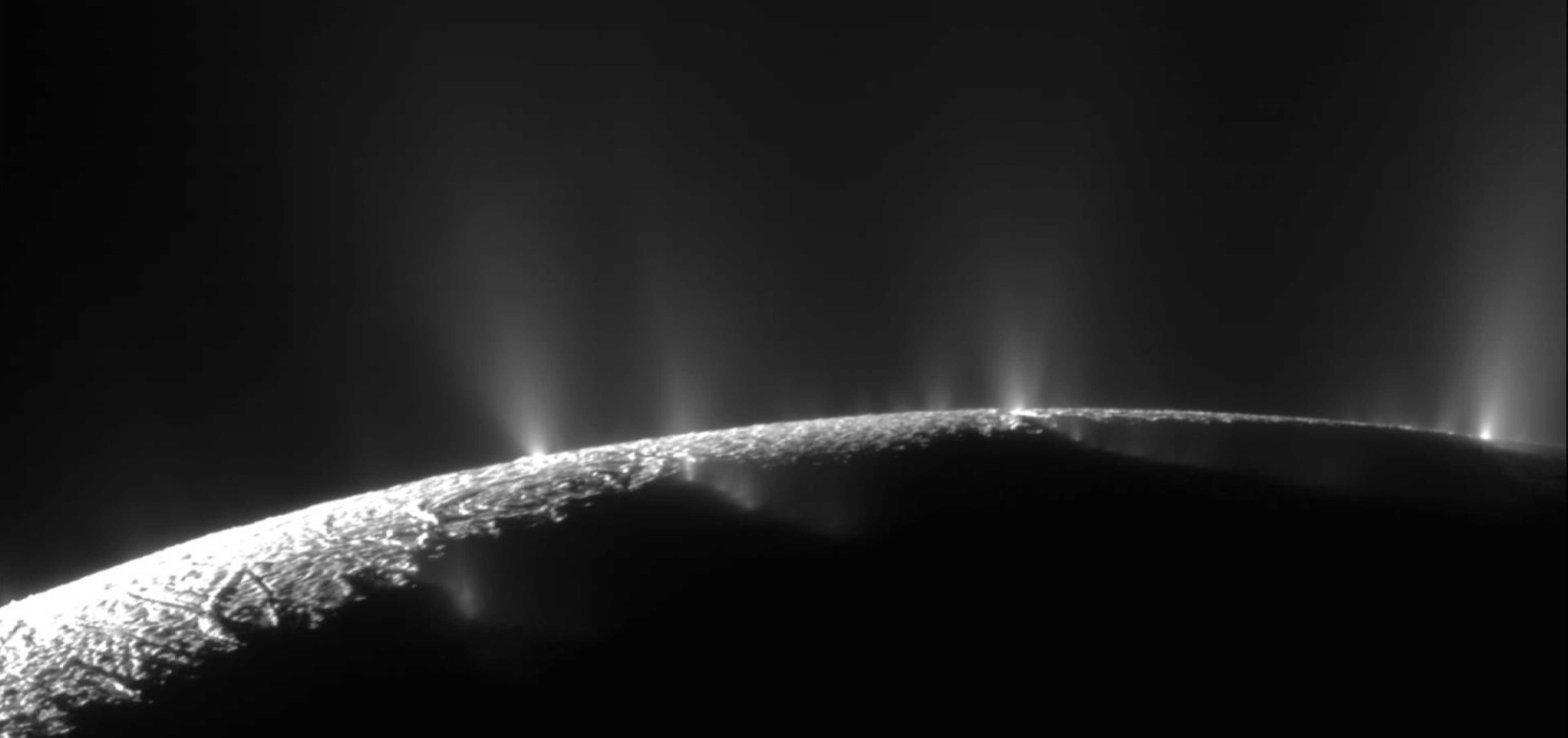
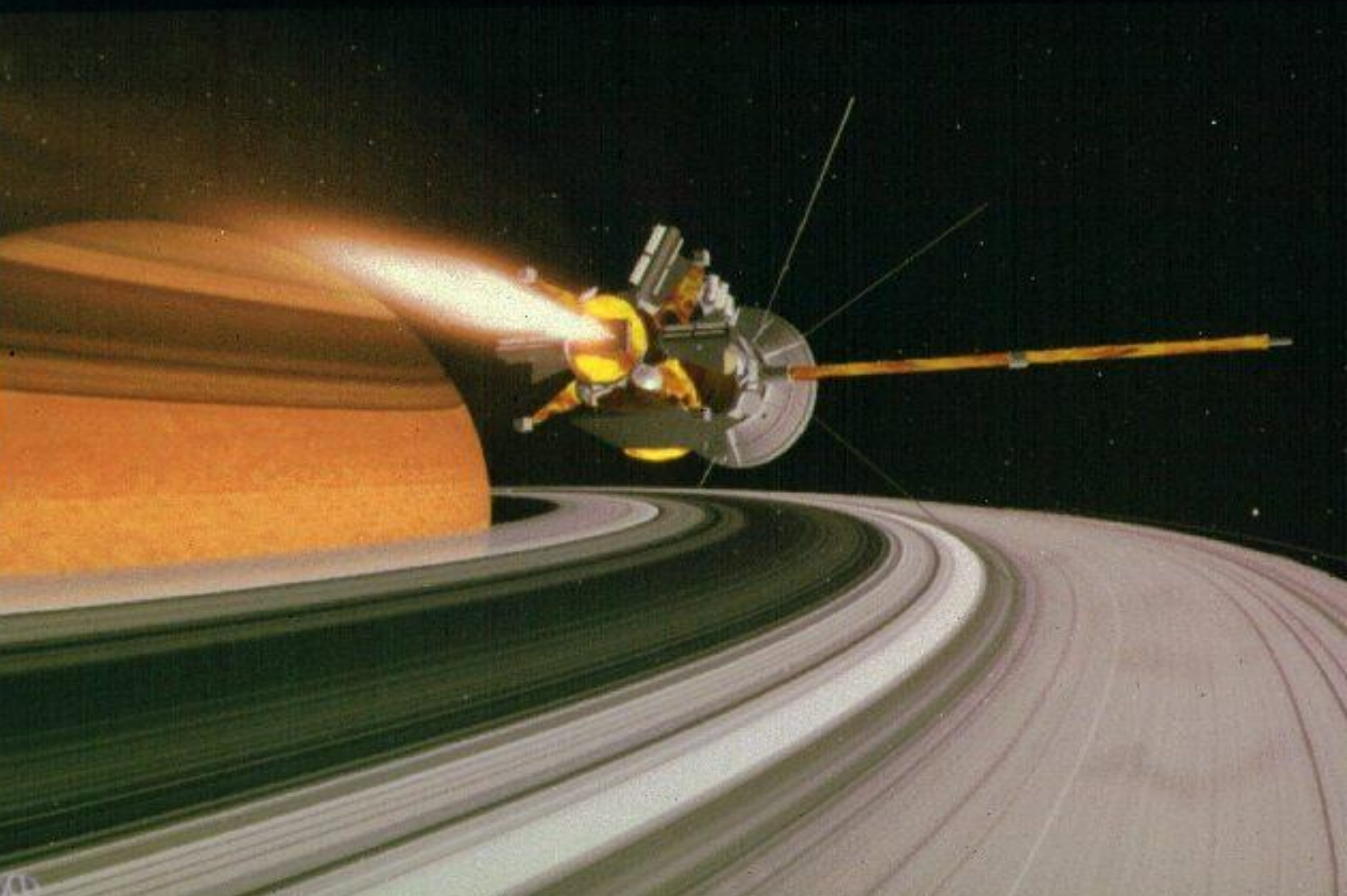
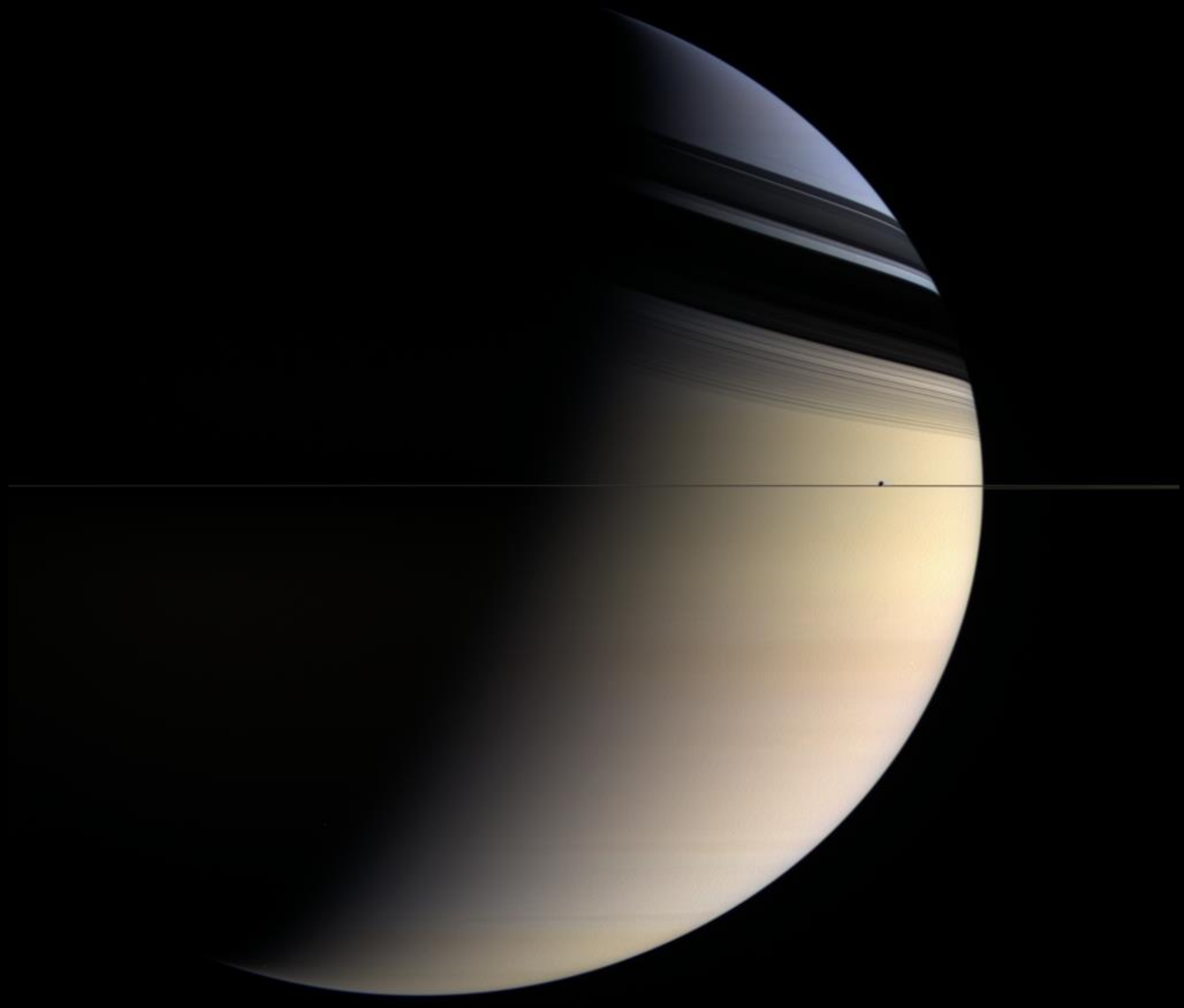
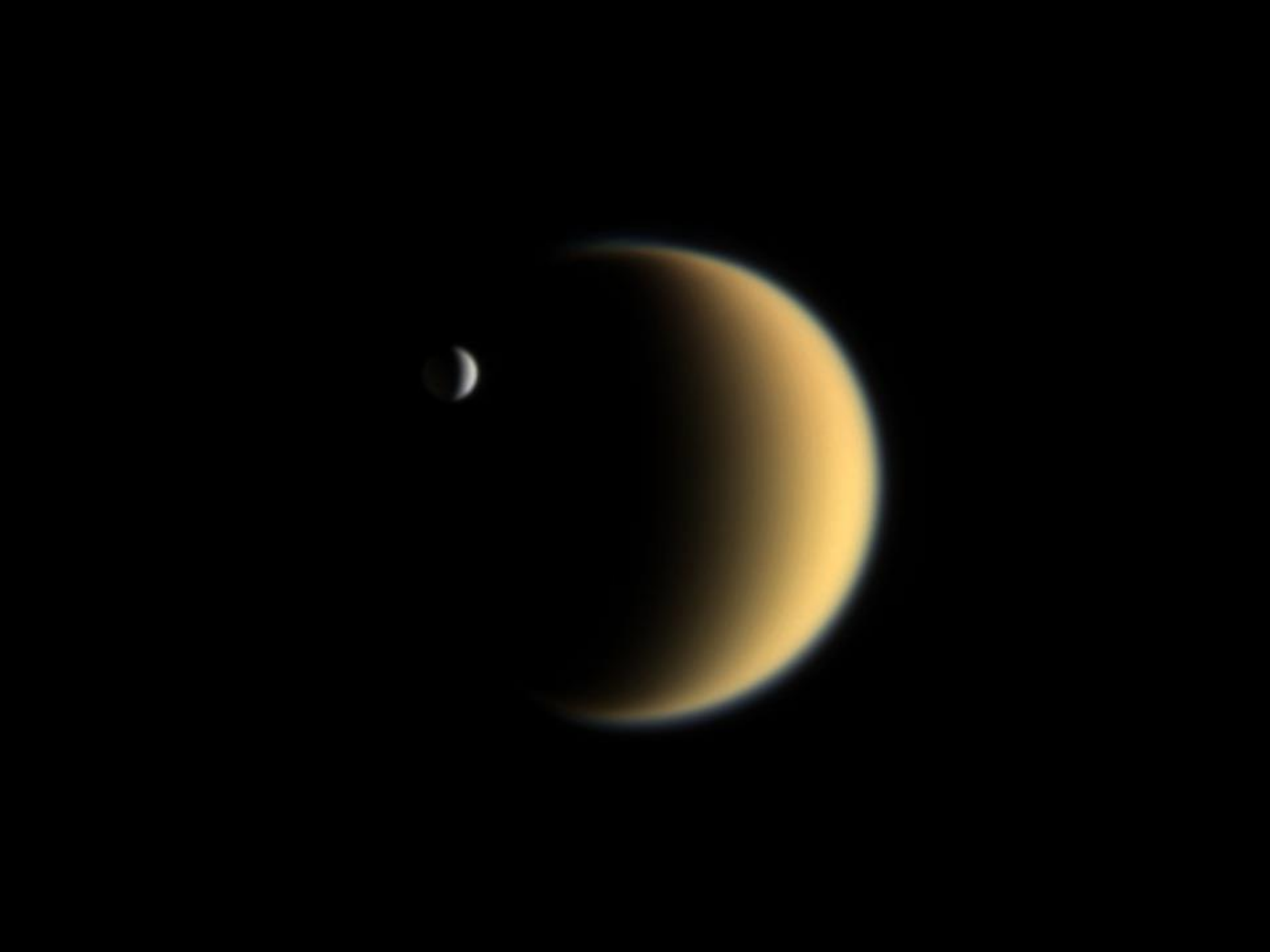
Case for Enceladus

