Ion energy distribution and density in the Enceladus plume

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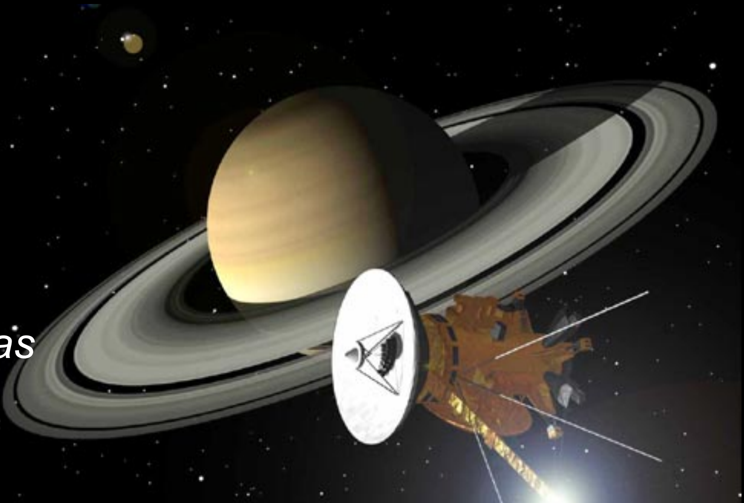
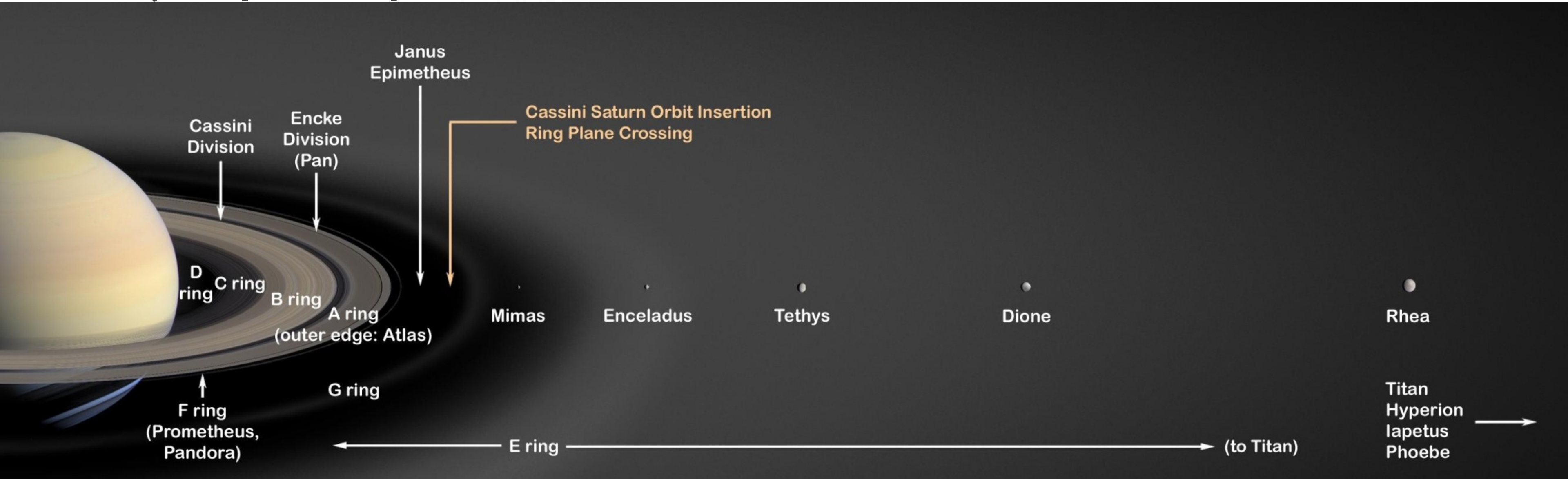


Saturn's system

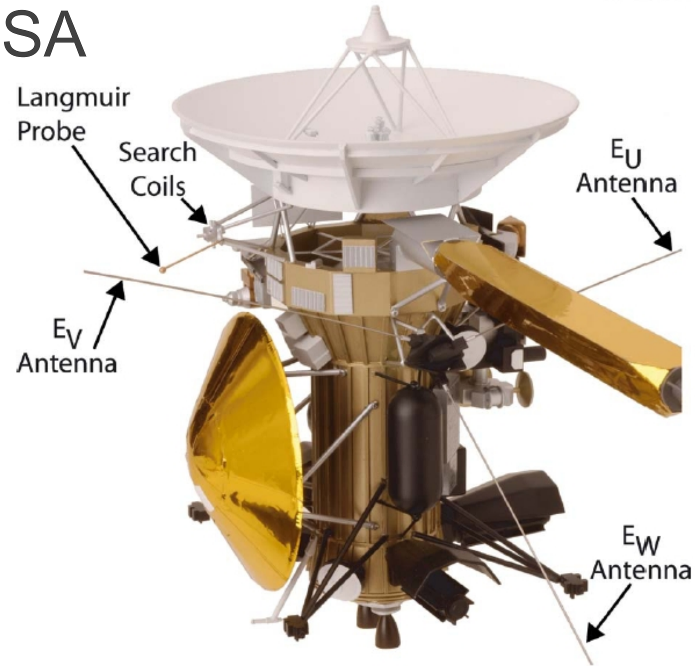
- Beautiful Rings
  - D, C, B, A, F, G and E rings from inside
- Many Satellites
  - 64 satellites
  - Titan, Enceladus, Mimas, Tethys, Dione, Rhea, Hyperion, Iapetus, Phoebe, …

Saturn's system [*NASA/JPL*]



Cassini

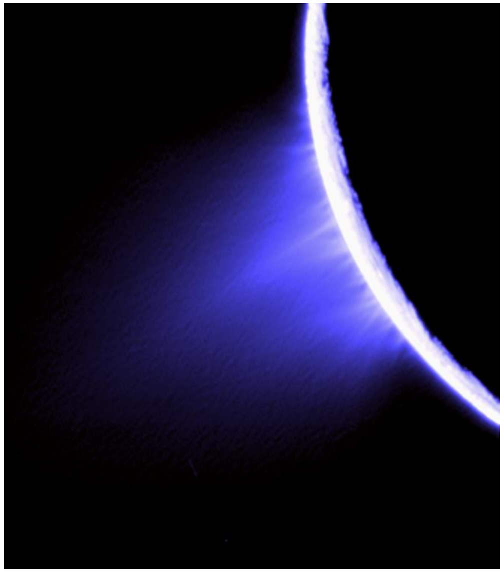
- Outline
  - Launch date: 15 Oct. 1997
  - Development & Operation: NASA, ESA
  - Orbit Insertion: Dec. 2004
  - Now Operating
    - Until Sep. 2017
- Instruments (3 major packages)
  - Optical remote sensing
  - Electric-magnetic field, particles and wave observation
  - Microwave remote sensing



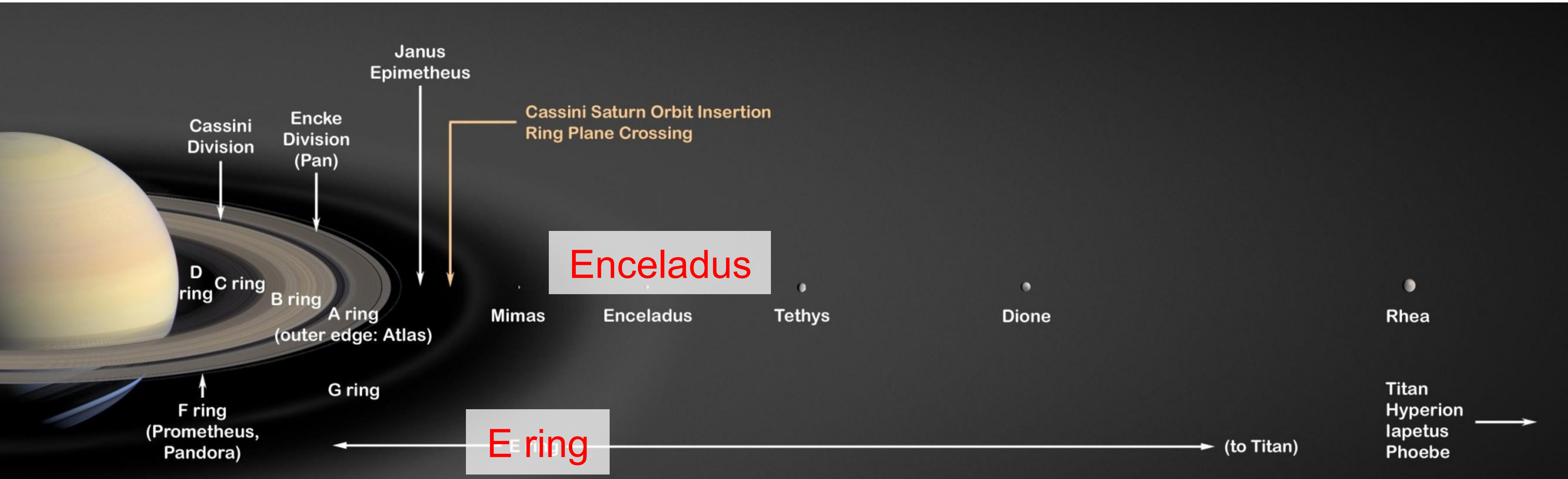
Cassini [*Gurnett et al.*, 2004]

Enceladus plume & E ring

- Enceladus plume (~3.95 Rs)
  - Water gas
- E ring
  - 3 – 8 Rs
  - Water group ion
  - Dust
  - Source: Mainly Enceladus plume

