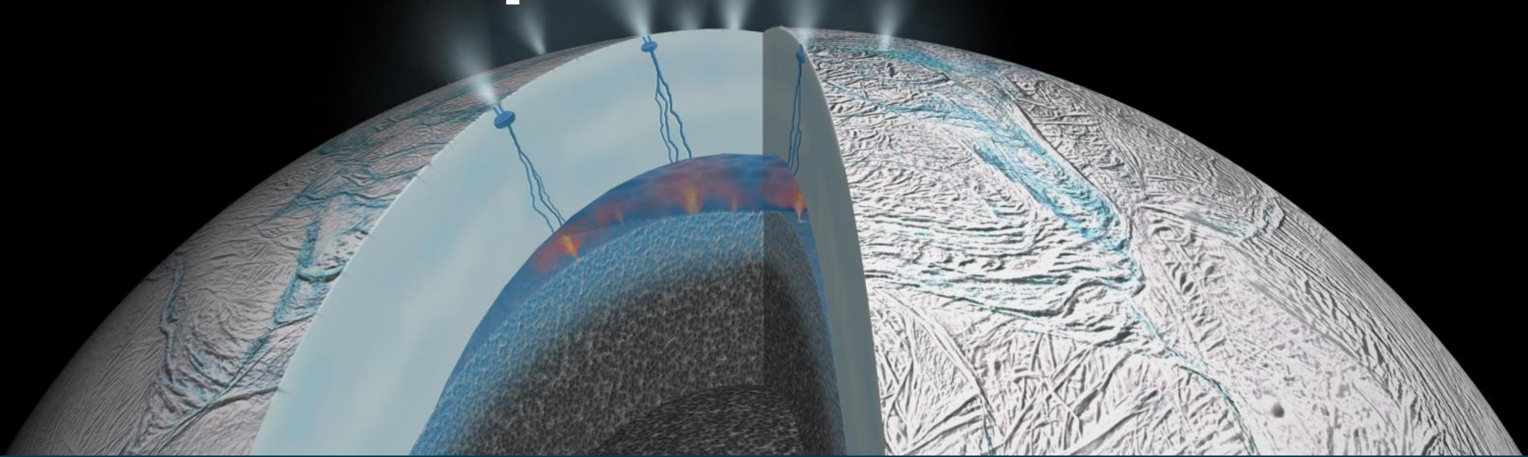
Mullard Space Science Laboratory, Department of Space & Climate Physics

Fast and slow water ion populations in the Enceladus plume



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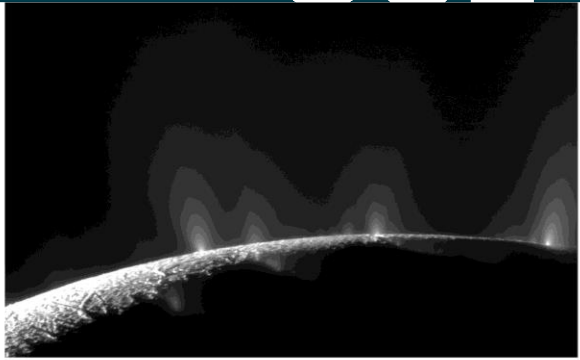
Enceladian plume dynamics



- Dust jets have been found to exist within the plume using optical images [*Spitale and Porco, 2006*]

- Gas jets were found to coincide with the dust jets *[Hansen+, 2008]*

The gas component of the plume has been shown to contain two parts *[Teolis+, 2017* and refs therein*]:*

- Bulk thermalized plume emission (500-750 ms^{-1})

- High-speed gas emission (1.2 – 6 kms^{-1})

