INTERCHANGE INSTABILITIES AT SATURN: WAVE-PARTICLE INSIGHT INTO RAYLEIGH-TAYLOR LIKE PLASMA TRANSPORT

Eddy Symposium 2026

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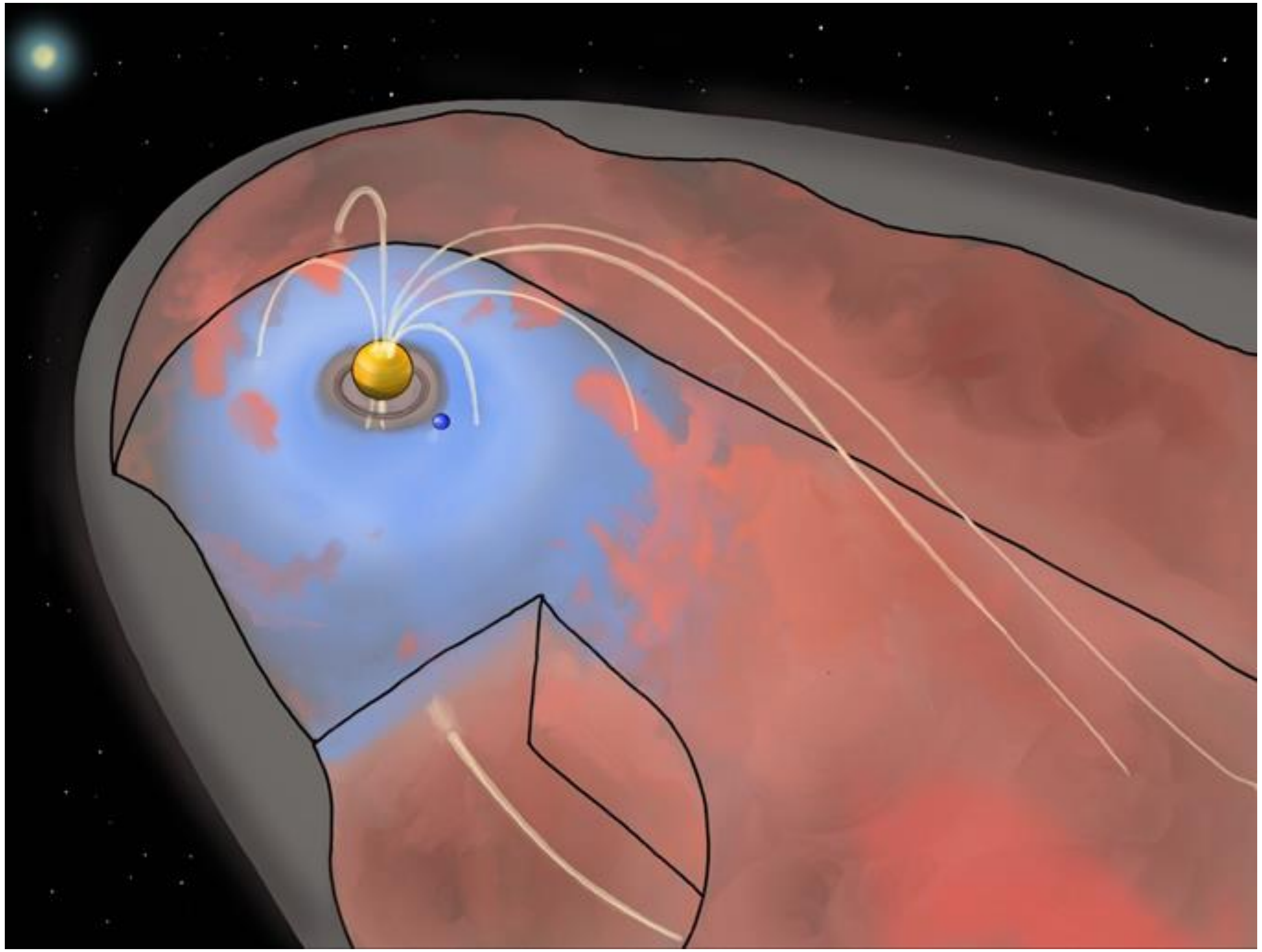
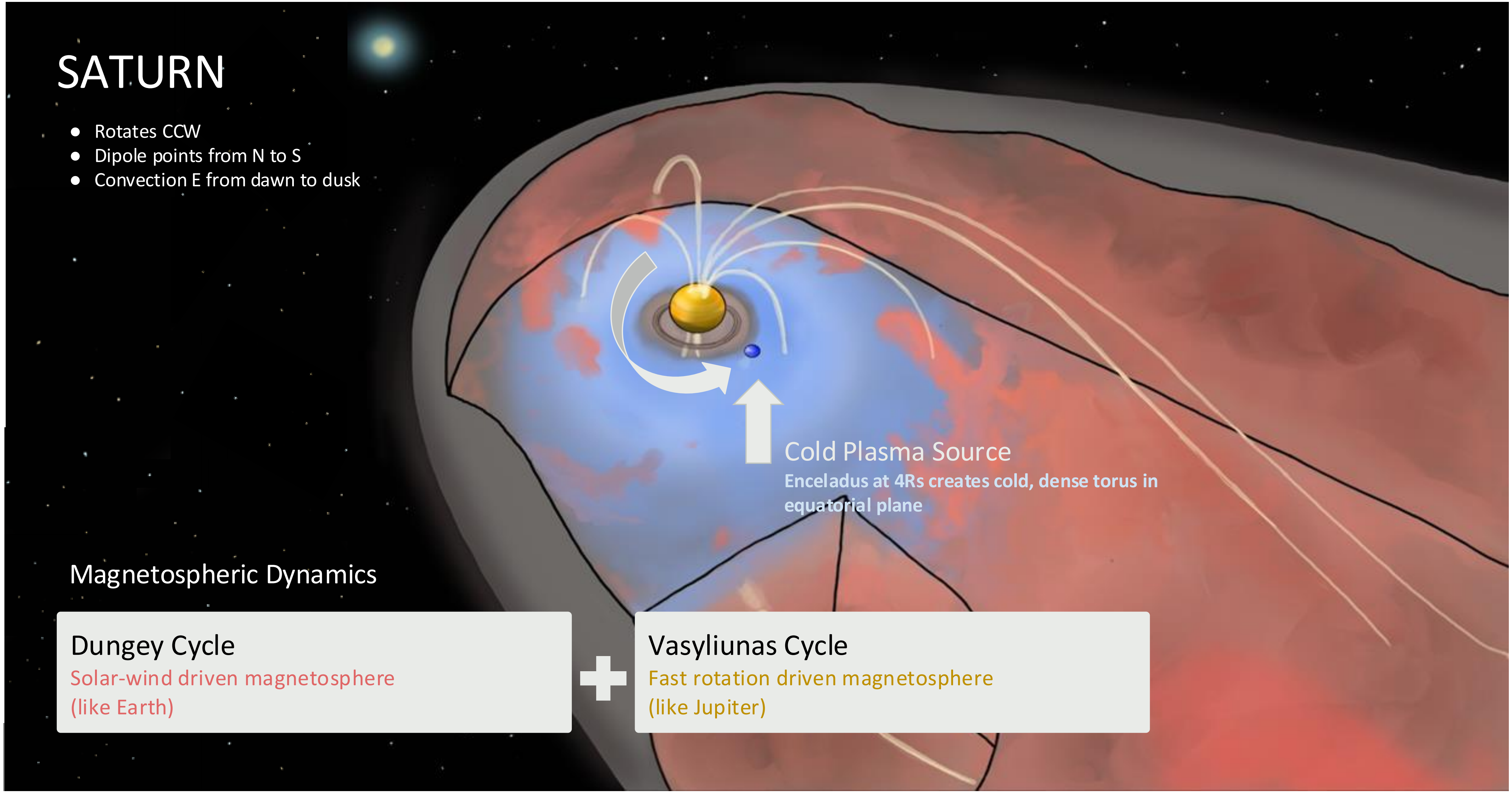
INTERCHANGE INSTABILITY INJECTION

- Density instability at outer planets driven by the centrifugal force
- Many instability names in literature:
  - Rayleigh-Taylor-like, Interchange, Centrifugal, Injection, Ballooning-mode, Gravitational, Flute, etc…
- Comparable to
  - Ballooning-mode instability in Earth's plasmasheet/magnetotail
  - Spread-F and Equatorial Plasma Bubbles in Earth's ionosphere





SATURN

- Rotates CCW
- Dipole points from N to S
- Convection E from dawn to dusk

Cold Plasma Source

Enceladus at 4Rs creates cold, dense torus in equatorial plane

Magnetospheric Dynamics

Dungey Cycle

Solar-wind driven magnetosphere
(like Earth)

