The Saturnian System - the Dusty Point of View by Cassini-CDA

Part 2: Dynamics of dust in the Saturnian System

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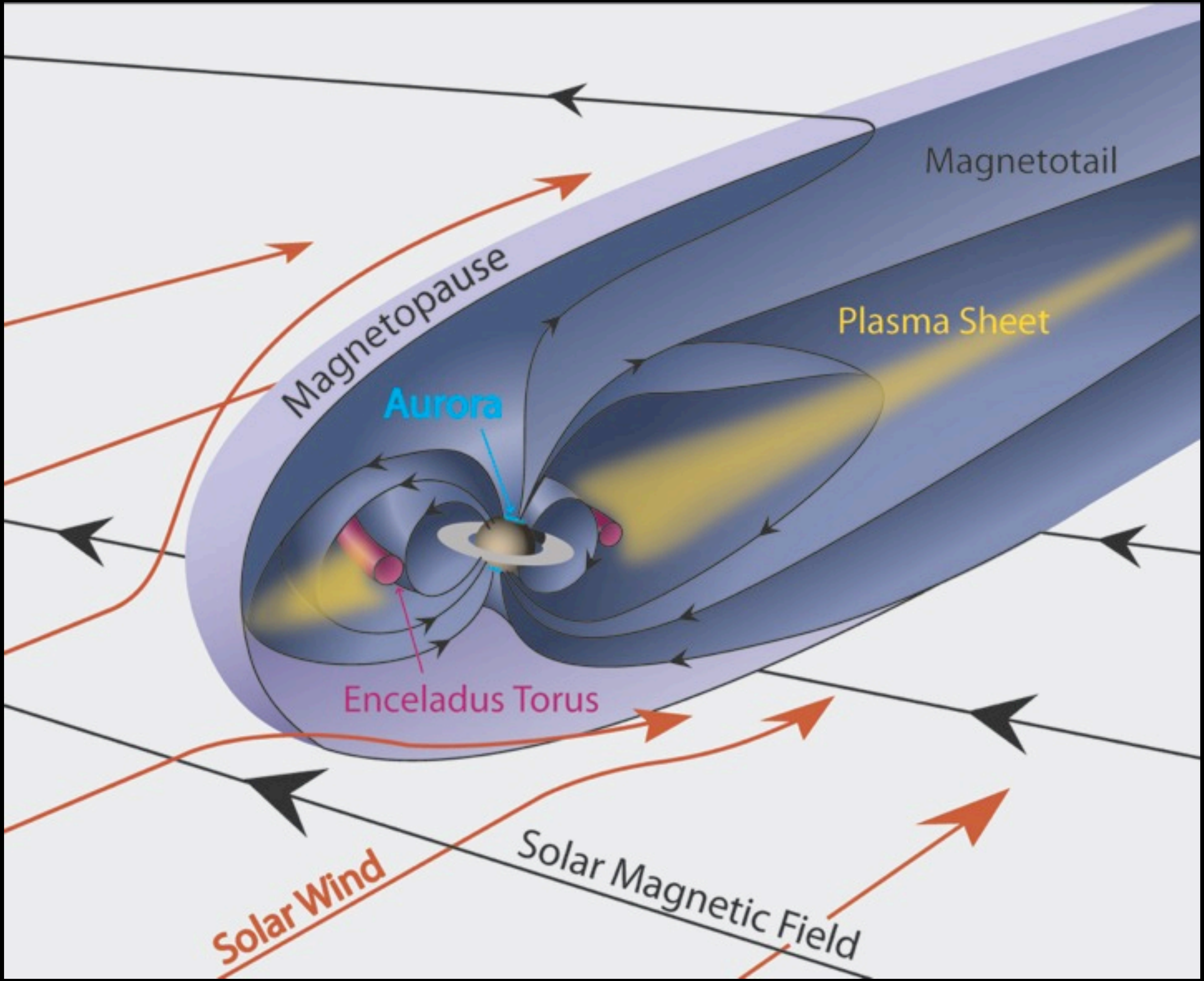
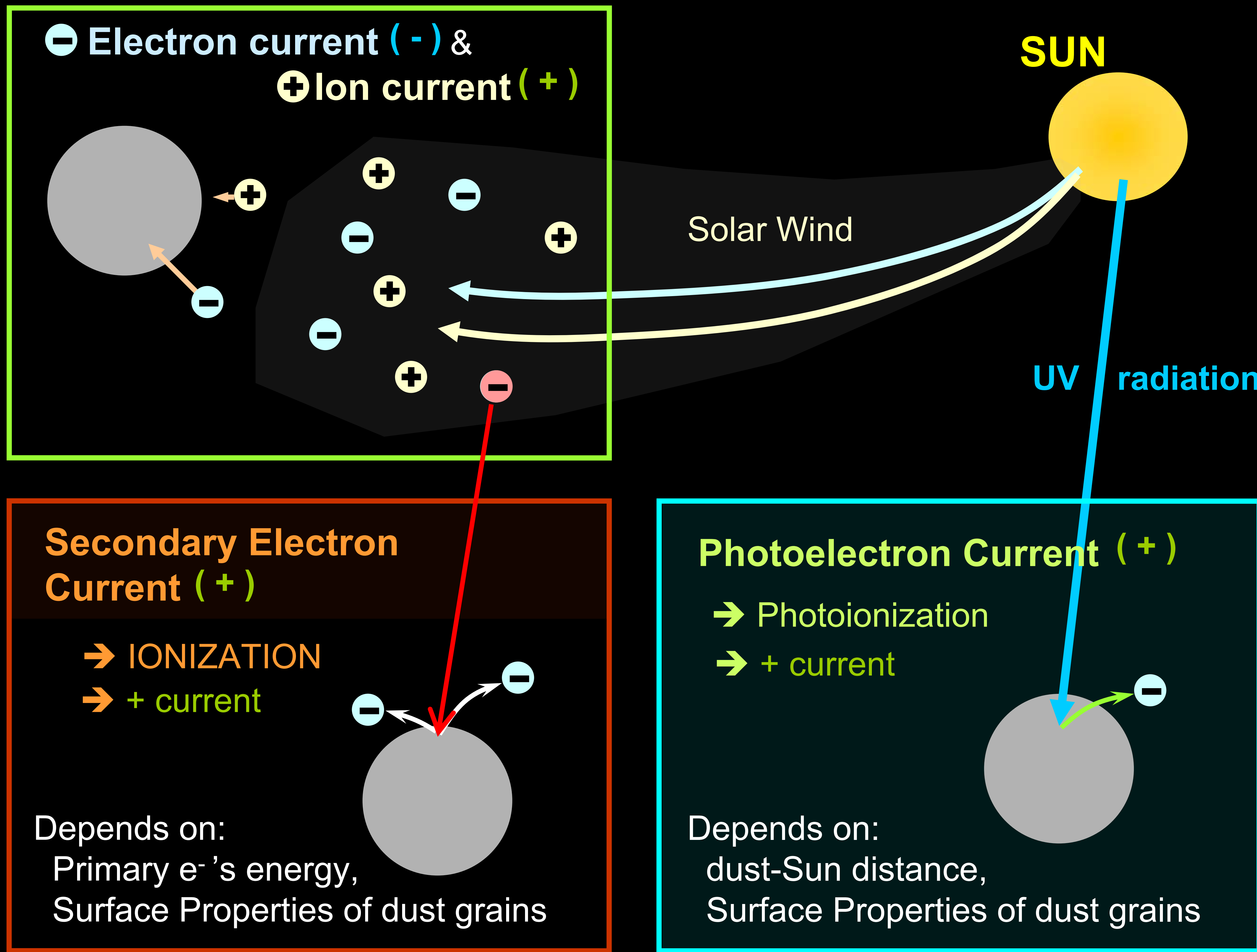
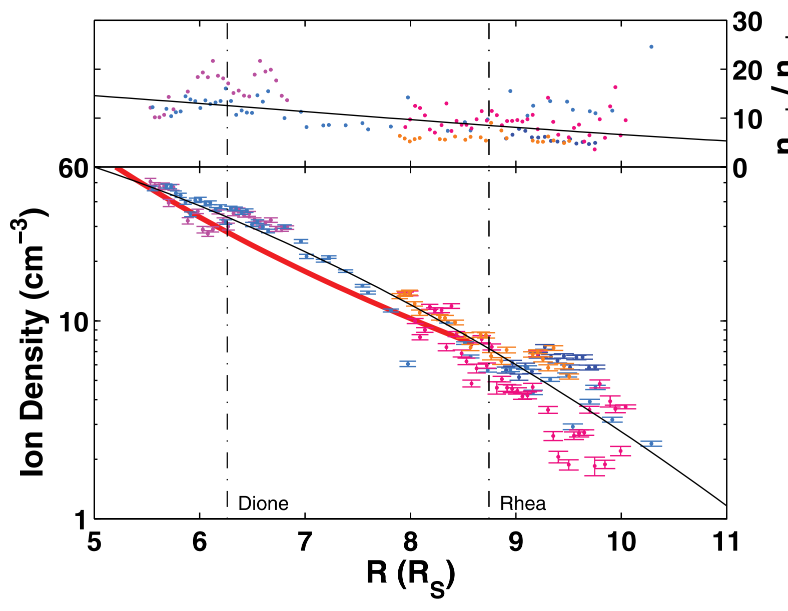
- Dust-Magnetosphere interactions
  - dust charging
  - plasma sputtering erosion
  - dusty / dust-laden plasma
- Dust dynamics
  - E ring
  - Nanodust stream particles
- In situ dust measurements as a remote sensing tool to study the Saturnian system
  - Source of stream particles
  - Composition mapping of Saturn's main rings

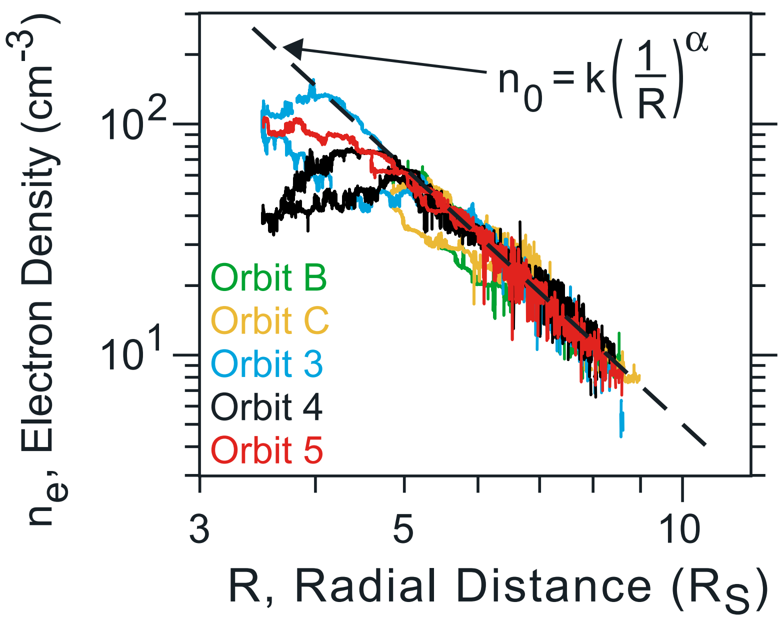
Configuration of Saturn's magnetosphere

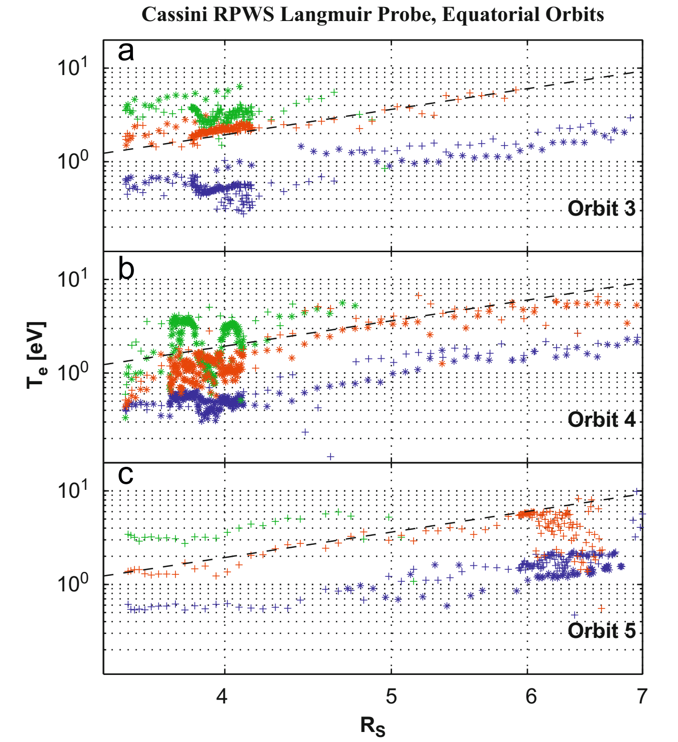


Fran Bagenal & Steve Bartlett


Electron current (-) &
Ion current (+)
SUN
Solar Wind
UV radiation
Secondary Electron Current (+)
→ IONIZATION
→ + current
Depends on:
Primary e⁻'s energy,
Surface Properties of dust grains
Photoelectron Current (+)
→ Photoionization
→ + current
Depends on:
dust-Sun distance,
Surface Properties of dust grains