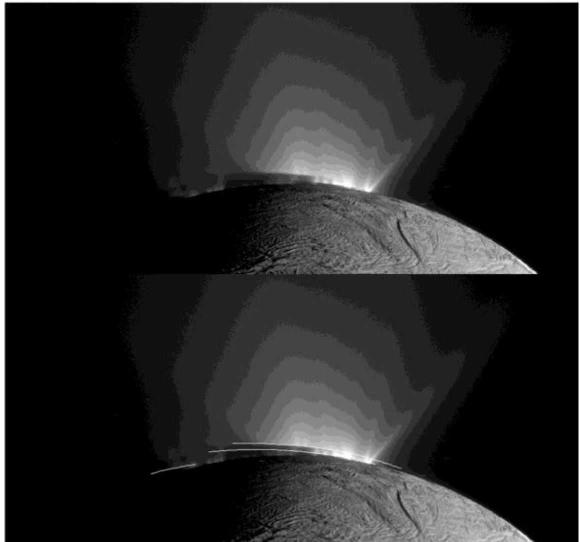
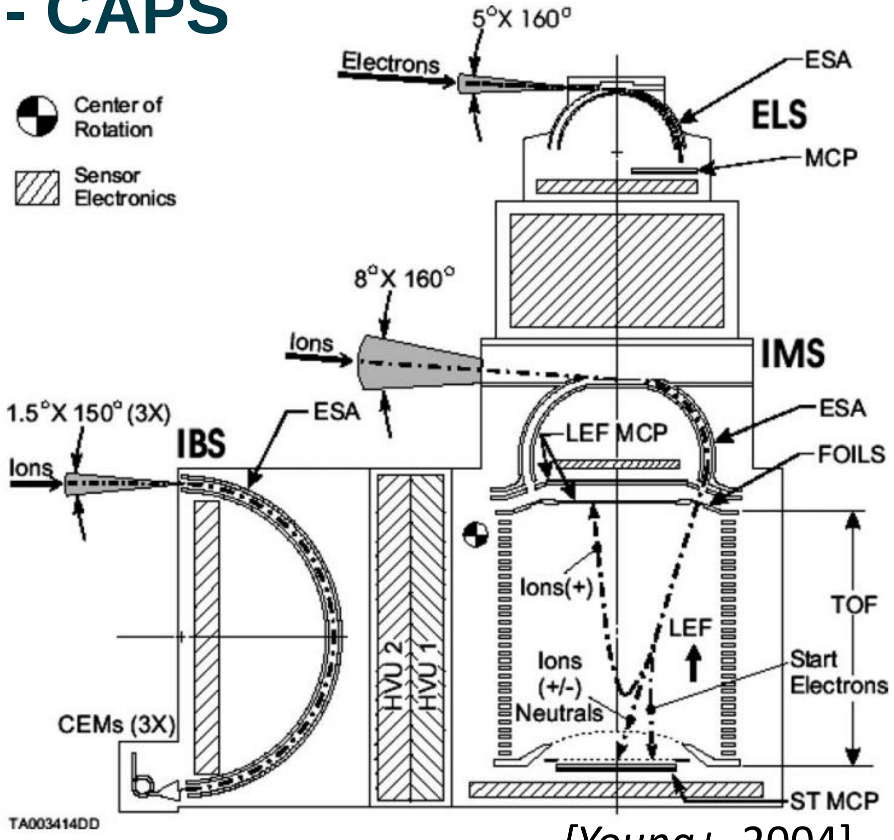


Image Credit: NASA/JPL-Caltech/Space Science Institute

Cassini Plasma Spectrometer - CAPS

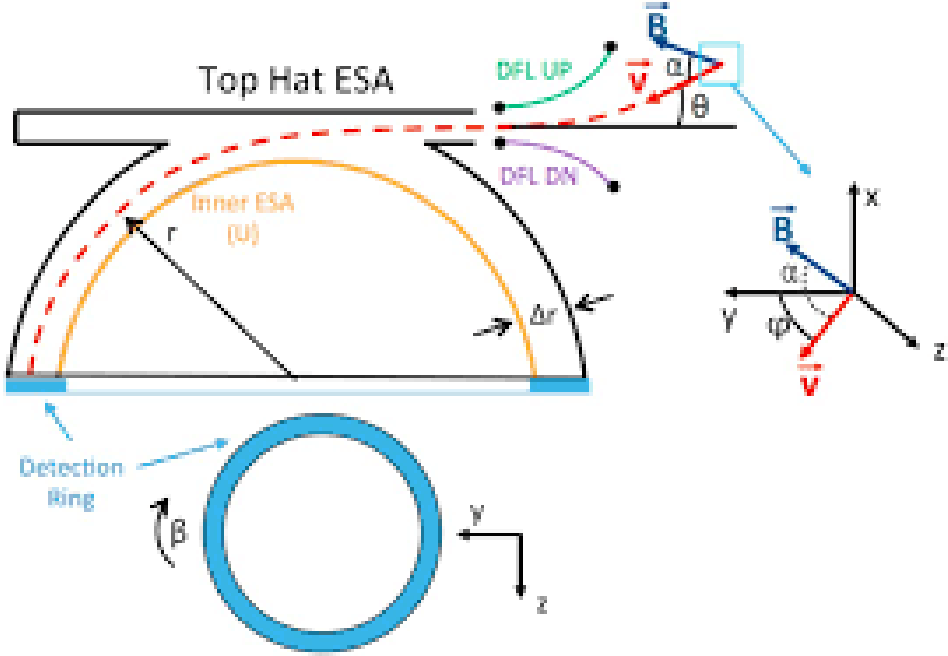
- Three electrostatic analysers:
  - Electron Spectrometer (ELS)
  - Ion Mass Spectrometer (IMS)
  - Ion Beam Spectrometer (IBS)
- Instruments can be actuated to align with spacecraft velocity vector



[Young+, 2004]

Electrostatic Analysers

- Electrostatic analysers work by biasing two curved electrodes
- This generates an electric field between the electrodes
- Only charged particles with the ”correct” energy will travel through to the detector
- Particles of different energies can be selected by varying the bias



[Clark+, 2016]

Methods – Ion Ramming

- "Cold" plasma appears as a directed supersonic beam in spacecraft frame ($v_{sc} > 14$ km s^{-1})

- Allows ion energies to be associated with masses, although spacecraft potential and ion velocities affects the particle energy

- The ion velocity term v_i describes the ion velocity component parallel to the spacecraft track

$$E_\alpha = \frac{1}{2} m_\alpha (v_{sc} + v_i)^2 \pm e\Phi_{sc}$$

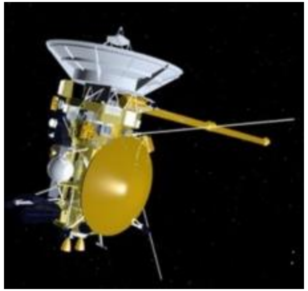
[Crary+, 2009; Coates+, 2010; Westlake+, 2014]