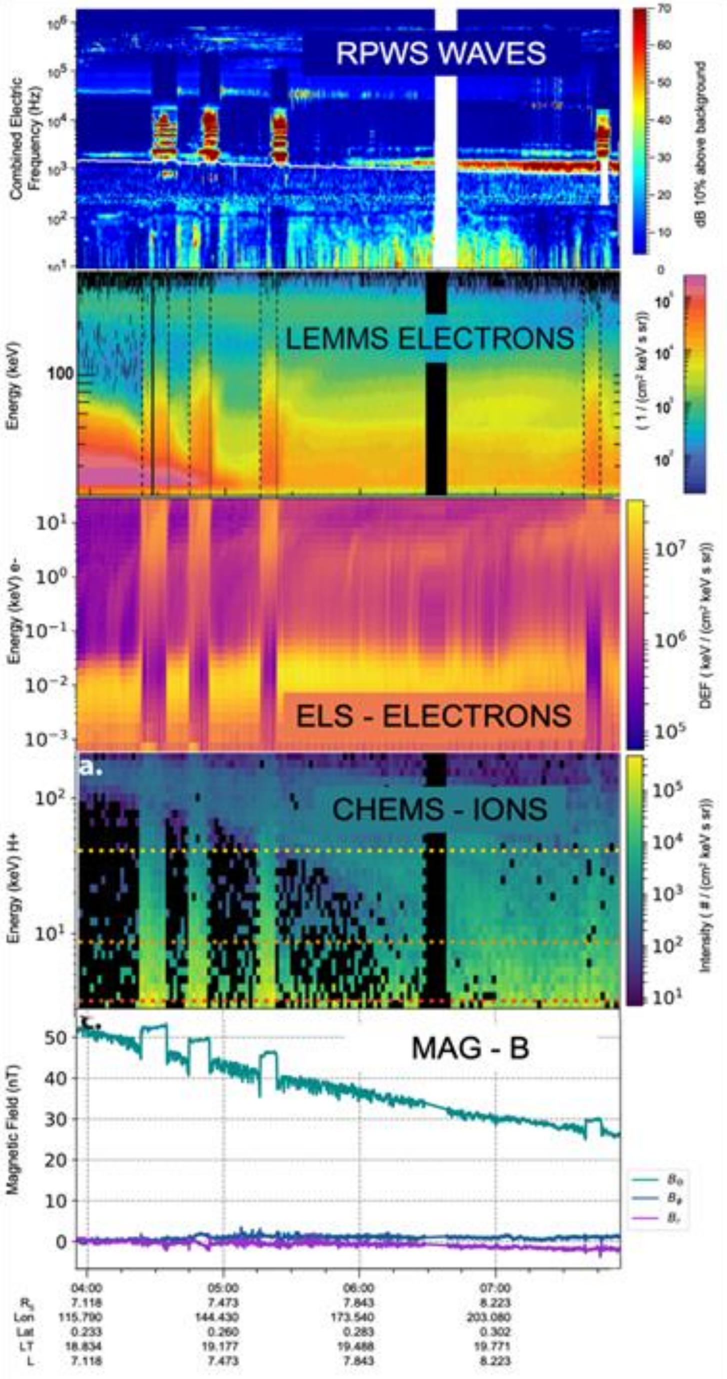
+

Vasyliunas Cycle

Fast rotation driven magnetosphere
(like Jupiter)

Features Seen Across Plasma Instruments on Cassini

Statistical Study	**Radio Plasma Wave Spectrometer** Kennelly et al. 2013	**Cassini Plasma Spectrometer ELS & IMS** Chen & Hill 2008	**Magnetosphere Imaging Instrument CHEMS** Azari et al. 2018	**Magnetometer** Lai et al. 2016
Studied	Events 4-11 Rs Focuses on young IIJs Signature: depression of Upper Hybrid Emission	Events 4.6-14.8 Rs Excludes very young IIJs (width < 0.25 hrs or 0.1 Rs) Signature: V-shape in linear energy-time plot	Events 5-12 Rs Signature: Enhancements of 3-220 keV	Events L<18 Signature: Magnetic perturbation > 30s
Width *Occurs*	Chen & Hill 2008 found most events < 1 Rs. Azari et al. 2018 small intensity IIJs ~ 0.25 Rs and high intensity IIJs 0.4 Rs, and most events are < 15 min wide.			
Ages	Chen & Hill found most events < 2 hrs old. Lai et al. 2016 found flux tubes break down as events aged. 75%/49% of magnetic enhancements/depressions lasting < 5 min.			
LT *Occurs at all LT*	Clustering Post-noon and near-midnight	Clustering at pre-noon	Clustering nightside, w/ dawn preference for high intensity IIJs	-
Distance *Inner Mag*	-	95% in L=5-10	Strongest events 6-9 Rs	-



Interchange Injection Event(s) : March 21, 2006 (UTC)

Only some events are seen across all plasma instruments. Why?

Occurrence

- No preference in LT or Radial distance
- Minutes long duration
- Magnetic enhancement or depression used as event start/stop (Lai et a. 2016)
  - Azari et al. 2018 (MIMI) signatures have similar start and stop.
  - Kennelly et al. 2013 (RPWS) and Chen & Hill 2008 (ELS) have similar start and stop, often after event is identified in Lai et al. 2018 (MAG) and Azari et al. 2018 (MIMI).
    - Could cause lower bound in number of identified events.

Overall signatures

- Clean, magnetic signatures of flux tubes w/ particle signature content
  - All electrons/ions have dispersion – events are not extremely young.
  - Some can be bubbles, most are more likely to be morphologically fingers
  - Wave signature is variable.
  - Some events have mixed intermediate temperature (not hot injection or cold thermal background) electron content

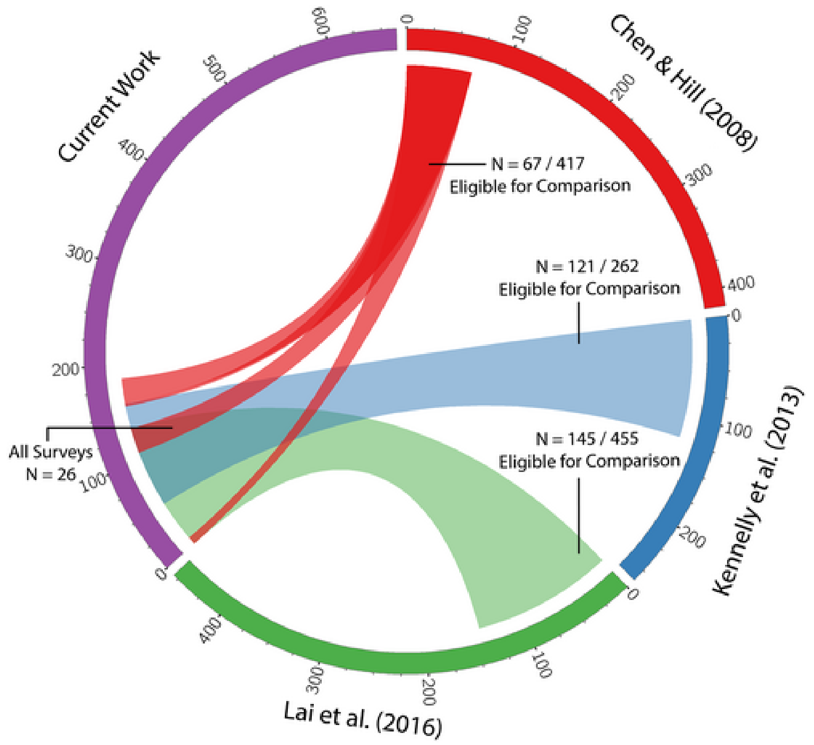
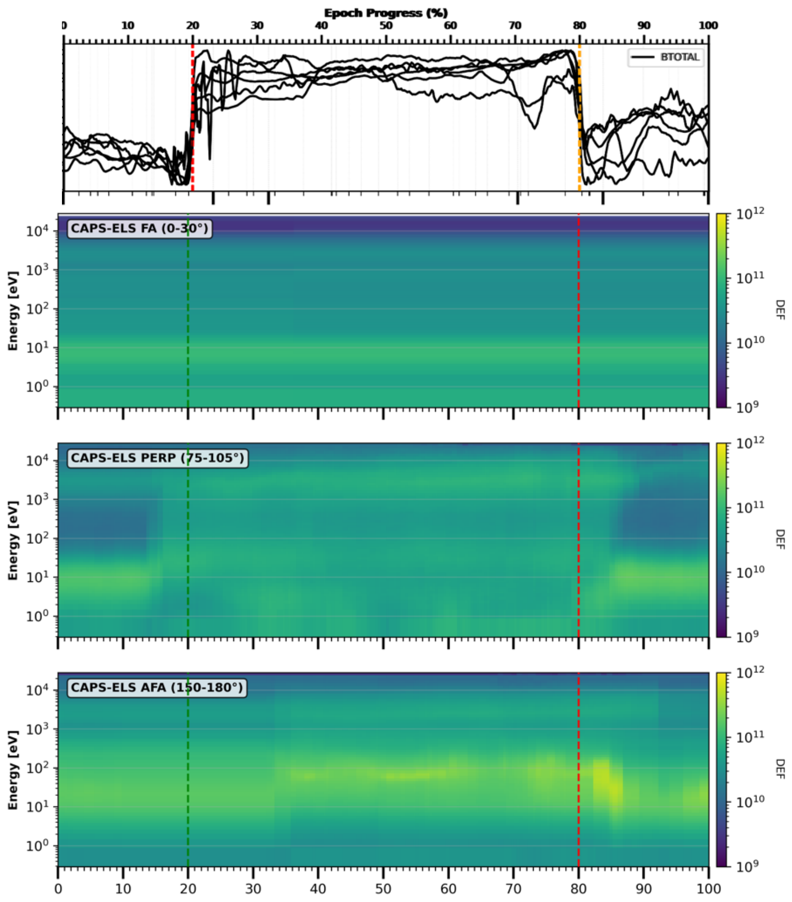


