Relative fractions of water-group ions in Saturn's inner magnetosphere

O^+, OH^+, H_2O^+, H_3O^+

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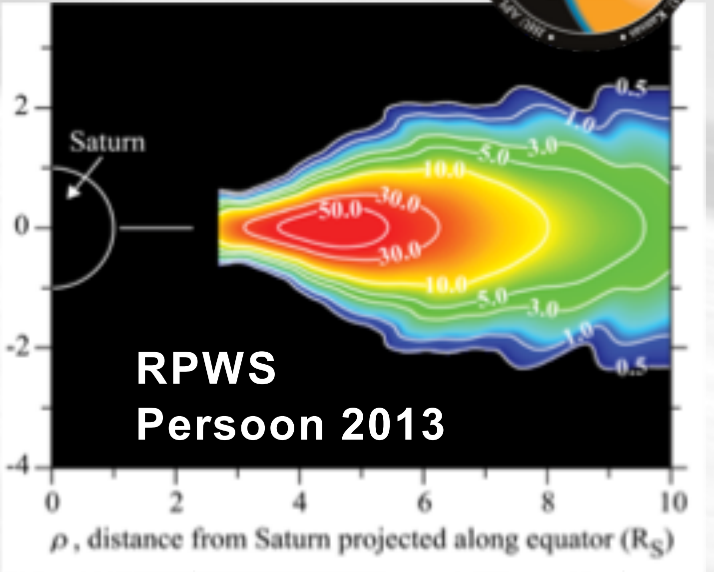
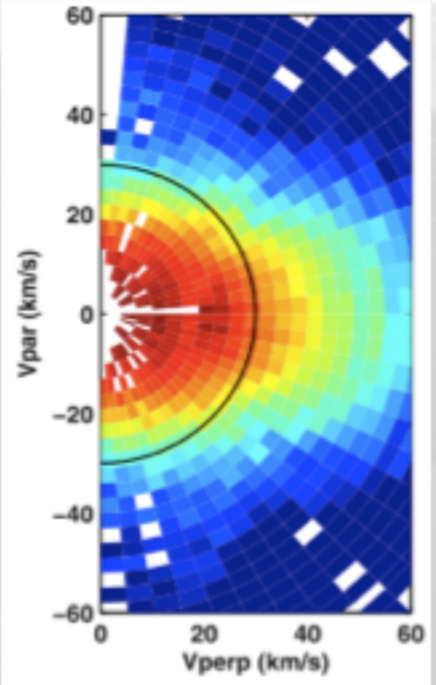
The plasma in Saturn’s inner magnetosphere

- Water ions comprise the bulk of Saturn’s plasma.
  - Nitrogen from Titan is less than 10%.
- From the Cassini Plasma Spectrometer (CAPS), know the temperature, density, and velocity distribution of the ions.
  - The water source is Enceladus, so neutral and ion densities peak near 4 R_S, and decay outward and inward.
  - Saturn’s inner magnetosphere is neutral dominated.
- Since the four water-group ions have similar masses and energies, it is challenging to extract the detailed composition of the water-group ions from CAPS data.
- The water-group fractions are sensitive probes of the source, transport, and loss mechanisms that govern Saturn’s magnetosphere.





Velocity-space densities at 4-4.5 Rs (Tokar 2008)

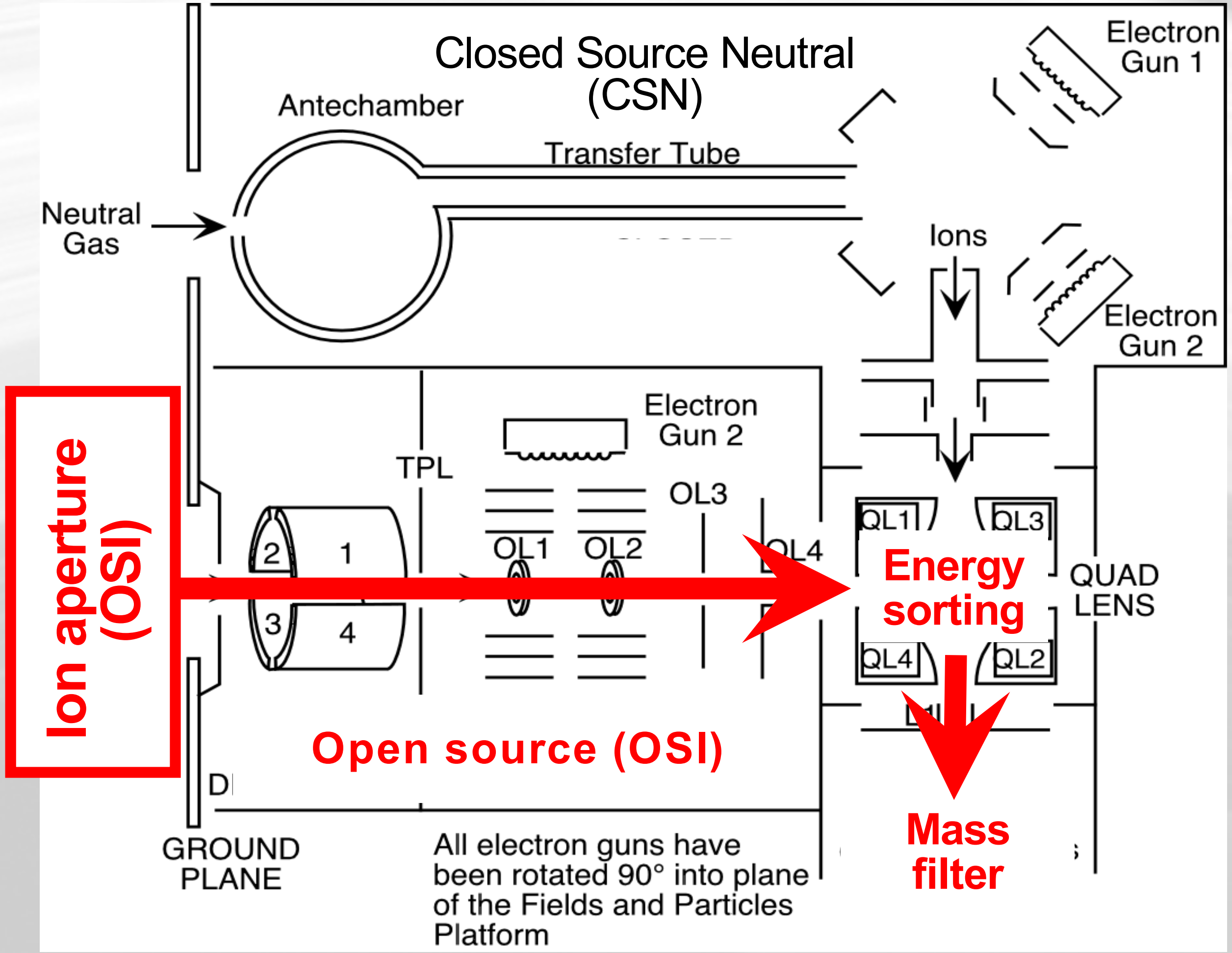
INMS measures ion mass, directly

- Cassini's Ion and Neutral Mass Spectrometer (INMS) measures the individual ions separately.
  - No assumptions or fitting required.
  - One mass, one velocity at a time.
- Each measurement samples a small portion of velocity space at a time.
  - **Narrow FOV** (2° radius); ±1 km/s.
  - Limitation 1: Densities and count rates are low, sometimes requiring the aggregation of 10,000 measurements (IPs) for a 2σ result.
  - Limitation 2: velocity-space variations are convolved with changes due to other factors, complicating interpretation.
  - Maximum velocity for water ions: 20 km/s.

