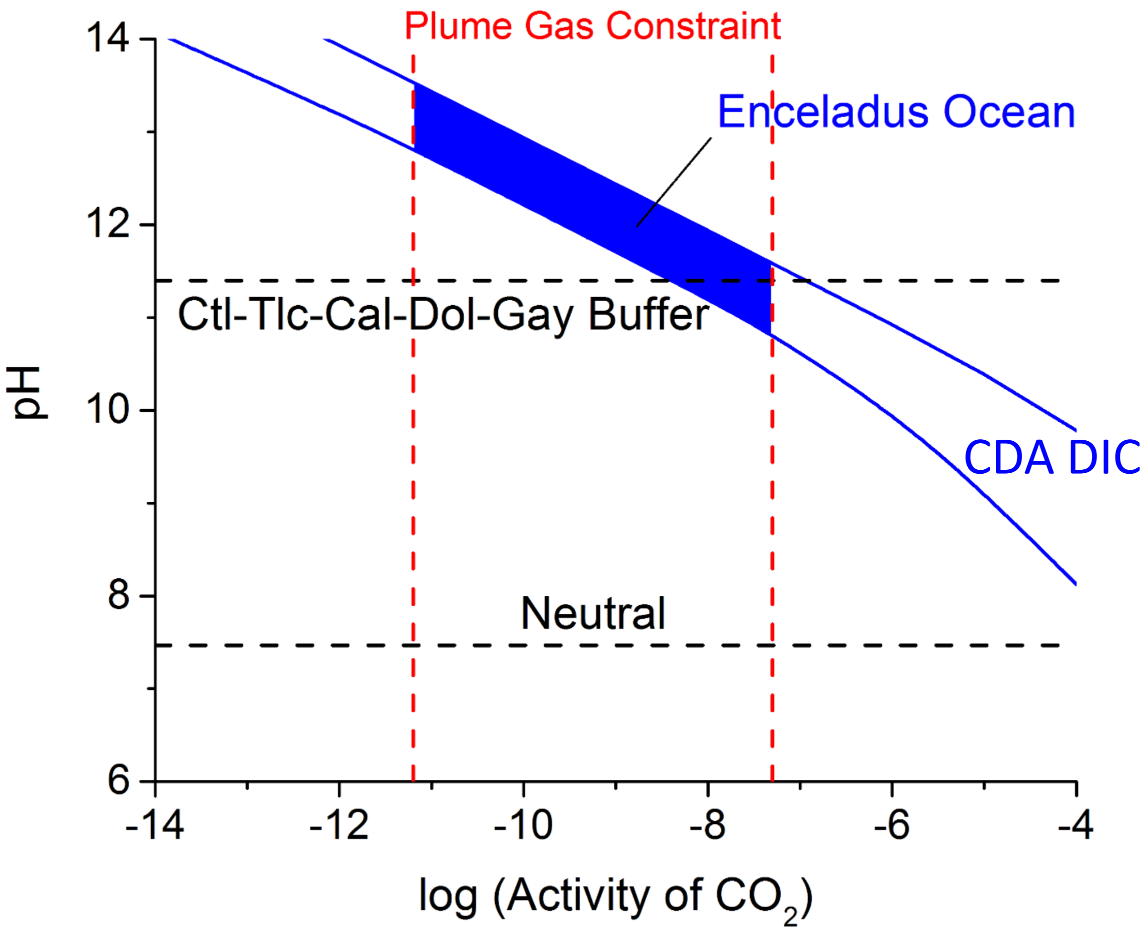
$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$



Chemical energy → Ecosystem

Hydrothermal ultramafic rock alteration (serpentinization) on Enceladus

Silica particles (Hsu et al., 2015)
form when hot vent fluids mix with cold ocean water at the ocean floor



Alkaline ocean (Glein et al., 2015)

What exactly is serpentinization?

A Geochemical Process

California
state rock

For example:

No!

Yes!

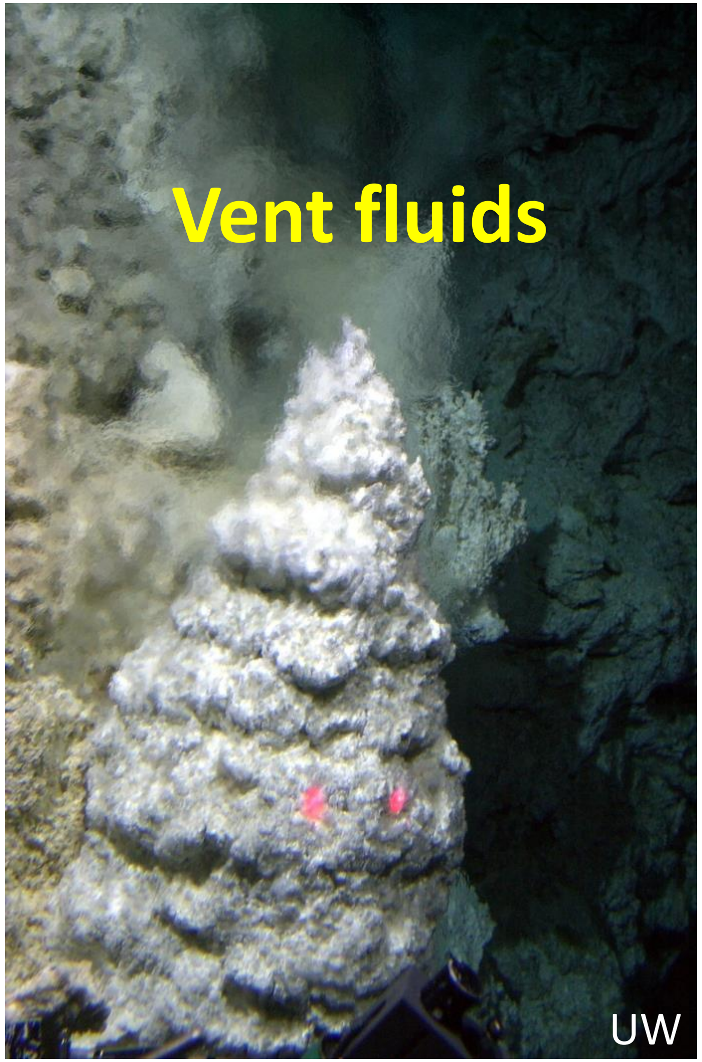
$Mg_2SiO_4 + MgSiO_3 + 2H_2O \rightarrow Mg_3Si_2O_5(OH)_4$

Ultramafic Rock

Serpentine (aka asbestos)

