

The Role of Shock-Generated Transients in Particle Acceleration at Planetary Bow Shocks

Savvas Raptis

APL/JHU, Laurel, MD, USA

Acknowledgments:

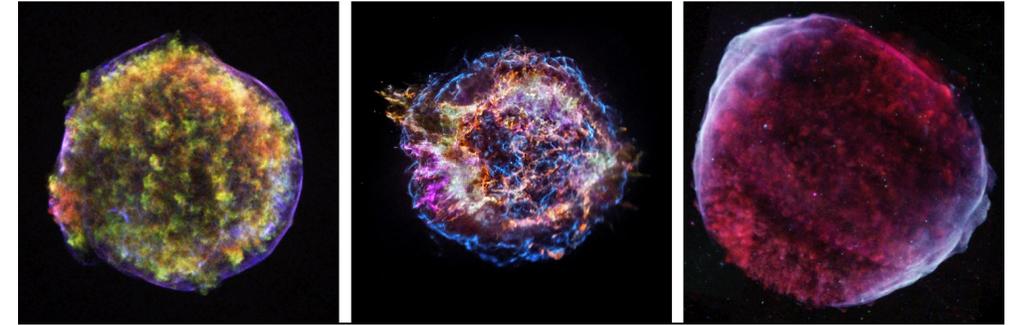
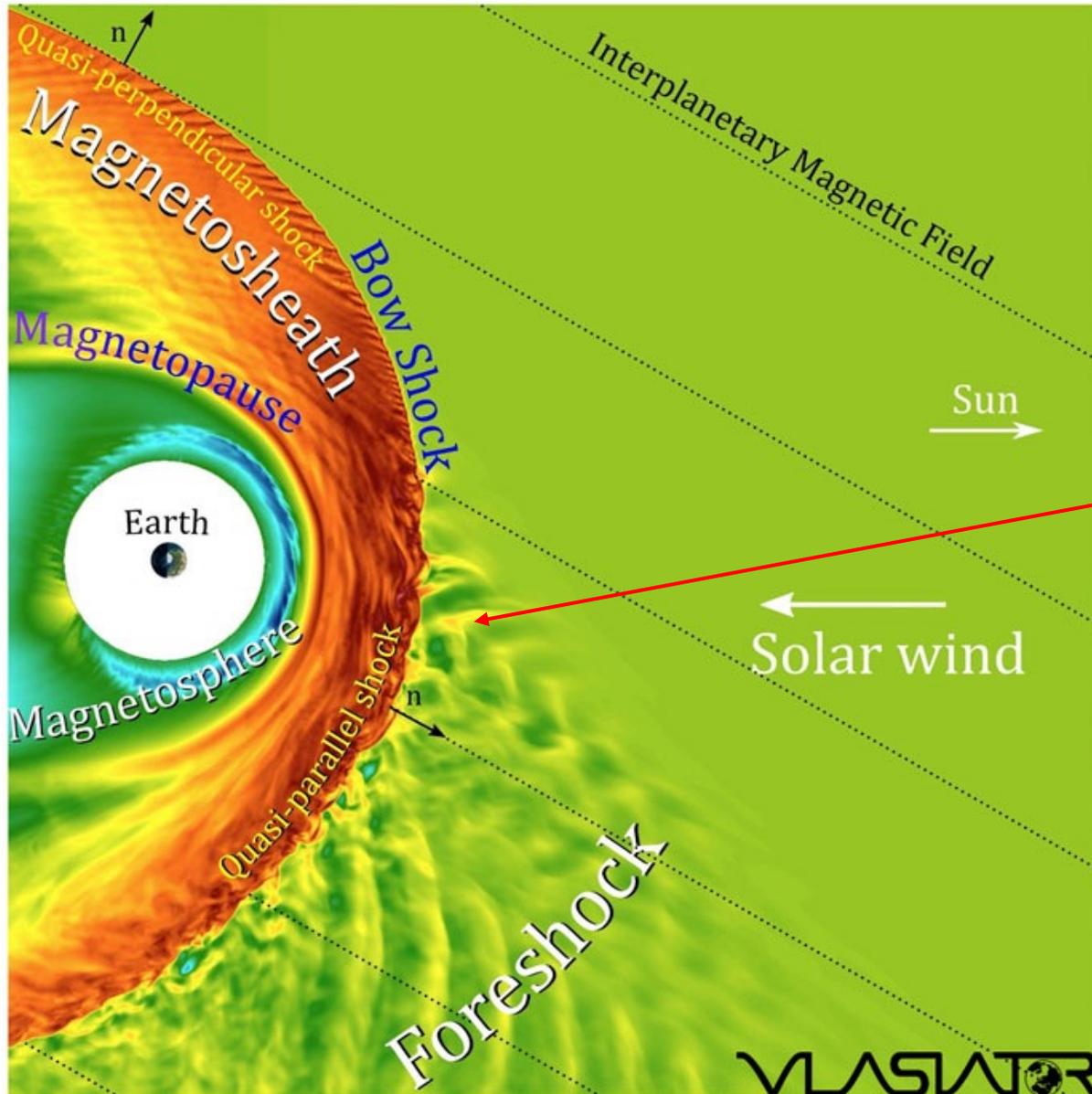
- MMS Early Career Grant and APL R&D program
- ISSI Team: P. Kajdič - Foreshocks Across The Heliosphere: System Specific Or Universal Physical Processes?
- GEM Focus group: **Multiscale Dayside Transients (MDT)** and their Effect on Earth's Magnetosphere
- APL R&D program