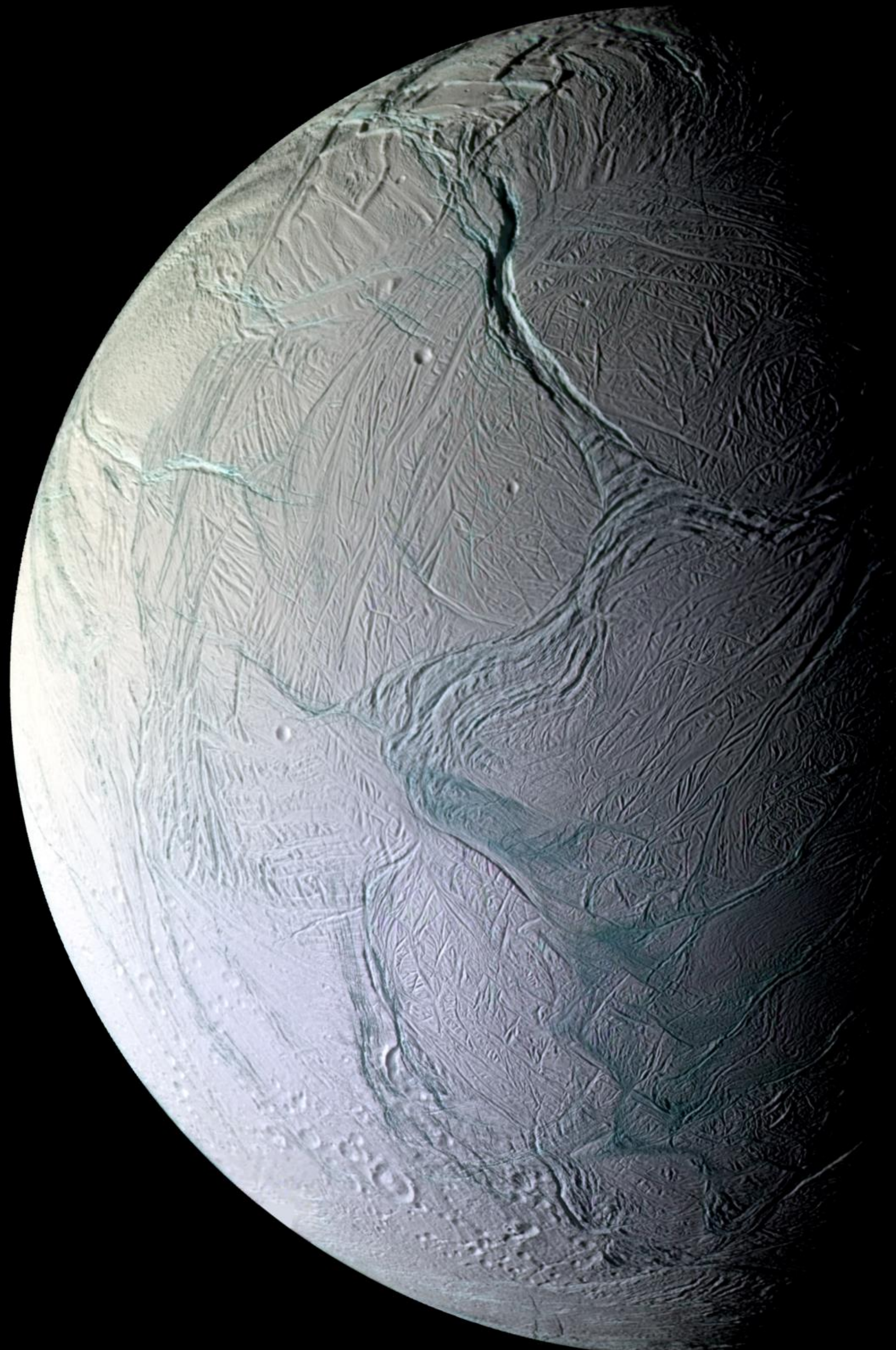
Carolyn Porco

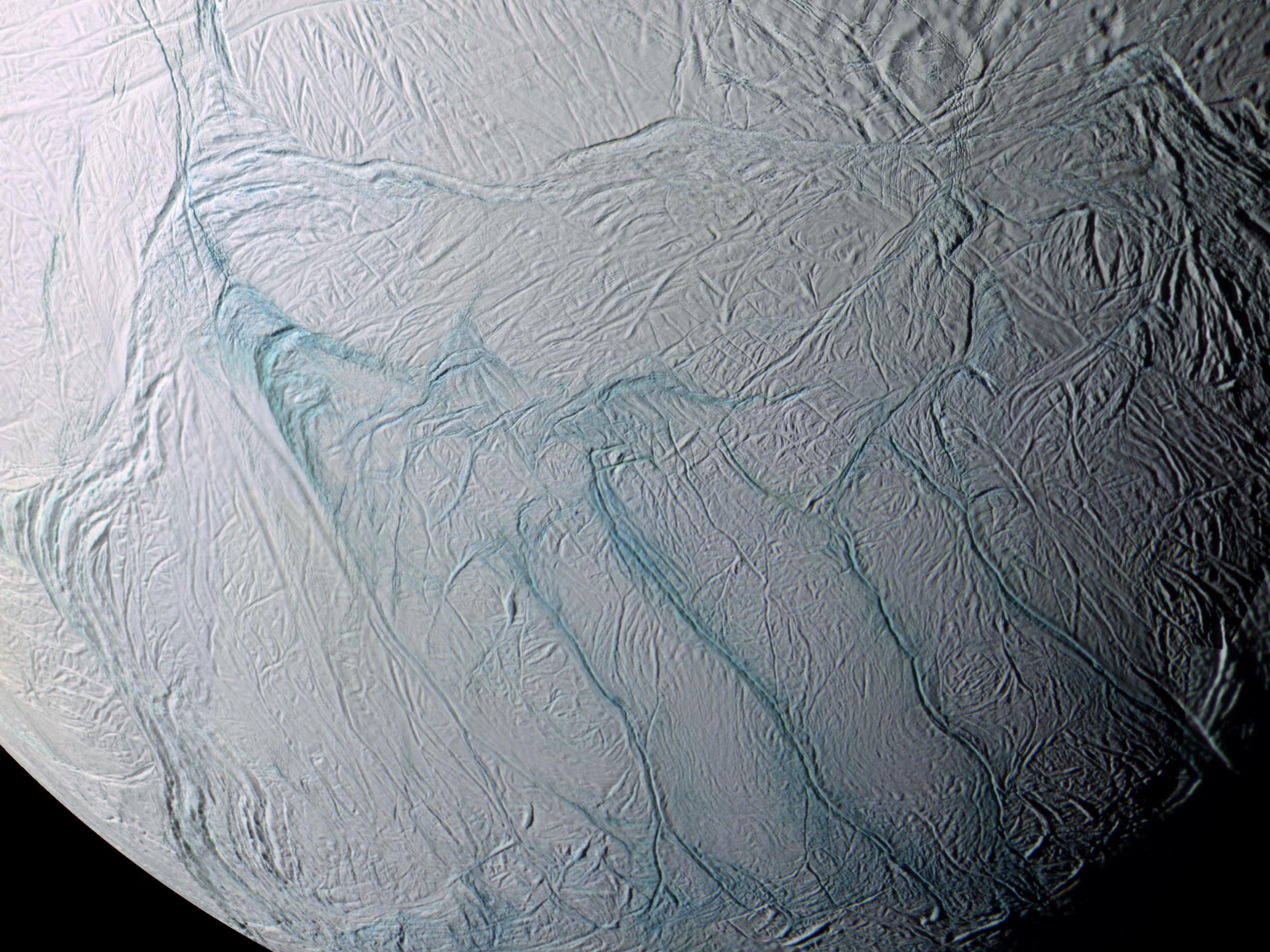


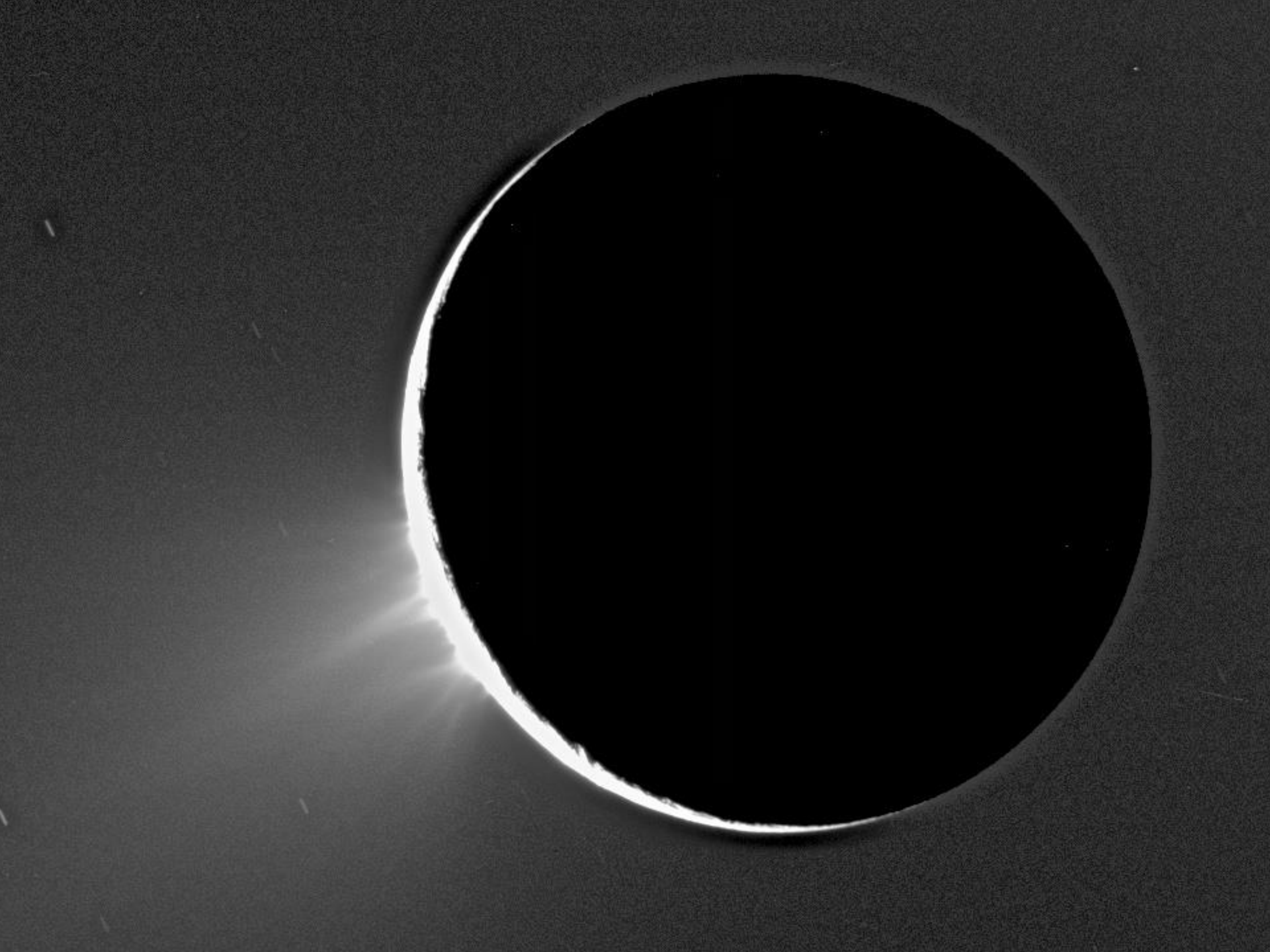


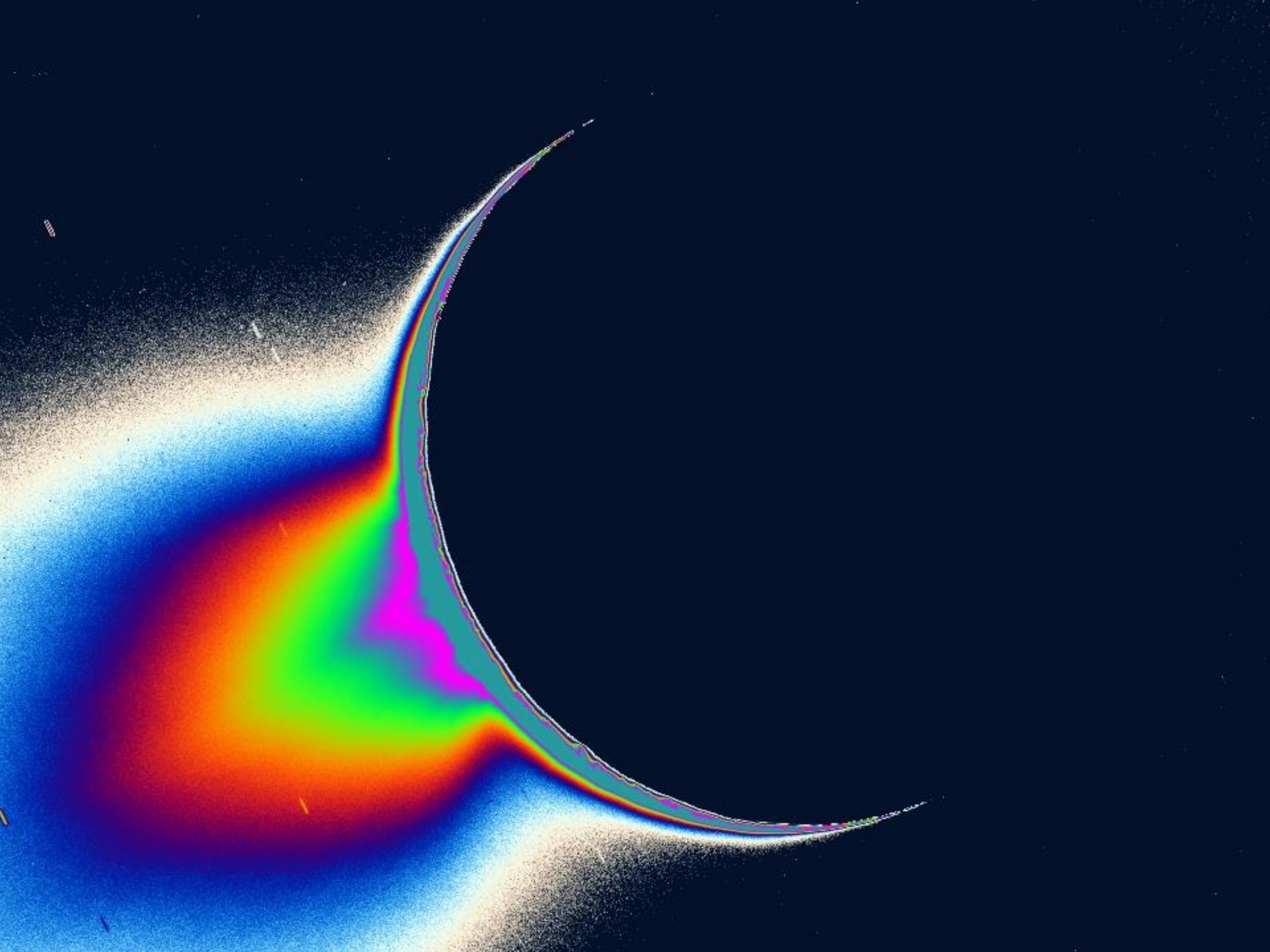






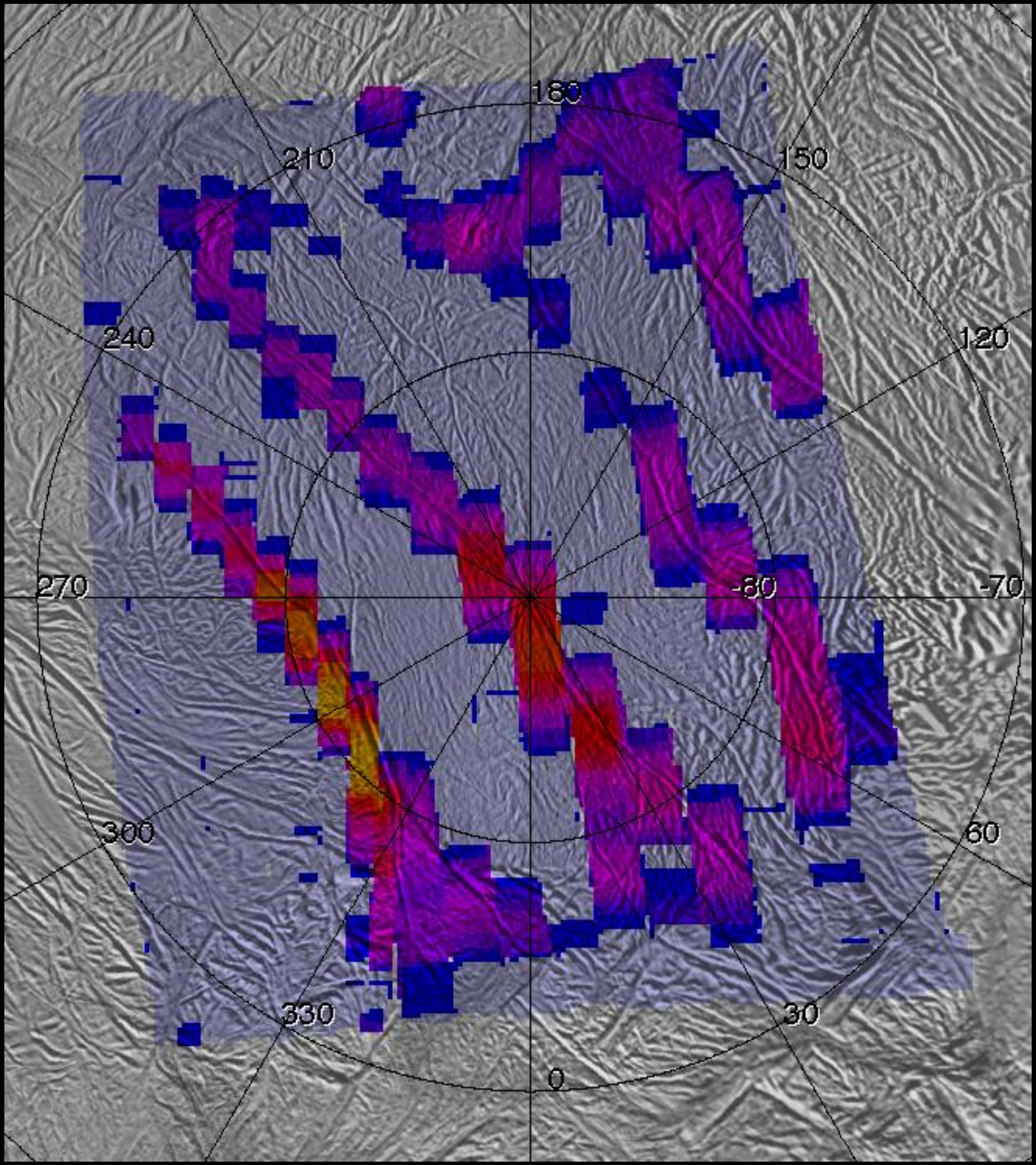






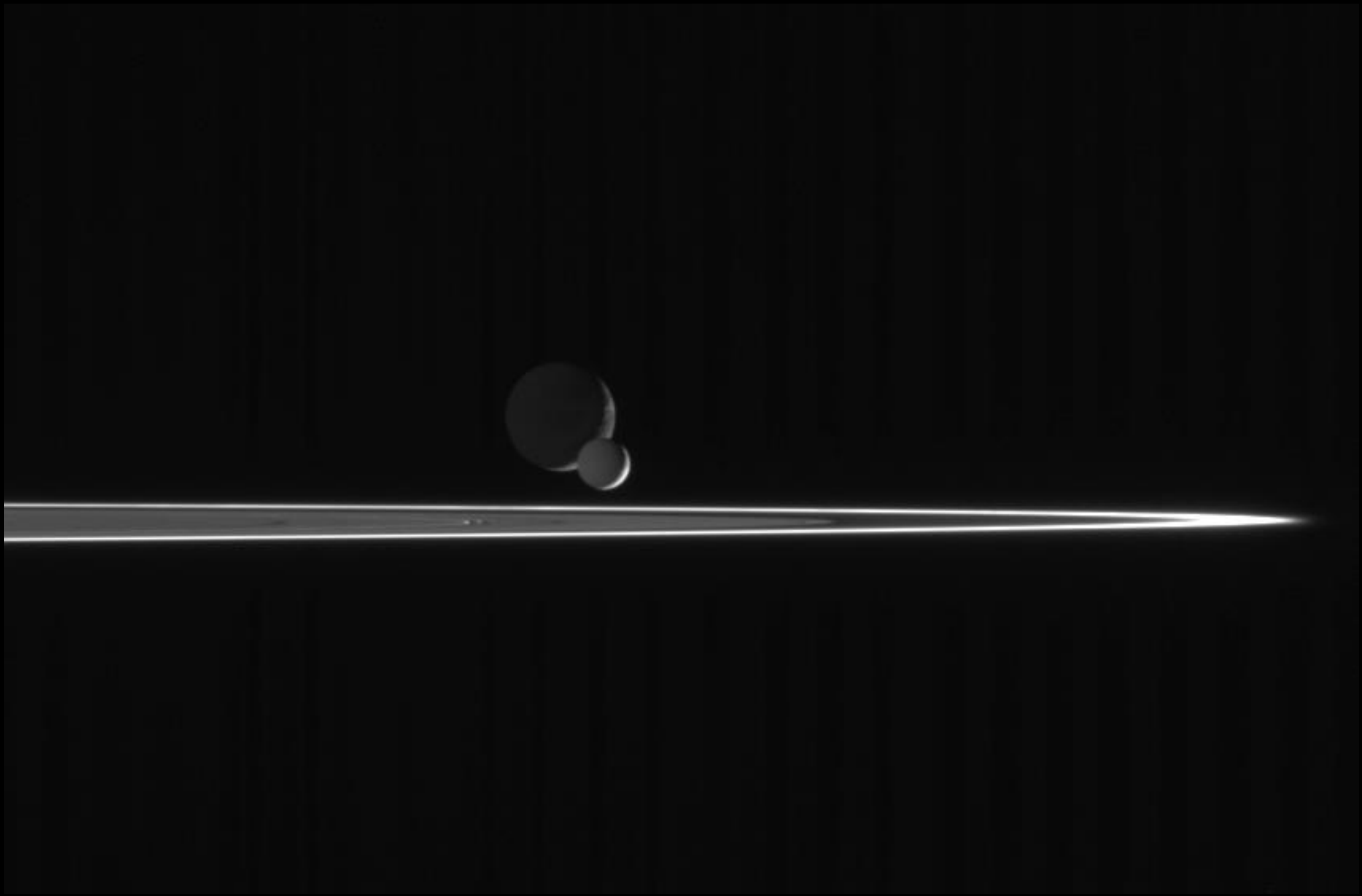
Thermal Radiation

(Howett et al 2011)



Total measured excess radiation from the fractures: ~ 4 GW

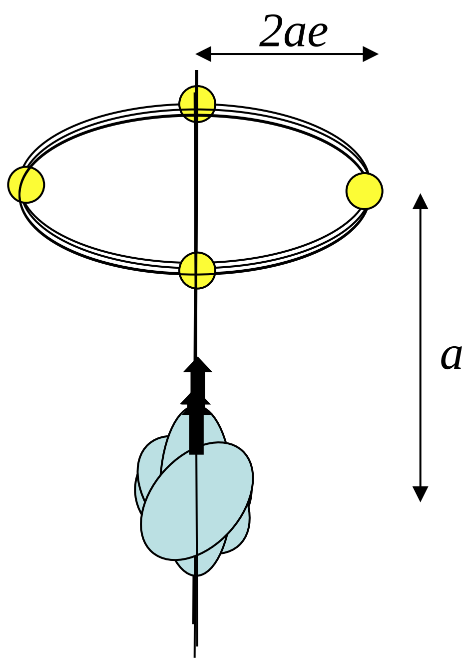
Still not clear how much is arising in between the fractures



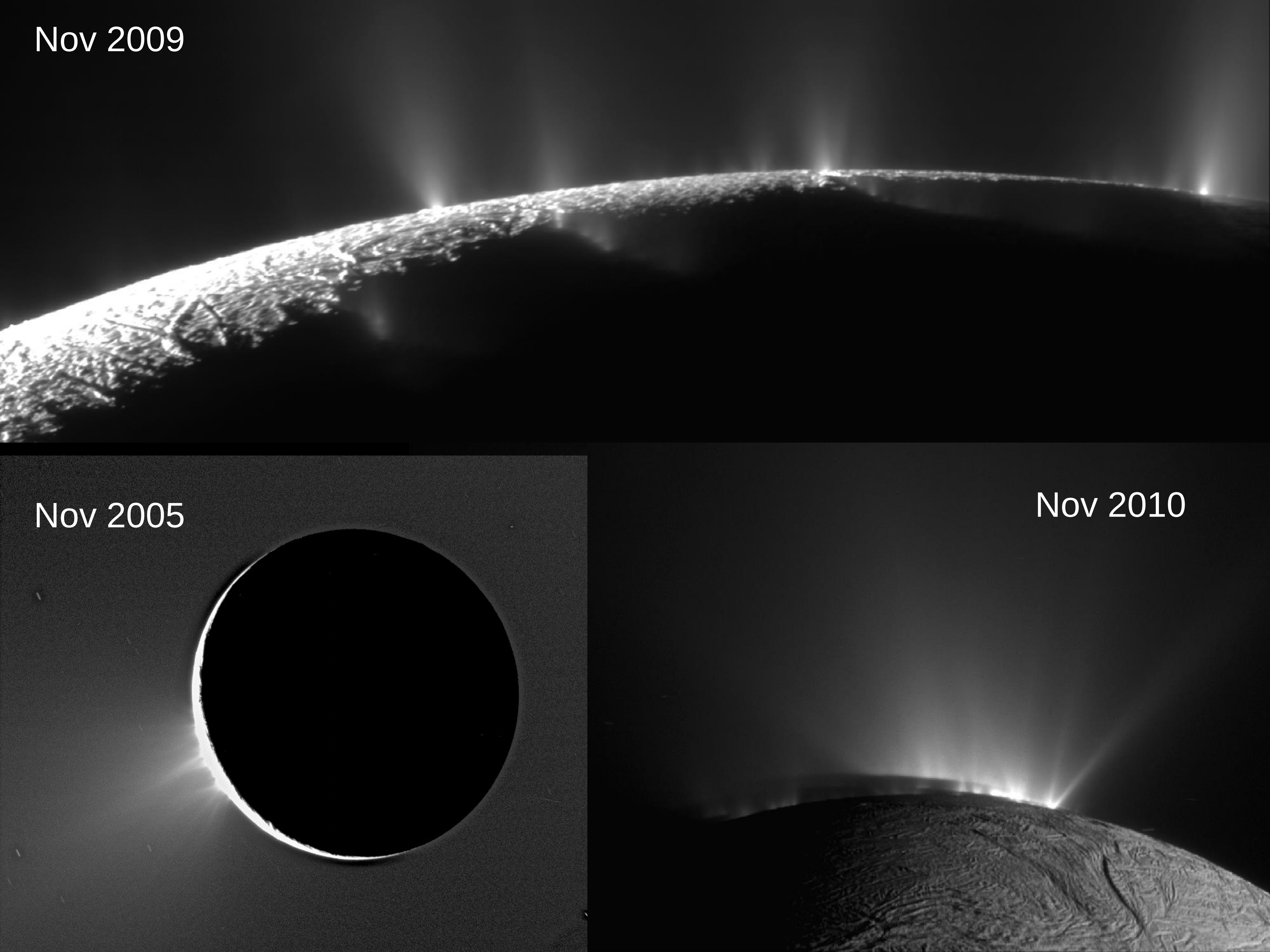
Diurnal Tides

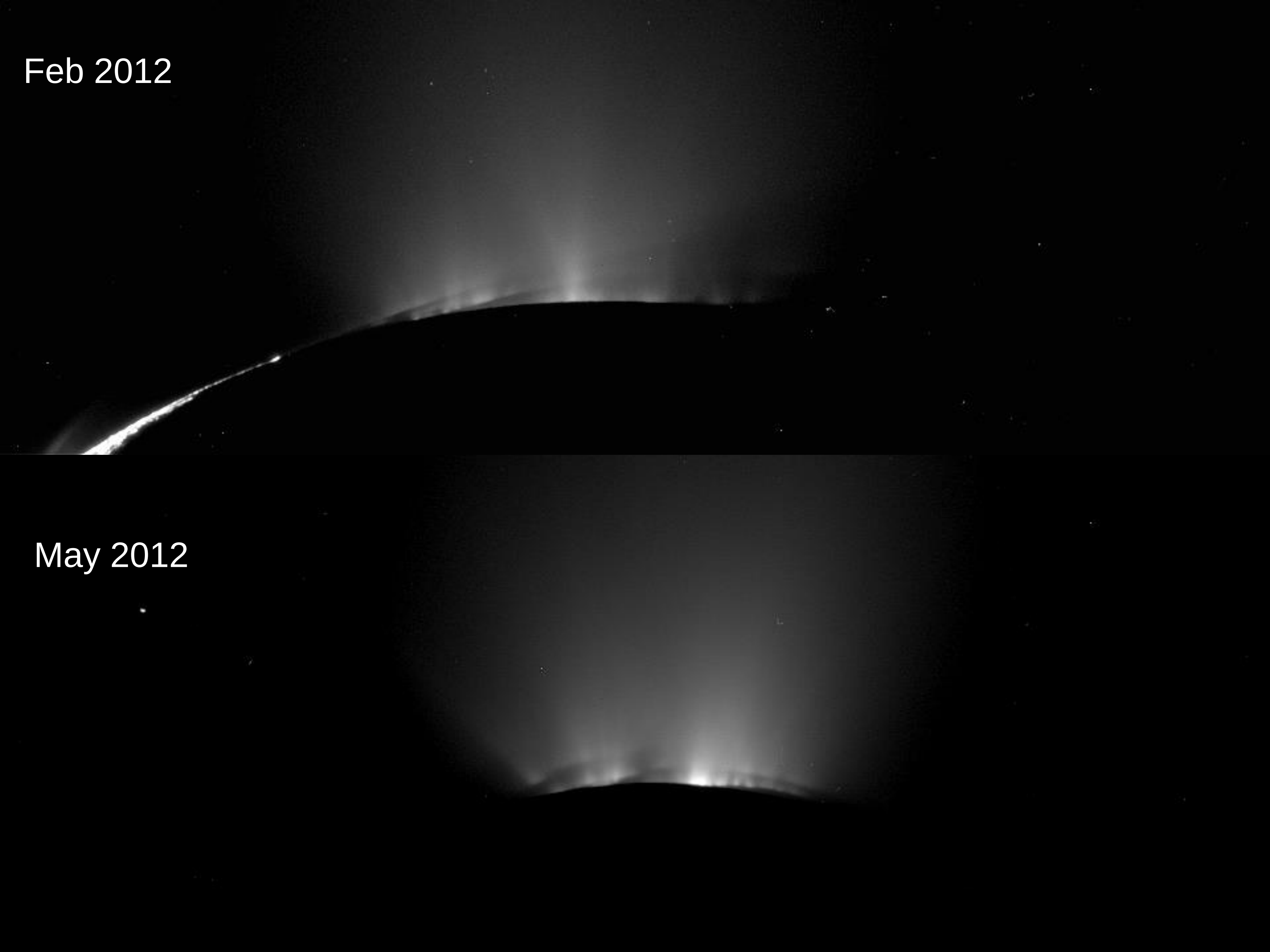
- Enceladus is synchronously rotating & in an eccentric orbit forced by 2:1 orbital resonance with Dione

