Sodium salts in cryo-volcanic ice particles
–
Evidence for liquid water on Enceladus

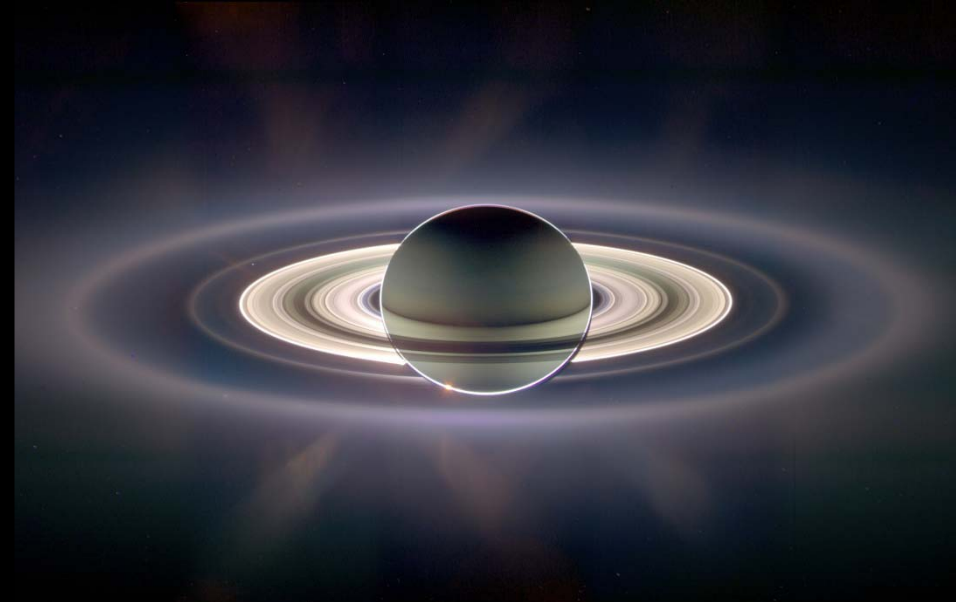
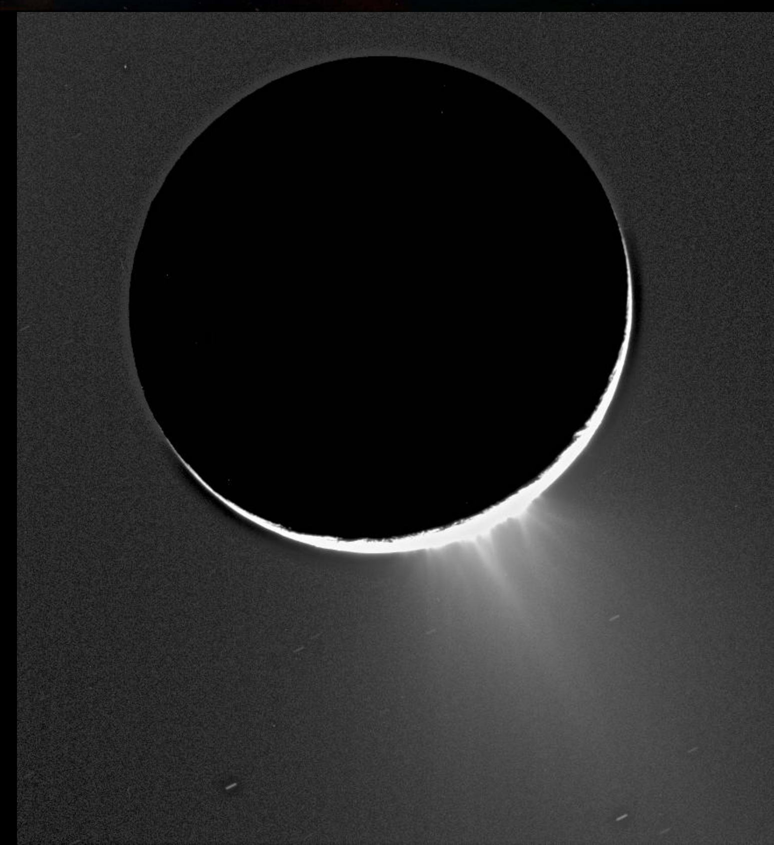
Nature 459, 1098-1101 (2009)

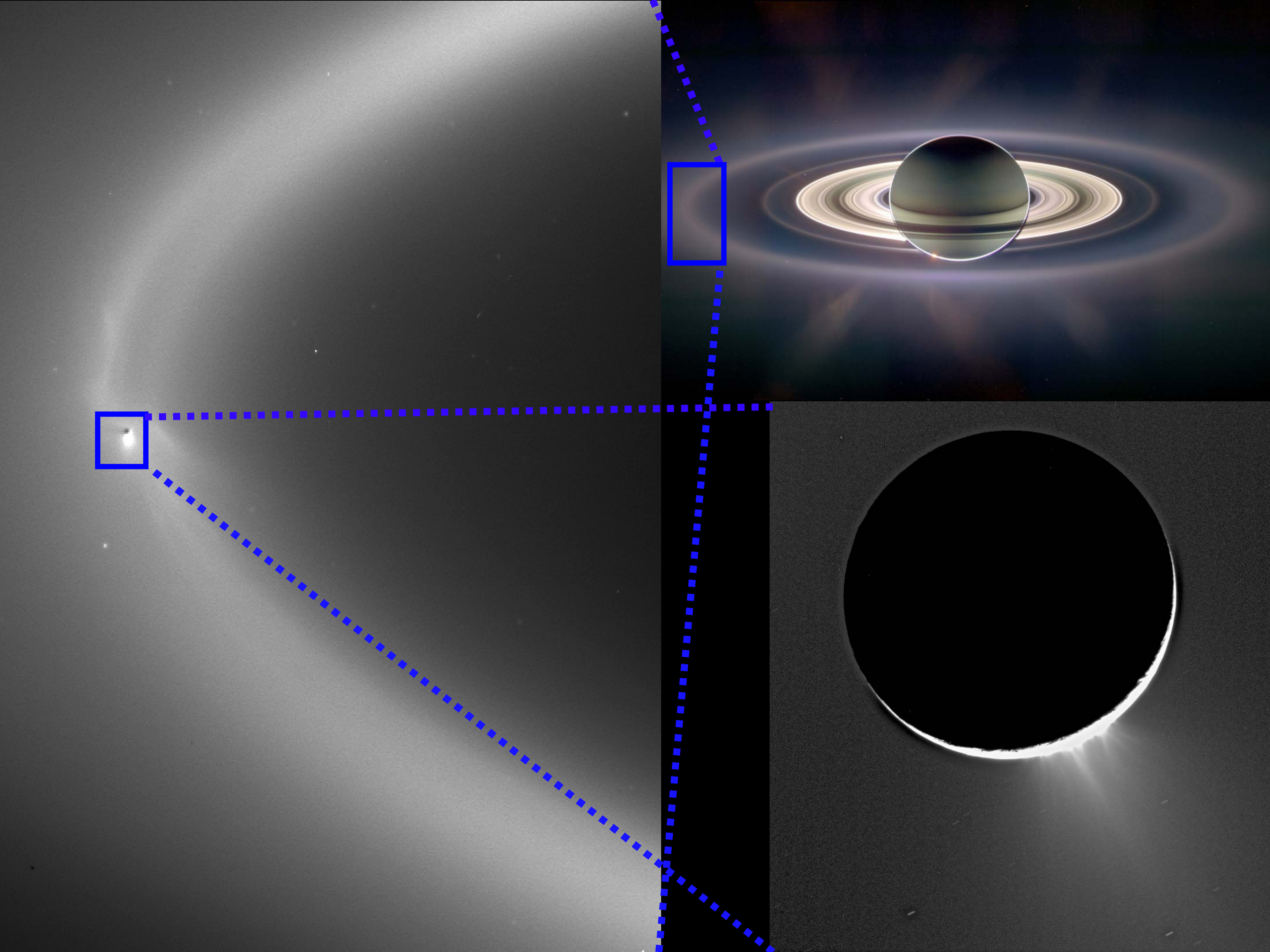
Frank Postberg[1,2]

&

The CDA Team

[1] Inst. f. Geoscience, Heidelberg University; [2] MPI f. Kernphysik, Heidelberg; Frank.Postberg@mpi-hd-mpg.de



