JOHNS HOPKINS
APPLIED PHYSICS LABORATORY

Shock Kinetic Processes and Particle Energization

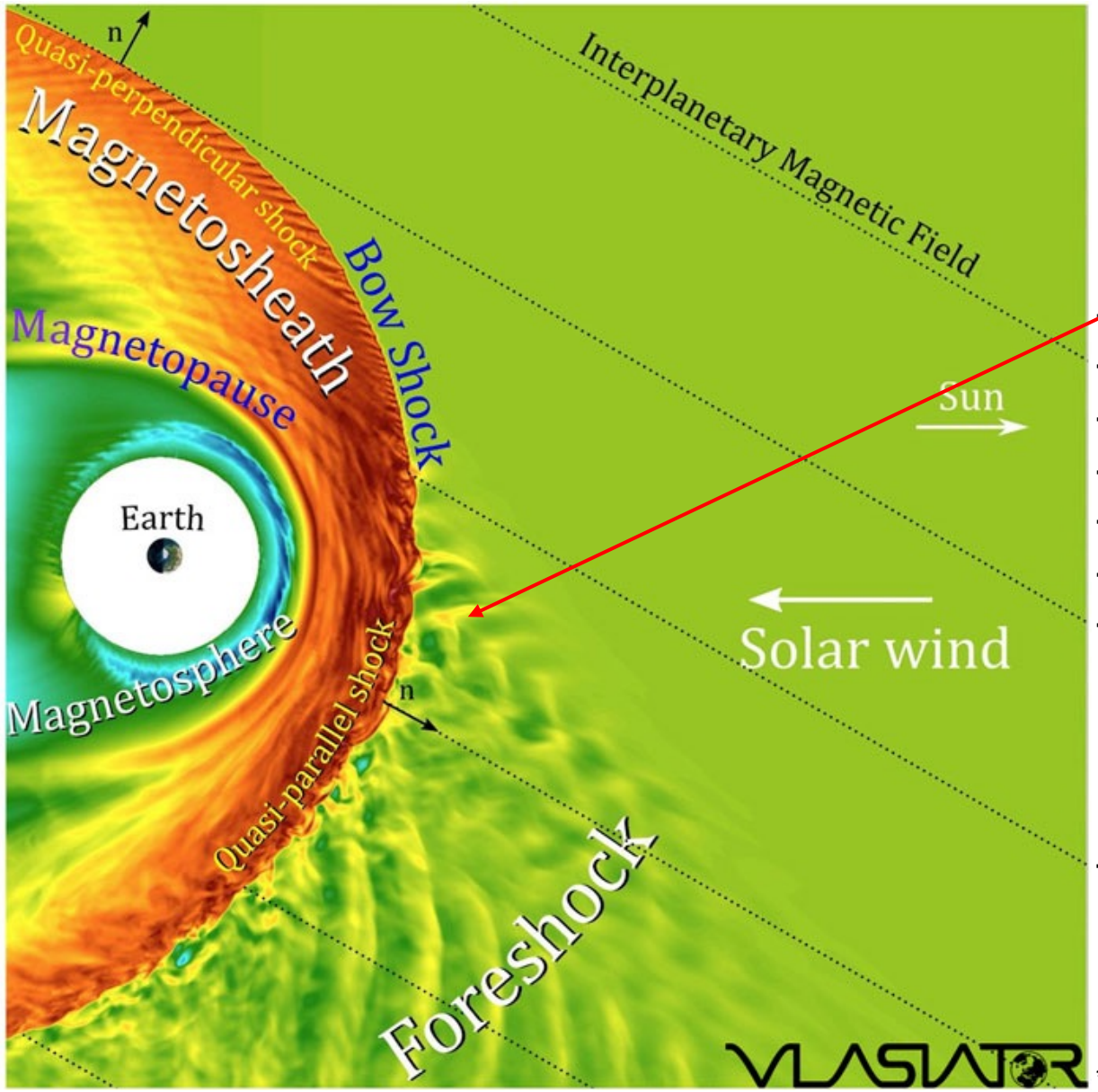
Savvas Raptis

Collaborators: Ahmad Lalti, Martin Lindberg, Drew L. Turner, Damiano Caprioli, James L. Burch, Primoz Kajdic, Ian Cohen, Athanasios Kouloumvakos, Tomas Karlsson, Ian Cohen, Adnane Osmane, Adam Michael, Mike Shumko, Eva Krämer, Xóchitl Blanco-Cano, Lynn B. Wilson III , Hadi Madanian, Lucille Turc, Yufei Zhou, Christos Katsavrias, Terry Liu, Laura Vuorinen, Philippe Escoubet, David G. Sibeck+ +

Supported by Johns Hopkins University Applied Physics Laboratory independent R&D fund.

savvas.raptis@jhuapl.edu / https://savvasraptis.github.io

Earth's Qpar bow shock and foreshock



Qpar shocks ($\theta_{Bn} < \sim 45^\circ$)

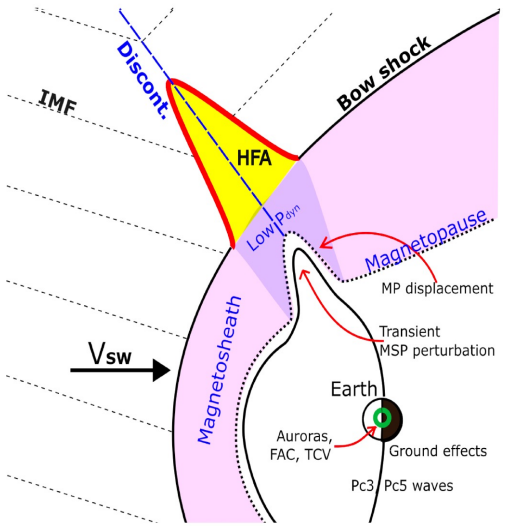
- Very **efficient particle accelerators**
- **Transient phenomena** upstream and downstream*
- ULF waves upstream and downstream
- Kinetic plasma physics
- Wave particle interaction
- Turbulence
- Current sheets & reconnection

Term to use: Shock-generated transients**

** Credits: Heli Hietala? https://www.youtube.com/watch?v=SJ88e8rwoDg

The anatomy of an HFA

How many: ~several per day!
How big: ~10s of Re



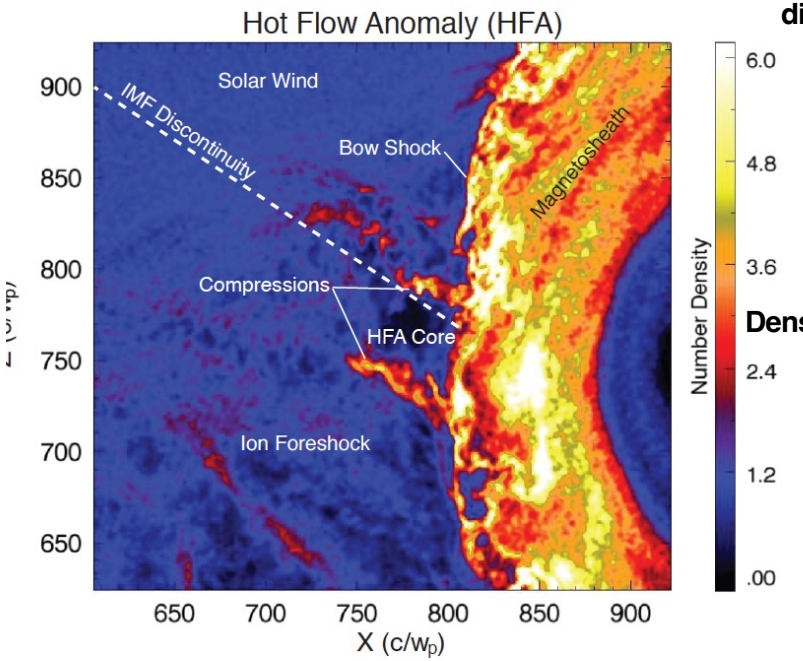


Figure by Nick Omidi

Hot Flow Anomalies (HFA)

Kajdič+ (2024)