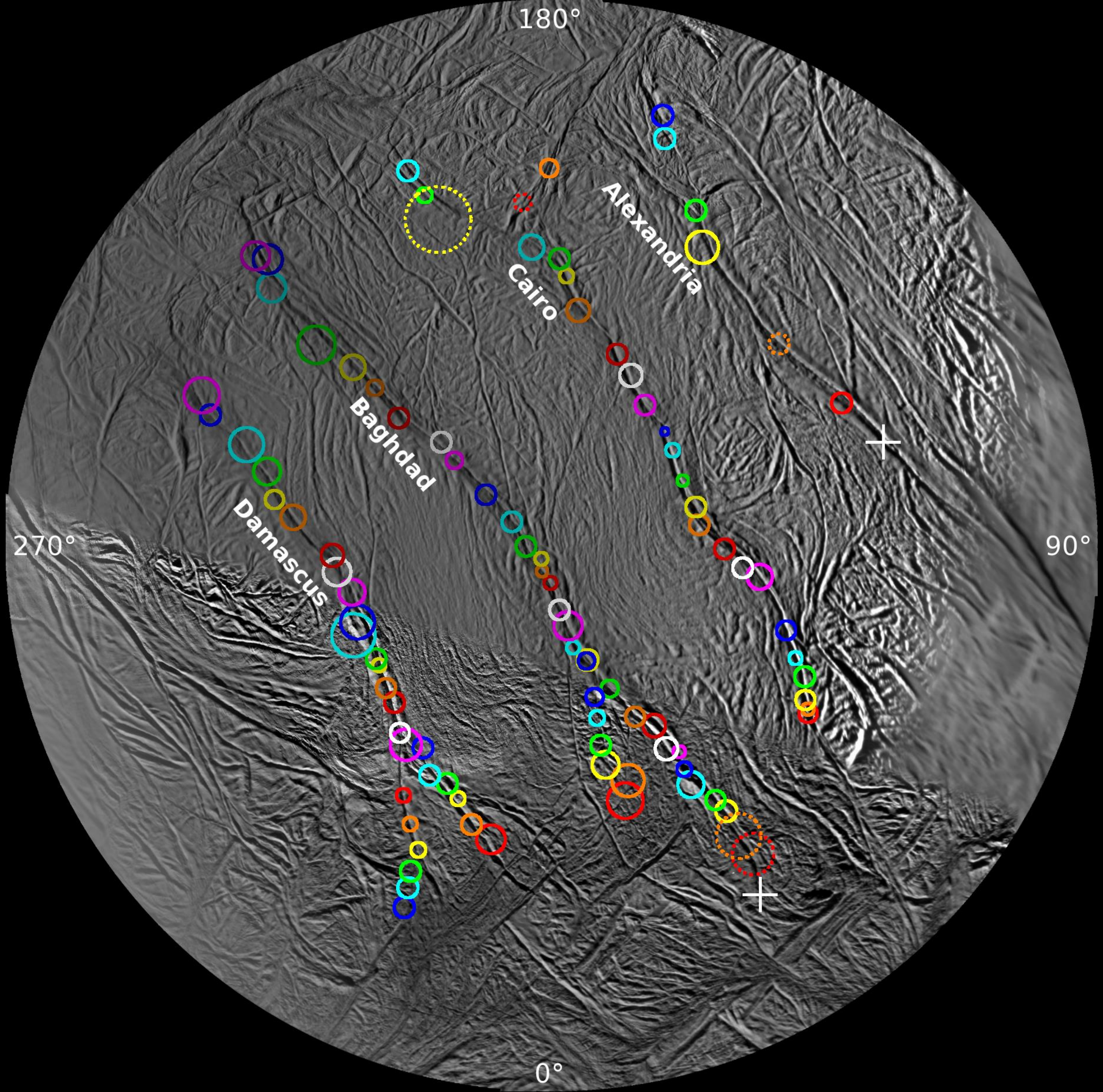
- Both the size and the orientation of the diurnal tidal bulge will change over the course of each orbit