Some Parameters

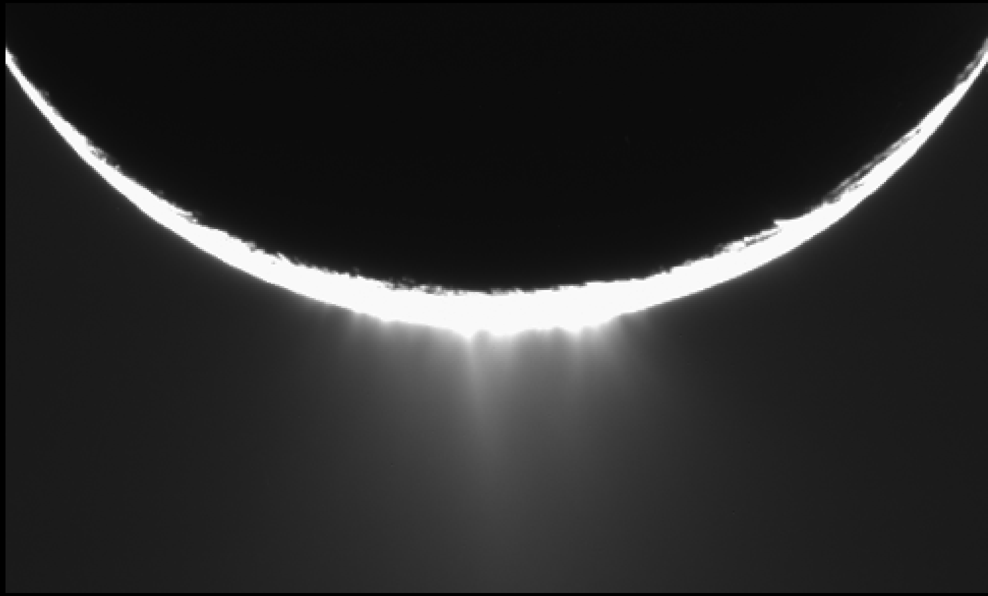
- Eff. Diameter: $D = 504$ km/s
- Density: $\rho = 1610\ kg/m^3$
- Surface Temp.: $T_{Aequator.} \approx 80K$

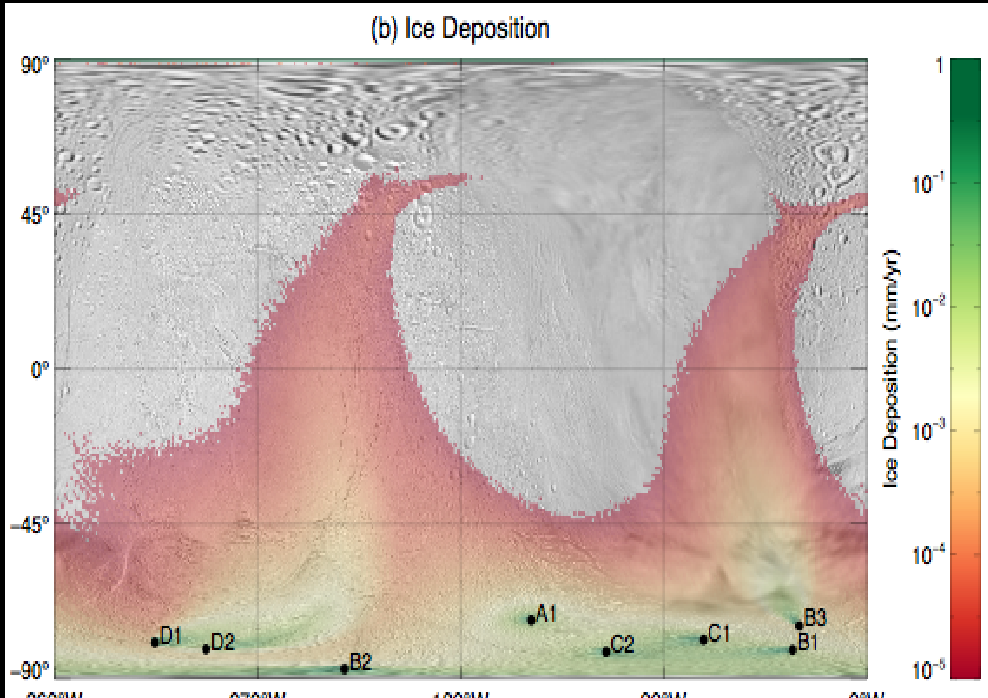
  $T_{Tiger\ Str.} \approx 180K$
- Production rate ≈ 200 kg/s Gas

  ≈ 20 kg/s Ice-dust
- Escape Speed: $V_{Escape} \approx 230 - 300$ m/s

  $V_{Gas} \approx 500$ m/s

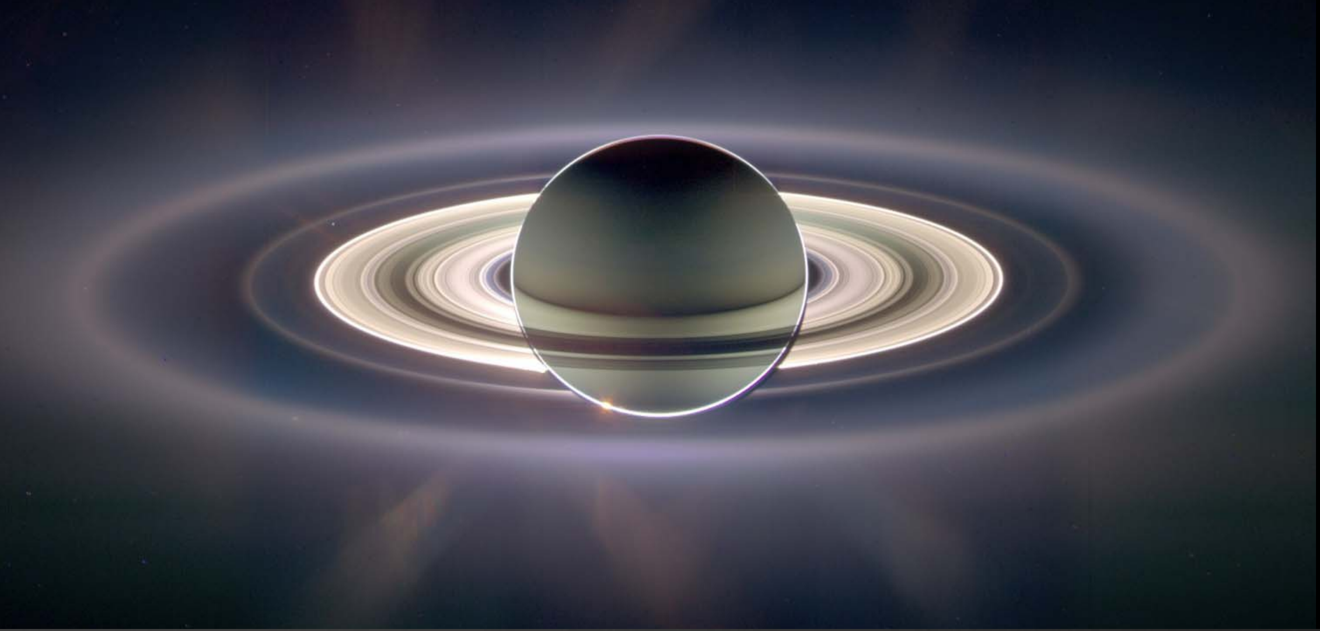
  $V_{Dust} \approx 150$ m/s
- Gas and particle flow are decoupled
- 1 - 5 % of the ice grains are emitted into the E-ring (0.2 – 1 kg/s)





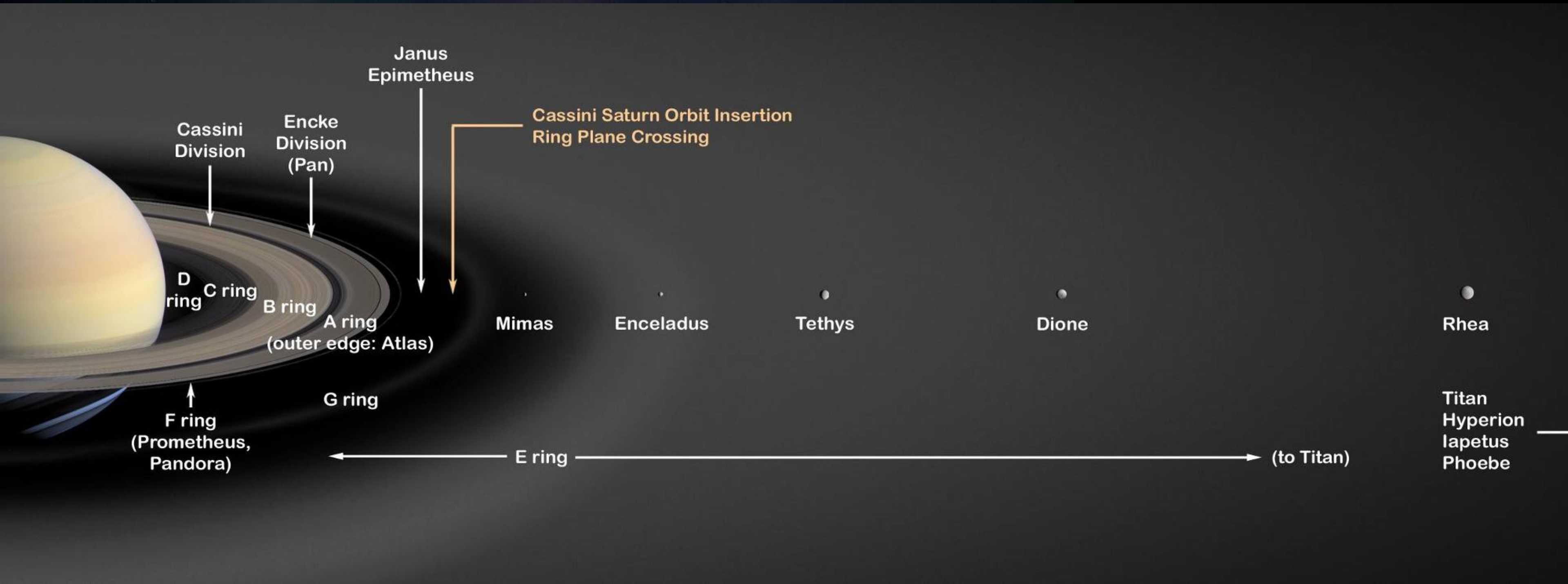
Kempf et al., Icarus 2009

- Saturn's E-ring, the largest known planetary ring



Cassini crosses the E ring in most of its orbits:

- In situ sampling of Enceladus' plume grains
- Excellent statistics
- Particle sizes 0.1 – 1.5 μm



- Why Sodium is important

- If liquid water on Enceladus is in contact with a rocky planetary core:

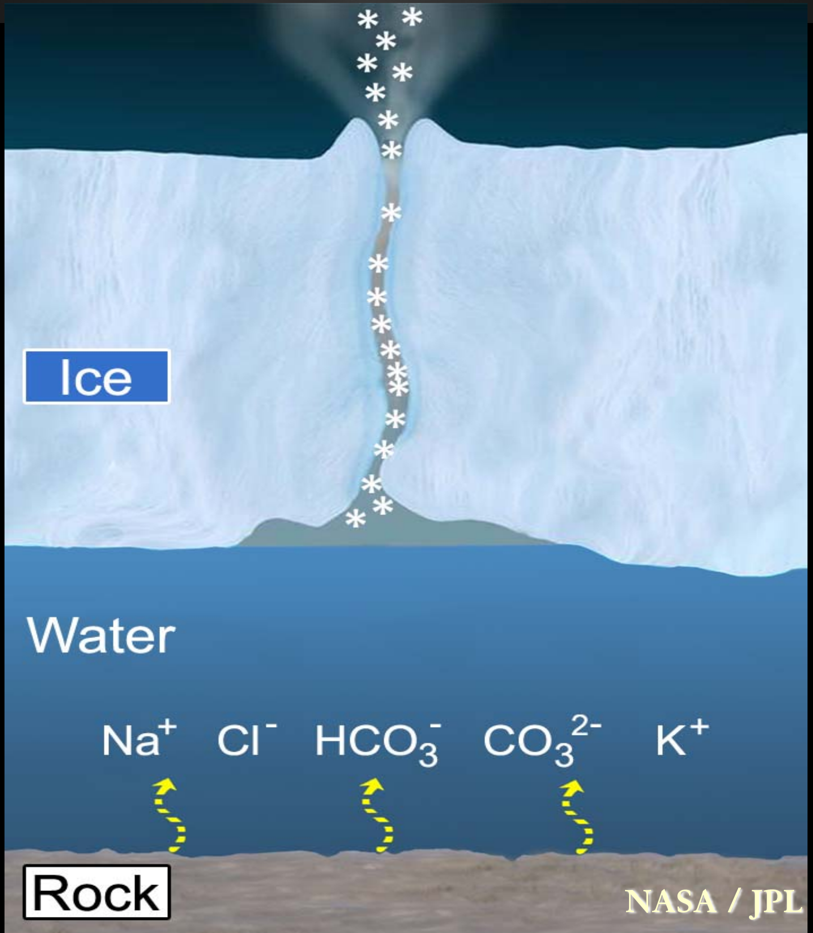
⇨ Na-salts are the major dissolved solids (Zolotov, 2007)

⇨ Na-salts doesn't stay in the ice during slow freezing (phase separation)

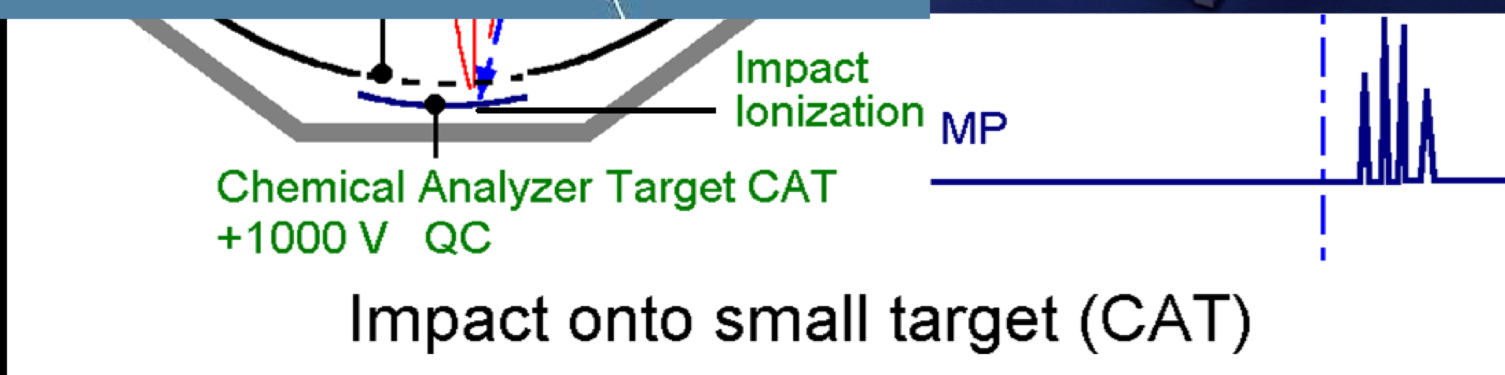
Na – detection

=

Litmus test for liquid water as plume source

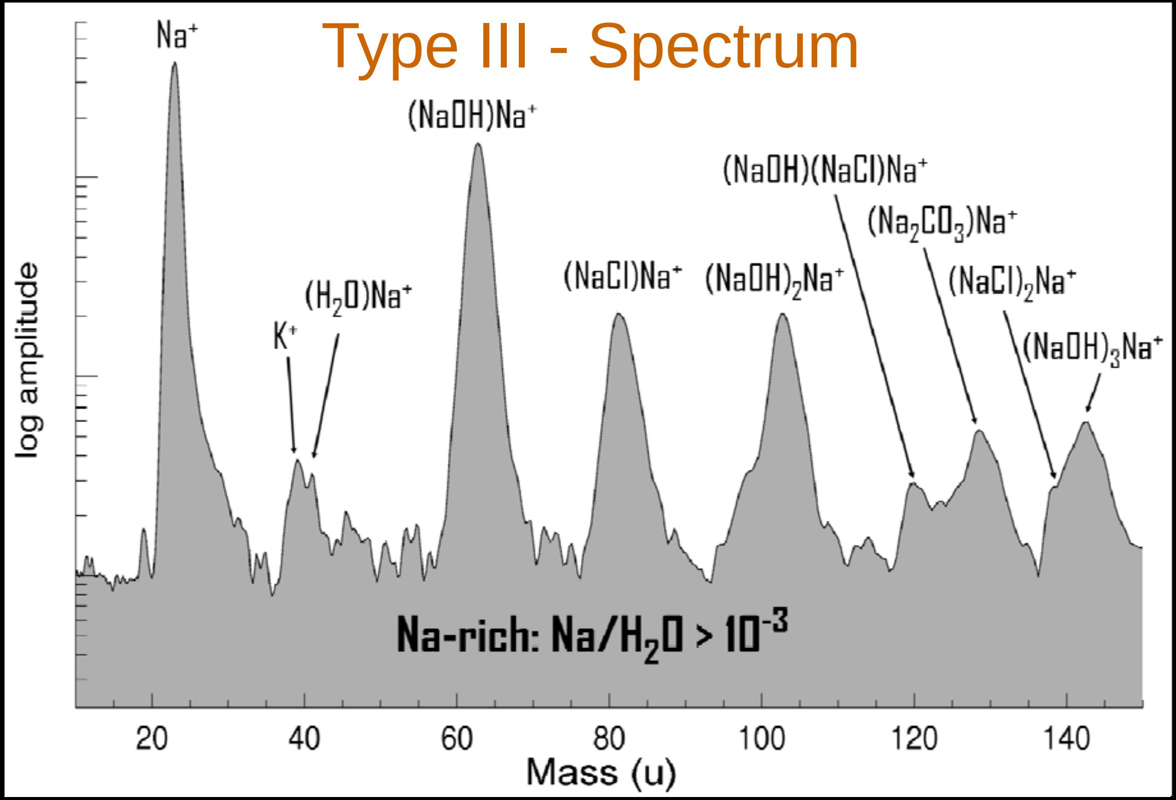


- Our detector: the Cosmic Dust Analyser (CDA)



