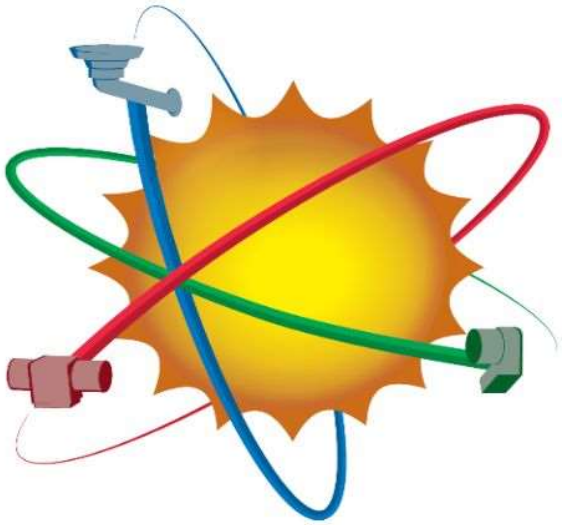
Tracing the Cosmic Energy Flow with Parker Solar Probe: Universal Processes



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20th Annual Astrophysics Conference
2022 Nov 02

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Heliophysics is multi-disciplinary

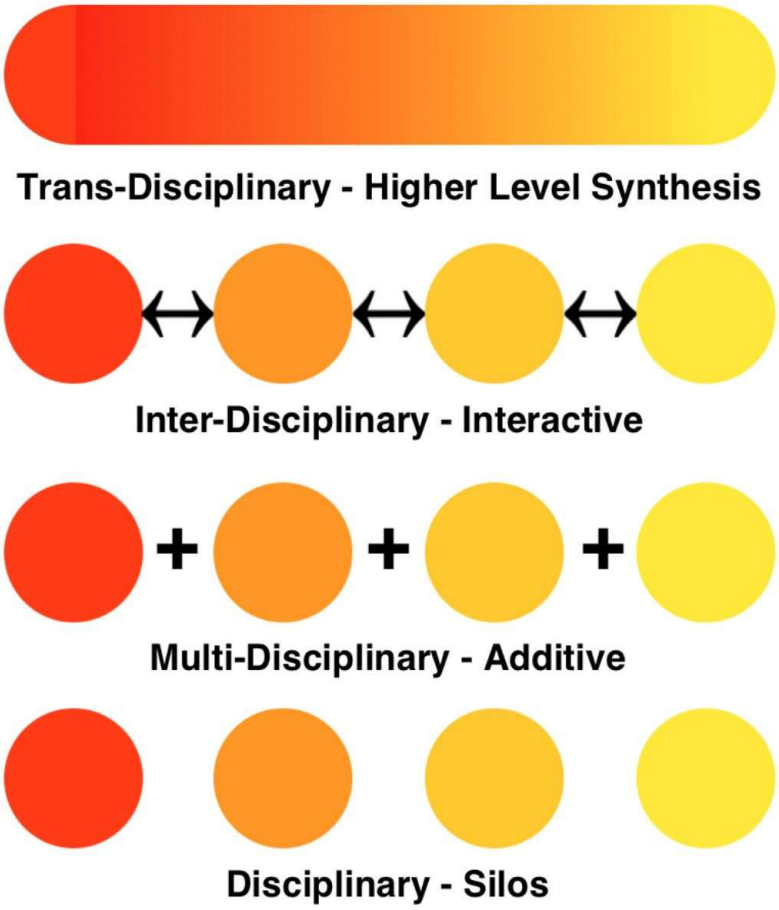
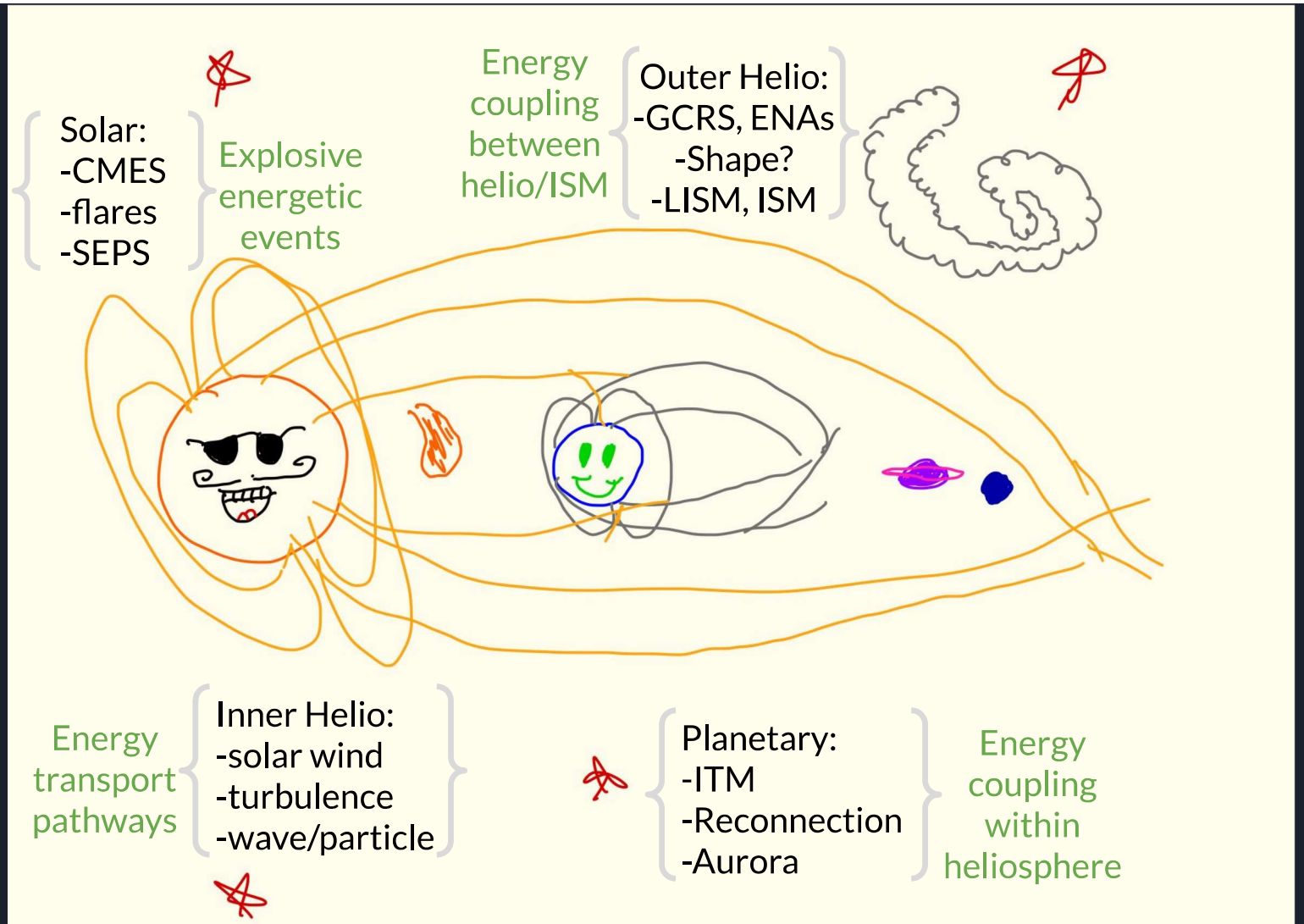
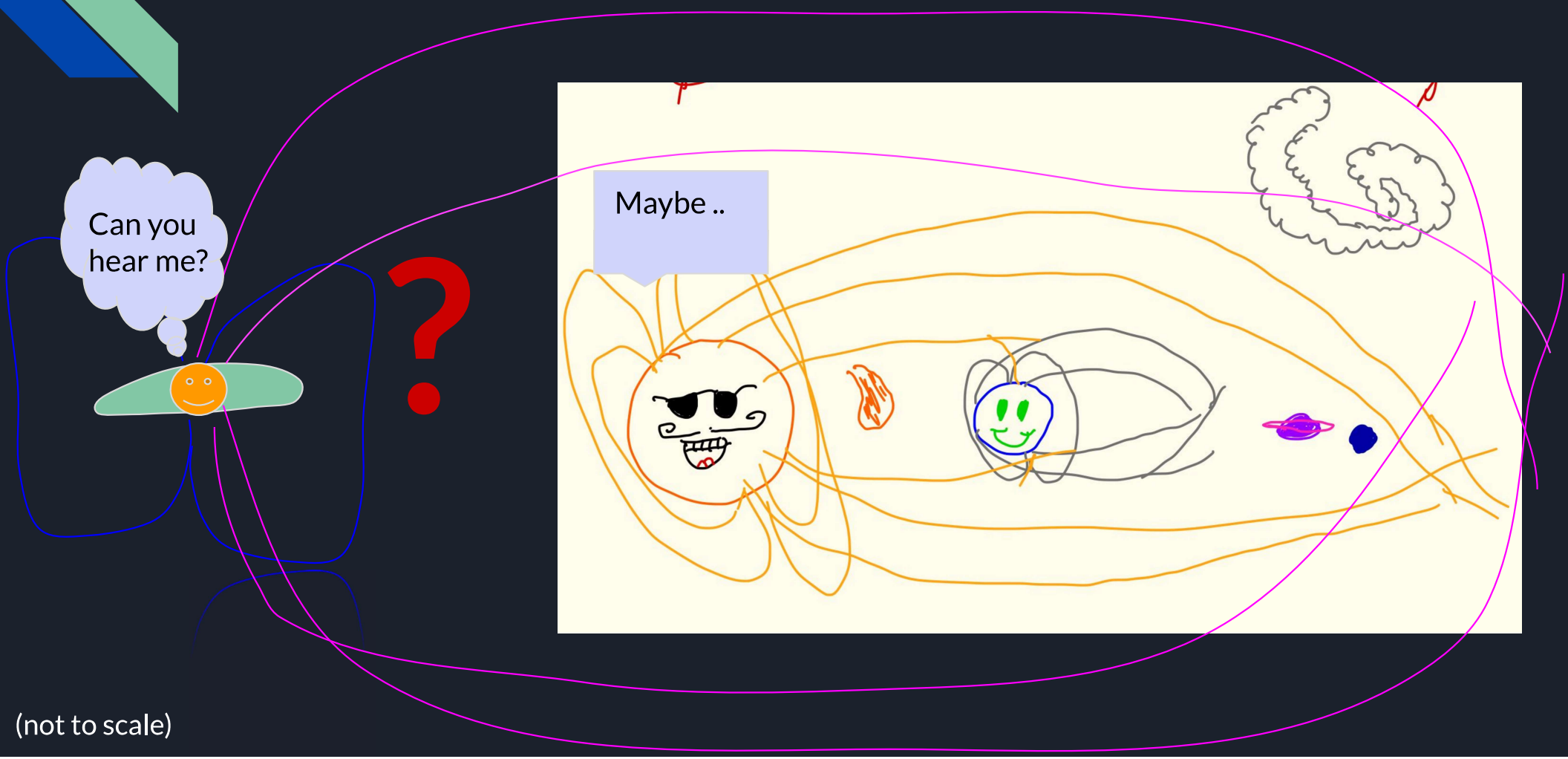


Image credit:
https://www.uts.edu.au/about/uts-business-school/our-research/hub-sustainable-enterprise/anthropocene-transition-project


Solar:
-CMES
-flares
-SEPS
Explosive energetic events
Energy coupling between helio/ISM
Outer Helio:
-GCRS, ENAs
-Shape?
-LISM, ISM
Energy transport pathways
Inner Helio:
-solar wind
-turbulence
-wave/particle
Planetary:
-ITM
-Reconnection
-Aurora
Energy coupling within heliosphere
(not to scale)

Open Question: How does a Black Hole's "sphere of influence" affect the heliosphere?

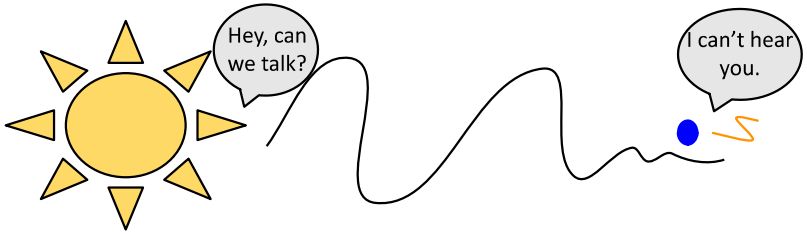


(not to scale)

Common Fundamental Processes

- Turbulence
- Wave-Particle interactions
- Kinetic Instabilities
- Evolution of Particle Velocity Distribution Functions (VDFs)
- Dust
- Magnetic Reconnection
- Shocks
- Much more!

Parker Solar Probe is supporting an ongoing investigation…



1. *Who* is involved in the story of marco-scale to micro-scale cosmic energy flow?
2. *What* is the nature of the mechanisms mediating cross-scale energy transfer?
3. *Why* do kinetic-scale features show signatures of macroscale processes?
4. *When* does cross-scale energy transfer occur?
5. *Where* in the heliosphere can we witness it?
6. *How* does cosmic energy flow heat plasmas?