Thanks to co-authors and collaborators: Ahmad Lalti, Drew Turner, Terry Liu, Martin Lindberg, Damiano Caprioli, Lynn Wilson III, Yufei Zhou, David Sibeck, Primoz Kajdic, Adnane Osmane, Ian Cohen, Philippe Escoubet, Jim Burch, George Clark, Jamey Szalay ++ many more

1. Shocks & Transient Phenomena
2. Particle Acceleration

Shocks & Transient Phenomena

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

*Astro references on Qpar importance: Caprioli+2014, Giuffrida+2022, Vink+2024

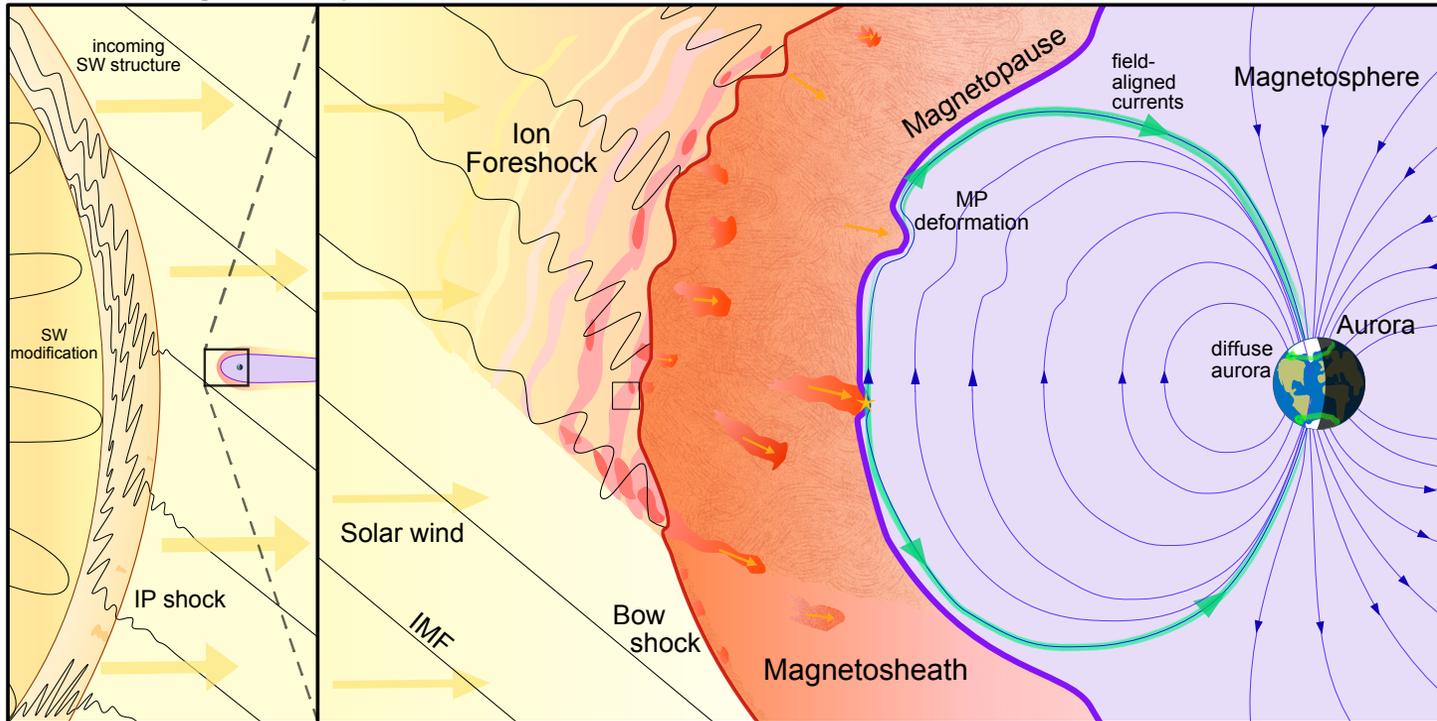
What is a Dayside Transient?



← New review paper about high-speed jets!

