Hydrothermal Activities within Enceladus

CDA analysis of “Stream particles”

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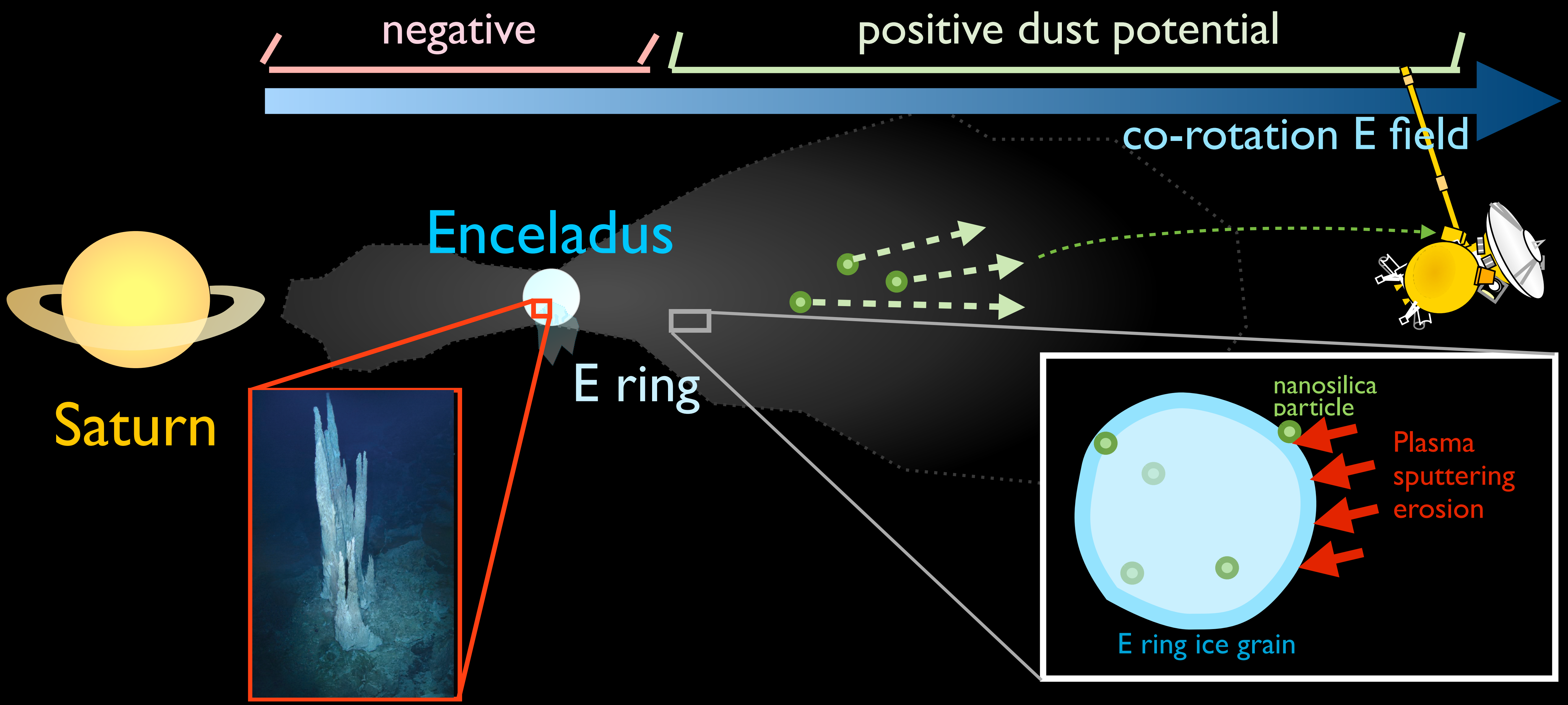
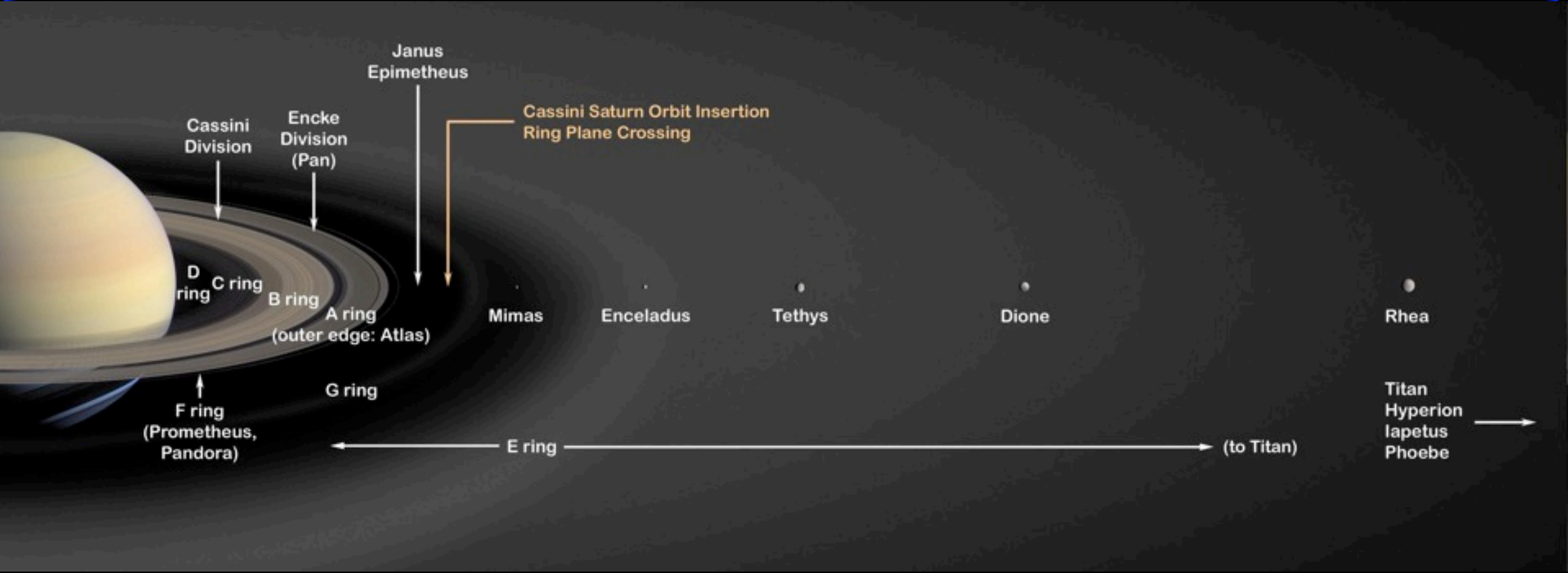
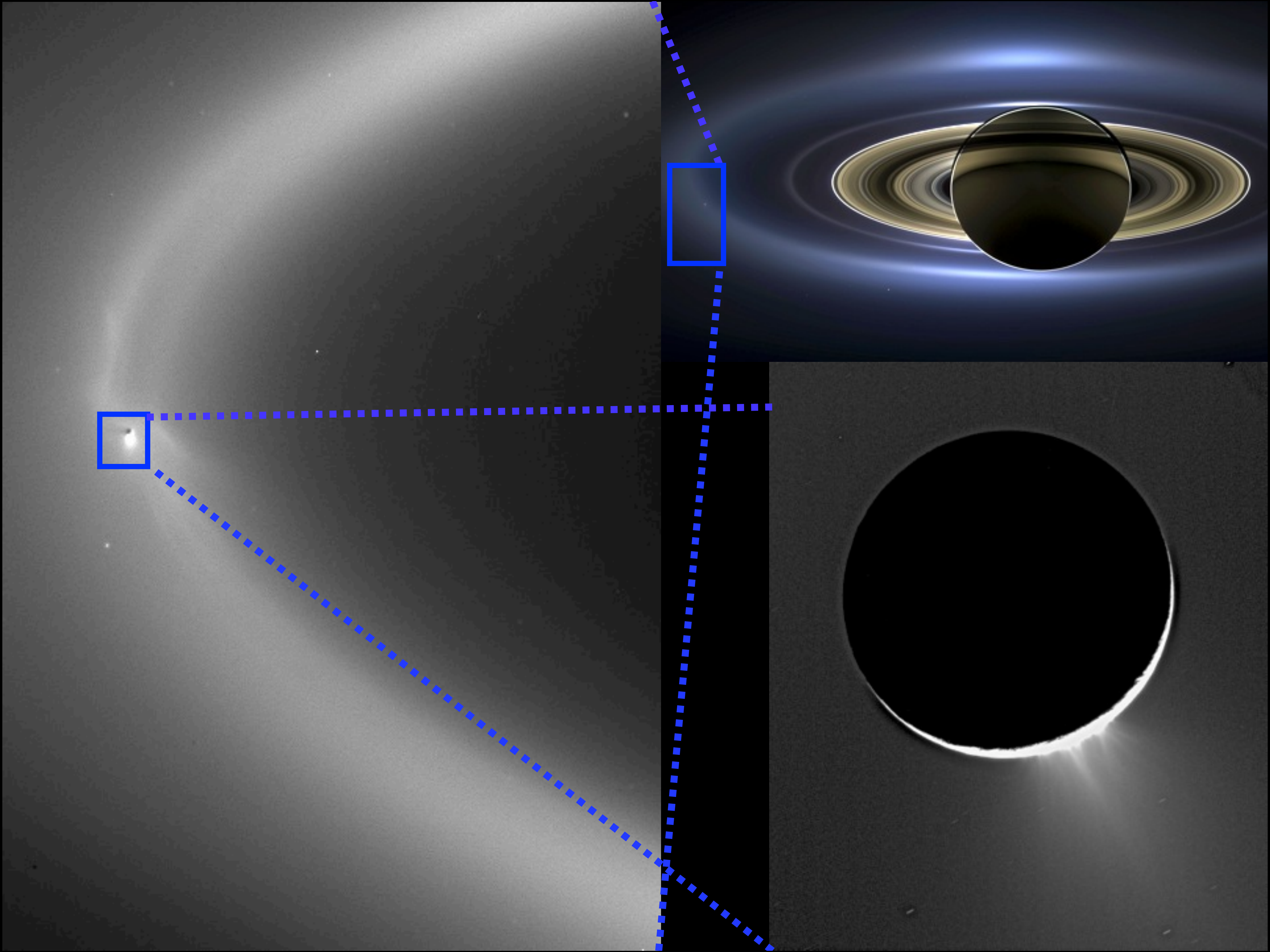


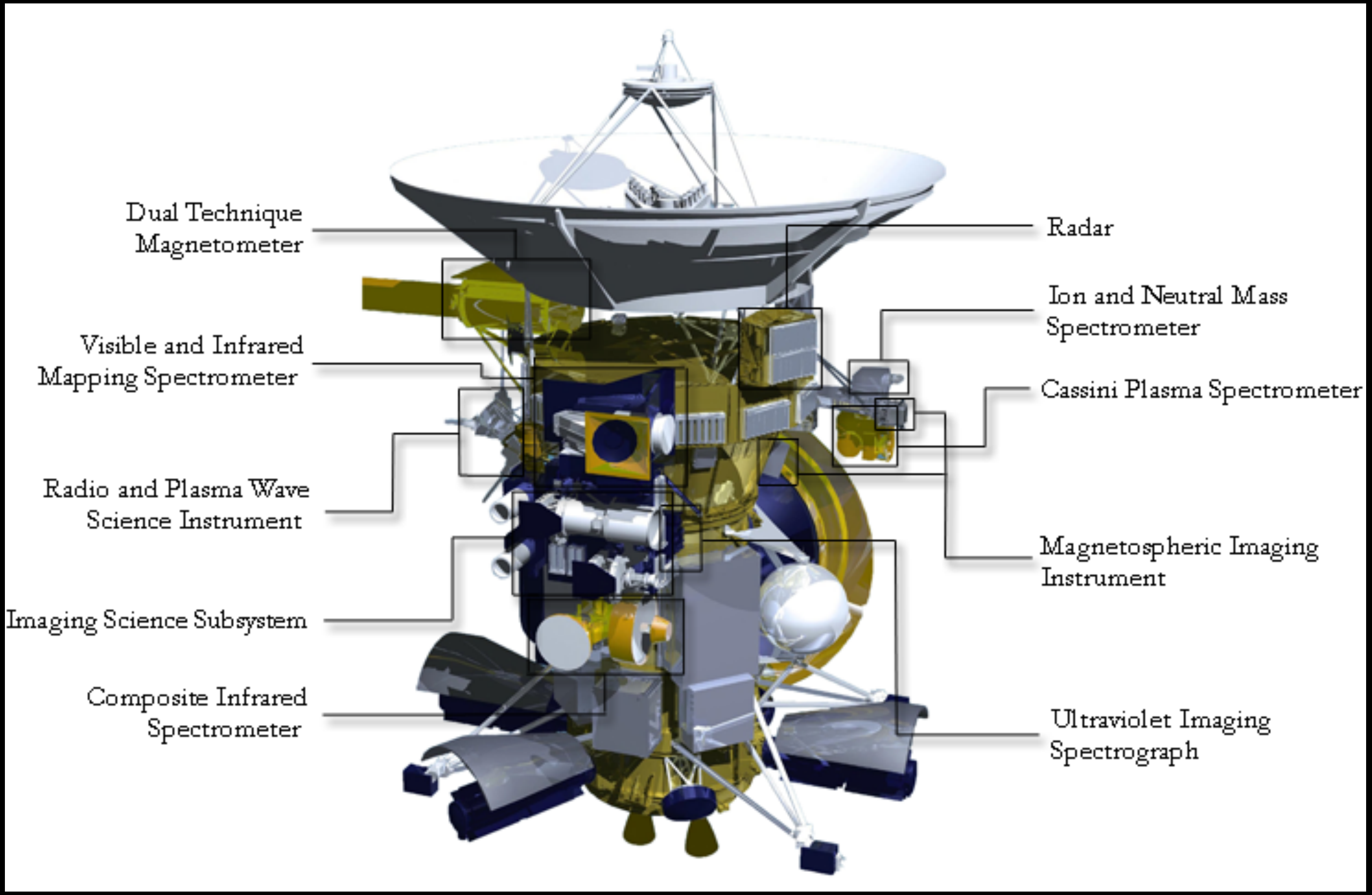
Saturn's Satellites and Ring Structure

All bodies are to scale except for Pan, Atlas, Telesto, Calyso and Helene, whose sizes have been exaggerated by a factor of 5 to show rough topography.





