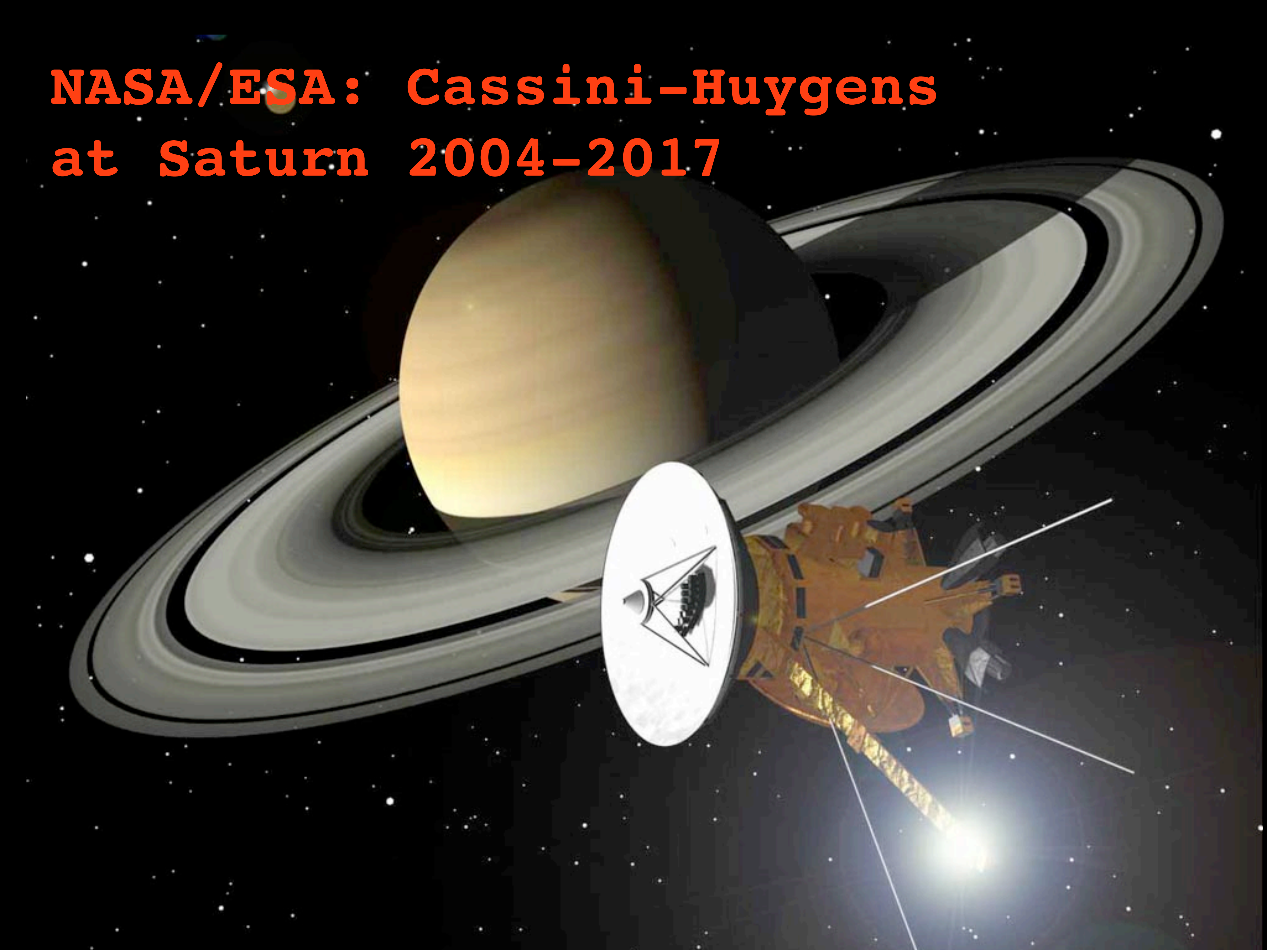
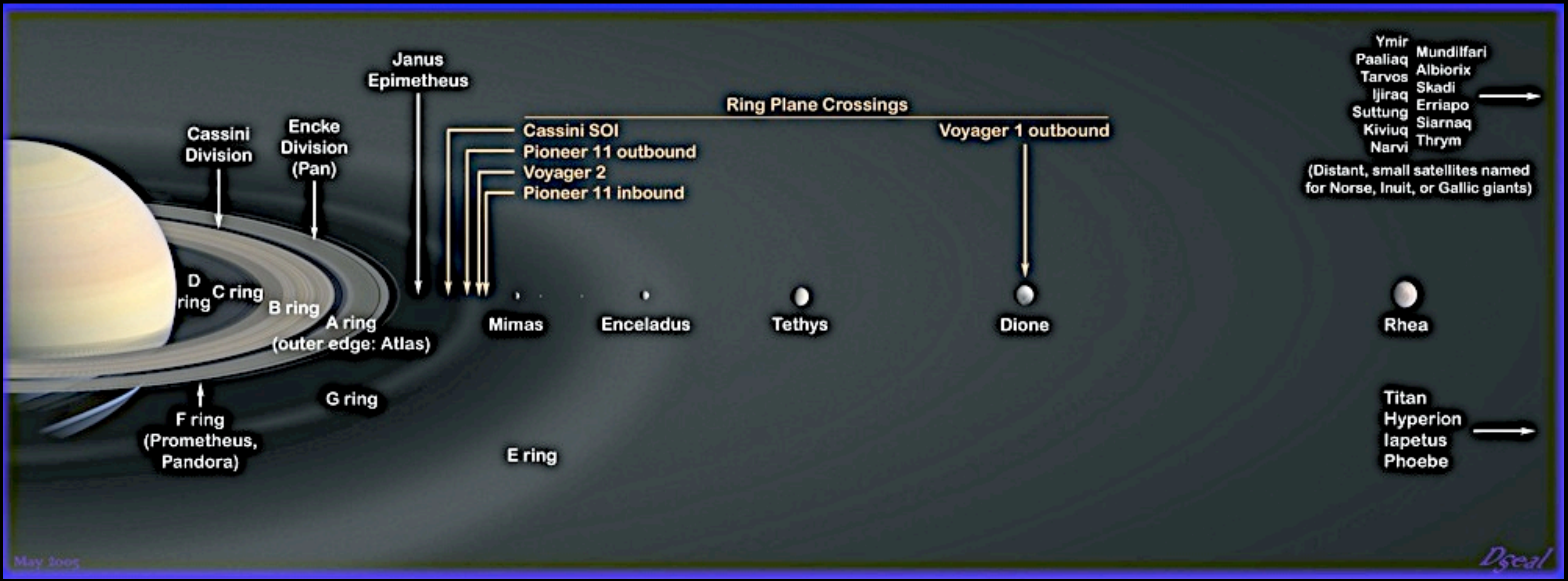
The CASSINI Cosmic Dust Analyzer: In-situ Measurements in the Plume of Saturn’s Moon Enceladus

J Schmidt, F Postberg
J Hillier, S Kempf, F Spahn
R Srama

Images: NASA/JPL

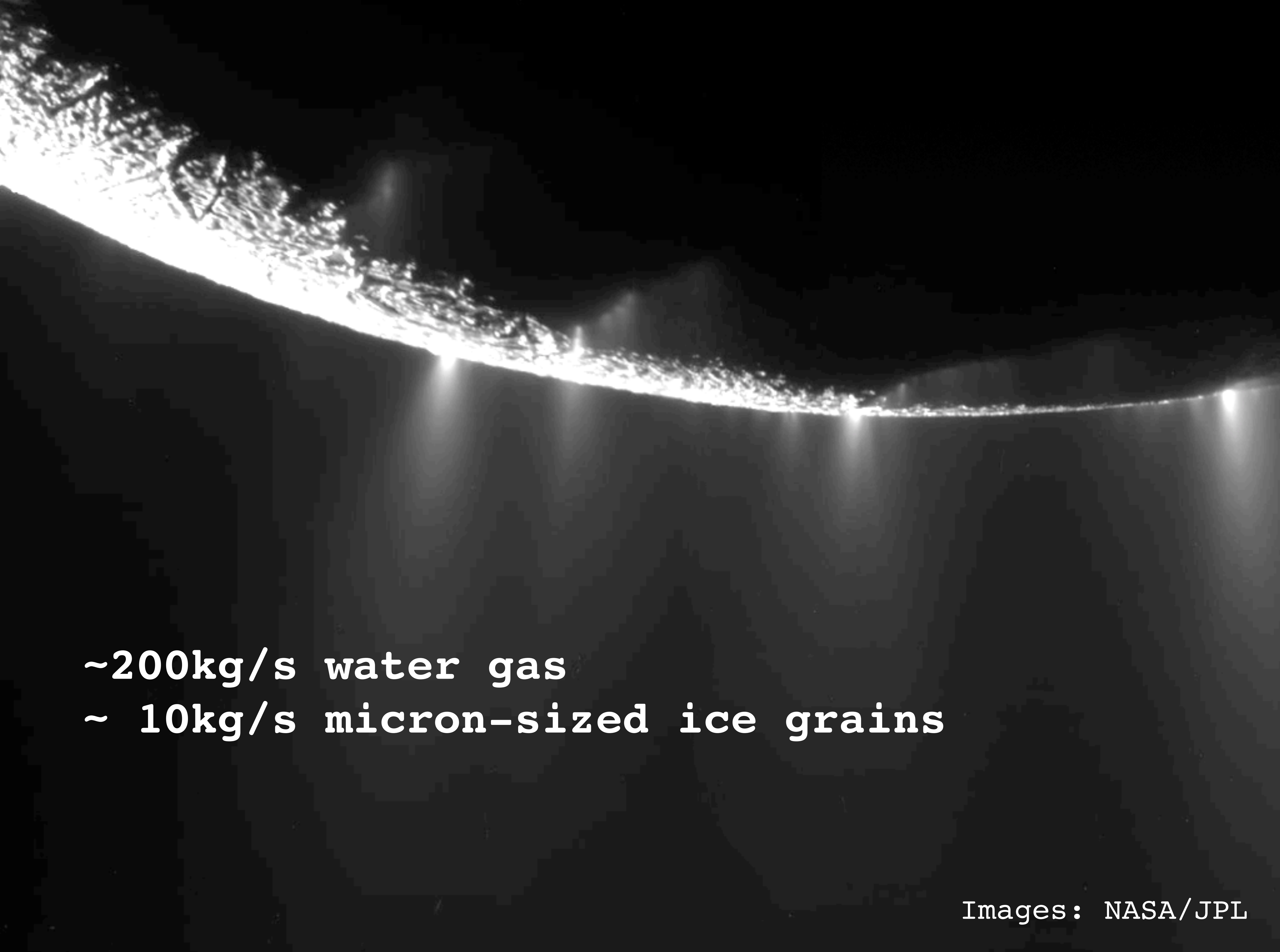
Background


NASA/ESA: Cassini-Huygens
at Saturn 2004-2017

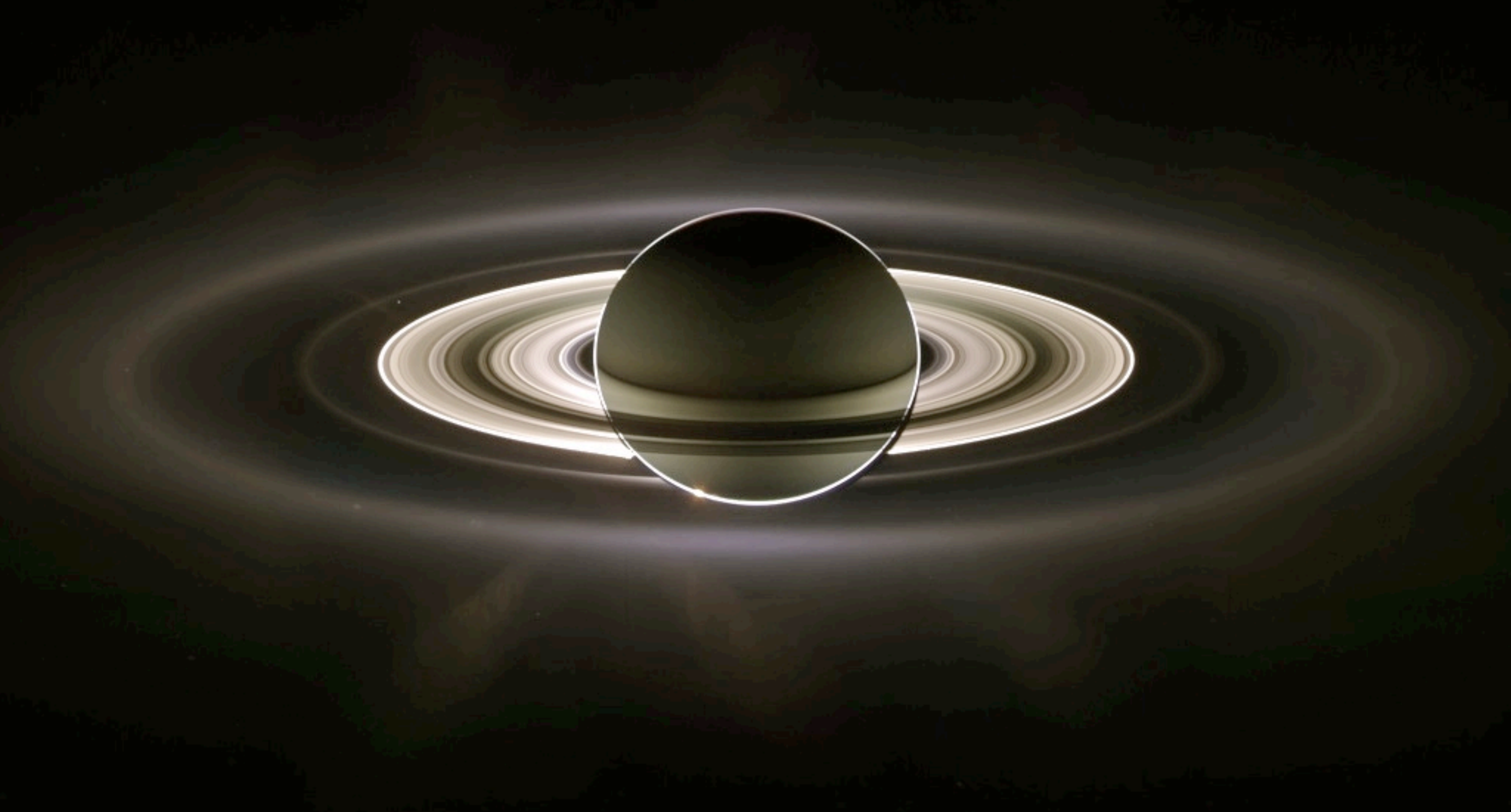

Janus
Epimetheus
Ring Plane Crossings
Cassini Division
Encke Division (Pan)
Cassini SOI
Pioneer 11 outbound
Voyager 2
Pioneer 11 inbound
Voyager 1 outbound
Ymir
Paaliaq
Tarvos
Ijiraq
Suttung
Kiviuq
Narvi
Mundilfari
Albiorix
Skadi
Erriapo
Siarnaq
Thrym
(Distant, small satellites named for Norse, Inuit, or Gallic giants)
D ring
C ring
B ring
A ring (outer edge: Atlas)
Mimas
Enceladus
Tethys
Dione
Rhea
F ring (Prometheus, Pandora)
G ring
E ring
Titan
Hyperion
Iapetus
Phoebe
May 2005
Dseal

(D Seal)


Images: NASA/JPL


~200kg/s water gas
~ 10kg/s micron-sized ice grains
Images: NASA/JPL

Enceladus plume:
supplies material for Saturn's dusty E-ring



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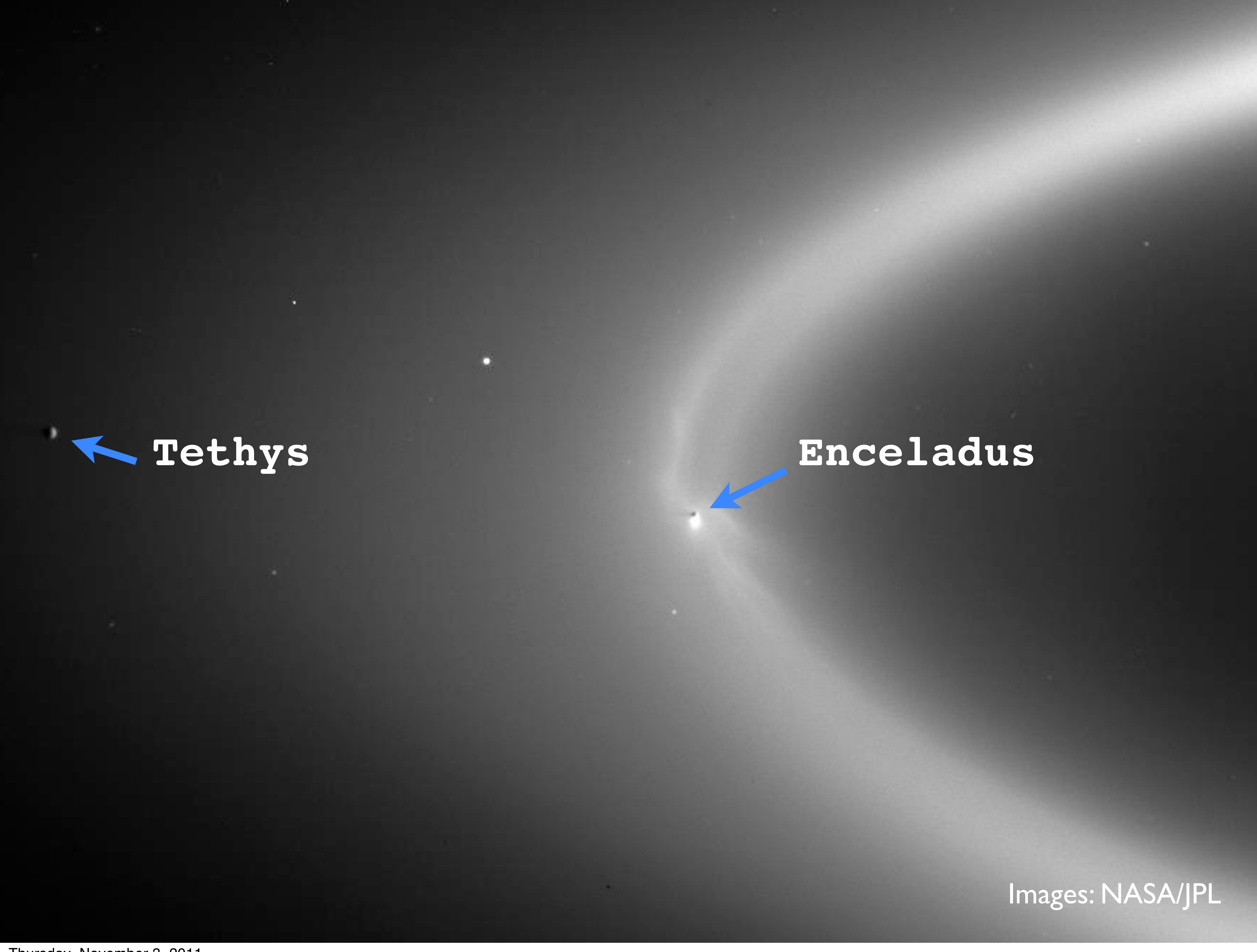
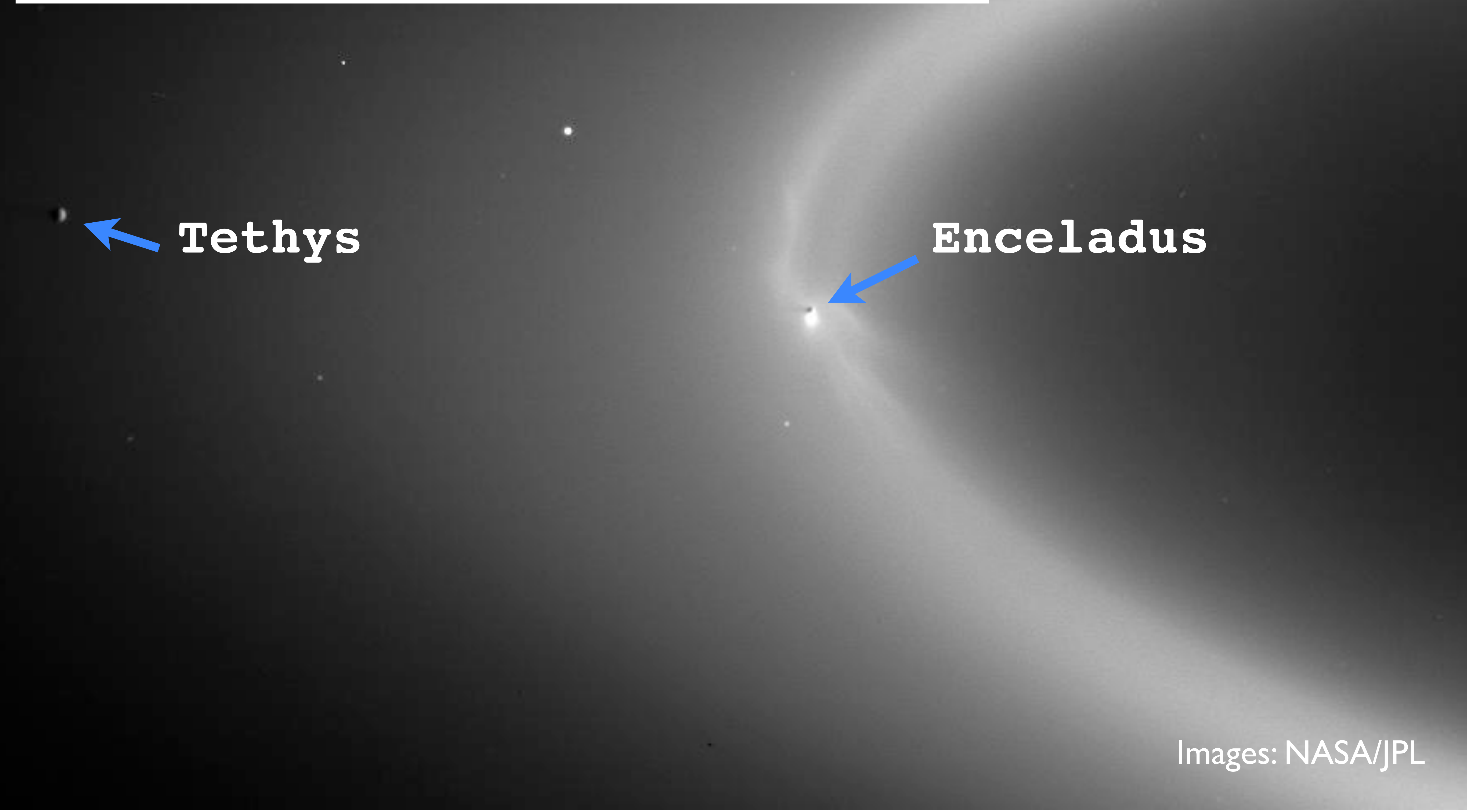
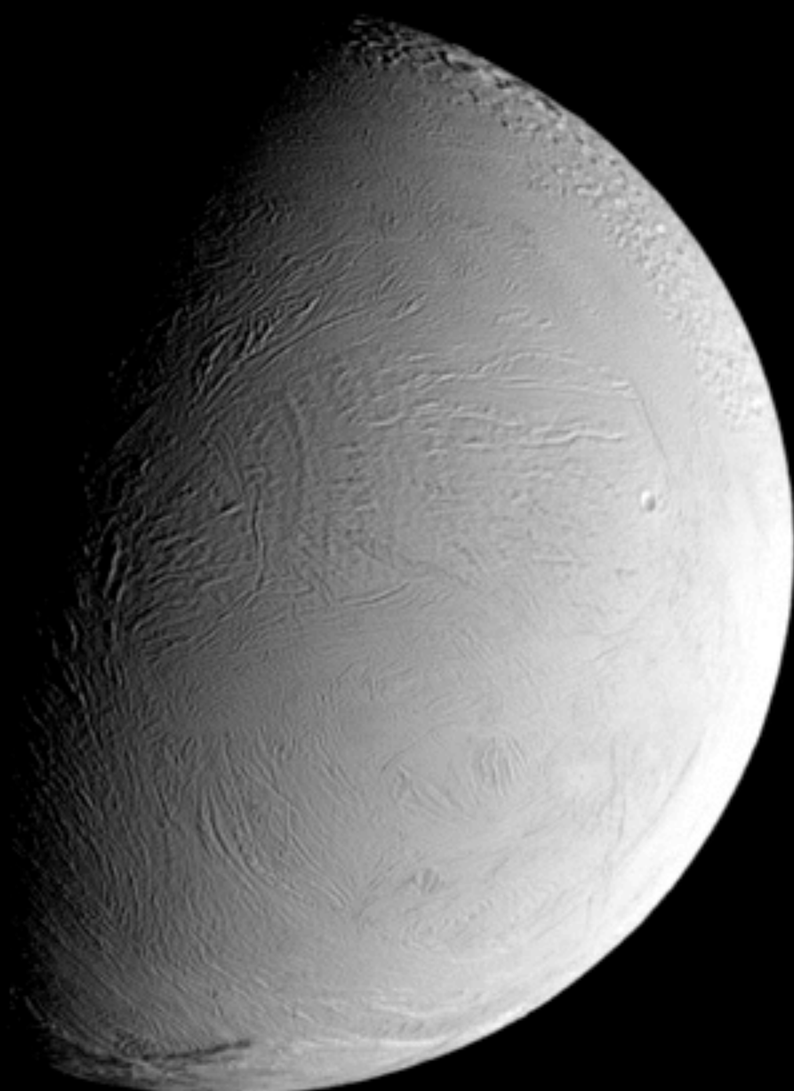

Tethys
Enceladus
Images: NASA/JPL

Showalter, Cuzzi, Larson, Icarus, 1991:
Structure and Particle Properties of Saturn's E Ring

The narrow size distribution is suggestive of a liquid or gas origin and, in this regard, the ring's close proximity to Enceladus is likely not coincidental.



Enceladus



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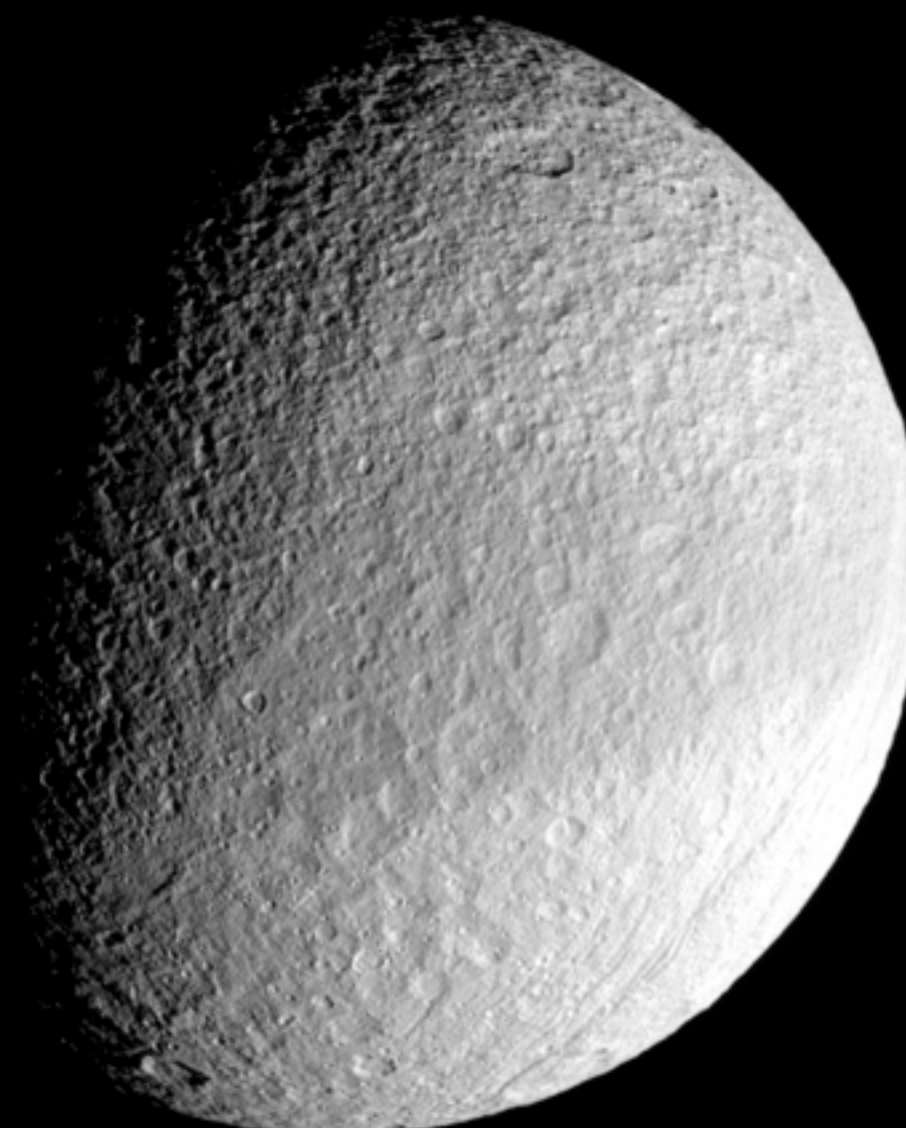
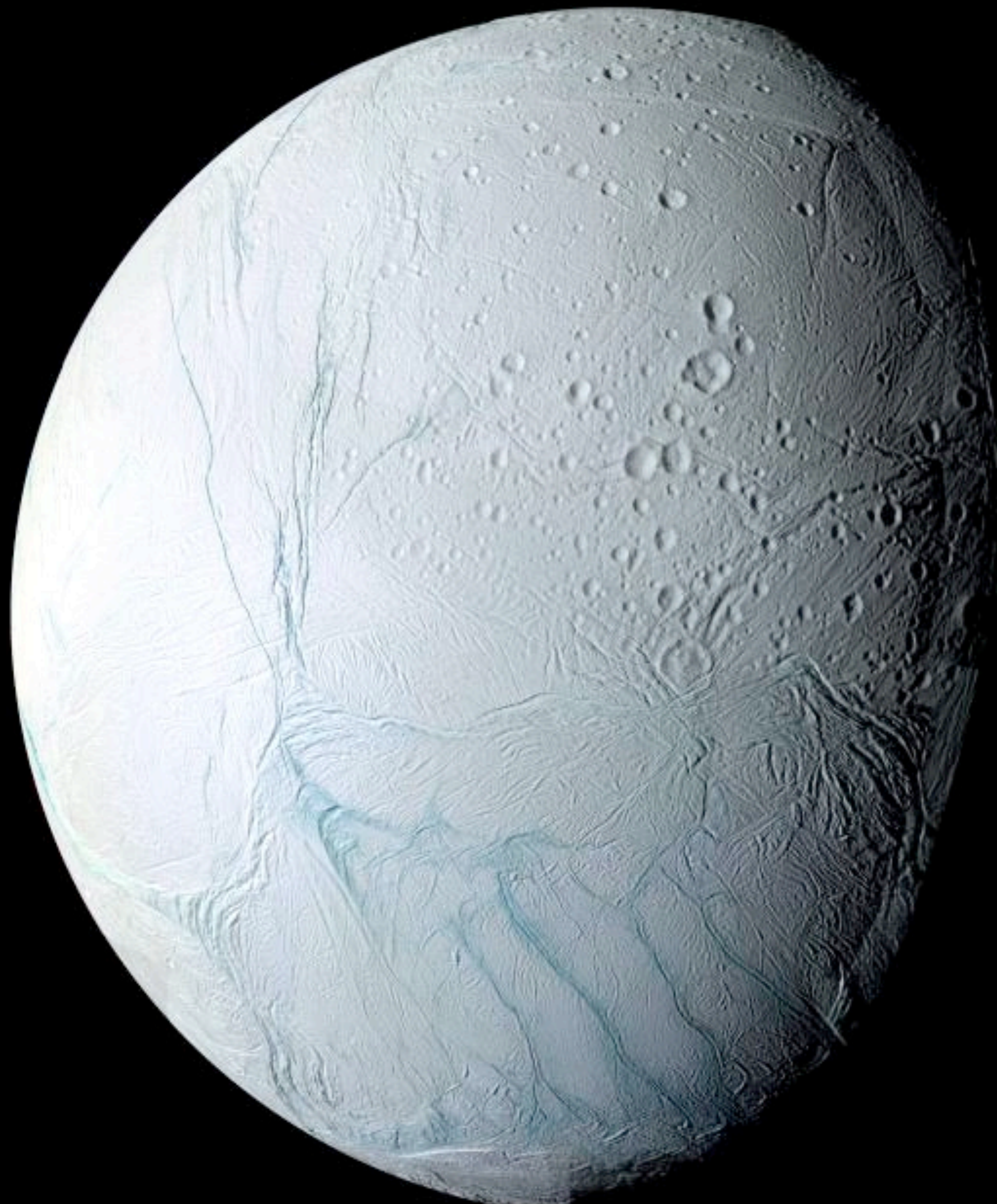


Enceladus



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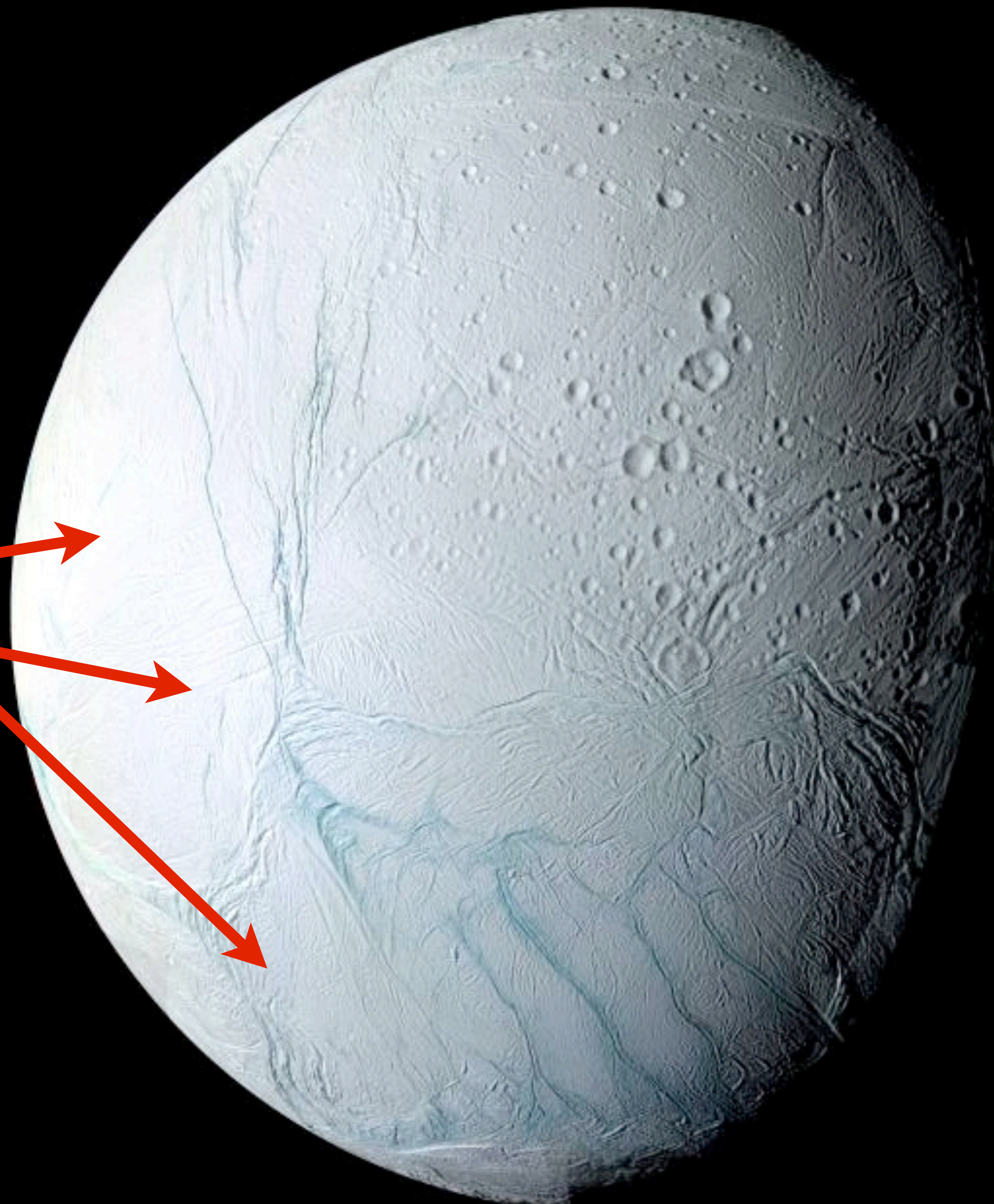
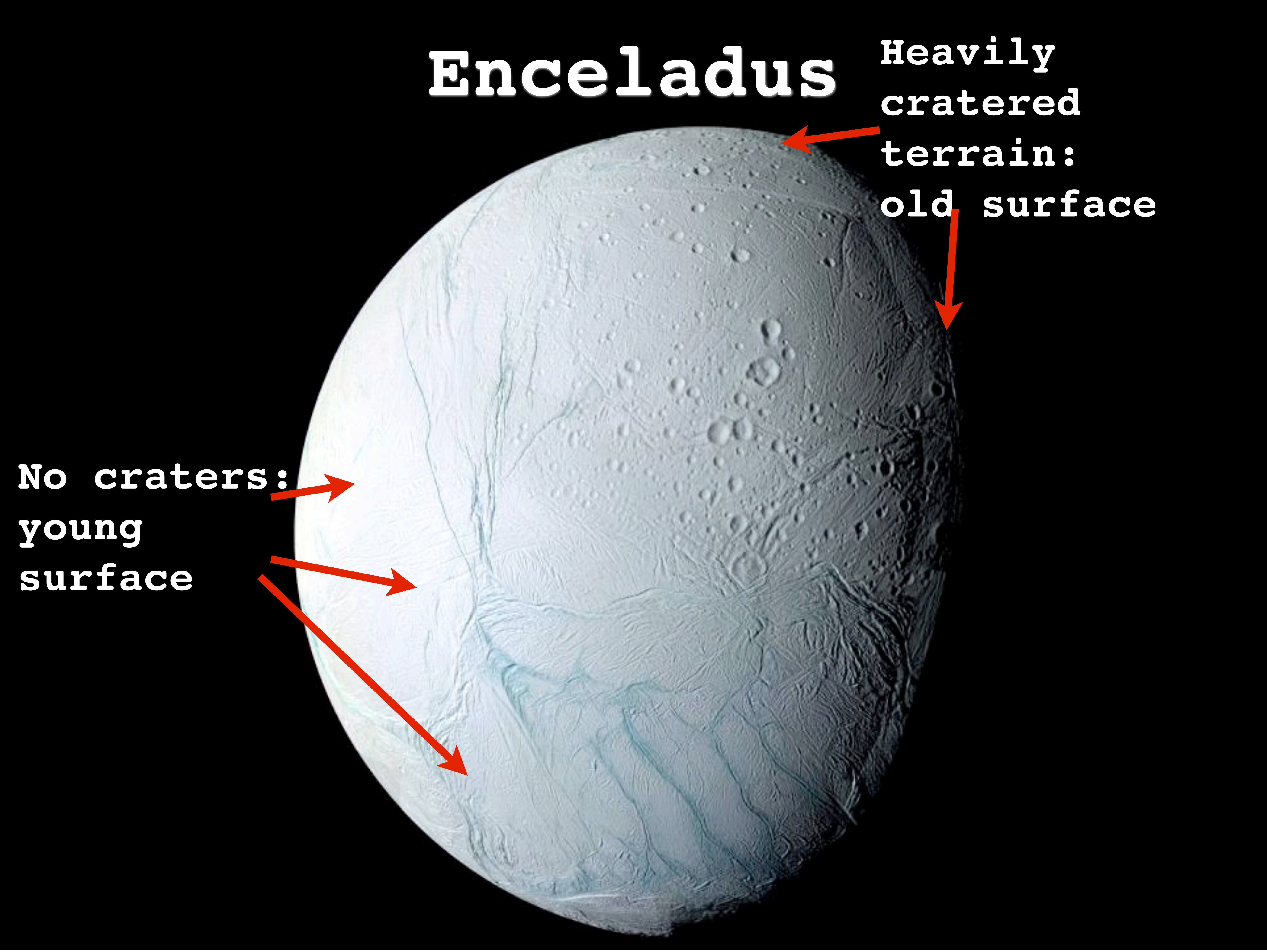