Serpentinization leads to high pH (rock enriched in bases) and…

Serpentinizing hydrothermal systems on Earth produce large quantities of H_2

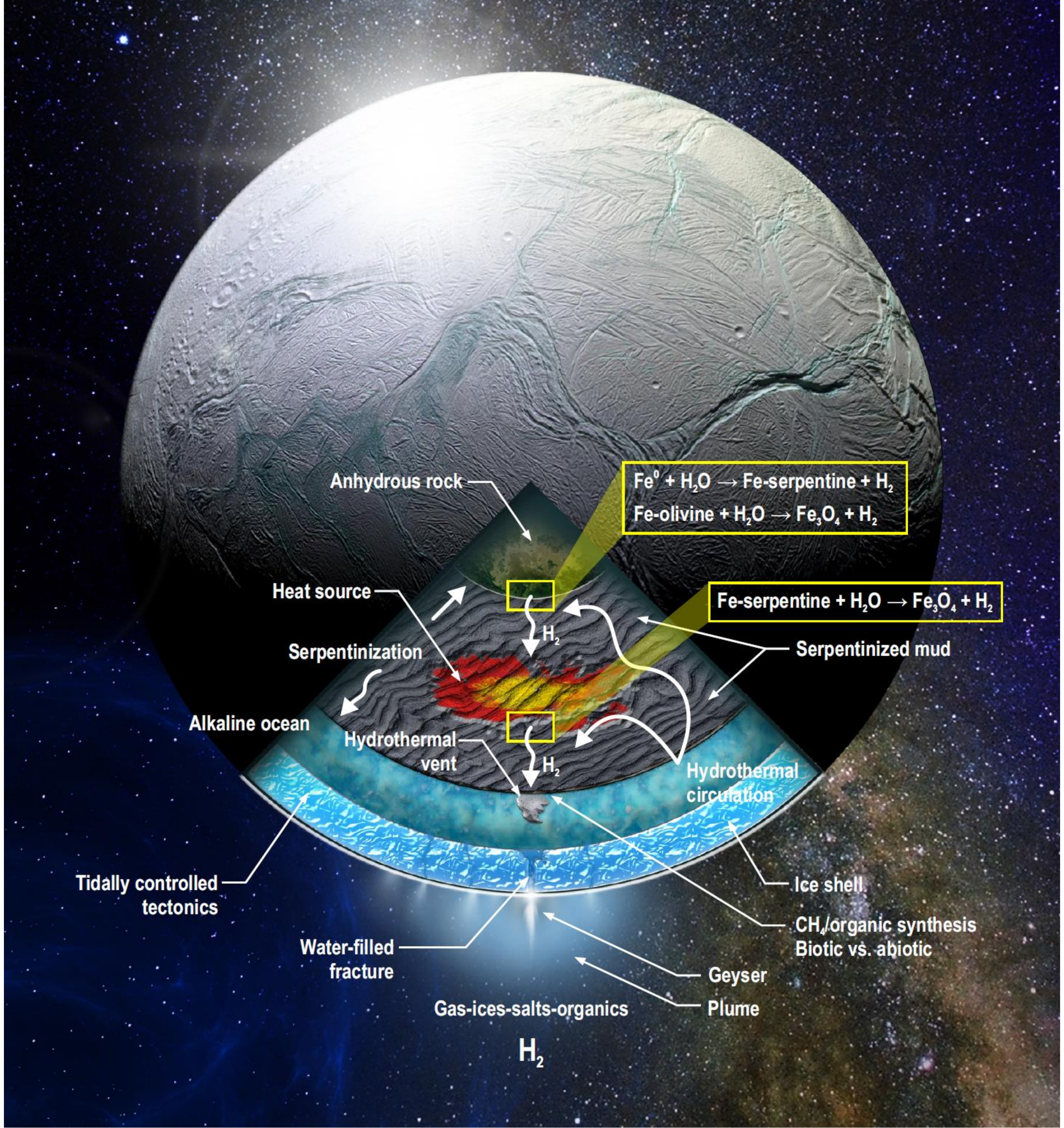


Lost City as a geochemical analogue of Enceladus

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

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

mM = mmol per kg of H_2O

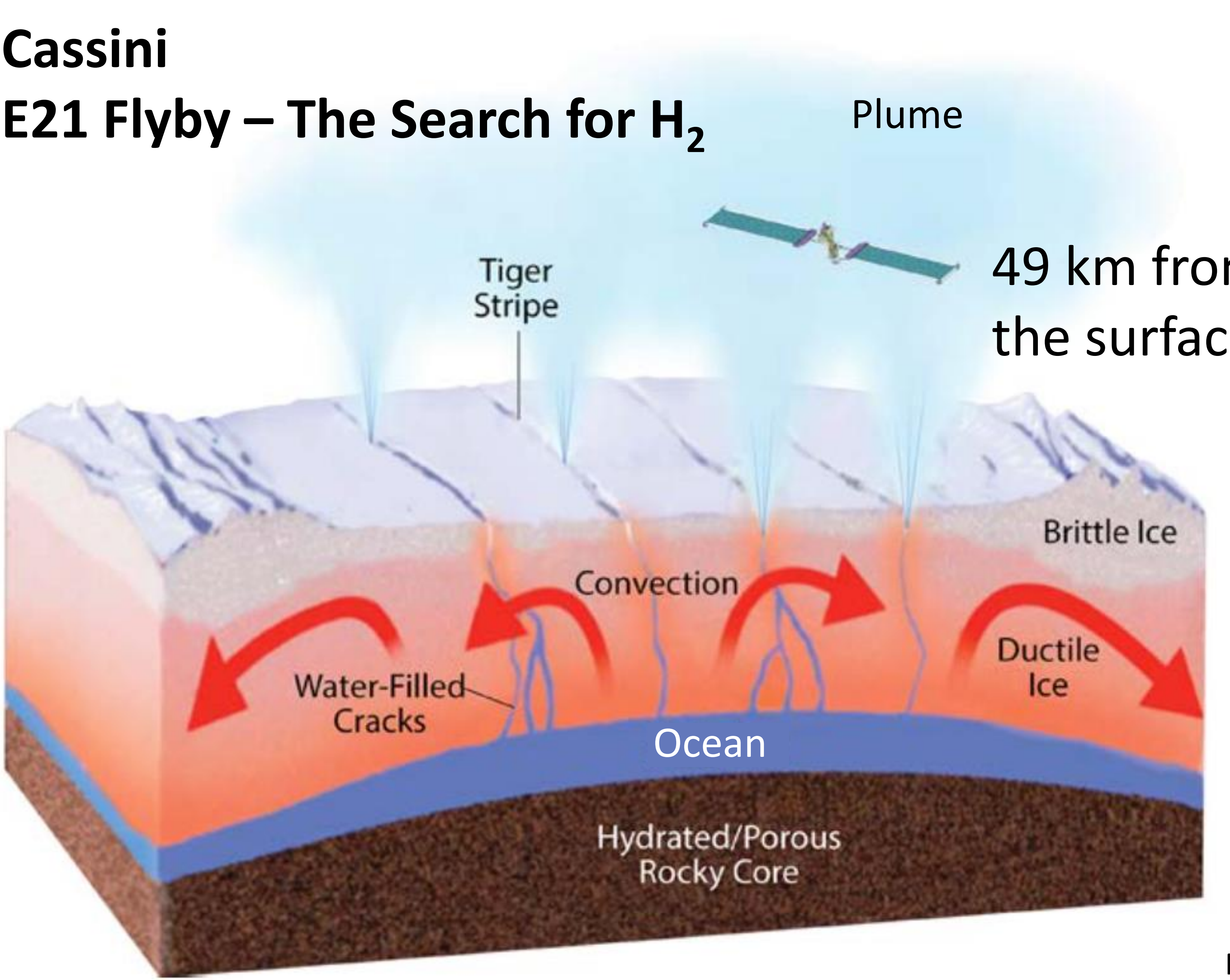


Model of hydrothermal serpentinization suggested by previous data

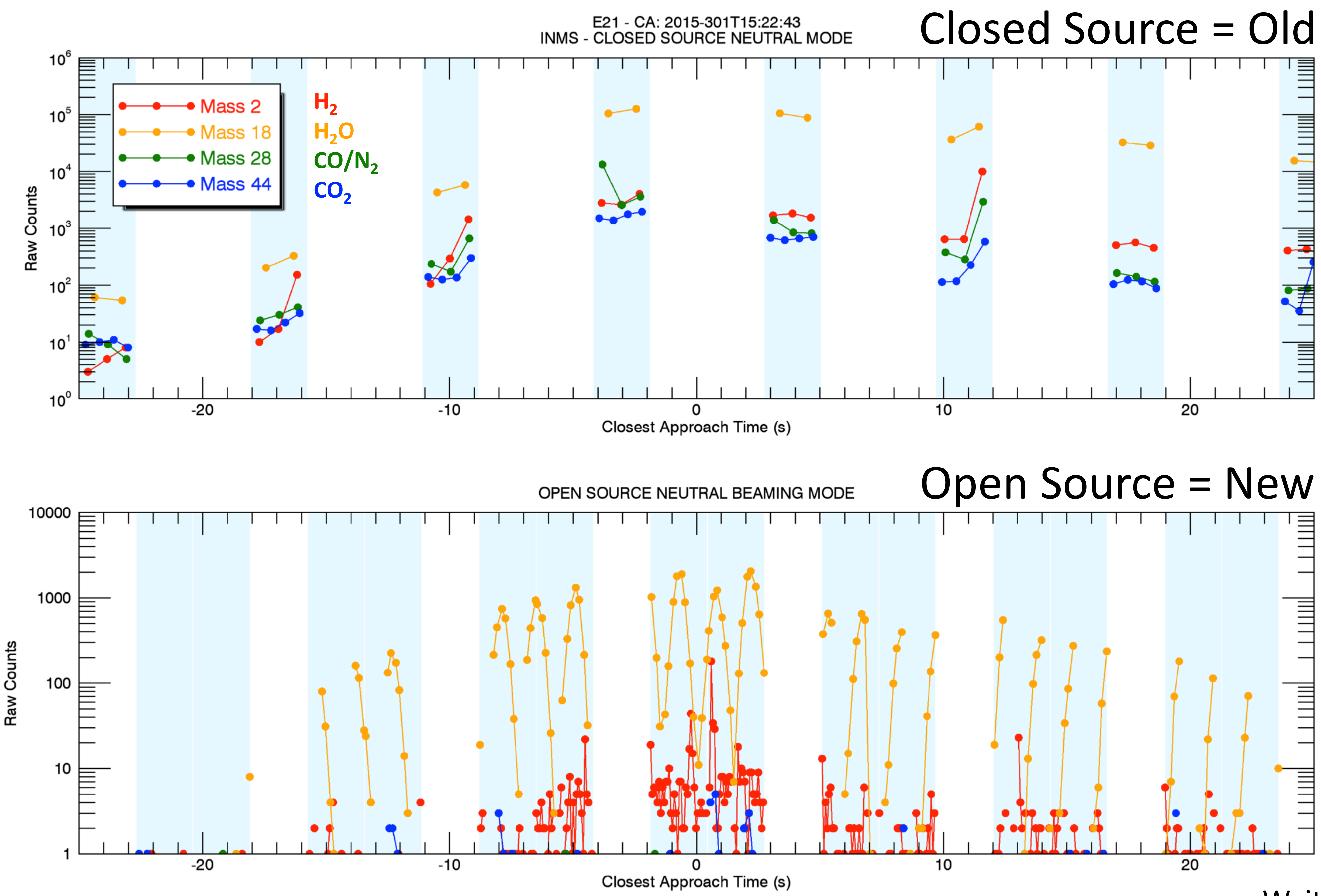
H_2 is the key missing piece

Cassini

E21 Flyby – The Search for H_2

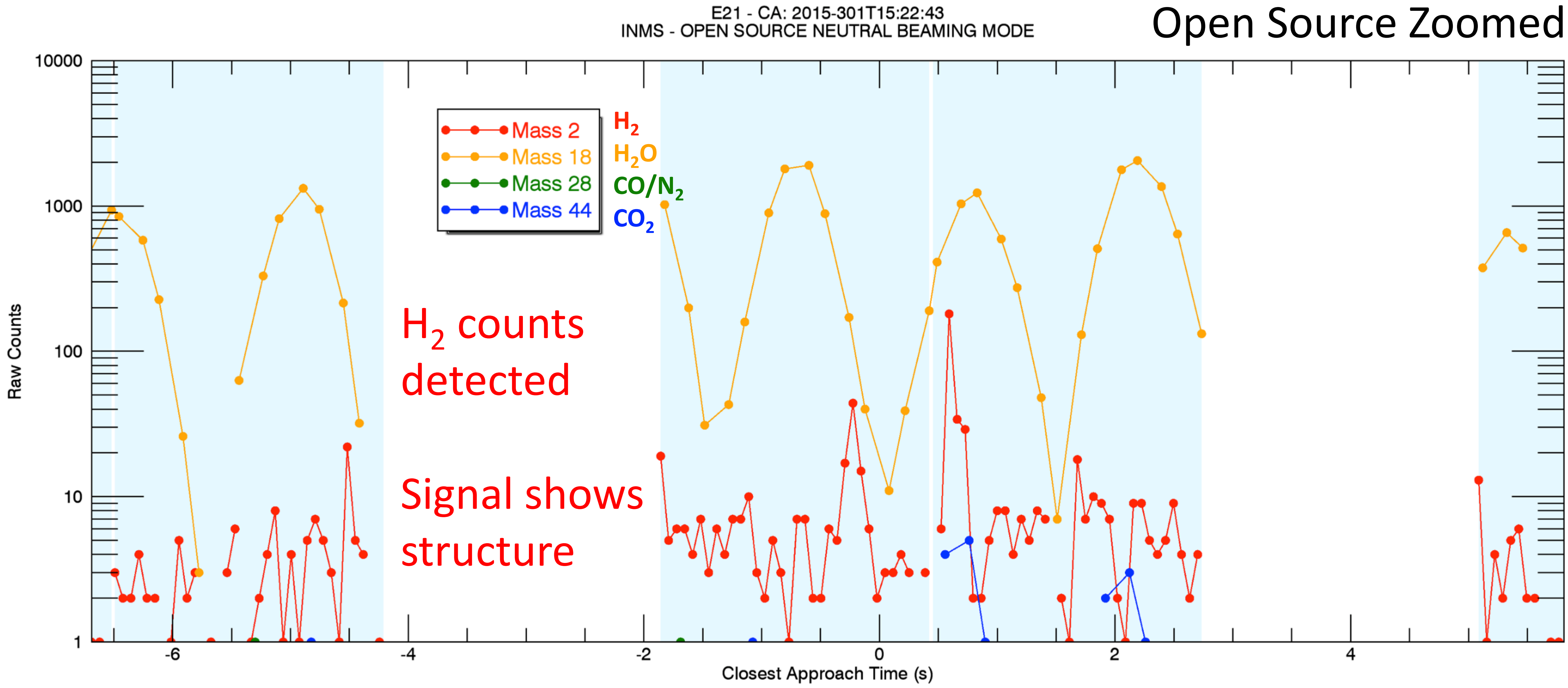


Porco et al. (2014)



Waite et al. (2017)

Open Source Zoomed



Waite et al. (2017)

Mass 2 Counts Observed in OSNB Mode

H_2 & H_2O enter the OPEN SOURCE

1. H_2 from Enceladus
2. H_2^+ generated from dissociative ionization of H_2O in the open source

Cross section obtained from Itakawa and Mason, J. Phys. Chem. Ref. Data, Volume 34, Number 1, 2005

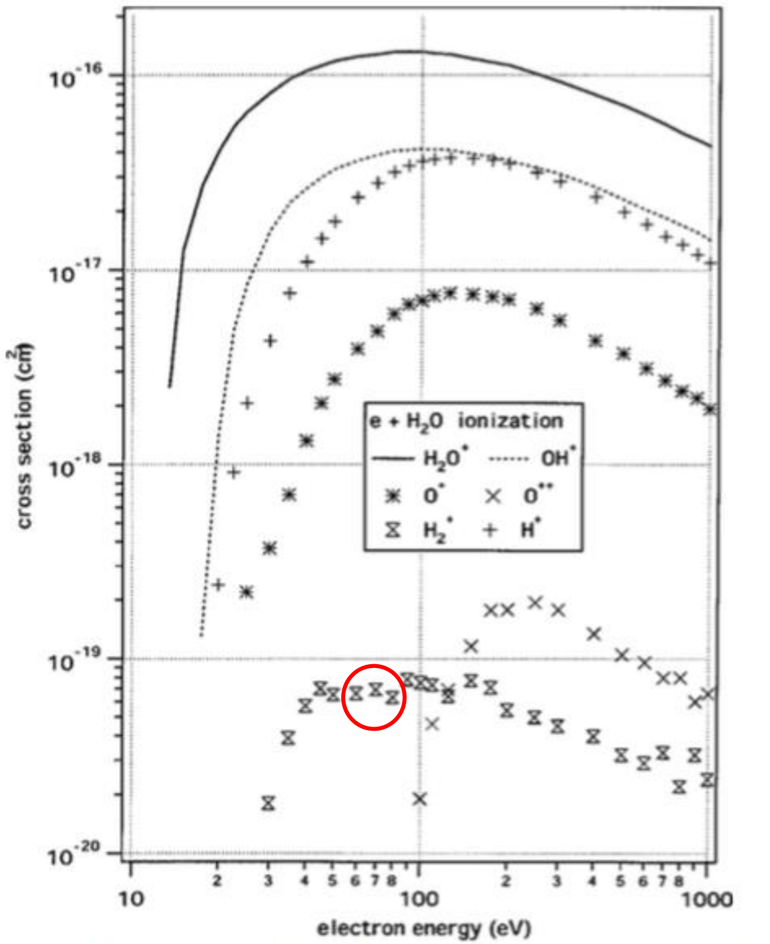
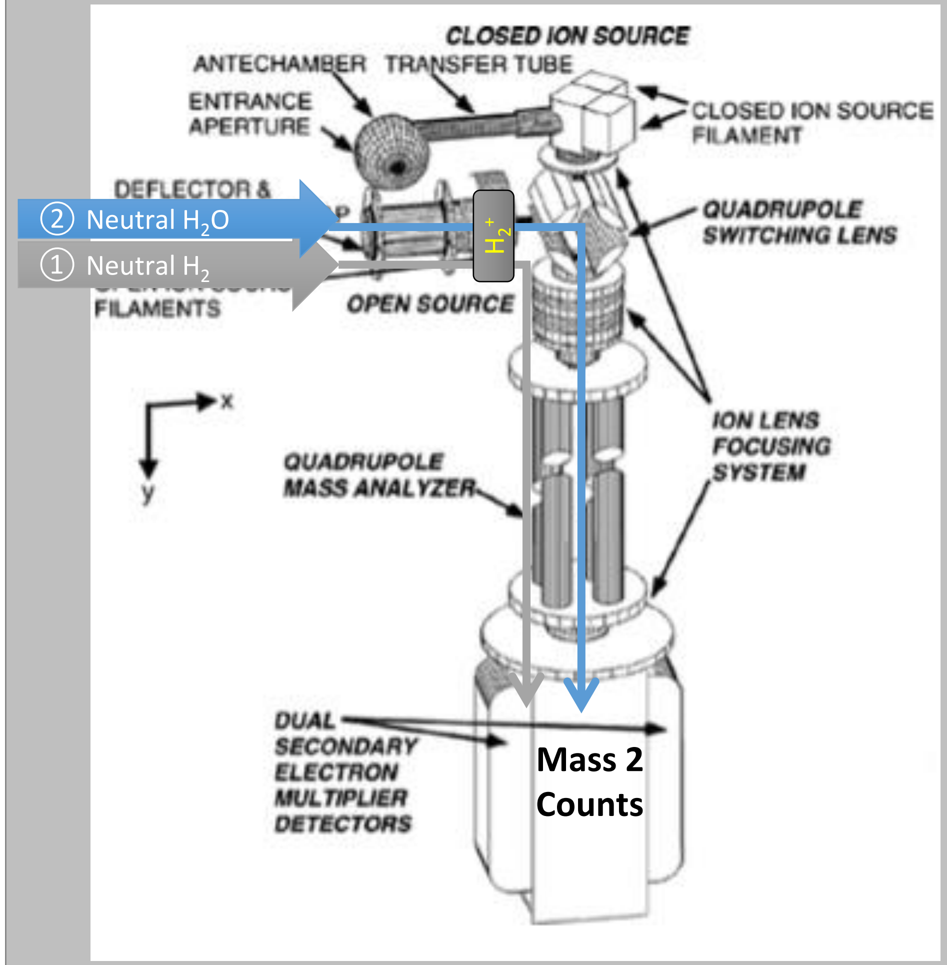


FIG. 11. Recommended values of the partial ionization cross sections of H_2O for the production of H_2O^+, OH^+, O^+, O^{++}, H_2^+, and H^+.