Cassini instruments



CIRS,
ISS,
RADAR,
Radio science,
UVIS,
VIMS

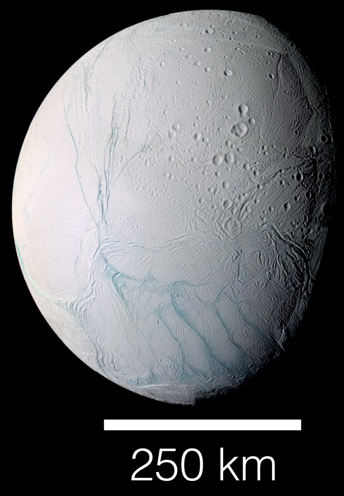
remote sensing

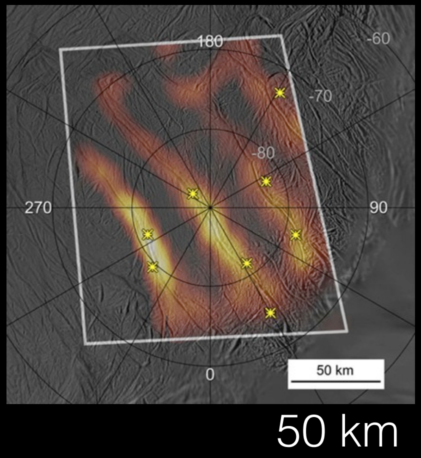
in situ

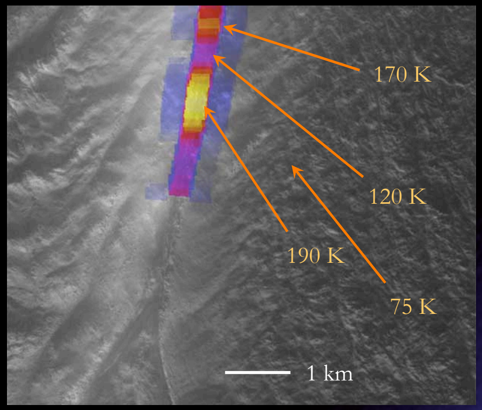
in its original place

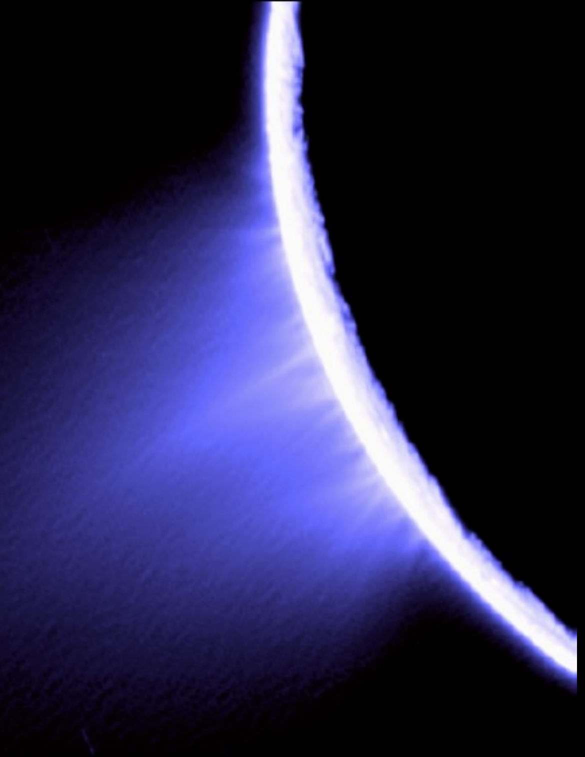
CAPS,
CDA,
INMS,
MAG,
MINI,
RPWS

remote sensing









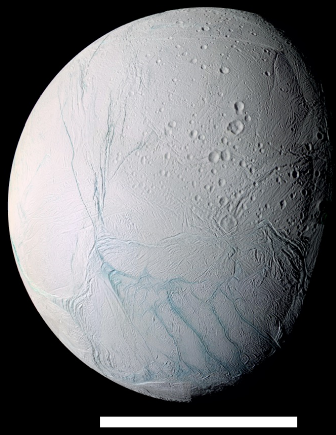
in situ

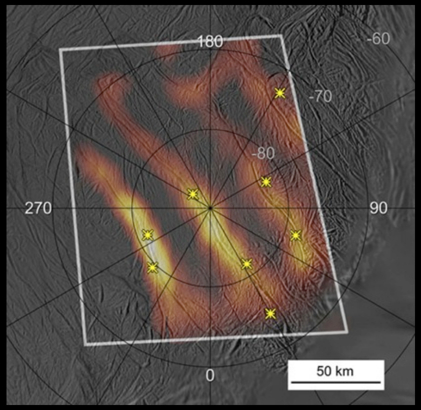
CAPS,
CDA,
INMS,
MAG,
MINI,
RPWS

Plume of Enceladus

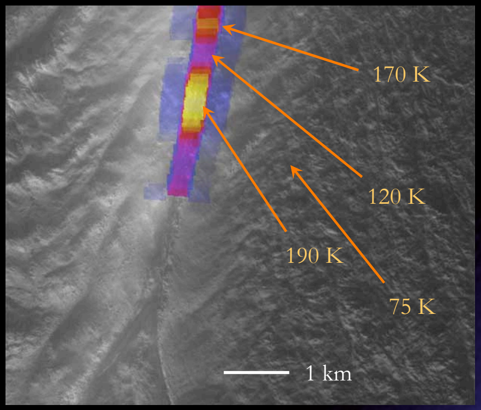
- solid
- ~~liquid~~
- gas

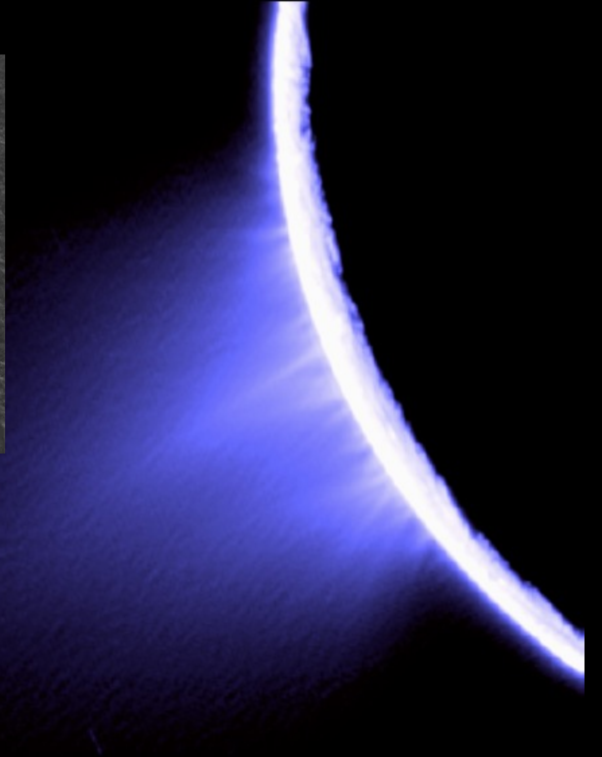
remote sensing





50 km





in situ

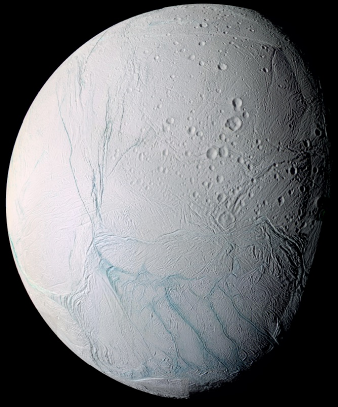
CAPS,
CDA,
INMS,
MAG,
MINI,
RPWS

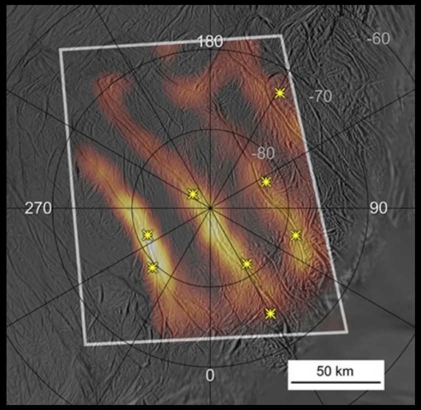
Plume of Enceladus

- solid
- ~~liquid~~
- gas

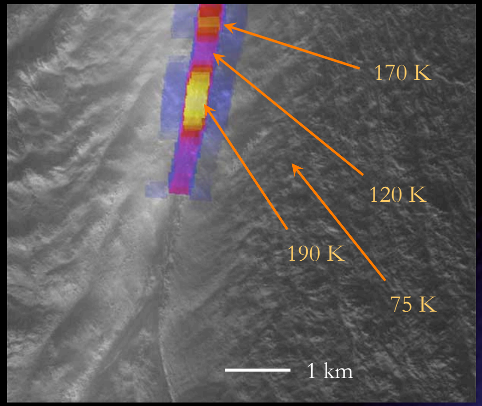
H_2O: > 90%
CO_2: ~0.6%
NH_3: ~0.9%
CH_4: ~0.2%
H_2: 1-10%
C_2 group: <0.5%
C_3 group: <0.01%

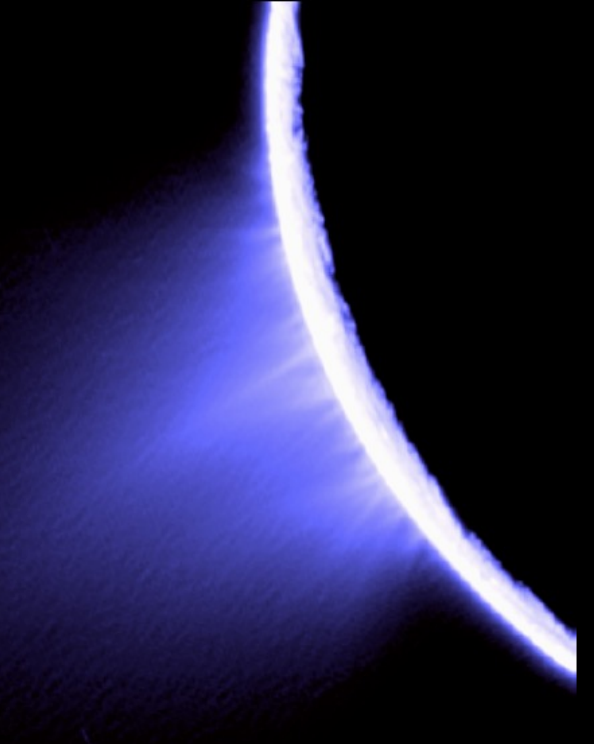
remote sensing


250 km



50 km





in situ

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CDA,
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Plume of Enceladus

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C_3 group: <0.01%

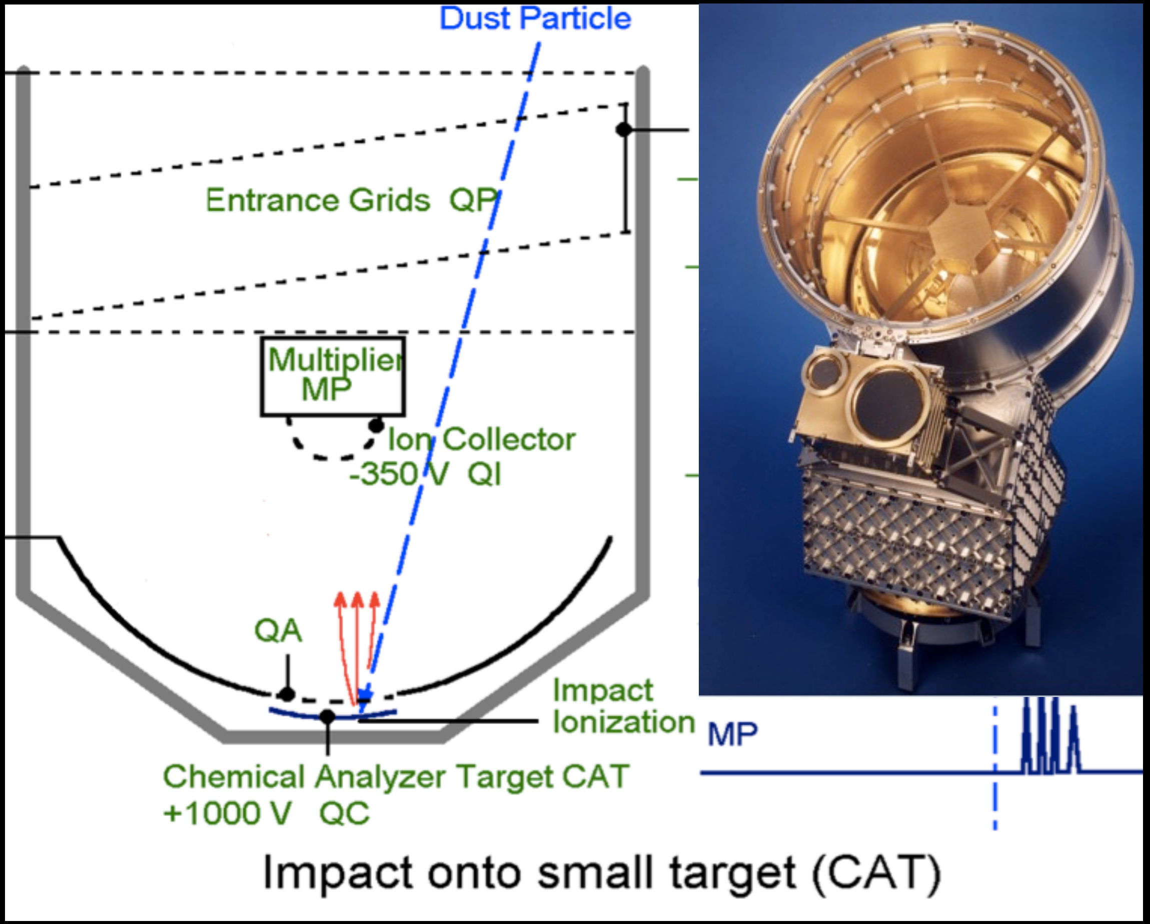
"plume dust"

- seen in images (μm or ↗)
- **Cosmic Dust Analyser**
- unexpectedly detected by several Cassini instruments during plume crossings
- populating the diffuse E ring of Saturn

✦ Cosmic Dust Analyser (CDA)

detection principle:

impact-ionization



Impact onto small target (CAT)

❖ Composition

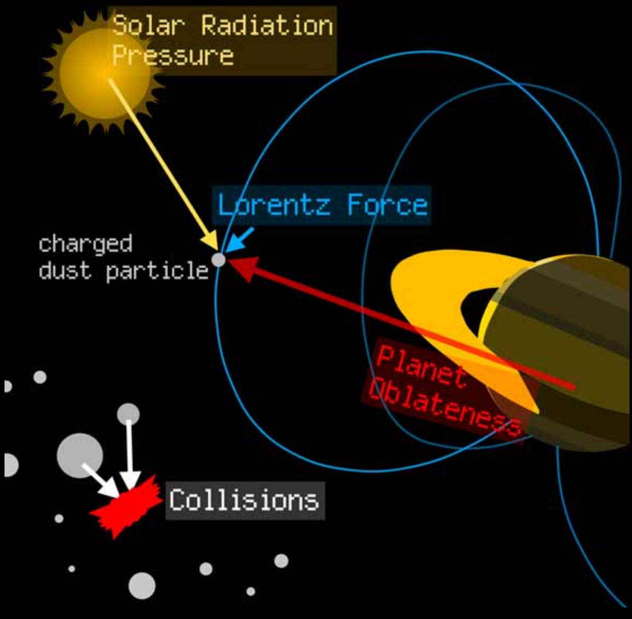
- Time-of-flight Mass Spectrometer
- elementary composition

