RPWS Observations during Grand Finale

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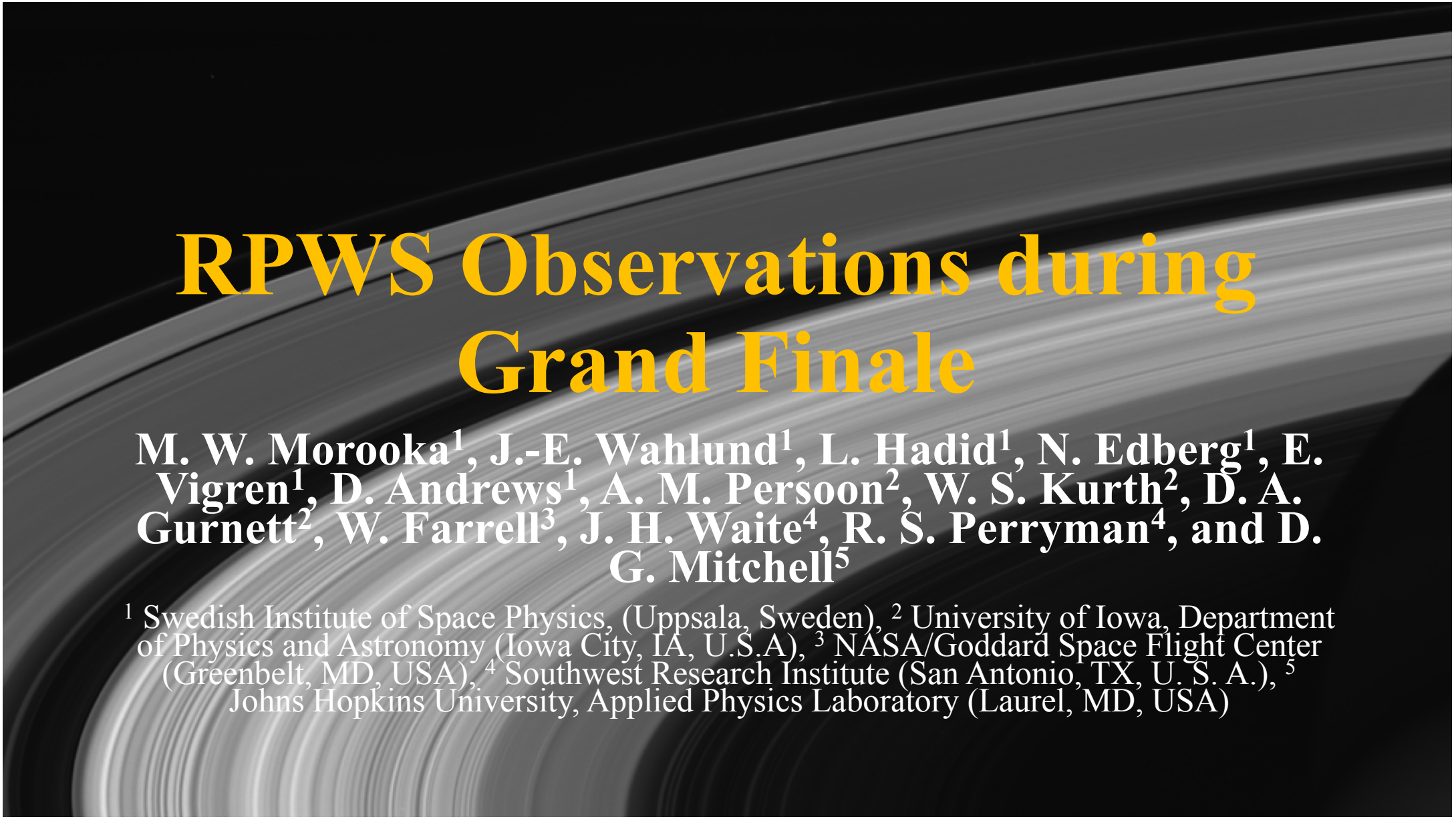
We presented the RPWS observations of the electron and ion densities from Cassini's Grand Finale orbits. In total 22 Grand Finale orbits travel through the ionosphere on the dayside from north to south with different perikrone altitudes. During the last plunge the Langmuir probe (LP) measured the electron density down to 1,400 km and identified a Chapman type density peak around 1,500 km (slide 3).

The observation from the first Grand Final orbit showed a plasma density trend that gradually increasing toward the planet and confirmed that the ionosphere consists of mainly hydrogen (H^+) above 3,000 km (Wahlund et al., 2018, also slide 13 and 15). However, some other orbits indicated that the ionosphere is partially affected by the heavy ring materials. Especially, one of the orbits which crossed the D ring showed the discrepancy between the electron and ion density, which indicates the presence of a dusty plasma, a plasma that contains negatively charged heavy particles predominantly.

In the last five low altitude orbits spacecraft went down to 1,600 km at perikrone. During these orbits the LP revealed rapid increases of the plasma densities and, again, discrepancies between the electrons and ions densities (N_e and N_i) near the closest approach.

The Ion and Neutral Mass Spectrometer (INMS) measured the ion densities with light ion mass (< 4 amu), which was surprisingly much lower than the electron density below 2,500 km. This indicates the presence of heavy ion. Interestingly the LP observation showed total ion density even larger than the electron densities. The neutral observation INMS identifies the heavy organic components in the ionosphere. Also nano-meter size dust grains are detected both near the D ring and the deep ionosphere by the high energy particle detector (MIMI: Magnetospheric Imaging Instrument).

In summary Cassini observations from the Grand Finale indicates that the ionosphere of Saturn affected by the material that precipitates from the ring and as a result, consists of heavy cluster ions in both negative and positive charge state.



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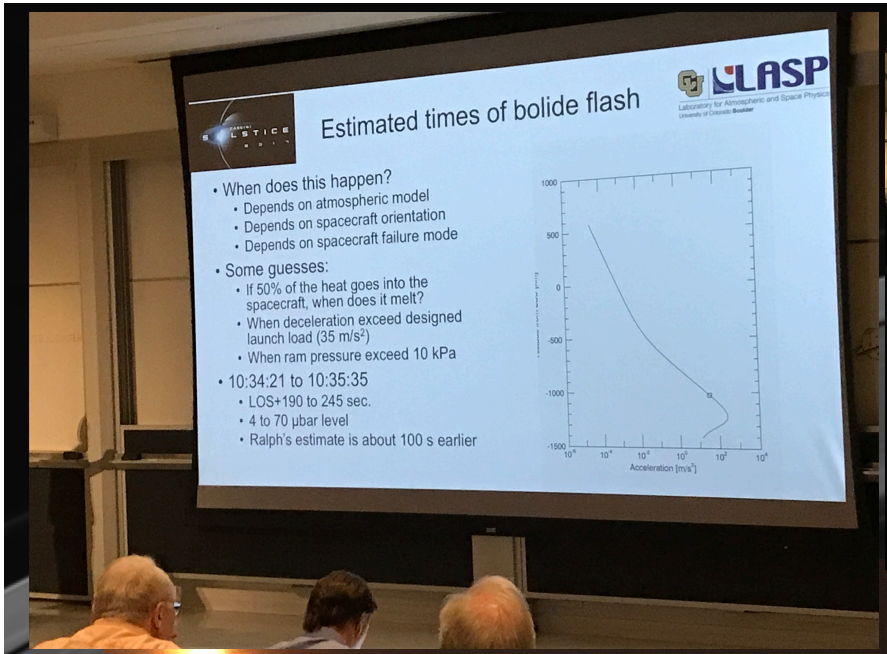
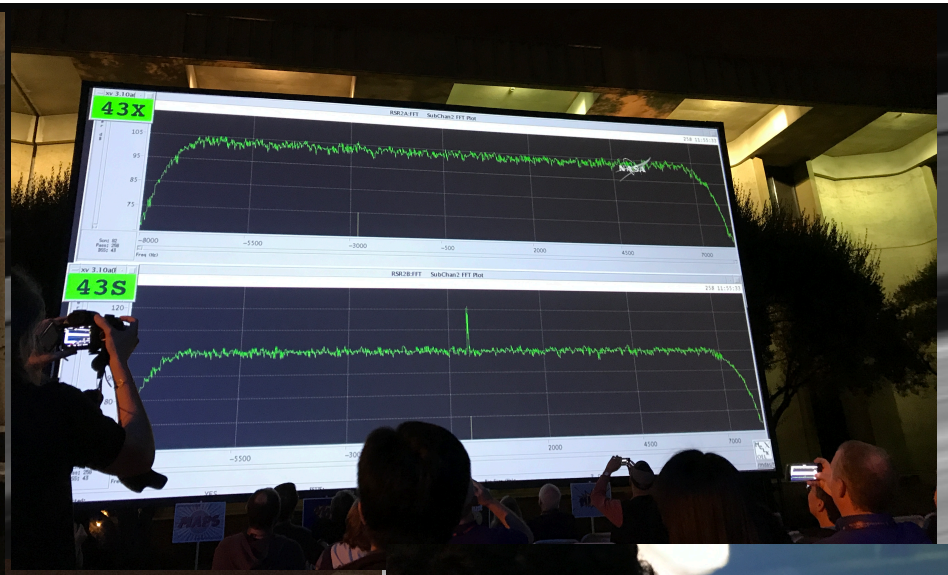
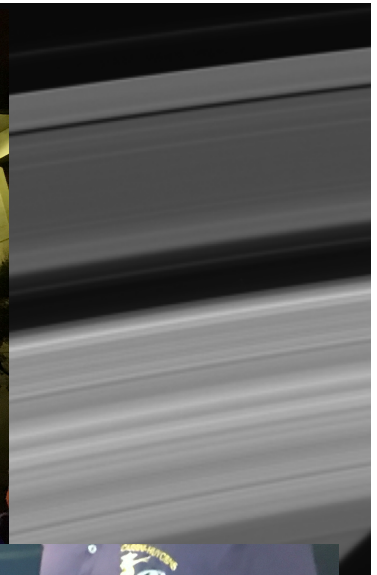
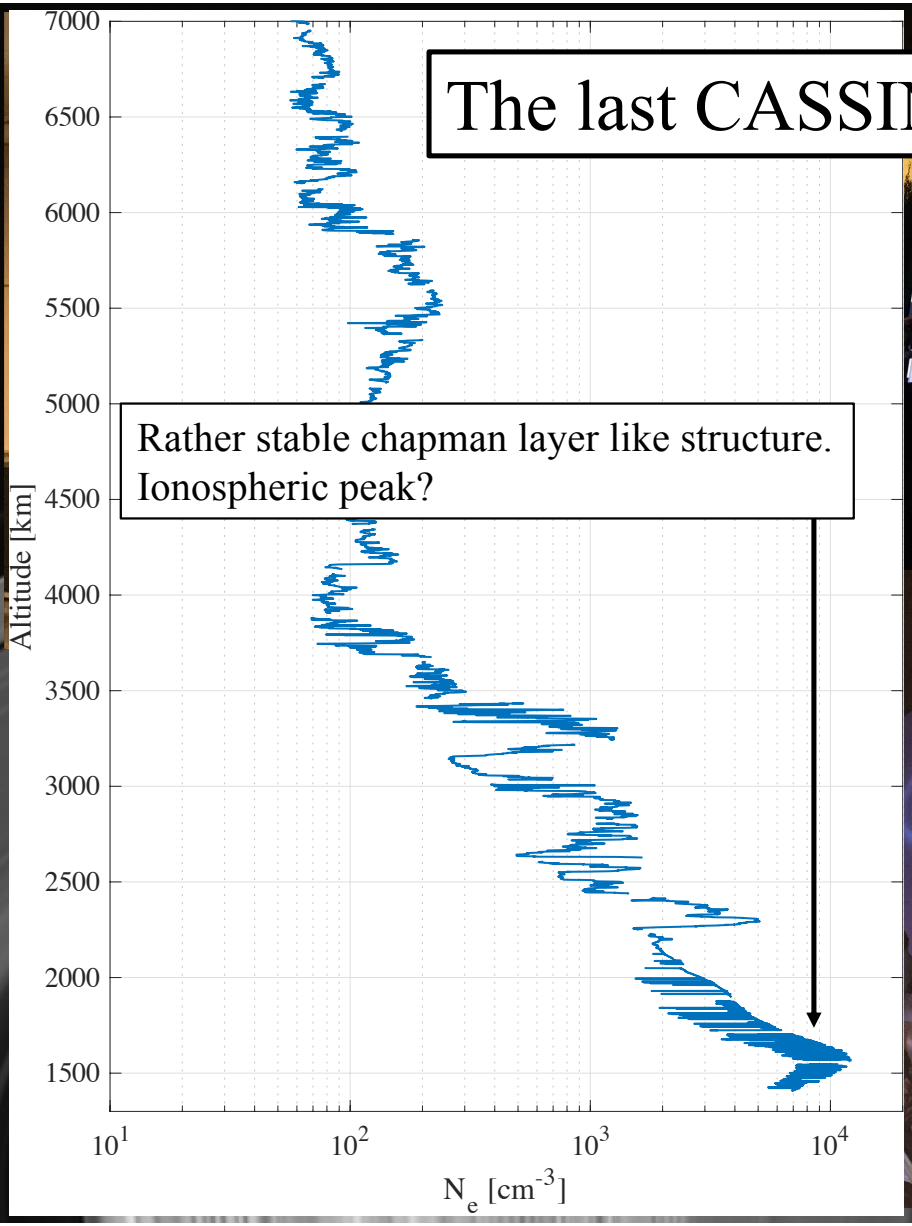

Estimated times of bolide flash
LASP
Laboratory for Atmospheric and Space Physics
University of Colorado Boulder
• When does this happen?
• Depends on atmospheric model
• Depends on spacecraft orientation
• Depends on spacecraft failure mode
• Some guesses:
• If 50% of the heat goes into the spacecraft, when does it melt?
• When deceleration exceed designed launch load (35 m/s²)
• When ram pressure exceed 10 kPa
• 10:34:21 to 10:35:35
• LOS+190 to 245 sec.
• 4 to 70 µbar level
• Ralph's estimate is about 100 s earlier
Acceleration [m/s²]

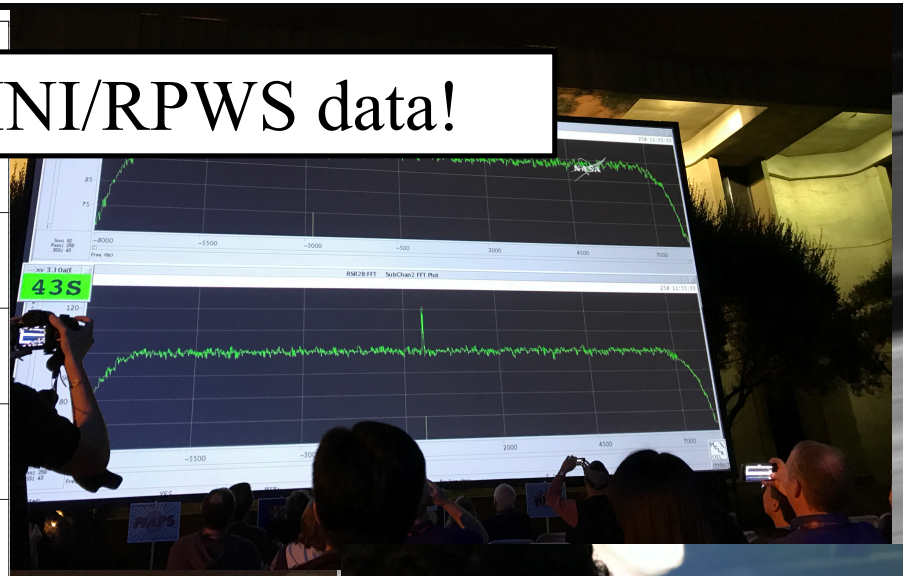

43X
43S
NASA

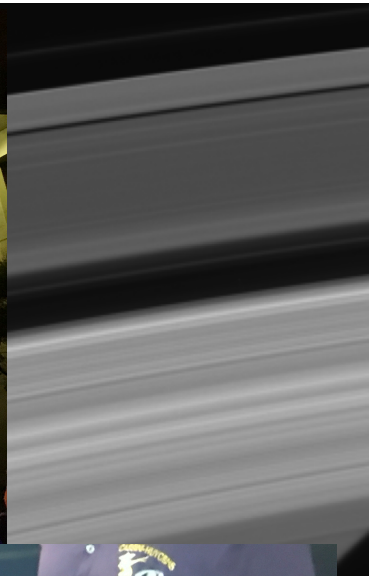



CASSINI

The last CASSINI/RPWS data!