Is the detected H_2 real?



Instrument Background Estimation

Mass 2 Counts Observed in OSNB Mode

H_2 & H_2O enter the OPEN SOURCE

① H_2 from Enceladus

② H_2^+ generated from dissociative ionization of H_2O in the open source

Cross section obtained from Itakawa and Mason, , J. Phys. Chem. Ref. Data, Volume 34, Number 1, 2005

H_2 & H_2O enter the CLOSED SOURCE

③ H_2 and H_2O gas ionized in the closed source and H_2^+ leaks through the potential barrier on the quad lenses and into the quadrupole (Measured in INMS lab)

④ H_2 and H_2O gas (not yet ionized in the closed source) travels into the open source ionization region (Measured in INMS lab)

Thermal gas in the instrument

⑤ Thermal H_2 & H_2O gas measured during OSNB mode (Measured in INMS lab)

INMS surface effects

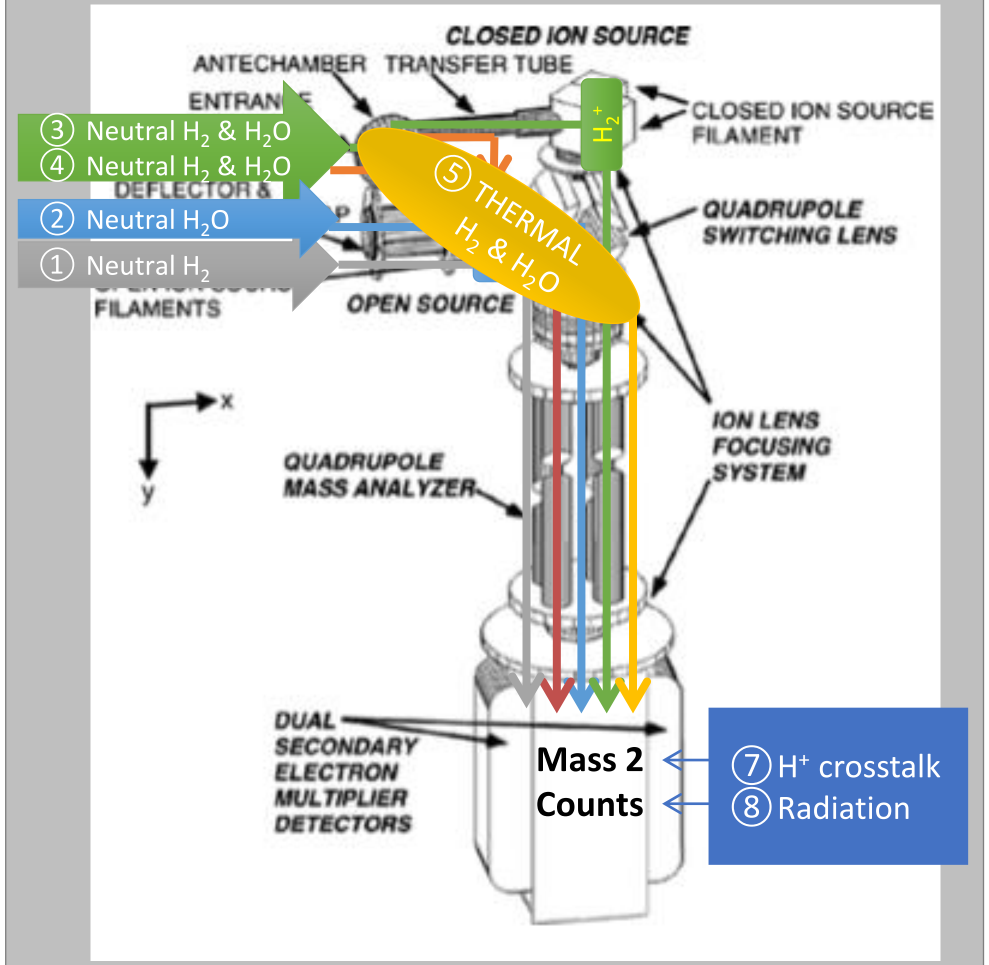
⑥ H_2 created from interactions with the surfaces of the instrument

Other sources of Mass 2 counts

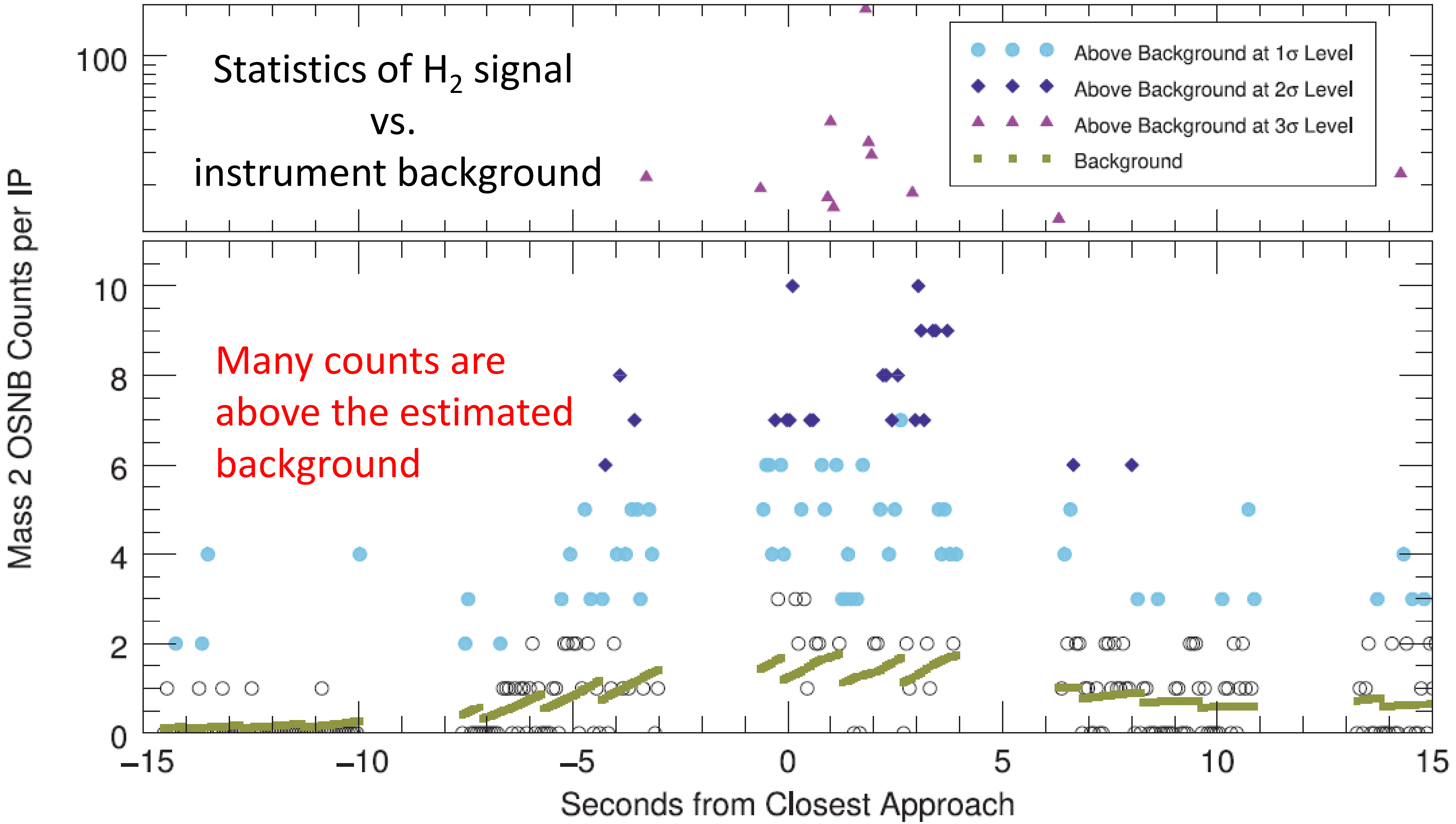
⑦ H^+ crosstalk

⑧ Radiation background

Is the detected H_2 real?

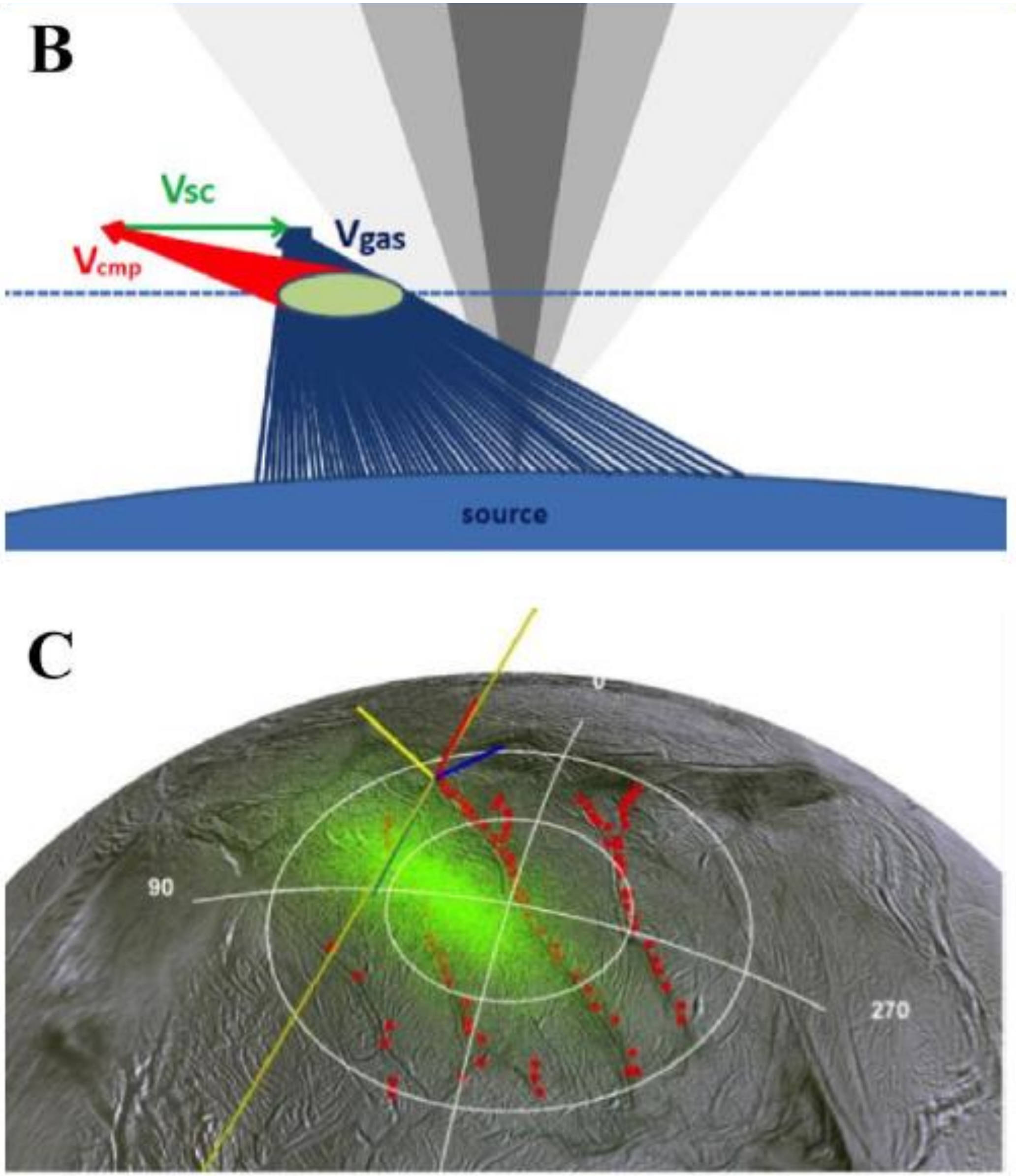


Instrument Background Estimation



Waite et al. (2017)

Model of plume outflow to derive the H_2 fraction



Waite et al. (2017)