Crater-like B-field and IMF discontinuity

Density compressions and cavity

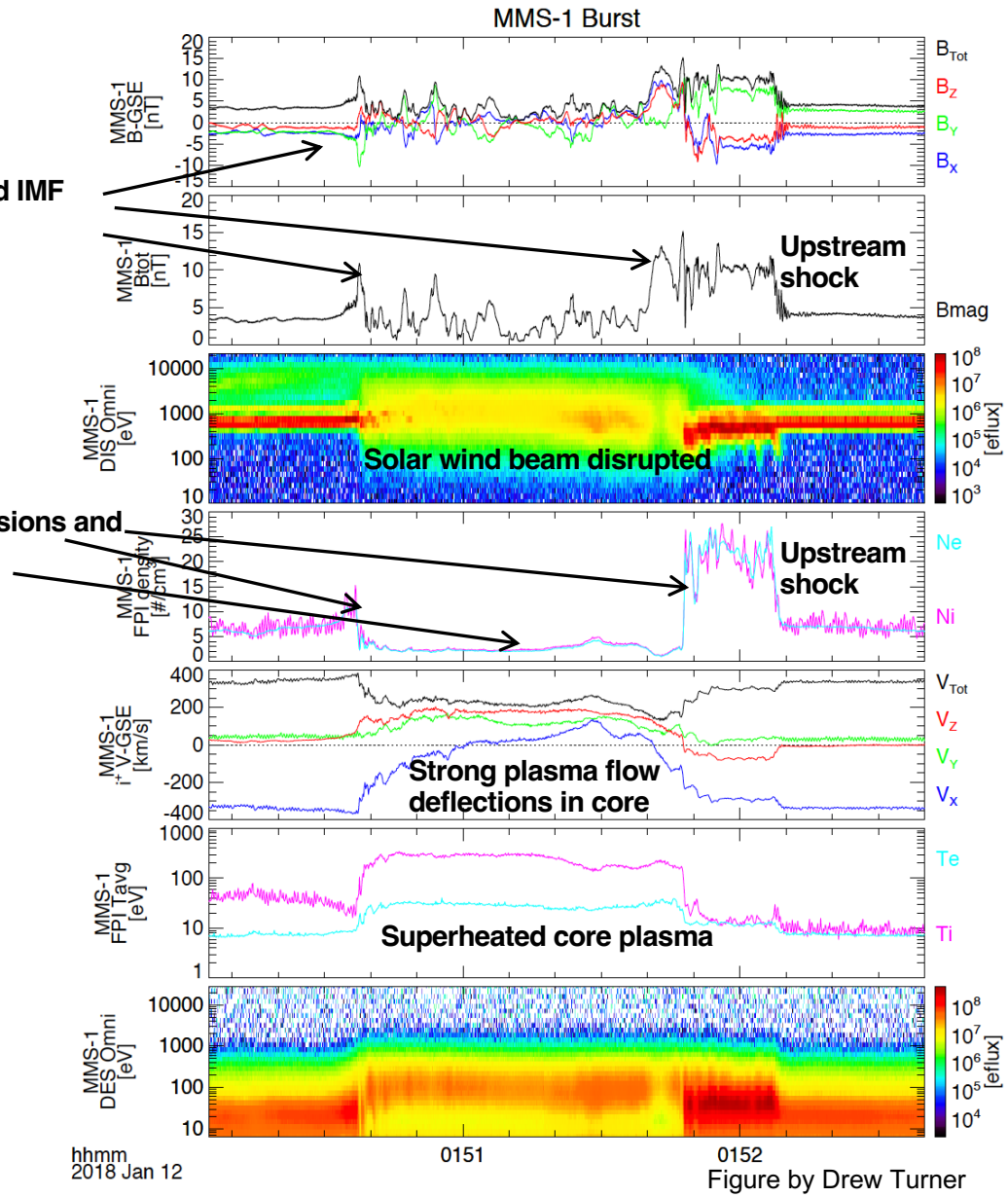
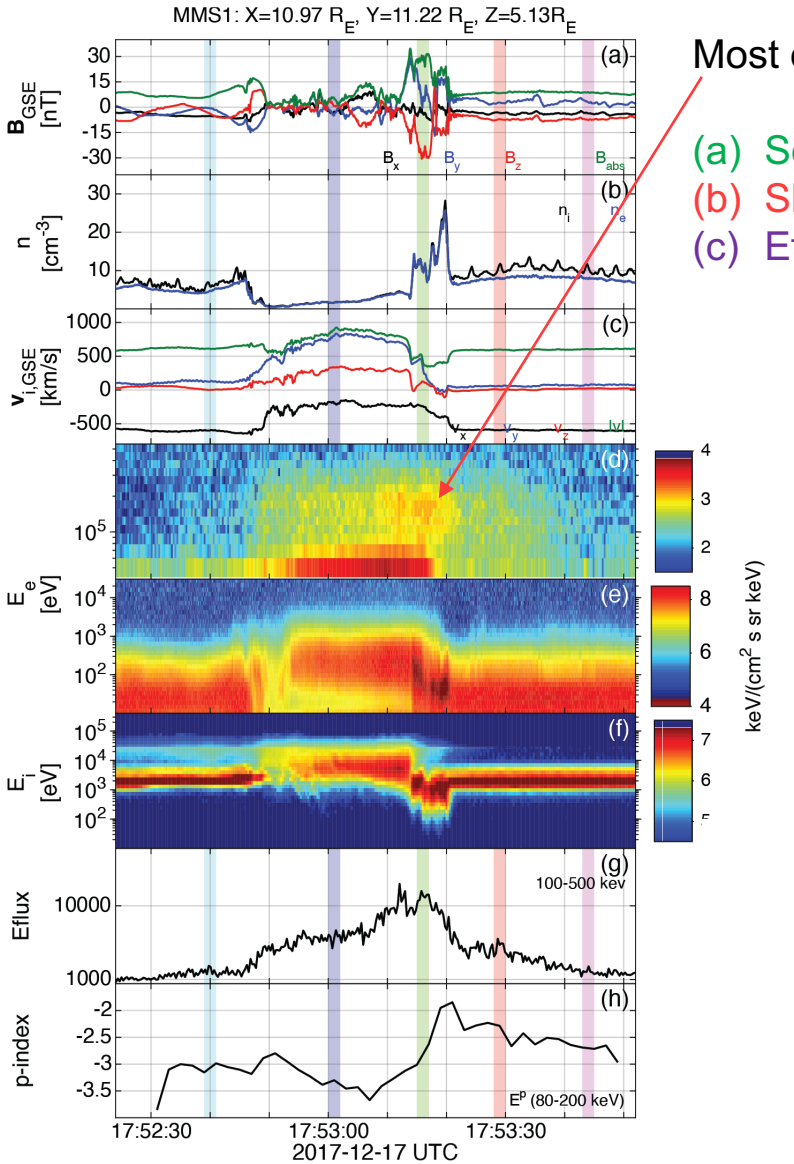


Figure by Drew Turner

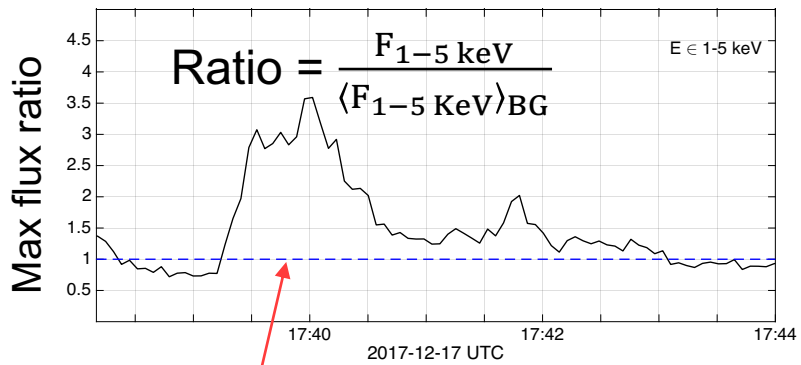
Discontinuity intersects the bow shock and the convection electric field (–V X B) points towards the sheet on at least one side.

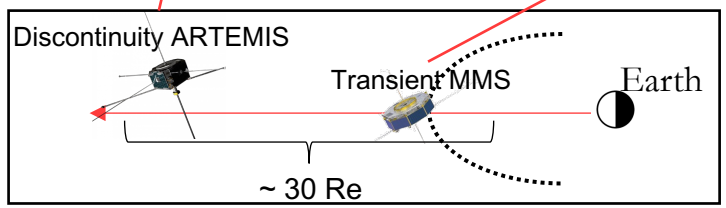
Reinforced Shock Acceleration of Relativistic Electrons

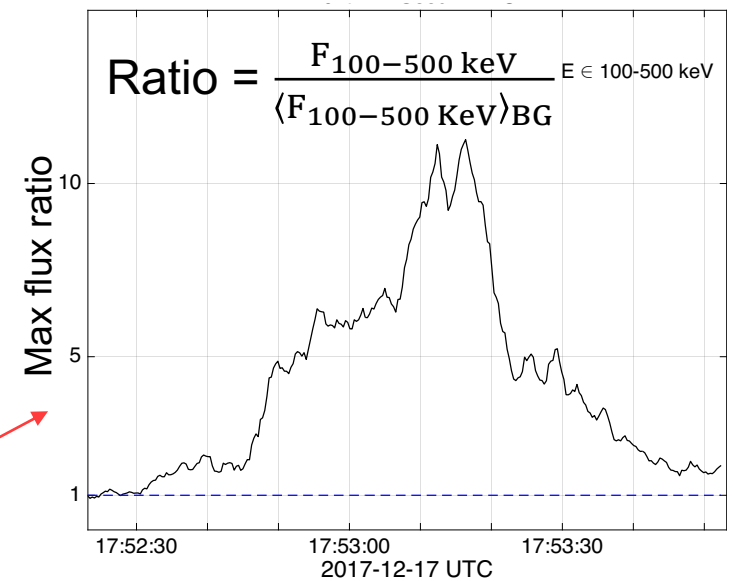


Most energetic electrons observed **(500+keV)** at foreshock transients by MMS showing:

(a) Seed population from fast solar wind at suprathermal energy range (1-5 KeV)
(b) Shock acceleration (SDA/DSA) + Wave particle interaction (high frequency "chorus" waves)
(c) Efficiency factors (Trapping and scattering – geometry with bow shock)