Some of Grand Finale results

- RPWS: Wahlund et al., Science, 2018
  In situ measurements of Saturn's ionosphere show that it is dynamic and interacts with the rings.

Several other Science papers to come

- INMS: Waite et al.,
  Chemical Interactions between Saturn's Atmosphere and Rings
- MIMI: Mitchell et al.,
  Cassini/MIMI Dust Measurements in Saturn's Ionosphere and Upper Atmosphere
- RPWS: Lamy et al.,
  The low frequency source of Saturn's Kilometric Radiation

Several other GRL issues to come

- Electron density profile of Saturn's ionosphere
- Electron temperature of Saturn's ionosphere
- Plasma density on the L shell of main rings
- Z mode emission source (possible associated current system?)
- Etc..

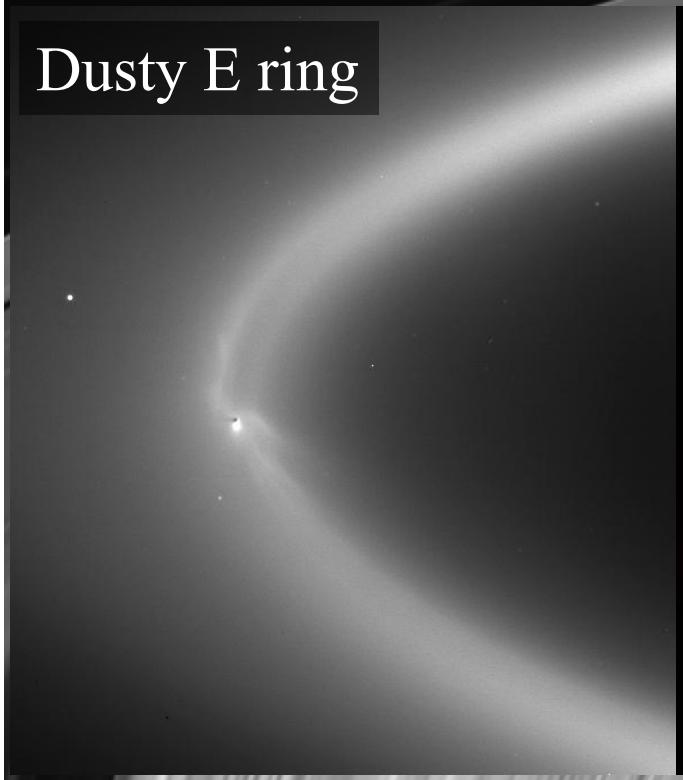
Cassini/RPWS Grand Finale Observations

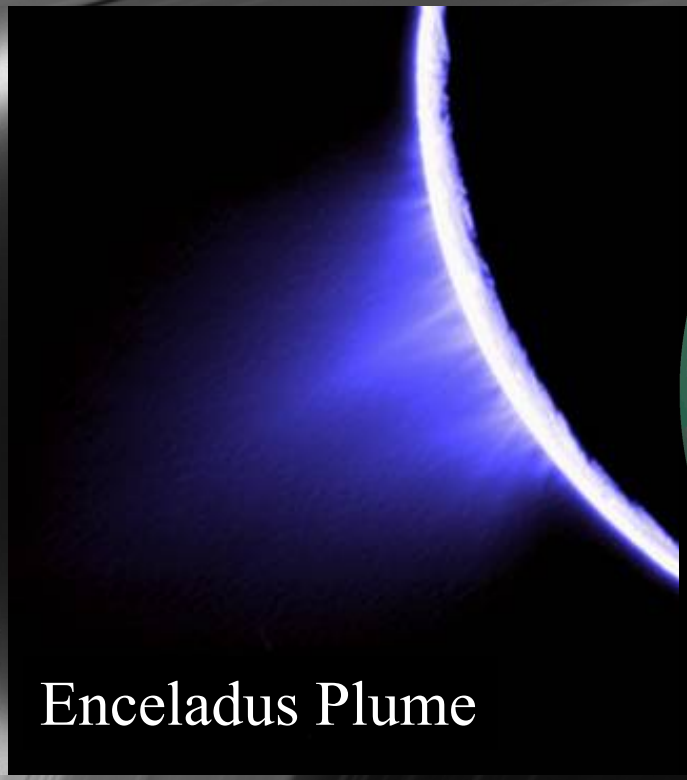
During both Ring Grazing and Grand Finale orbits RPWS instruments observed the plasma affected by the dust of Rings.

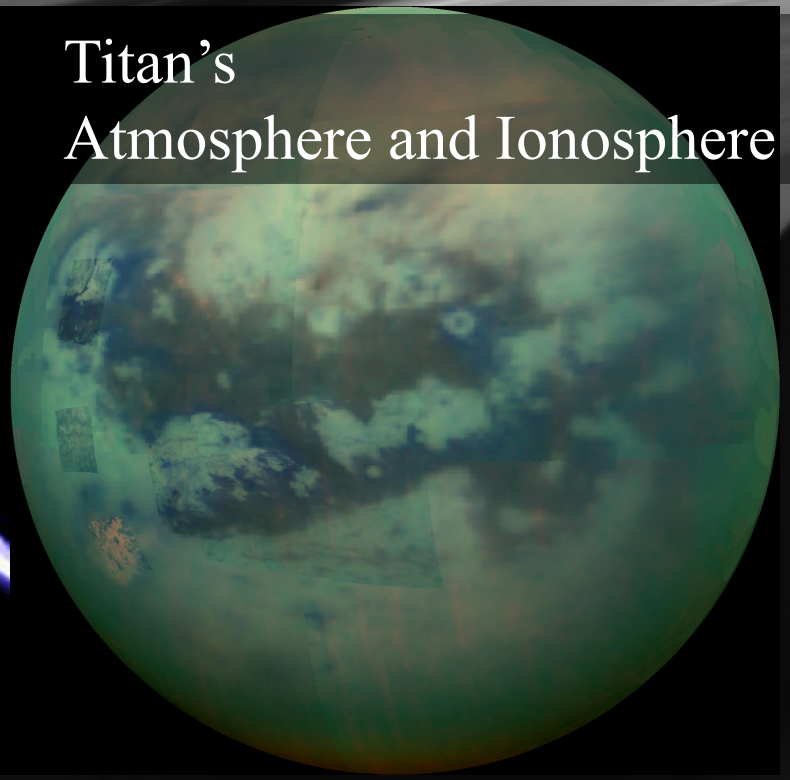
- Ring Grazing orbits:
  - Dusty plasma of nm to sub-μm size dust around the Janus/Epimetheus ring.
  - Similar to what was found near Enceladus, but the grains are smaller.
- Grand Finale orbits:
  - Grains from the main rings influence on Saturn's ionosphere was expected.
  - Ring particle does affect the ionosphere characteristics, but …

Dusty Plasma World of Saturn

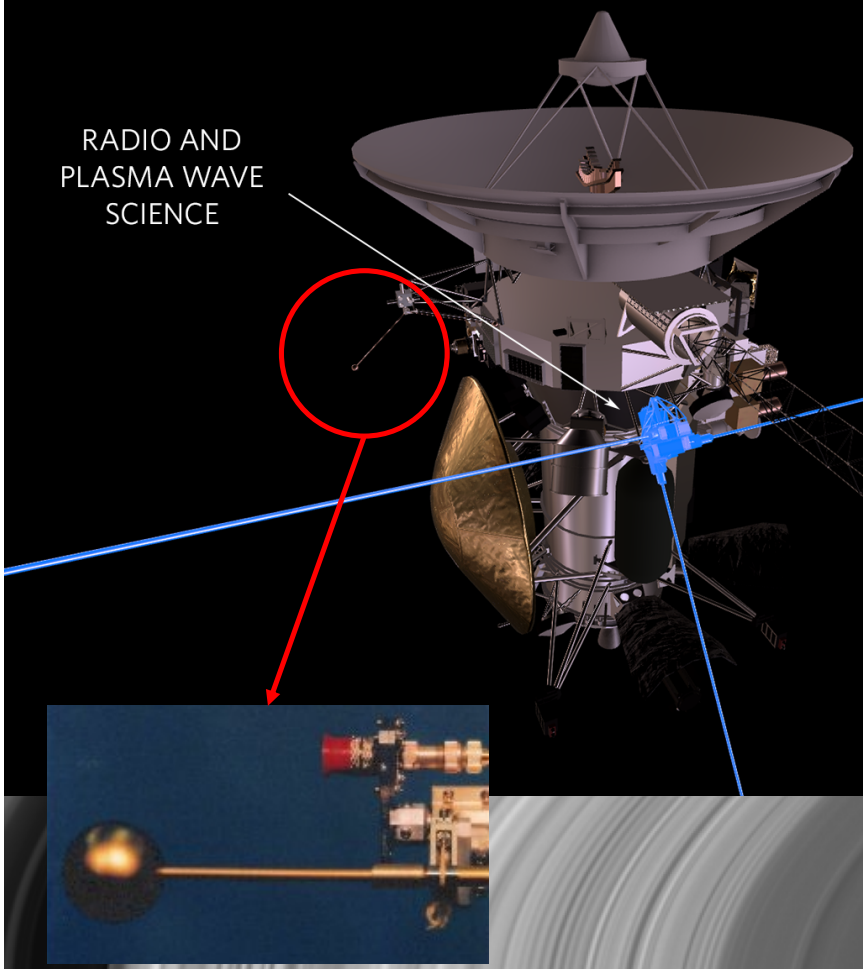
Small dust grains (nm to μm size) are get charged and become a part of Plasma.







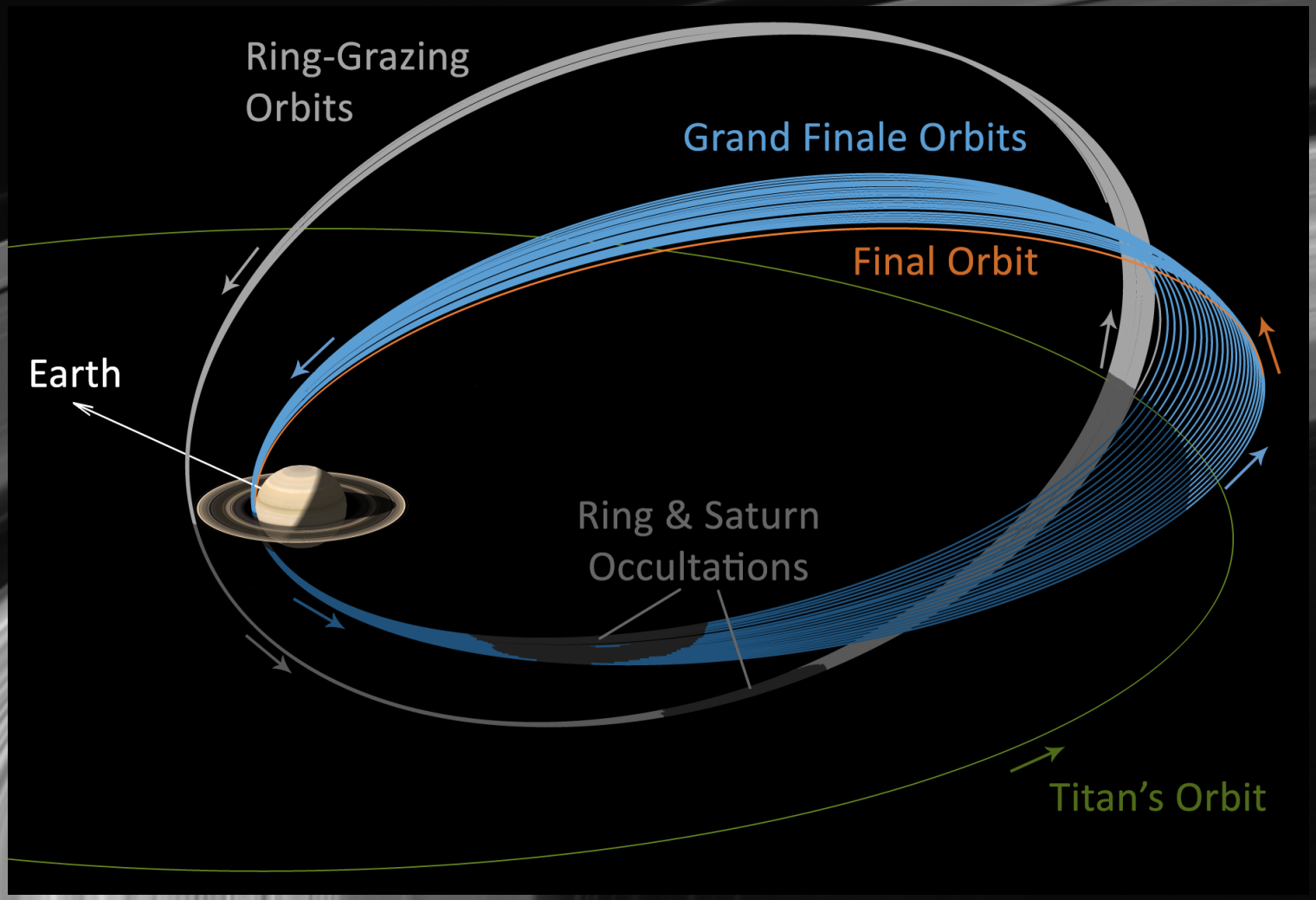
Cassini RPWS instruments



Composed of:

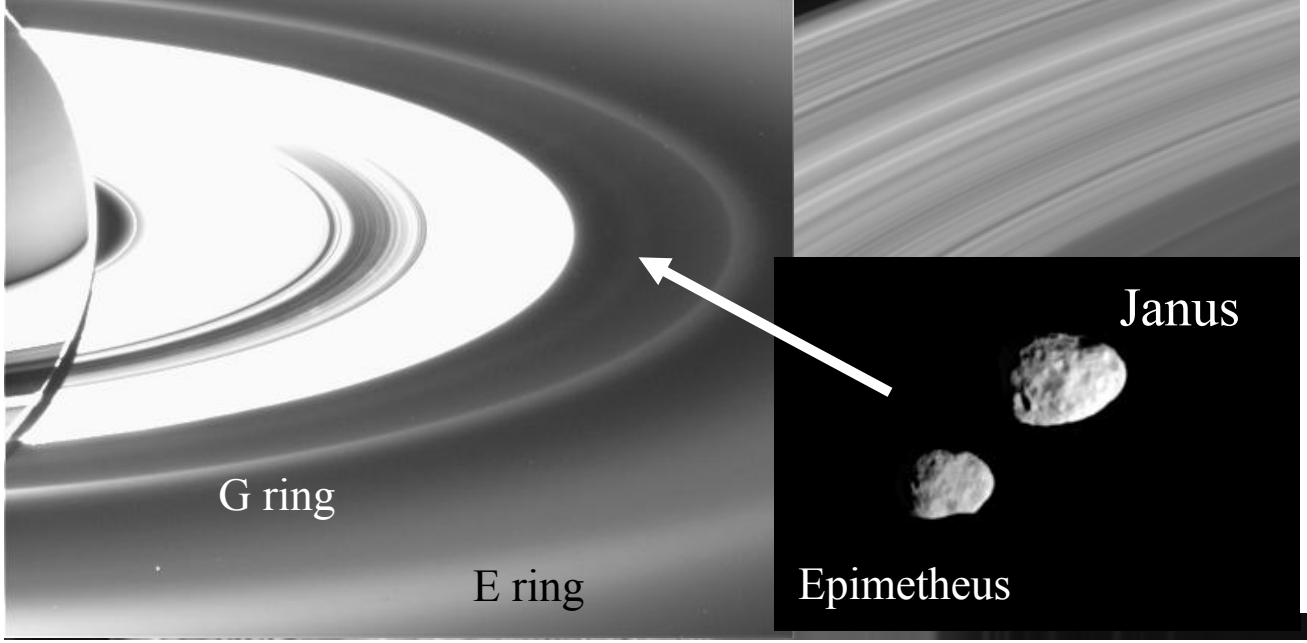
- Three axial E-field and search coiled B-field antenna
  - Detect Radio and Plasma waves such as:
    Plasma frequency, Cyclotron frequency
  - Also capable to detect μm dust grain impact to the spacecraft.
- Langmuir Probe
  Measure the current from the ambient plasma to determine:
  - Electron density, temperature
  - Ion density, mass

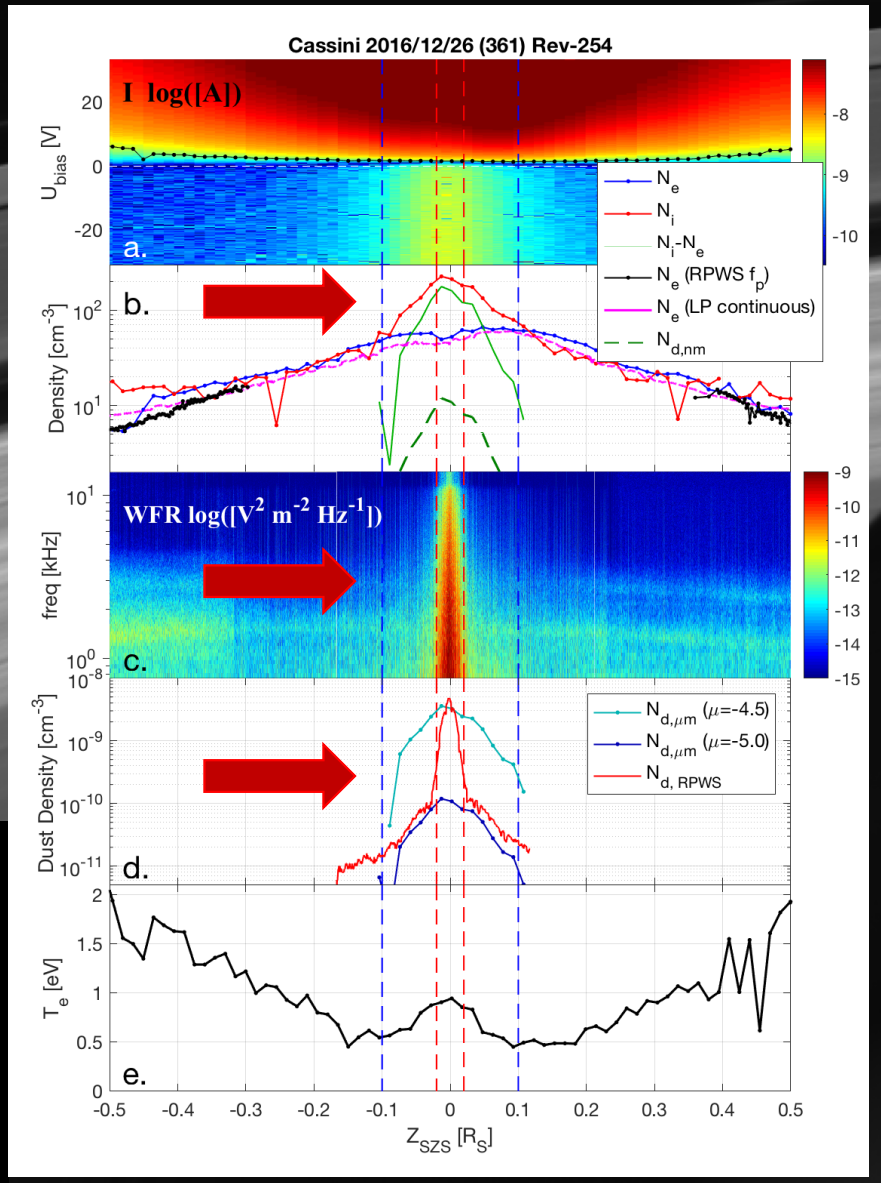
Ring Grazing and Grand Finale Orbits



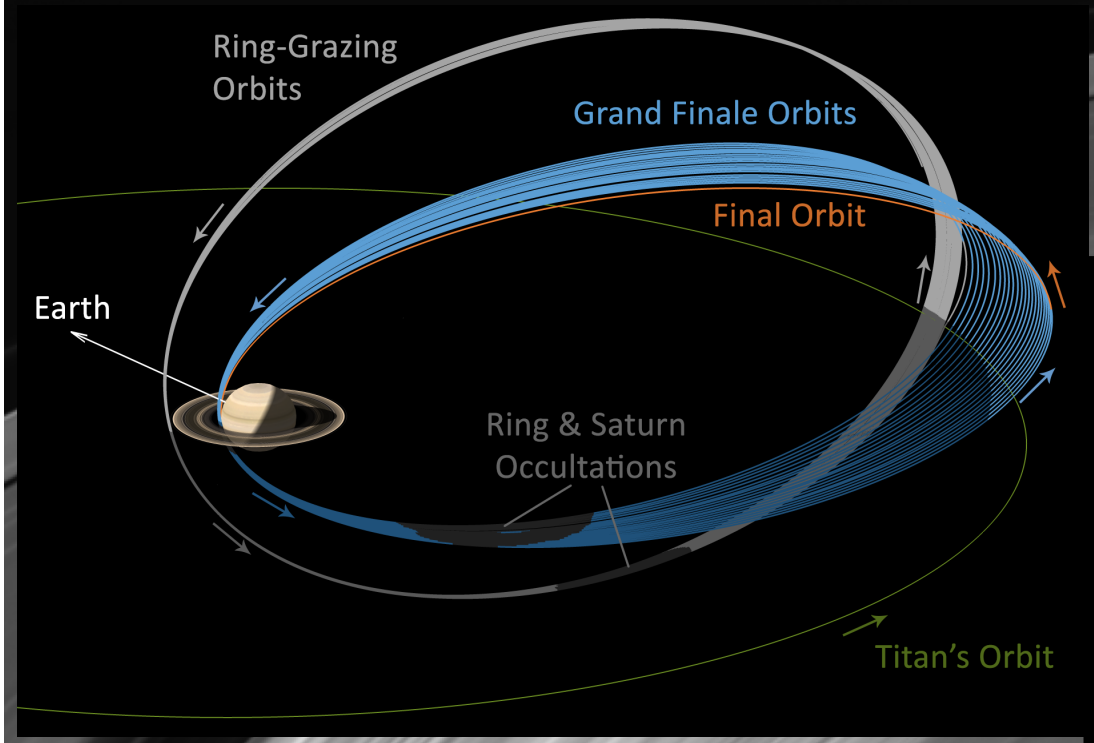
Ring Grazing Orbits

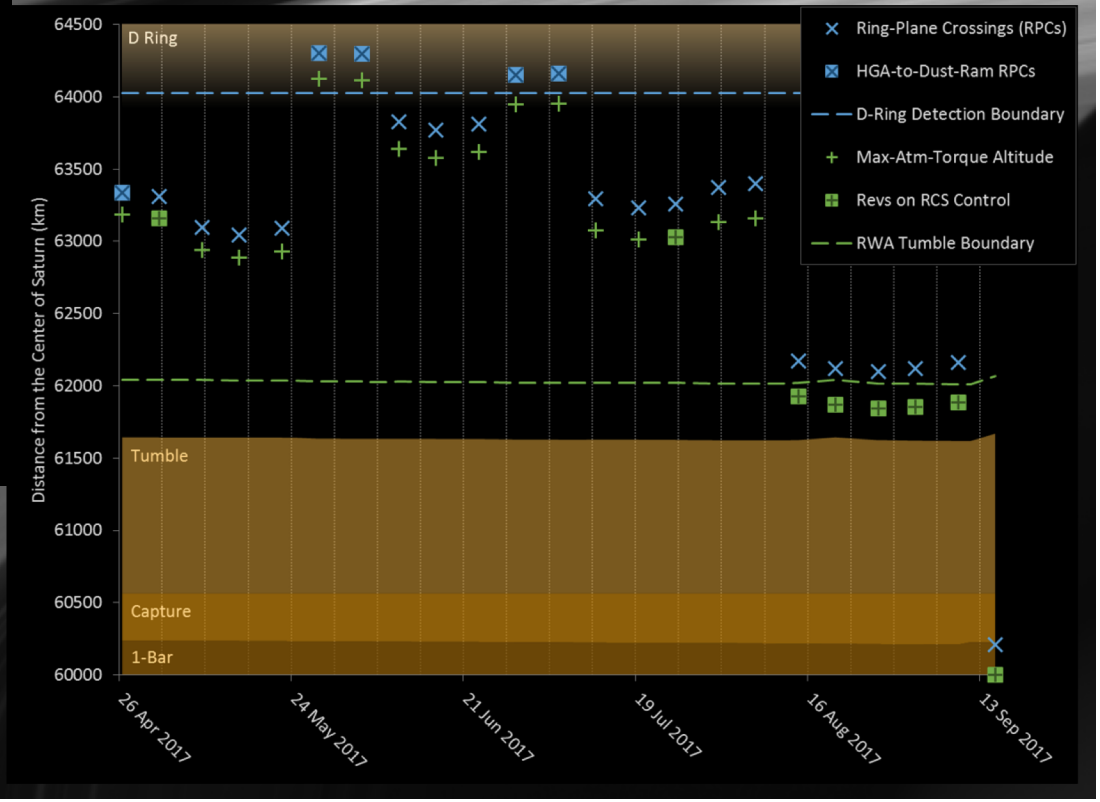
- $N_i >> N_e$
- μm size dust at $|Z| < 0.02R_S$
- Faint Janus/Epimetheus ring is surrounded by dusty plasma of small nm dust.