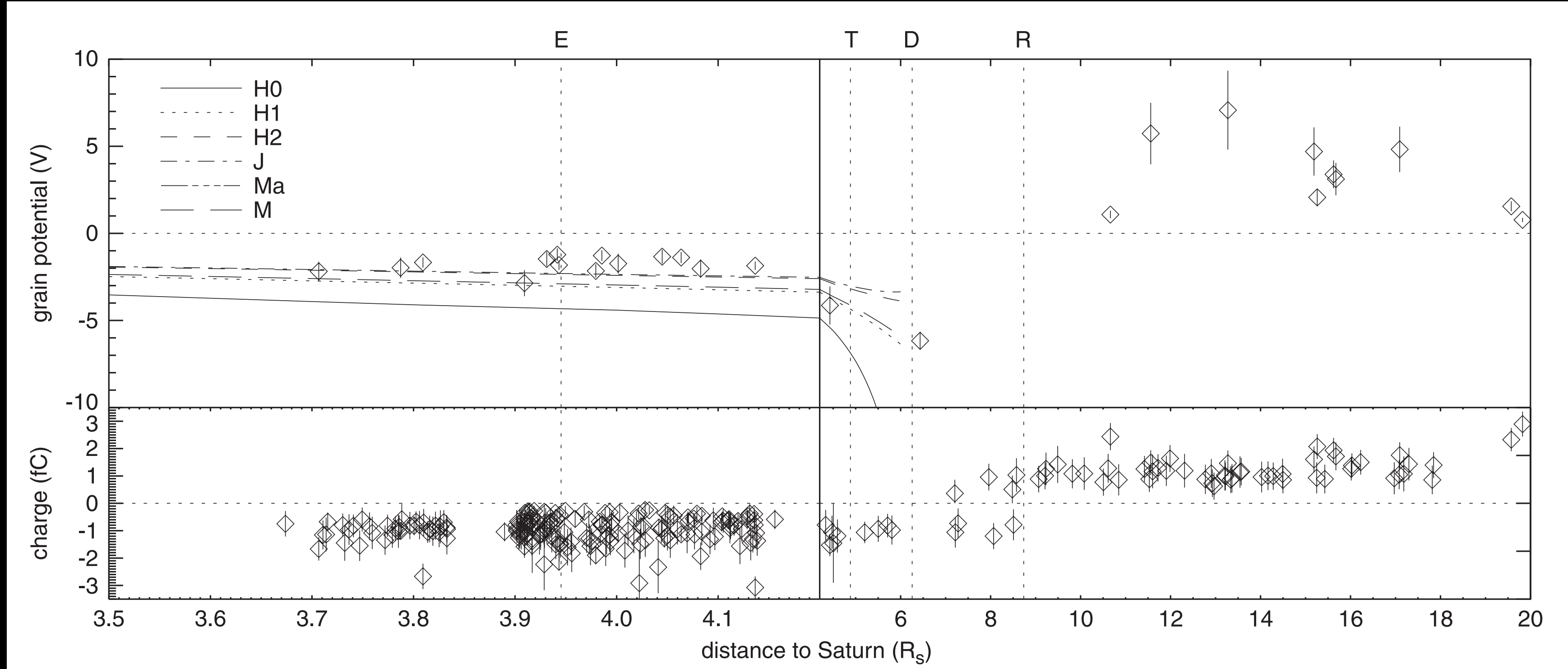


Wilson et al., 2008

Persoon et al., 2005

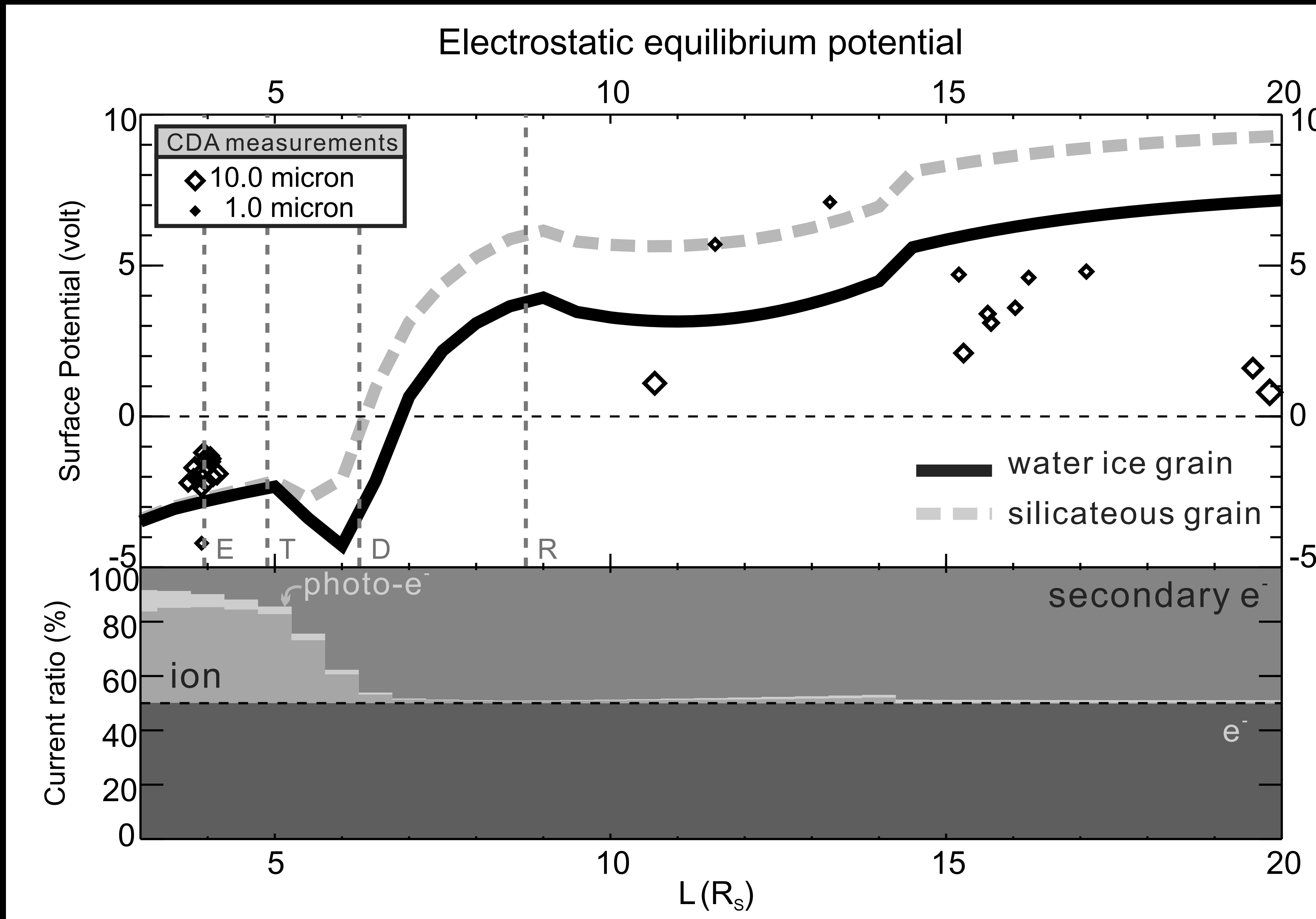
Gustafsson and Wahlund, 2010

Plasma vs. dust charge measurements in Saturn's magnetosphere



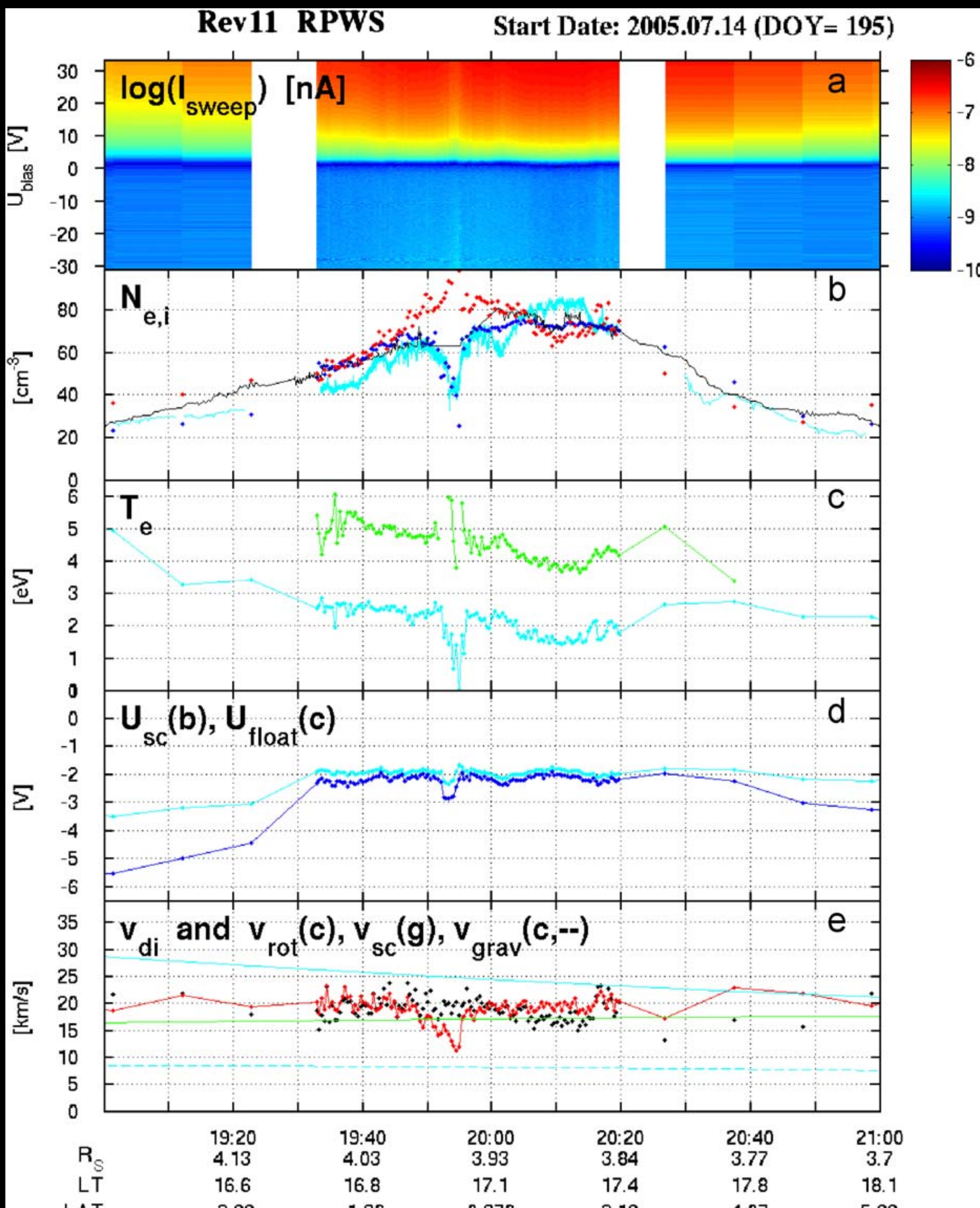
Kempf et al., 2006

Dust potential in Saturn's magnetosphere

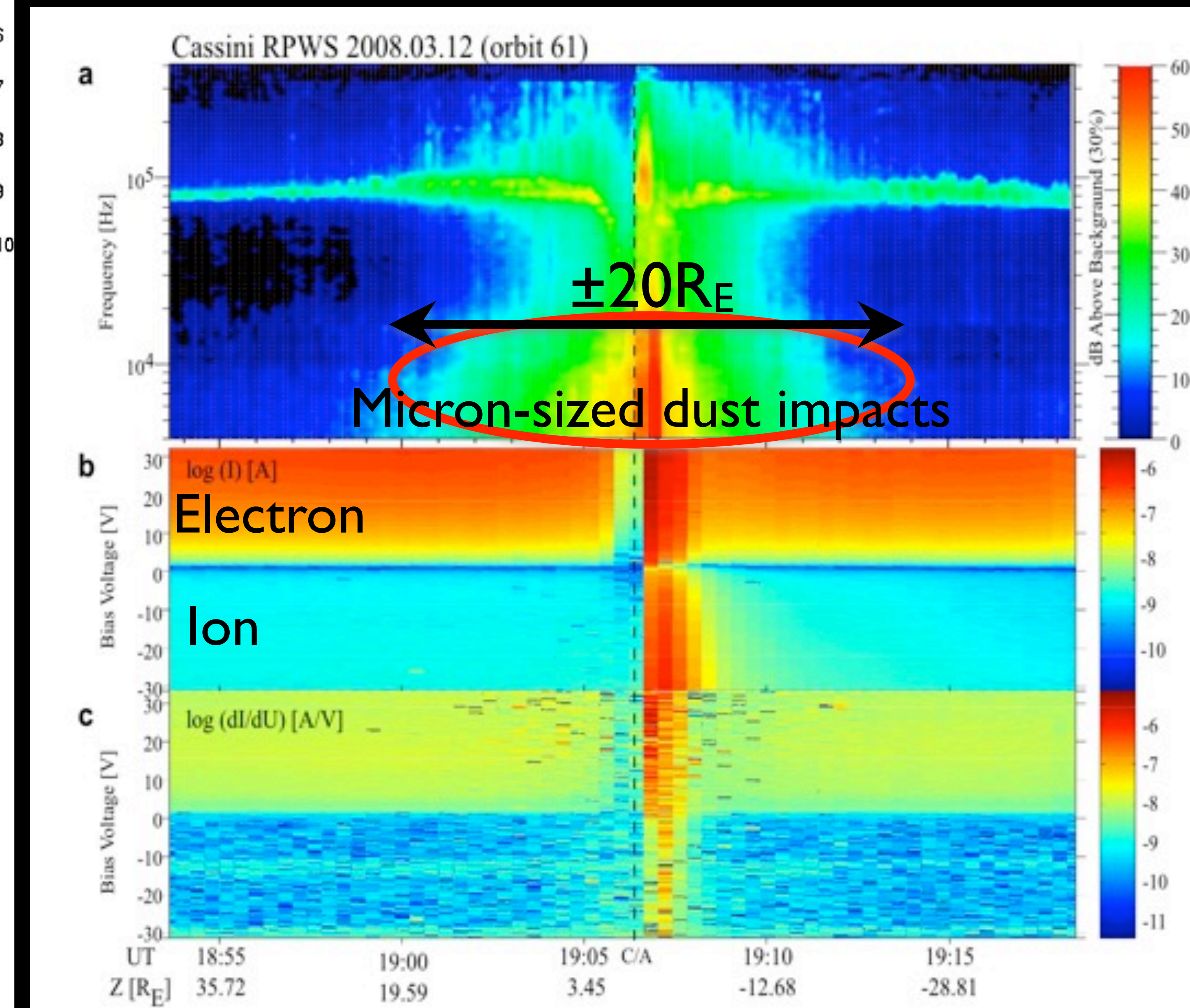


Hsu et al., 2010

A complex dust-plasma system inferred from observations of Cassini Radio and Plasma Wave Science

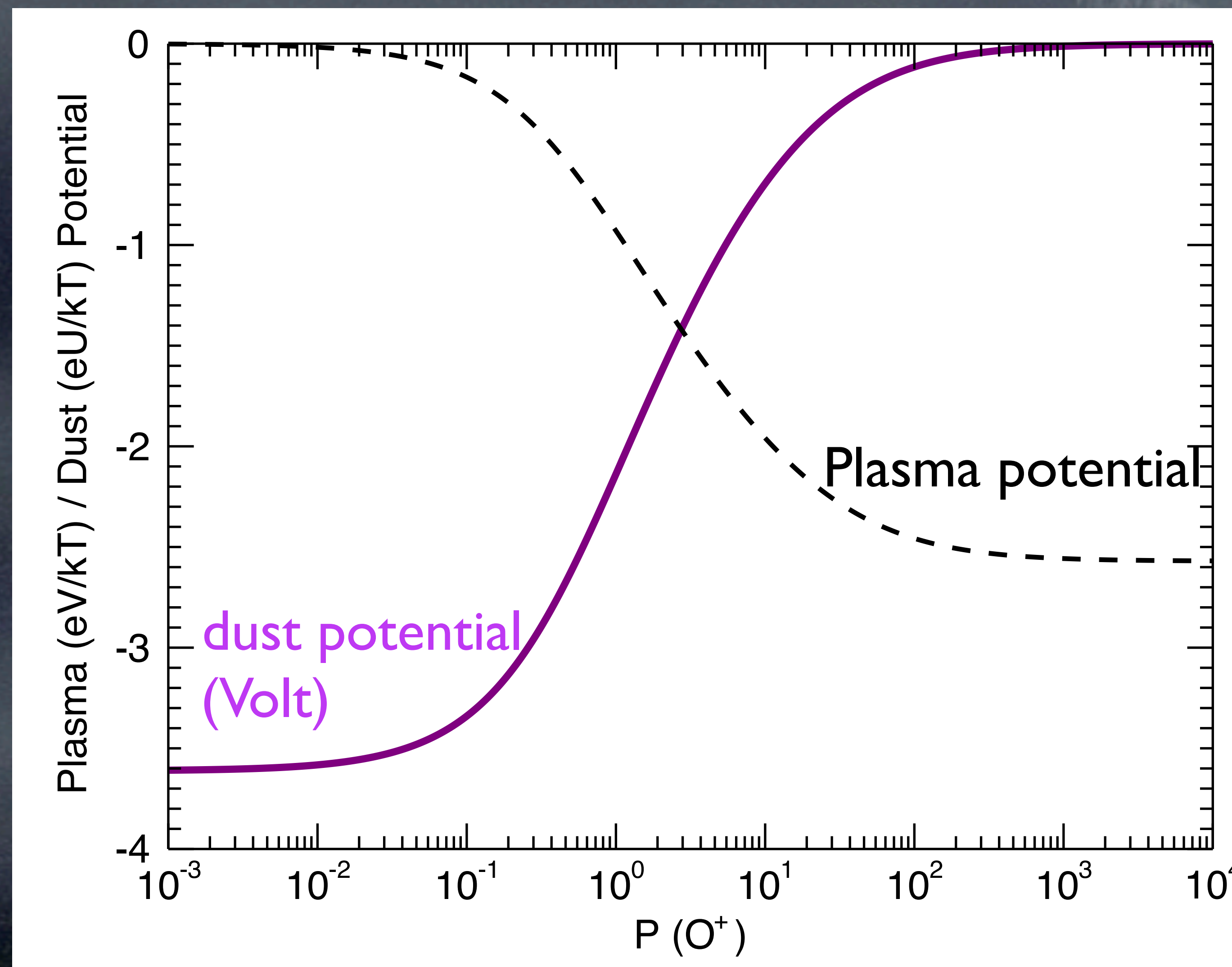


Wahlung et al., 2009



Marooka et al., 2011

Dusty Plasma conditions at Enceladus



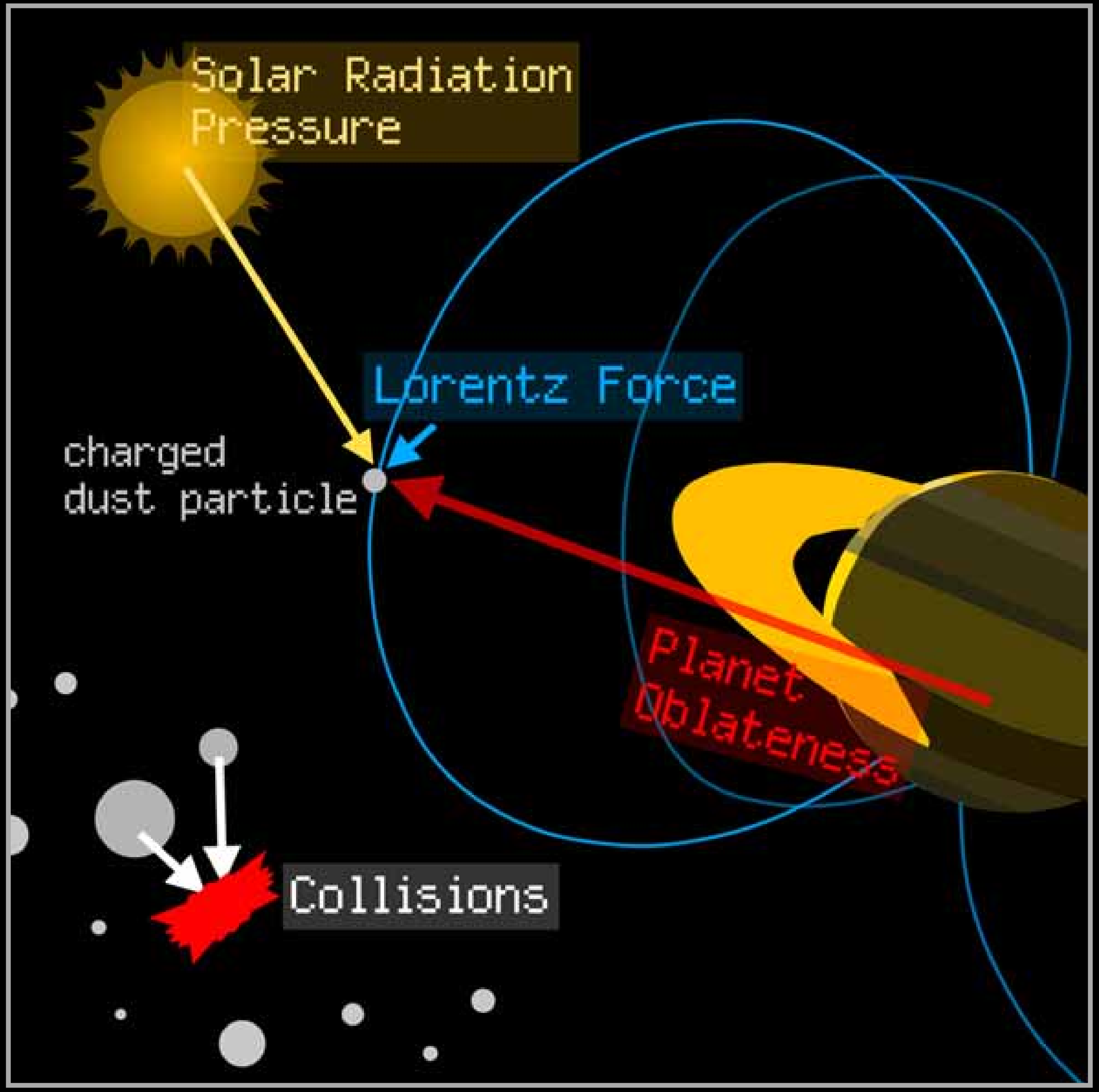
dust charge / plasma charge

reproduced from Havnes et al., 1990

The Saturnian system as a laboratory of dust dynamics

Diffuse E ring

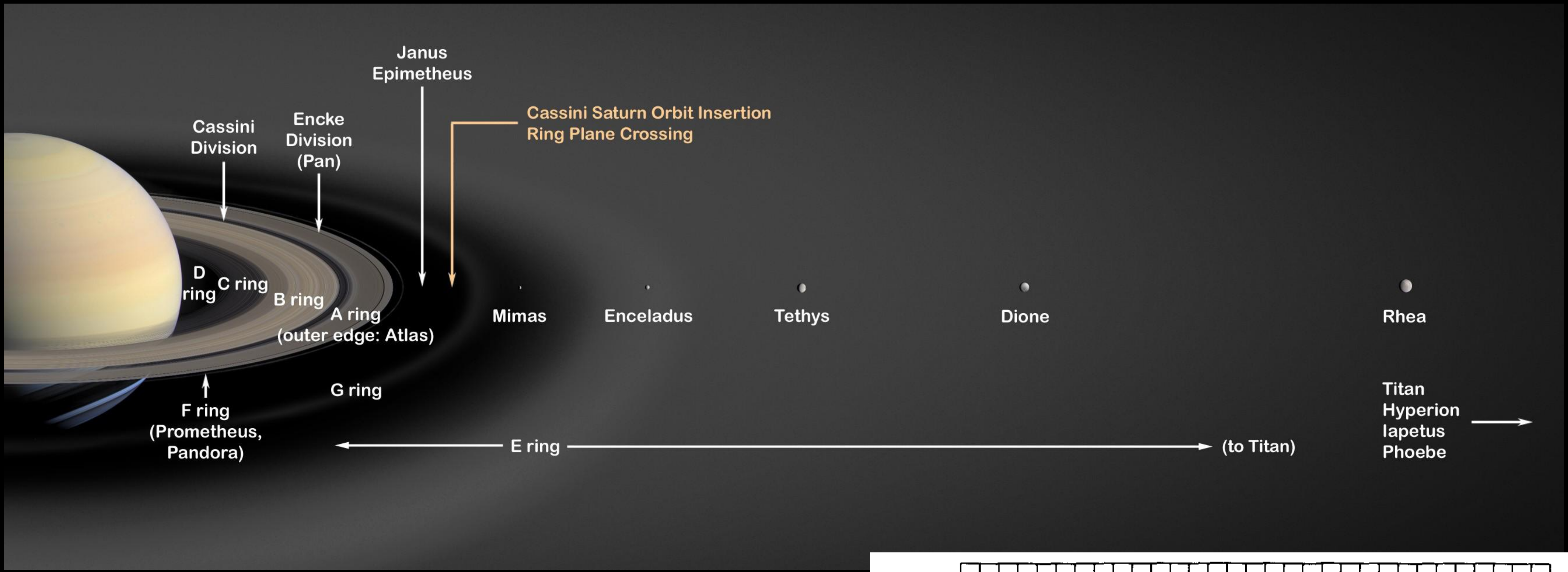
- mostly 0.1 - few micron icy grains
- Various forces and processes shaping the ring
- Size-dependent dynamical evolution



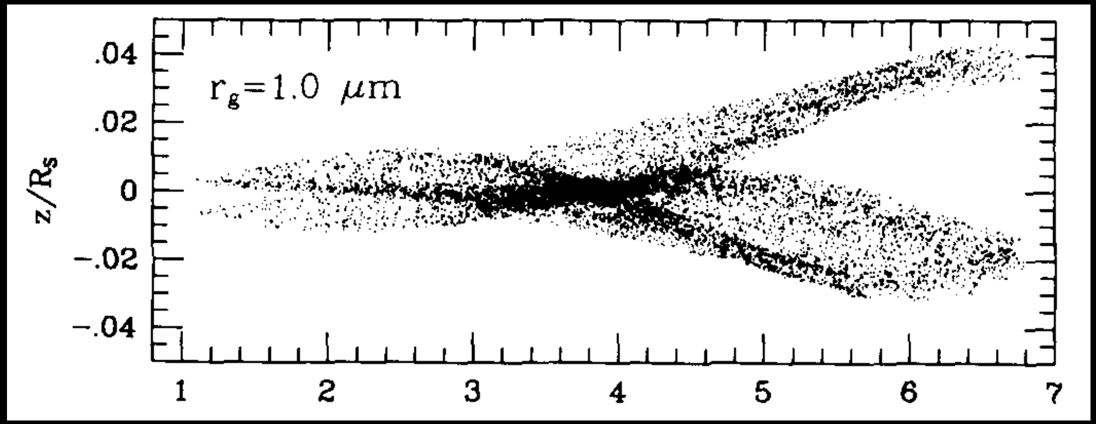
Fast nanoparticles (stream particles)