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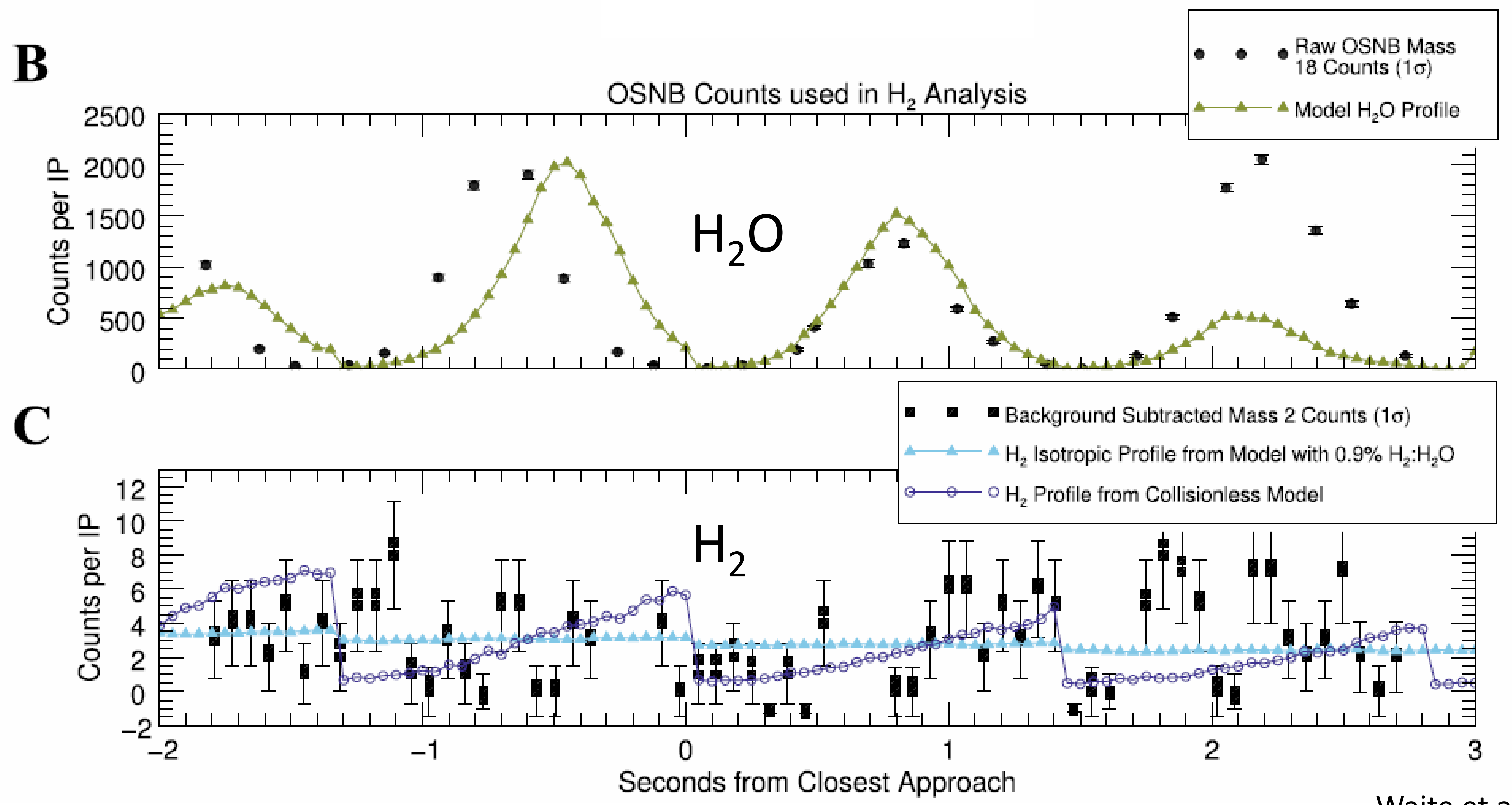
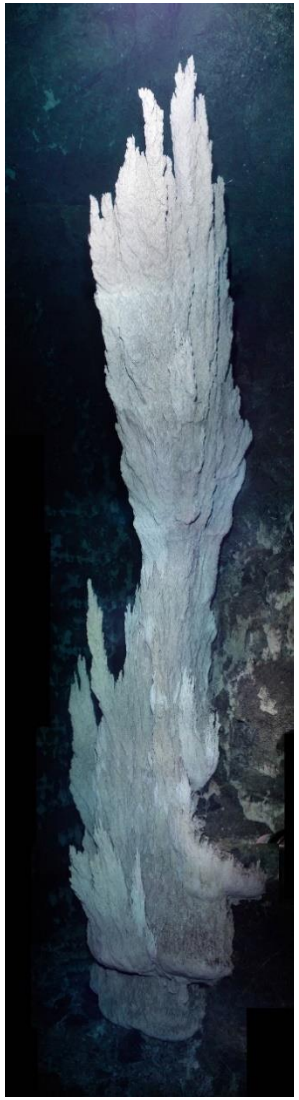


Waite et al. (2017)

H_2 = Hydrothermal?



H_2 = Hydrothermal?

Theoretical,
Observational

	Alternative source	Suggested inconsistency
Primordial	Gravitational capture of nebular H_2 e.g., Pollack et al. (1996)	Enceladus too small (>10M_E), He not detected in plume
	Trapping of H_2 in amorphous ice (<20 K) e.g., Bar-Nun & Prialnik (1988)	No evidence of such cold material in comets (OPR), lack of Ar, Ne, CO/N_2 in plume
Homemade		

H_2 = Hydrothermal?

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

A Bottom-Up Test of the Hydrothermal Model

- *Main idea: H_2 production from H_2O is coupled to Fe oxidation*

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

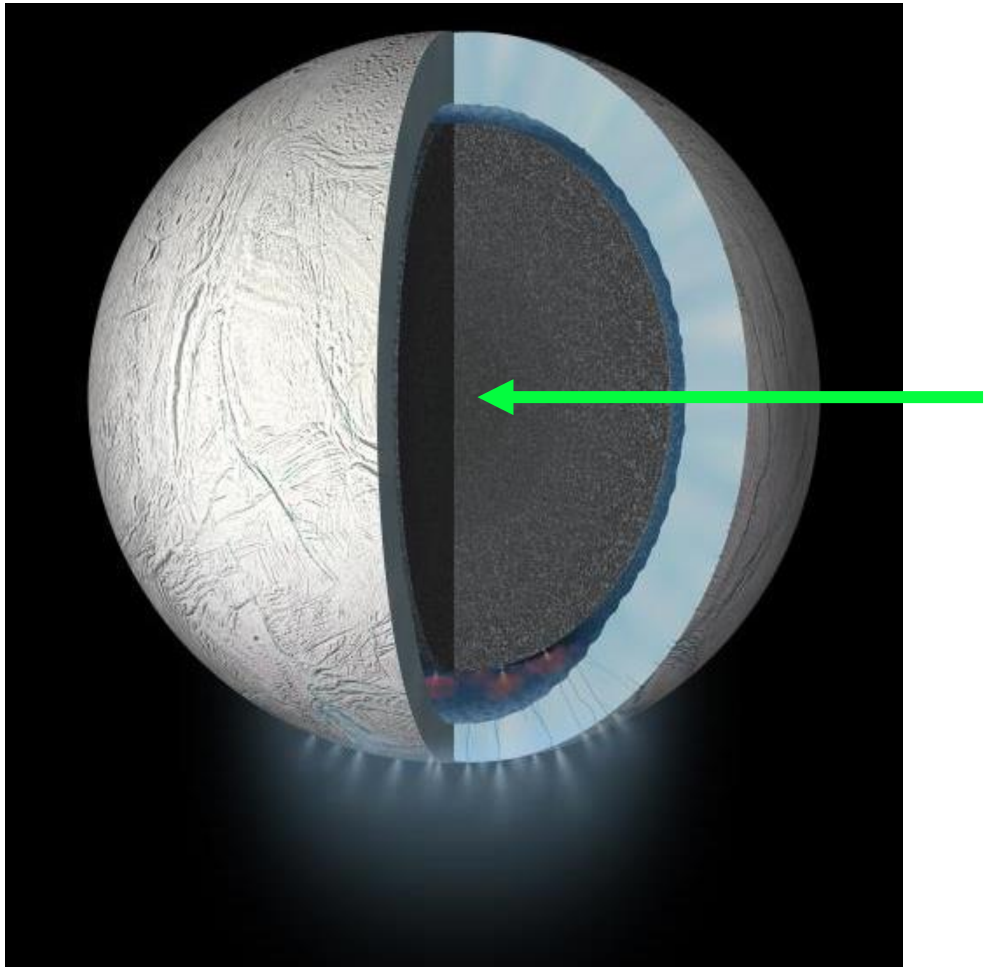
- Key geochemical reactions in the Fe-Si-O-H system:

  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)

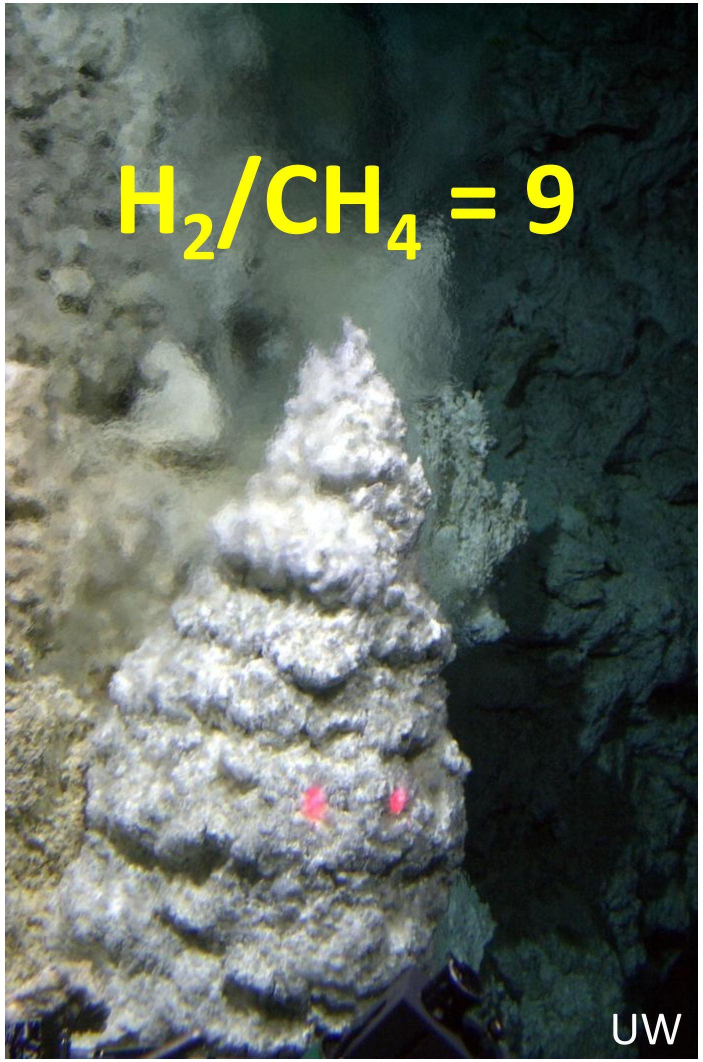
- Mineralogy of rock based on solar elemental abundances (Lodders, 2003) and alteration phases in carbonaceous chondrites (Brearley, 2006)

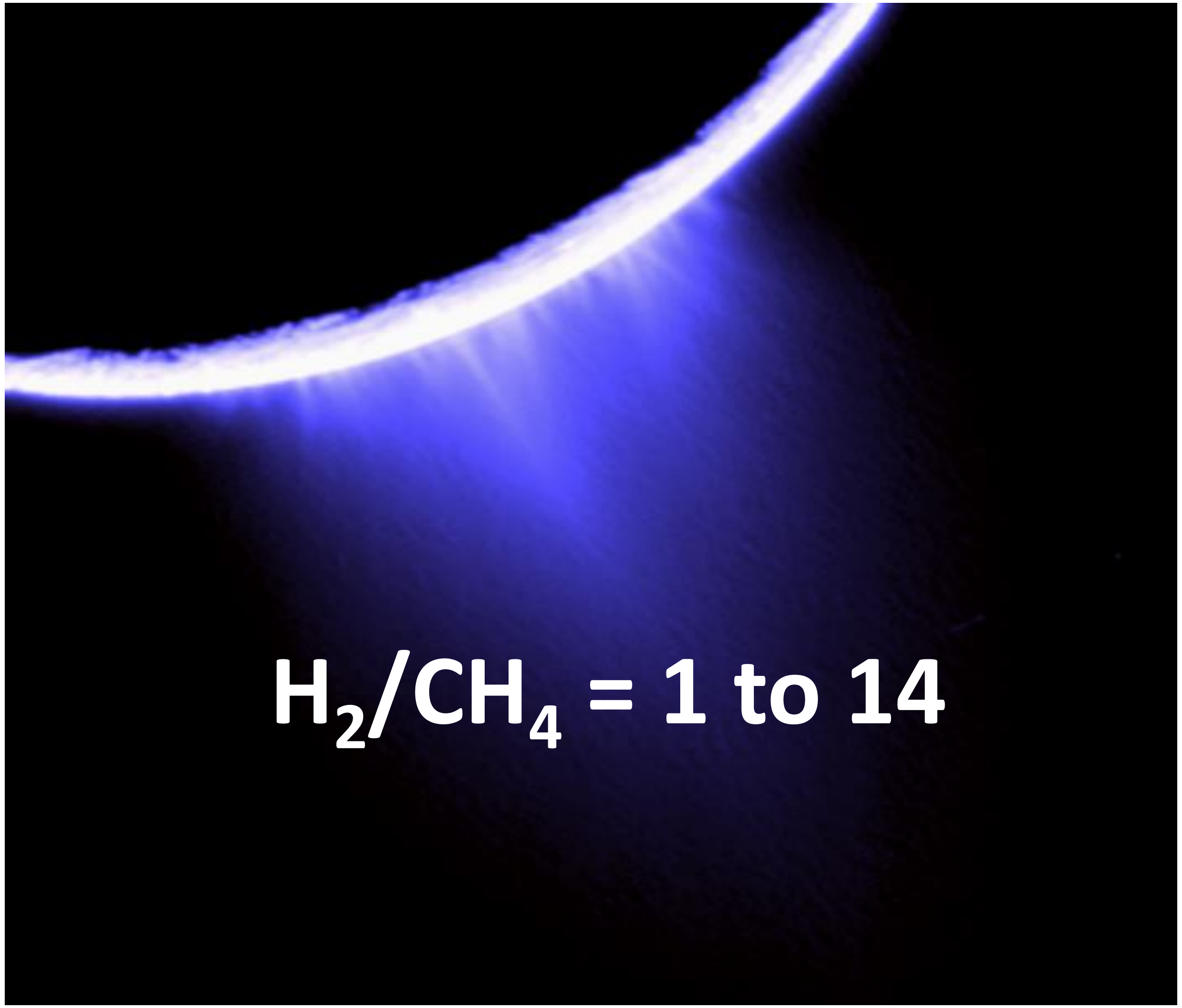
- **Example:** 1% anhydrous accreted rock in the core can sustain ~1% H_2 in the plume at today's outgassing rate (Hansen et al., 2011) for ~500 Myr