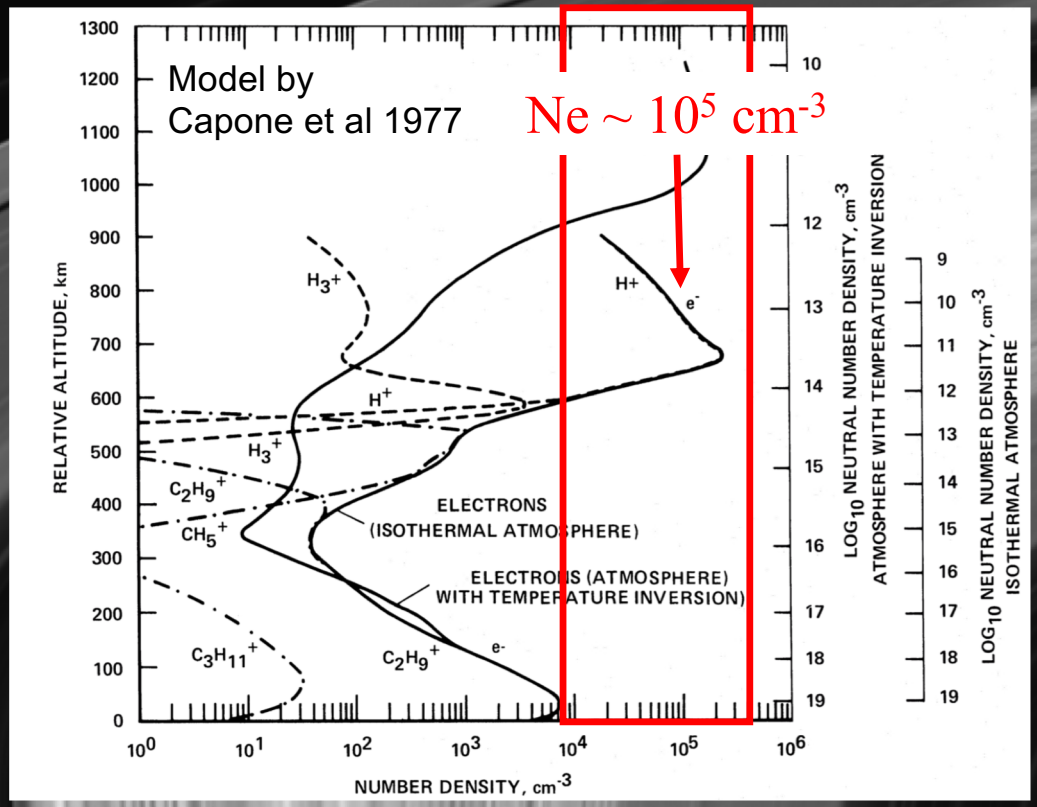
Ring Grazing and Grand Finale Orbits

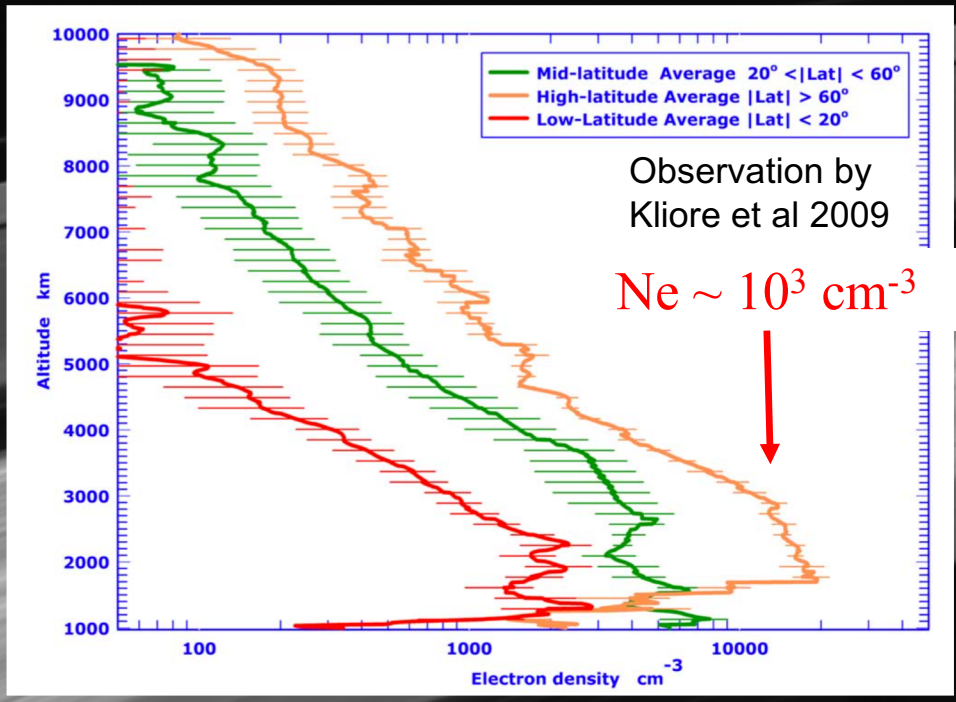




Saturn's Ionosphere

Discrepancies between the model and the observation.





Electron density was much smaller than the predicted value.

‘Ring rain’ hypothesis

Ionosphere chemistry

$$h\nu + H_2 \rightarrow H_2^+ + e \quad (90\%)$$

$$H^+ + H + e \quad (10\%)$$

$$H_2^+ + H_2 \rightarrow H_3^+ + H$$

$$H_3^+ + e \rightarrow H_2 + H$$

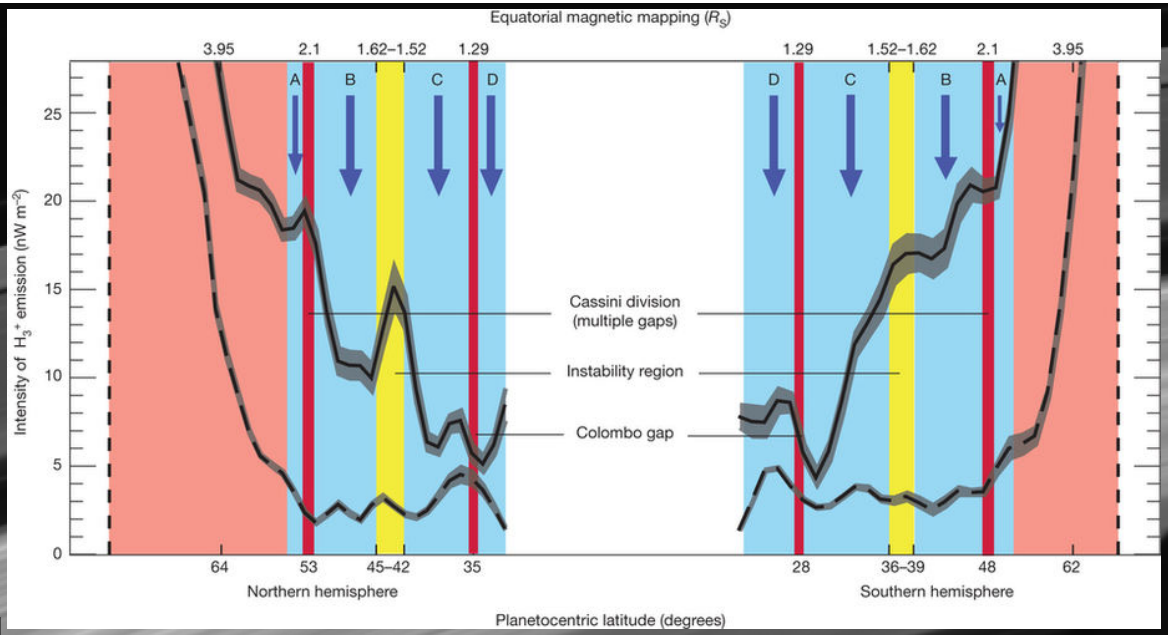
H+ only recombines with electrons 10^4 times less efficient.

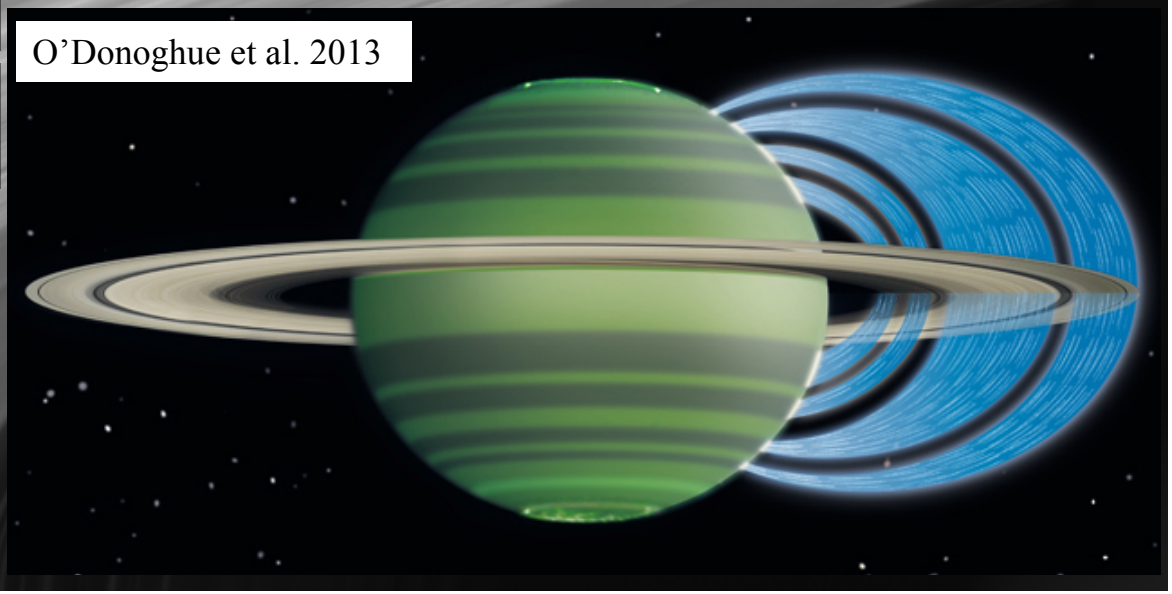
In order to address the excessive electron densities, it was suggested:

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

$$H_2O^+ + H_2 \rightarrow H_3O^+ + H$$

$$H_3O^+ + e \rightarrow \begin{cases} H_2O + H \\ OH + 2H \end{cases}$$

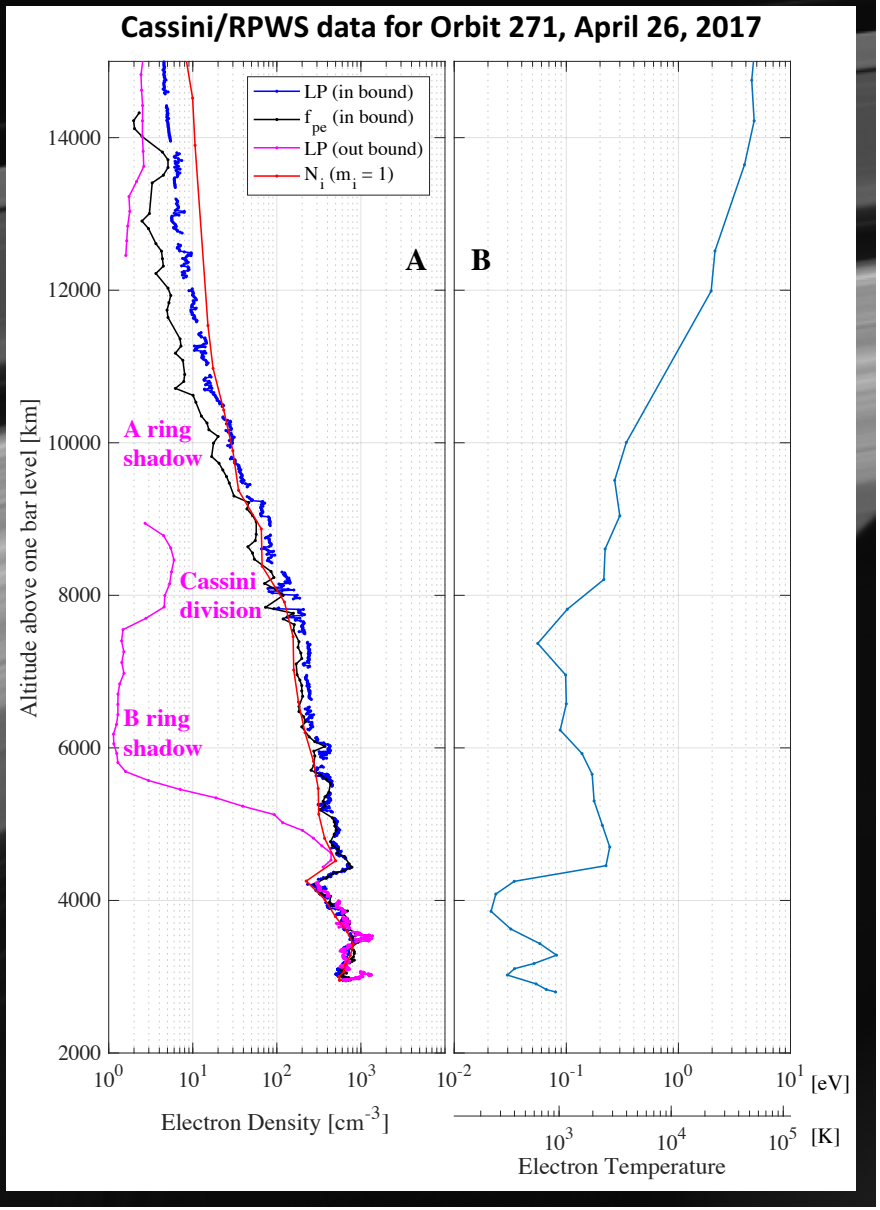




N_e during Grand Finale

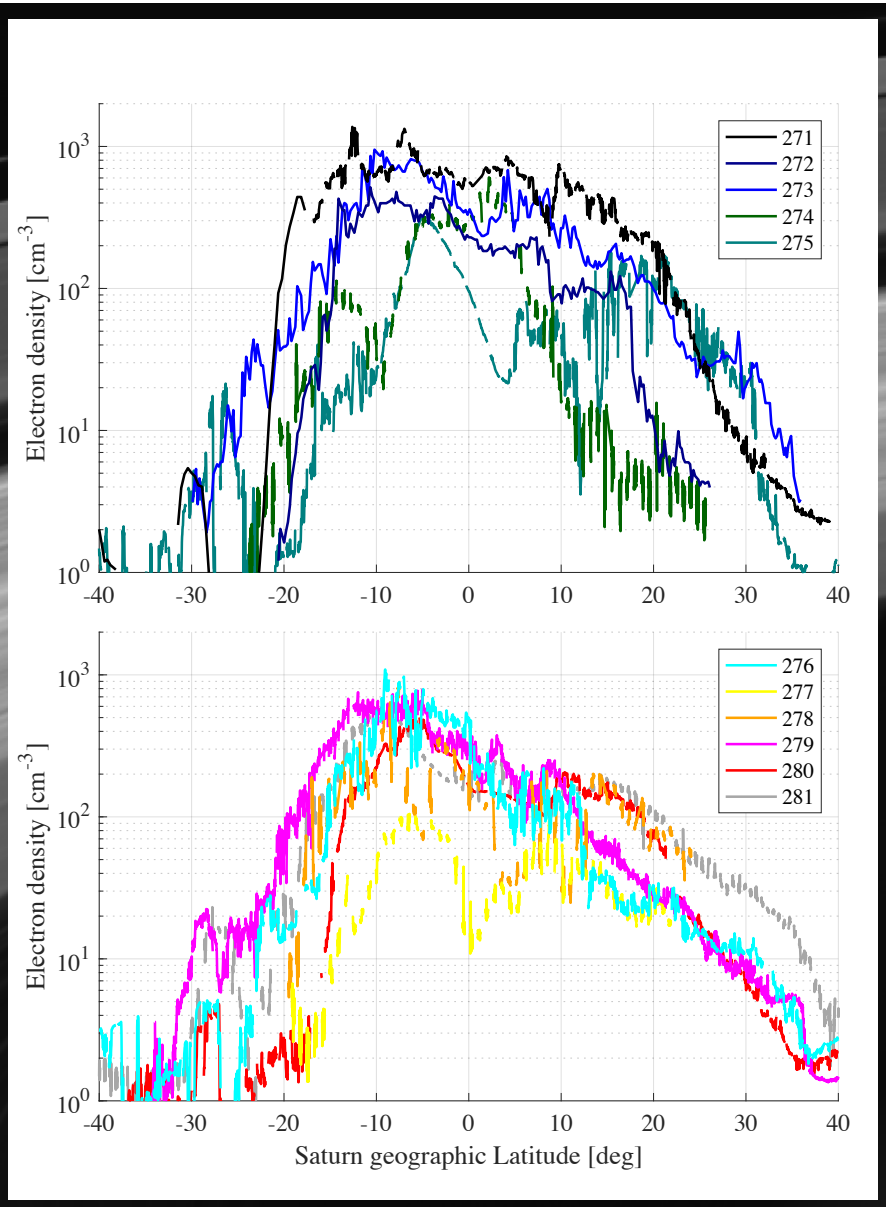
- First in-situ detection
  - Langmuir probe electron current
  - Whistler emission cut-off (f_{pe})
  - LAT – Altitude cut of topside ionosphere
- Ionizing EUV ring shadow effect detectable on outbound
  - D- or C-ring are optically thin.
  - Optically thick A & part of B rings.
  - Cassini division effect.
- Consistent with H^+ dominance
  - LP ion current