No craters:
young
surface

Enceladus


Heavily
cratered
terrain:
old surface
No craters:
young
surface

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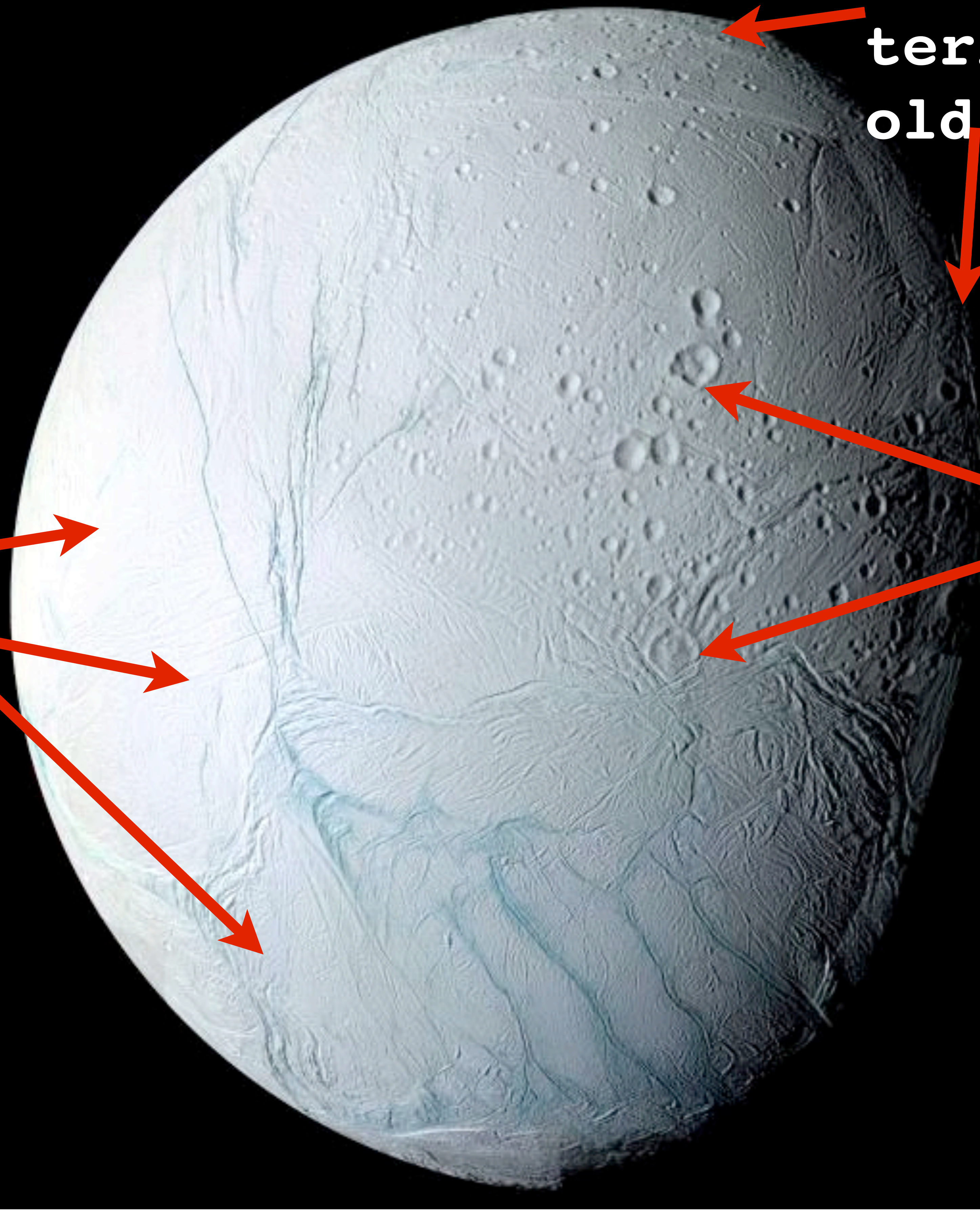
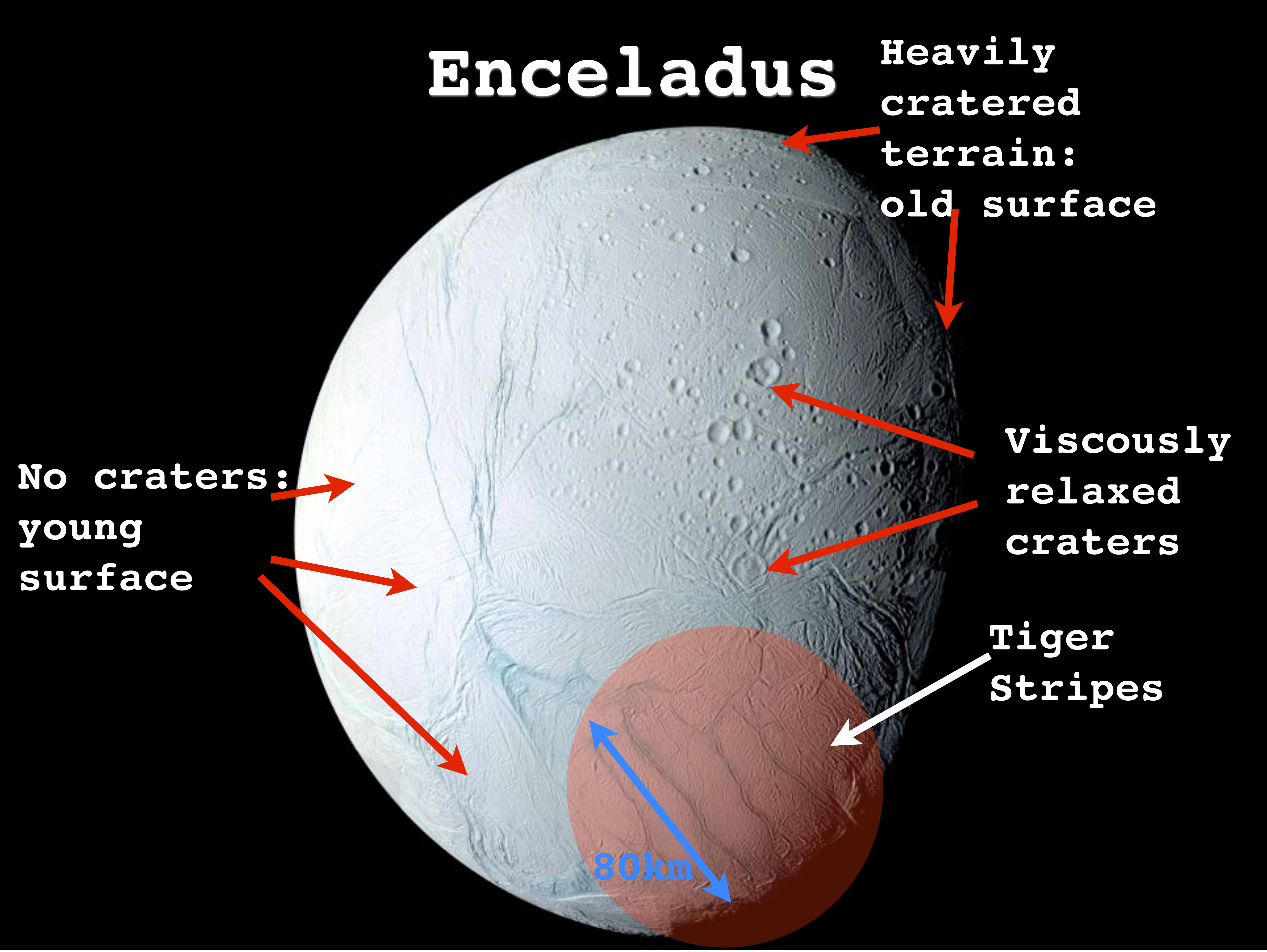
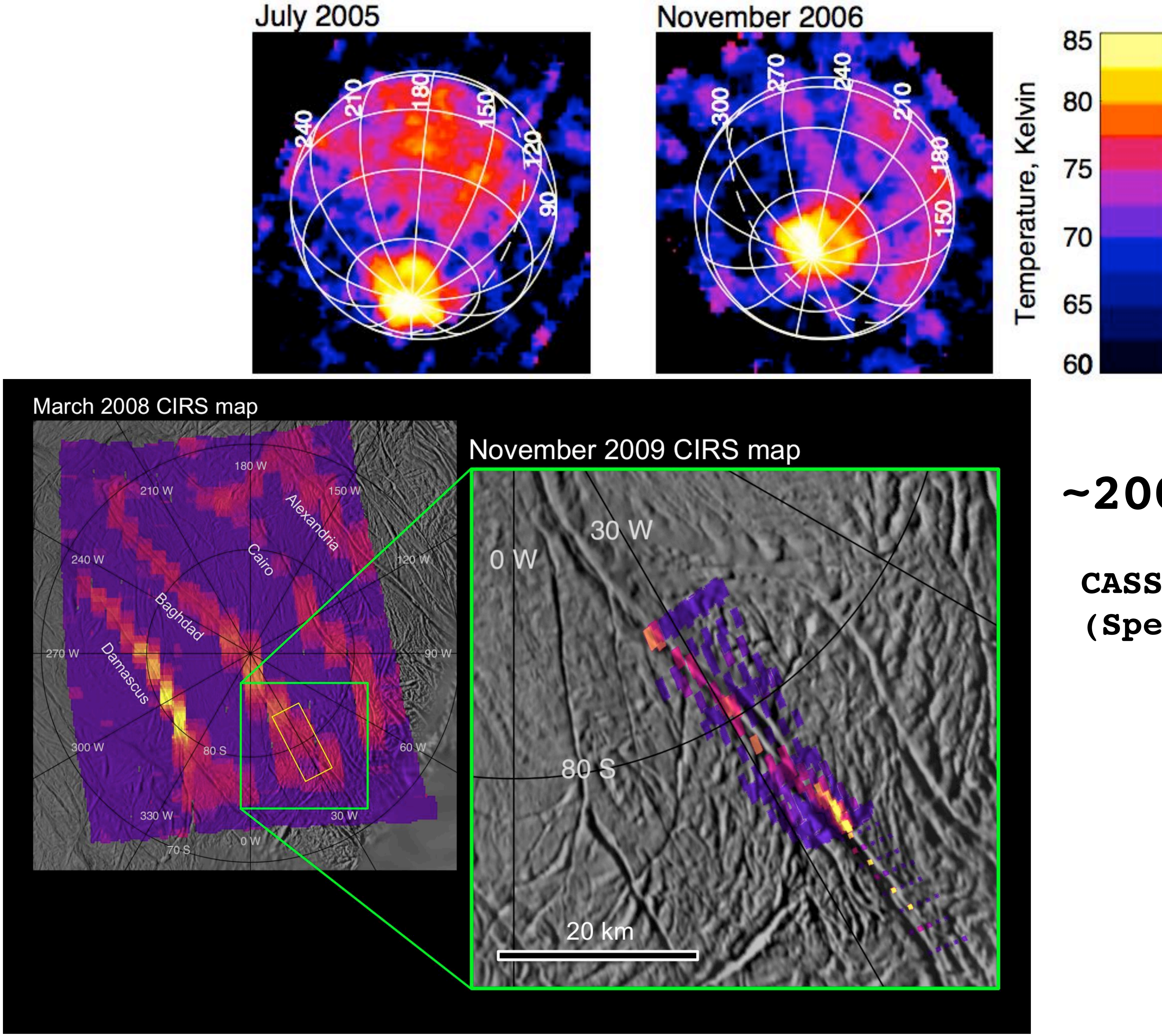
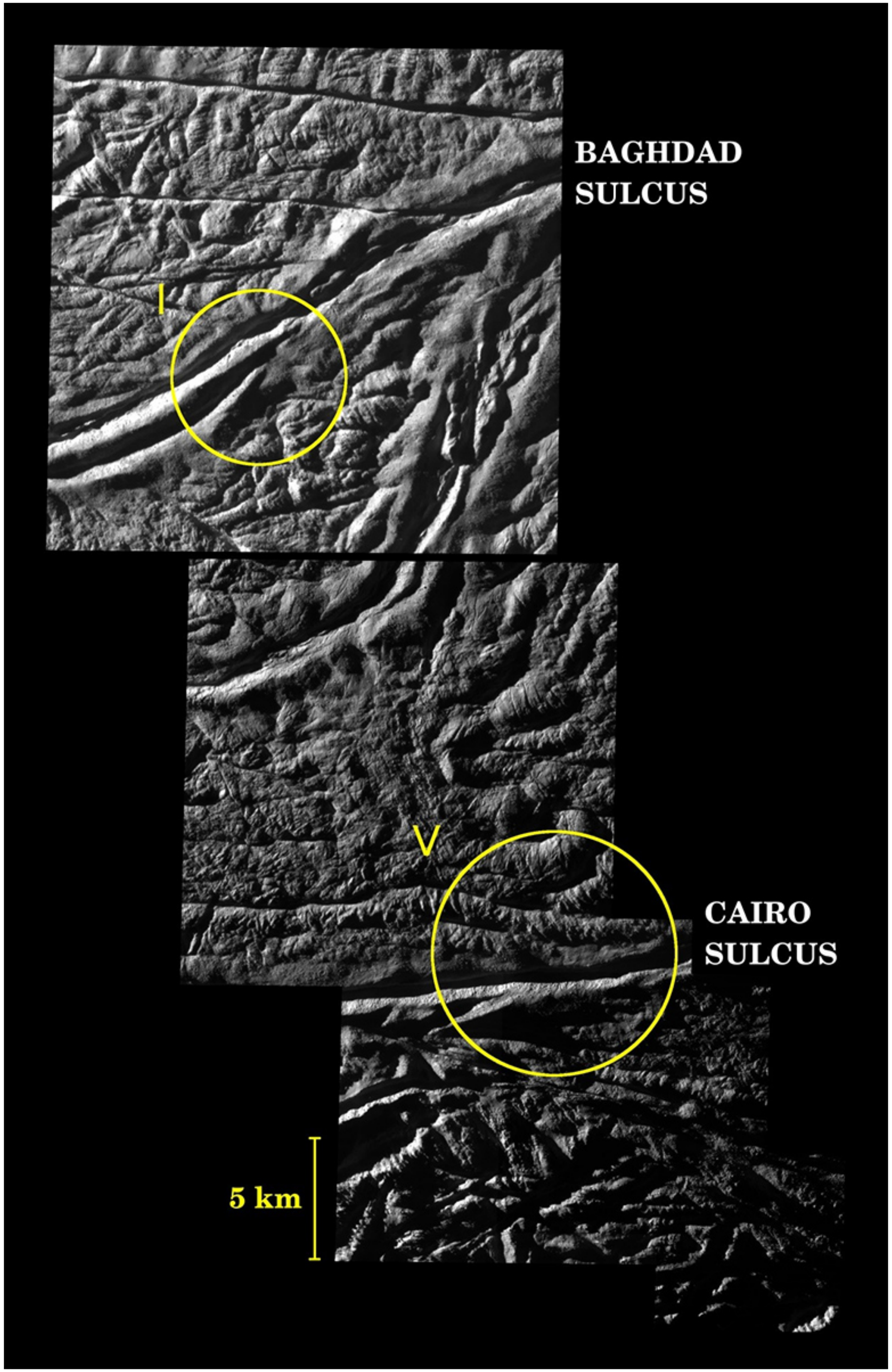

Heavily cratered terrain: old surface
No craters: young surface
Viscously relaxed craters


Enceladus
Heavily cratered terrain: old surface
Viscously relaxed craters
No craters: young surface
Tiger Stripes
80km



~200K max

CASSINI CIRS
(Spencer et al.)



hi-res images
15 m/pixel

from closest approach
at flyby in 2008

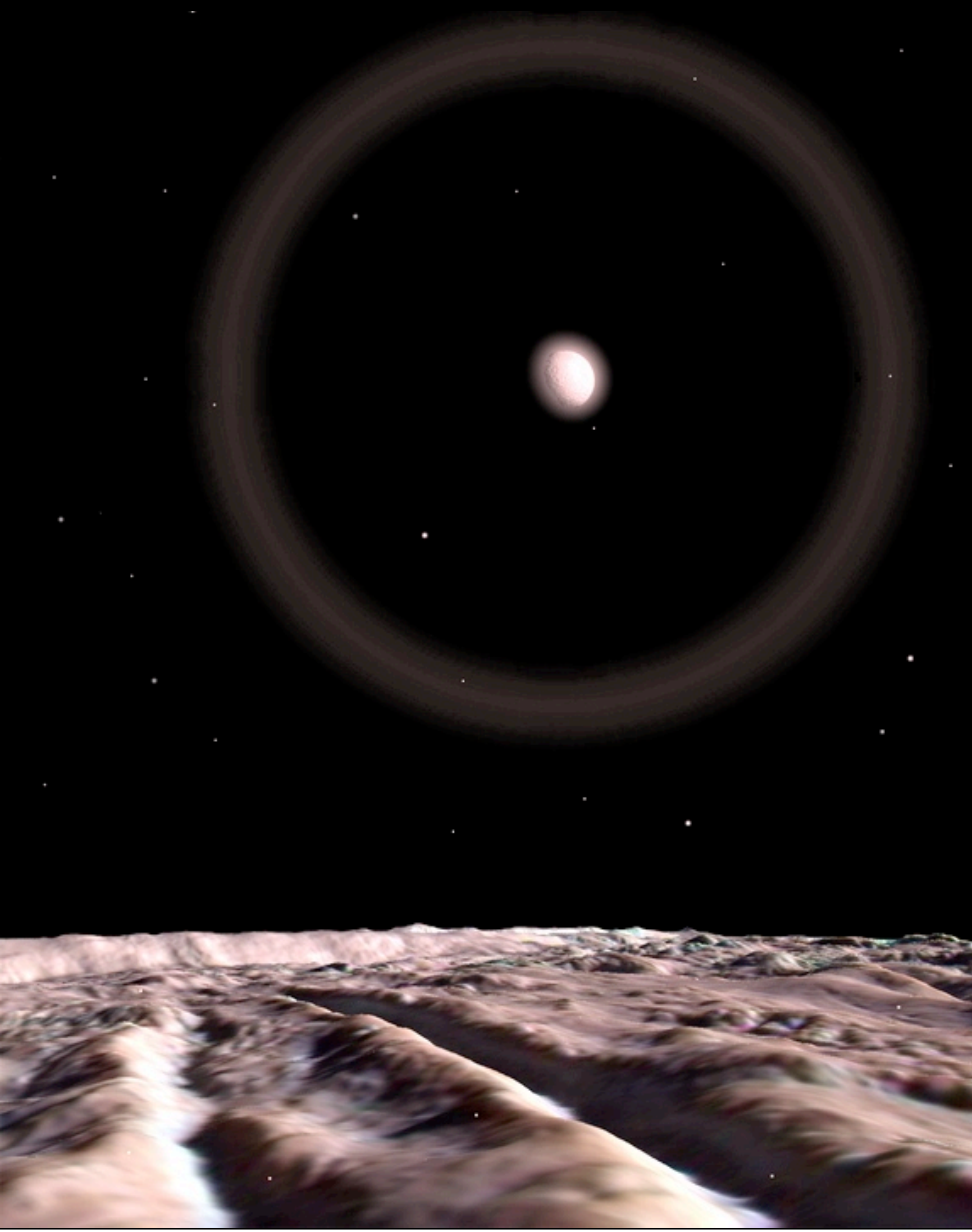
tiger stripes are
300m deep with
V-shaped inner walls

yellow circles:
plume locations

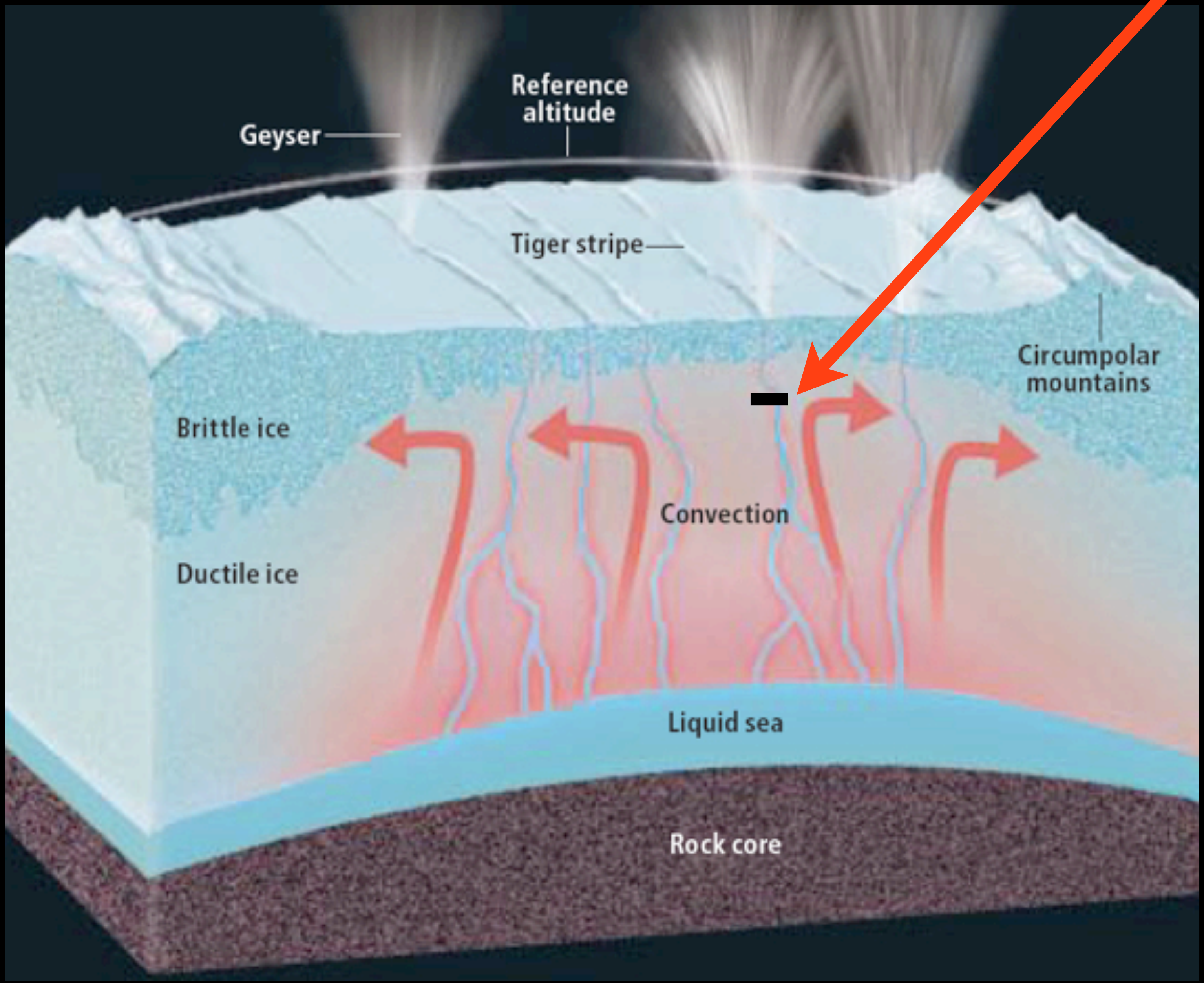
(from Dennis Matson)


2 km

(From: C. Porco, Scientific American, 2008)



from Paul Schenk

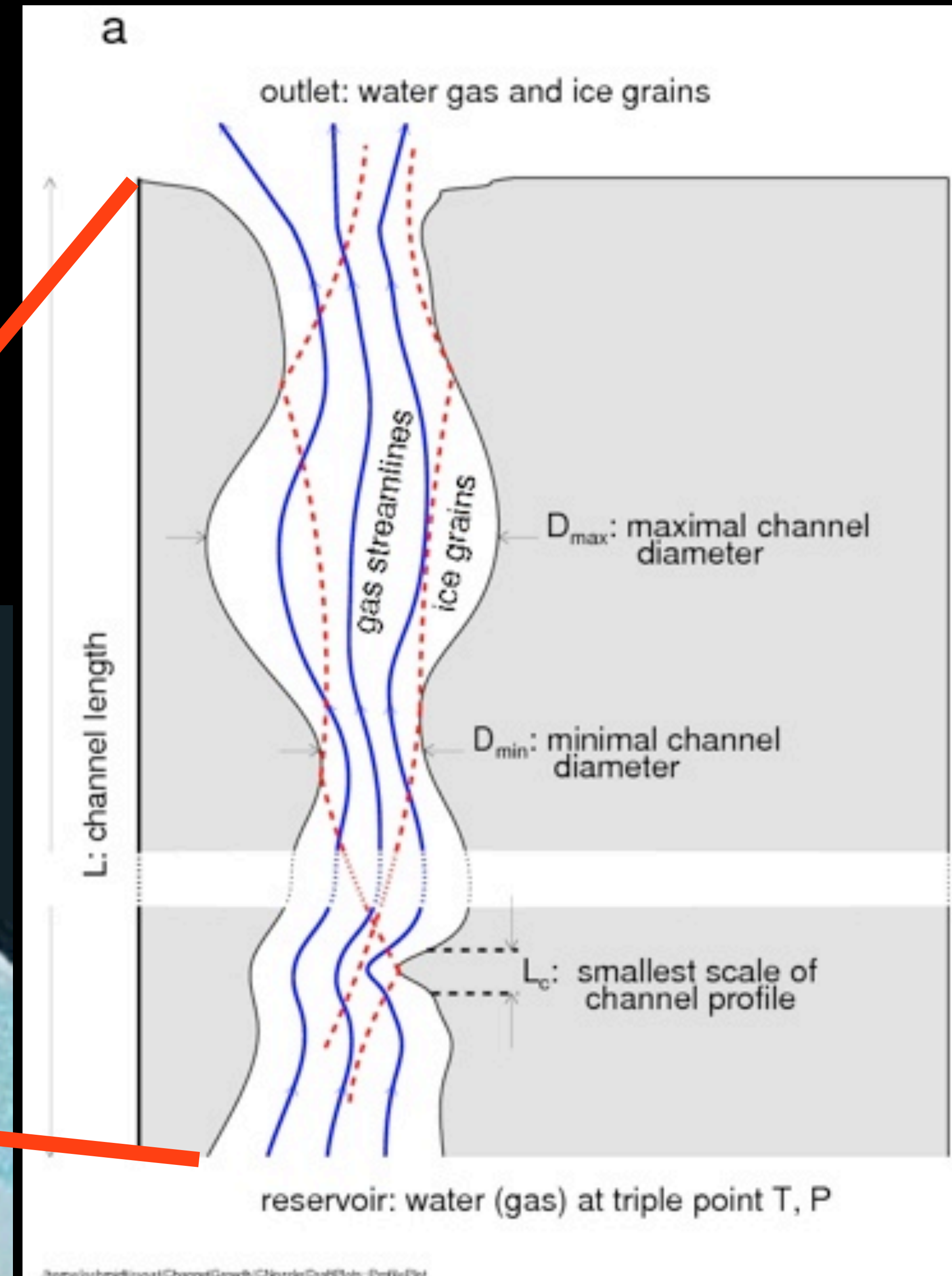


(From: C. Porco, Scientific American, 2008)

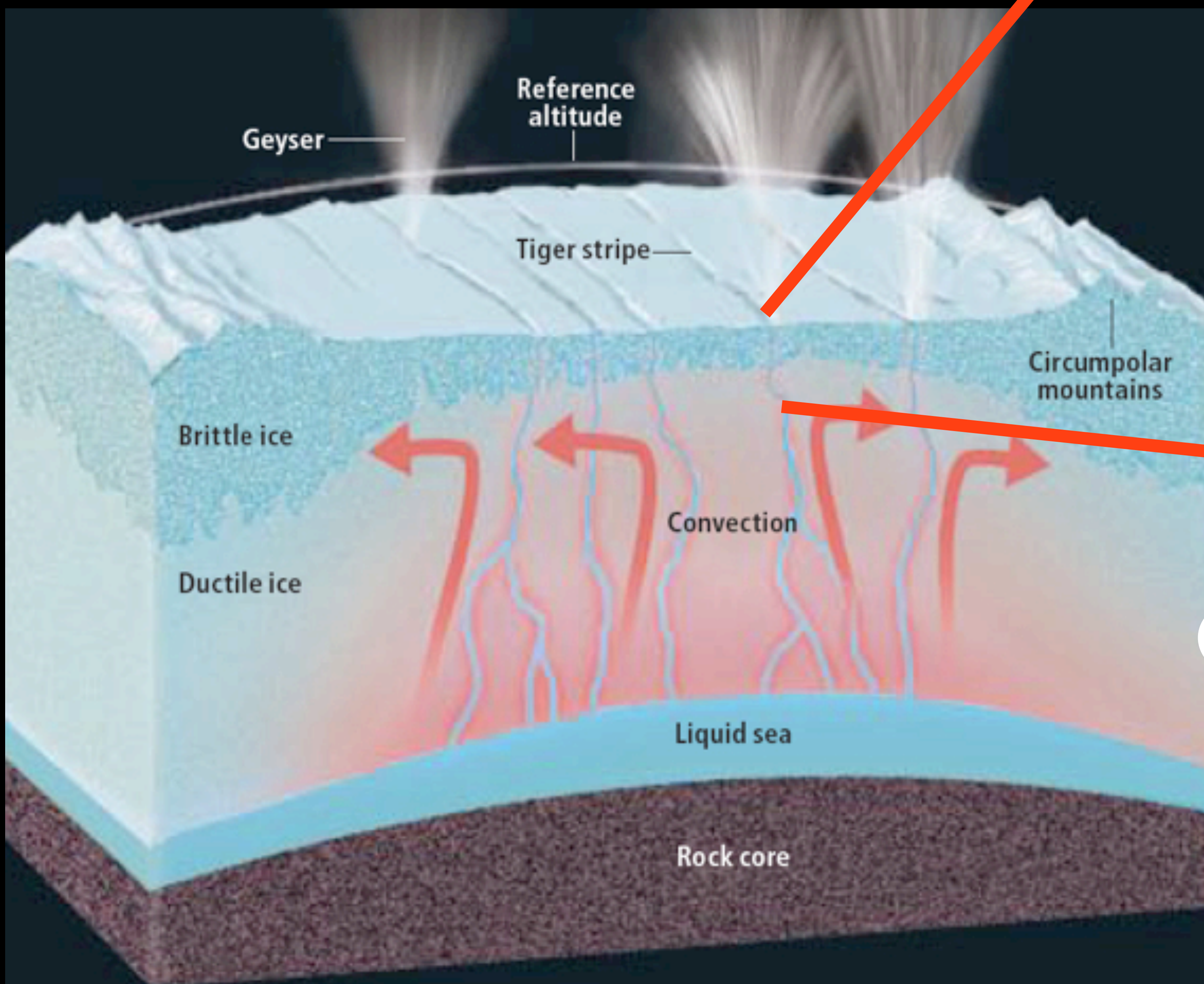
- NO Geysers! (one plume, multiple jets)
- Waterline?
- NO liquid ejected.
- Heat production?

-> ~15 GWatt output: tidal heating + radiogenic heating are insufficient

- Why at the south pole?
- Why not Mimas?



(Schmidt et al, Nature, 2008)



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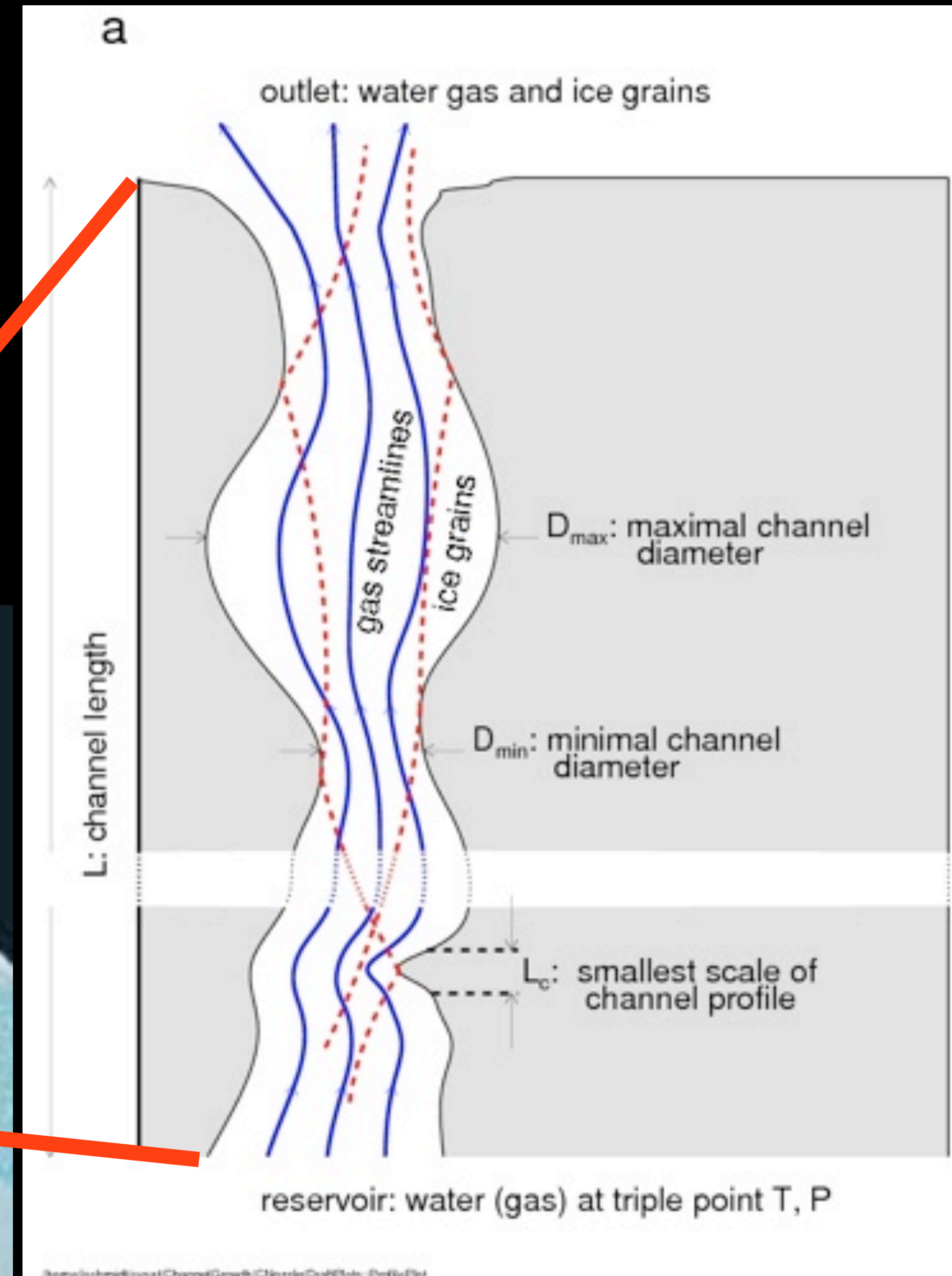
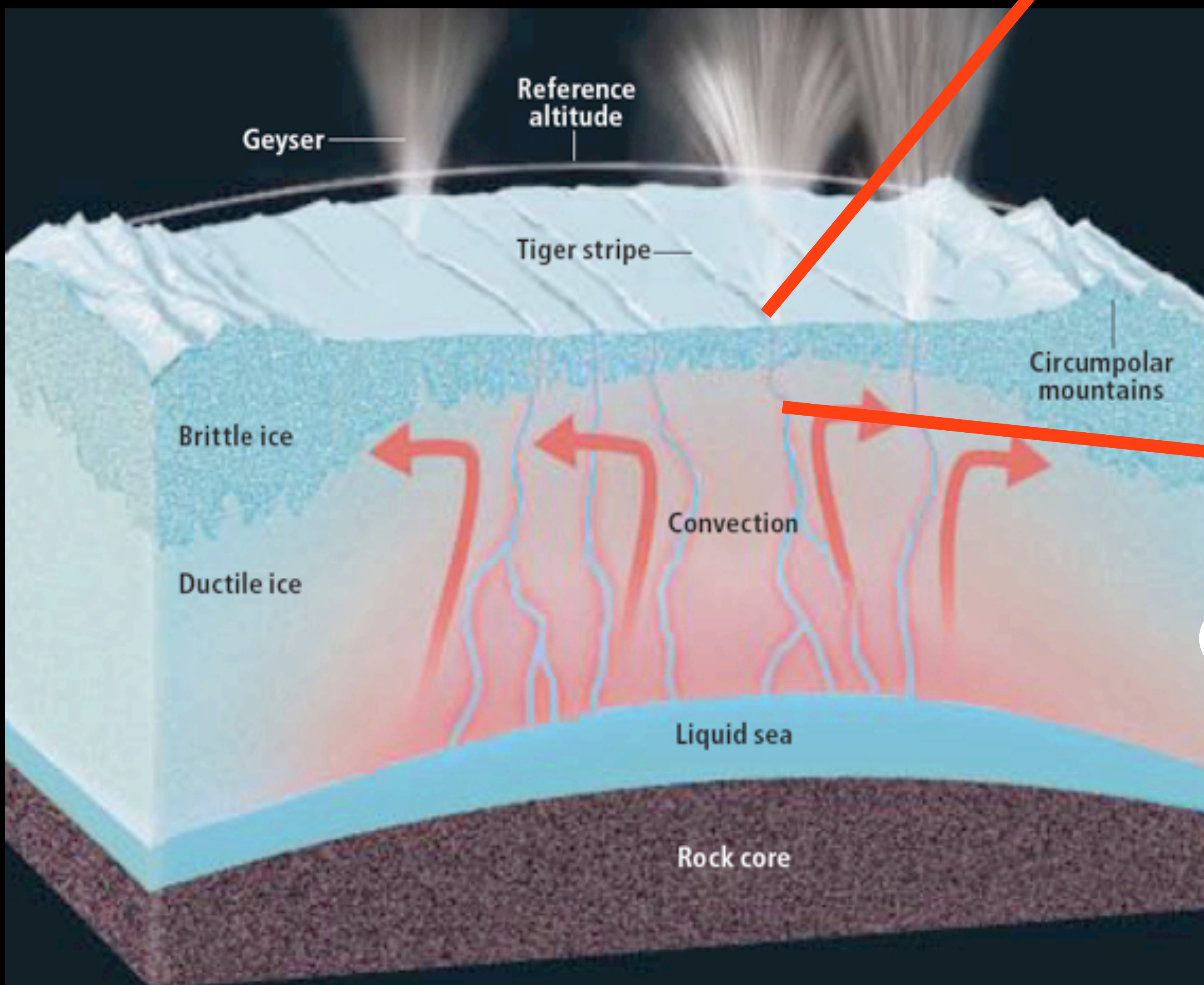


(Schmidt et al, Nature, 2008)

-> vapor flow through ice cracks of variable cross-section

-> condensation of grains



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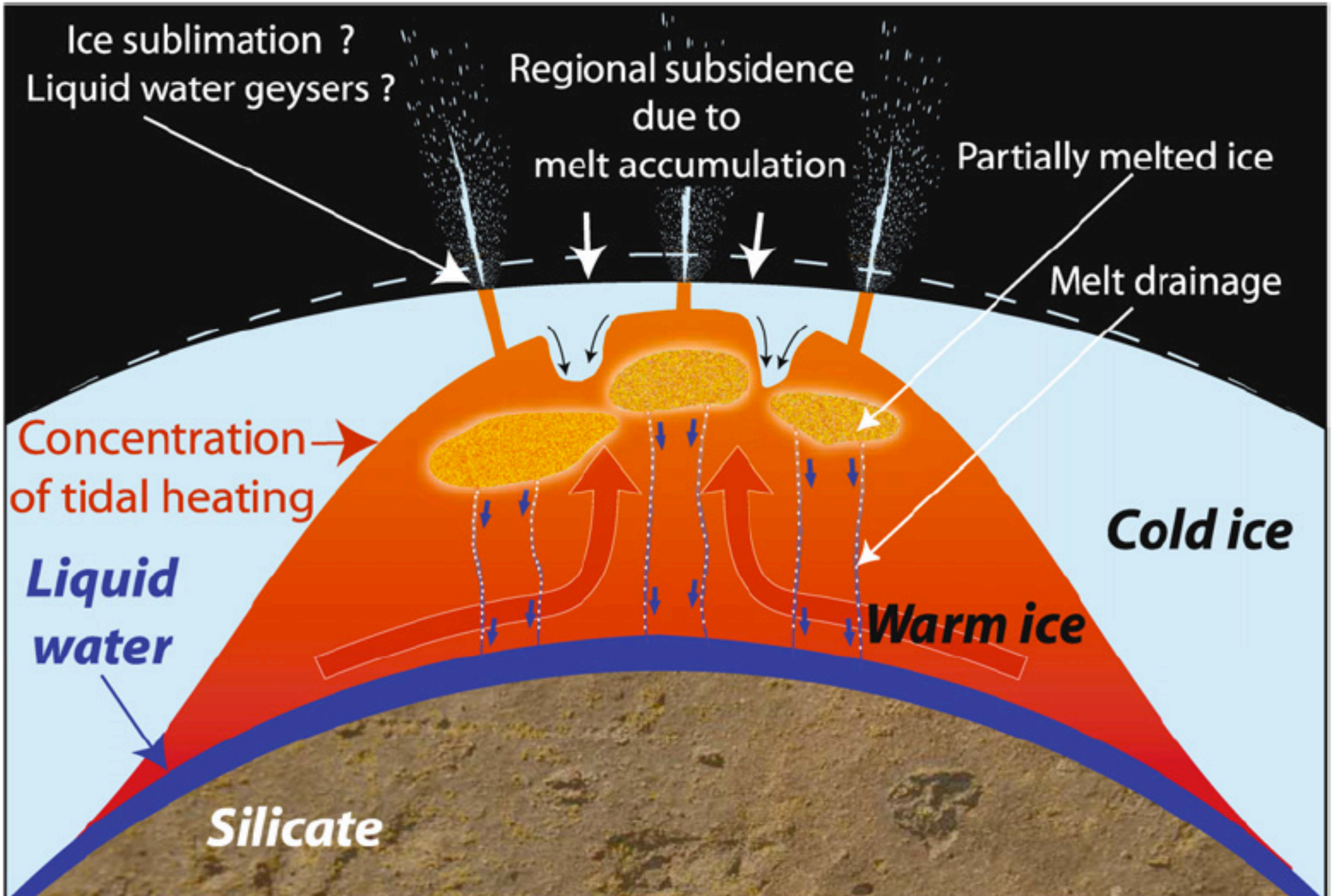
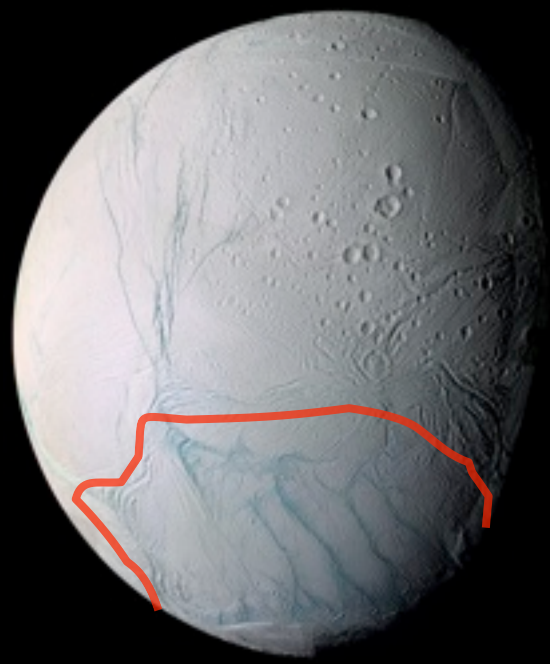
G. Tobie et al. / Icarus 196 (2008) 642–652



heat production:

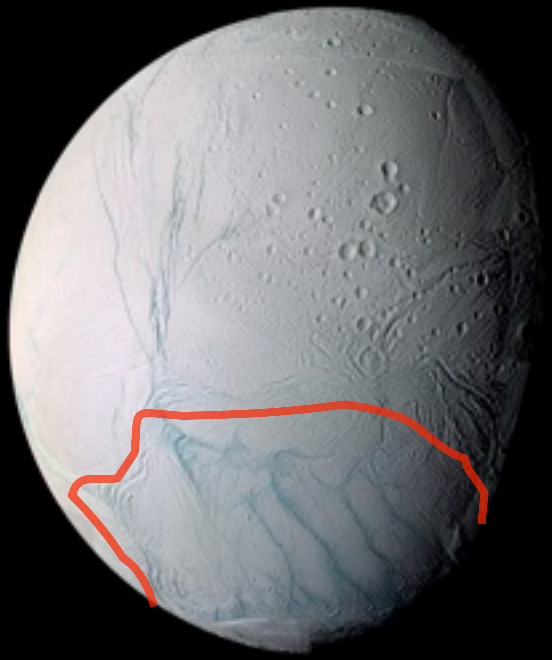


enceladus south pole: 250 mW/m^2

(from Dennis Matson)

heat production:

earth:
87 mW/m^2



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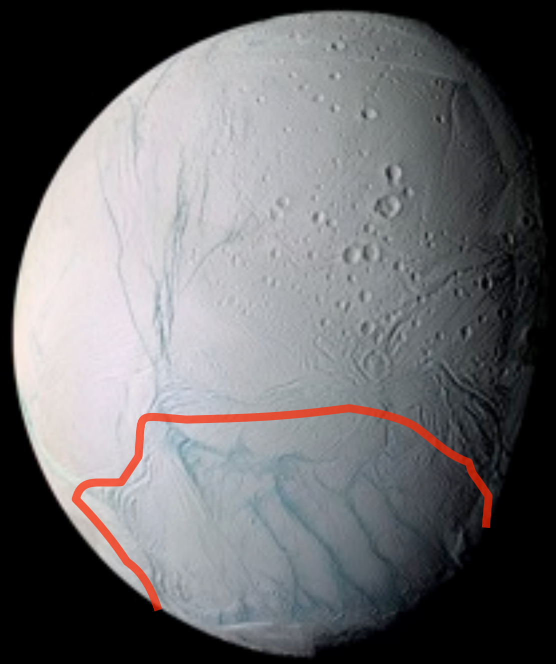

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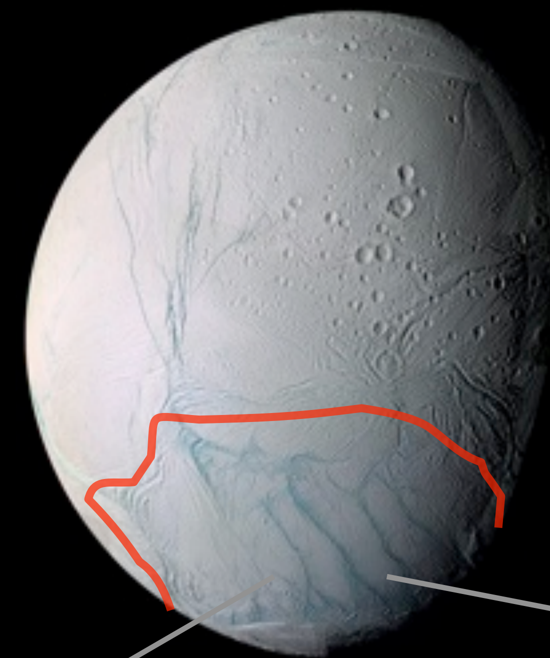

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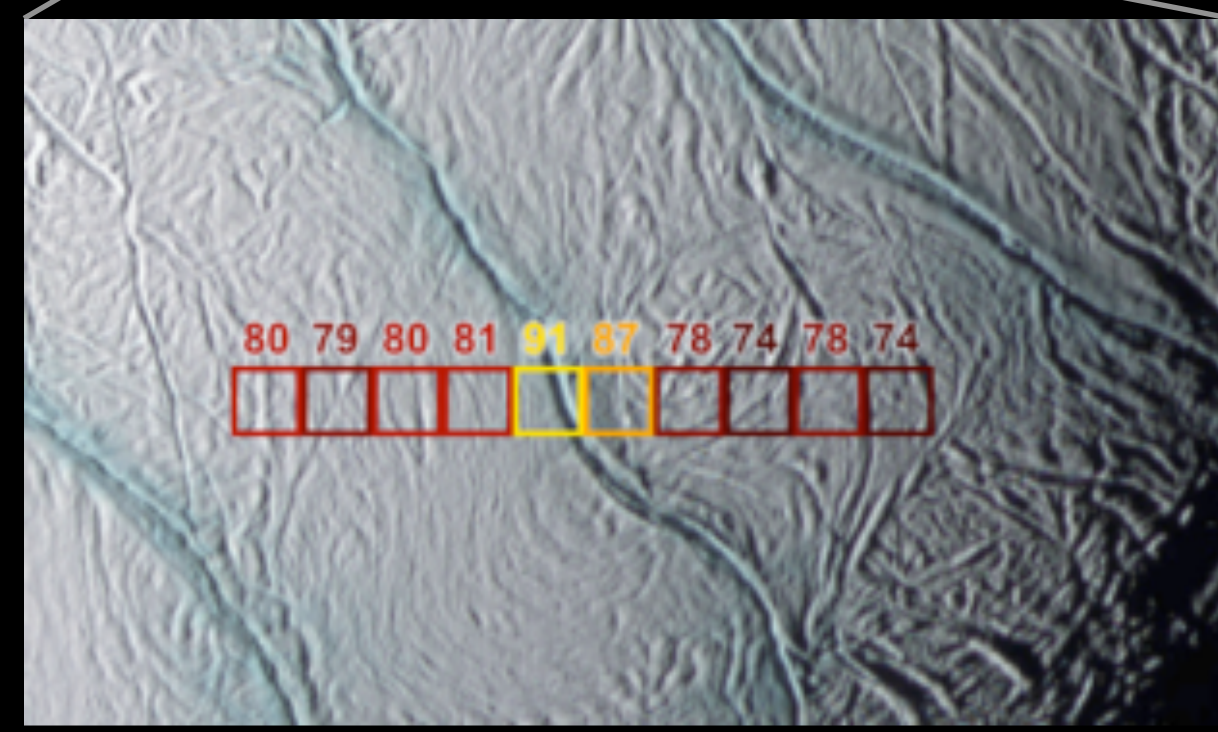


(from Dennis Matson)

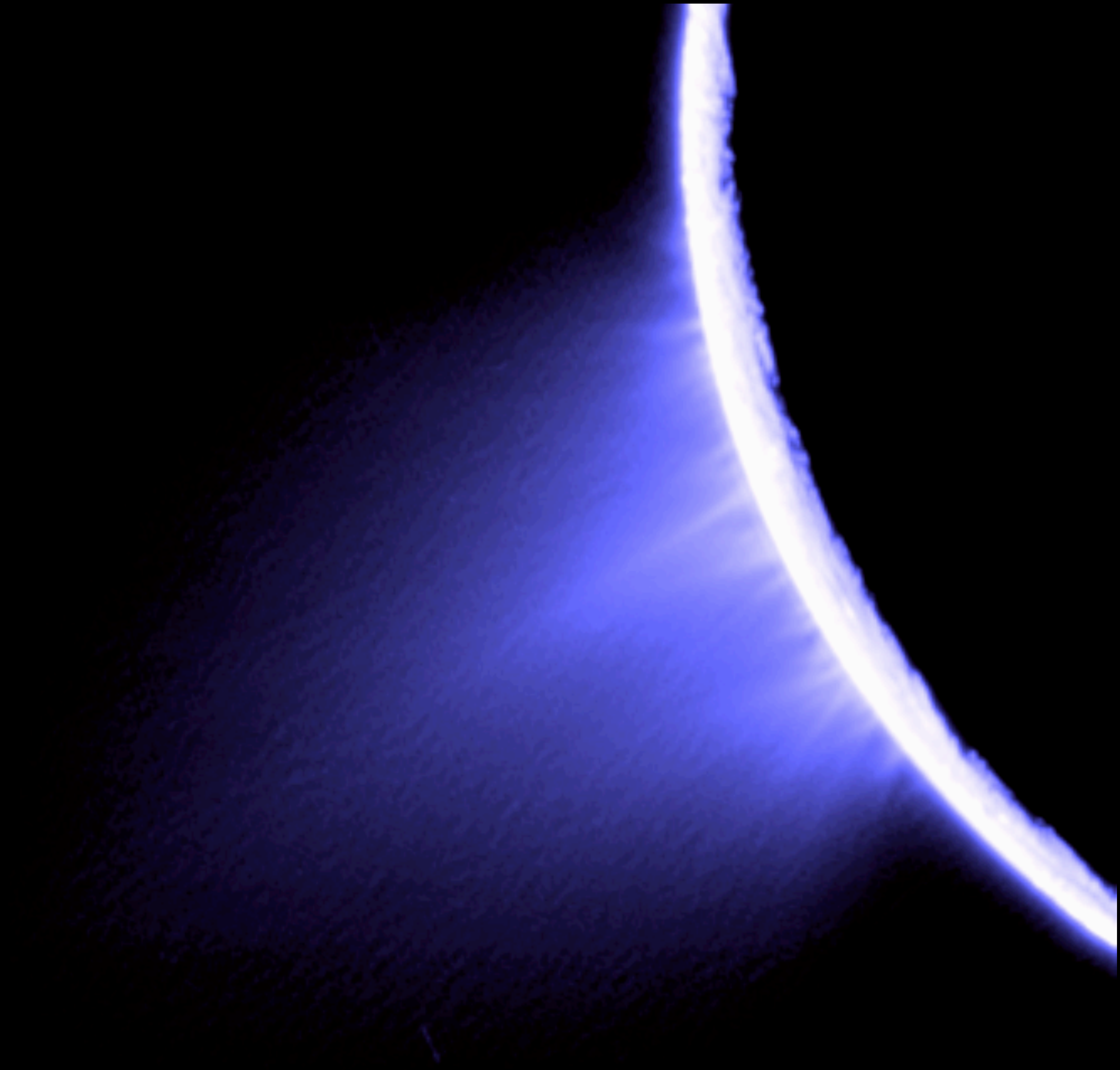
yellow stone:
2500 mW/m^2

tiger stripes:
13.000 mW/m^2

enjoy the Enceladus spa with your extraterrestrial friends?