Top-level PSP Science Question (Fox, 2016)

The story of a proton beam

Departures from local thermodynamic equilibrium in particle velocity distribution functions (VDFs) can provide free energy for wave generation

Non-Maxwellian features, such as beams, have been observed by SPAN-I, a subset of the particle instrument suite, SWEAP

→ 3D ion distributions with mass discrimination

Simultaneous electromagnetic field data from FIELDS shows hints of energy transfer via wave-particle interactions

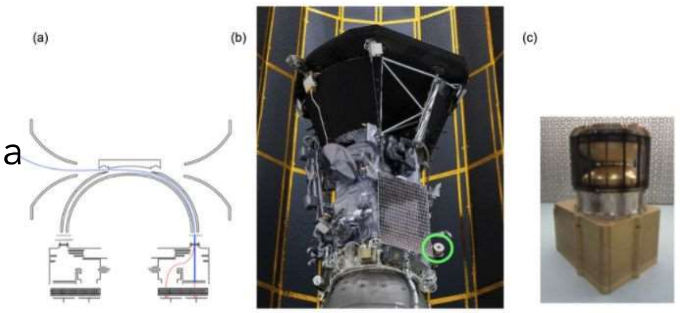
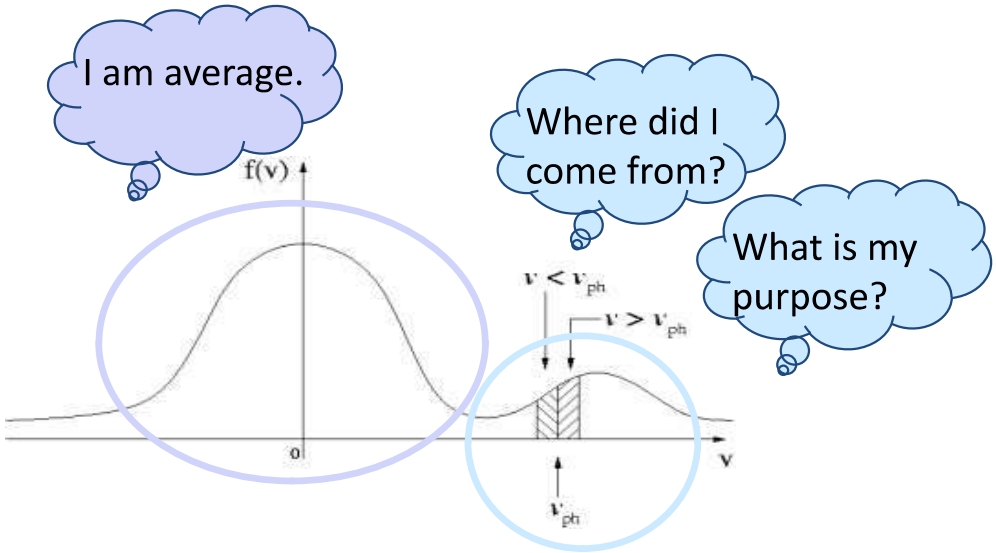


Fig. 2. SPAN-I: (a) Top-hat design (b) Highlighted on PSP within green circle (c) Close-up taken in lab (at SSL)

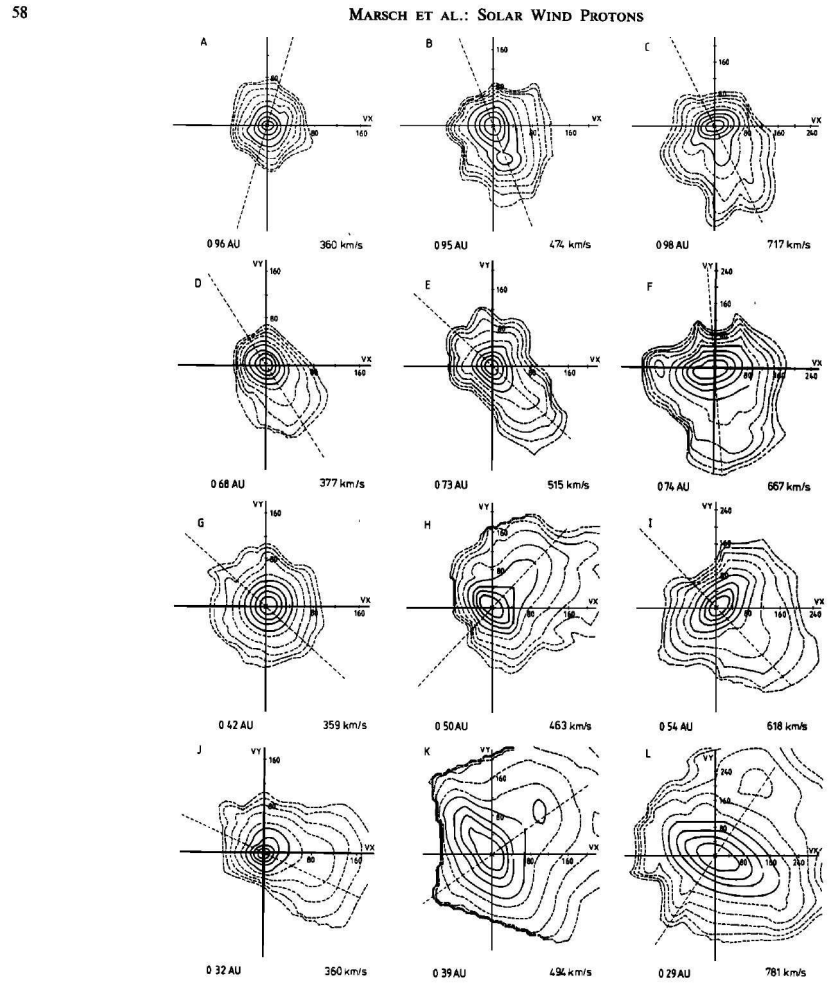
[Livi et al, 2021]

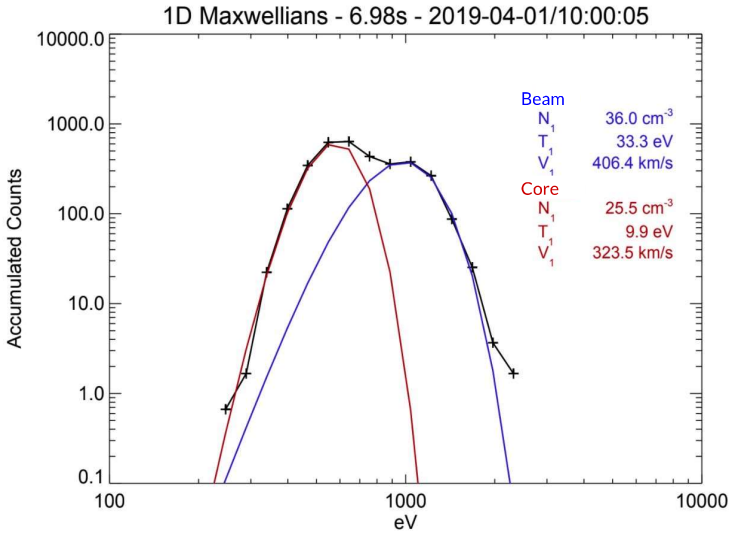


Example non-Maxwellian feature, a bump-on-tail instability that could lead to wave growth. Particles moving slightly slower (faster) than the wave phase velocity can participate in resonant interaction, leading to energy transfer from the particles to the wave.

Image Credit: CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=279802

Helios saw the proton beam in Marsch et al. (1982)





$$f_{pj}(\mathbf{v}) = \frac{n}{\left(\sqrt{\pi}\psi_j\right)^3} \exp - \left(\frac{v^2}{\psi_j^2}\right)$$

$$\psi_j = \sqrt{\frac{2k_B\mathbf{T}_j}{m_j}} \qquad \mathbf{T}_j = (T_\perp, T_\parallel)$$

$$f(\mathbf{v}) = \sum_{j=1}^{2} f_{pj}(\mathbf{v})$$

~ 36 Solar Radii

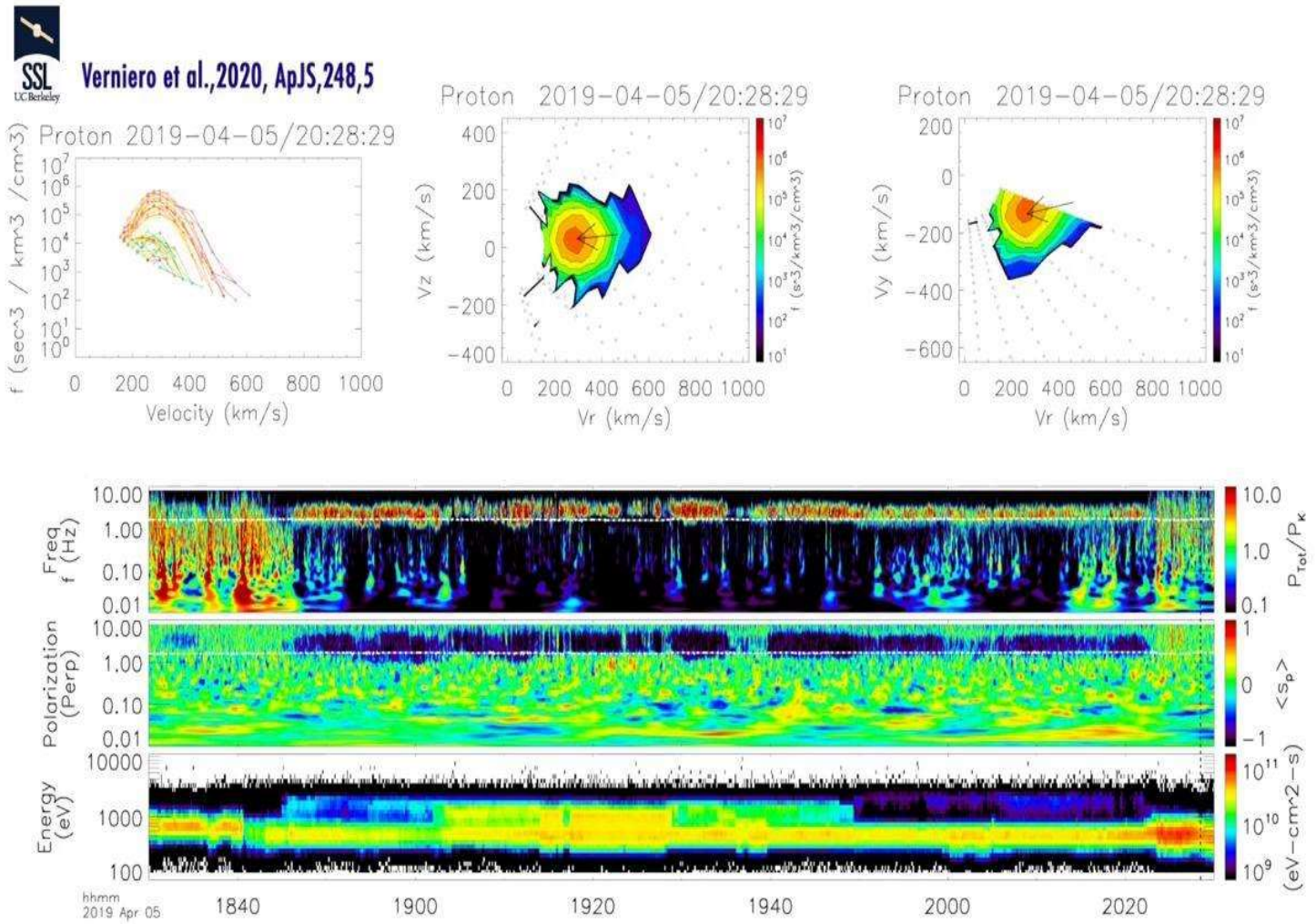
(Left) SPAN-I 3D VDF, each line is energy sweep at different elevations

(Middle/Right) SPAN-I 2D VDF Contour Elevations, black arrow = magnetic field direction

Narrow band ion-scale wave frequency

Blue = Left-Handed Circular Polarization (spacecraft frame)

SPAN-I Measured Energy Flux



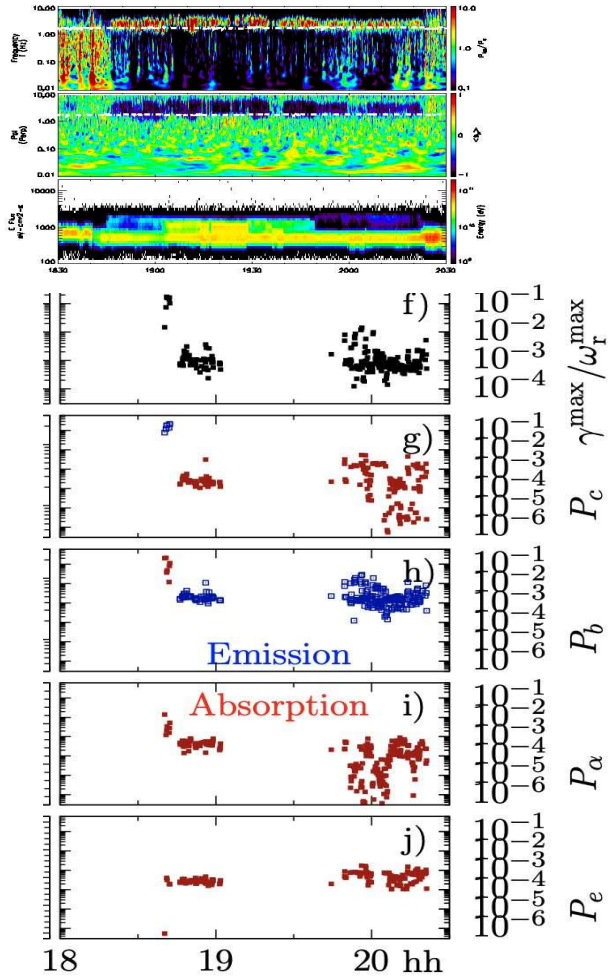
https://drive.google.com/file/d/18h38fkFvku6_nop0kgPXJ3aMykHv-MEi/view?usp=sharing