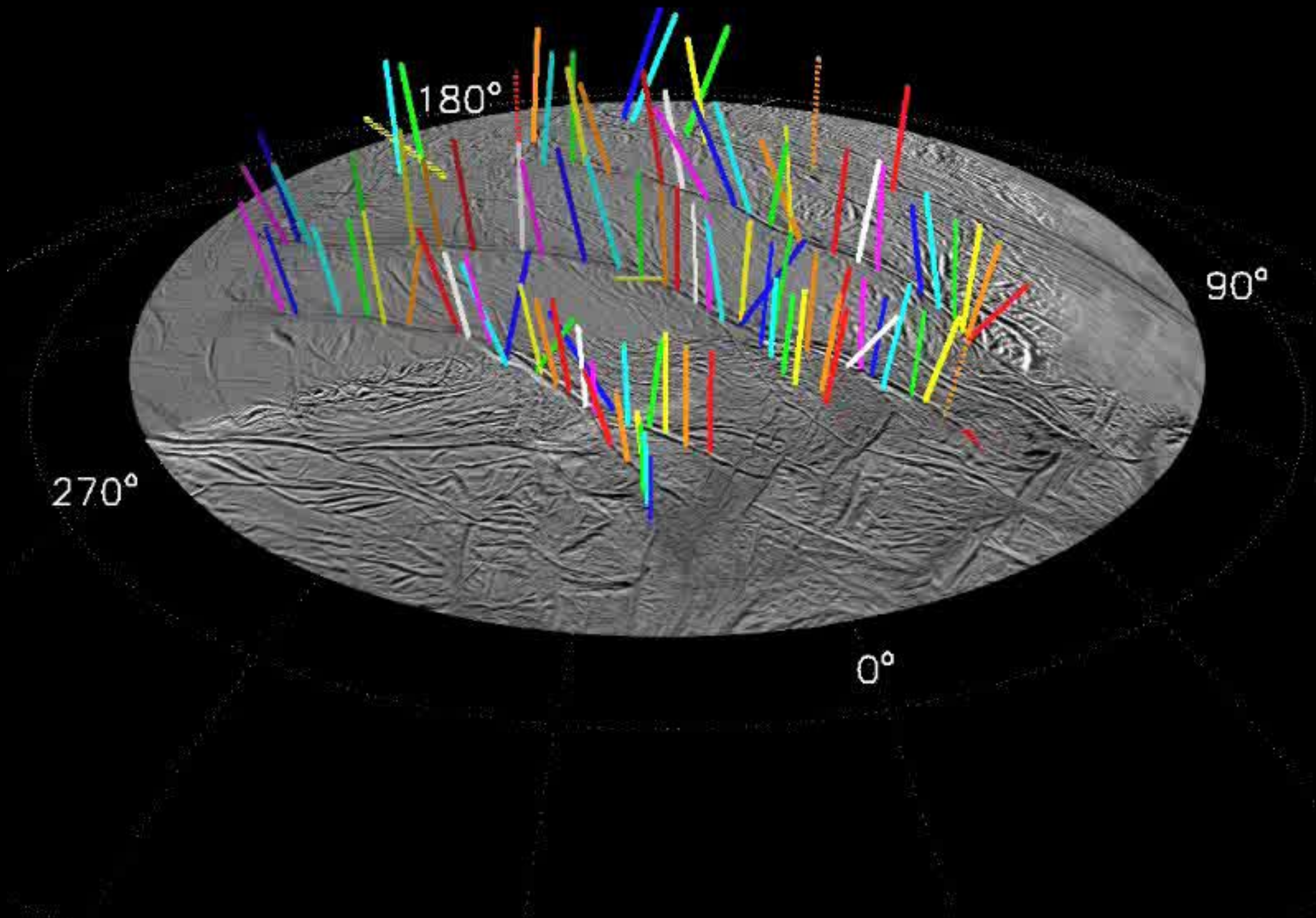


SOUTH POLAR BASIN SURVEY


Nov 2009
Nov 2005
Nov 2010

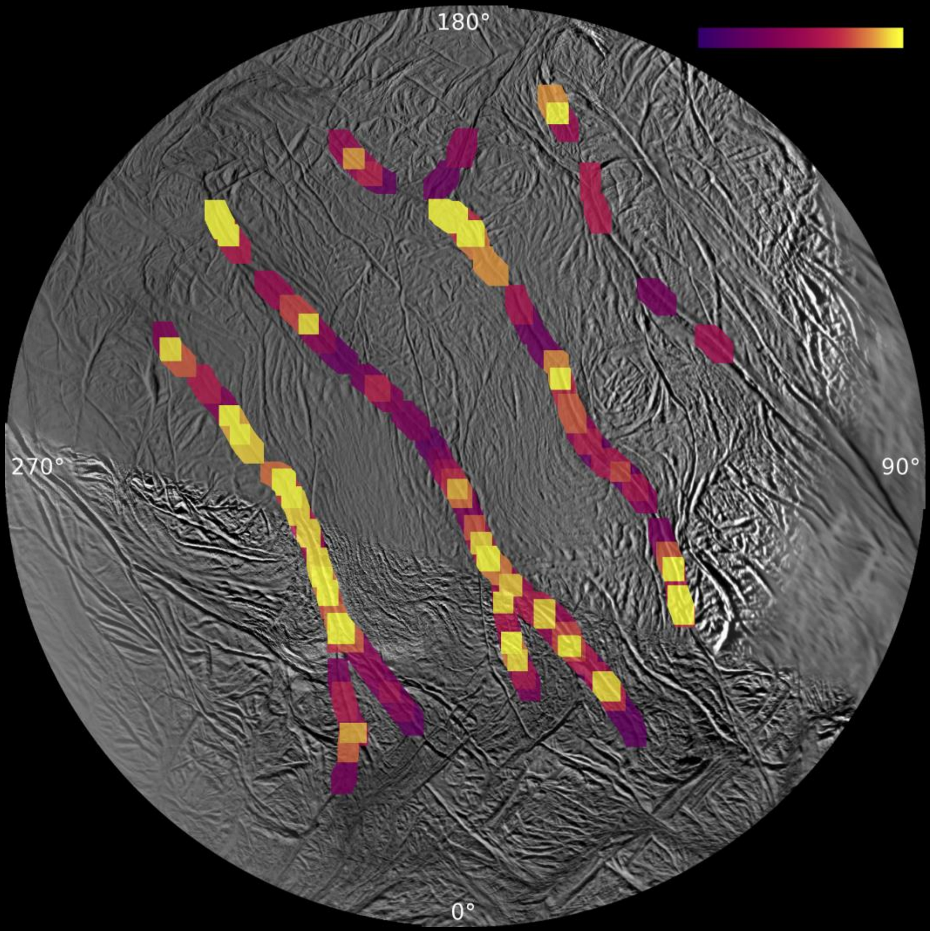

Feb 2012
May 2012


180°
270°
90°
0°
Alexandria
Cairo
Baghdad
Damascus

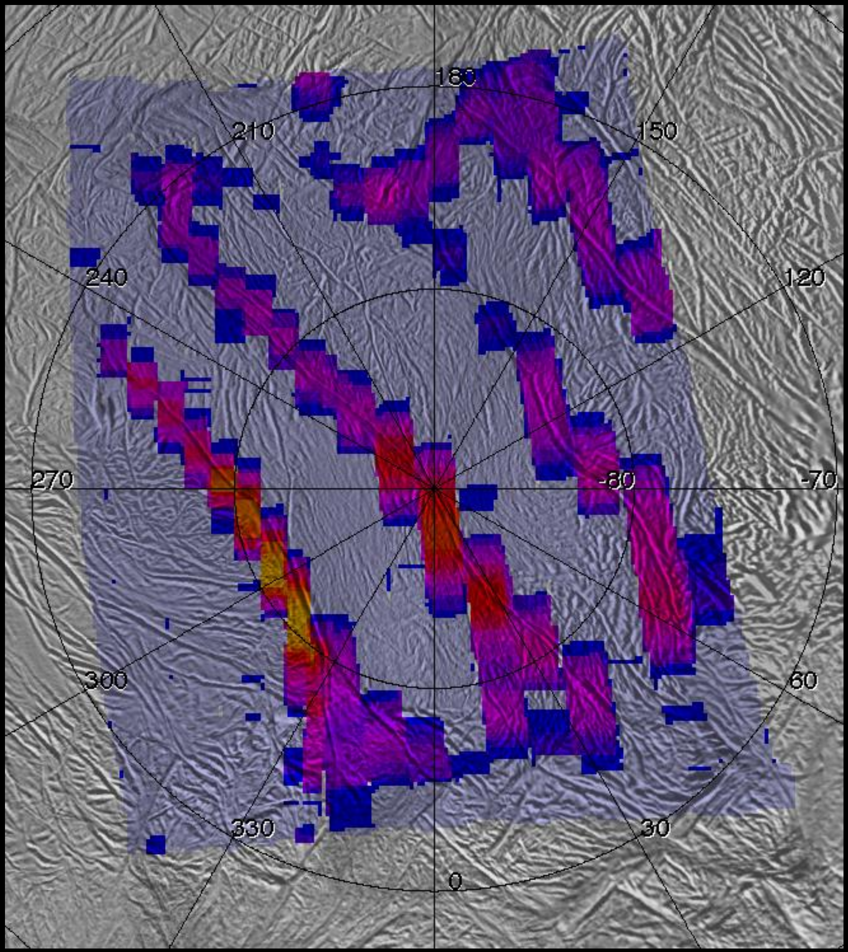


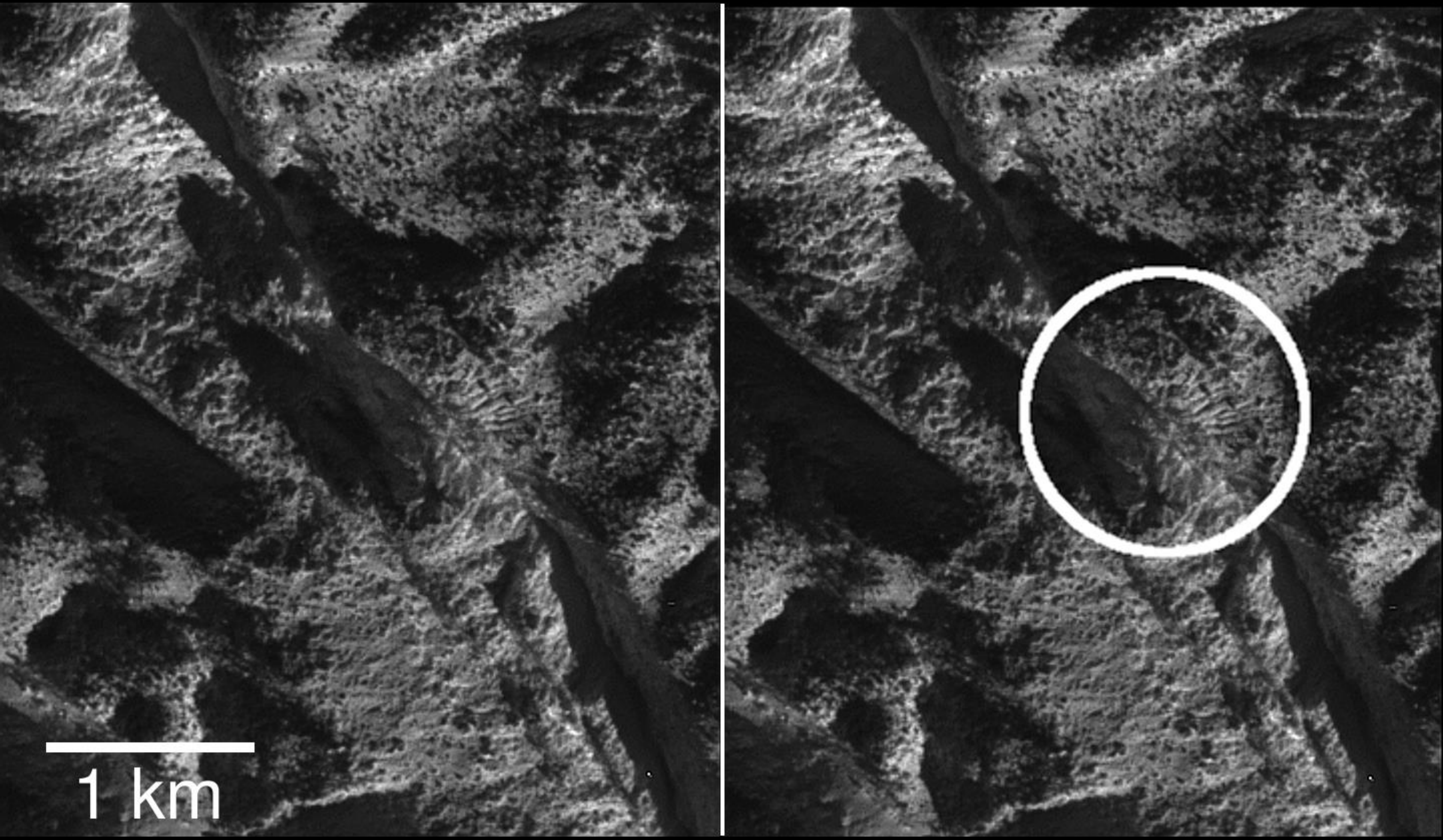
180°
90°
270°
0°

Jet Activity

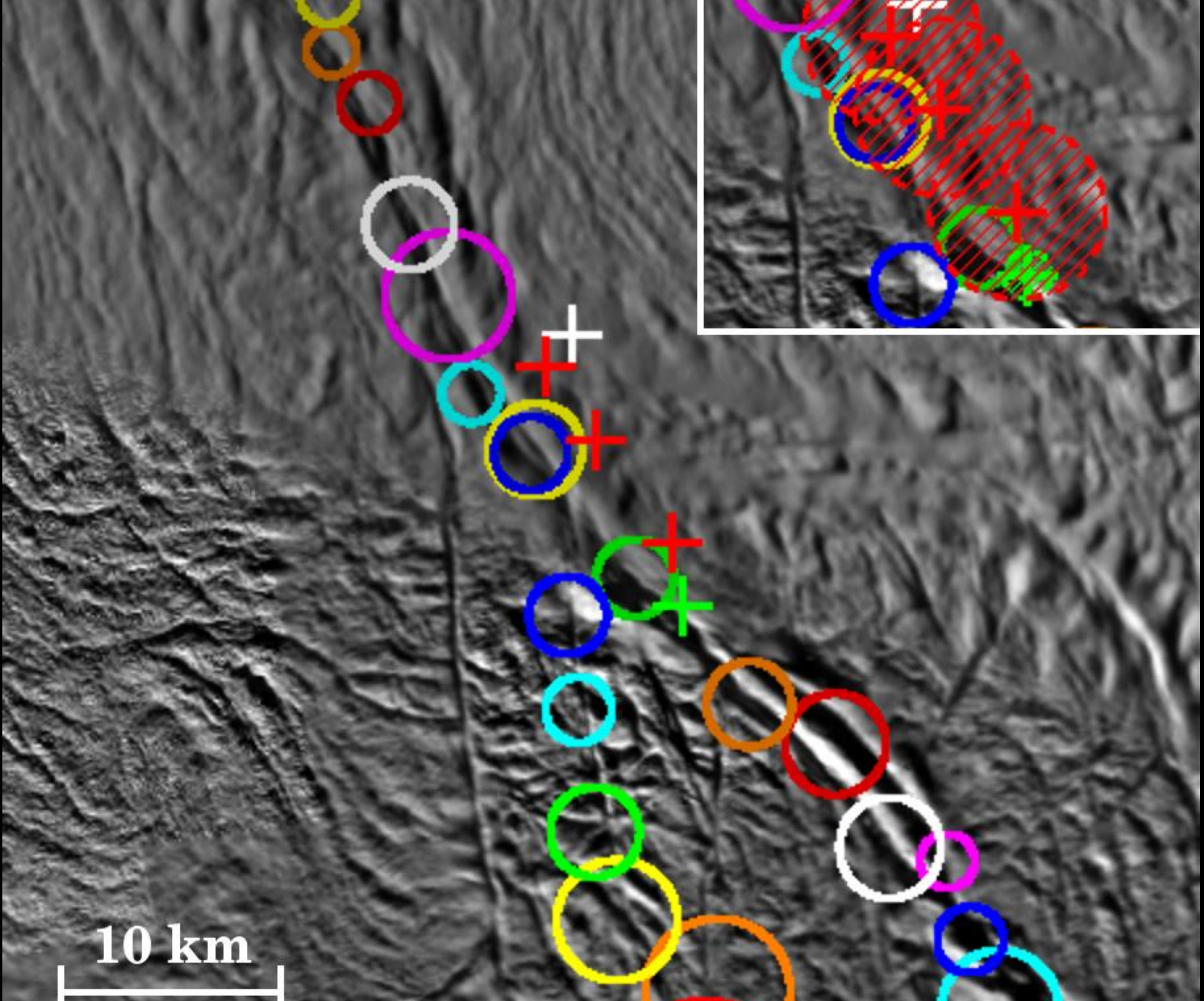


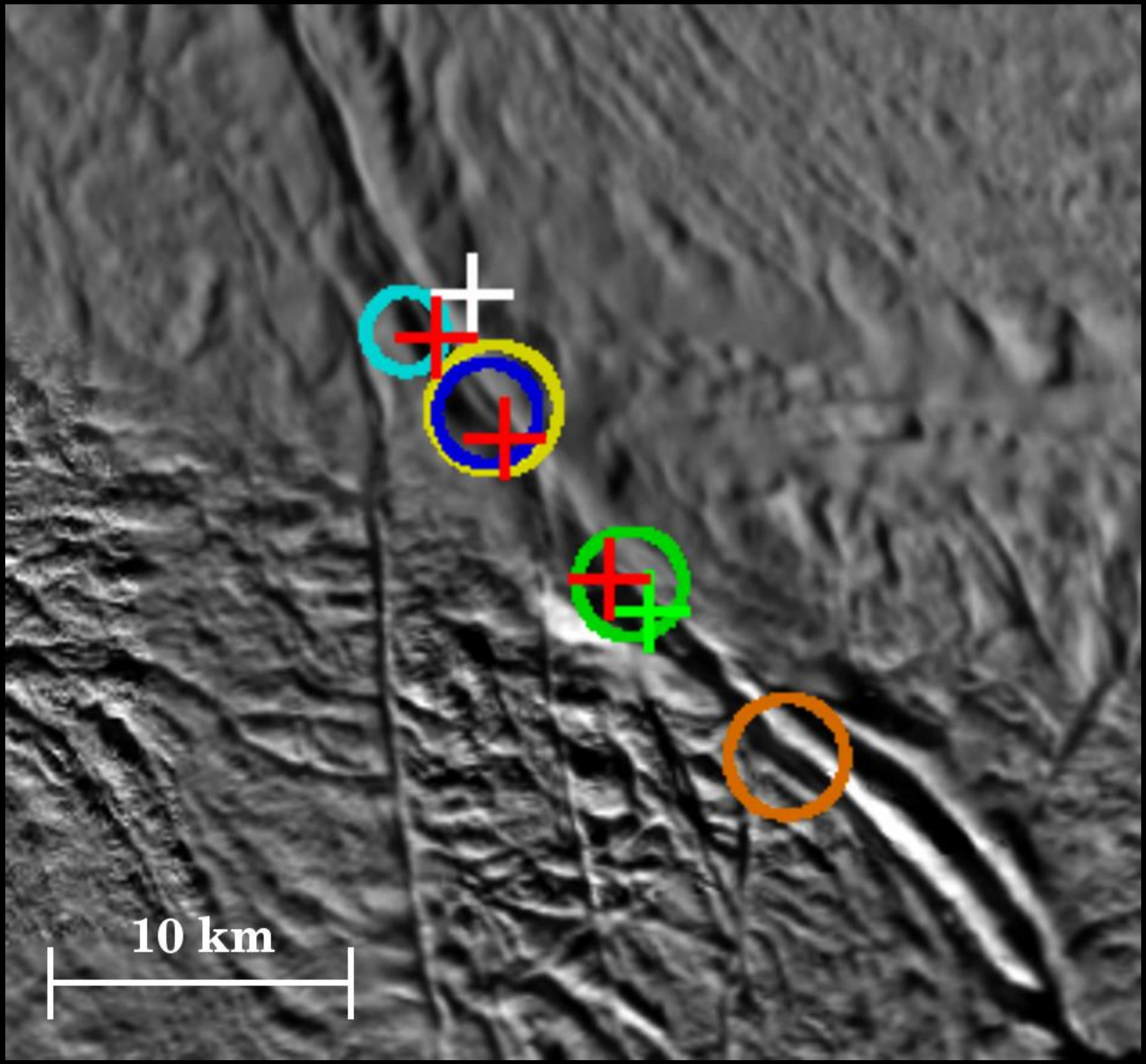
Thermal Emission





Helfenstein & Porco 2015


10 km


10 km

Plume/Particle Characteristics: Remote Sensing

- **Modeling of the vertical brightness profile of jets**
  (ISS, 2006)

. Particle velocities << thermal speed of vapor

v_0 ~ 100 m/sec << 430 m/sec (T ~ 200K)

➔ decoupled

➔ particles on ballistic trajectories

. Particle mass flux from below: ~ 50 kg/sec (but variable)

. Most particles fall back to surface: ~ 9% escape into E ring

[v_{esc} ~ 235 m/sec]

Plume/Particle Characteristics: Remote Sensing

- **Mass flux in vapor (UVIS stellar occulatations) ~ 200 kg/sec**

  ➔ Particle mass flux ≈ 0.2 to 1.0 of vapor mass flux

  ➔ Solid particles are mostly condensed from liquid droplets, not vapor **(ISS: 2006)**

- **VIMS plume spectral maps:**
  – Between 50 – 300 km, particle sizes 1 – 3 microns
  - Some > 5 microns in plume inferred from 3.2 micron absorption asymmetry (Dhingra et al. 2016)
  – Particle size gradient: larger nearer the surface, smallest above

Plume/Particle Characteristics: *In Situ* Results

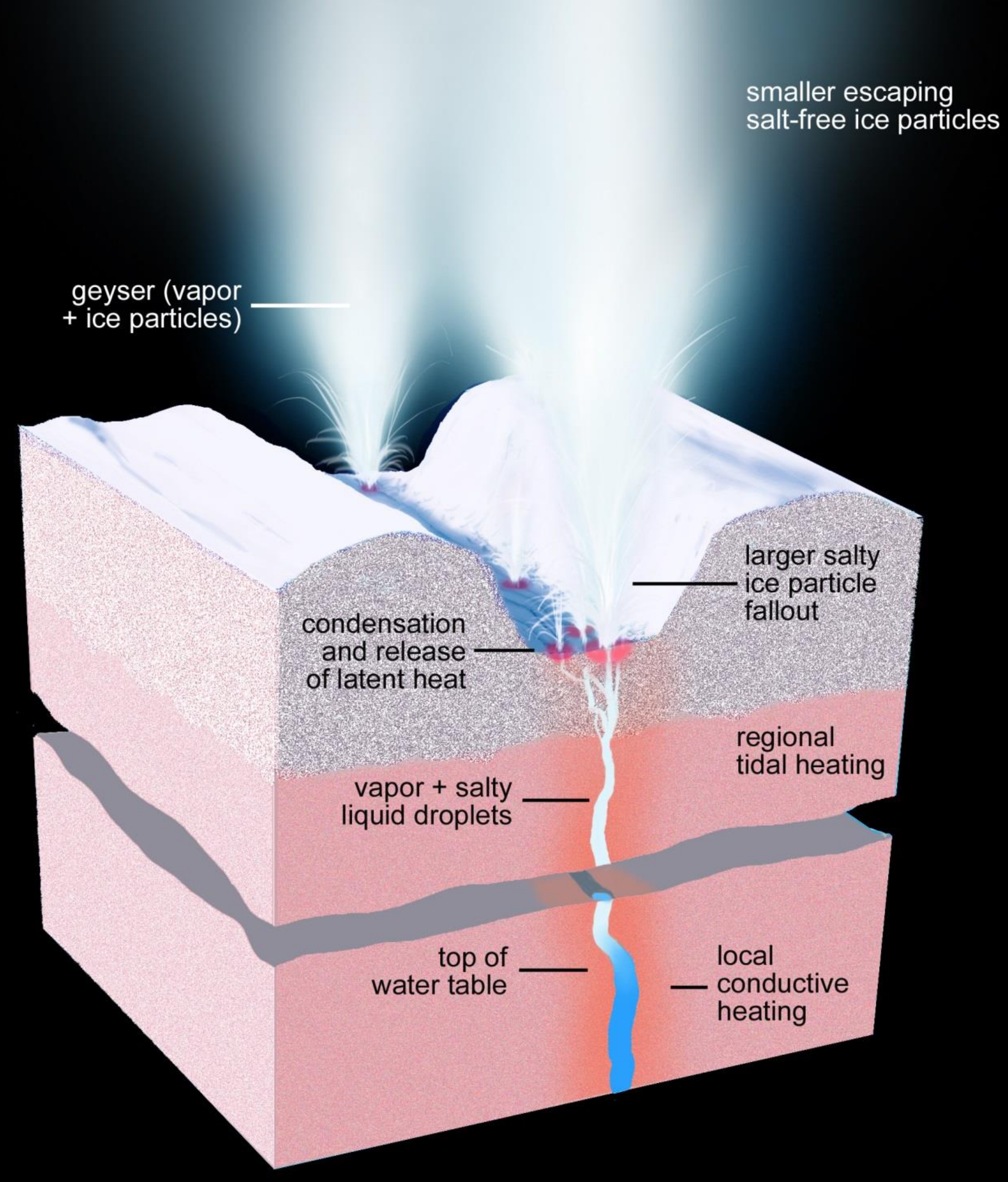
- **CDA (Cosmic Dust Analyzer)**

. E ring particles low in salts; <1 micron in size
. Particles near 170 km are > 2 microns

. BUT…. Most of the particles near the surface are rich in sodium & potassium salts
…. Salinity is ≥ 0.5 – 2% by mass, comparable to Earth's ocean (3 - 4%)

➔ salt-rich particles originate as droplets from a salty liquid reservoir (consistent with S/V ratio)
➔ reservoir in contact with rocky core
➔ CDA + VIMS: larger salty particles near surface, smaller escape to E ring

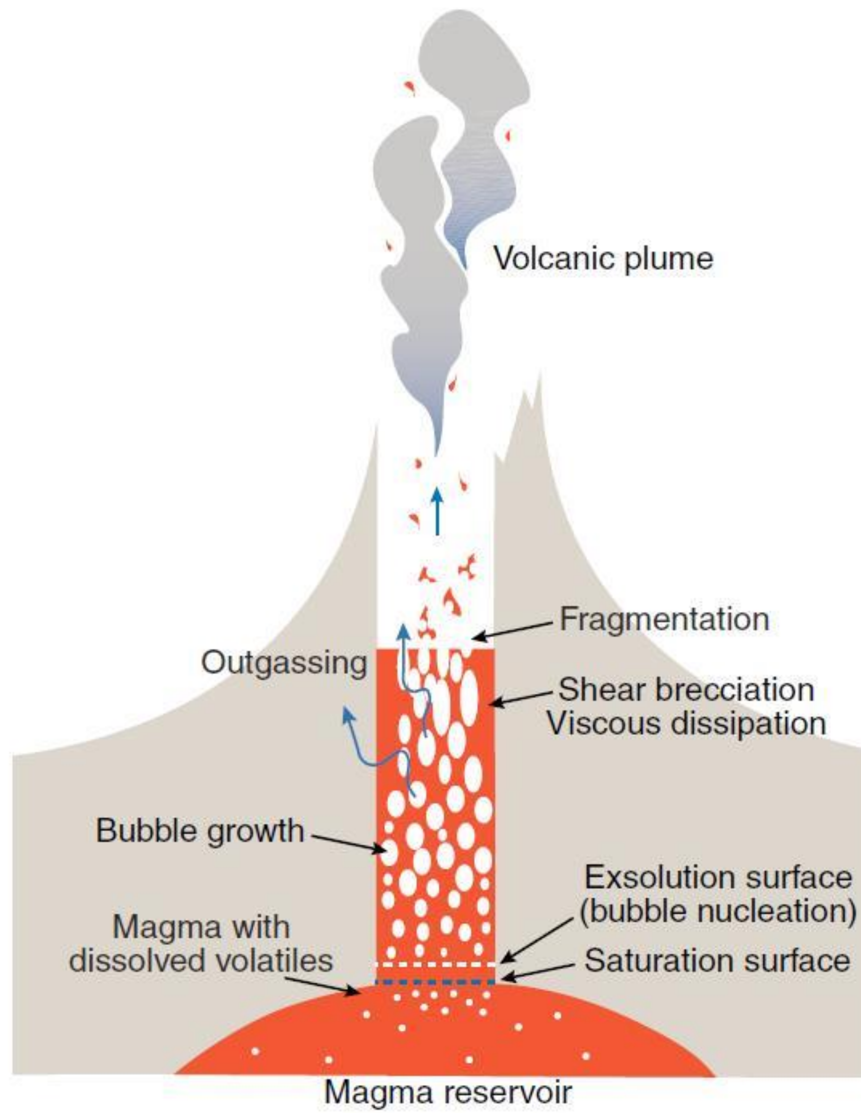
. Silica nanoparticles too ➔ can only be produced in low temp hydrothermal zone (Lost City)


smaller escaping
salt-free ice particles
geyser (vapor
+ ice particles)
larger salty
ice particle
fallout
condensation
and release
of latent heat
regional
tidal heating
vapor + salty
liquid droplets
top of
water table
local
conductive
heating

Why is particle size distribution so important? In terrestrial volcanology…

1. Information about transport and deposition

2. Insight into fragmentation



Insights from particle size and shape

- Height
- Collapse
- Role of moisture
- Wet vs dry eruptions
- Fragmentation depth and process
- Overwater travel?
- Country rock

What the gas does

Gas flow

Temperature: T

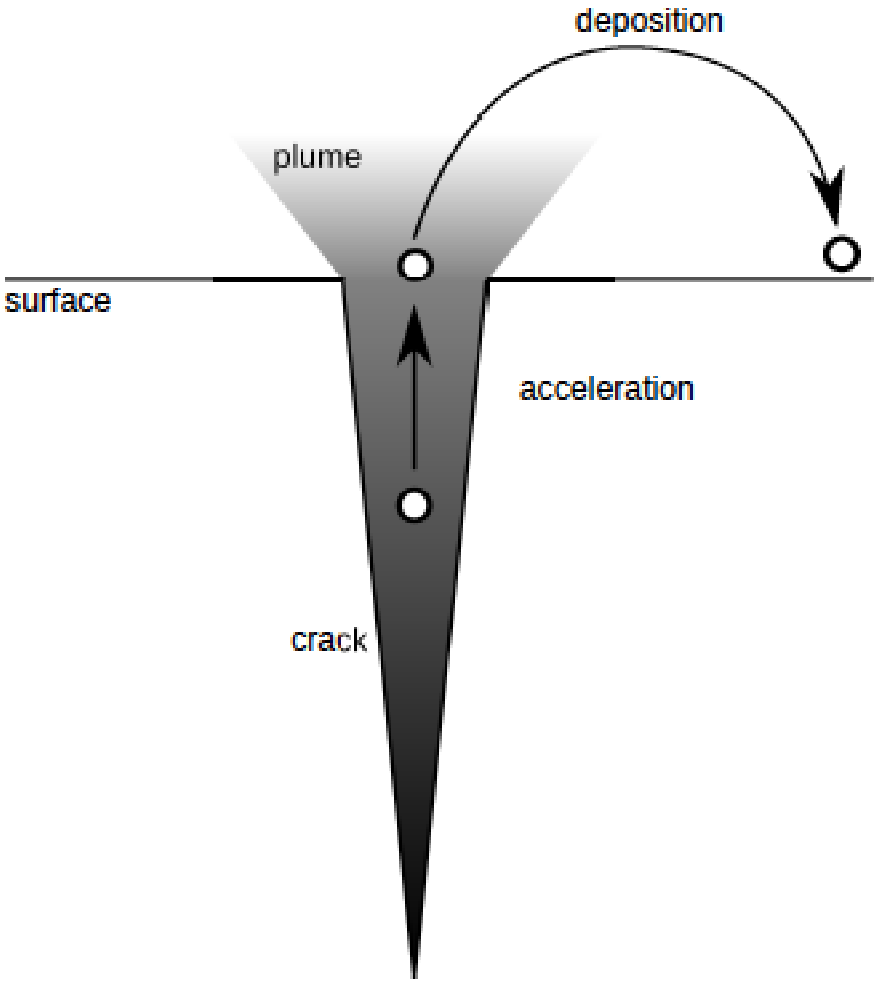
Pressure: $P = A\exp\left(\frac{-B}{T}\right)$

Density: $\rho_g = \frac{P}{RT} = \frac{Pm_0}{k_B T}$

Velocity: $u_g = \sqrt{RT}$

Viscosity: $\eta = 0.925 \times 10^{-5}\left(\frac{T}{300}\right)^{1.1}$

(Ingersoll and Pankine 2010)



What the particles do

Particle acceleration

$$M_p \frac{du_p}{dt} = \frac{1}{2} \rho_g C_D \pi R_p^2 |u_g - u_p| (u_g - u_p)$$

Drag coefficient

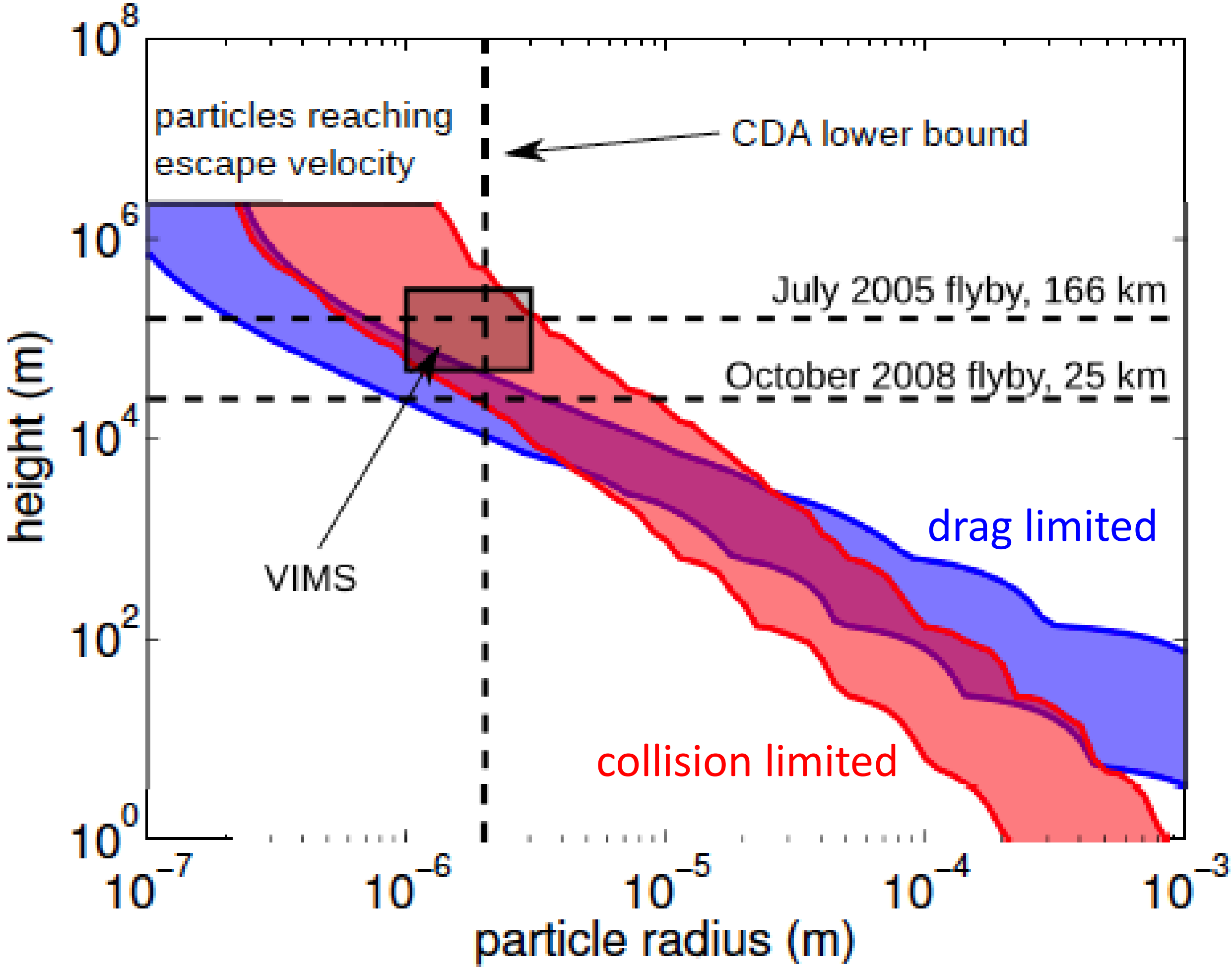
$$C_D = 2 + \left(\frac{24 f_1}{\mathrm{Re}} - 2 \right) \exp\left(-3.07 f_2 \frac{\mathrm{Ma}}{\mathrm{Re}} \right) + \frac{f_3}{\mathrm{Ma}} \exp\left(-2 \frac{\mathrm{Re}}{\mathrm{Ma}} \right)$$

$$f_1 = 1 + 0.15\,\mathrm{Re}^{0.687} + \frac{0.0175}{1 + 42500\,\mathrm{Re}^{-1.16}}$$

$$f_2 = \frac{1 + \mathrm{Re}(12.278 + 0.548\mathrm{Re})}{1 + 11.278\mathrm{Re}}$$

$$f_3 = \frac{5.6}{1 + \mathrm{Ma}} + 1.7$$

Maximum height vs size



In Situ Results

- **INMS (Ion and Neutral Mass Spectrometer): Vapor**

  $H_2O \approx 90\%$
  $CO_2 \approx NH_3 \approx CH_4 \approx 1\%$
  Mass 28amu (C_2H_4, CO, N_2) ≈ 2%
  Hydrocarbons with > 6 Carbons possible; not well understood at this time

