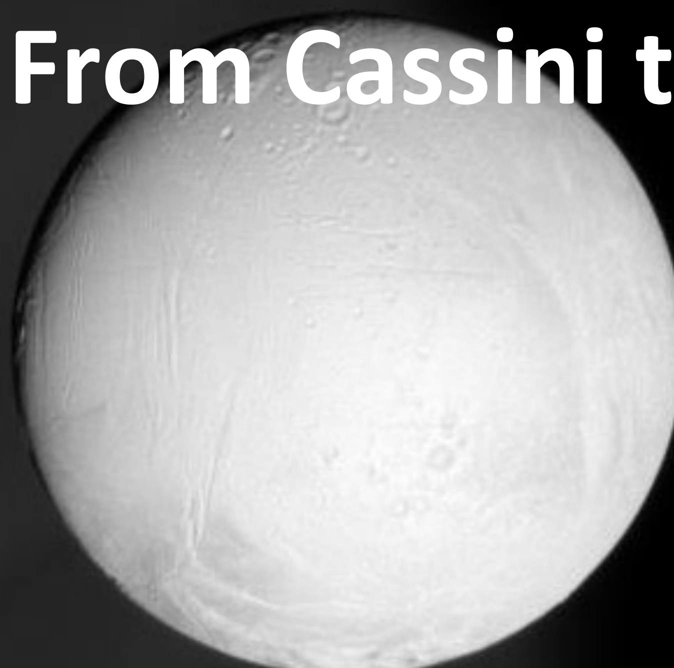
Cosmochemistry geochemistry, & astrobiology on icy satellites: From Cassini to JUICE



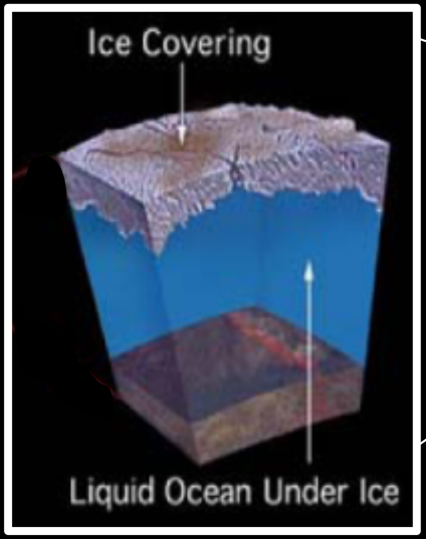
Yasuhito Sekine
Univ. Tokyo
ELSI kick-off meeting,
29 March 2013

What are icy satellites?

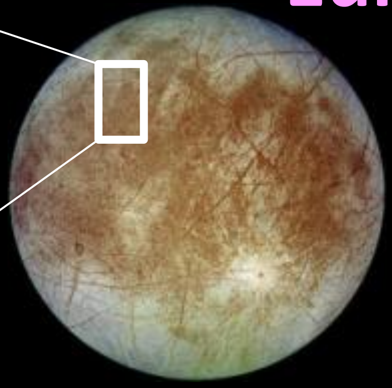
- **Ice-covered moons** around giant planets
- **Wide variety** in activity, surfaces, & interiors