Na-rich water ice

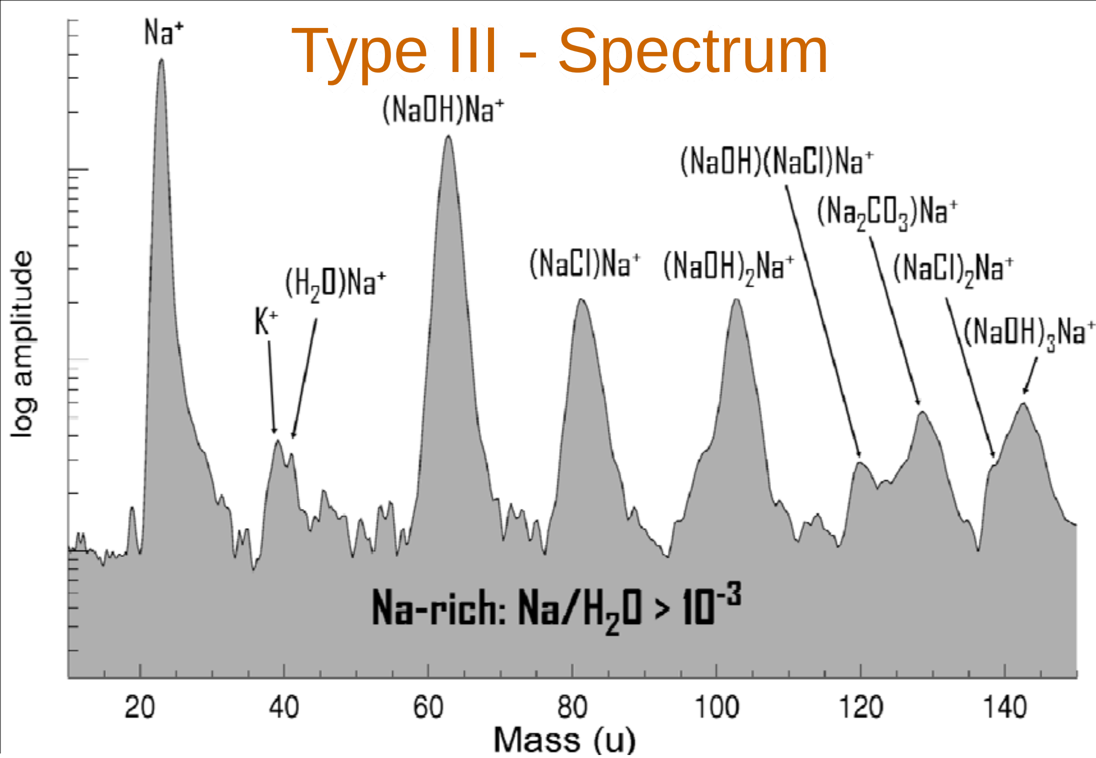
- ~ 6% of E ring ice particle spectra
- Na abundance far above level of possible instrument contamination

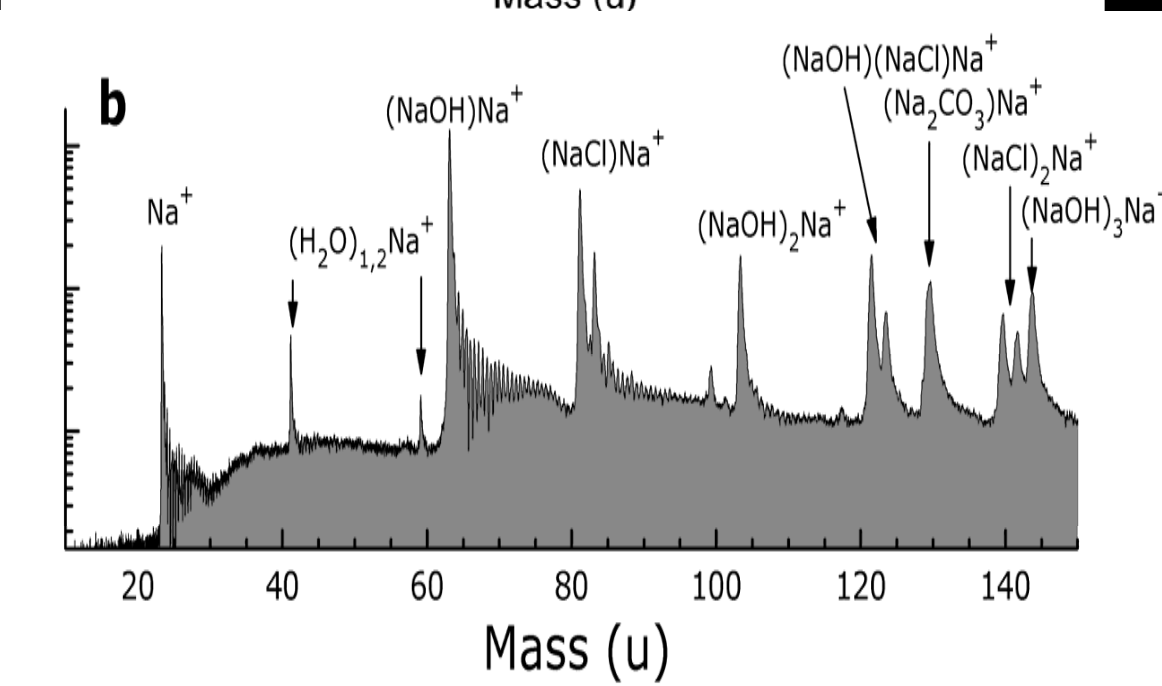


- $(NaOH)_nNa^+$ cluster prove alkaline water and high Na content ($Na/H_2O > 10^{-3}$)
- $(NaCl)_nNa^+$ and $Na(Na_2CO_3)$ Na^+ cluster:

⇨ NaCl , $NaHCO_3$ / Na_2CO_3 , minor K component

⇨ Compounds predicted to be most abundant in an Enceladus ocean (Zolotov, 2007)

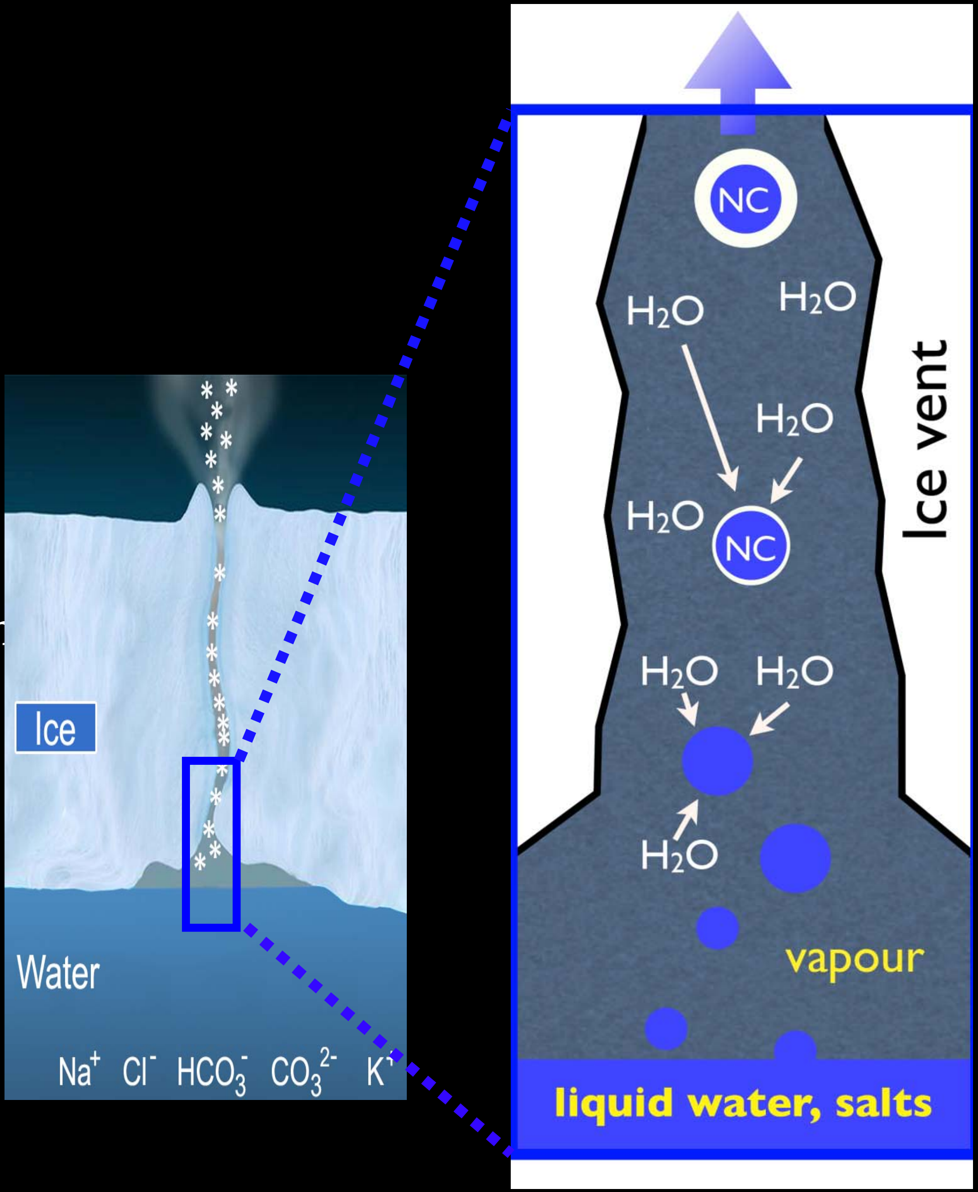




- **Reproducing CDA spectra in the laboratory**
  - No ice with embedded salt grains, but frozen saltwater.
- **Best agreement with**
  - NaCl: 0.1 - 0.2 M/l
  - $NaHCO_3$: 0.05 - 0.1 M/l
  - pH - value: ~ 9.0
  - Na/K: 100 - 200
- **Predictions for early Enceladus Ocean** (Zolotov, 2007)
  - NaCl: 0.05 - 0.1 M/l
  - $NaHCO_3$: 0.01 - 0.05 M/l
  - pH - value: 8 – 11
  - Na/K: 10 - 100