- sizes: a few nm
  speed: ~100 km/s
- governed by EM forces

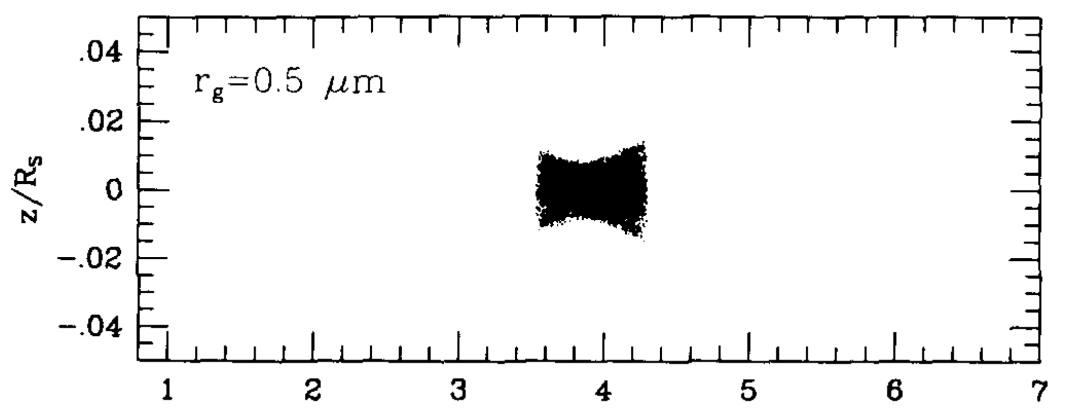
The ring system

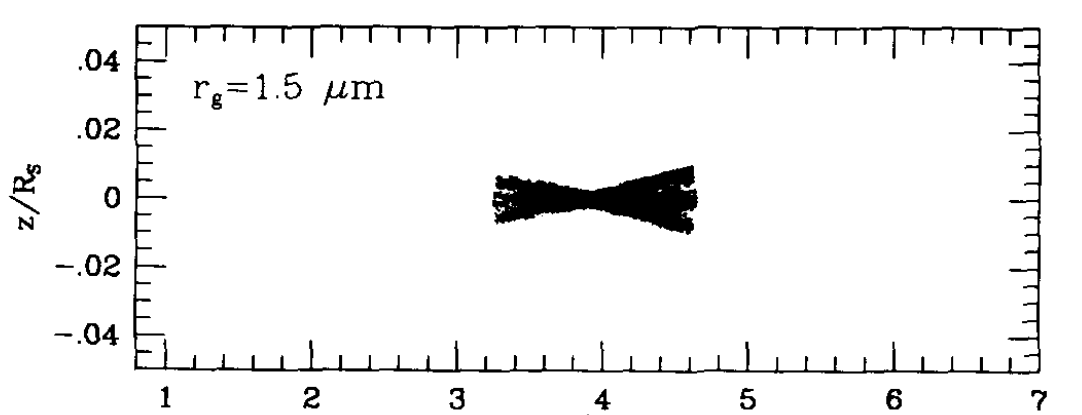


Size-dependent dust dynamical evolution

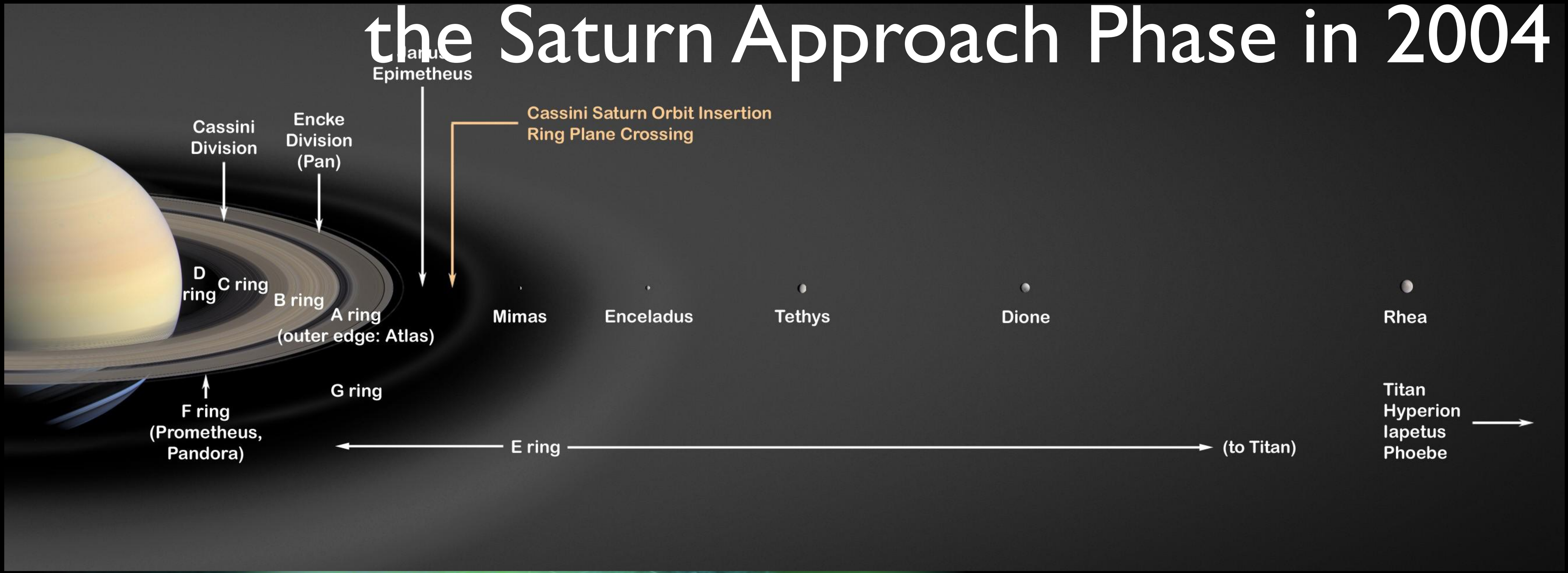


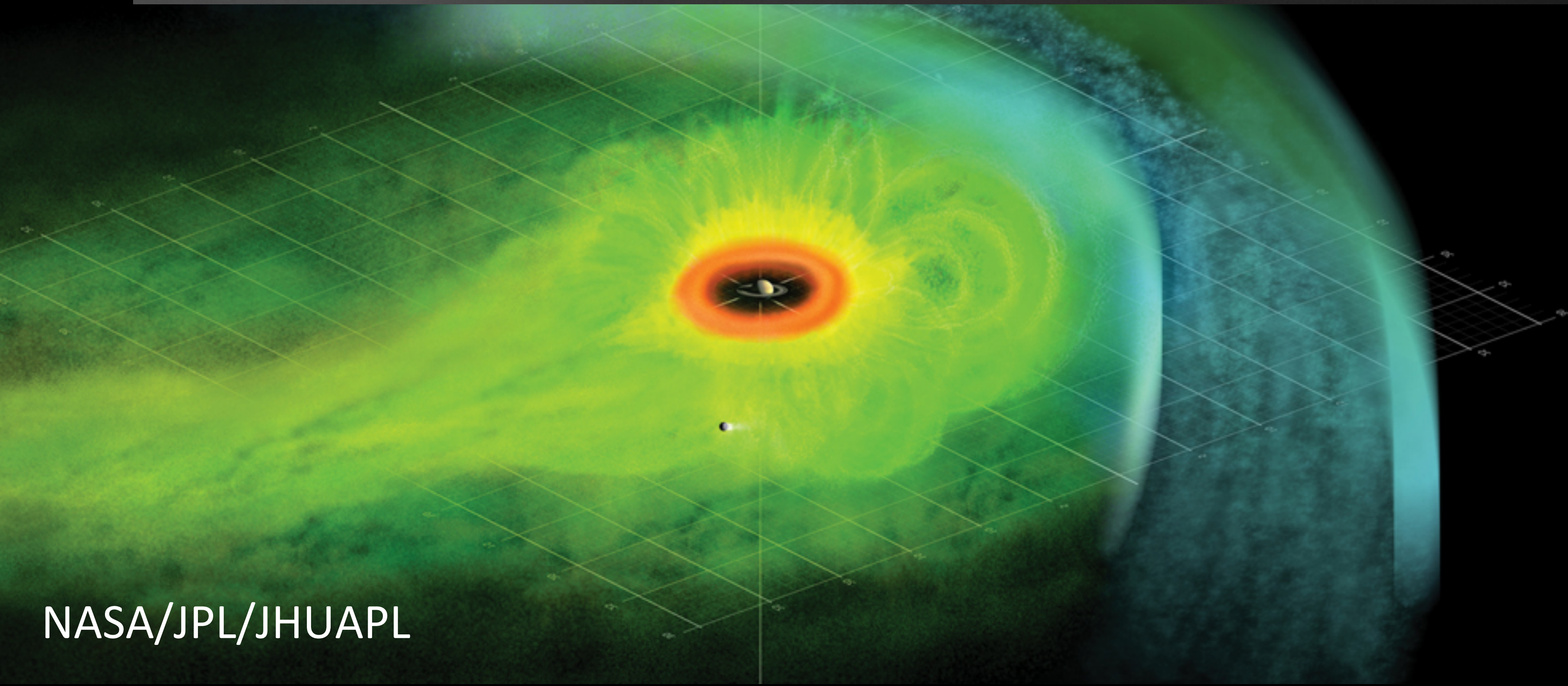
Horányi et al., 1992





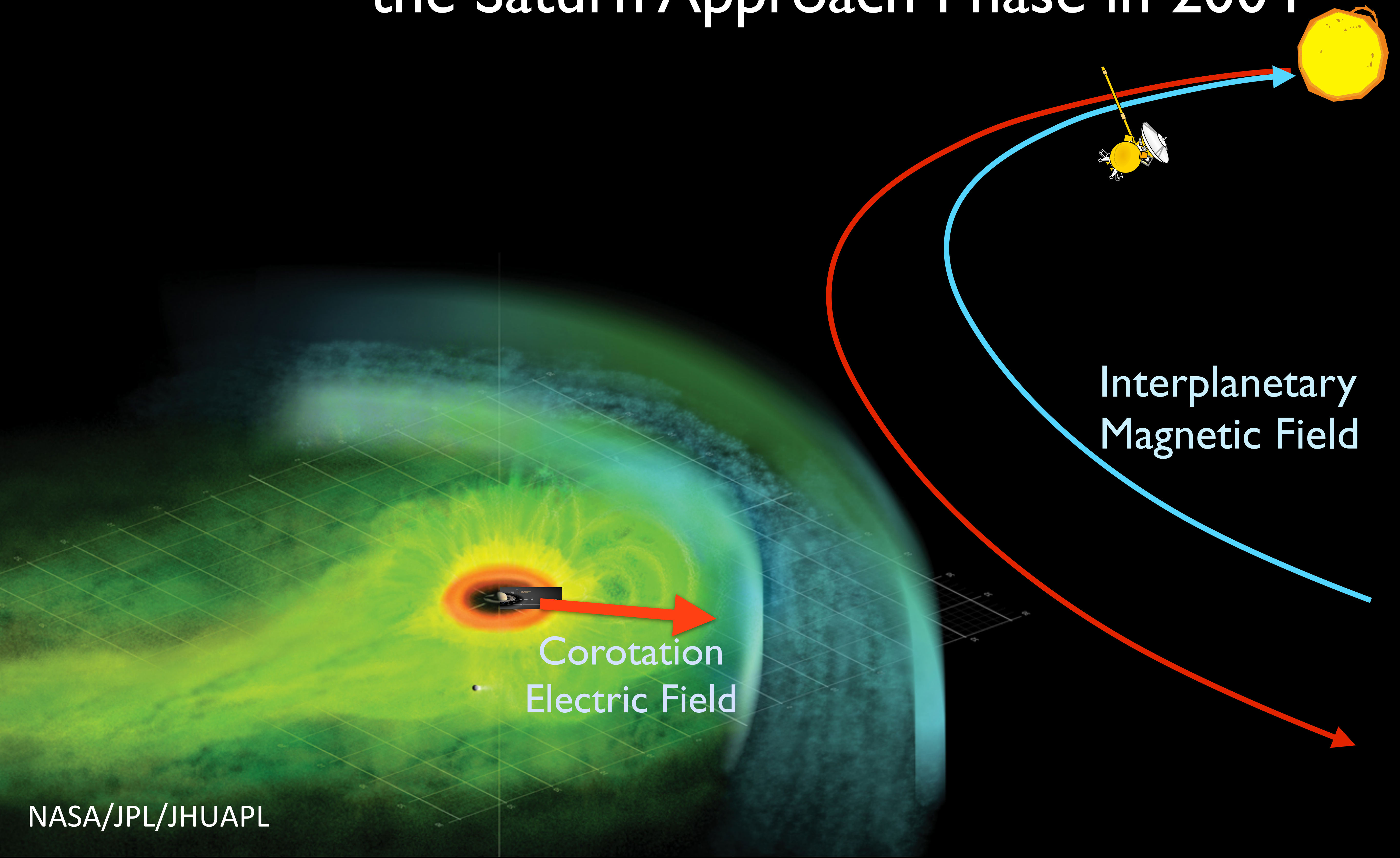
CDA Stream Particle Measurements during the Saturn Approach Phase in 2004



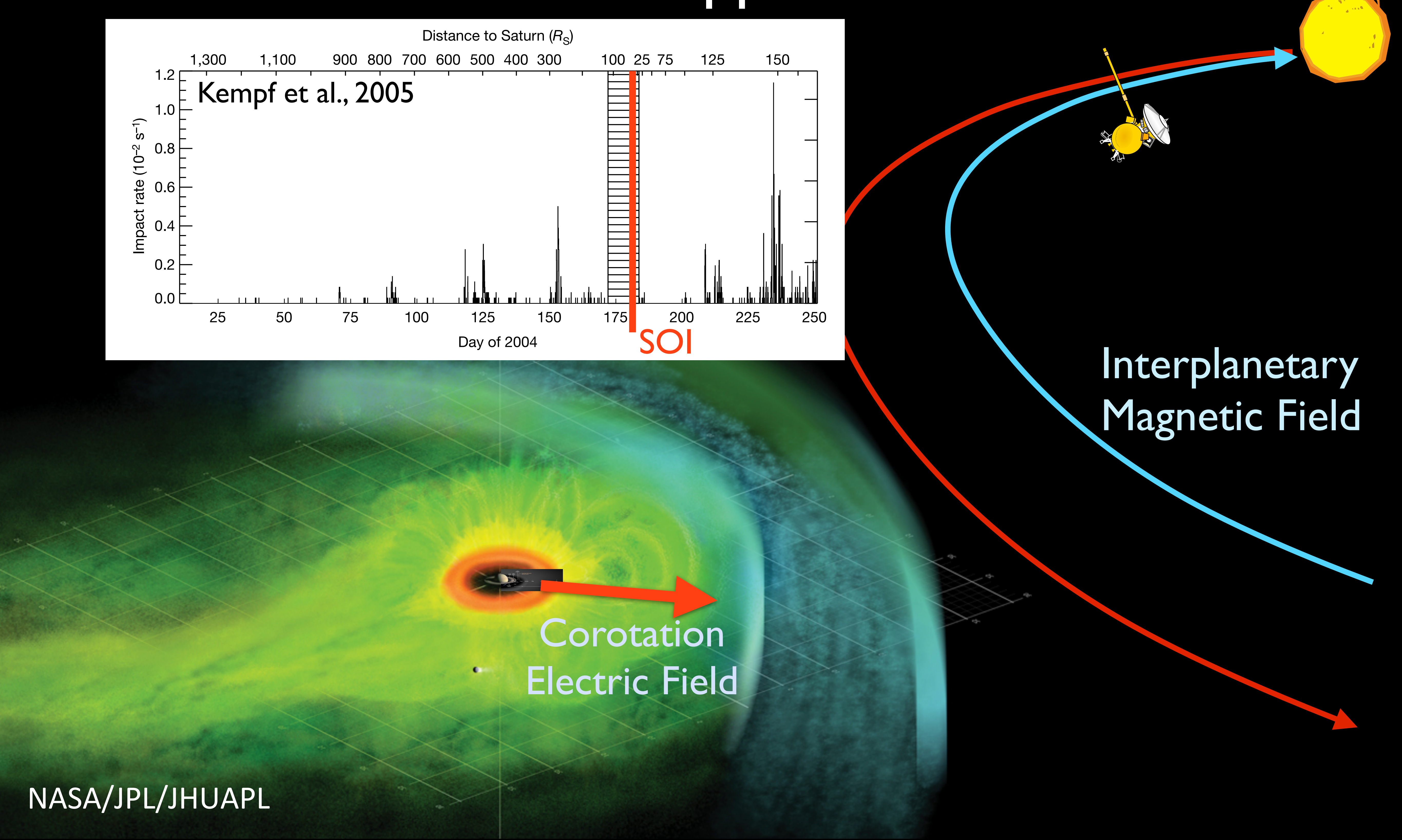


NASA/JPL/JHUAPL

CDA Stream Particle Measurements during the Saturn Approach Phase in 2004

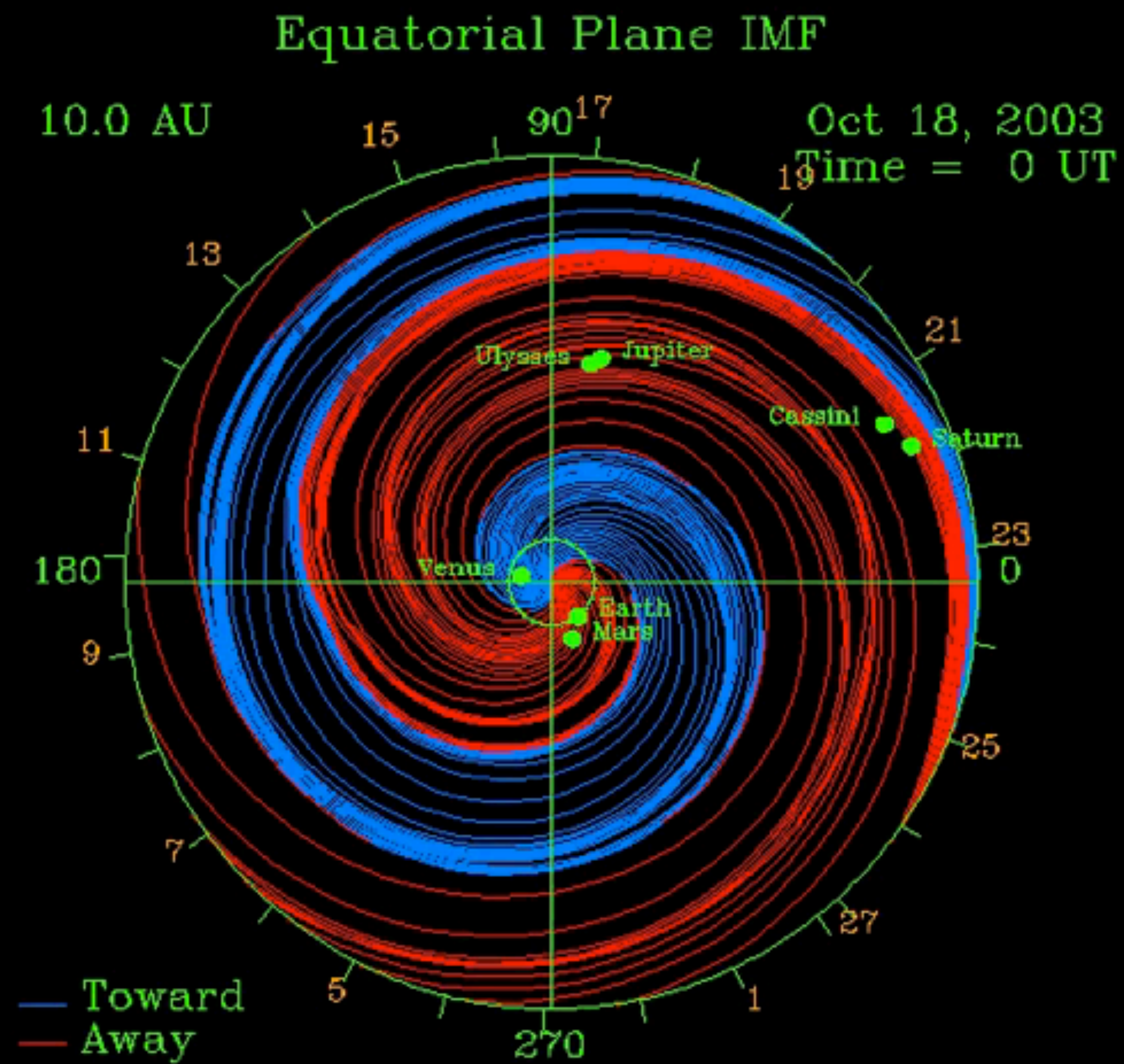


CDA Stream Particle Measurements during the Saturn Approach Phase in 2004



Interplanetary Magnetic Field (IMF)

- A two-sector structure
- *Corotating Interaction Region* (CIR) forms outside 2 AU
- Sector boundaries are embedded in the compression region



CDA Stream Particle Measurements during the Saturn Approach Phase in 2004

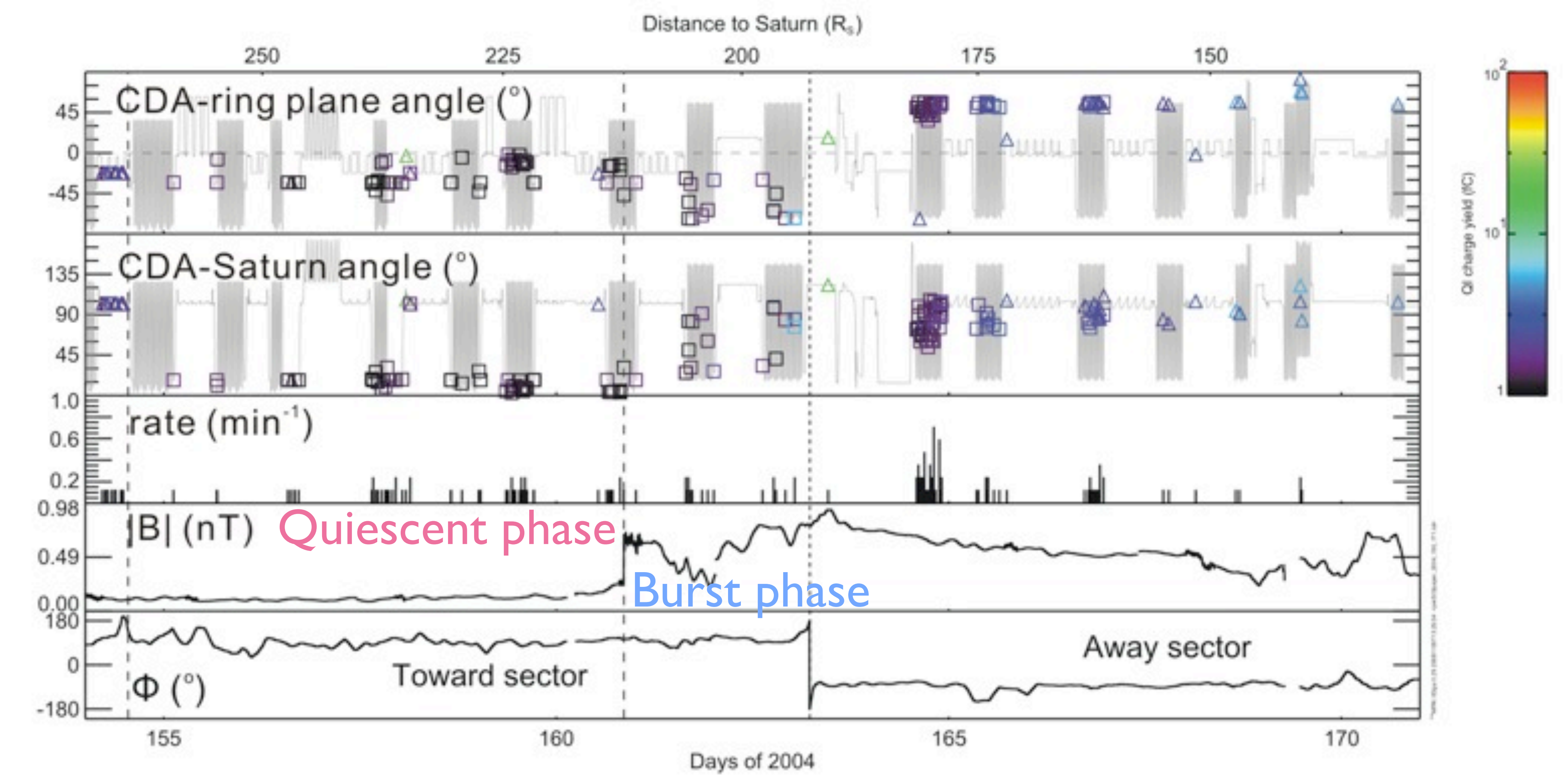
Impact Directionality

Angle between CDA & the ring plane / Saturn

Impact Rate

IMF Strength

IMF Direction

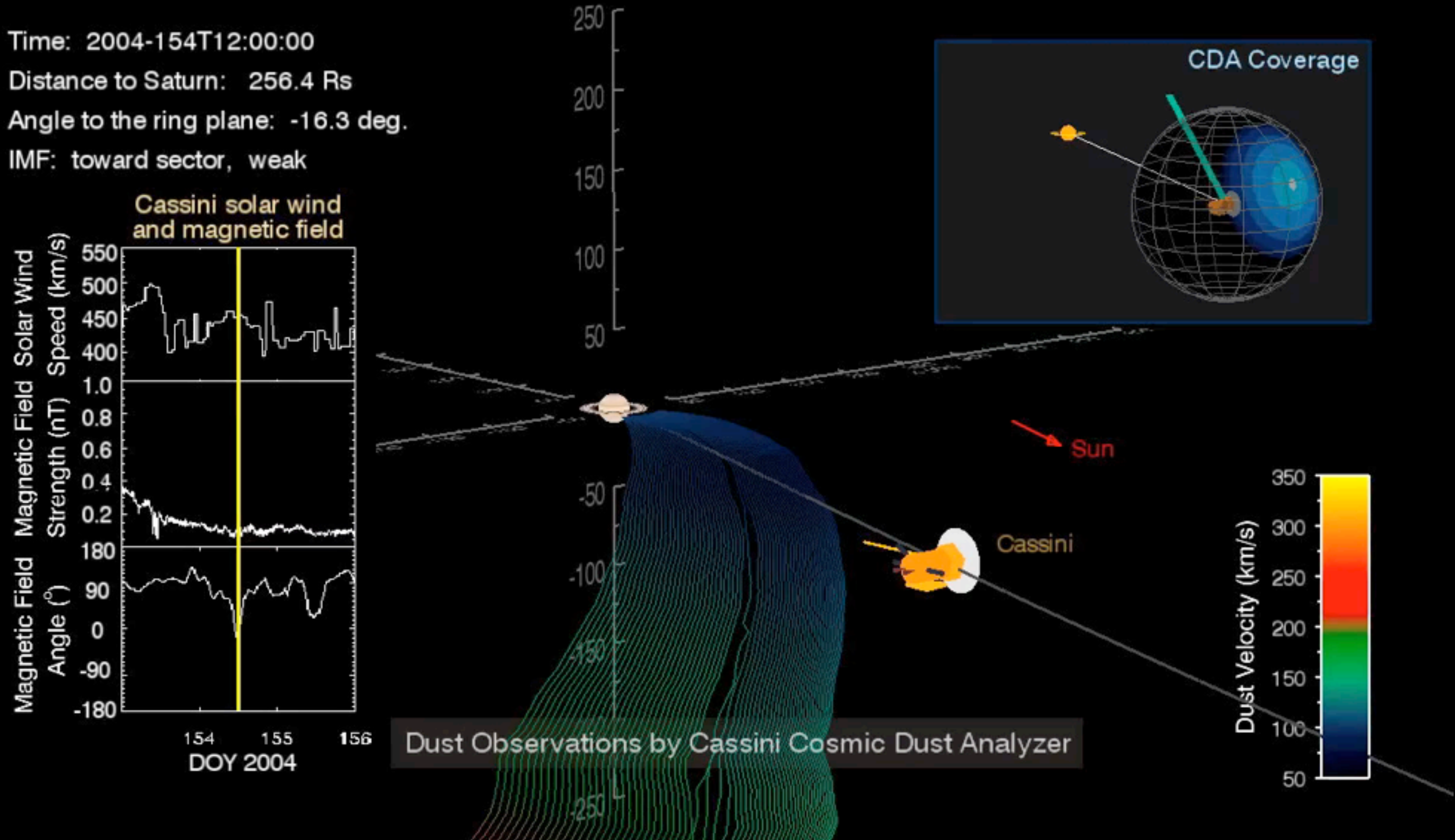


Quiescent phase:
weak IMF,
faint impacts from Saturn LOS

Burst phase:
strong IMF, energetic impacts from direction deviated from Saturn LOS

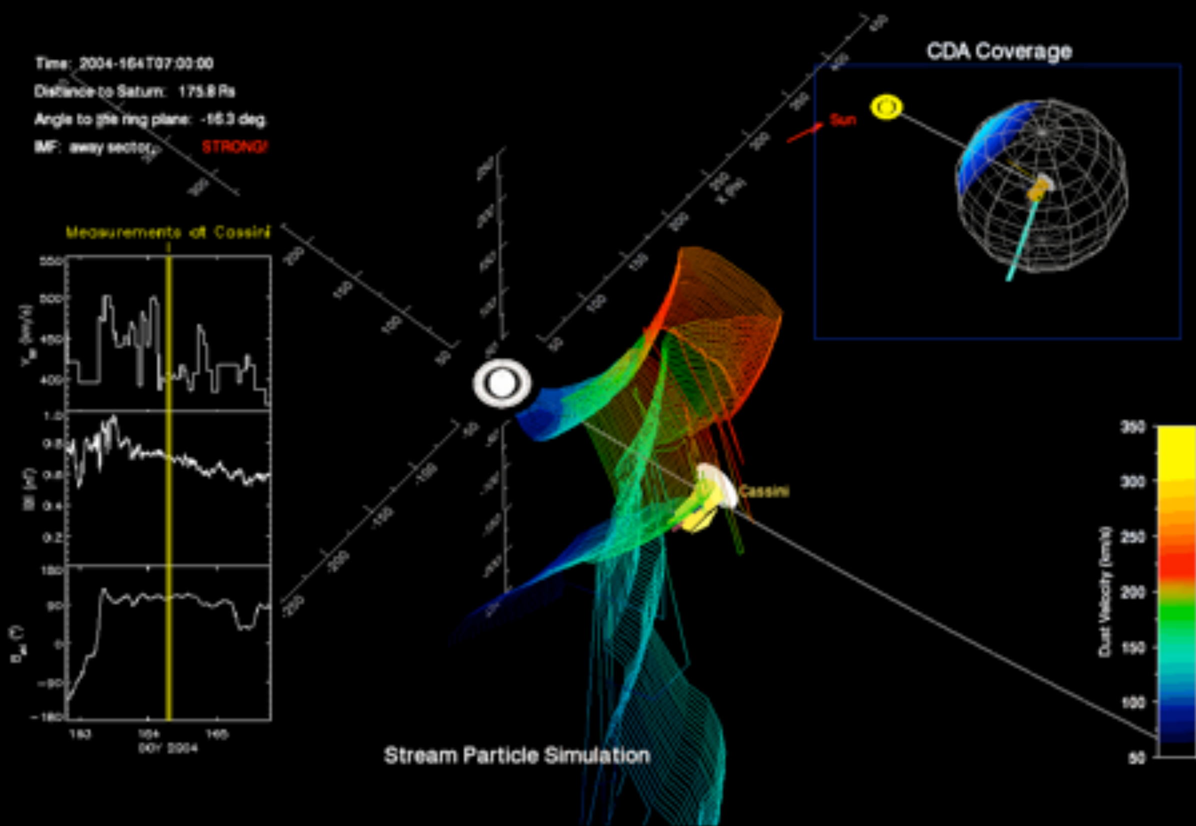
CDA Stream Particle Measurements during the Saturn Approach Phase in 2004