<u>Quadrupole mass spectrometer</u>

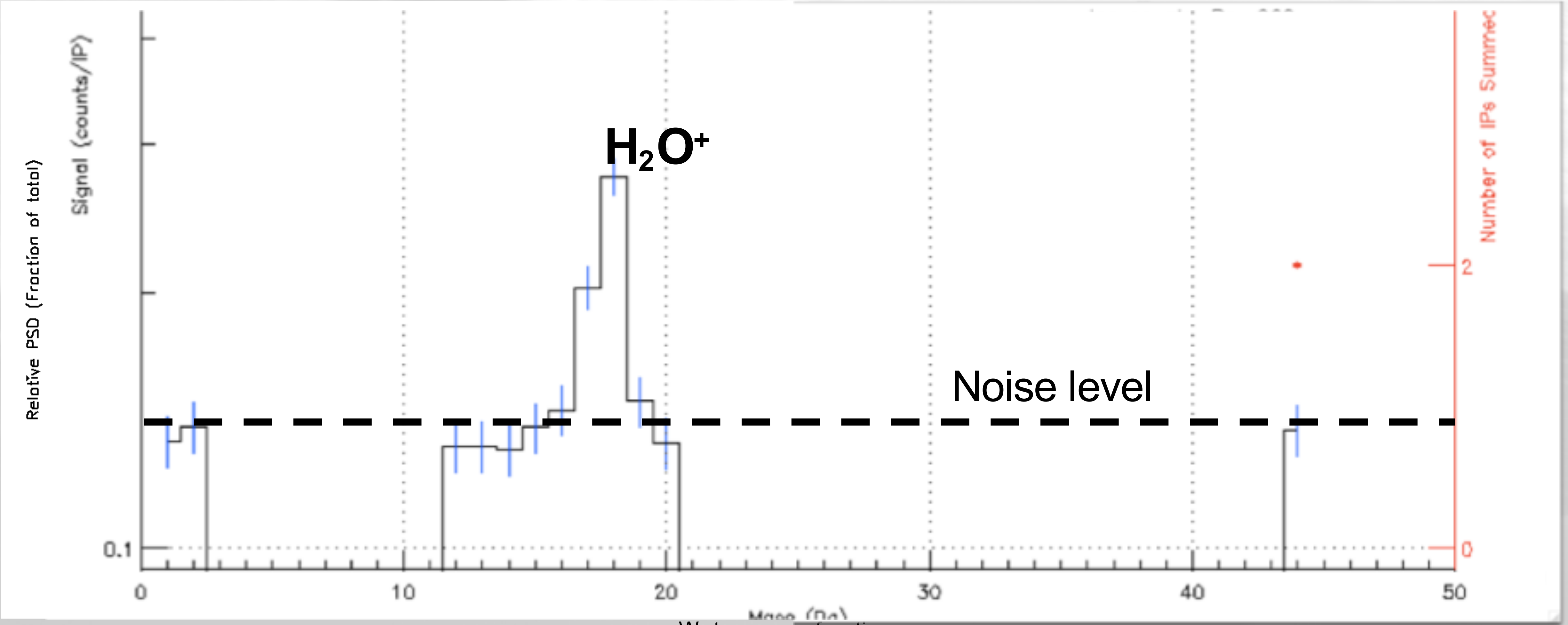
Mass range: 1-8, 12-99 u (AMU or Da)