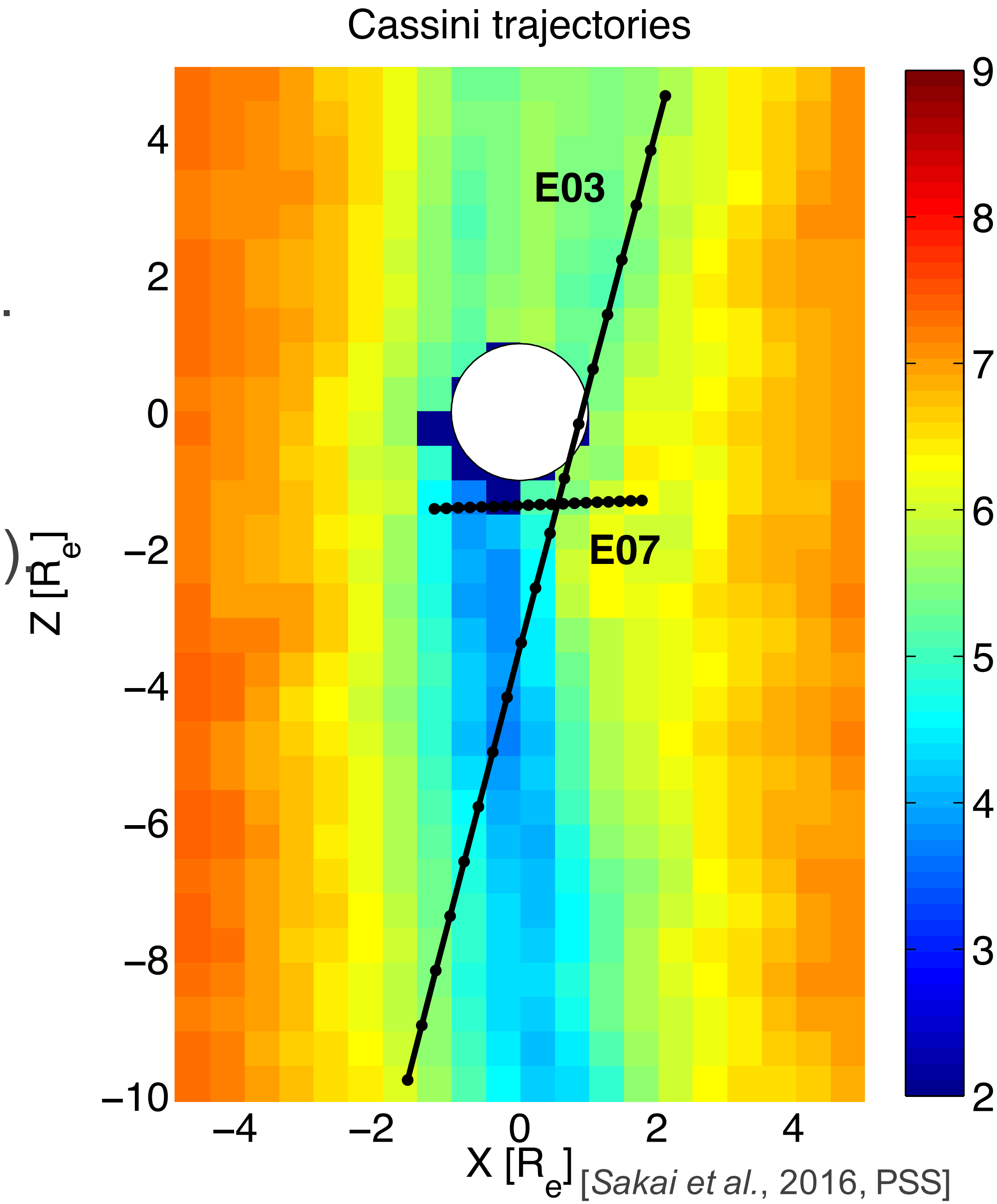


Enceladus & E ring [*NASA/JPL*]



Enceladus flybys

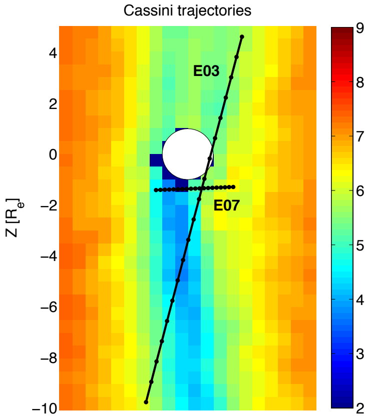
- Enceladus plume encounter
  - Cassini had 20 Enceladus orbits so far.
    - It will have 2 more Enceladus orbits (Oct. and Dec. 2015).
  - E03 and E07 orbits are the focus of talk.

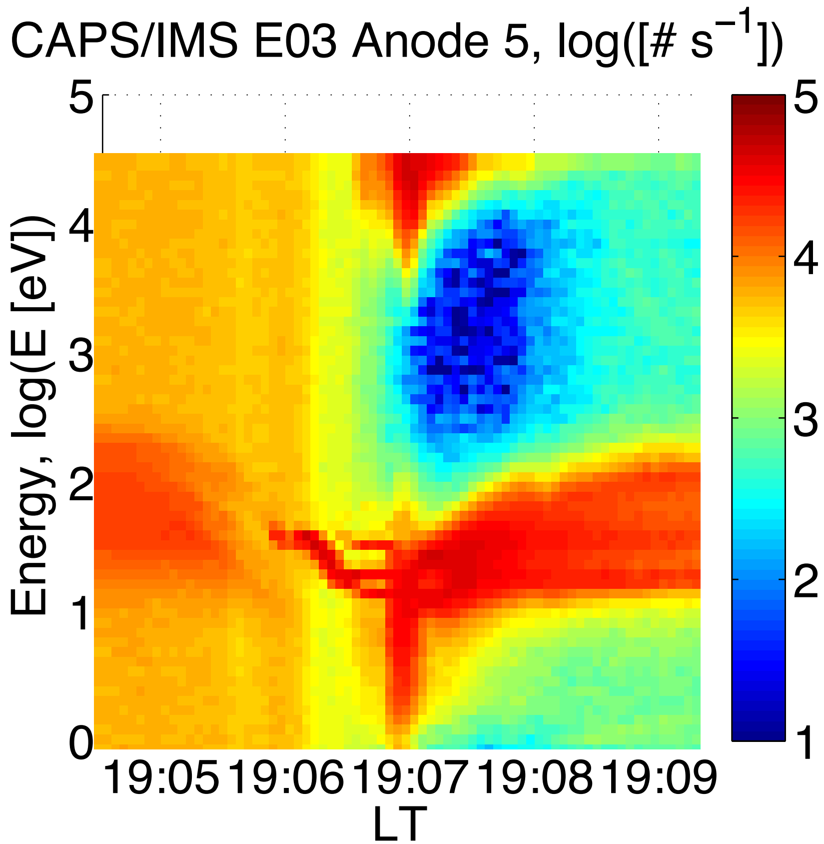


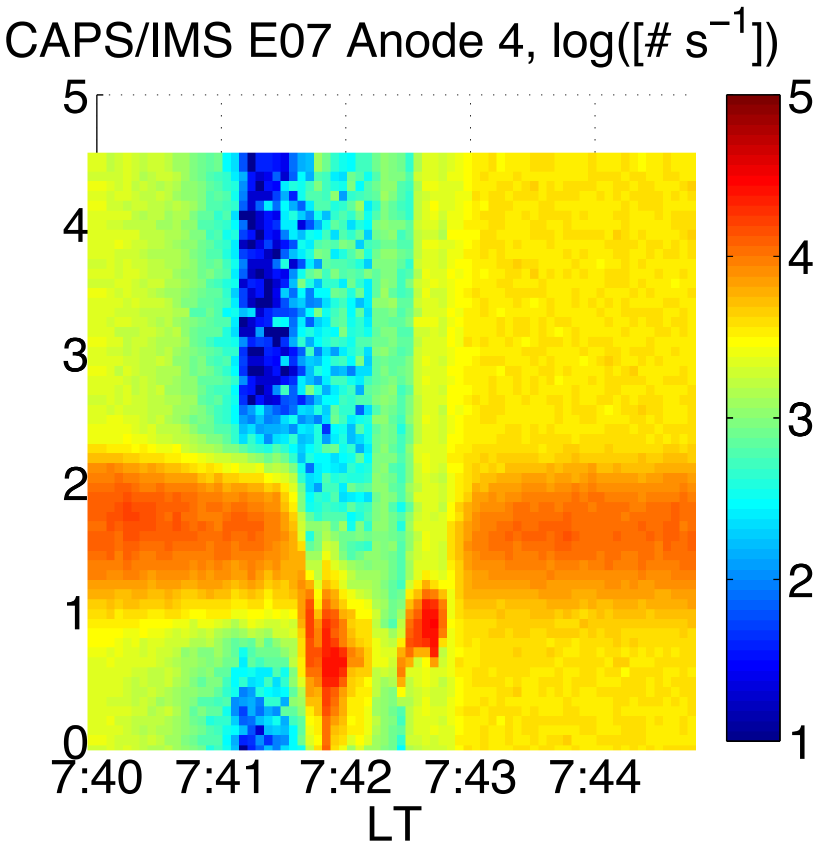
[*Sakai et al.*, 2016, PSS]

CAPS E03 & E07

- CAPS energy spectrum
  - Low energy plasma
    - ~19:07 for E03; ~07:42 for E07







[*Sakai et al.*, 2016, PSS]