$$\text{plasma production} \sim m_d \cdot v_d^{3.5}$$

m_d: dust mass, v_d: impact speed

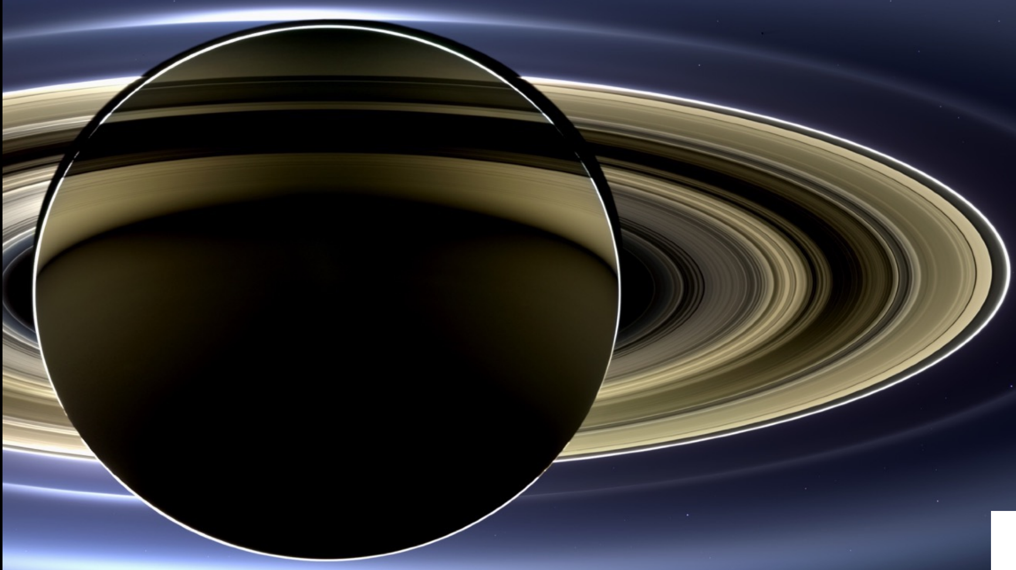
❖ Dust mass/size → Dynamics

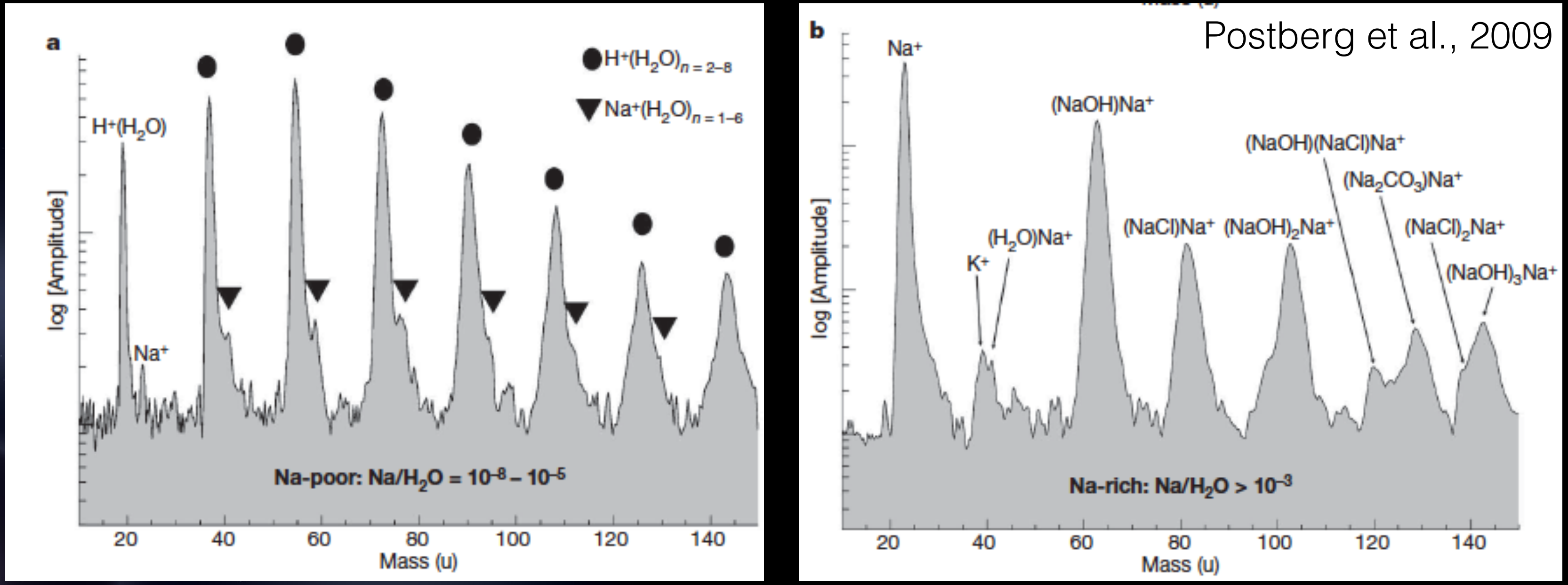
- µm (10^{-6} m) and ↗
- sub-µm
- nanometer (10^{-9} m)



Saturn's E ring

- **Composition**
  - ToF Mass Spectrometer
  - elementary composition



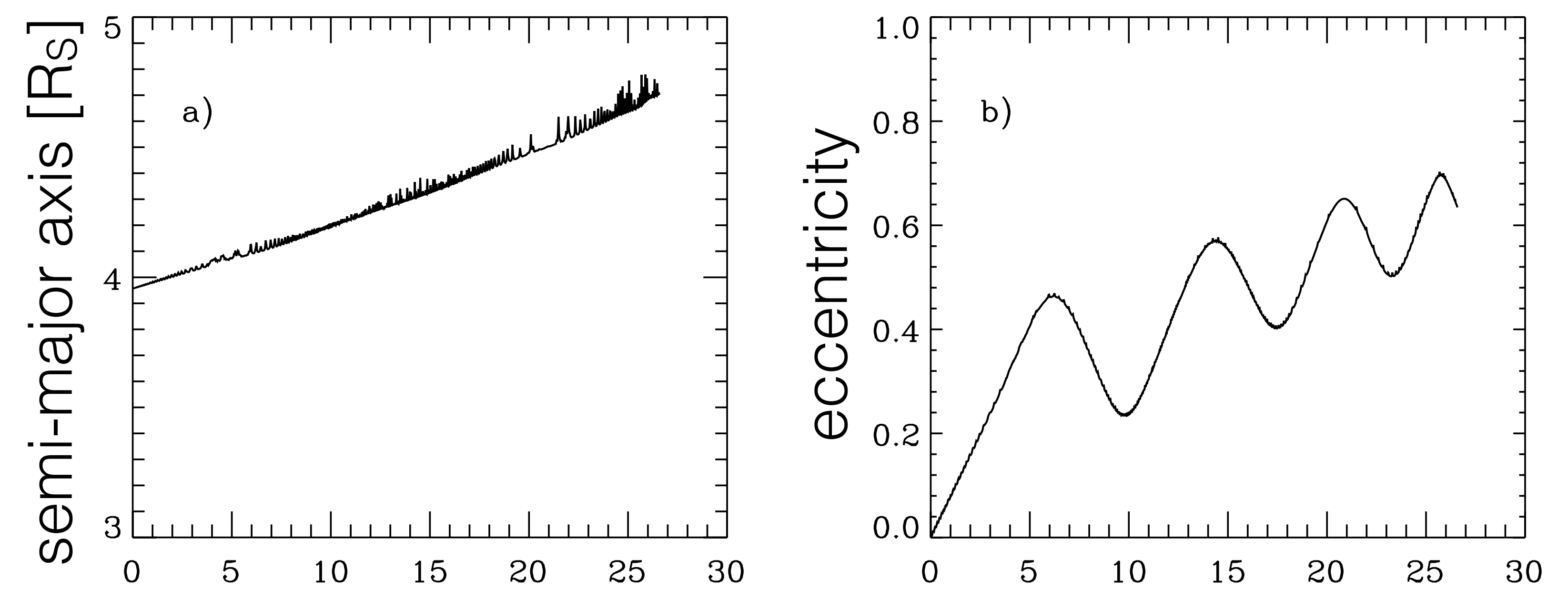


Postberg et al., 2009

Mass spectra of **salt-poor** & **salt-rich** ice grains

- **Dynamics**
  - µm (10^{-6} m) and ↗
  - sub-µm
  - nanometer (10^{-9} m)

Dynamical evolution of a 1.4 µm grain from Enceladus

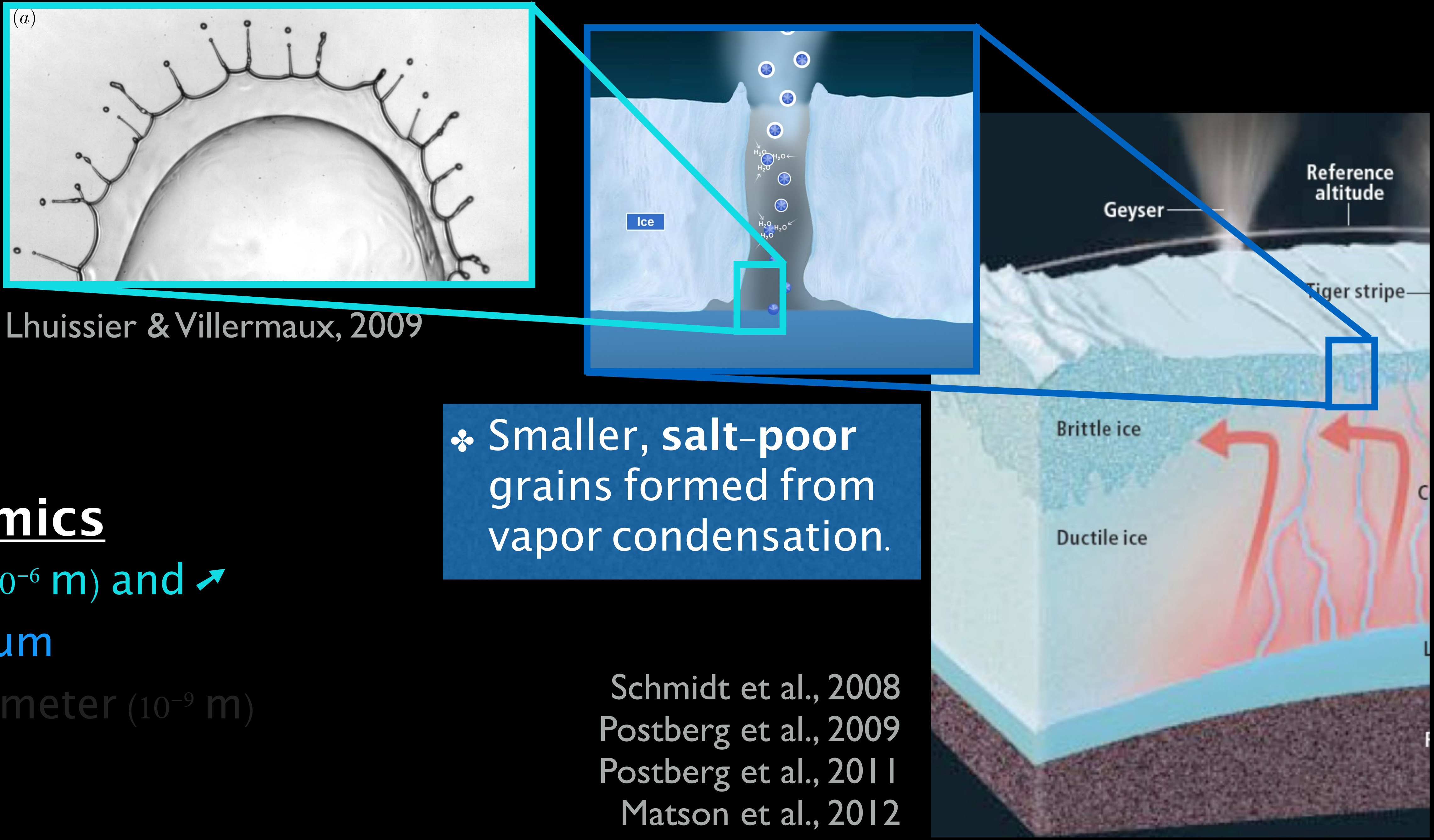


Juhasz & Horanyi 2002

from E ring to Enceladus

❖ Composition

- Heavier, **salt-rich** grains formed from frozen droplets.



Lhuissier & Villermaux, 2009

- Smaller, **salt-poor** grains formed from vapor condensation.

Schmidt et al., 2008
Postberg et al., 2009
Postberg et al., 2011
Matson et al., 2012

❖ Dynamics

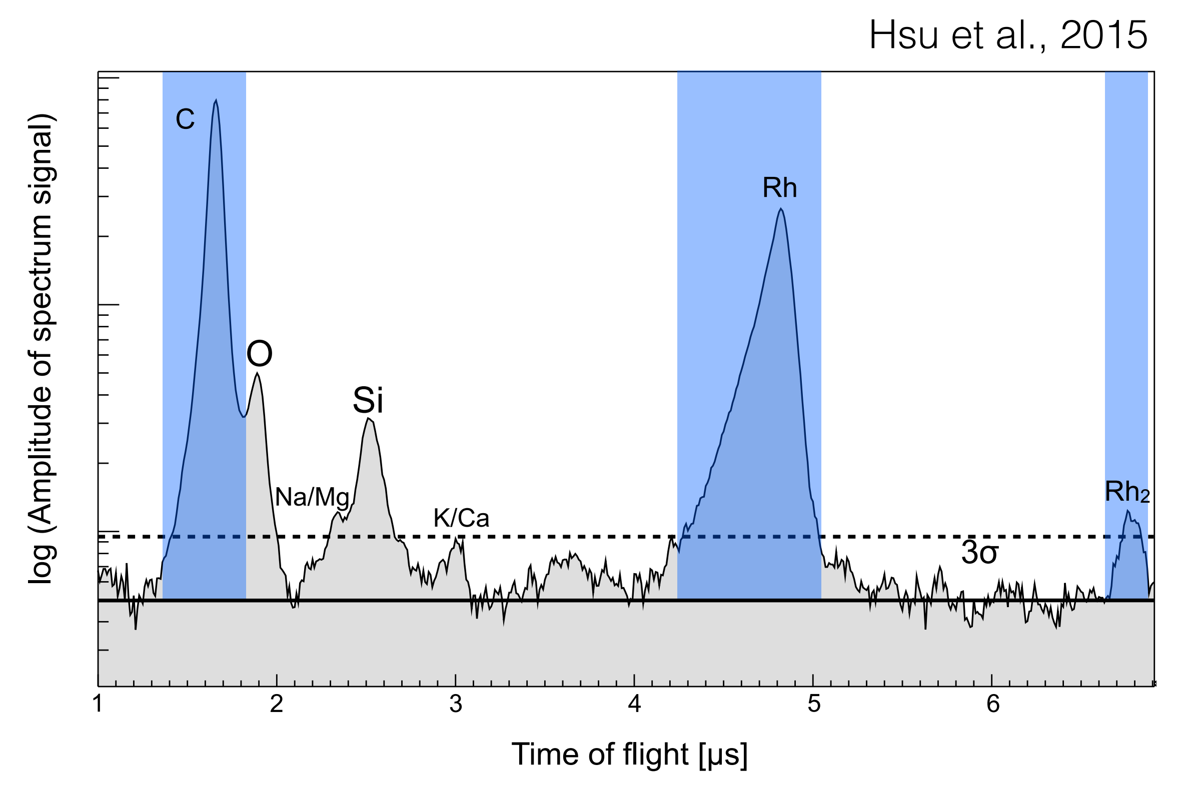
- μm (10^{-6} m) and ↗
- sub-μm
- nanometer (10^{-9} m)