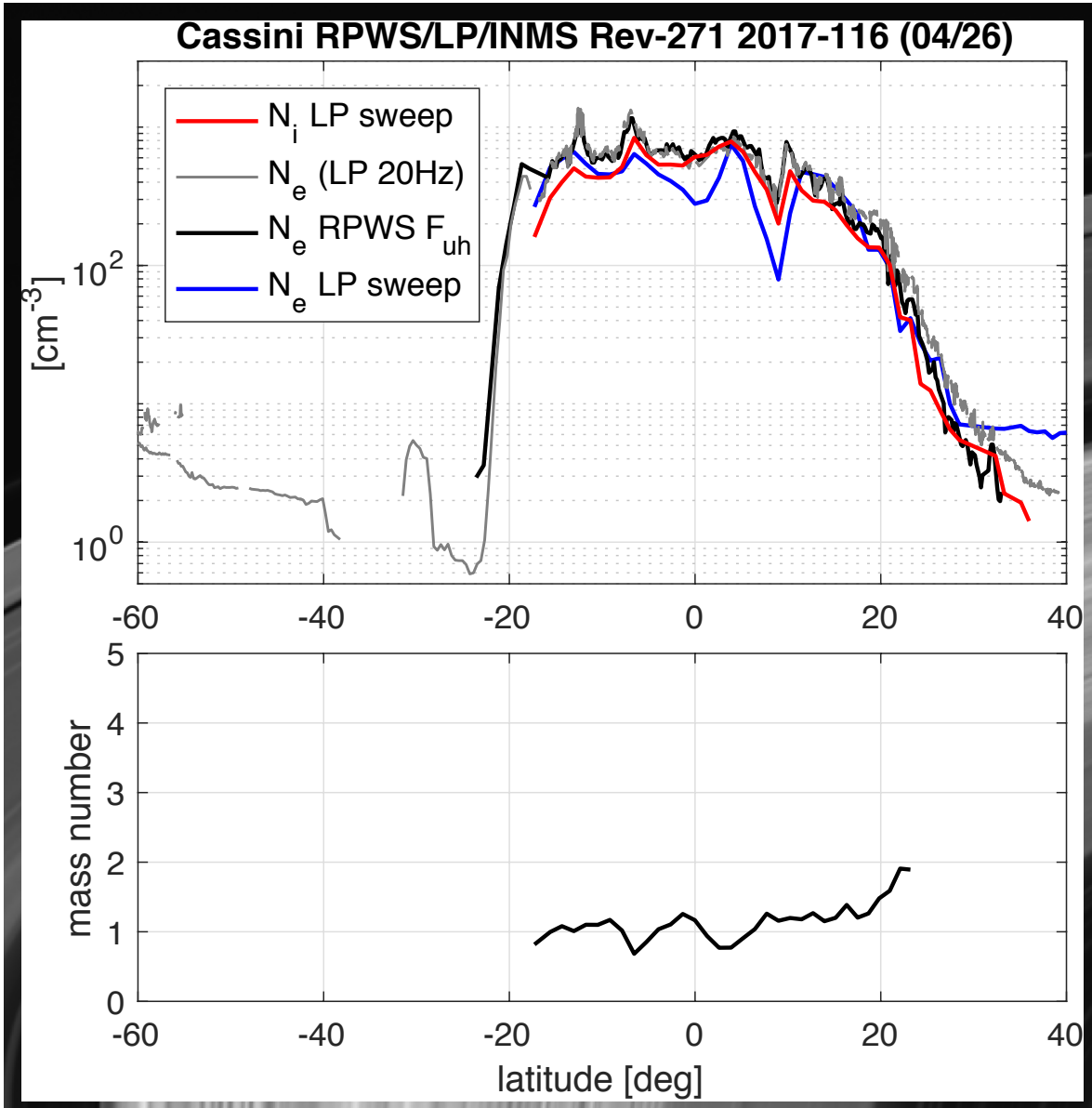
Wahlund et al. 2018, Science

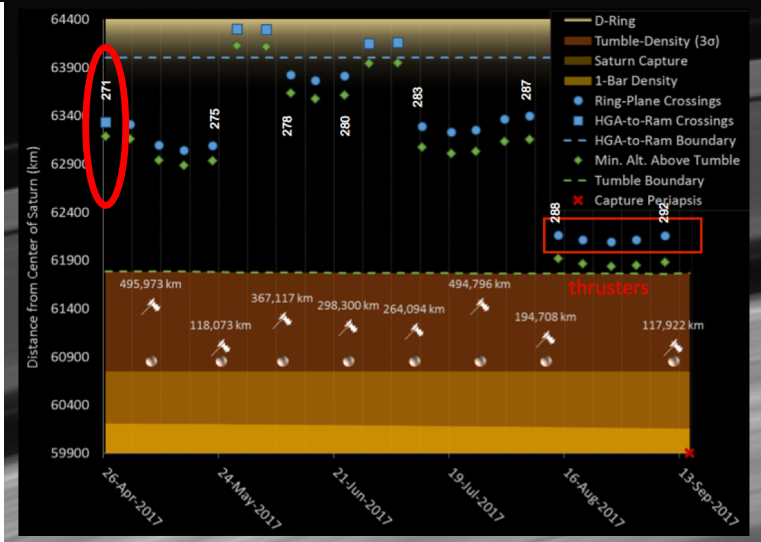


Ionosphere variability

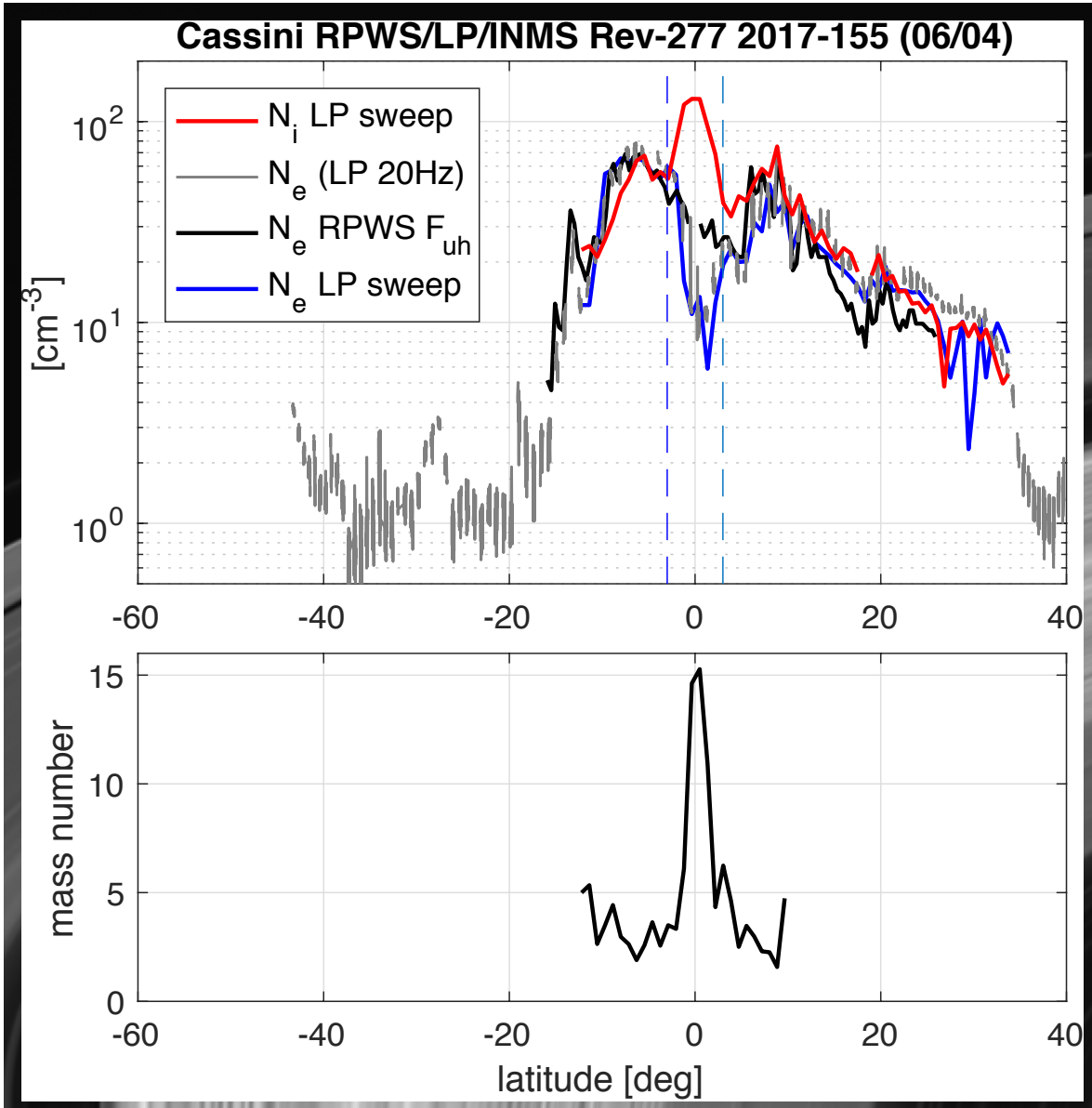
- 2 orders of magnitude variation.
- 6.5 days between flybys
- ~30 min flybys