Figure from Azari 2018

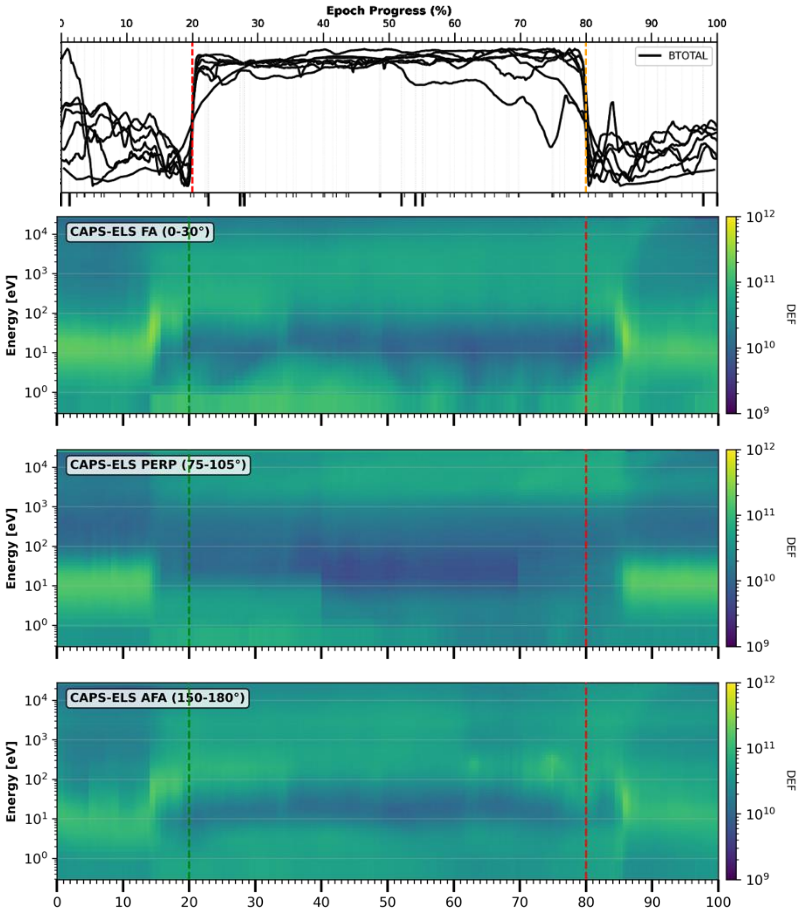
Comparison limited by latitudinal and radial extent of surveys. Instrument availability and resolution also creates limitation.

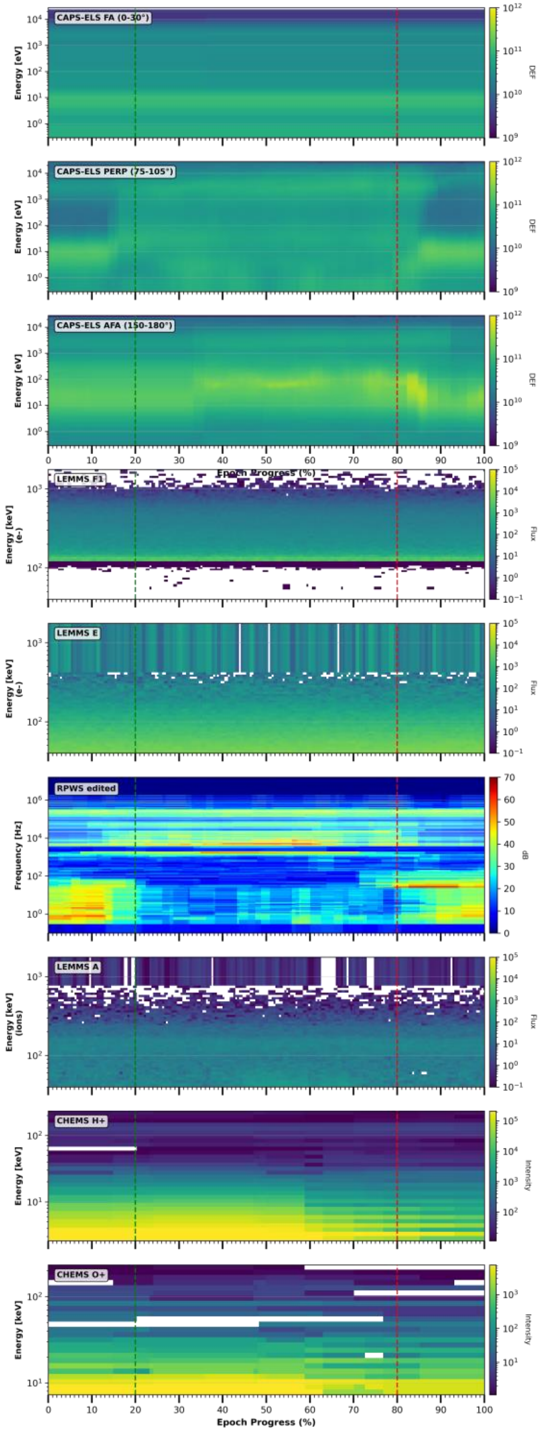
Categorizing Common Events Using ELS Instrument

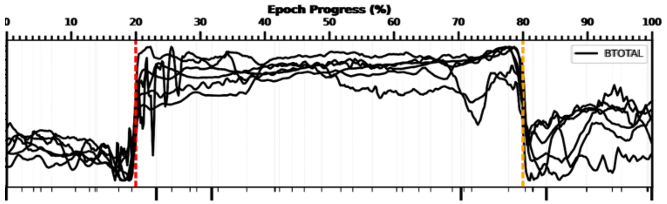
Flux tube w/ muddled Mixed Origin Electrons

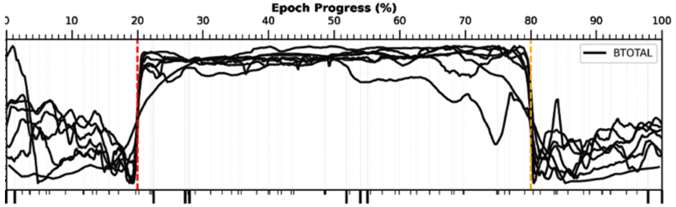


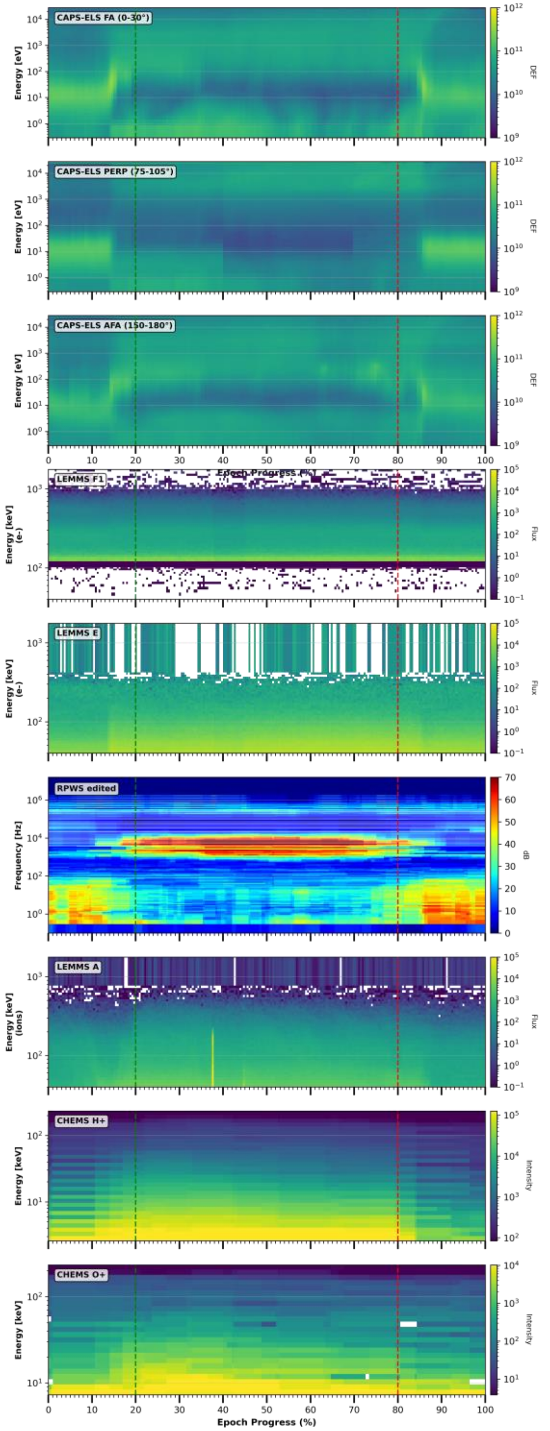
Flux tube w/ Clear Origin Electrons











Mixed Origin Electron Flux Tube ‘Filled’

- Mixed electron population (cold thermal background + hot injection)
- Pitch angle dependence
- Hot injection electrons (1-25 keV) show more dispersion
- Hot injection ion signatures show more dispersion
- Less wave activity
- Clear magnetic enhancement
- Tend to be shorter

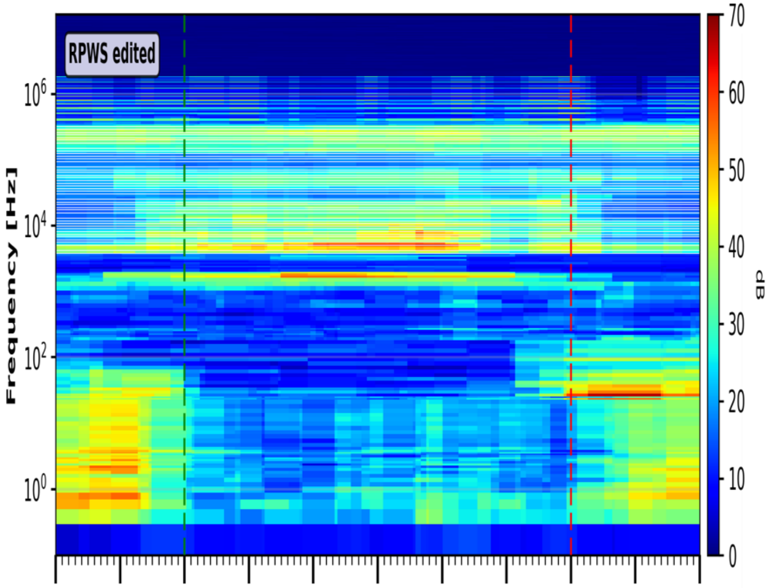
Clear Origin Electron Flux Tube ‘Empty’

- Clear enhancement of hot injection and lack of cold thermal background electrons
- Pitch angle dependence