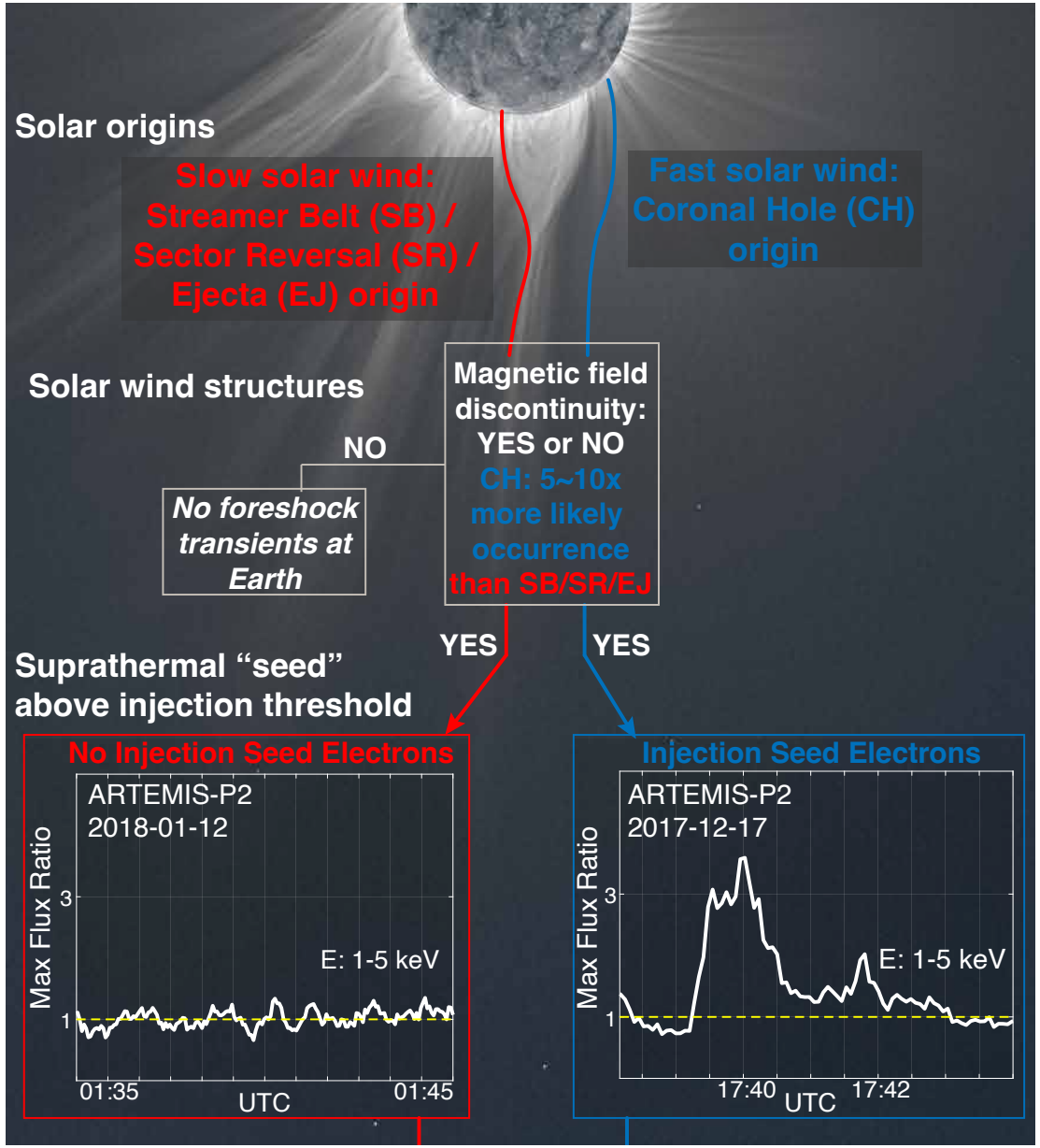


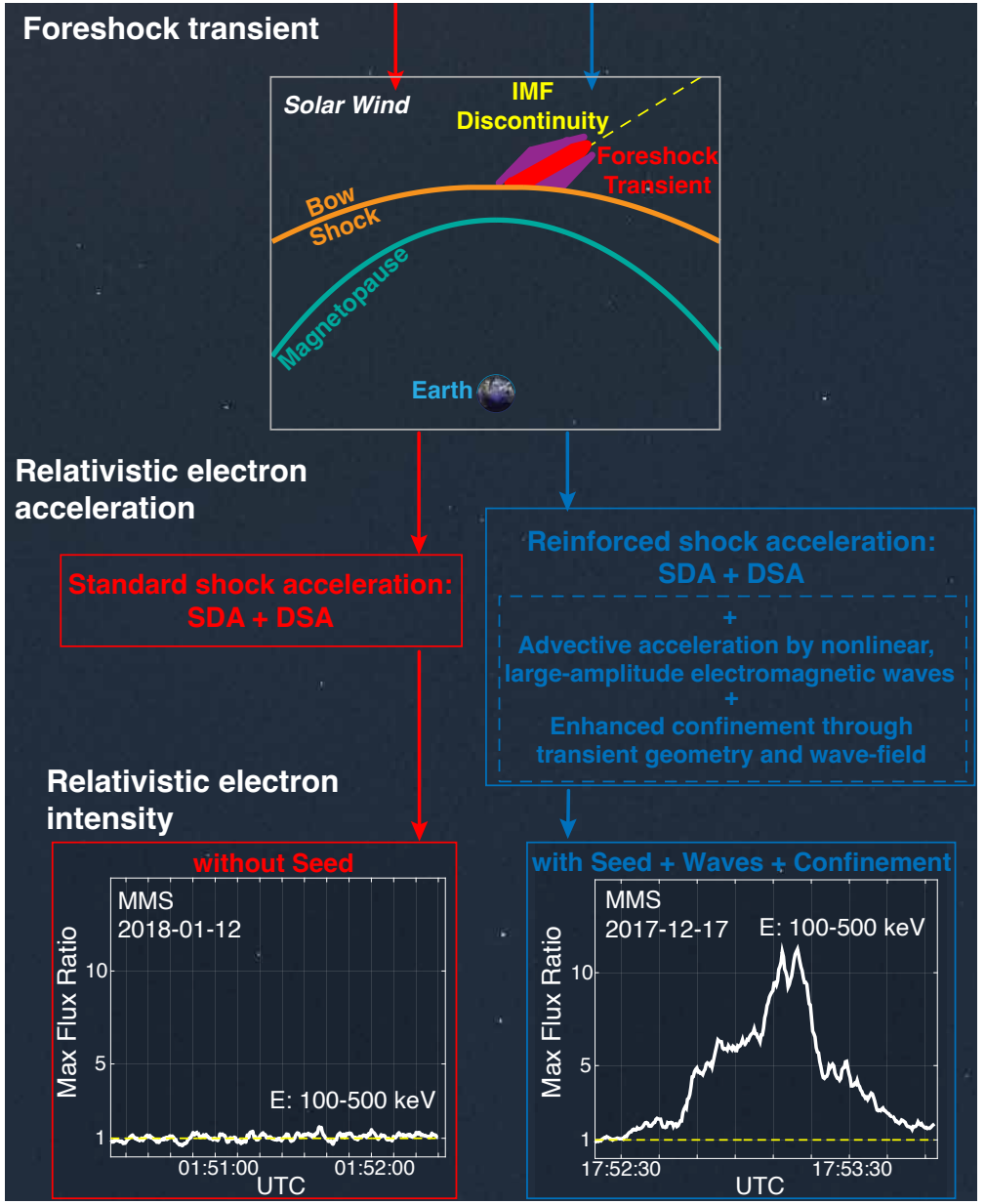


Key-point:
Seed + Foreshock's Shock + Waves + Efficiency factors = **~MeV electrons before** reaching the bow shock.