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

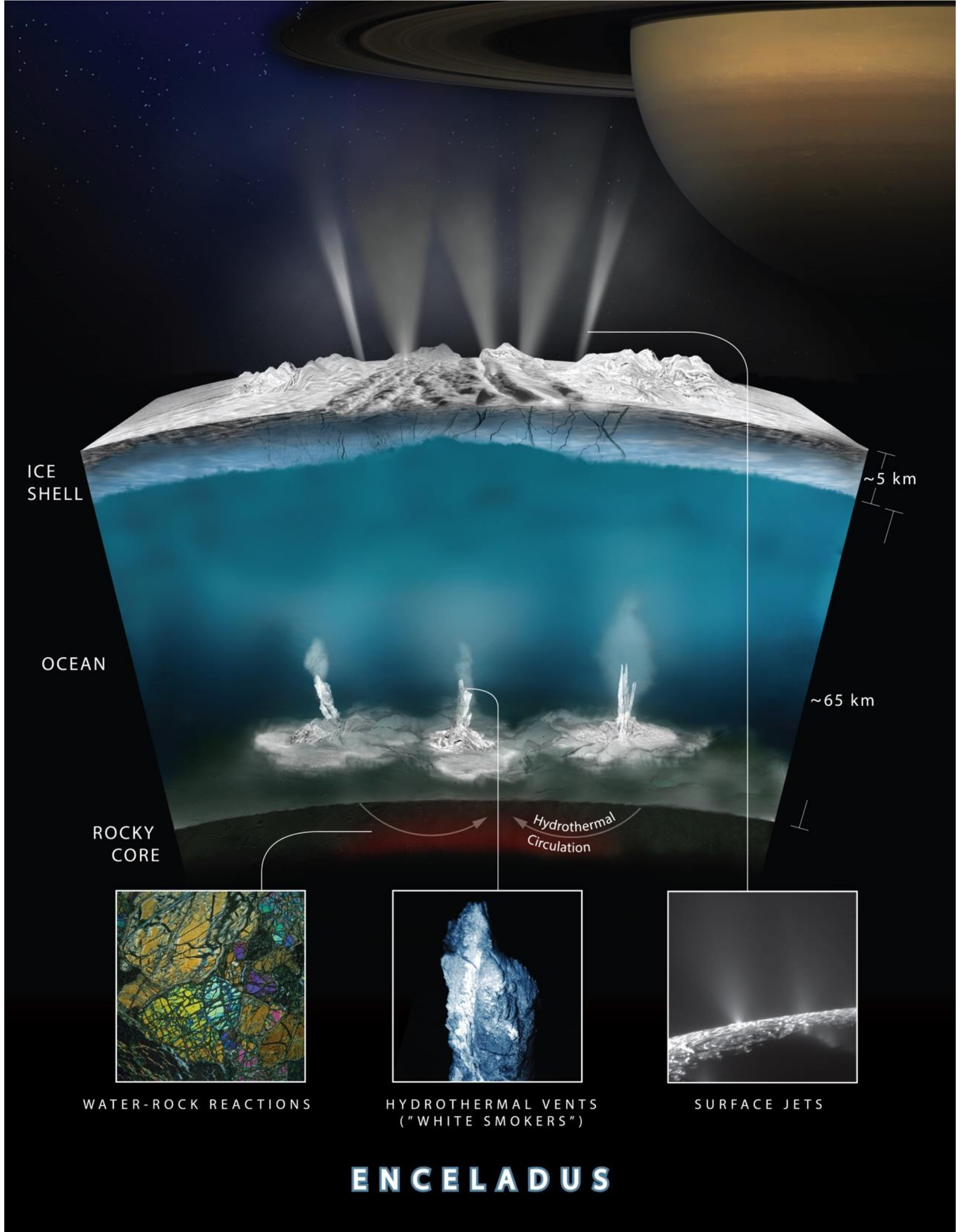
- Compatible with a low density core (McKinnon, 2015) that may be dominated by hydrated silicates containing some pore water

H_2/CH_4 ratio similar to Lost City vents



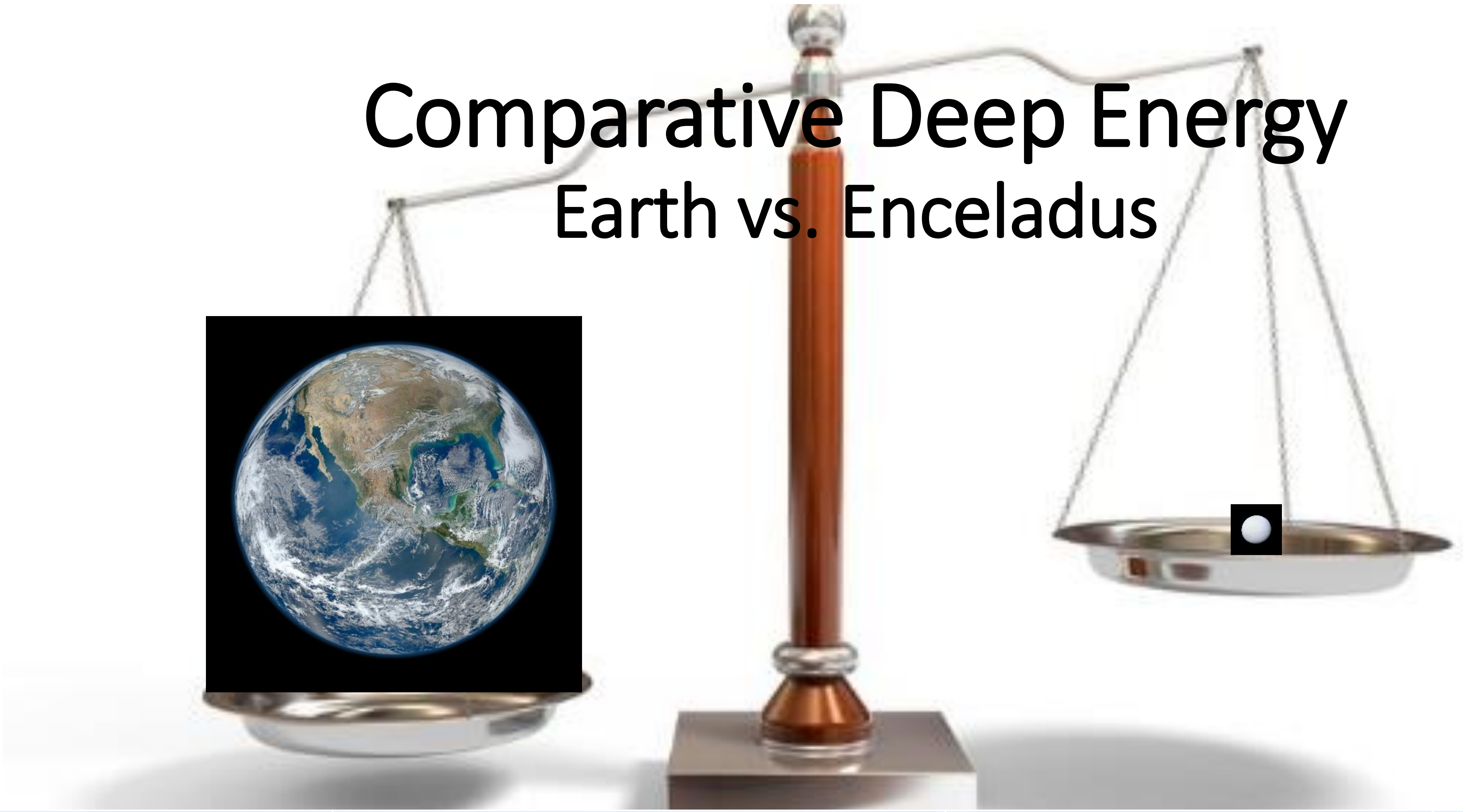


The hydrothermal model is supported by the data



https://photojournal.jpl.nasa.gov/catalog/PIA21442

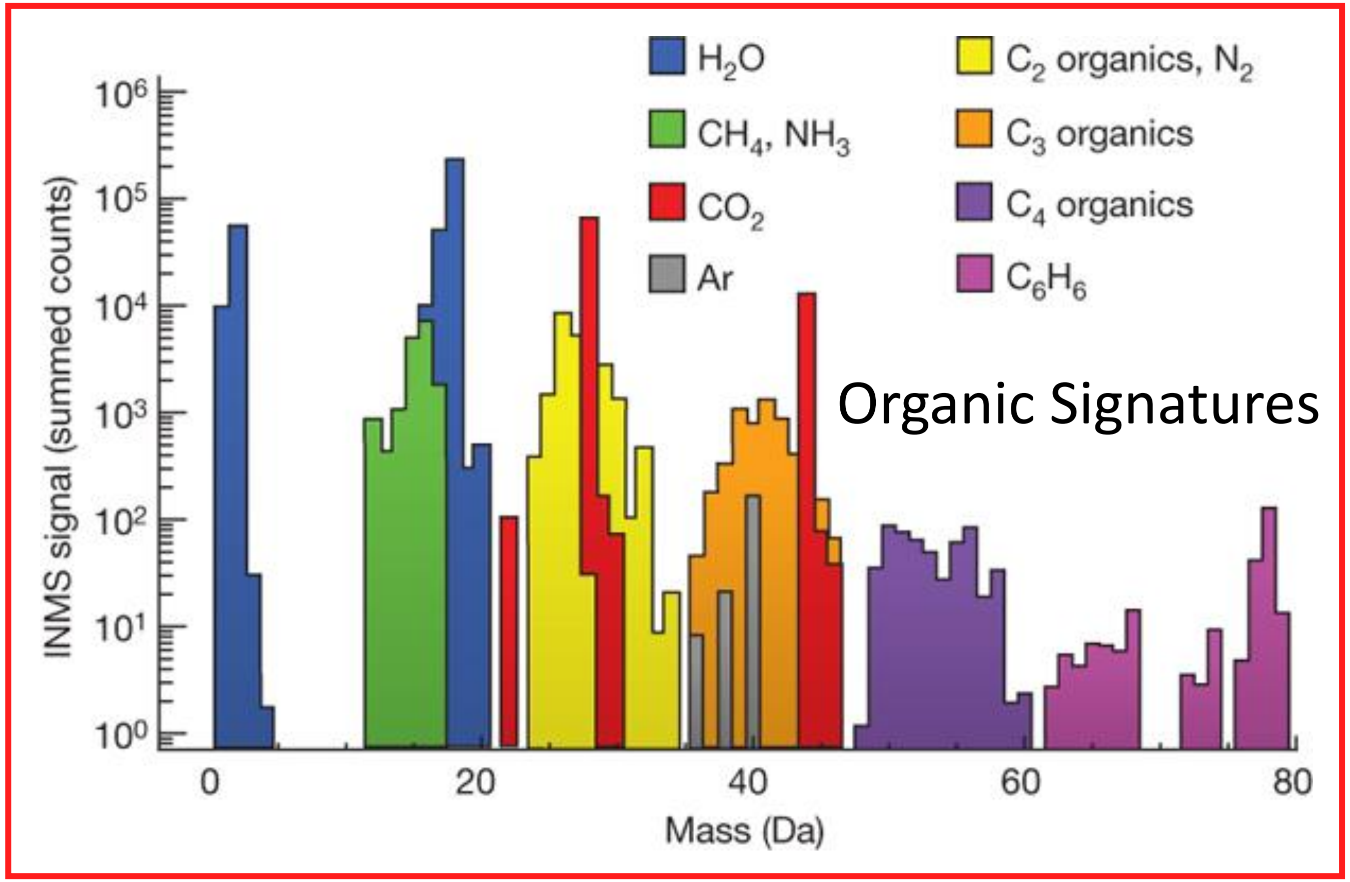
Comparative Deep Energy
Earth vs. Enceladus