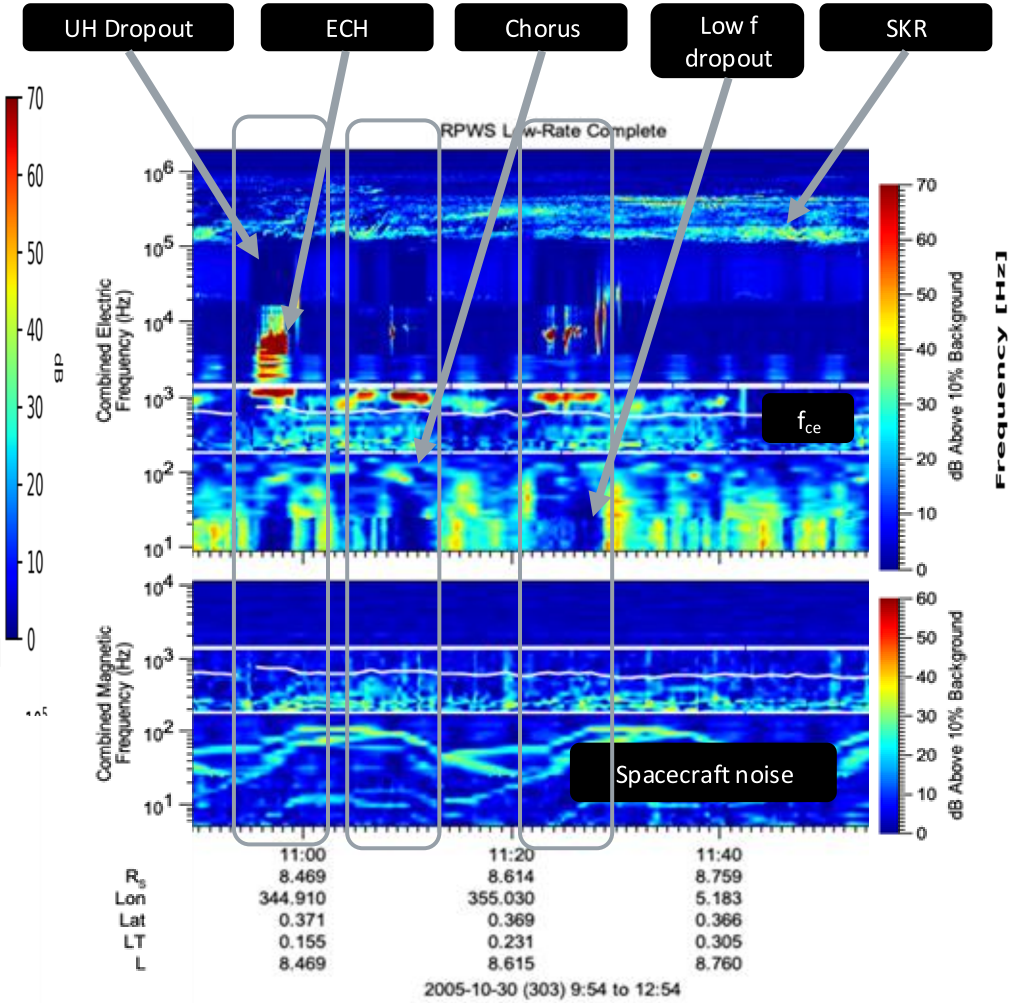
Event mixes within the flux tube as it gets older, maintaining structure

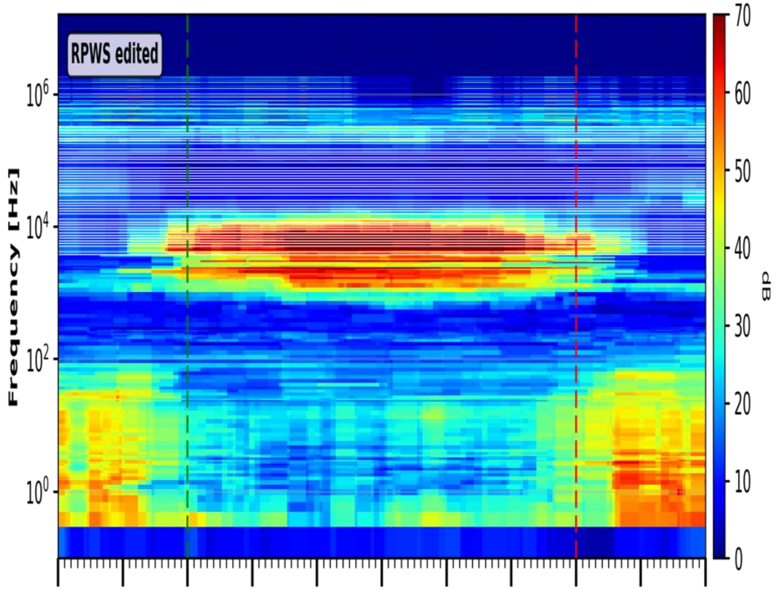
- More wave activity
- Clear magnetic enhancement w/ more dramatic flux tube walls
- Tend to be longer

Can We Look At Wave Signature To Understand How Particle Content Is Evolving With The Environment?



Mixed Origin Electron Flux Tube
‘Filled’

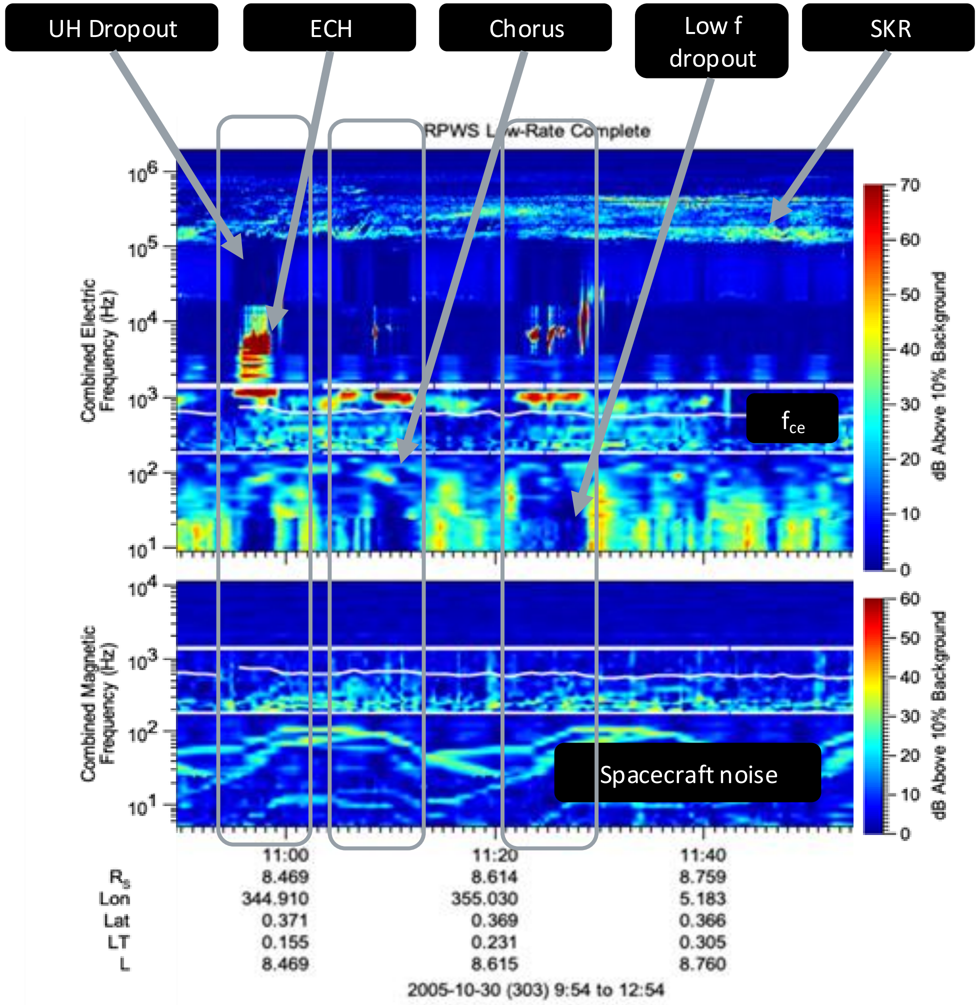




Clear Origin Electron Flux Tube
‘Empty’

Can We Look At Wave Signature To Understand How Particle Content Is Evolving With The Environment?

- 249 events in Kennelly et al. 2013 extended from to 430 events by Dr. George Hospodarsky (Univ. Iowa)
- Wave events identified by lowering of the Upper Hybrid
- Events checked if they have:
  - Enhanced Electron-cyclotron harmonics (ECH)
  - Enhanced Chorus
  - Enhanced Upper Hybrid (UH) (at the lowered frequency)
  - Drop out of low-frequency activity.