Nanodust Stream Particles

❖ **Composition**

In contrast to the water-rich system, they are

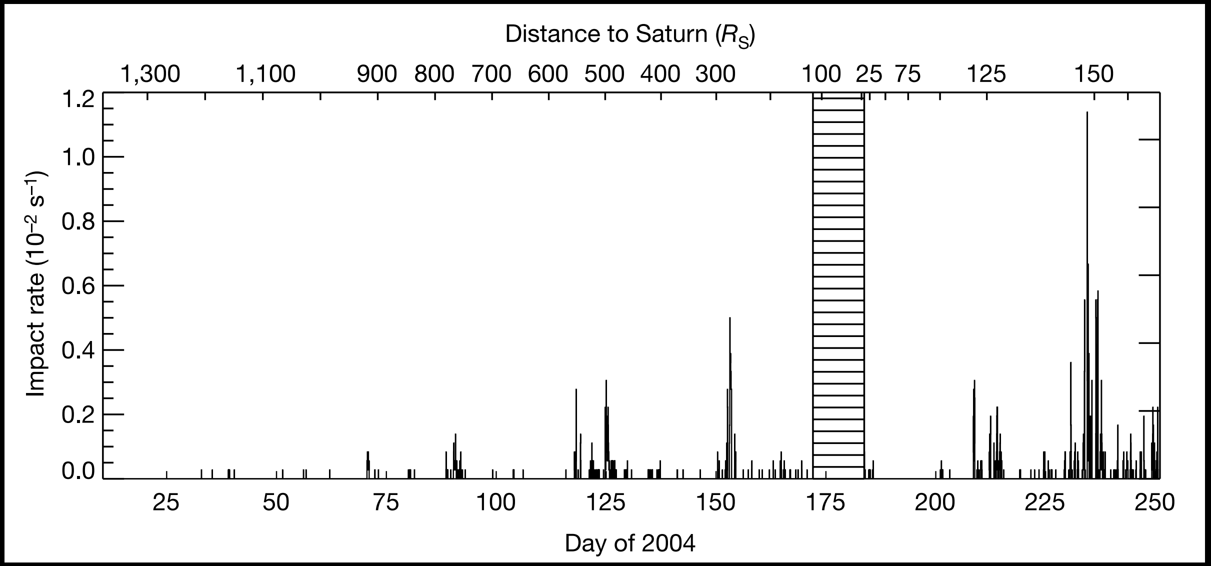
- silicon-rich
- extremely metal-poor



Hsu et al., 2015

❖ **Dynamics**

- impact speed > 70 km/s
- impact rate is correlated with solar wind activities



Kempf et al., 2005

Nanodust Stream Particles

❖ Composition

In contrast to the water-rich system, they are

➡ rock-related

➡ not typical rock-forming minerals

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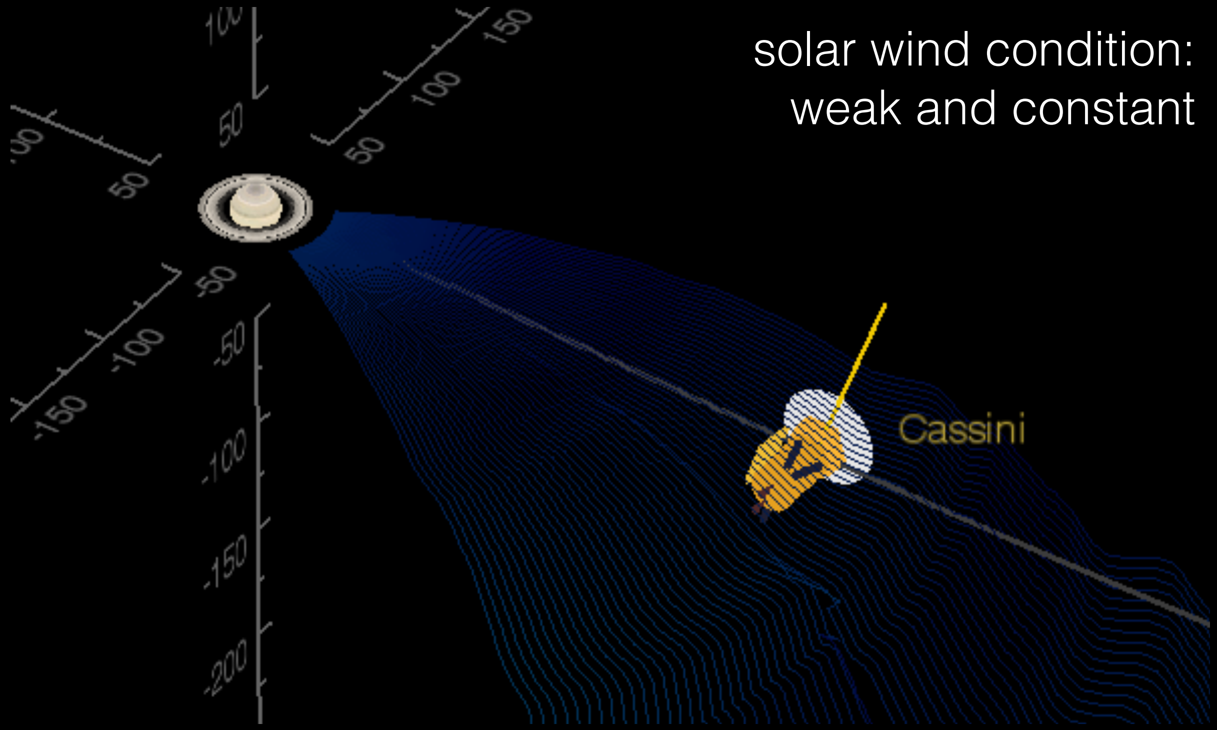
http://en.wikipedia.org/wiki/Feldspar

http://en.wikipedia.org/wiki/Pyroxene

olivine
$(Mg,Fe)_2SiO_4$

feldspar
$(K,Na)AlSi_3O_8$
$CaAl_2Si_2O_8$

Pyroxene
$XY(Si,Al)_2O_4$
X:Ca, Na, Fe, Mg, ...
Y:Cr, Al, Fe, Mg, Mn, ...

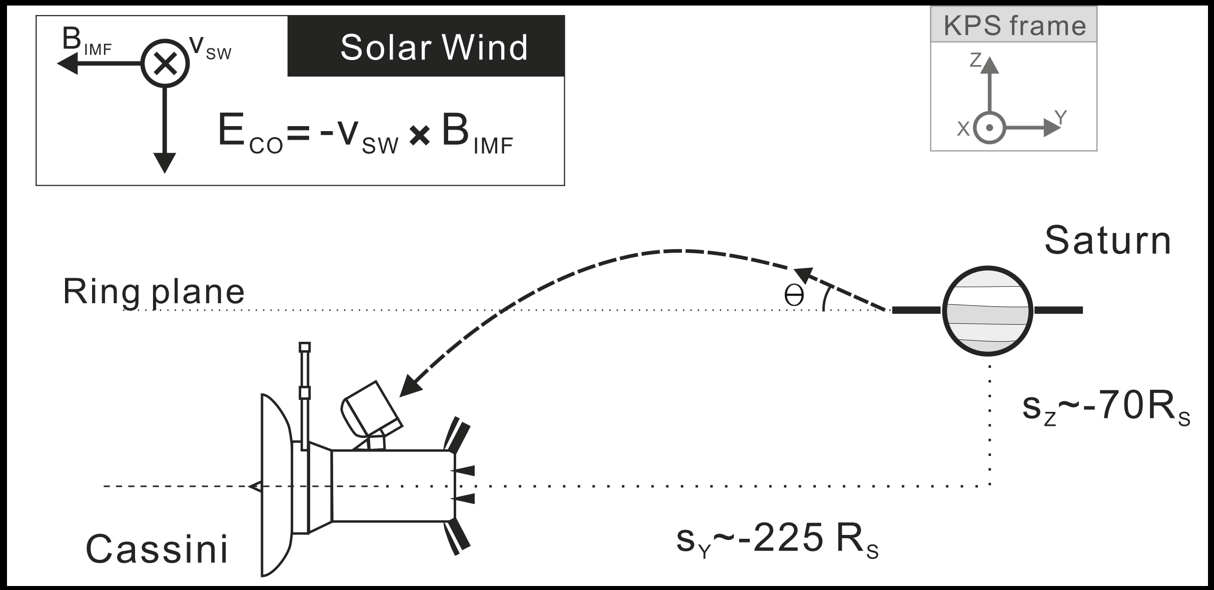


solar wind condition:
weak and constant

❖ Dynamics

➡ radii of a few nm

➡ dust-solar wind interactions provide constraints on their ejection speeds & mass/size



Hsu et al., 2010

Nanodust Stream Particles

- **Composition**

  In contrast to the water-rich system, they are
  - ➡ rock-related
  - ➡ not typical rock-forming minerals

commons.wikimedia.org

olivine

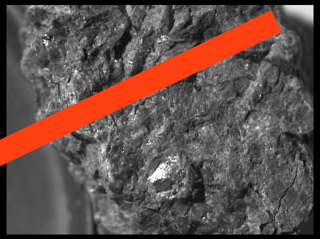
$(Mg,Fe)_2SiO_4$

http://en.wikipedia.org/wiki/Feldspar

feldspar

$(K,Na)Al\ Si_3O_8$

$CaAl_2Si_2O_8$



http://en.wikipedia.org/wiki/Pyroxene

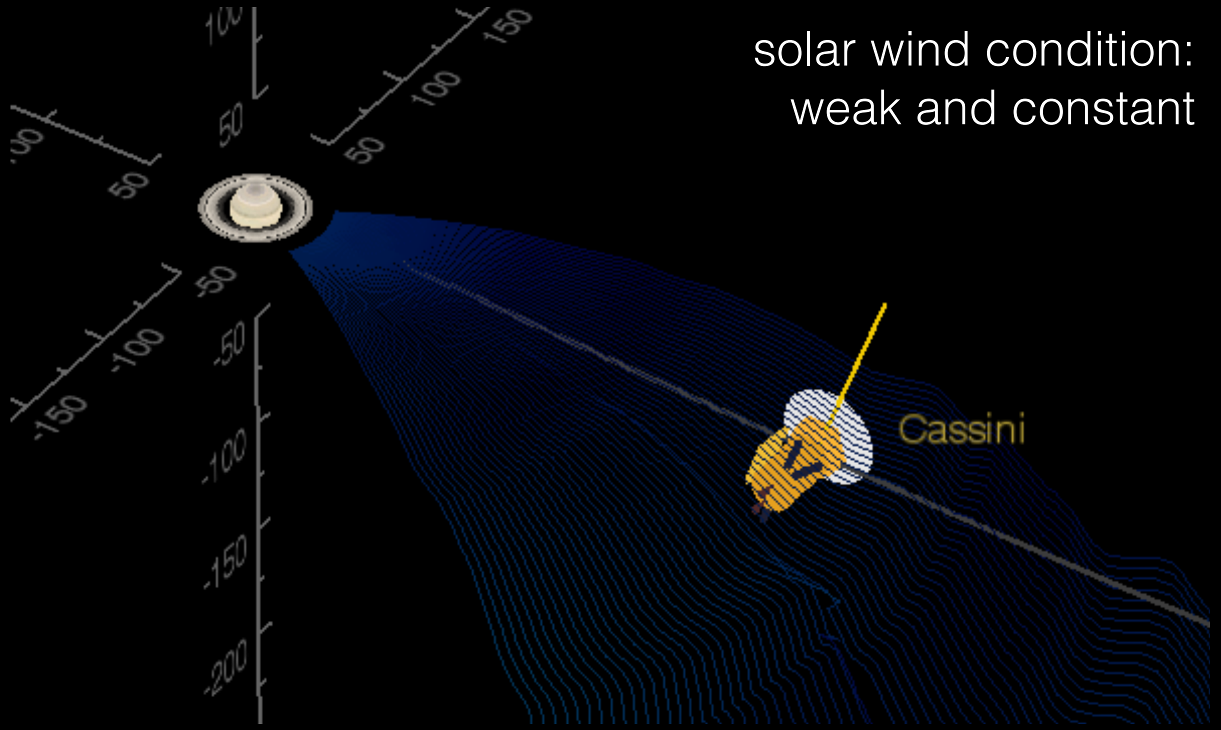
Pyroxene

$XY(Si,Al)_2O_4$

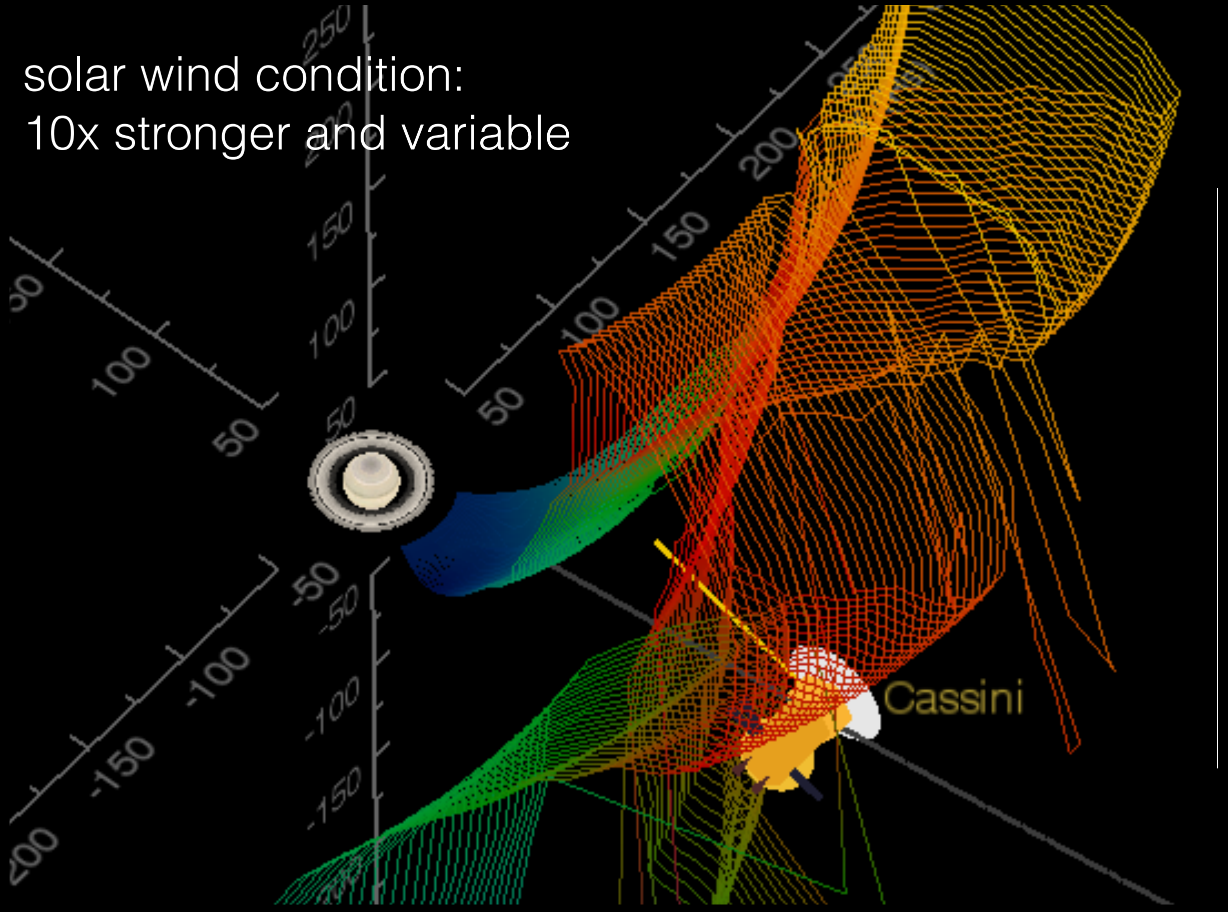
X:Ca, Na, Fe, Mg, ...

Y:Cr, Al, Fe, Mg, Mn, ...

- **Dynamics**
  - ➡ radii of a few nm
  - ➡ dust-solar wind interactions provide constraints on their ejection speeds & mass/size



solar wind condition:
weak and constant



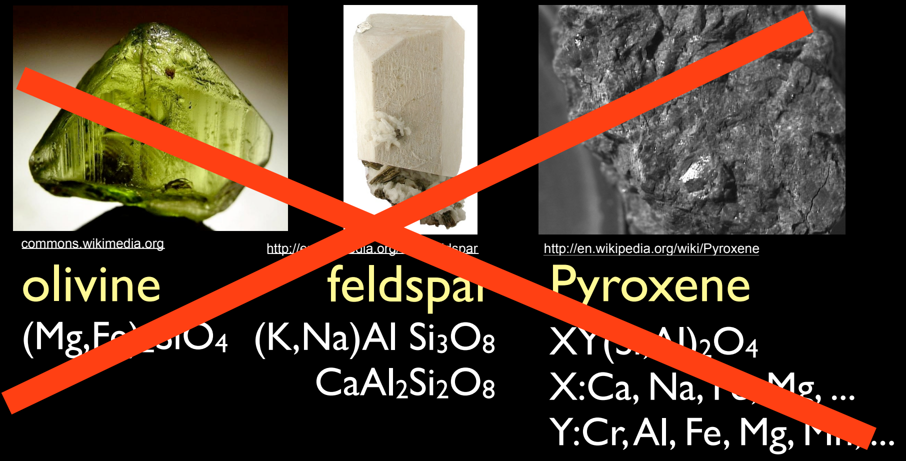
solar wind condition:
10x stronger and variable