Both INMS (CO_2) and CDA (carbonate salts $NaHCO_3$ /Na_2CO_3) results used in chemical model of ocean

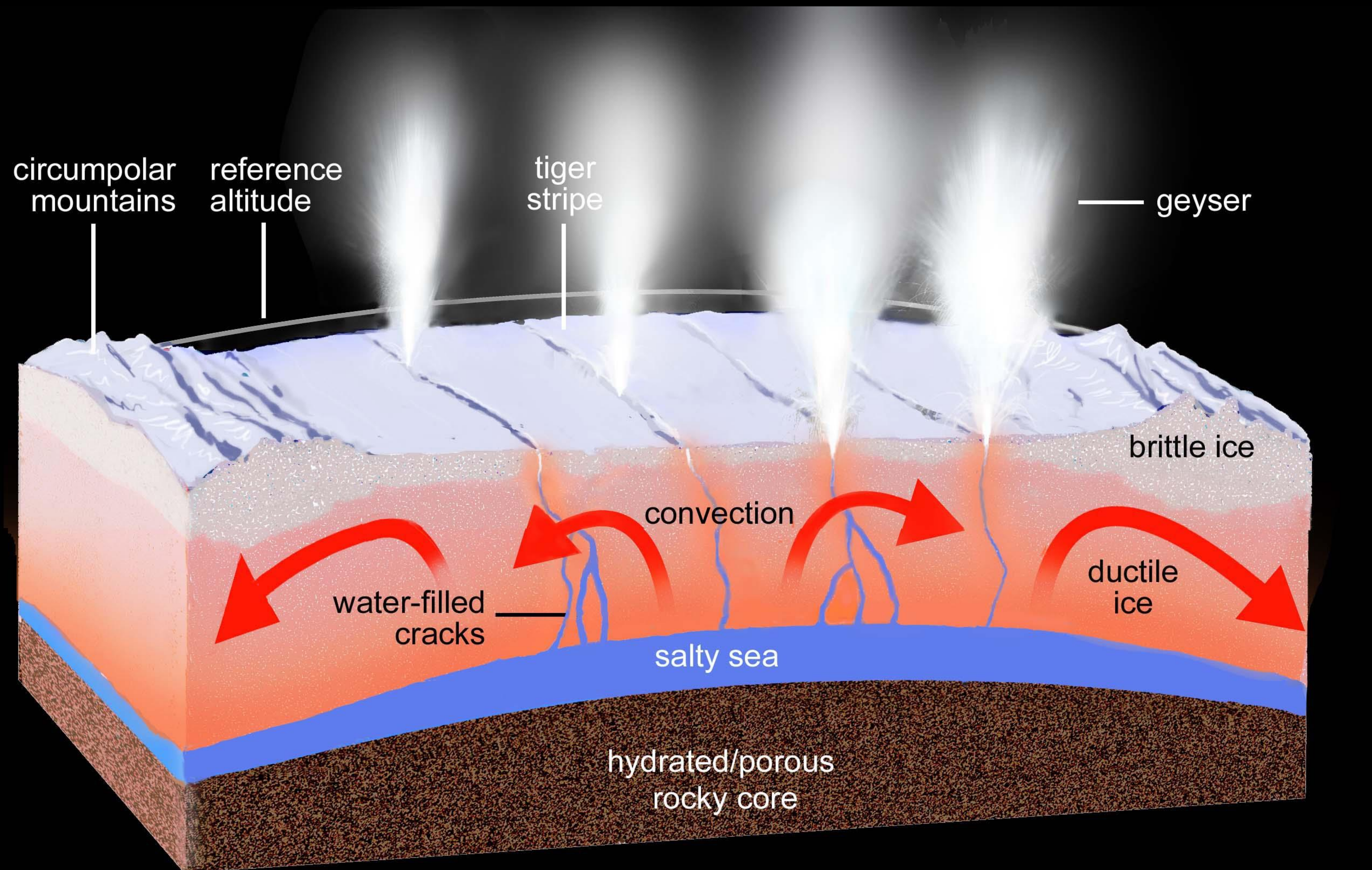
➔ pH ~ 11 - 12
➔ serpentization: H_2 in the plume?
➔ CO_2 outgassing

Water-rock interaction on Earth:

- controls chemistry of oceans, natural waters, and atmosphere
- supports chemosynthetic primary production
- may have facilitated the origin of life
- controls the thermal structure of the oceanic lithosphere

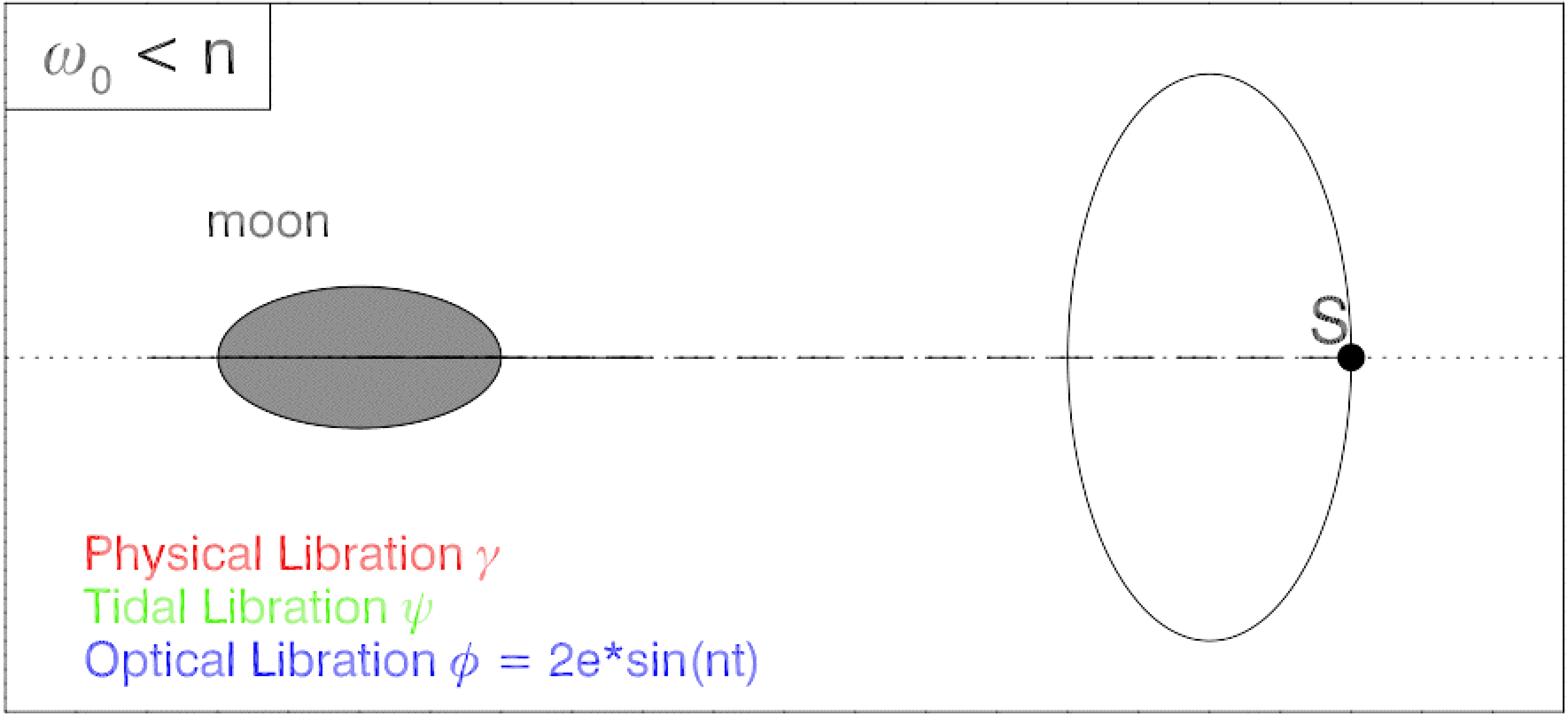
Evidence for water-rock interaction on Enceladus:

- Presence of a liquid ocean in contact with a rocky core
- Core density ~2400 kg m^{-3} consistent with hydrated rock
- Estimated pH of liquid ocean
- Composition of cryovolcanic plume (salts, silica, CH_4)

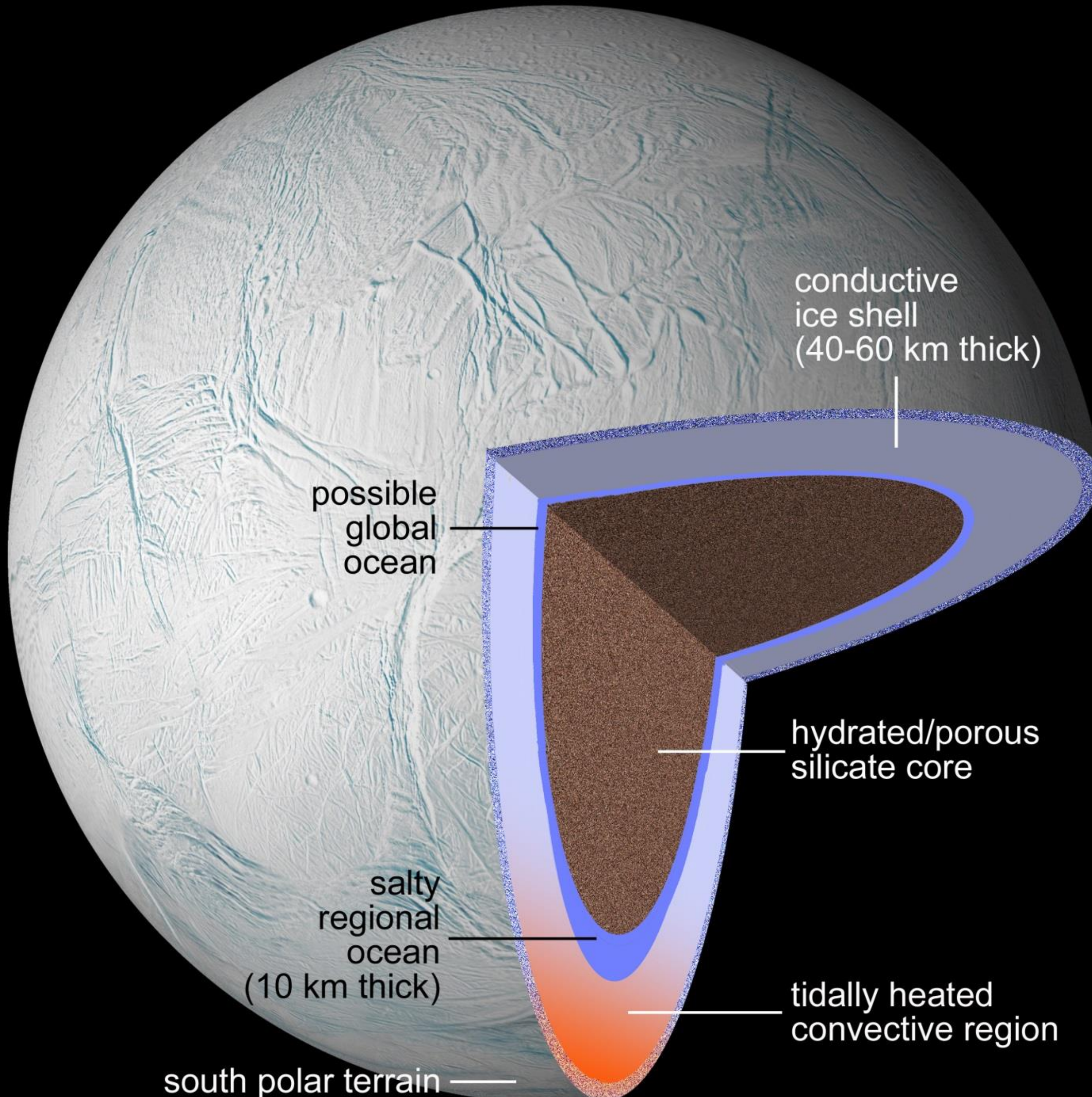


circumpolar mountains
reference altitude
tiger stripe
geyser
brittle ice
convection
ductile ice
water-filled cracks
salty sea
hydrated/porous rocky core

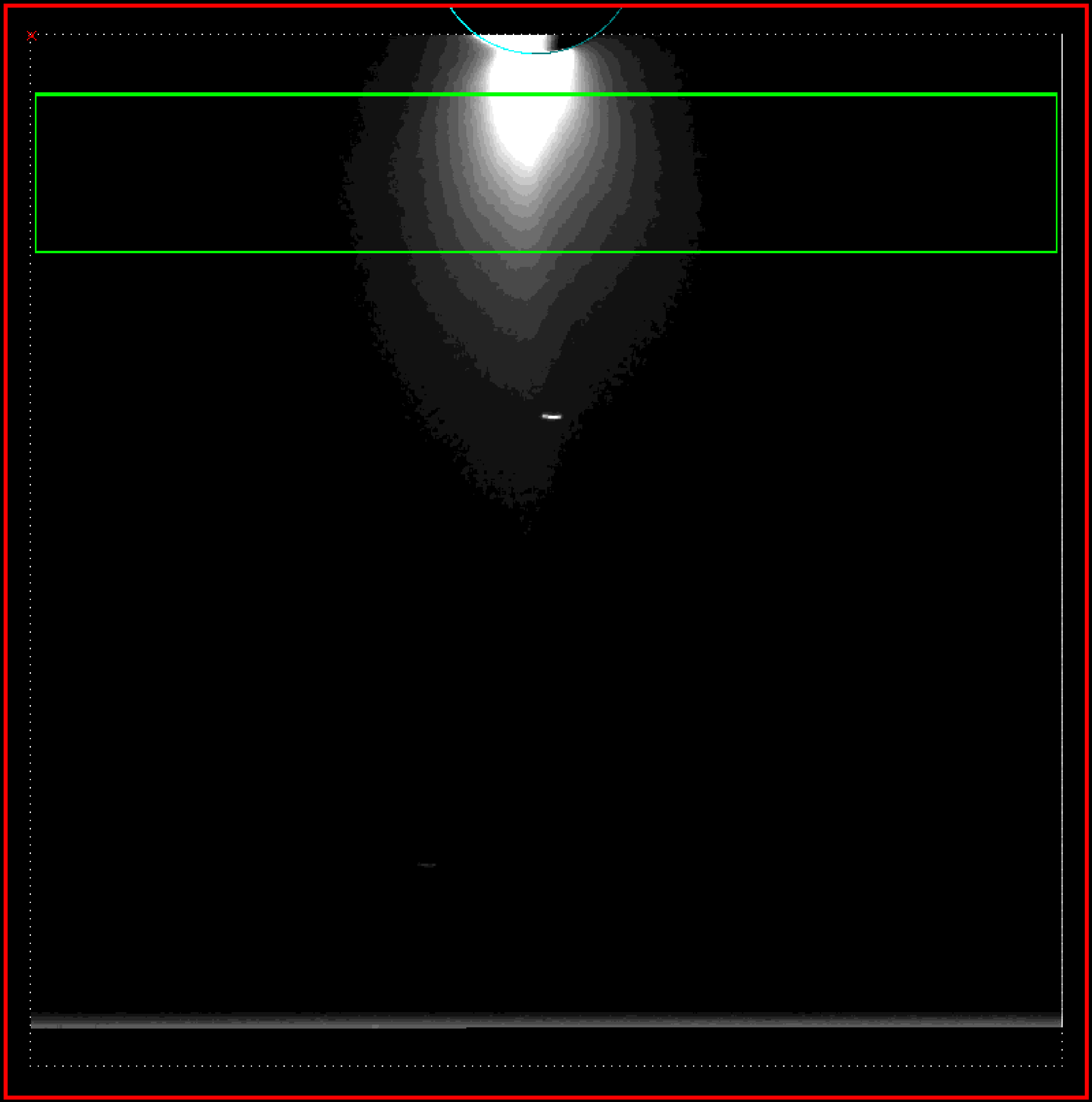
Other Results

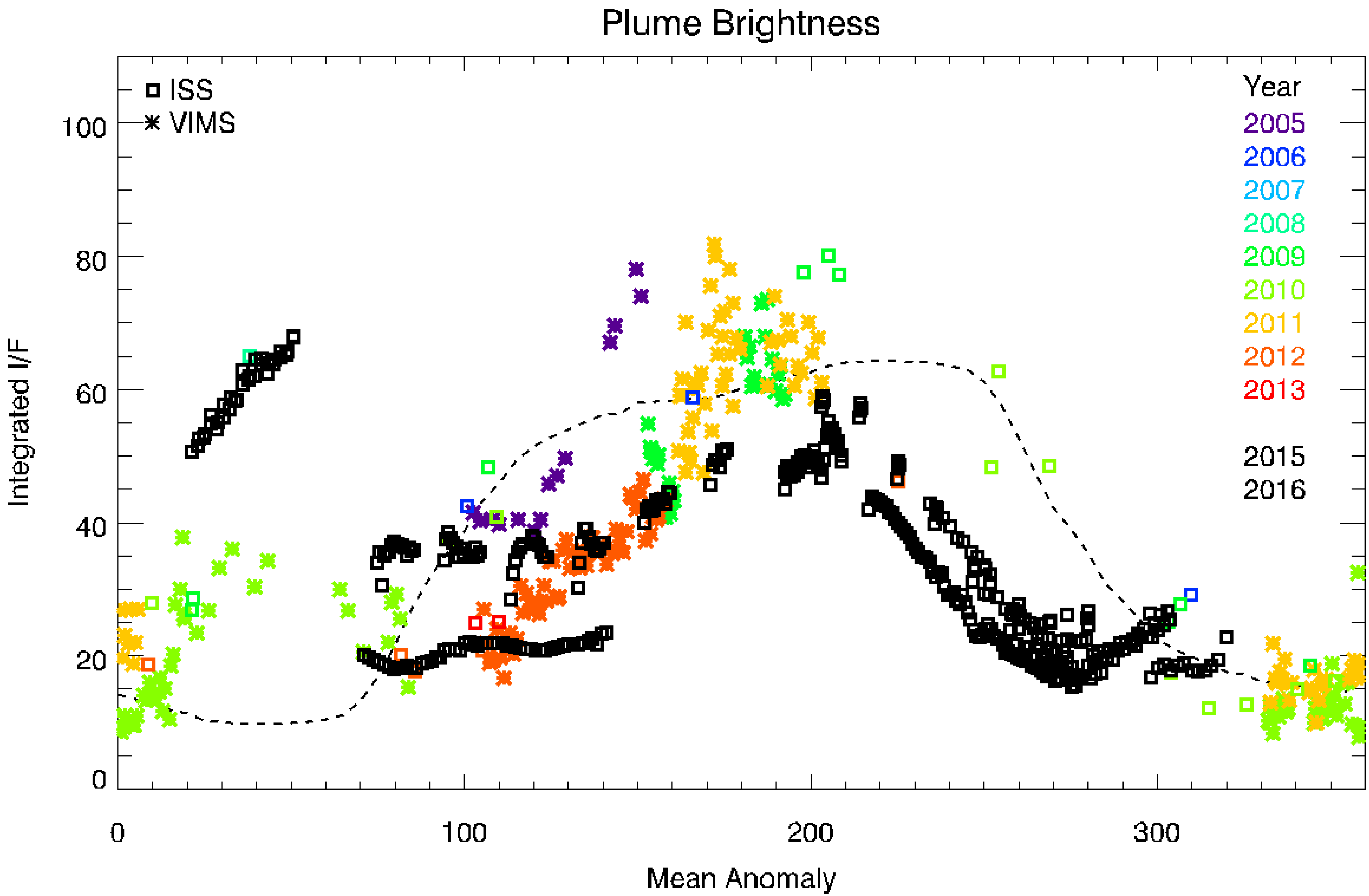


$\omega_0 < n$
moon
S
Physical Libration γ
Tidal Libration ψ
Optical Libration ϕ = 2e*sin(nt)