Water group ion in the plume

Cluster ions

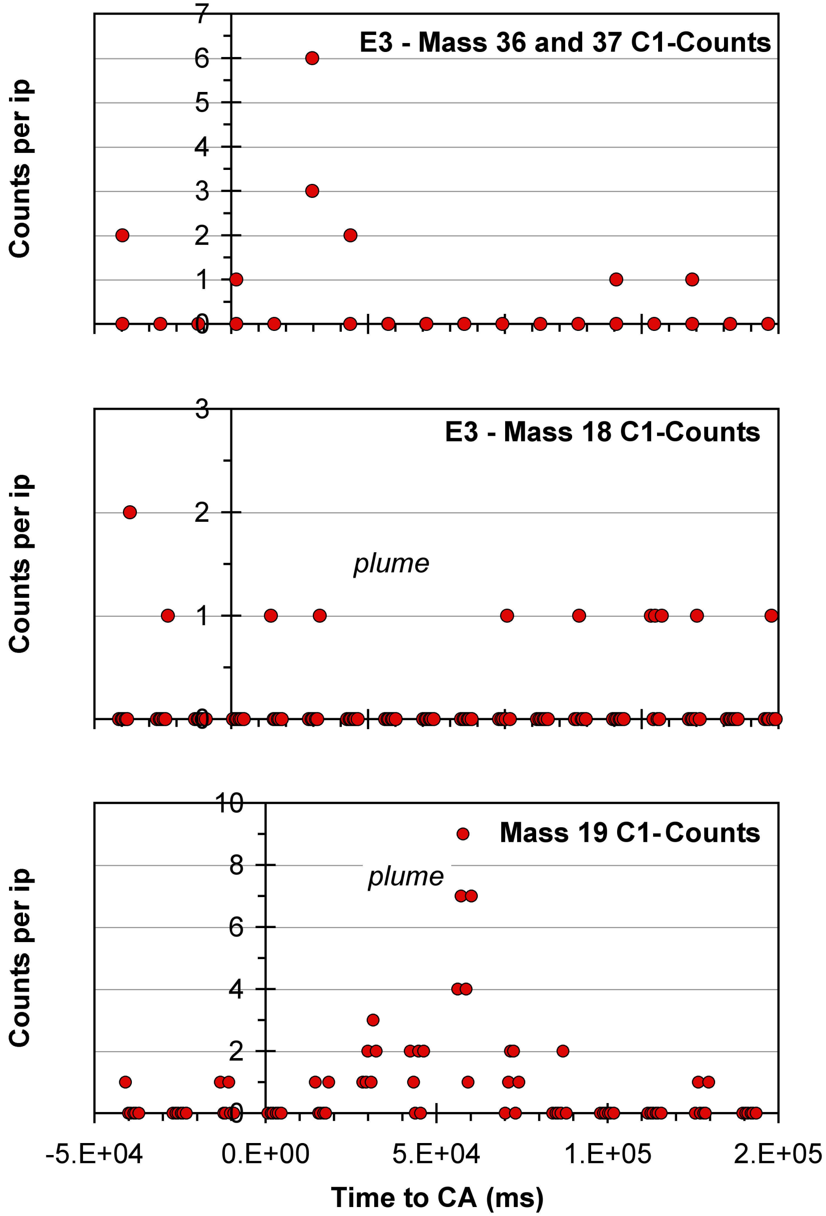
$H_2O^+ - H_2O$

$H_3O^+ - H_2O$

H_2O^+

H_3O^+

- INMS ion count vs. time



[*Cravens et al.*, 2009, GRL]

Ion species in the plume

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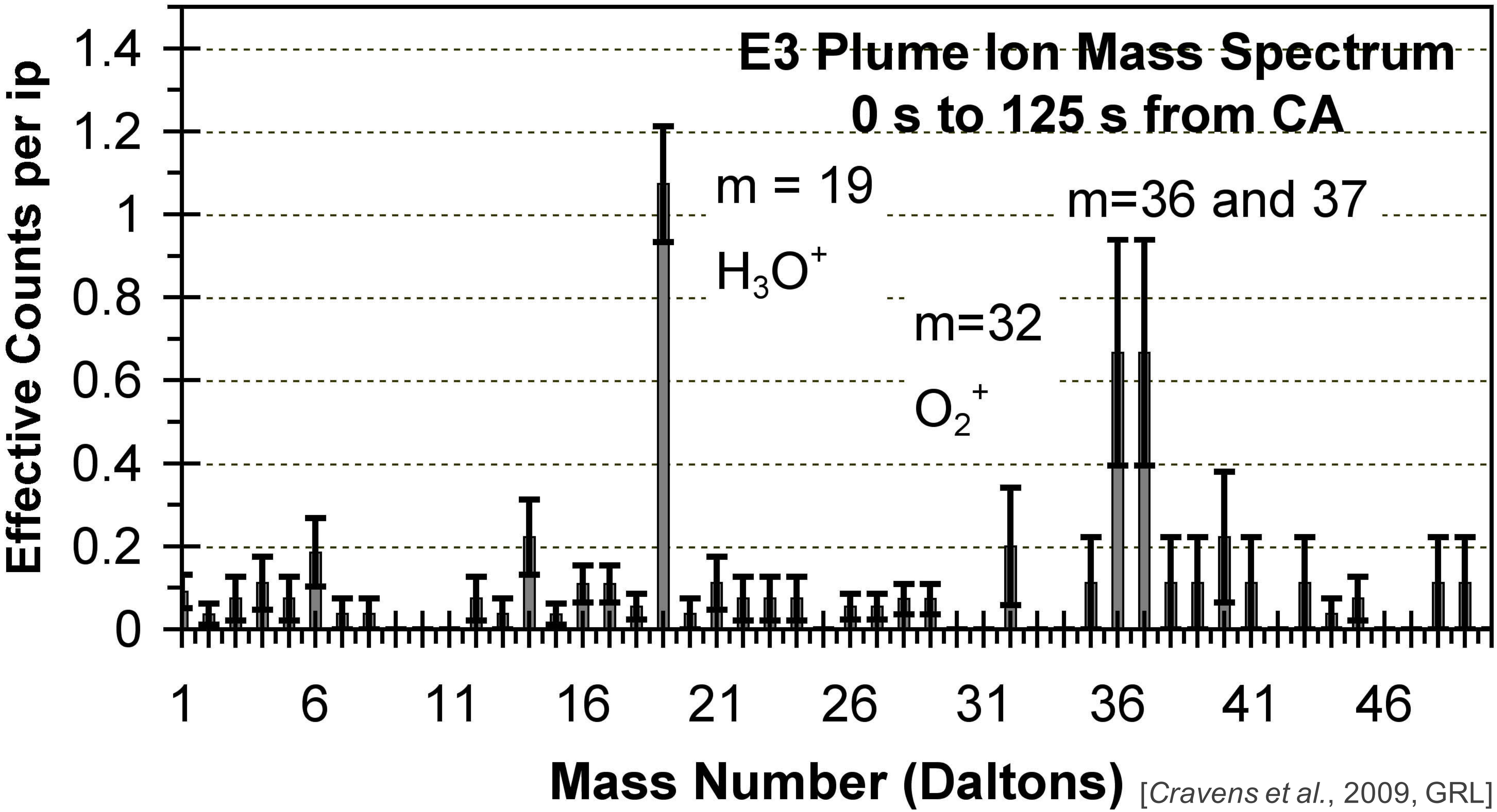
- INMS observations in the plume for E03 orbit
  - H_3O^+ is dominant. $H_2O^+ + H_2O \rightarrow H_3O^+ + OH$



[*Cravens et al.*, 2009, GRL]

Motivation & Method

- Investigation of ion environment in Enceladus plume
  - Where is low energy ion from?
  - What is the physical processes to explain CAPS and INMS data?
    - Electric field or Magnetic field?

- Method
  - Test-particle simulation of water group ions

Test particle simulation

- Momentum equation

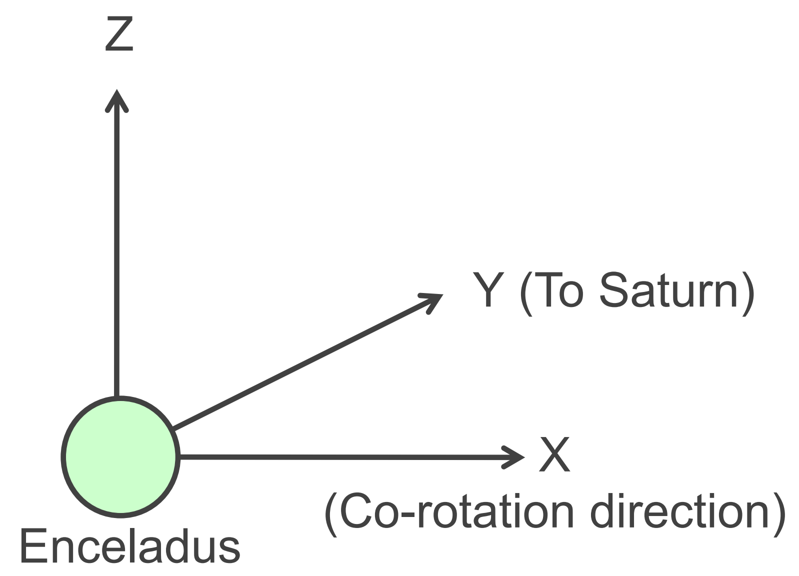
$$m_i \frac{d\mathbf{v}_i}{dt} = q\left(\mathbf{E} + \mathbf{v}_i \times \mathbf{B}\right) + \mathbf{R}$$