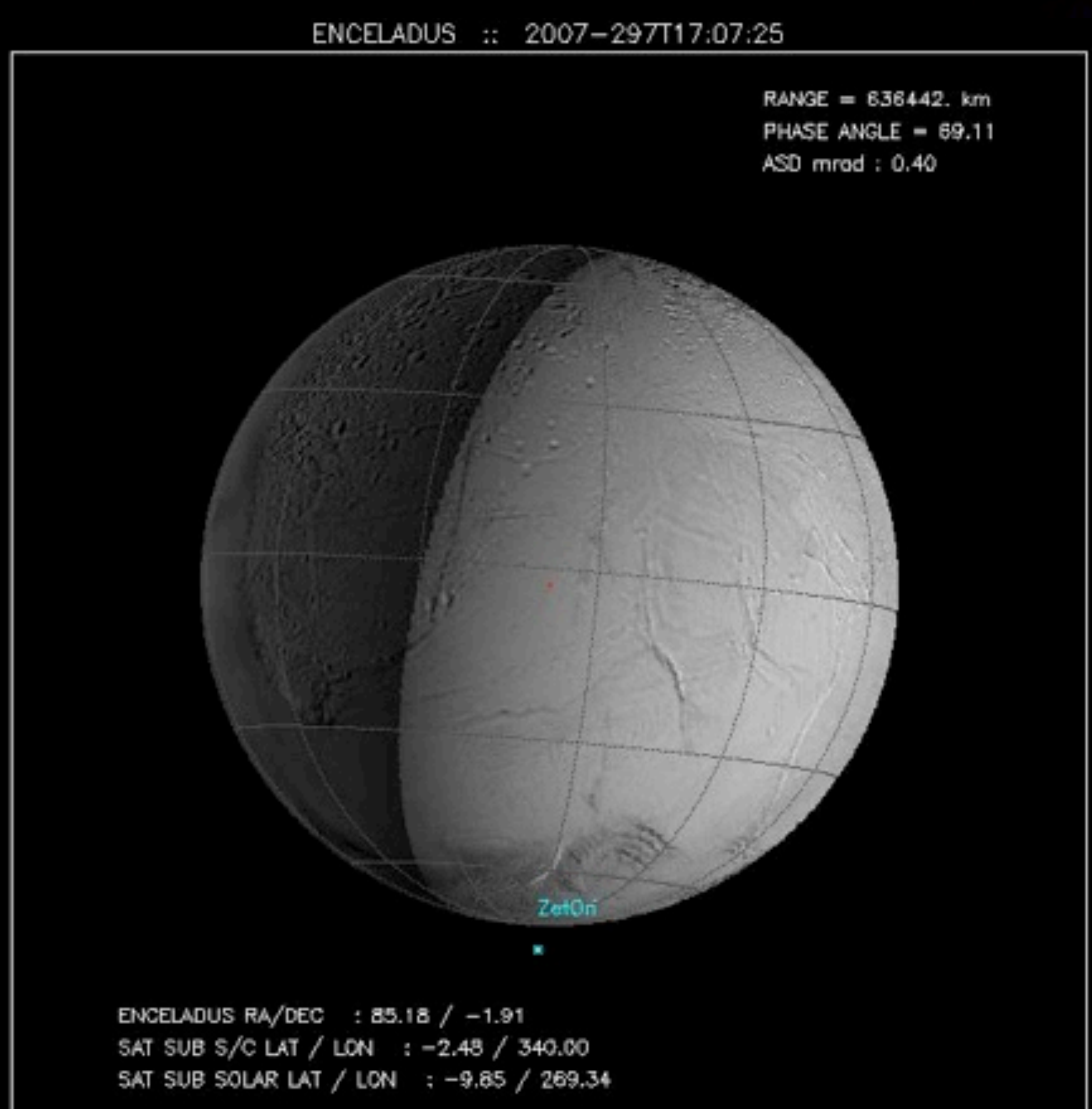
(from Dennis Matson)

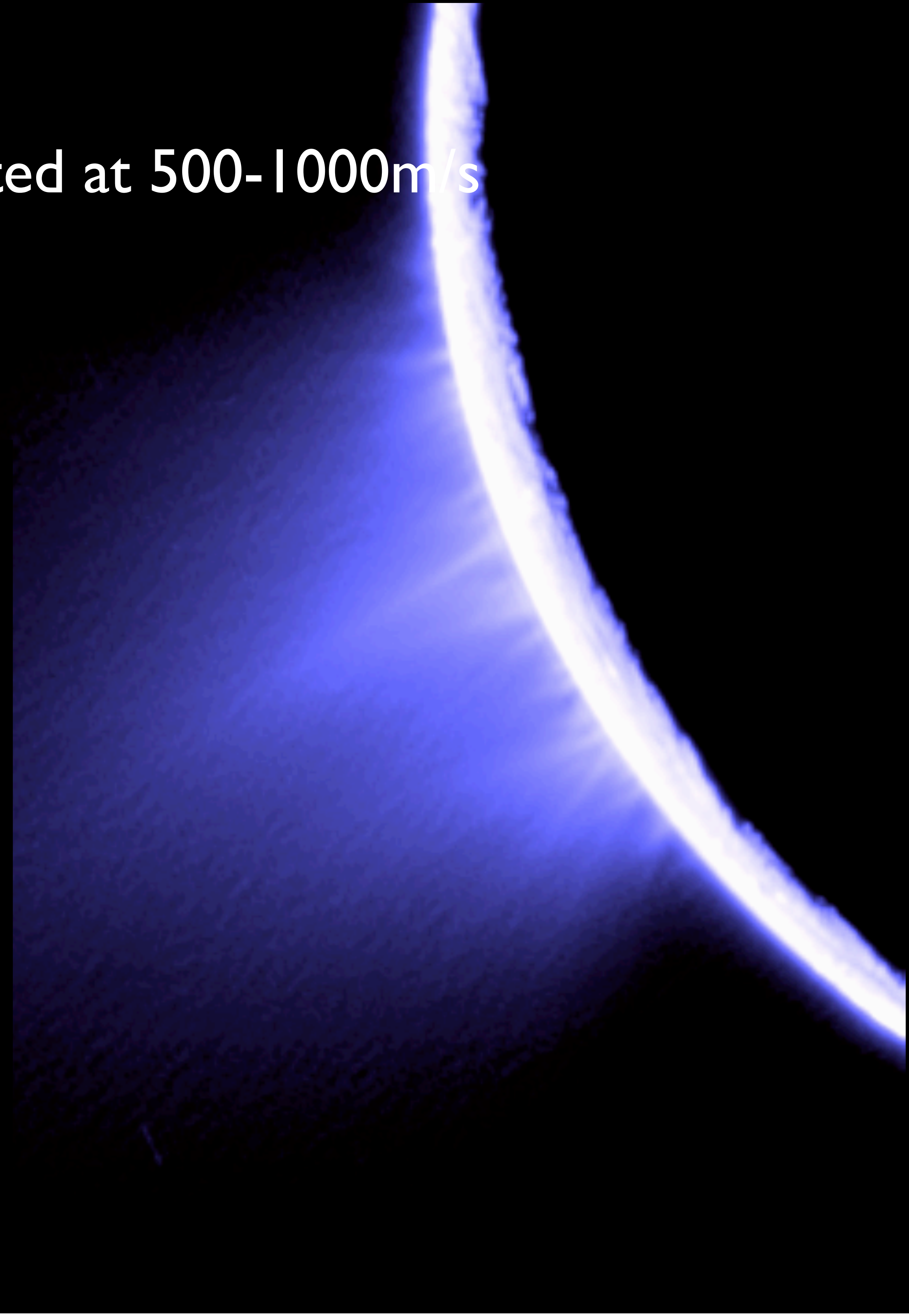
Constraints



Constraints

- about 200 kg/s water vapor ejected at 500-1000m/s (Ultra Violet Imaging Spectrograph)





Hansen et al: Science (2005), Nature (2009)

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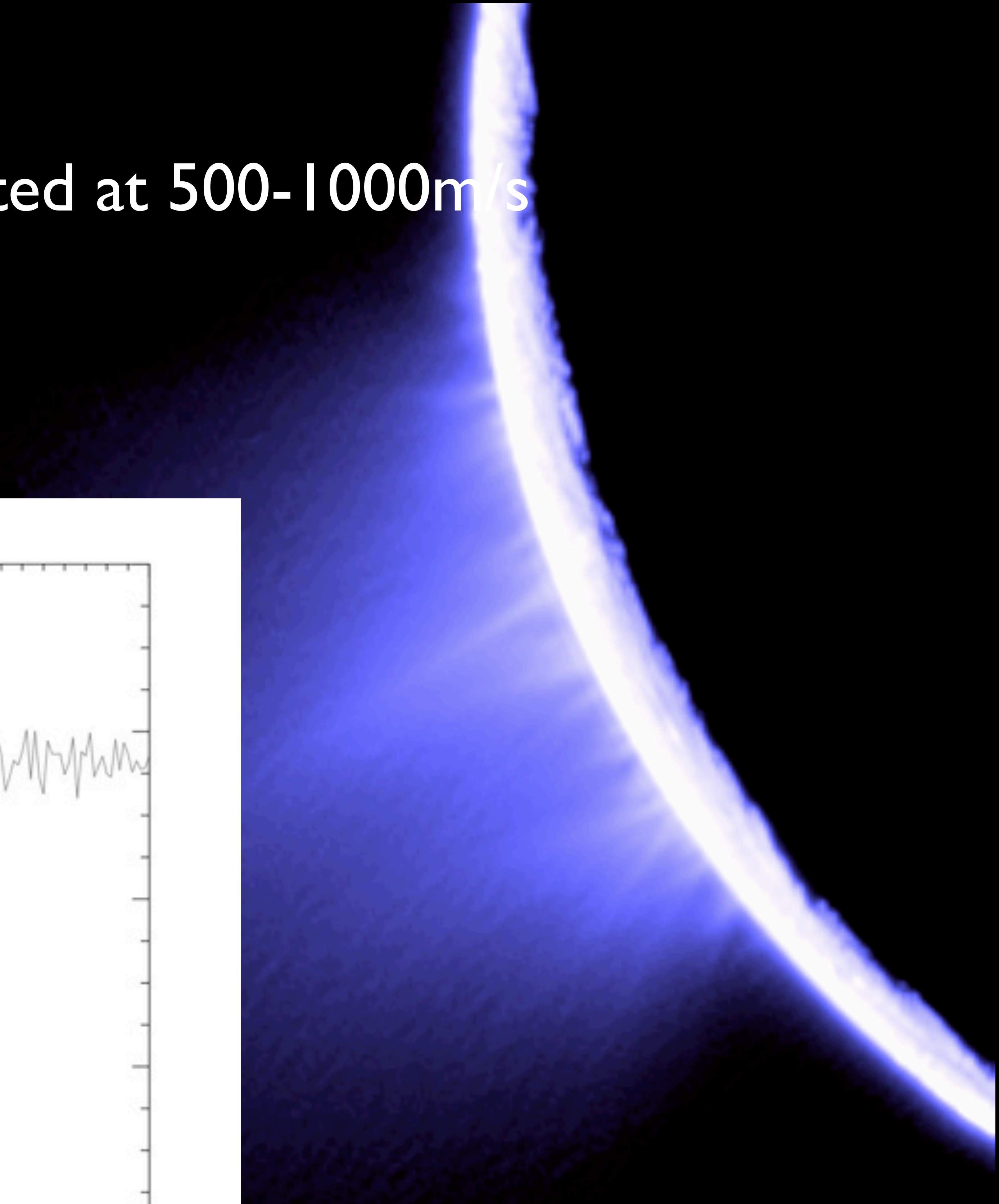

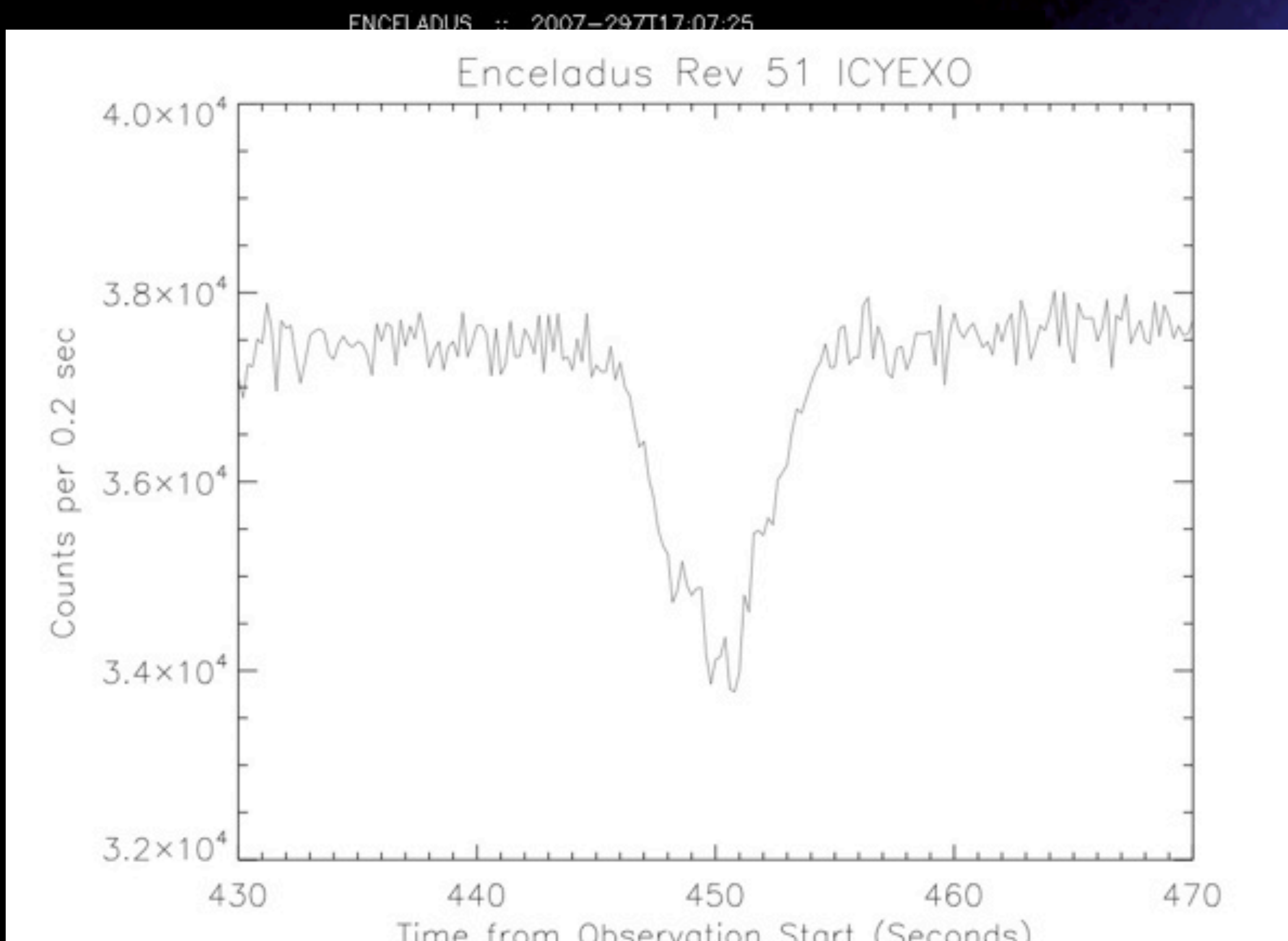

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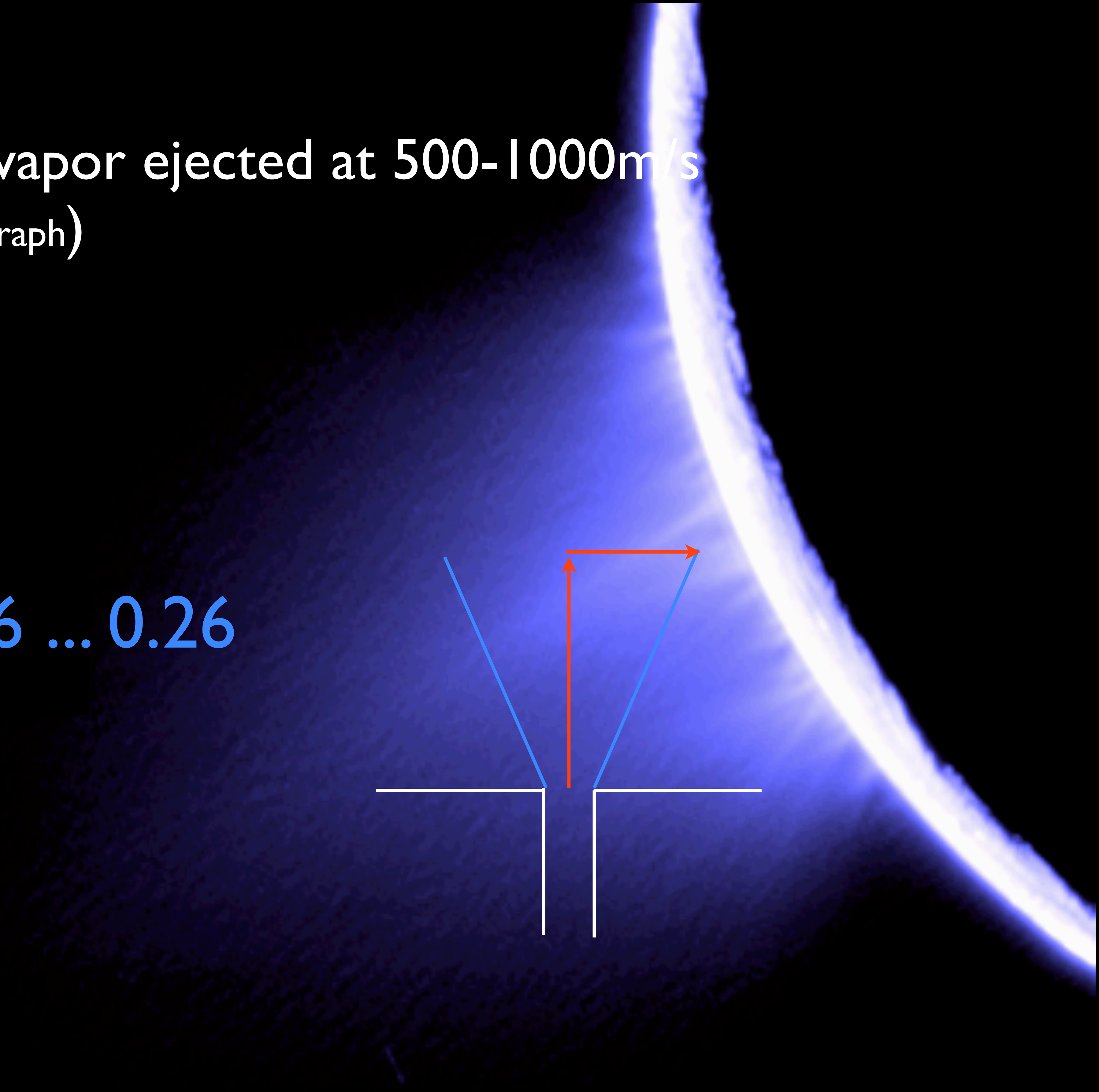
$$\frac{v_{therm}}{v_{jet}} \approx 0.6 \ldots 0.26$$



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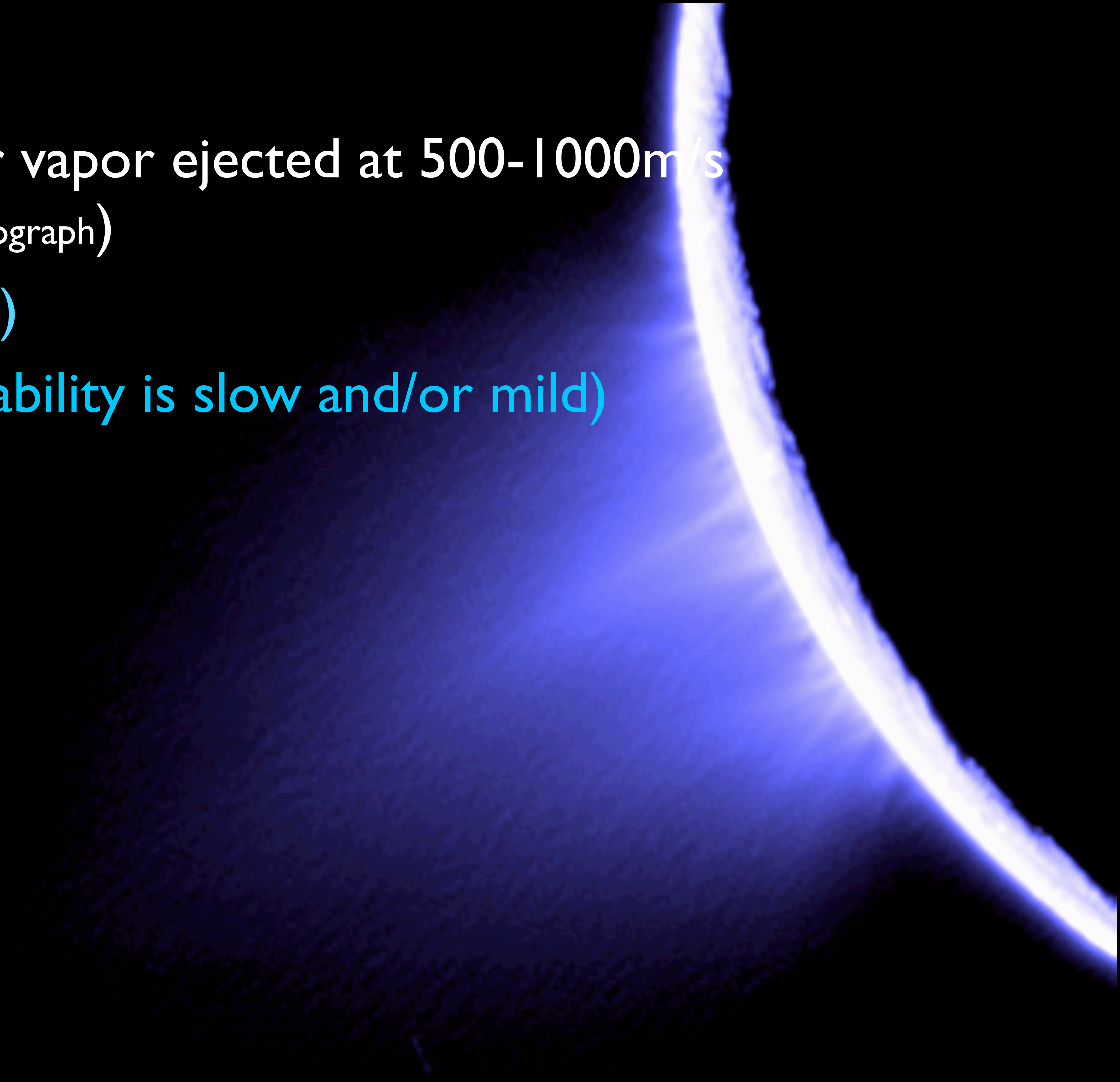

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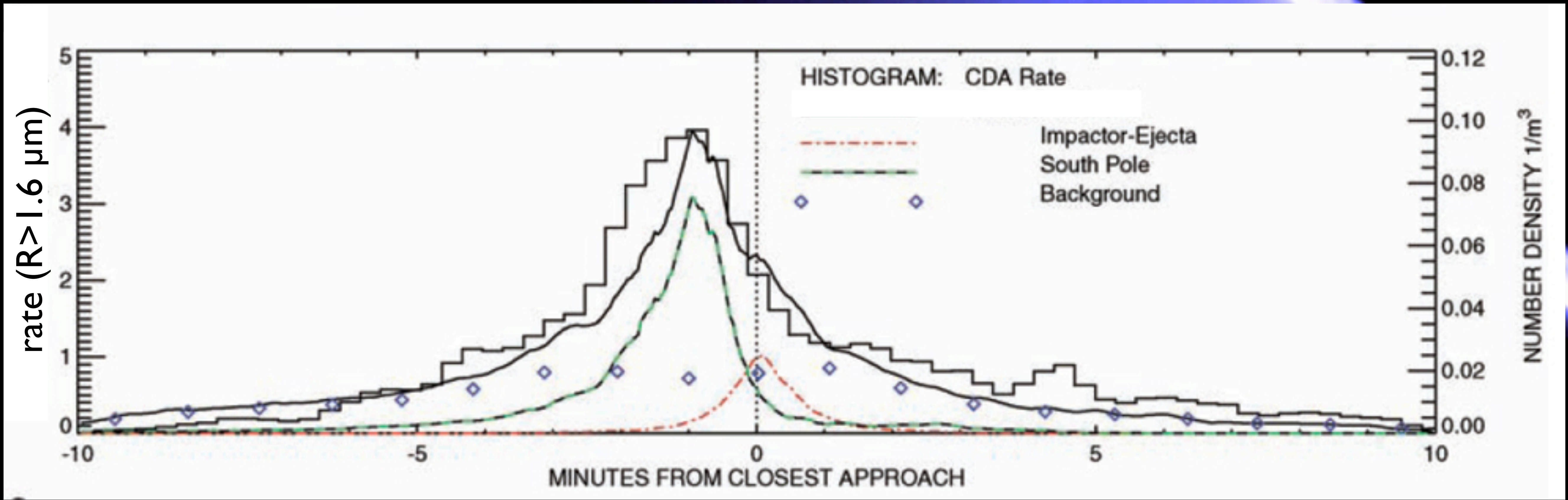

Spahn et al, Science (2006)

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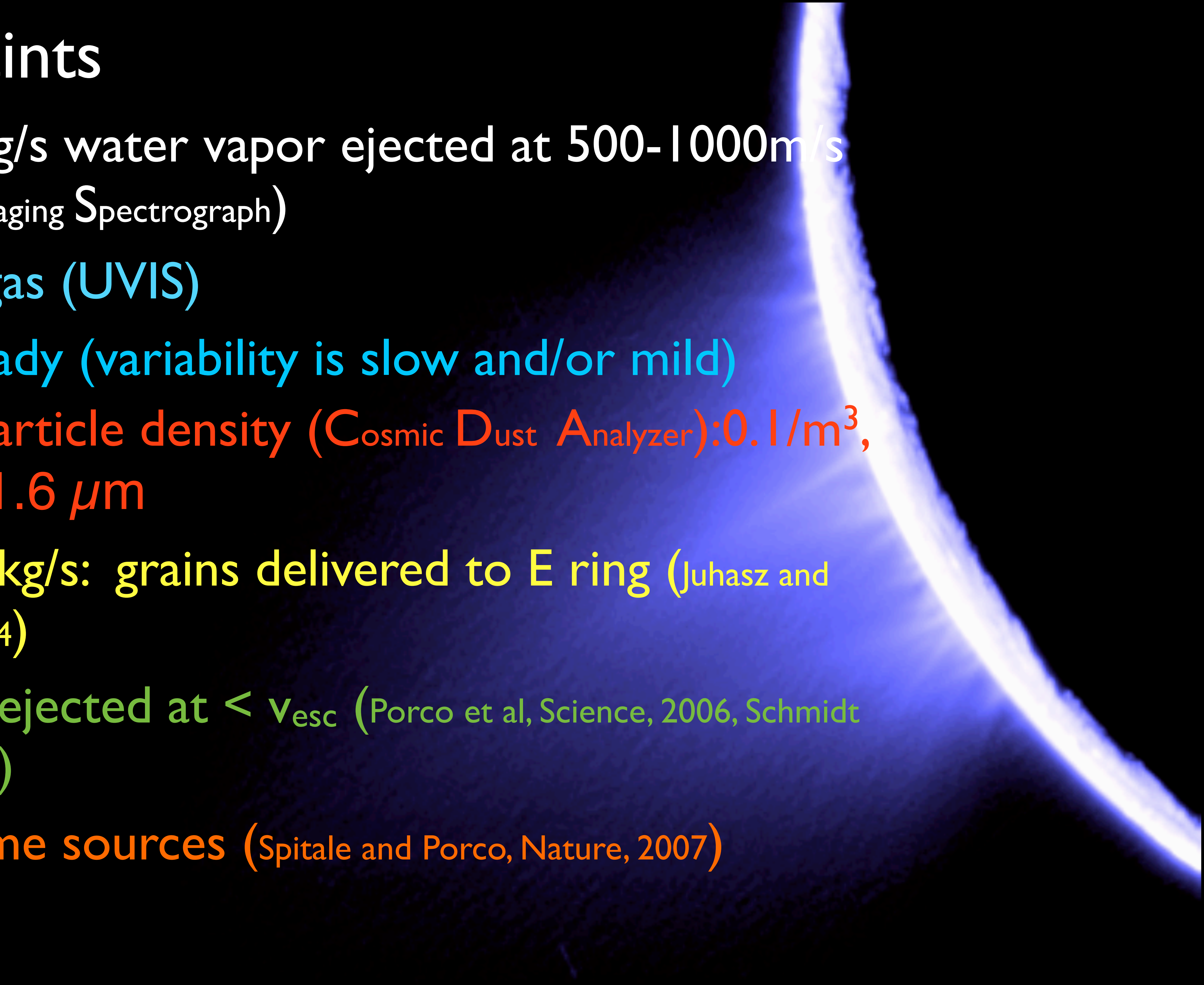

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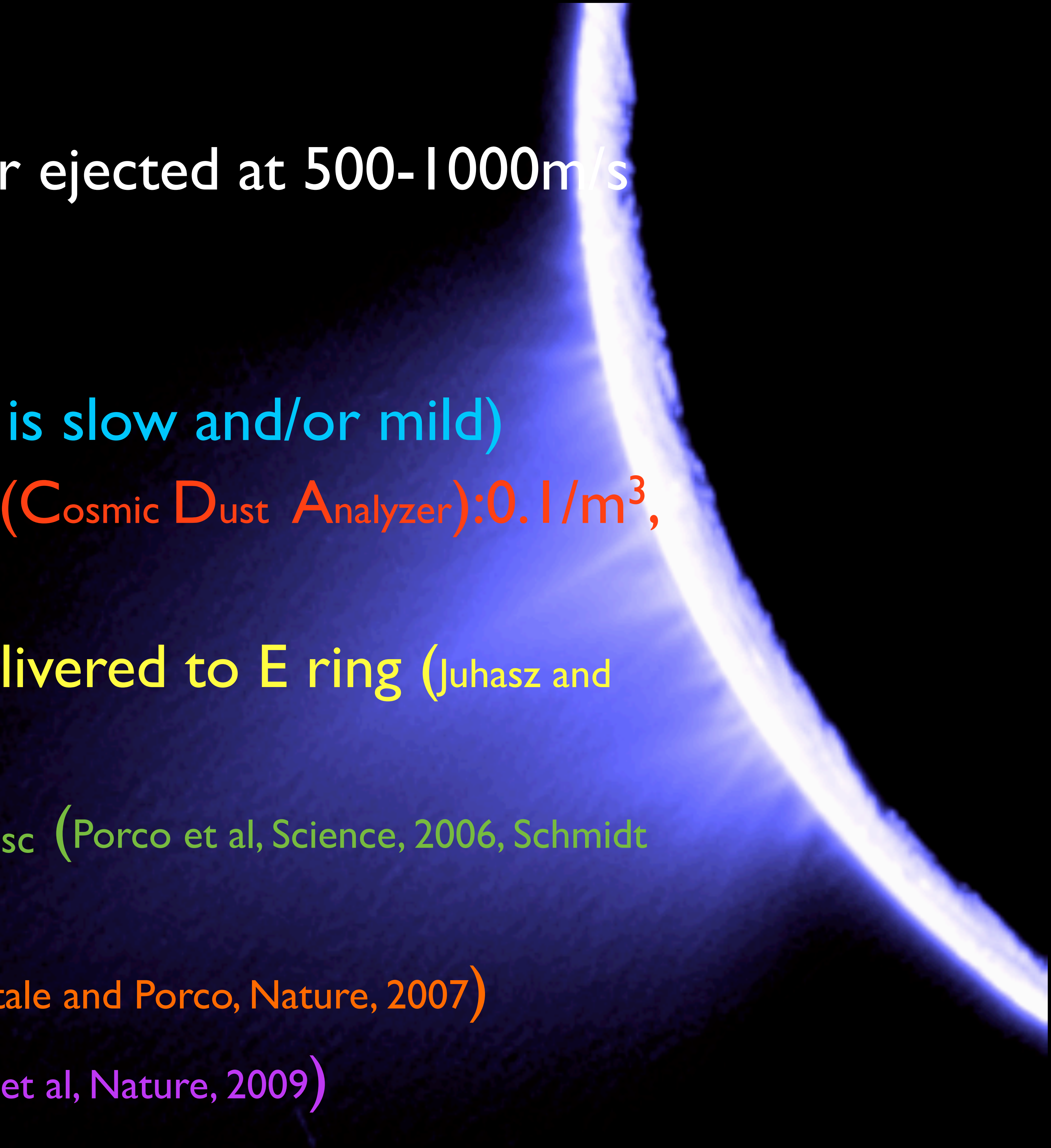

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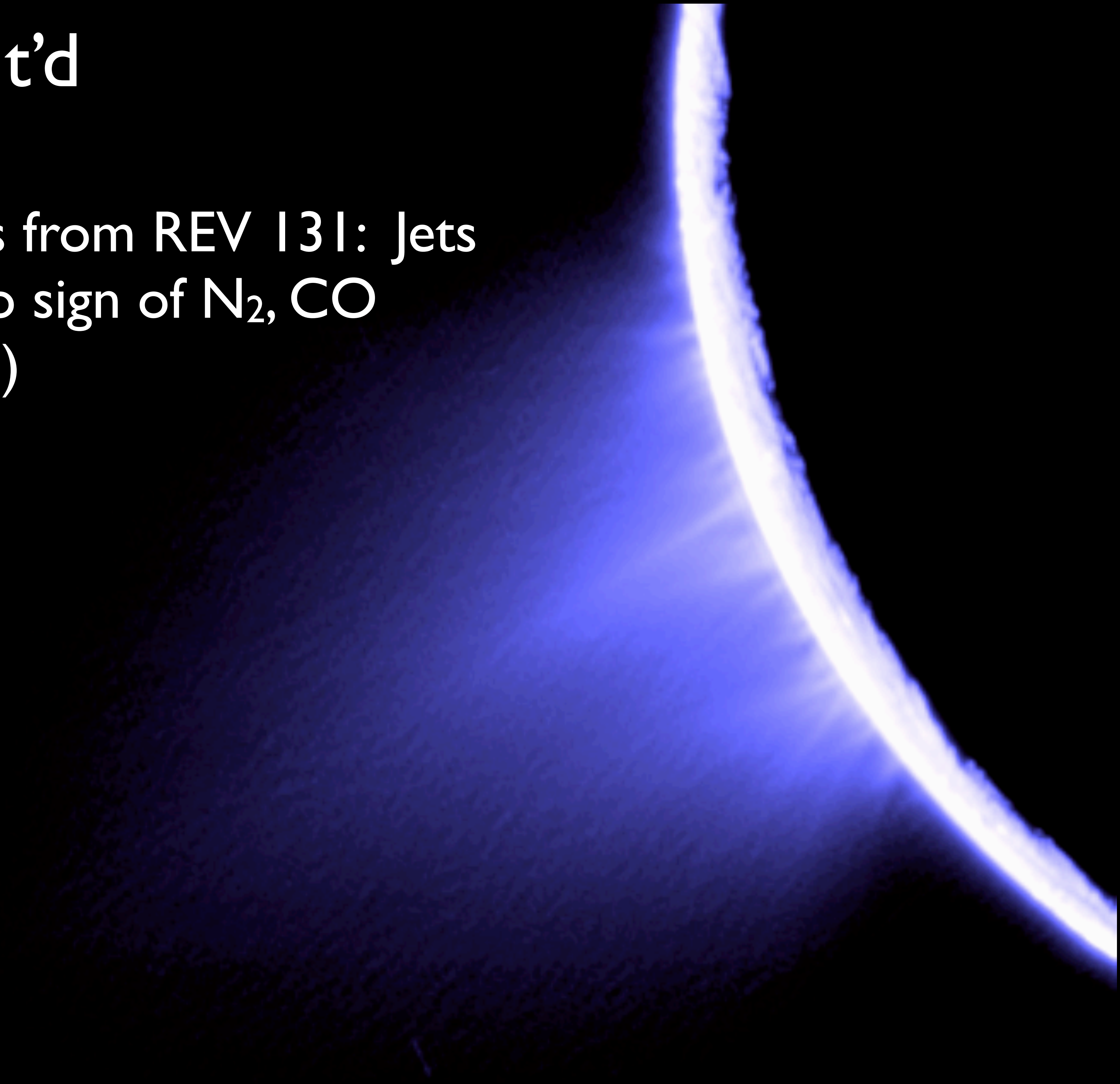
- Volatile gases in plume, CO, or N_2, or C_2H_2< 3%-10%, (Waite, Nature, 2009)

Constraints cnt'd

- New UVIS results from REV 131: Jets nearly Mach 4. No sign of N_2, CO (Hansen et al, 2011)



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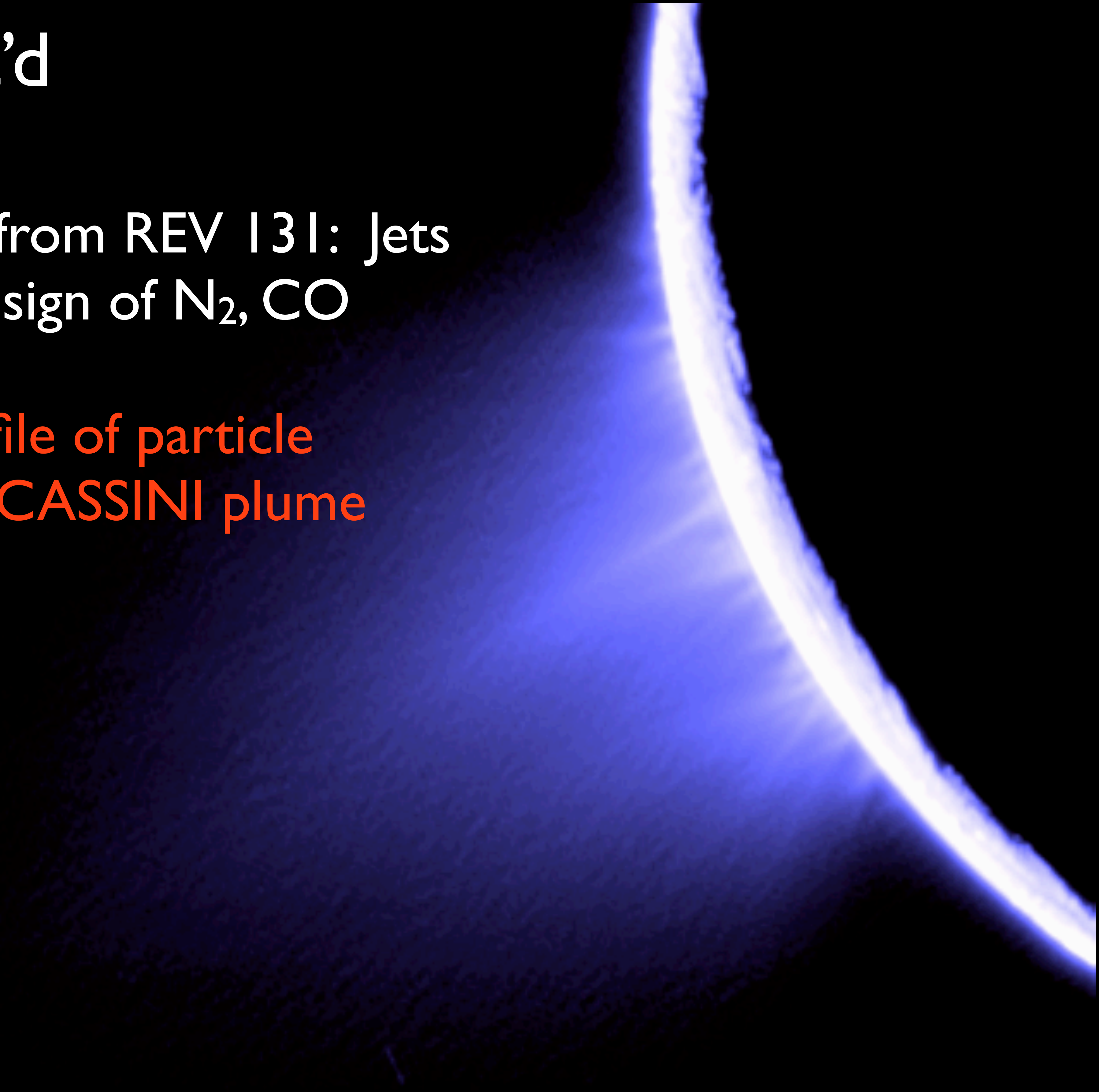

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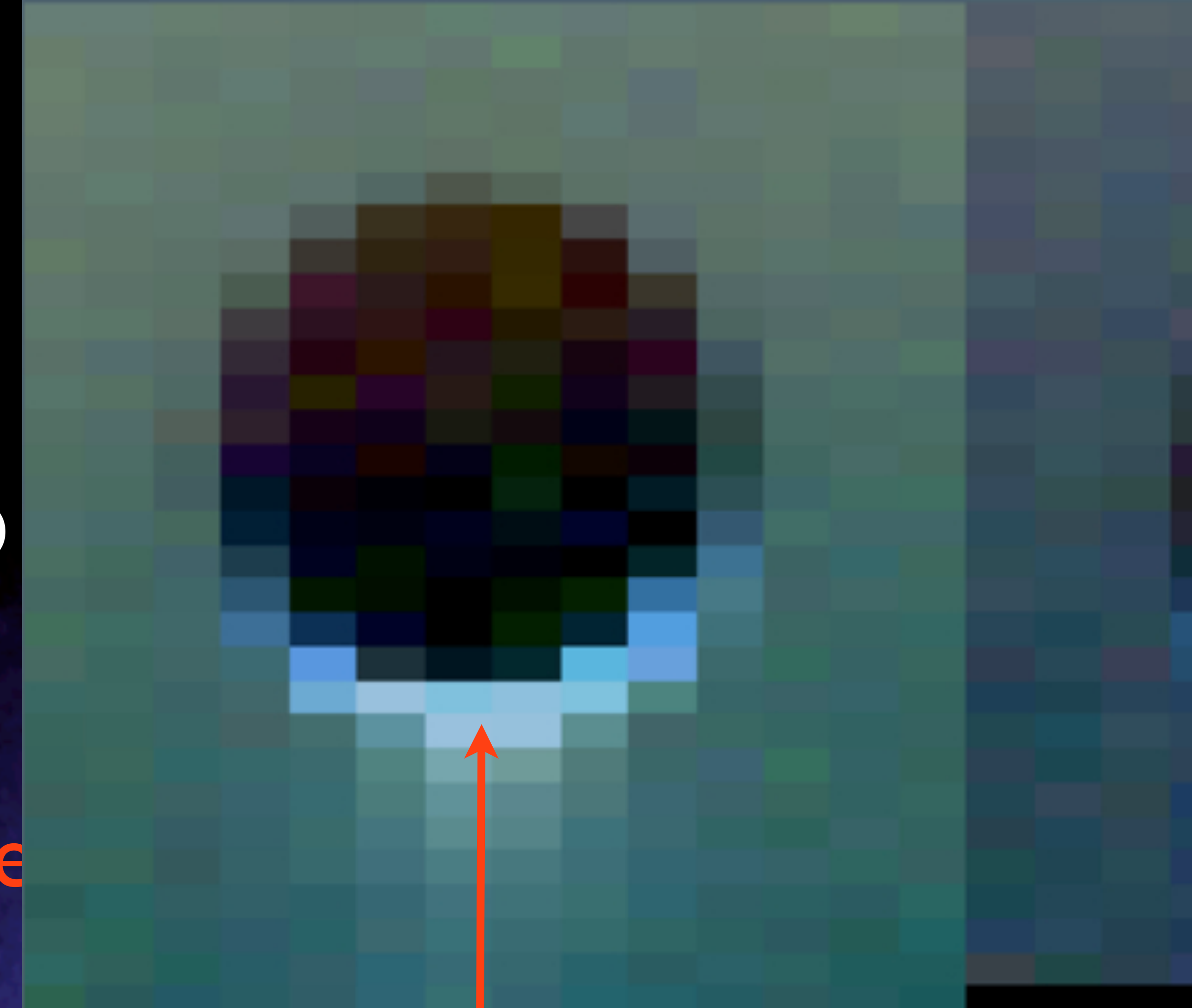

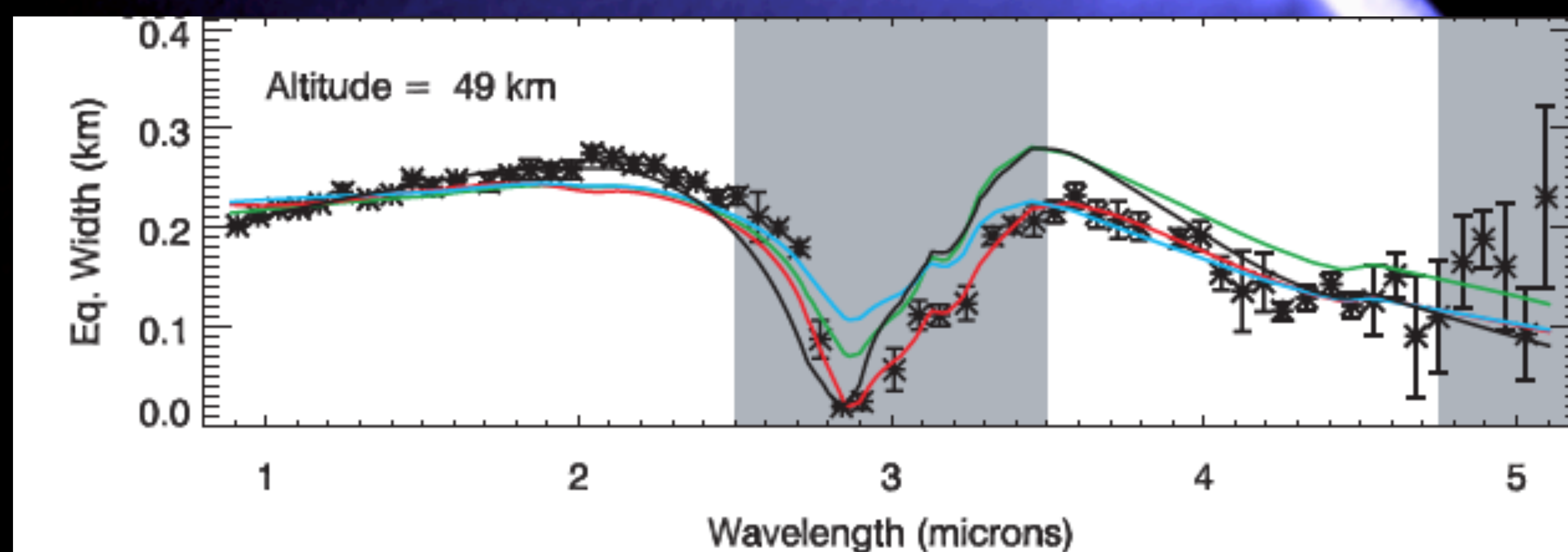

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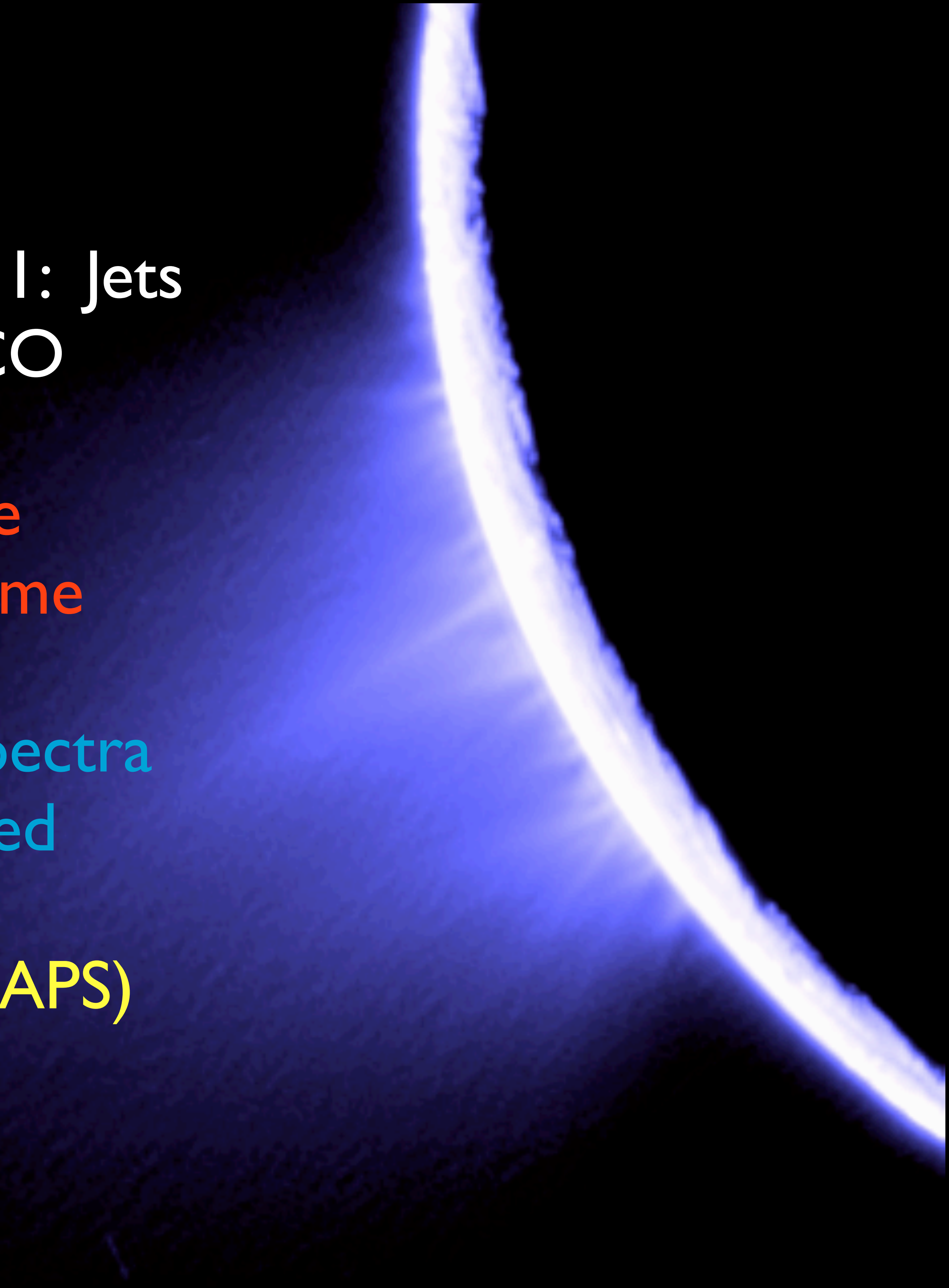
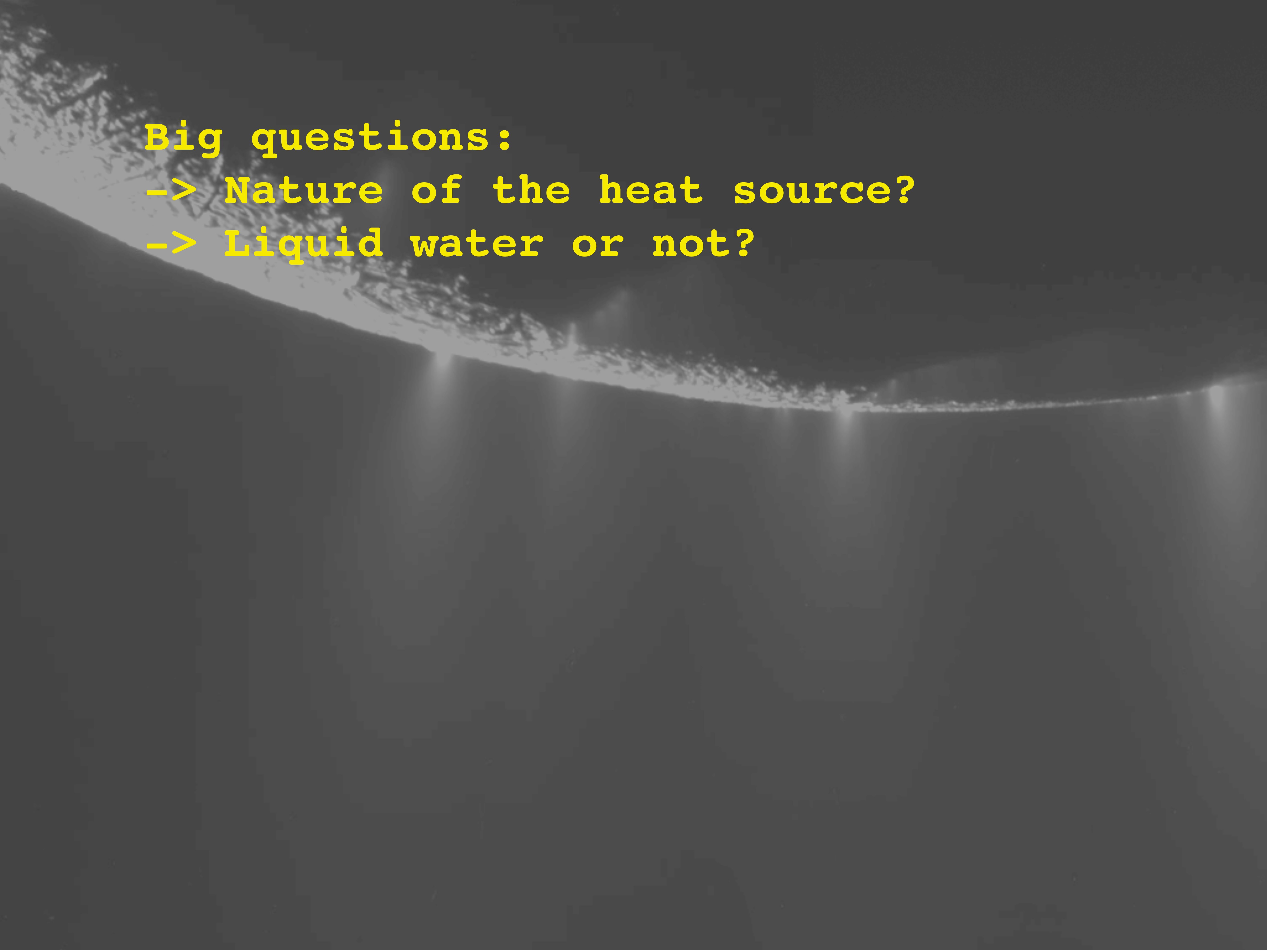
- CASSINI plasma intsrument (CAPS) detection of nano-sized grains associated with jets (G. Jones)




Big questions:
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-> Liquid water or not?