UH Dropout

ECH

Chorus

Low f dropout

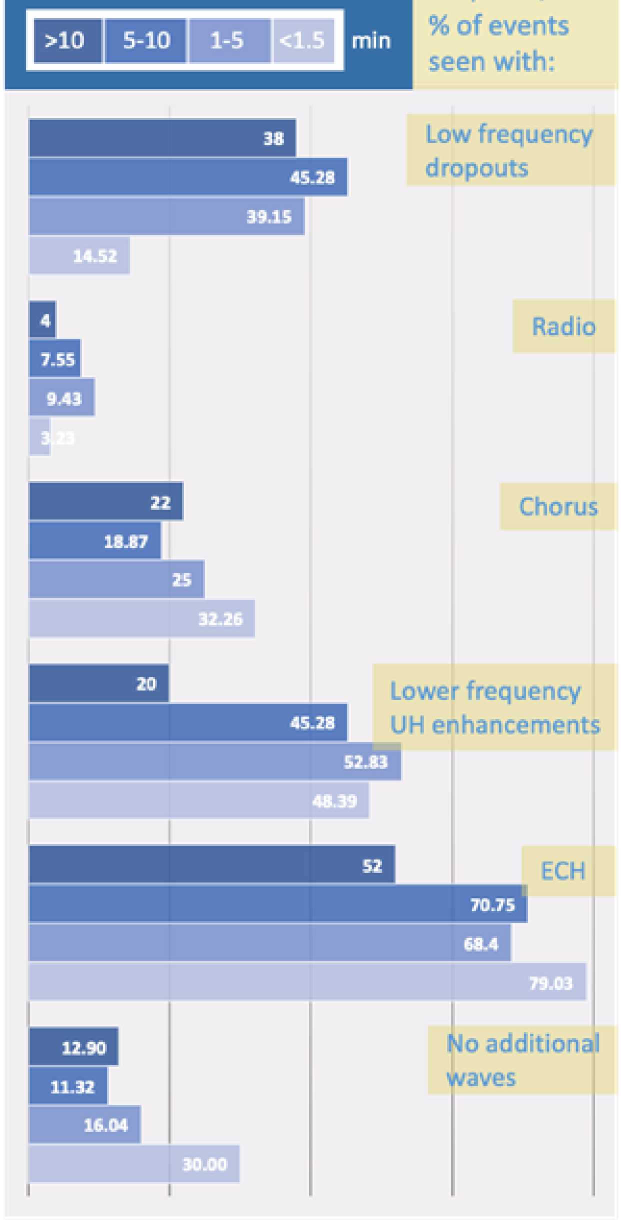
SKR

f_{ce}

Spacecraft noise

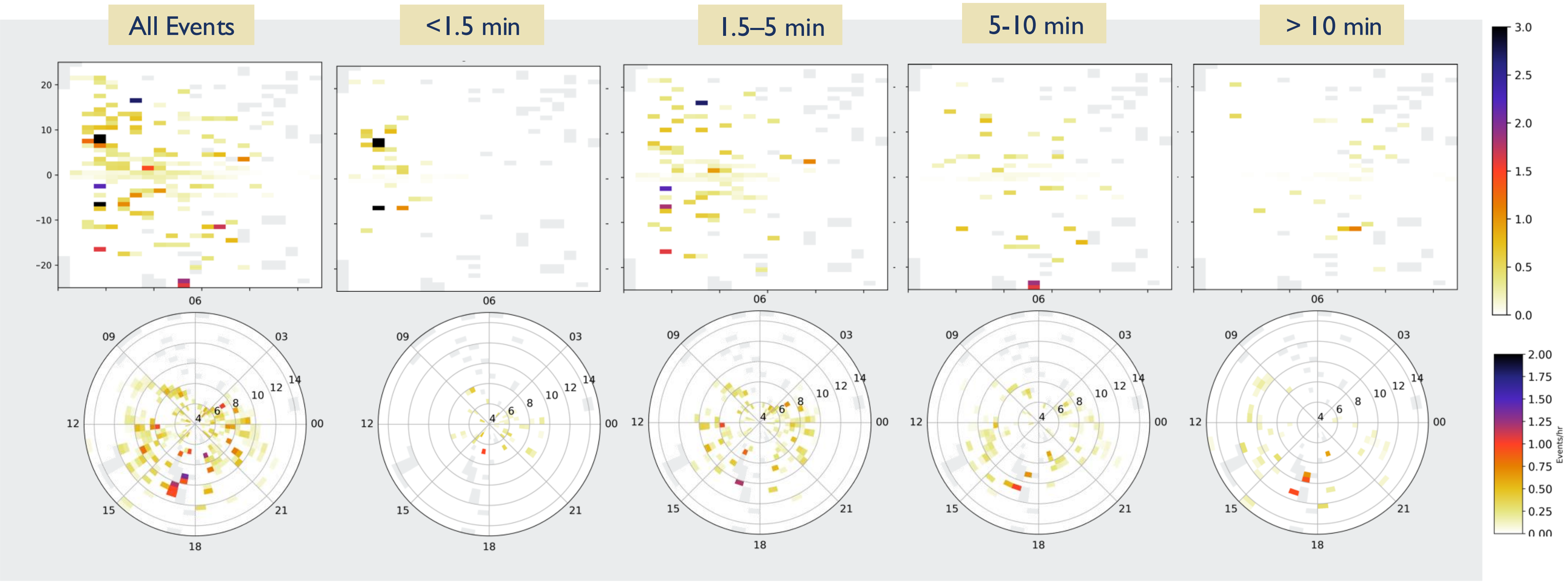
Wave types in RPWS IIJ List

In addition to event threshold UH dropouts, % of events seen with:



Wave Signatures Of Interchange Events

- Lack of wave events in Dawn segment
- Most events have duration of 1.5 – 5 (49.3%) or 5 – 10 minutes (24.7%)
- Most wave types do not have a latitudinal preference (except: Chorus)
- ECH enhancements are often seen with:
  - UH enhancements … strongest occurrence rate location is similar, and decrease as we go to increase in radial distance
  - Low f dropout
  - No significant trend with Chorus enhancements .



Waves Across Comparative Magnetospheres

	Injection Events at Saturn	Saturn	Earth
ECH	Beautiful multiple harmonics, up to n=9/2 bands	Magnetic equator, fall off rapidly beyond 8Rs. Decrease at Enceladus torus. Peak at L ~ 7.5	Dominant source near equator outside plasmapause 4 < L < 7
Chorus	Lower + Upper band containing two times more power	Lower band, 4.5 < L < 7.5 between 5 < lat < 10, concentrated night side but power is about the same all LT	4<L<9 for lower band, 3<L<7 for upper band

Menietti et al. 2017

Menietti et al. 2014, Hospodarsky et al. 2008

- Open question for low-frequency dropout.
- Could ECH dependence be based on injection tubes 'Trapping' or 'Non-trapping' electrons?

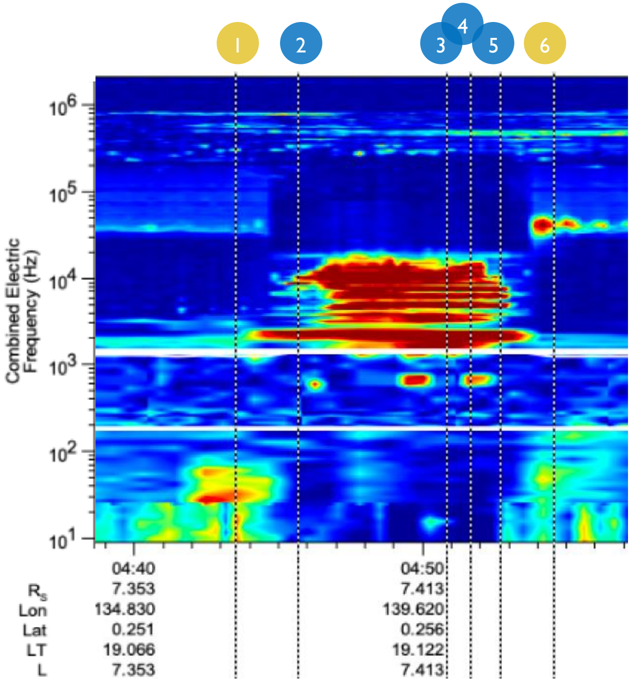
Yin et al. 2023, 2025

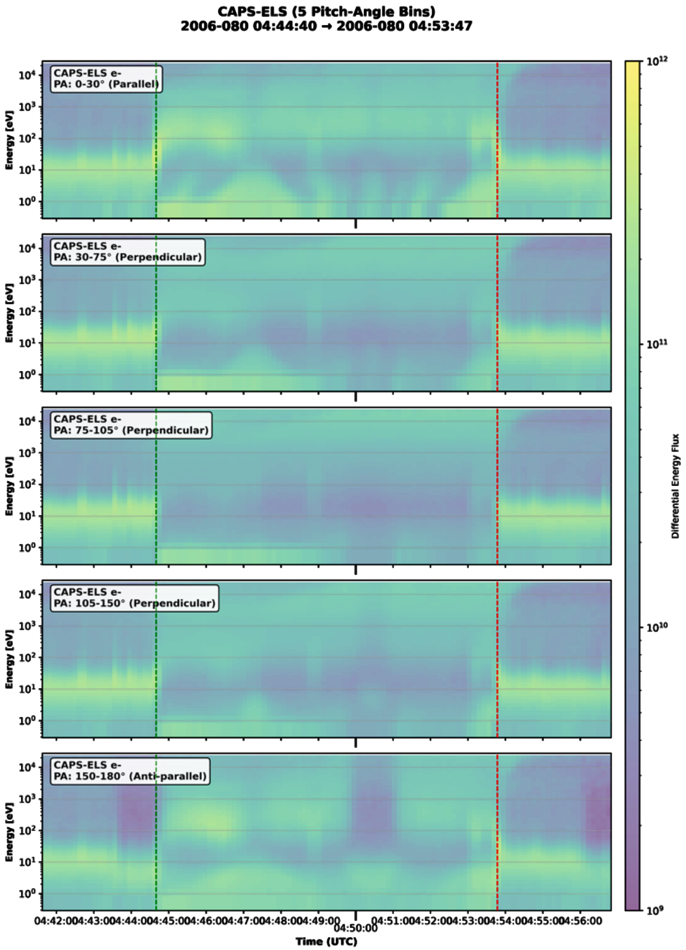
Dispersion on Perpendicular + Field Aligned