- Charge exchange & Chemical reactions

$$H_2O^+ + H_2O \rightarrow H_2O + H_2O^+$$

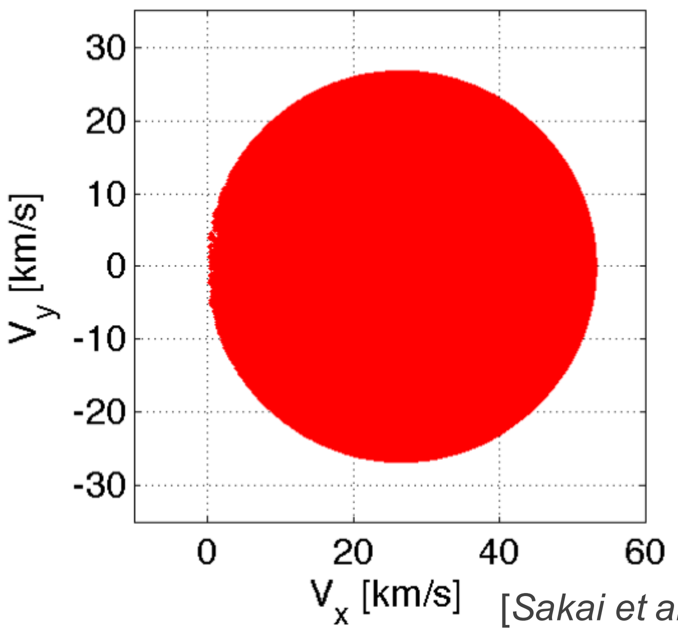
$$H_2O^+ + H_2O \rightarrow OH + H_3O^+$$

- Enceladus coordinate system

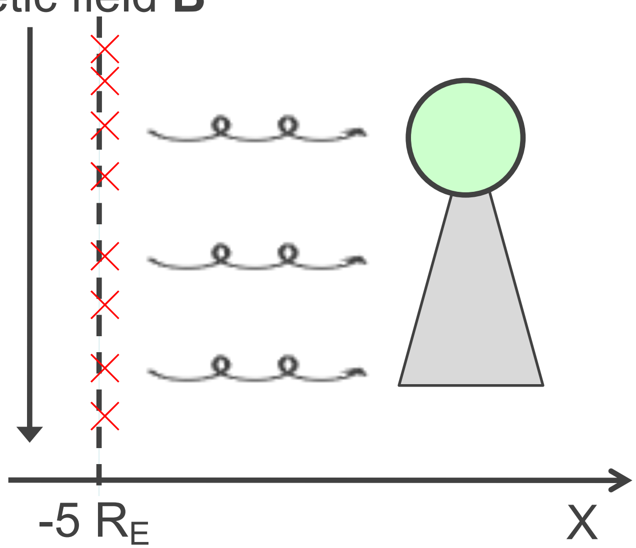


Simulation settings

- CX Front Model (CX)
  - Interaction of the background ion with the plume gas
  - Particle generator: H_2O^+ at $X = -5\ R_E$ ($-5\ R_E < Y < 5\ R_E$, $-10\ R_E < Z < 5\ R_E$)
  - Initial V based on the gyromotion: $V_z = 0$
    - Disk input
      - Ion velocity is smaller than the co-rotation velocity in the inner magnetosphere [*Holmberg et al.*, 2012, PSS, *Sakai et al.*, 2013, PSS].



[*Sakai et al.*, 2016, PSS]



Simulation settings

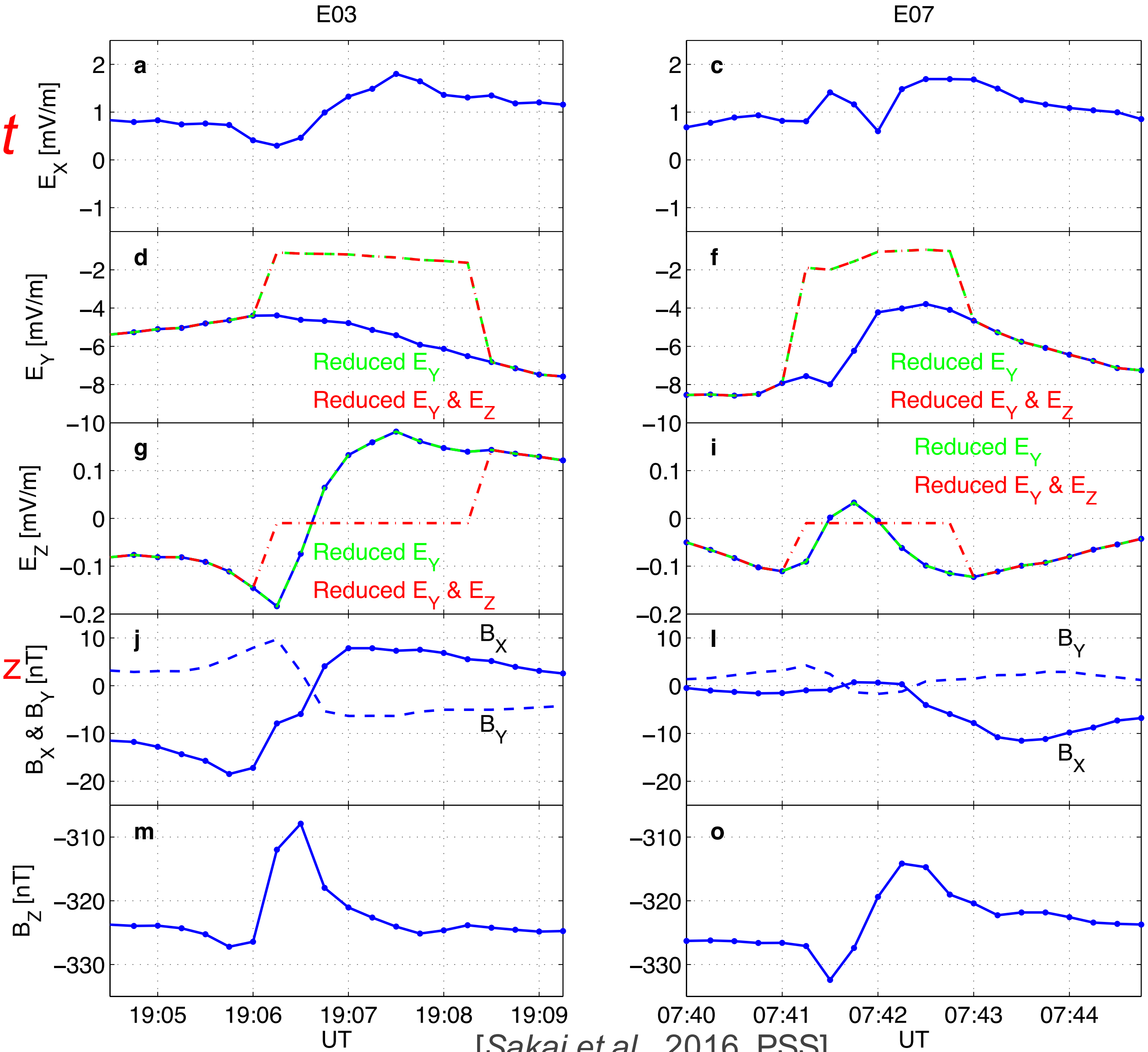
- Area of simulation
  - $-5\ R_E < X < 5\ R_E$; $-5\ R_E < Y < 5\ R_E$; $-10\ R_E < Z < 5\ R_E$
    - Move to next particle when a particle is out of this area.
- Plume neutral density (H_2O gas)
  - Based on *Saur et al.* [2008, GRL]

$$n_{plume} = n_0 \left(\frac{R_E}{r} \right)^2 \exp\left[-\left(\frac{\Theta}{H_\Theta} \right)^2 - \frac{r - R_E}{H_d} \right]$$

  - $n_0 = 2.5 \times 10^9\ cm^{-3}$, $H_\Theta = 12$ deg., $H_d = 948$ km [*Fleshman et al.*, 2010, GRL]

BE fields for E03 & E07

- Magnetic and electric fields used in this simulation
- Based on *Omidi et al.* [2010, JGR]
- Reduced electric field cases in the plume
  - Reduced E_y
  - Reduced E_y & E_z

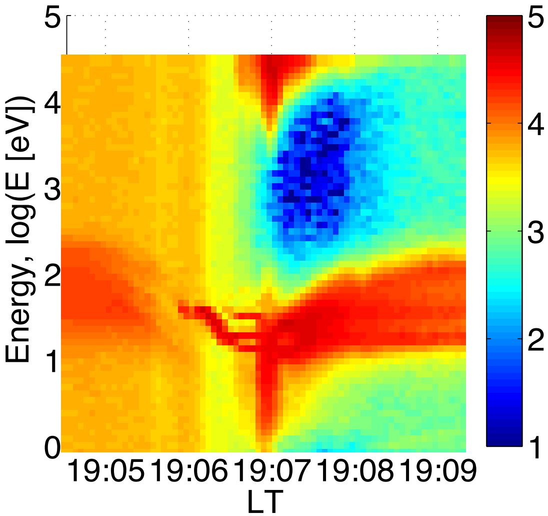


[*Sakai et al.*, 2016, PSS]