Raptis+ 2024 (Revealing an Unexpectedly Low Electron Injection Threshold via Reinforced Shock Acceleration – Accepted)

Reinforced Shock Acceleration of Relativistic Electrons





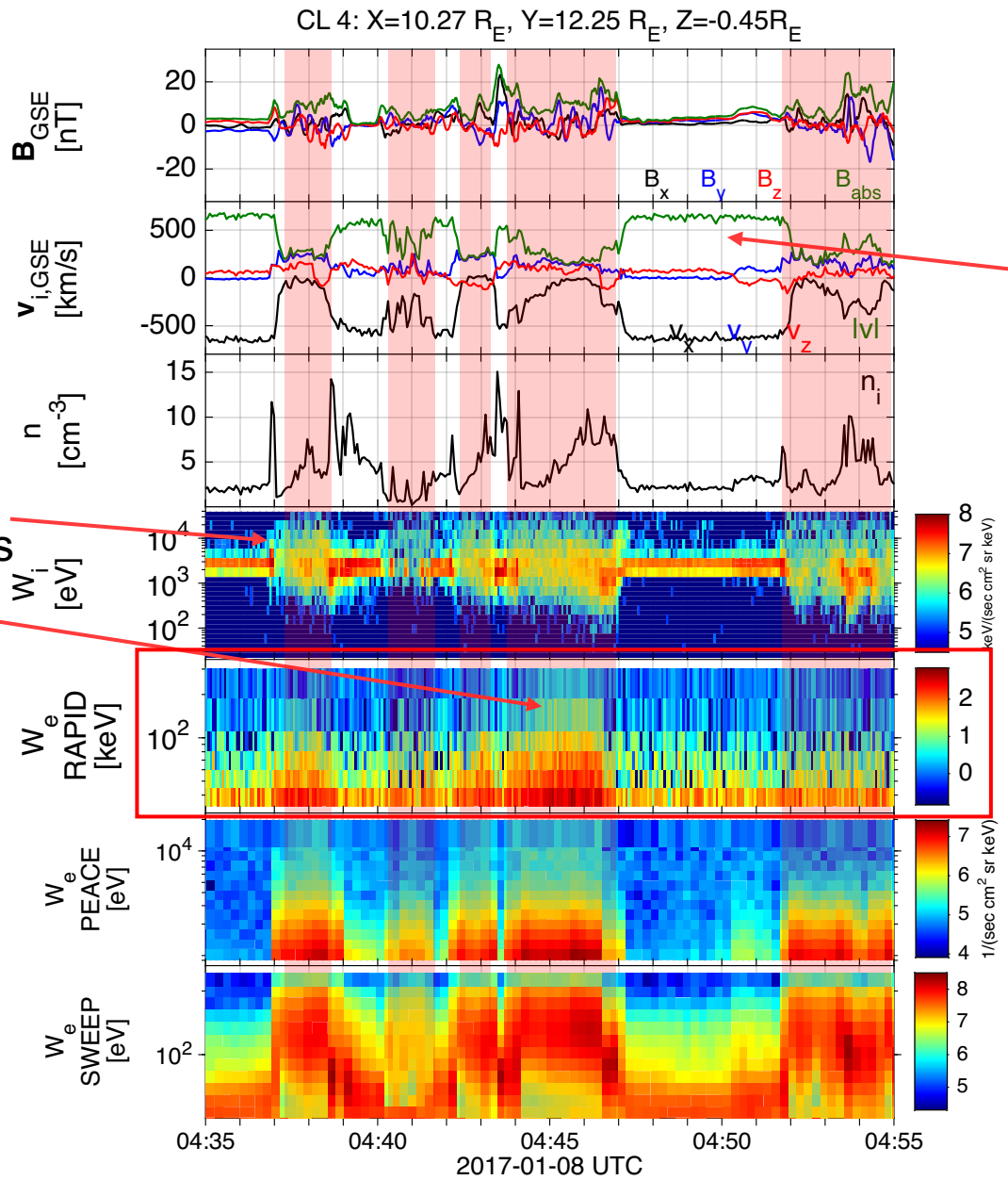
Raptis+ 2024 (Revealing an Unexpectedly Low Electron Injection Threshold via Reinforced Shock Acceleration – Accepted)

What happens when we move downstream?

Raptis+ 2024/2025 (to be submitted next week)

Multi-Mission Observations of Relativistic Electrons and High-Speed Jets Linked to Shock Generated Transients

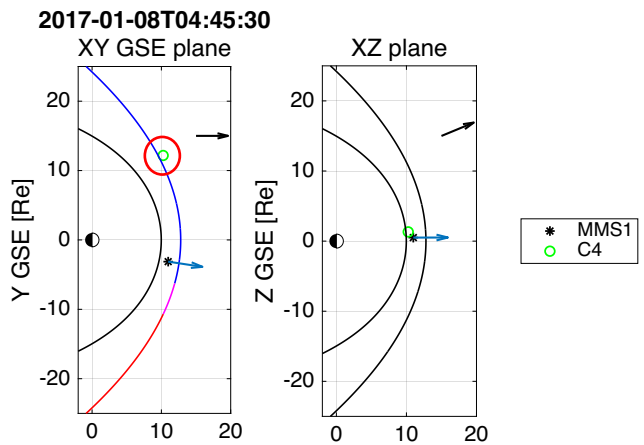
Cluster upstream showing foreshock transients



- Several Foreshock Transients
- ~200 keV electrons

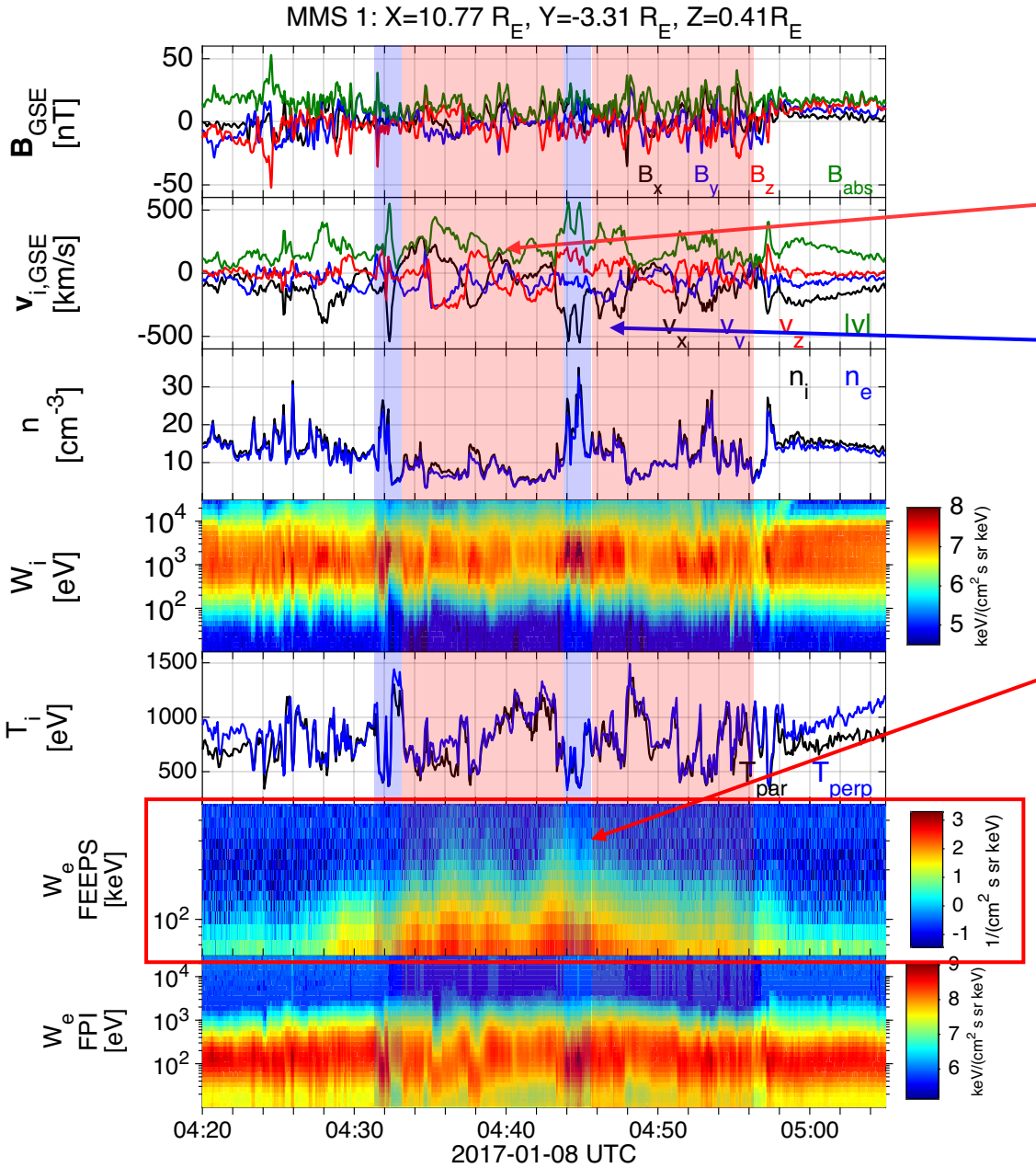
700 km/s Solar Wind!