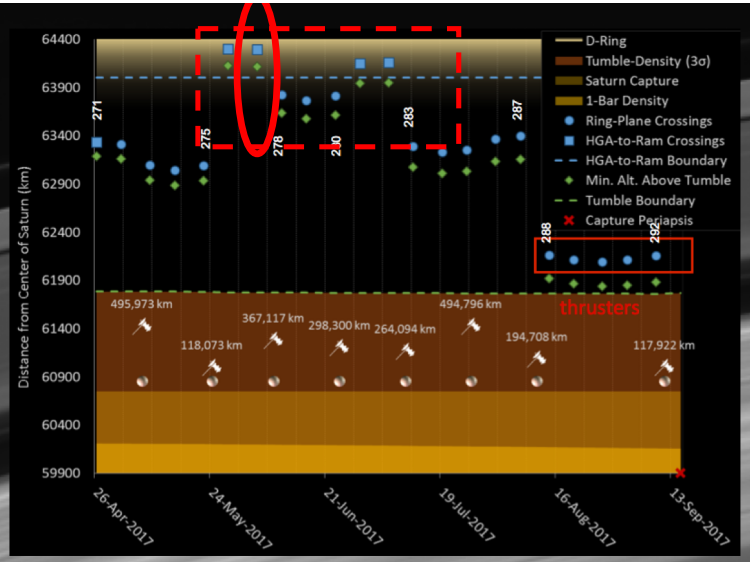




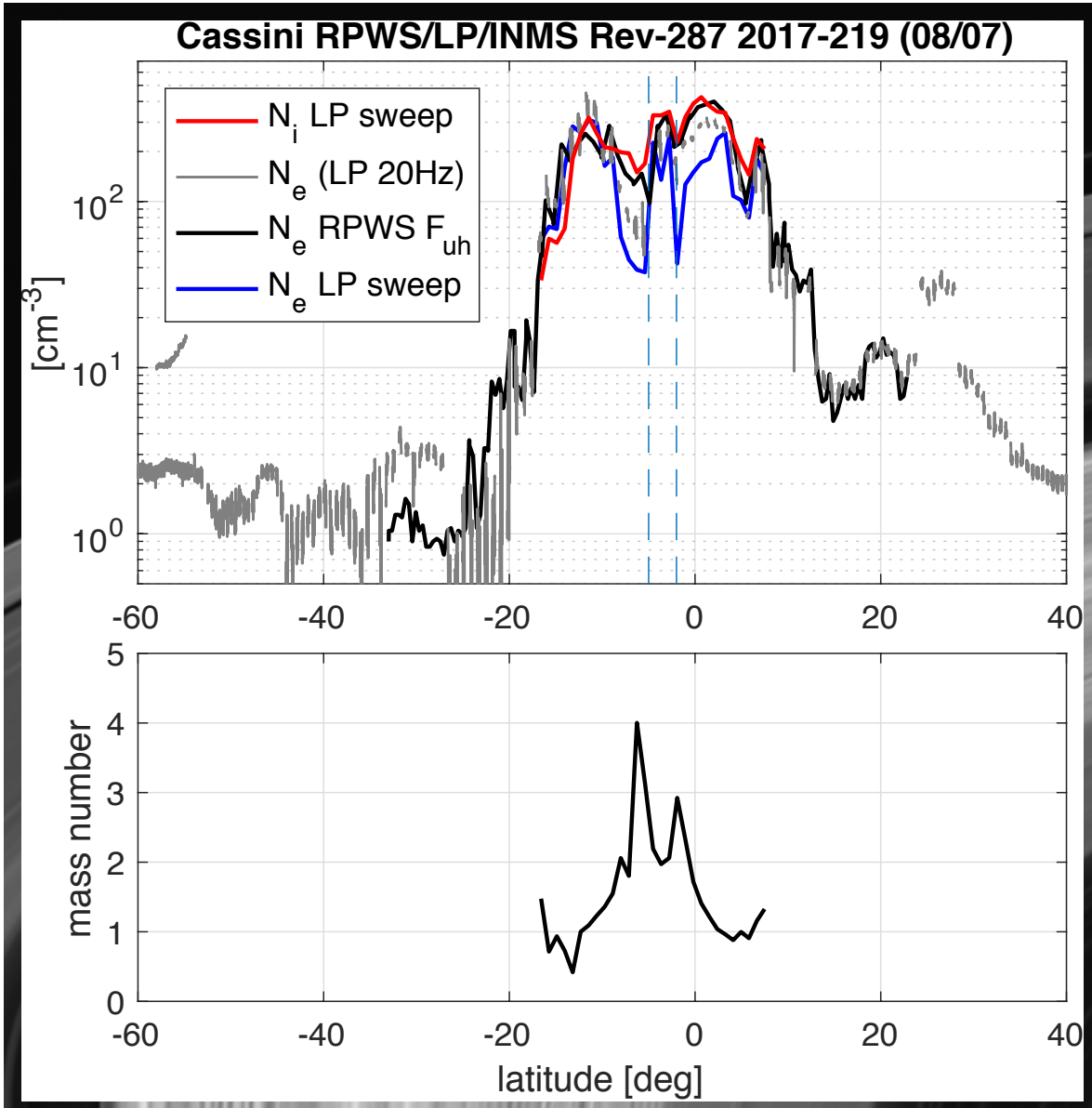


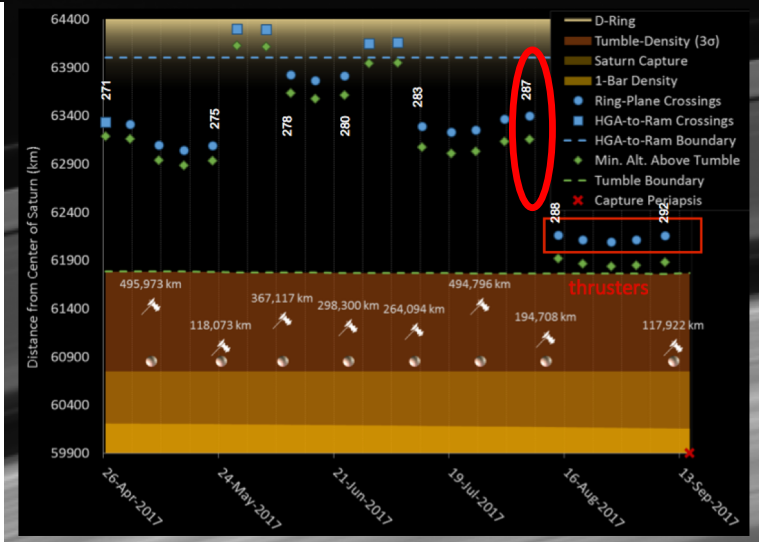
- The first proximal orbit data showed all consistent densities with H^+ plasma.



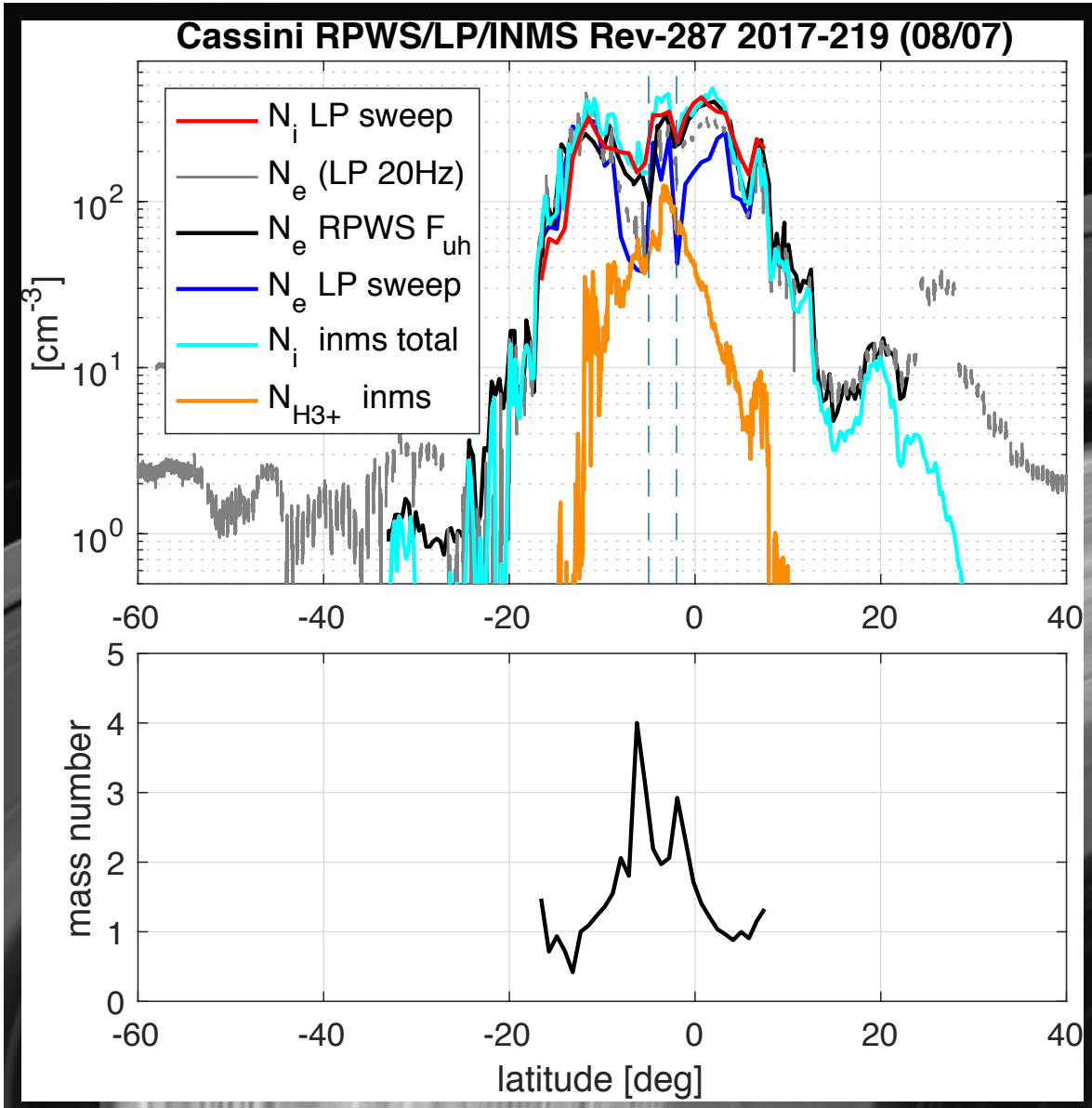


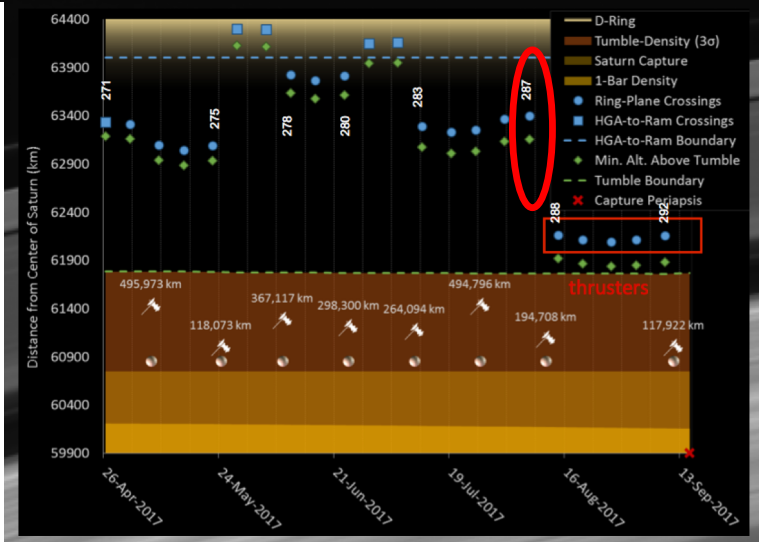
- The first proximal orbit data showed all consistent densities with H^+ plasma.
- But some orbits observed $N_i > N_e$ and $m_i > 1$.
- At high altitudes orbits (Rev276 - 282), $N_i > N_e$ occurred at latitude 0°.





- Some orbits observed $N_i > N_e$ and $m_i > 1$.
- At high altitudes orbits (Rev276 - 282), $N_i > N_e$ occurred at latitude 0°.
- During Rev-287 (middle altitude), $N_i > N_e$ region shifted to lower latitude.





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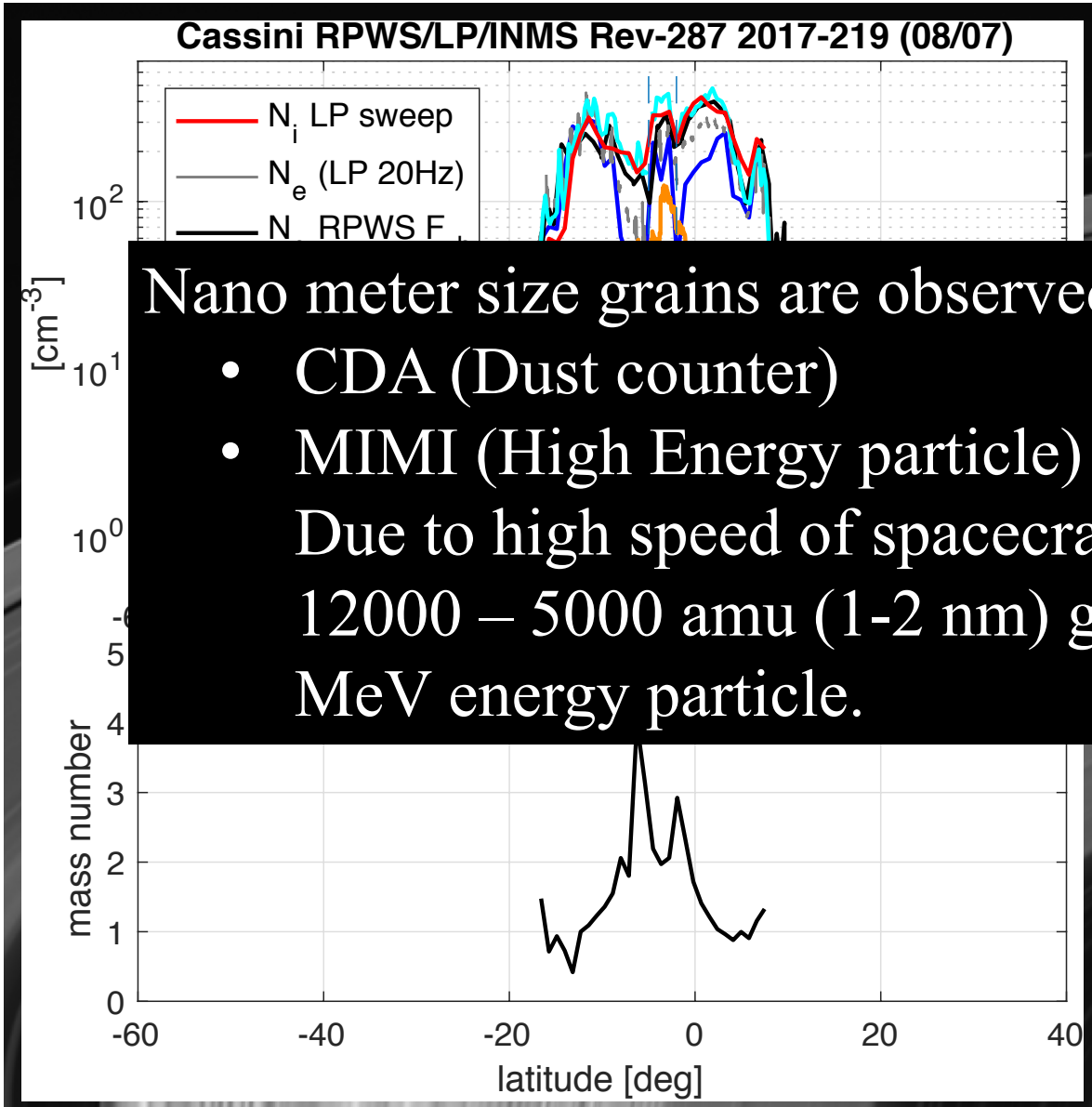
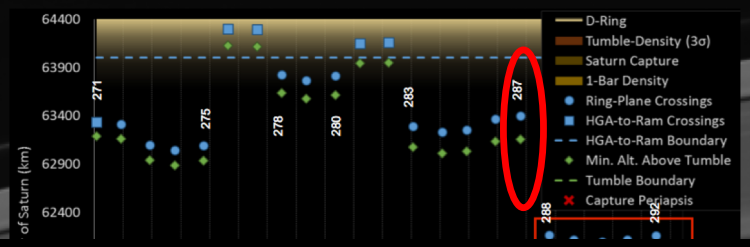
- At high altitudes orbits (Rev276 - 282), $N_i > N_e$ occurred at latitude 0°.
- During Rev-287 (middle altitude), $N_i > N_e$ region shifted to lower latitude, and associated with H^{3+} increasing.
- $m_i > 1$ estimated.





Nano meter size grains are observed here by

- CDA (Dust counter)
- MIMI (High Energy particle)

Due to high speed of spacecraft (31 km/s), 12000 – 5000 amu (1-2 nm) grains are detectable as MeV energy particle.

282), $N_i > N_e$ occurred at latitude 0°.