Transient phenomena are events that disrupt the steady-state plasma conditions, occurring temporarily and introducing dynamic changes to the physical system

Figure adapted from Krämer et al., 2025, Credits: Florian Koller



NOTE: Transients can be intrinsic (e.g., ULF waves, SLAMS) or driven (e.g., HFAs)

- Global (Solar):
 - Coronal Mass Ejection (CME)
 - High-Speed Stream (HSS)
 - Pressure Pulse / IP Shocks
- Fluid scale:
 - Flux Transfer Event (FTE)
 - Magnetopause (bursty) Reconnection

Mesoscale:

- Hot Flow Anomalies (HFAs)
- Foreshock Bubbles (FBs)
- Magnetosheath High Speed Jets (HSJs)

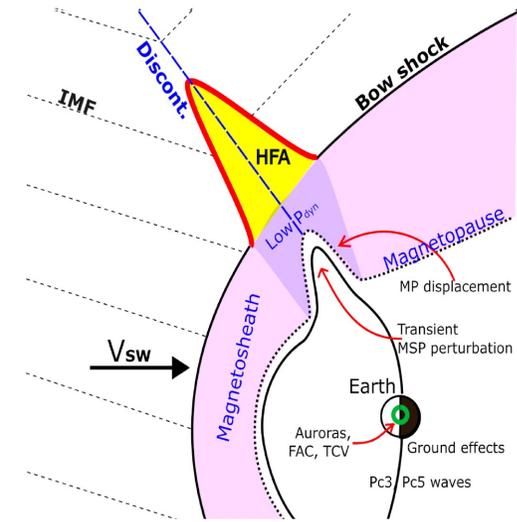
Kinetic:

- ULF waves
- Shocklets
- SLAMS

GEM FG: Multiscale Dayside Transients and their Effect on Earth's Magnetosphere
(2025 - 2029; Savvas Raptis, Ivan Vasko, Imogen Gingell, Terry Z. Liu, Ying Zou)

The anatomy of an HFA

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



Hot Flow Anomalies (HFA)

Kajdič+ (2024)