Fast coronal hole plasma consistent with our previous work ✓

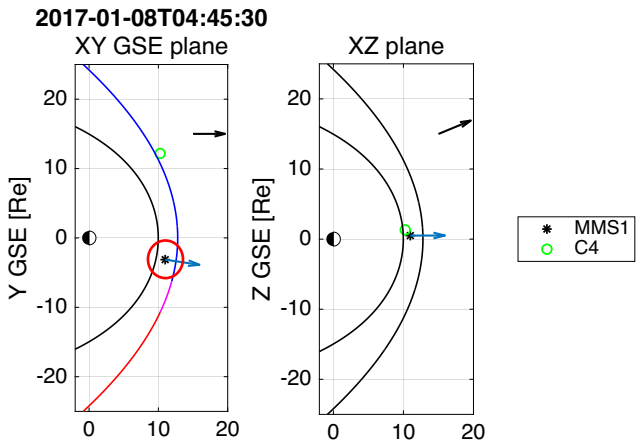


Raptis+ (under preparation)

MMS downstream shows the transmission



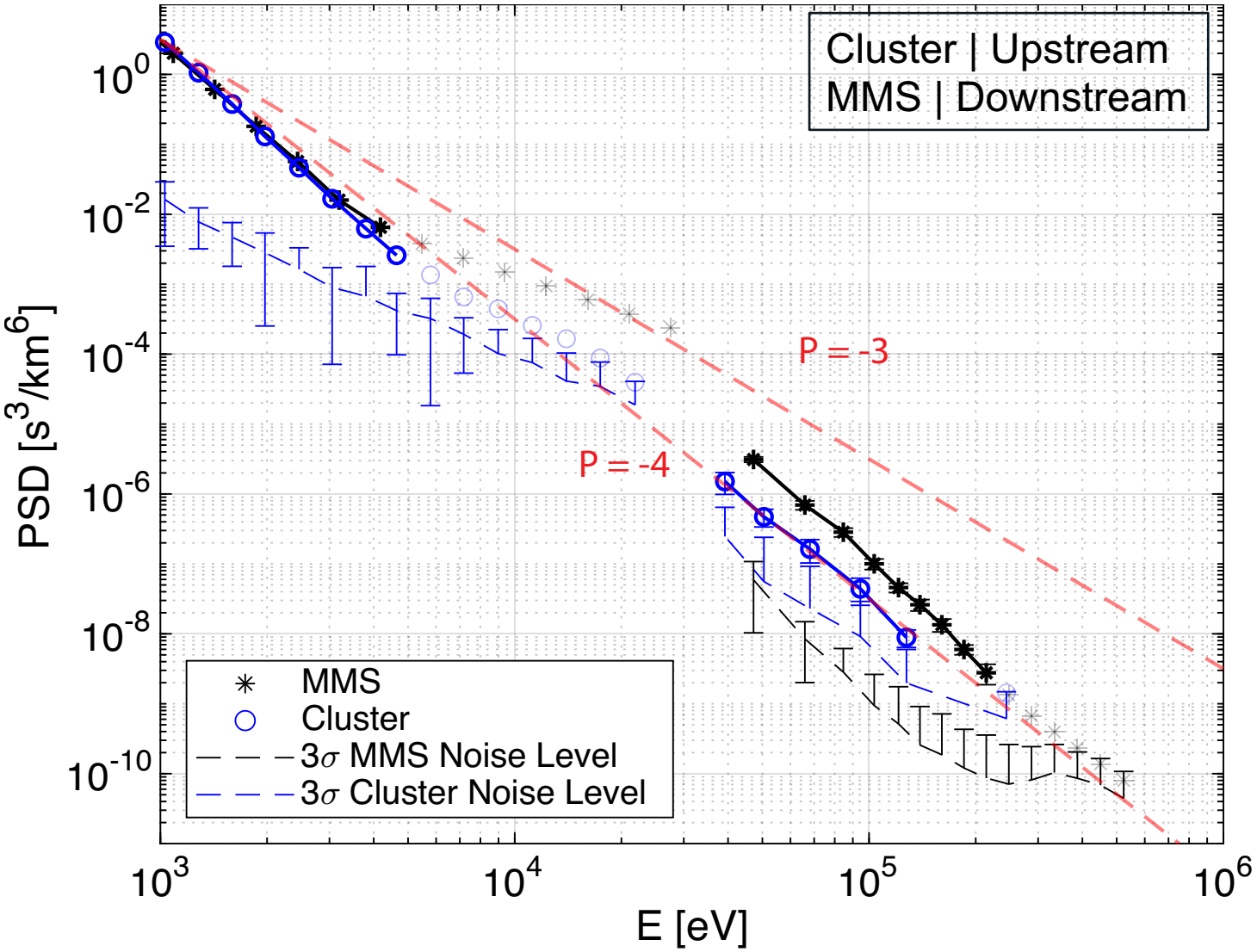
- Series of flow anomalies similar to upstream
- Localized jets at edges (both density and velocity peaks)
- Extended ~300+ KeV electron interval confined (~ 30 mins)



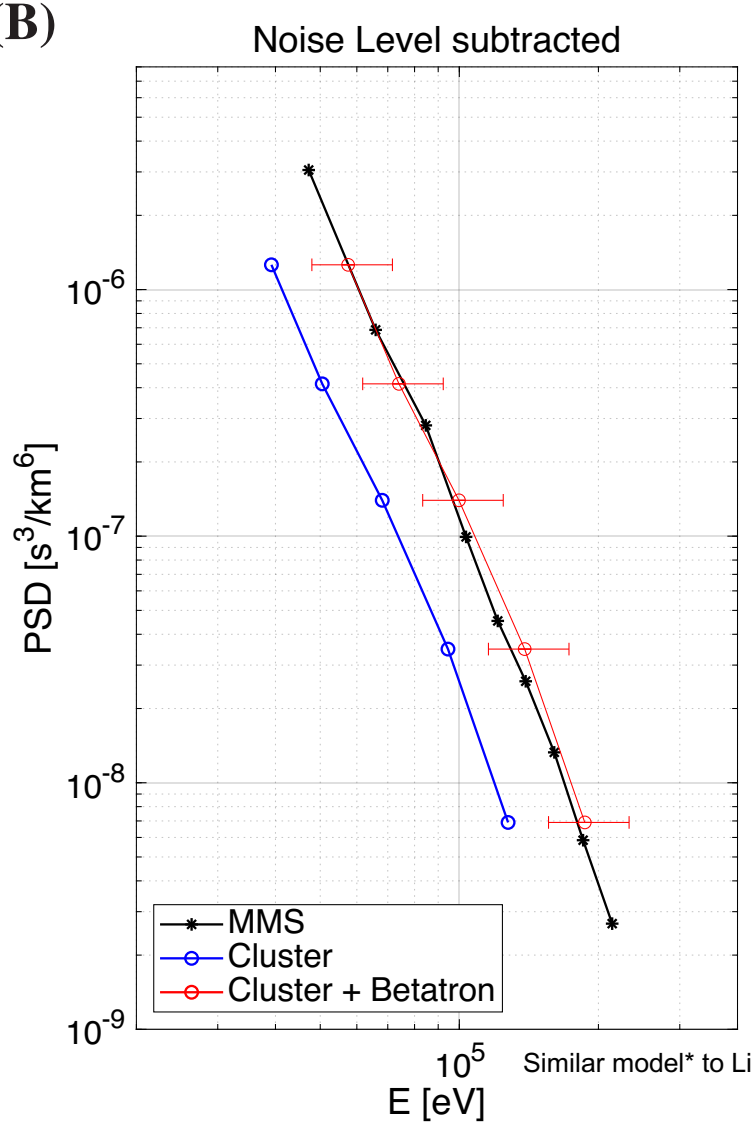
Raptis+ (under preparation)

Electron energization upstream to downstream

(A)



(B)



Similar model* to Liu et al., 2019

*Betatron in strong scattering → $\frac{\Delta E}{E_0} = \frac{2}{3}\frac{\Delta B}{B_0}$, where $\Delta X = X_{down} - X_{up}$

Raptis+ (under preparation)

Summary: Electron Multiscale Acceleration

(A)