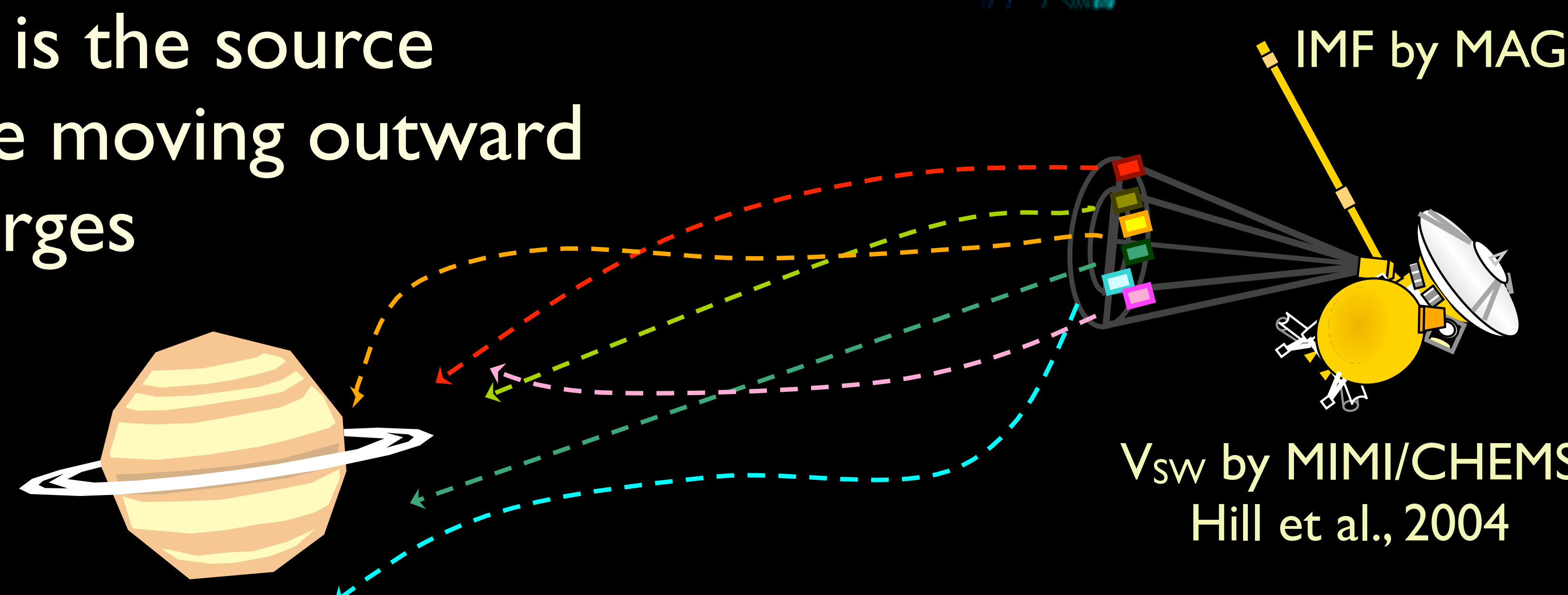
CDA Stream Particle Measurements during the Saturn Approach Phase in 2004



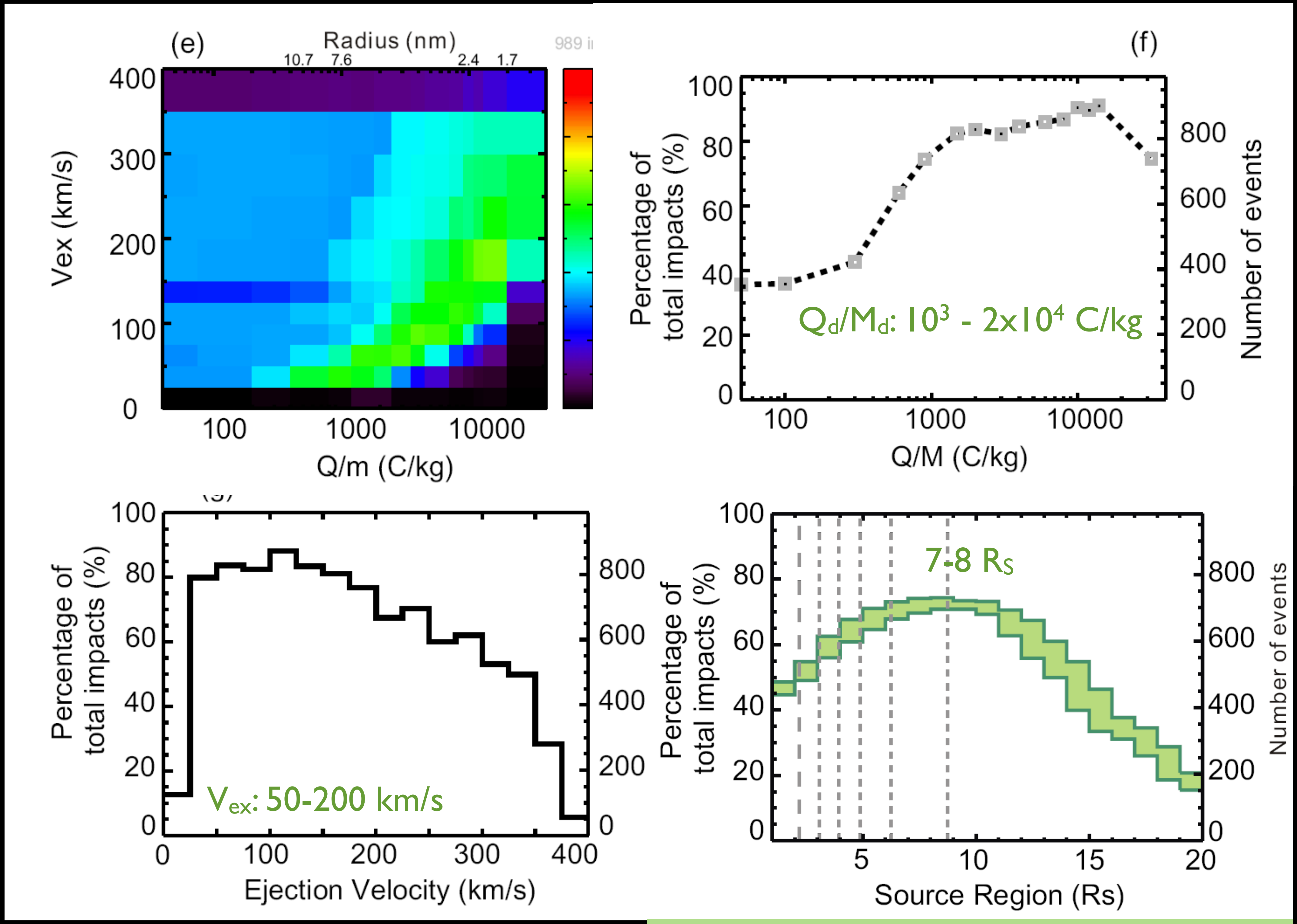
Tracing Backward in Time

- First applied to the Jovian stream particles based on Ulysses measurements
  (Zook et al., 1996)
- Considering:
  - The Lorentz force
    (Cassini solar wind measurements)
  - Gravitational forces
    (Sun & Saturn)
- Assumptions:
  - The Saturnian system is the source
  - IMF keeps intact while moving outward
  - Constant particle charges





Backward Tracing Simulation Results



Hsu et al., 2011

Energy Conservation: $$\frac{1}{2}m_d v_{ex}^2 = -\frac{GM_S m_d}{2r_0} + \int_{r_0}^{r_{ms}} f_{co} \cdot Q_d \cdot \mathbf{E}_c \, dr.$$

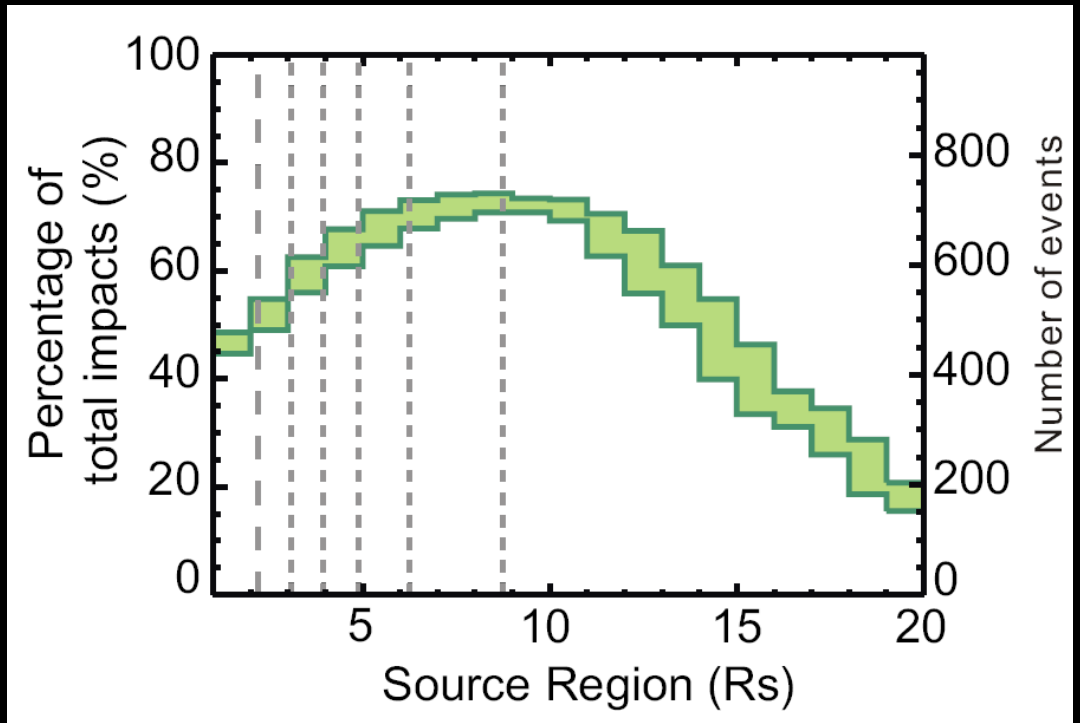
The "Ejection Region"

The "Ejection Region" at 7-9 R_S

- defined from the dynamics perspective.
- indicates the location where the particles start to be accelerated outward
- is the combined effect of:
  particle properties, *charging (plasma) conditions*, and
  the location of the real source

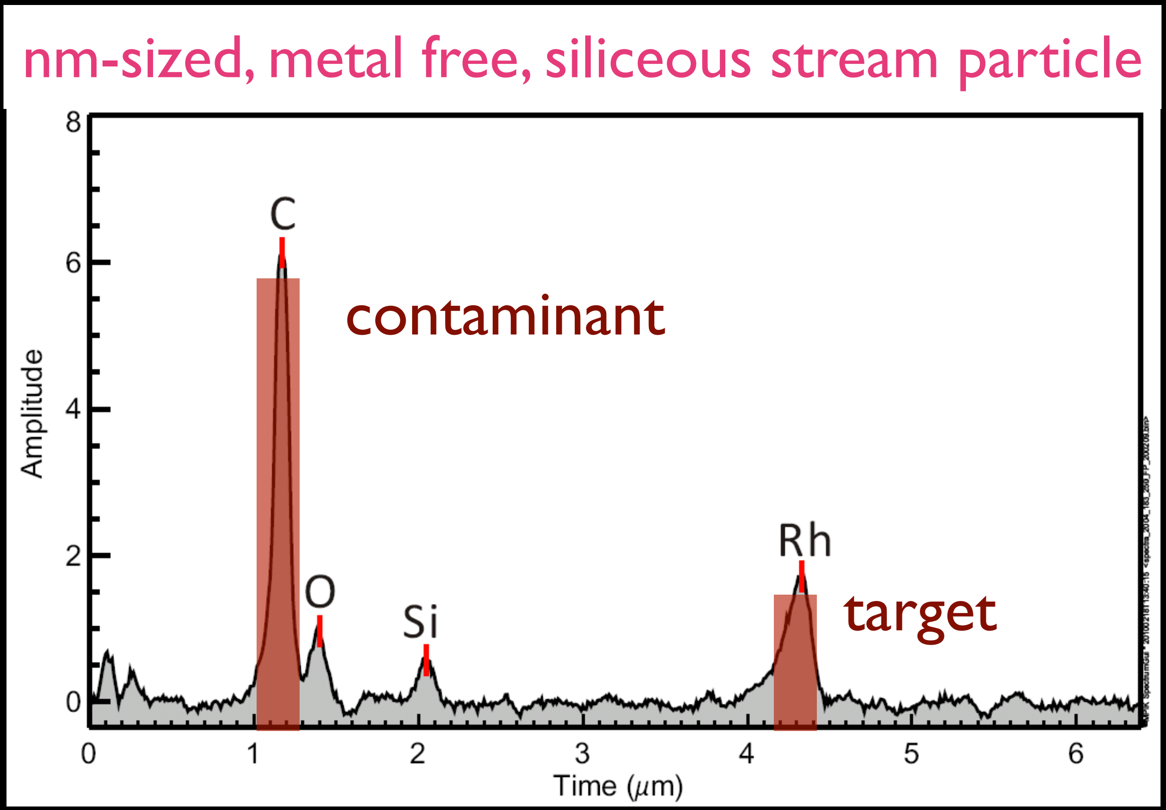
Likely sources:

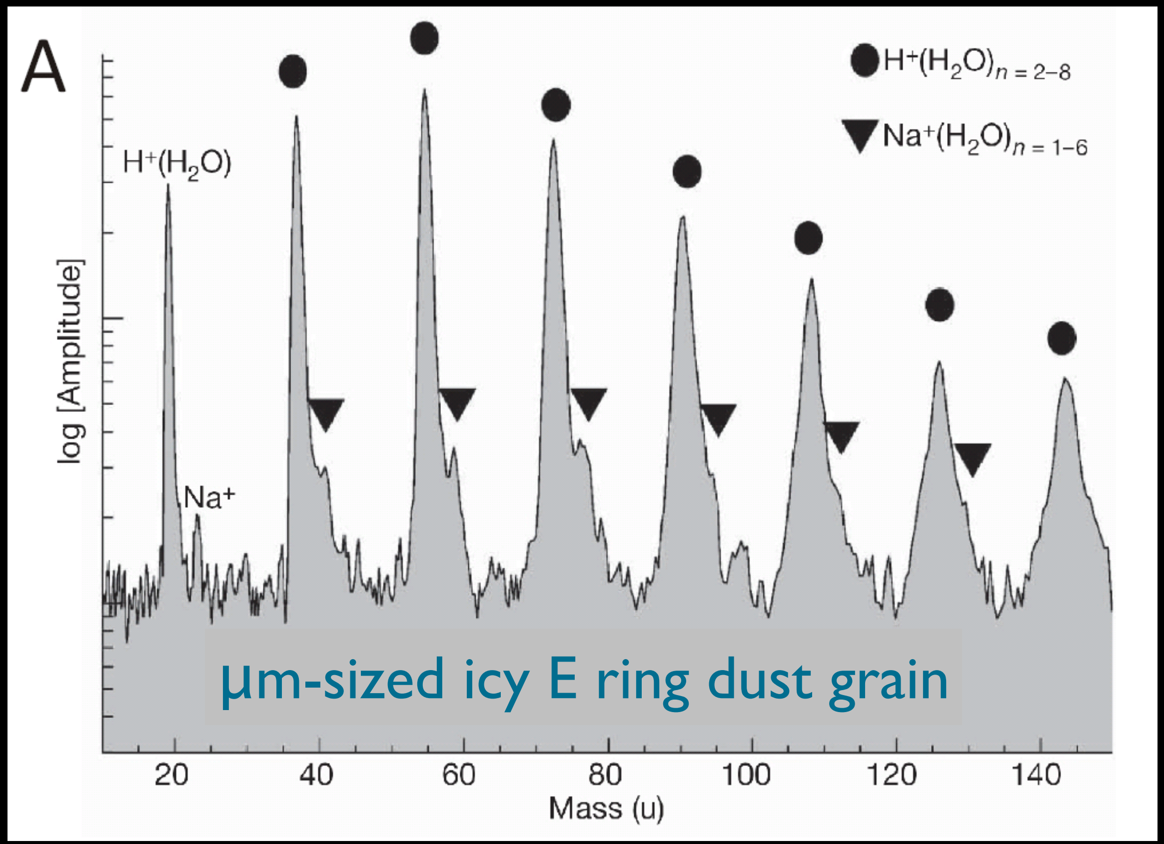
- dense rings (<2.2R_S)
- Enceladus' plume (4 R_S)
- E ring particles (3-20 R_S)



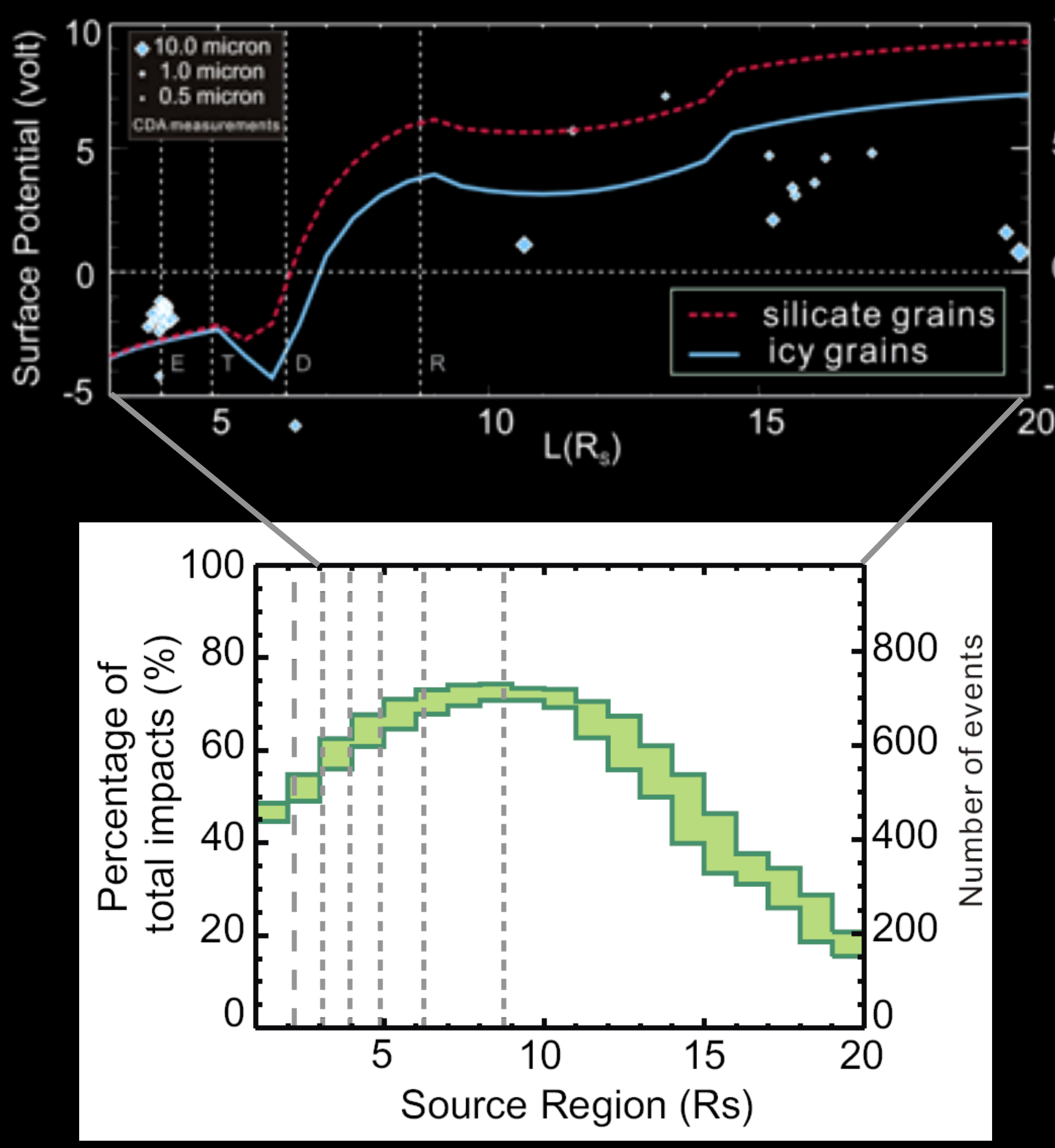
$$\frac{1}{2}m_d v_{ex}^2 = -\frac{GM_S m_d}{2r_0} + \int_{r_0}^{r_{ms}} f_{co} \cdot Q_d \cdot \mathbf{E}_c \, dr.$$

Nano-silica particles from a water-dominant world





Electrostatic Potential of E ring Particles

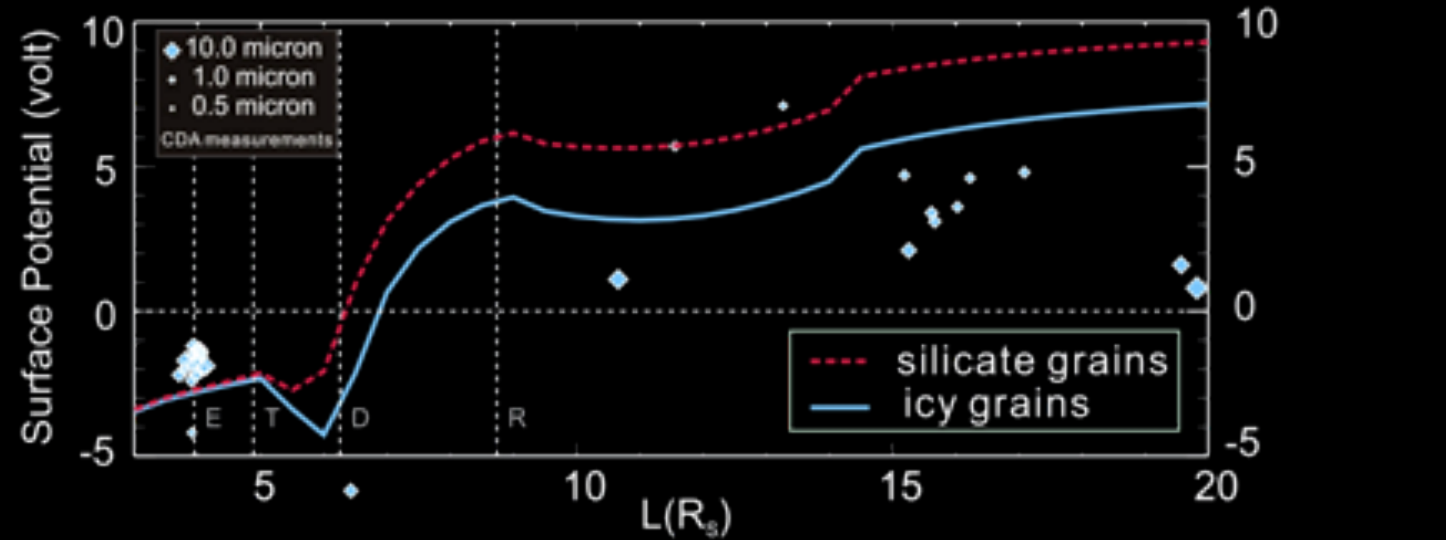


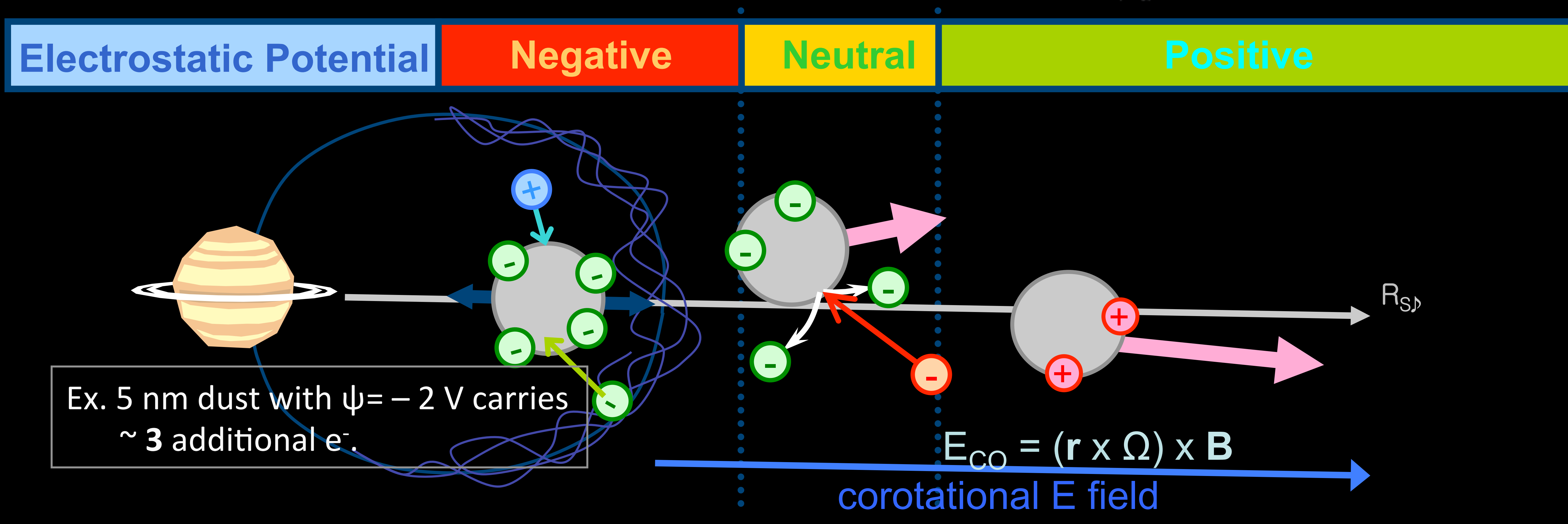
The “Ejection region” and the dust charging