Nanodust Stream Particles

❖ Composition

In contrast to the water-rich system, they are

- ➡ rock-related
- ➡ Si: O ratio is consistent with SiO_2



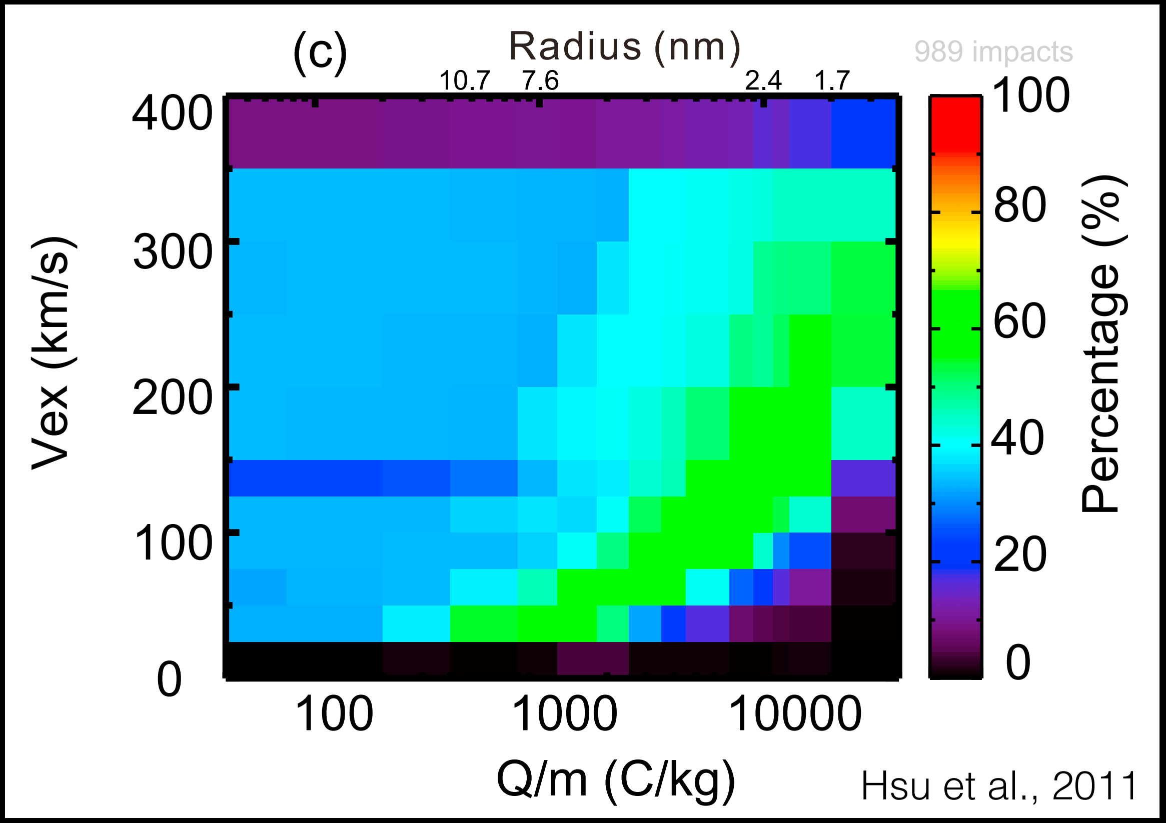
olivine
$(Mg,Fe)_2SiO_4$

feldspar
$(K,Na)Al\ Si_3O_8$
$CaAl_2Si_2O_8$

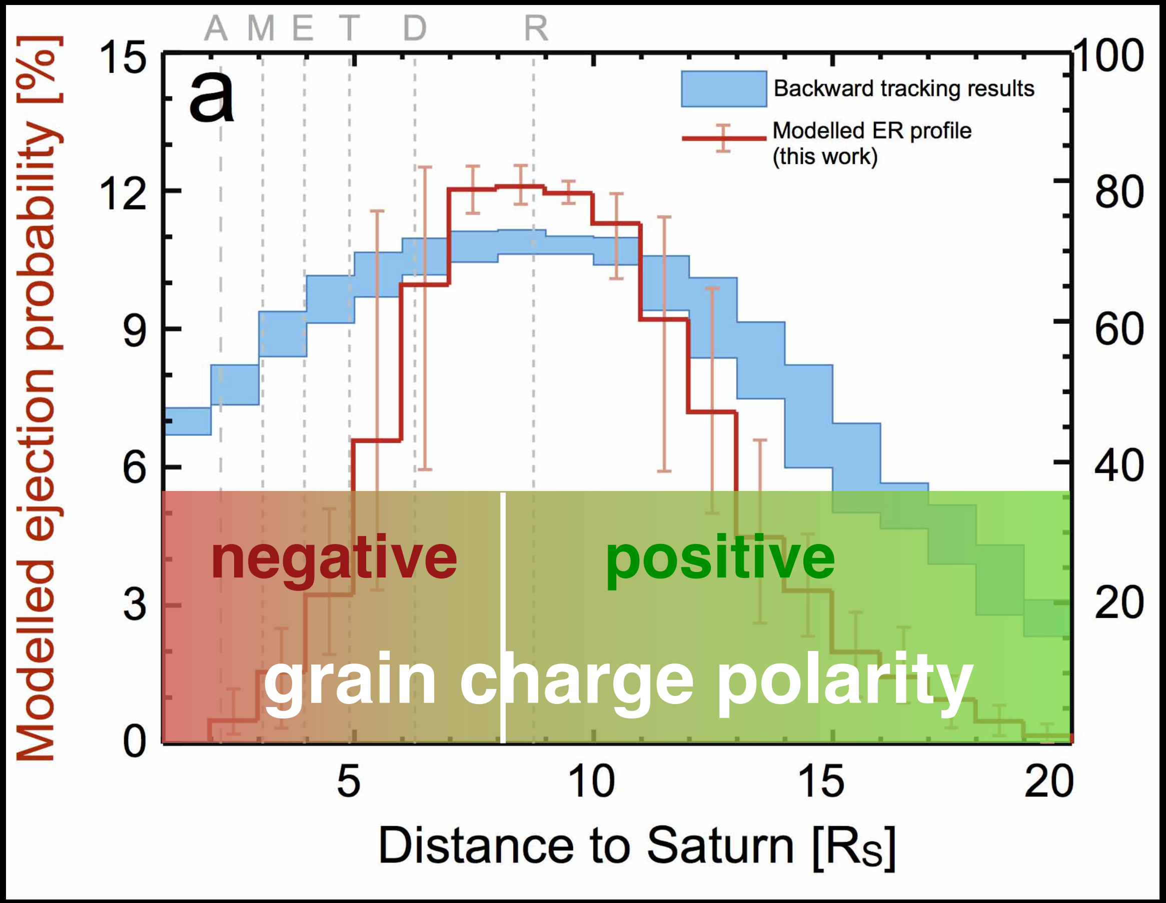
Pyroxene
$XY(Si,Al)_2O_4$
X:Ca, Na, Fe, Mg, ...
Y:Cr, Al, Fe, Mg, Mn, ...

❖ Dynamics

- ➡ radii ranging from 2 to 8 nm
- ➡ originate from the E ring region further outward from the orbit of Enceladus, where grain preferably charged positively

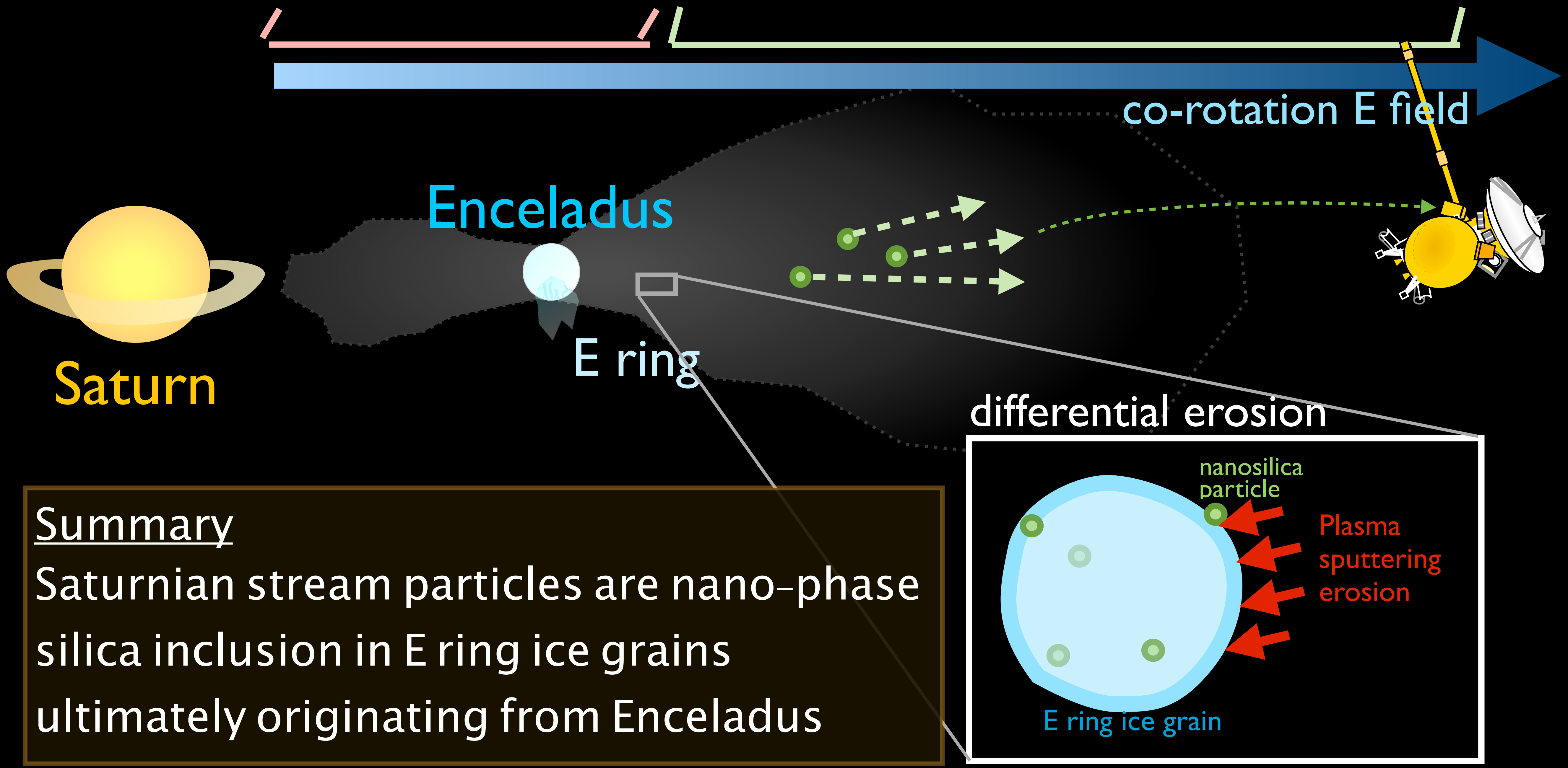


Hsu et al., 2011



cold, dense plasma in
the vicinity of
Enceladus leads to
negative grain charge

hot, tenuous plasma
at the outer part of
the E ring leads to
positive grain charge



co-rotation E field

Enceladus

Saturn

E ring

differential erosion

nanosilica particle

Plasma sputtering erosion

E ring ice grain

Summary

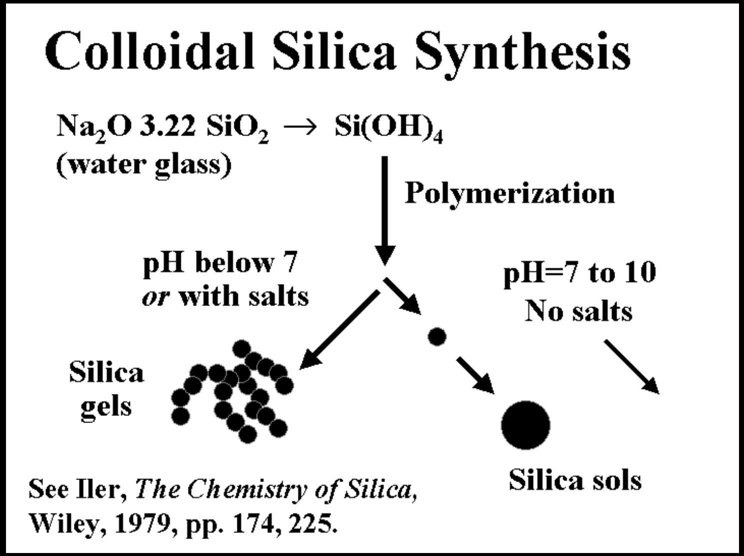
Saturnian stream particles are nano-phase silica inclusion in E ring ice grains ultimately originating from Enceladus

Nano-silica Dust Stream Particles

Formation & Implications

- nano-phase SiO_2
  ➔ top-down or bottom-up formation?
- radius ranging from **2** to **8** nm
  ➔ a narrow size range
- originating from Enceladus as E ring ice grain inclusions
  ➔ pre-exist in the source of the plume, i. e. , within Enceladus

fragmentation?



See Iler, *The Chemistry of Silica*, Wiley, 1979, pp. 174, 225.

Nano-Silica

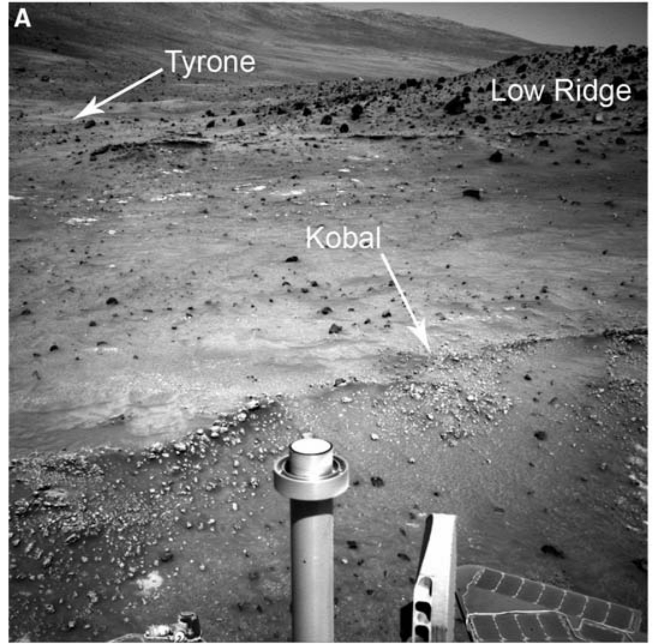
silica-water system

- Spontaneous, homogenous nucleation of nano-phase silica colloids occurs when the super-saturation is achieved when the solution pH and/or temperature change.

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

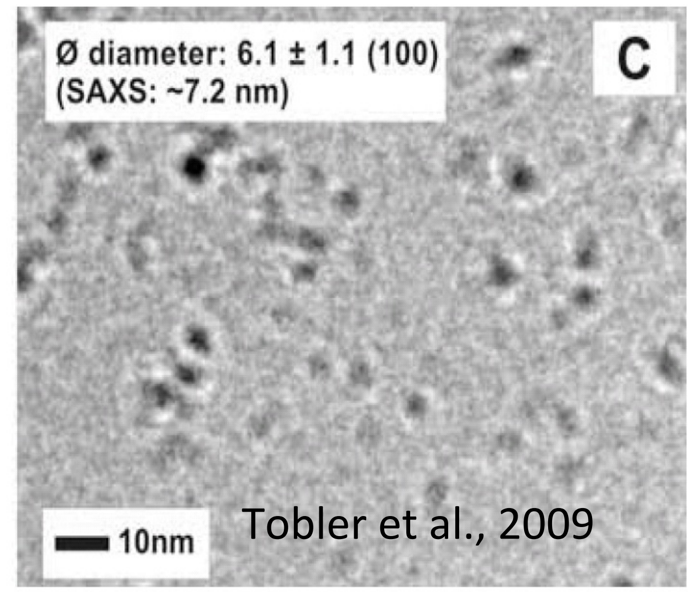
- SiO_2 is an indicator of hydrothermal reactions on Earth & Mars.