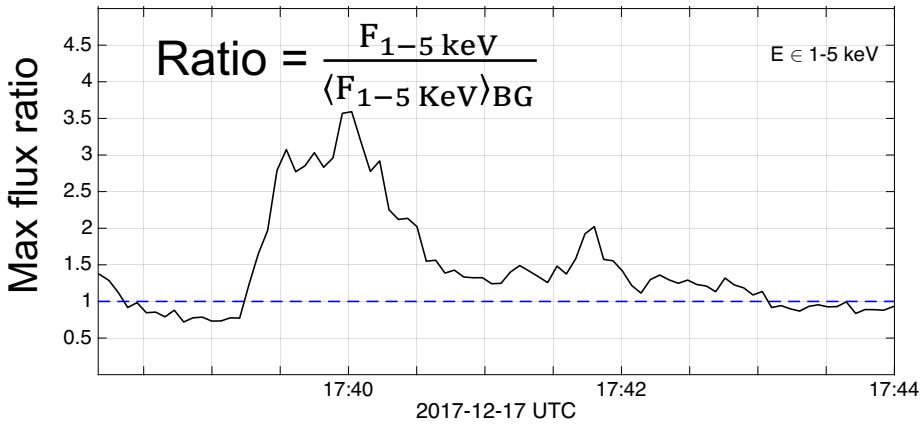
Discontinuity (SW) ARTEMIS

Transient (FS) MMS

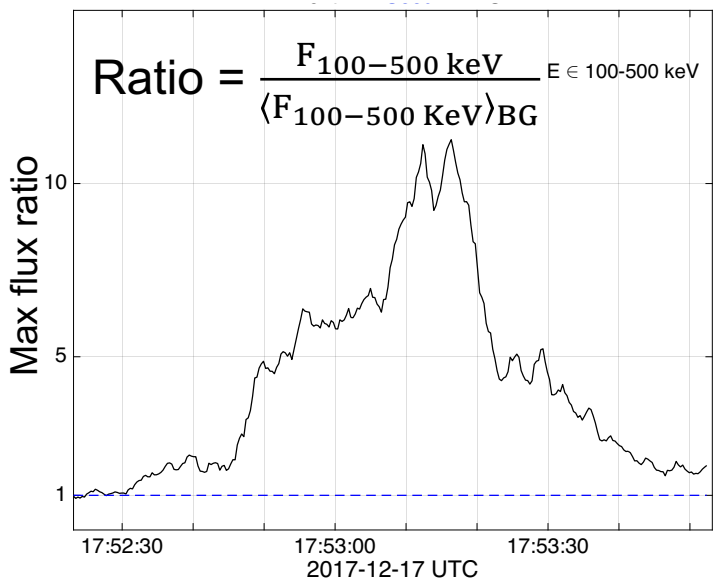
Coronal Hole SW
V> 500 km/s

~1 keV

>500 keV



SW - THEMIS

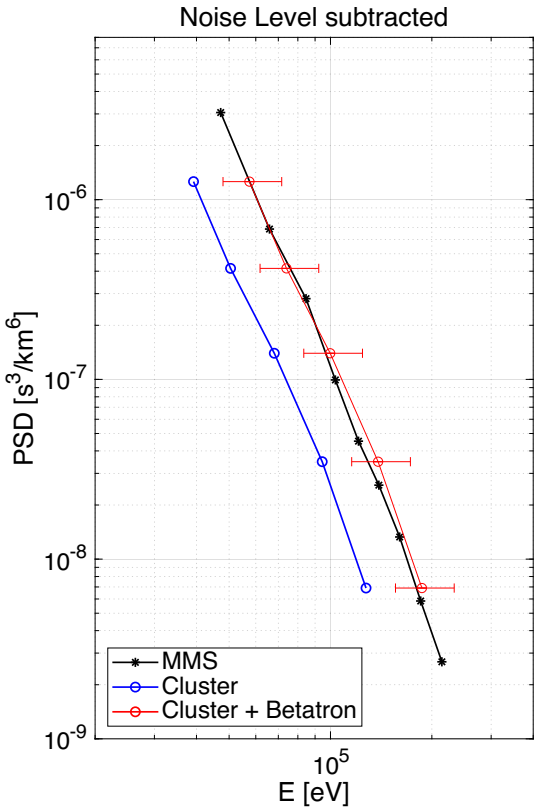


Foreshock - MMS

(B) Transient (FS) Cluster

Transient (MSH) MMS

200 → 300 keV



Magnetosheath – CL/MMS

(A) : Raptis+ 2024 (“Accepted”) - *Revealing an Unexpectedly Low Electron Injection Threshold via Reinforced Shock Acceleration*

(B) : Raptis+ 2025 (to be submitted) - *Multi-Mission Observations of Relativistic Electrons and High-Speed Jets Linked to Shock Generated Transients*

Key take away

(A) : Raptis+ 2024 (Accepted) - *Revealing an Unexpectedly Low Electron Injection Threshold via Reinforced Shock Acceleration*
(B) : Raptis+ 2025 (Ongoing) - *Multi-Mission Observations of Relativistic Electrons and High-Speed Jets Linked to Shock Generated Transients*

(A) Raptis+ 2024 ("Accepted")

1. **Revealed that electron injection threshold to obtain relativistic electrons (> 500 keV) at Earth's foreshock** can be at the **low suprathermal range of ~1-5 KeV**

2. This **seed population** is a systematic **feature of the fast coronal hole solar wind plasma.**

(B) Raptis+ 2025 (Ongoing)

1. **Energized electrons (~200 keV) get further accelerated as transients get transmitted (~300 keV)**

2. **Transmitted Shock-Generated transients produce localized high-speed jets**

Strongest electron acceleration may not happen at the shock transition
Transient phenomena are making shocks much more efficient accelerators

Final words

<u>As written on our latest ongoing draft:</u>

“The multi-mission observations presented here emphasize the importance of adopting a multi-scale approach to address shock-related phenomena and reinforce the necessity of obtaining such data…. proposed missions such as the Plasma Observatory (PO) mission will be critical to advance our understanding of collisionless shock physics and associated particle energization. “

What ChatGPT thinks PO will do →

Extras

Reinforced Shock Acceleration of Relativistic Electrons

Injection Threshold
"Seeding"

Seed from
CH plasma
(**~1-5 keV**)

Electron acceleration at Foreshock Transient

Shock
Acceleration

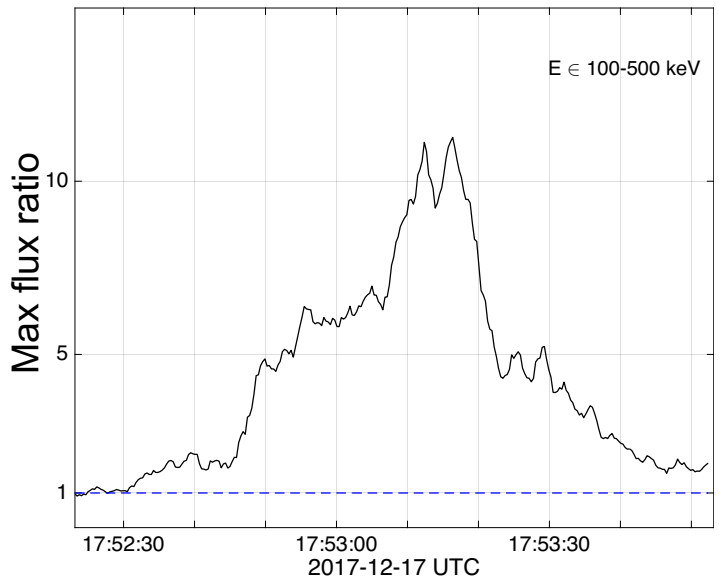
+

Wave particle
interactions

Efficient PA scattering & confinement:

- LF whistler waves (Shock Transition)
- Wavefield of HFA's core (ΔB>>B)
- "Magnetic bottle" between edges of HFA and Earth's bow shock (geometry)
- Betatron (electron acceleration, temperature anisotropy)

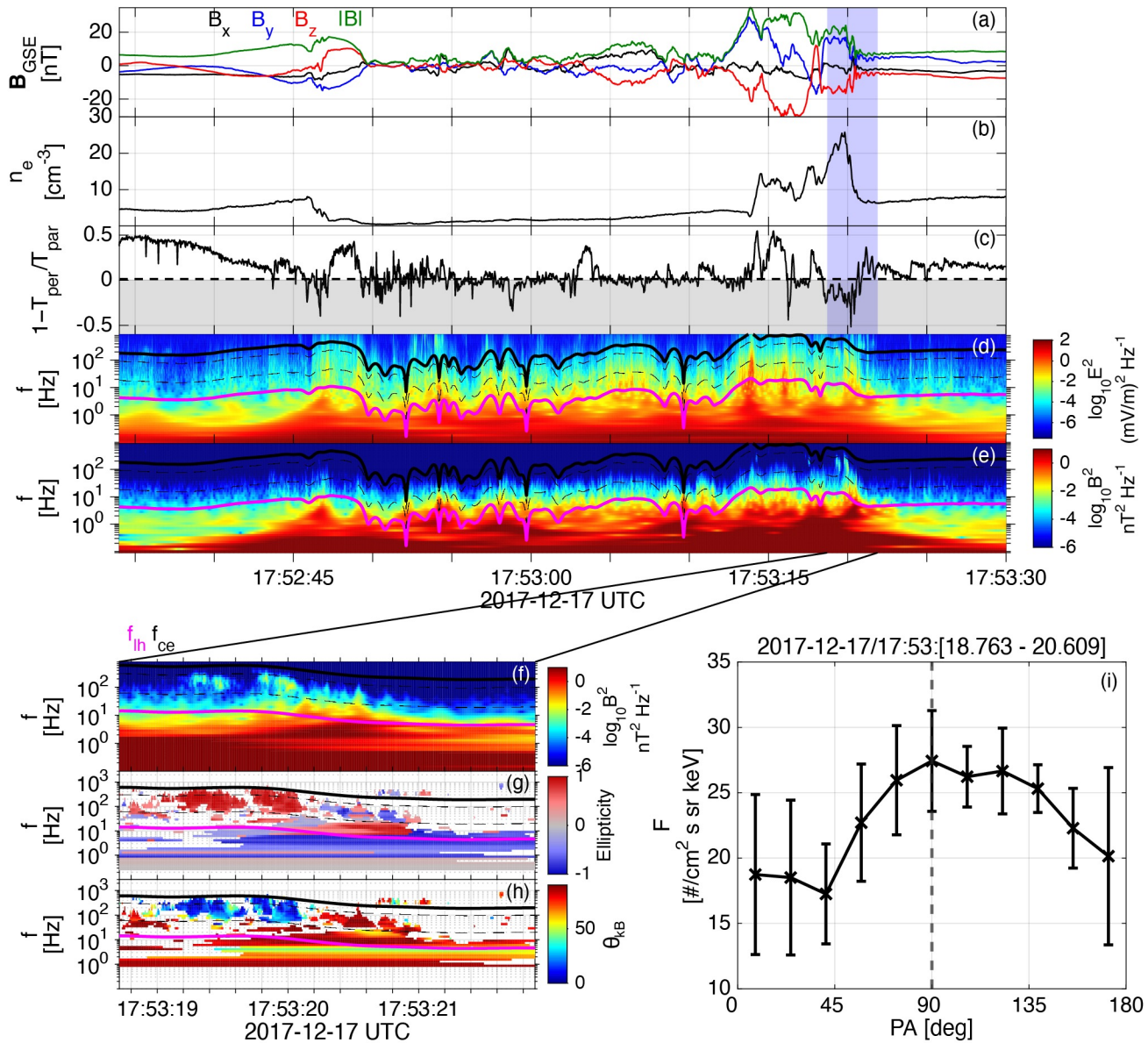
$$\text{Ratio} = \frac{F_{100-500\ \text{KeV}}}{\langle F_{100-500\ \text{KeV}} \rangle_{BG}}$$



Key-point:
Seed + Foreshock's Shock + Waves + Efficiency factors = **~MeV electrons before** reaching the bow shock.