Mass resolution: 0.12 AMU



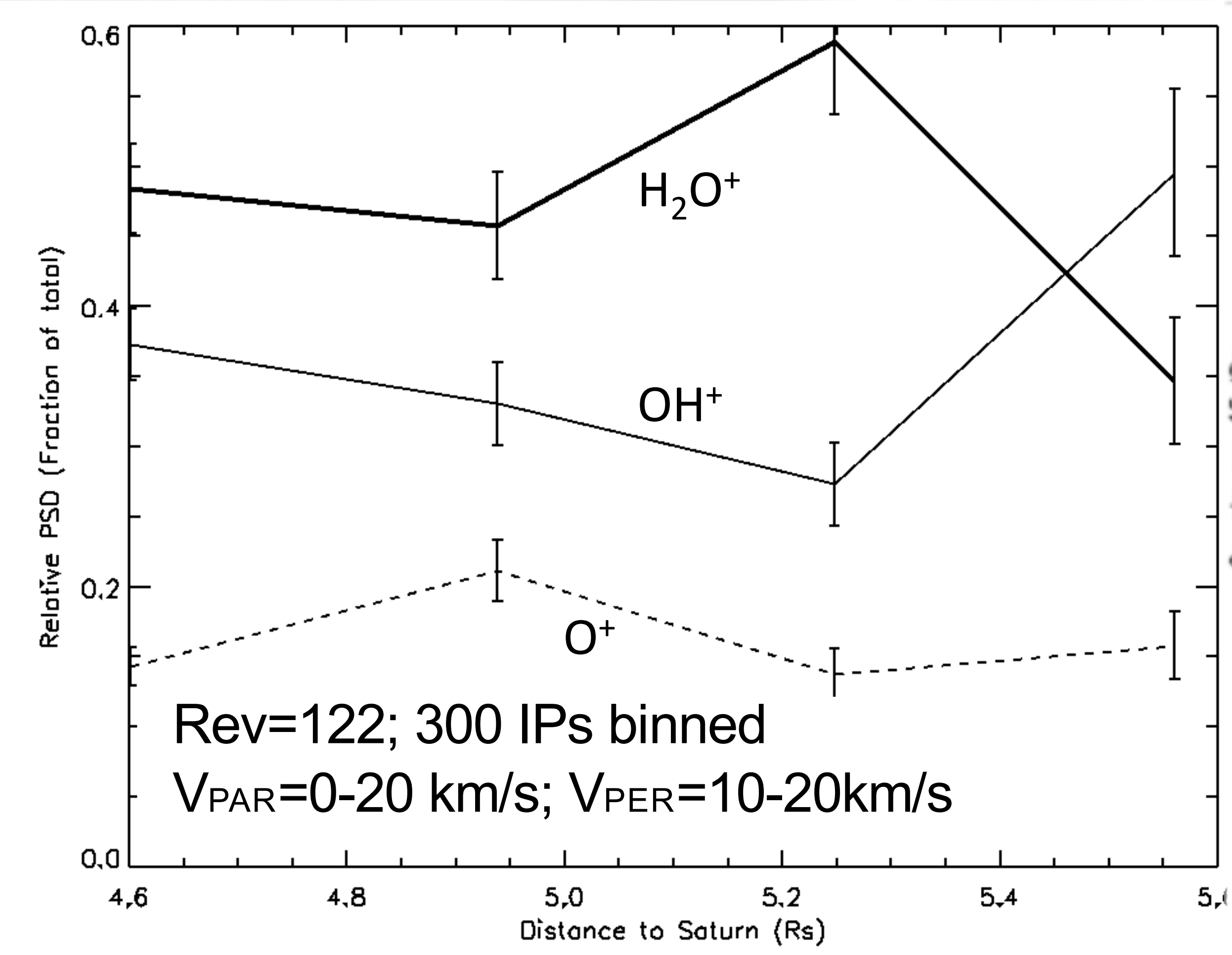
Raw data

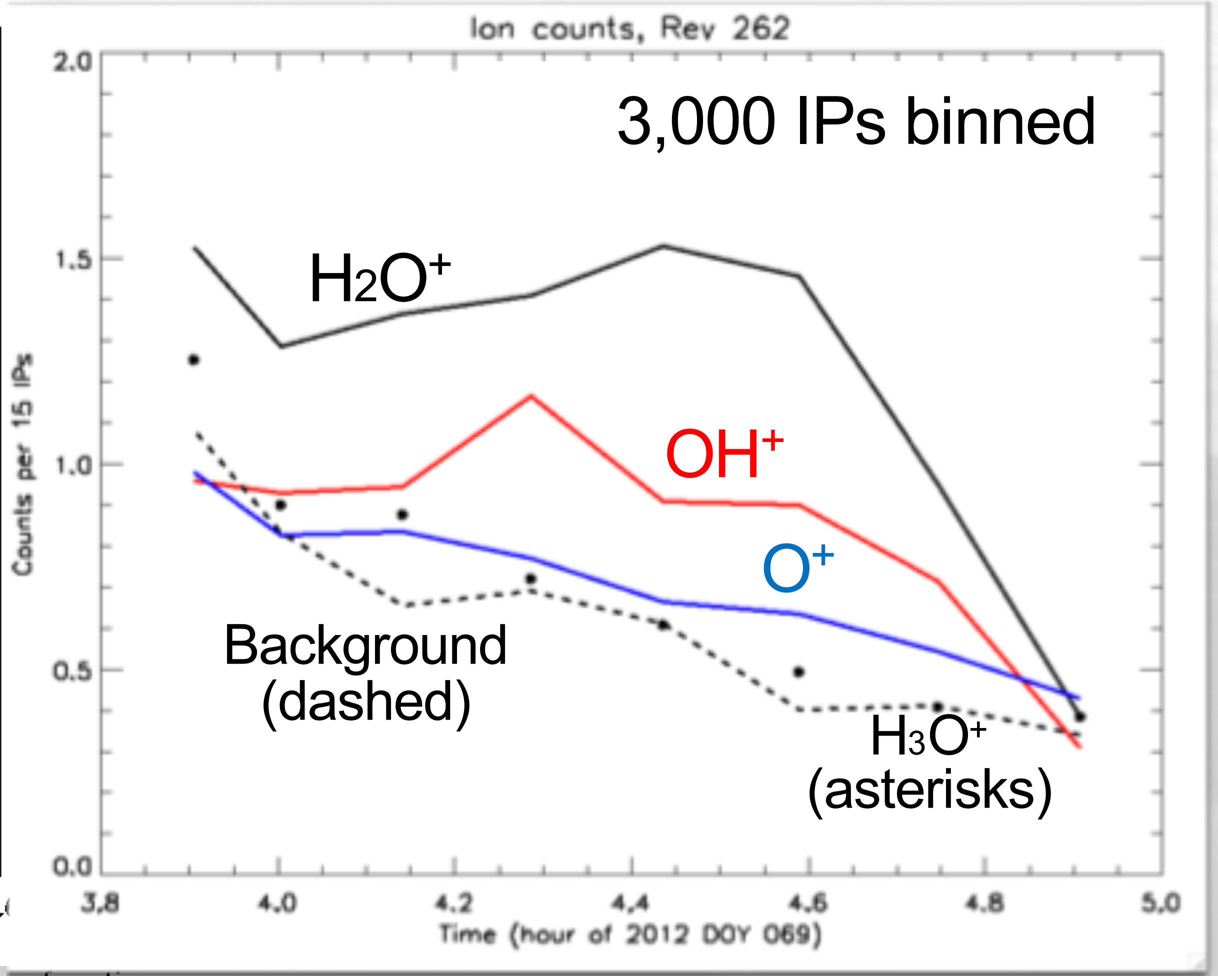
- Uncertainty due to shot noise (low number of counts), not fitting.
- Later data are sampled at higher rate.



Data from single orbits

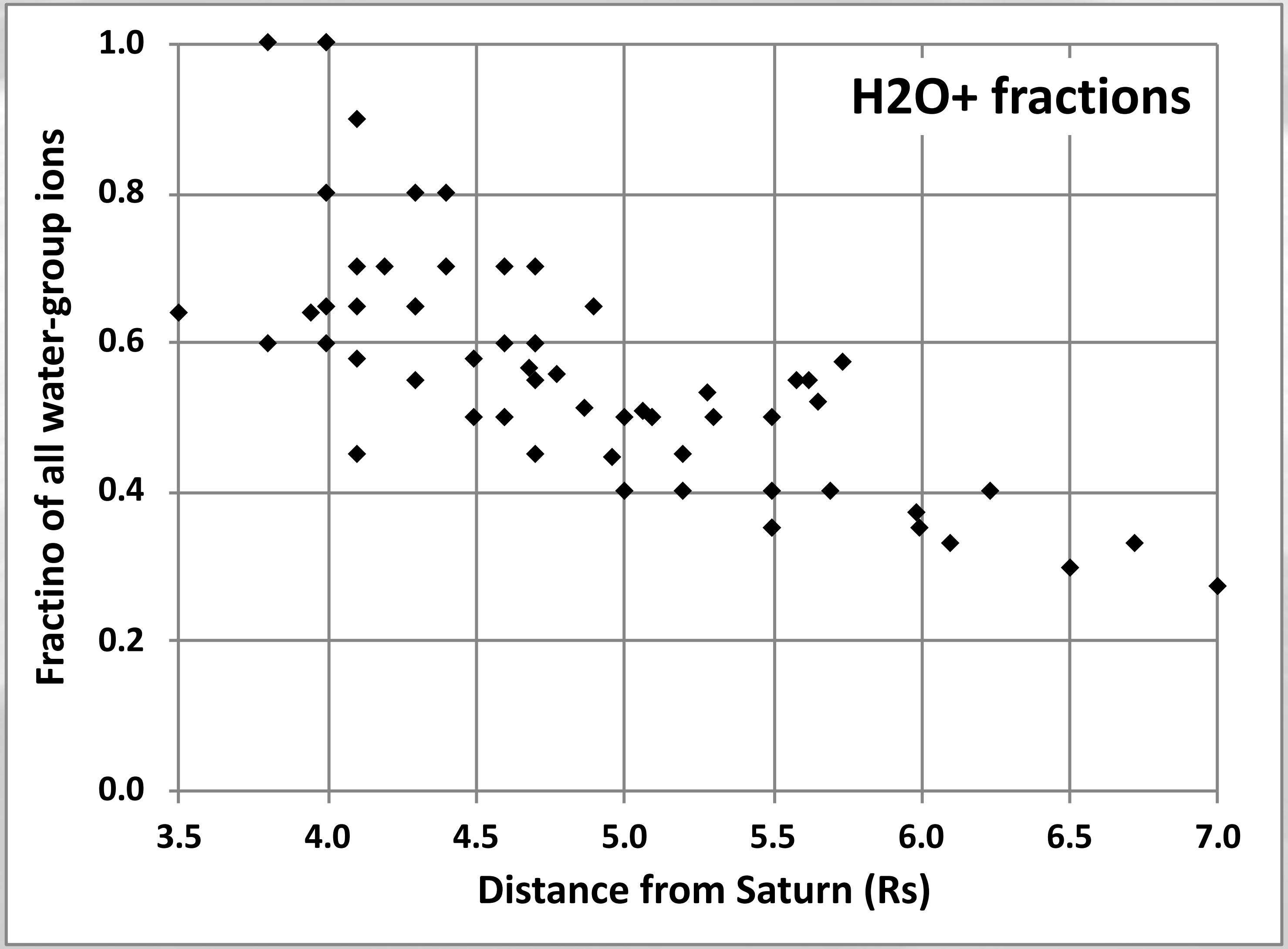
- Uncertainty due to shot noise (low number of counts), not fitting.
- Later data are sampled at higher rate.