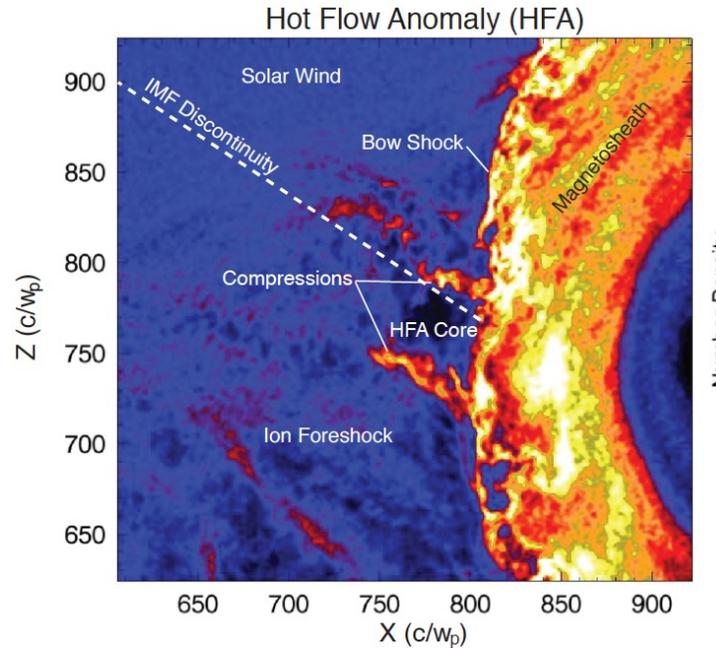


Figure by Nick Omidi

Crater-like B-field and IMF discontinuity

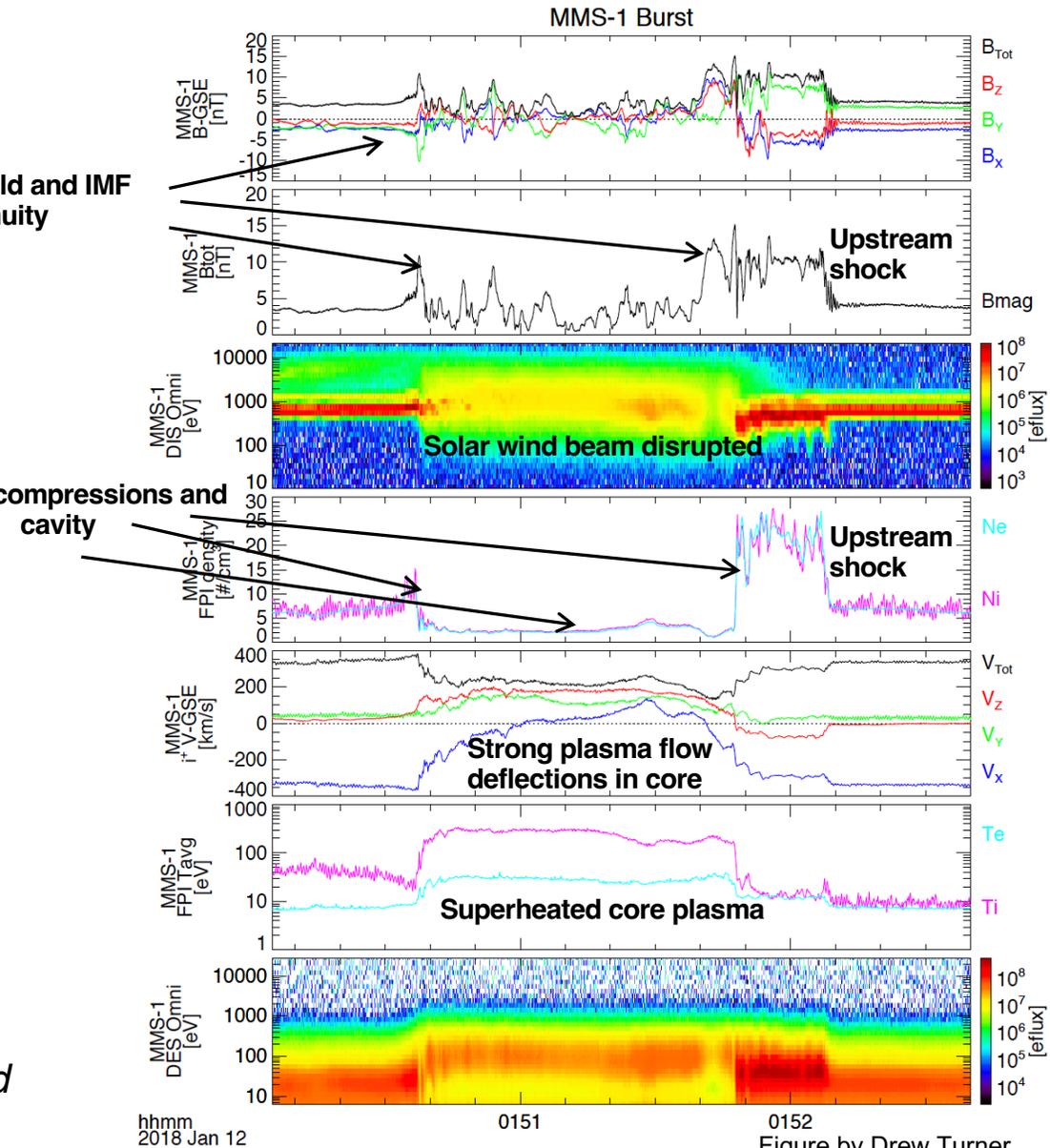


Figure by Drew Turner

How they form?

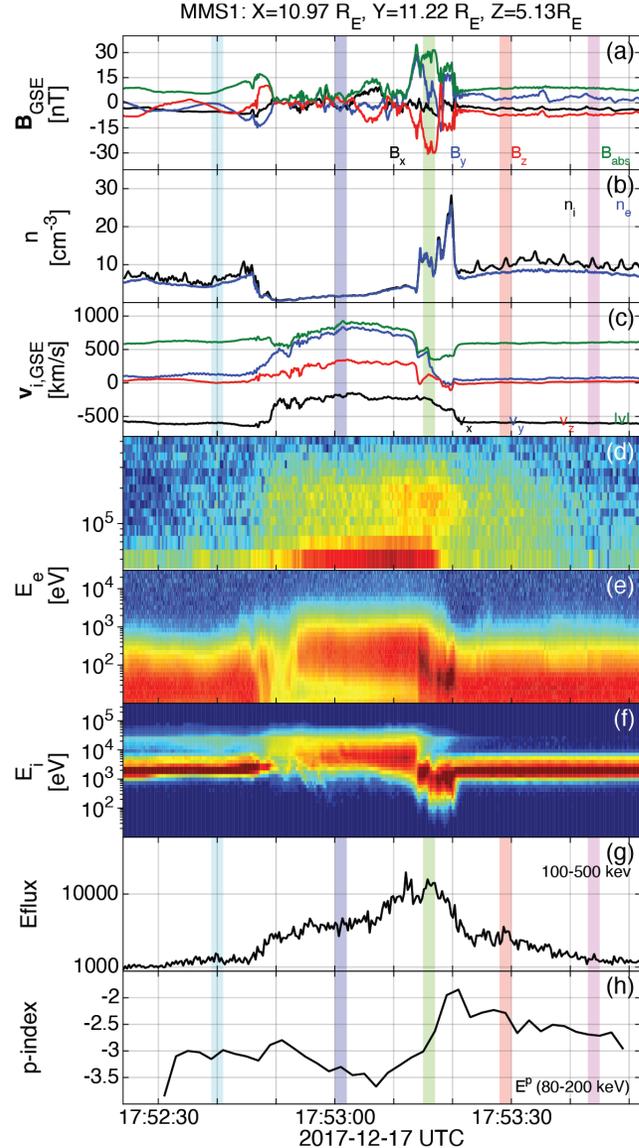
Discontinuity intersects the bow shock and the convection electric field ($-V \times B$) points towards the sheet on at least one side.