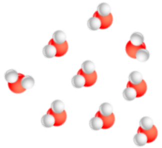
Planetary frame

17 km/s →

0 km/s

Stationary ions



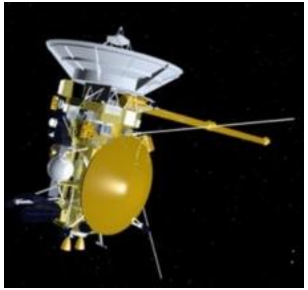


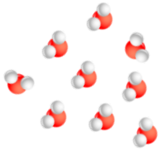
Spacecraft frame

0 km/s

← 17 km/s

Ions appear at Cassini velocity





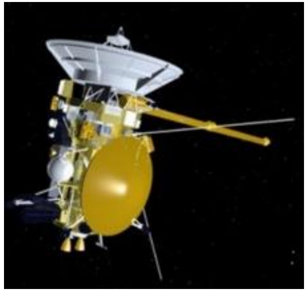
Not to scale

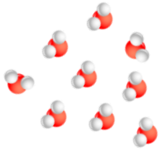
Planetary frame

17 km/s

4 km/s

Non-stationary ions



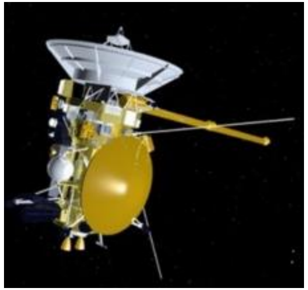


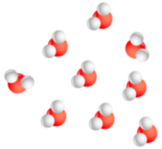
Spacecraft frame

0 km/s

13 km/s

Ions appear to be travelling slower

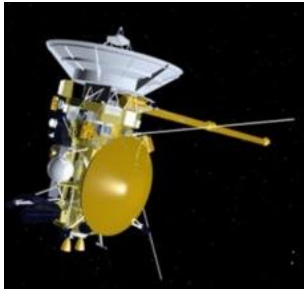