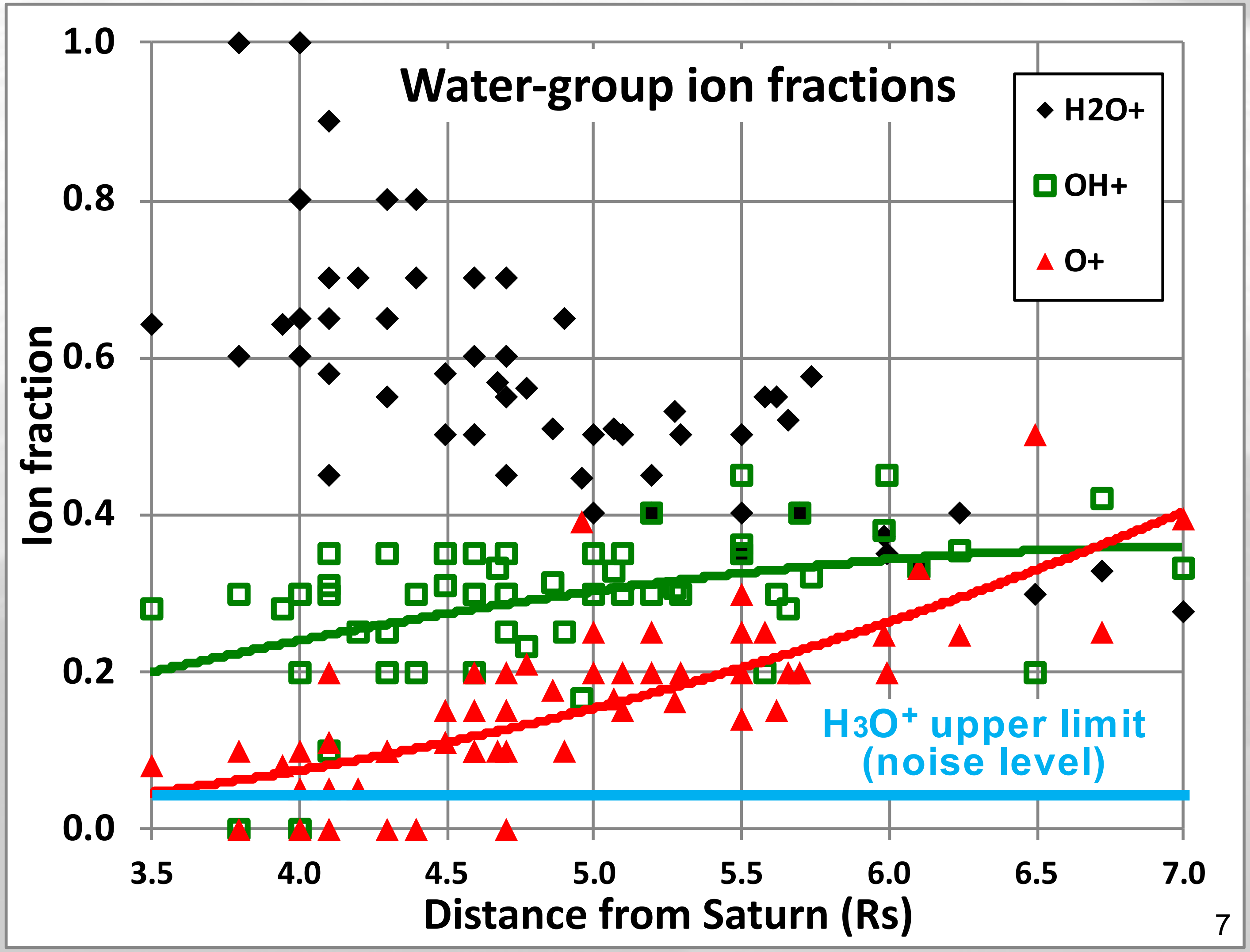
H_2O^+ ion fractions from INMS

- 19 orbits with INMS data of sufficient quality to measure the relative fractions of water-group ions.
- The highest fractions of H_2O^+ are near 4 R_S, the orbit of Enceladus, the source of neutral water.
  - Fraction of H_2O^+ falls with increasing distance from Enceladus.
- Total density of ions also falls from a peak at 4.5 R_S.
- INMS densities, both total and velocity space, agree with CAPS.



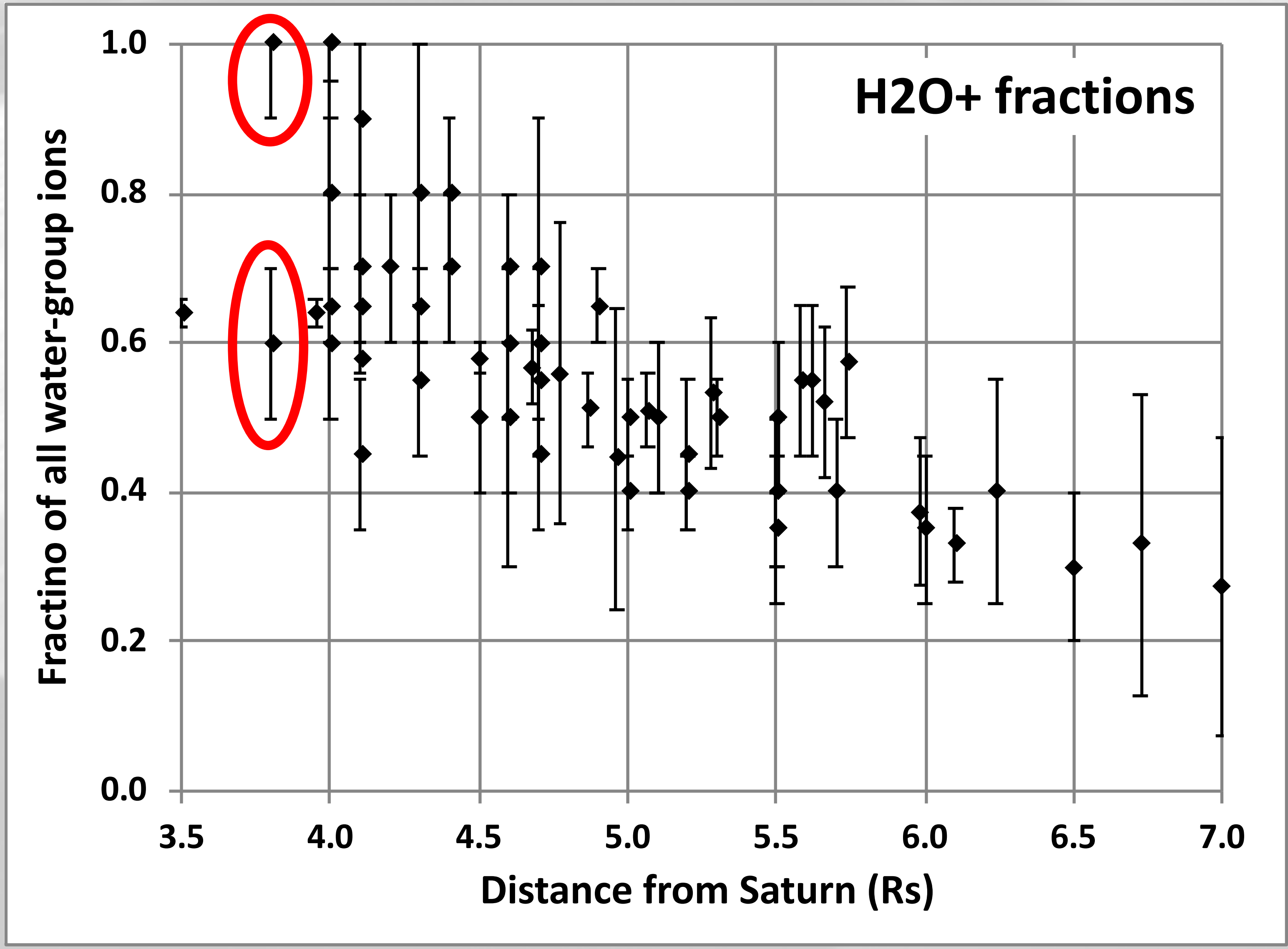
Relative fractions for the water-group ions

- The INMS results show trends that are used to constrain magnetosphere models.
- Far from Enceladus, more O^+ than early models.
- H_3O^+ is usually inseparable from the noise floor, but can be 5%.
- H_3O^+ abundance from INMS has the greatest discrepancy with analysis of CAPS data and ther early models.
  - Prompted by INMS results, H_3O^+ reactions reviewed and corrected.
- What drives ion abundances?
  - An important factor is the local abundance of neutrals.
  - Transport timescales longer than most lifetimes.