Spirit, Squyres et al., 2008



hydrothermal silica deposits & colloids

Laboratory experiments

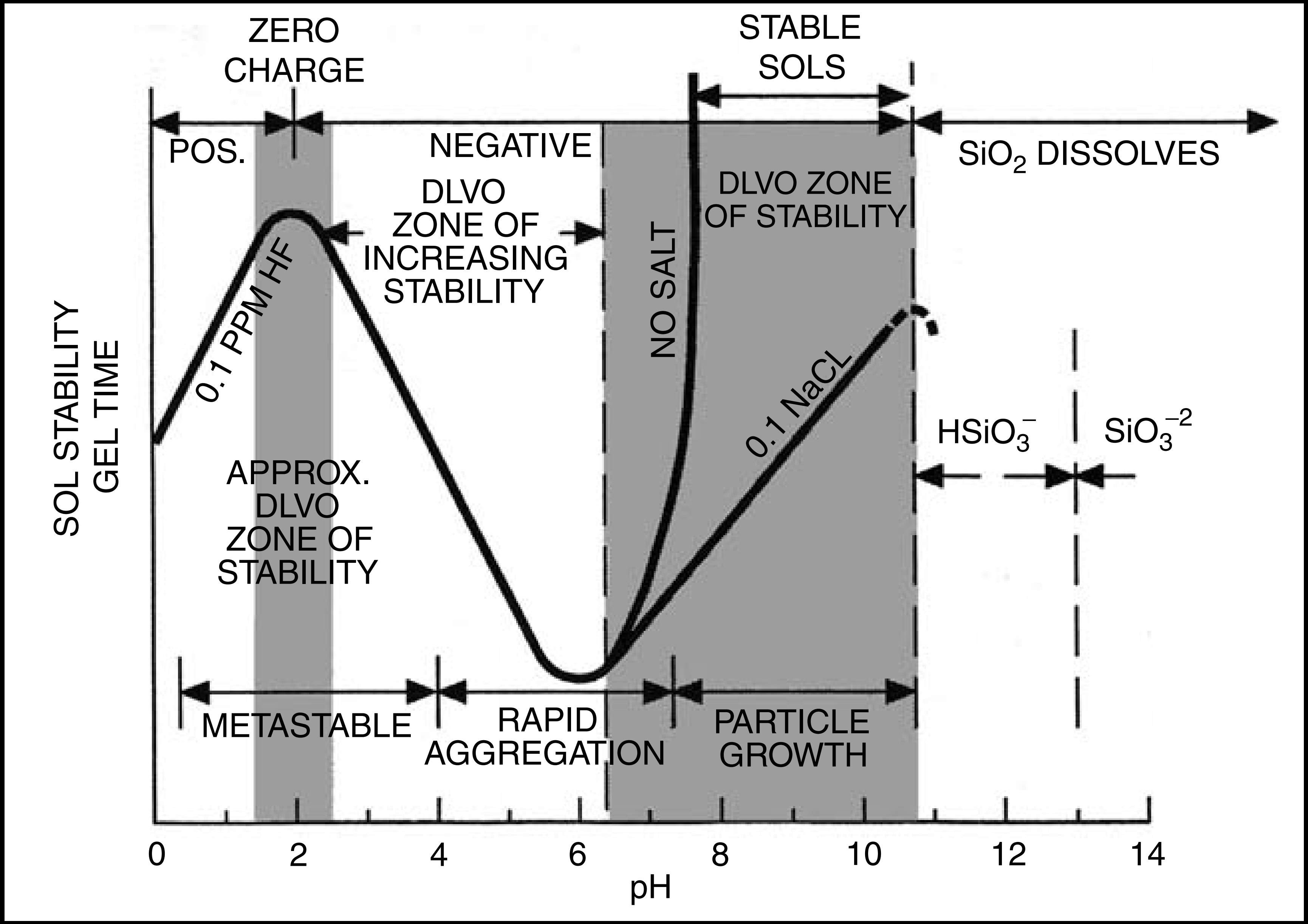


Tobler et al., 2009

Nano-Silica

(1) Stability vs. pH

Nano-silica are stable @ pH 7-10.5



Bergna and Roberts, 2006

Nano-Silica

(2) Stability vs. Salinity

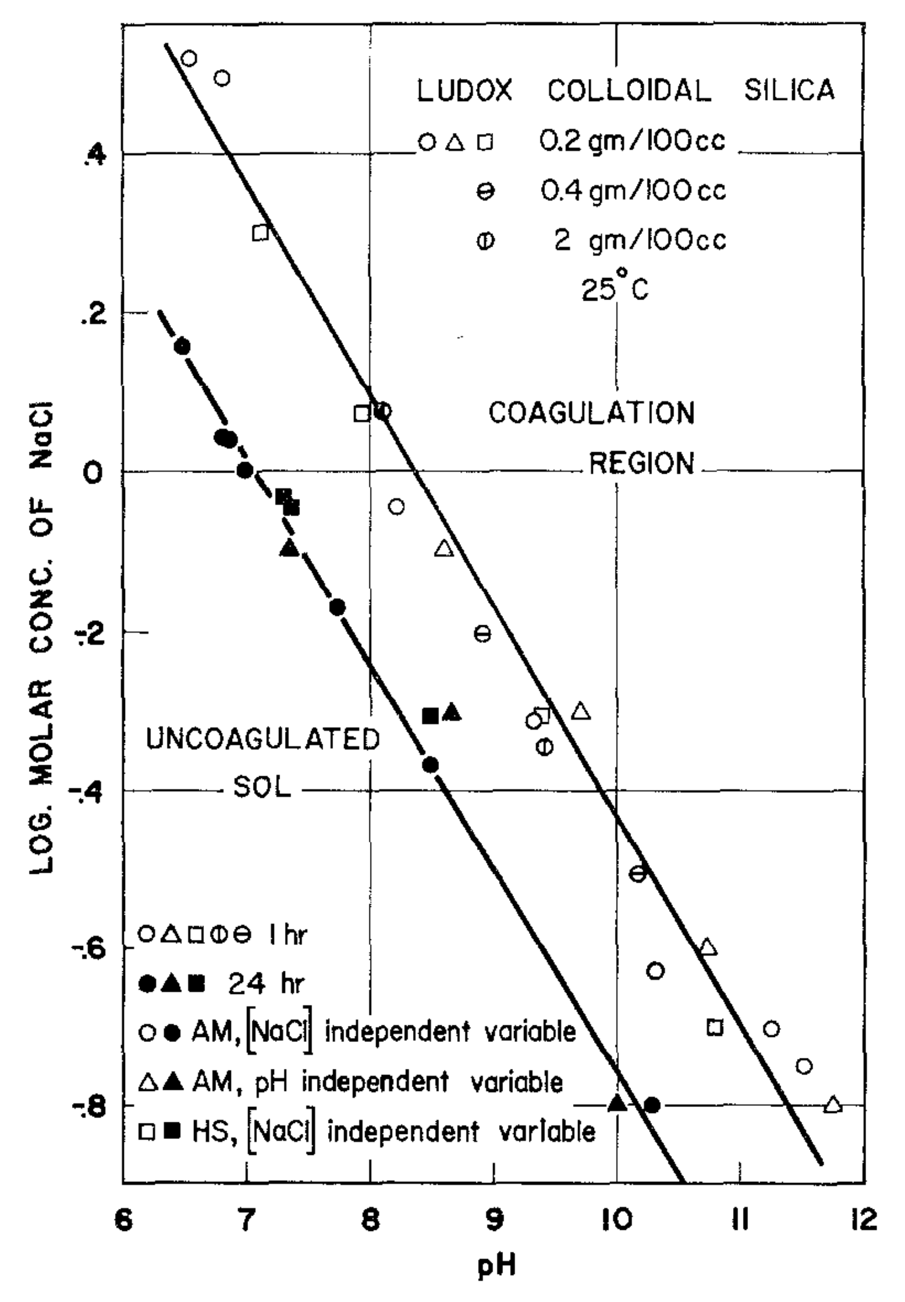


FIG. 4. Critical coagulation concentrations of NaCl for Ludox silica as a function of pH at 1 and 24 hours after mixing.

Nano-silica

are stable @ <1.5-4% of NaCl

⇒ ~~brine phase~~

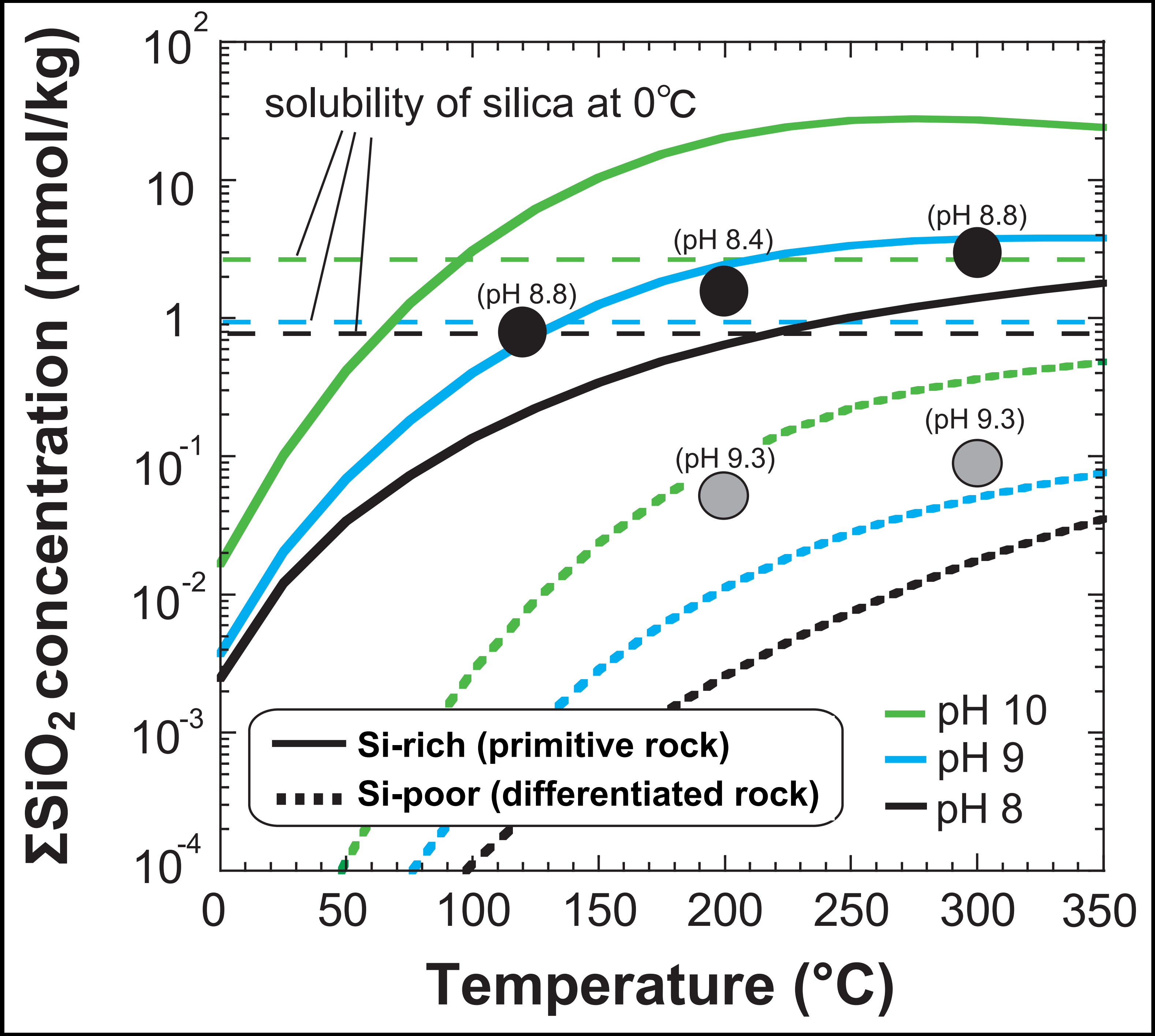
⇒ *currently* produced

than preserved over geological time scale

Allen and Matijevic, 1969

Nano-Silica

(3) Formation vs. Rock Composition

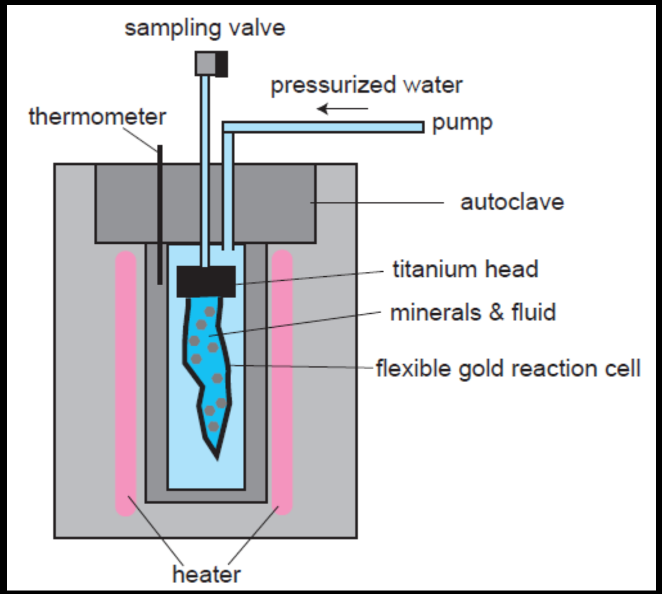


Hsu et al, 2015

Si-poor rock composition (Mg/Si ~1; ex. pyroxene)

⟹ sufficient dissolved silica to form colloids after cooling

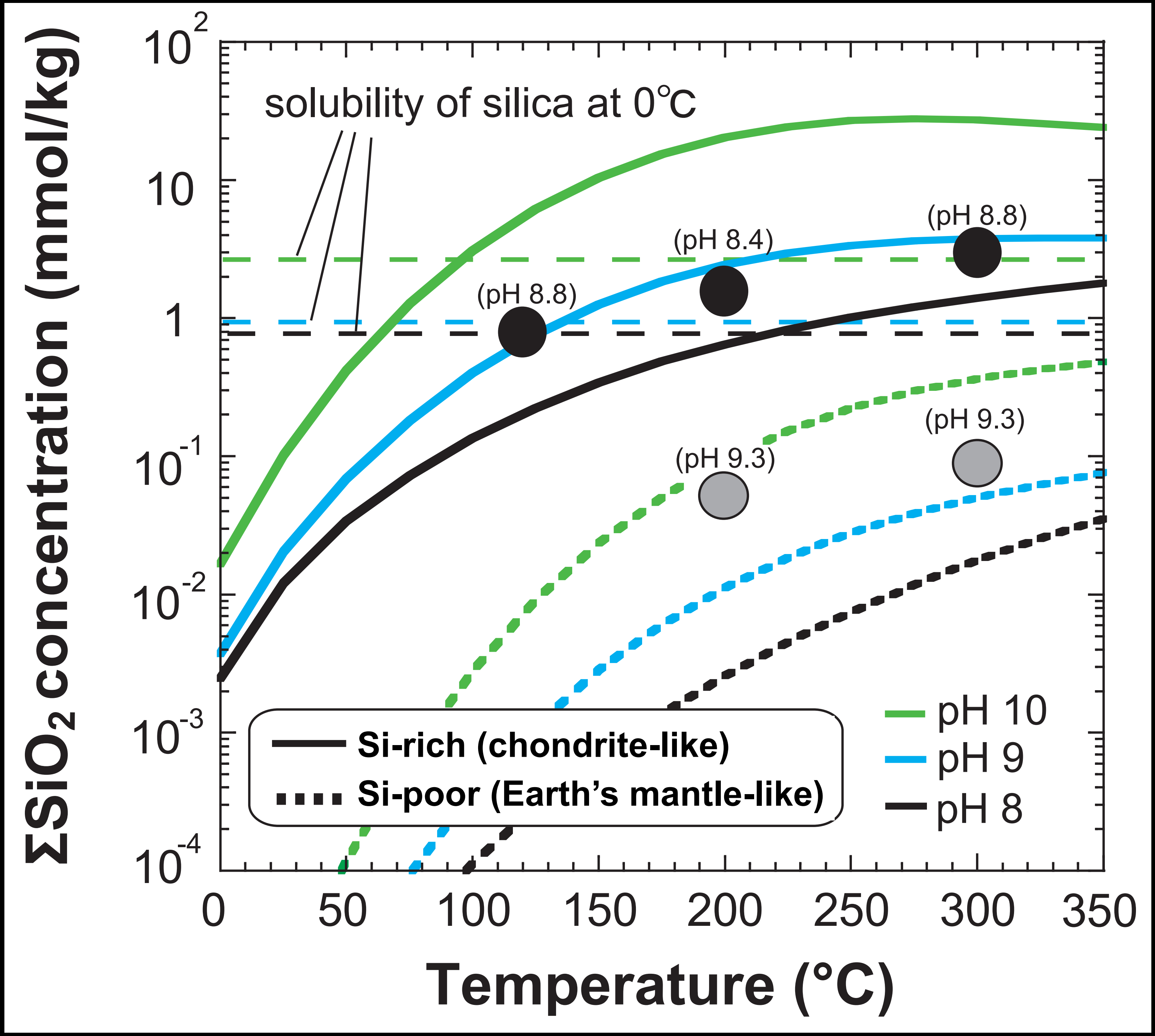
⟹ in good agreement with an **undifferentiated, porous** core