Initial instability characterization with PLUMAGE

[Klein et. al 2017, JGR; Klein et. al 2019, ApJ]

..in reduced parameter space

$T_\perp/T_\parallel = 1$



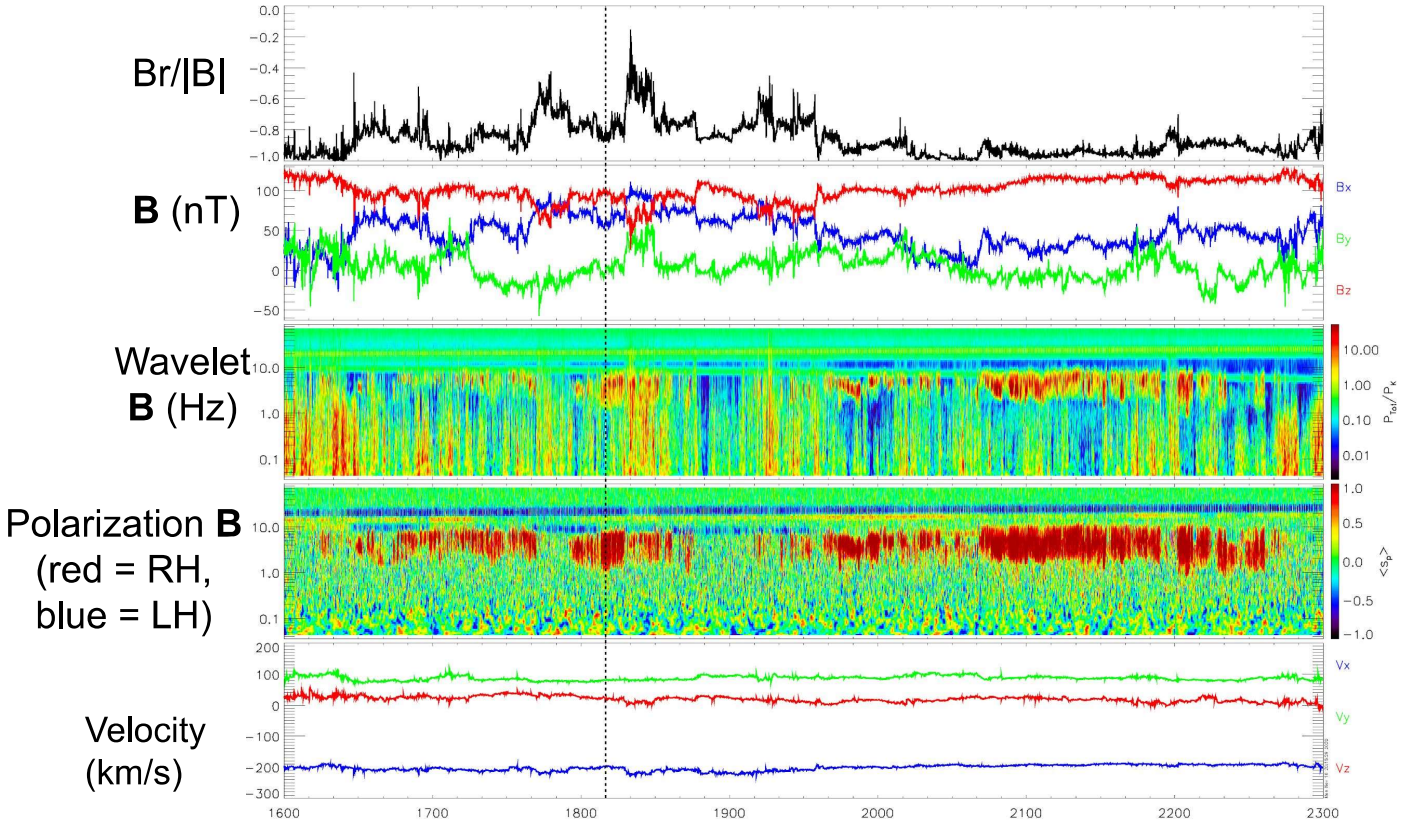
1D Maxwellian fits of VDFs showed many instabilities, with the beam as the primary driver for positive wave growth rates

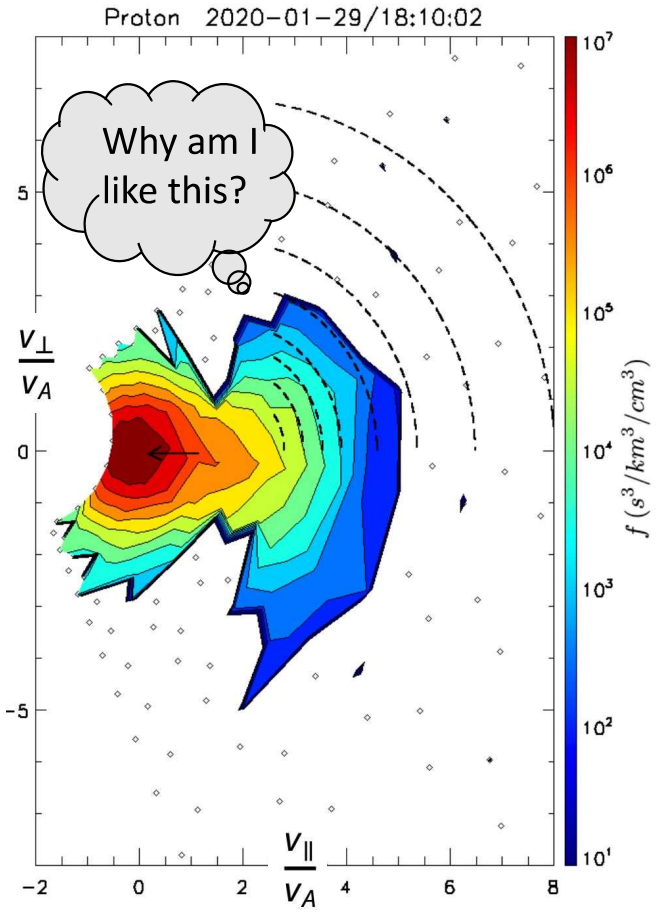
Verniero et al., 2020, ApJS, 248, 5
https://doi.org/10.3847/1538-4365/ab86af

The proton beam started to change...

~22 Rs

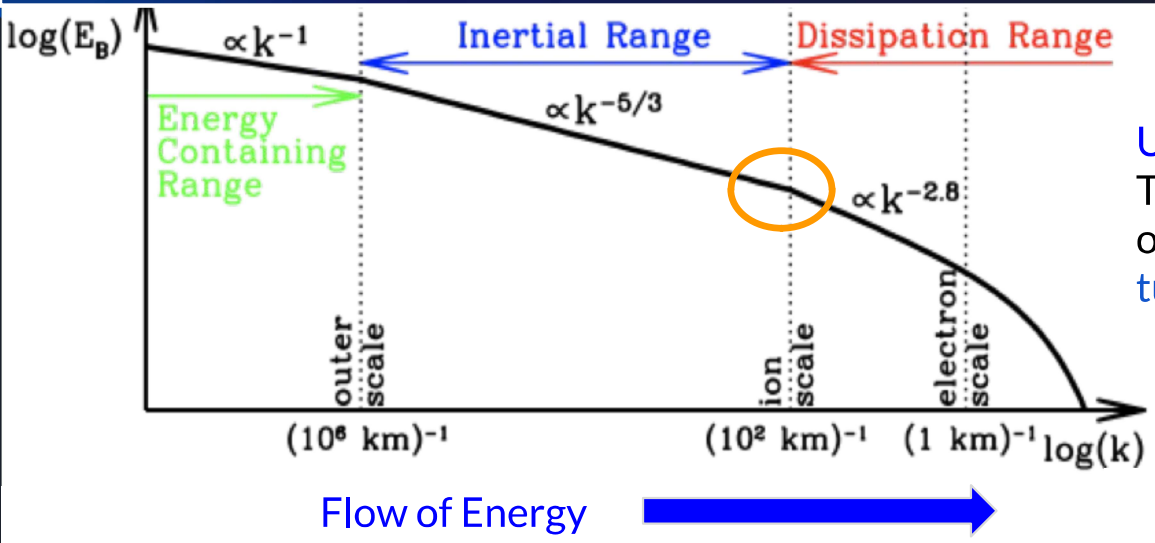
"Kinetic shells"
Isenberg et al. 2001





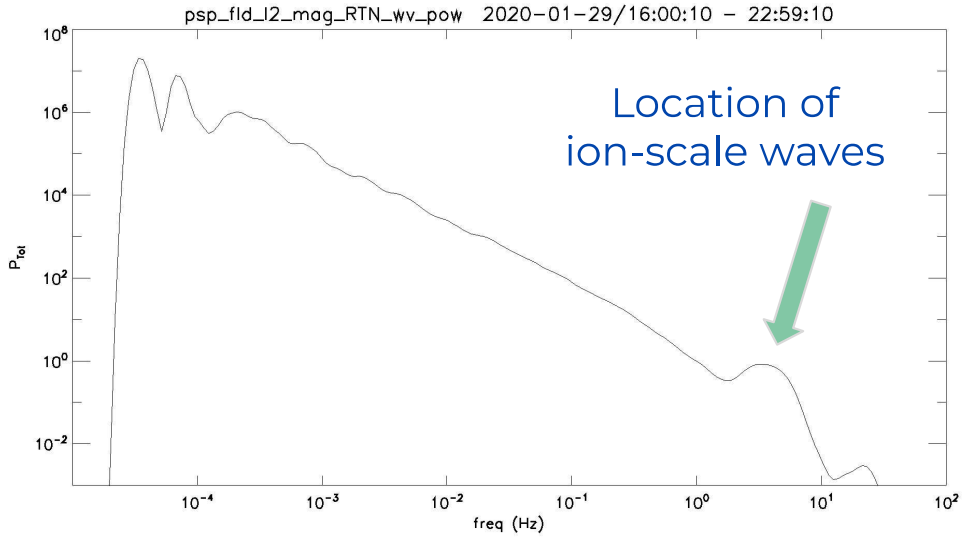
[Verniero *et al*. 2022 et al 2022 ApJ 924 112
DOI: 10.3847/1538-4357/ac36d5]

Turbulence in the Near-Earth Solar Wind

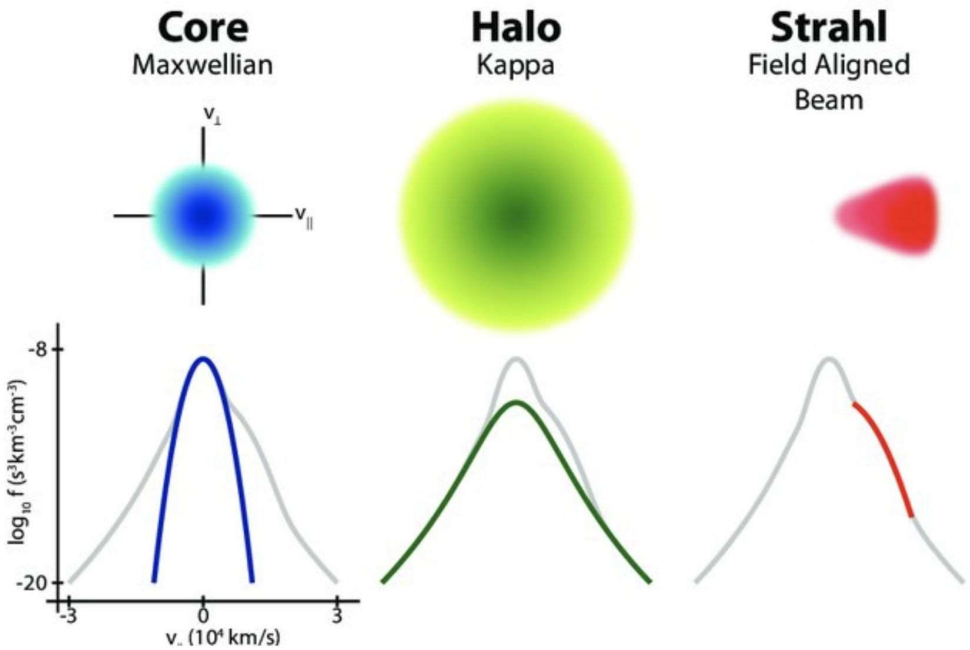


Flow of Energy

Ultimate goal:
To understand the dynamics and energetics of the entire cascade, from large scale turbulent motions to plasma heat



But what about electron beam (strahl)?