Ion fractions have dependencies other than radial distance

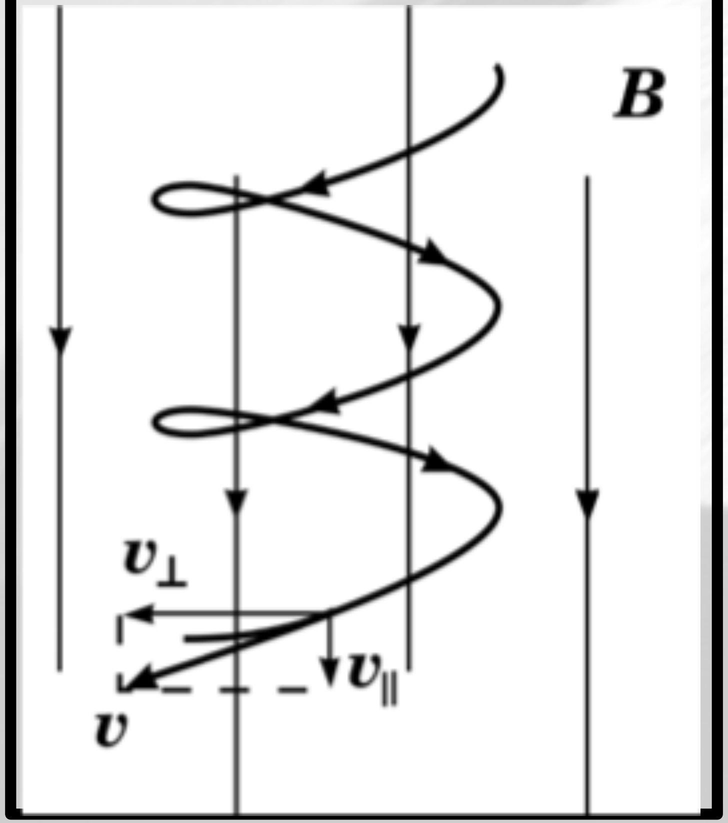
- Measurement uncertainty causes some variation, but there is also true separation, particularly near 4.0 Rs.
- With such sparse data, it is difficult to isolate the many factors that affect fractions.
  - No apparent dependence on velocity, location in velocity space, azimuth, Enceladus orbit phase, or density.
  - Each INMS measurement is a spot sample of these factors.
- Fractions are constant through most of velocity space.