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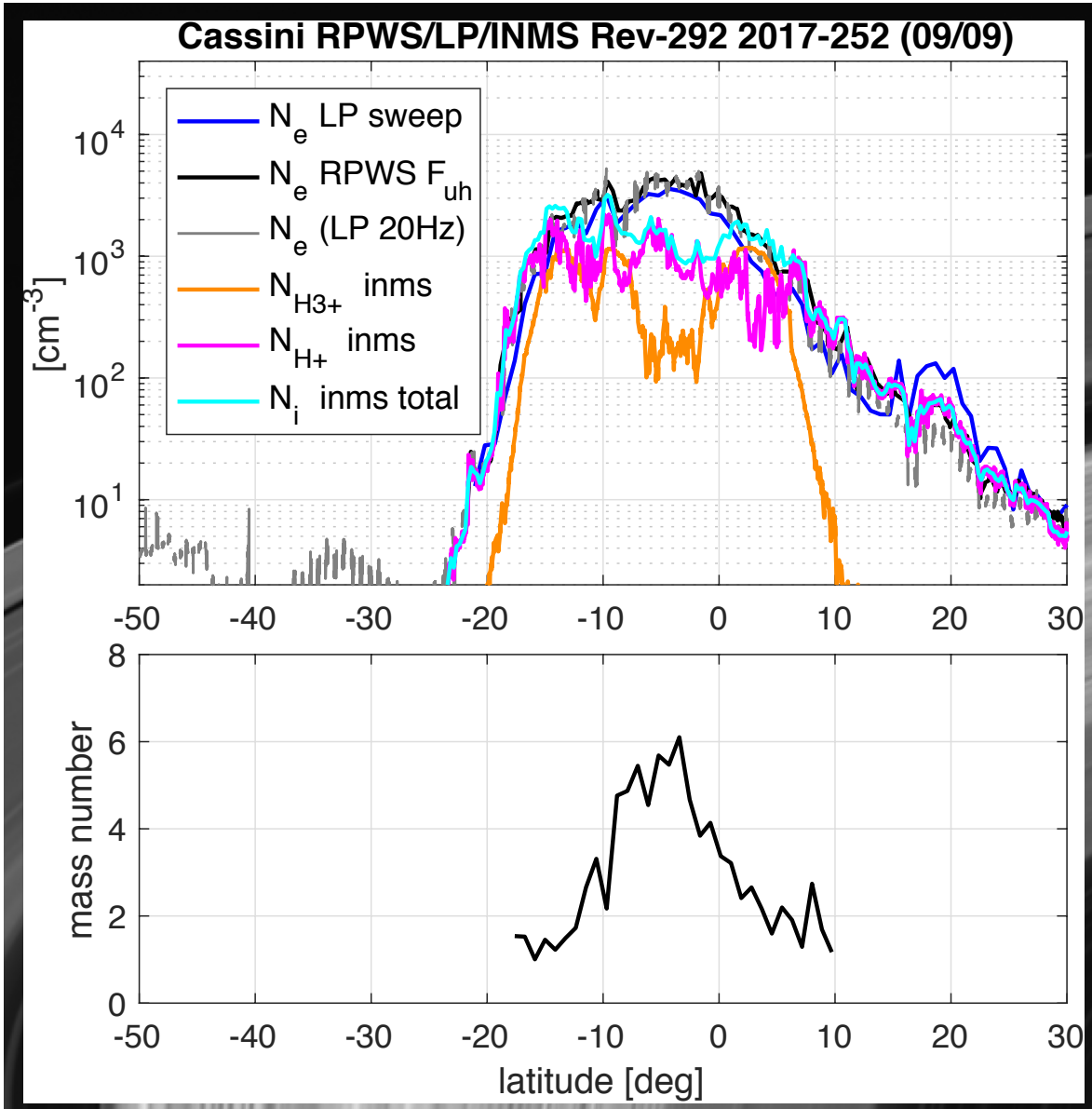
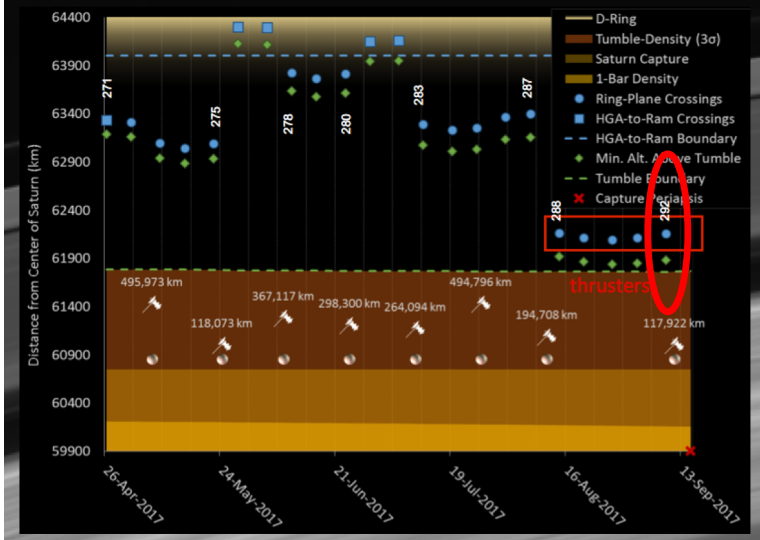
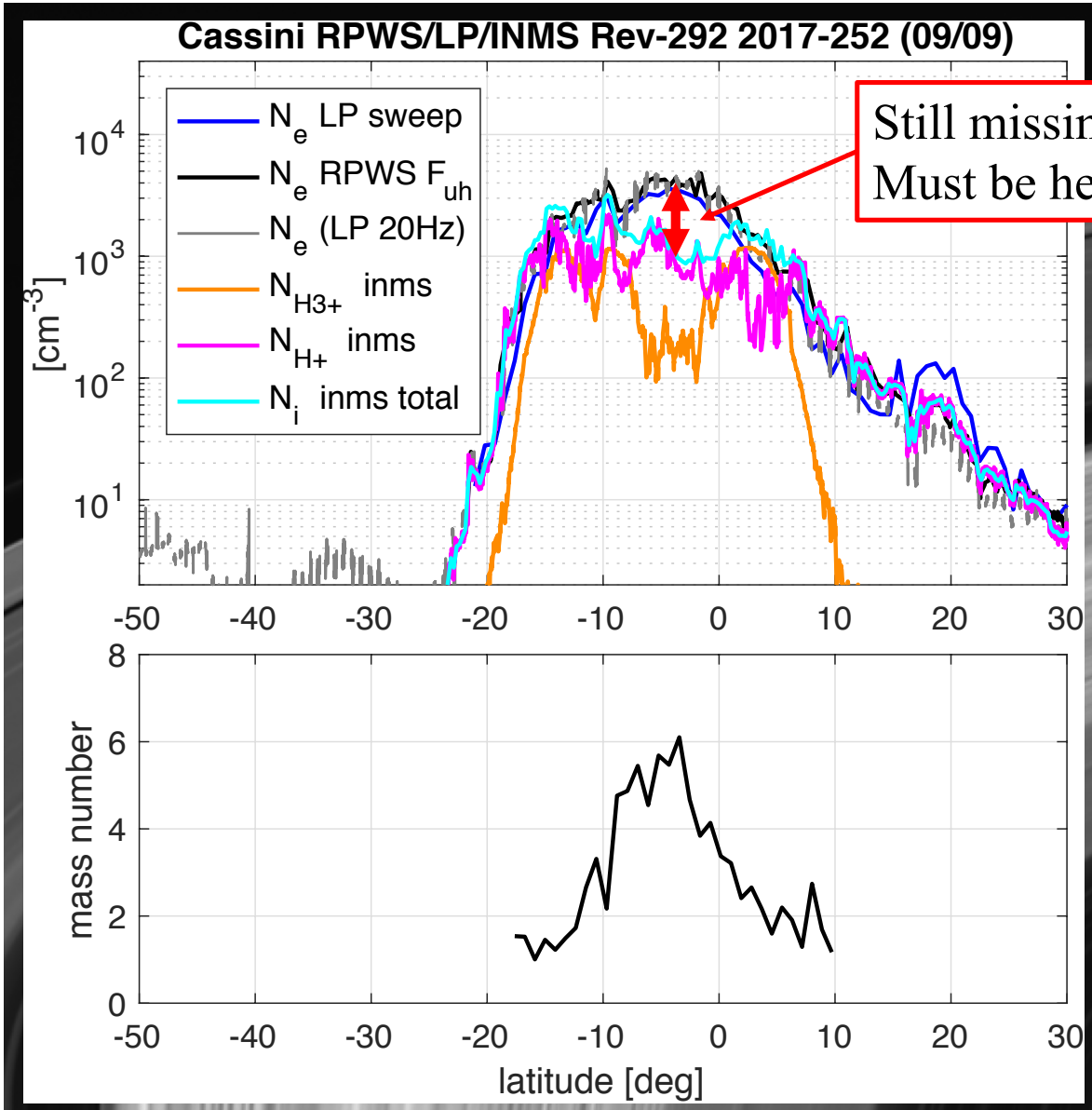
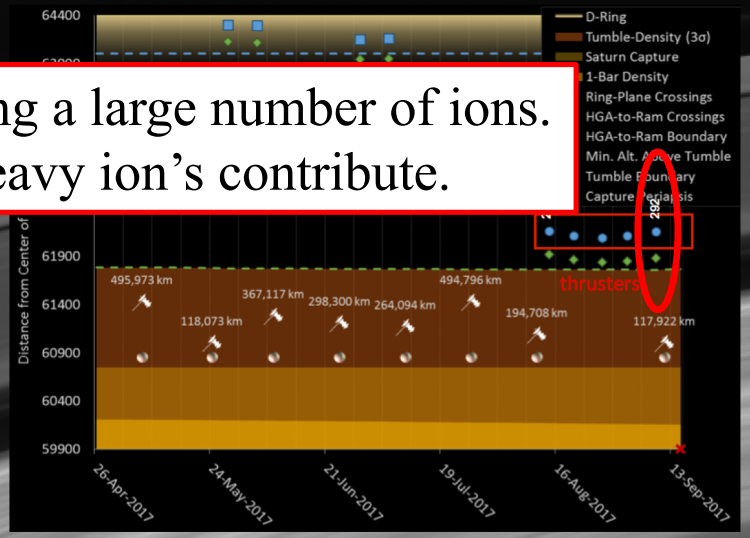




- During Rev 293 (low altitude), N_e increases as decreasing altitude.
- H^{3+} dominance also showed at low altitude, but density dip appears at closest approach while $N_{I,LP}$ continue increase at low altitude.



Still missing a large number of ions. Must be heavy ion's contribute.



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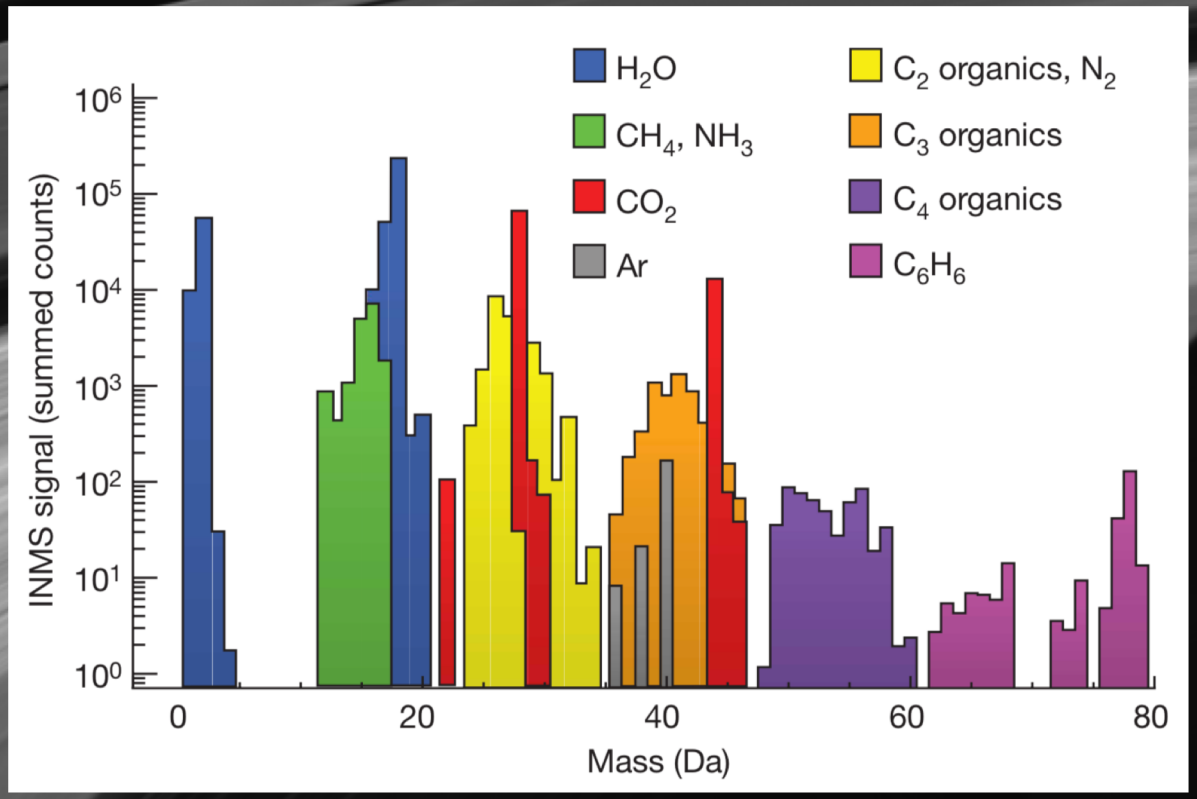
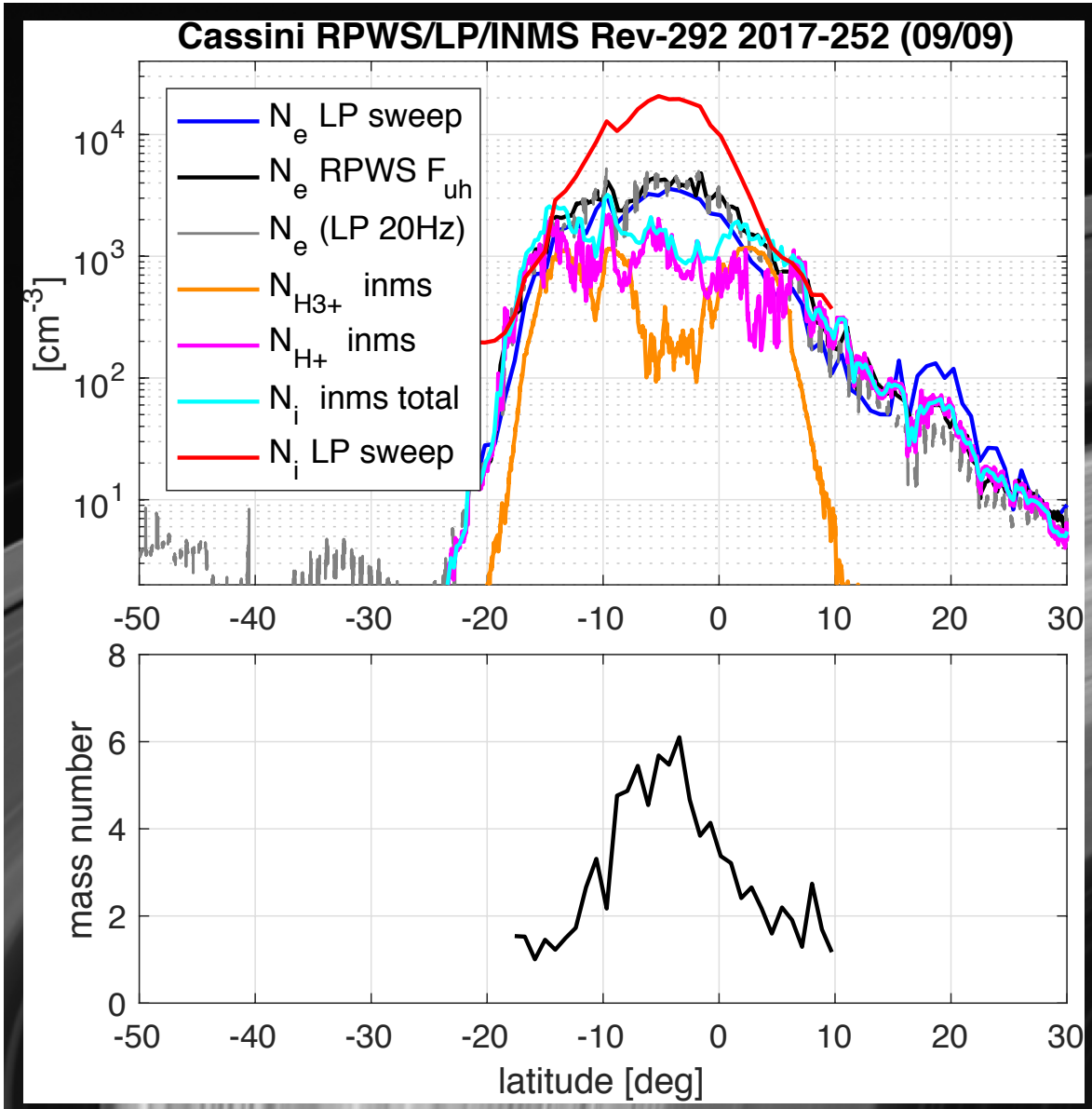
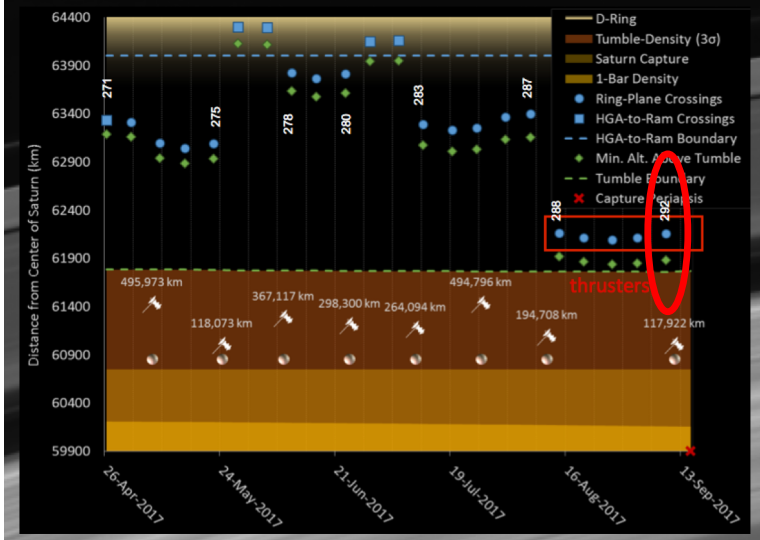
Organic molecules