Hydrothermal experiments mimicking Enceladus' conditions

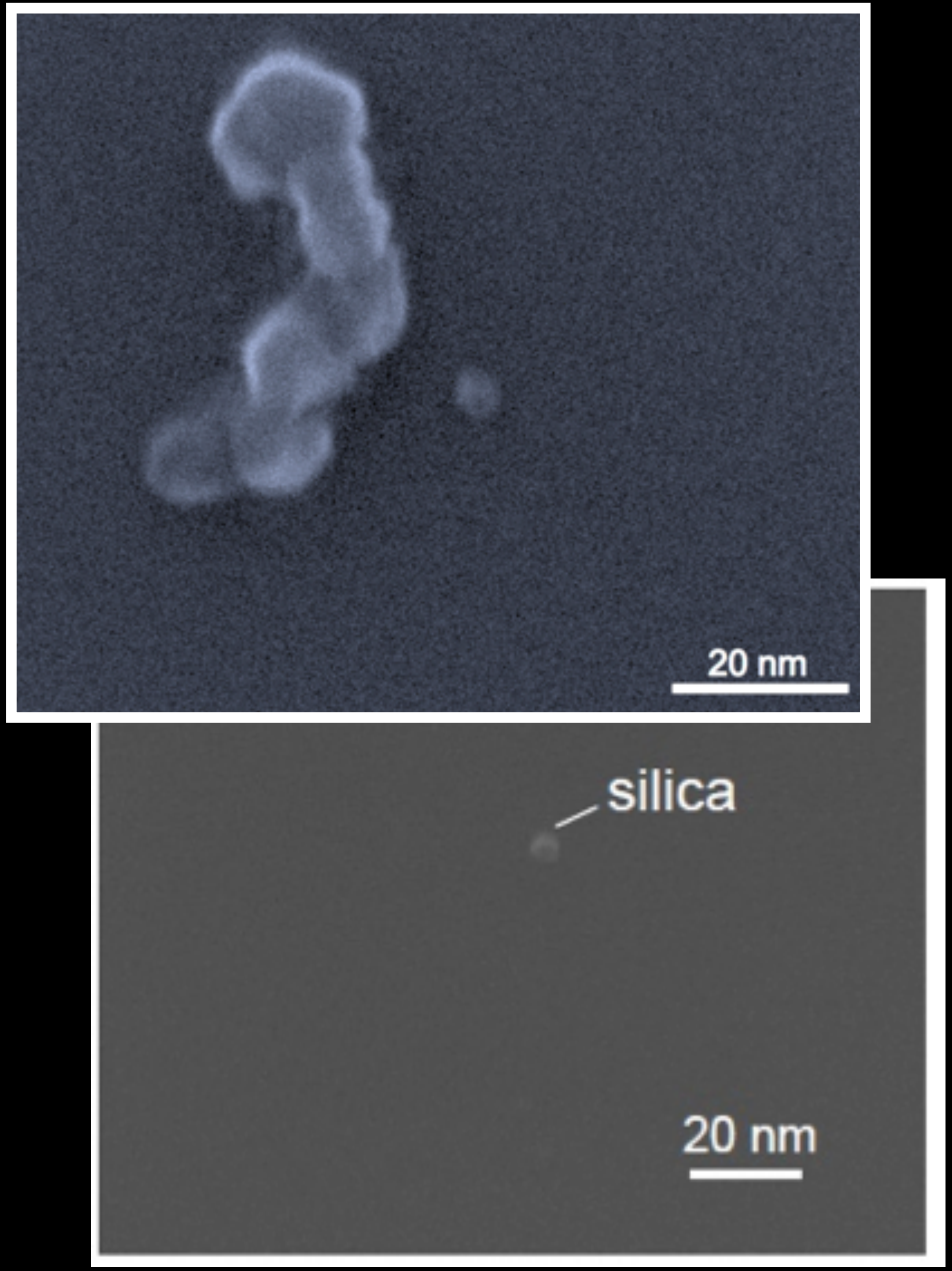
Nano-Silica

(3) Formation vs. Rock Composition



Hsu et al, 2015

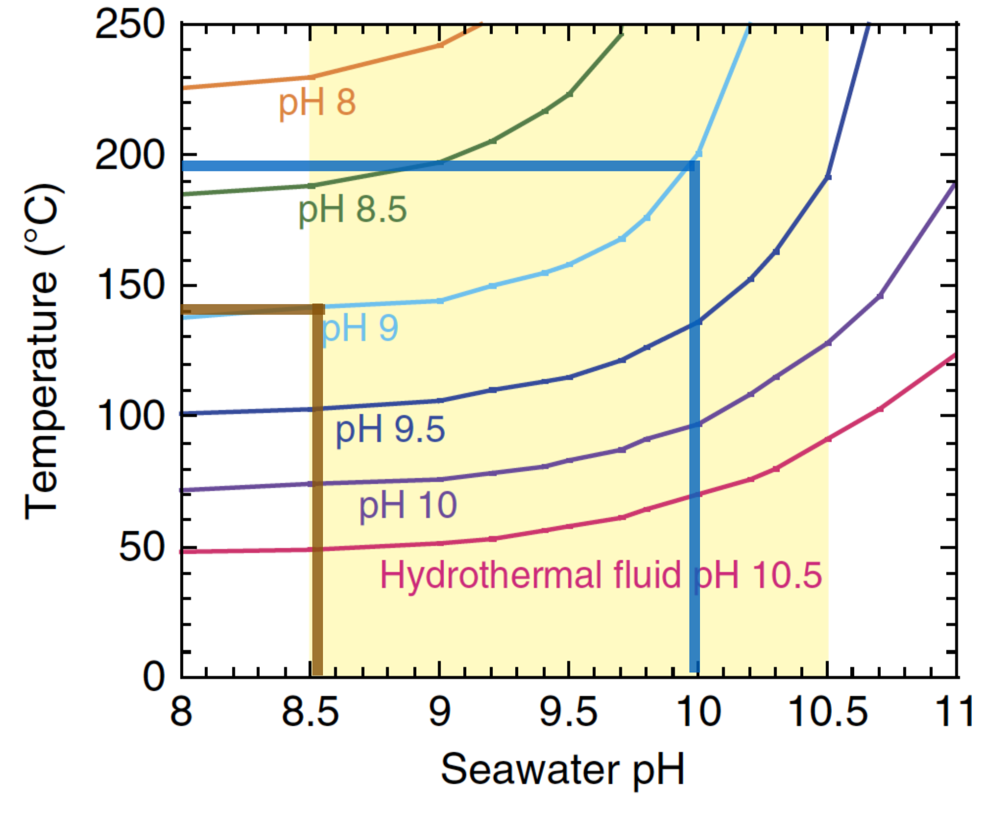
Image of nano-silica formed in hydrothermal experiments.



Nano-Silica

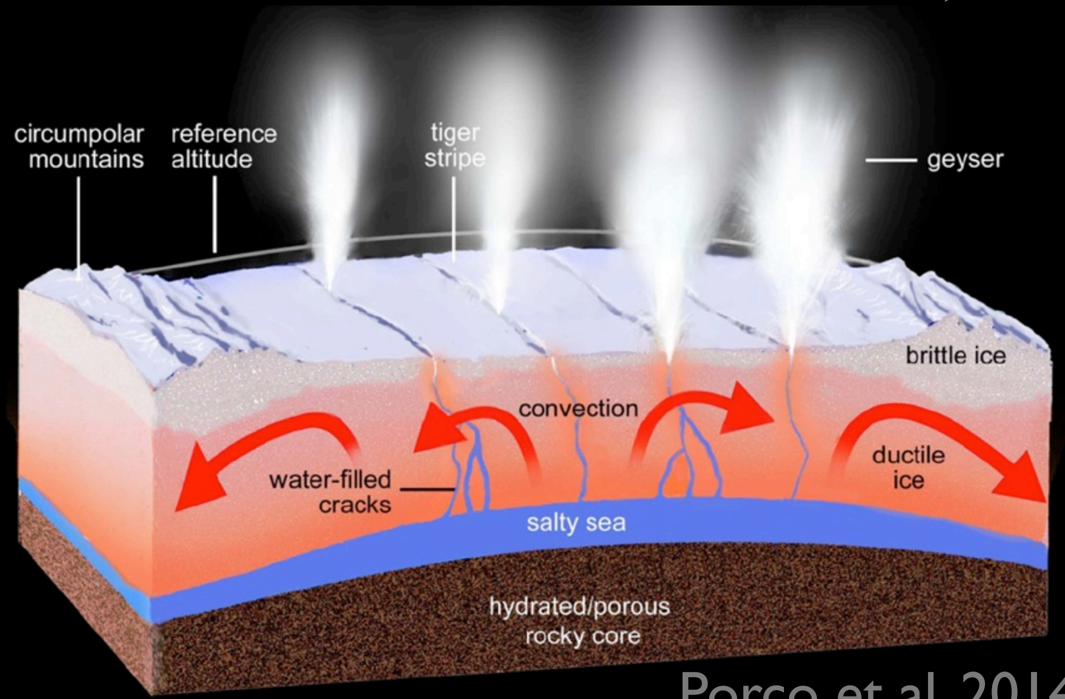
(4) Formation vs. Ocean Temperature

- Disequilibrium scenario
  - e.g., terrestrial hydrothermal vents
  - Hydrothermal fluid in strong disequilibrium with ocean & ice shell.
  - pH might drop upon cooling (e.g., pH from 9 to 8.5, 140°C)



Sekine et al, 2015

- Equilibrium scenario
  - Hydrothermal fluid, ocean, & ice shell are close to chemical equilibrium.
  - Water composition is mostly governed by rock-water interactions.
  - pH of hydrothermal fluid increases upon cooling (e.g., pH from 9 to 10, 195°C).



Porco et al, 2014

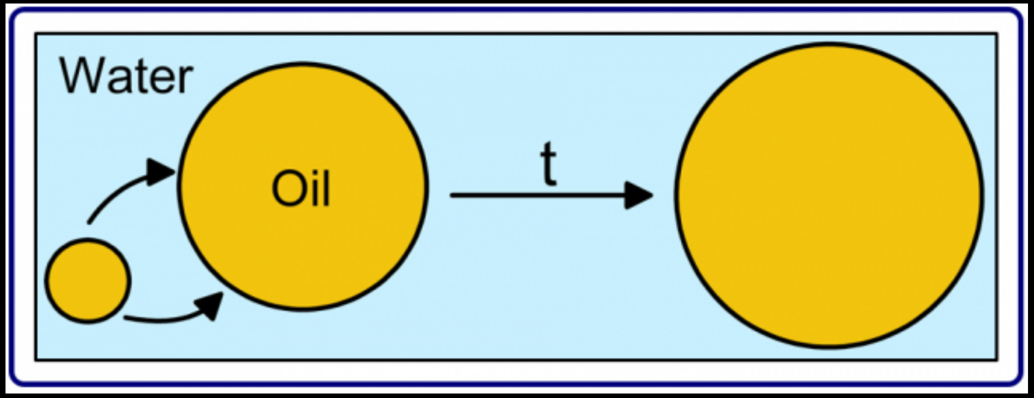
Nano-Silica

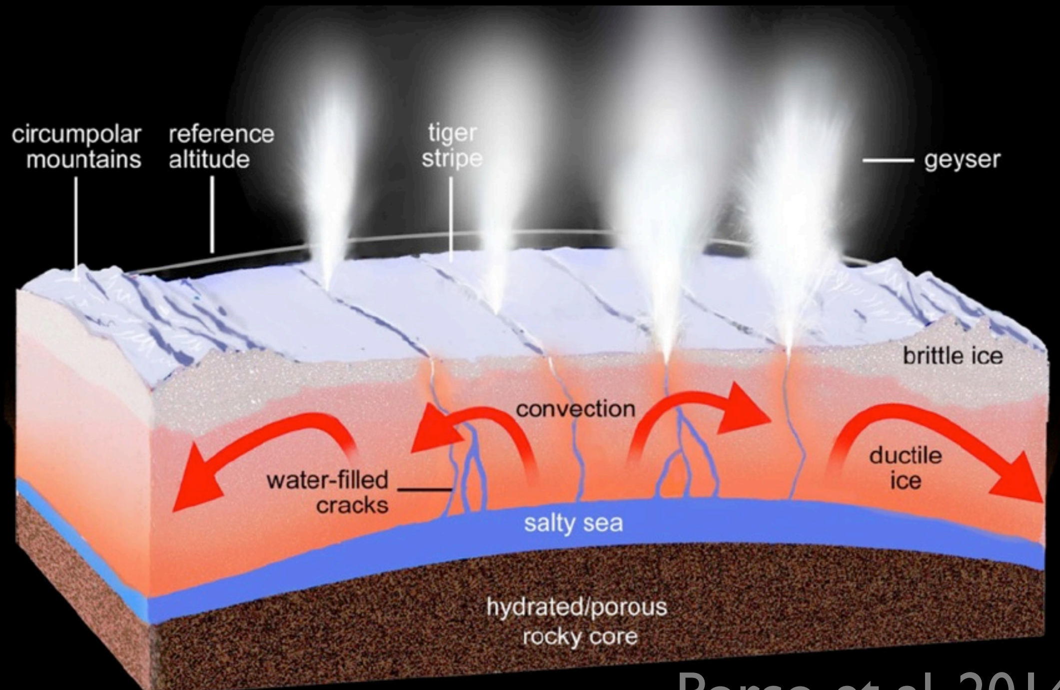
(5) Stability over Time

- Colloidal particles initially form with 2-4 nm radii, then grow slowly by Ostwald ripening.
- nano-silica with radii of < 10 nm implies:
  - they have likely formed recently (within 1 year)
  - fast upward transport likely due to large scale convection
  - likely no strong disequilibrium between hydrothermal sites and ocean