Callisto

Low geological activity

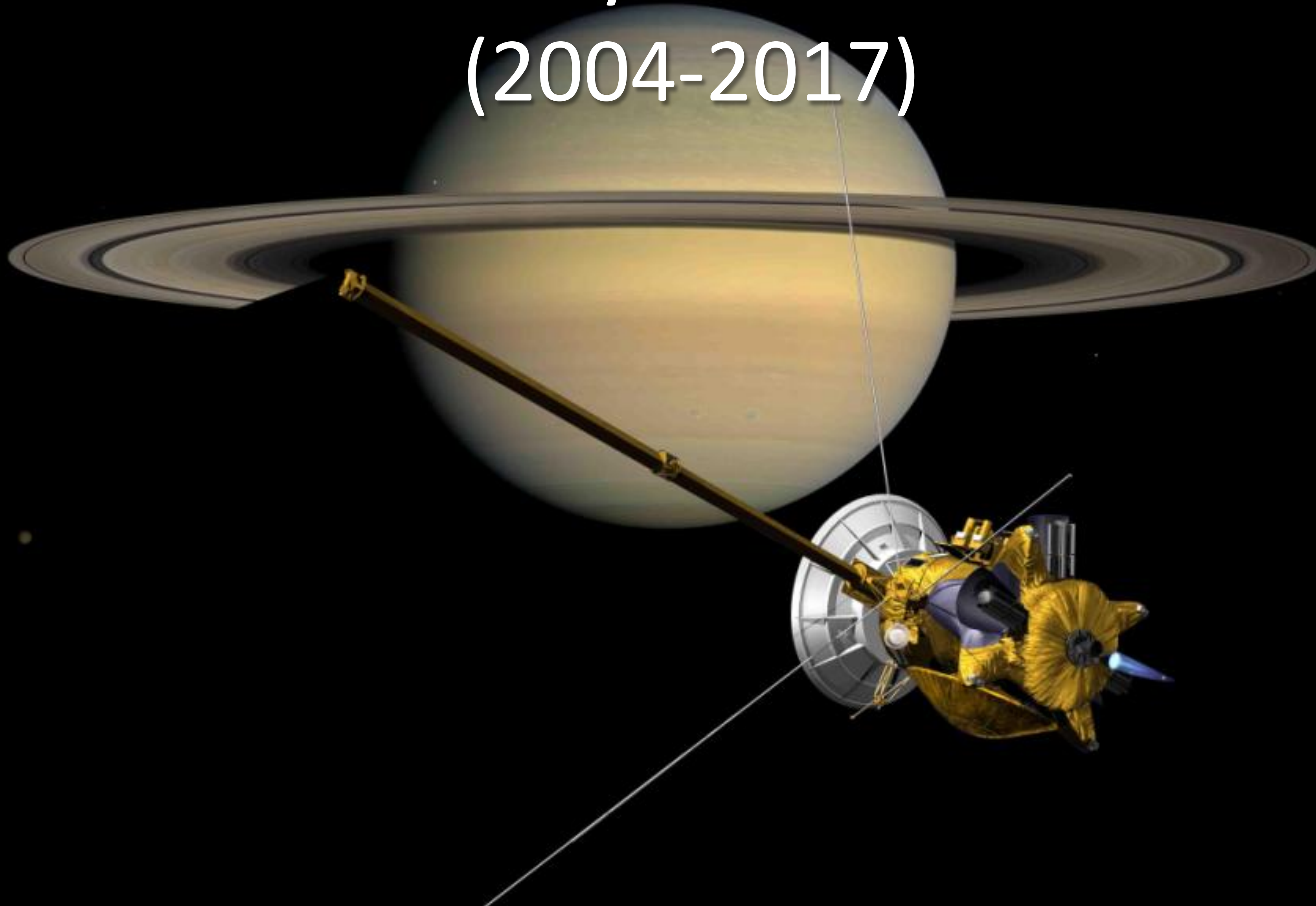


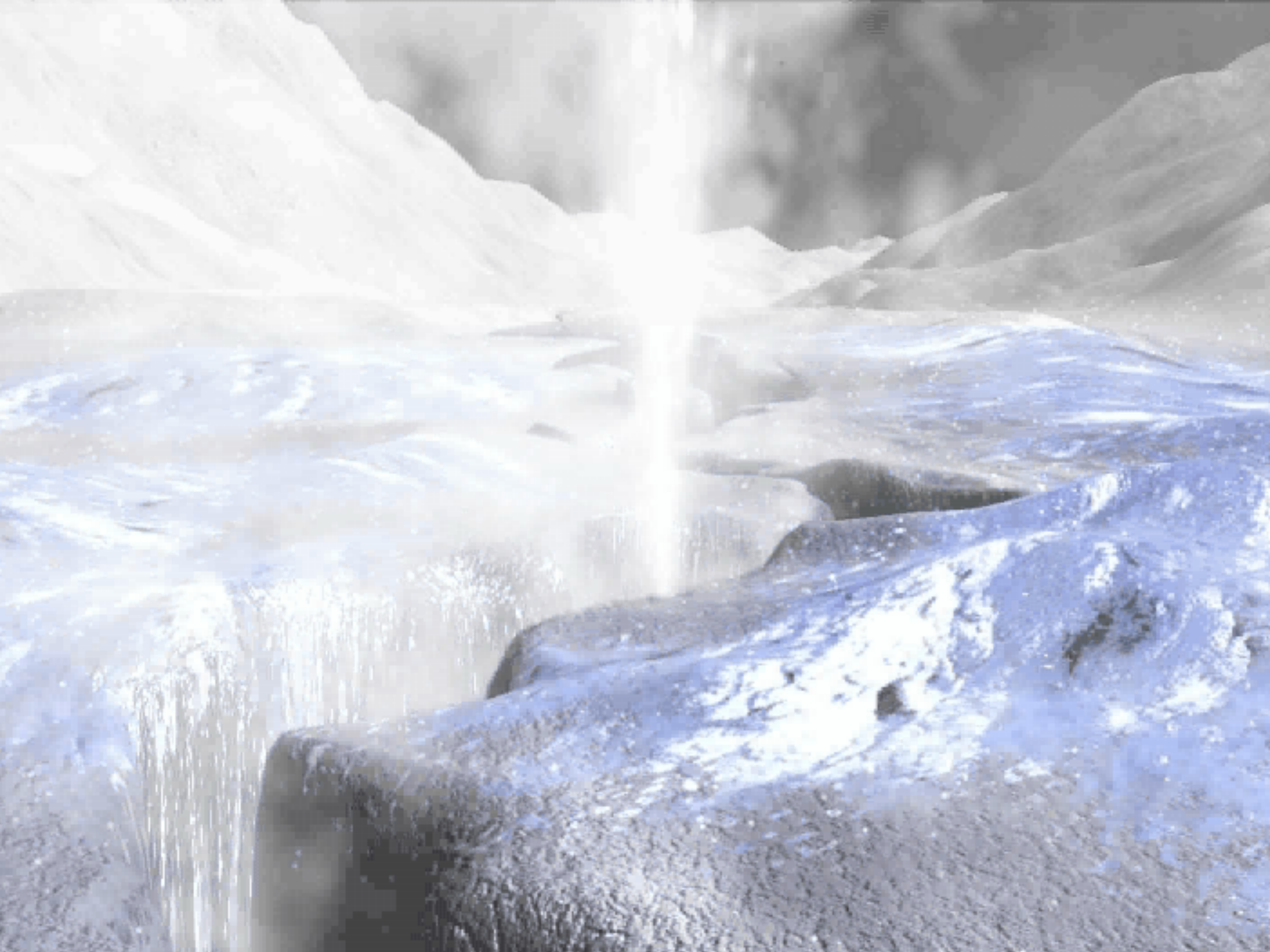
Europa



Extensive & prolonged activity, interior ocean

Cassini mission to Saturnian system (2004-2017)



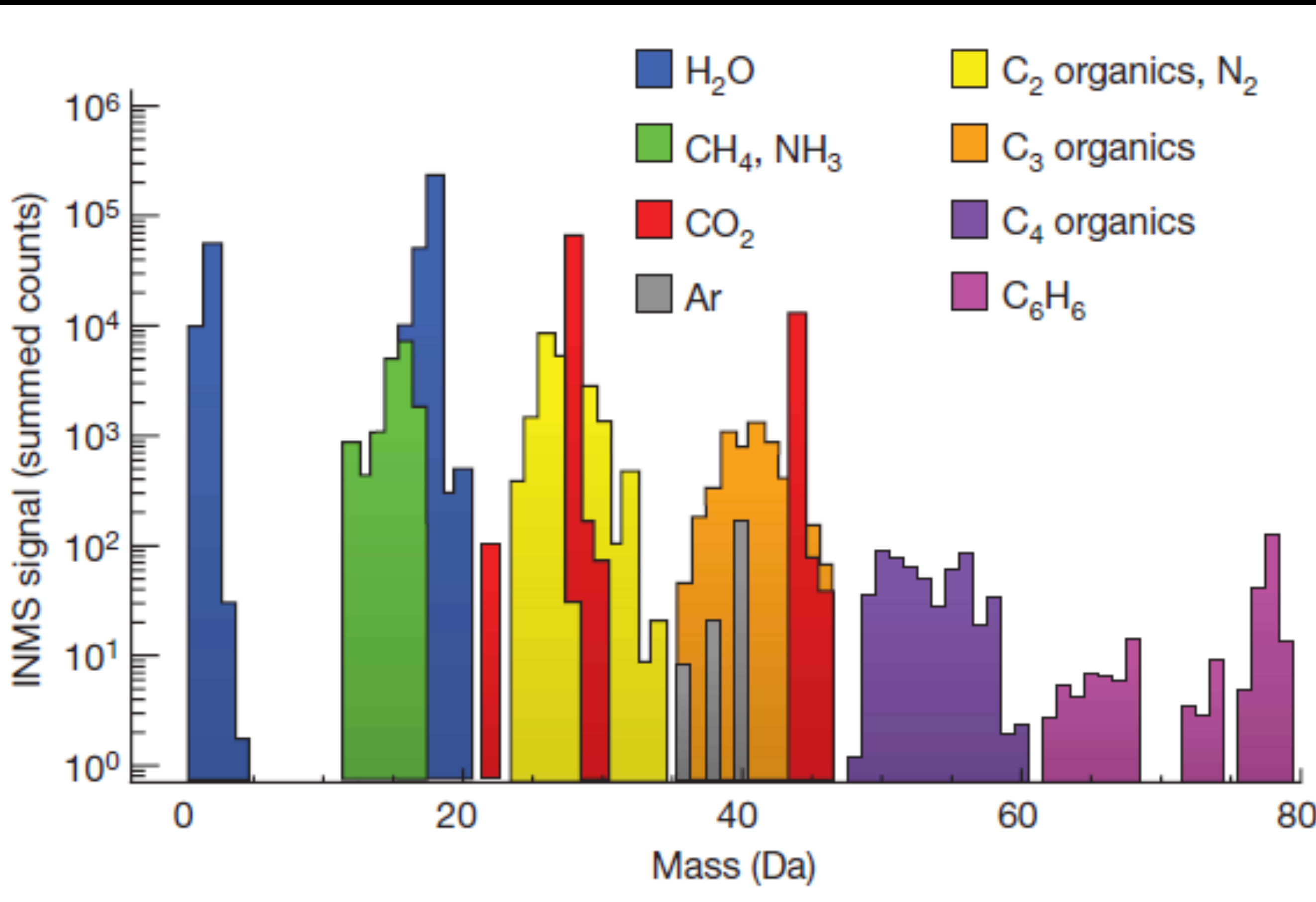


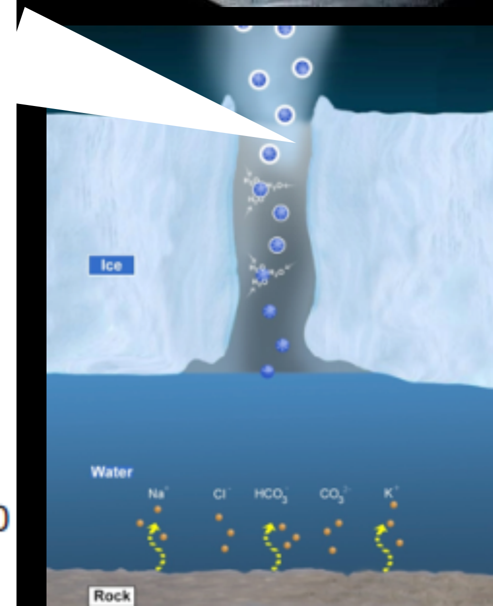
Mass spectra of Enceladus' plume

Gas: H_2O + C-species (CO_2 (1-5%), CH_4 (1%), alcohols, aldehydes)

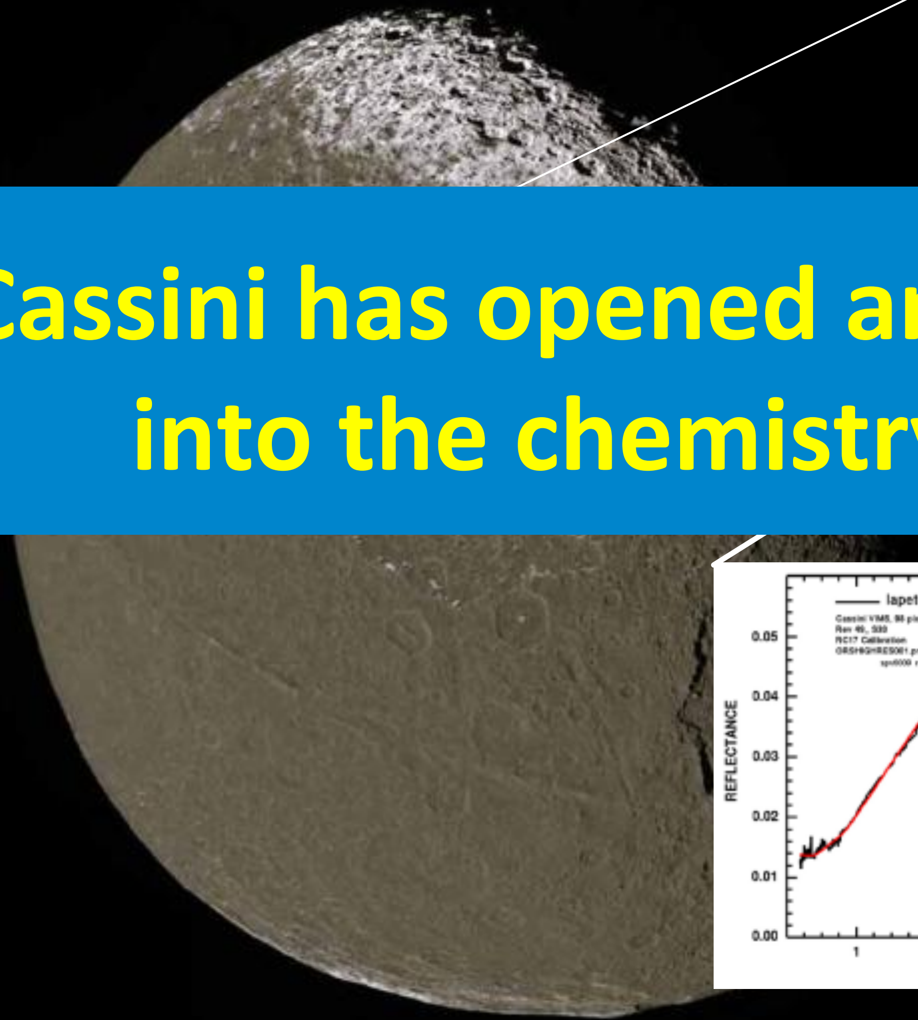
+N-species (NH_3 (1%), HCN) (Waite et al. 2009)