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This talk:

CASSINI Cosmic Dust Analyzer (CDA)

-> Salts (Na, Ka) in E ring grains

6% are salt-rich

(Postberg, Schmidt et al., 2009, Nature)

Big questions:
-> Nature of the heat source?
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This talk:

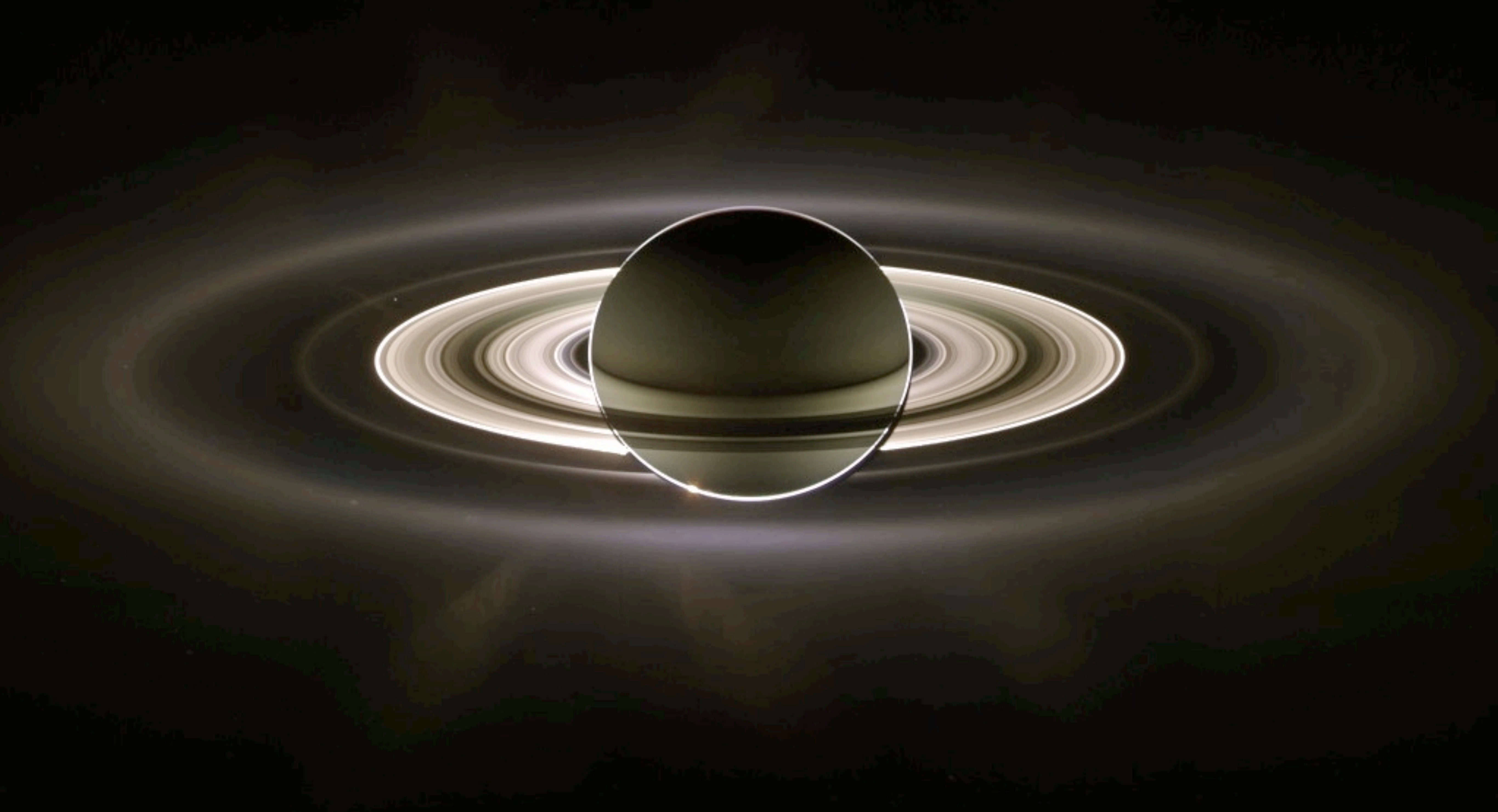
CASSINI Cosmic Dust Analyzer (CDA)
-> Salts (Na, Ka) in E ring grains
6% are salt-rich
(Postberg, Schmidt et al., 2009, Nature)

-> Data from flyby E5:
Composition varies with position in the plume
=> nearly all ejected dust is salt-rich
(Postberg, Schmidt et al., 2009, Nature)

CDA: compositional measurements in the E ring

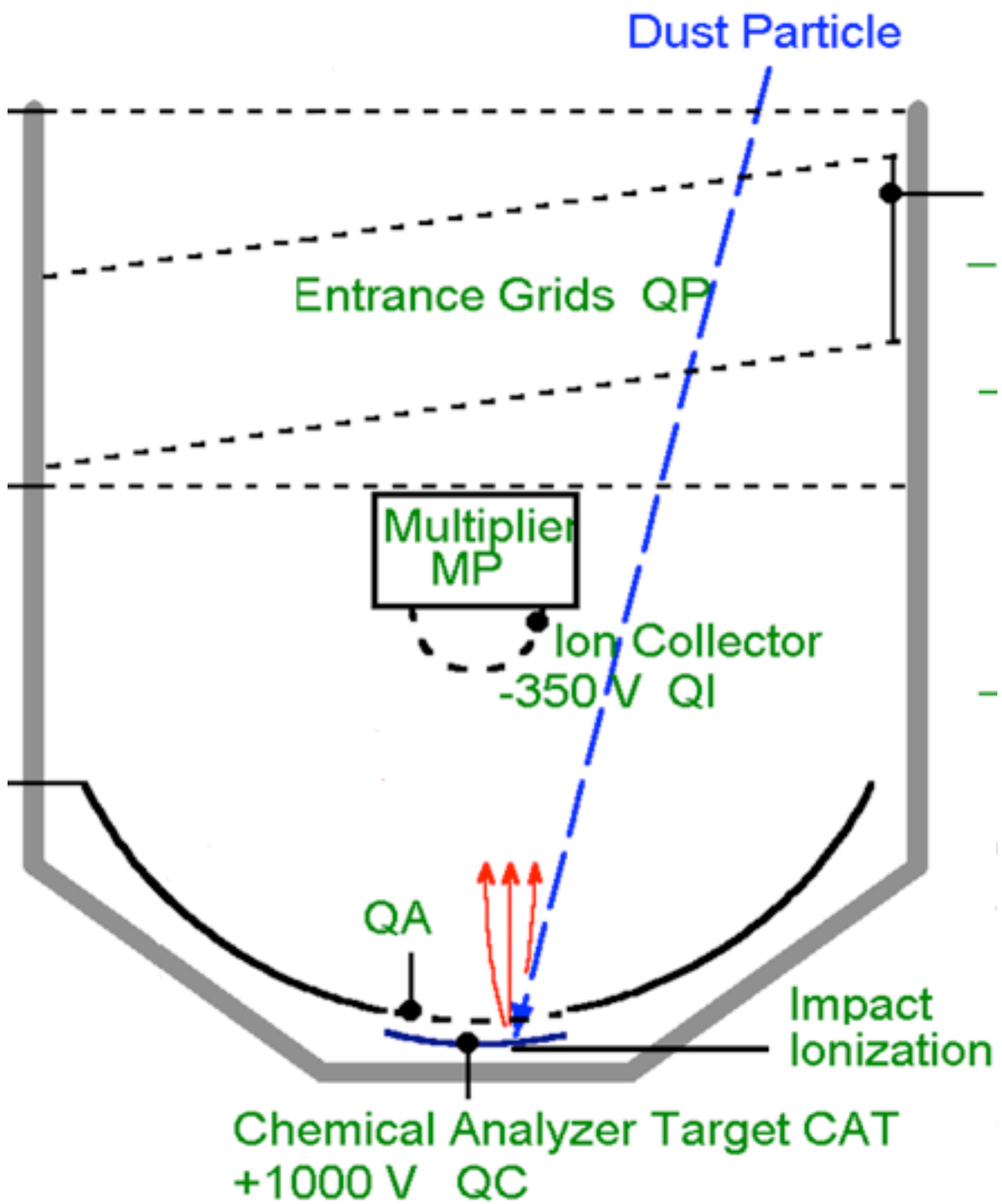
Hillier et al., 2007,
Postberg et al., 2008, 2009

Enceladus plume:
supplies material for Saturn's dusty E-ring

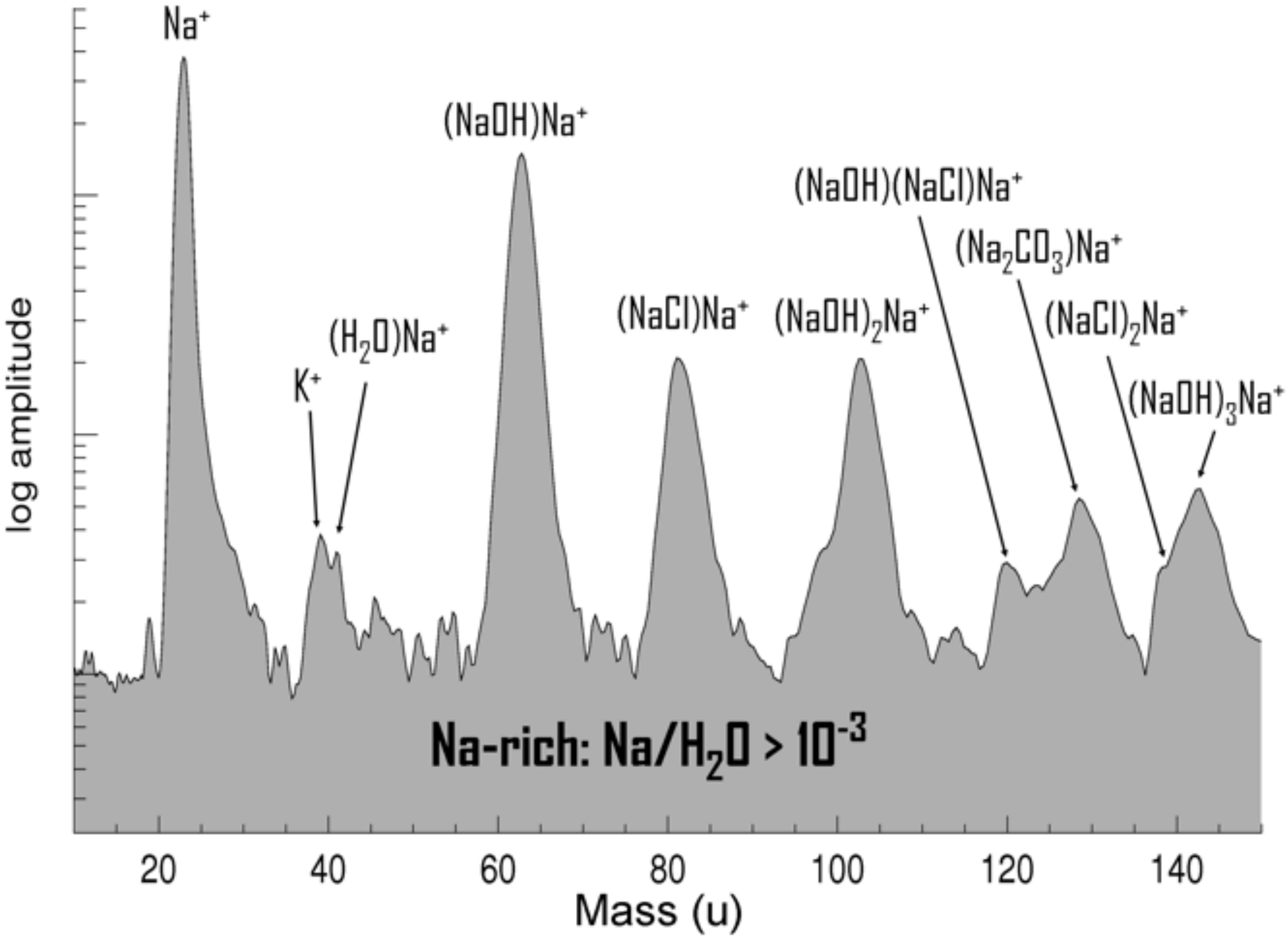


Images: NASA/JPL

Measurements with the CASSINI Cosmic Dust Analyzer



Example: Mass spectrum of a salt-rich E ring grain



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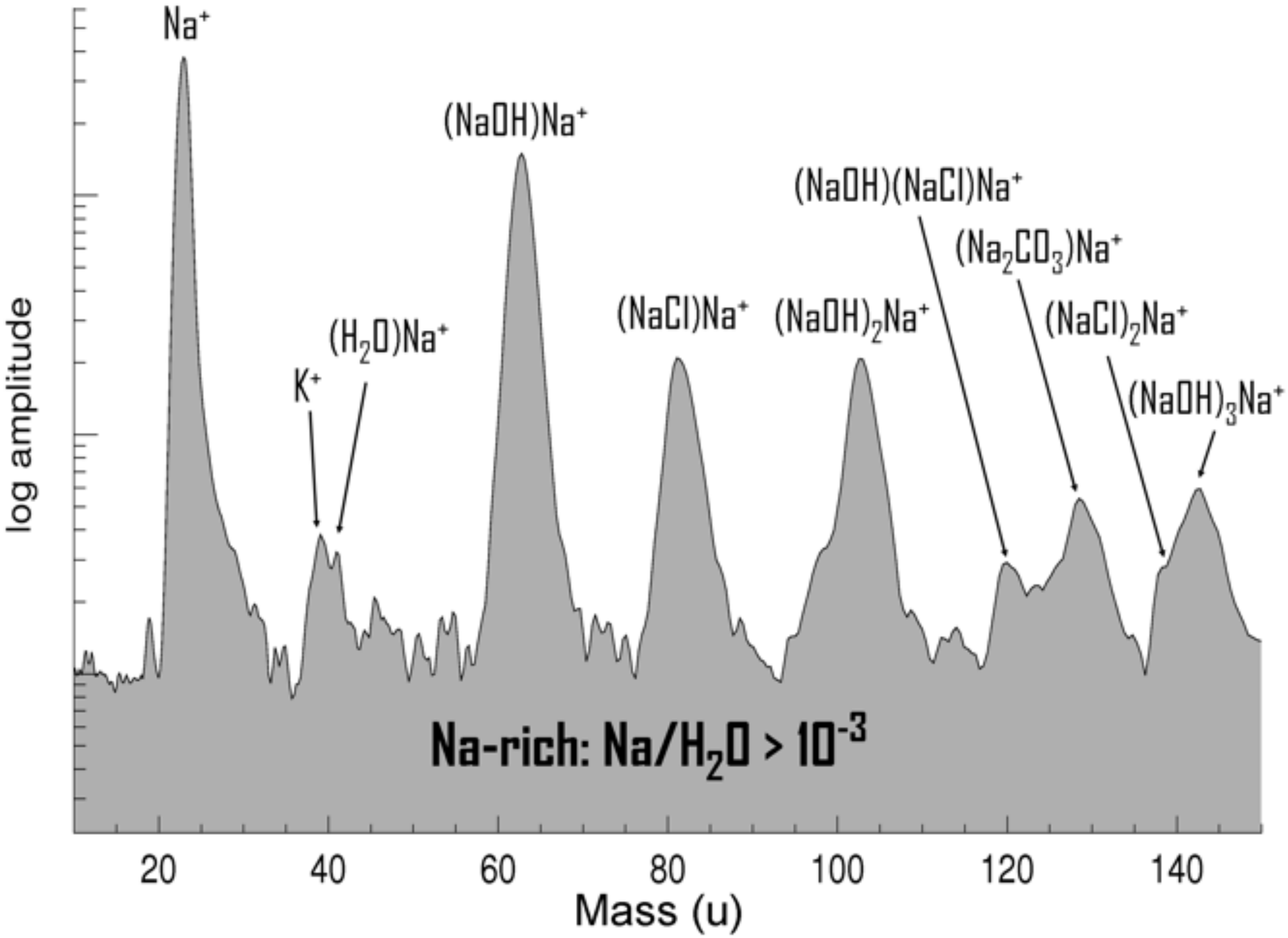

abundant	Na^+
and hydroxy-cluster ions	$Na(NaOH)_n^+$
comparison to lab spectra:	$Na/H_2O > 10^{-3}$

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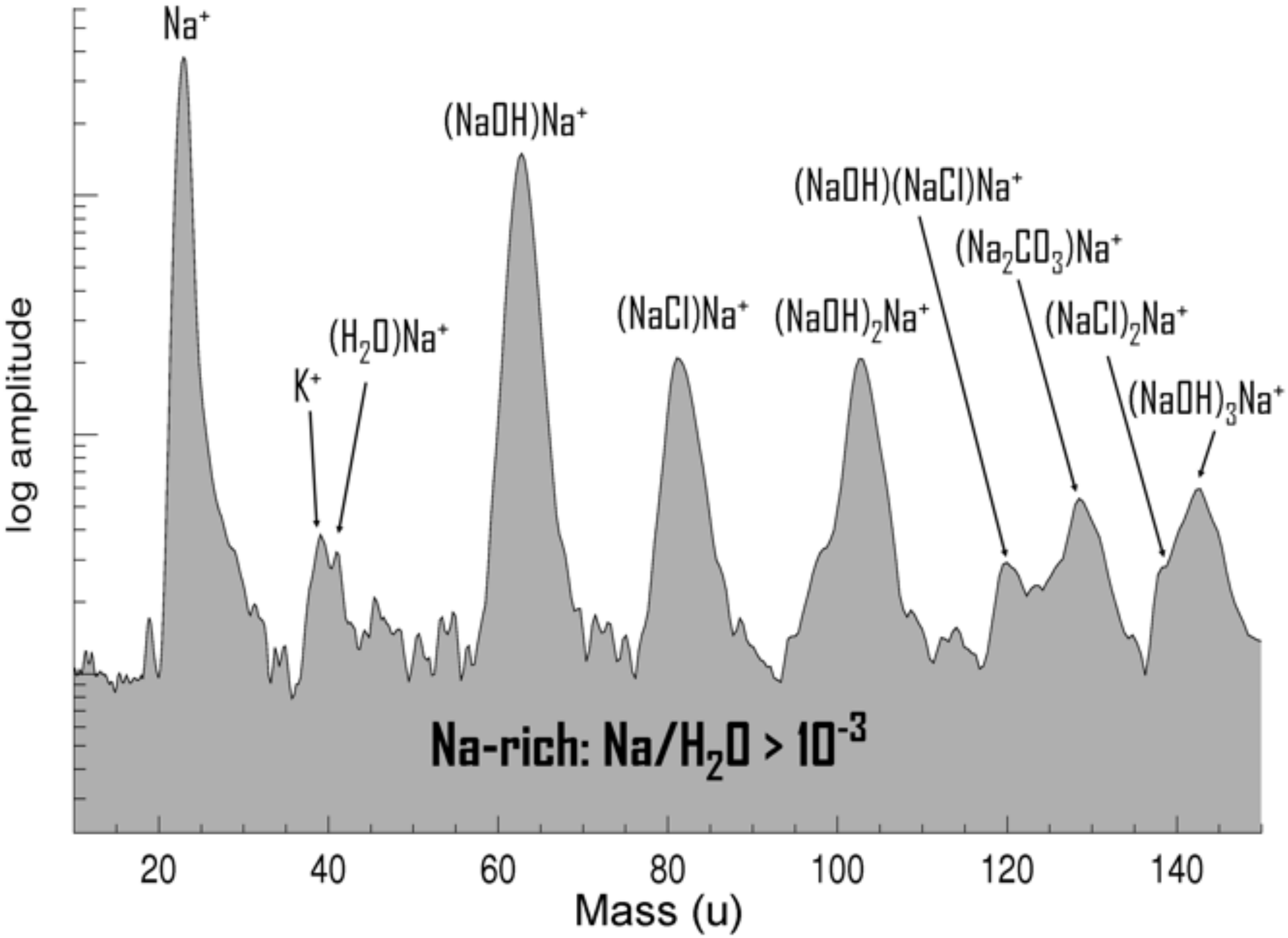

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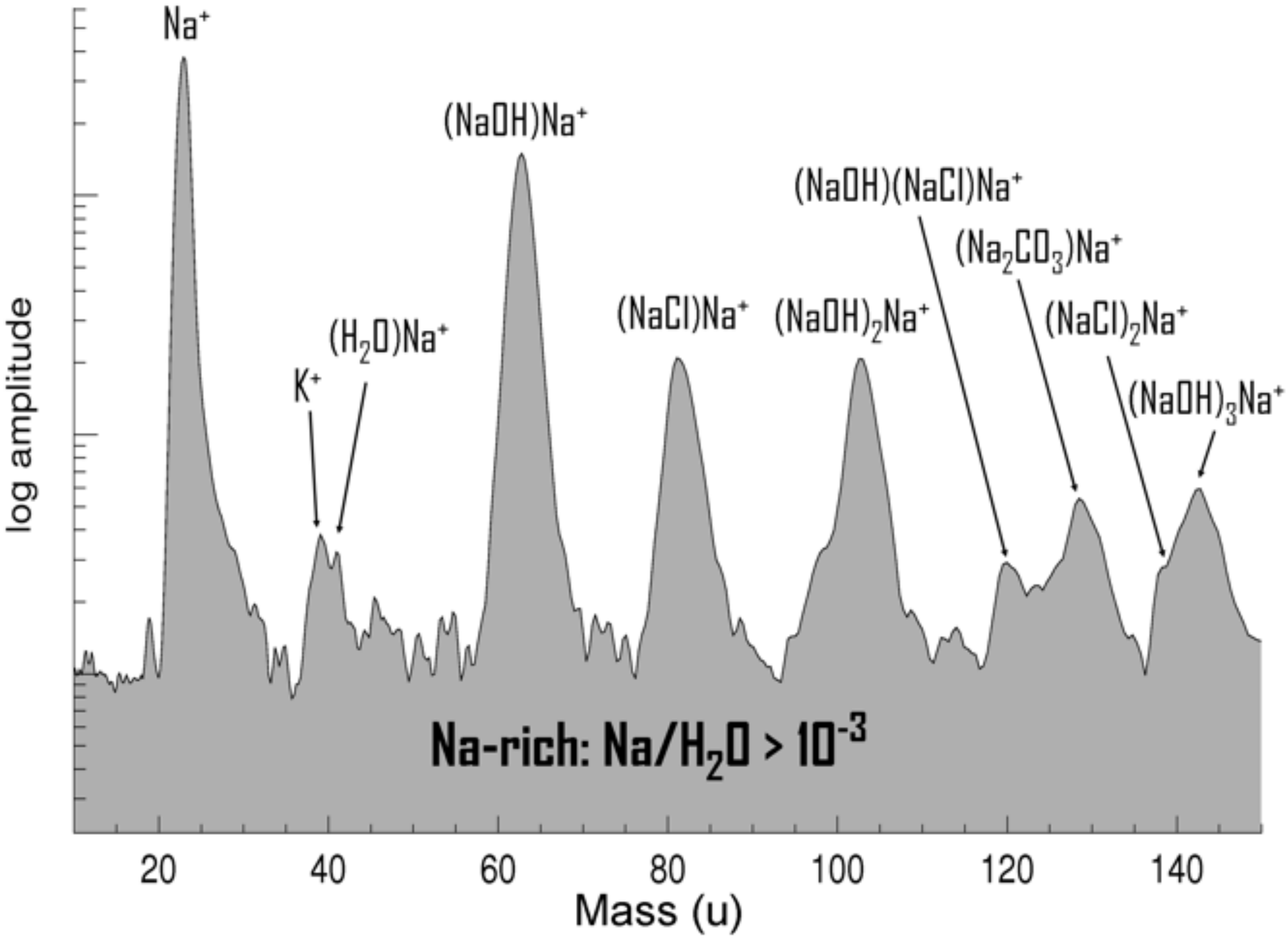
peaks due to $Na(NaCl)_n^+$ $Na(Na_2CO_3)^+$

imply Na_2CO_3 **and/or** $NaHCO_3$

Example: Mass spectrum of a salt-rich E ring grain



Make 6% of all spectra obtained in the E ring

abundant Na^+
and hydroxy-cluster ions $Na(NaOH)_n^+$

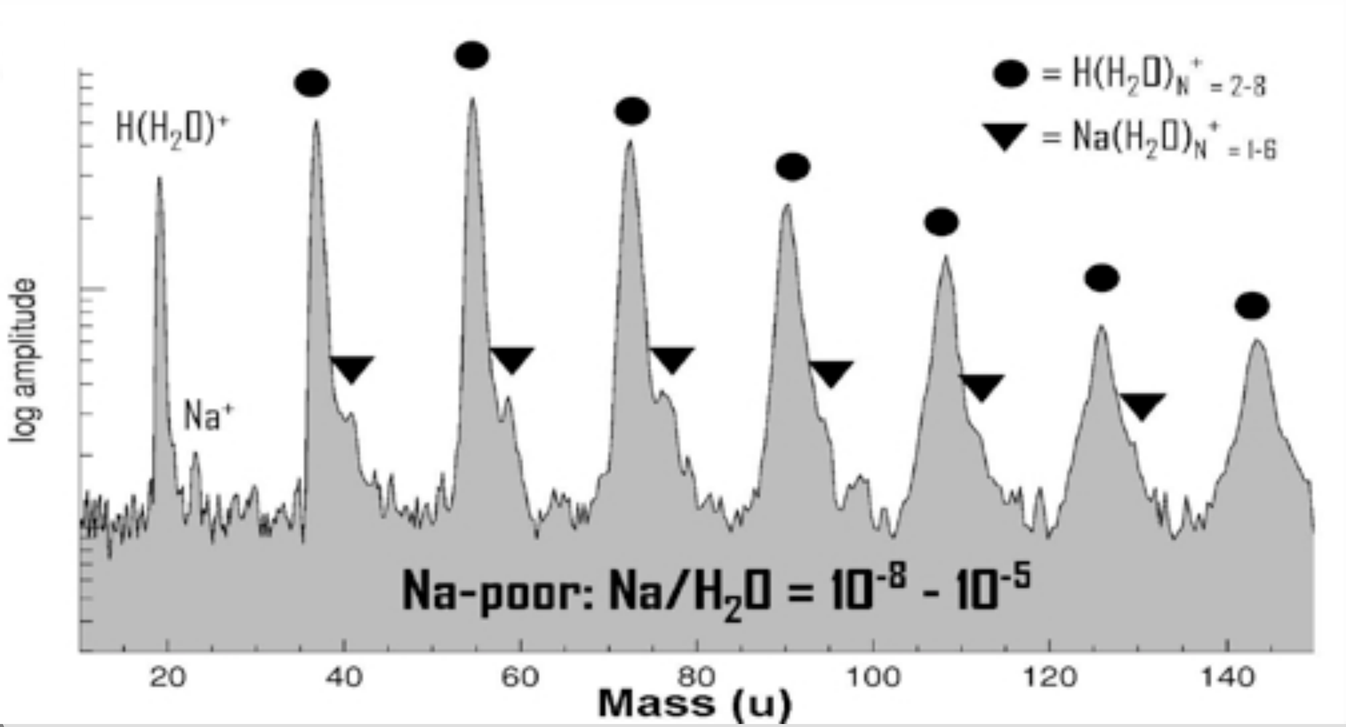
comparison to lab spectra: $Na/H_2O > 10^{-3}$

peaks due to $Na(NaCl)_n^+$ $Na(Na_2CO_3)^+$

imply Na_2CO_3 **and/or** $NaHCO_3$

Sodium poor E ring grains

CDA spectra:



90% of all E ring spectra

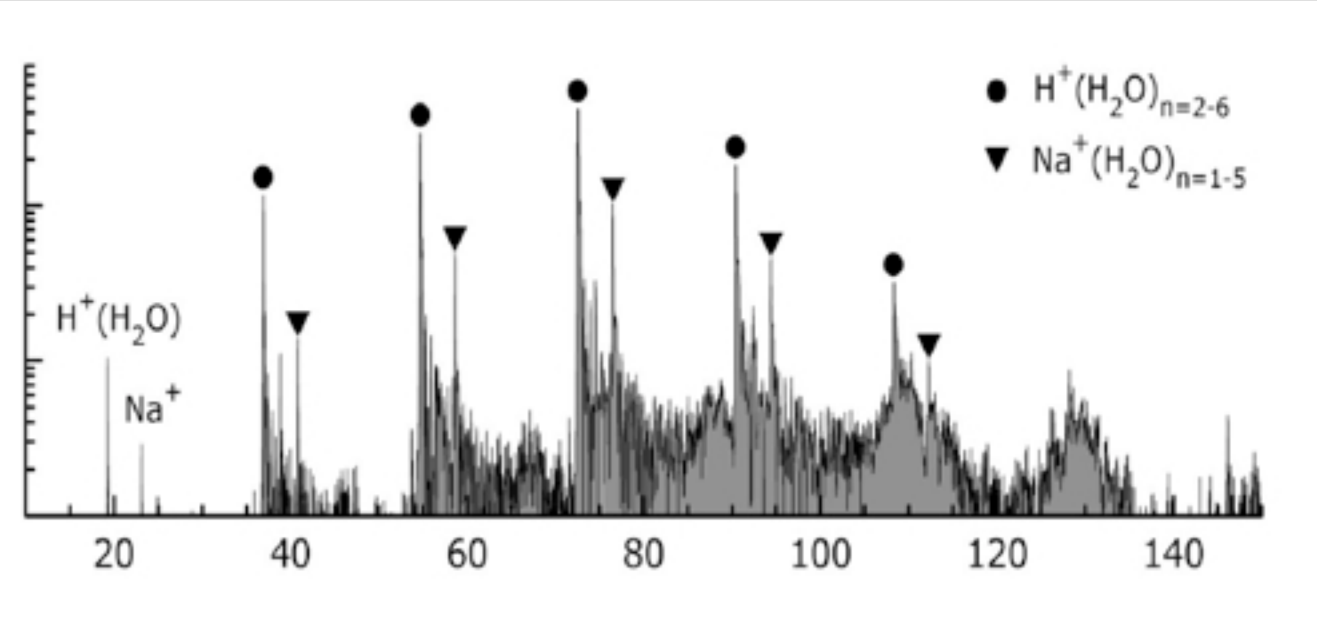
weak Na^+

abundant water clusters $H(H_2O)_n^+$

and hydrates $Na(H_2O)_n^+$

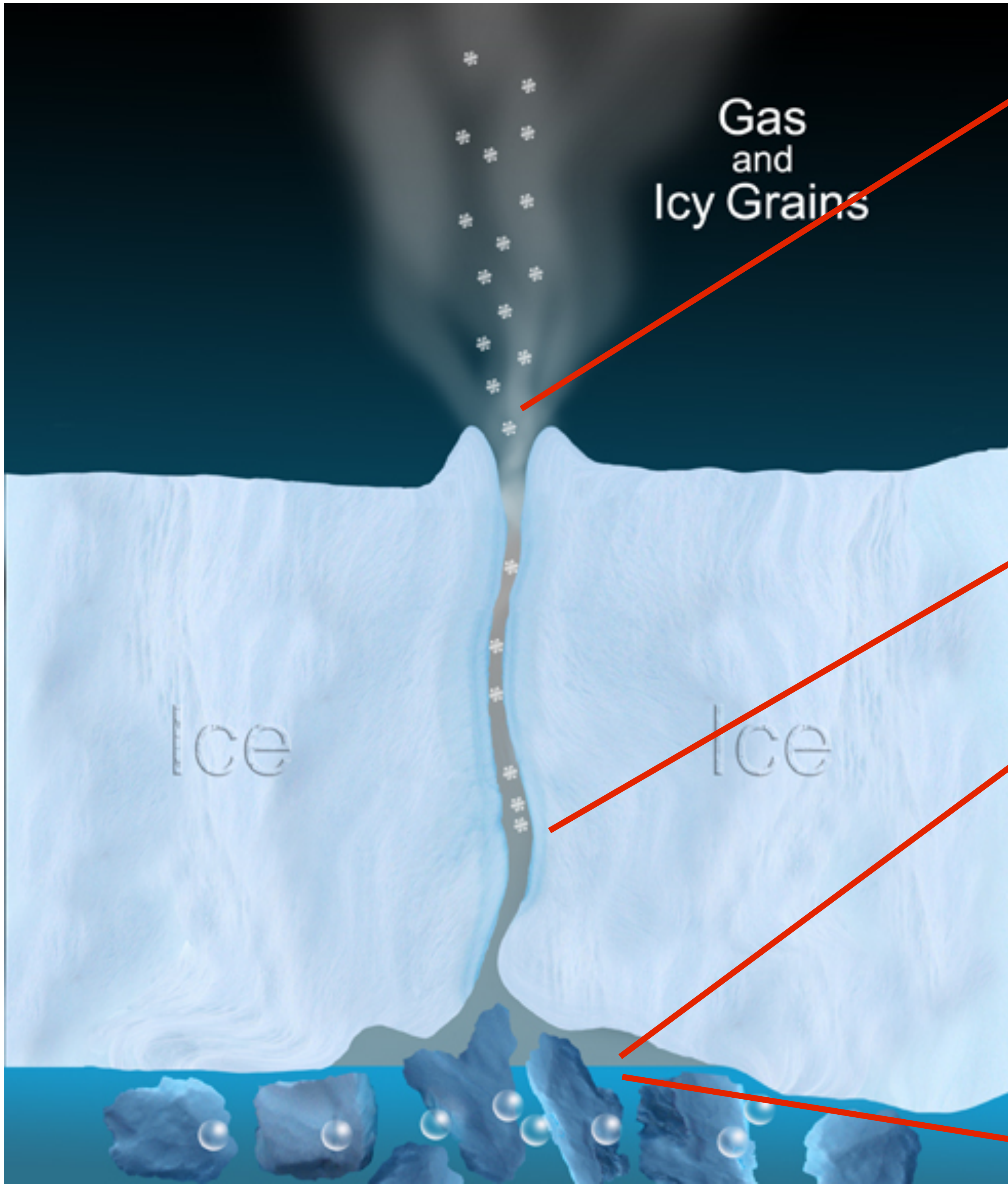
comparison to lab spectra: $Na/H_2O < 10^{-7}$

Lab reproduction of spectra:

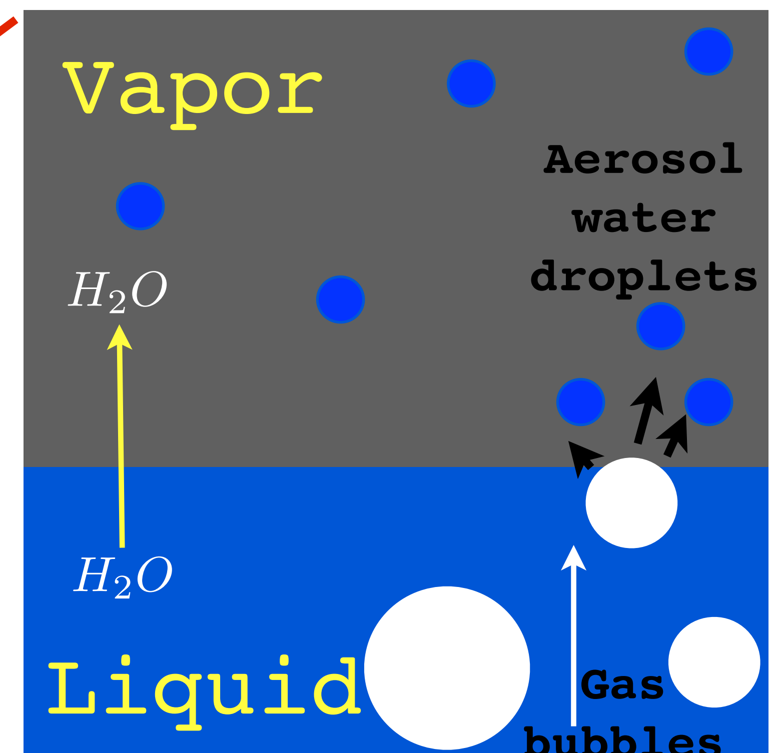


Spectrum of
water with 10**-6 mole/kg NaCl

=> reproduces clustering
characteristics of
Na-poor CDA spectra



(Schmidt et al., Nature, 2008)

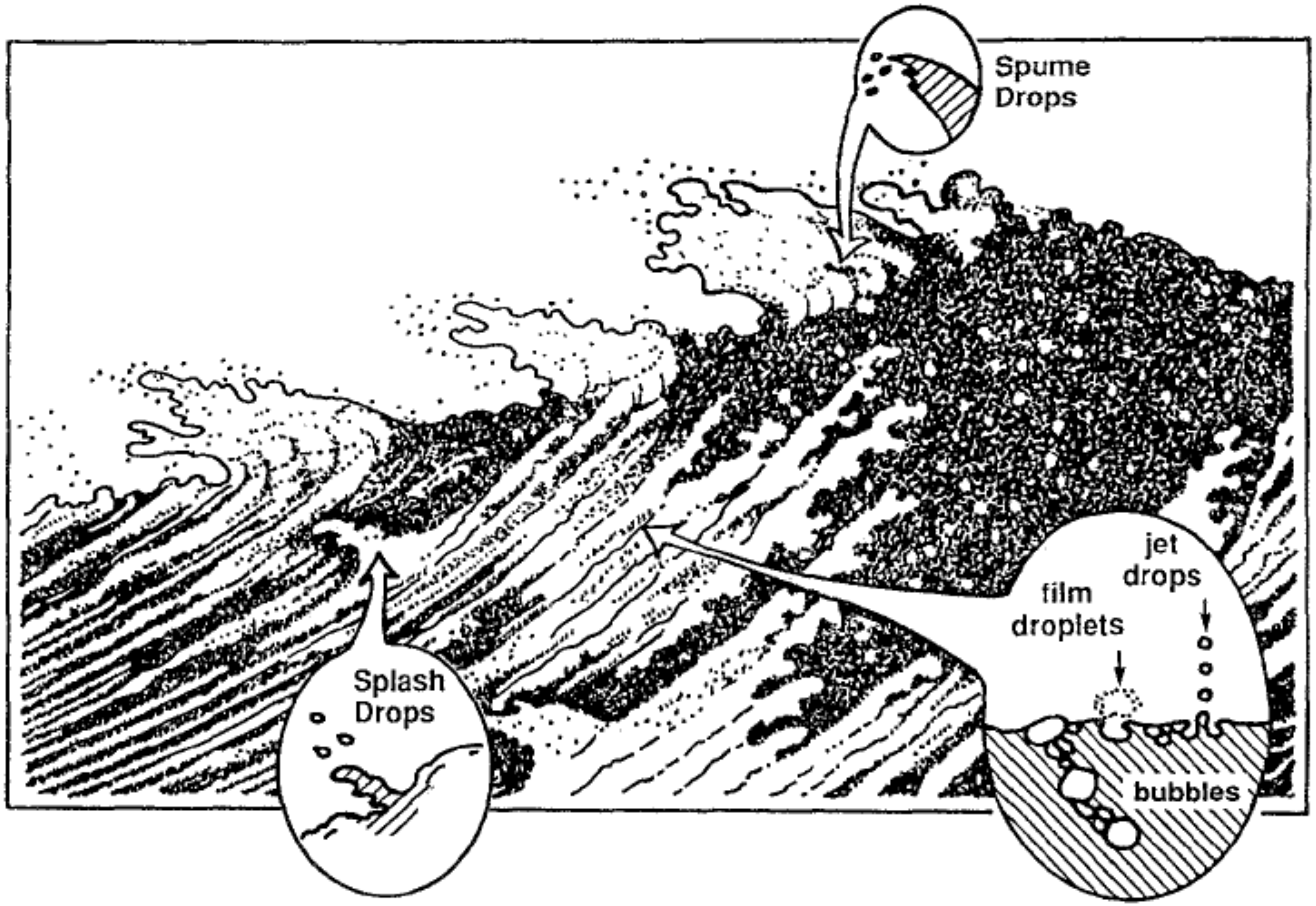


(Postberg et al., Nature, 2009)

Volatile gases: N_2, CO_2, CH_4

(Waite et al., 2006, Matson et al., 2011)

(E. Andreas et al., *Boundary-Layer Meteorology* 72: 3-52, 1995.)