Na-rich grains by liquid dispersion

- Aerosol like droplets (sub-micron spray) form and freeze
- Salt content of the ocean water is preserved
- Rapid acceleration in the vent
- Condensation of additional water from the supersaturated water vapour



● How to create a spray of water droplets?

Turbulences are mandatory

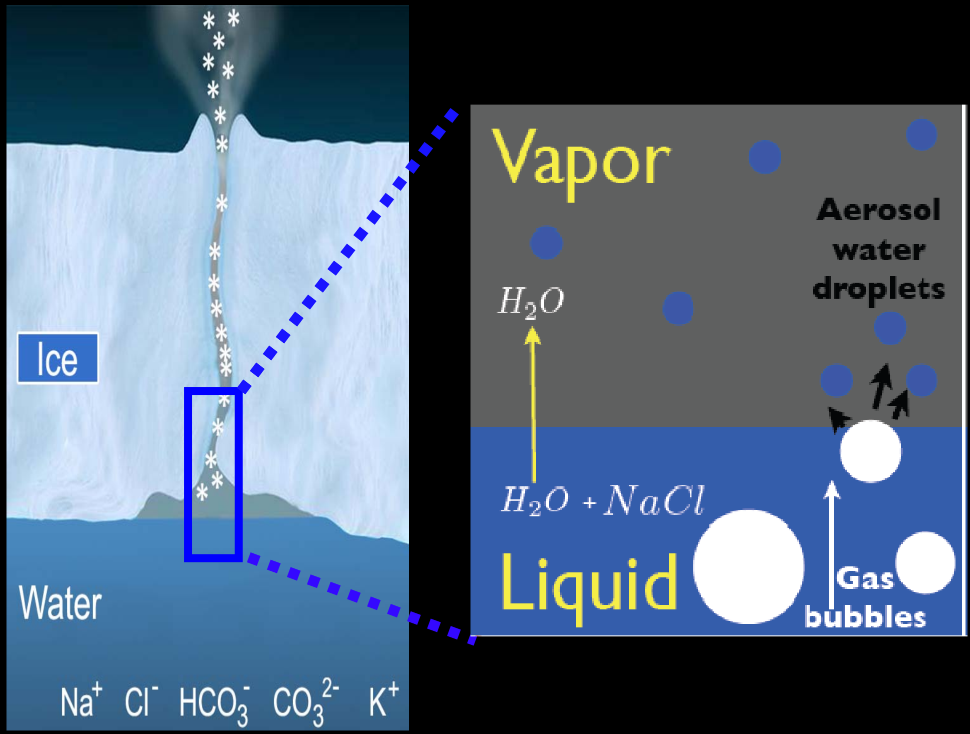
→ sizzling water from bubbles of up-streaming volatile gases → Cassini- INMS (Waite et al., 2009)

Possible sources:

- Dissolved bicarbonate: CO_2

- Clathrate decomposition at water/ice interface:

  CO_2 , CH_4, N_2 , NH_4 ,organic gas

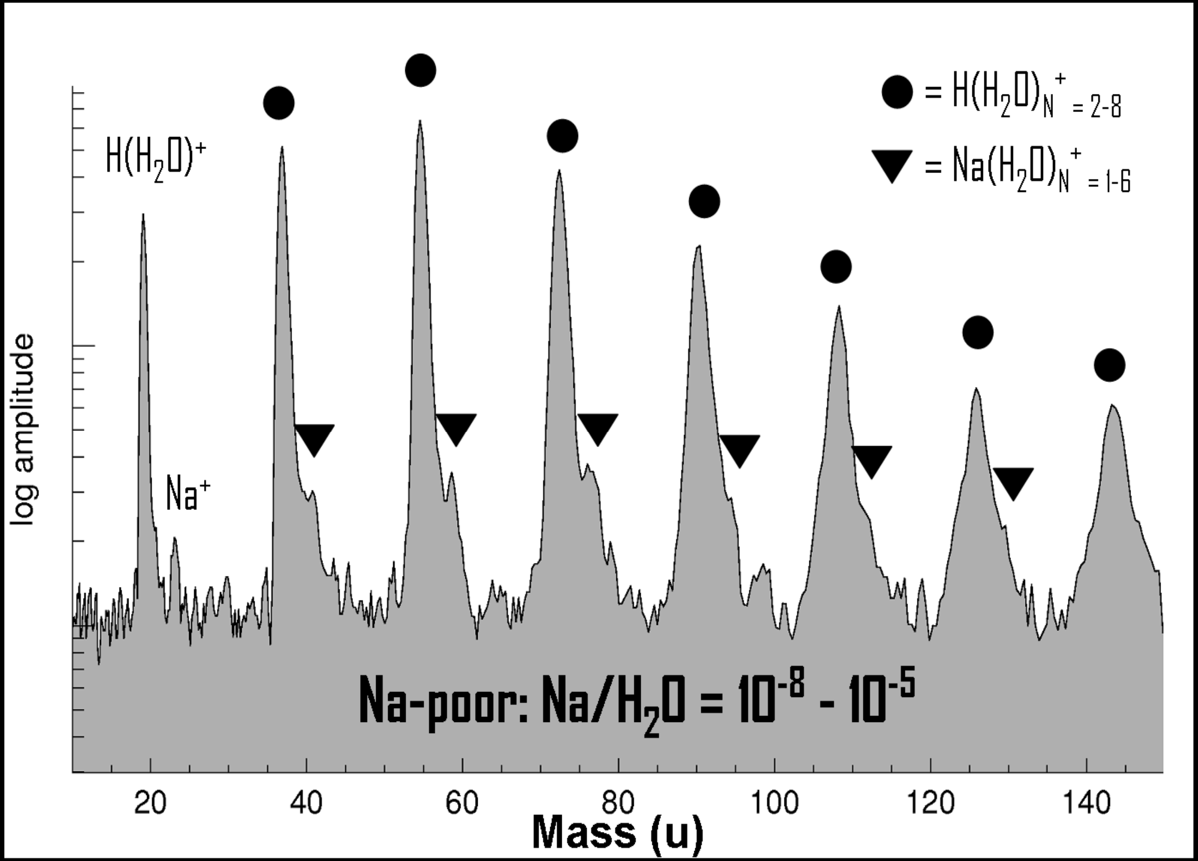


- Hydrothermal processes:

  N_2 , CH_4 , organic gases

Na-poor water ice (Type I+II)

- ~ 90% of E ring particle spectra
- $(H_2O)_nNa^+$ cluster prove water ice with low Na content ($Na/H_2O < 10^{-5}$)

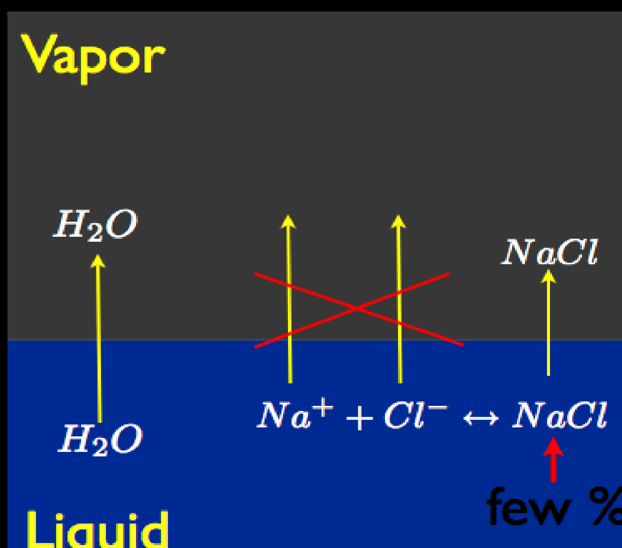


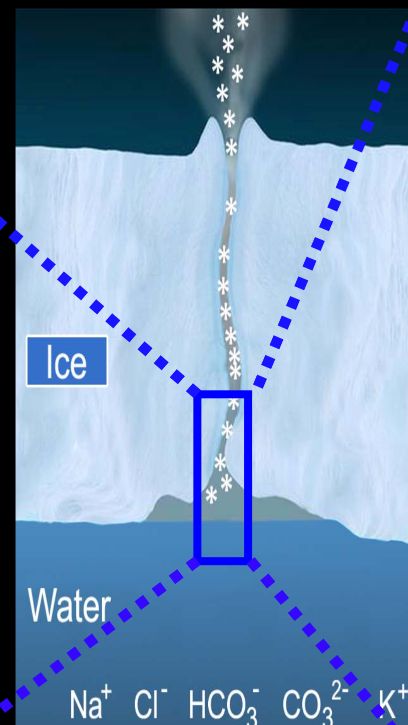
- Laboratory calibration experiments indicate $Na/H_2O = 10^{-7} - 10^{-9}$
- K minor component