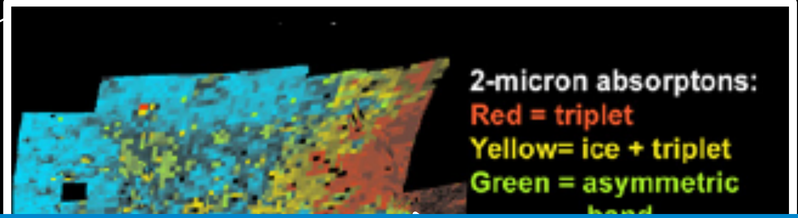
Solids: H_2O ice with Na-salts, carbonates (Postberg, 2009; 2011)



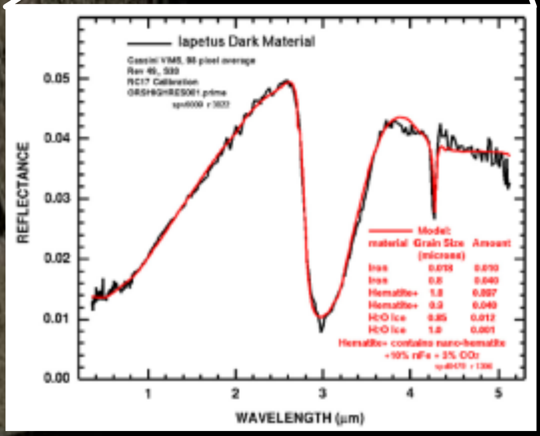


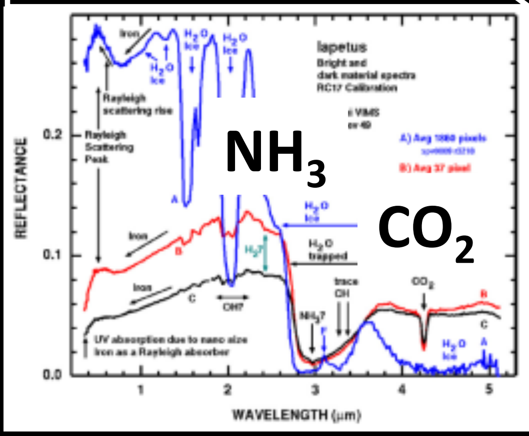
Mapping of ices & organics by Cassini





Cassini has opened an important window into the chemistry of icy satellites





Clark et al., 2012

Iapetus: a Saturn's mid-sized moon

Why think about chemistry?

Present-day composition =

initial conditions + subsequent evolution

- Protoplanetary disk
- Giant planet formation

- Geological processes
- Geochemical products

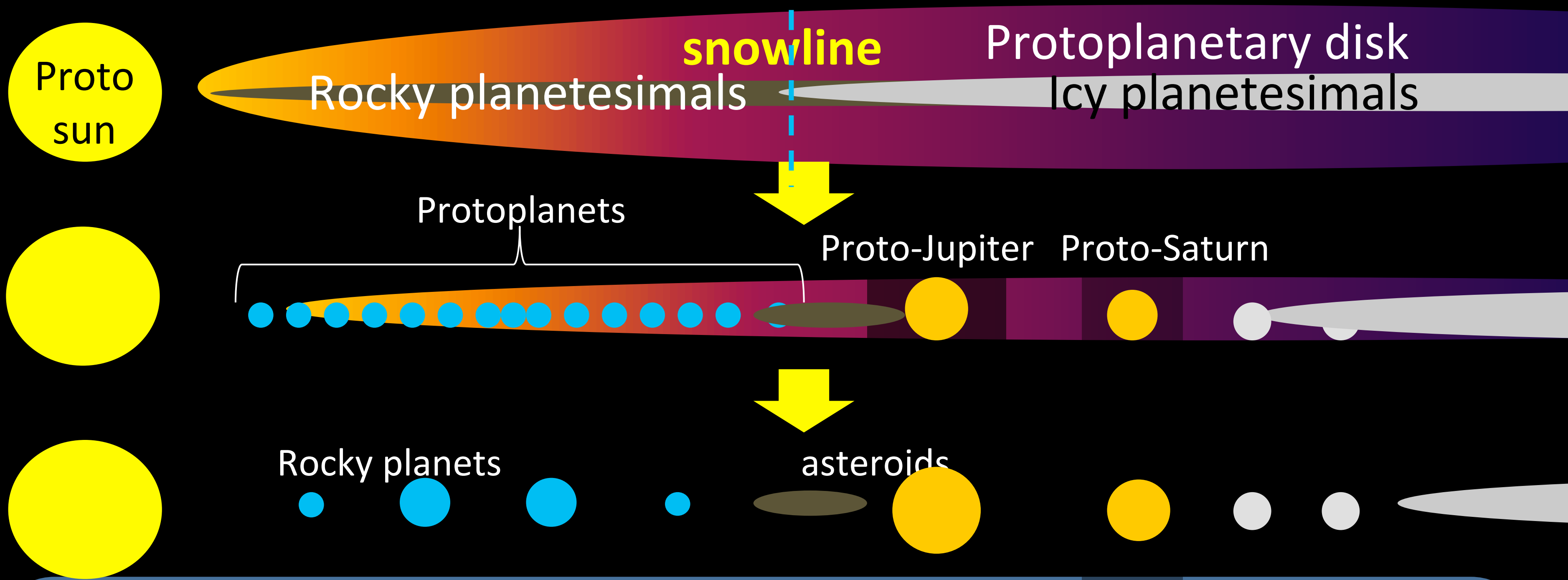
Callisto: “fossils”

Satellites that are not active

Europa, Enceladus

Active satellites

Formation of solar system & icy satellites



Giant planet formation (e.g., Canup & Ward, 2002)

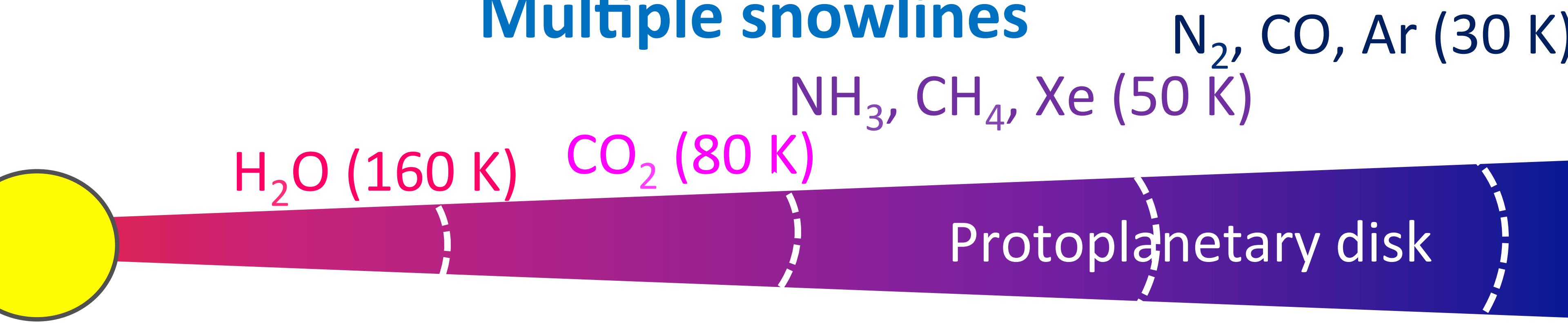
1. Formation of proto-planet in a disk
2. Gas & solid accretion & a sub-disk around planet
3. Satellite formation

Initial comp. ⇔ solids in protoplanetary disk/sub-disk

Ice composition: proxy for temperature

Trapping of gas into ice: Gas species are trapped in solids, but the condensation **temperature** depends on the gas species (e.g., Hersant et al., 2004; Alibert & Mousis, 2007)

Multiple snowlines



Cassini: **Enceladus & Titan**→lack ^{36}Ar, lots CH_4 & NH_3

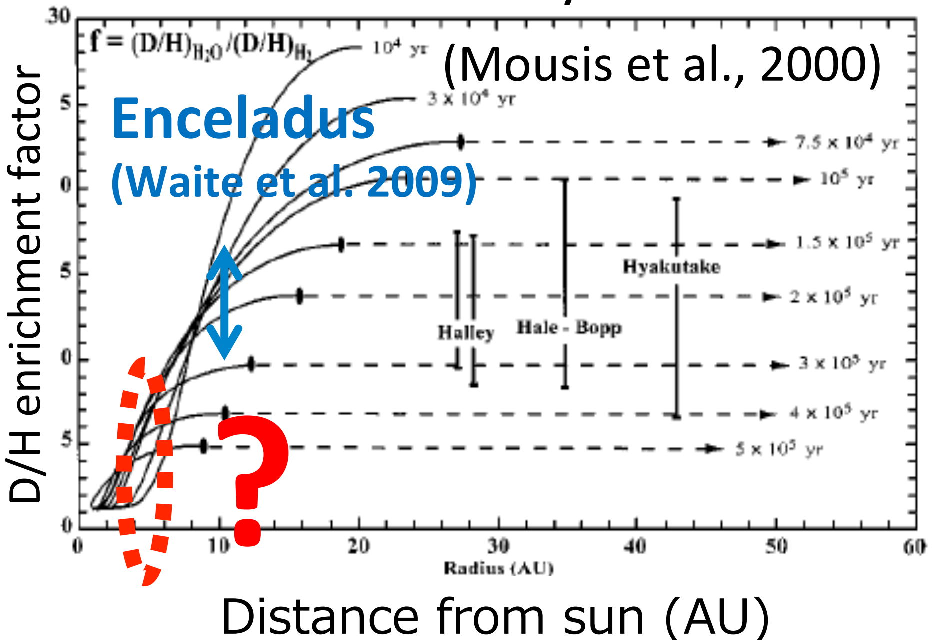
→ **disk temp @ Saturn: ~30–50 K** **(Mousis et al., 2009)**