Not to scale

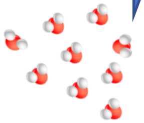
Planetary frame

17 km/s

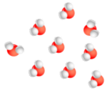


Fast and slow ions

1 km/s

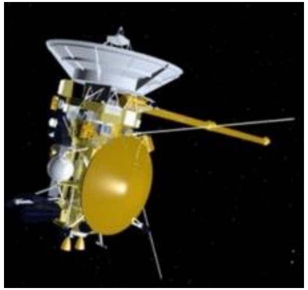


8 km/s



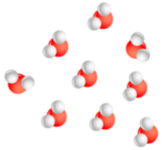
Spacecraft frame

0 km/s

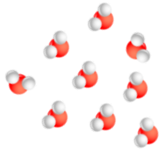


Faster ions appear to be travelling slower

16 km/s



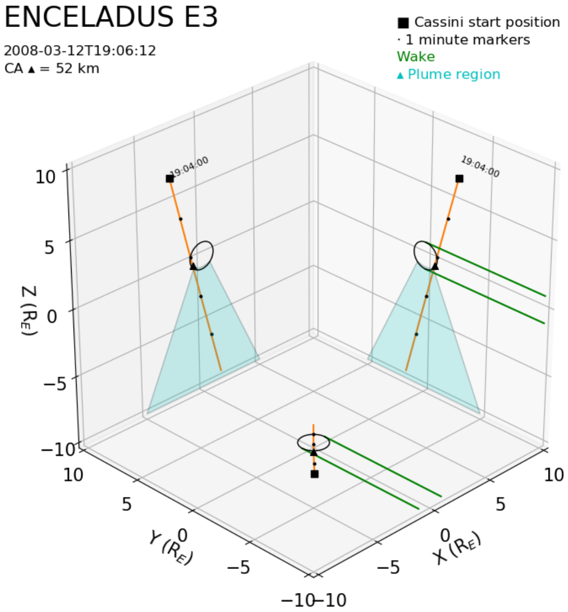
9 km/s

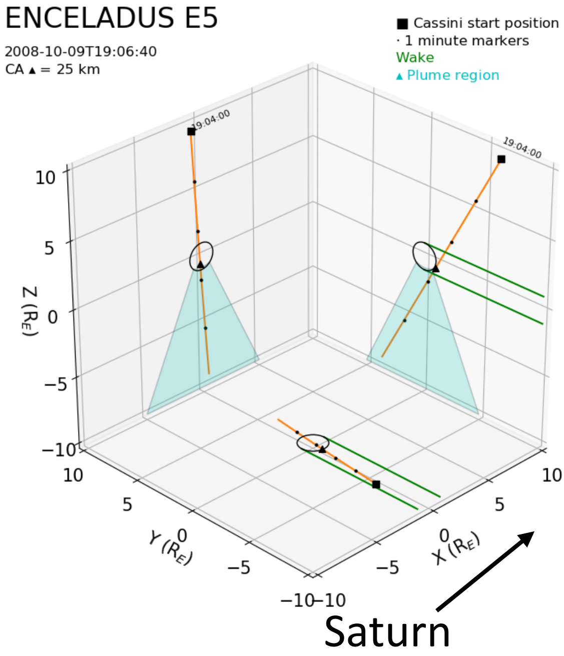


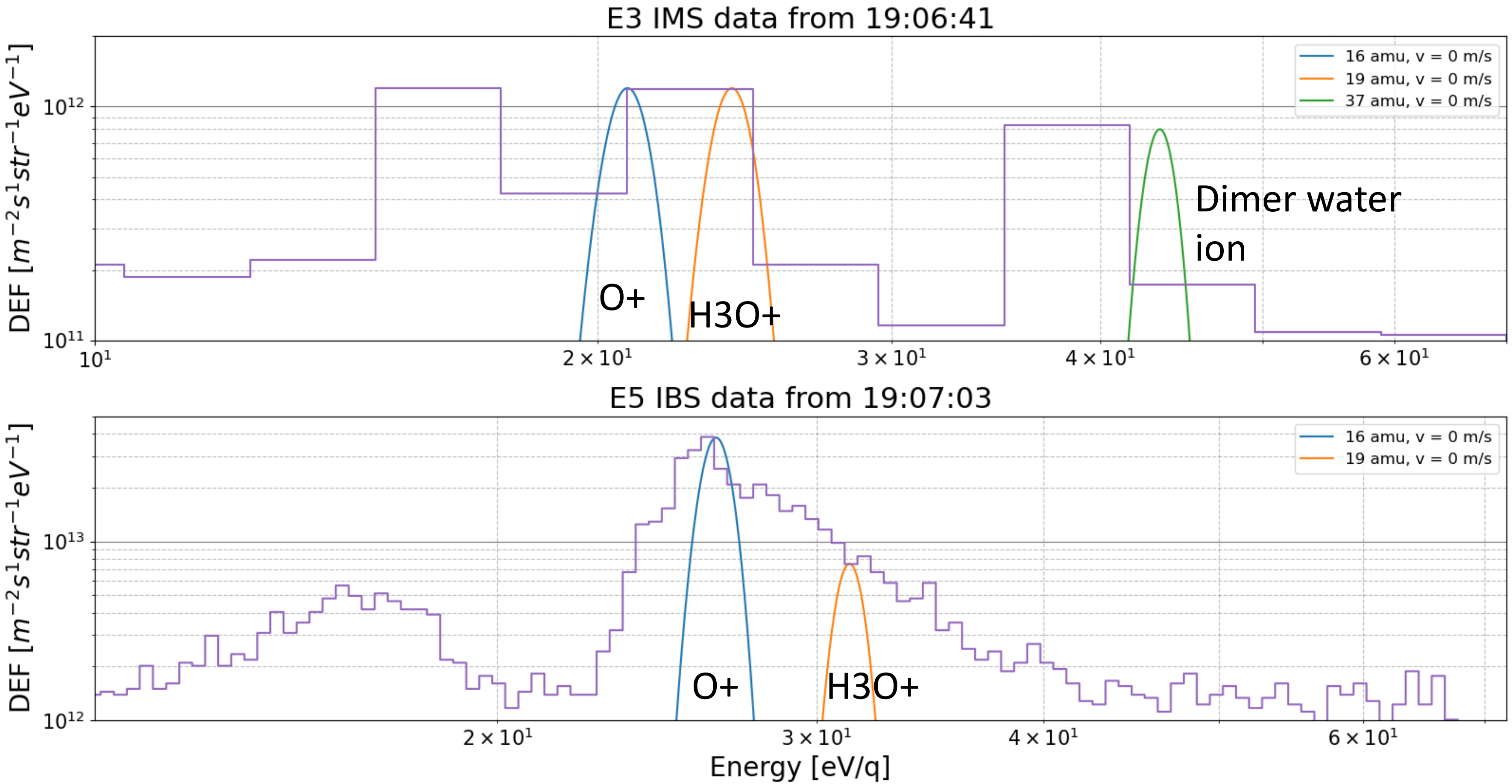
Not to scale

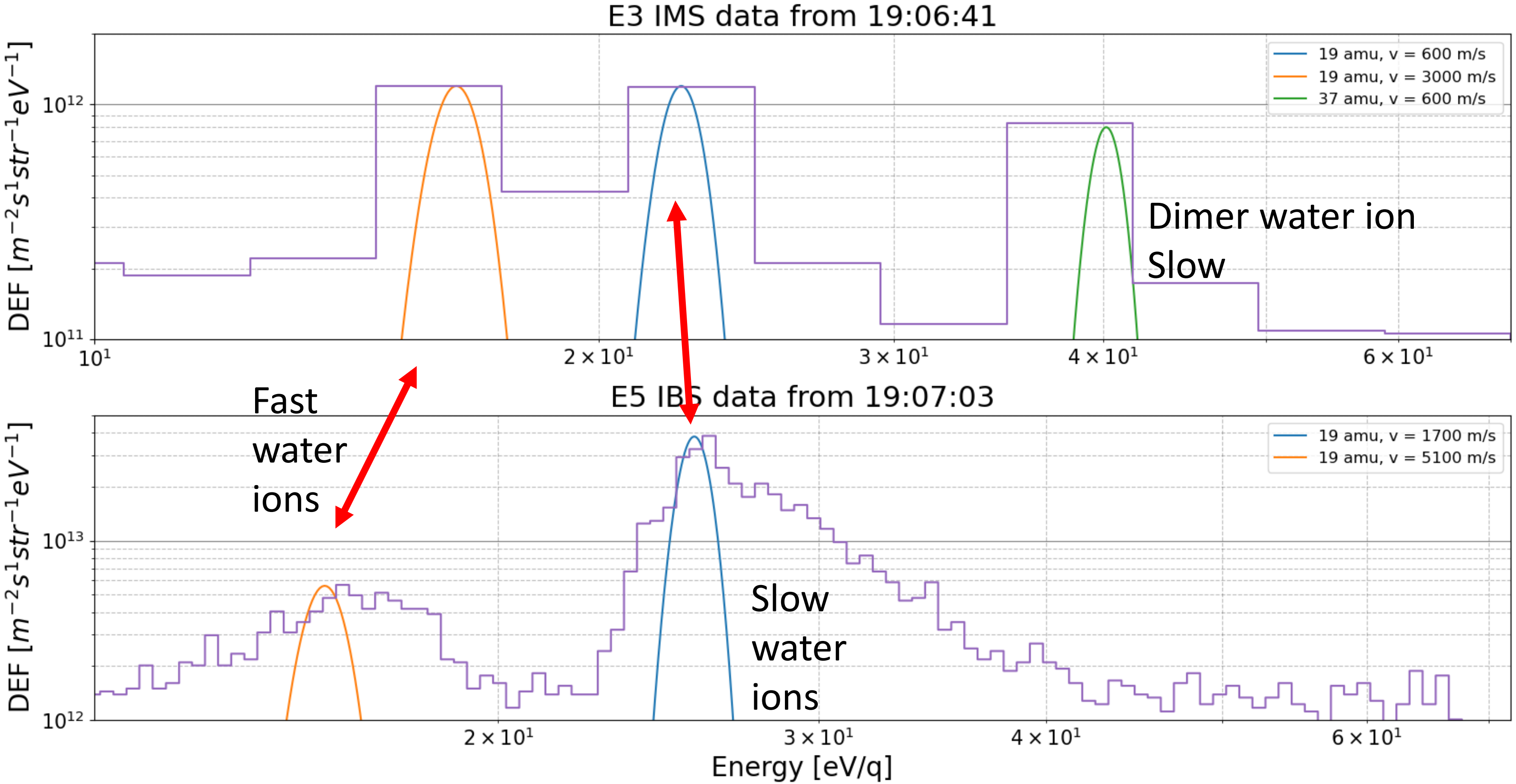
Studied flybys