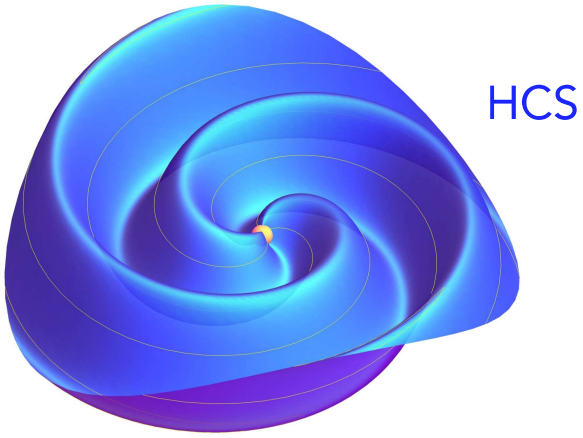


Electron VDF components. Credit: M. Pulupa

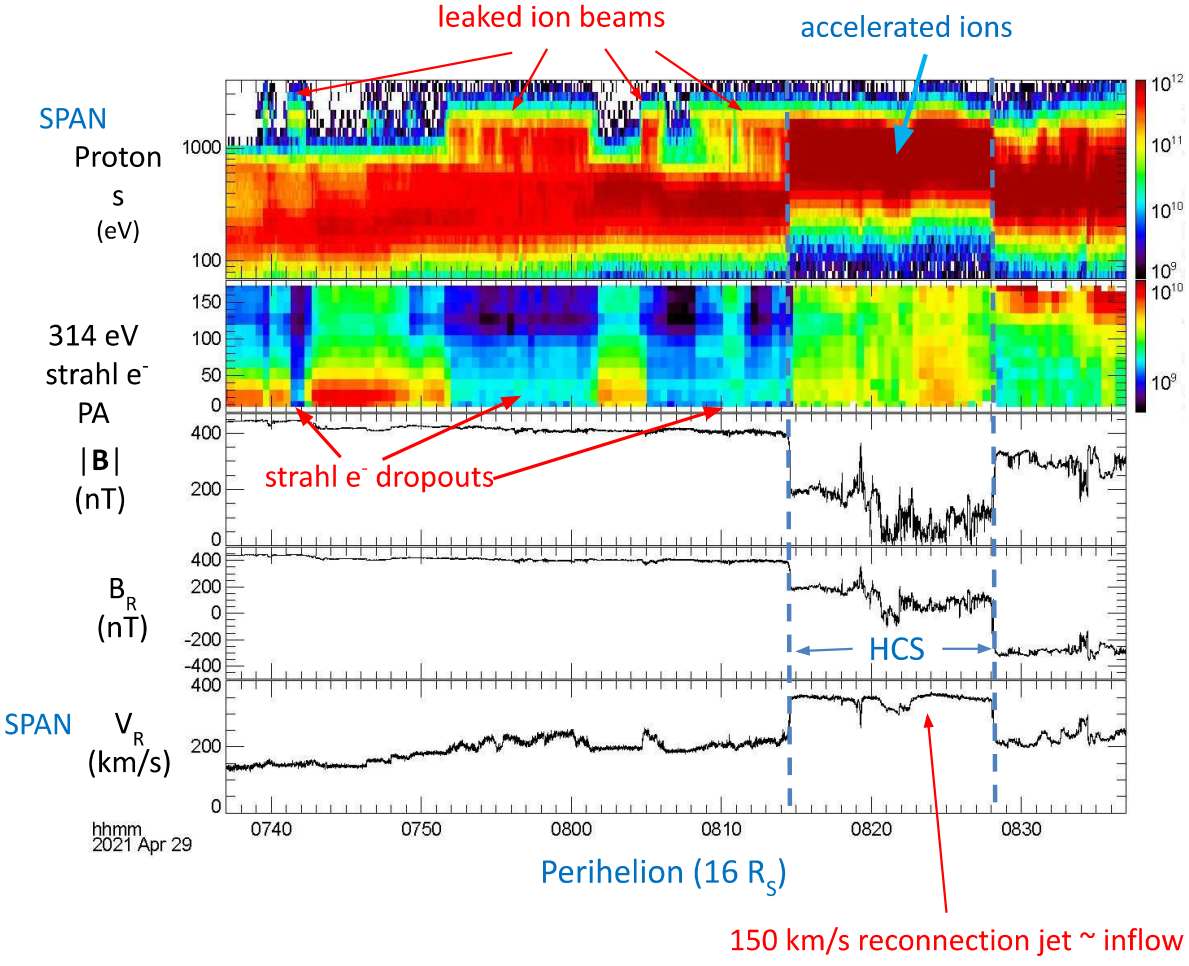
Behaviour of electron strahl indicates magnetic connection to Sun

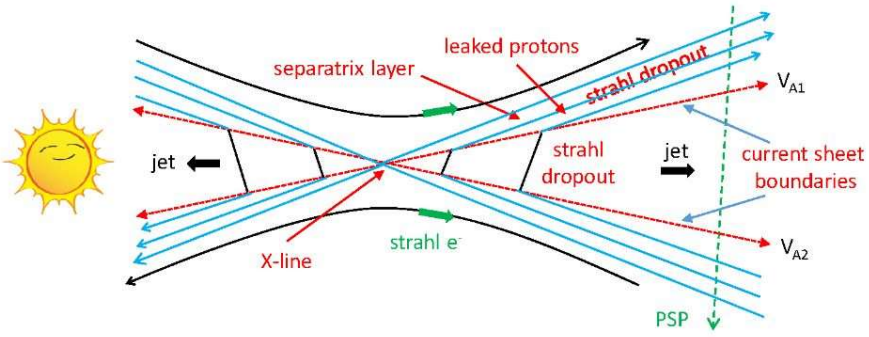
The electron VDF participates in electron-scale wave-particle instabilities

The electron VDF is known to depend on location from Heliospheric Current Sheet (HCS)



PSP Encounter 08 HCS at 16 R_s: Reconnection producing high-energy proton beams observed around the HCS



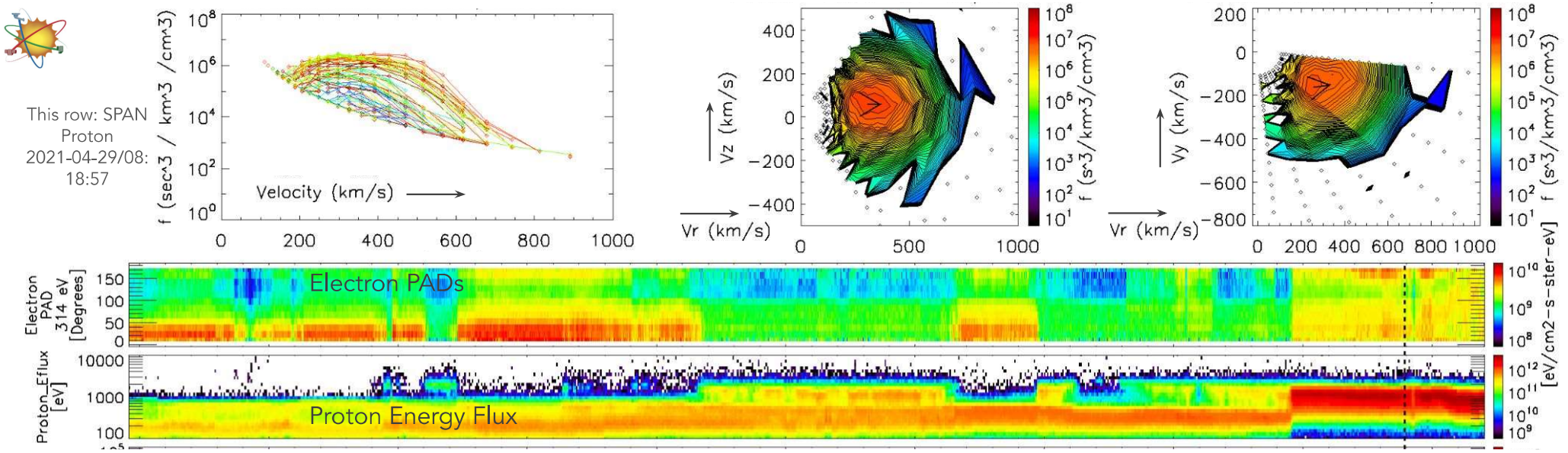


Evidence for proton beams originating from the HCS exhaust:

- Same upper energy
- Energy dispersion
- Strahl electron dropouts implying disconnection from Sun

Phan, T. D., Verniero, J. L., Larson, D., Lavraud, B., Drake, J. F., Øieroset, M., et al. (2022). Parker Solar Probe observations of solar wind energetic proton beams produced by magnetic reconnection in the near-Sun heliospheric current sheet. Geophysical Research Letters, 49 e2021GL096986. https://doi.org/10.1029/2021GL096986

PSP Encounter 08 HCS at 16 R_s: reconnection



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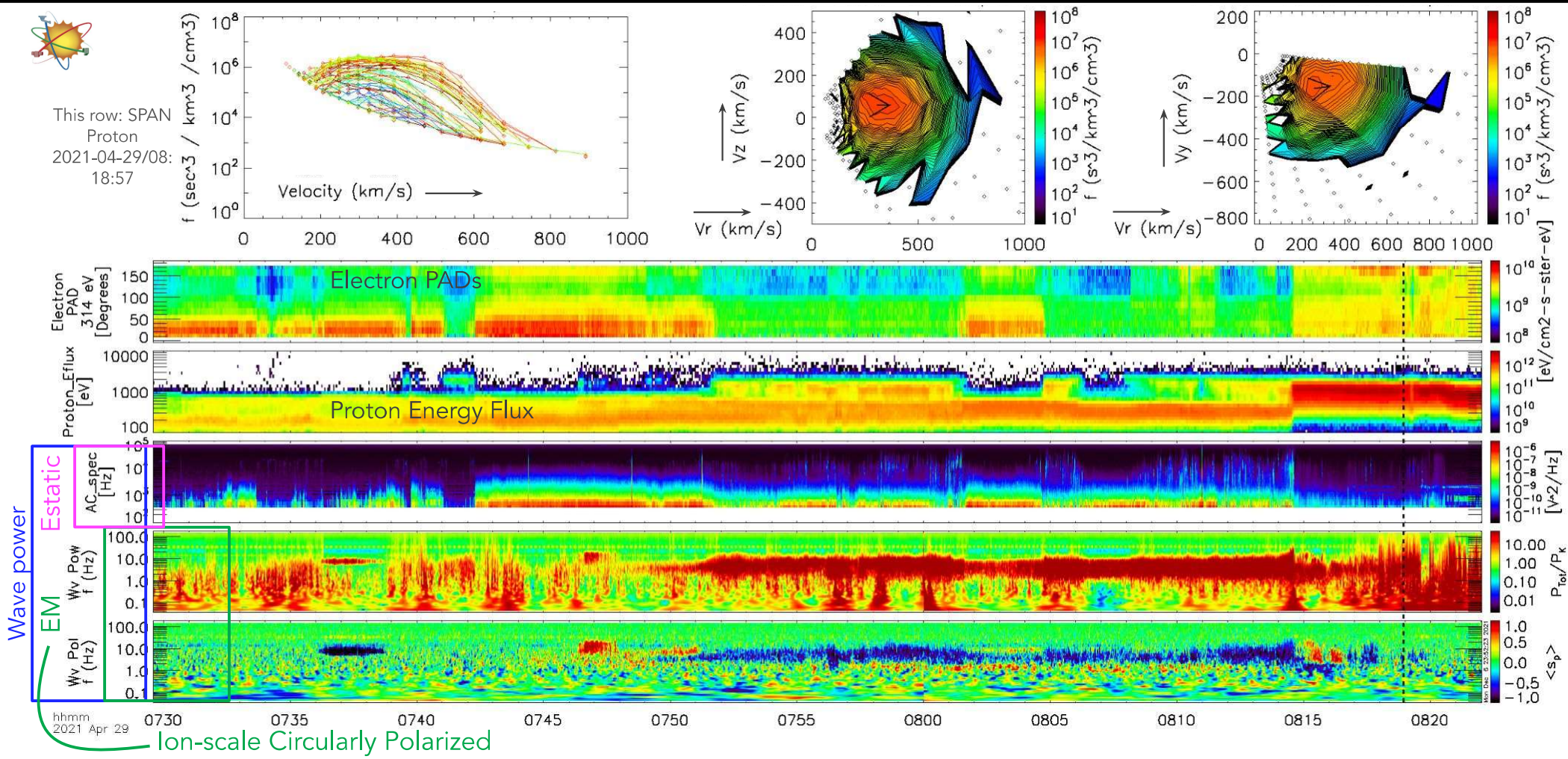