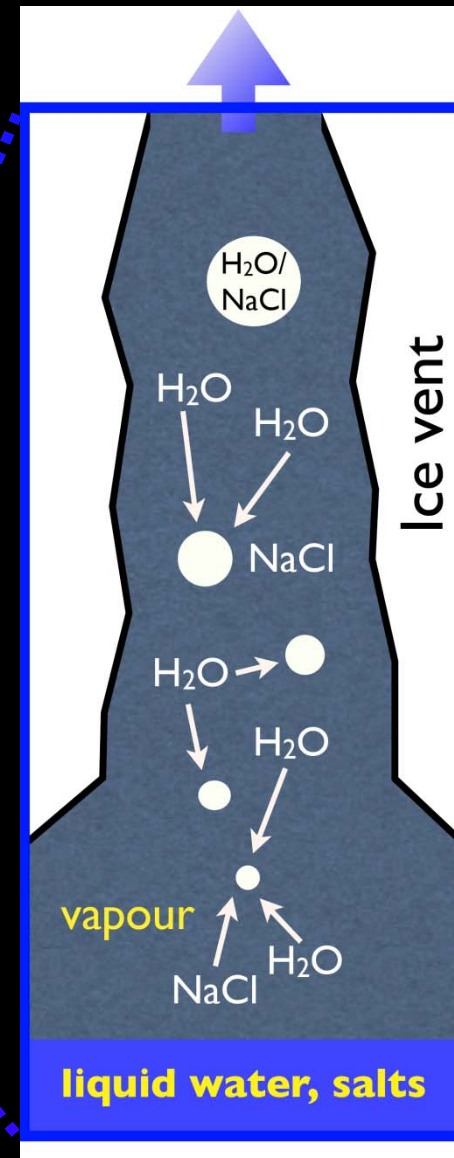
Na-poor grains by homogenous nucleation from vapour

- Water vapour above a salty liquid is heavily depleted in salt components

$$n_{gas}(NaCl) = n_{liquid}(NaCl)\ \exp\left[\frac{W_{sol}}{k_B T}\right]$$

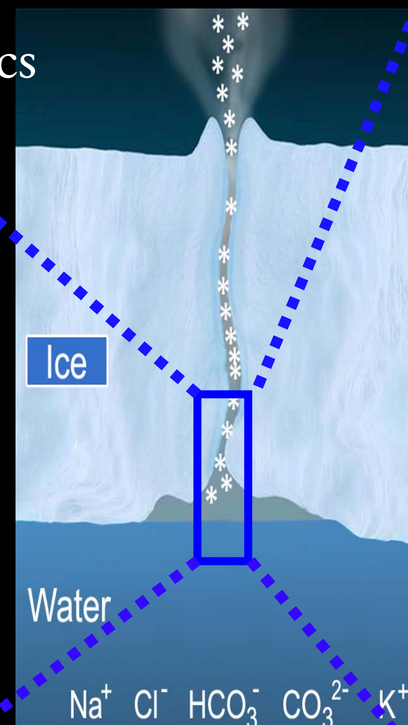


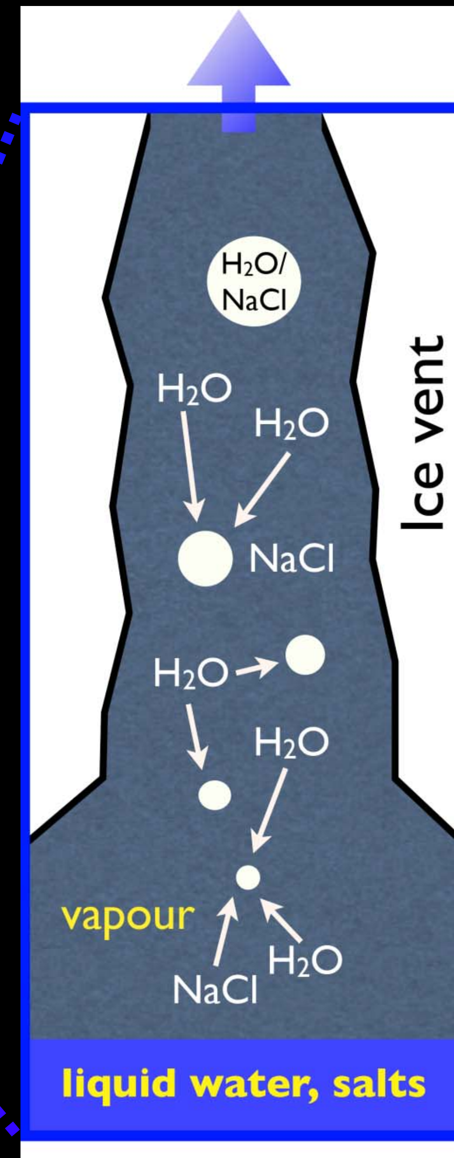




- Na-poor grains by homogenous nucleation from vapour

- Ice grains form from vapour when the gas is compressed (e.g. at nozzles in the vent)
- This has been modelled for Enceladus' vents and reproduces observed plume dynamics (Schmidt et al. 2008)





- Why not detected by other instruments ?

A) Direct detection of Na in plume vapour:

- Na concentration in the plume vapour ≤ Na-poor grains ($Na/H_2O \sim 10^{-7}$)

  ⇨ below detection limit of other instruments

B) Detection of Na from sputtered E ring grains:

- Average content in Na-poor (~90%) + Na-rich (~6%) E ring grain: $Na/H_2O \sim 10^{-4}$
- Enceladus Emission into E ring: ~ 0.5 kg/s ice grains ~200kg/s water vapour

  ⇨ Sputtered Na is diluted by a factor of ~ 400

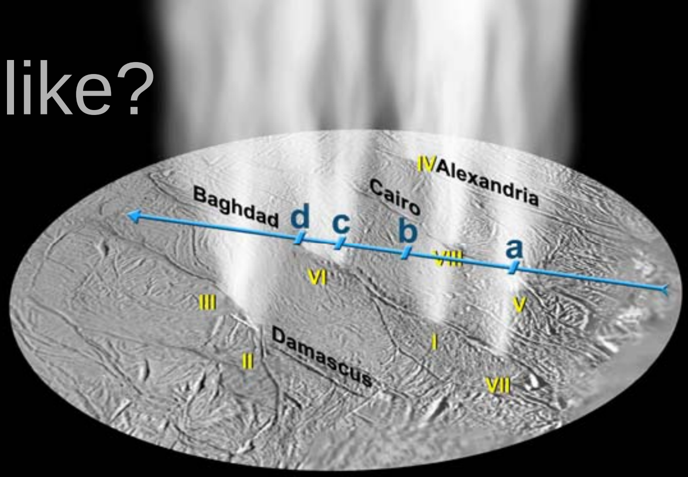
  ⇨ below detection limit of Earth bound spectroscopy (Schneider et al., 2009)

C) Detection of salts on Enceladus surface:

- Most ice grains fall back to the Tiger Stripes

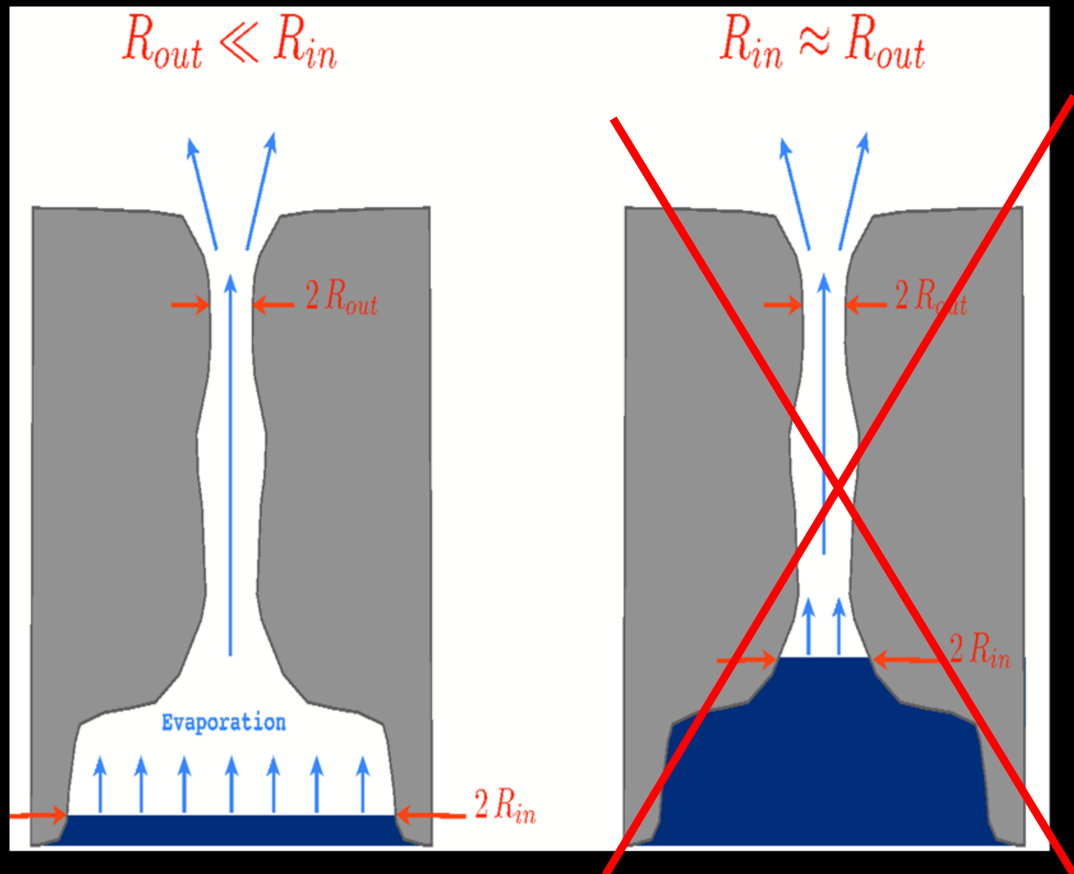
  ⇨ Deposition of Na-rich and Na-poor grains: $Na/H_2O \sim 10^{-4}$

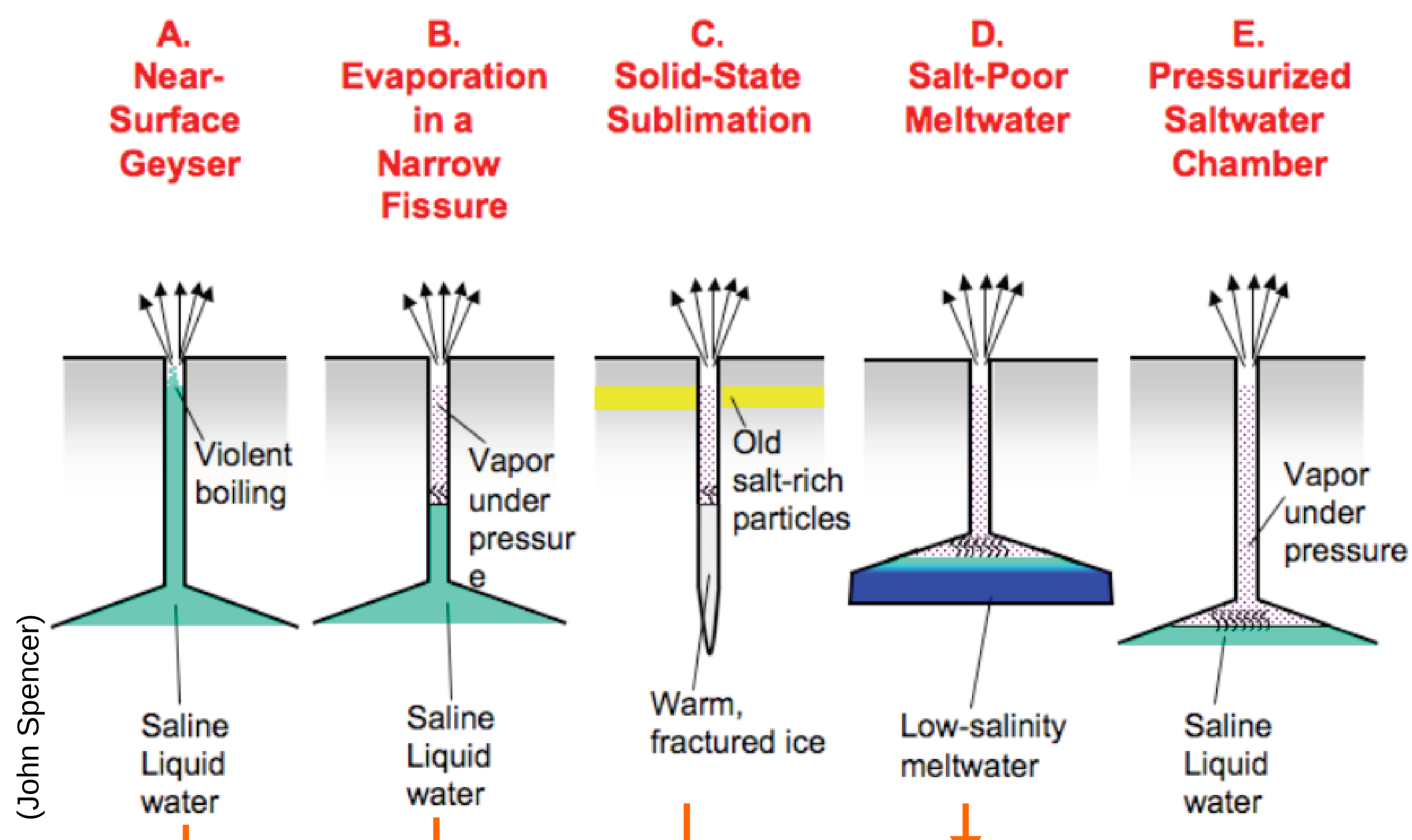
- How does the liquid reservoir look like?



- **Evaporation from liquid water:**
  - Evaporation of 200 kg/s cools the water surface
  - To avoid freezing due to latent heat:

    $\rightarrow$ **$R_{out} << R_{in}$**
  - **R_{out} ~ 1 m**
  - Exact surface area depends on amount of convection in reservoir
  - 1 km^2 < A_{in} < 10,000 km^2



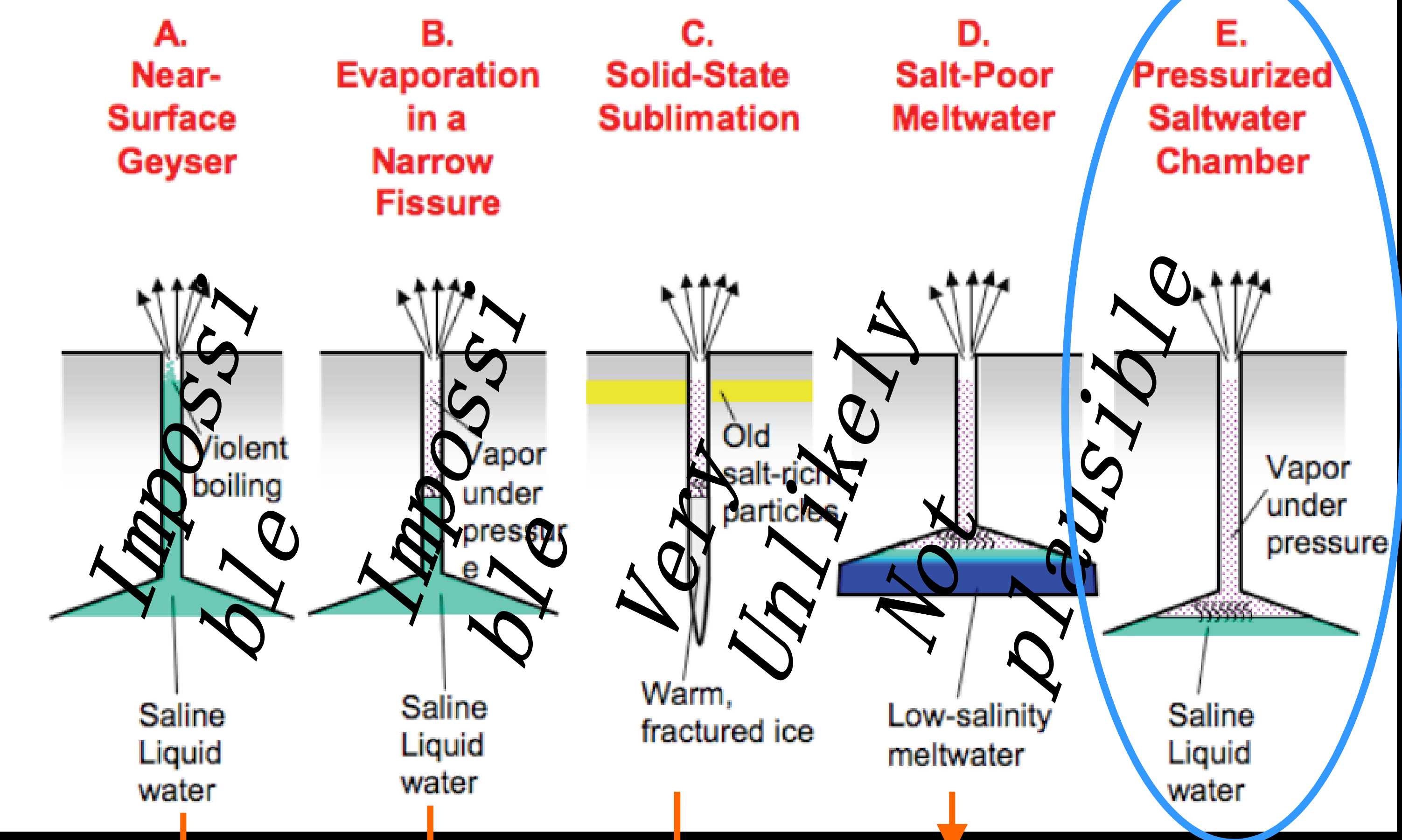


Upper part of liquid enriched by salt evaporation?
- Diffusion would rapidly smooth salinity gradient