Secondary Electron Yield:

- water ice
  $Y_{max} = 2.3$, $E_{max} = 340$ eV
- SiO_2
  $Y_{max} = 3.9$, $E_{max} = 430$ eV

Electrostatic Potential of E ring Particles





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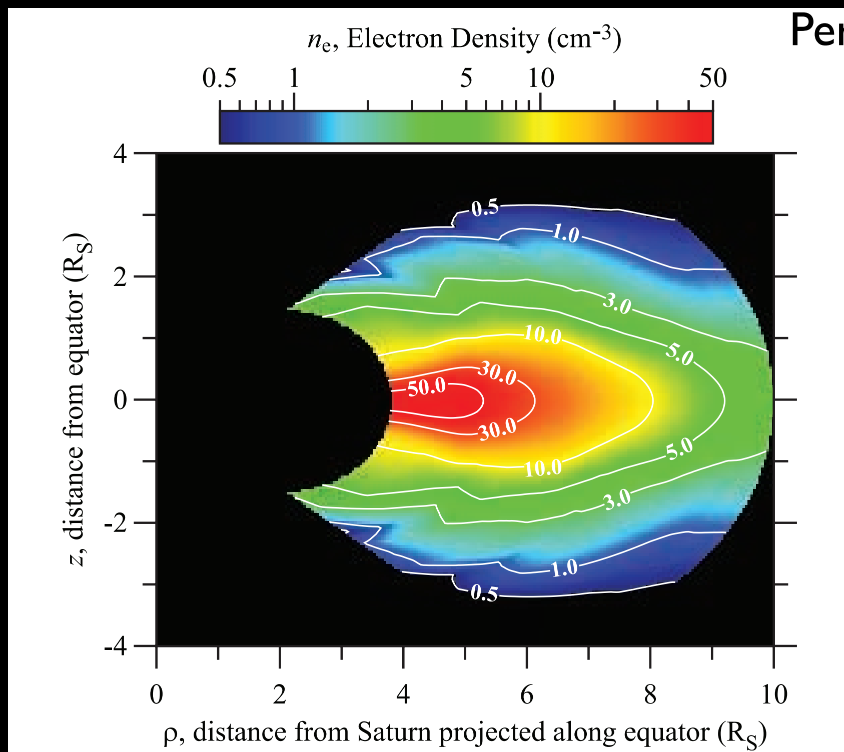
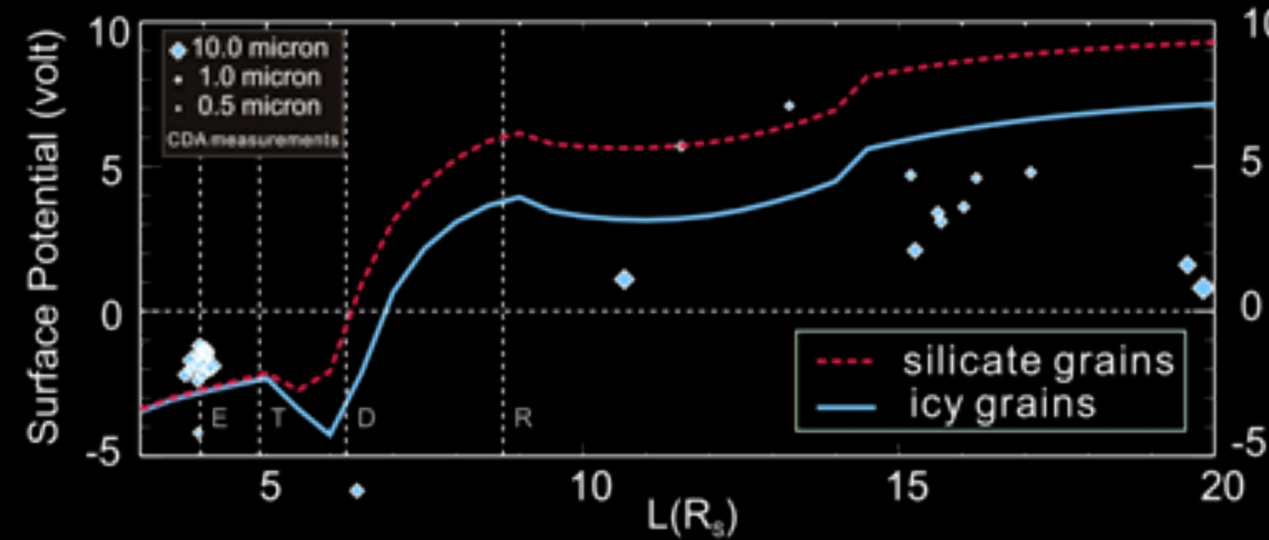
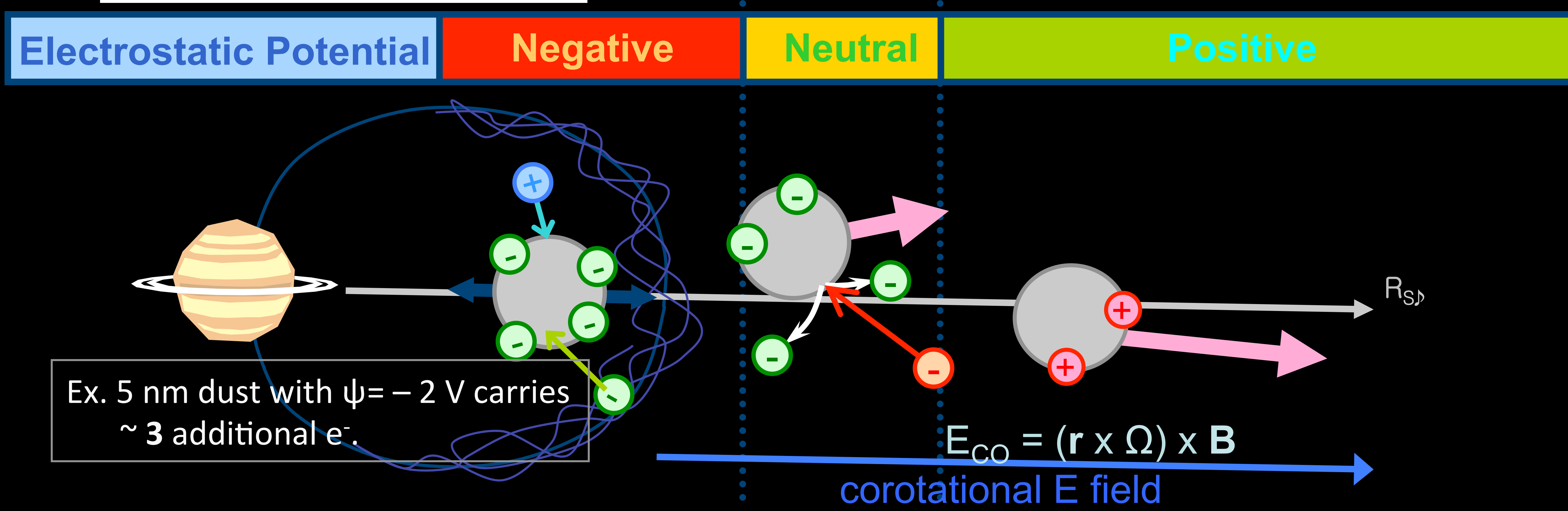


Persoon et al., 2009

Electrostatic Potential of E ring Particles



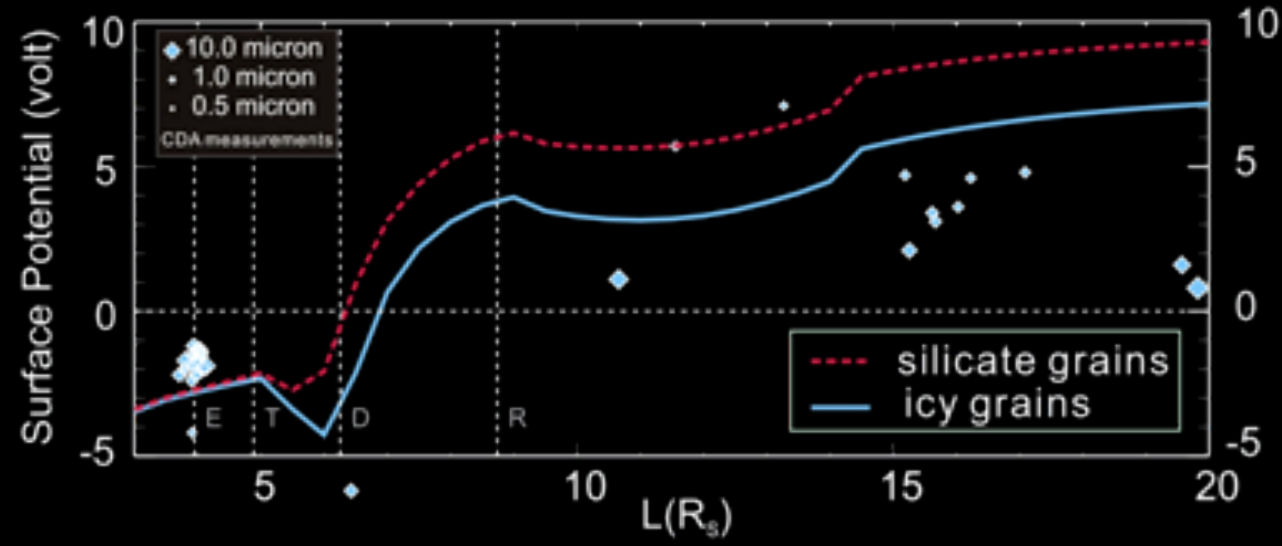


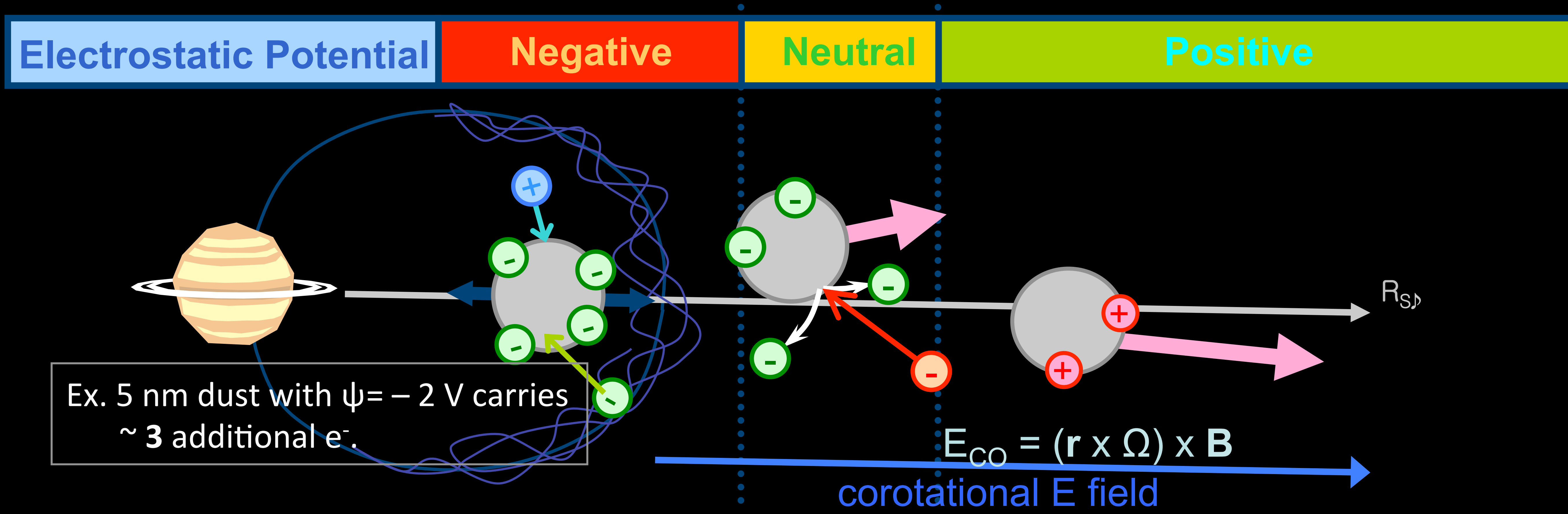
Axial-symmetric Ejection Model

To understand:

- the dynamical evolution of nanoparticles
- the composition discrepancy (water ice vs. SiO_2)
- the source of stream particles

Electrostatic Potential of E ring Particles





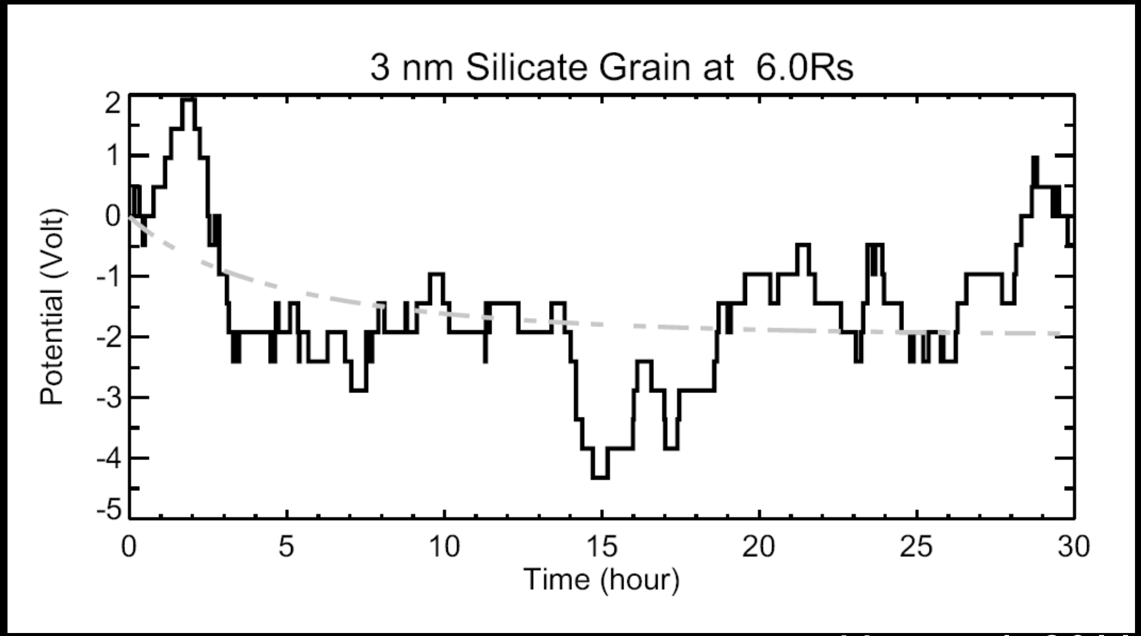
Ex. 5 nm dust with ψ= – 2 V carries ~ **3** additional e^-.

Axial-symmetric Ejection Model

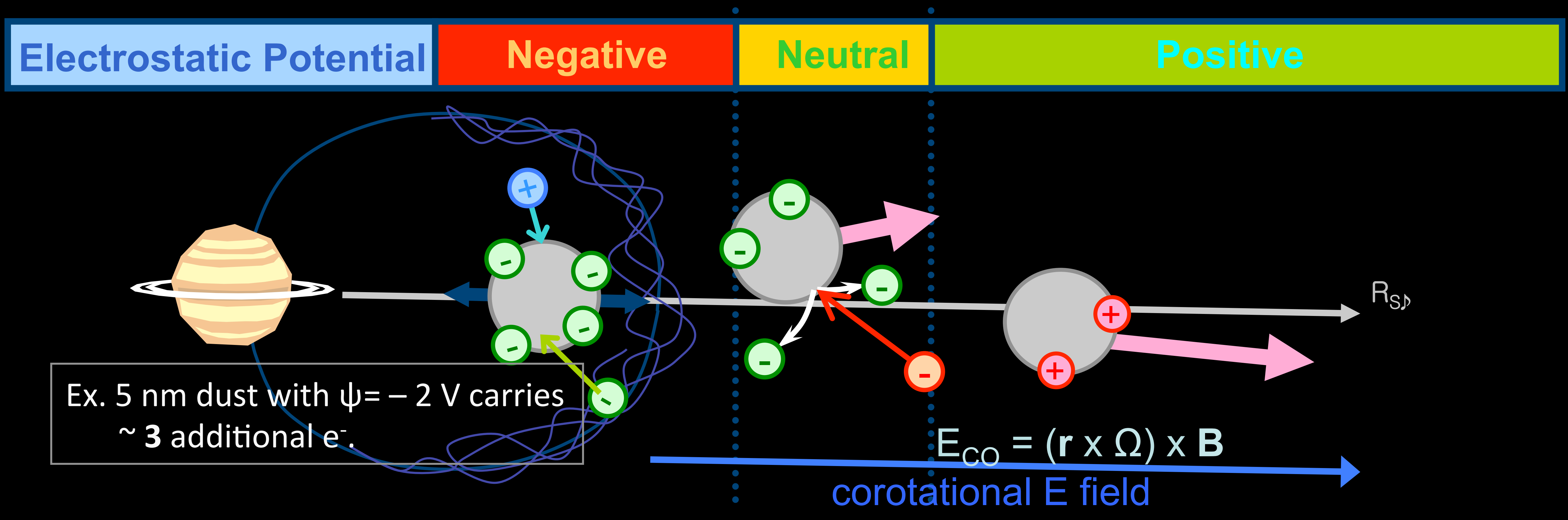
- Describe the charging process by an inhomogeneous Poisson process:

$$P(\lambda_{12},k) = \frac{e^{-\lambda_{12}} \cdot \lambda_{12}^{k}}{k!}, \quad k = 0,1,2,\ldots$$

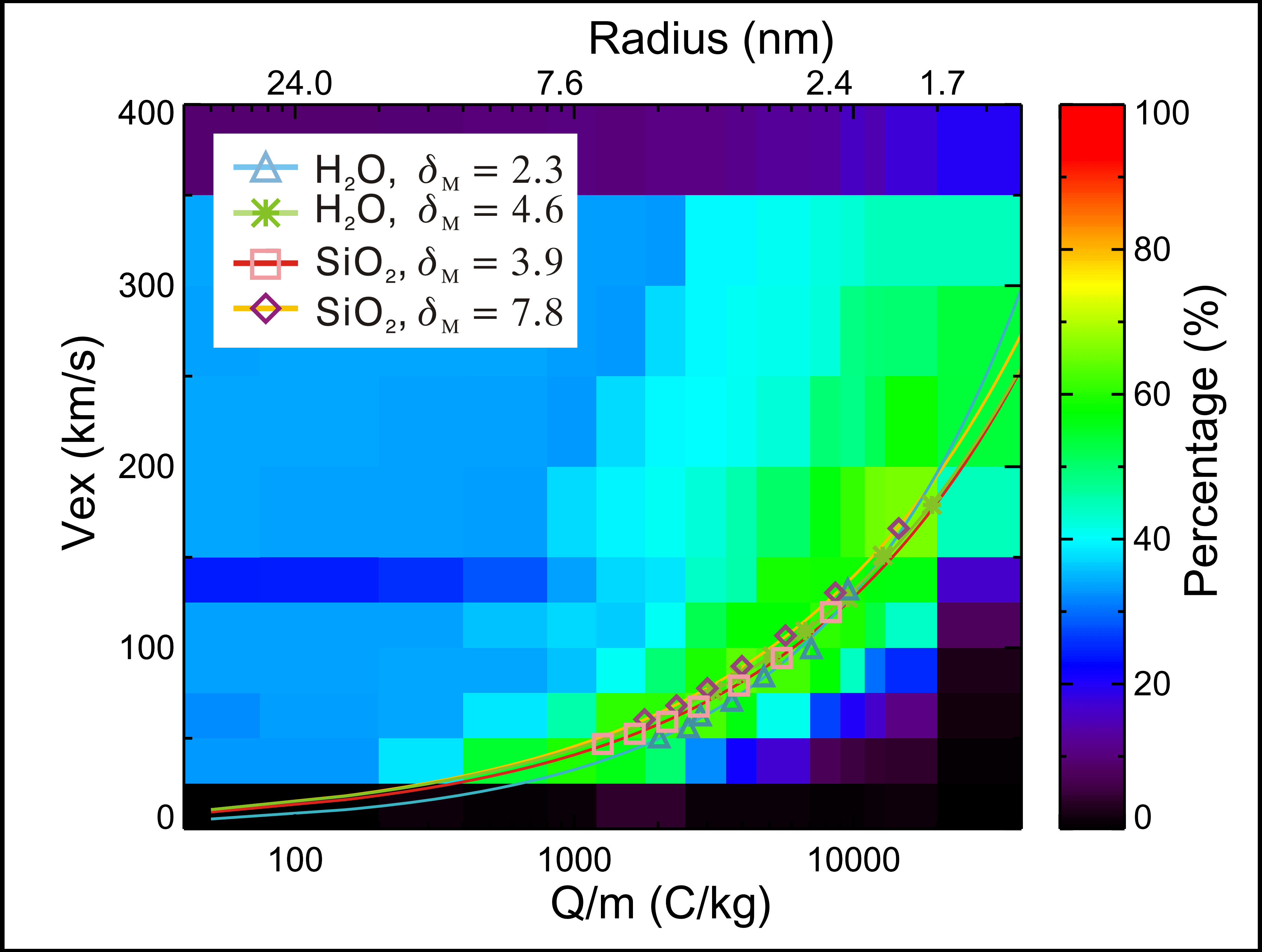
λ12: expected event rate
k: number of events