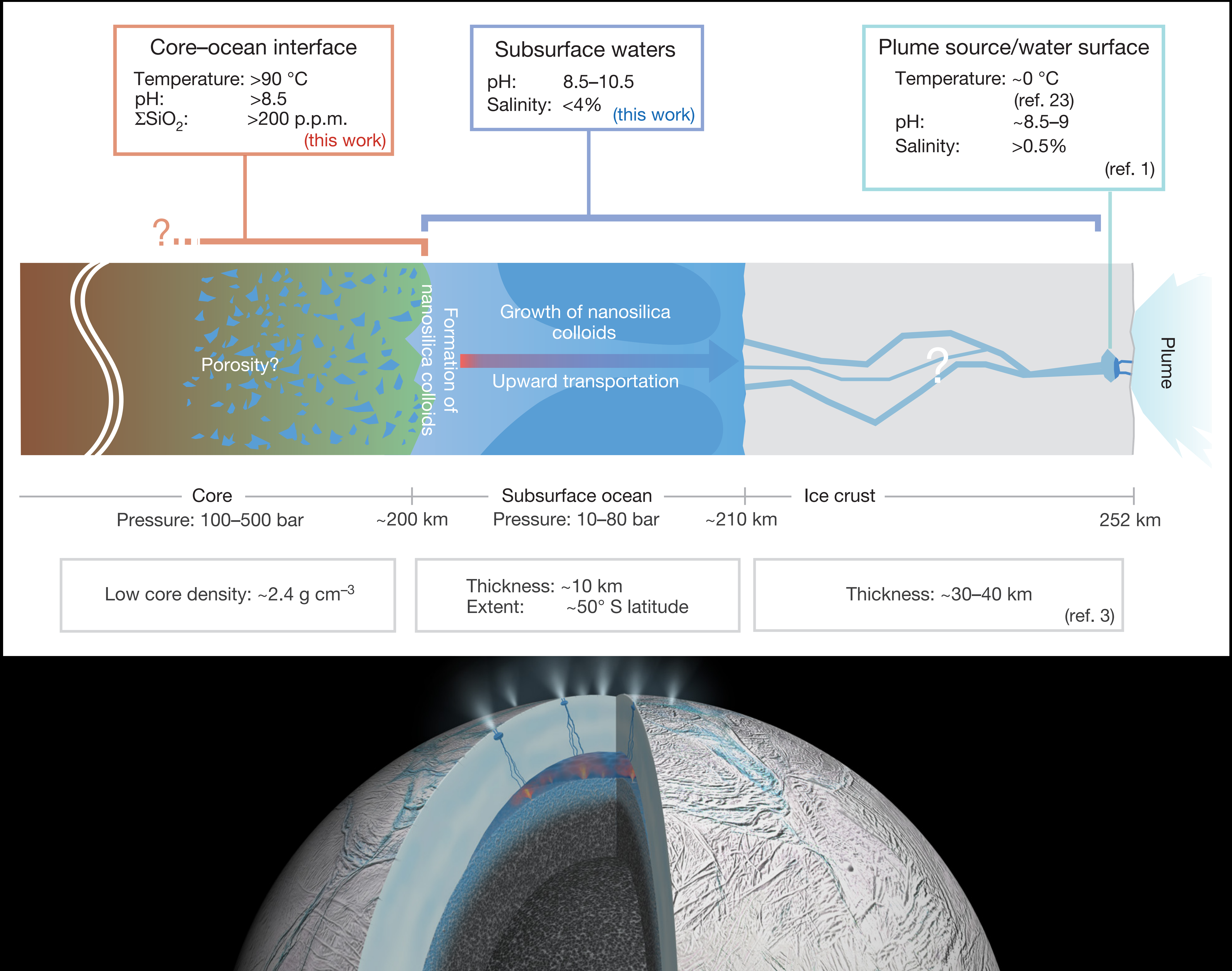
Ostwald ripening

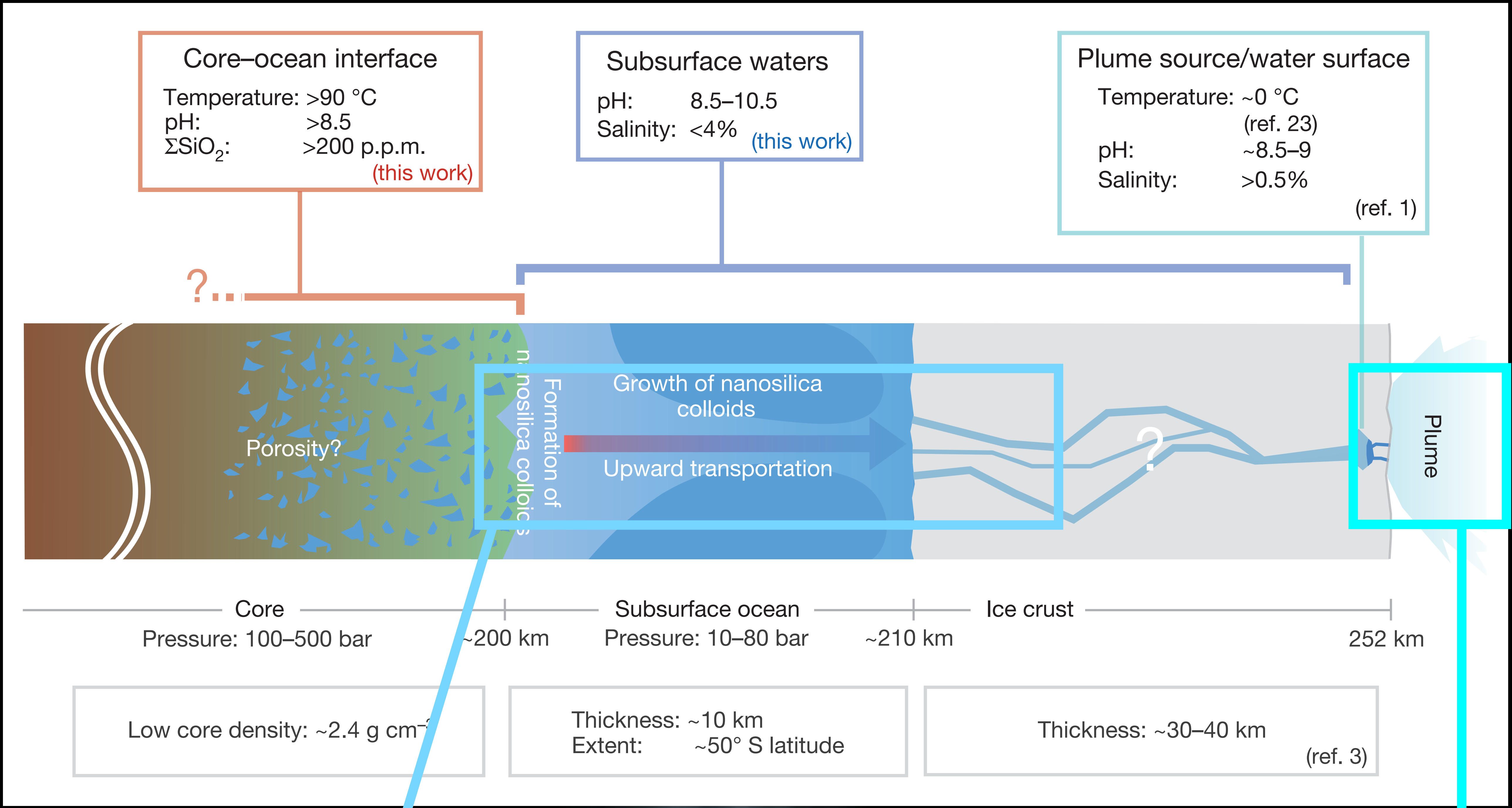
www.lsinstruments.ch





Porco et al, 2014


Core–ocean interface
Temperature: >90 °C
pH: >8.5
ΣSiO$_2$: >200 p.p.m.
(this work)
Subsurface waters
pH: 8.5–10.5
Salinity: <4%
(this work)
Plume source/water surface
Temperature: ~0 °C
(ref. 23)
pH: ~8.5–9
Salinity: >0.5%
(ref. 1)
?...
Porosity?
Formation of nanosilica colloids
Growth of nanosilica colloids
Upward transportation
?
Plume
Core
Pressure: 100–500 bar
~200 km
Subsurface ocean
Pressure: 10–80 bar
~210 km
Ice crust
252 km
Low core density: ~2.4 g cm^{-3}
Thickness: ~10 km
Extent: ~50° S latitude
Thickness: ~30–40 km
(ref. 3)



Core–ocean interface

Temperature: >90 °C
pH: >8.5
ΣSiO_2: >200 p.p.m.
(this work)

Subsurface waters

pH: 8.5–10.5
Salinity: <4%
(this work)

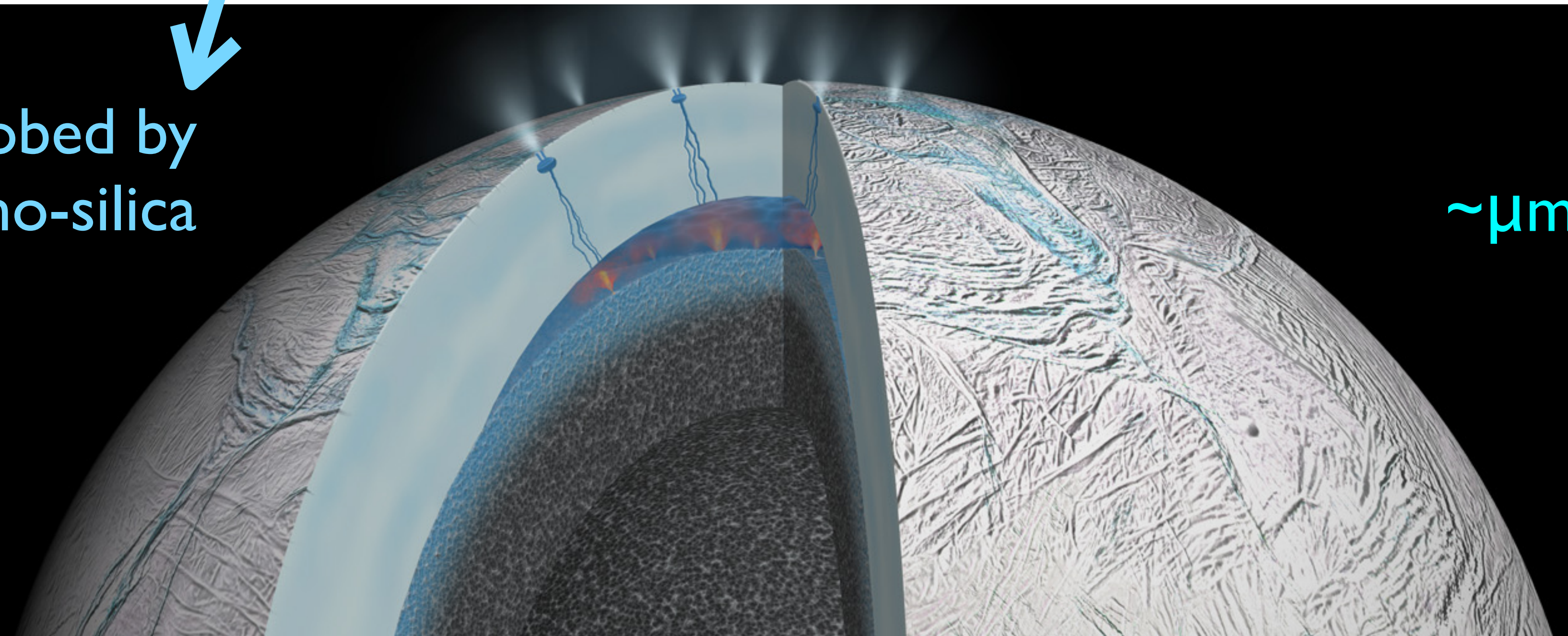
Plume source/water surface

Temperature: ~0 °C (ref. 23)
pH: ~8.5–9
Salinity: >0.5%
(ref. 1)

Low core density: ~2.4 g cm^{-3}

Thickness: ~10 km
Extent: ~50° S latitude

Thickness: ~30–40 km
(ref. 3)



probed by
nano-silica

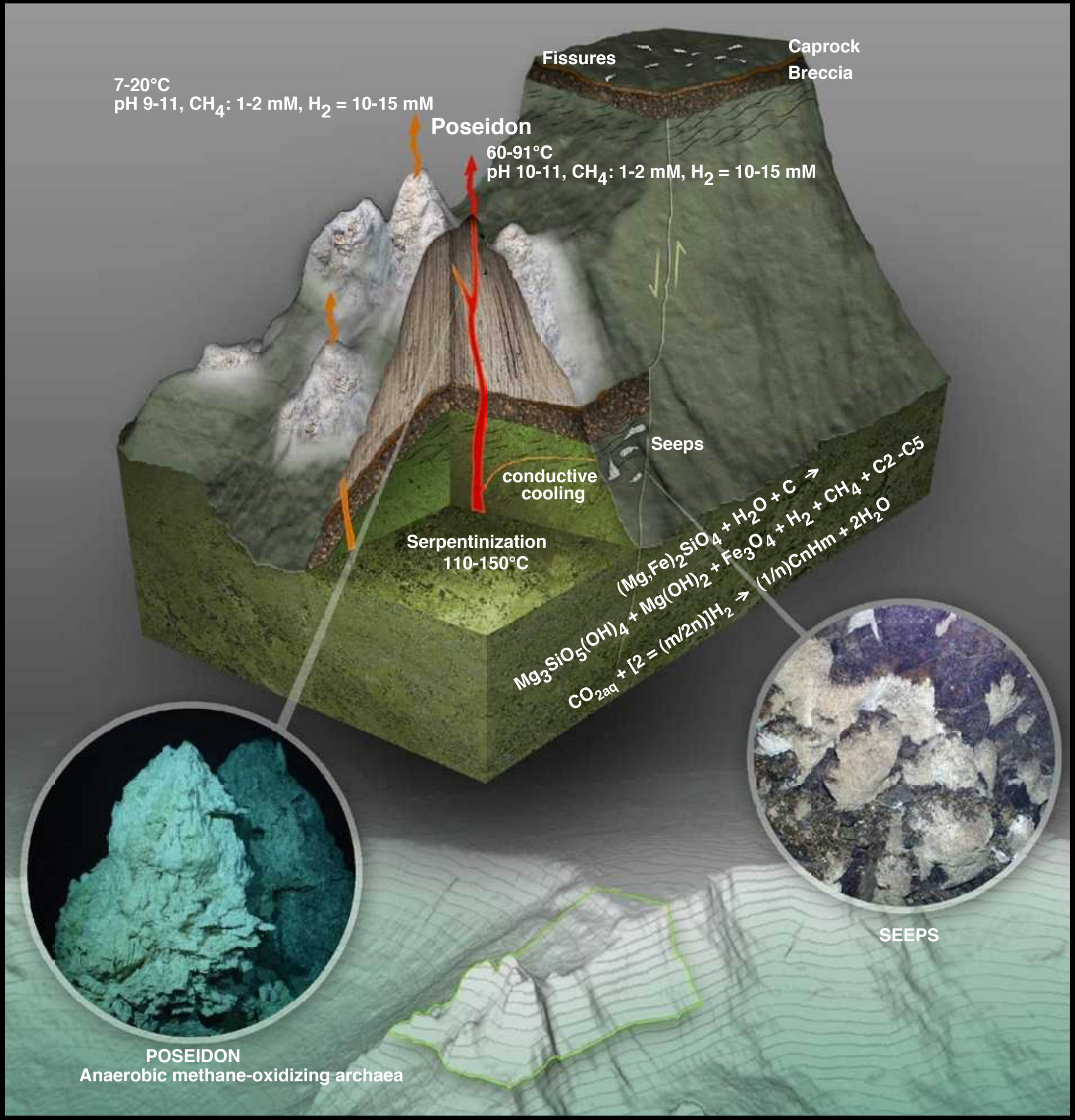
probed by
~µm-sized ice grains

Terrestrial Analogs

Lost City Systems

Kelly et al., 2001, Martin et al., 2008.

High pH, off-MOR axis,
Active for > 100,000 yrs

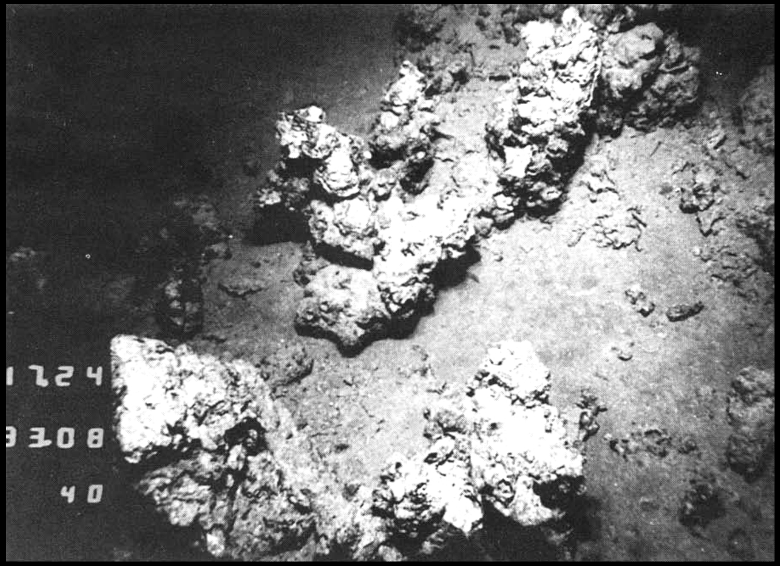


Inactive Silica Chimneys

Galapagos Spreading Center

Cooling from
>175 to 40°C

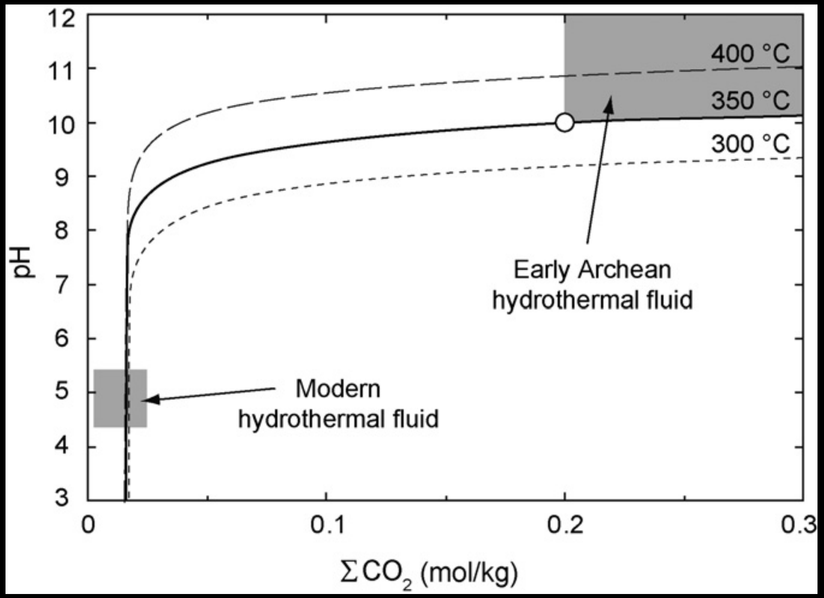
Herzig et al., 1988



In Early Archean Ocean

Shibuya et al., 2010

High CO_2
condition



Astrobiology & Future Exploration

- ❖ Alkaline hydrothermal vents can support an ecosystem independent of sunlight with energy source such as H_2 from serpentinization.
- ❖ Such systems are considered to be good candidates where life first emerged on Earth (Martin et al., 2014).
- ❖ The concept of "Dust Astronomy" proposed by Grün et al., 2001:
  "using dust to study the conditions at their source(s), which cannot be probed otherwise"
  can be applied to other active bodies, such as Io, Europa, Triton, …etc.