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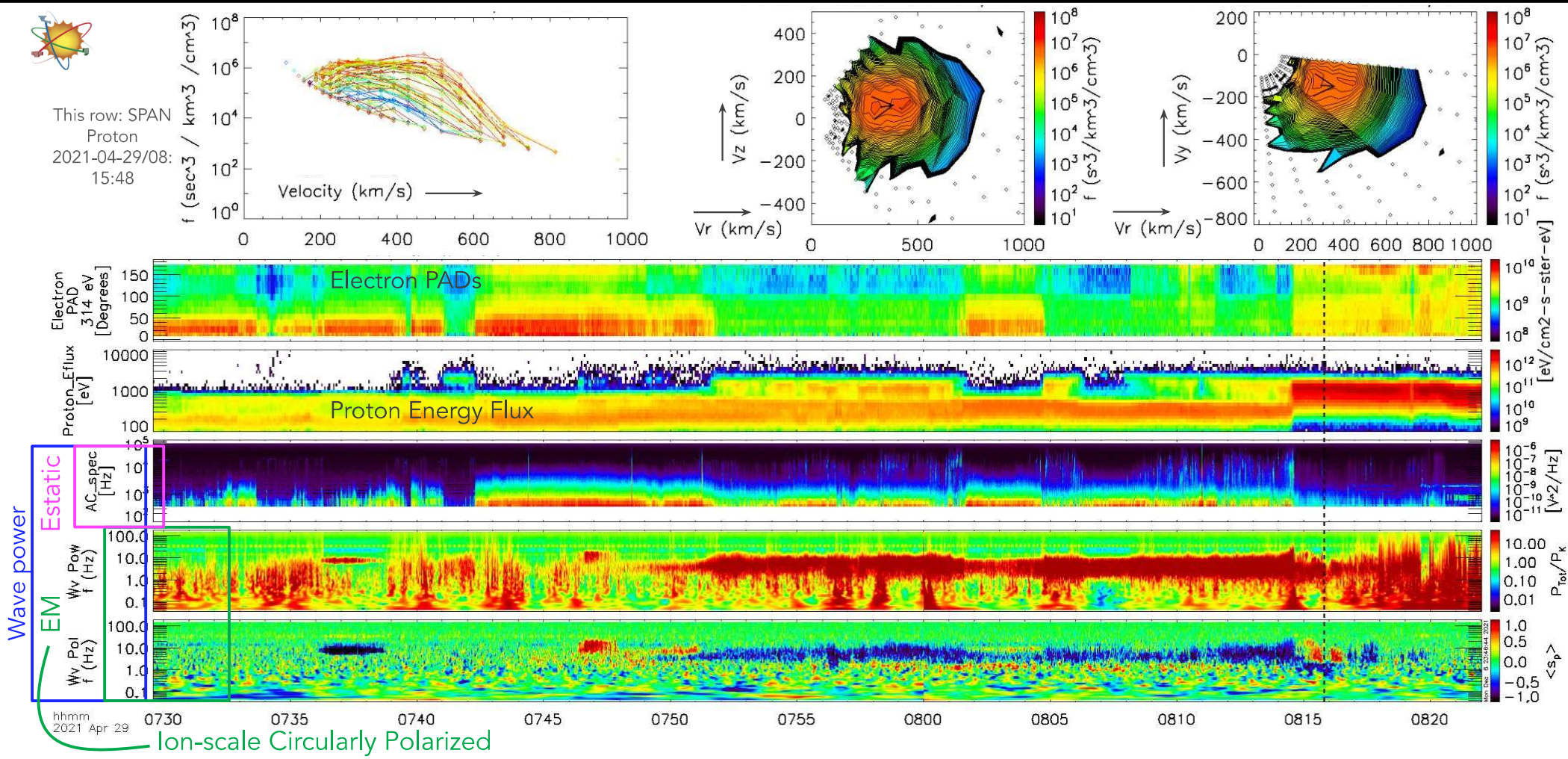

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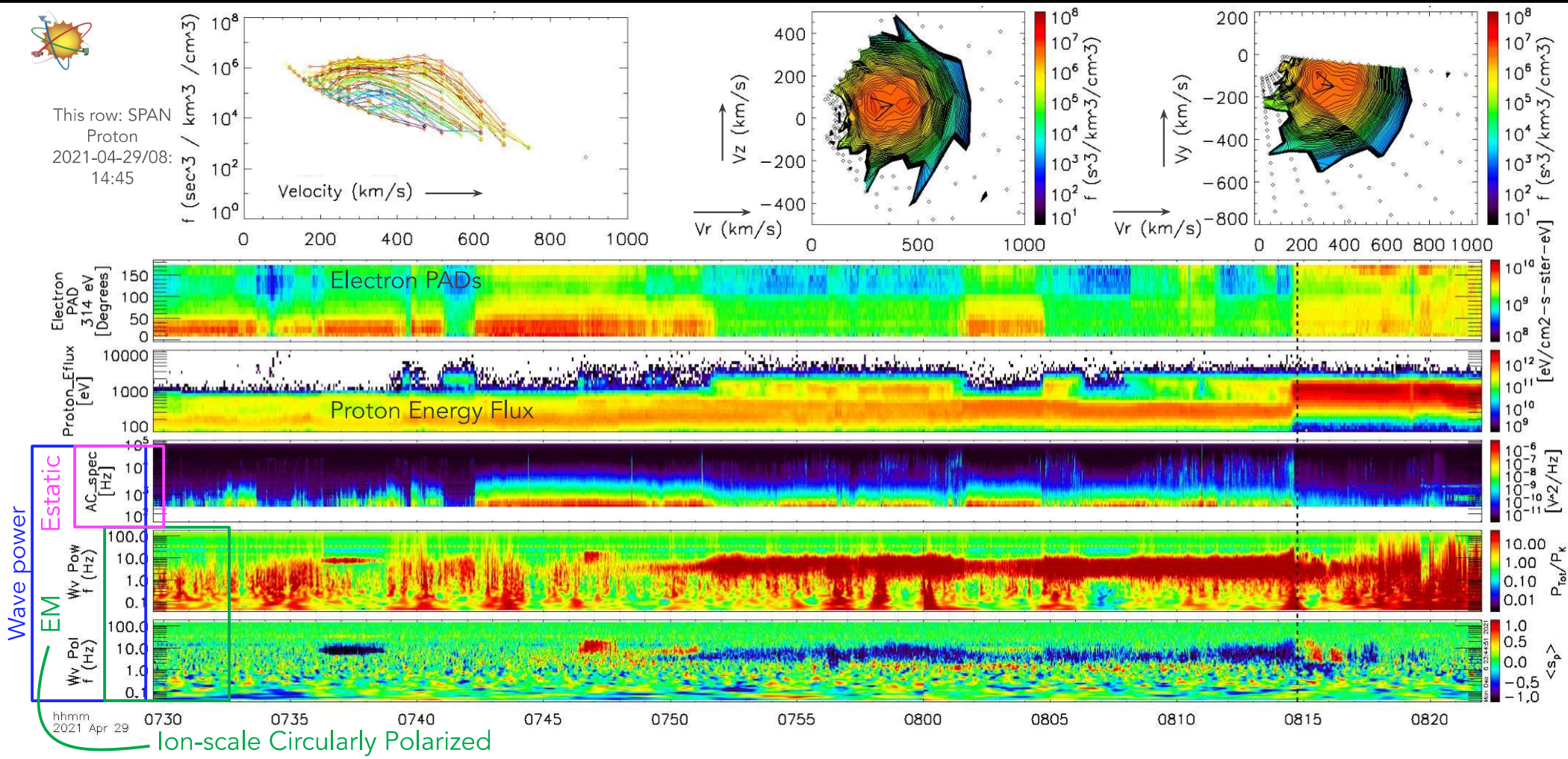

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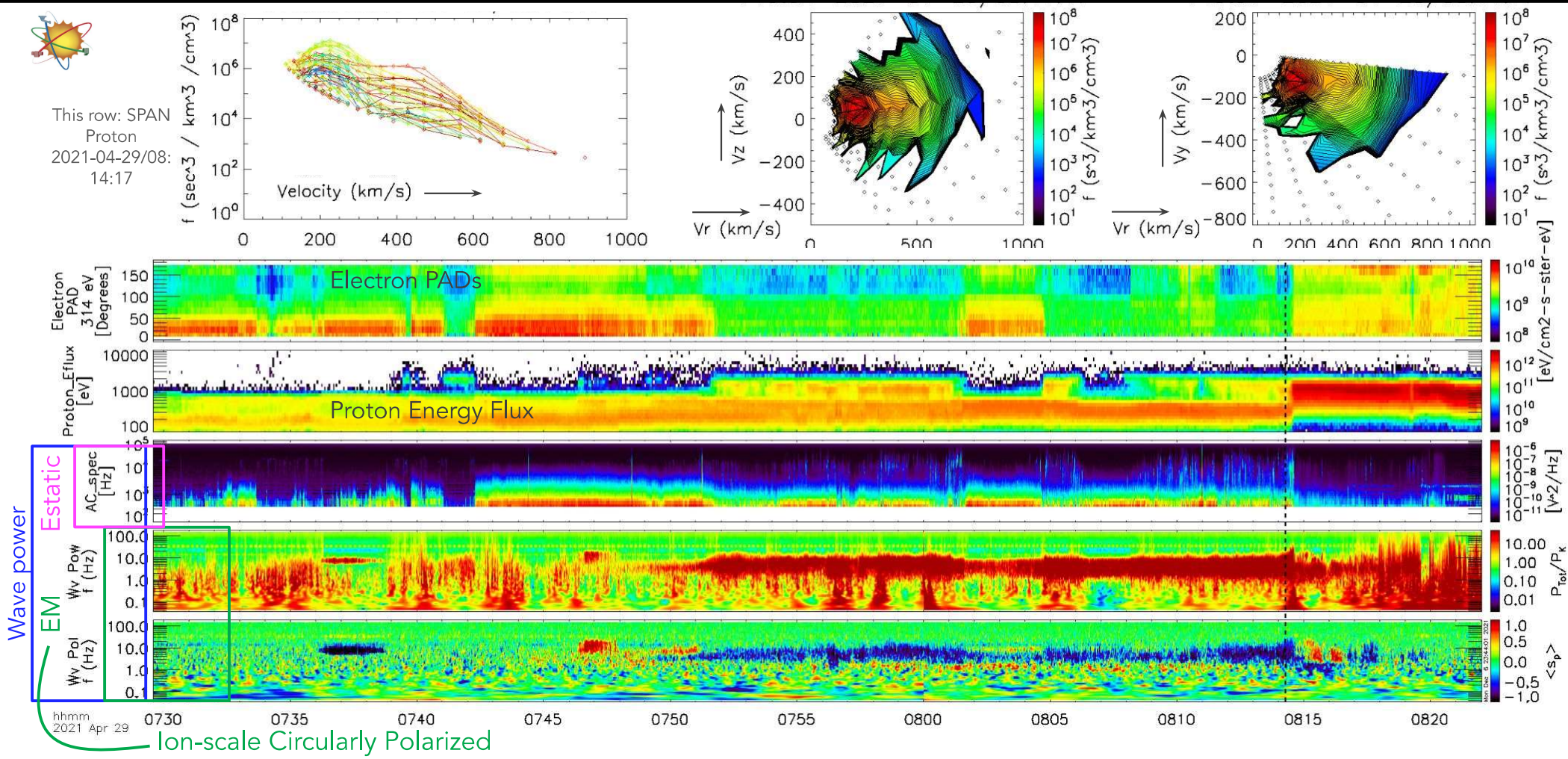
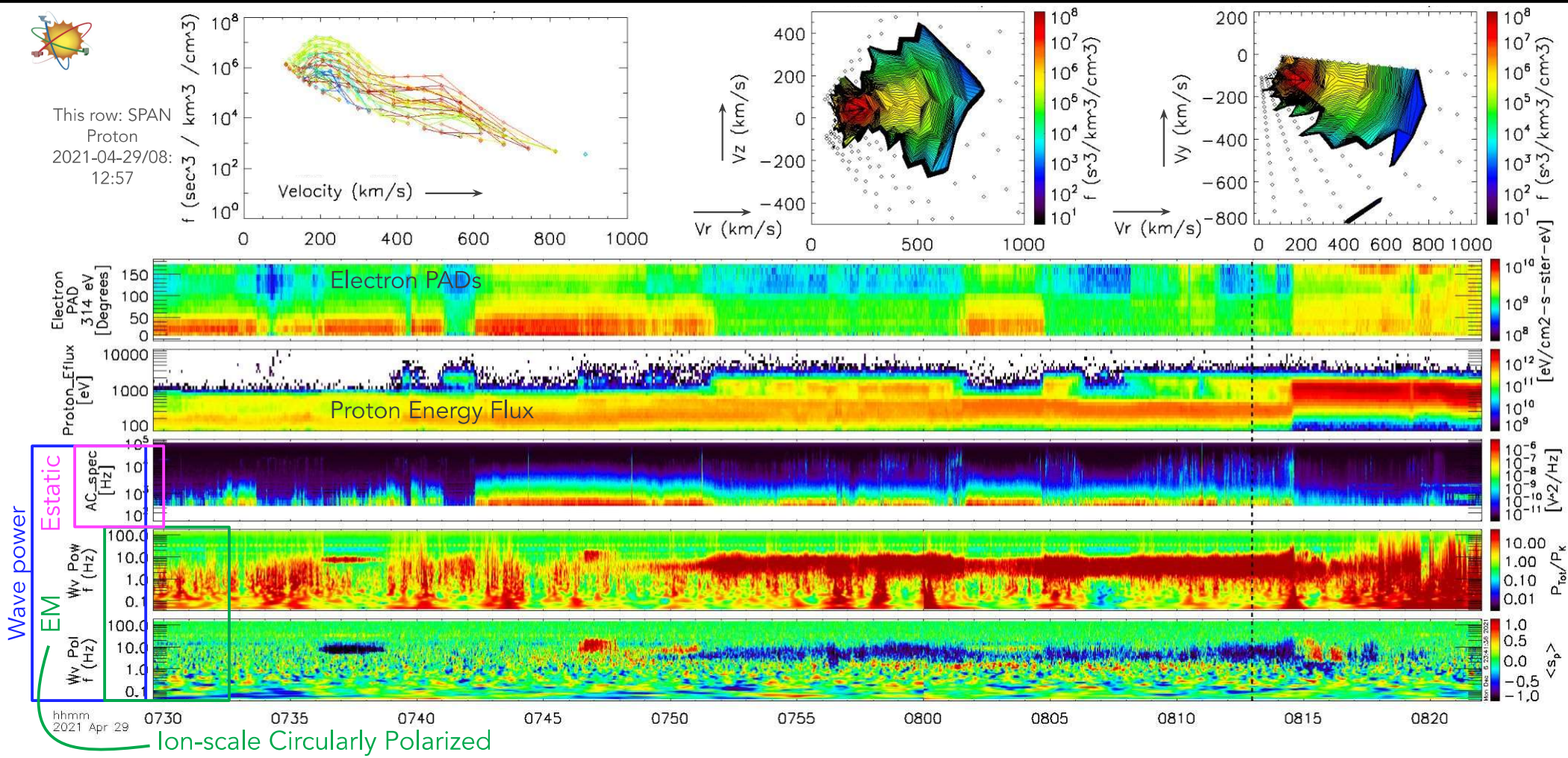