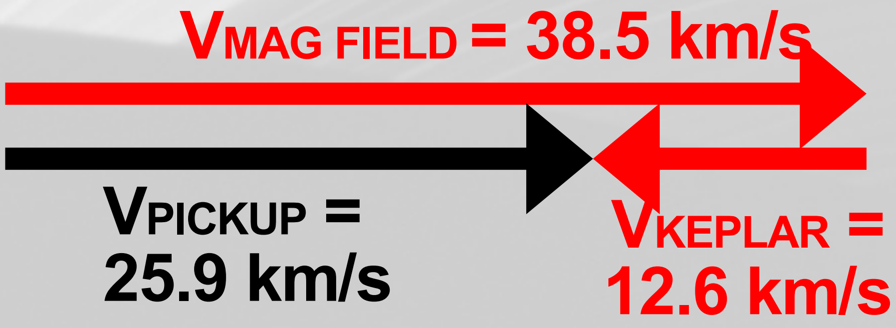
Water group fractions

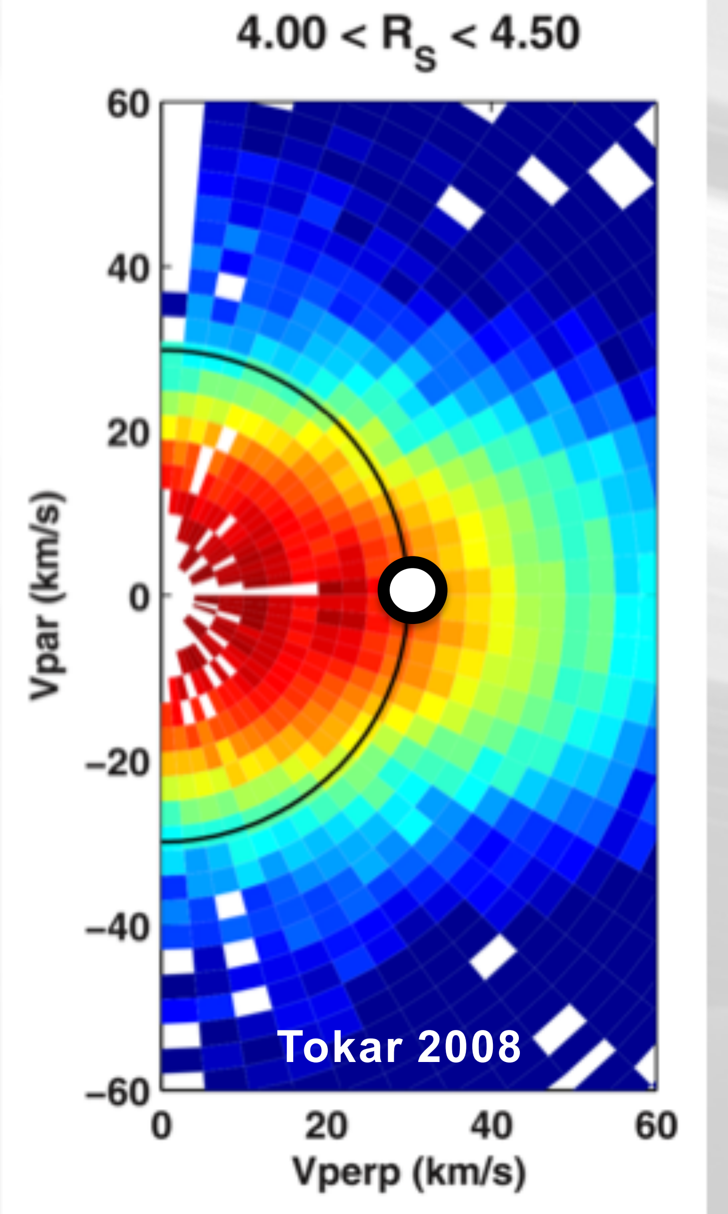
Ions are dispersed in velocity space

Velocity is fully defined by two parameters: V_{PAR} and V_{PERP}



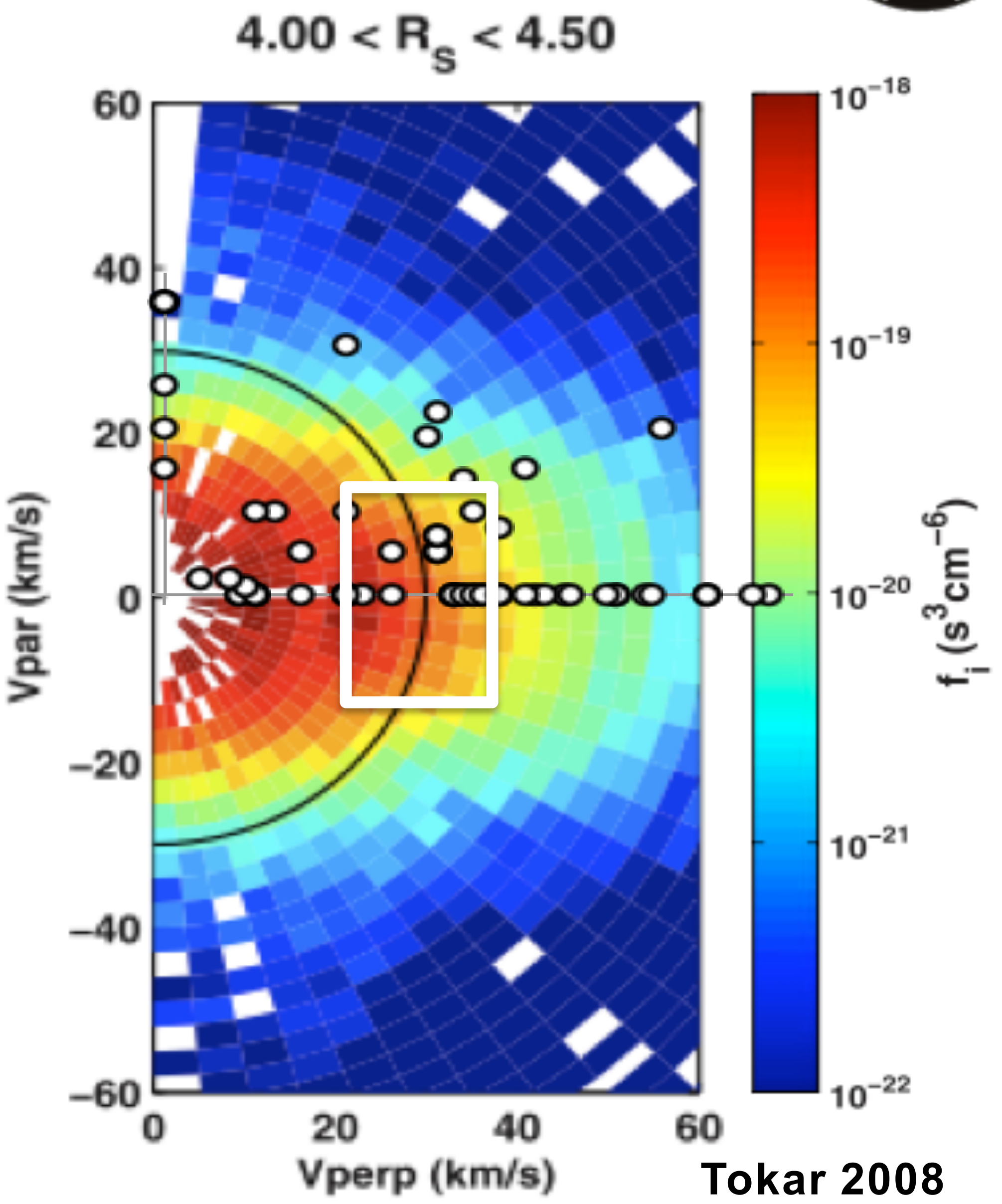
- When a neutral is ionized, it enters velocity space with
  $V_{PAR} = 0$
  V_{PERP} = pickup velocity
- Pickup velocity is
  V_{PICKUP} =
  $V_{MAG\ FIELD} - V_{KEPLAR}$





Location of INMS measurements in velocity space

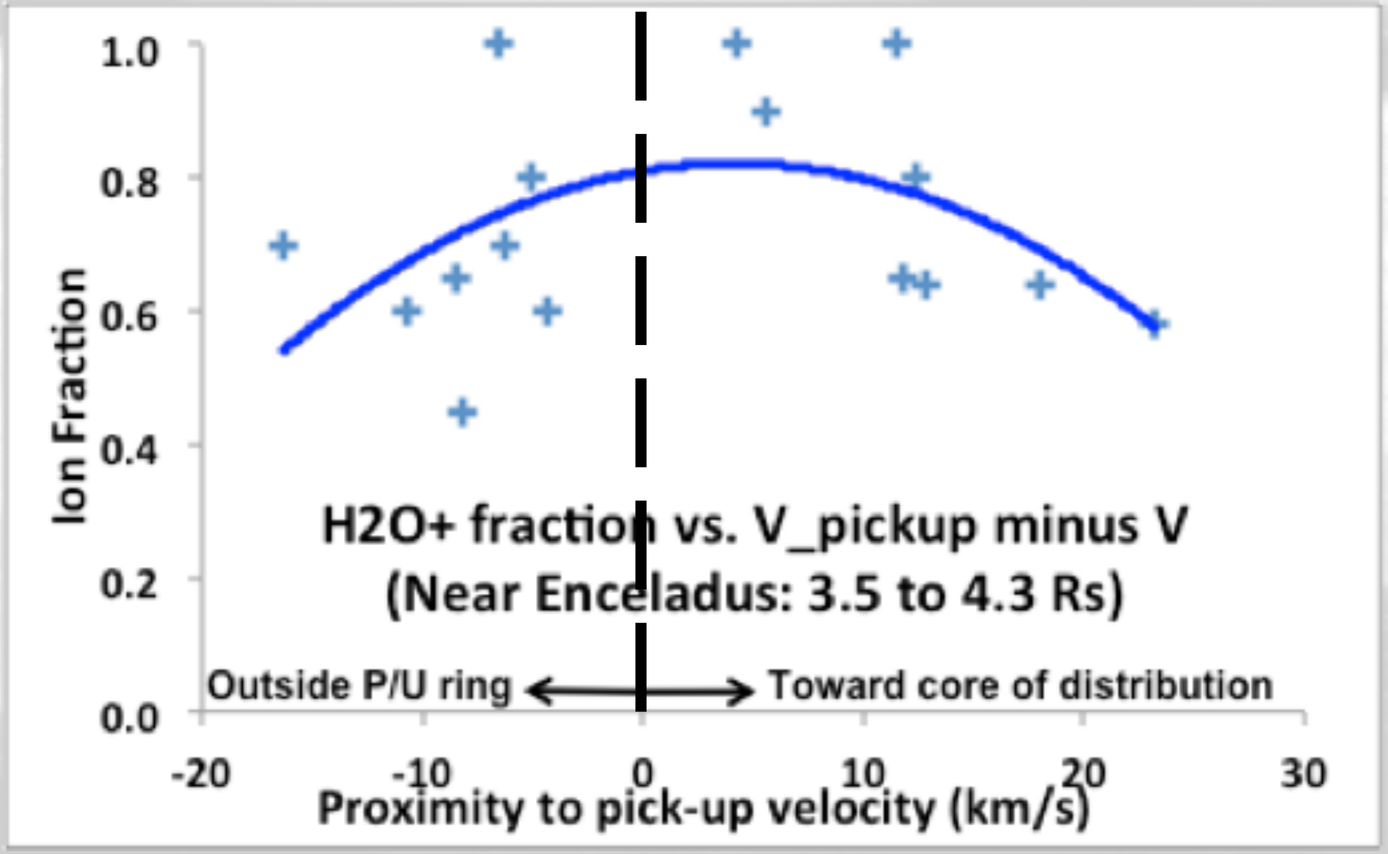
- This plot of CAPS data from Tokar et al. 2008 shows the water-group ion densities near 4 R_S.
- INMS measurements (white circles) cover a broad portion of velocity space.
  - –Radial distances range from 3.5 to 7 R_S.
- Plot shows detection of pick-up ions, which are marked by white box.
- INMS found higher fractions of H_2O^+ for the pickup ions near the pick-up velocity and near Enceladus.