Body:	Earth	Enceladus	Enceladus/Earth
Production Rate:	1×10^{12} mol H_2/yr (Sherwood Lollar et al., 2014)	3×10^{9} mol H_2/yr (~*1% H_2 in plume*)	0.003
Surface Flux:	2000 mol H_2/yr km^2	4000 mol H_2/yr km^2	2

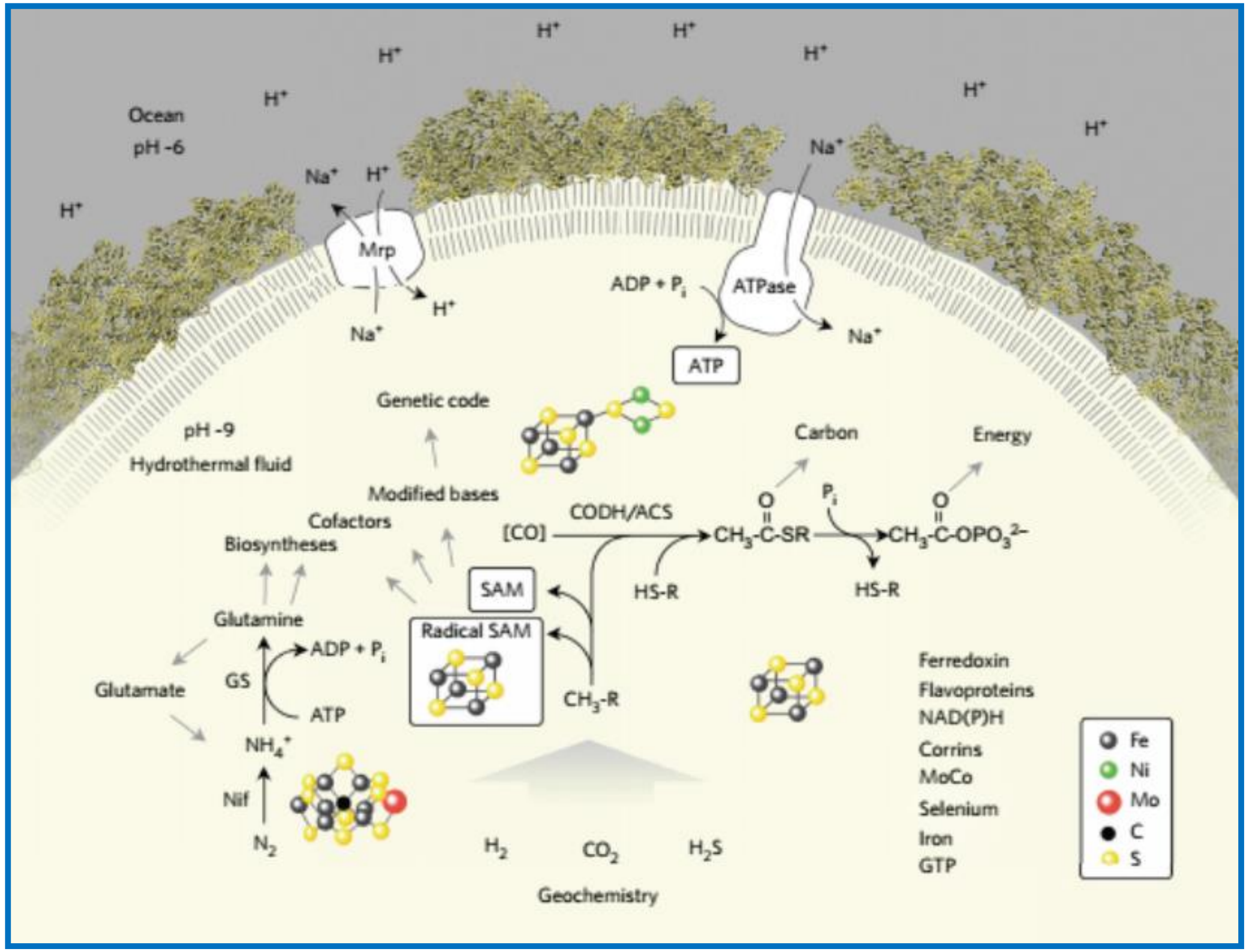
H_2 links the inorganic and organic/living worlds

- Organic synthesis
  $CO_2 + H_2 \rightarrow$ Organics + H_2O

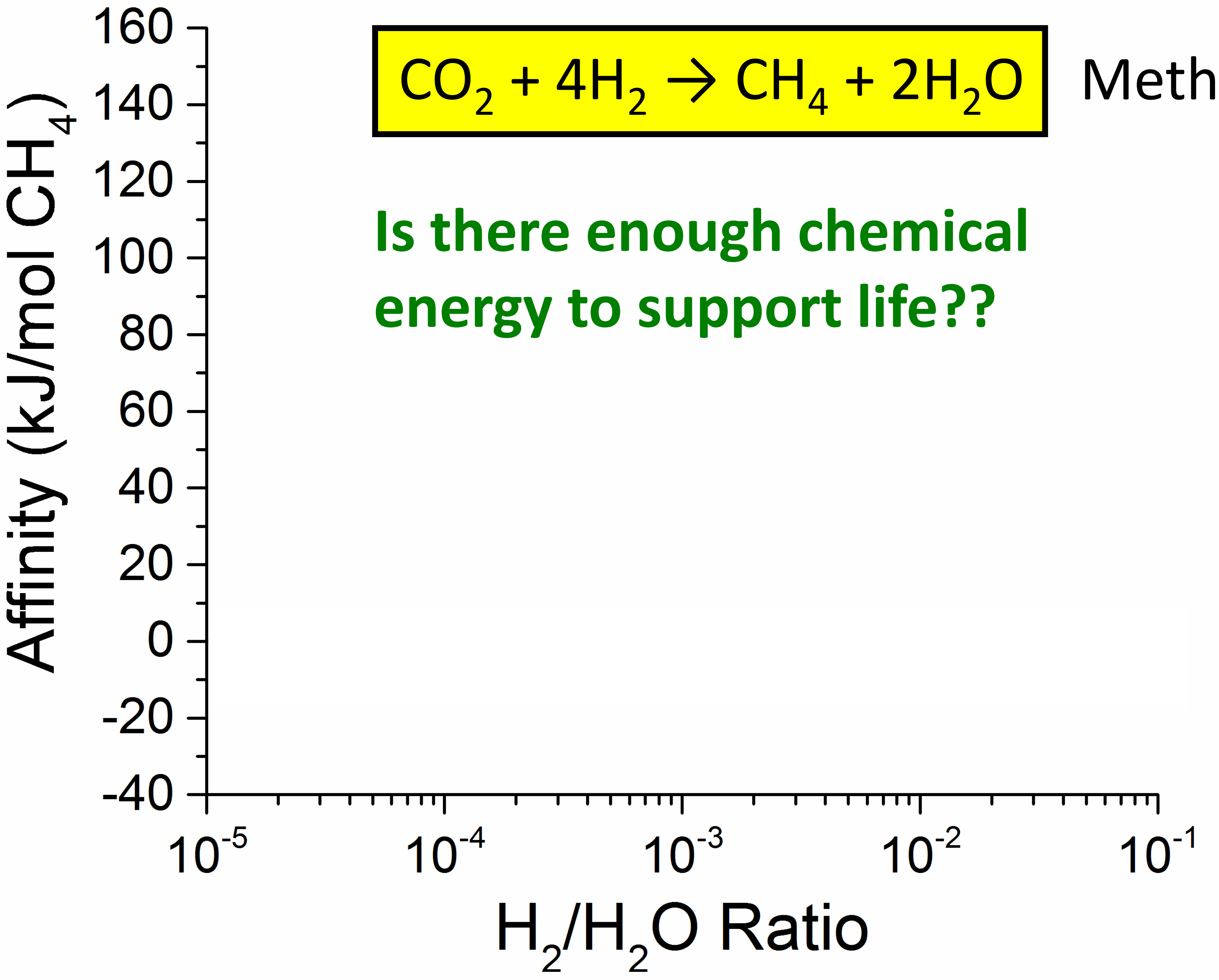


H_2 links the inorganic and organic/living worlds

- Organic synthesis
  $CO_2 + H_2 \rightarrow$ Organics + H_2O
- Prebiotic chemistry
  Current model: Life began at *alkaline* hydrothermal vent
- Chemical energy for life
  H_2/CH_4-based metabolisms



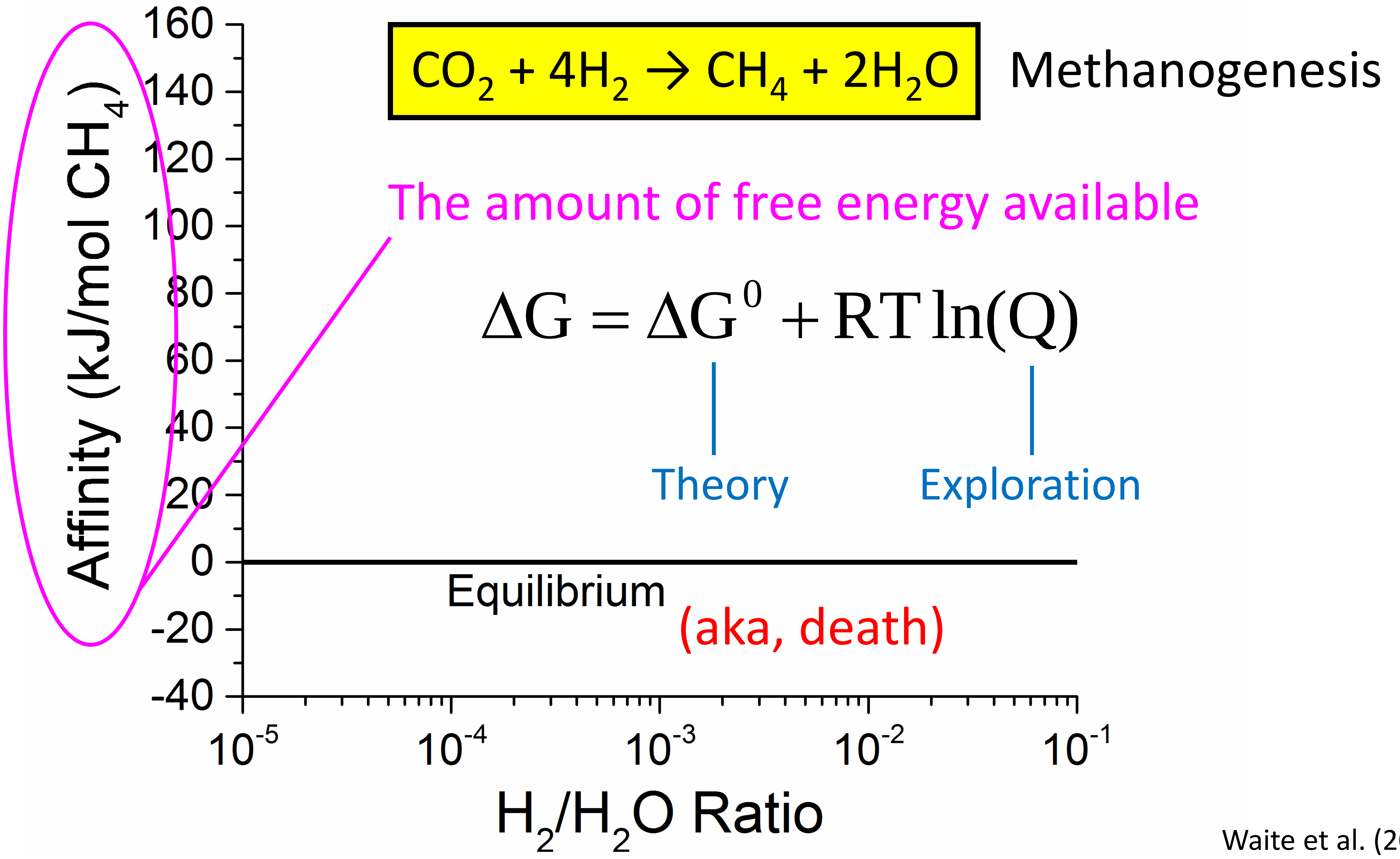
Weiss et al. (2016, Nat. Microbiol. 1, 16116)