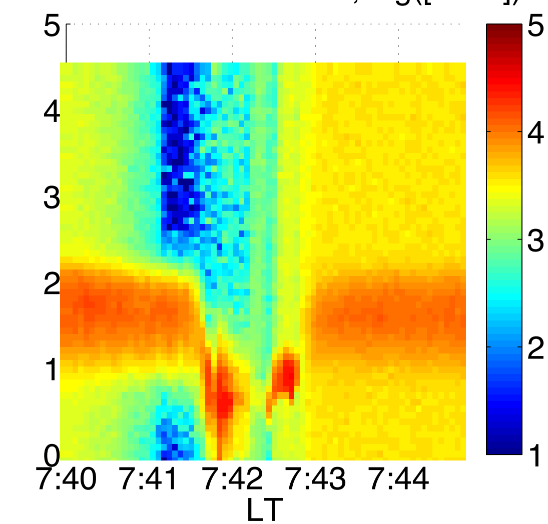
Flux for E03 & E07

- Energy-Flux distribution in each bin for E03 and E07

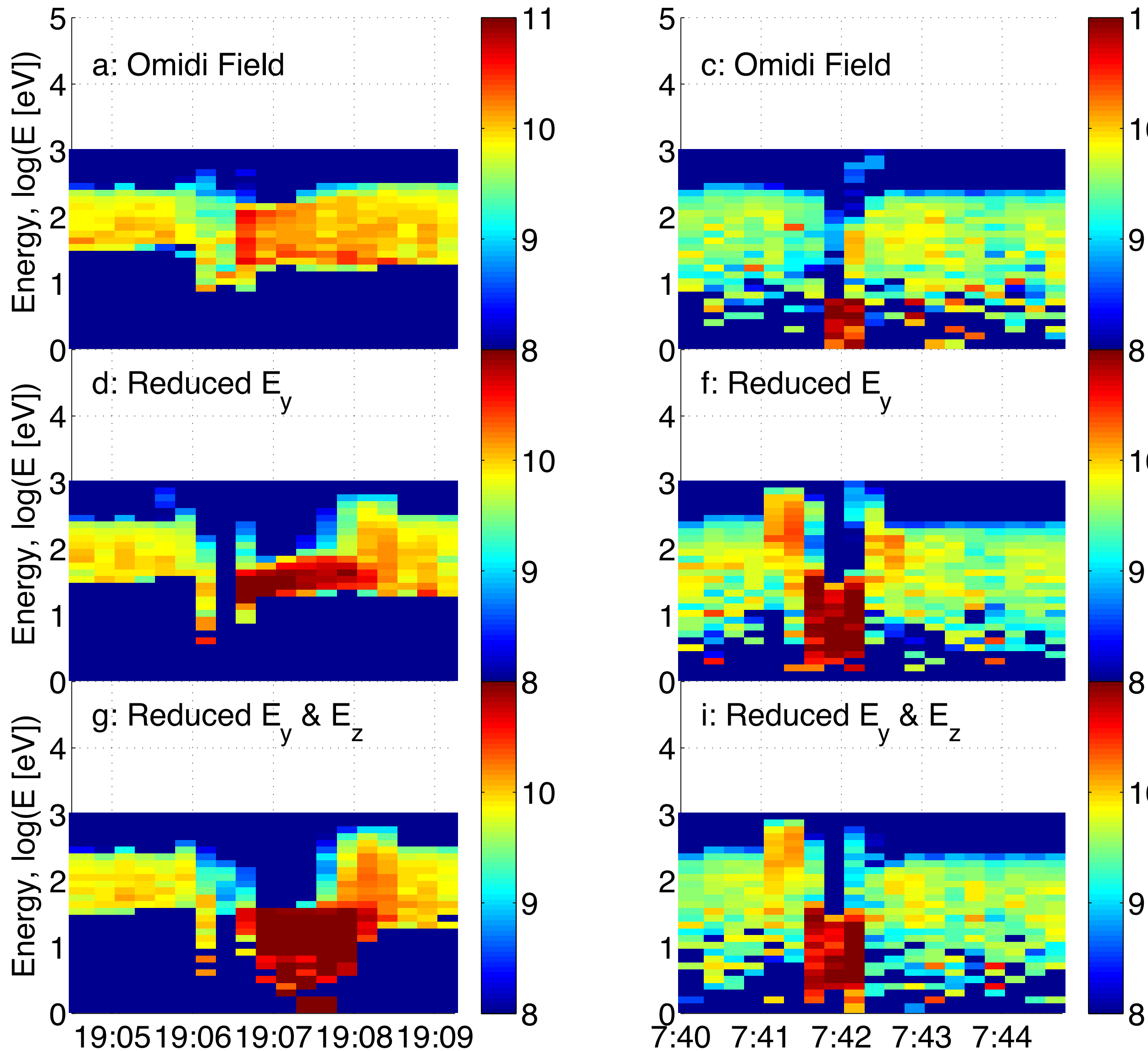
CAPS/IMS E03 Anode 5, log([# s^{-1}])



CAPS/IMS E07 Anode 4, log([# s^{-1}])



E03, $H_2O^+ + H_3O^+$, $\log(\Phi_0)$ [m^{-2} s^{-1} eV^{-1}] E07, $H_2O^+ + H_3O^+$, $\log(\Phi_0)$ [m^{-2} s^{-1} eV^{-1}]

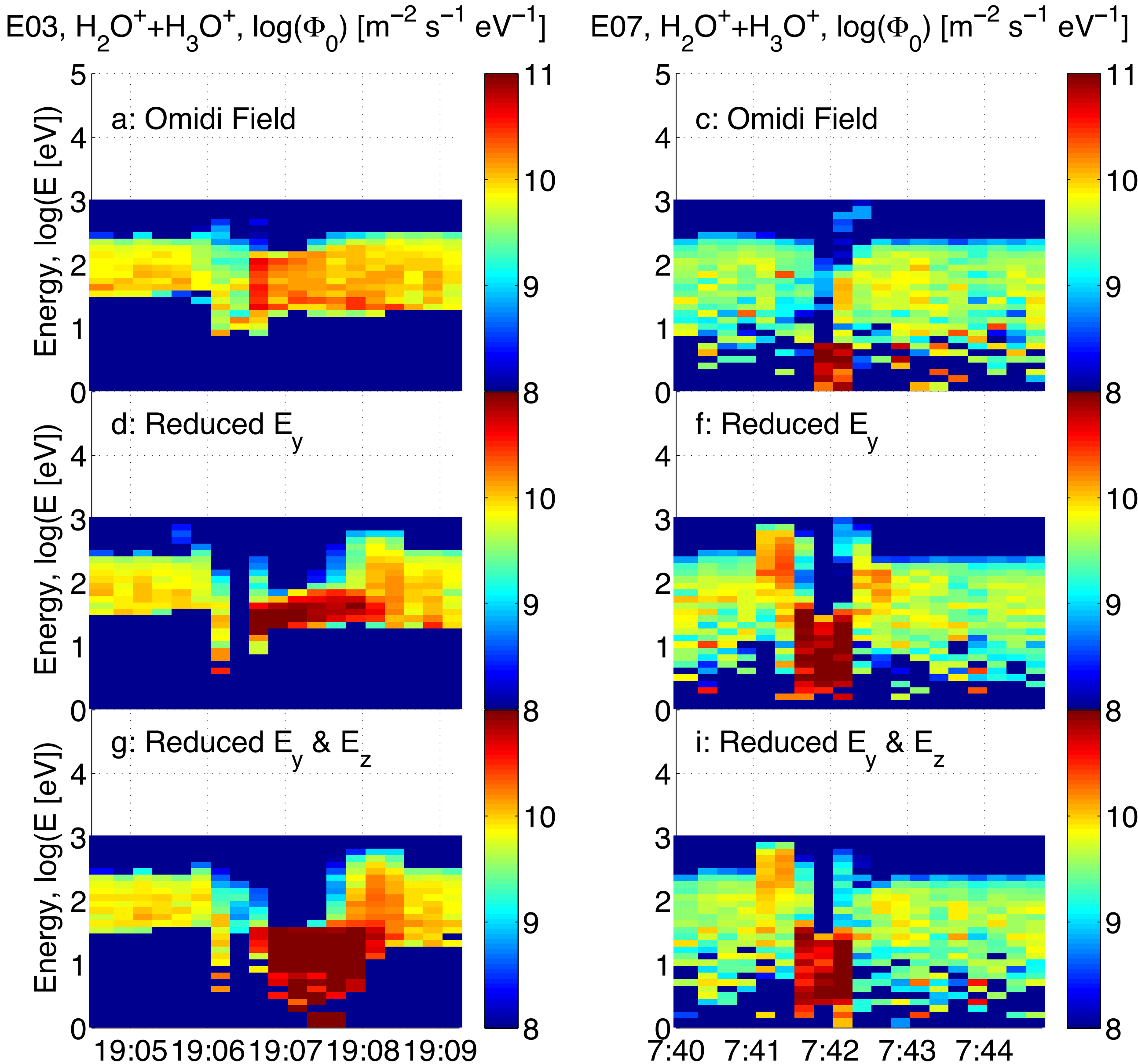


[*Sakai et al.*, 2016, PSS]