	E3	E5
Date	12th March 2008	9th October 2008
v_{rel}	14.4 km/s	17.7 km/s
Closest Approach	52 km at 19:06:12	25 km at 19:06:40
	Steeply inclined, north-south trajectories, following plume	

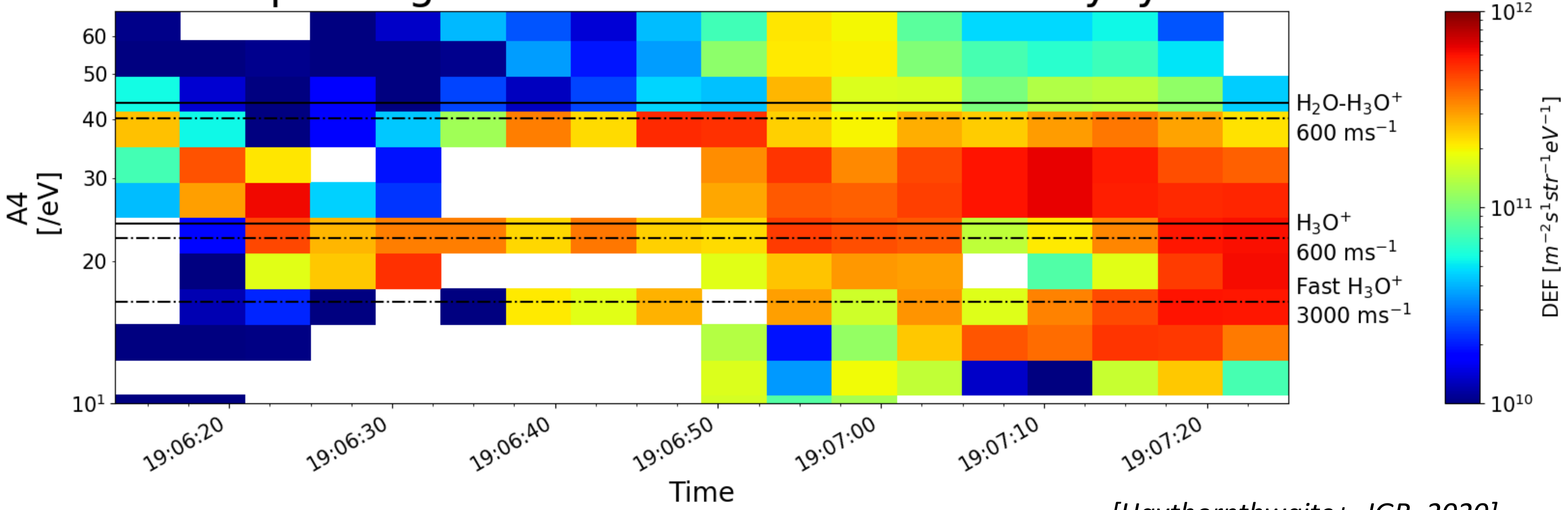





E3 IMS data from 19:06:41
DEF $[m^{-2}s^{1}str^{-1}eV^{-1}]$
16 amu, v = 0 m/s
19 amu, v = 0 m/s
37 amu, v = 0 m/s
O+
H3O+
Dimer water ion
10^{12}
10^{11}
10^1
2×10^1
3×10^1
4×10^1
6×10^1
E5 IBS data from 19:07:03
DEF $[m^{-2}s^{1}str^{-1}eV^{-1}]$
16 amu, v = 0 m/s
19 amu, v = 0 m/s
O+
H3O+
10^{13}
10^{12}
2×10^1
3×10^1
4×10^1
6×10^1
Energy [eV/q]