1. Shocks & Transient Phenomena
2. Particle Acceleration

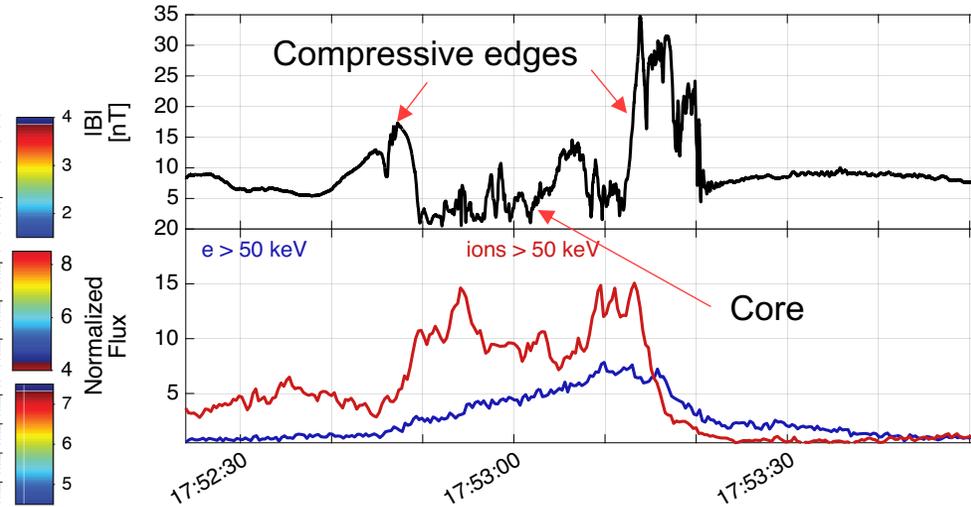
Particle Acceleration Recent Results*

*See also: Wilson III L. et al. 2016; Turner et al. 2018; Liu et al. 2019; Shi et al. 2023,2025 ; Tonoian et al. 2023; Kamaletdinov et al. 2024; Li et al. 2025

Relativistic Electrons with MMS



New plot, much easier to understand!



With respect to SW/FS:

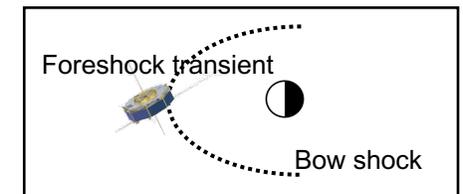
- Electron fluxes ($>50 \text{ keV}$) up to x6
- Ion fluxes ($>50 \text{ keV}$) up to x15

Typical properties of transient:

- Depleted Core (low B, n)
- Mature HFA ($\Delta B/B_0 \sim 1-4$)
- SW beam disrupted
- Strong density and magnetic field compressive boundaries
- Formation of a Qperp “shock”
- Flow anomaly (velocity decreasing)