PSP Encounter 08 HCS at 16 R_s: reconnection



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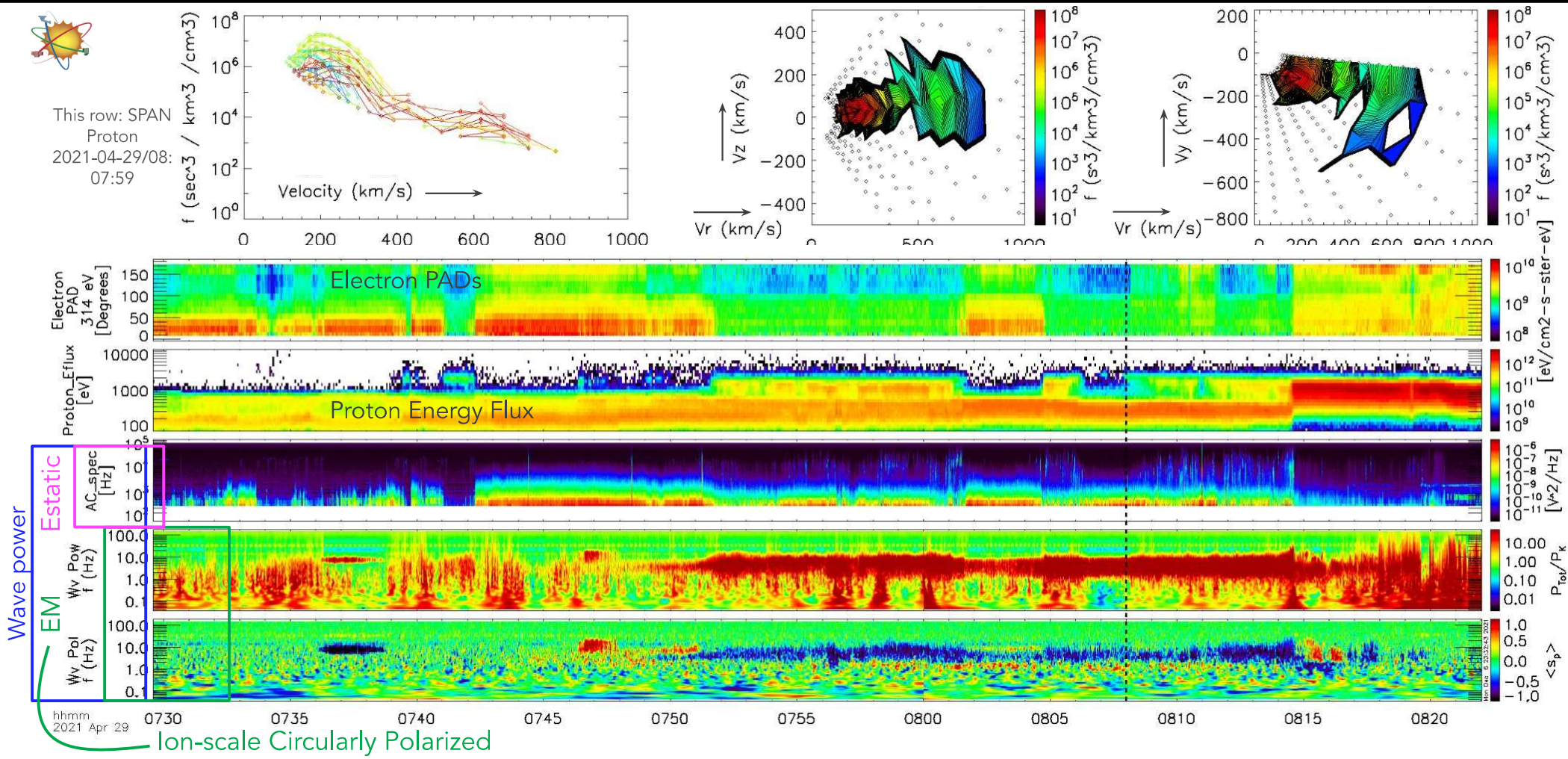

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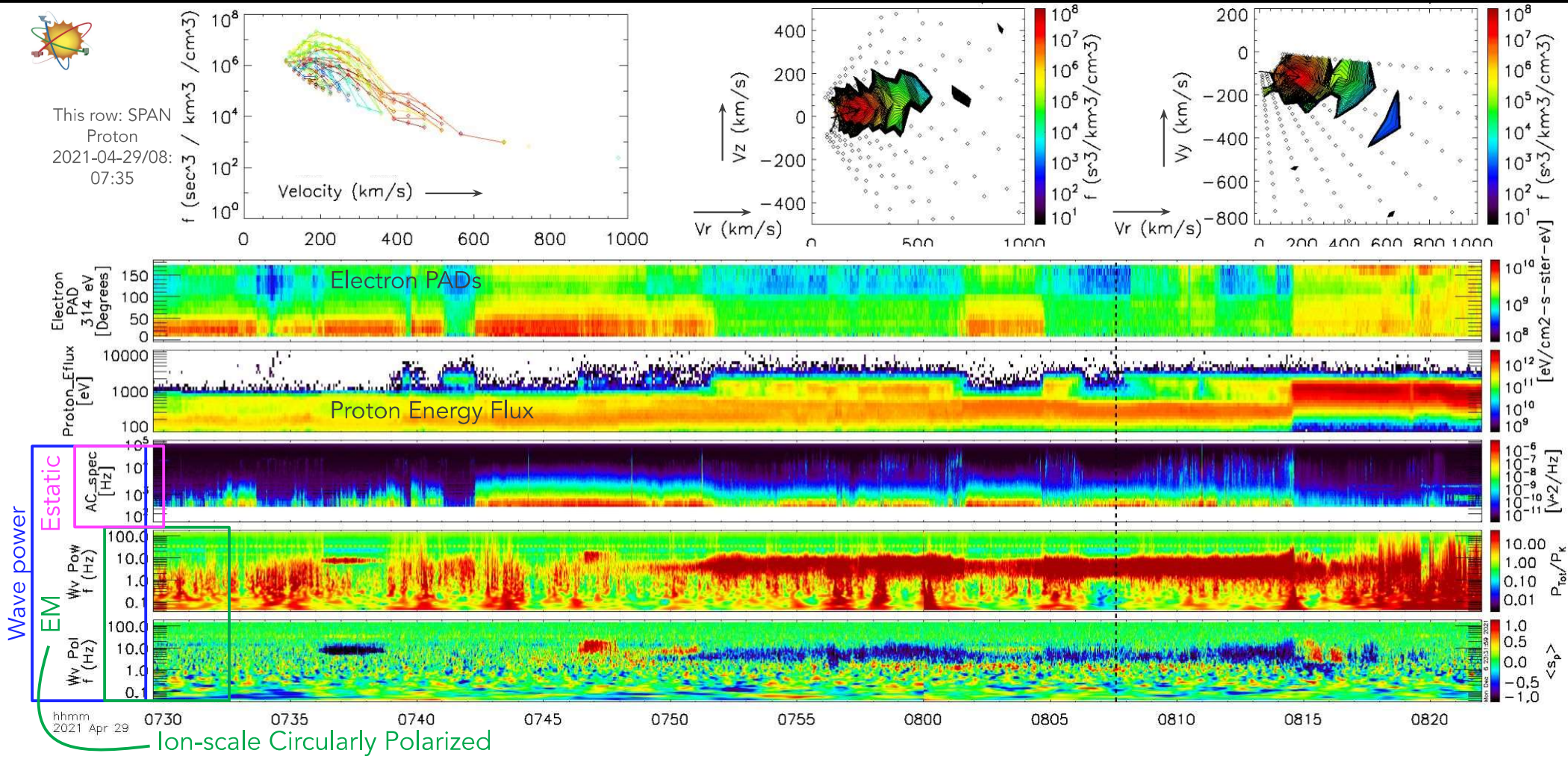

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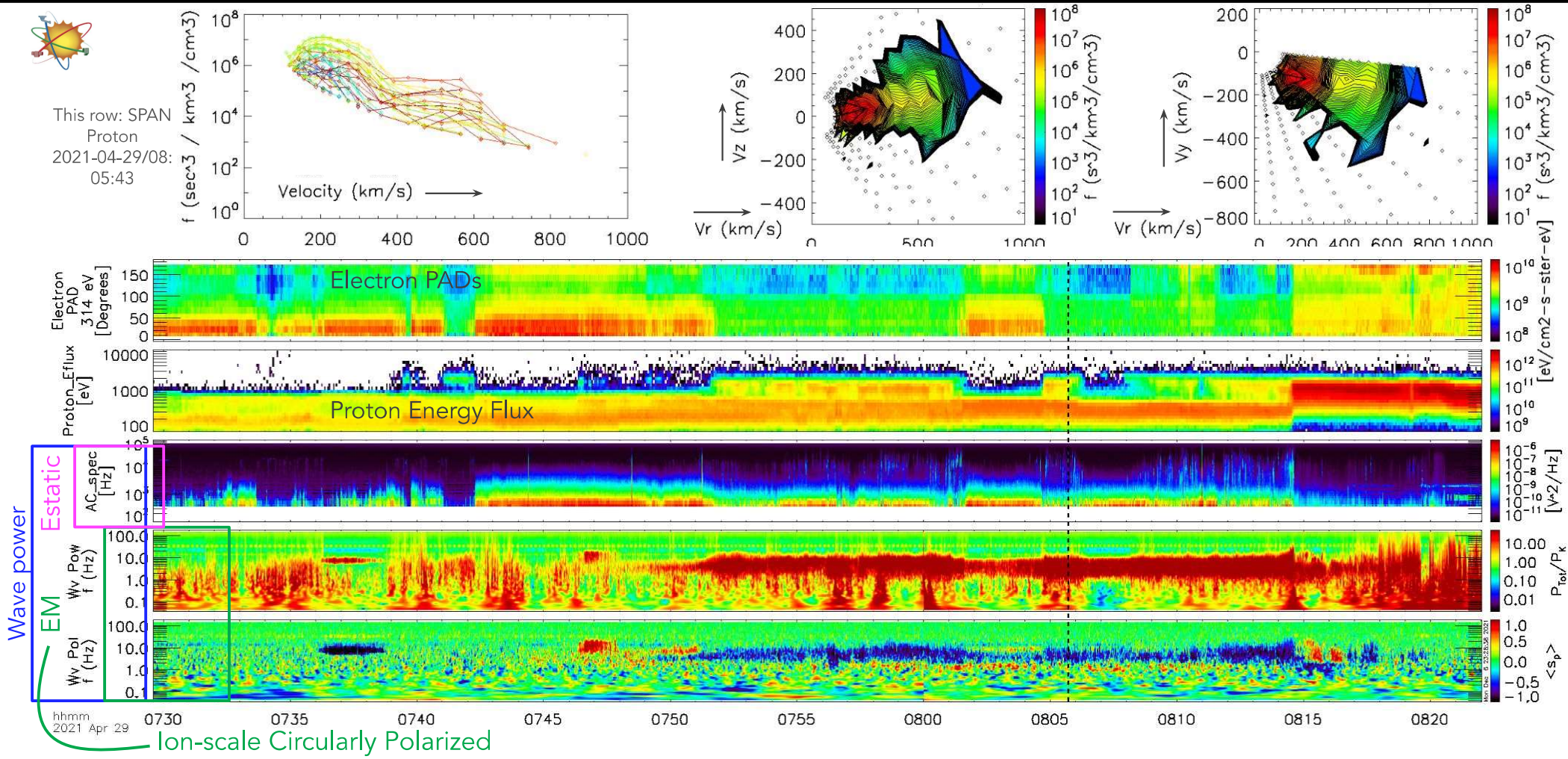