Ice fracture crosses salty ice layer (frozen from ancient ocean?)
- Self limiting process: salt-near the crack soon exhausted
- Geophysically unlikely

- Heat flow problem: vents would rapidly freeze

- Self limiting process: Cannot maintain observed steady jets
- Would expell sodium with liquid: Not seen by KECK
- Would create only Na-rich grains: Not observed by CDA



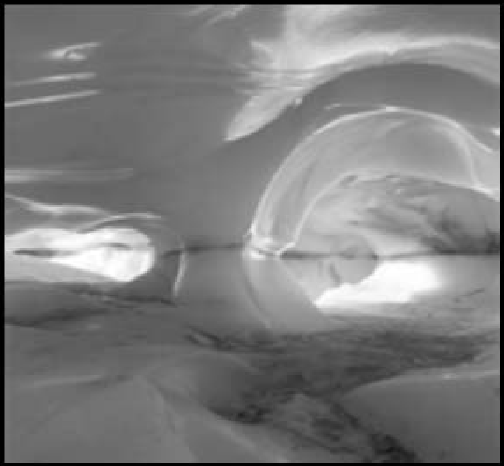
- Large liquid/gas interface
- Gas-flow back-pressure in cracks
- Supersaturated gas (Na-poor grains)
- Na-rich grains from aerosols above liquid
- Good agreement with prediction for ocean composition
- Consistent with KECK non-detection of Na

Upper part of liquid enriched by salt evaporation?
- Diffusion would rapidly smooth salinity gradient

Ice fracture crosses salty ice layer (frozen from ancient ocean?)
- Self limiting process: salt-near the crack soon exhausted
- Geophysically unlikely

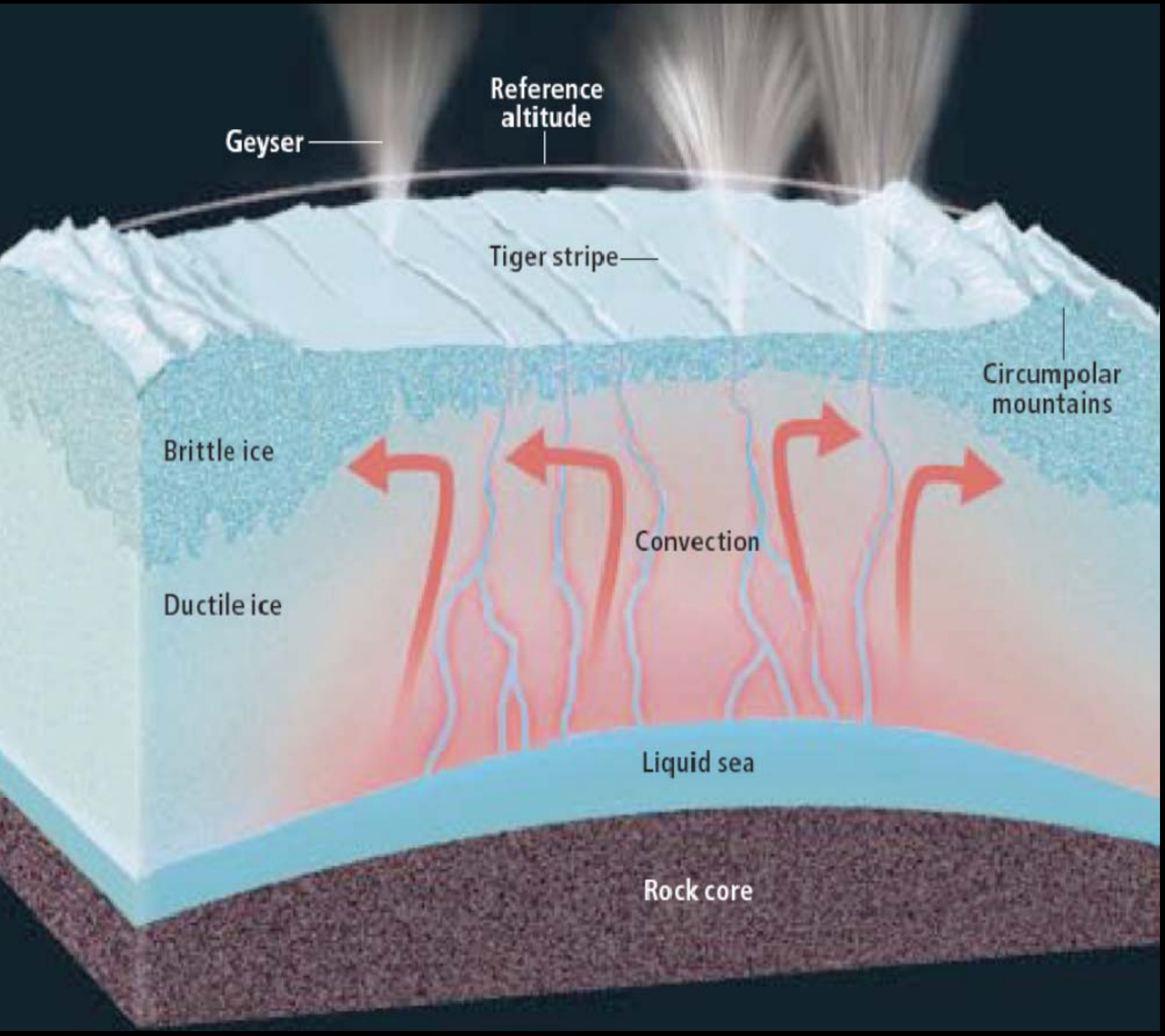
- Heat flow problem: vents would rapidly freeze

- Self limiting process: Cannot maintain observed steady jets
- Would expell sodium with liquid: Not seen by KECK
- Would create only Na-rich grains: Not observed by CDA



- Multiply connected archings and pillars ?
- 1.2 % Earth's gravity → No principal stability problem

Plume Reservoir = Ocean ?



Salt-ice grains:

- Reservoir is (or has been) in enduring contact with rock.

Geophysical stability:

- ‚Stable' cracks cannot go deeper than few kilometers = maximum depth of water surface

Three principal models:

a) Large & deep (60 km) ocean under thin ice crust

b) Small isolated salt water pockets (V > 1 km³)

c) Shallow ocean which supplies plume reservoir(s) → Figure

But:

- NO geysers! Better: jets
- NO water surface in narrow ice channels

Summary I

- Na-rich E ring ice grain population
  - ~ 6 % of E ring particles
  - Main sodium bearing compounds are NaCl and Na-(bi)carbonate (“Soda”
  - K salts minor component
  - Total salinity ~0.5 - 2 % ($Na/H_2O > 10^{-3}$), alkaline pH

  ⇨ not consistent with a clathrate decomposition model

  ⇨ not consistent with ice sublimation model

  ⇨ very good agreement with liquid water in contact with rocky core

- Na-poor E ring ice grain population
  - ~ 90 % of E ring particles
  - $Na/H_2O = 10^{-5} - 10^{-9}$

  ⇨ good agreement with liquid water vapour above salty liquid

Summary II

- Two particle formation processes likely
  - Na-rich: direct freeze out of submicron ocean water droplets
  - Na-poor: nucleation of salt-depleted water vapour (Schmidt et al. 2008)

- Results in agreement with Na non-detection by spectroscopy (Schneider et al., 2009)

- Evaporation from liquid requires large water surfaces
  - No violent boiling of near surface geysers
  - More likely: evaporation into vapour chambers which narrow down to cracks

- Connection to large Ocean? Three principal possibilities:
  - Large & deep (60 km) ocean under thin ice crust
  - Small isolated salt water pockets ($V > 1\ km^3$)
  - Shallow ocean which supplies plume reservoir(s) → Most plausible

… at the moment …