Unique property

$>500 \text{ keV}$ electrons throughout the core and shock region

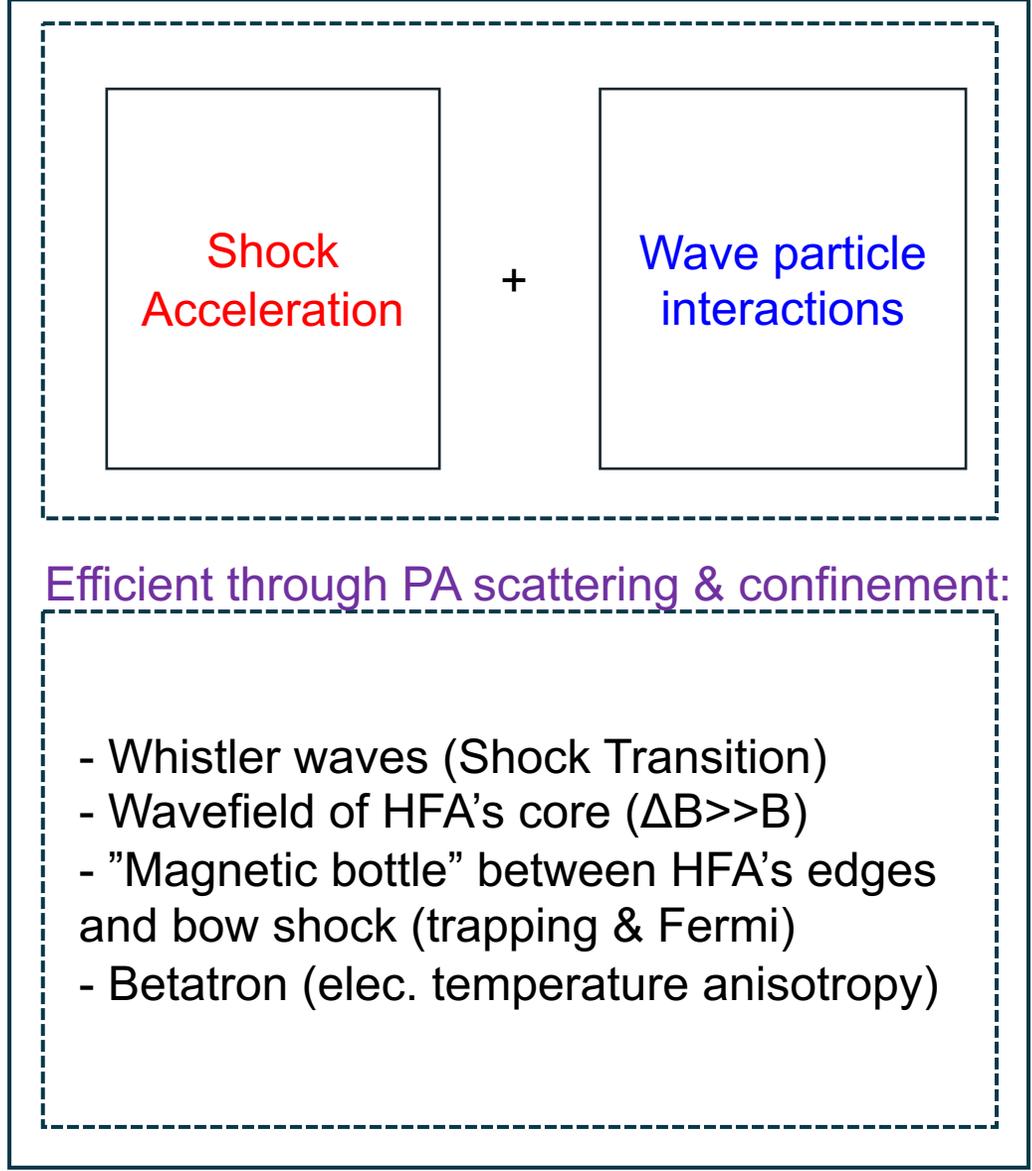


Reinforced Shock Acceleration of Relativistic Electrons

Electron acceleration at Foreshock Transient

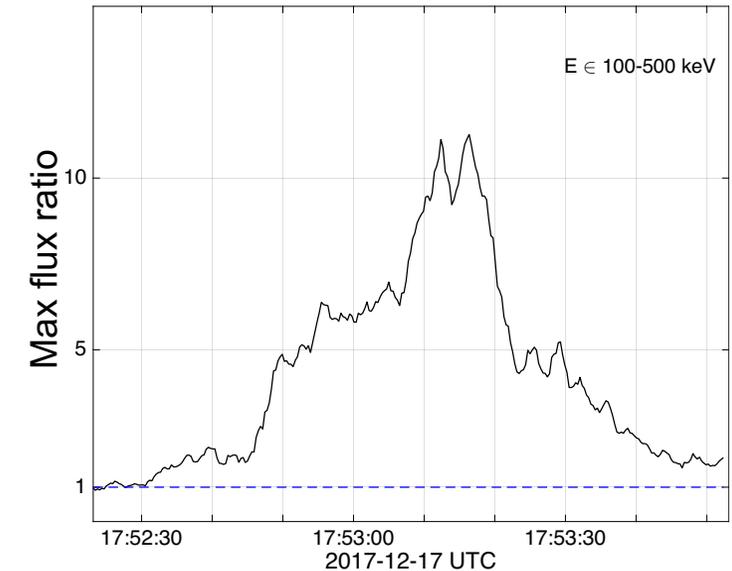
“Seeding”

Seed from CH plasma (1-5 keV)