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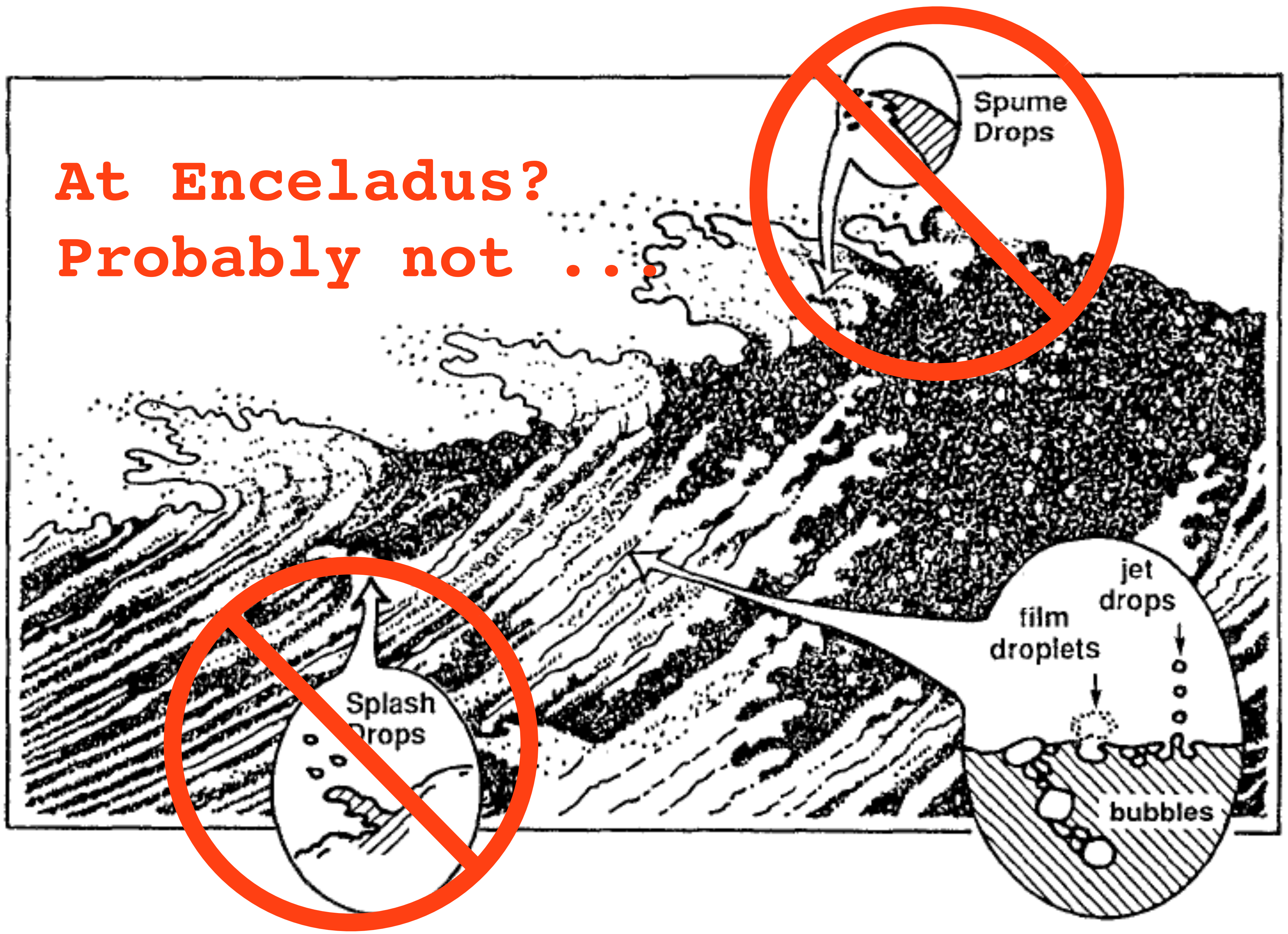

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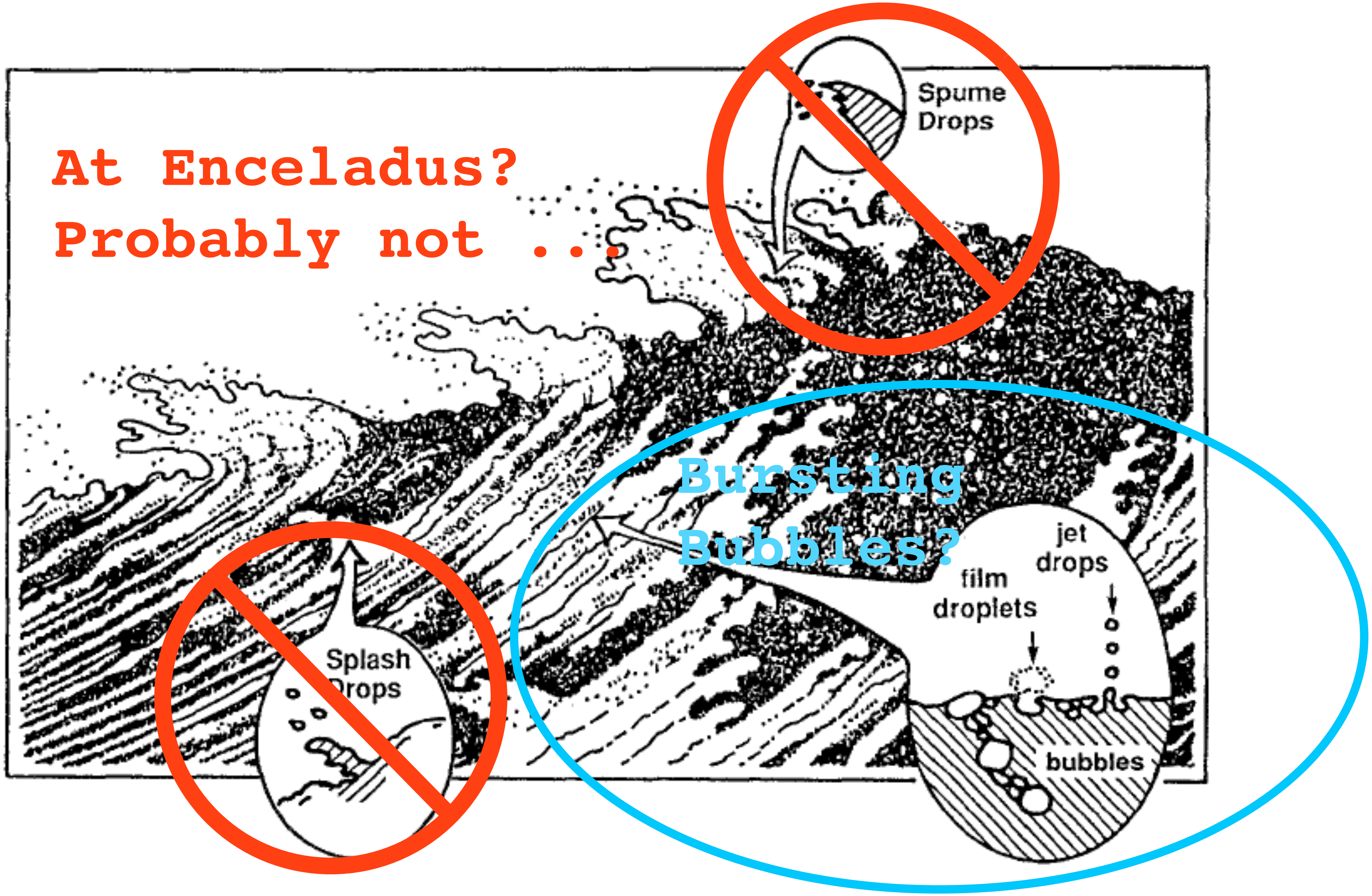
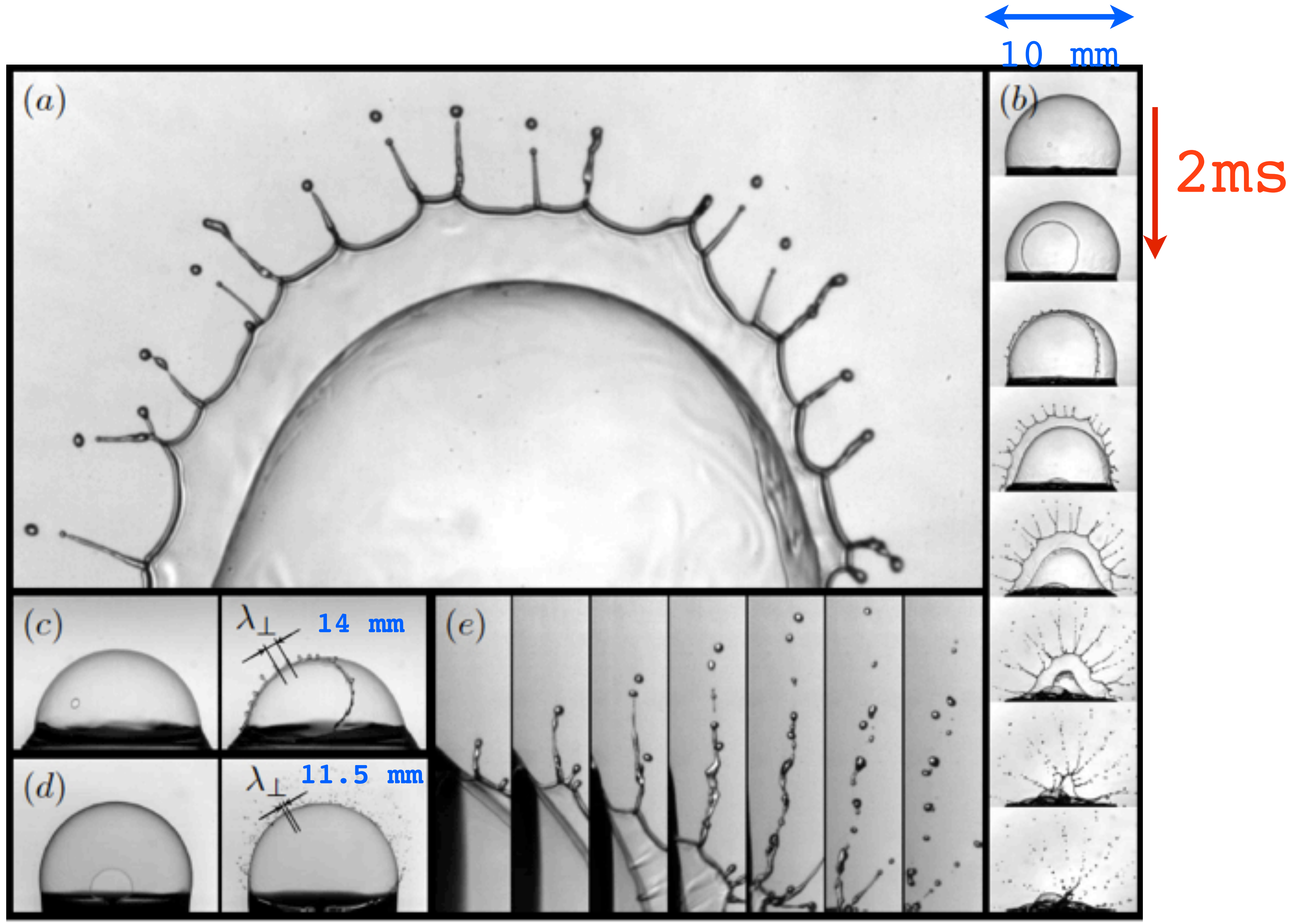


Bursting Bubbles

(Lhuissier and Villermaux, PHYSICS OF FLUIDS **21**,

- **Air volume rising in water pool**



Bursting Bubbles

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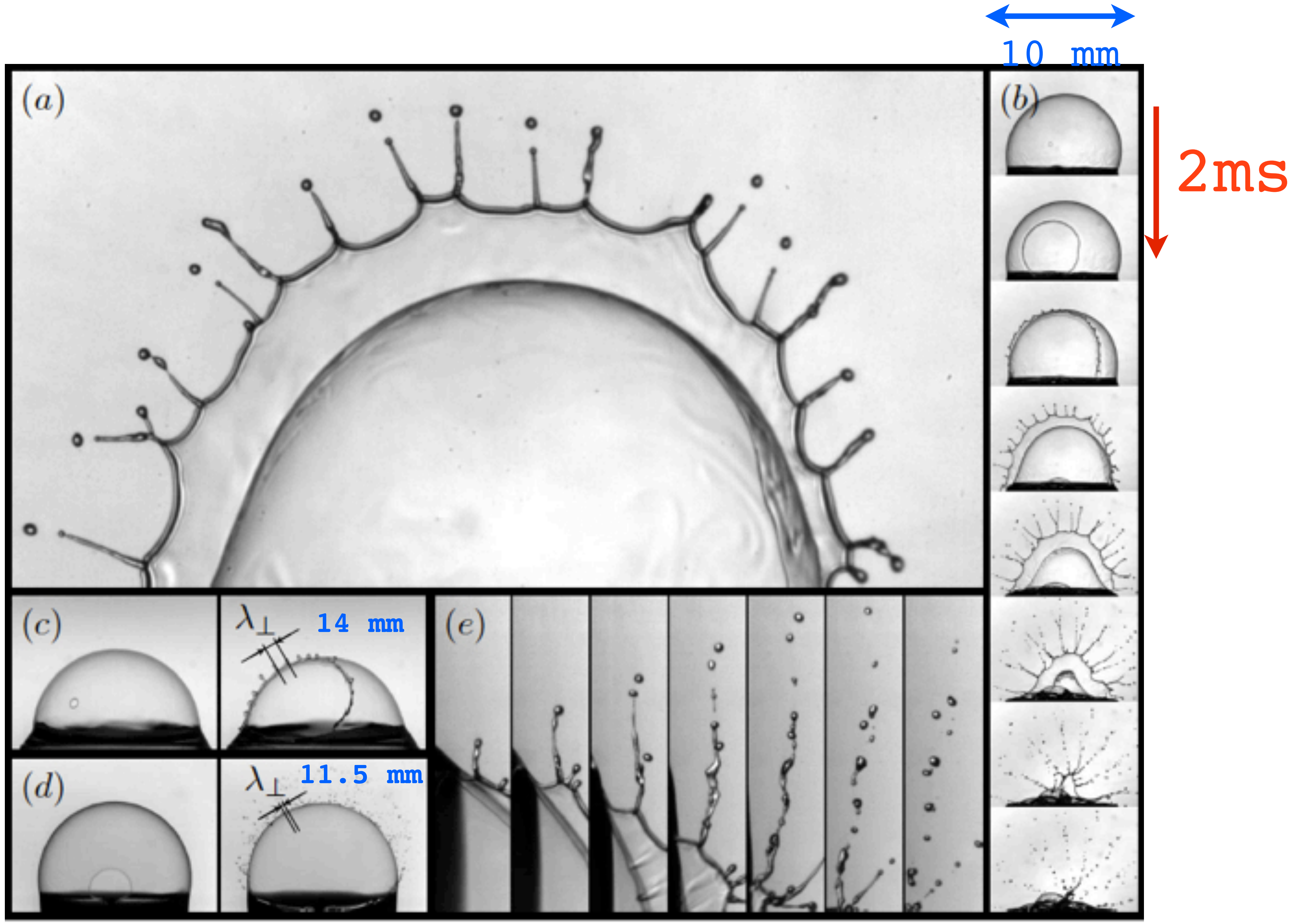
- **Air volume rising in water pool**
- **burst by nucleating a hole**



Bursting Bubbles

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- **Air volume rising in water pool**
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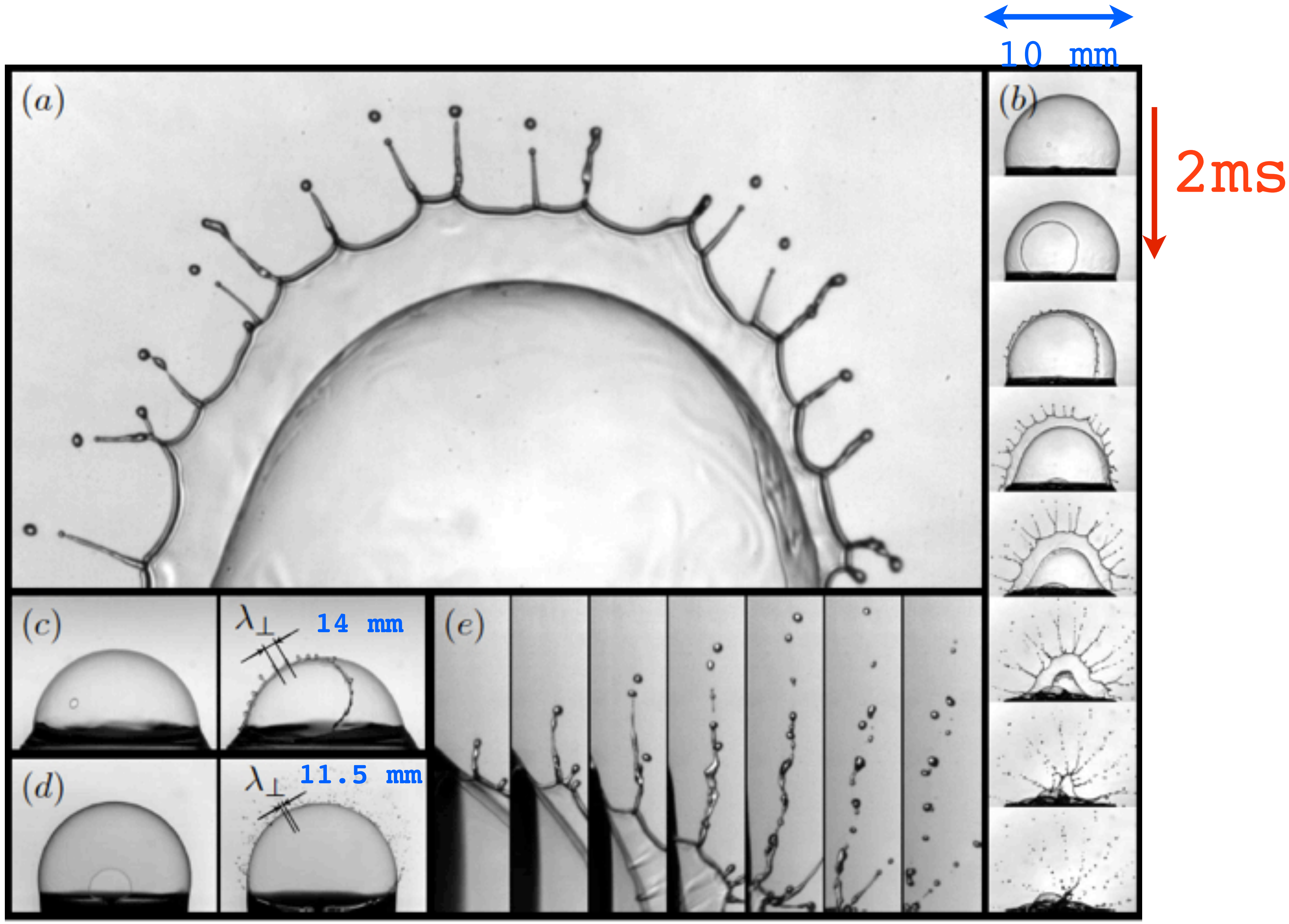

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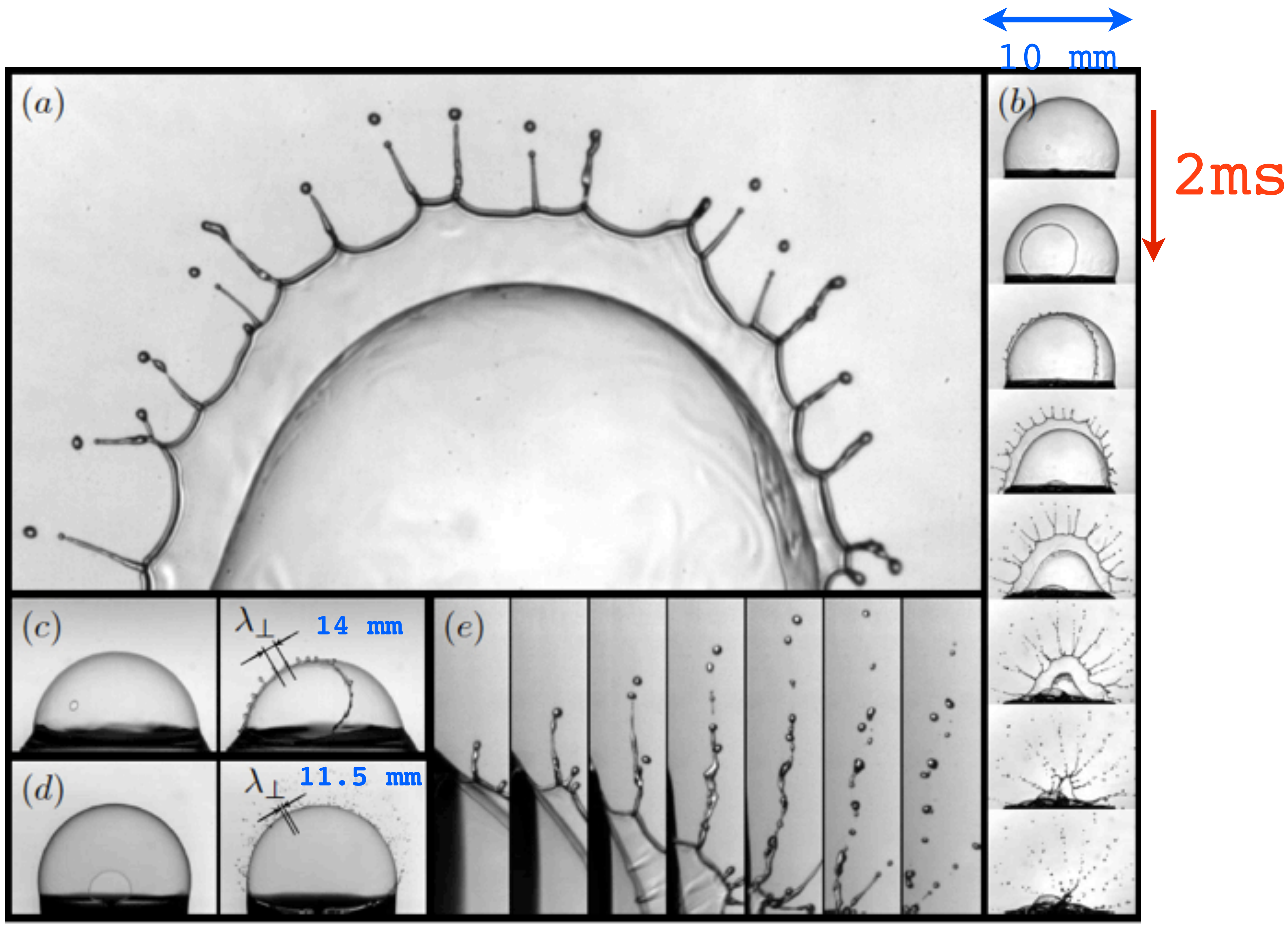

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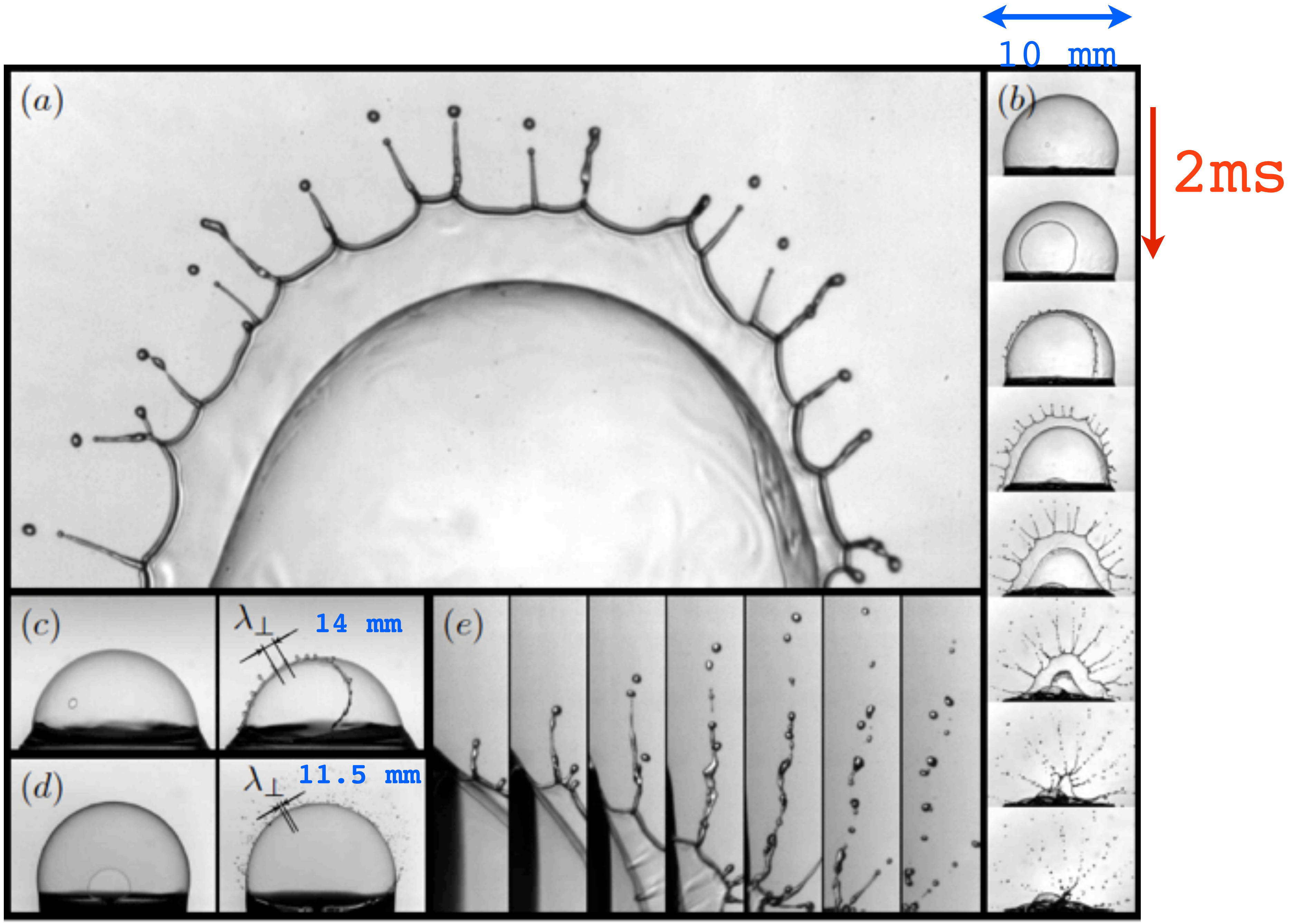

Bursting Bubbles

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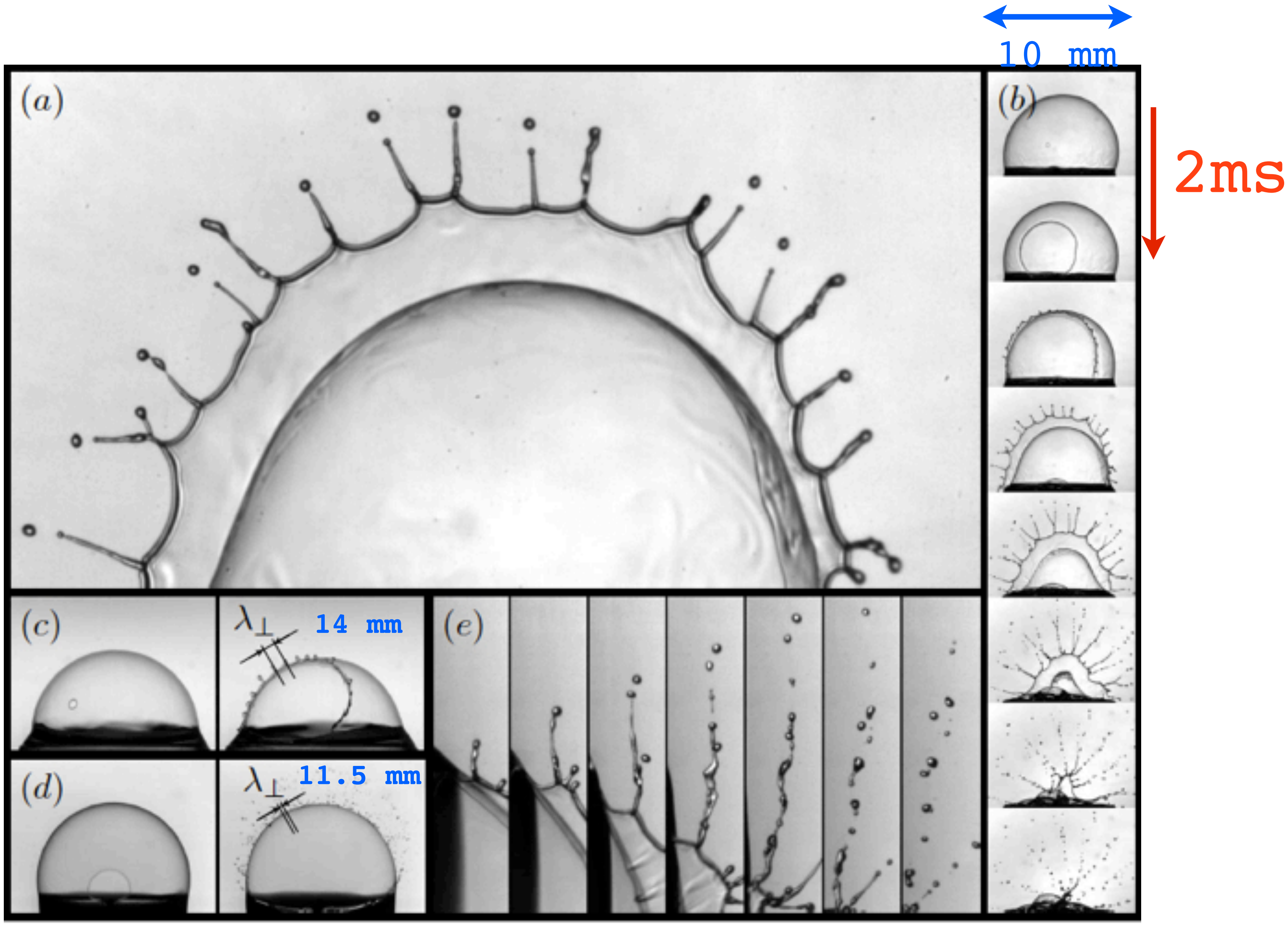
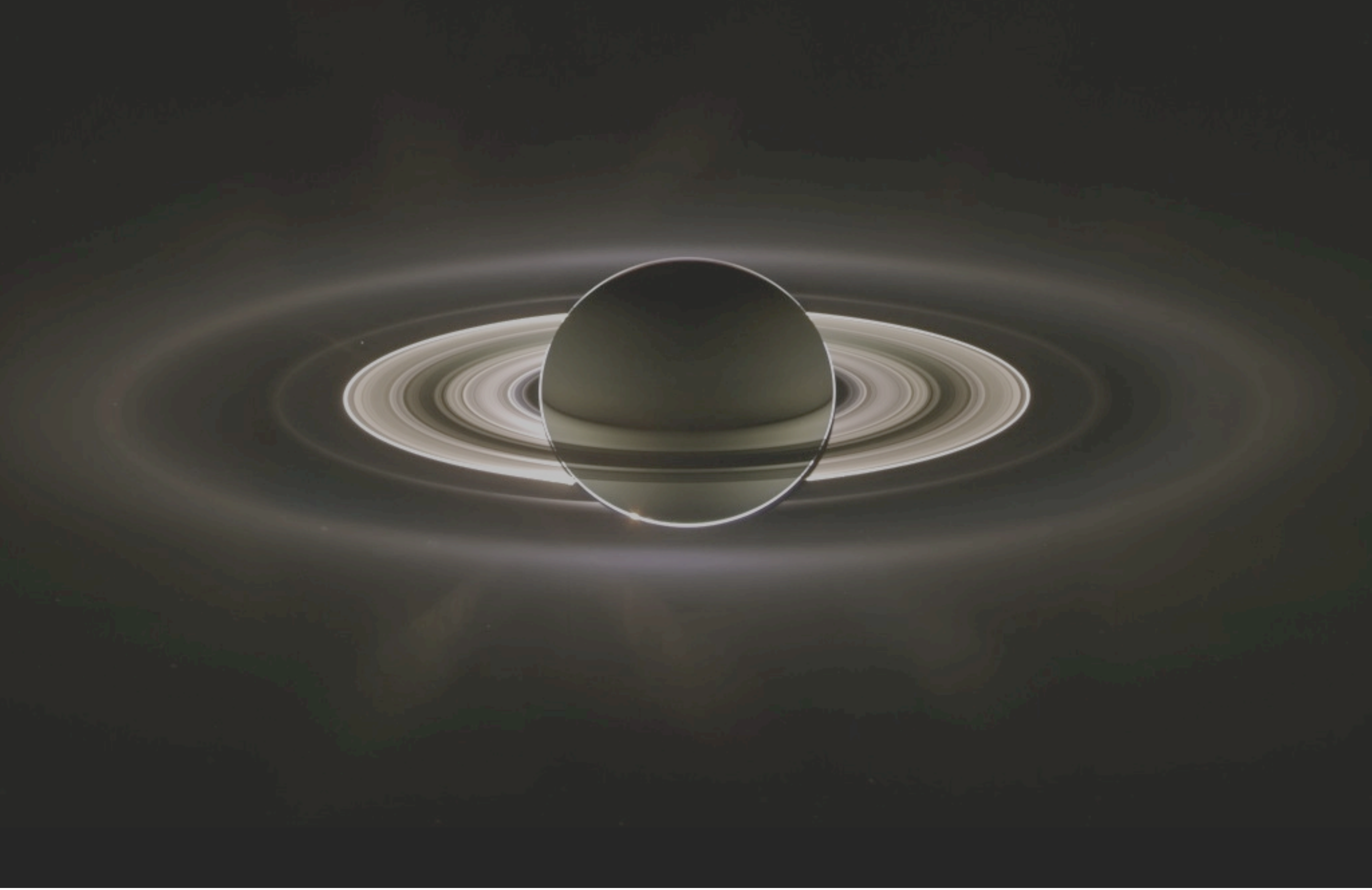
- Air volume rising in water pool
- burst by nucleating a hole
- moving rim is unstable (Rayleigh-Taylor) and forms ligaments
- ligaments are stretched and break up by capillary instability
- radius corrugations of ligaments set size distribution of droplets
- here: droplets are 10s of microns and smaller

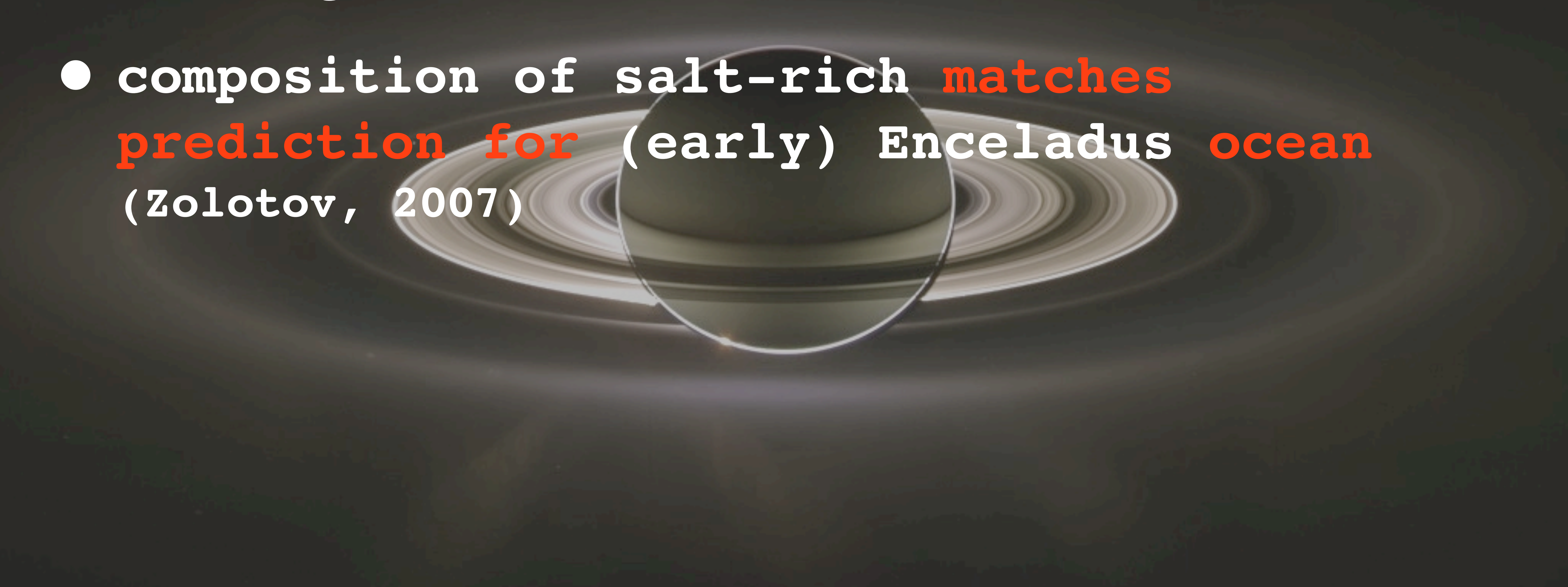


Summary for E ring



Summary for E ring

- 90% of grains are **salt-poor**: $Na/H_2O > 10^{-7}$
- 6% of grains are **salt-rich**: $Na/H_2O > 10^{-3}$
- composition of salt-rich **matches prediction for** (early) Enceladus **ocean** (Zolotov, 2007)



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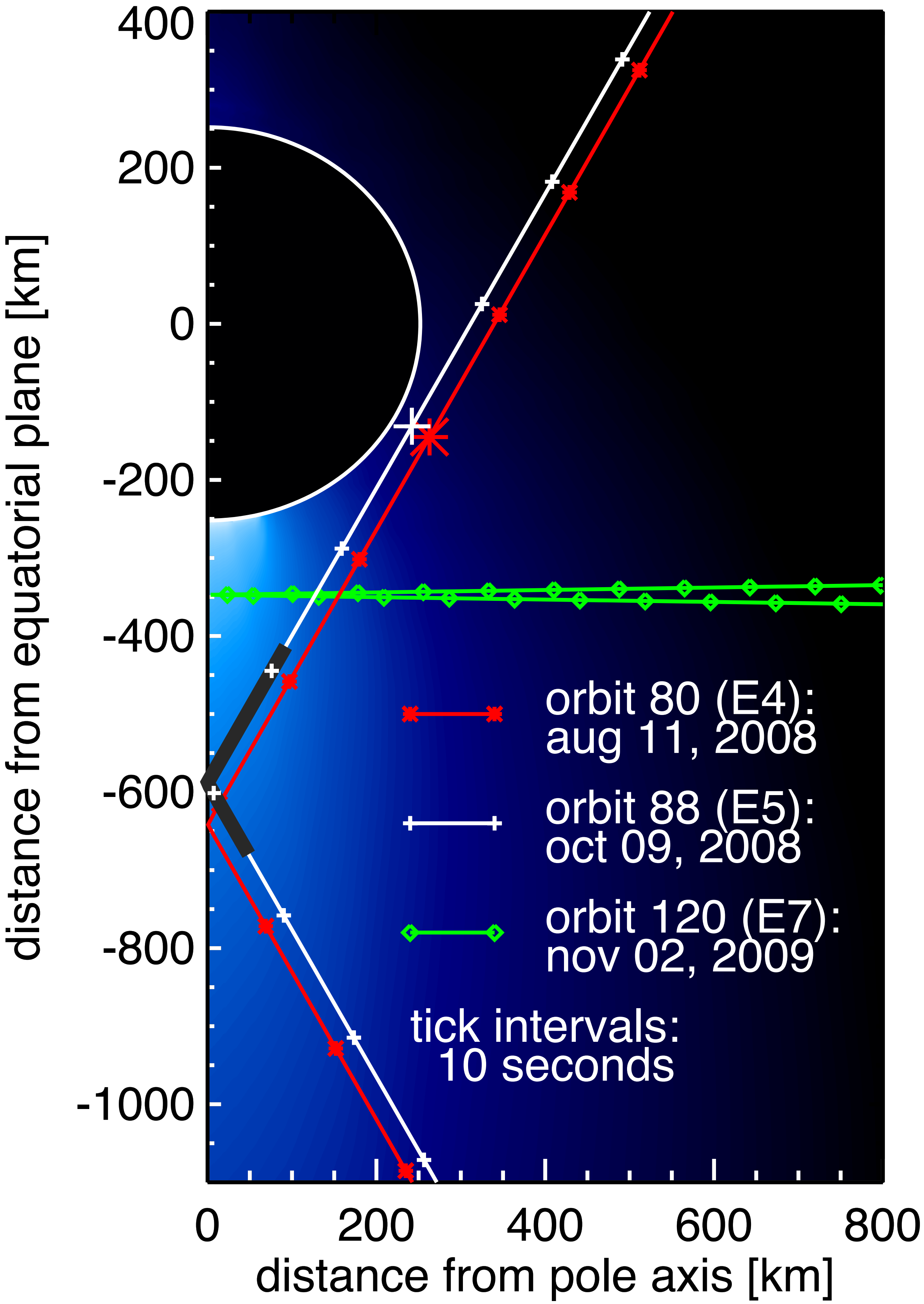
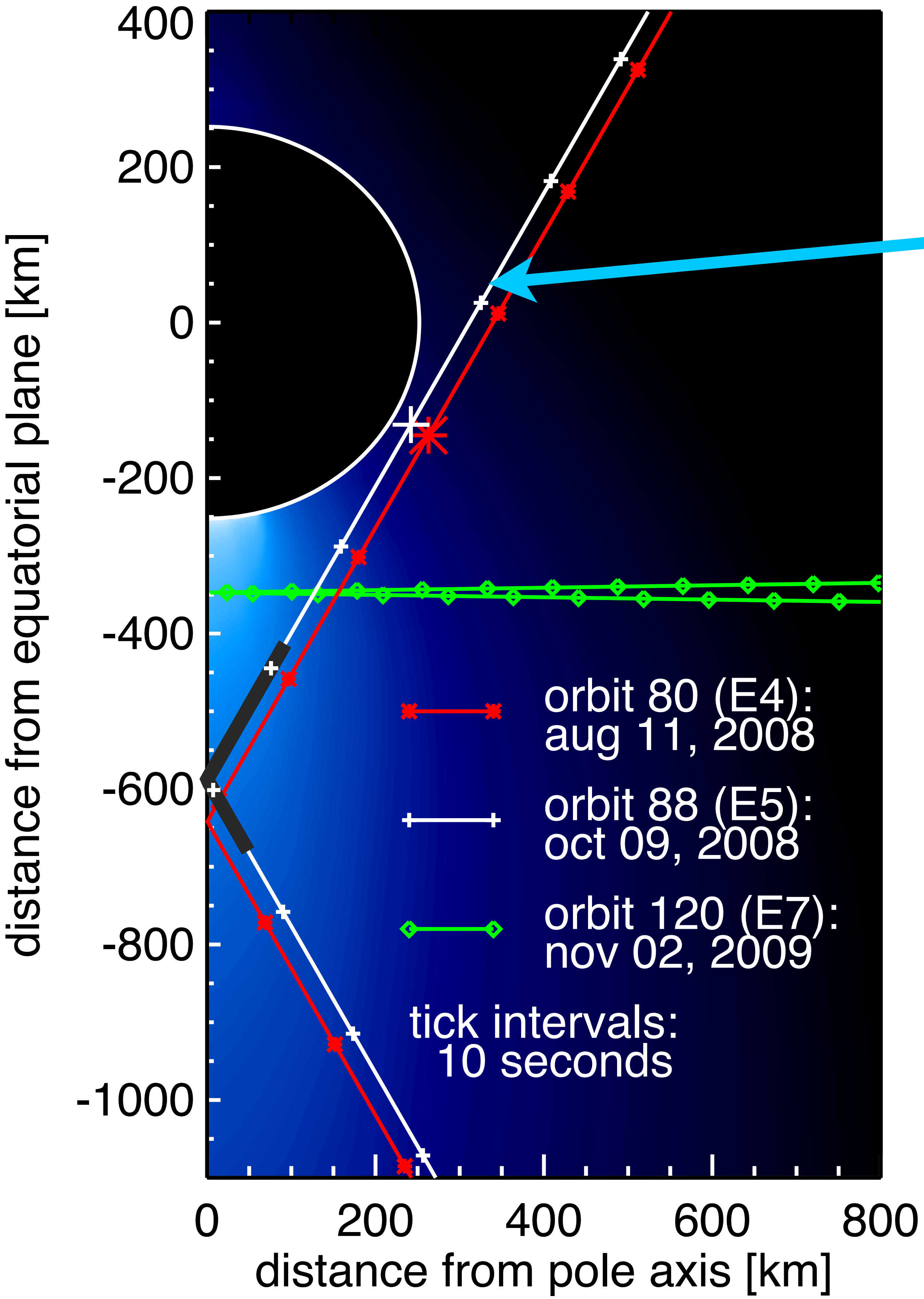
- 6% of grains are salt-rich: $Na/H_2O > 10^{-3}$
- composition of salt-rich matches prediction for (early) Enceladus ocean (Zolotov, 2007)

=> clear indication for aqueous processes
=> formation of salt-rich: direct dispersion from (present day) liquid is easiest
=> salt-poor: condensation from vapor above salty water

CDA measurements in the plume

CDA spectra from three Enceladus flybys





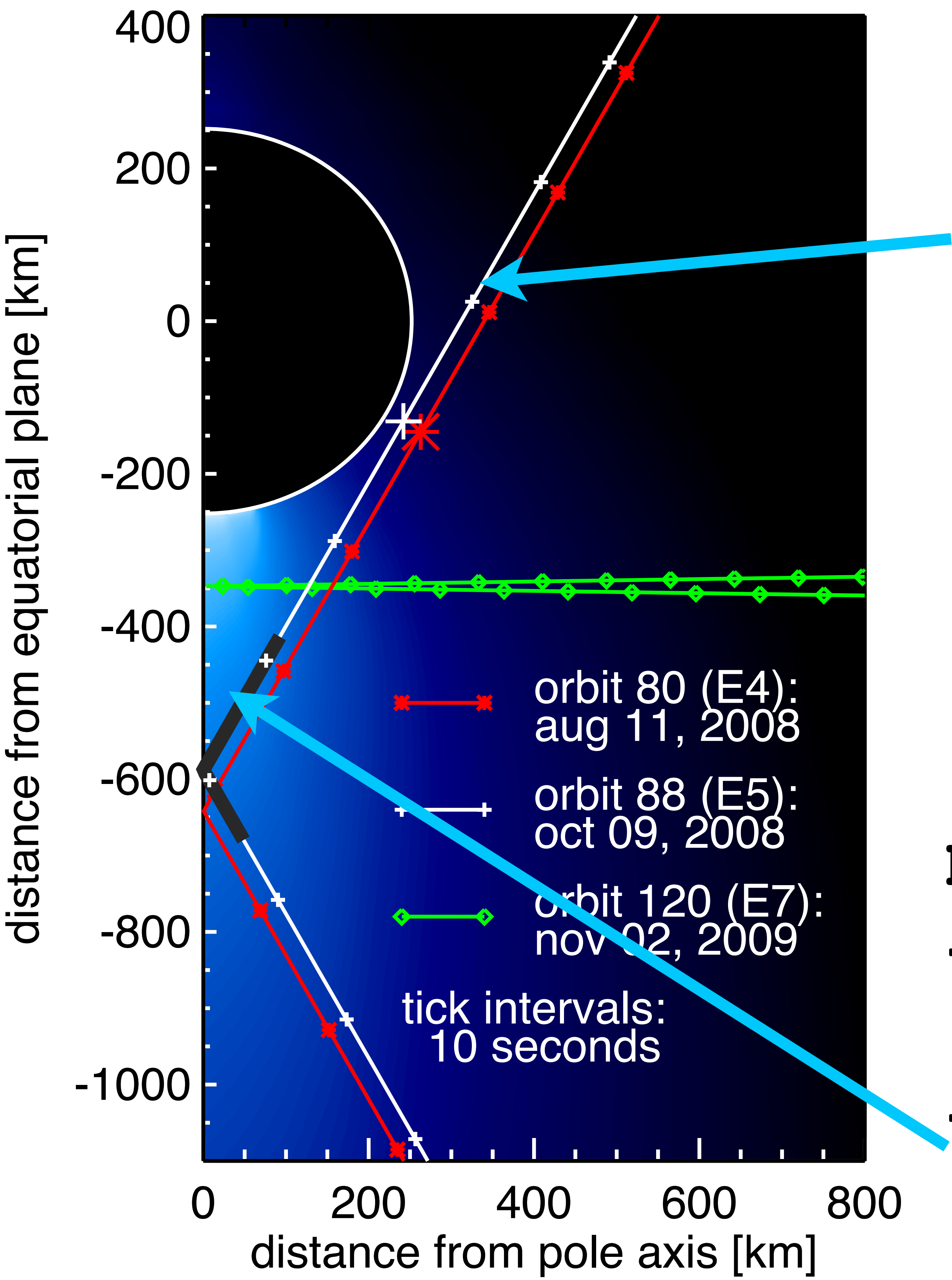
CDA spectra from three Enceladus flybys

Rev88 (E5):