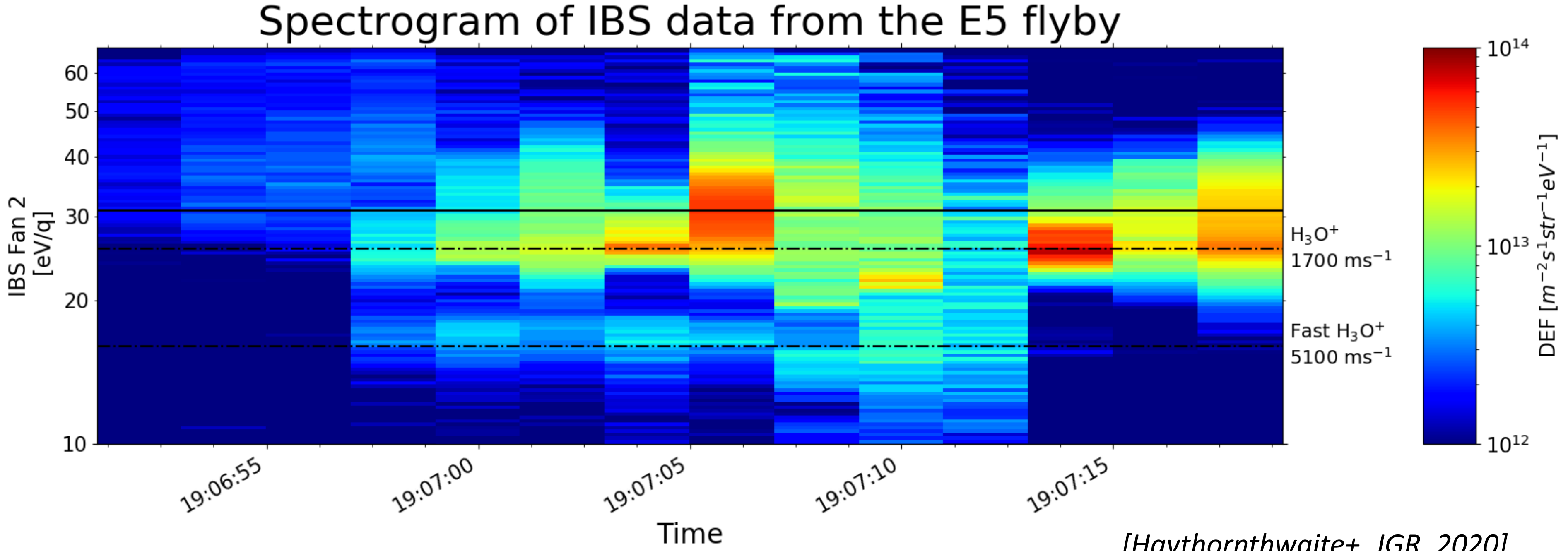

E3 IMS data from 19:06:41
19 amu, v = 600 m/s
19 amu, v = 3000 m/s
37 amu, v = 600 m/s
Dimer water ion
Slow
Fast
water
ions
E5 IBS data from 19:07:03
19 amu, v = 1700 m/s
19 amu, v = 5100 m/s
Slow
water
ions
DEF [m⁻²s¹str⁻¹eV⁻¹]
Energy [eV/q]

Spectrogram of IMS data from the E3 flyby



[Haythornthwaite+, JGR, 2020]

- Bulk thermal population seen (200, 2000 ms^{-1})
- Dimer peak seen during E3 flyby in contrast to E5
- Secondary faster population is also seen, similar to E5 (2300, 4800 ms^{-1})