Hsu et al., 2011



Ejection Model Results

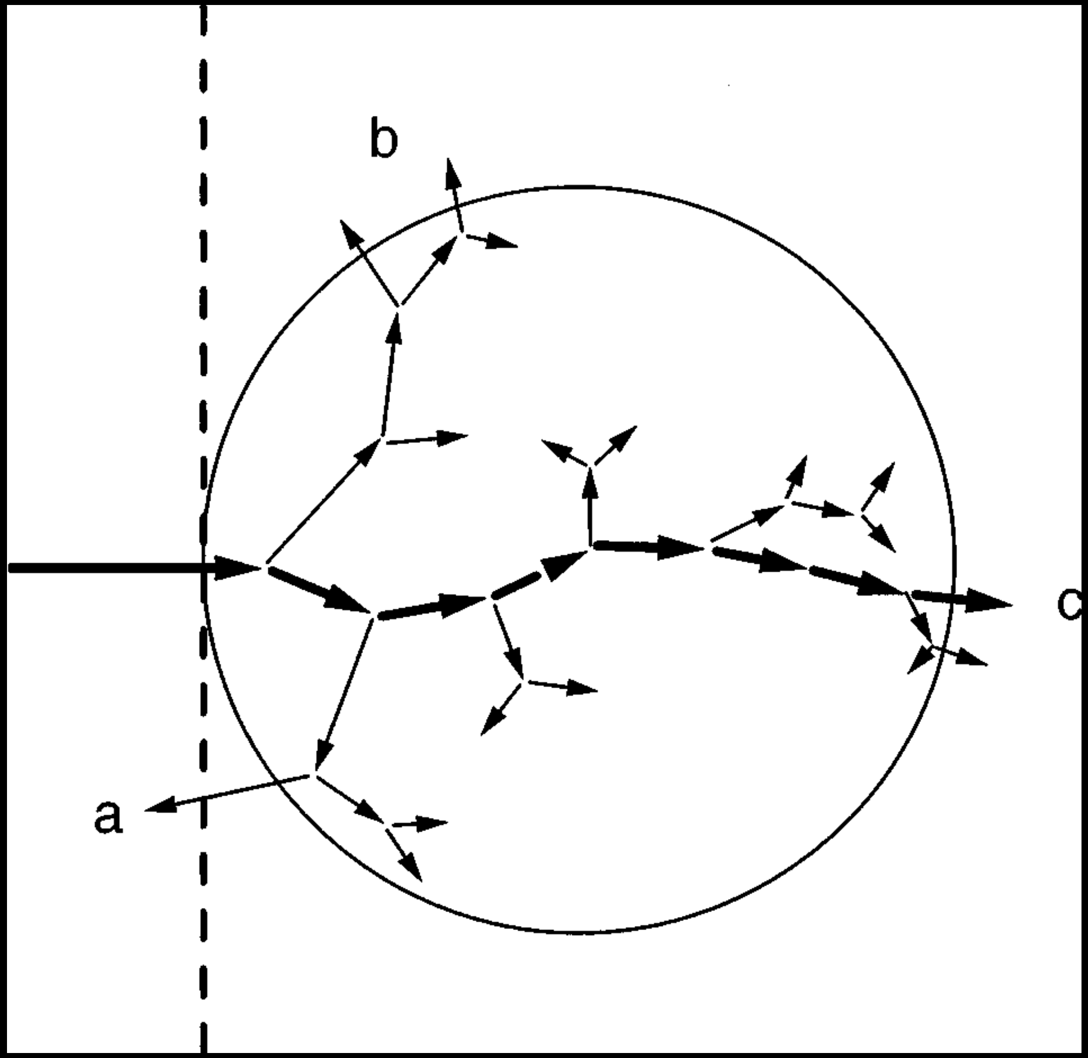


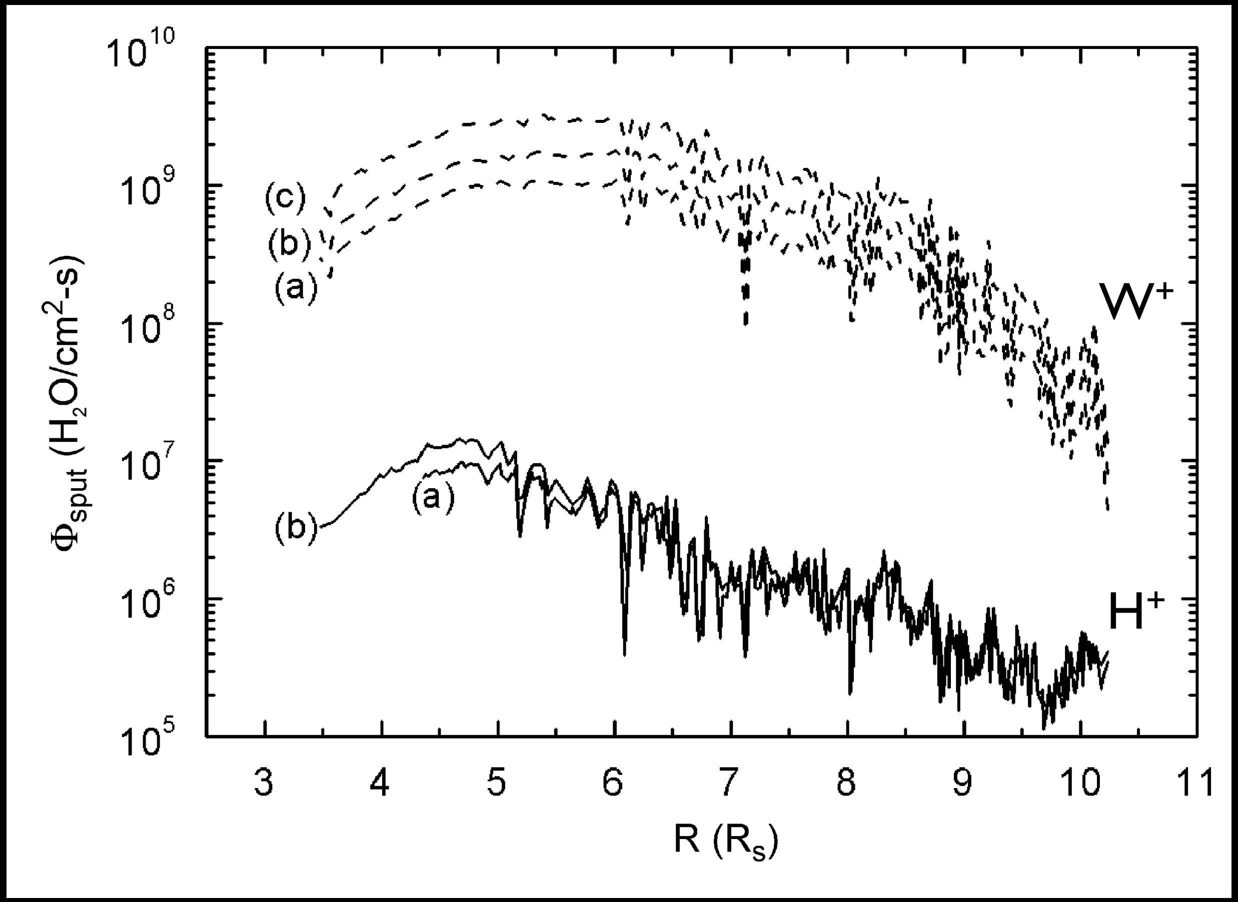
Hsu et al., 2011

Contour: **Backward tracing** - *Solar wind measurements*

Symbols & lines: **Ejection model** - *Magnetosphere plasma measurements*

Plasma sputtering erosion of icy grains



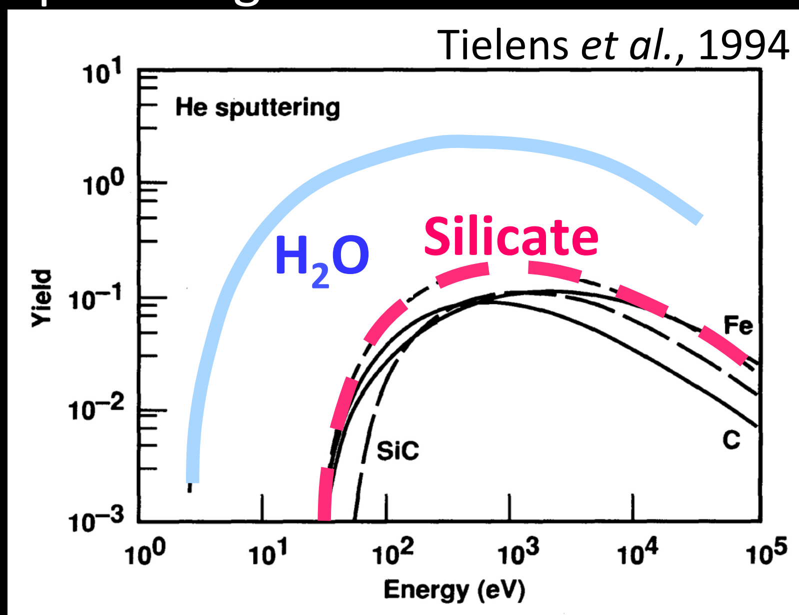


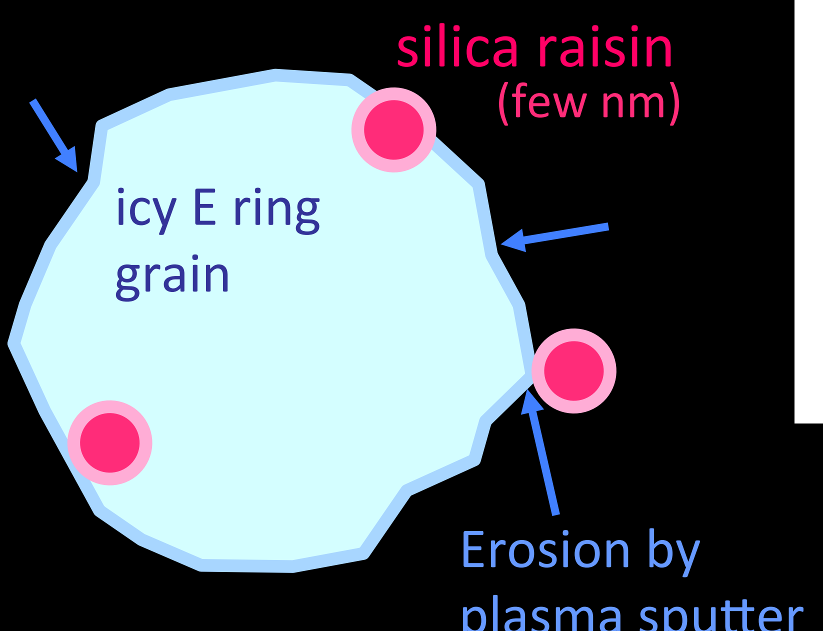
Jurac et al., 2001 show that, sputtering erosion is a major loss mechanism of Saturn's E ring. The lifetime of an 1µm E ring grain is ~50yrs.

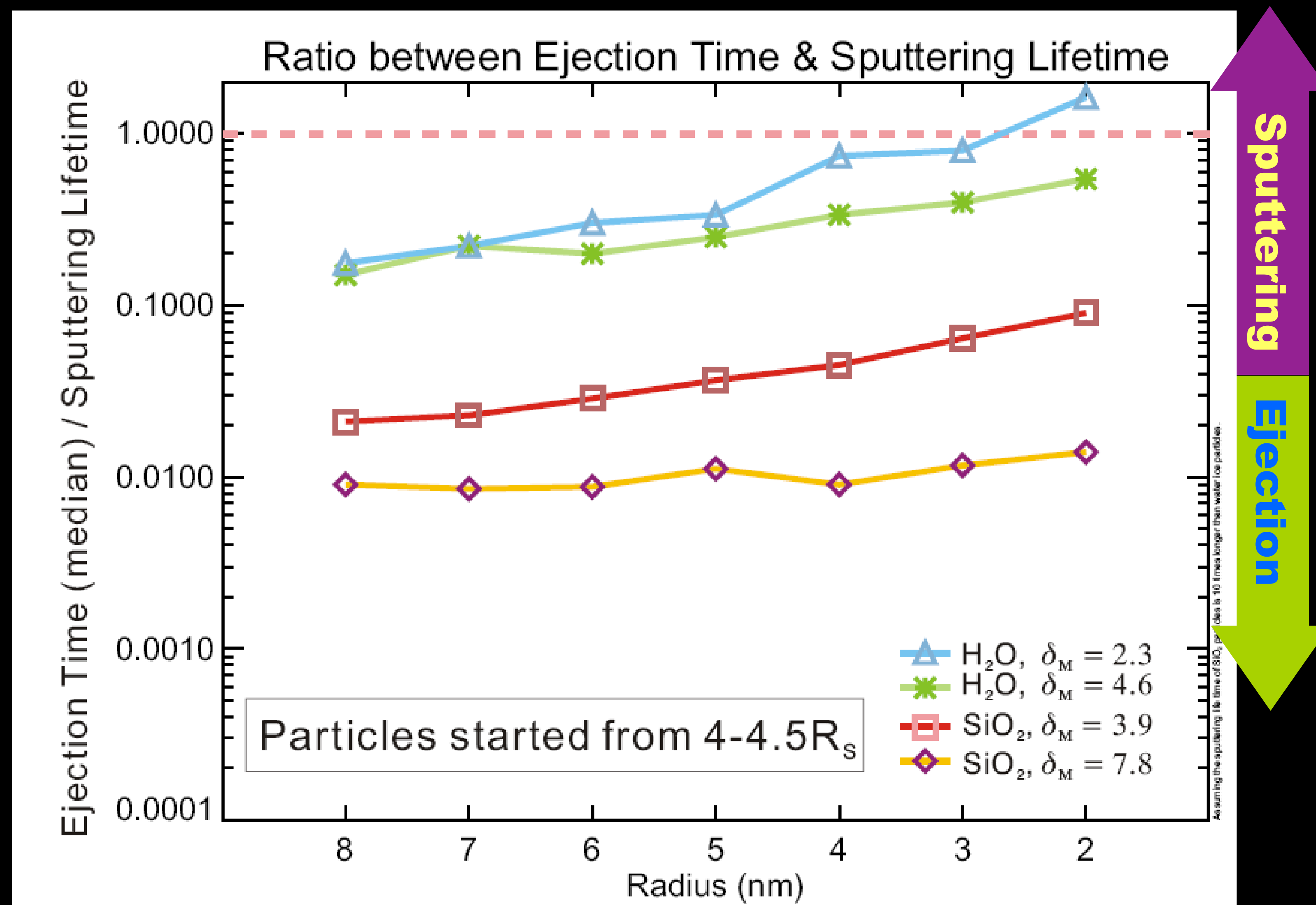
Based on Cassini water group ion measurements, Johnson et al., 2008 show that the sputtering erosion peaks at about 5-6 Rs.

Taking Plasma Sputtering into account…

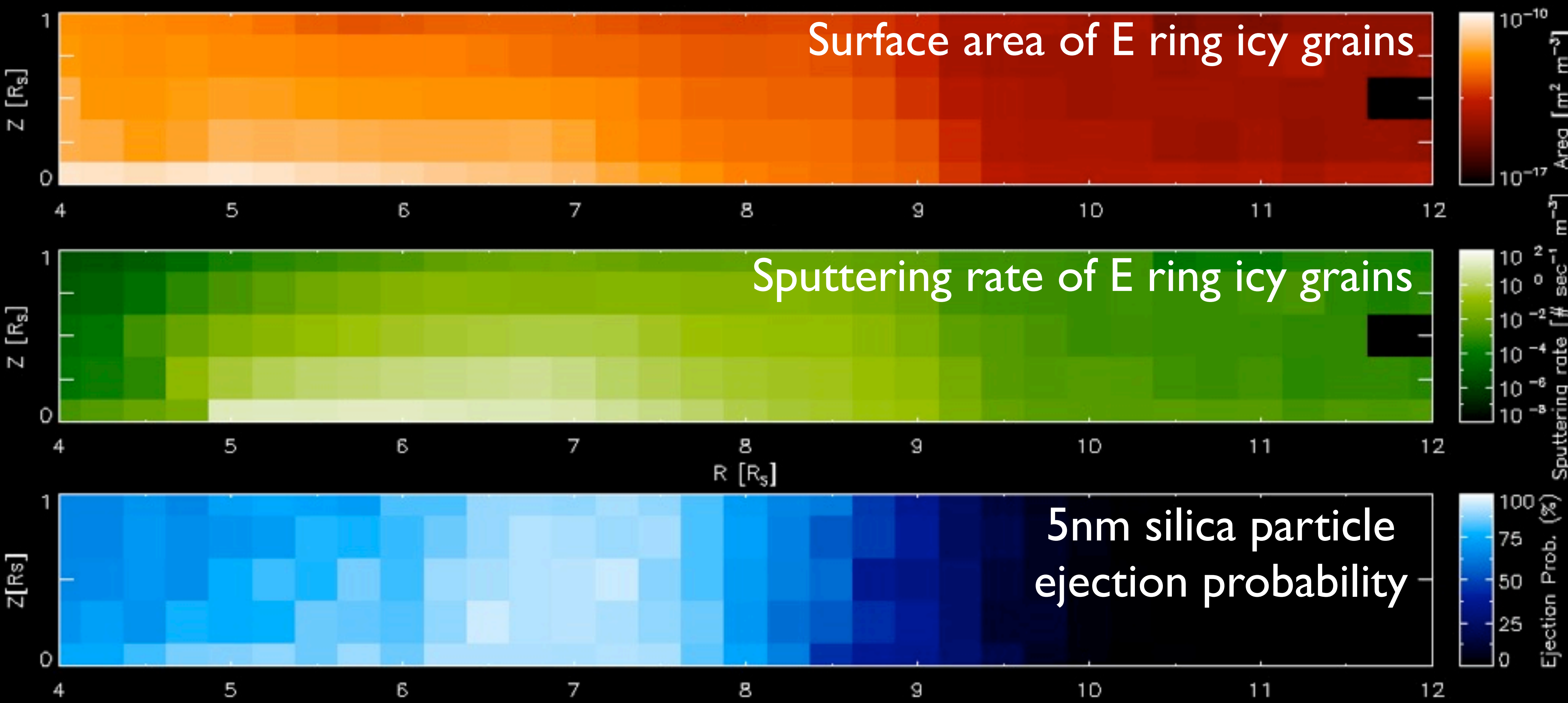
Sputtering Yield







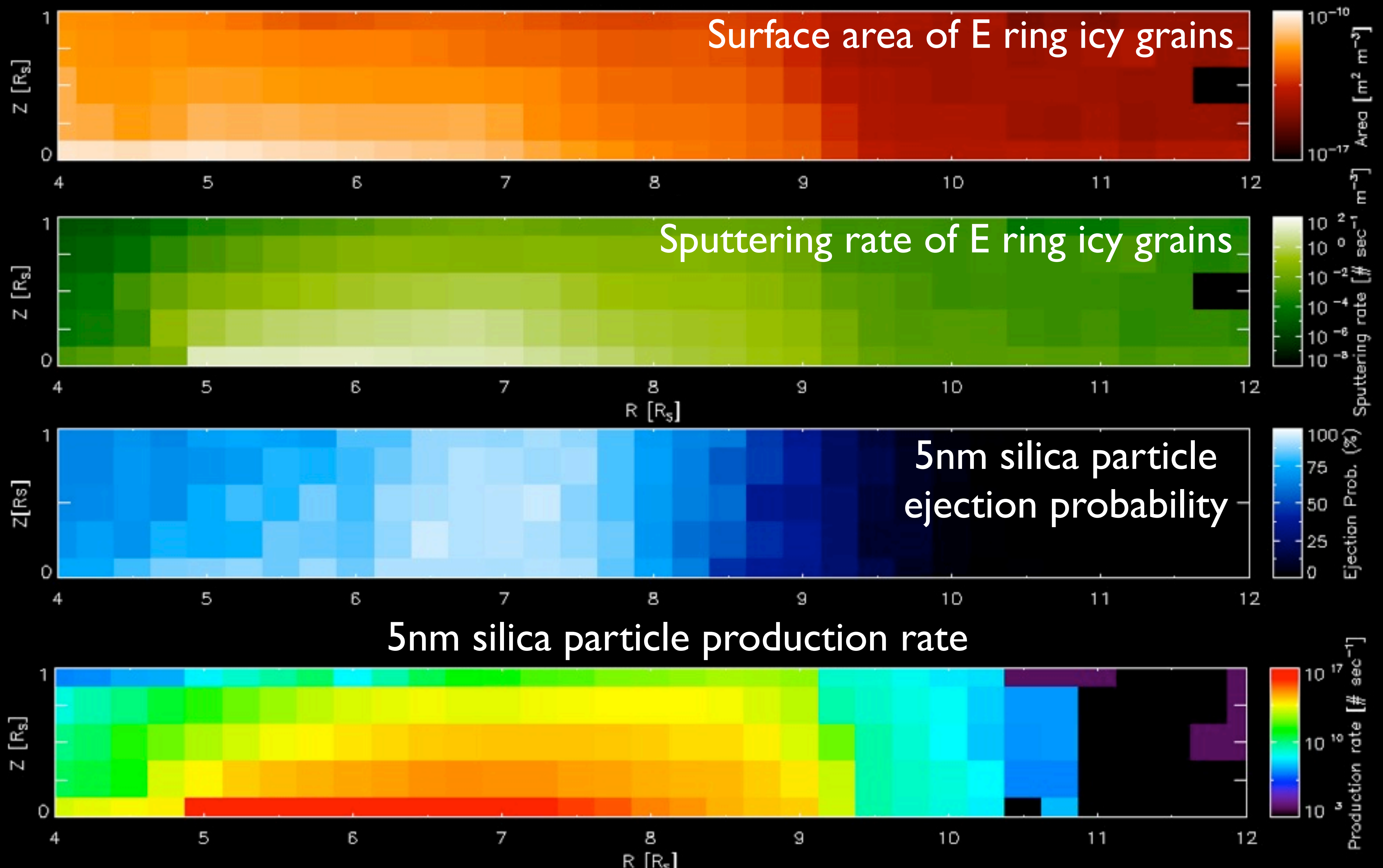
Stream particle production model



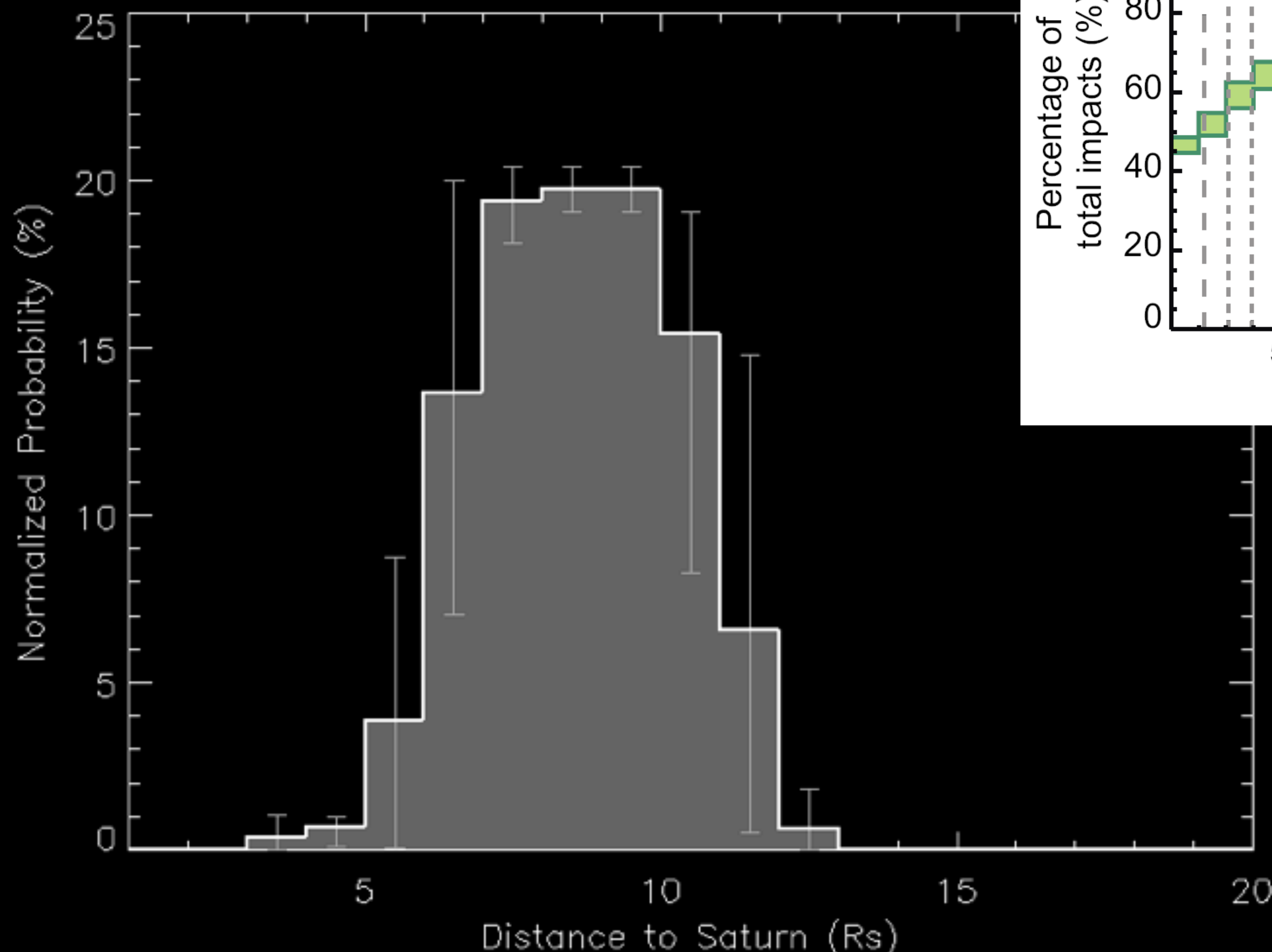
$$\dot{m} = Y_{sput}(r,z) \cdot Area(a_E, r, z) \cdot m_{H_2O}$$