Flux for E03 & E07

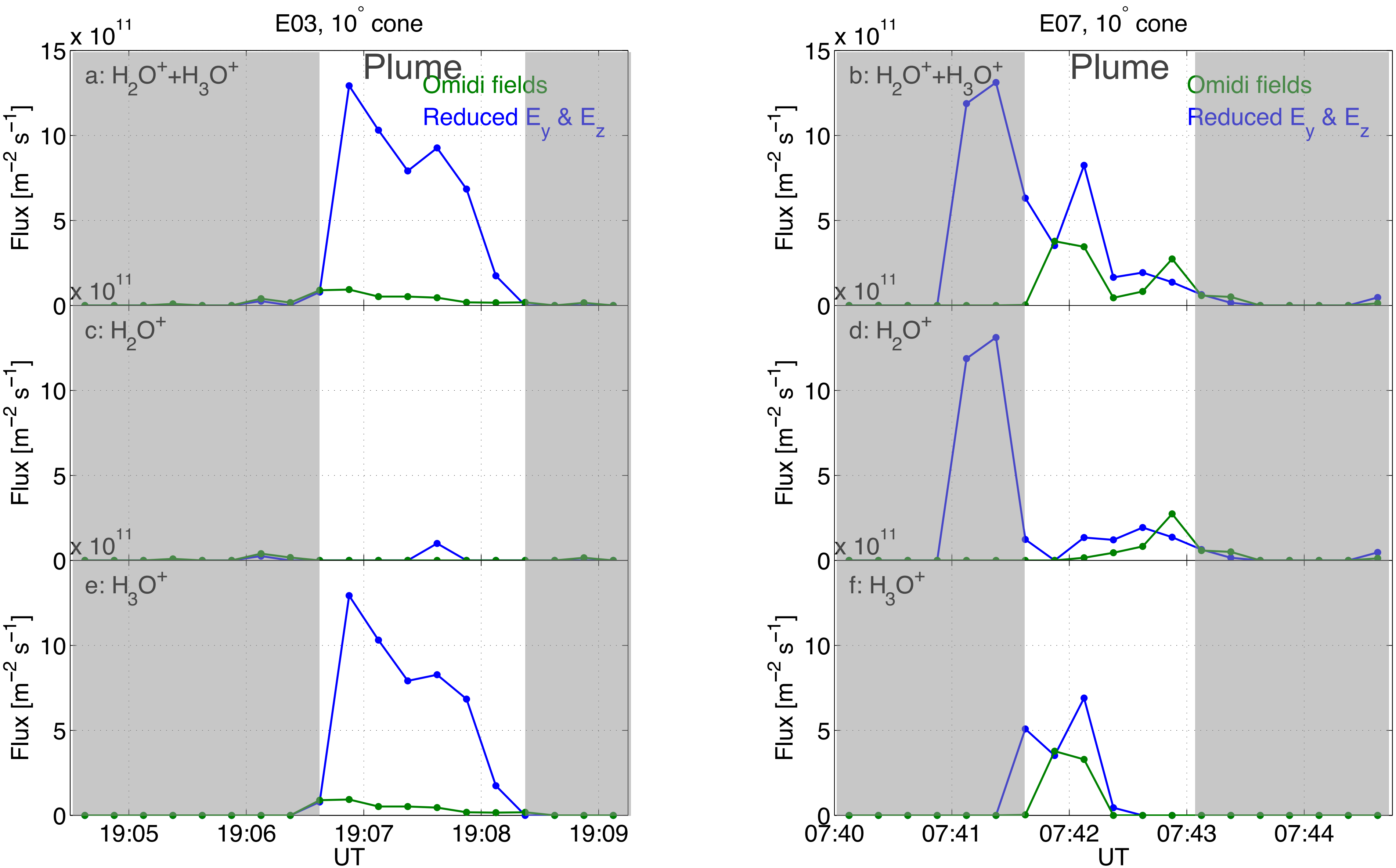
- Energy-Flux distribution in each bin for E03 and E07

- E_z is important for obtaining the low energy ion.
- Ions are moving to –Z direction.
- E_z can be generated by dust [e.g., *Farrell et al.*, 2010, GRL] or pressure gradient of electron in Z direction.



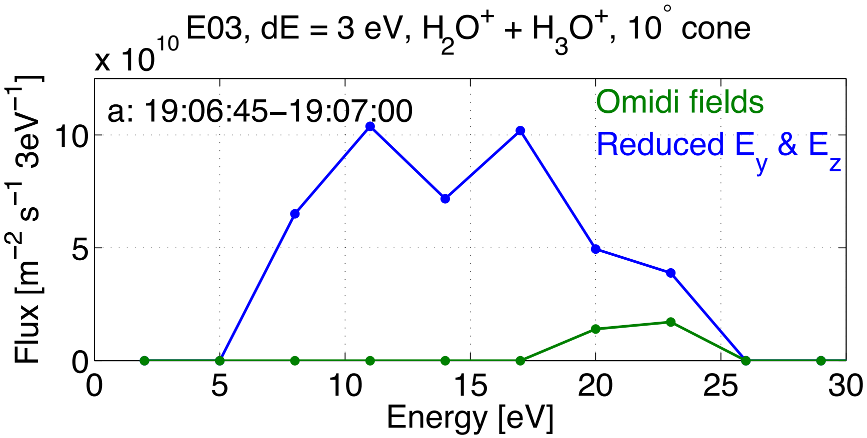
Ion species from total flux

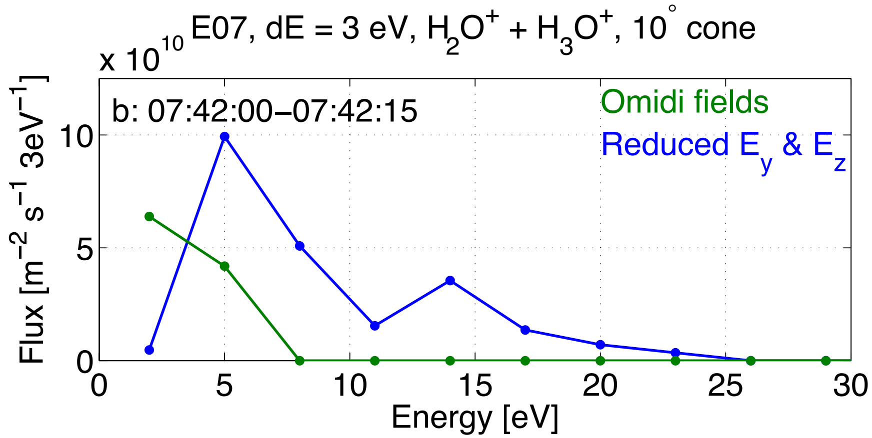
- H_2O^+ vs. H_3O^+



Energy distribution in the plume

- Energy distribution for E03 and E07





- Ion below 30 eV is obtained with 10° cone.
  - Ion is confined to low energy.
- Ion flux is higher in the case of reduced fields than in the case of Omidi's fields.
  - It is because the ion energy is lower with reduced fields than with Omidi's fields.

Energy distribution in the plume

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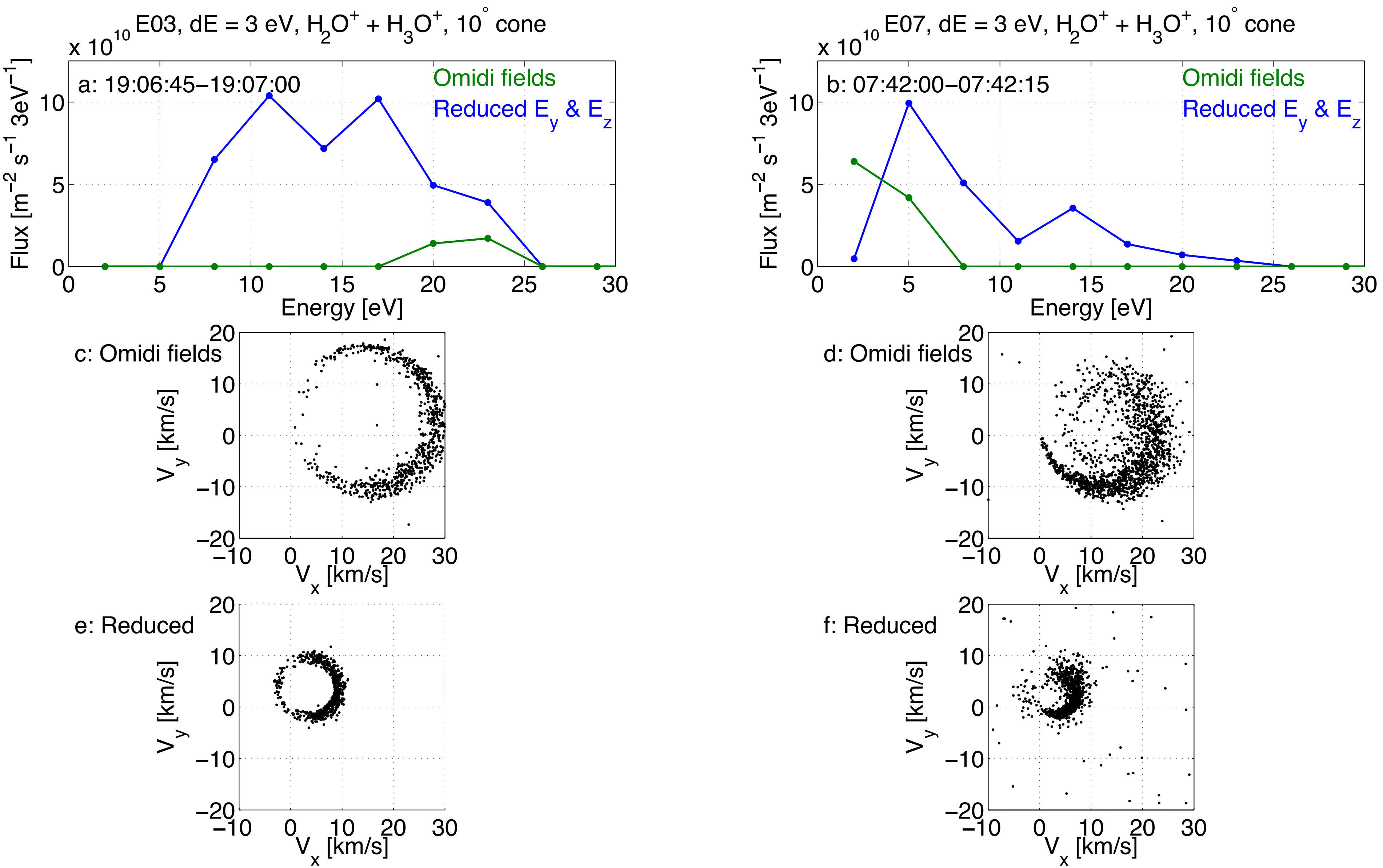
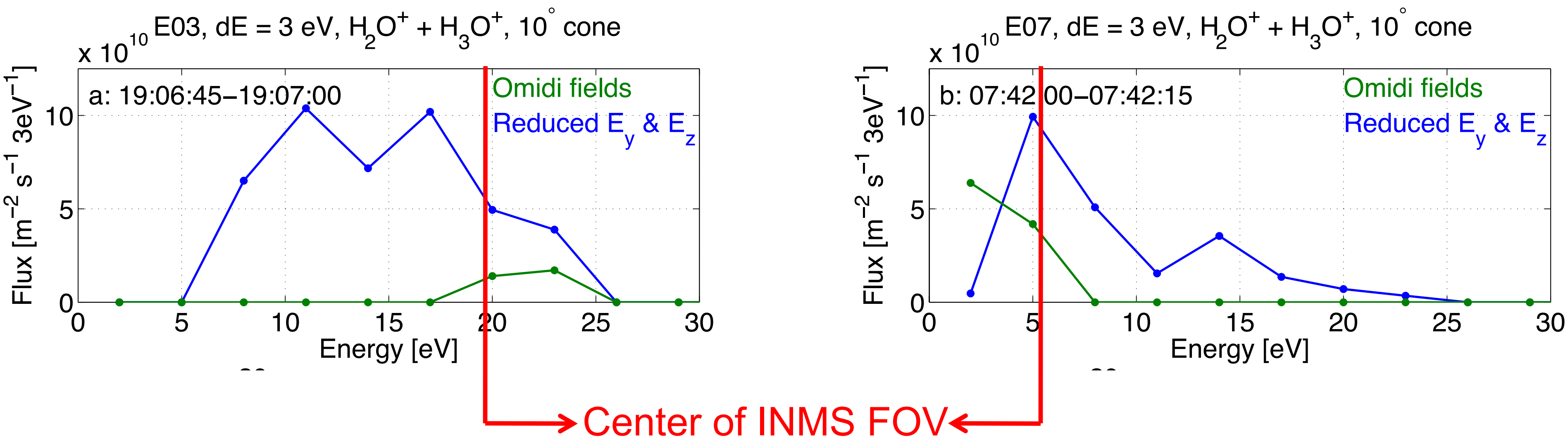
- Energy distribution for E03 and E07