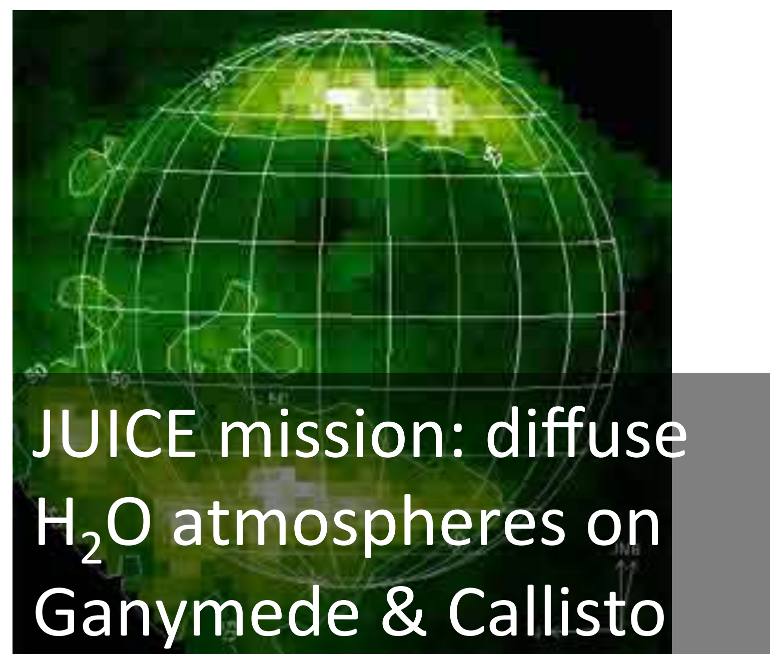
JUICE mission: High-resolution observations of volatiles on Jupiter’s moons

Isotopes of volatiles: D/H of water

- **D/H ratio of H_2O: Isotope exchange** between H_2O & H_2 occurred as a function of **disk temperature, viscosity, & timing of gas dissipation** (e.g., Drouart et al., 1999; Mousis et al., 2000)

Coefficient of viscosity α ~0.003



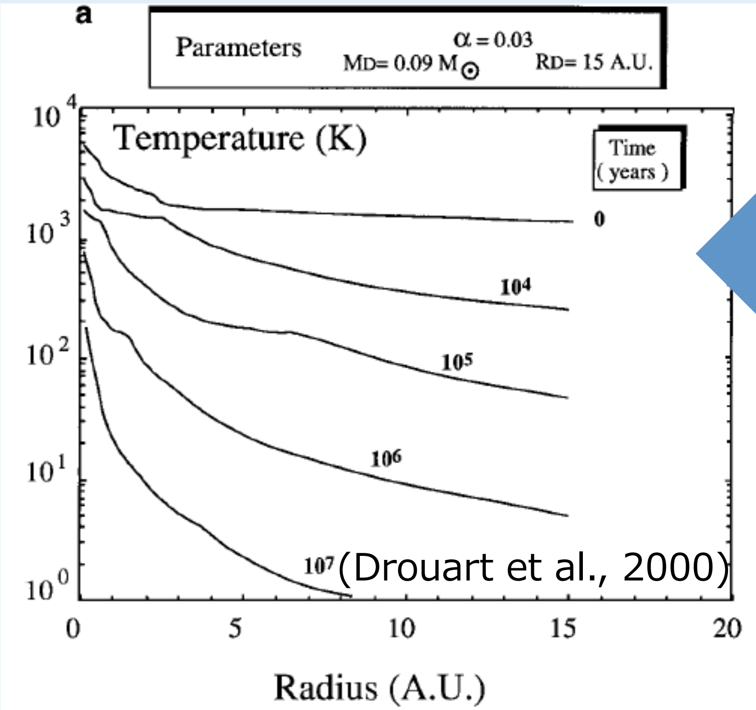


Characterization of our solar system

Theoretical disk models

Temperature profile of our disk

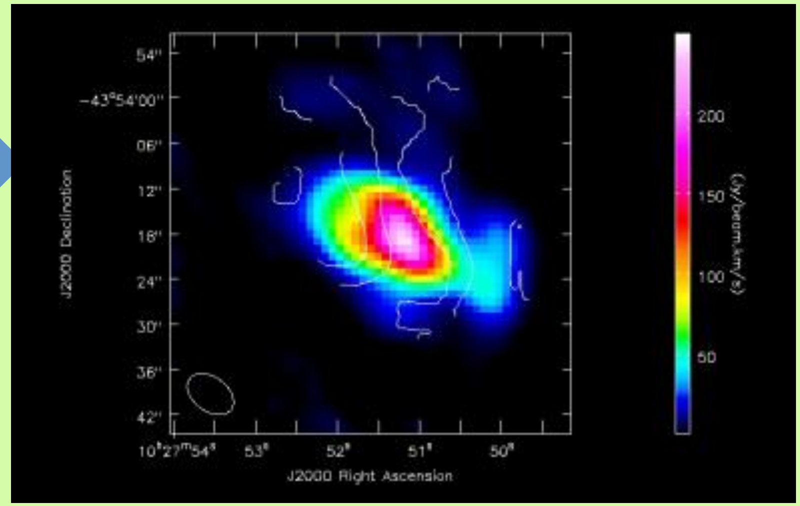
Building materials of Earth



High-resolution observations (ALMA, TMT)

Structure of protoplanetary disks

How common is the initial condition



High-resolution observation of protoplanetary disks (c) ALMA

Exploration of the solar system: Factual evidence to characterize our solar system

Why think about chemistry?

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- Protoplanetary disk
- Giant planet formation

Callisto: "fossils"