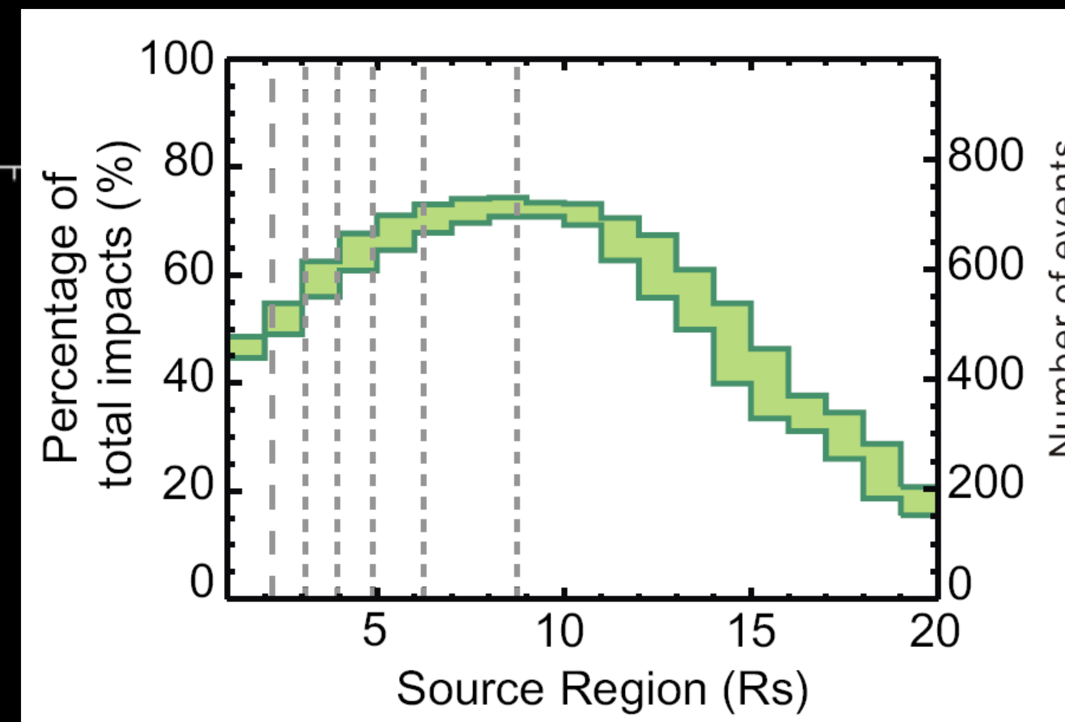
$$N_{ej}(a_{sp}) = \dot{m}(r,z) \cdot f_{SiO_2} \cdot P_{ej}(a_{sp}, r, z) \cdot P_m(a_{sp}) / m_{sp}(a_{sp})$$

Stream particle production model



Dynamical fingerprints of stream particles - ejection region

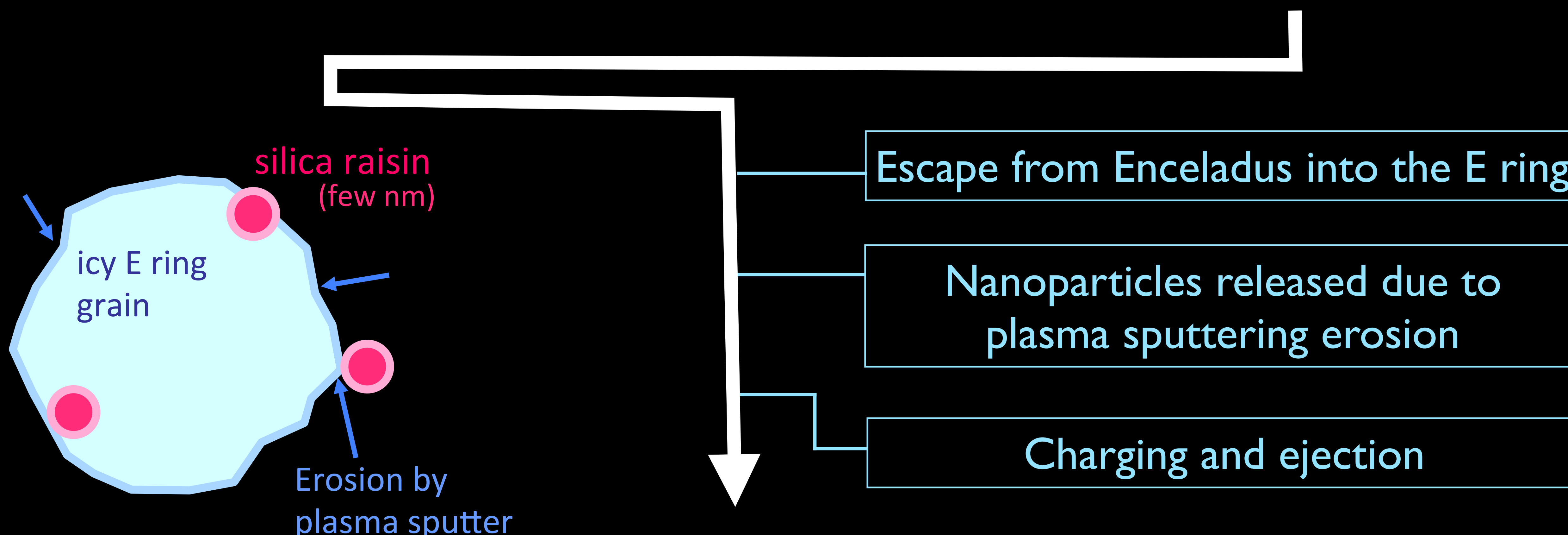




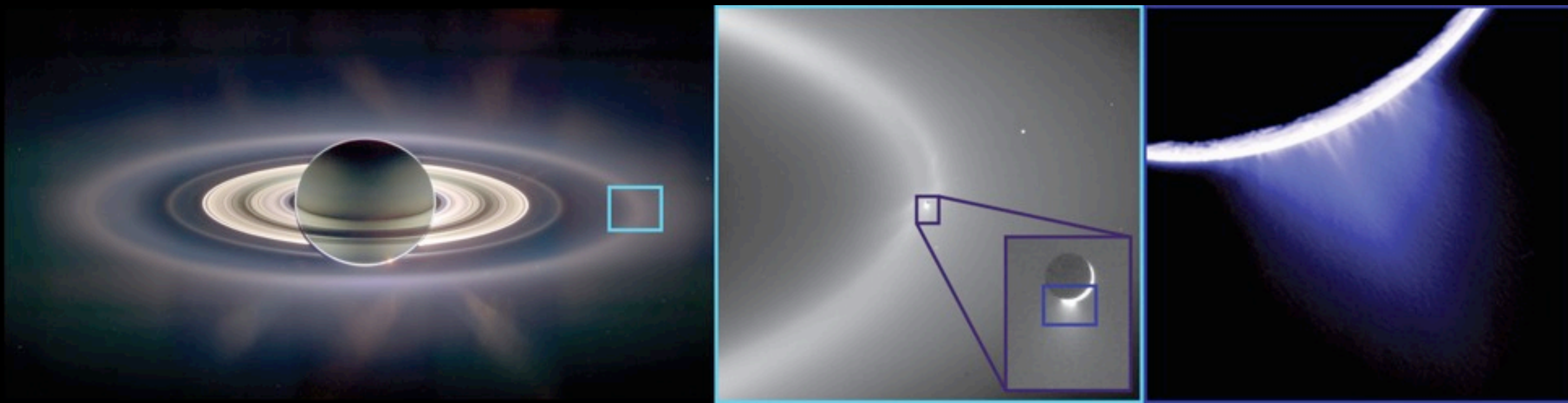
The source of non-water ice stream particles

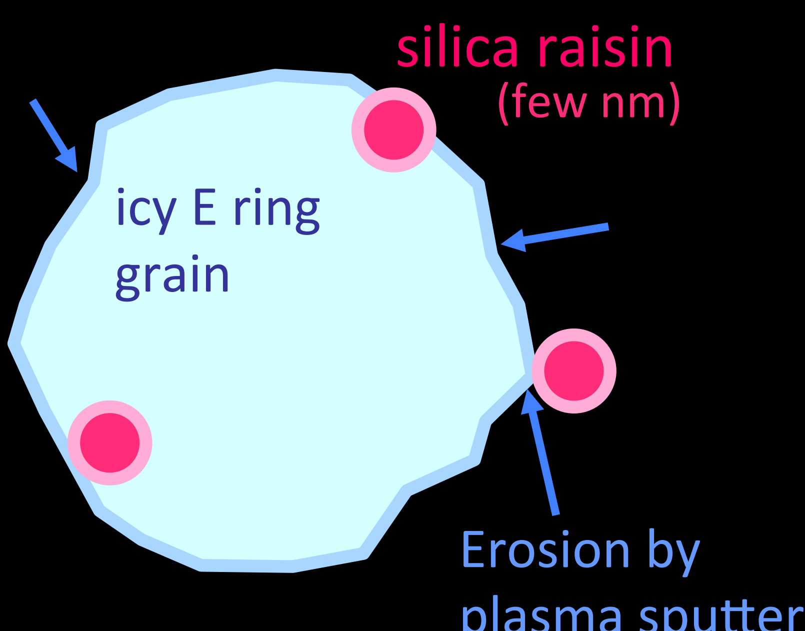
Origin:

- ~~Nanoparticles detected by CAPS in the plume~~ (Jones et al., 2009)
- ~~Dense rings~~
- E ring grains



The source of non-water ice stream particles



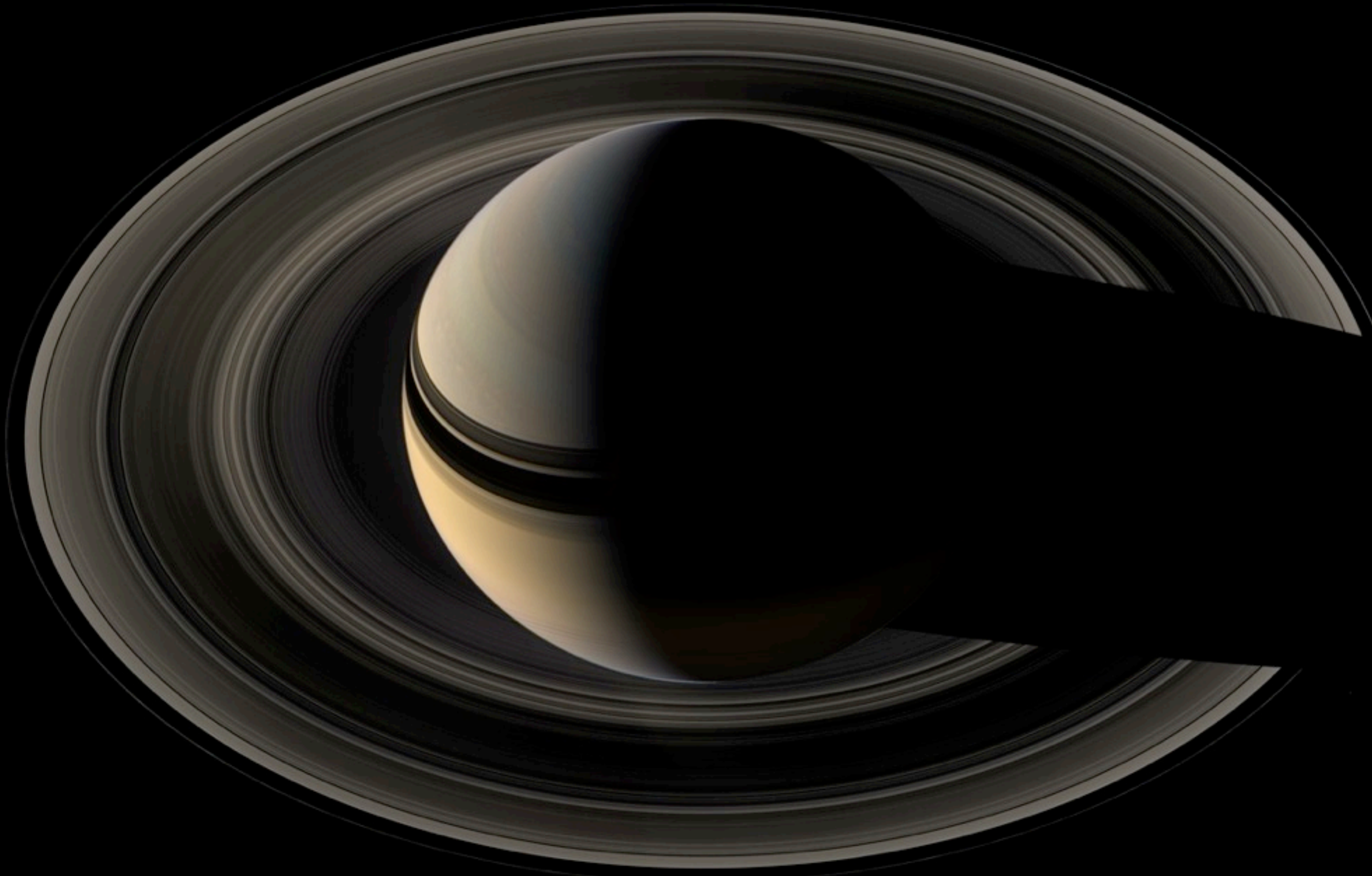


Escape from Enceladus into the E ring

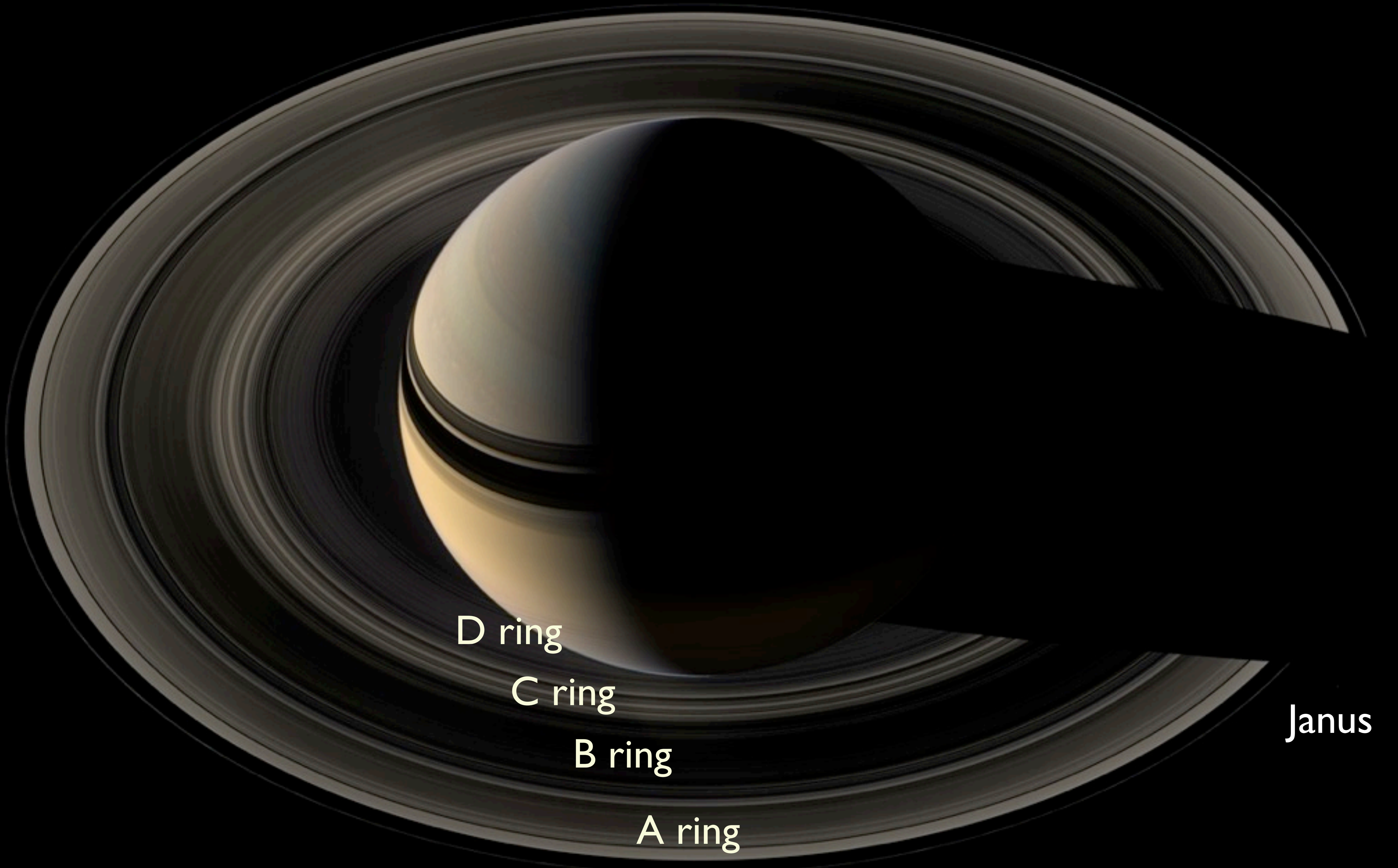
Nanoparticles released due to plasma sputtering erosion

Charging and ejection

Modeling main ring impact ejecta



Modeling main ring impact ejecta



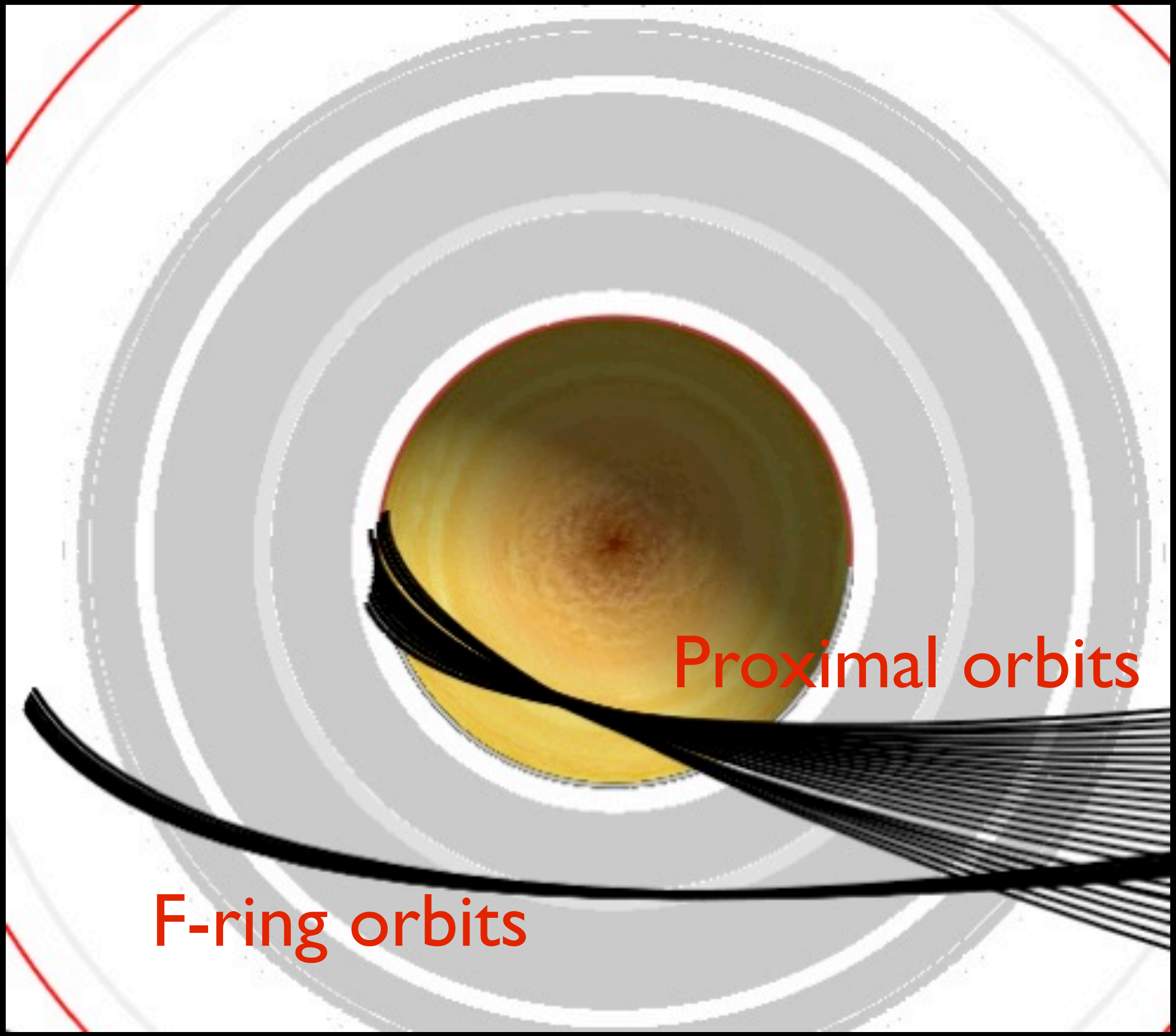
F-ring & Proximal Orbits

- **F-ring orbits**
  2016-Nov - 2017-Apr
  [V_{sc}, V_{kep}, V_{co}] = 21, 16, 25 km/s

- **Proximal orbits**
  2017-Apr - 2017-Sep
  [V_{sc}, V_{kep}, V_{co}] = 34, 25, 10 km/s