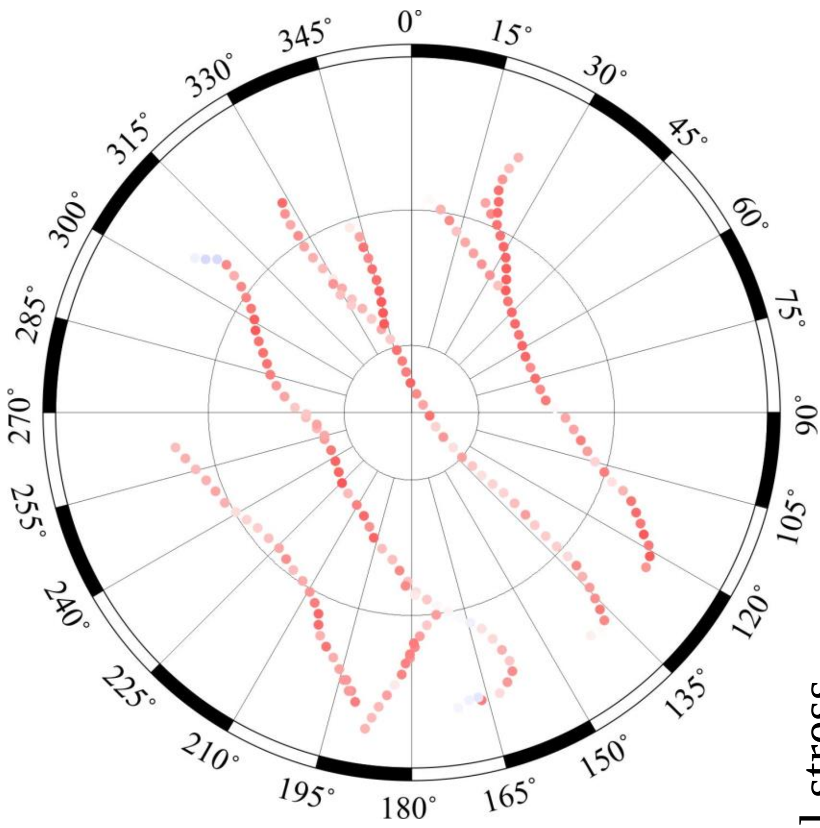

conductive
ice shell
(40-60 km thick)
possible
global
ocean
hydrated/porous
silicate core
salty
regional
ocean
(10 km thick)
tidally heated
convective region
south polar terrain

TEMPORAL VARIABILITY

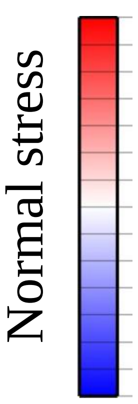


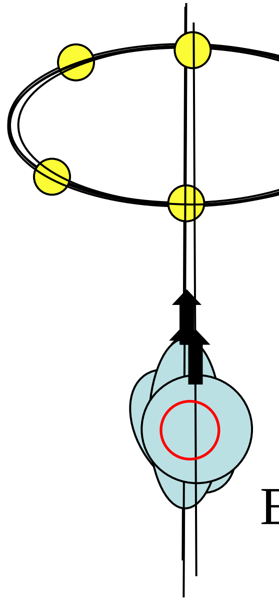

Plume Brightness
ISS
VIMS
Year
2005
2006
2007
2008
2009
2010
2011
2012
2013
2015
2016
Integrated I/F
Mean Anomaly
0
20
40
60
80
100
0
100
200
300

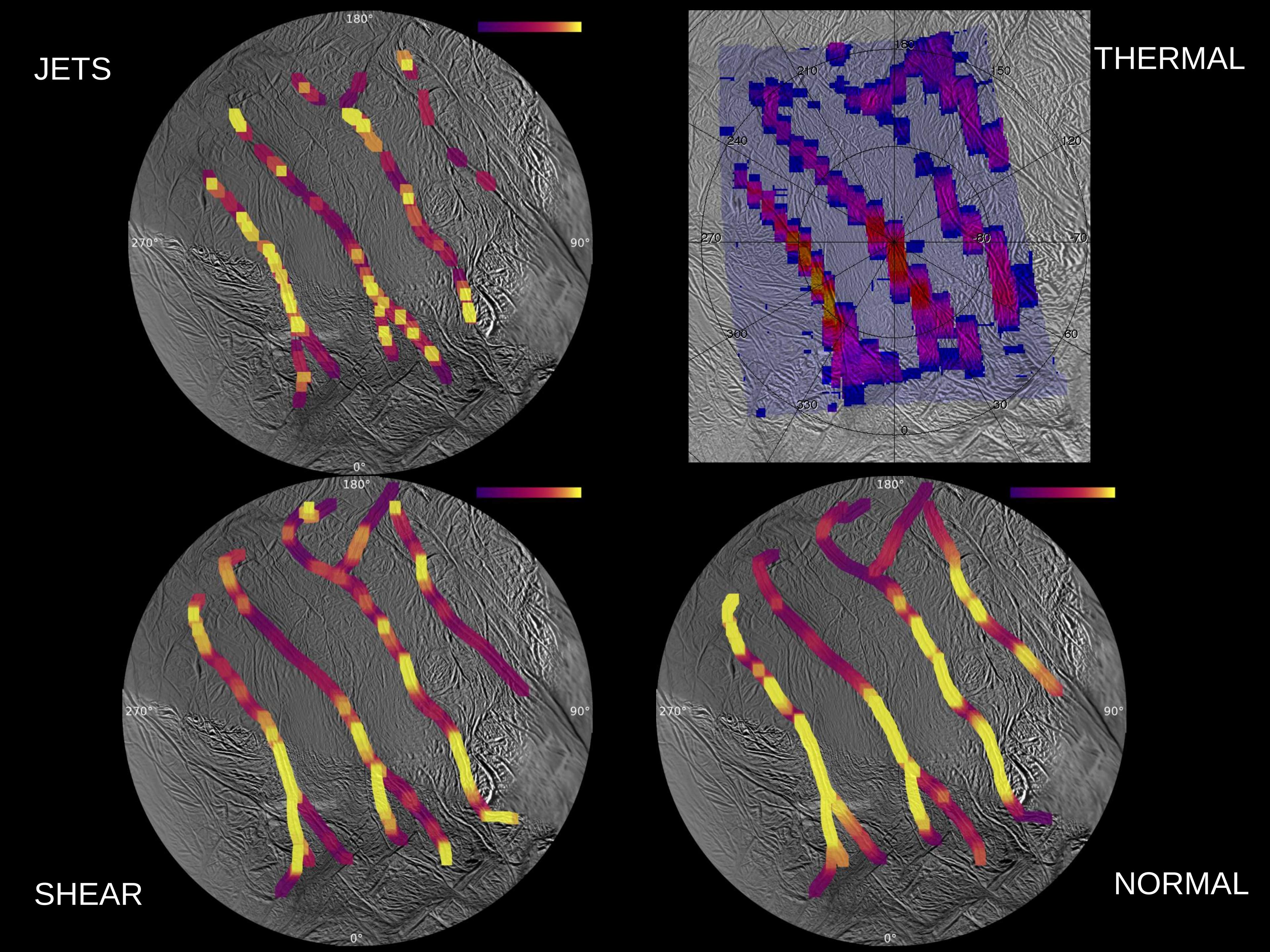
Time-varying stresses



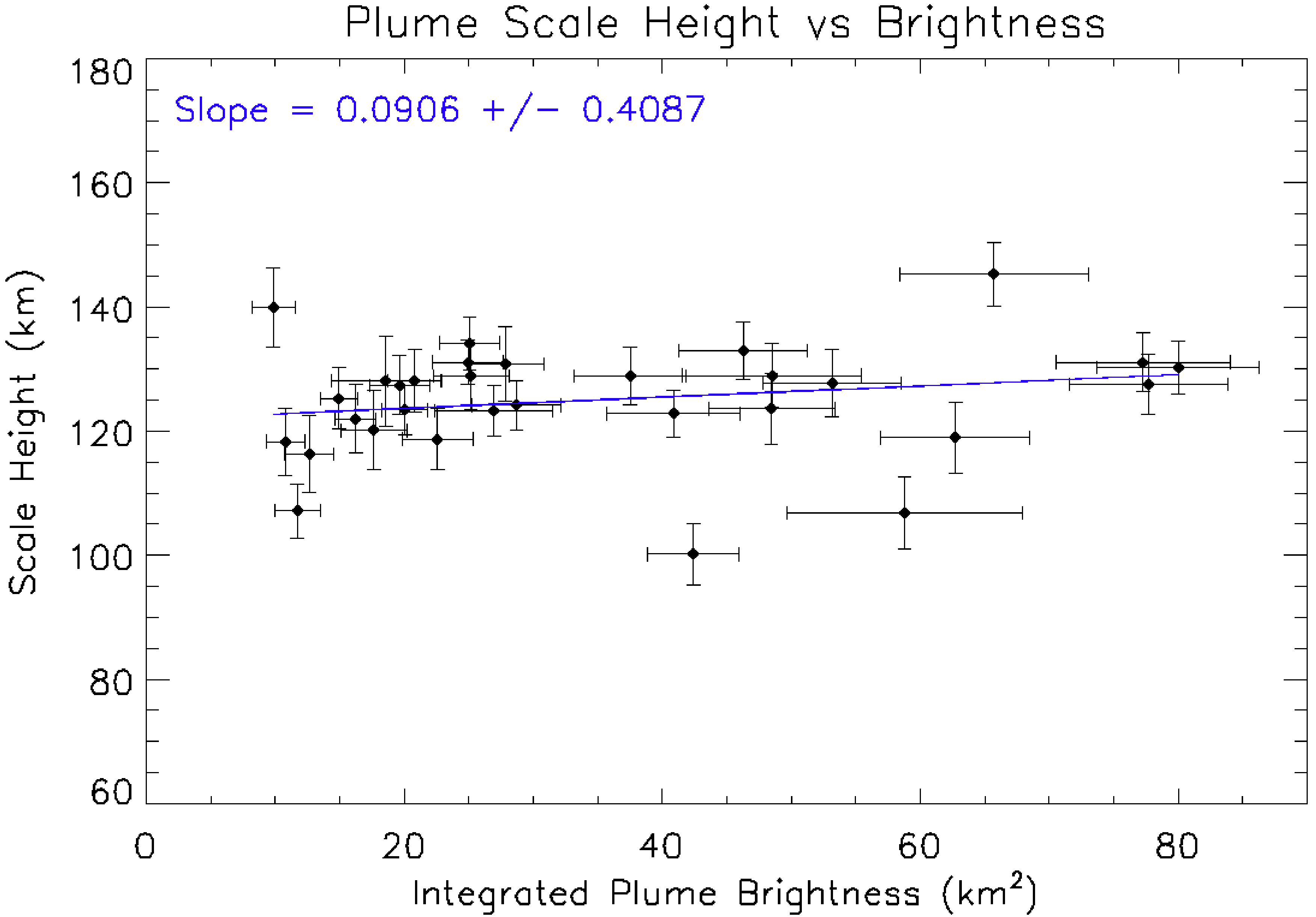
Pericentre
Apocentre
1/4 orbit later







JETS
THERMAL
SHEAR
NORMAL
180°
270°
90°
0°
180
210
150
240
120
270
-80
-70
300
60
330
30
0


Plume Scale Height vs Brightness
Slope = 0.0906 +/- 0.4087
180
160
140
120
100
80
60
Scale Height (km)
0
20
40
60
80
Integrated Plume Brightness (km^2)

THE FUTURE

WE KNOW:

Formal requirements for habitable zone exist: liquid water, organics, chemical energy, salts, nitrogen-bearing compounds. But …

WE WANT TO KNOW:

. Do conditions for life or even pre-biotic chemistry exist?

. Is Enceladus’ ocean actually inhabited?!

At Enceladus, we can do this NOW!

HOW COULD WE FIND OUT?

Sample the plume & analyze the ocean!

. Characterize the environment & its evolution

_ Temperature, ph, oxidation state, available chemical energy

_ H_2 ? Produced by rock/water reactions

Methanogens eat this

HOW COULD WE FIND OUT?

Sample the plume & analyze the ocean!

. Characterize the environment & its evolution

. Search for:

_ Parent molecules of detected light hydrocarbons

Needs mass specs for gas & solids more capable than Cassini

HOW COULD WE FIND OUT?

Sample the plume & analyze the ocean!

. Characterize the environment & its evolution

. Search for:

_ Parent molecules of detected light hydrocarbons

_ Disequilibria and hi-temp alteration (eg, isotopes)

Available chemical energy?

HOW COULD WE FIND OUT?

Sample the plume & analyze the ocean!

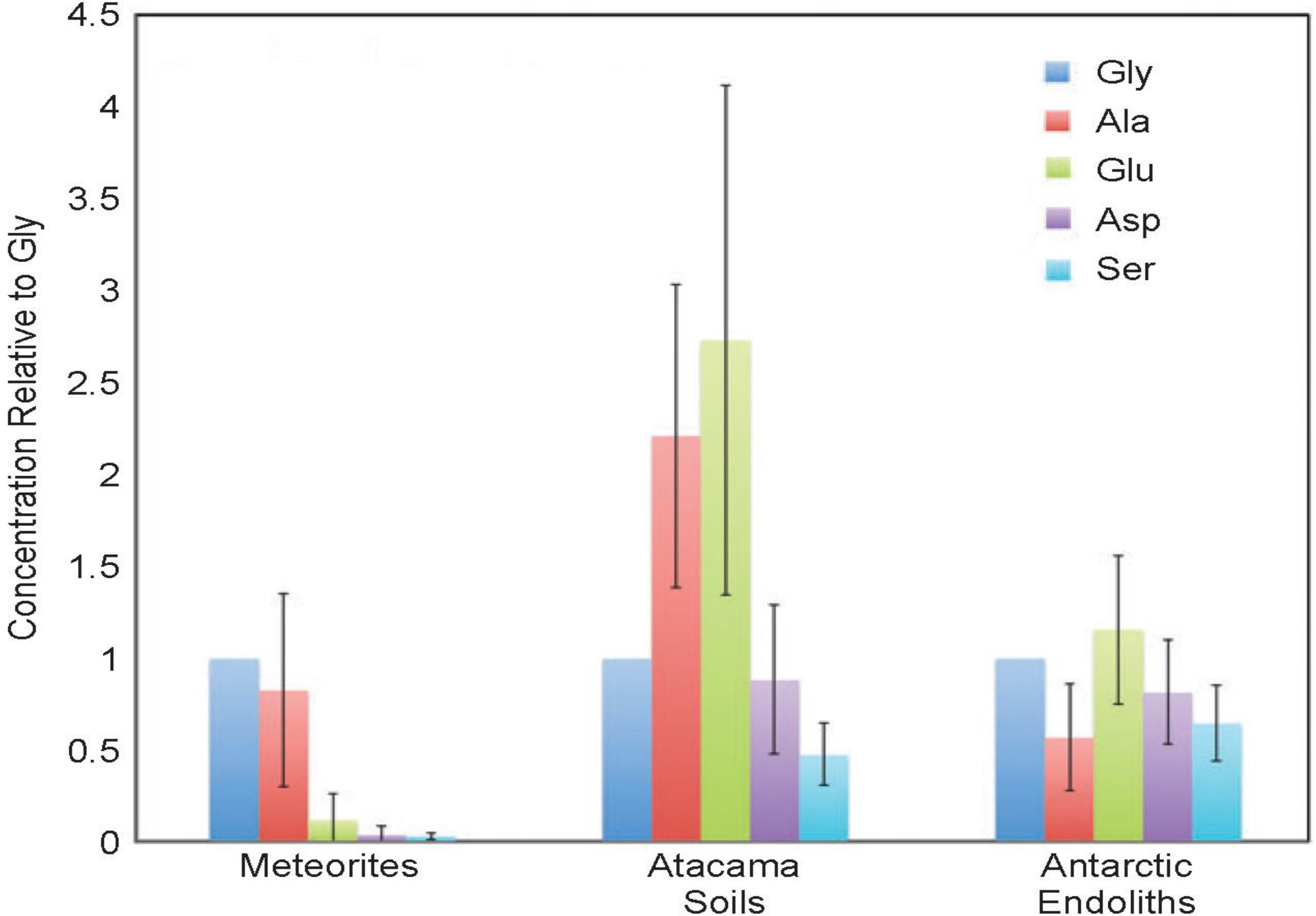
. Characterize the environment & its evolution

. Search for:

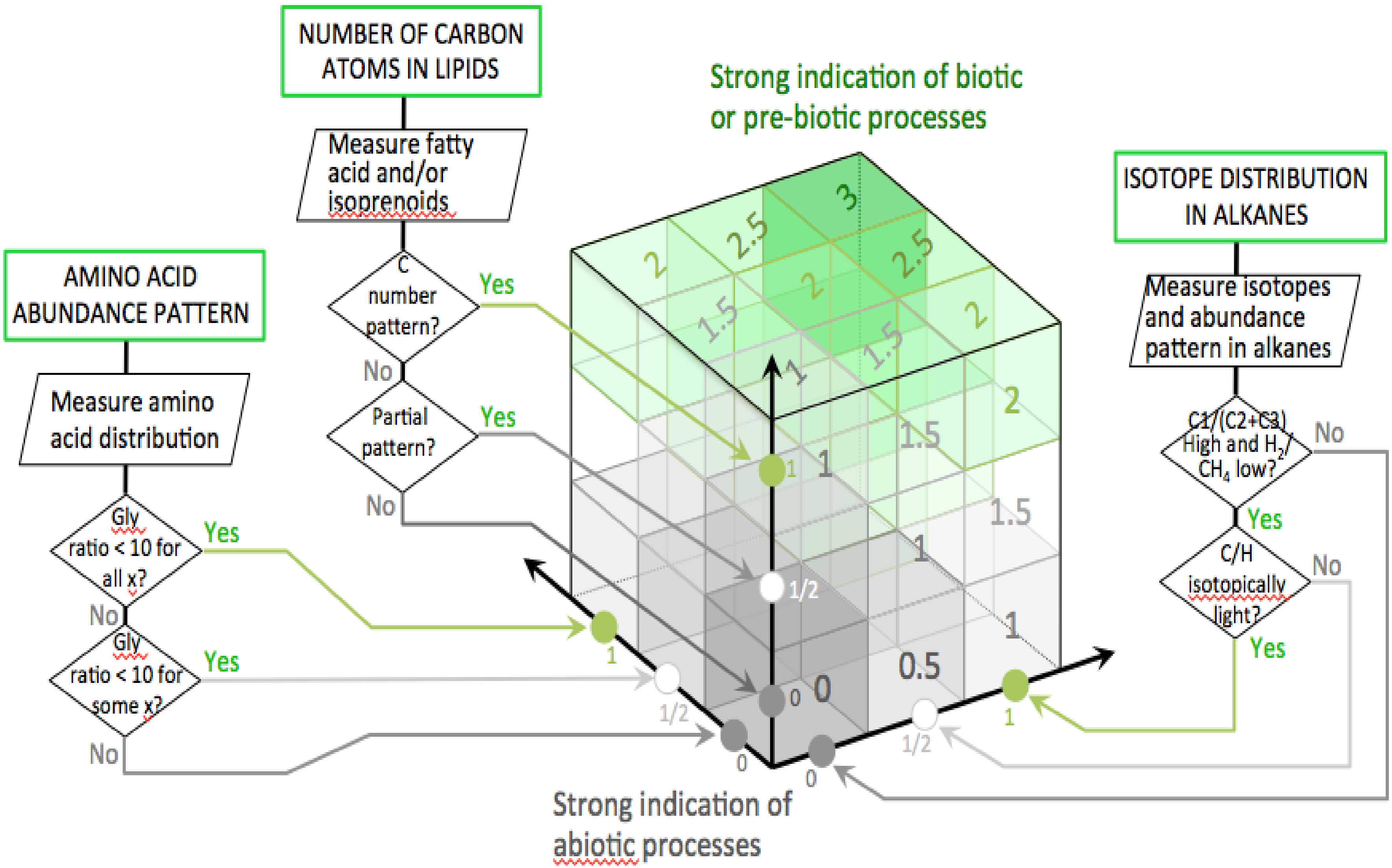
_ Parent molecules of detected light hydrocarbons

_ Disequilibria and hi-temp alteration (eg, isotopes)

_ Biologically produced abundance patterns in constituents (eg, amino, fatty, nucleobases, others)



Concentration Relative to Gly
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
Gly
Ala
Glu
Asp
Ser
Meteorites
Atacama Soils
Antarctic Endoliths


NUMBER OF CARBON ATOMS IN LIPIDS
Measure fatty acid and/or isoprenoids
C number pattern?
Yes
No
Partial pattern?
Yes
No
AMINO ACID ABUNDANCE PATTERN
Measure amino acid distribution
Gly ratio < 10 for all x?
Yes
No
Gly ratio < 10 for some x?
Yes
No
ISOTOPE DISTRIBUTION IN ALKANES
Measure isotopes and abundance pattern in alkanes
C1/(C2+C3) High and H$_2$/CH$_4$ low?
No
Yes
C/H isotopically light?
No
Yes
Strong indication of biotic or pre-biotic processes
Strong indication of abiotic processes
3
2.5
2.5
2
2
2
2
1.5
1.5
1.5
1.5
1
1
1
1
1
1
0.5
0
1/2
1/2
1/2
0
0
0

HOW COULD WE FIND OUT?

Sample the plume & analyze the ocean!