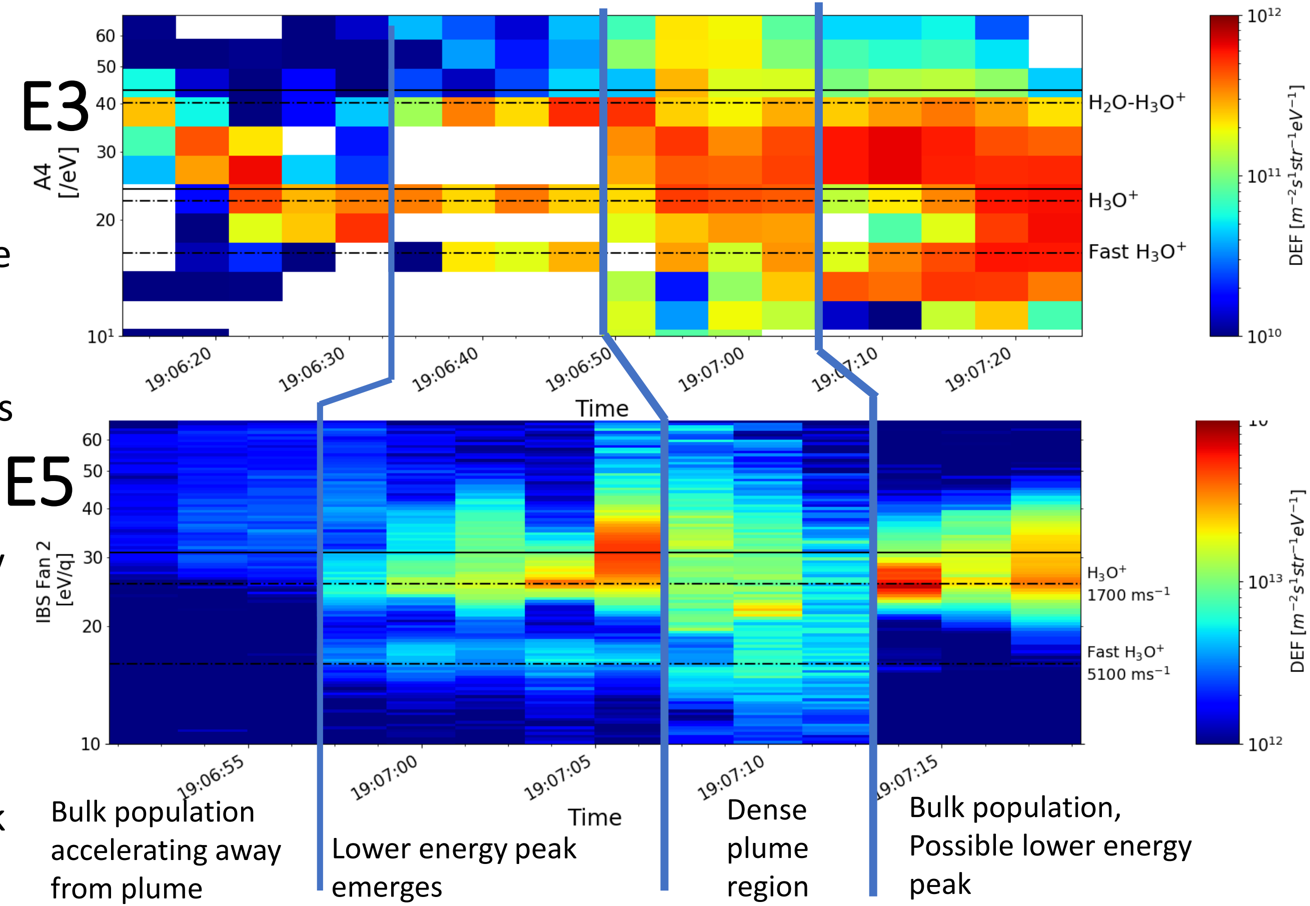


[Haythornthwaite+, JGR, 2020]

- Bulk thermal population seen (1400, 2200 ms^{-1})
- Secondary faster population is also seen (4550, 5800 ms^{-1})

A similar structure can be seen in both positive ion datasets:

- Acceleration of plume material away from the plume
- A secondary energy peak occurs once the main plume is encountered
- A dense plume region directly south of Enceladus
- Bulk population returns in addition to a possible signature of a secondary peak



Discussion

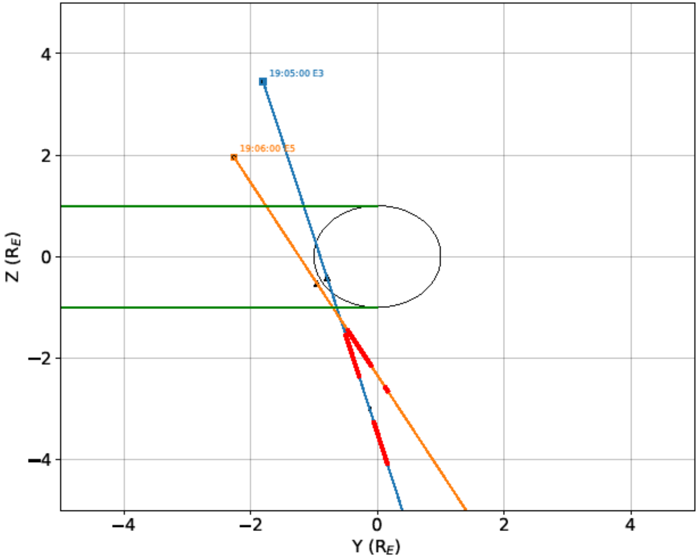
- The lower energy peak is not seen in later horizontal plume flybys (E7, E17, E18) implying a directed phenomenon which is consistent with a gas jet source

- Also agrees with INMS not measuring significant O+ in plume during E3 [*Cravens+, 2009]*

- Charge exchange is a major ionization process in the plume, this would create ions with similar velocities to their neutral progenitors

- Differences between neutrals and ions could result from acceleration within the plume by EM fields

- Tentative detection of negative ions during E5 that have been decelerated



[Haythornthwaite+, JGR, 2020]

	E3	E5
Slow H_3O^+	[200, 2000]	[1400, 2200]
Fast H_3O^+	[2300, 4800]	[4550, 5800]
Slow OH^-	[-1800, -300]	[-1600, 450]
Fast OH^-	-	[3000, 5000]