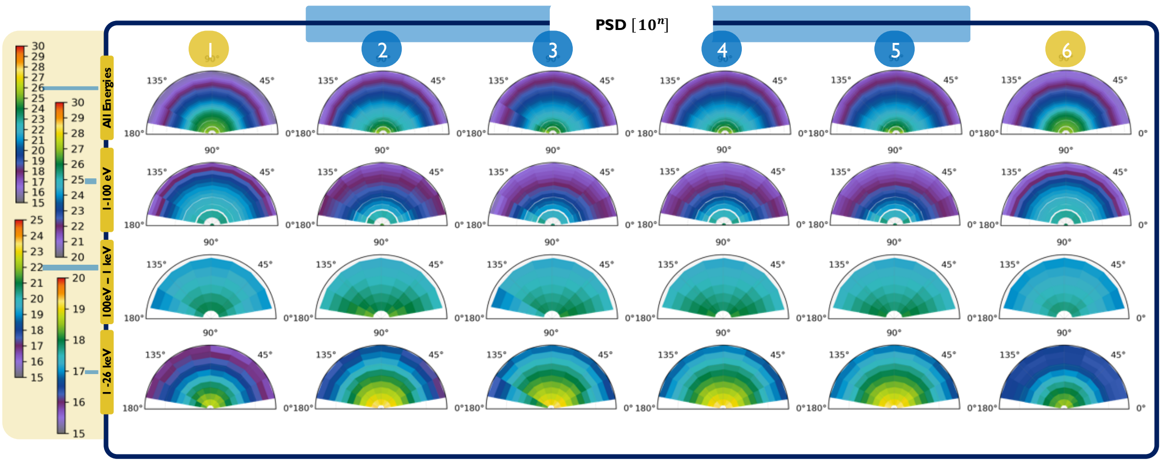
Dispersion on Field Aligned

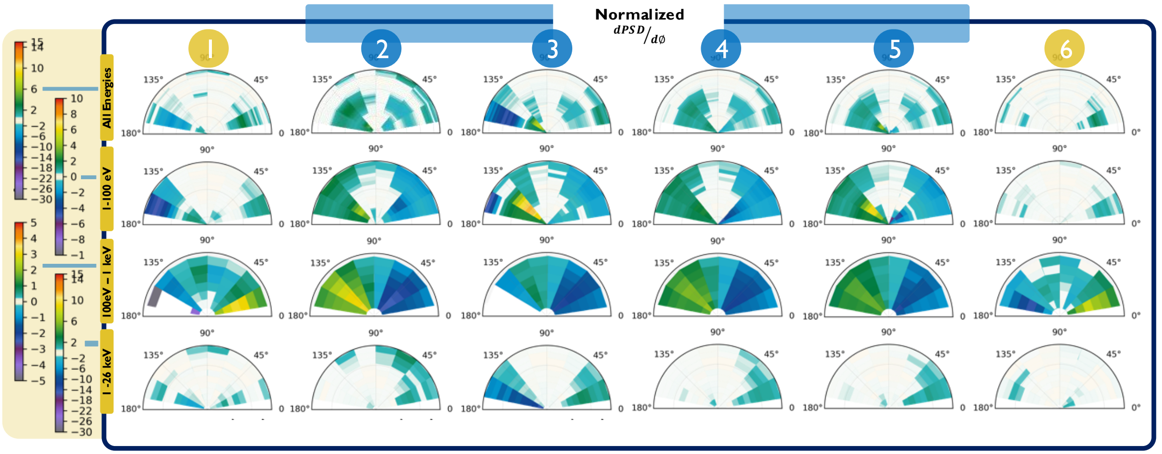
'EMPTY FLUX TUBE'
CLEAR ORIGIN ELECTRONS

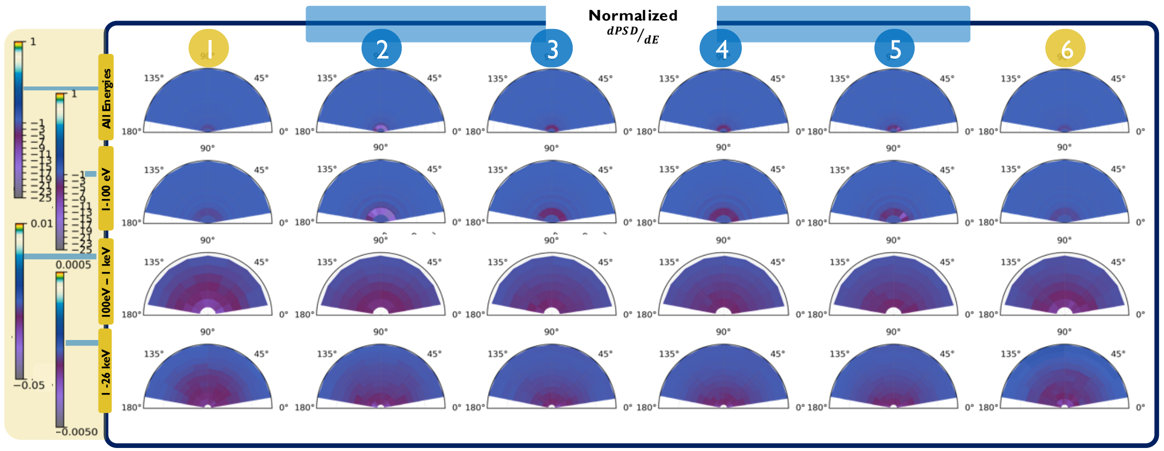
2006-3-21 4:44:40 to 4:53:47





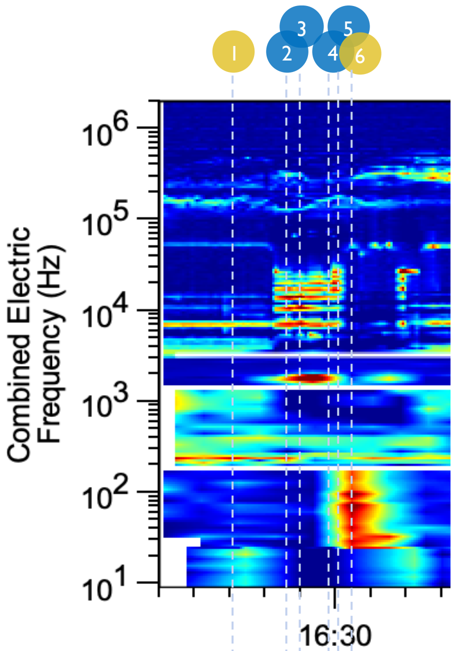




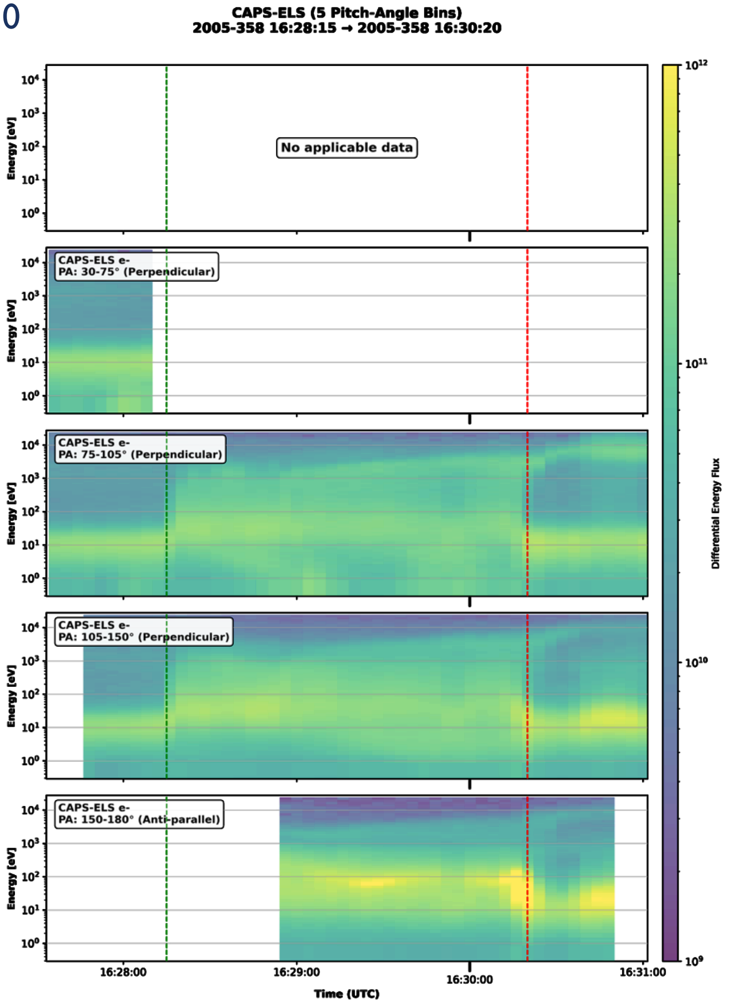


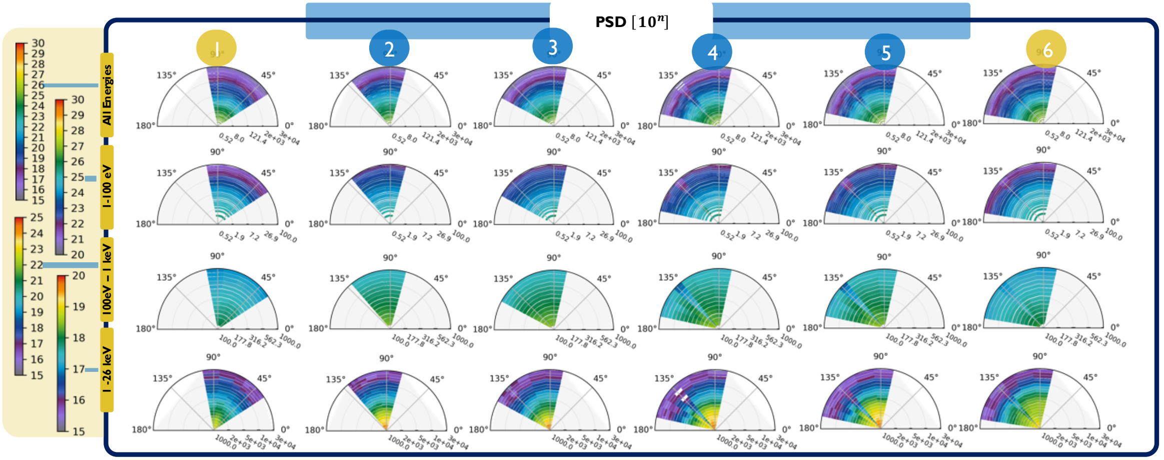
‘FILLED FLUX TUBE’
MIXED ORIGIN ELECTRONS