-> special flight software

-> up to 5 spectra per second

-> compositional profile



CDA spectra from three Enceladus flybys

Rev88 (E5):

-> special flight software

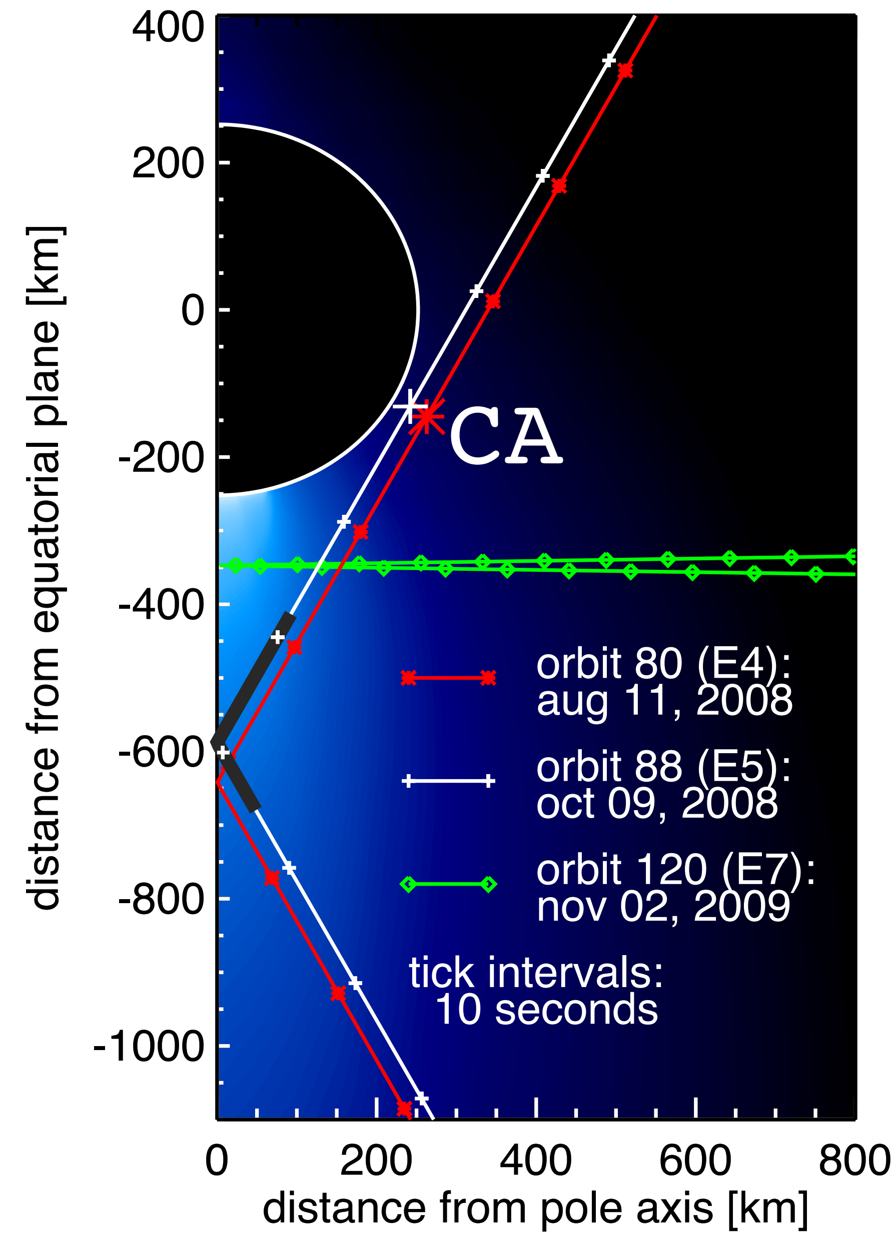
-> up to 5 spectra per second

-> compositional profile

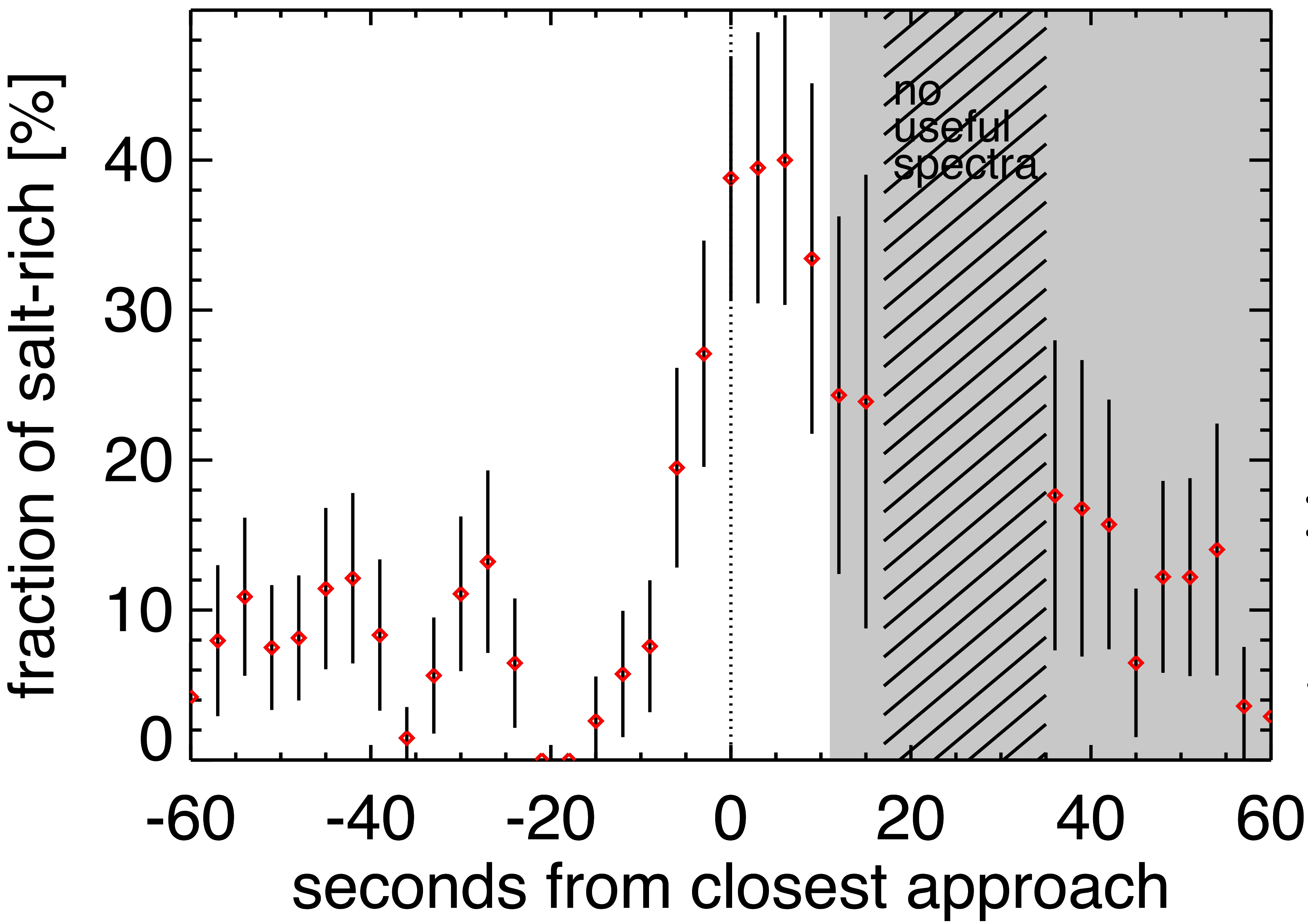
But:

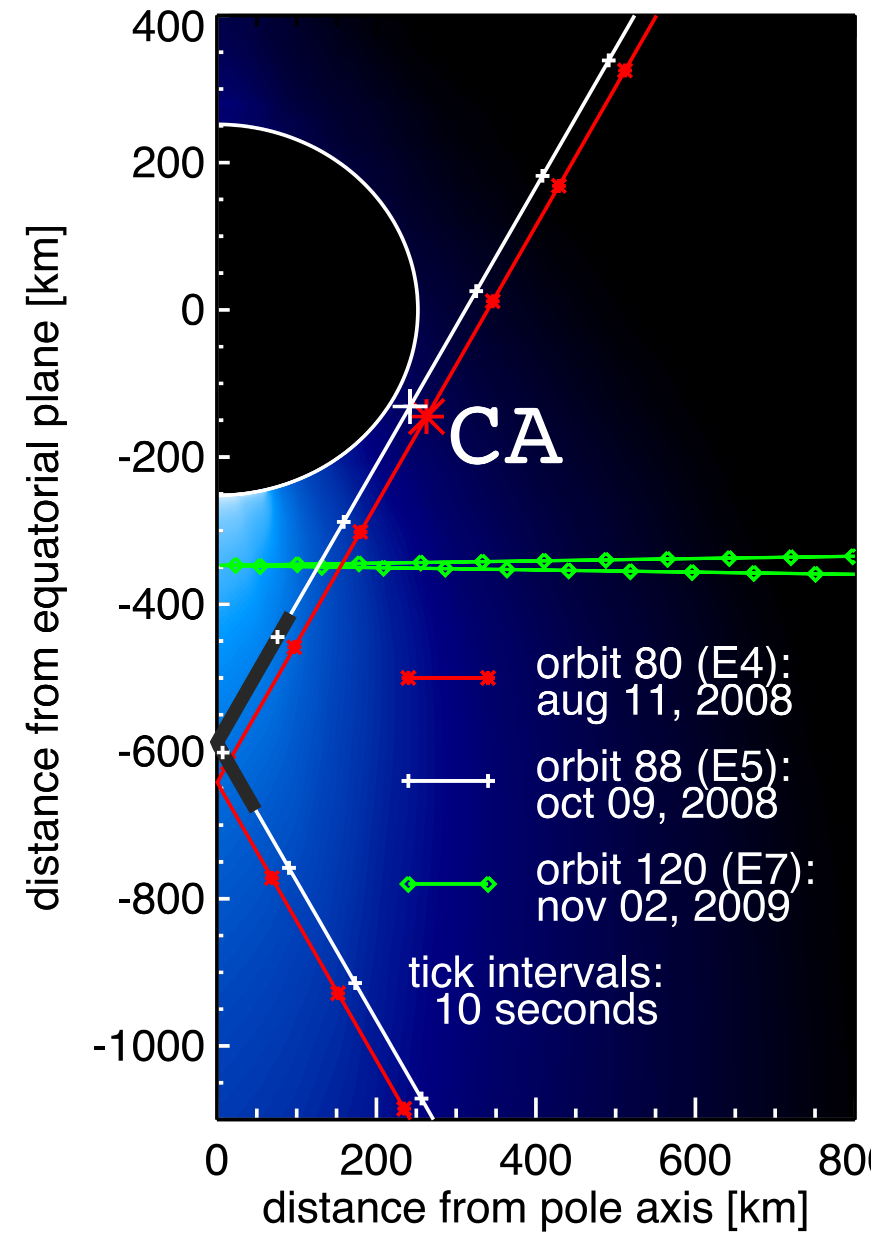
-> no information on mass, speed, charge

-> instrumental stress in densest plume



CA
orbit 80 (E4): aug 11, 2008
orbit 88 (E5): oct 09, 2008
orbit 120 (E7): nov 02, 2009
tick intervals: 10 seconds
distance from equatorial plane [km]
distance from pole axis [km]
400
200
0
-200
-400
-600
-800
-1000
0
200
400
600
800



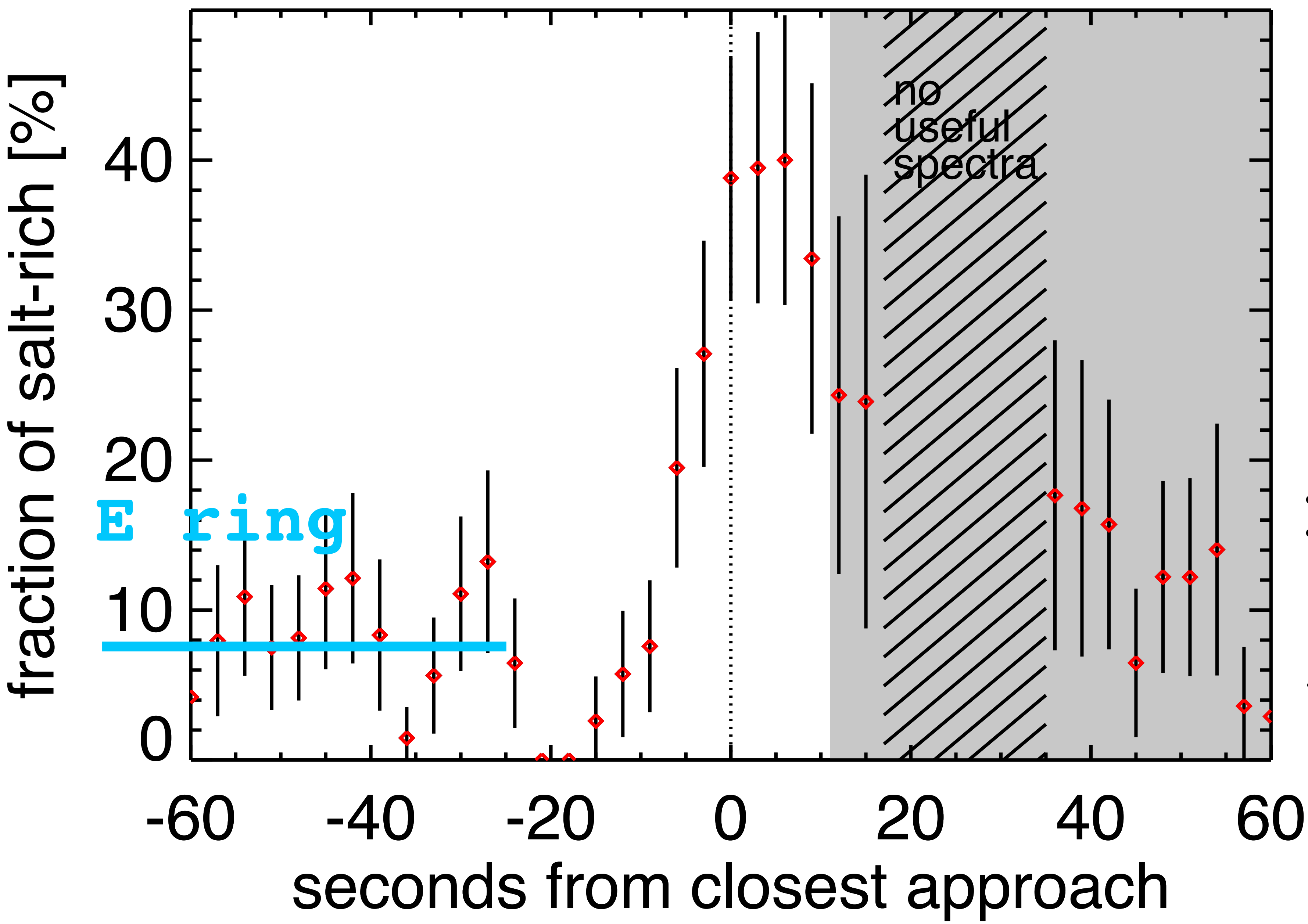


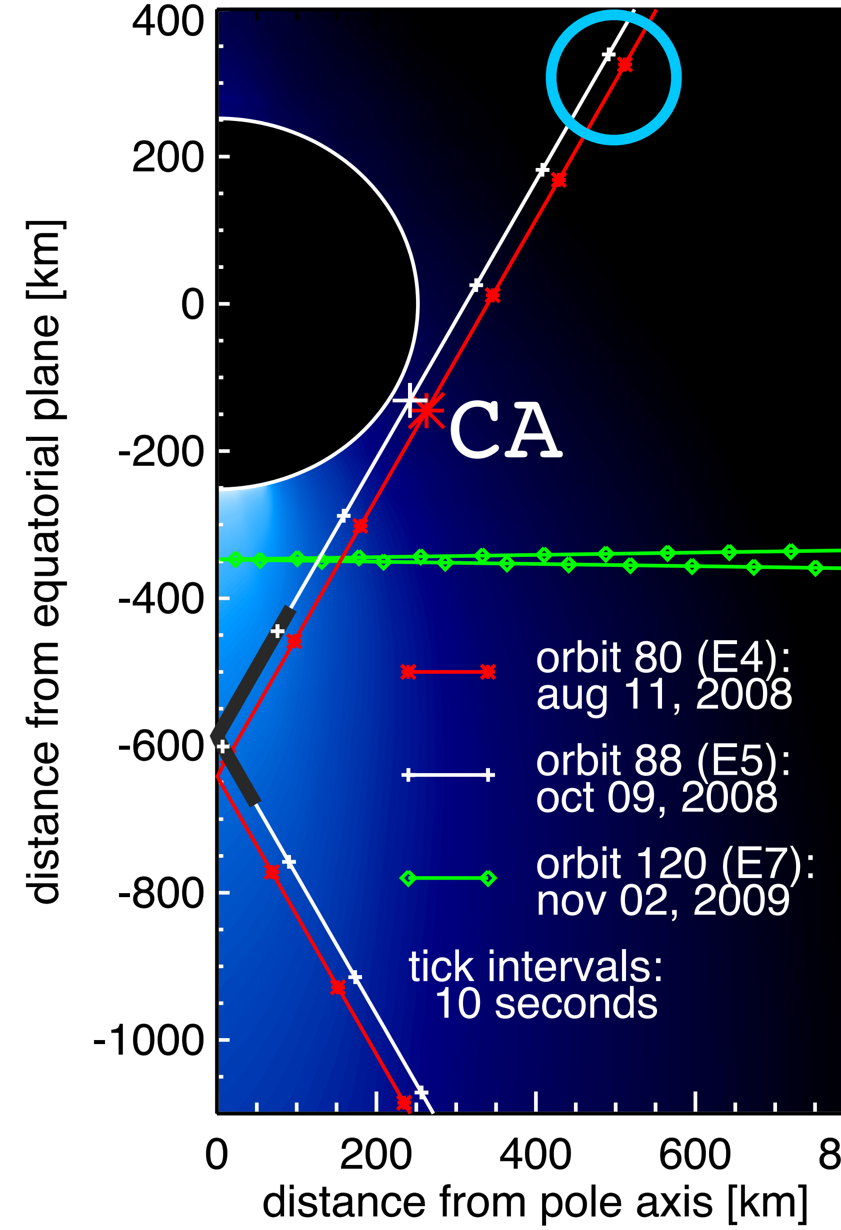
Box-car average:

9s bins

~40 spectra each

/Users/jschmidt/Projects/PlumeE5SodiumCDA/BackFireIntegrations/Rev88TwoBodyModels::DraftFig2Plot jschmidt Mon Mar 21 10:09:26 2011





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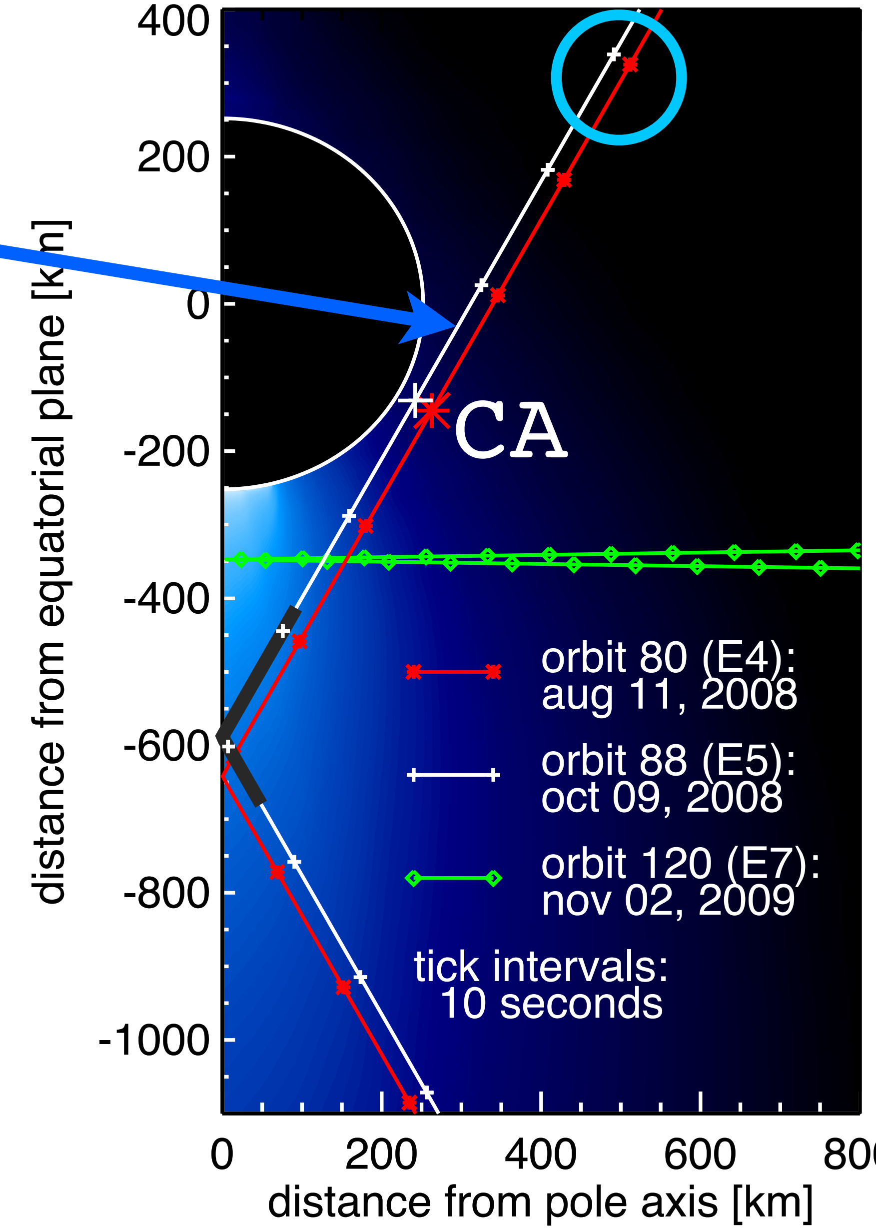
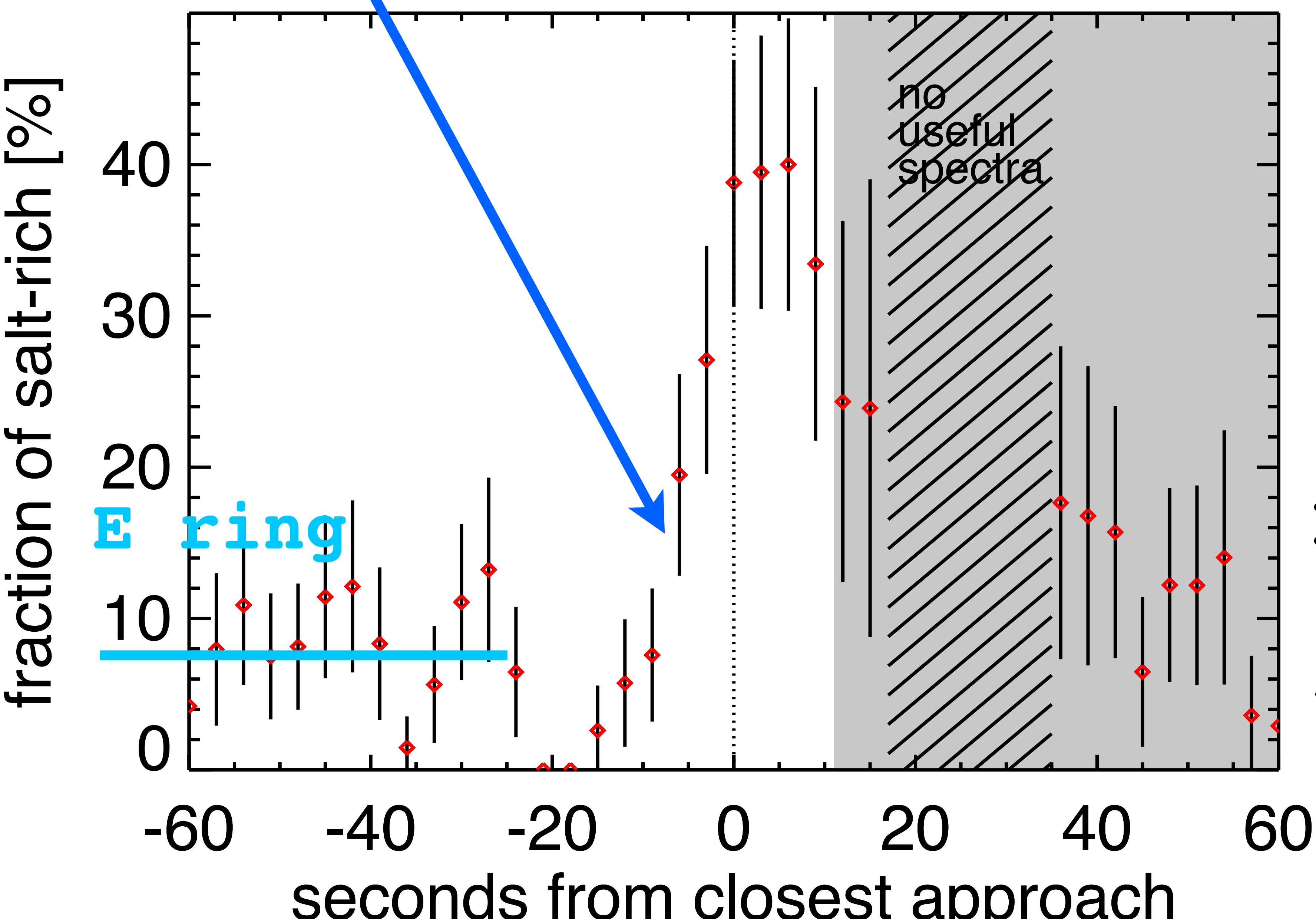
/Users/jschmidt/Projects/PlumeE5SodiumCDA/BackFireIntegrations/Rev88TwoBodyModels::DraftFig2Plot jschmidt Mon Mar 21 10:09:26 2011

-> before CA: fraction of salt-rich increases

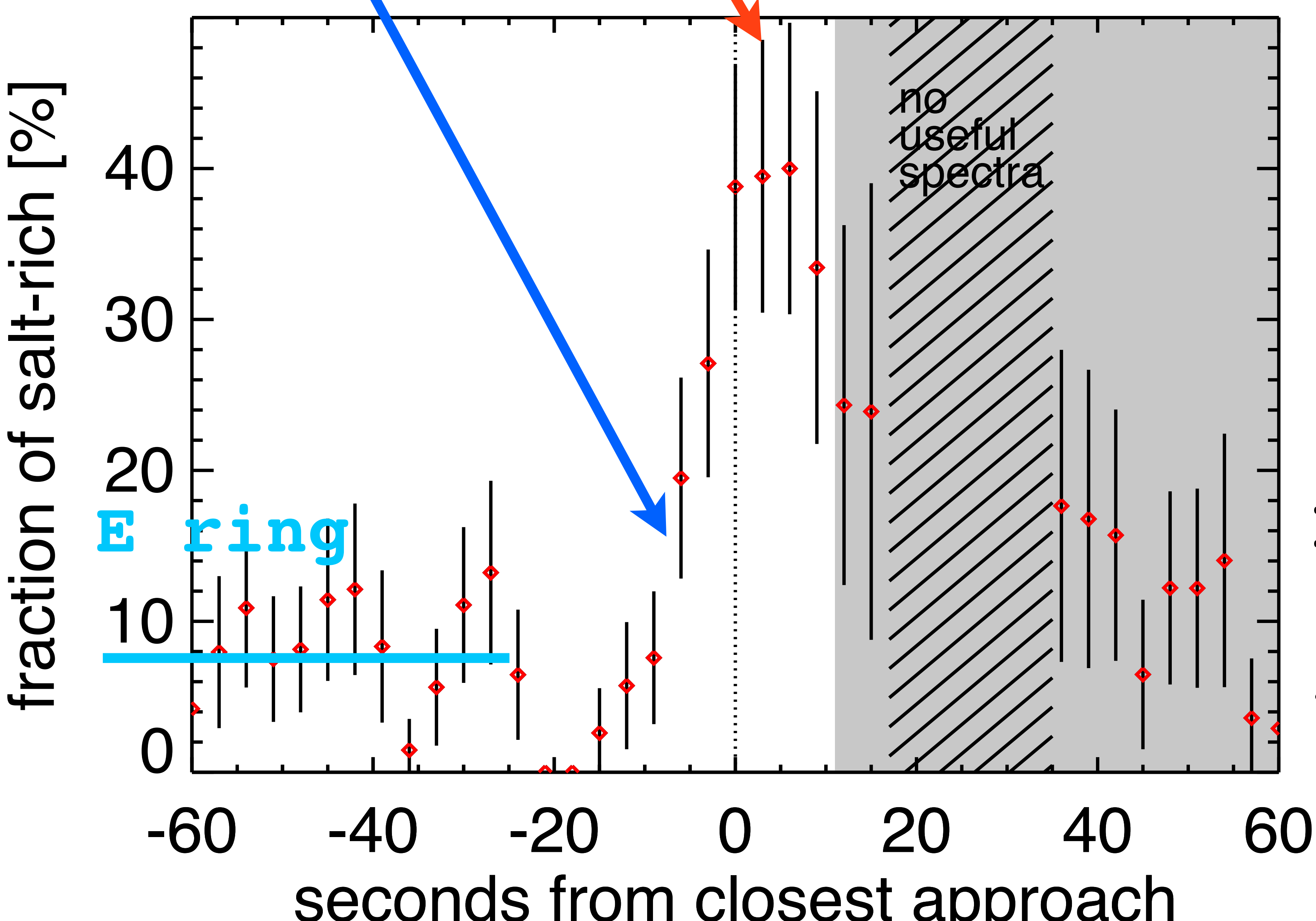


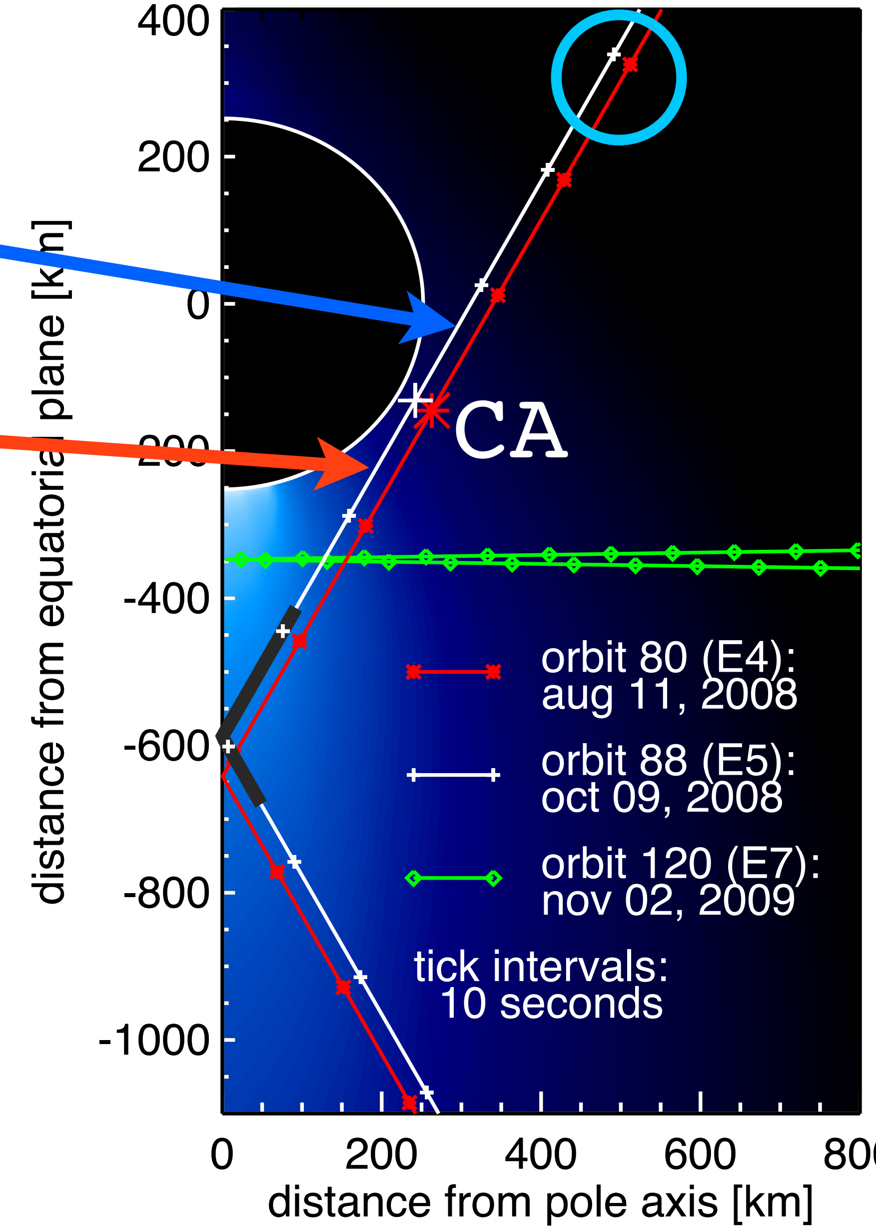


Box-car average:
9s bins
~40 spectra each

-> before CA: fraction of salt-rich increases

-> maximum: 40%, 5s after CA





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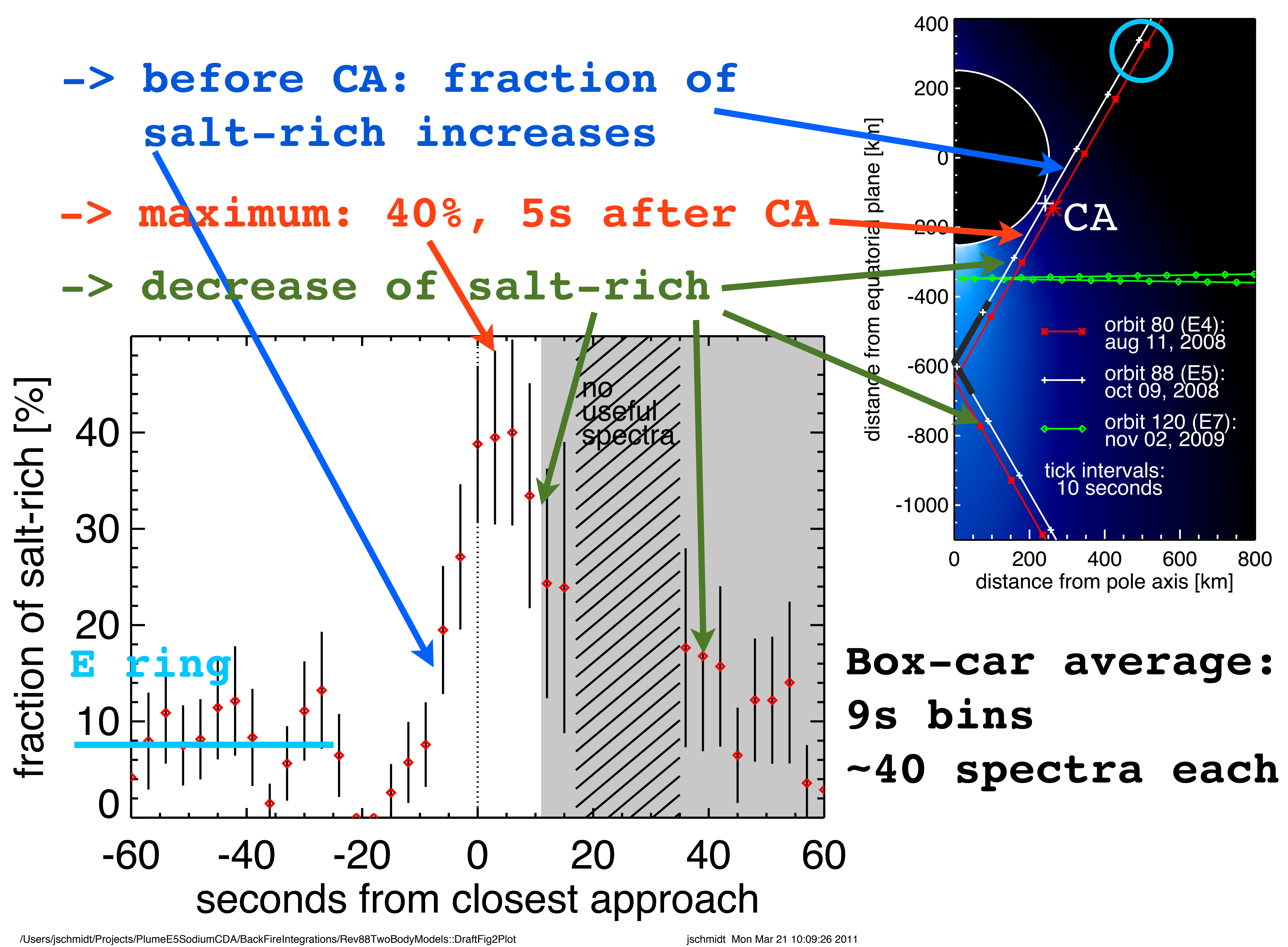

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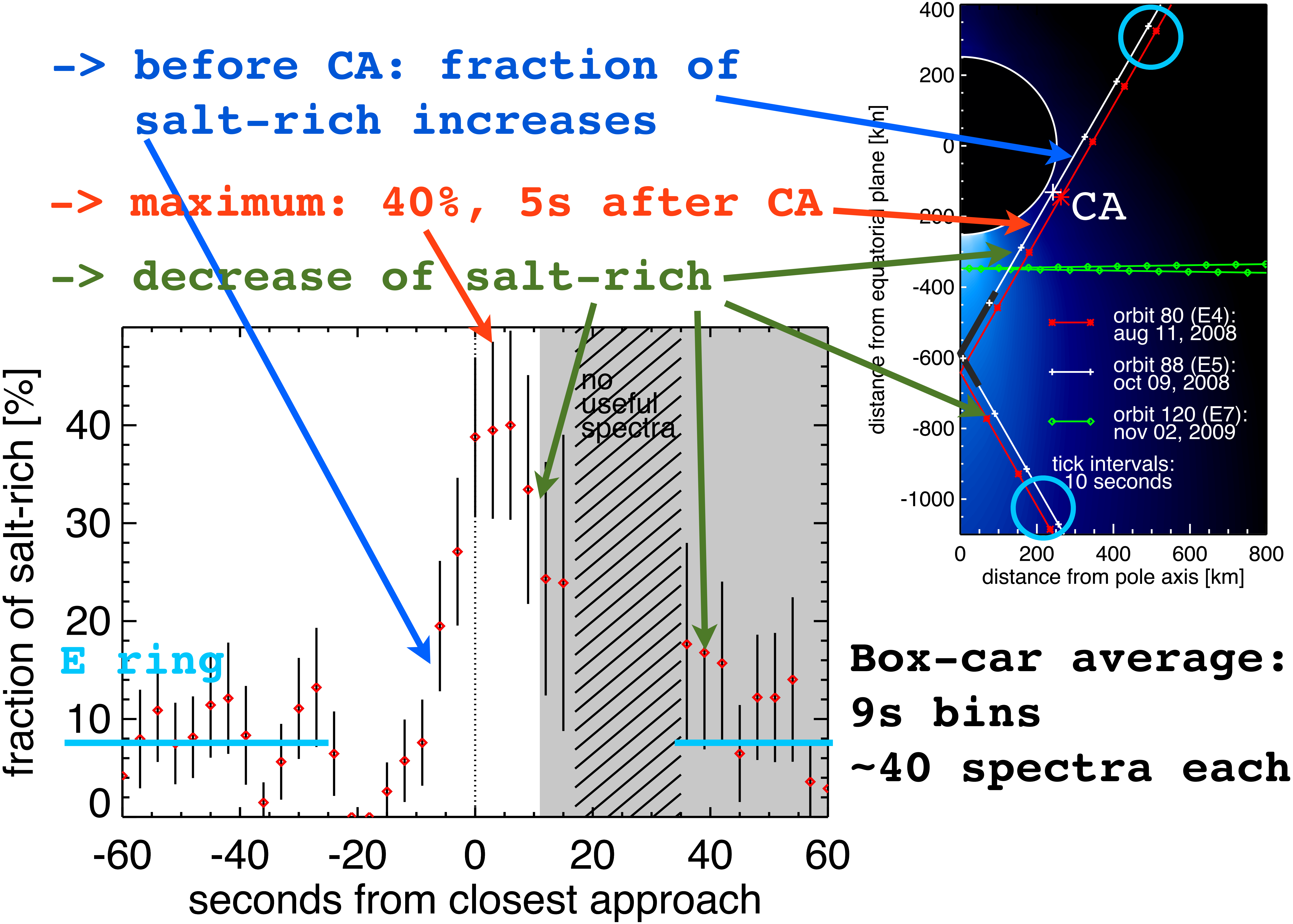


/Users/jschmidt/Projects/PlumeE5SodiumCDA/BackFireIntegrations/Rev88TwoBodyModels::DraftFig2Plot jschmidt Mon Mar 21 10:09:26 2011

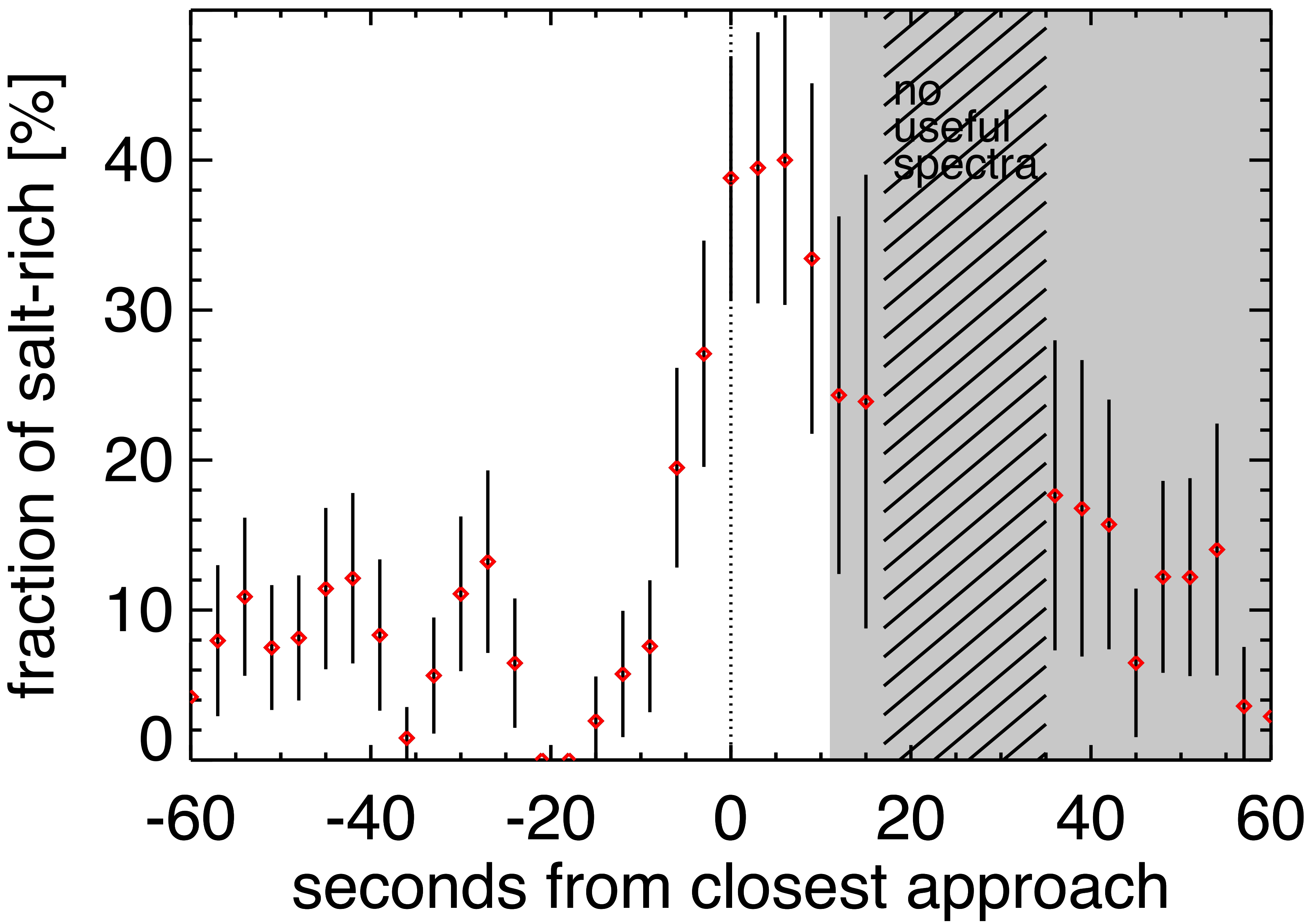
Hypothesis:

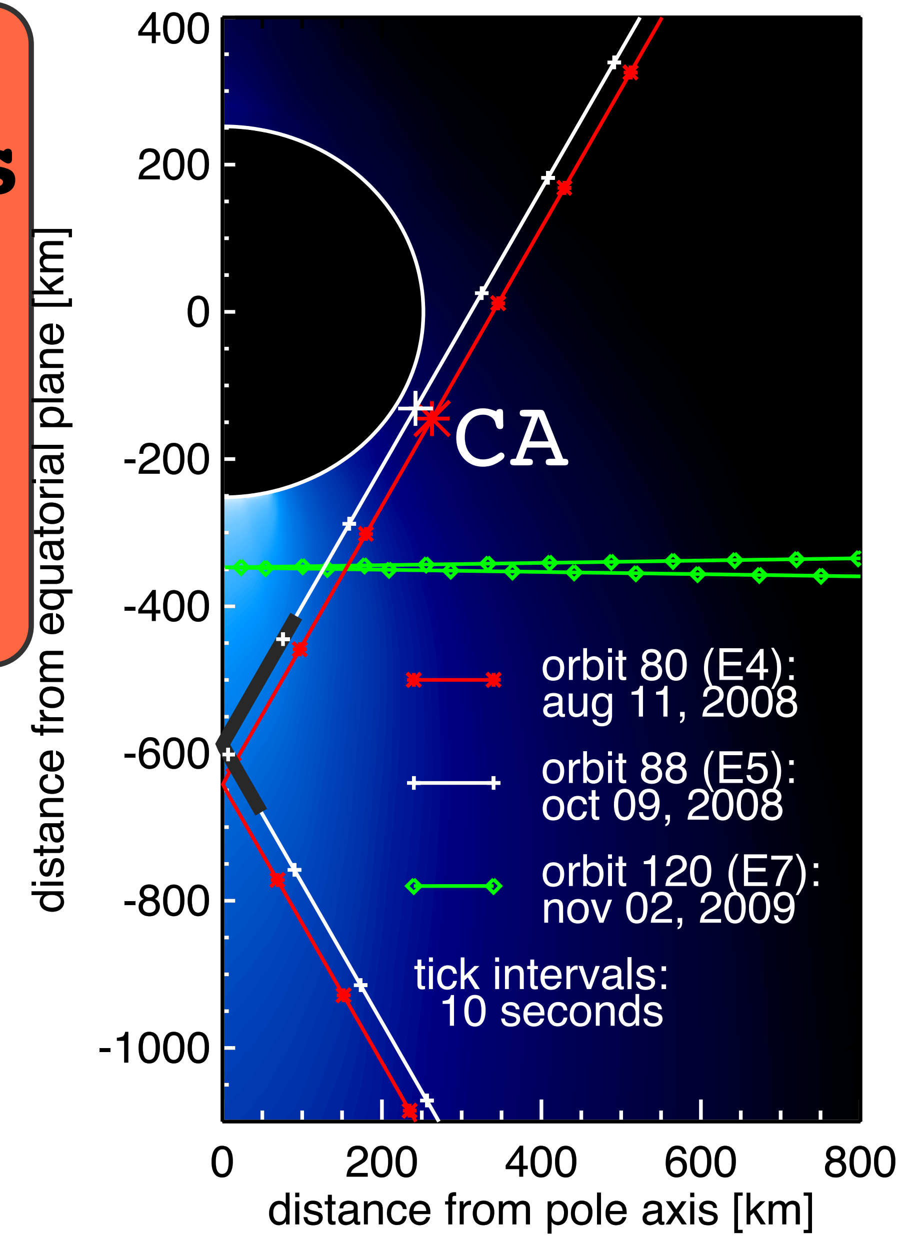
-> salt-rich are heavier grains

-> smaller ejection speeds, populate lower plume

Schmidt et al., Nature, 2008 (CDA)

Hedman et al., ApJ, 2009 (VIMS)





/Users/jschmidt/Projects/PlumeE5SodiumCDA/BackFireIntegrations/Rev88TwoBodyModels::DraftFig2Plot jschmidt Mon Mar 21 10:09:26 2011

Ion-yield at CDA measurement:

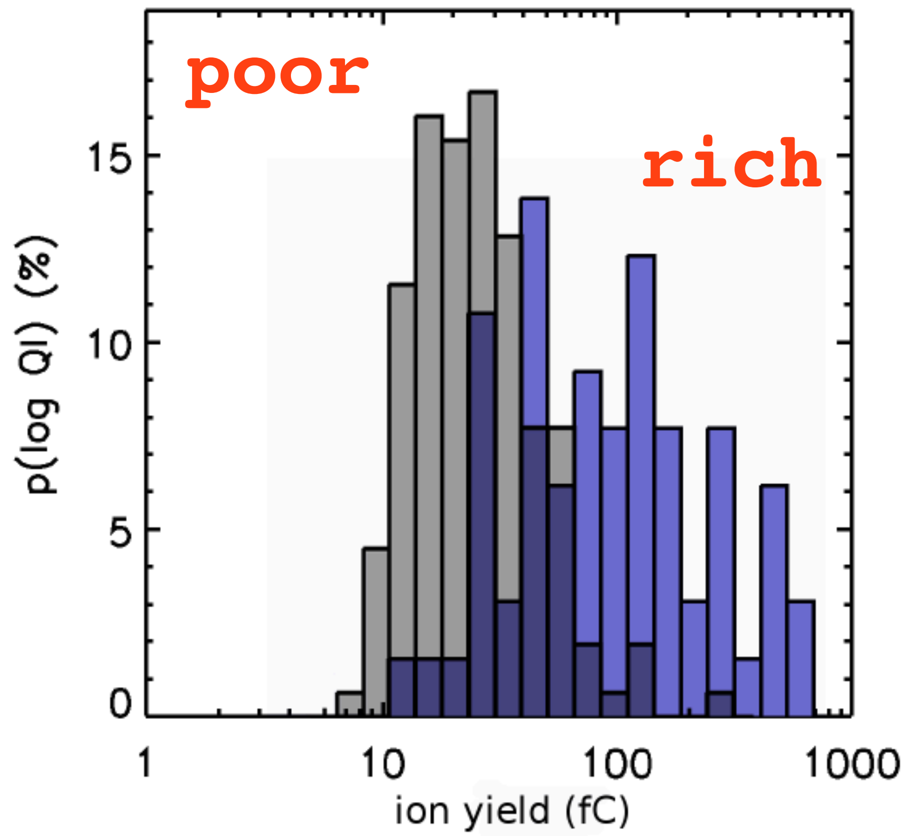


Figure 5: Frequency of ion yields of Type 3 (blue) and Type 1 impacts (grey). The ion yield is inferred from CDA's QI channel.Impacts with high ion yields are predominately salt-rich. Salt-poor grains mostly show ion yields below 50 fC.