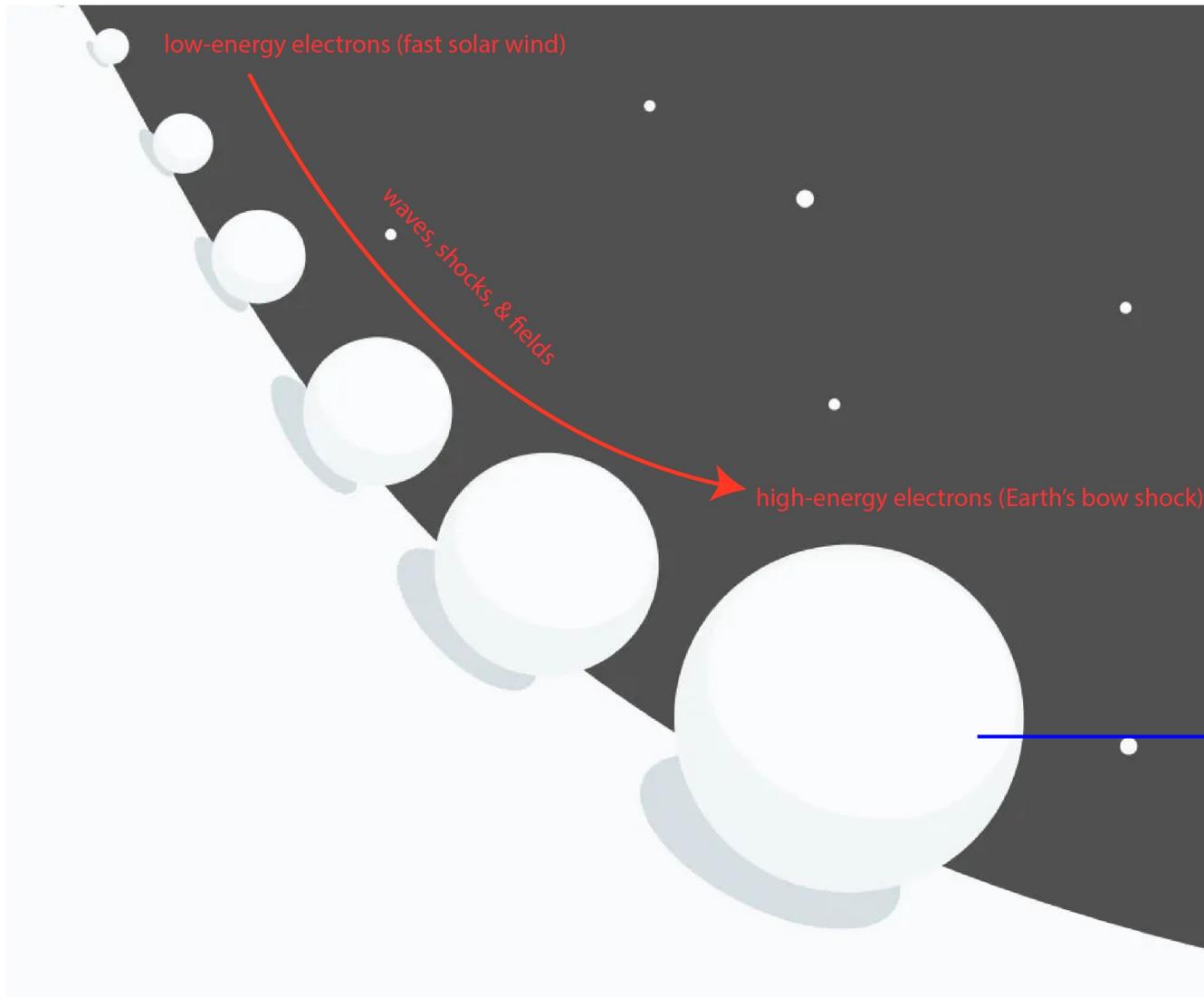
Note: Other framework is consistent with all other studies (e.g., Wilson+2016, Liu+2019, Shi+2025)

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



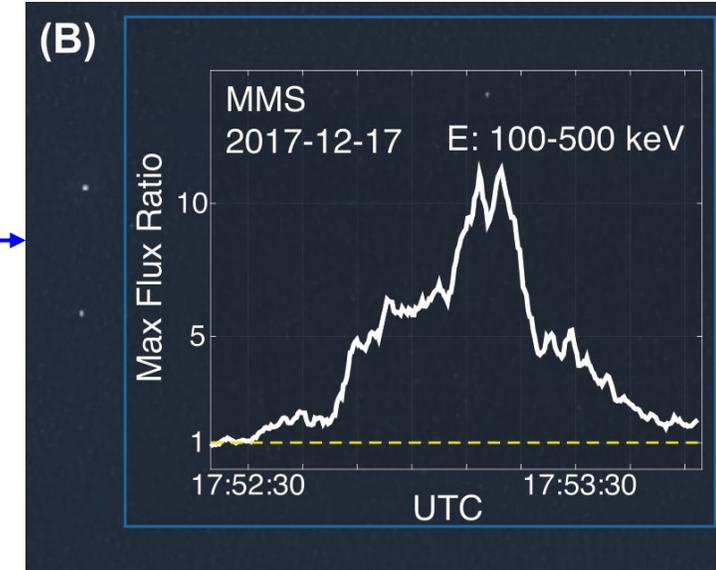
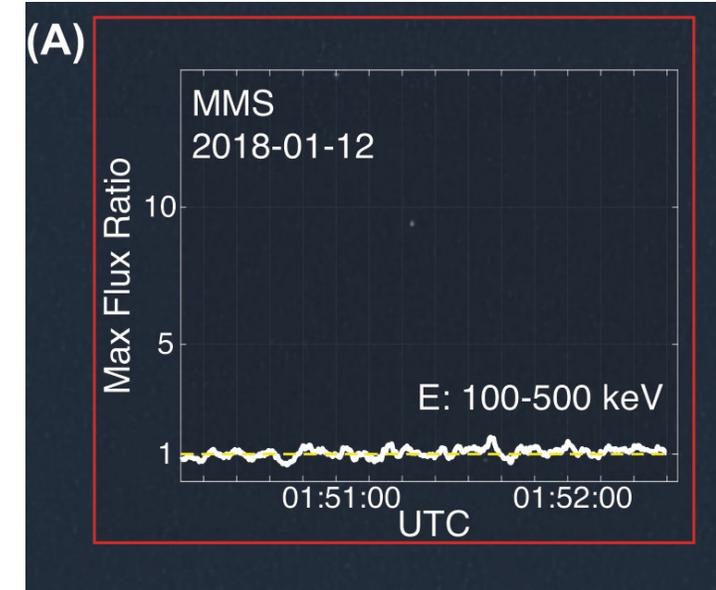
Key-point:
Seed + Foreshock's Shock + Waves + Efficiency factors = ~MeV electrons before reaching the bow shock.