- **Summer Solstice**
  2017-Mar-24

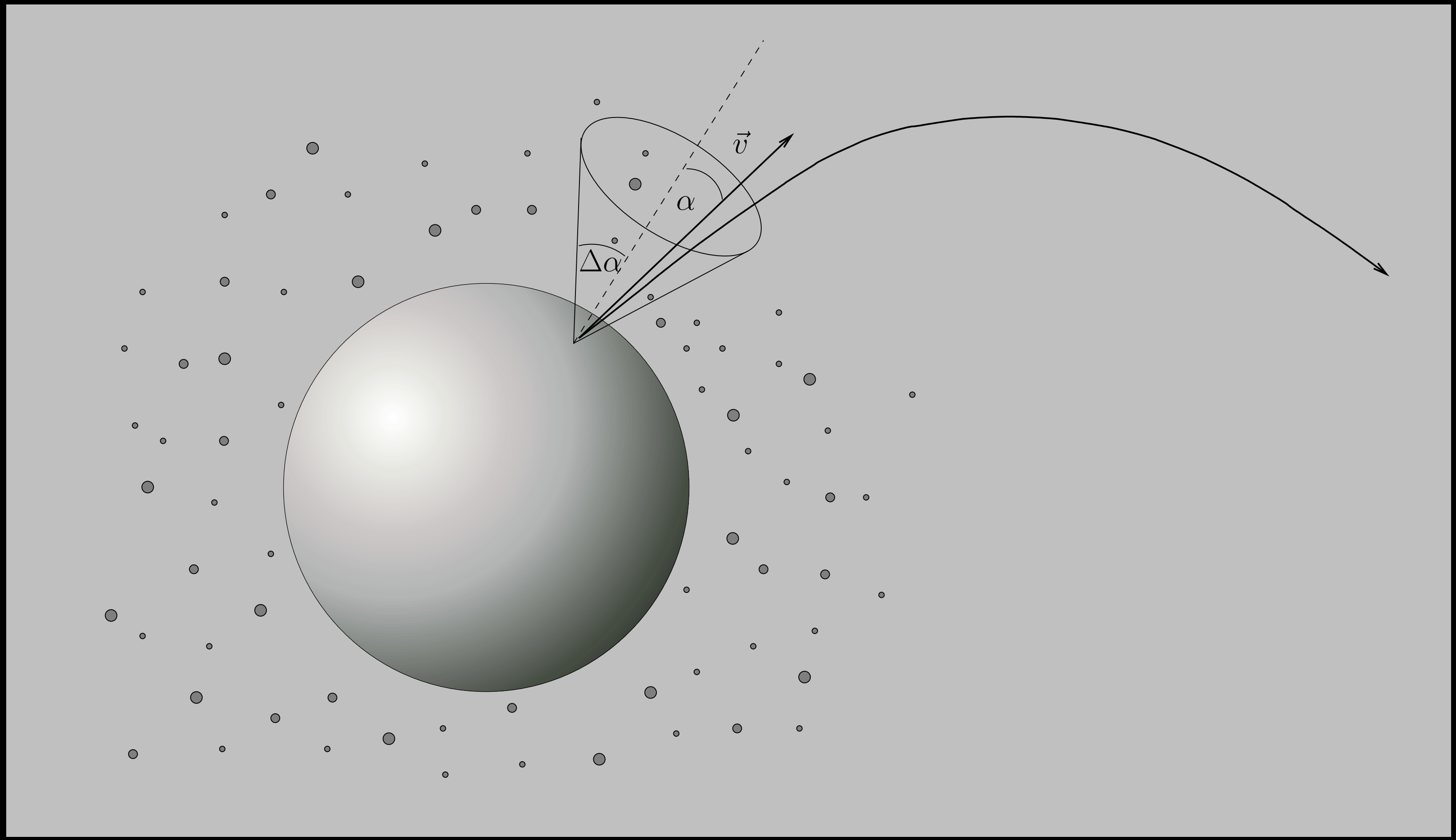
- **Orbit inclination ~ 60°**



http://www.planetary.org/

CDA F-ring/Proximal orbit

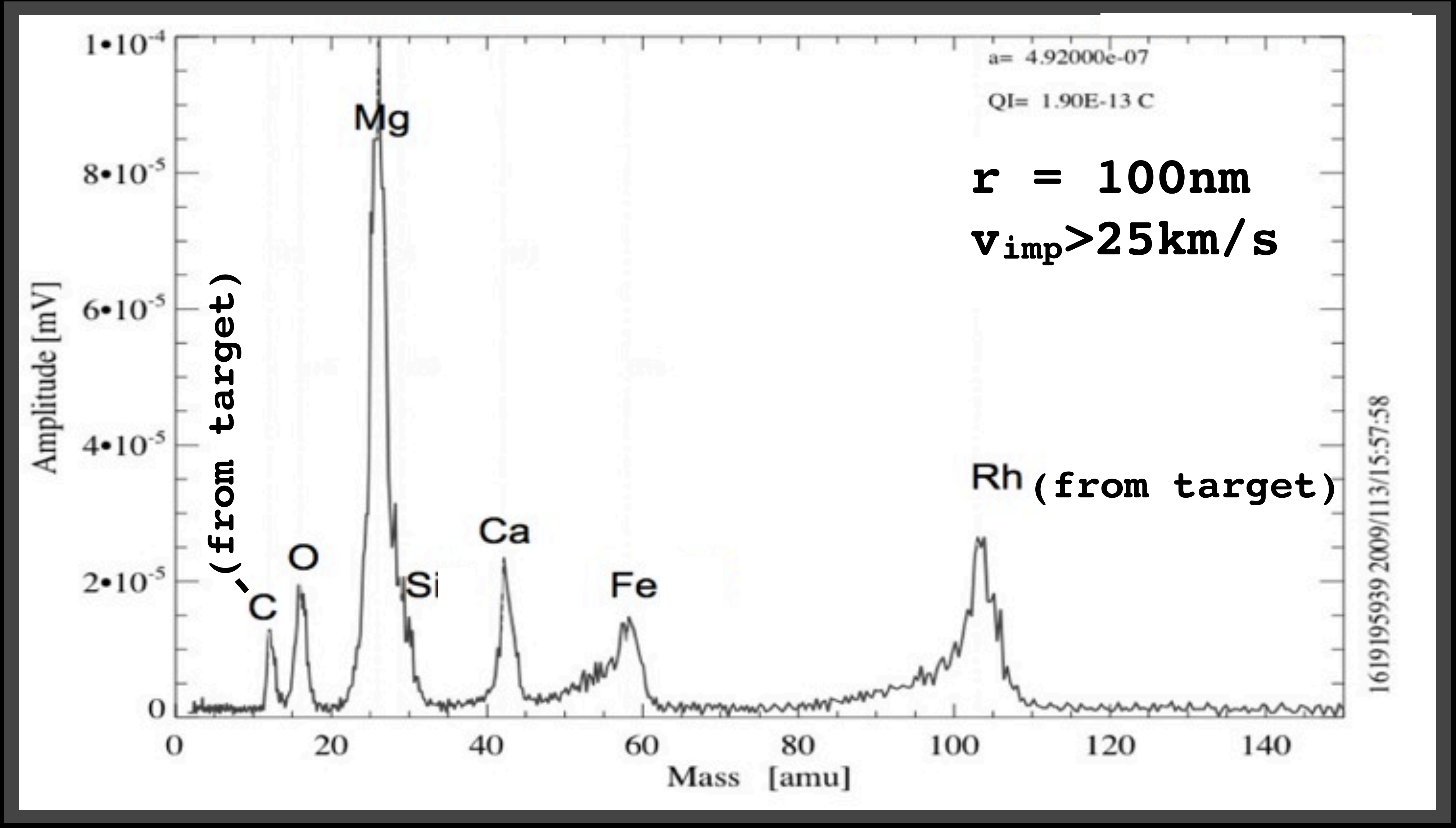
- in situ ring composition measurements & composition mapping <silicates, Tholins, PAHs, nano-hematite>
- Impactor-ejecta process: lofted ejecta produced from impacts between exposed surface and exogenic particles.



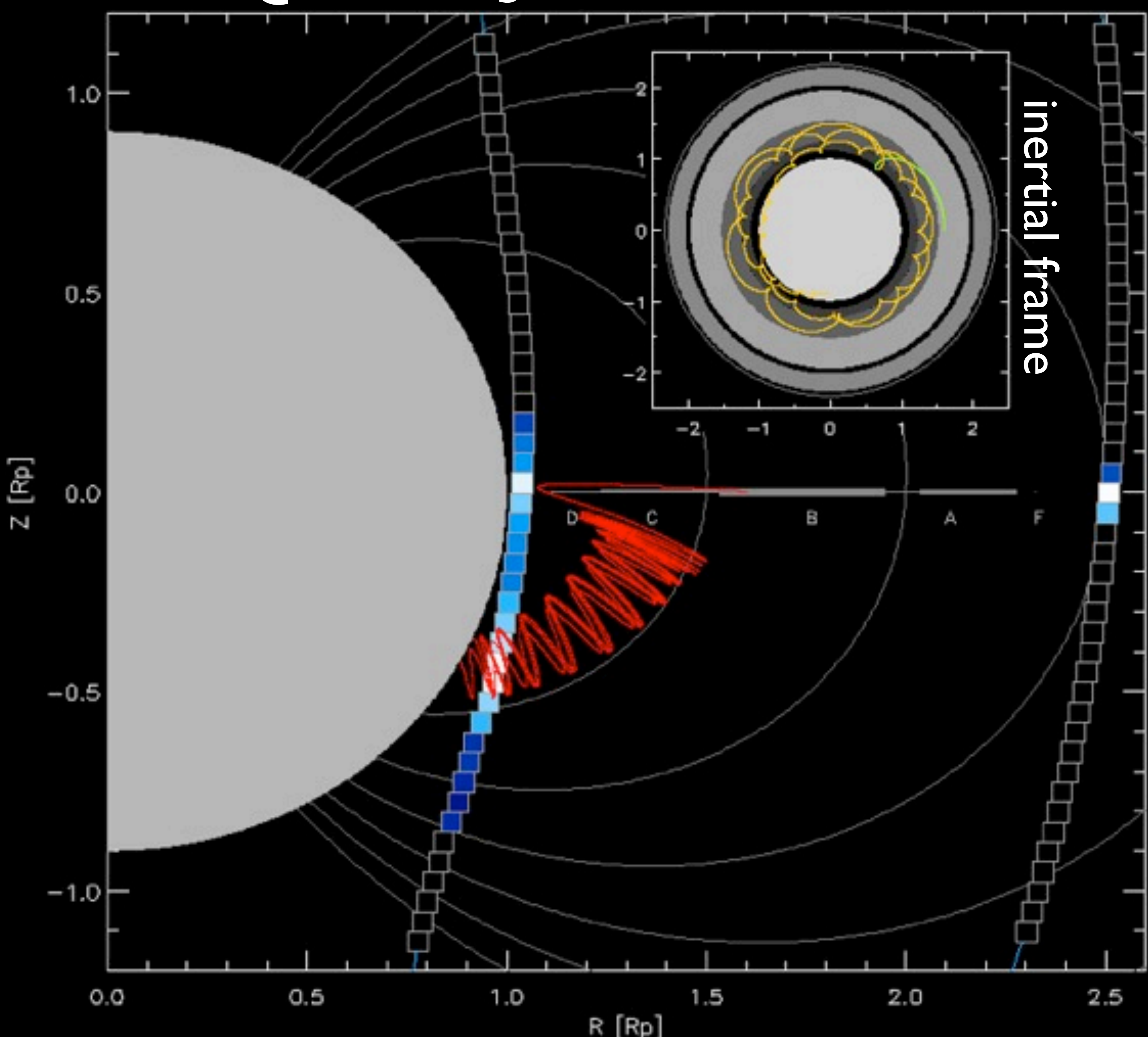
CDA F-ring/Proximal orbit

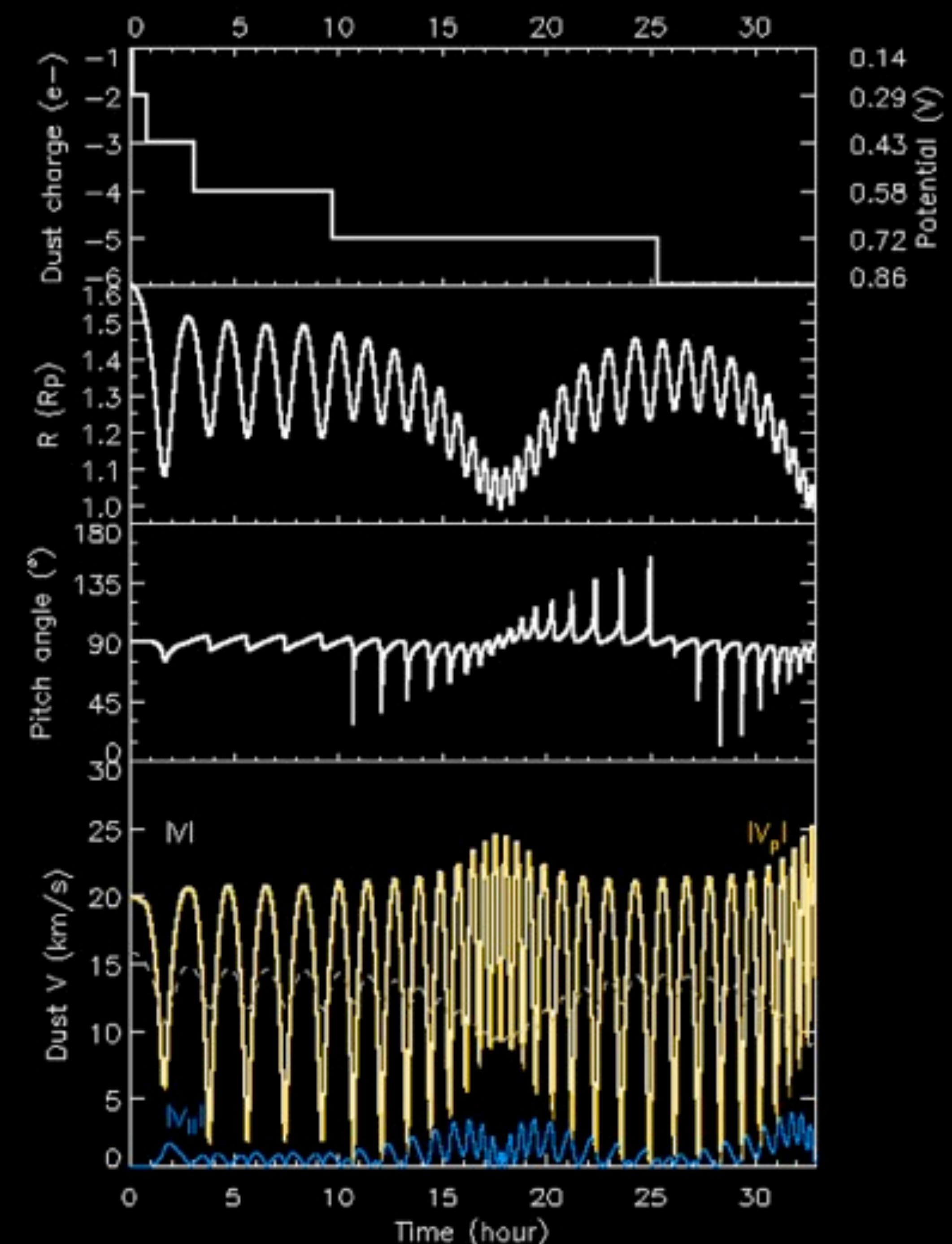
- in situ ring composition measurements & composition mapping <silicates, Tholins, PAHs, nano-hematite>

100 nm grain registered in the Saturnian system

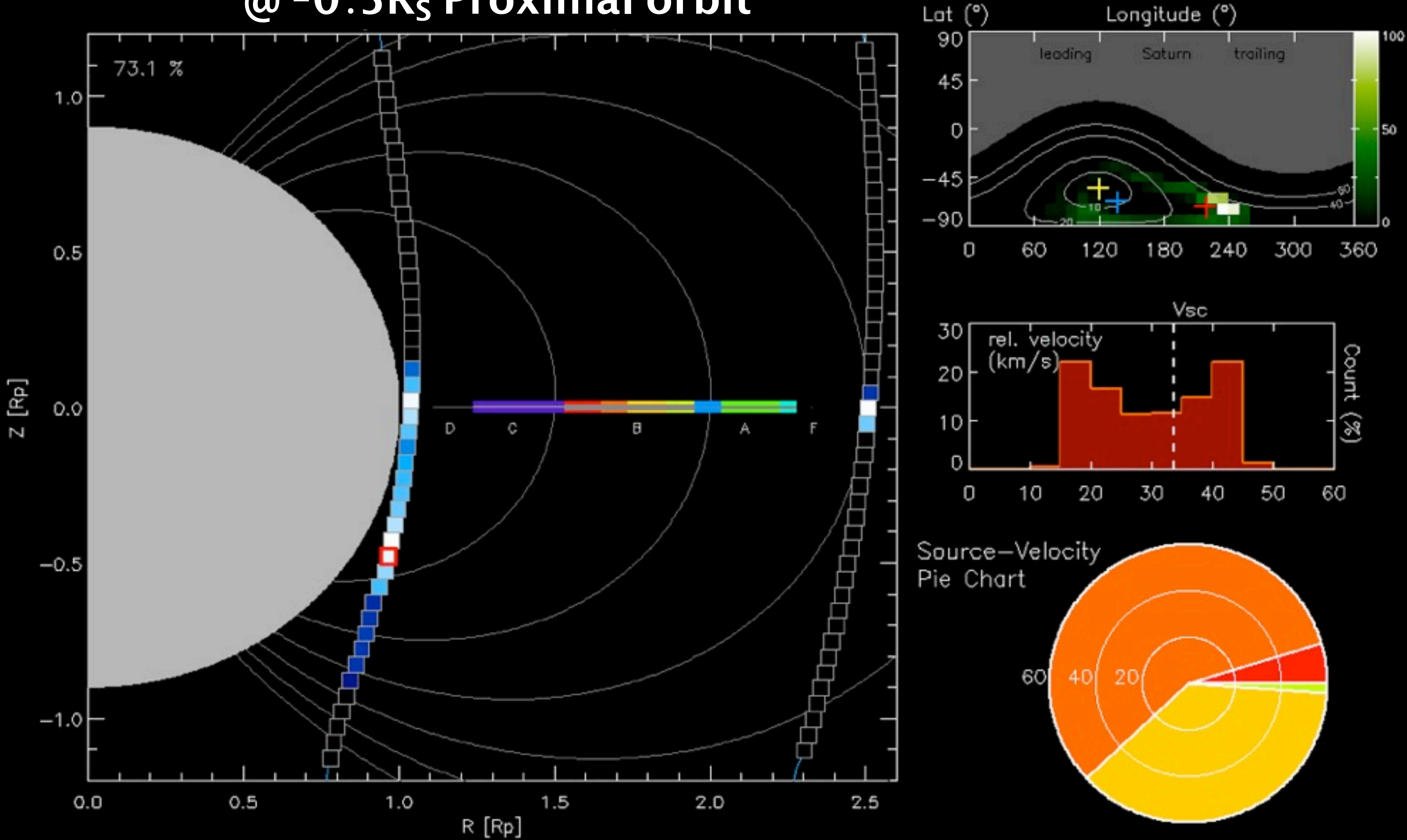


10 nm, v_{ej} = 50m/s – falling to Saturn @ –0.5R_S Proximal orbit





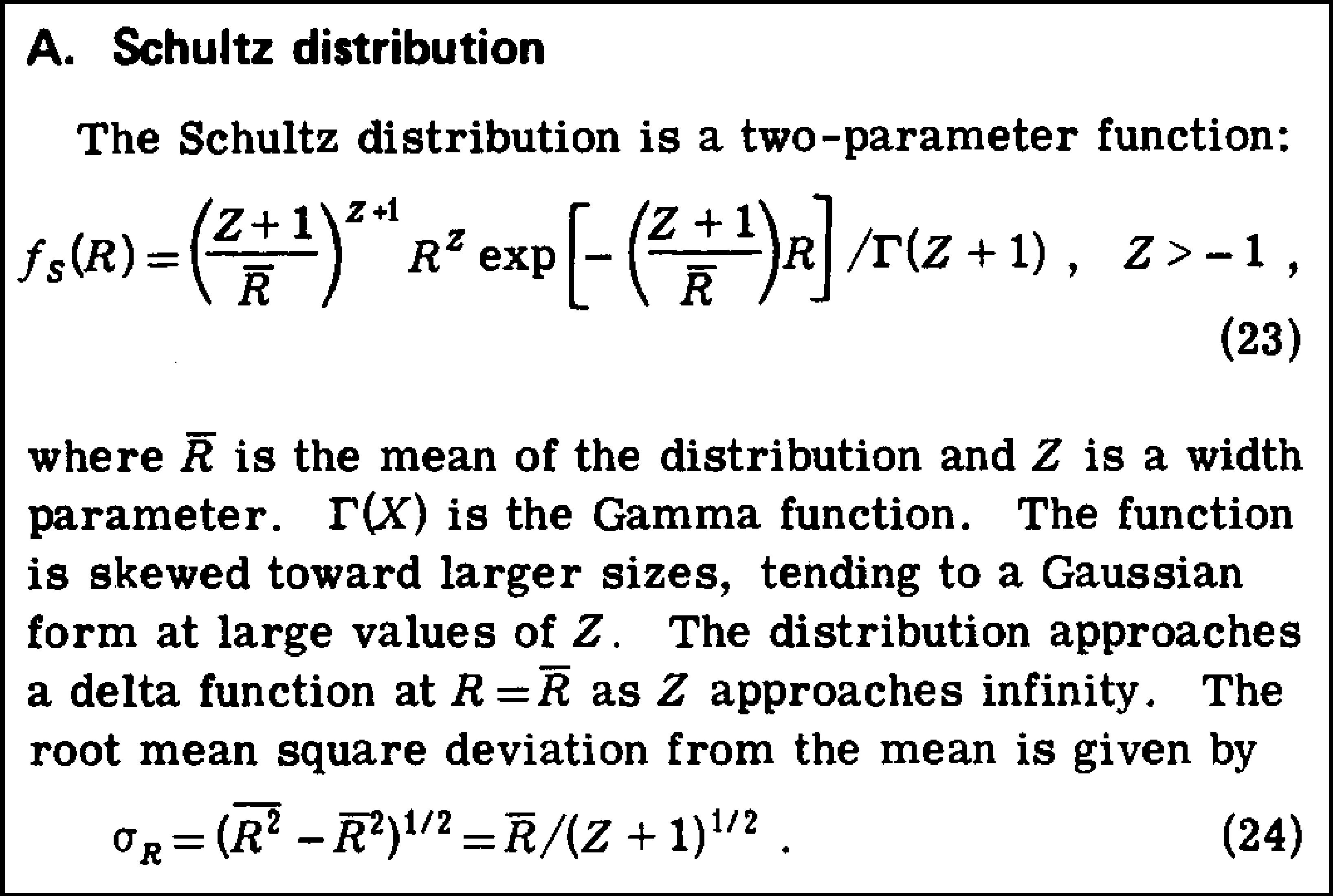
10 nm, v_{ej} = 5-100m/s @ -0.5R_S Proximal orbit



Summary

- Knowledge on dust dynamics allows us to use in situ dust measurements as remote sensing tools to study planetary systems.
- Various processes that shape the E ring indicate Saturnian stream particles are of E ring / Enceladus origin - information on the Enceladus.
- Modeling the dynamics of impact ejecta from the main rings provides the key element for the ring composition mapping.

Assumed colloid size distribution



A. Schultz distribution

The Schultz distribution is a two-parameter function:

$$f_S(R) = \left(\frac{Z+1}{\overline{R}}\right)^{Z+1} R^Z \exp\left[-\left(\frac{Z+1}{\overline{R}}\right)R\right] / \Gamma(Z+1) \ , \quad Z > -1 \ , \tag{23}$$

where $\overline{R}$ is the mean of the distribution and Z is a width parameter. $\Gamma(X)$ is the Gamma function. The function is skewed toward larger sizes, tending to a Gaussian form at large values of Z. The distribution approaches a delta function at $R = \overline{R}$ as Z approaches infinity. The root mean square deviation from the mean is given by

$$\sigma_R = (\overline{R^2} - \overline{R}^2)^{1/2} = \overline{R}/(Z+1)^{1/2} \ . \tag{24}$$

Kotlarchyk & Chen, JCP, 1983

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