Calculated ion velocities within the plume

Enceladus study conclusions

- CAPS data from two north-south Enceladus flybys was examined
- A low energy ion peak occurs in both flybys during transit of the plume centre
- This has been associated with the collimated high velocity jets that have been found in the neutral gas emissions
- The velocities of the slow and fast water ion populations have been calculated along the Cassini track

Haythornthwaite, R. P., Coates, A. J., Jones, G. H., & Waite, J. H. (2020). Fast and slow water ion populations in the Enceladus plume. *Journal of Geophysical Research: Space Physics*, 125, e2019JA027591. https://doi.org/10.1029/2019JA027591

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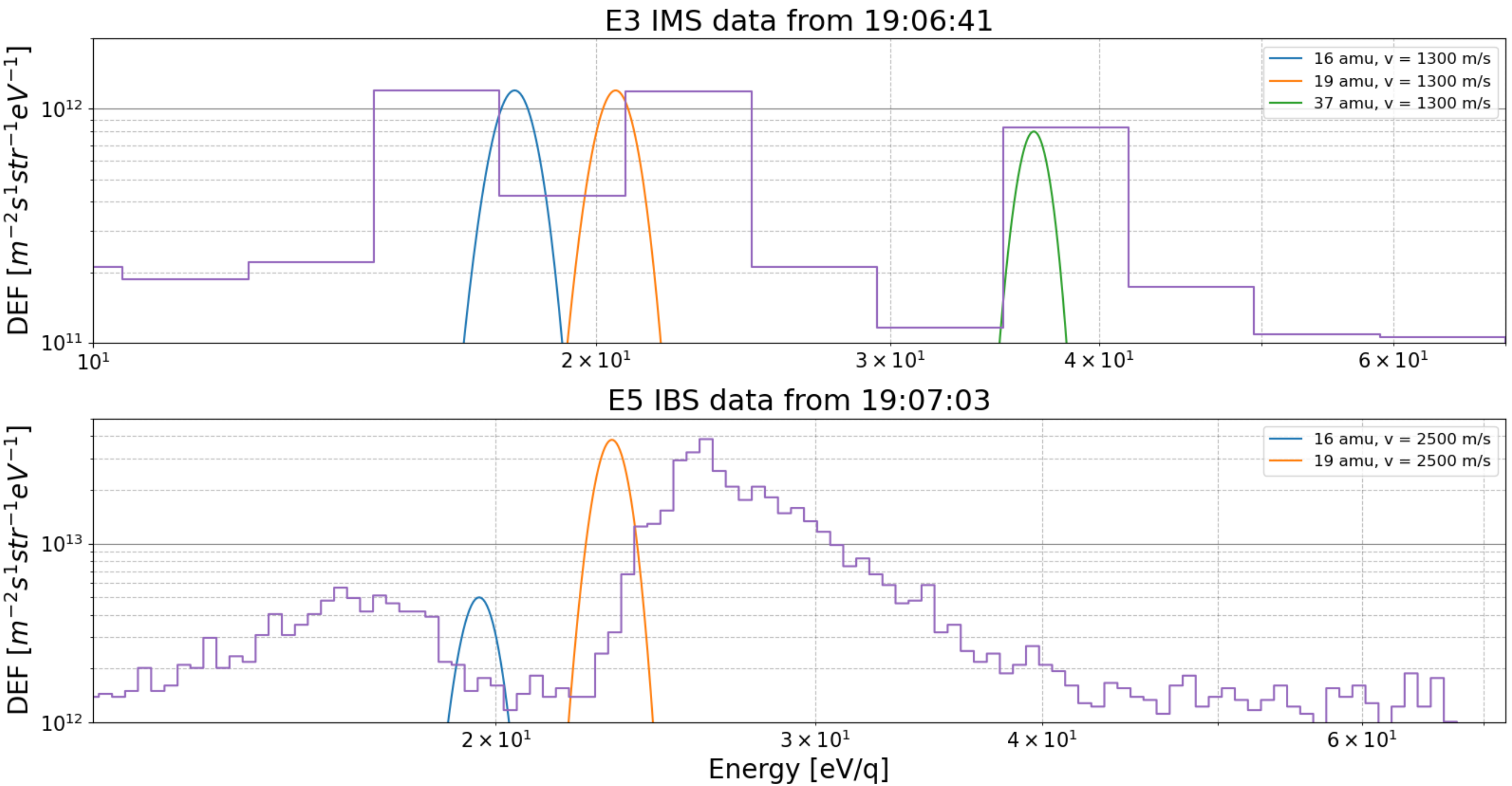
@SpaceHaythorn

Extra Slides

Queries

- O^+, OH^+, H_2O^+ ions probable causes of peak broadening at slow or fast velocities
- Velocities ranges are calculated over multiple energy sweeps



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3×10^{1}
4×10^{1}
6×10^{1}
16 amu, v = 1300 m/s
19 amu, v = 1300 m/s
37 amu, v = 1300 m/s
E5 IBS data from 19:07:03
DEF $[m^{-2}s^{1}str^{-1}eV^{-1}]$
10^{13}
10^{12}
2×10^{1}
3×10^{1}
4×10^{1}
6×10^{1}
16 amu, v = 2500 m/s
19 amu, v = 2500 m/s
Energy [eV/q]