Tokar 2008

Relationship to pick-up velocity

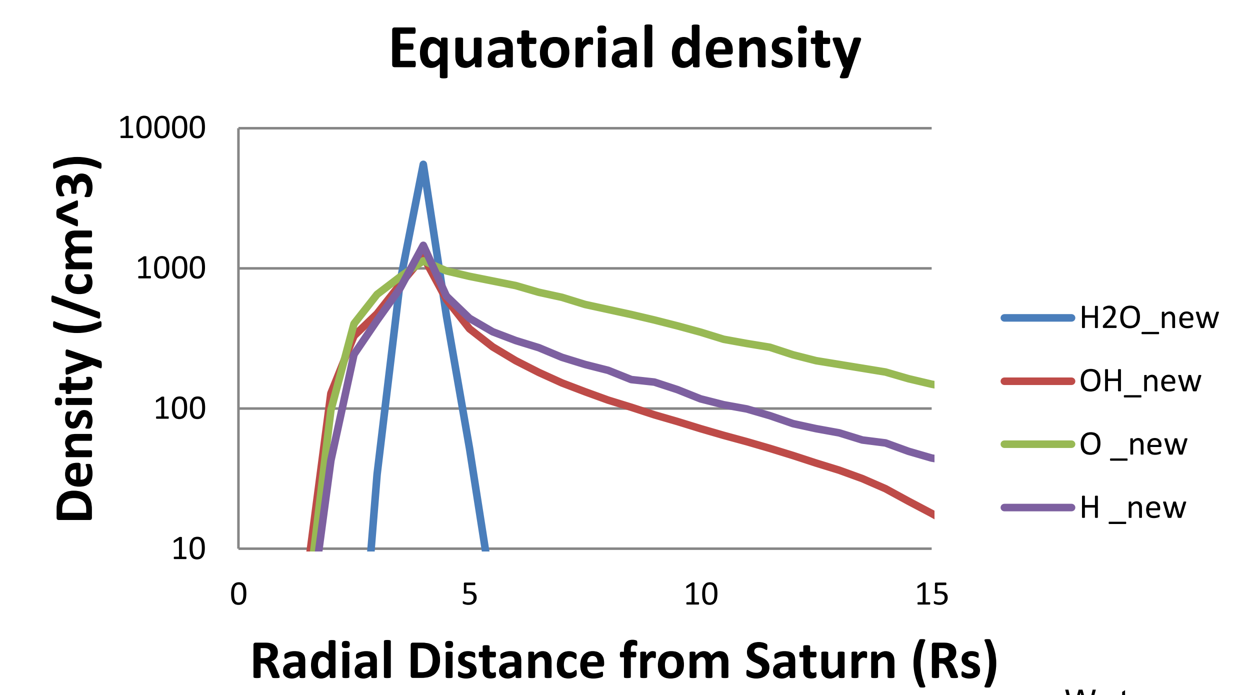
- Expect ions close to the pickup velocity to have fractions that reflect the local neutral abundance.
- Near 4Rs, the local neutrals are mostly H_2O, and the ions near the pick-up velocity have the highest fraction of H_2O^+.
- Core ions have higher fractions of OH^+ and O^+.
  - Core ions are older, processed; some converted to OH^+ or O^+.
  - Charge exchange with neutrals is slower for core ions.
  - Scatter is still large, indicating that other factors are relevant.

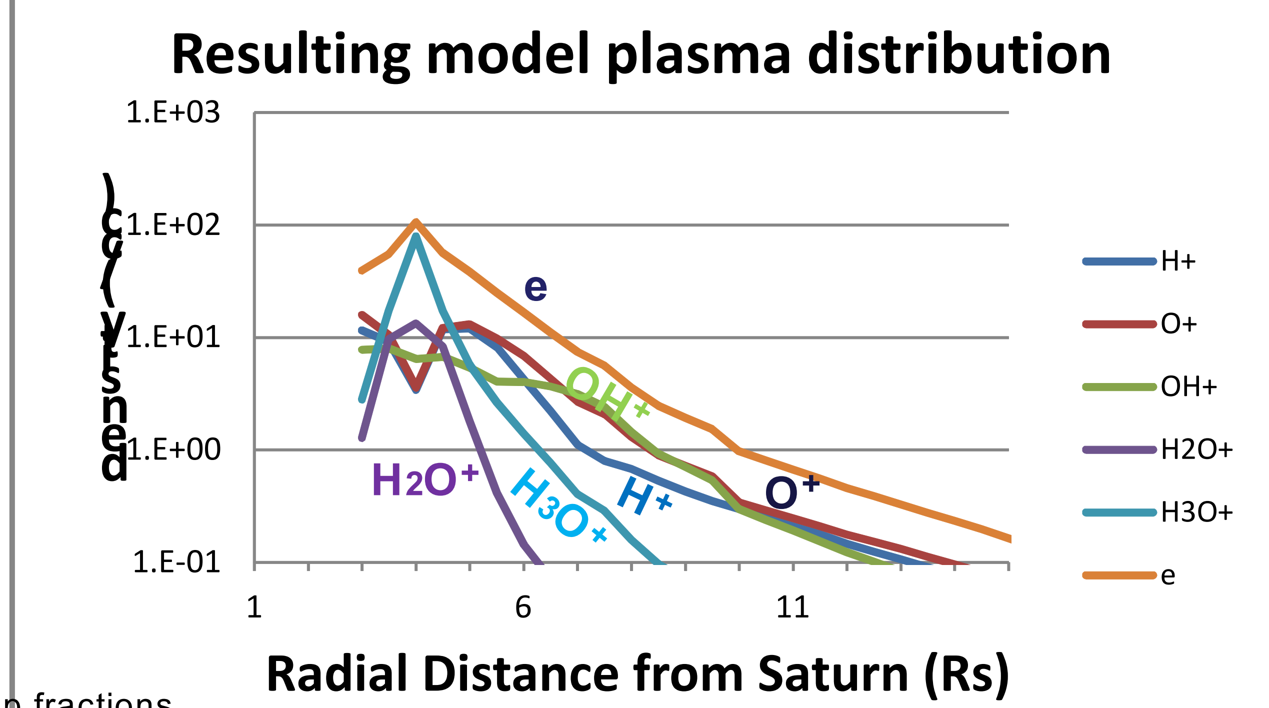


INMS found highest fractions of H_2O^+ for the ions near Enceladus and near the pick-up velocity.

New, self-consistent modeling

- What can we do with these data?
- Smith and Richardson are using INMS data to calibrate their new models that are self-consistent between neutrals and ions.
- Also aids in understanding neutral distribution.