. Characterize the environment & its evolution

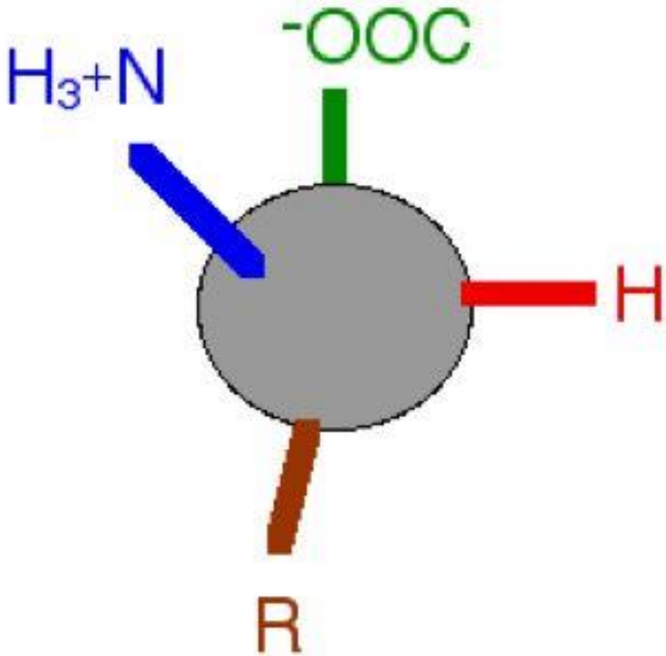
. Search for:

_ Parent molecules of detected lighter species

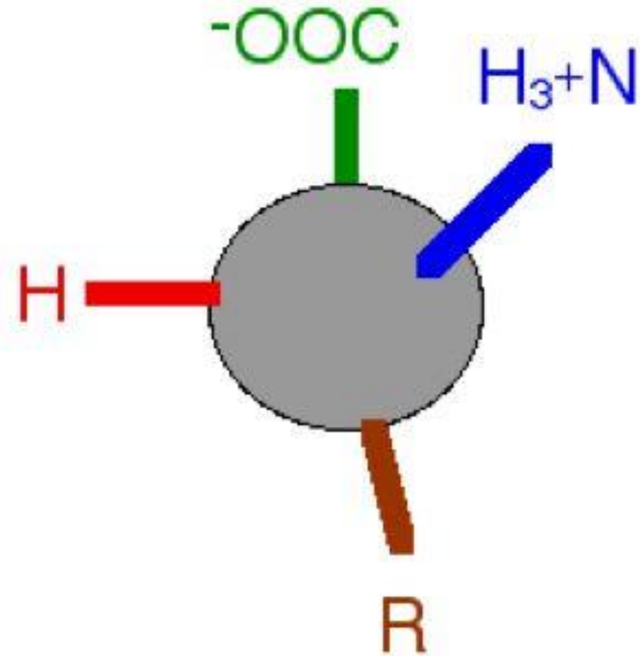
_ Disequilibria and hi-temp alteration (eg, isotopes)

_ Biologically produced abundance patterns in constituents (eg, amino, fatty, nucleobases, others)

_ Chirality



L - amino acids
used in proteins



D - amino acids
not in proteins

HOW COULD WE FIND OUT?

Sample the plume & analyze the ocean!

. Characterize the environment & its evolution

. Search for:

_ Parent molecules of detected lighter species

_ Disequilibria and hi-temp alteration (eg, isotopes)

_ Biologically produced abundance patterns in constituents (eg, amino, fatty, nucleobases, others)

_ Chirality

_ Are there Enceladan microbes in largest ice grains?

➔ imaging microscope!

WHAT KINDS OF MISSIONS?

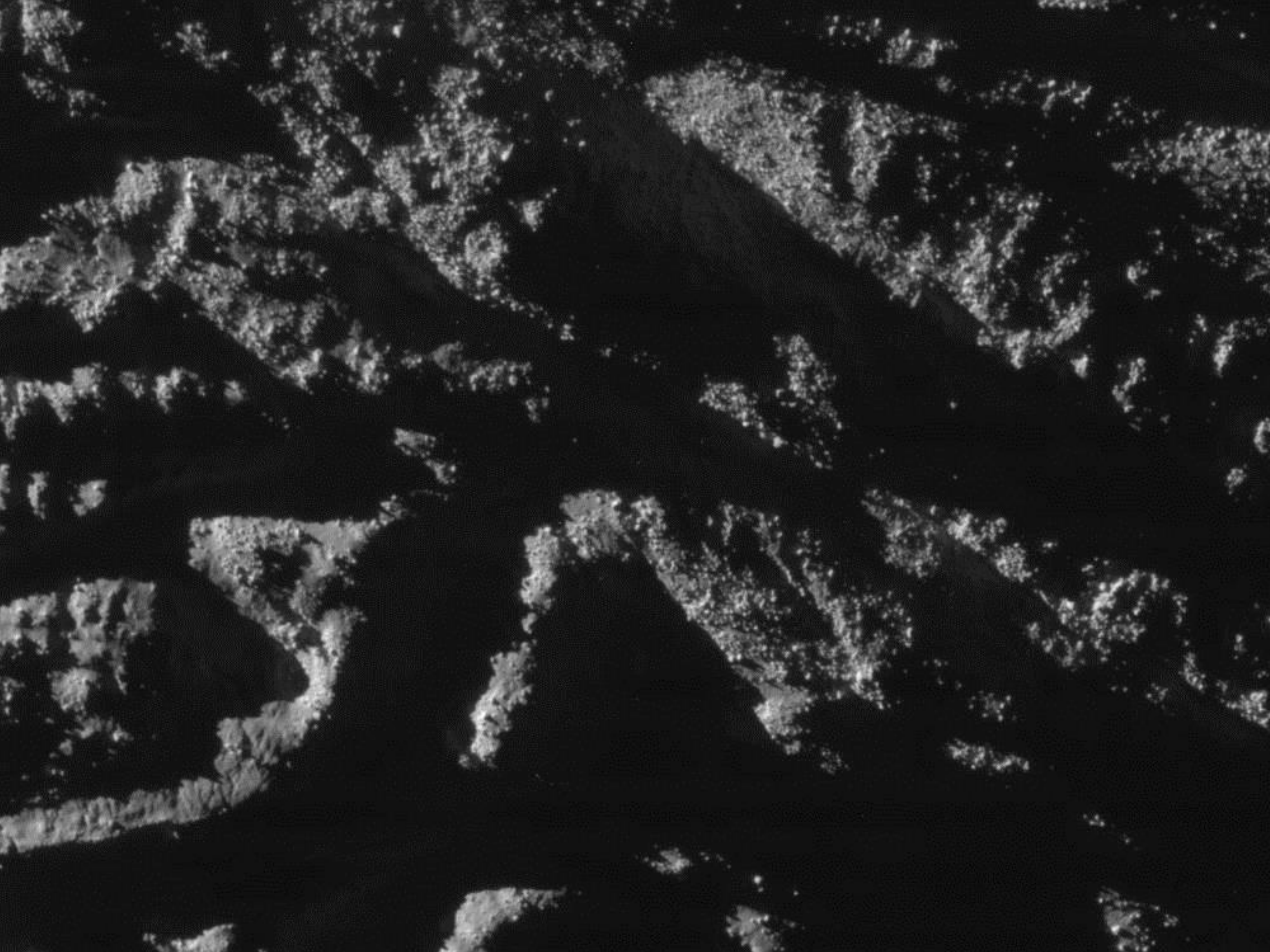
. Saturn orbiter with plume fly-throughs (being studied)

. Sample return with fly-through for *in-situ* corroboration (being studied)

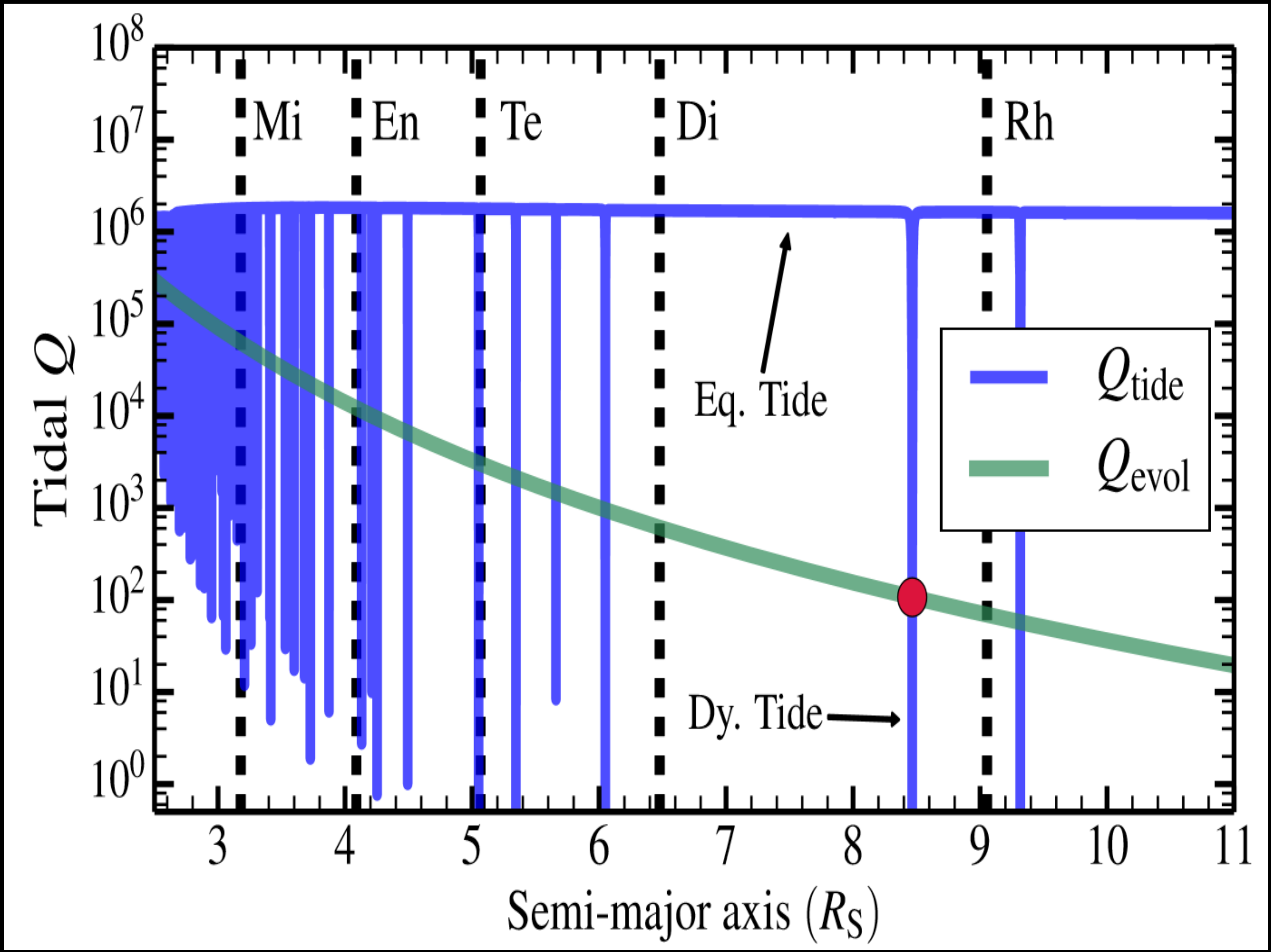
. It’s snowing all the time!

- Landers? Not necessary for astrobiology
- Enceladus orbiter → soft capture

THE END



Modeling Saturnian Tides

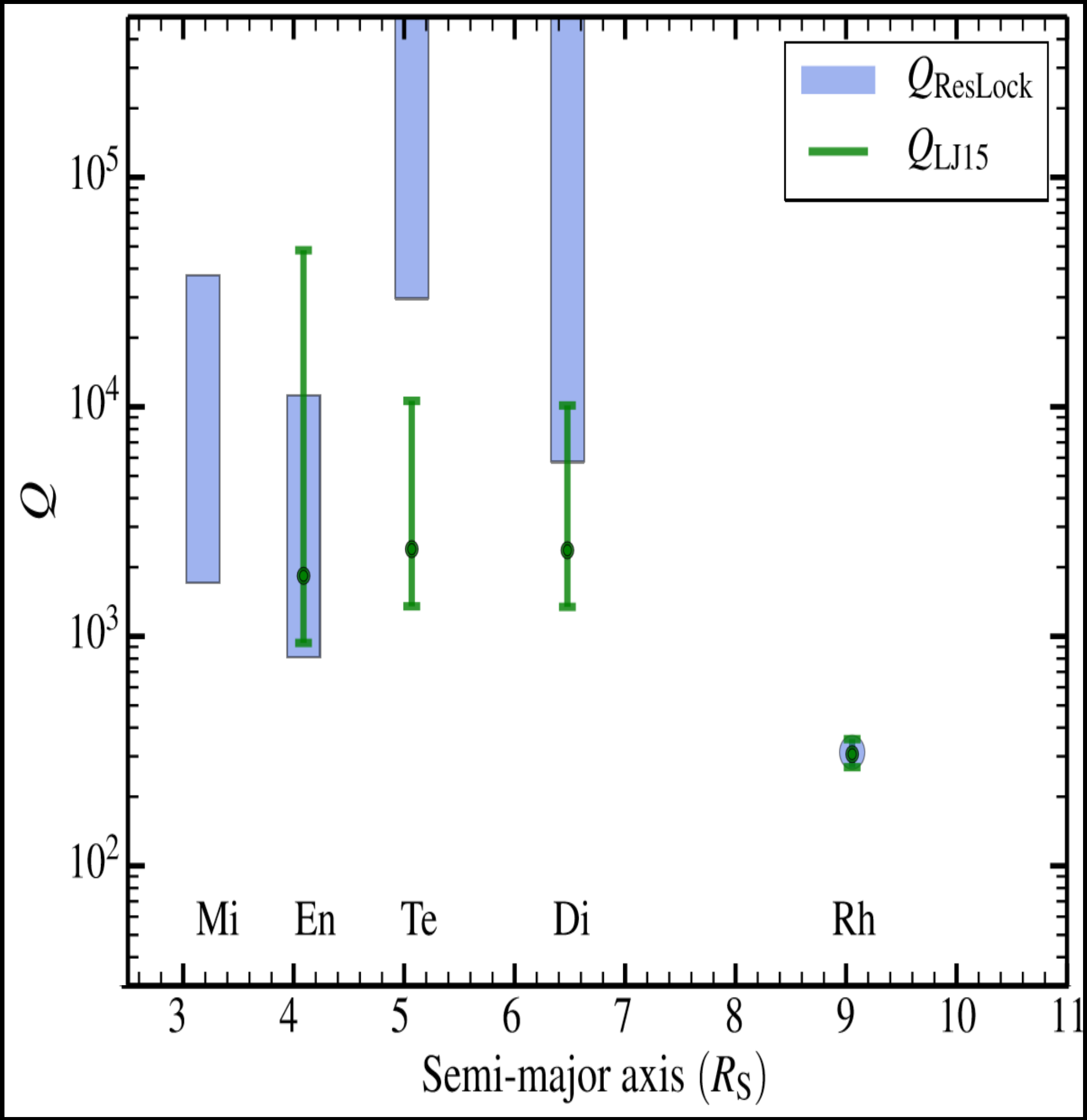


Measurements

- Outward migration rates measured by Lainey et al. (2009,2012,2015) using astrometric data

- Measured effective *Q* values are different from one another and smaller than expected

- Inconsistent with equilibrium tides



CONCLUSIONS

- *Enceladus has a subsurface ocean w/ a thicker lens beneath its SPT (Gravity results, ISS topography, libration)*
- *Geysers are surface manifestation of deep cracks, modulated in width by normal tidal stresses, reaching to sea below.*
- *Liquid water may be present within few km's of the surface and maybe ON the surface!*
- *Greatest source of 4GW of heat emitted by the tiger stripe fractures is the condensation of vapor, arising from sea below, onto the crack walls within ~50 - 100m of the surface.*
- *Shell flexure and viscous bulk heating may explain any heat, if present, produced throughout the SPT. Data from last 2015 flybys should tell.*

CONCLUSIONS (cont'd)

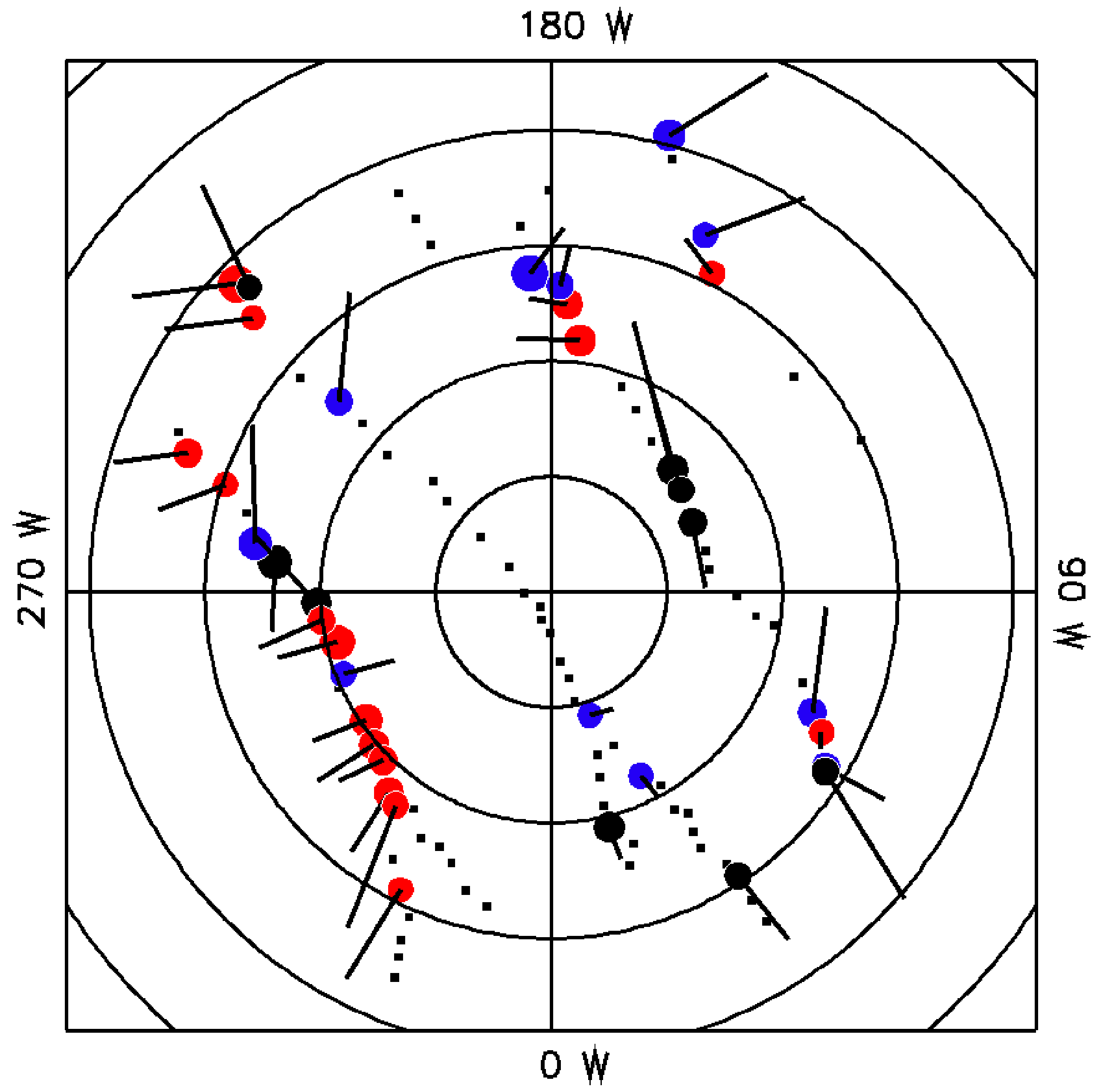
- *What is ultimate source of heat? Enc:Dione*
- *Heat produced long ago and today through tidal flexure is escaping today in form of liquid. Regional heat?*
- *Tidal Q lower than assumed ➔ enough heat to match observed*

- *Sea is salty and suffused with organic materials*
- *Hydrothermal springs apparently exist at ocean bottom*
- *Could it be snowing microbes?*

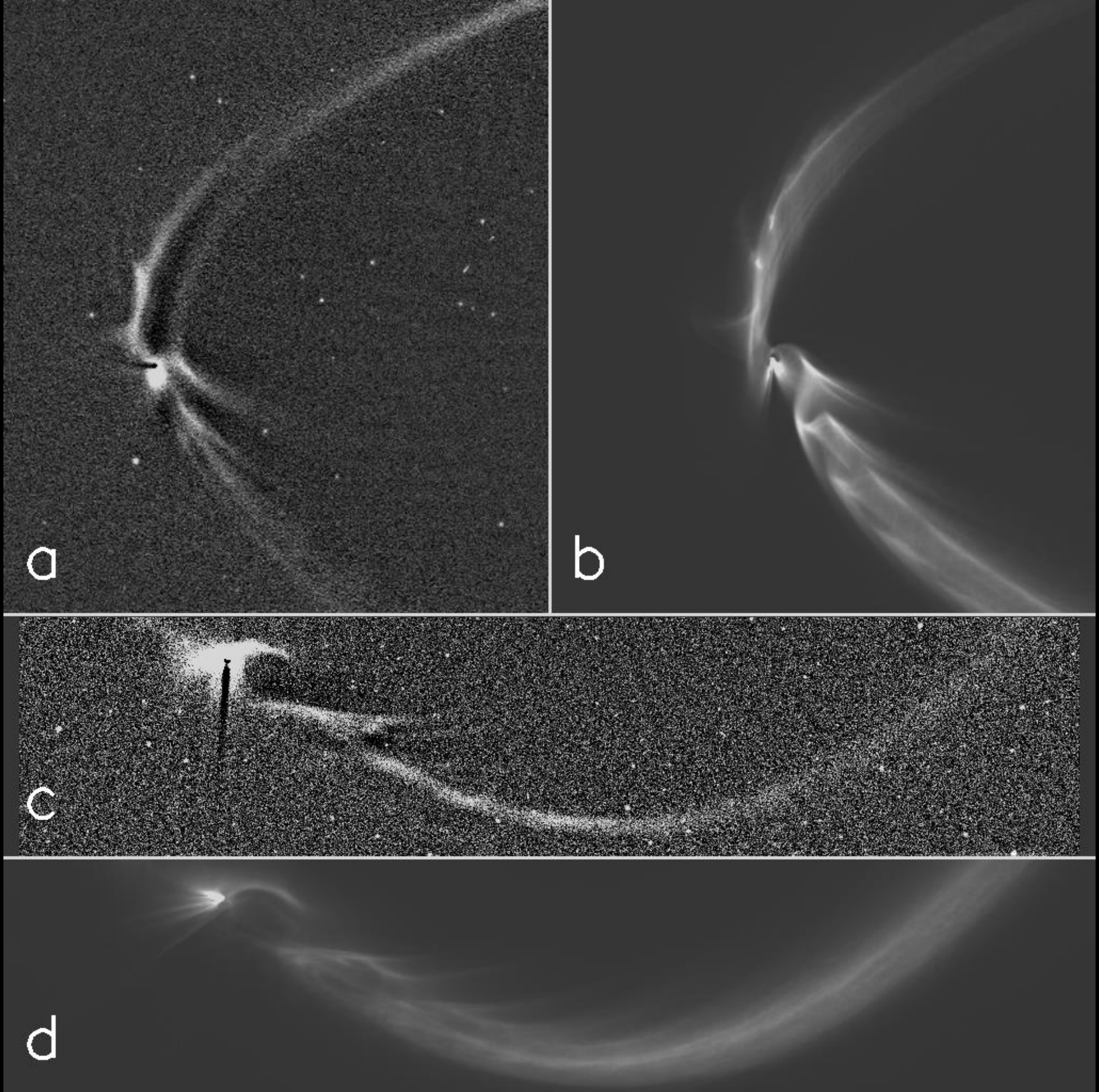
AN ACCESSIBLE HABITABLE WORLD!