Satellites that are not active

- Geological processes
- Geochemical products

Europa, Enceladus

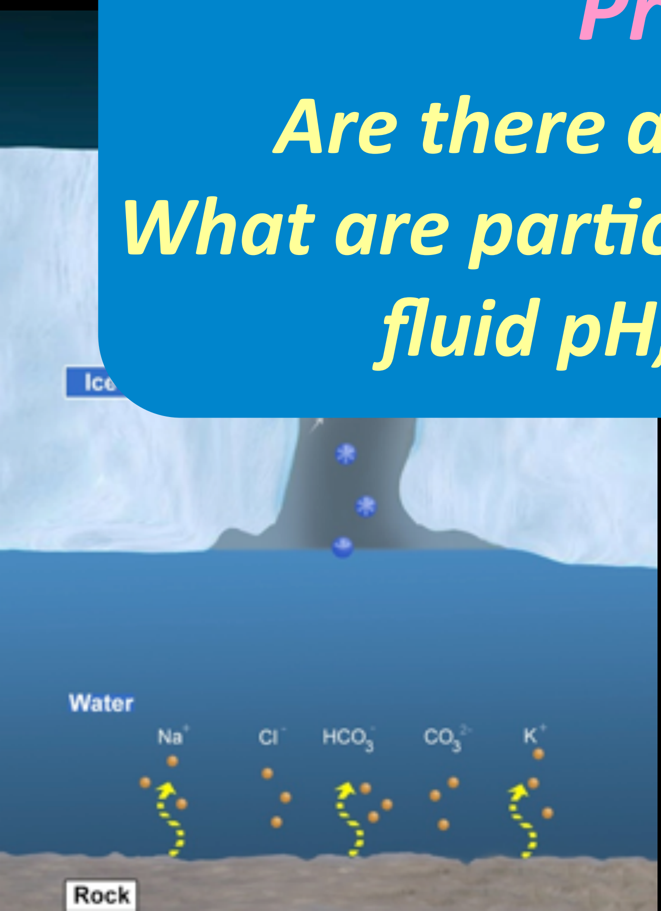
Active satellites

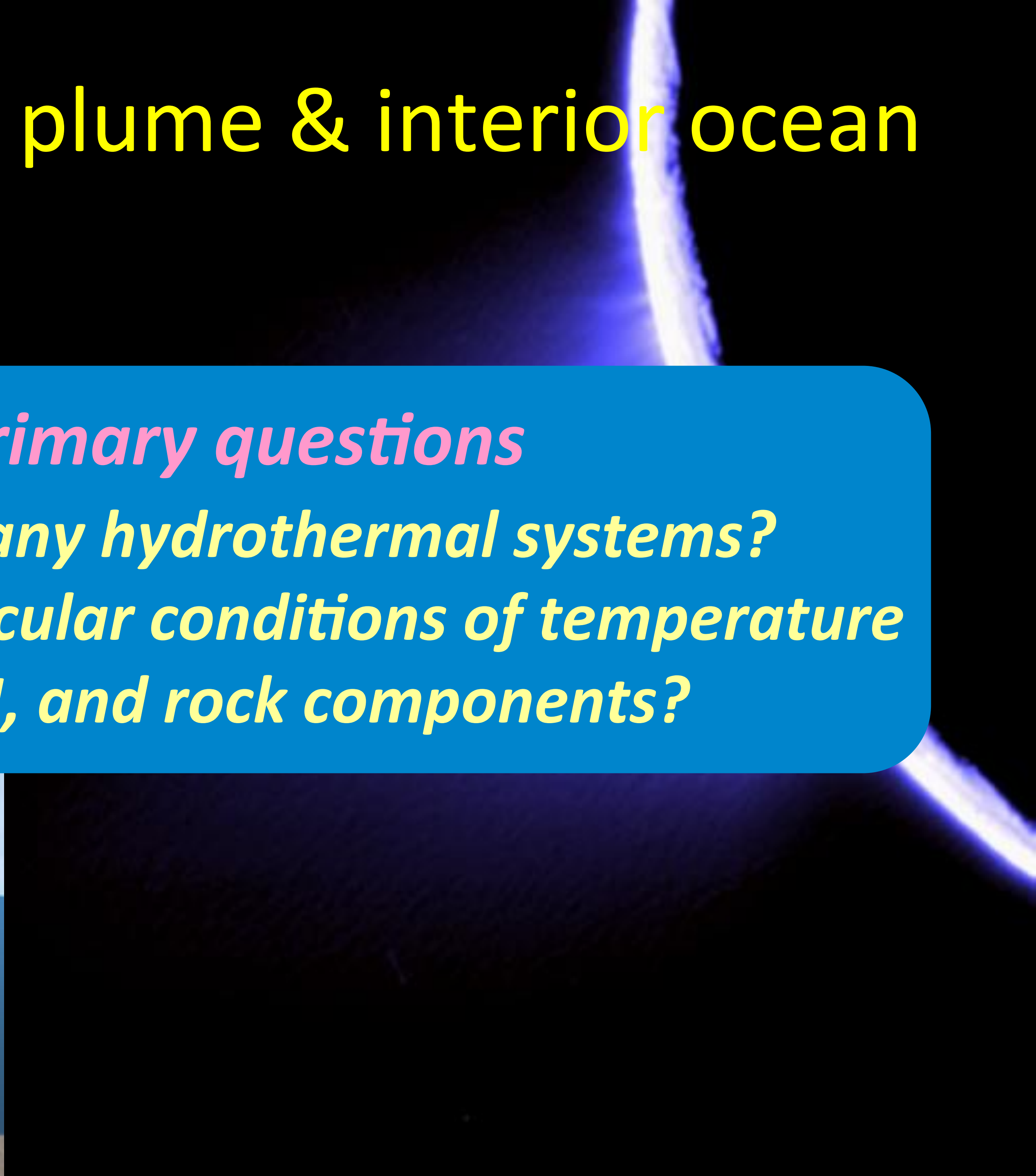
Enceladus' plume & interior ocean

Primary questions

Are there any hydrothermal systems?

What are particular conditions of temperature fluid pH, and rock components?





Cold or hot in Enceladus?

- If hot, N_2 should be observed in the plumes formed by thermal dissociation of NH_3: **$2NH_3 \Rightarrow N_2 + 3H_2$** (Matson et al. 2007).

Cold interior (< ~0℃)

The lack of N_2

↓

Low temp. << 150℃

↑

lack of N_2 & abundance of NH_3 in the plumes
(Hansen et al., 2011)

?

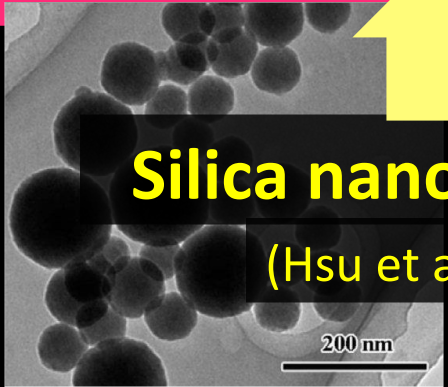
Warm interior

The presence of N_2 (～1% relative to H_2O)

↓

High temperature

↑



Silica nanoparticles
(Hsu et al., in prep.)

Experimental

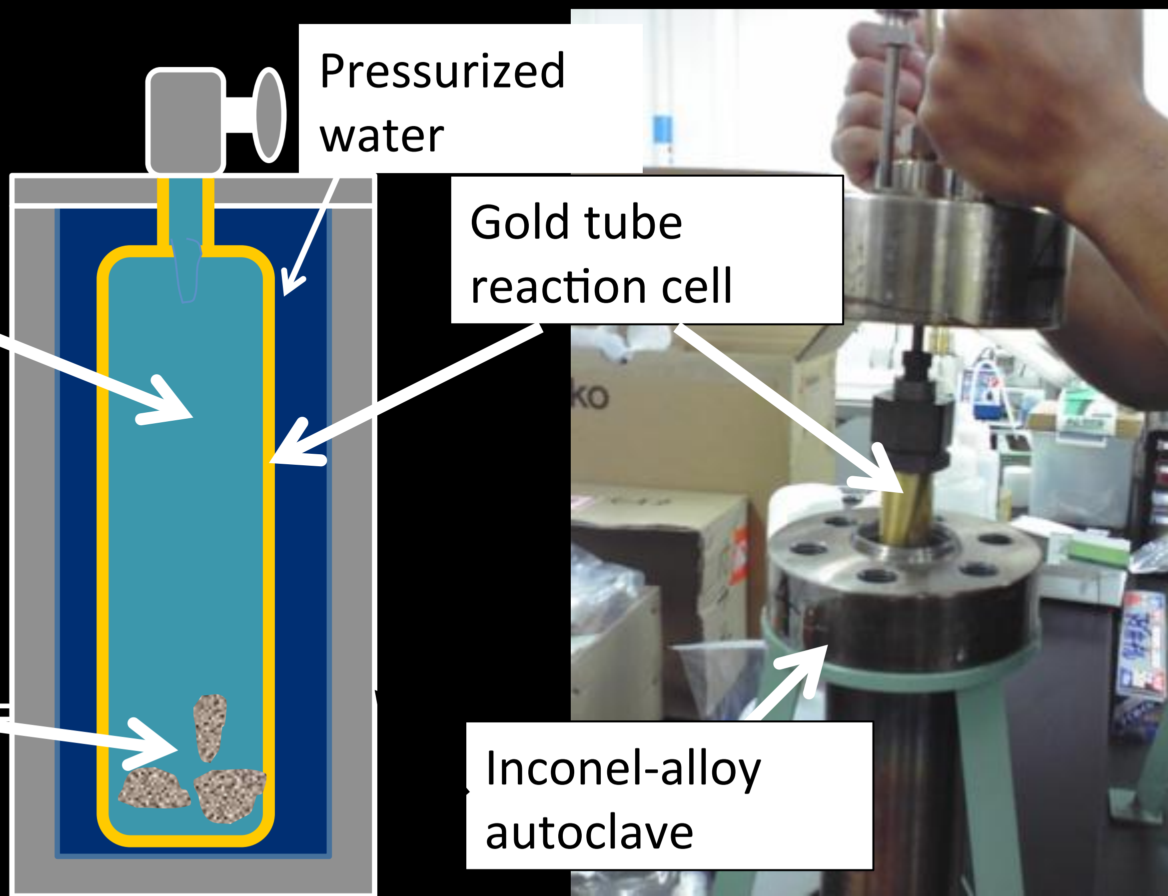
Enceladus interior ~ Earth's sea floors

P = 100–400 bar & T < 400°C

- **Starting materials**

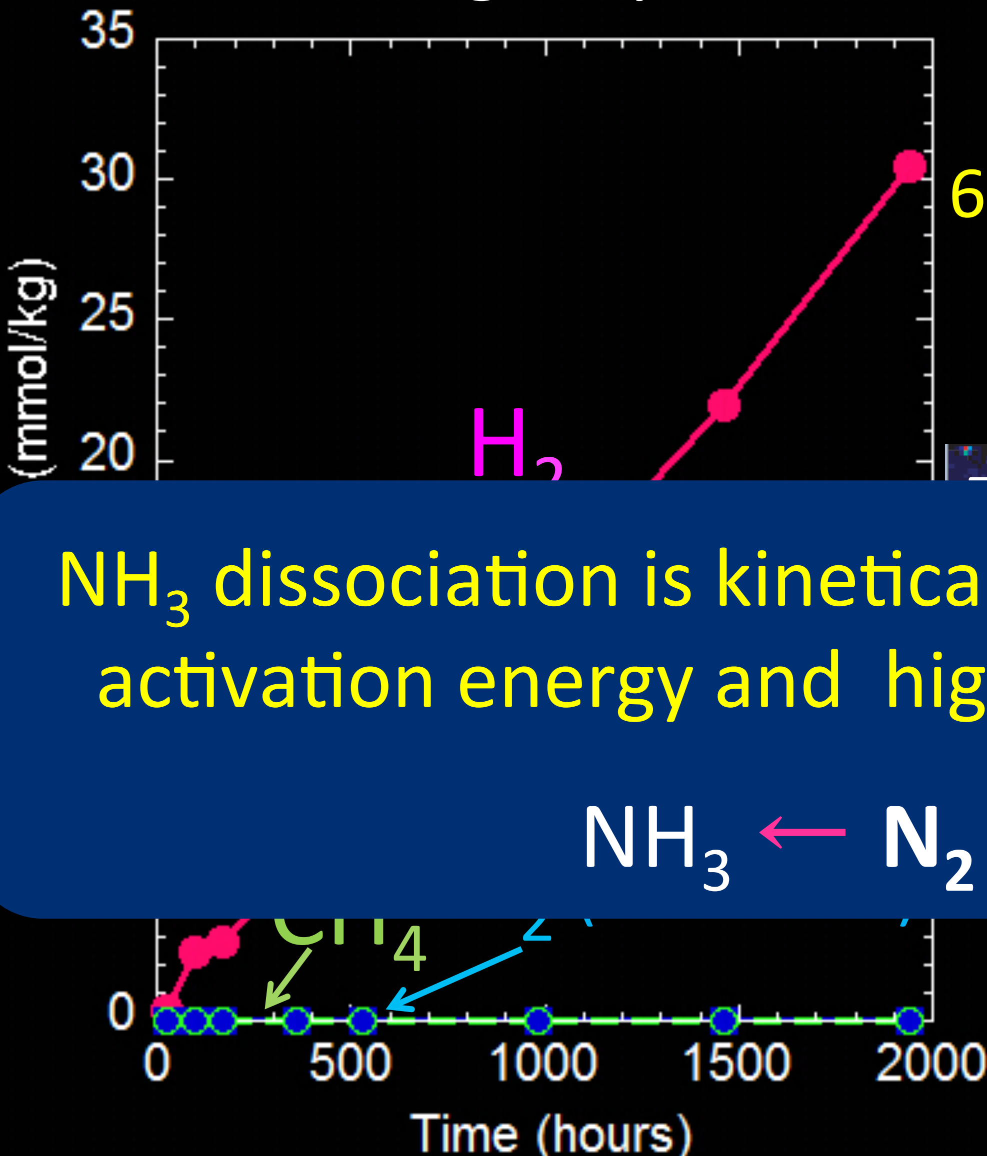
An aqueous solution of
NH_3 (1%) & $NaHCO_3$ (CO_2) (0.1% or 3%) (pH = 10)