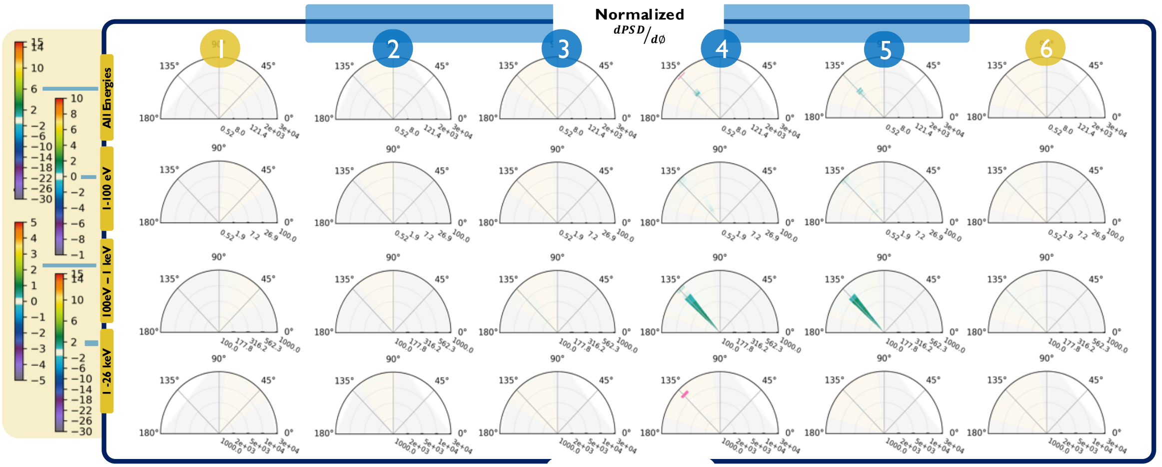
2005-12-24 16:28:15 to 16:30:20

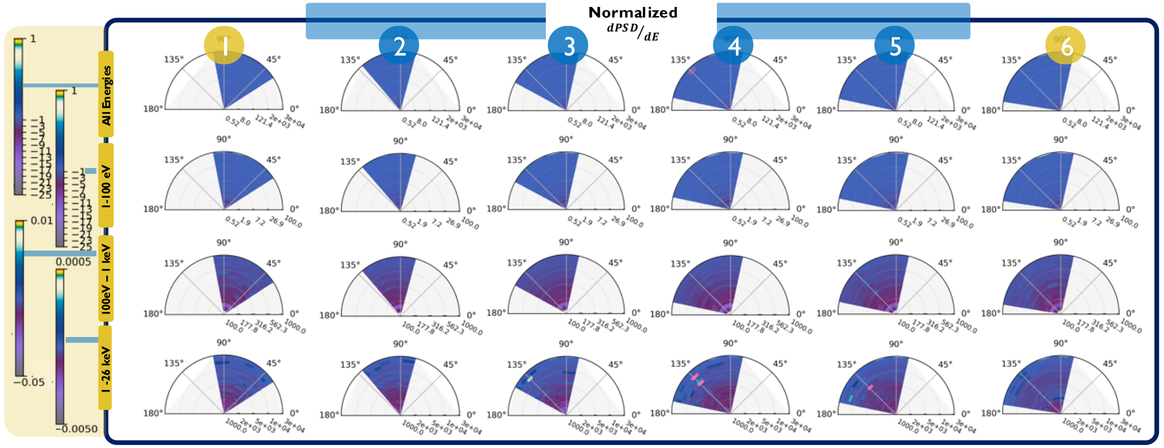


	16:30
R_S	5.515
Lon	264.700
Lat	-0.177
LT	14.665
L	5.515









Particle Evolution In Flux Tube

Outside event → Inside event → Outside event

	Clear Origin Flux Tube 'Empty'	Mixed Origin Flux Tube 'Filled'
1—100 eV	Isotropic → Towards Pancake (90 degrees) → Isotropic Higher PSD → Lower PSD → Higher PSD	Not much PSD evolution Higher PSD → Lower PSD → Higher PSD
100 eV – 1 keV	Towards Cigar → Towards Pancake (90 degrees) → Towards Cigar Same PSD → Same PSD → Same PSD	Not much PSD evolution … Slight PA 135 going towards 90 Same PSD → Same PSD → Same PSD
> 1 keV	Isotropic → Isotropic (slight Cigar) → Isotropic Lower PSD → Higher PSD → Lower PSD	Not much PSD evolution Same PSD → Same PSD (Higher PSD for 1-2 keV) → Same PSD Wave growth at PA 135

- Which different PSD can be causing the low-frequency dropout?
- 'Empty' vs 'Filled' flux tube is not dependent on injection tubes 'Trapping' or 'Non-trapping' electrons …

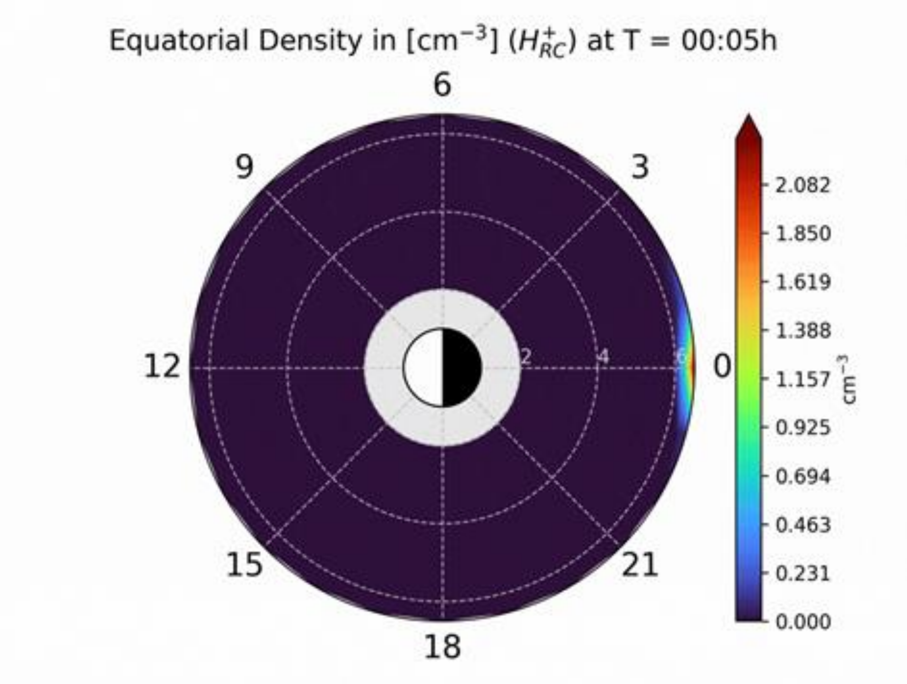
… Age… … Flux tube content …

Cross-Disciplinary Approach
Confirming IIJ particle behavior

Kinetic Modeling w/ HEIDI

- Earth-based Inner Magnetosphere model Hot Electron Ion Drift Integrator (HEIDI)

- Solves for the Ring Current distribution



$$\frac{\partial Q}{\partial t}+\frac{1}{R_o^2}\frac{\partial}{\partial R_o}\left(R_o^2\left\langle\frac{dR_o}{dt}\right\rangle Q\right)+\frac{\partial}{\partial\phi}\left(\left\langle\frac{d\phi}{dt}\right\rangle Q\right)+\frac{1}{\sqrt{E}}\frac{\partial}{\partial E}\left(\sqrt{E}\left\langle\frac{dE}{dt}\right\rangle Q\right)+\frac{1}{h(\mu_o)\mu_o}\frac{\partial}{\partial\mu_o}\cdot\left(h(\mu_o)\mu_o\left\langle\frac{d\mu_o}{dt}\right\rangle Q\right)=\left\langle\frac{\partial Q}{\partial t}\right\rangle$$

New features (Verified)	Working features
• Coupled with Space Weather Modeling Framework (SWMF) Global Magnetosphere (BATS-R-US) Model	• Physically representative background from moons as a source term
• #PLANETS command loads outer-planet parameters	• Centrifugal force as a loss term
• IIJ-representative localized injection feature to observe drift	• Waves as a source/loss term