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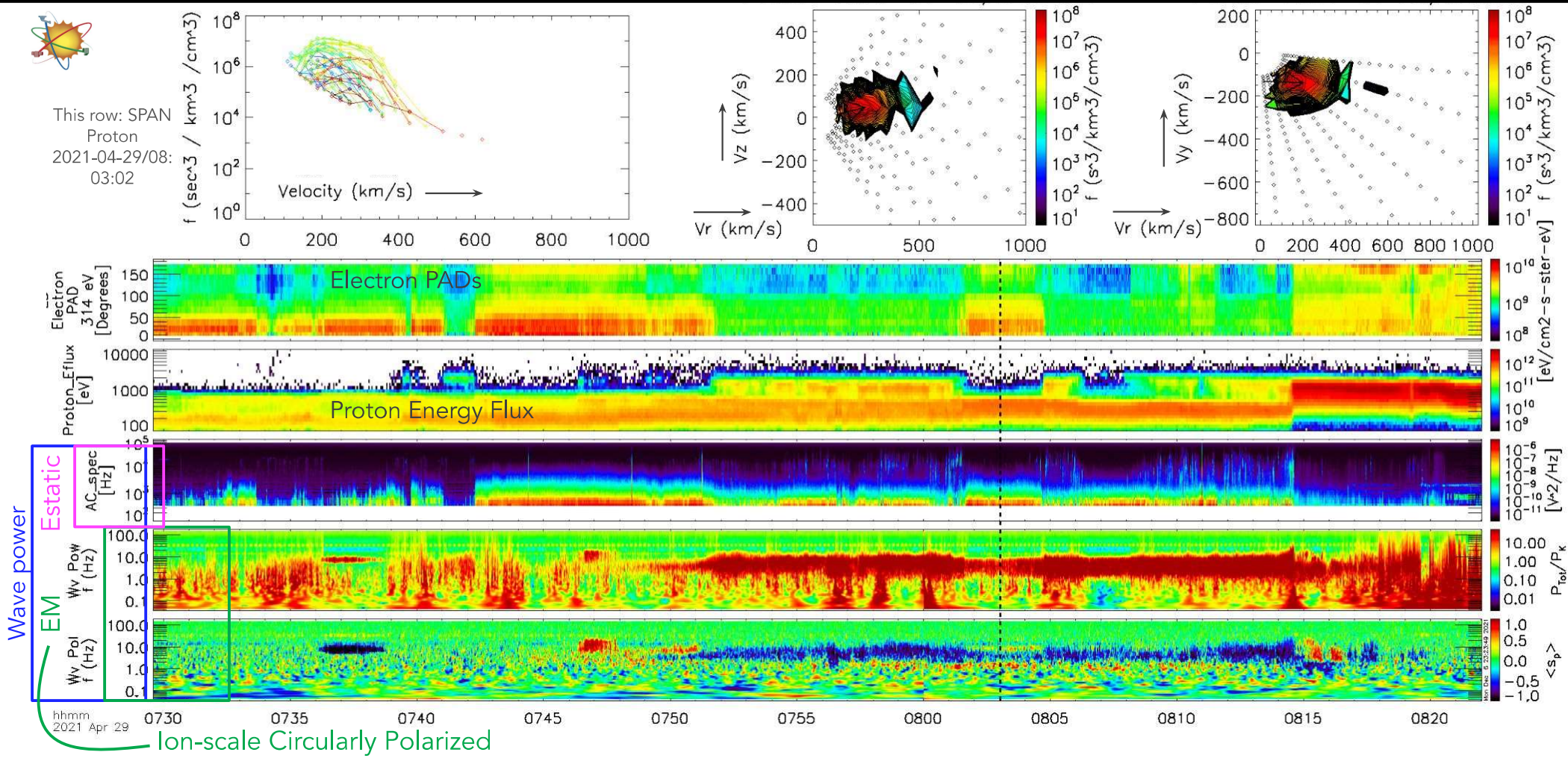

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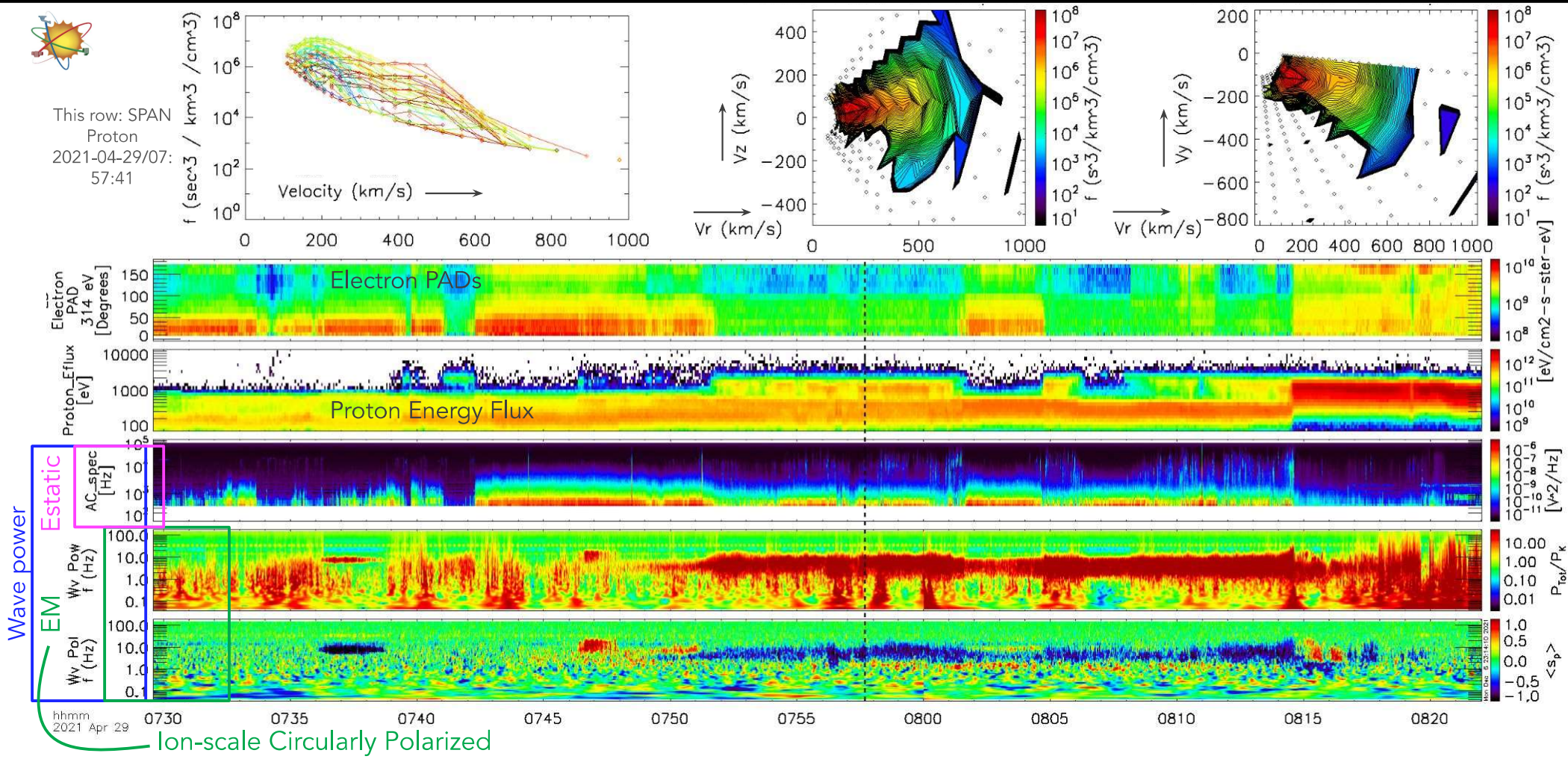


PSP Encounter 08 HCS: key results

314eV electron PADs (strahl)

Proton Energy Flux

AC Power

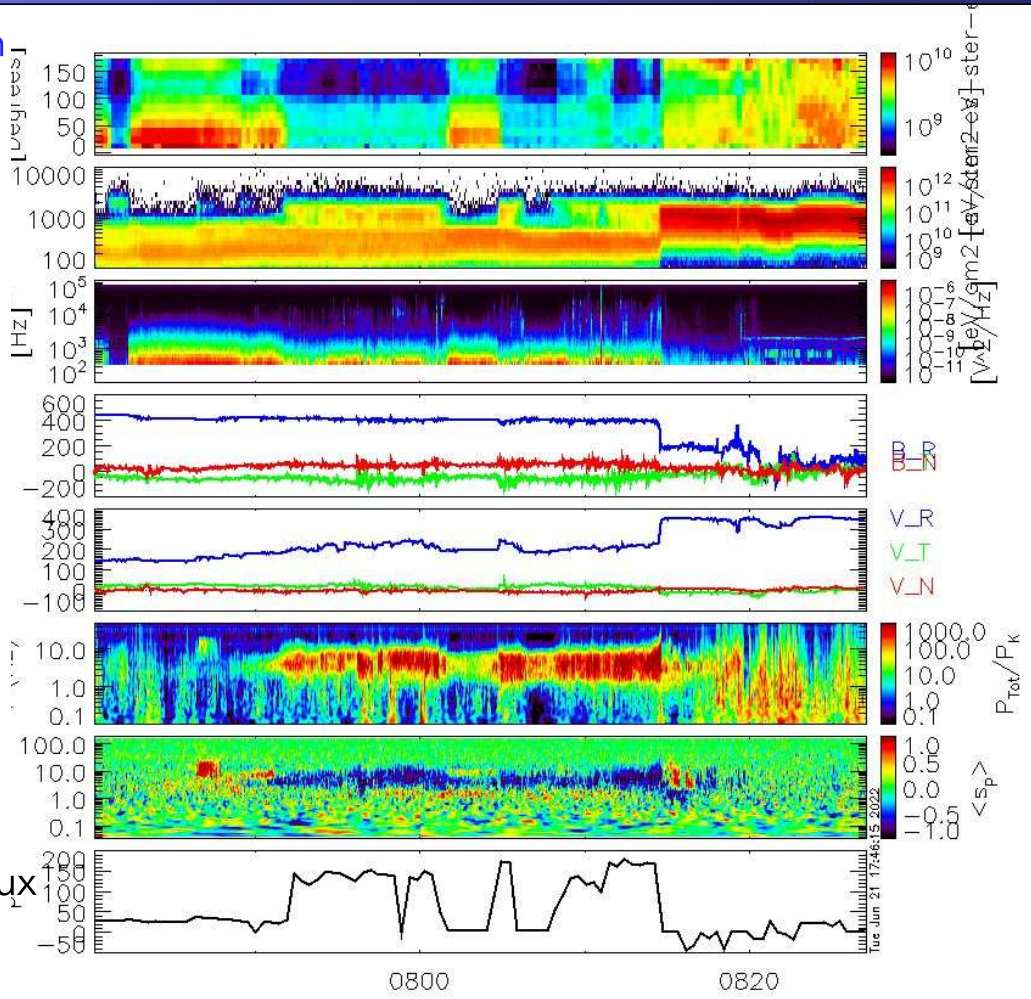
B (RTN)

V (RTN)

Ion Wave Power

Polarization

Proton Heat Flux



hhmm
2021 Apr 29

Proton Heat Flux

(derived from preliminary proton core-beam maxwellian fitting)

correlates with:

Ion-scale wave activity

Electron Strahl Dropout

Electrostatic wave activity

The proton beam provides macro-scale context

If proton beam intensity is connected to HCS, and electron strahl is connected to corona, then the proton beam is providing context for coronal field line connections

Closer to the Sun, we expected stronger acceleration of particles
→ more available energy for cosmic information flow

Not expected: Close to the HCS we have more energy scattering and leakage
→ could be a significant energy driving region

Ion heat flux (both protons and alphas) may play a more significant role in energy transfer within the HCS and associated rxn

Which instabilities (fluid and kinetic scale) are responsible for what and why?
Tearing mode? 2-fluid? Ion Acoustic? Ion Cyclotron?

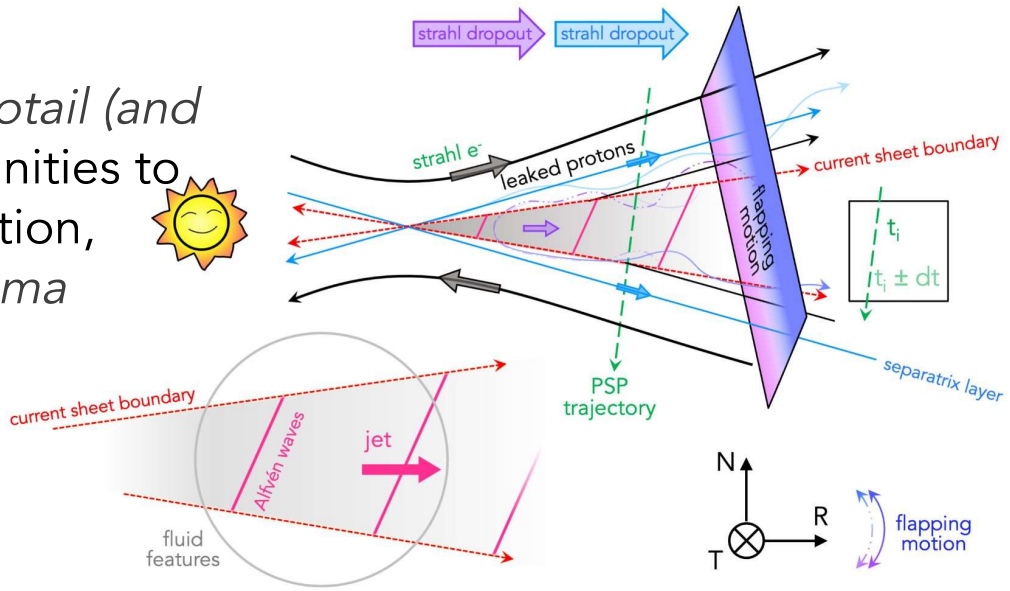
Mysteries and opportunities await us in the HCS

The HCS is more dynamic than previously thought

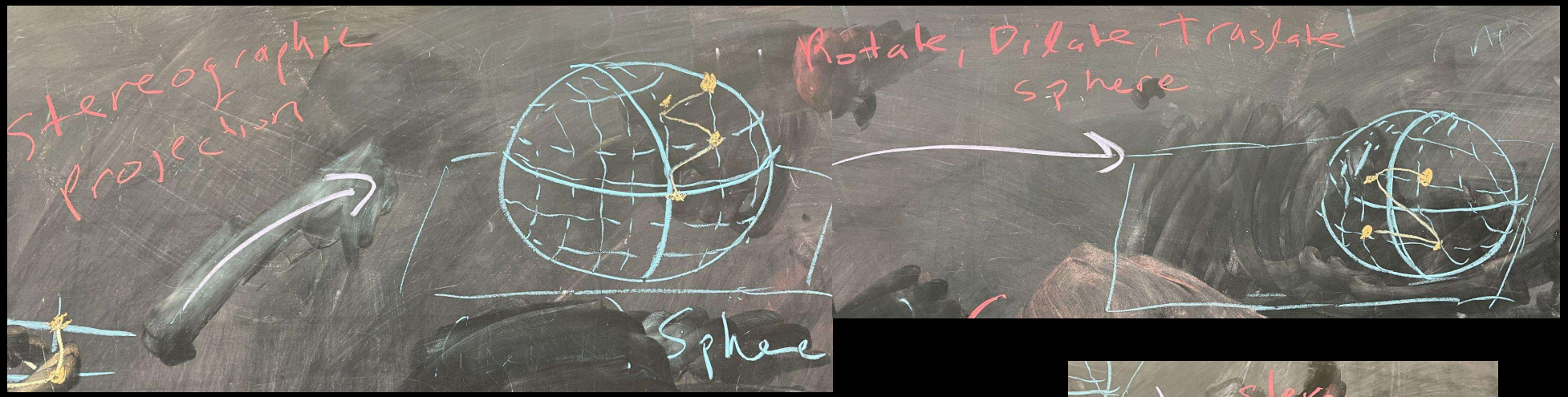
... simple picture needs to be revisited!