Energy distribution in the plume

- Energy distribution for E03 and E07



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- Ion flux is higher in the case of reduced fields than in the case of Omidi's fields.
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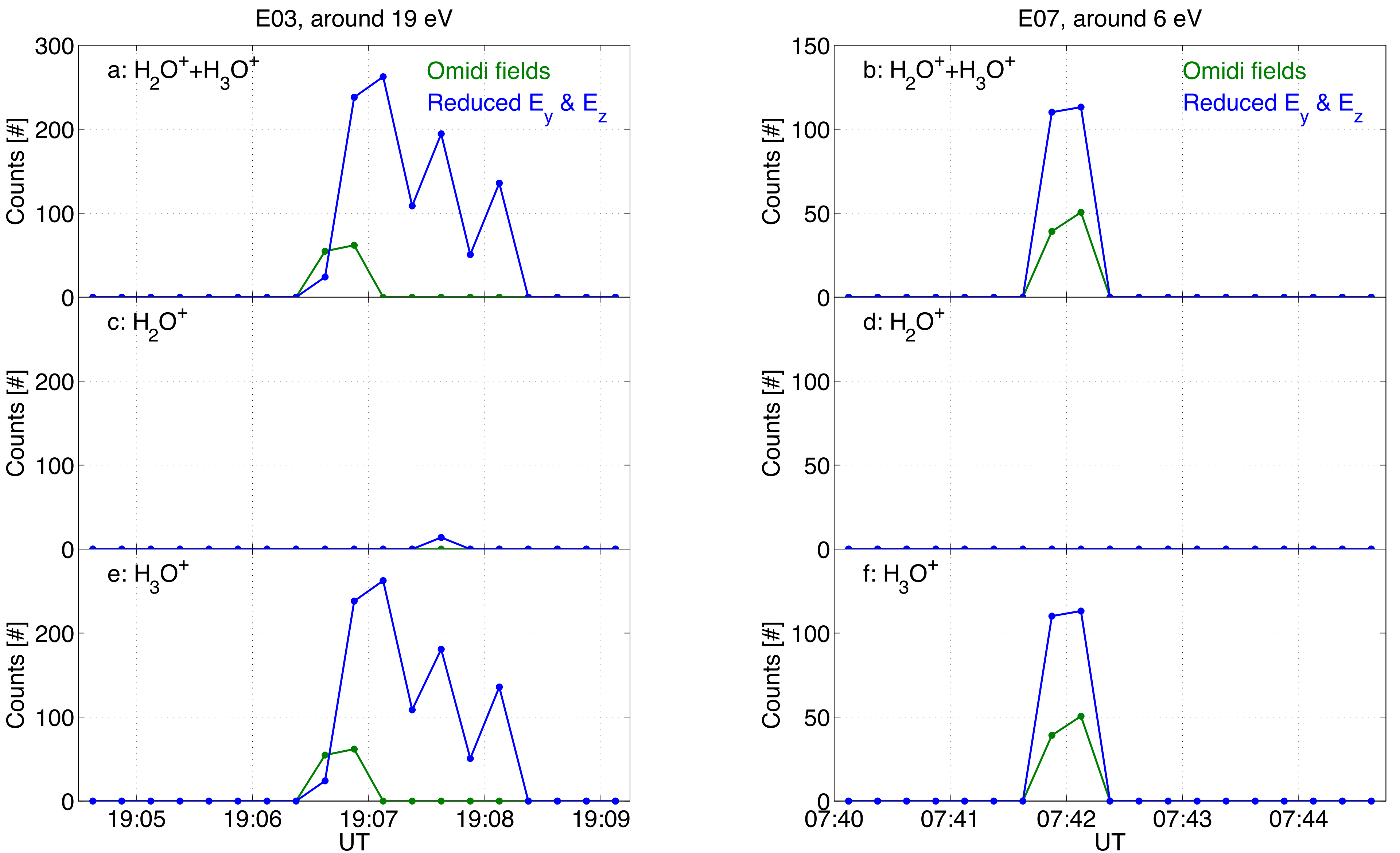
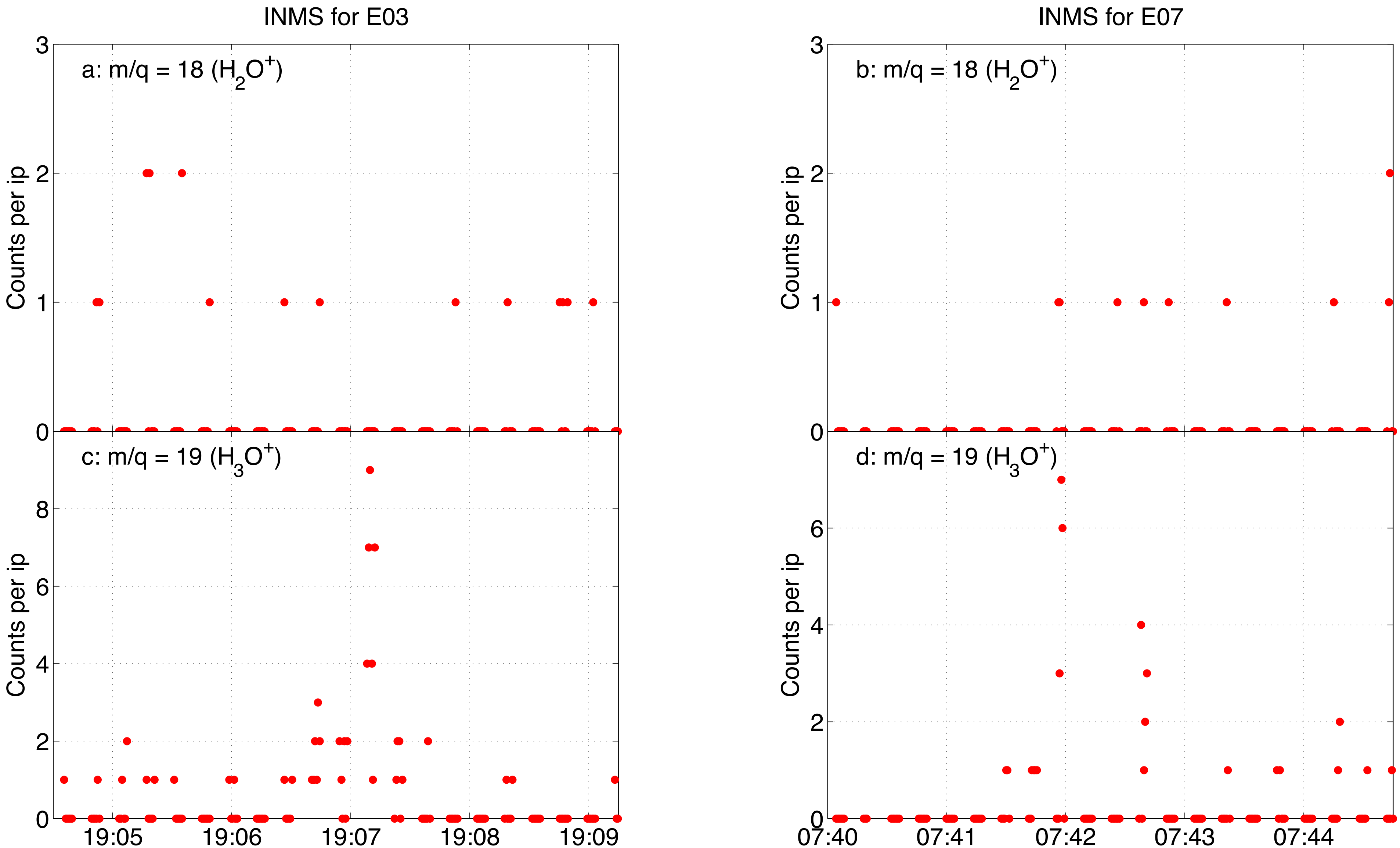
Ion total count