Raptis+ 2024 (Revealing an Unexpectedly Low Electron Injection Threshold via Reinforced Shock Acceleration – Accepted)

Wave analysis of event



Acceleration:

- Shock Acceleration
- Betatron → Temperature anisotropy
- High amplitude electron whistler waves (Chorus) resonance

Scattering & Trapping:

- LF whistler waves (Shock)
- Wavefield of HFA's core
- Geometry of HFA with respect to Earth's bow shock

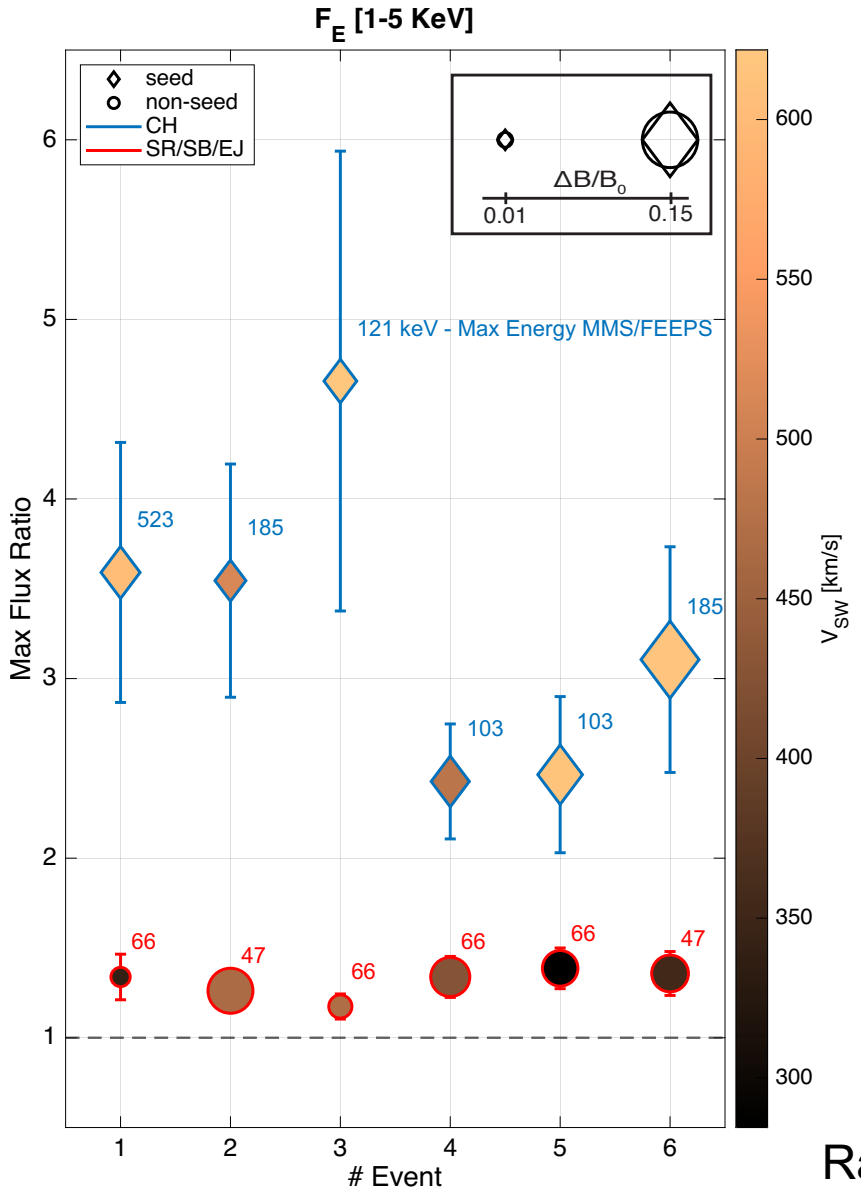
Particularly efficient acceleration:

$$\frac{U_E}{U_I} = \frac{\text{Energy density suprathermal electrons}}{\text{Energy density Solar Wind}} \sim 5\ \%$$

Raptis+ 2024 (Revealing an Unexpectedly Low Electron Injection Threshold via Reinforced Shock Acceleration – Accepted)

See Artemyev+, Xiaofei+, Vargas + Tonoian+ (2022 – 2024)

Statistics for seed and acceleration



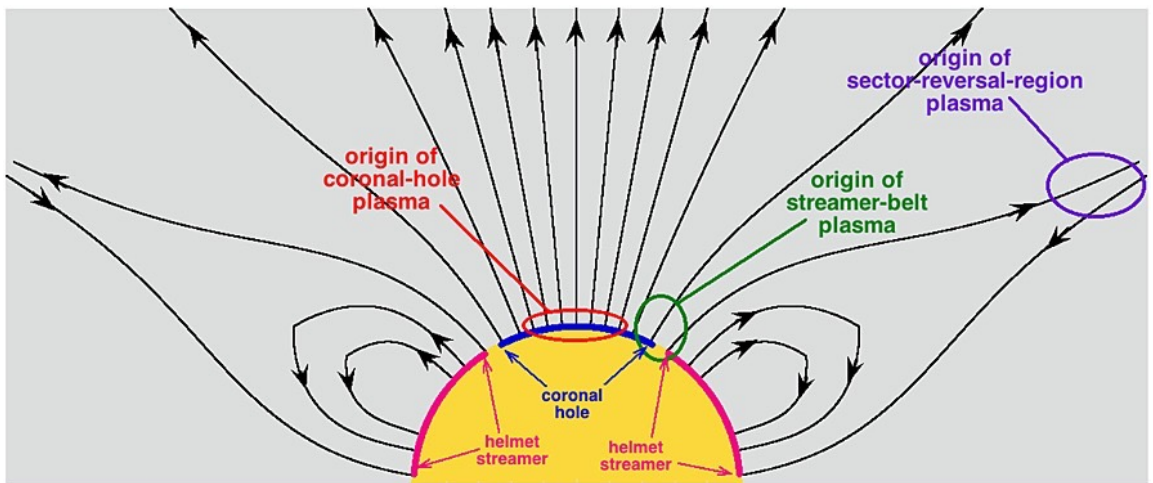
Seed events (FEEPS > 100 KeV)

CH (78%), CH (40%), CH(79%), CH (39%), CH(77%), CH(79%)

No-seed (FEEPS = Noise)

SB (80%), SB(42%), EJ (55%) SB (44%), SR(63%), SB (46%)

Using: [Xu and Borosvky 2014, Camporeale+ 2017] methodology



$$\text{Ratio} = \frac{F_{1-5\ KeV}}{\langle F_{1-5\ KeV}\rangle_{BG}}$$

Raptis+ 2024 (Revealing an Unexpectedly Low Electron Injection Threshold via Reinforced Shock Acceleration – Accepted)

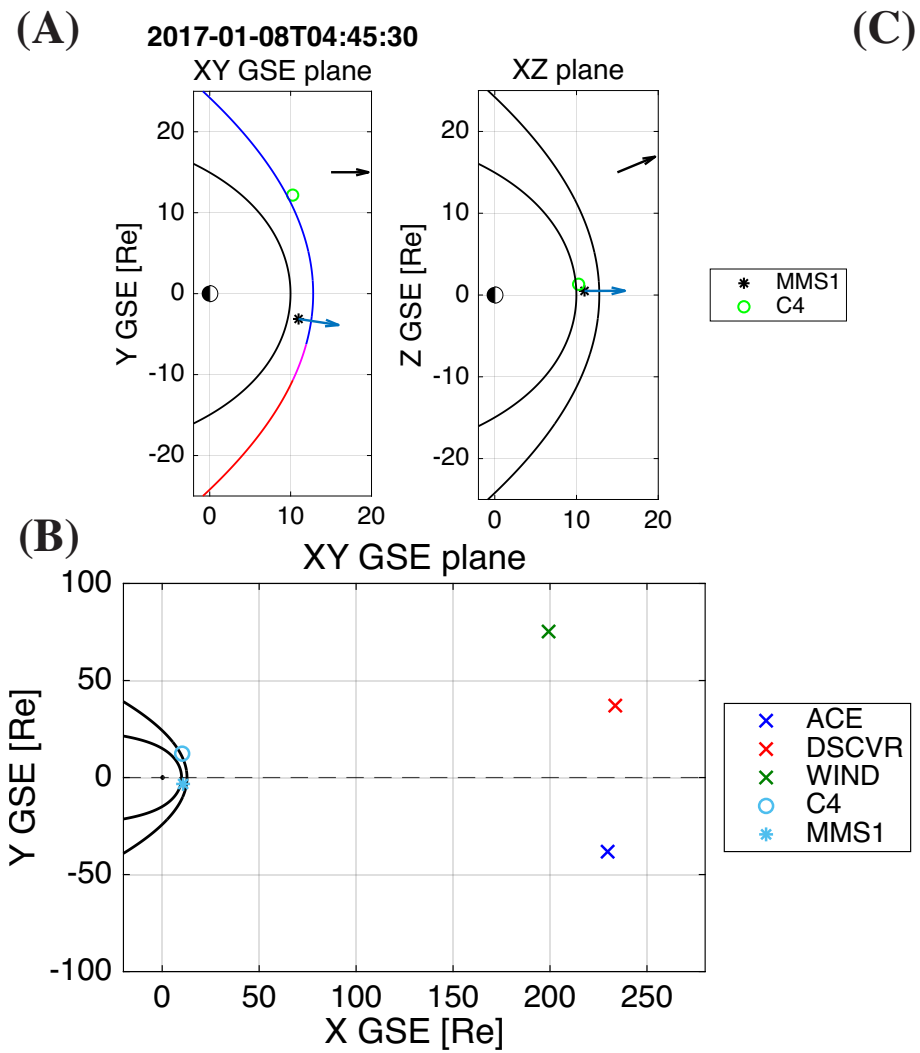
Terry Liu+ (2017) noticed similar trends