Confirming IIJ particle behavior

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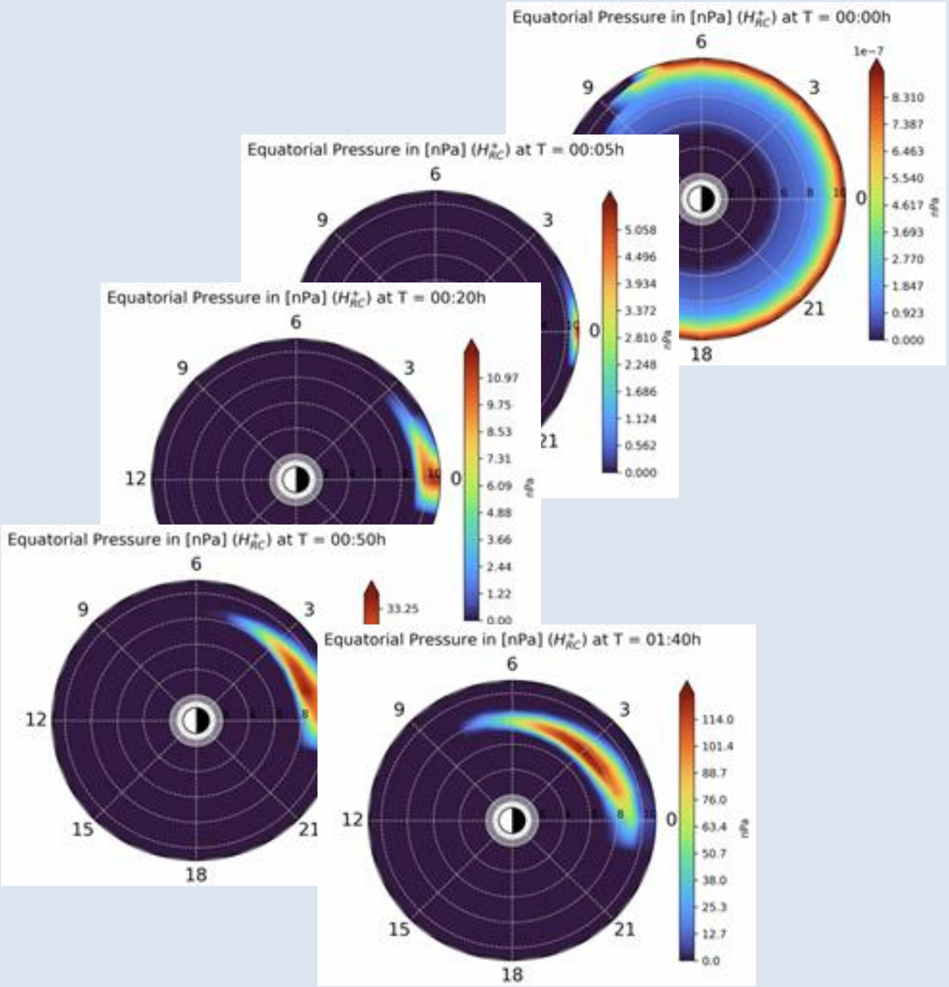

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THANK YOU ☺

All commentary and thoughts are appreciated!

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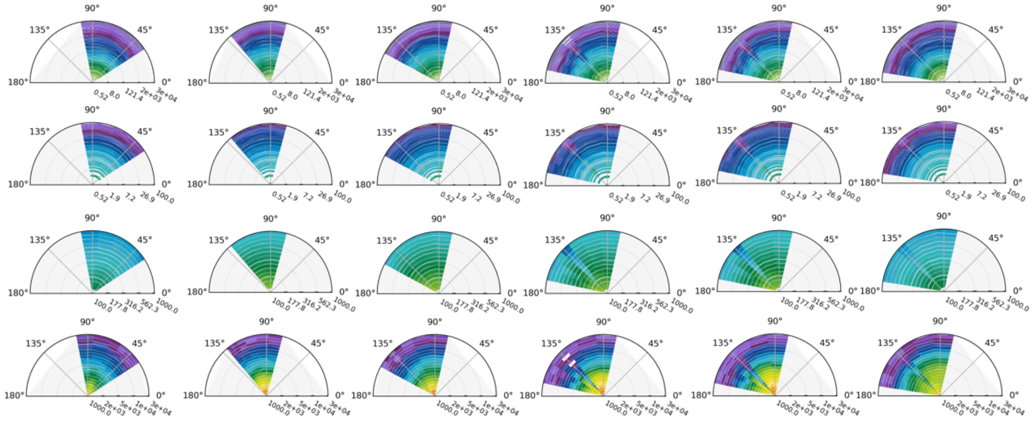
90°
135°
45°
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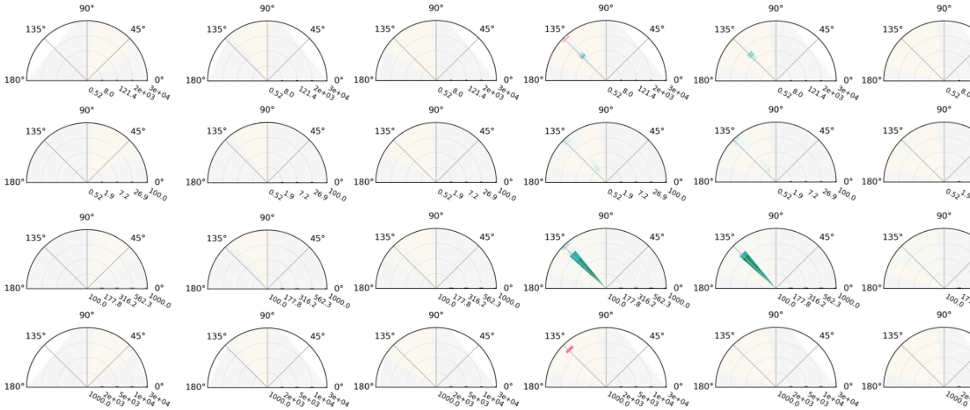
0°
0.52 8.0 121.4 2e+03 3e+04
0.52 1.9 7.2 26.9 100.0
100.0 177.8 316.2 562.3 1000.0
1000.0 2e+03 5e+03 1e+04 3e+04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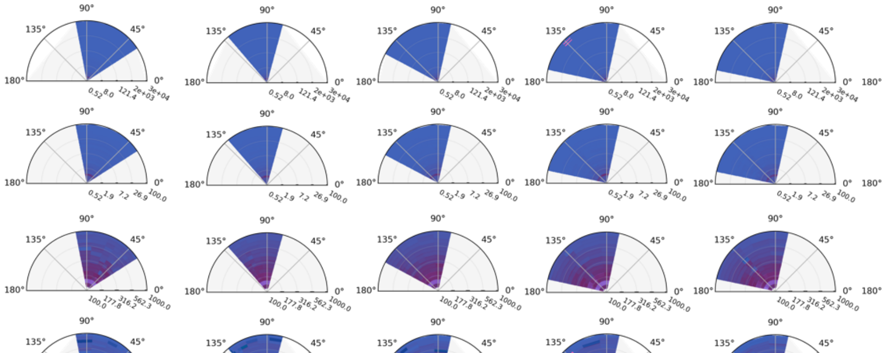
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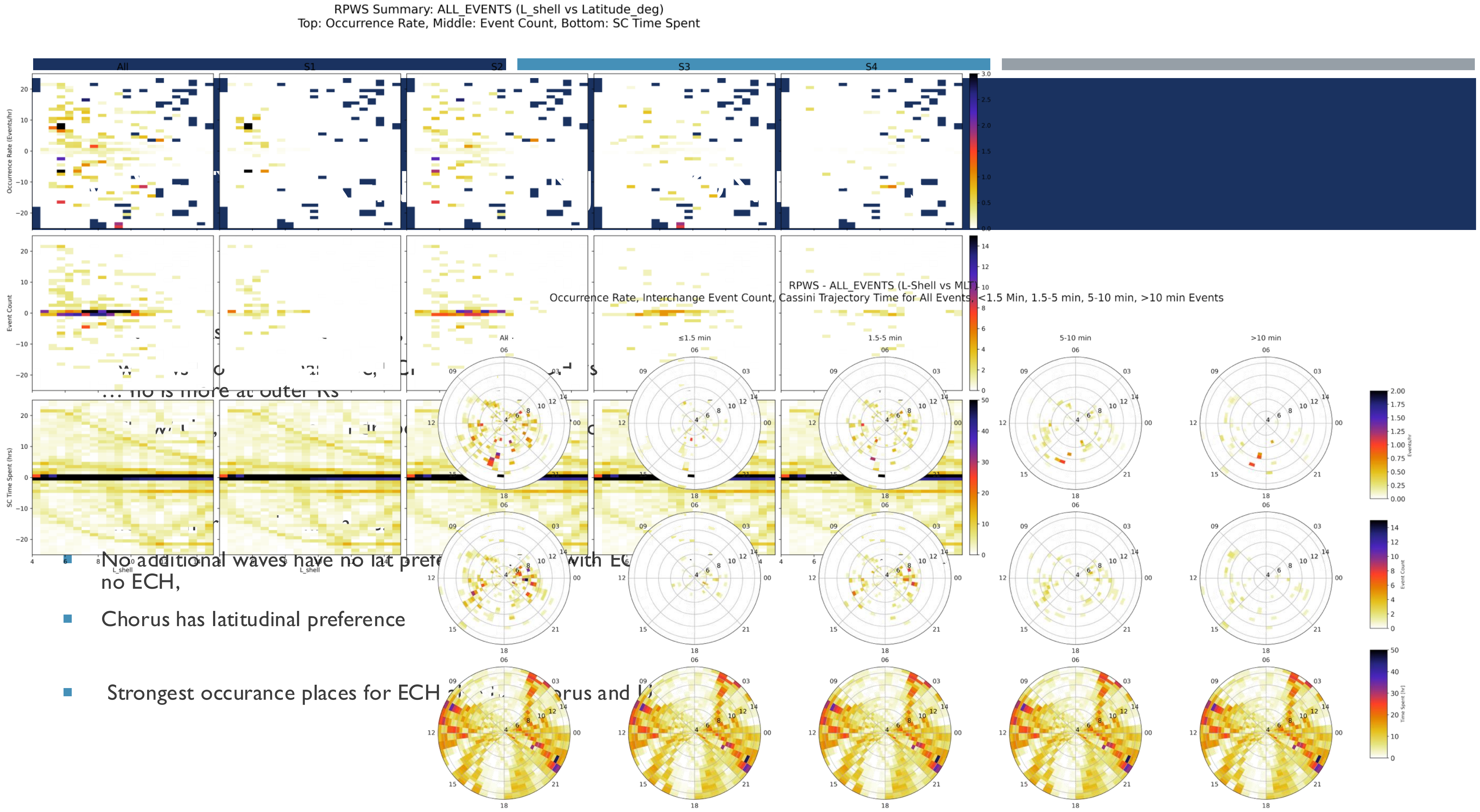

… no is more at outer Rs

- No additional waves have no lat prefe… with EC… no ECH,
- Chorus has latitudinal preference
- Strongest occurance places for ECH a… orus and U…