Powdered olivine + opx
(Mg# (=Mg/(Mg+Fe)) = 90) (rock:water = 1:5)



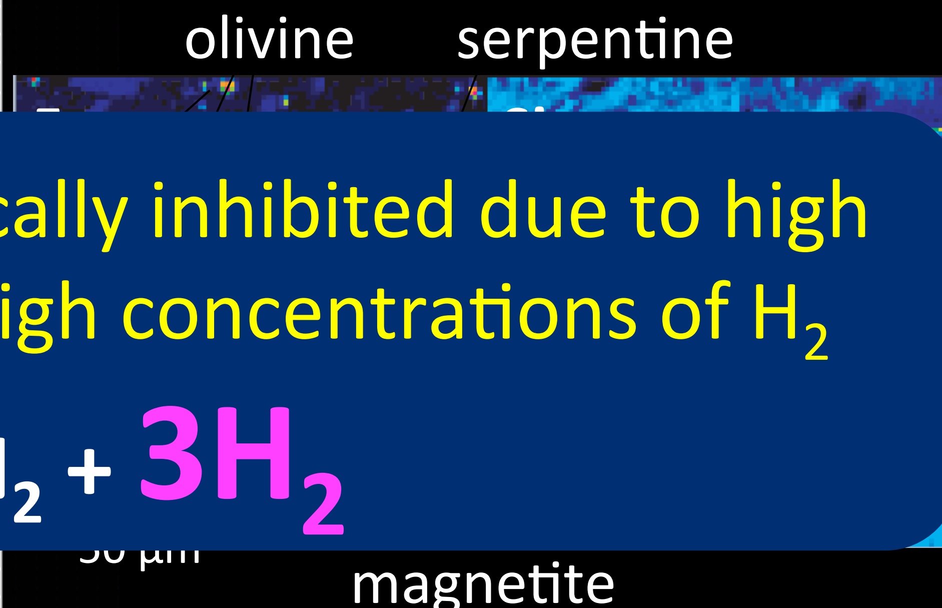
Results: at **300℃**

- Dissolved gas species



- Mineralogical analyses for the rock material

65% of olivine was converted to serpentine & magnetite



NH_3 dissociation is kinetically inhibited due to high activation energy and high concentrations of H_2

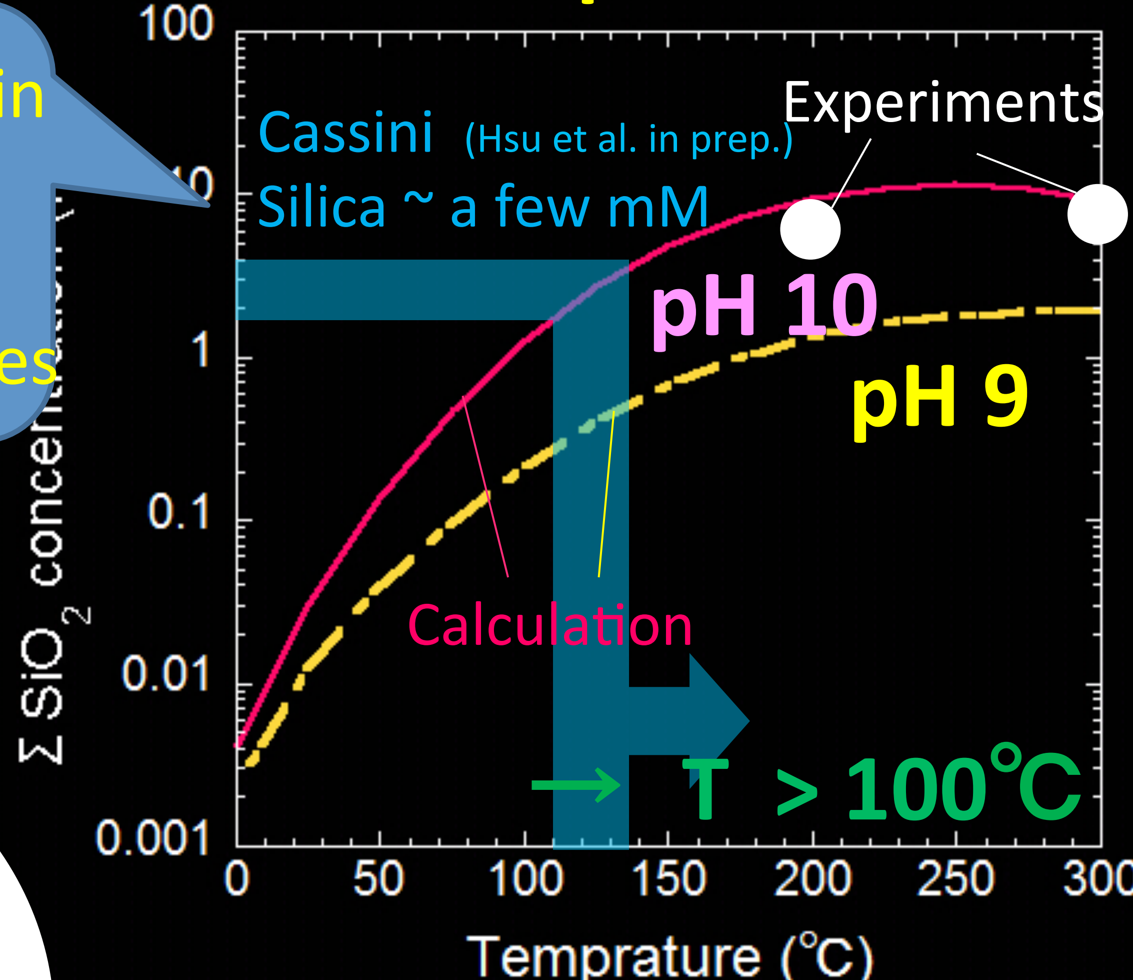
$$NH_3 \leftarrow N_2 + 3H_2$$

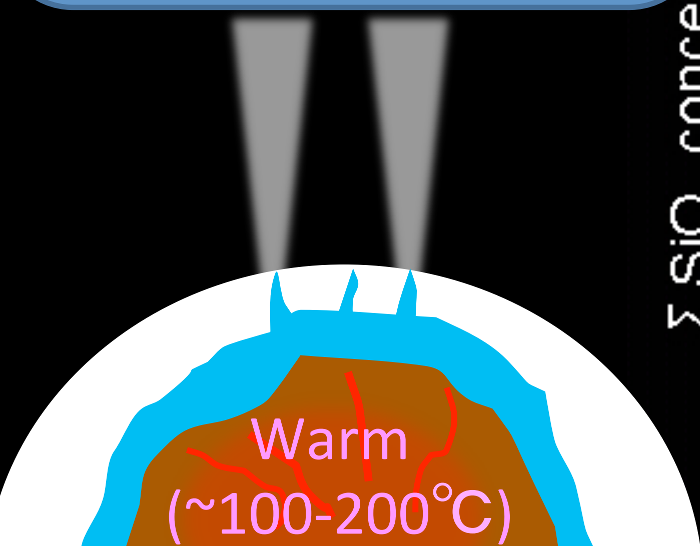
Results: pH, silica, & temperature

Fluid pH
- Earth: mineral (e.g., brucite ⇔ $Mg^{2+} + 2OH^-$)
- Enceladus: volatiles (e.g., NH_3 ⇔ $NH_4^+ + OH^-$)

→ **pH 9–10**

Silica concentration in fluids for pH 9 &10 with alteration minerals of chondrites





More important result

planetary science + geochemistry + biology
= oceanic planetology?