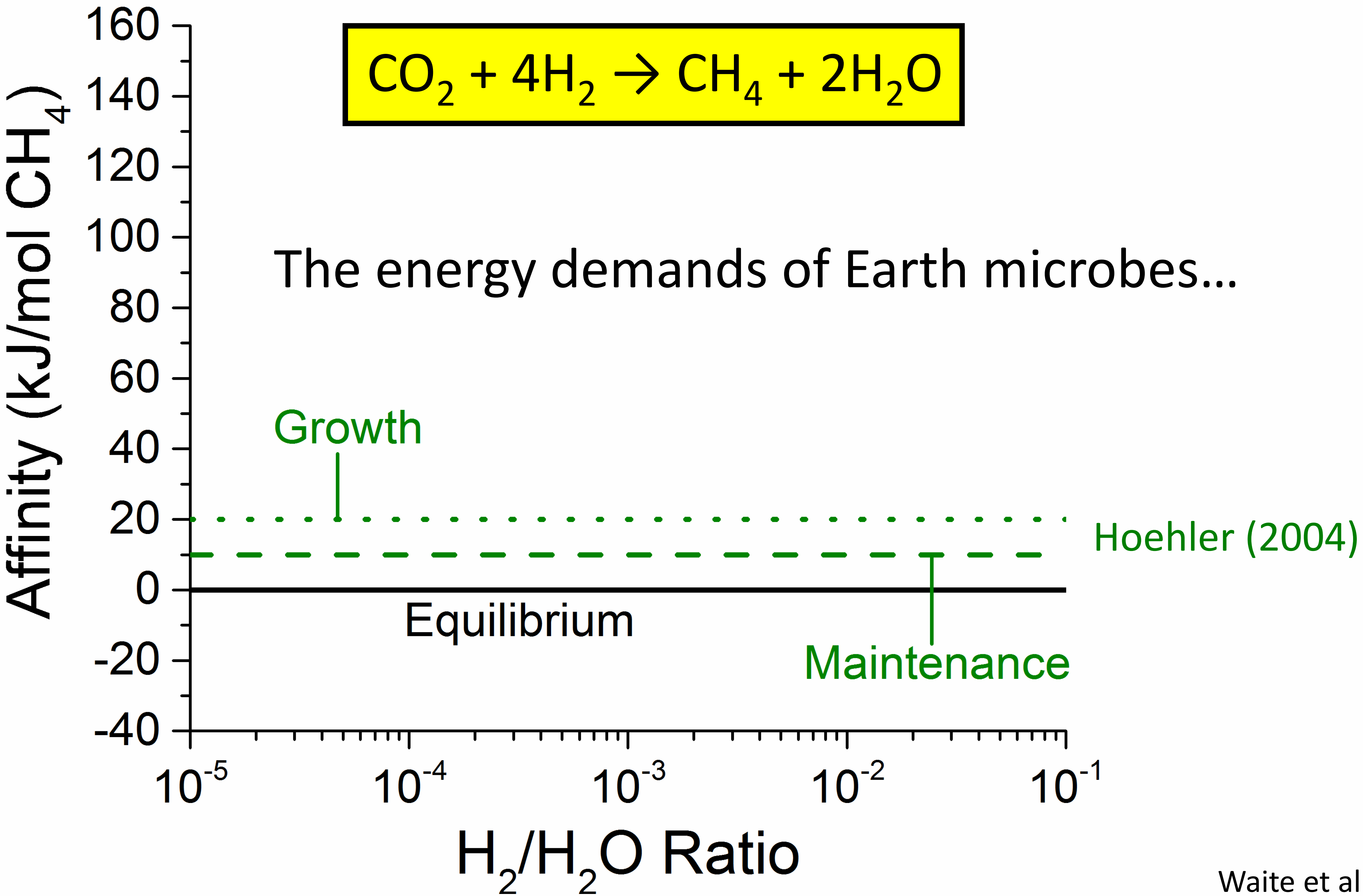
$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$ Methanogenesis

Is there enough chemical energy to support life??

Waite et al. (2017)



Waite et al. (2017)



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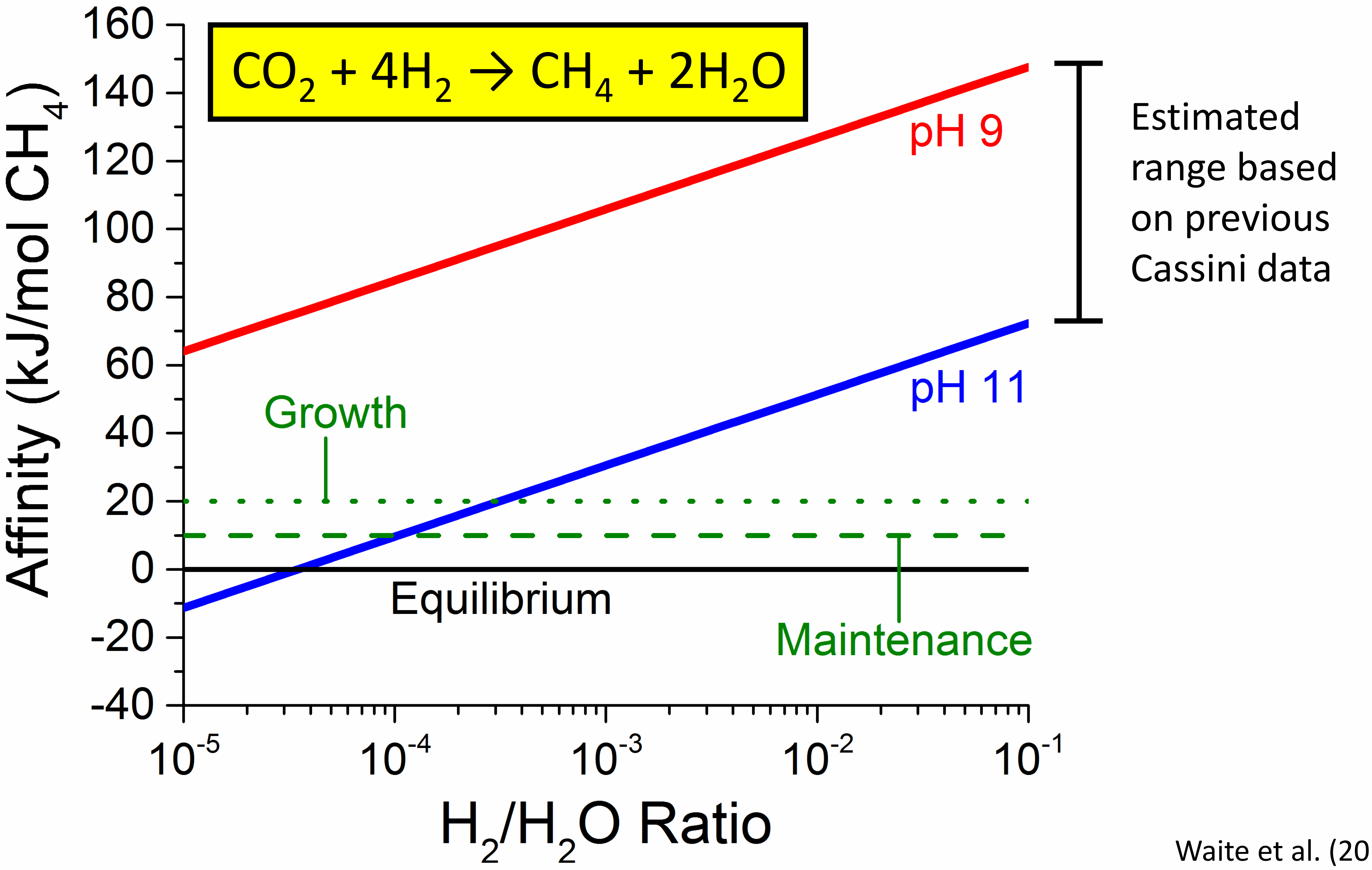
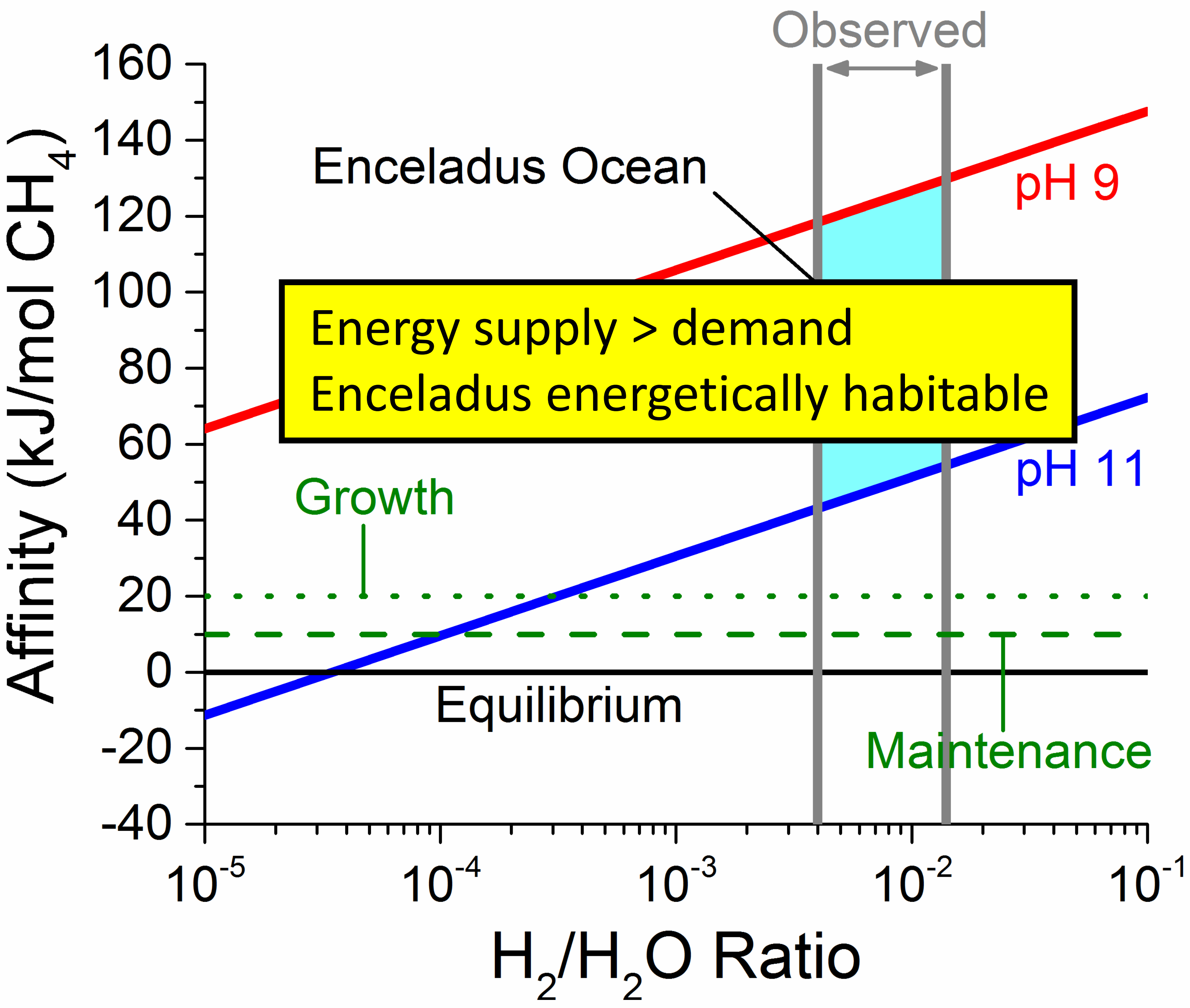
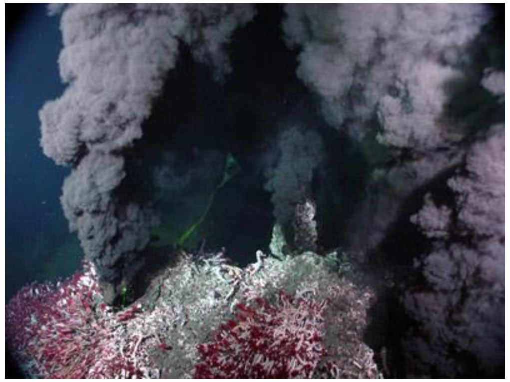


Waite et al. (2017)

Is there enough chemical energy to support life??

YES!





Waite et al. (2017)

H_2 evidence that Enceladus is energetically habitable

Jet Propulsion Laboratory
California Institute of Technology

Education | Intern Learn Teach News Events

Habitability: ✓

HOT-N-READY CHEESE

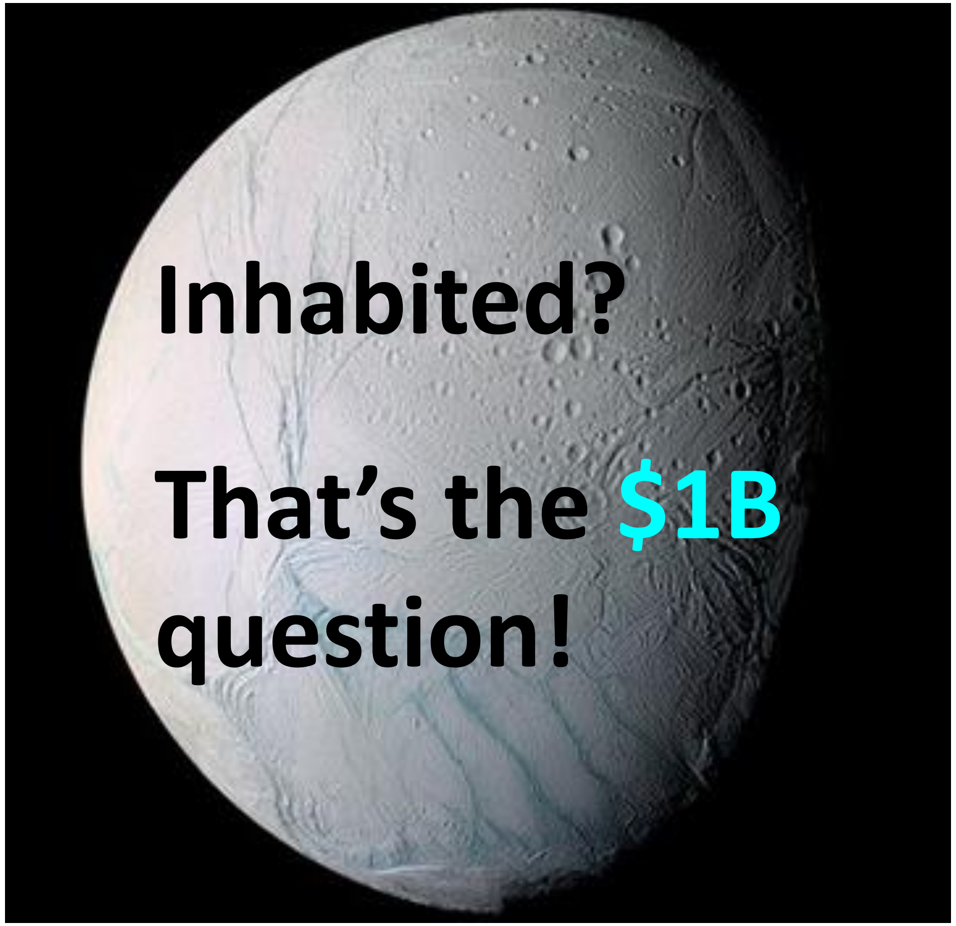
Caloric equivalent of ~300 pizzas every hour!