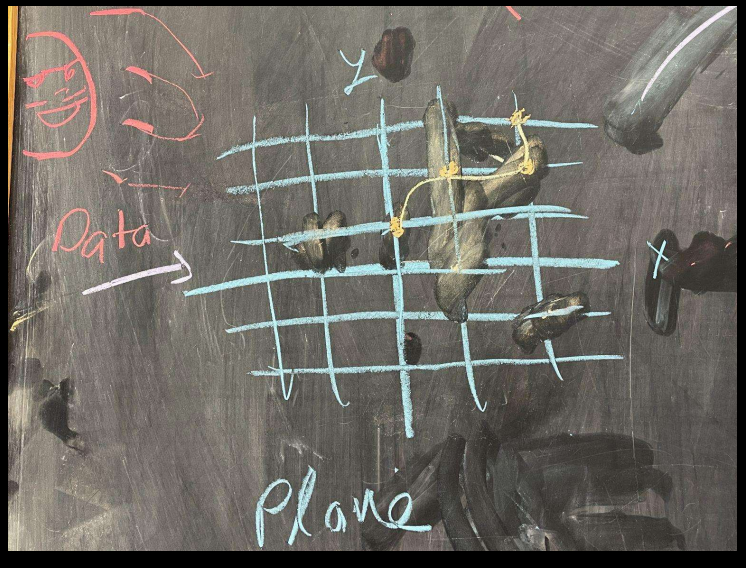
Can we infer the inherent 3D nature and non-steady state dynamics of the HCS?

HCS dynamics appear similar to the *magnetotail (and heliotail?)*. PSP data provides ample opportunities to assess the universality of magnetic reconnection, shocks, instabilities, across the *ocean of plasma regimes...*



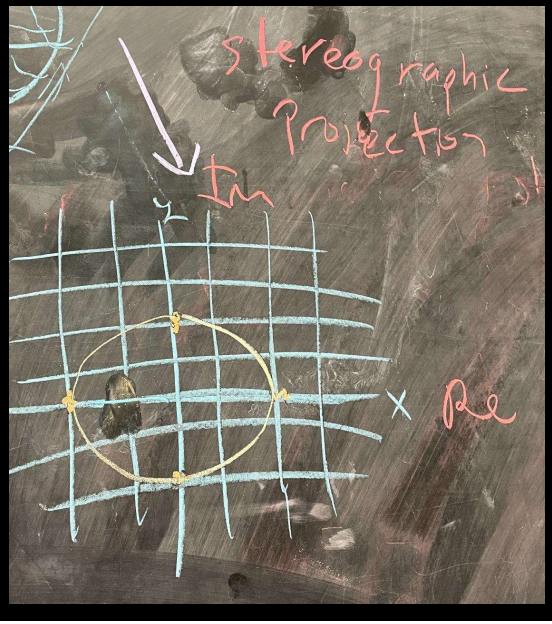
Toward a new coordinate system for optimally extracting (a)symmetries leading to multi-scale, explosive energetic phenomena: The Mobius Transformation



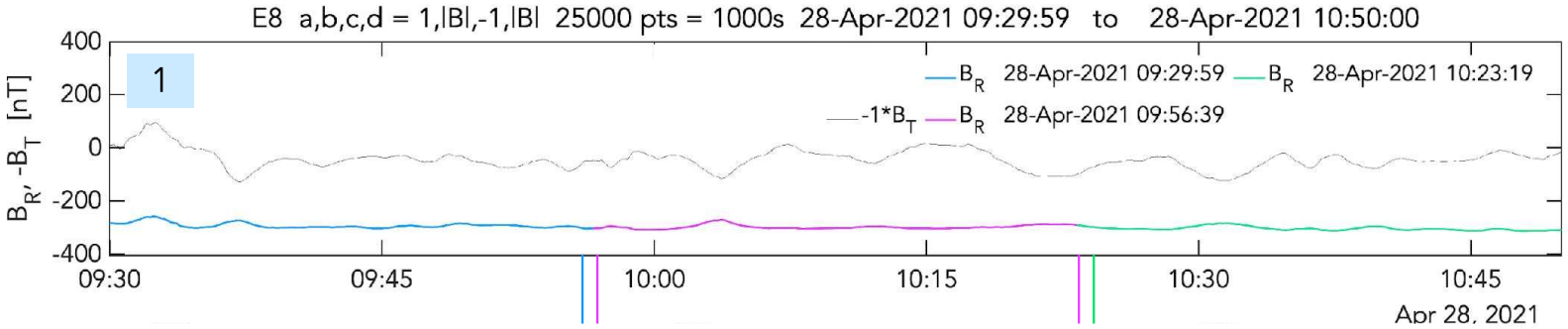


Seemingly uncorrelated data :(

Re-organization of data shows pattern :)



Möb: E8 ‘sine waves’ with ‘line-like’ transform



1. $f_0 = \mathrm{mov}(B_R - iB_N)$

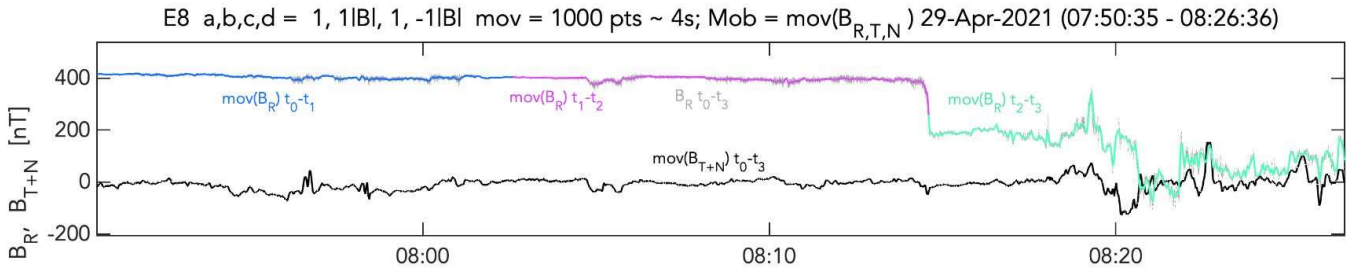
2. $f_0 = \mathrm{mov}(B_R) - \mathrm{mov}(iB_N)$

3. $f_6 = (f_0 + |B|)/(f_0 - |B|)$

E8 transformation

*The Mobius Transformation Applied to PSP Heliospheric Current Sheet Crossings Reveals **Singularity** at Multiple Scales:*

Diagnostic for Generalized Discontinuities in any Heliospheric Regime Associated With Magnetic Reconnection, Magnetic Field Topological Change, Plasma Instability, Nonlinear Dynamics, Shocks, Resonant Wave-particle Interactions, etc ..



Row 1
Mob inputs
(timeseries)
$Real_{input}$ = x-axis
Im_{input} = x-axis

Row 2
Mob inputs
$Real_{input}$ = x-axis
Im_{input} = y-axis

Row 3
Mob outputs
Real_{output} = x-axis
Im_{output}} = y-axis

Mob
definition =
(Input*a+b)
/(Input*c+d)

Where does the cosmic energy flow?

We are on our way toward connecting micro to macro scale physics in the inner heliosphere!

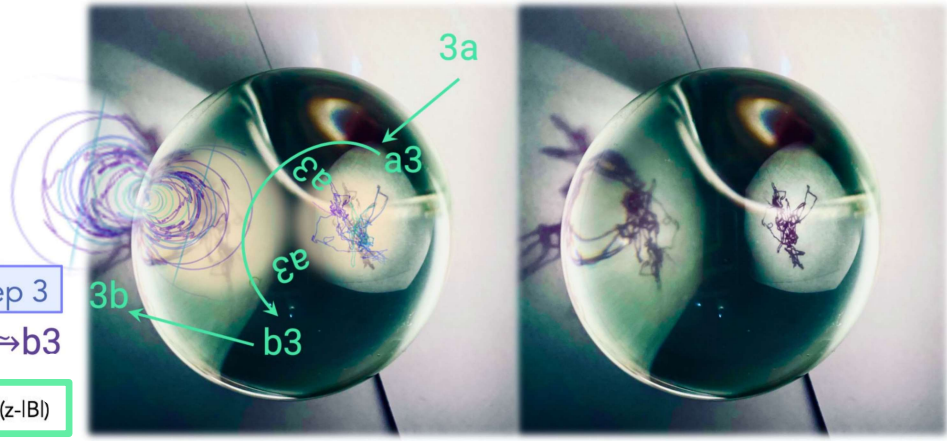
What is the origin of the VDF asymmetries?

VDFs may show energy flow signatures via: wave-particle interactions, solar stream sources, HCS proximity, reconnection (topological changes)...

How do those asymmetries contribute to energy transfer and plasma heating?

$x = B_{radial}$
$y = B_{tangential} + B_{normal}$
$z = x + iy$

Step 1 3a ⇒a3

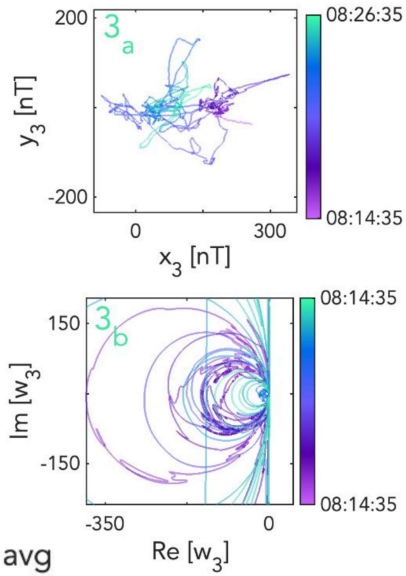


Step 3
b3 ⇒b3

$w = (z+|B|)/(z-|B|)$

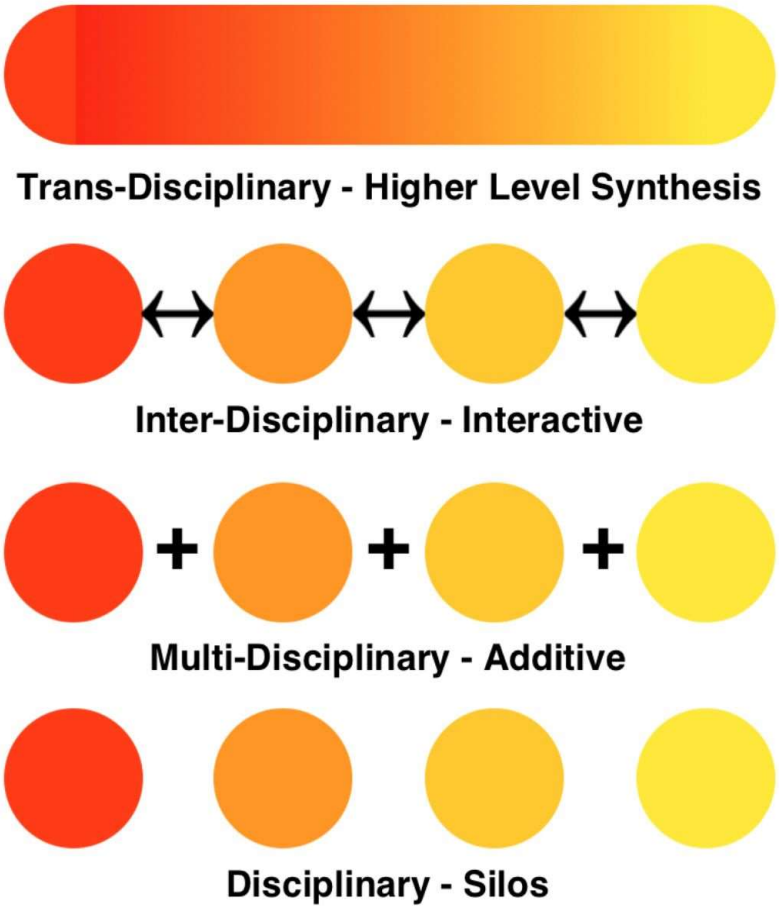
Step 2 a3 ⇒b3

29-Apr-2021 E8 PSP B-field 4s=10^3 pt avg



The future of heliophysics is trans-disciplinary

Astro ?



Think big!
Thanks :)
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