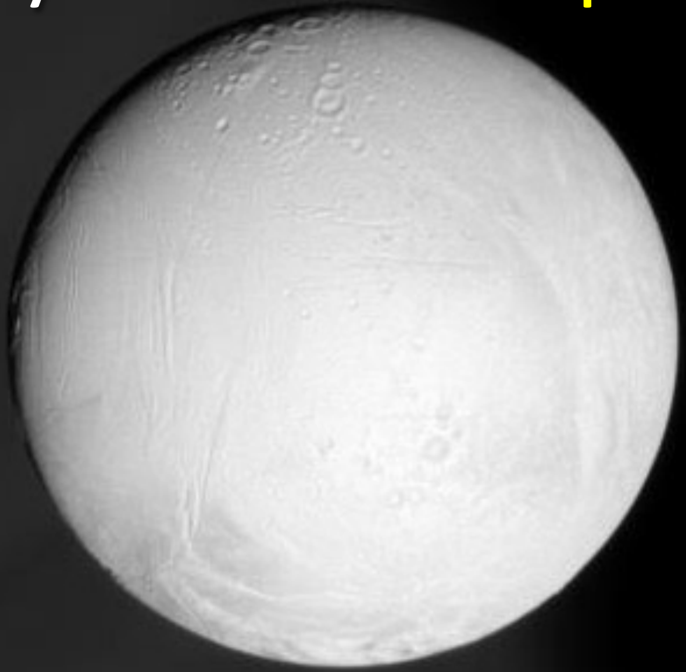
Ganymede

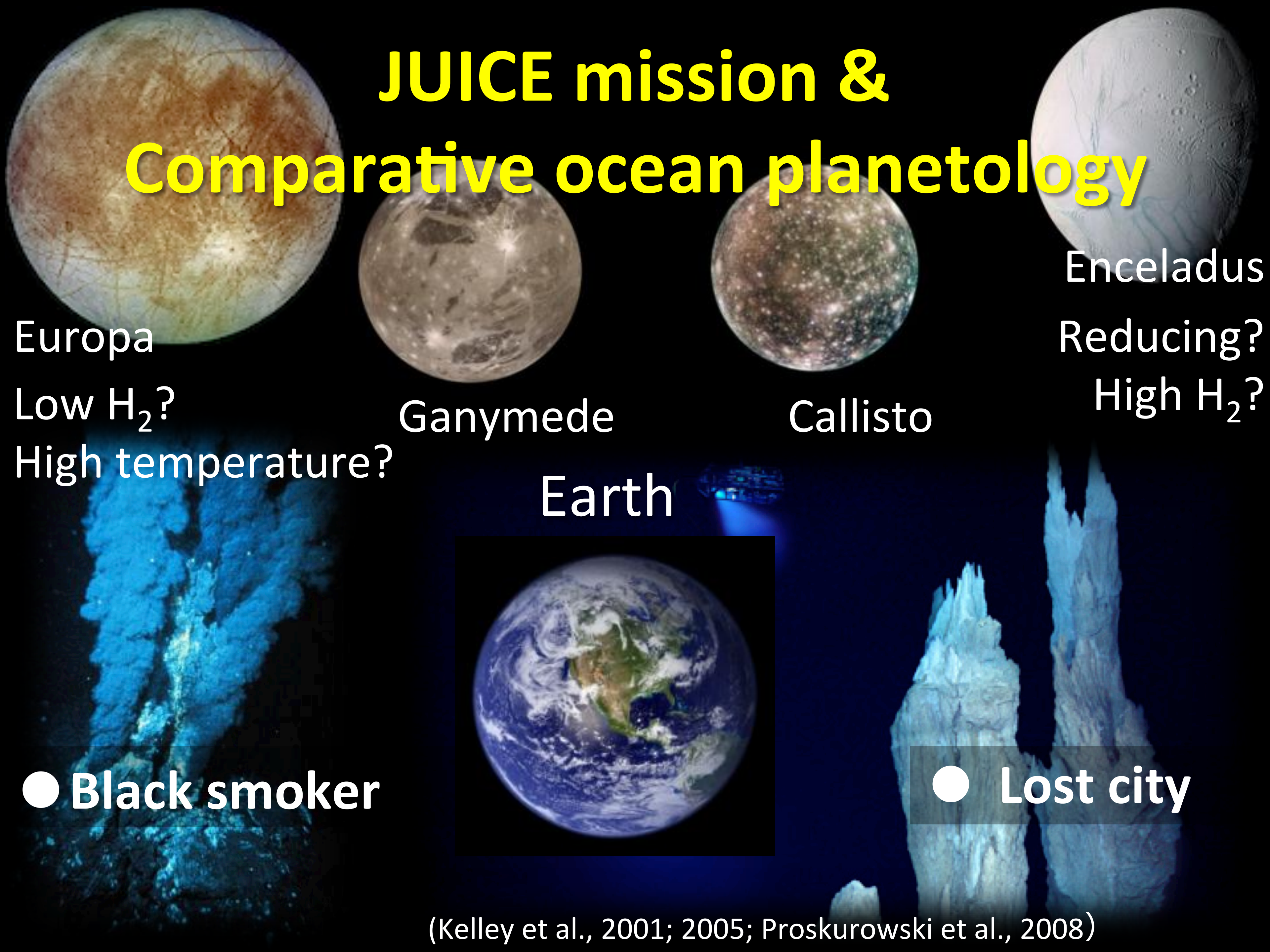
Europa

JUICE mission: detailed investigations of surface materials for Ganymede & Europa

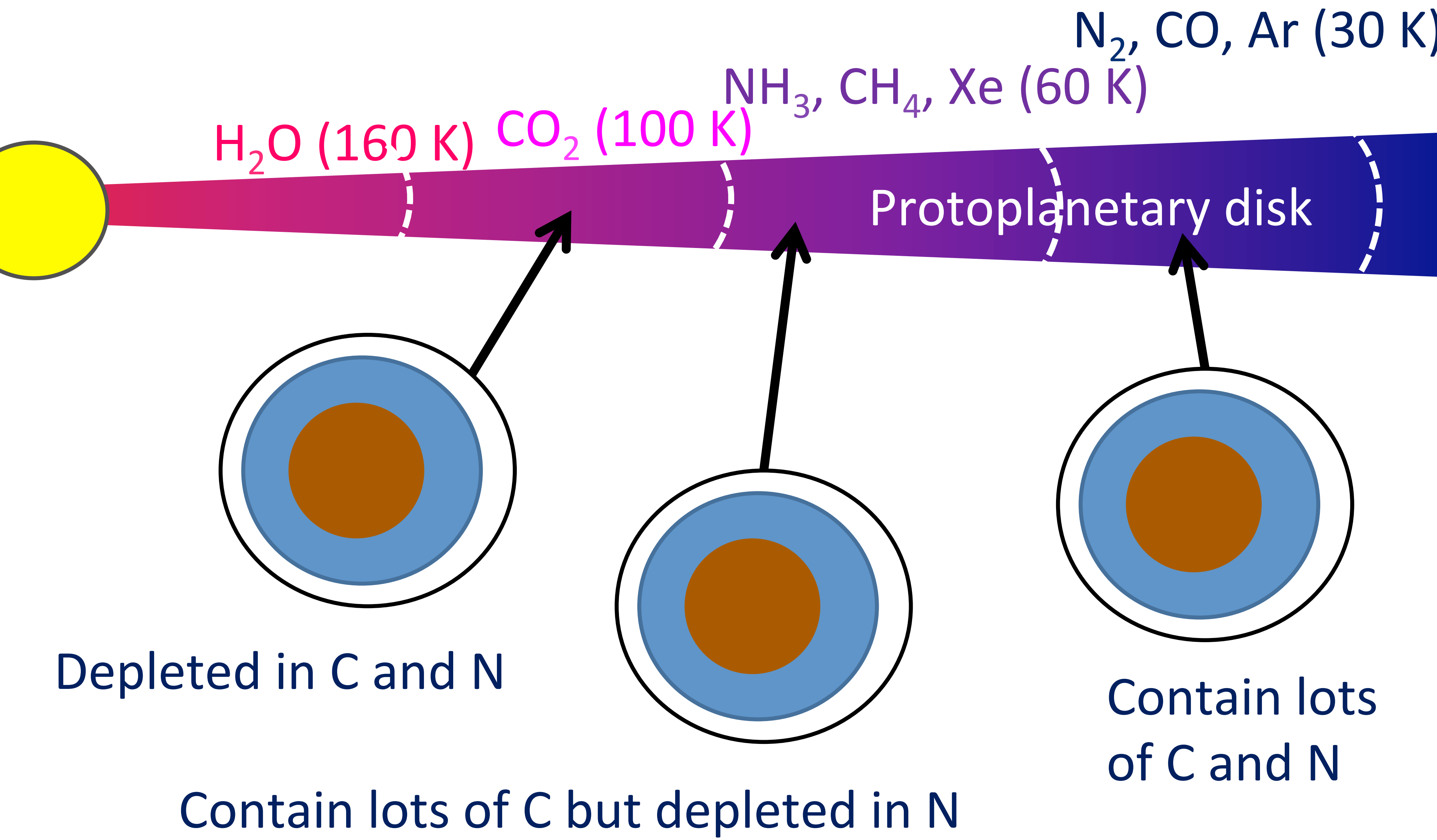
Conclusions

Icy satellites are a key for characterizing our solar system and geochemical processes and provide an opportunity for interdisciplinary researches.