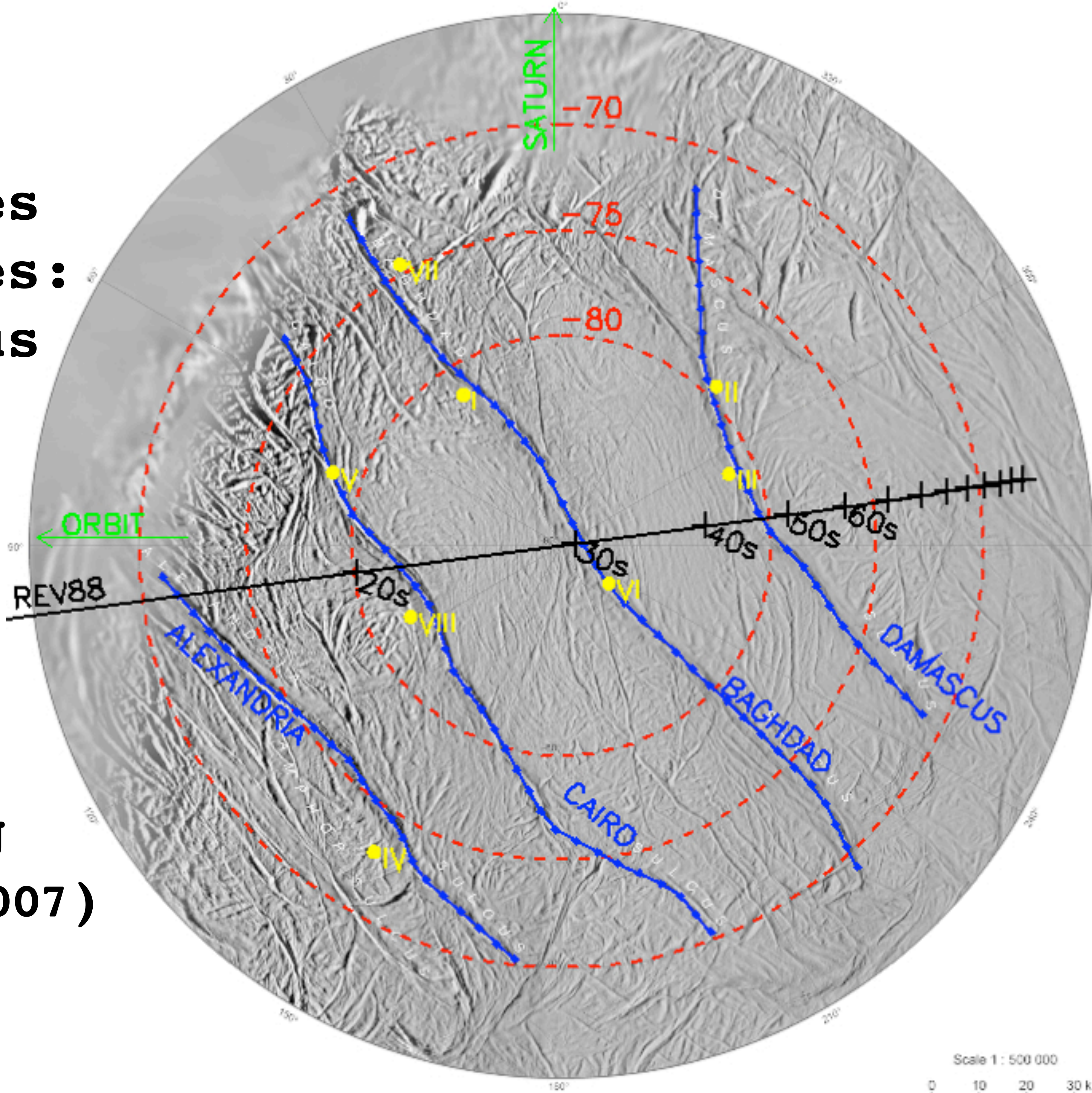
Indeed indicates that salt-rich grains are larger than salt-poor

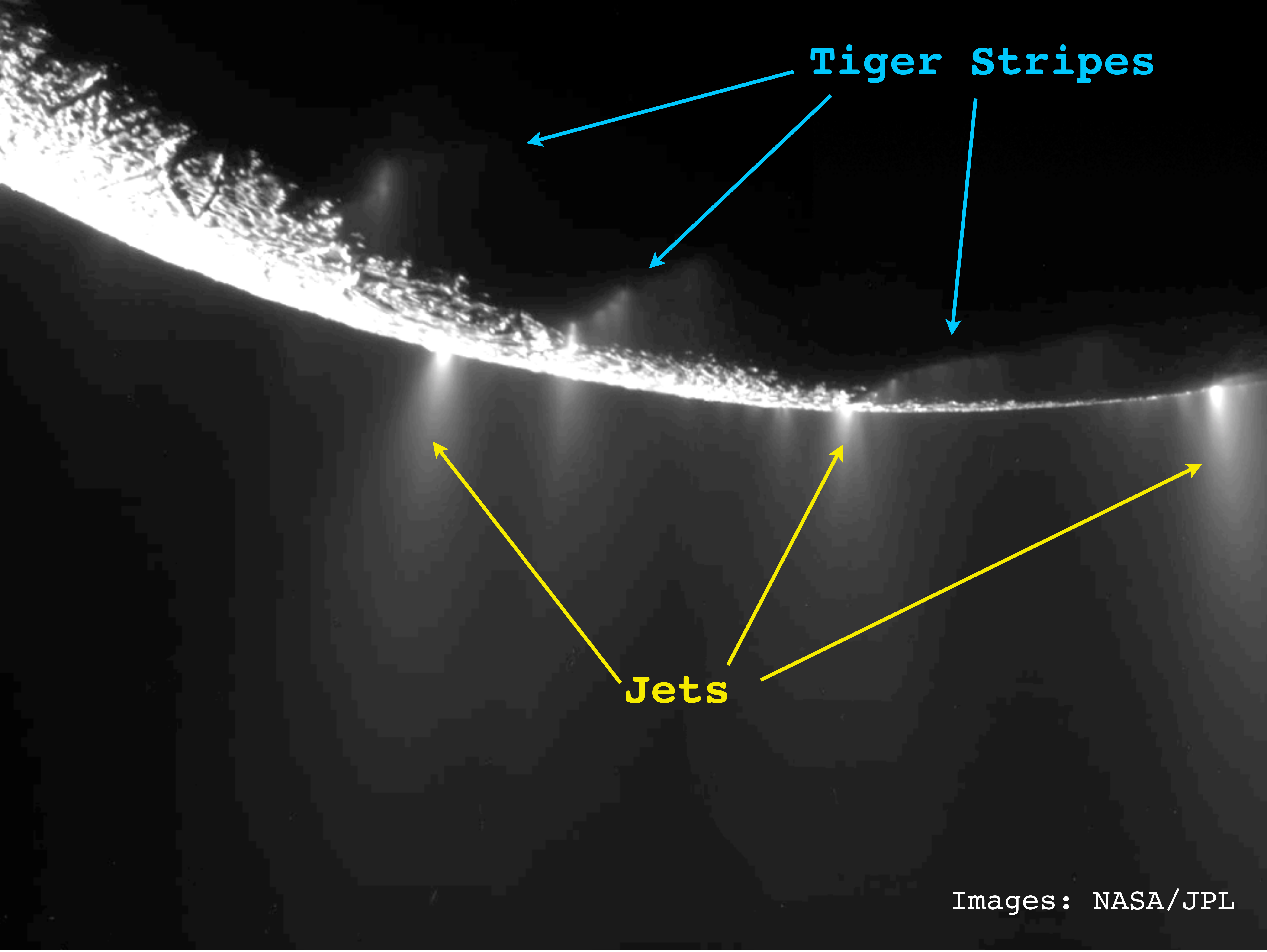
What fraction of the produced dust mass is actually salt-rich?

Modeling

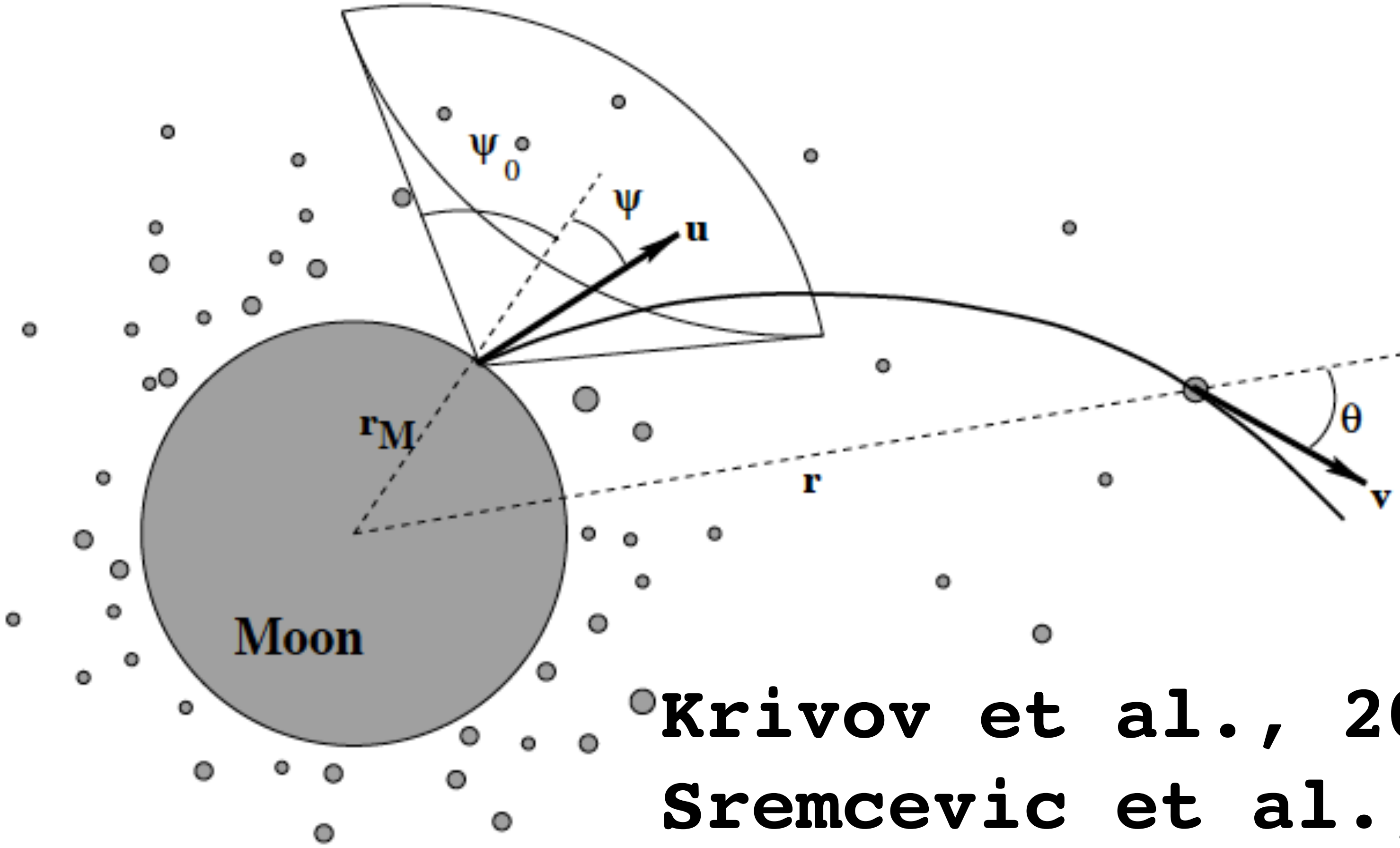
Large number of point sources on tiger stripes: quasi-continuous ejection of grains

And:
8 jet-sources identified in CASSINI imaging (Spitale&Porco, 2007)

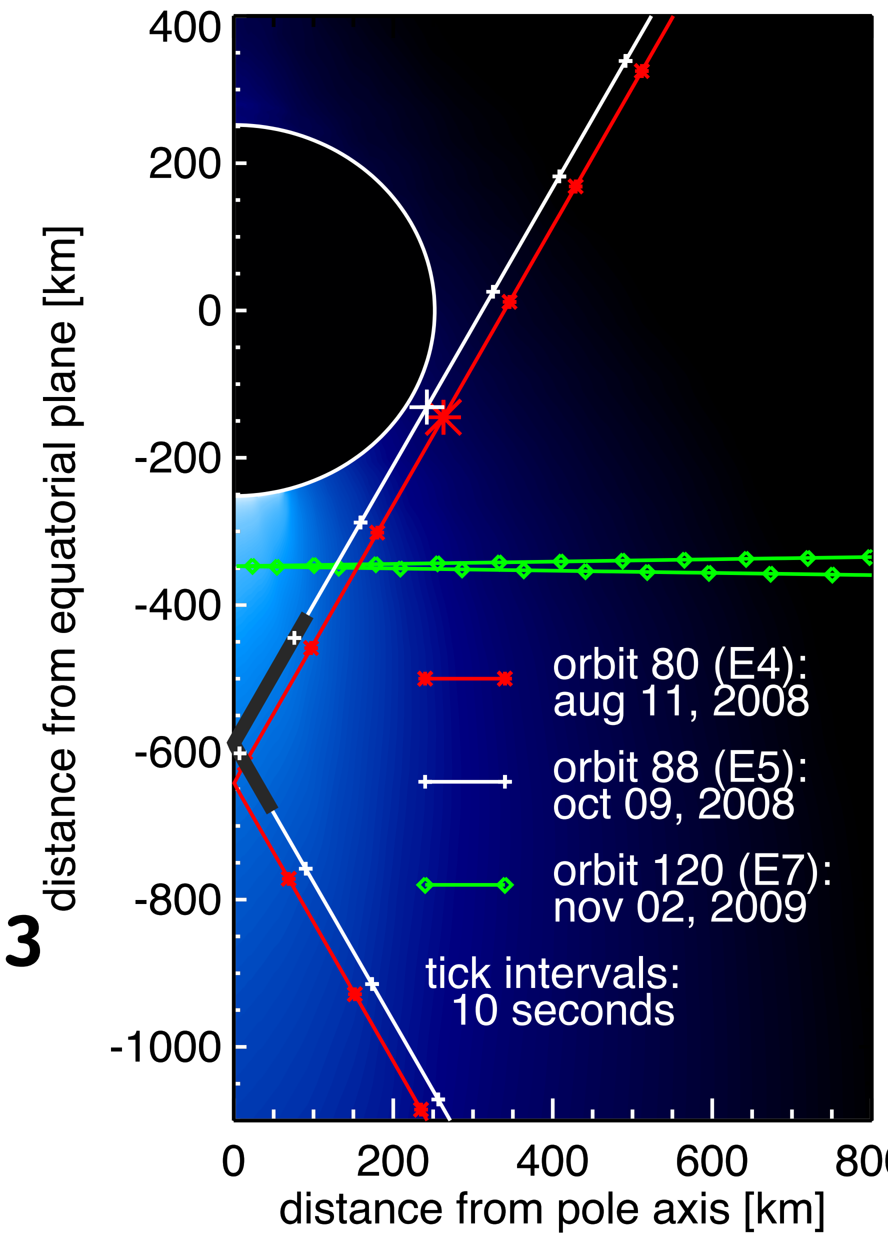



Tiger Stripes
Jets
Images: NASA/JPL

Modeling



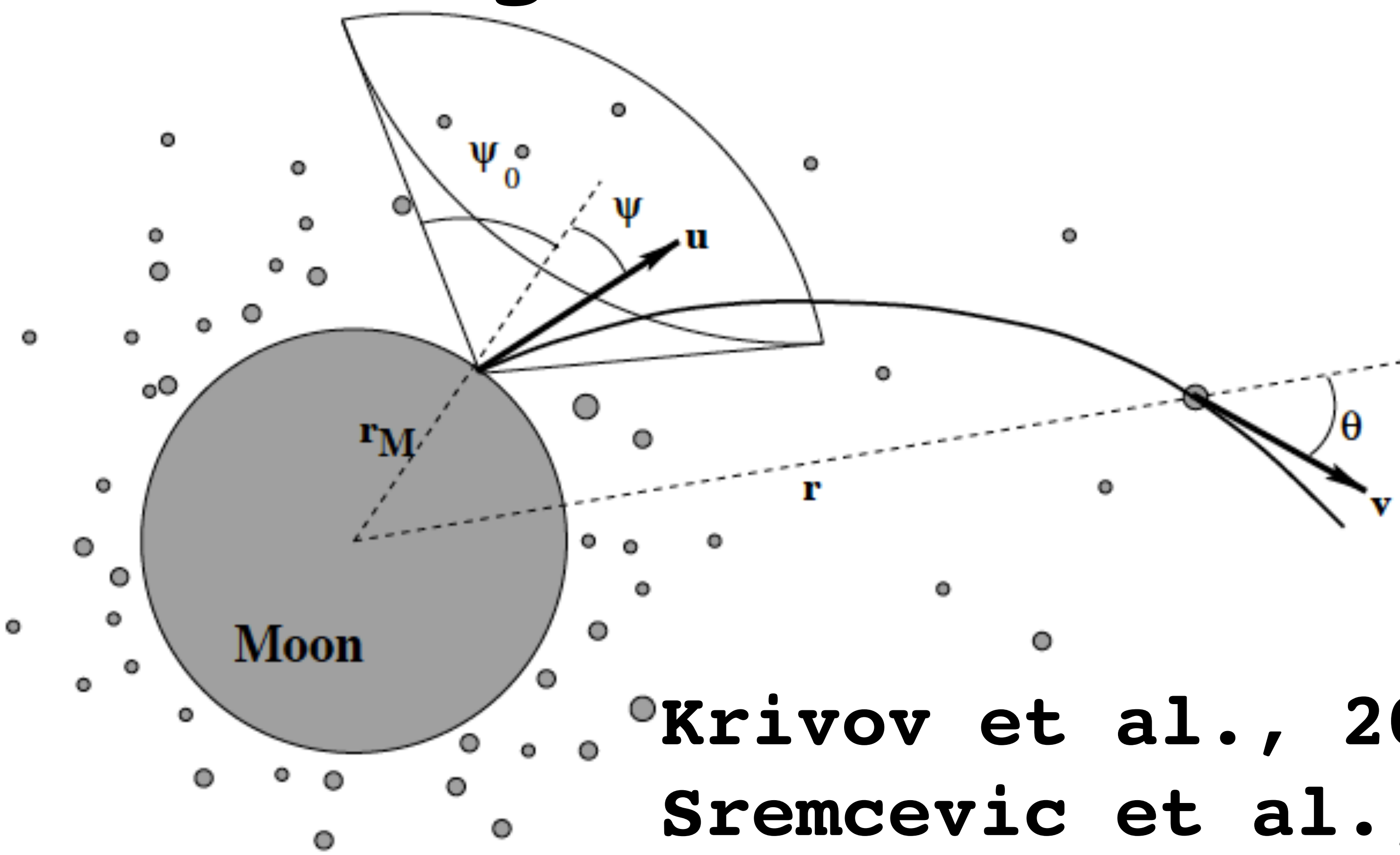
Krivov et al., 2003
Sremcevic et al., 2003



-> use two-body dynamics
to construct model plume

-> average over suitable distributions of
starting speeds, locations, and grain sizes
(Schmidt et al., Nature, 2008)

Modeling



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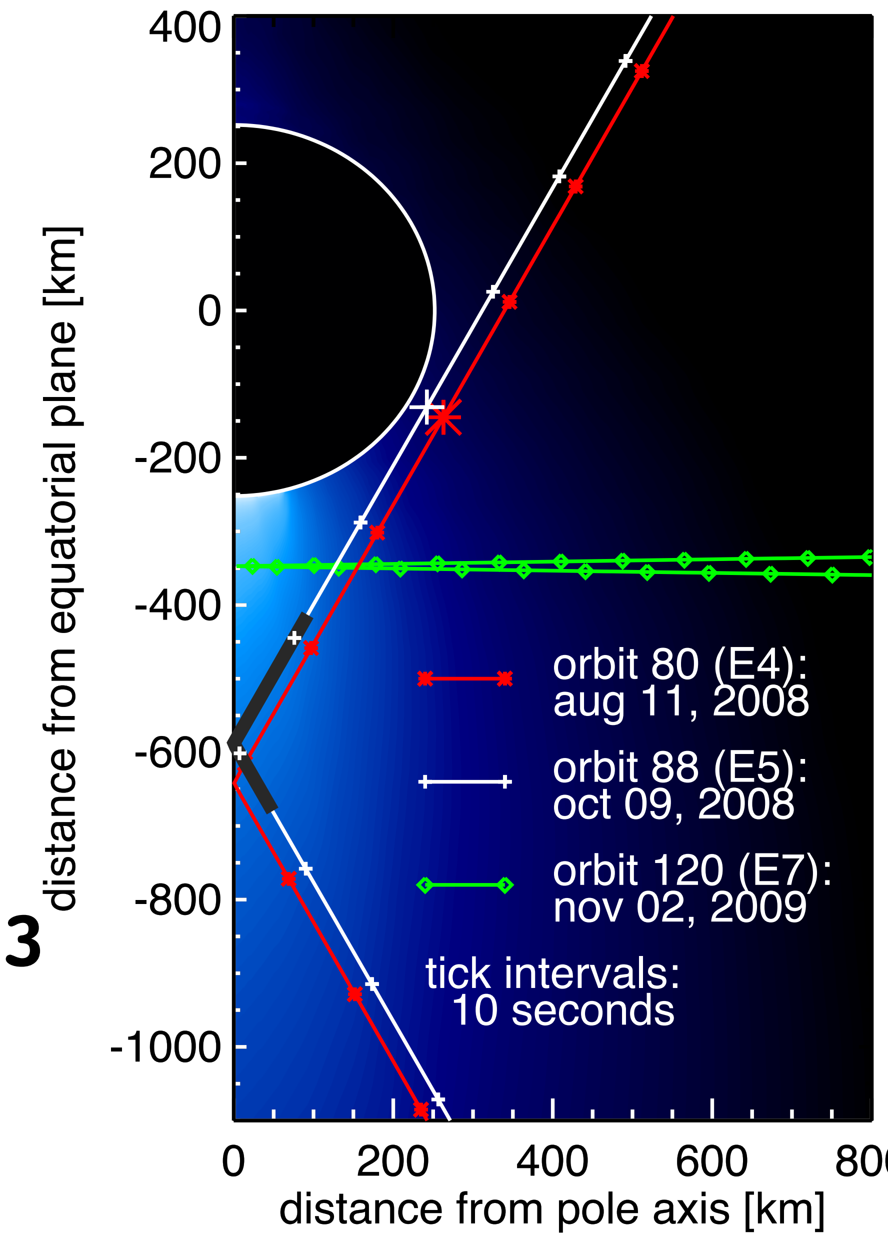

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(Schmidt et al., Nature, 2008)

Ejection angle:

$$f_\psi = c \exp\left(-\frac{(\psi - \psi_{max})^2}{2w^2}\right)$$

Modeling

Size-dependend speed distribution:

(Schmidt et al, 2008)

$$P(v)dv = \frac{R}{R_c}\left[1 + \frac{R}{R_c}\right]\frac{v}{u}\left[1 - \frac{v}{u}\right]^{\frac{R}{R_c}-1} dv$$

From dissipative interaction of gas and grains in the vents (near outlet)

- v: grain speed
- u: gas speed
- R: grain radius
- R_c: characteristic friction-length sub-micron

Modeling

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- **u: gas speed**
- **R: grain radius**
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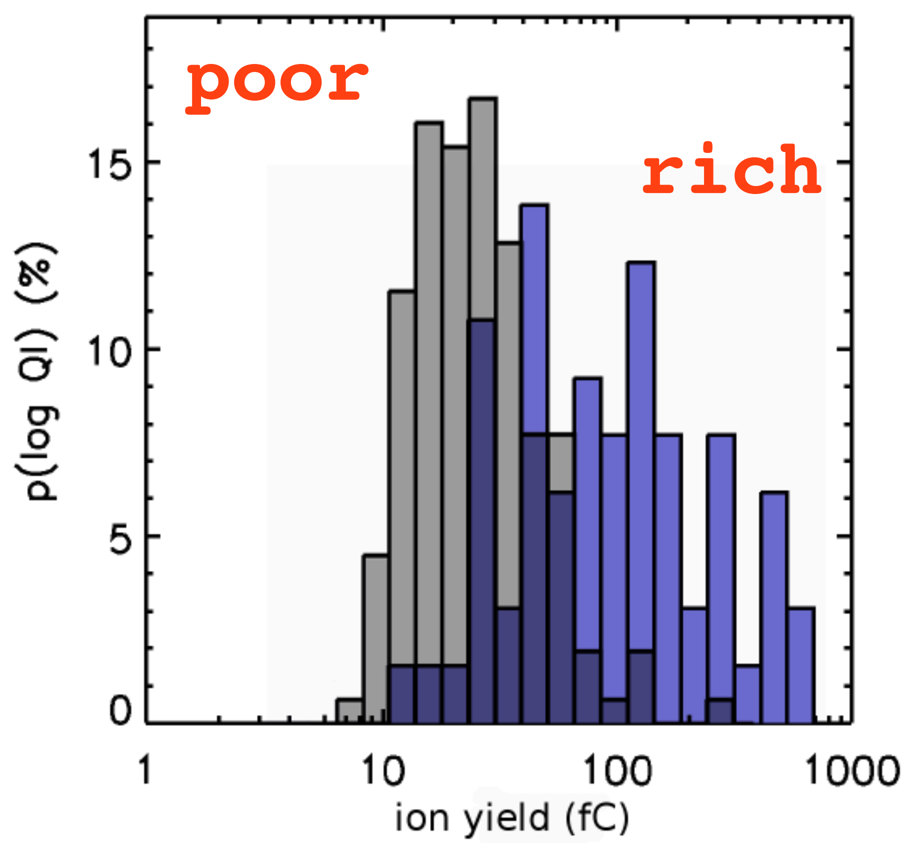
$$\langle v(R)\rangle = \frac{u}{1+\frac{R}{2R_c}}$$

Modeling

initial size distribution

Ion-yield at CDA measurement:



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Modeling

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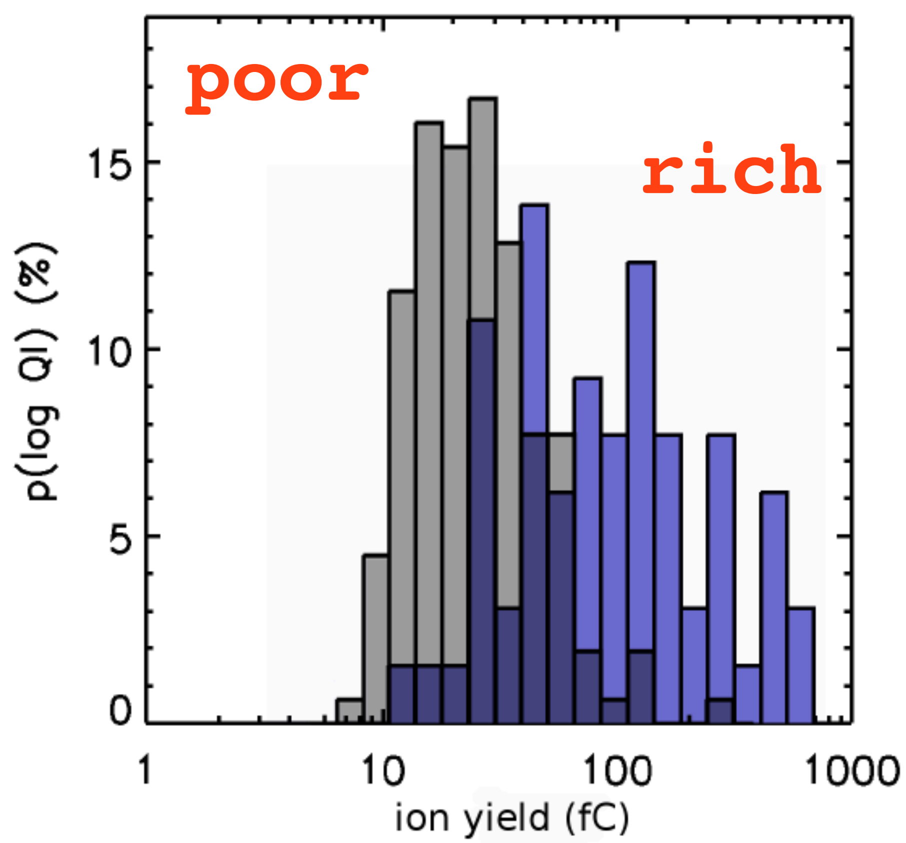

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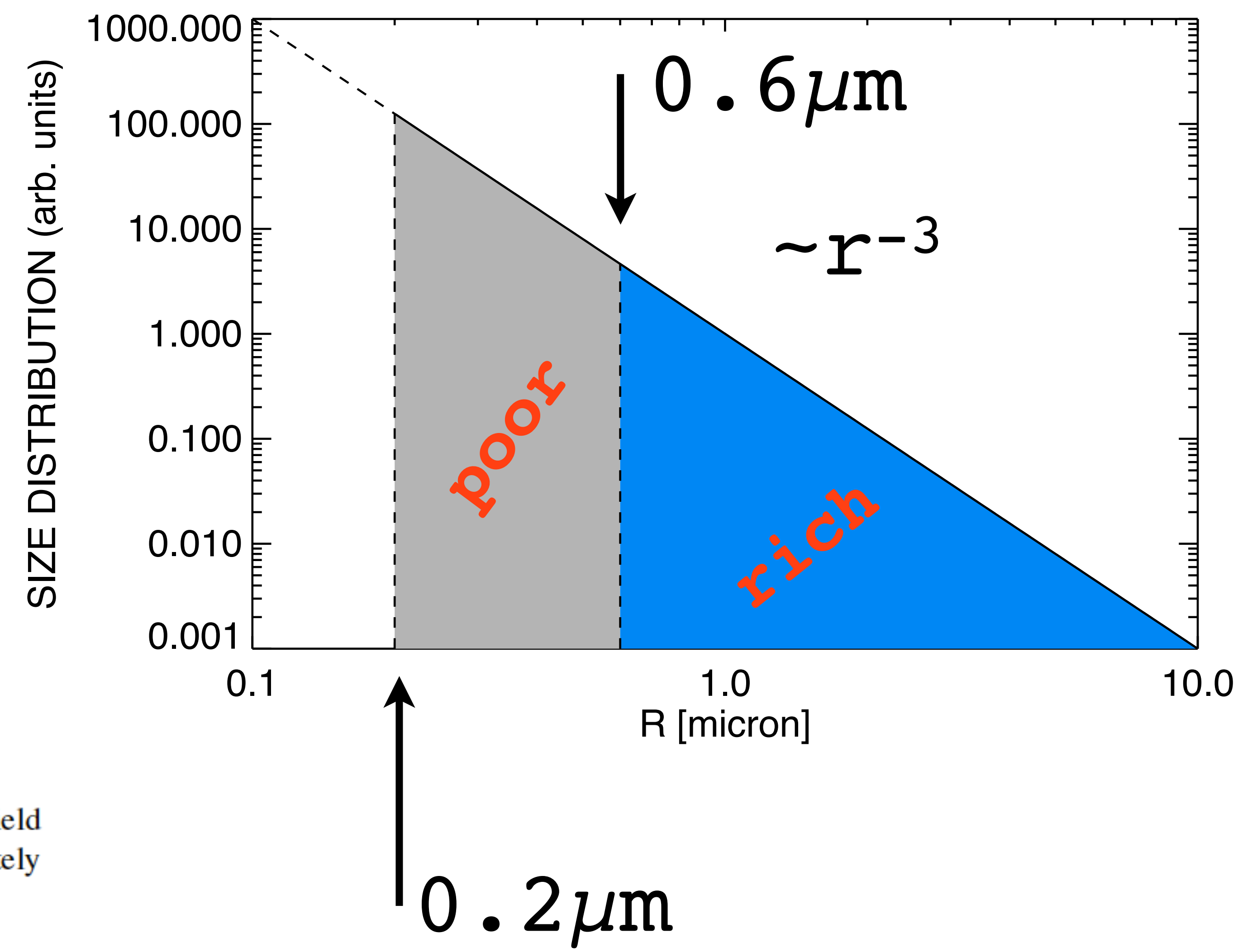
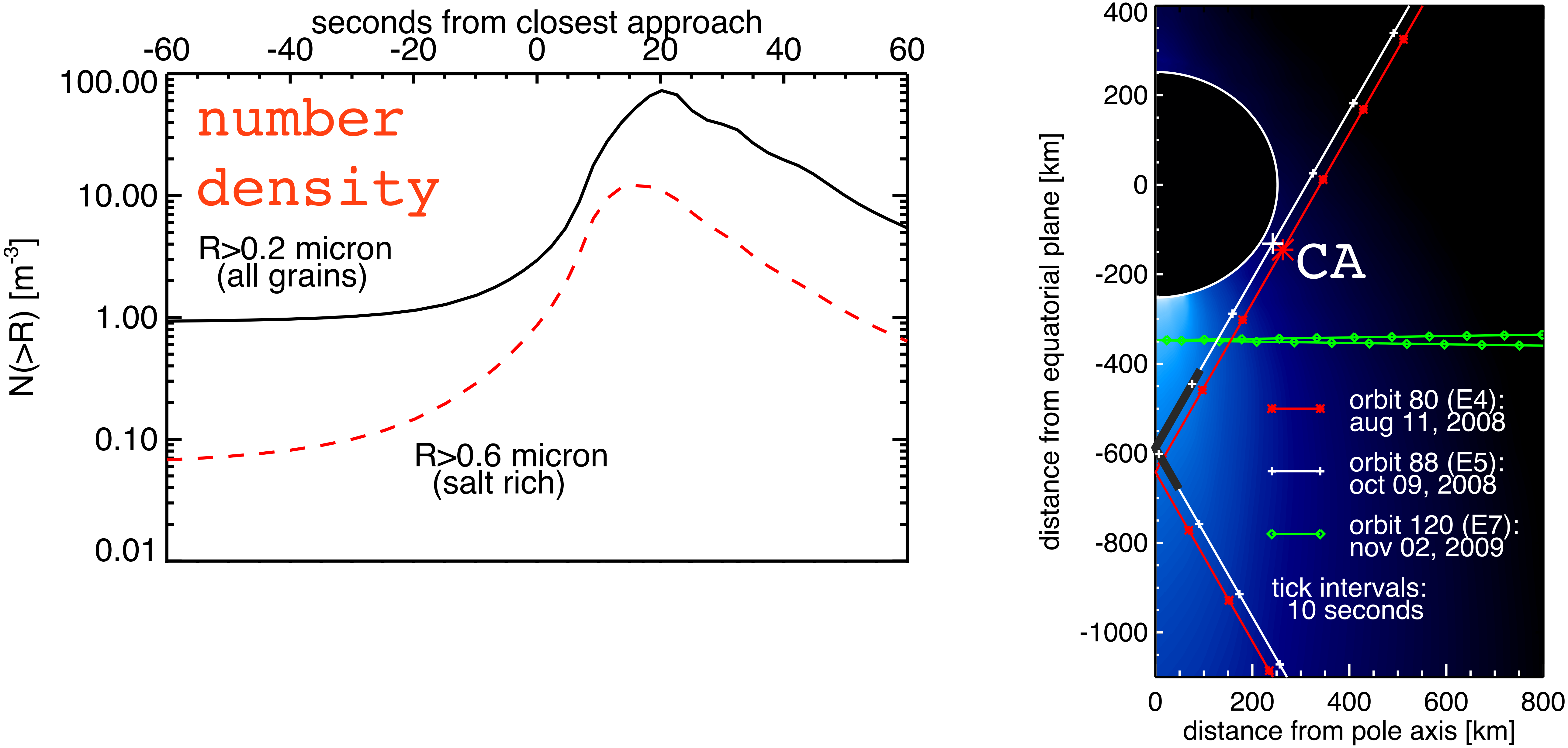
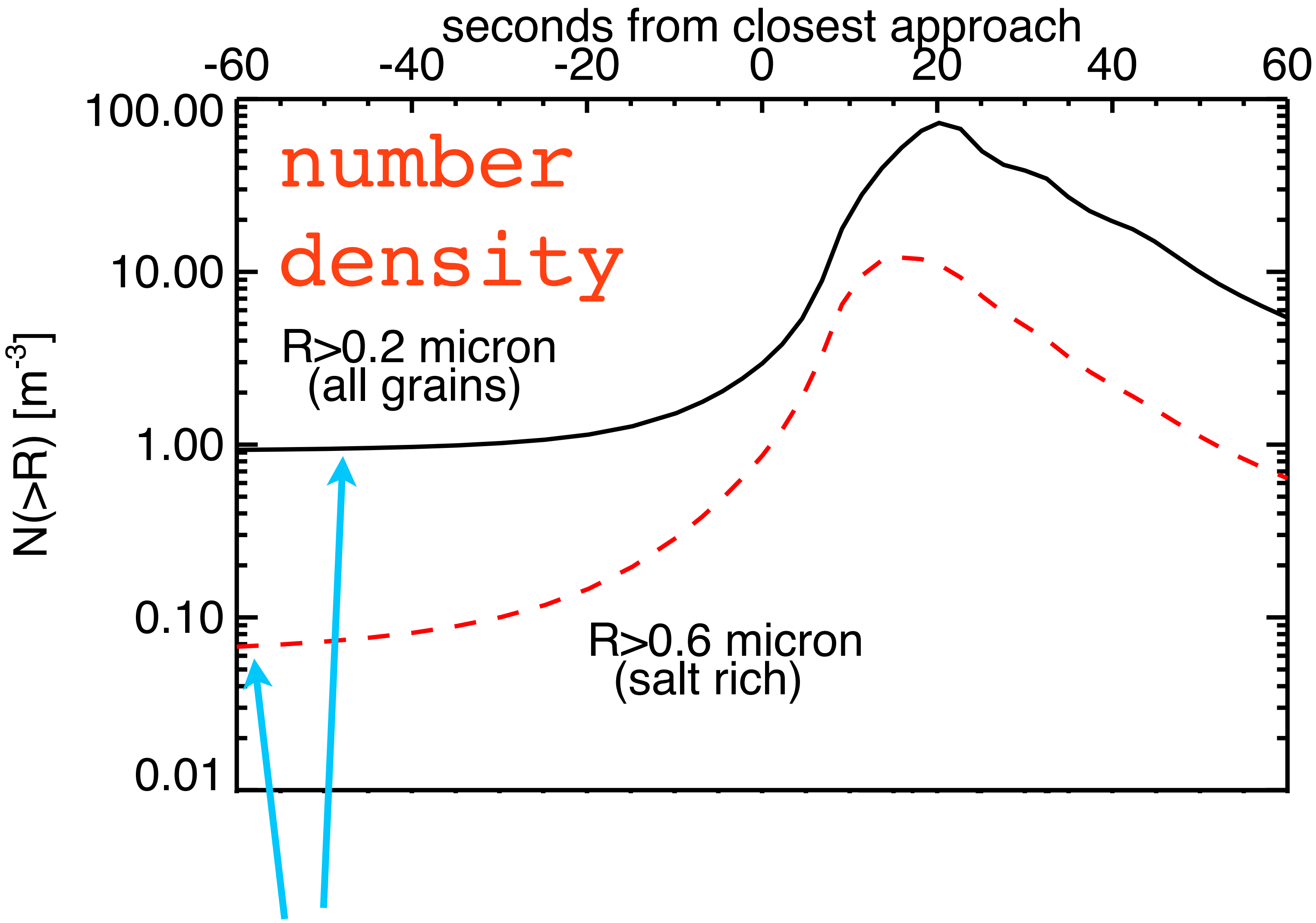
Model assumption continuous power-law:

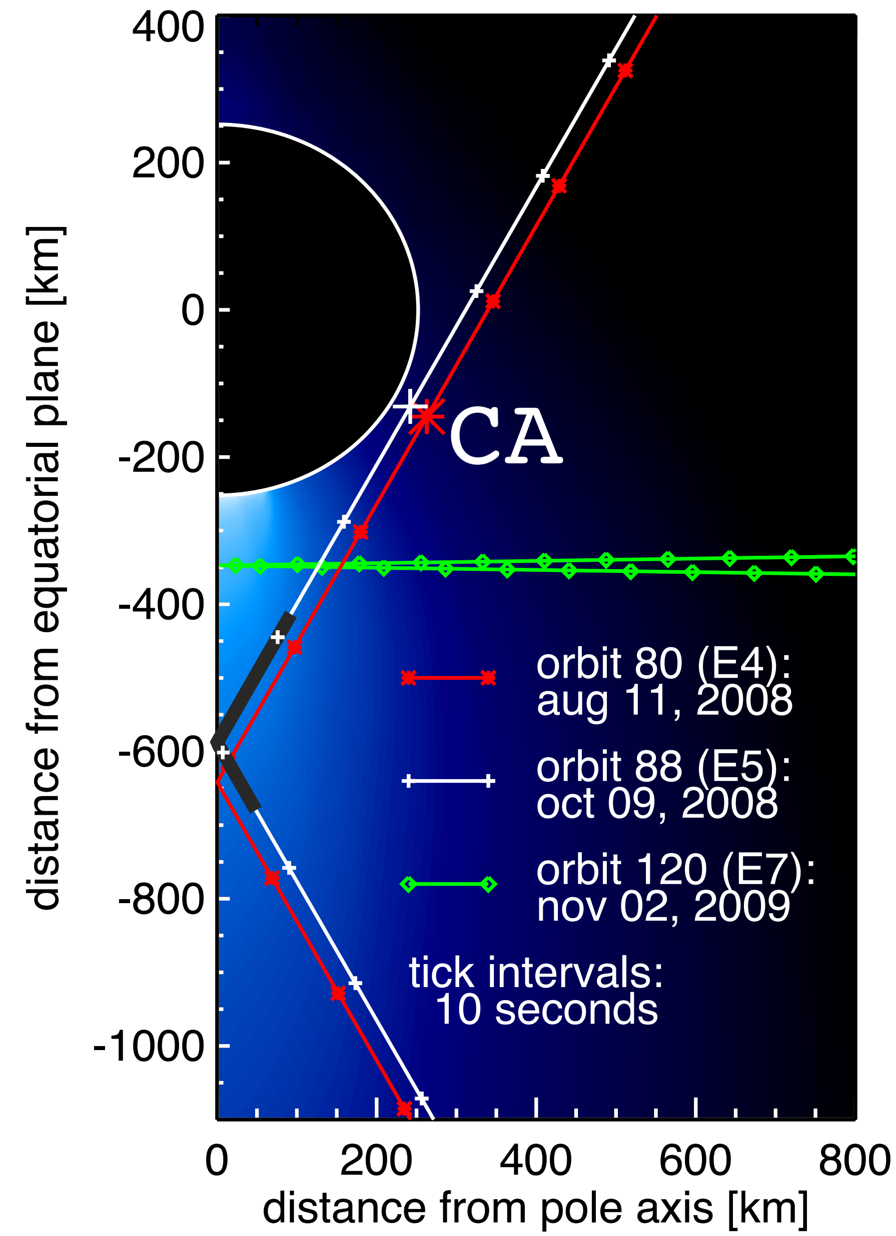




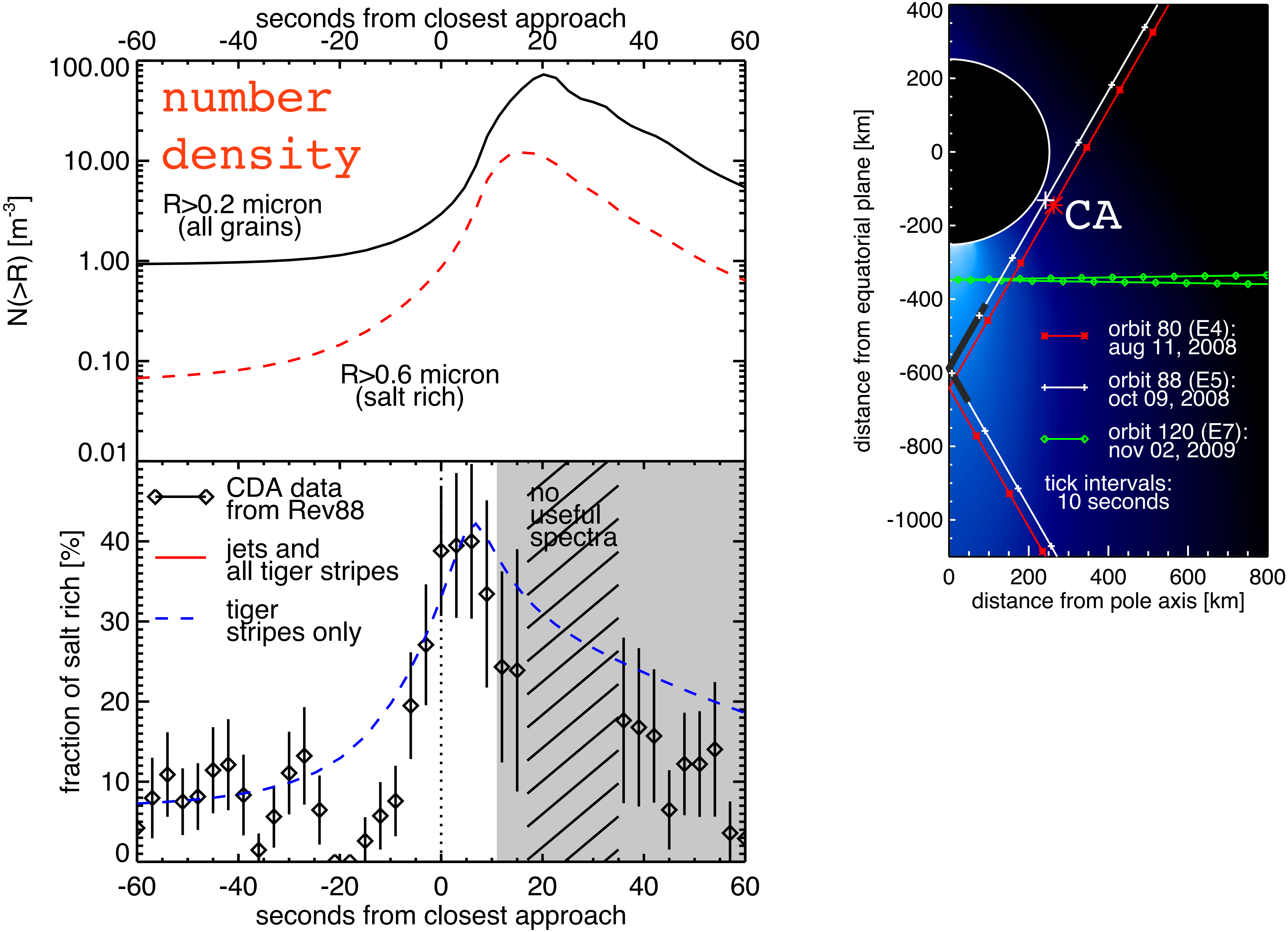
/Users/jschmidt/Projects/PlumeE5SodiumCDA/BackFireIntegrations/Rev88TwoBodyModels: DraftFig3Plot 16:06:44 2011