Enceladus Vicinity


Phase: 175 deg
128 km/pix



180 W
270 W
90 W
0 W


a
b
c
d

CAN WATER-FILLED CRACKS PROPAGATE THROUGH DUCTILE LAYER?

From Crawford&Stevenson (1988), two conditions, mechanical & thermal, must be satisfied for upwards propagation:

A. Stresses must exceed a critical value for water cracks to propagate.

On Enc: Minimum tensile stress required ~ 5kPa

Typical tidal stresses over regional subsurface sea ~ 50 kPa

➔ no problem fracturing even ductile ice

Maximum crack length for 100 kPa stresses ~ 20 km, comparable to the expected shell thickness

B. Propagation time < freezing time (bigger problem)

On Enc: Freezing time scale is dependent on crack width, Wc.

➔ If Wc >/~ 0.5 m, water-filled crack can propagate thru shell before freezing

Propagation speeds: a few to 10 cm/sec for 0.1 m <Wc < 1 m

CONCLUSIONS

- *Enceladus almost certainly has a sea beneath its SPT & with recent libration results, a thin global ocean too. New Cassini gravity results are consistent with this.*
- *Jets are surface manifestation of deep cracks, formed by normal tidal stresses, reaching to sea below.*
- *Plume variability seen by VIMS and ISS, and lack of evidence for shear heating, supports the suggestion that normal, not shear, tidal stresses modulate the jetting activity.*
- *Liquid water may be present within few km's of the surface and maybe ON the surface!*
- *Shell flexure and viscous bulk heating may explain any heat, if present, produced throughout the SPT*

CONCLUSIONS (cont'd)

- *Greatest source of 4GW of heat emitted by the tiger stripe fractures is the condensation of vapor, arising from sea below, onto the crack walls within ~50 - 100m of the surface.*

- *What is ultimate source of heat? Whatever produced the subsurface sea to begin with*

  ➔ *Heat produced long ago is escaping today*

  ➔ *Enceladus' interior structure likely varies cyclically, with brief bursts (10M yrs) of localized activity, followed by long periods (few 100M yrs) of dormancy.*

  ➔ *Some models suggest a persistent sub-surface regional sea (permissible even with equilibrium 1.1 GW power input)*

  ➔ *Longevity of global ocean?*

CONCLUSIONS (cont'd)

- *Apparent time lag of ~4 hrs between plume brightness & cap-summed fracture opening may be caused by:*

    - *a local dissipative region under SPT, thin lithosphere in fracture region, and a regional sea. (Behoukova et al…coming soon!)*

      … or …

    - *global ocean and an ice shell of variable width. To be tested...*

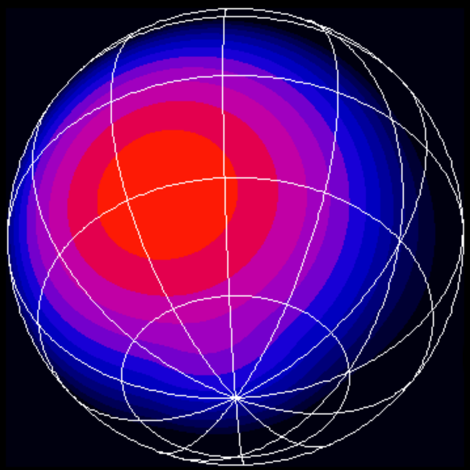
      … or …

    - *a delay in the eruptions.*

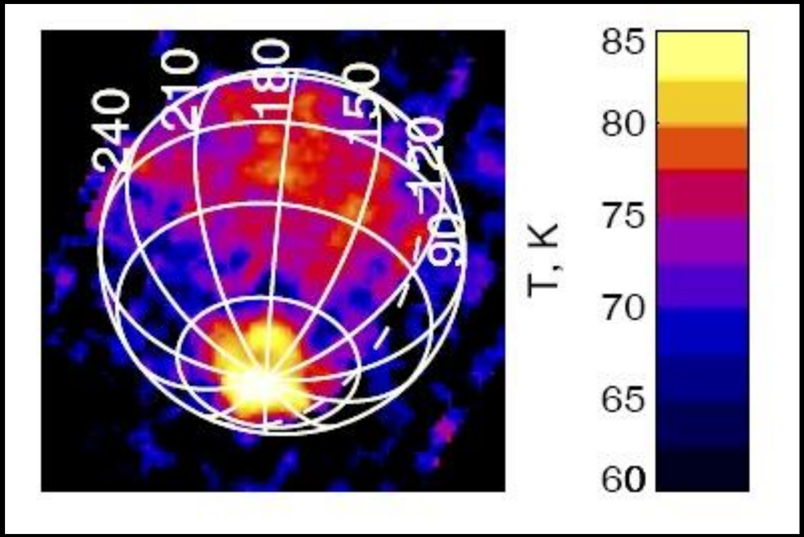
- *Sea is salty and suffused with organic materials:*

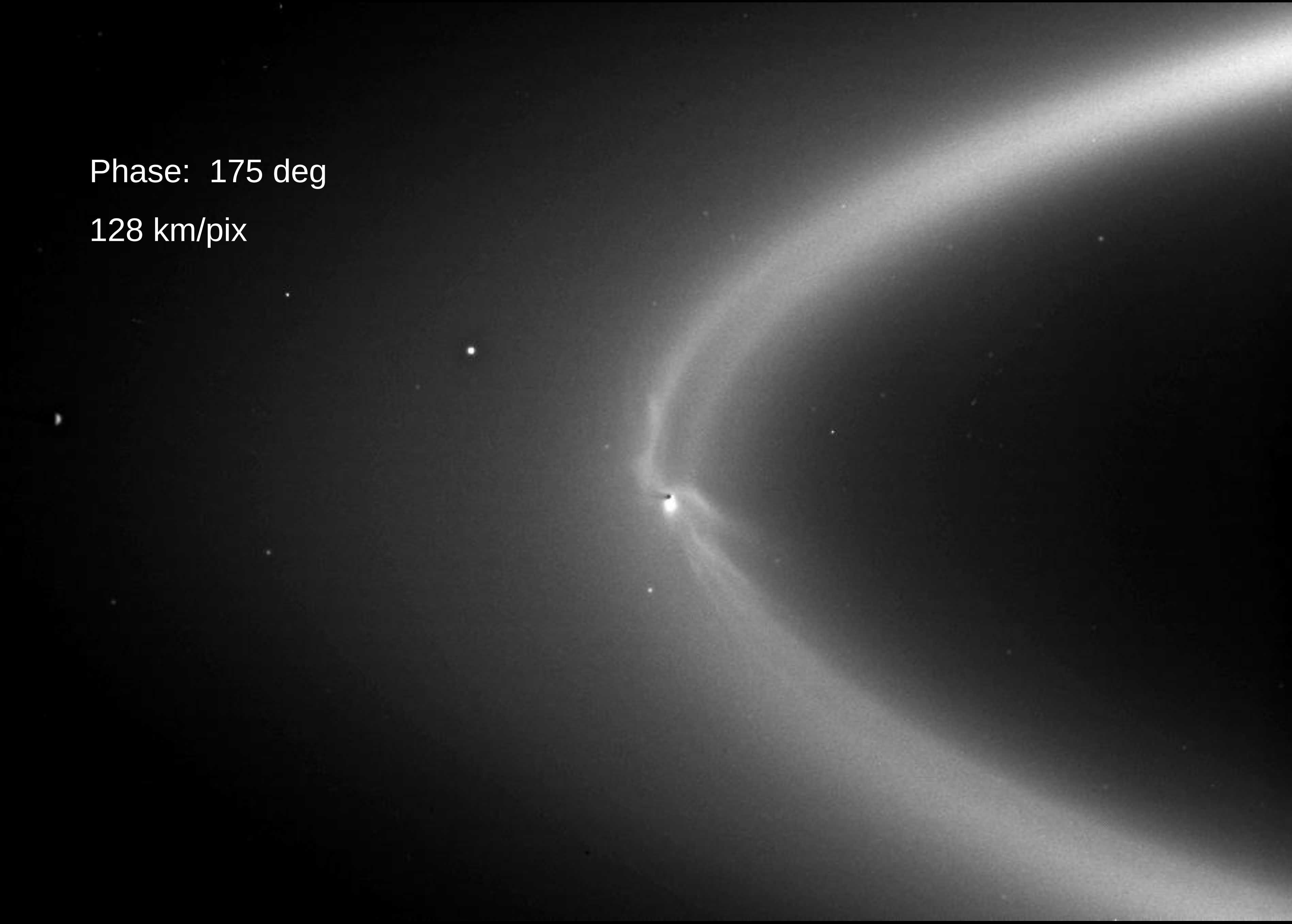
  AN ACCESSIBLE HABITABLE WORLD!!

CIRS (Cassini Infrared Spectrometer)



Predicted
Temperatures

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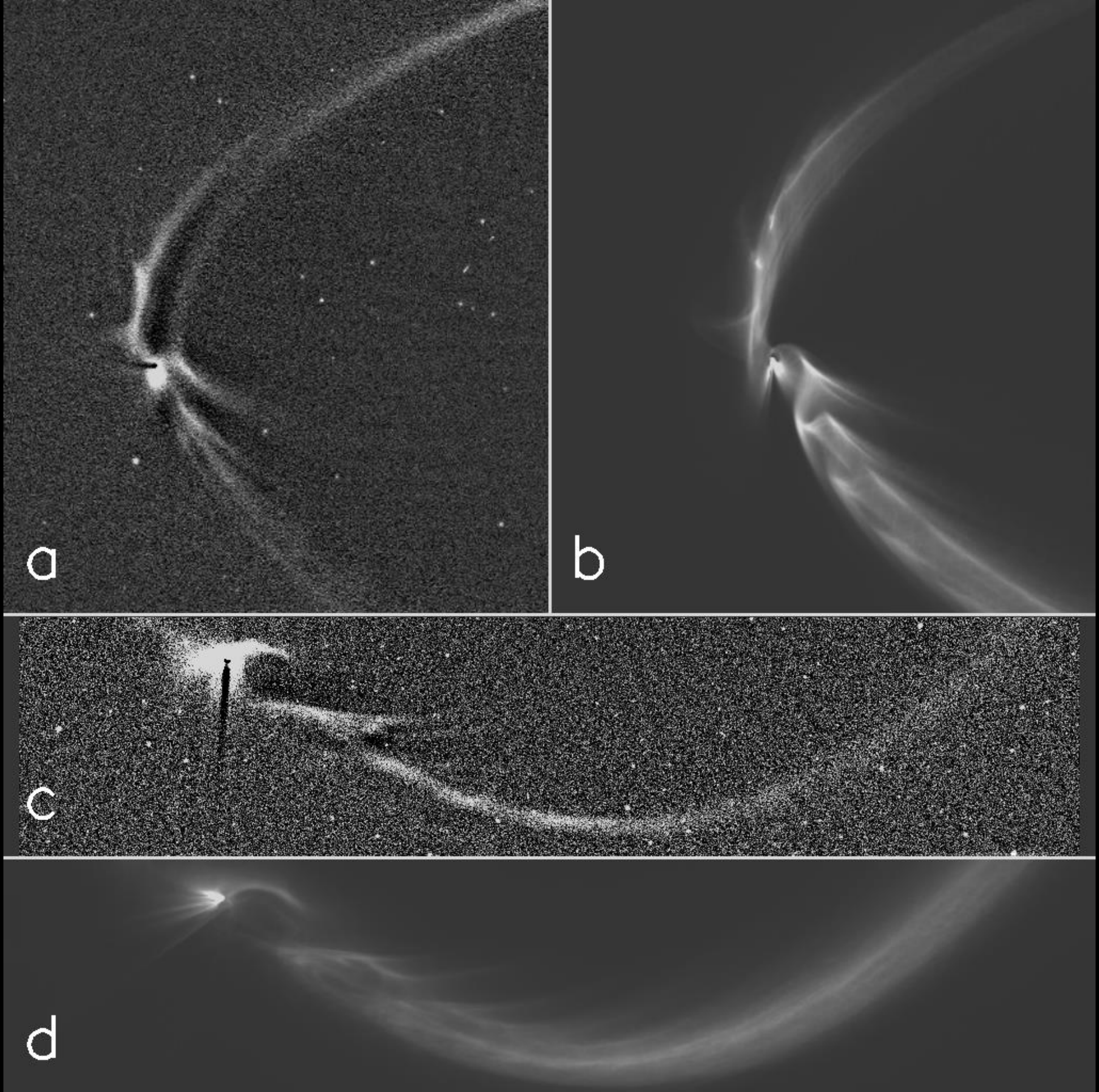
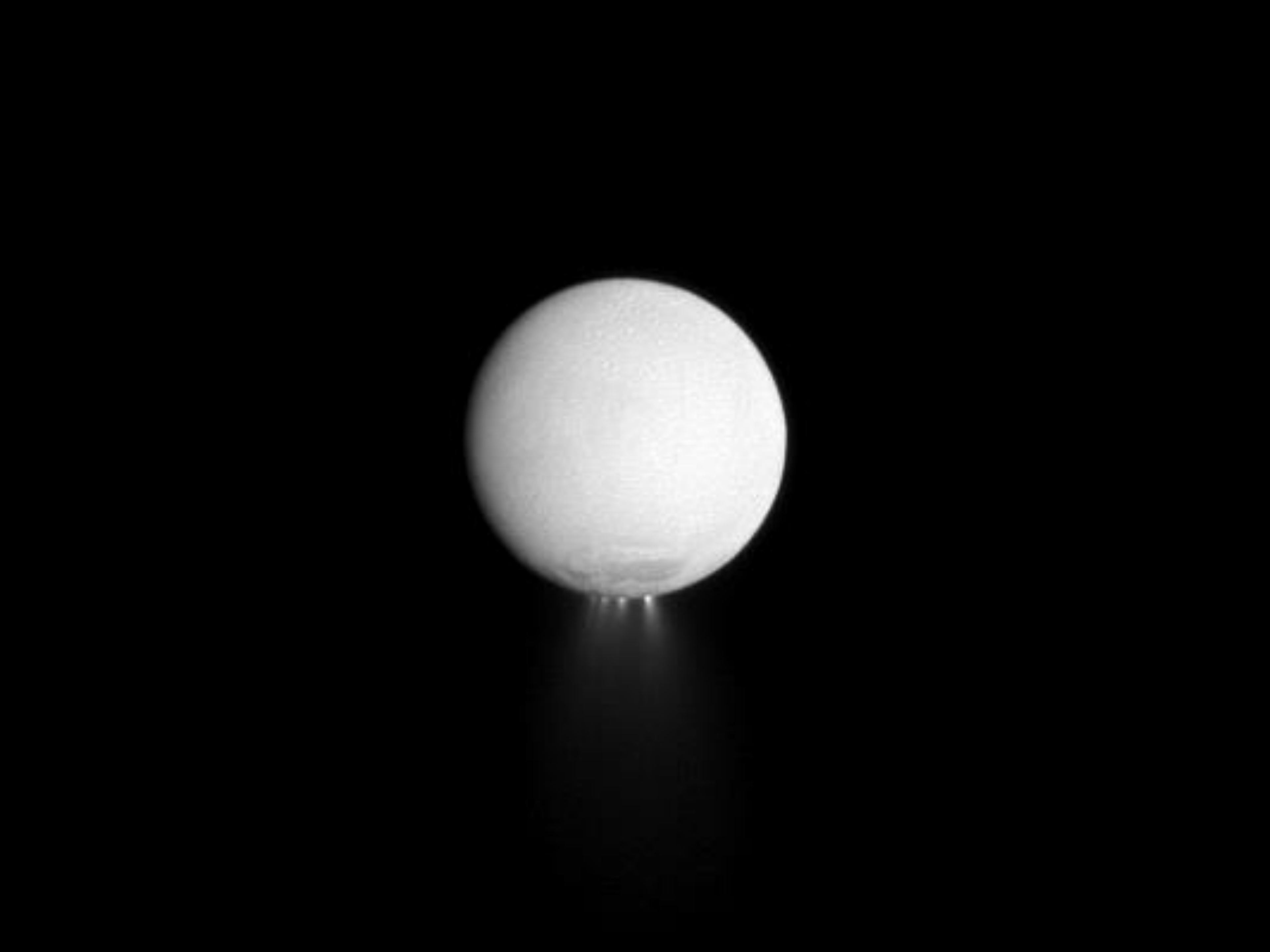
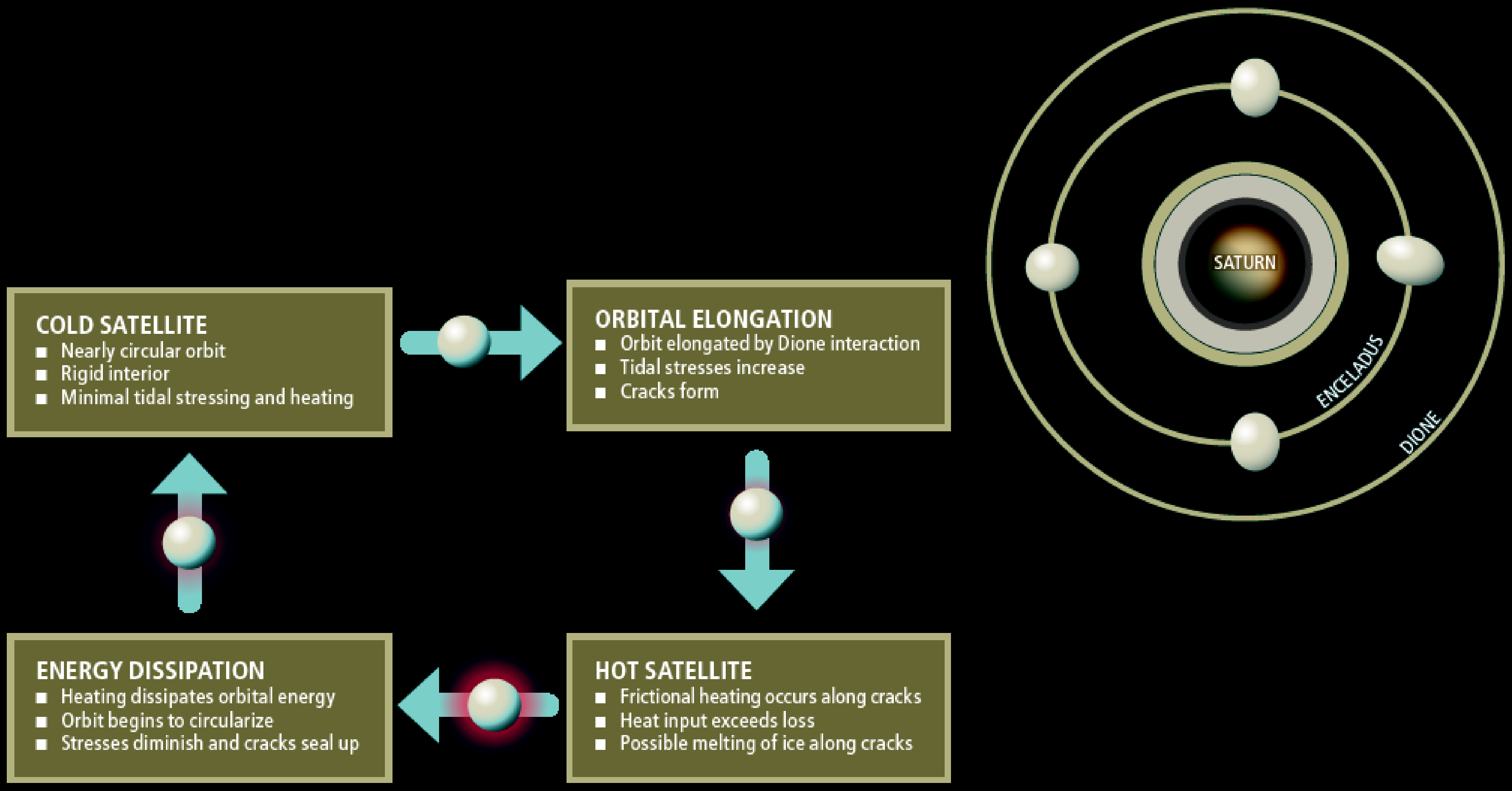
128 km/pix


a
b
c
d




COLD SATELLITE
Nearly circular orbit
Rigid interior
Minimal tidal stressing and heating
ORBITAL ELONGATION
Orbit elongated by Dione interaction
Tidal stresses increase
Cracks form
HOT SATELLITE
Frictional heating occurs along cracks
Heat input exceeds loss
Possible melting of ice along cracks
ENERGY DISSIPATION
Heating dissipates orbital energy
Orbit begins to circularize
Stresses diminish and cracks seal up
SATURN
ENCELADUS
DIONE