JUICE mission &
Comparative ocean planetology
Europa
Low H_2?
High temperature?
Ganymede
Callisto
Enceladus
Reducing?
High H_2?
Earth
● Black smoker
● Lost city
(Kelley et al., 2001; 2005; Proskurowski et al., 2008)

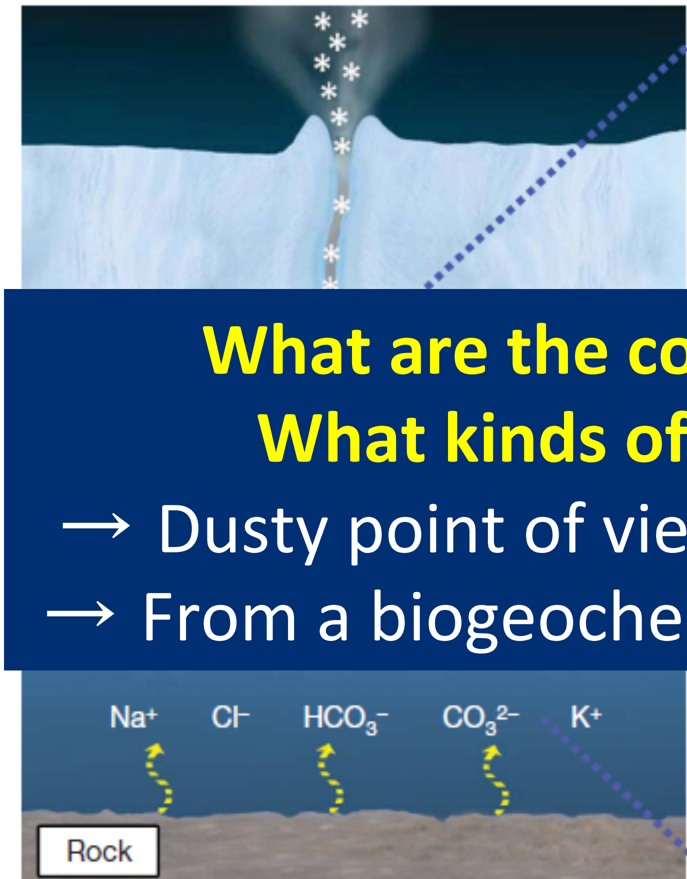
Availability of elements in icy satellites

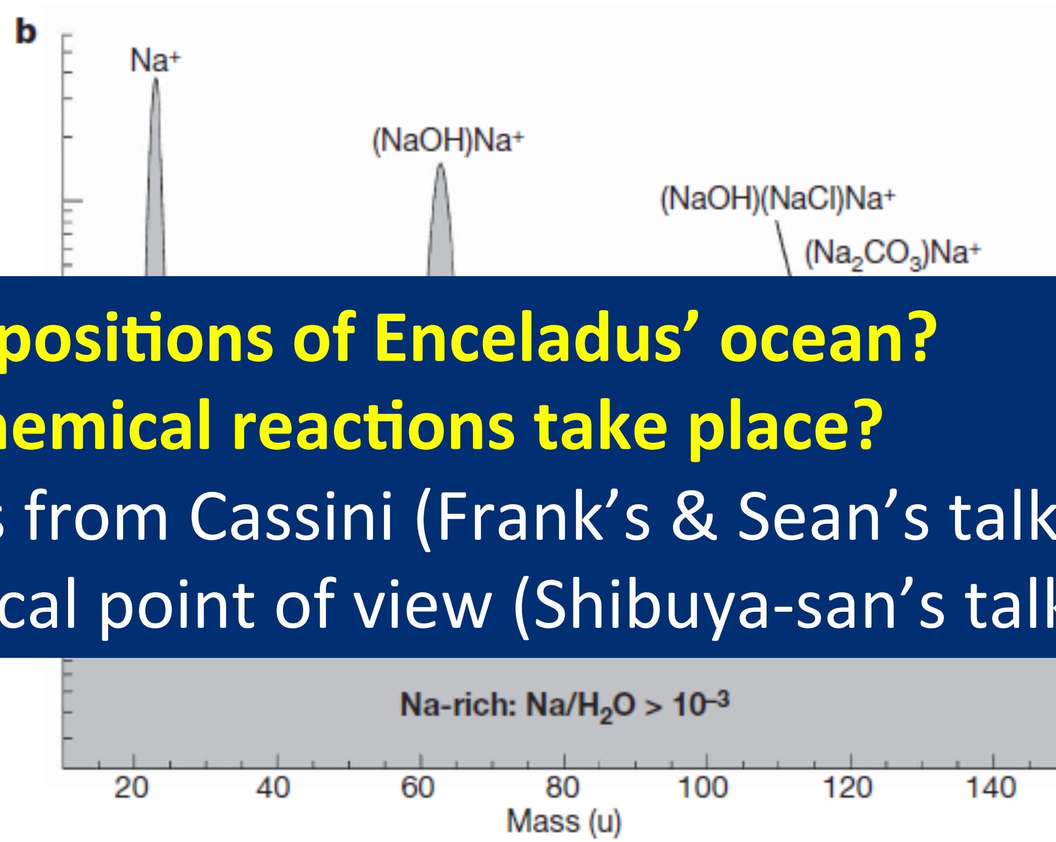


Habitability

- Constraints on oceanic environments beneath the surface from chemical compounds of dust particles

(Postberg et al., 2009; 2011)





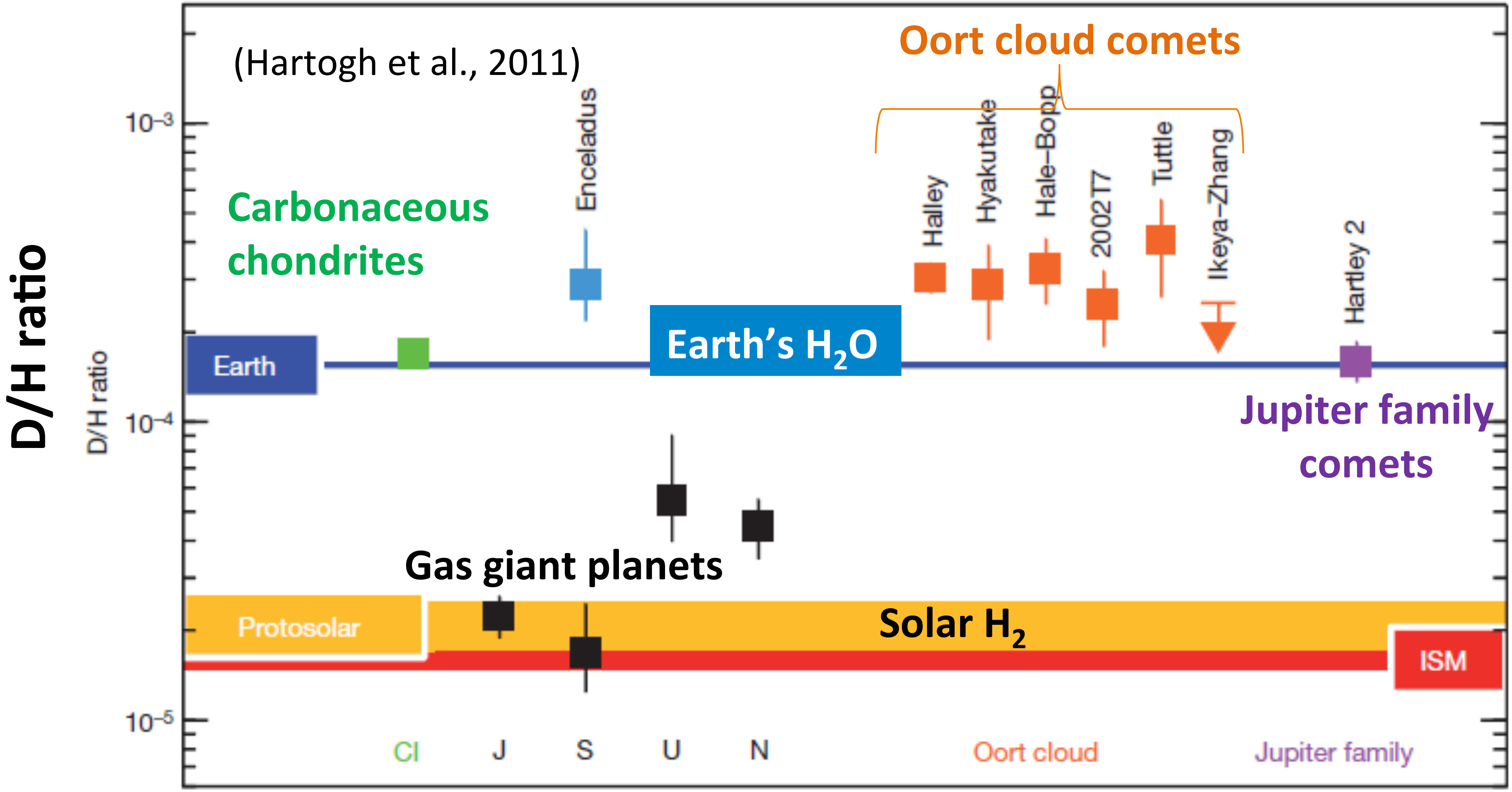
What are the compositions of Enceladus' ocean?
What kinds of chemical reactions take place?

→ Dusty point of views from Cassini (Frank's & Sean's talk)

→ From a biogeochemical point of view (Shibuya-san's talk)

Origin & distribution of water

- Source(s) of H, C, O, and N → Isotopic compositions of primordial volatiles (H_2O, CO, CO_2, N_2, & NH_3)
- Not a simple two component model



Isotopes of volatiles

- Evolutional model of protoplanetary disk including isotopic exchanges (e.g., Drouart et al., 1999; Mousis et al., 2000; Yurimoto & Kuramoto, 2004)

D/H evolution model in a disk

D/H of H_2O at Jupiter forming region

⇒ Disk temperature & gas dissipation