- INMS observed organic heavy materials in Enceladus plume, Titan's deep ionosphere.
- INMS observed signature organic heavy neutrals also in Saturn's ionosphere.







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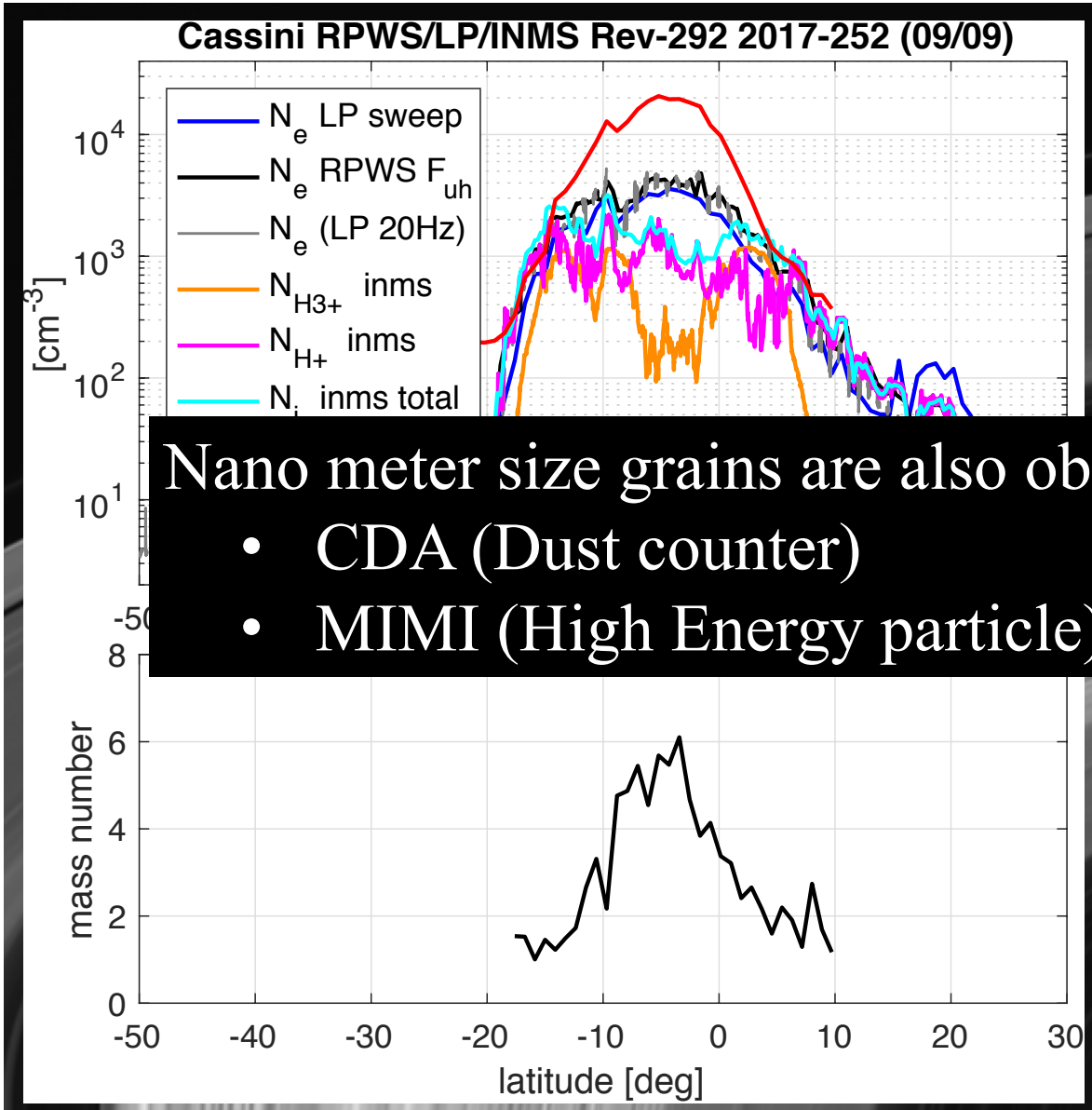
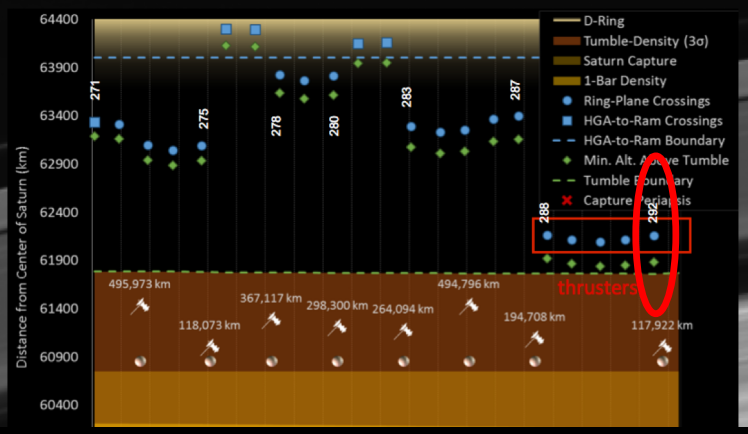
- H^{3+} dominance also showed at low altitude, but density dip appears at closest approach while $N_{I,LP}$ continue increase at low altitude.
- Ni exceeds Ne at closest approach.
- Estimated m_i increase as decreasing altitude.





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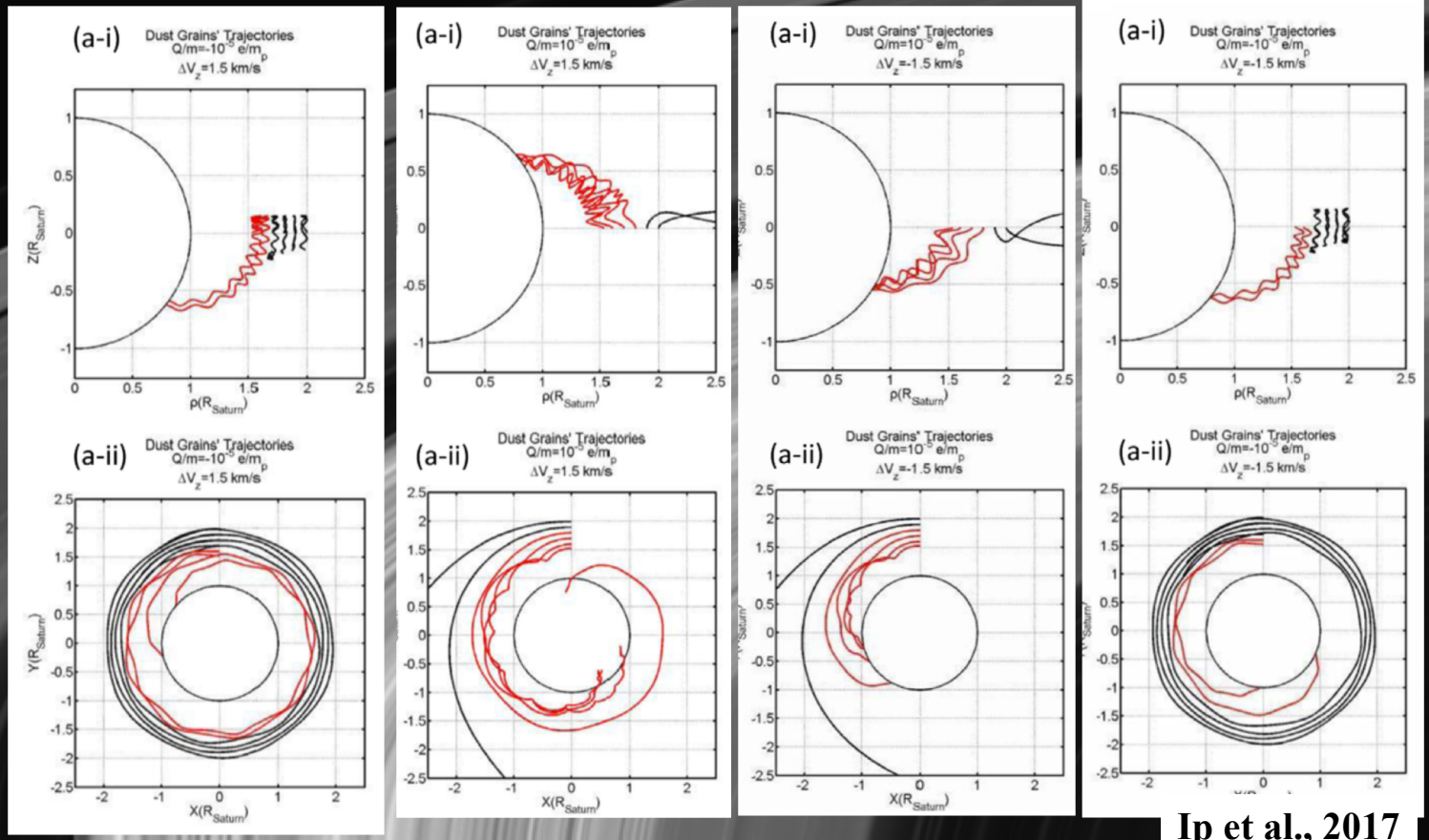
- H^{3+} dominance also showed at low altitude, but density dip appears at closest approach while $N_{I,LP}$ continue increase at low altitude.
- Ni exceeds Ne at closest approach.
- Estimated m_i increase as decreasing altitude.

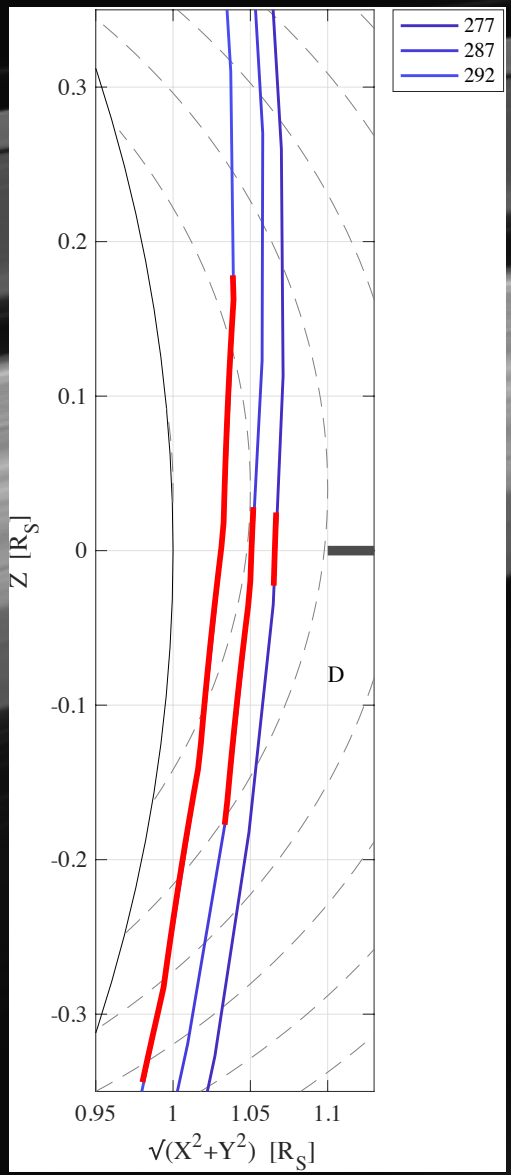
Ring particle cascade down to Saturn's ionosphere

Upward particle | **Downward particle**

Negative | **Positive** | **Negative** | **Positive**



Ip et al., 2017



Ring – Ionosphere interaction

- Grand Finale orbits gave unique opportunity to investigate Saturn's ionosphere at low latitudes.
- Classical 'Ring rain' effect (ring grain precipitates along the B-field and effect the ionospheric chemistry) has not confirmed, however, ring dust affect to the ionosphere significantly in different way, dusty plasma (or, heavy ion plasma).
- D ring dust in Saturn's ionosphere was confirmed by several instrument.
- Charged nano-meter sized dust precipitate into the ionosphere and further fragmented small cluster ions and become a complex dusty ionosphere of Saturn.