Thursday, November 3, 2011





E ring background: from independent measurements with the CDA High Rate Detector



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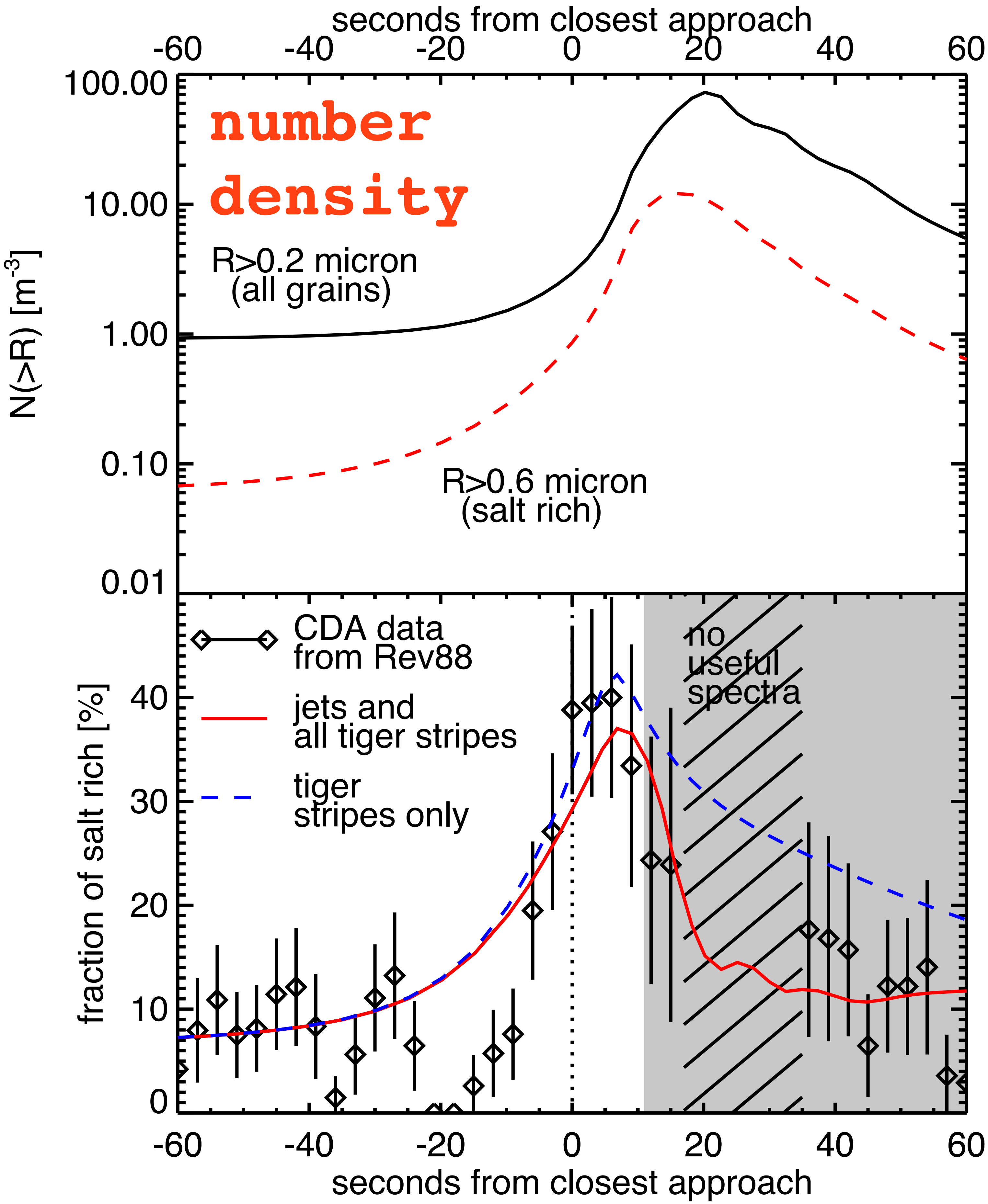
Thursday, November 3, 2011

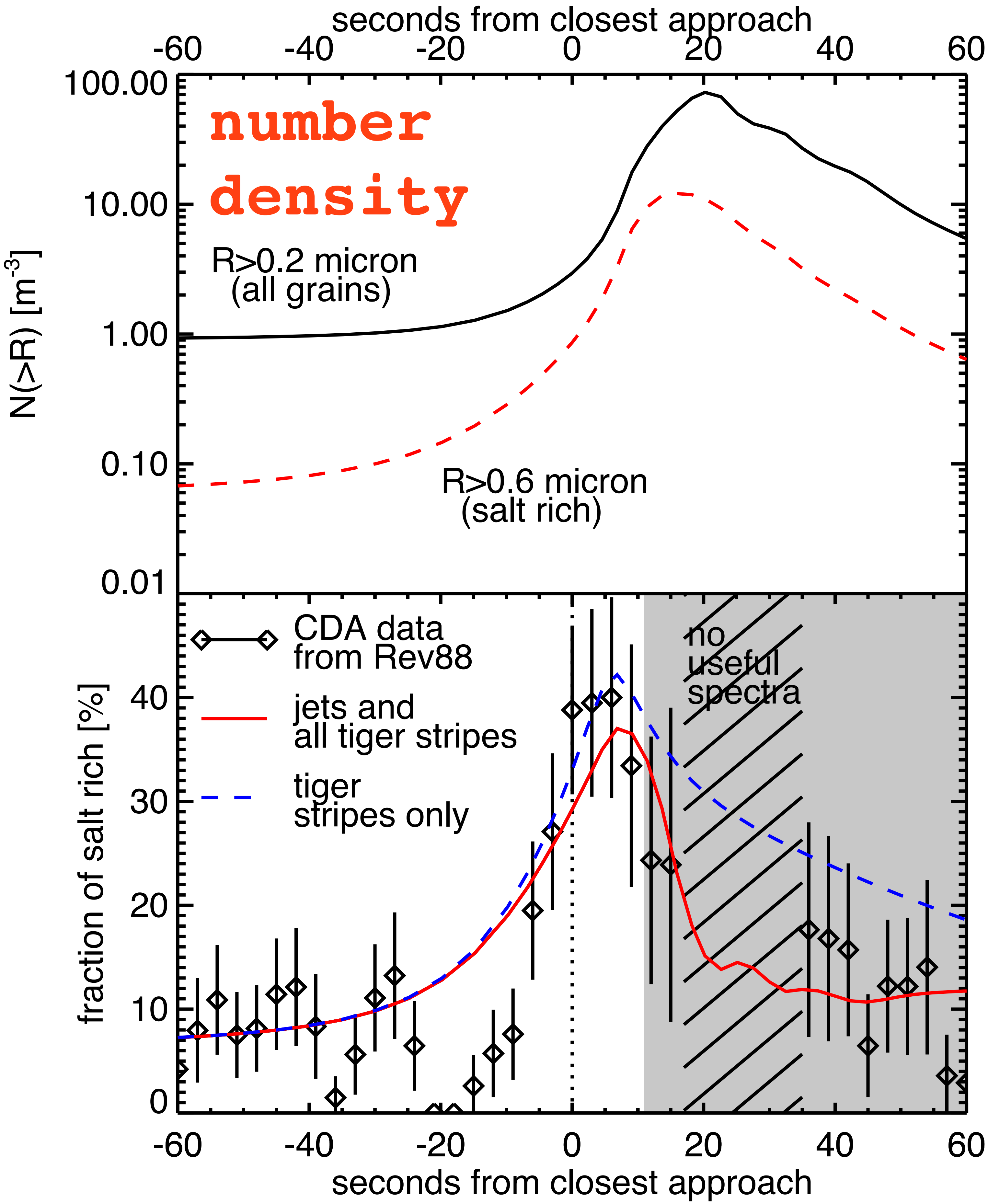


Tiger stripes:
$P(r) \sim r^{-2}$
$R_C = 0.3 \mu m$
$u_{gas} = 500 m/s$
$<\psi> = 30DEG$

Jet sources:
$P(r) \sim r^{-4}$
$R_C = 0.1 \mu m$
$u_{gas} = 1200 m/s$
$<\psi> = 15DEG$

/Users/jschmidt/Projects/PlumeE5SodiumCDA/BackFireIntegrations/Rev88TwoBodyModels: DraftFig3Plot jschmidt Mon Mar 21 16:04:07 2011

Thursday, November 3, 2011



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Jet sources:

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$u_{gas} = 1200 m/s$

$<\psi> = 15DEG$

CASSINI UVIS

Hansen et al., 2009

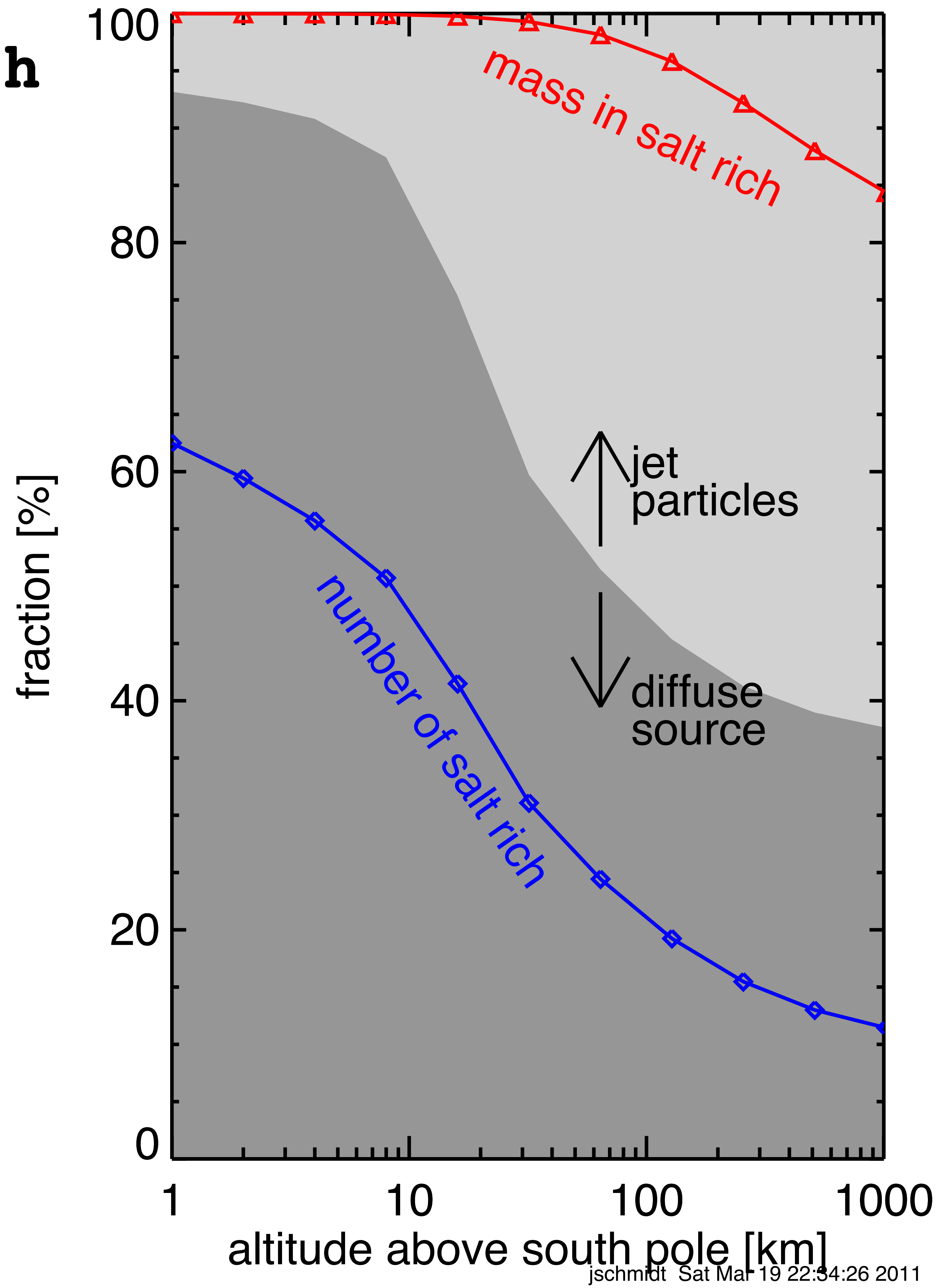
2011

/Users/jschmidt/Projects/PlumeE5SodiumCDA/BackFireIntegrations/Rev88TwoBodyModels:DraftFig3Plot jschmidt Mon Mar 21 16:04:07 2011

Thursday, November 3, 2011

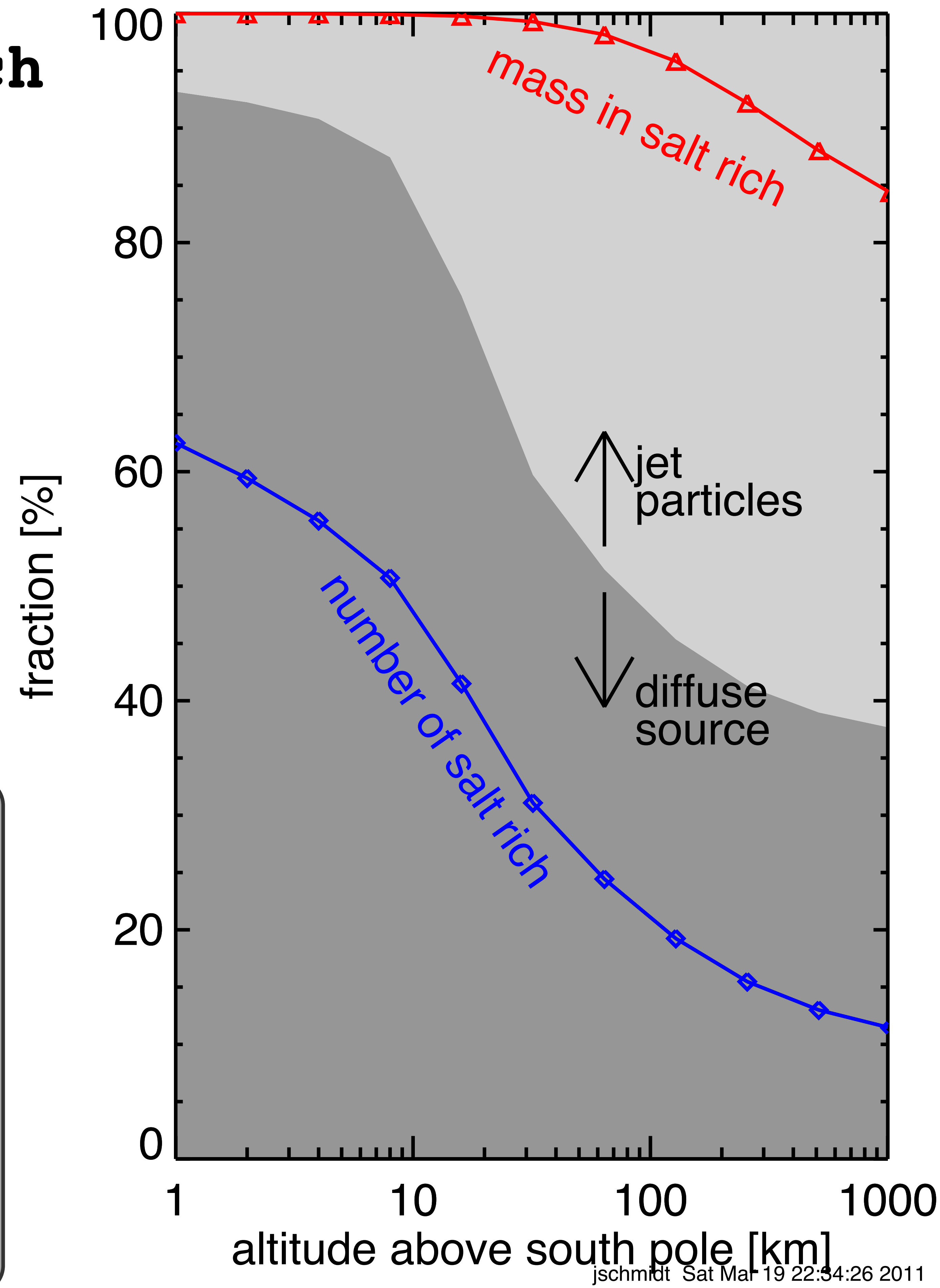
-> number of salt-rich grains increases towards surface ($R>0.2\mu m$)

-> mass-production is dominated by salt rich grains



-> number of salt-rich grains increases towards surface (R>0.2μm)

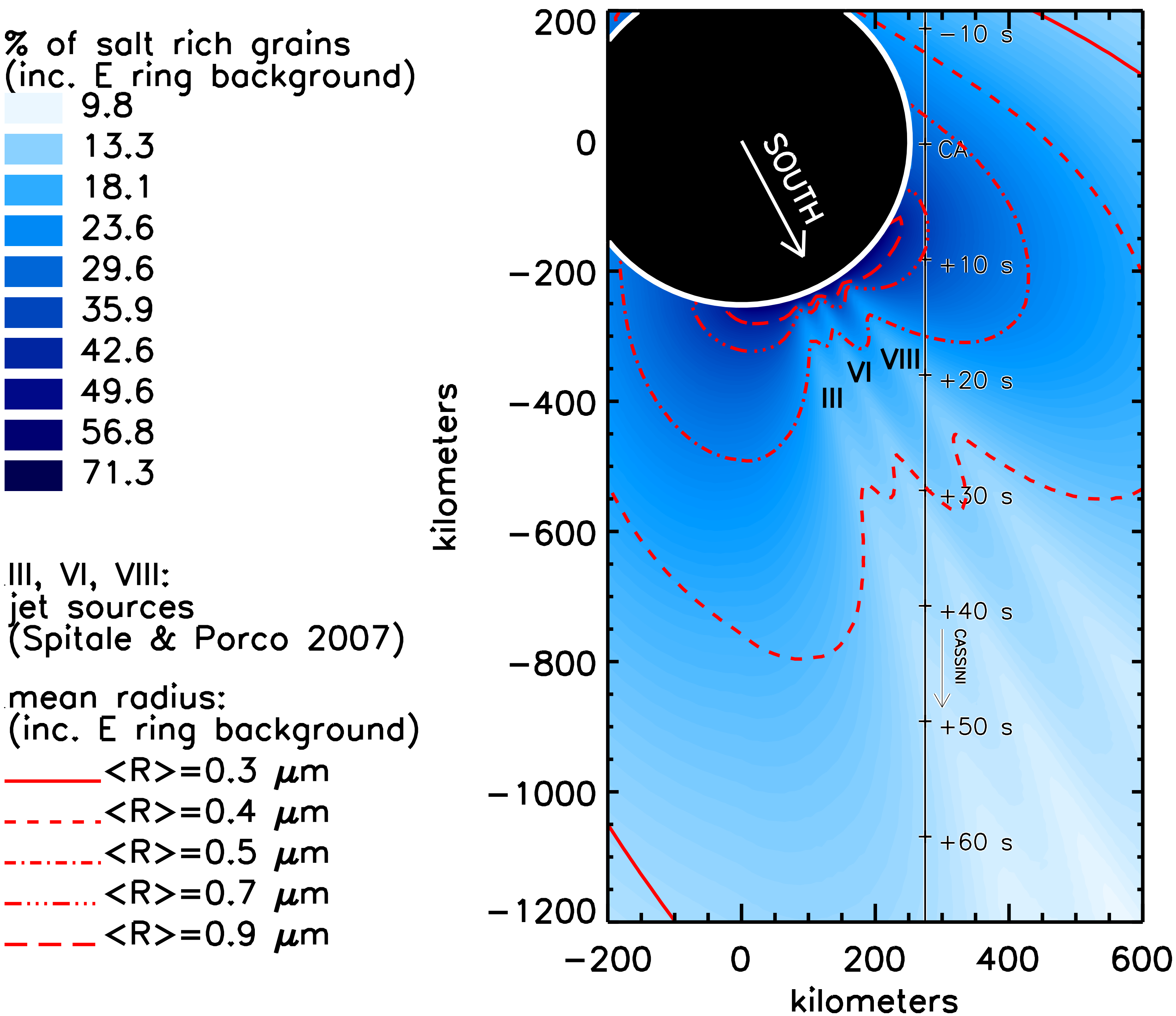
-> mass-production is dominated by salt rich grains



conclusion arises consistently for all choices of parameters that are in agreement with available data

plume stratification

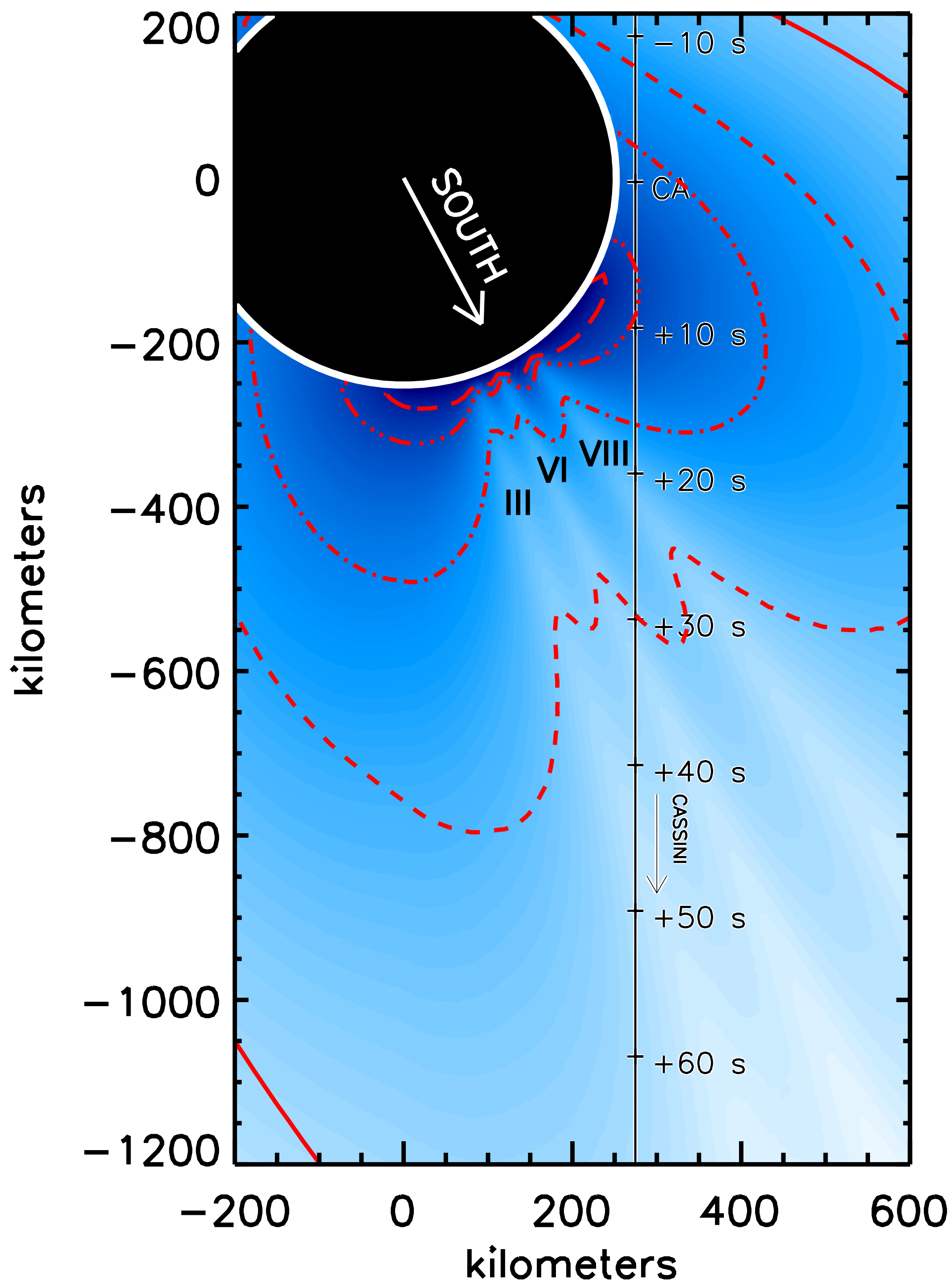
plume + E ring in Cassini’s orbital plane:



plume stratification

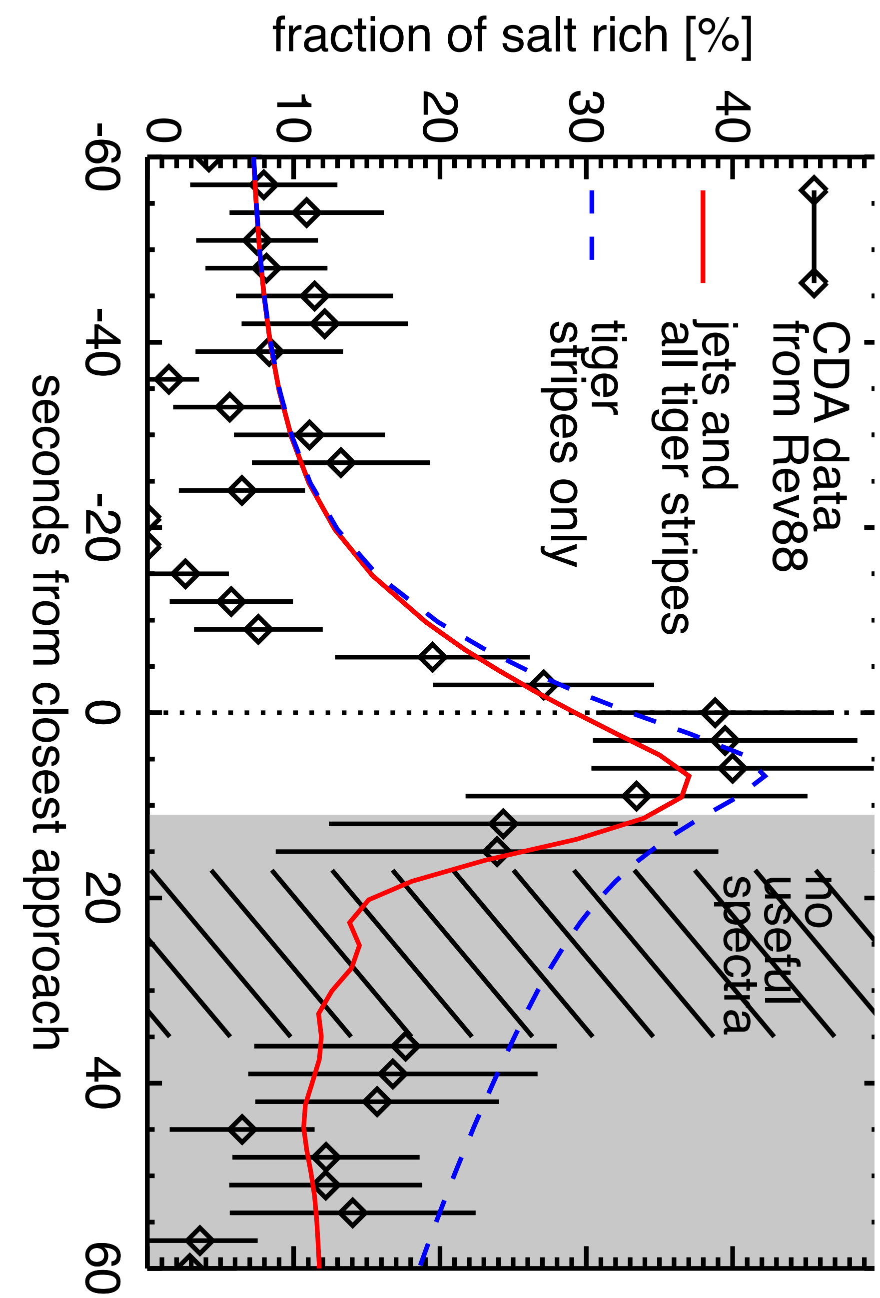
plume + E ring in Cassini's orbital plane:

% of salt rich grains
(inc. E ring background)
9.8
13.3
18.1
23.6
29.6
35.9
42.6
49.6
56.8
71.3



III, VI, VIII:
jet sources
(Spitale & Porco 2007)

mean radius:
(inc. E ring background)
<R>=0.3 μm
<R>=0.4 μm
<R>=0.5 μm
<R>=0.7 μm
<R>=0.9 μm



summary

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* dust/gas dynamics: link between grain number-density, size, composition, and position in plume

=> dynamical filtering of grain sizes and compositional types

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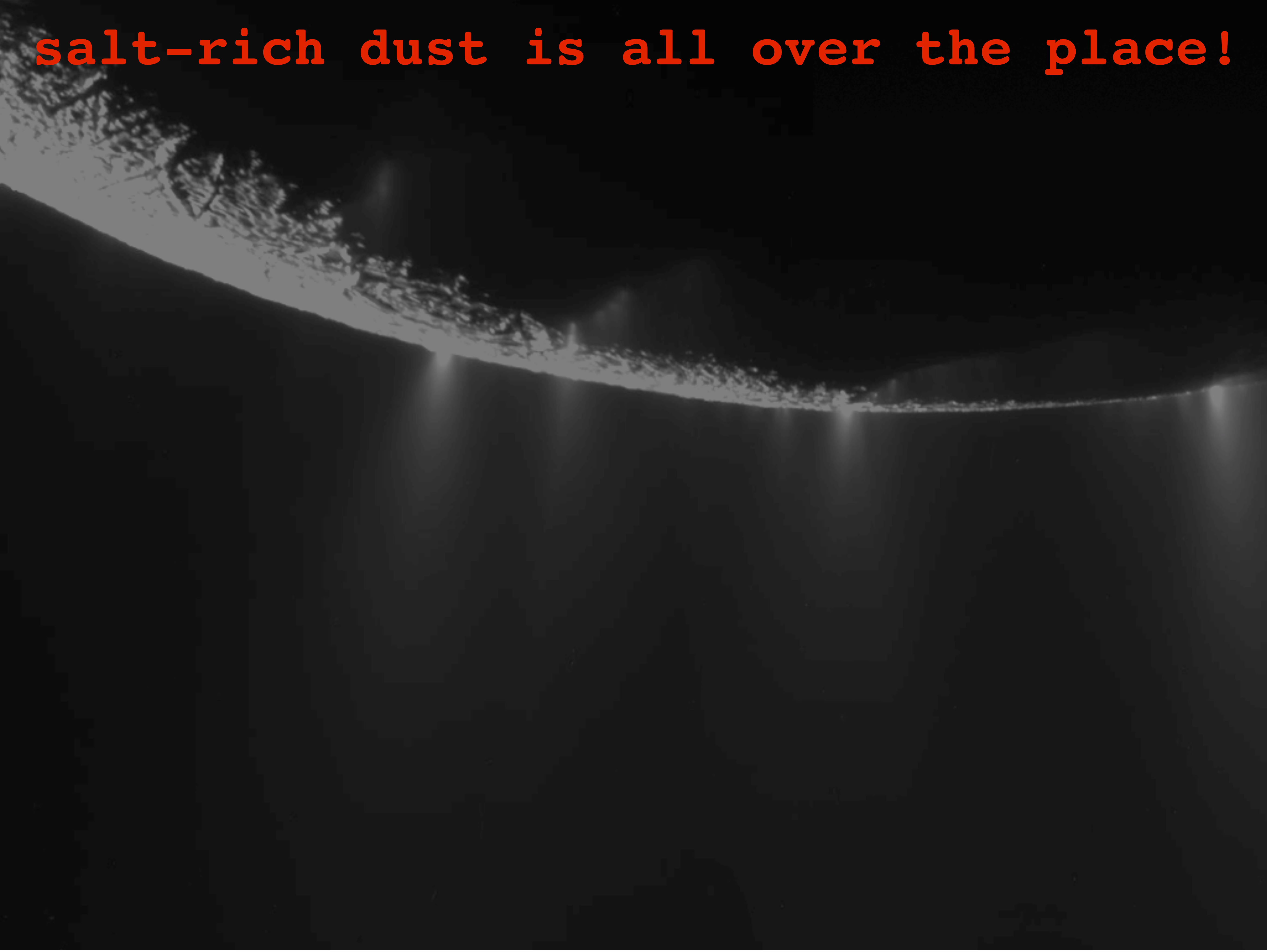
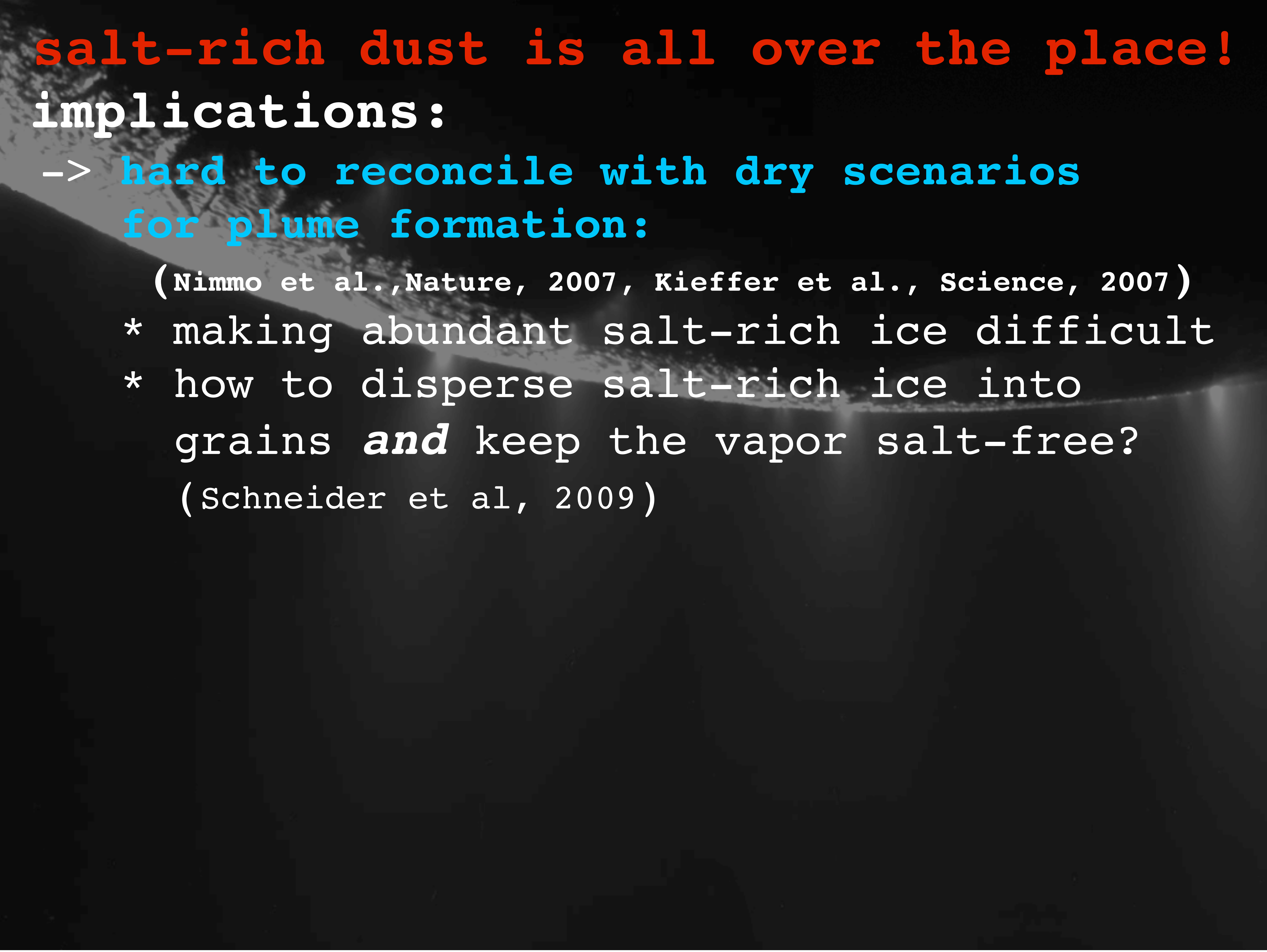
* stratified plume:
produces dominantly salt-rich ice grains
& salt-rich grains are more massive

=> >99% of the dust-mass is salt-rich (salinity ~1%)

salt-rich dust is all over the place!

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implications:
-> hard to reconcile with dry scenarios
for plume formation:
(Nimmo et al.,Nature, 2007, Kieffer et al., Science, 2007)
* making abundant salt-rich ice difficult
* how to disperse salt-rich ice into
grains *and* keep the vapor salt-free?
(Schneider et al, 2009)

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-> **easier to understand if there are ongoing aqueous processes:**

* direct dispersion from salty water
* small salt-poor grains: condense from the vapor
* volatile gases (INMS/UVIS) released from warm ice (gas hydrates?)

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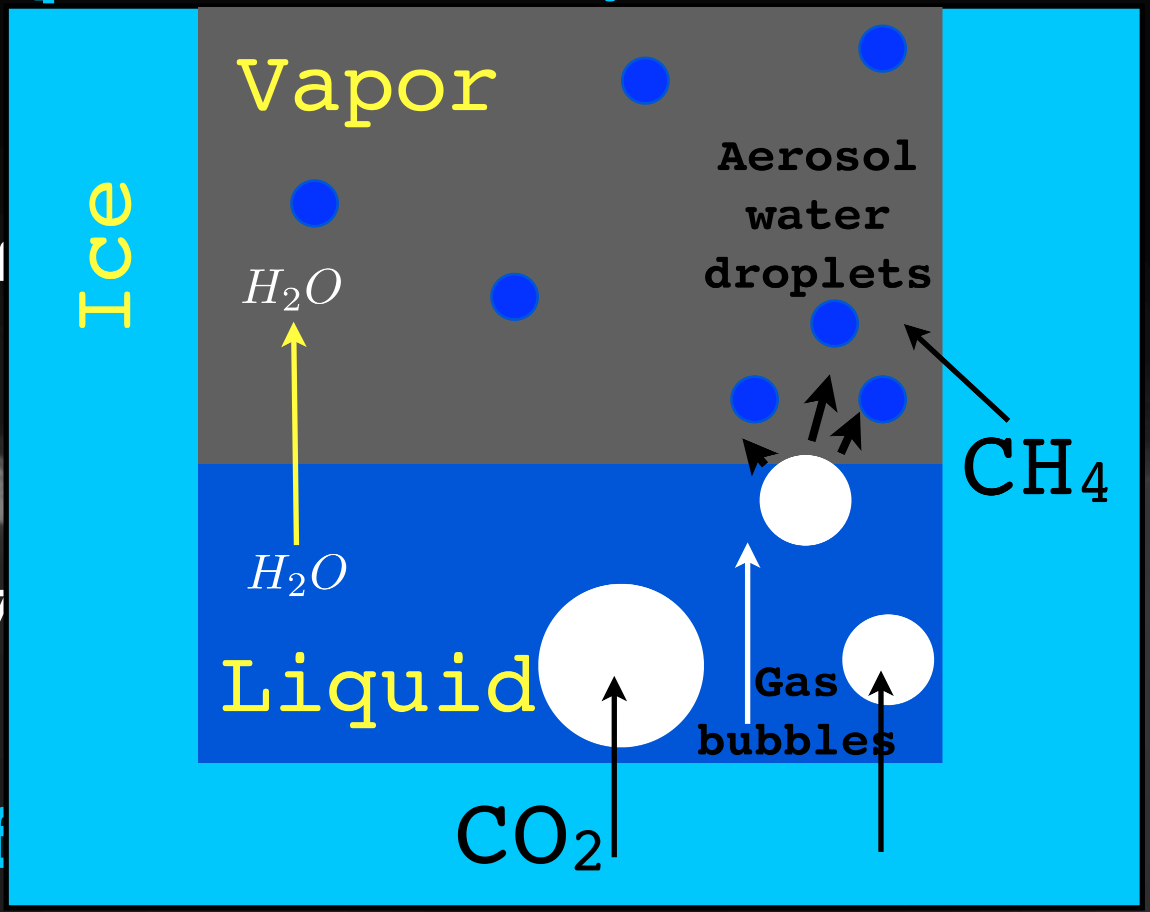

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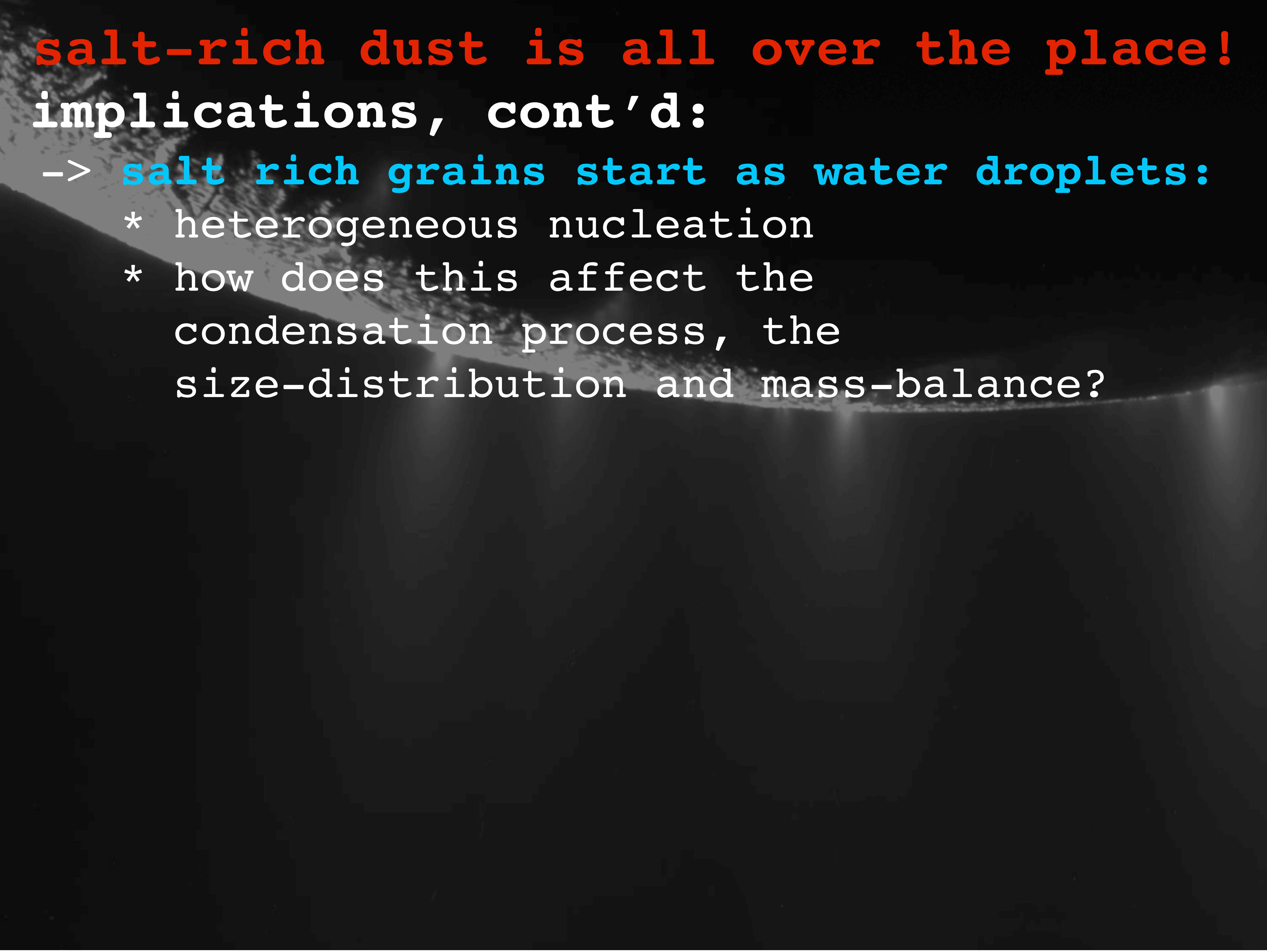
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implications, cont'd:
-> salt rich grains start as water droplets:
* heterogeneous nucleation
* how does this affect the condensation process, the size-distribution and mass-balance?

salt-rich dust is all over the place!

implications, cont'd:

-> **salt rich grains start as water droplets:**

* heterogeneous nucleation
* how does this affect the condensation process, the size-distribution and mass-balance?

-> **current models under-constrained**

* CDA: combined profiles of number density from various flybys
* imaging+VIMS: constrain altitude resolved speed+size-distribution and dust mass