- Total count along E03 and E07 orbits



Ion total count by INMS

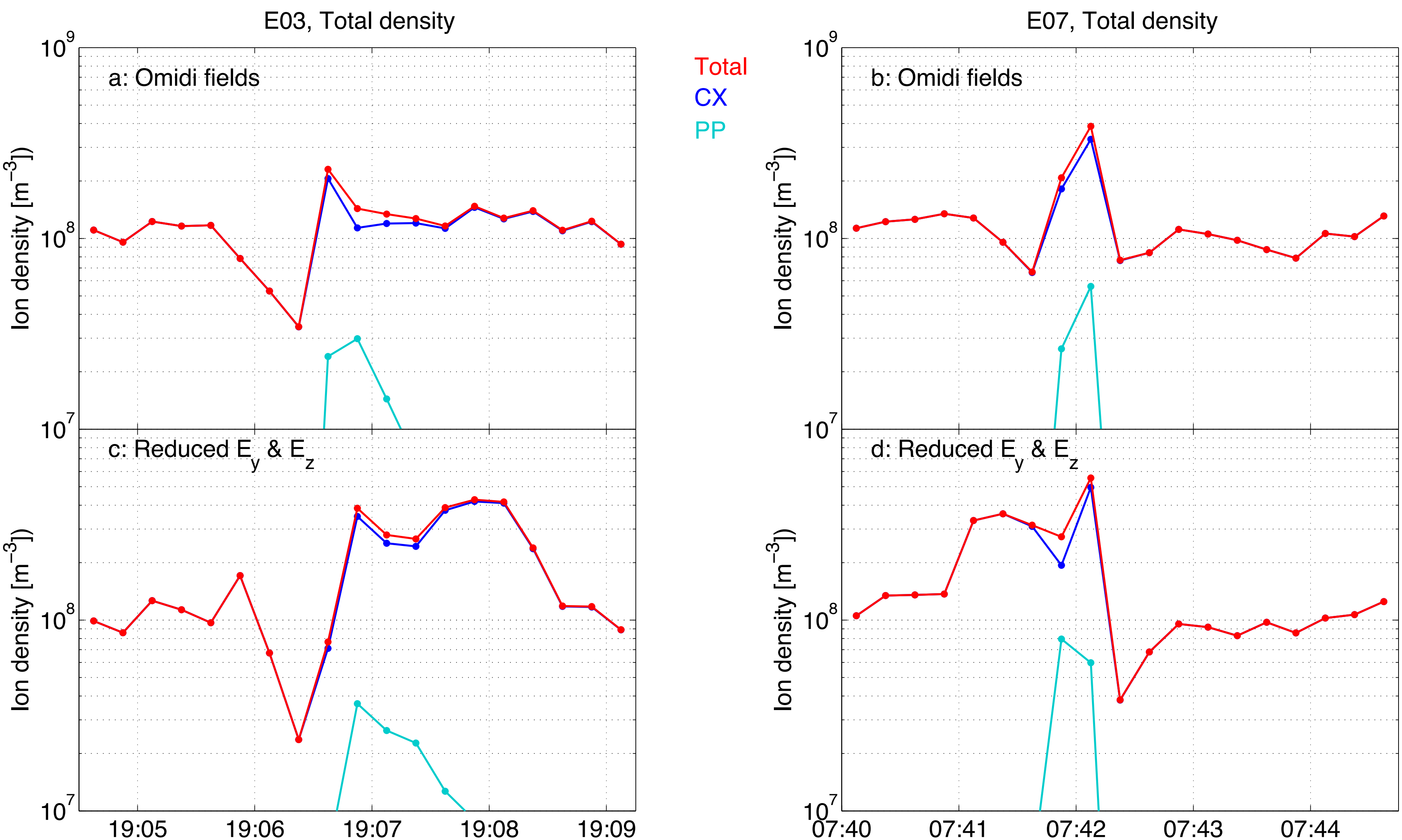
- E03 and E07



[*Sakai et al.*, 2016, PSS]

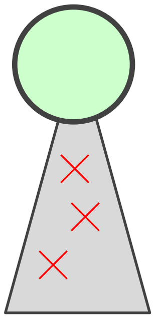
Ion density in the plume

- Ion density along E03 and E07



Photoionization

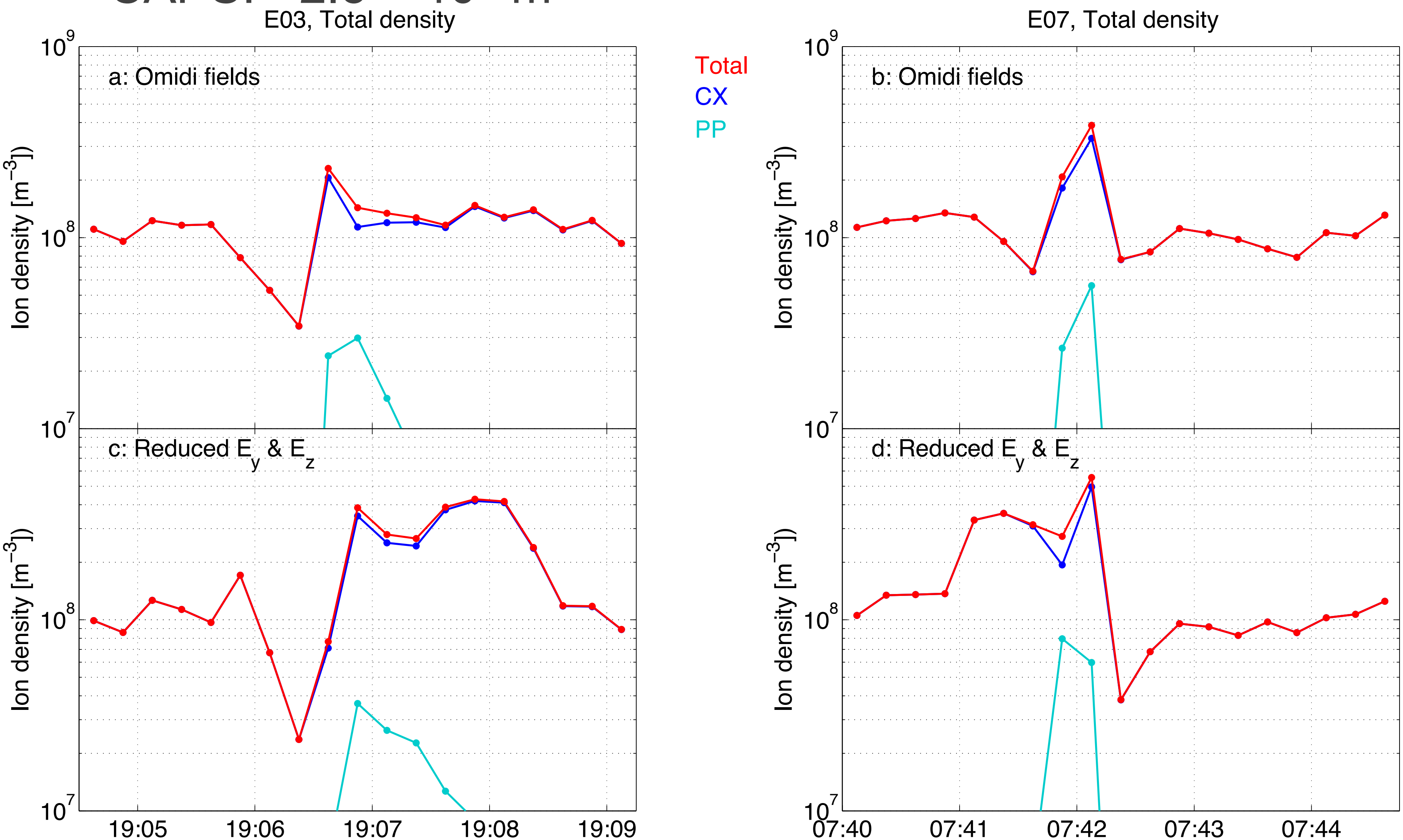
- Photo Plume Model (PP)
  - See ions generated by photoionization
  - Particle generator: H_2O^+ in the plume
  - Initial V = 0
  - Ion starts the gyromotion.



- Photoionization rate
  - $I = 5.1 \times 10^{-9}\ s^{-1}$ [e.g., *Moses and Bass*, 2000, JGR]

Ion density in the plume

- Ion density
  - Langmuir Probe: ~10^{10} m^{-3} [*Morooka et al.*, 2011, JGR]
  - CAPS: ~2.5×10^8 m^{-3}



Summary

- Energy-flux distribution
  - Vertical electric field, $-E_z$, is important for obtaining the low energy ion detected by CAPS.
  - The electric field could be generated by dust [*Farrell et al.*, 2010, GRL; *Morooka et al.*, 2011, JGR] or pressure gradient of electron in Z direction.
- Ion species
  - H_3O^+ is dominant which is consistent with INMS.
  - O_2^+ and cluster ions will be consider for future works.
  - Our total count is not consistent with INMS results.
    - It may be for issues of translation such as transmission factor.
- Ion density
  - 400-600 cm^{-3}
  - It is not consistent with LP, but almost consistent with CAPS.

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