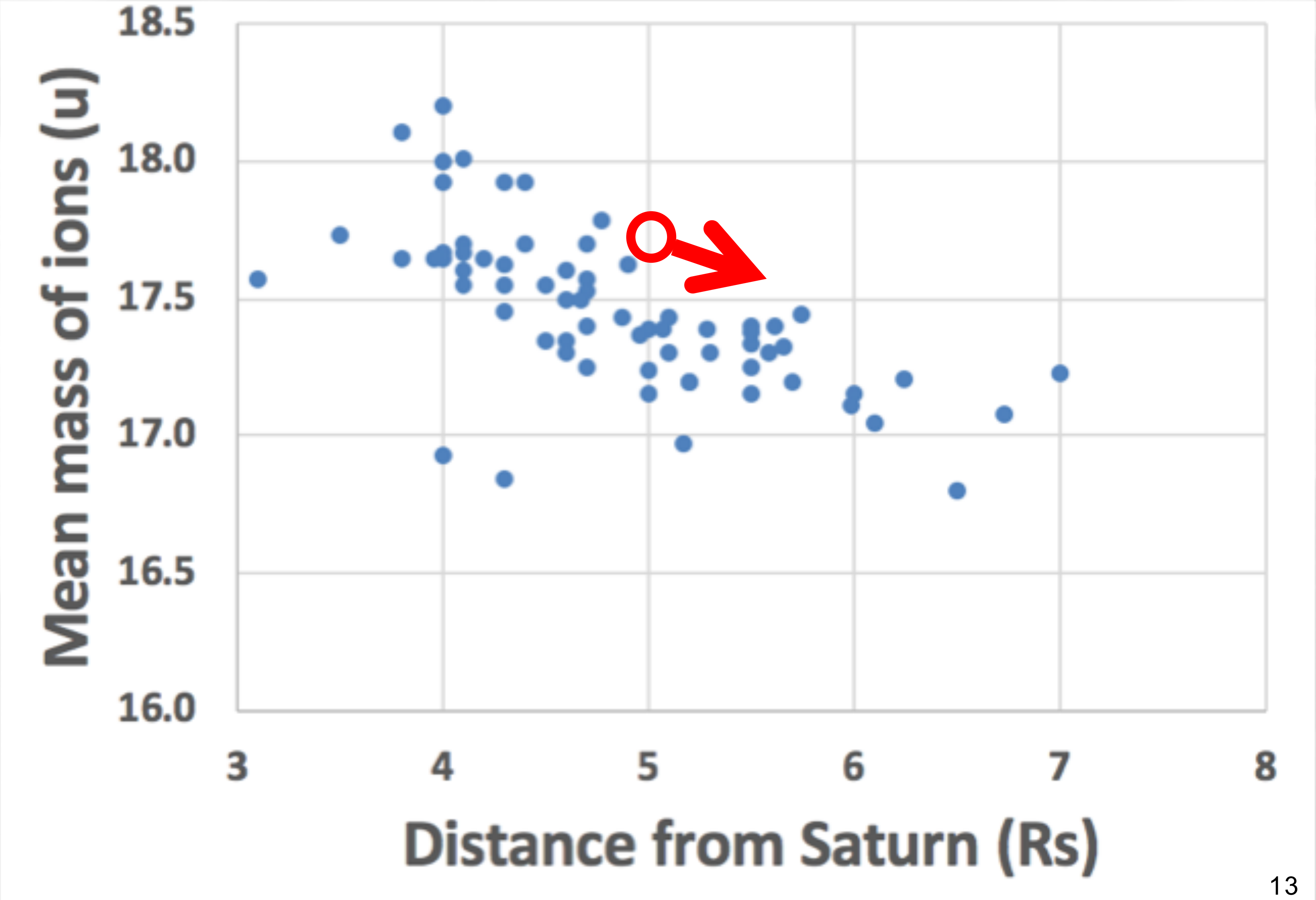




Water group fractions

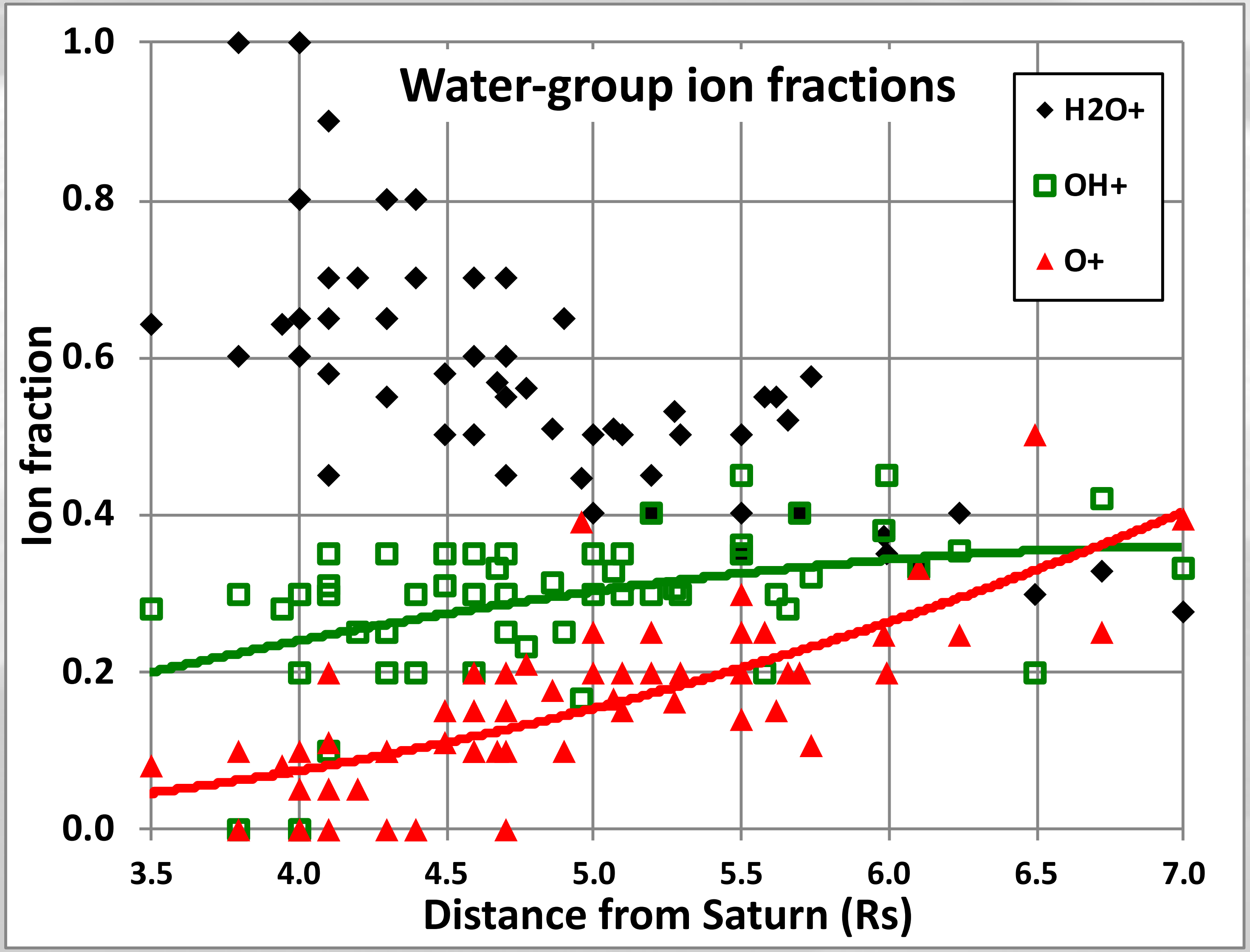
Mean mass of water-group ions

- CAPS data provide accurate measurement of the mean mass of the water-group ions.
- CAPS trend (red, from Crary and Cassidy, EGU2018) shows mean mass decreases from 5 to 10 Rs.
- INMS data (blue) show similar trend.



Summary

- INMS measured water group fractions, unambiguously.
  - The fractions differ from previous models and measurements.
- Some evidence that the relative fractions differ between the pick-up region and the ions closer to the core of the velocity distribution.
- The fractions are used to calibrate the next generation of neutral and plasma models of Saturn’s inner magnetosphere.



Water group fractions