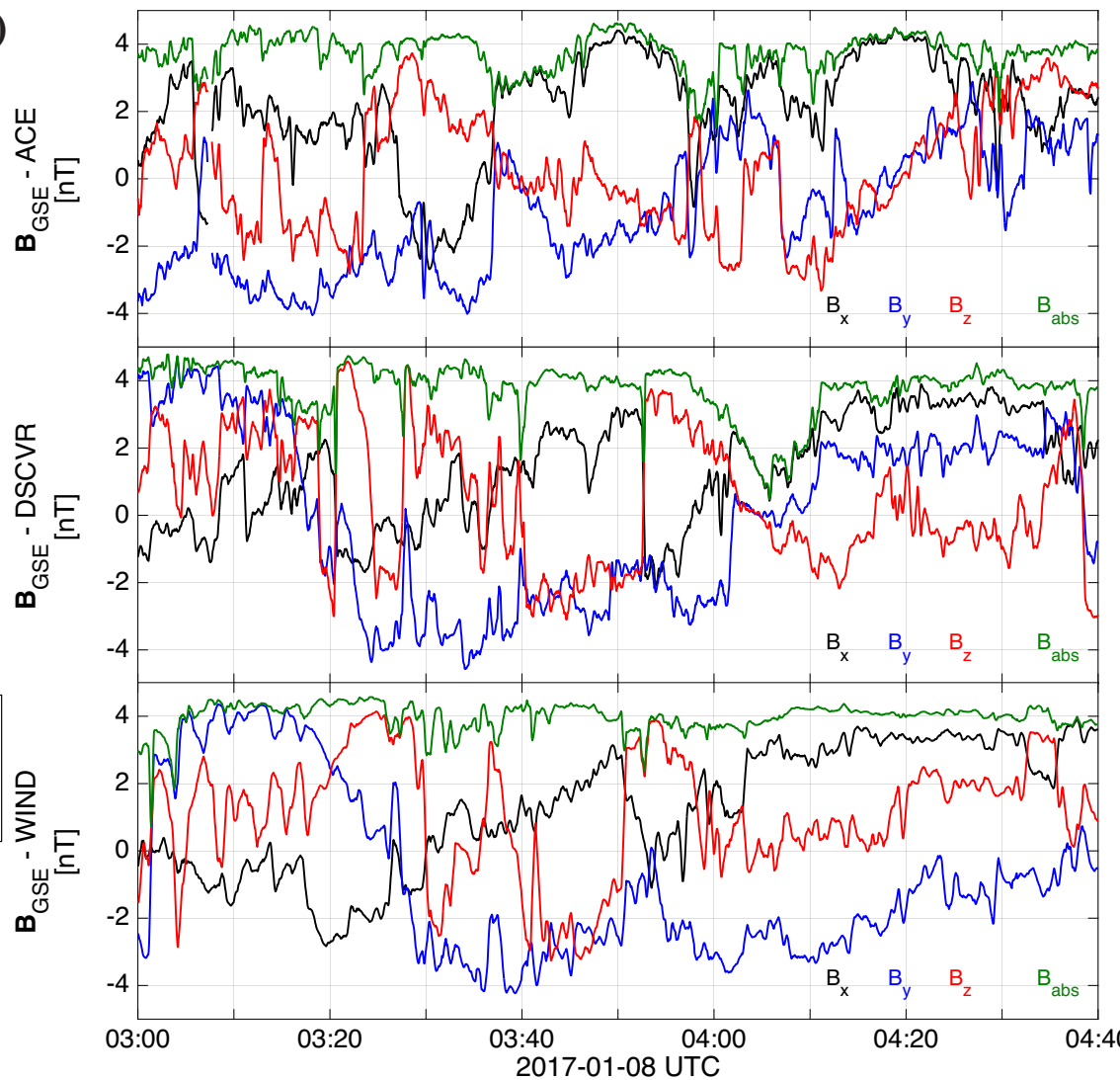
Location of SCs and IMF conditions

(A)
1. Cluster: Upstream
2. MMS : Downstream

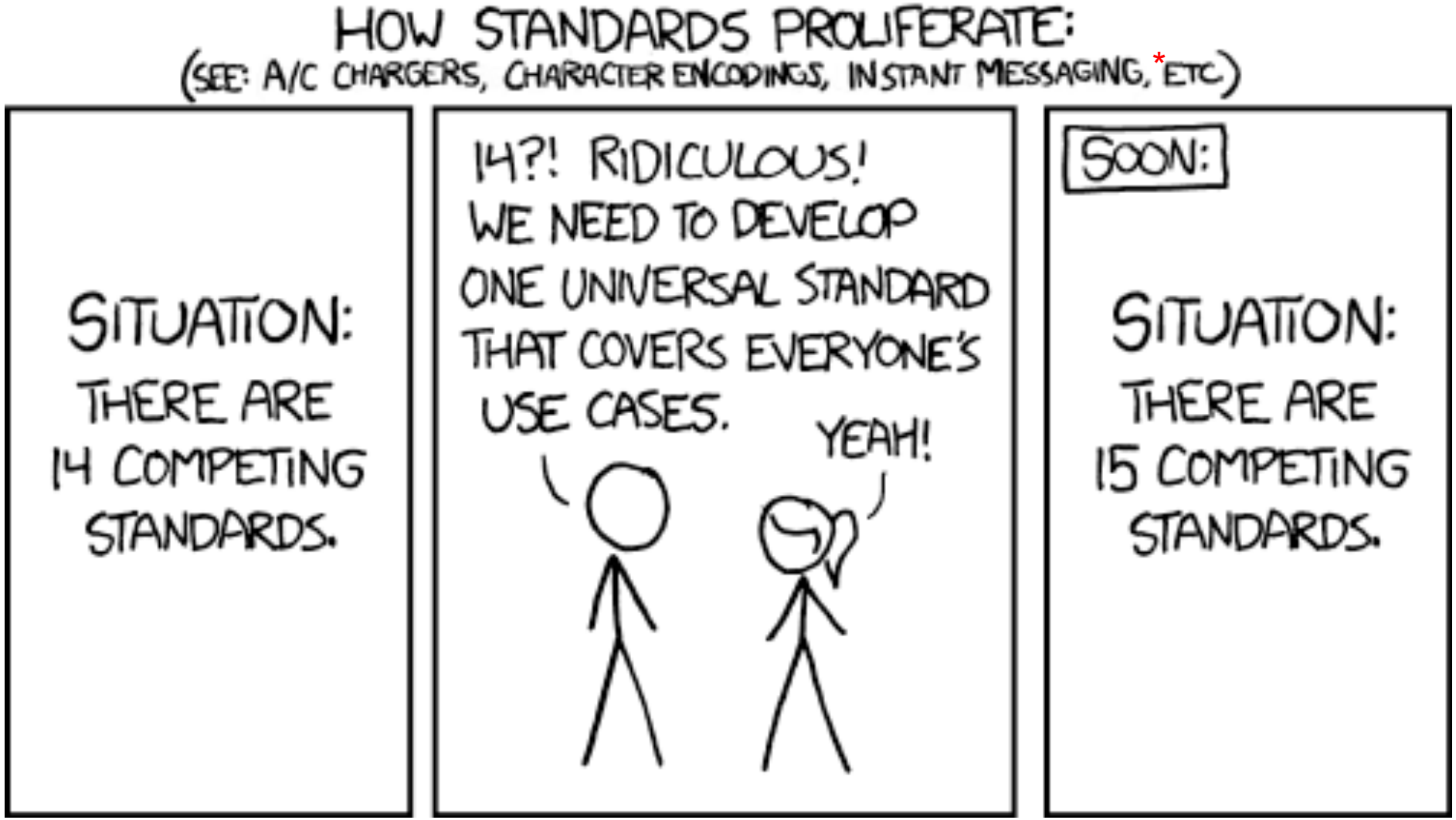
(B)
1. L1 monitors apart

(C)
1. Temporal & spatial Variability ++
2. Discontinuities ++





Discussing new models



*In our case models, mechanisms, explanations etc.