Free Energy

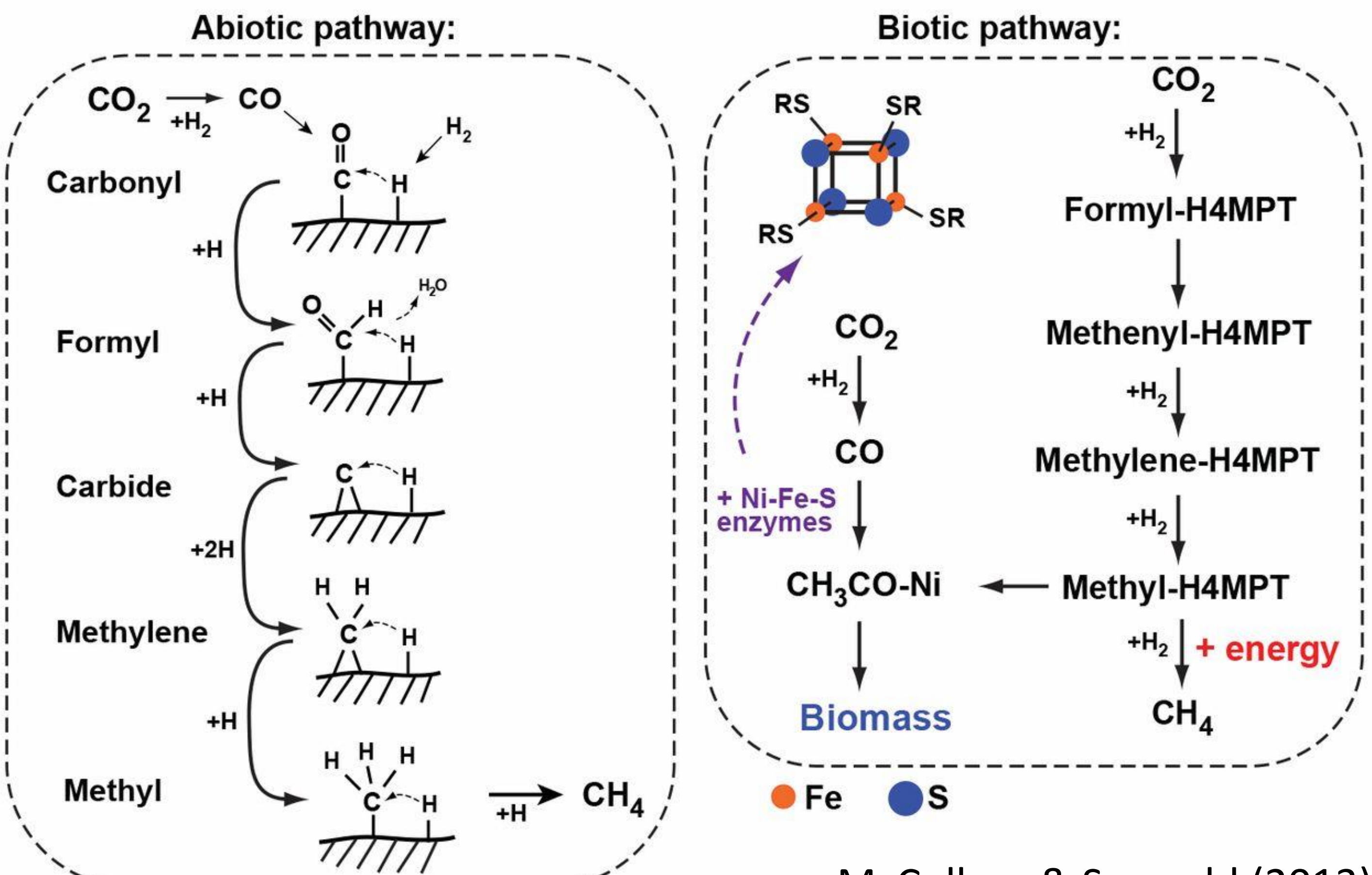
Liquid Water ✓

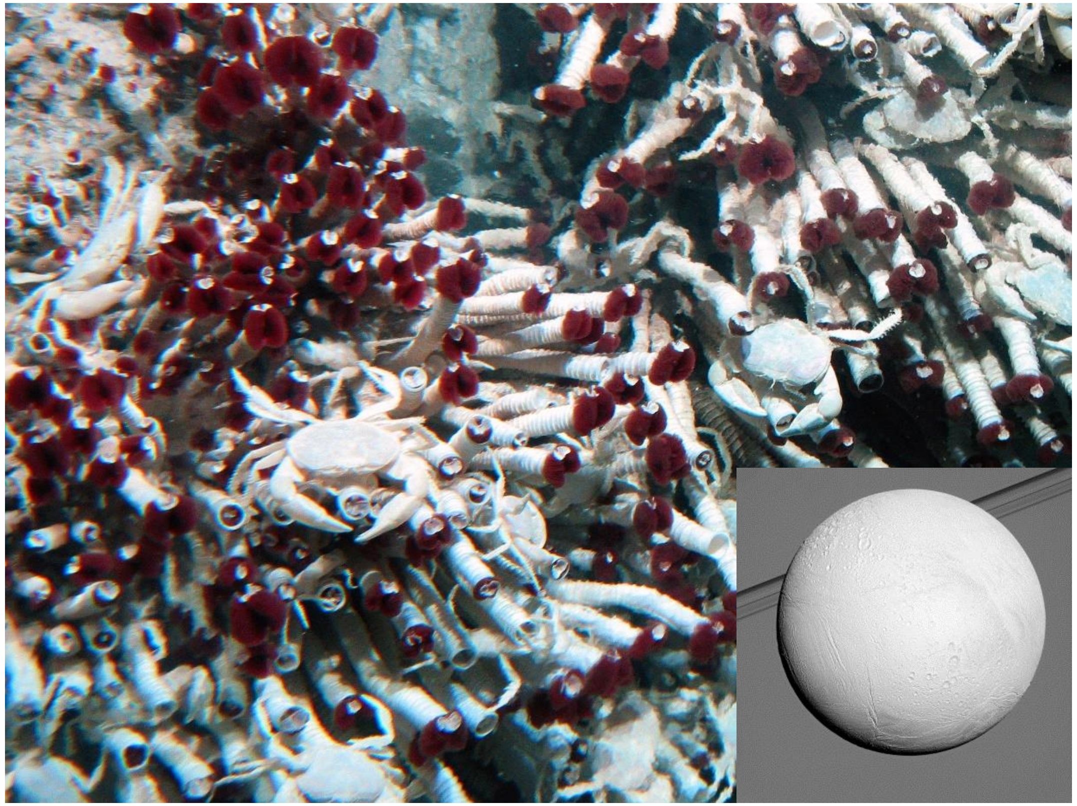
Essential Elements ✓

C, N, O, S? P?



H_2 and the drive to life as the next theme of Enceladus exploration

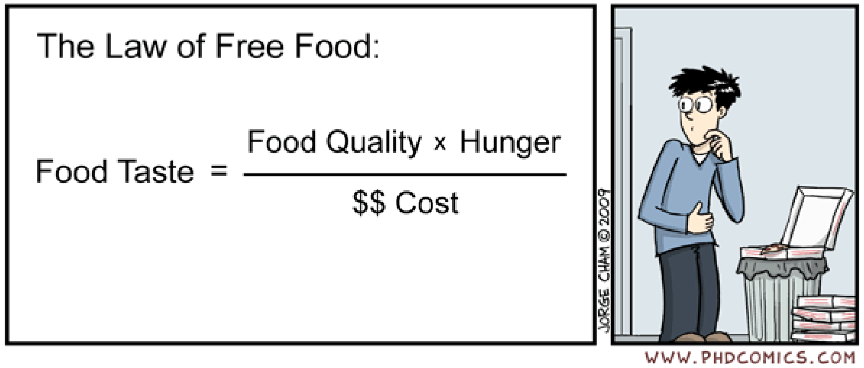


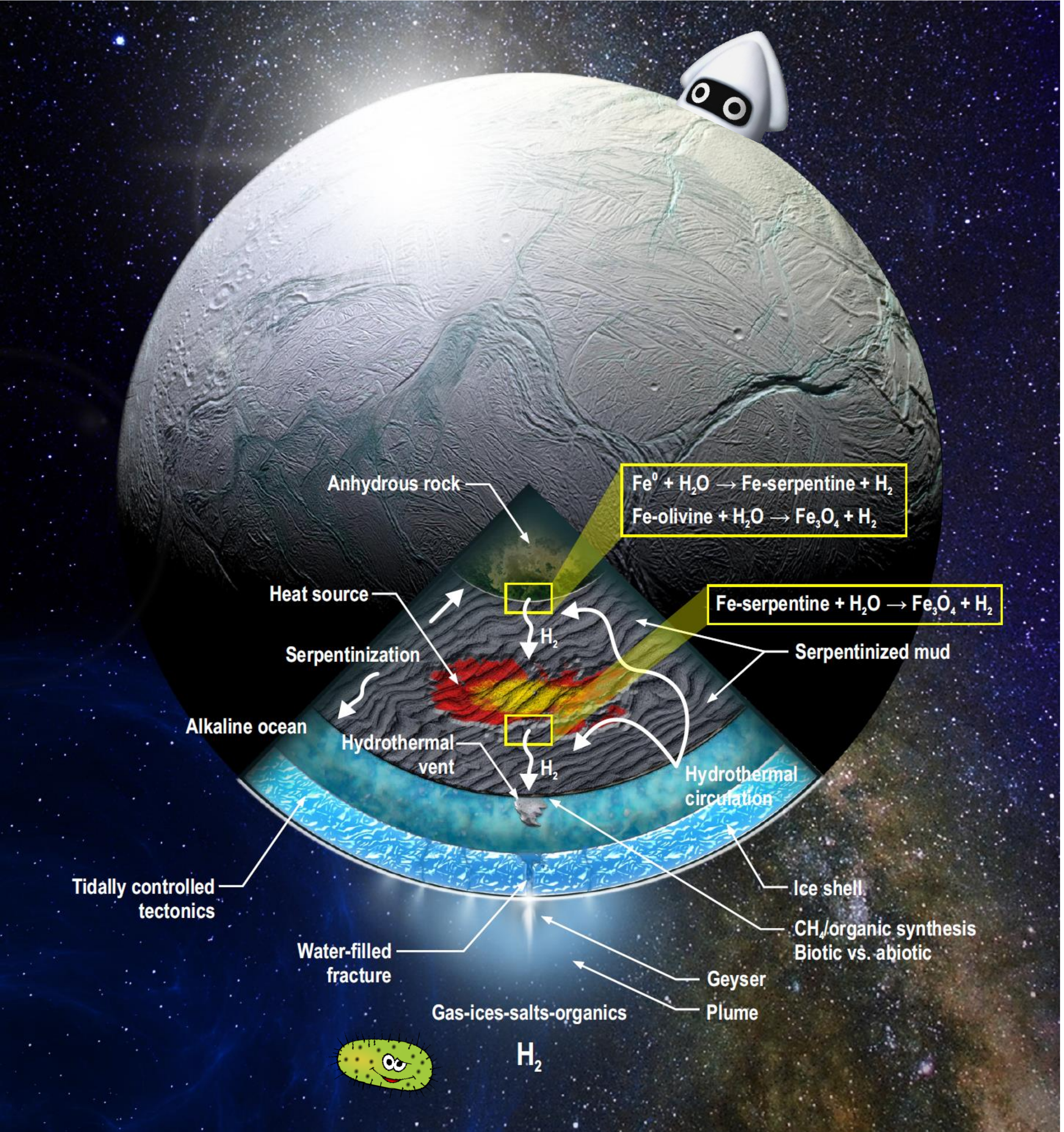


McCollom & Seewald (2013)

Geochemistry → Biochemistry → Ecology?

Energy availability sets the stage for future missions exploring relationships between habitability and the presence of life on ocean worlds





Conclusions

- Geochemical model of hydrothermal serpentinization
- Identified native H_2 in the plume from INMS
- Hydrothermal source of H_2
- H_2 is a potent and ancient energy source for microbes
- Made the first calorie count of an alien ocean
- Follow the H_2!