Simple Simplistic Picture to remember



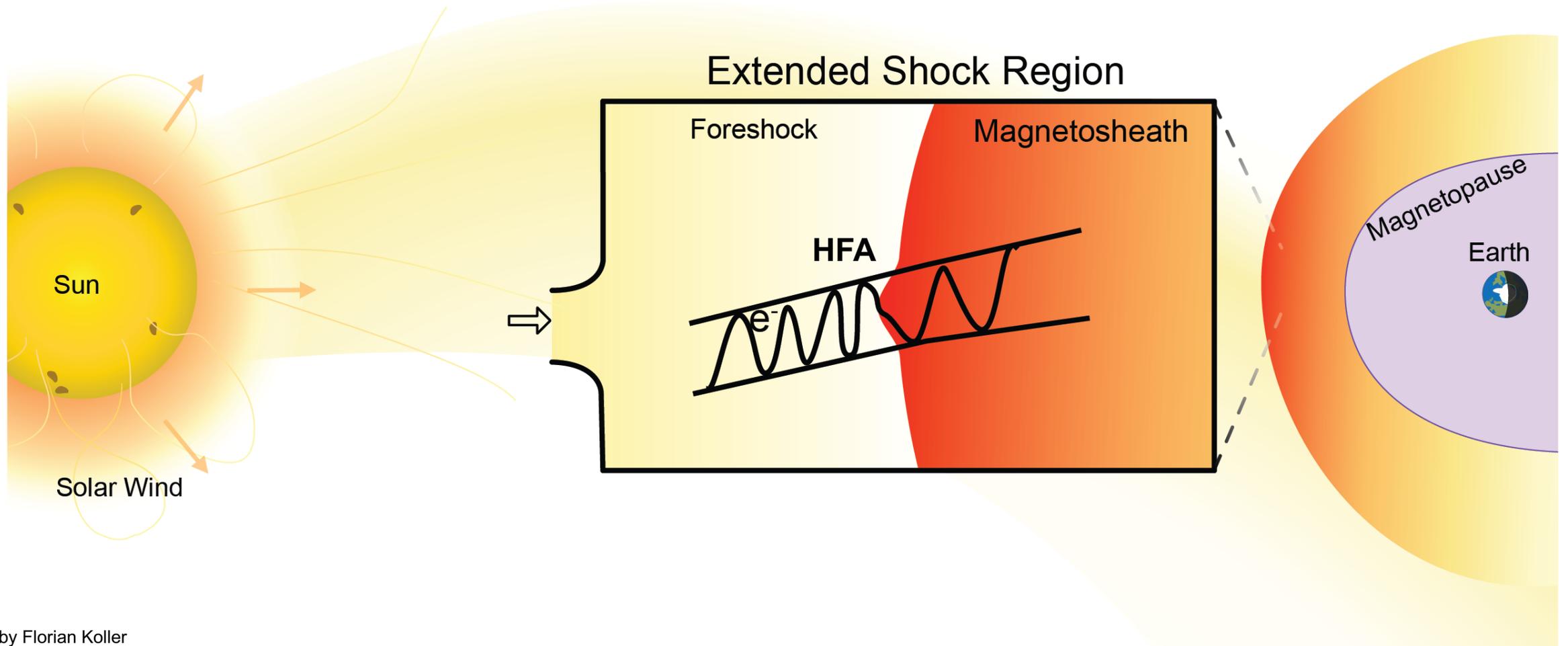
✗

✓



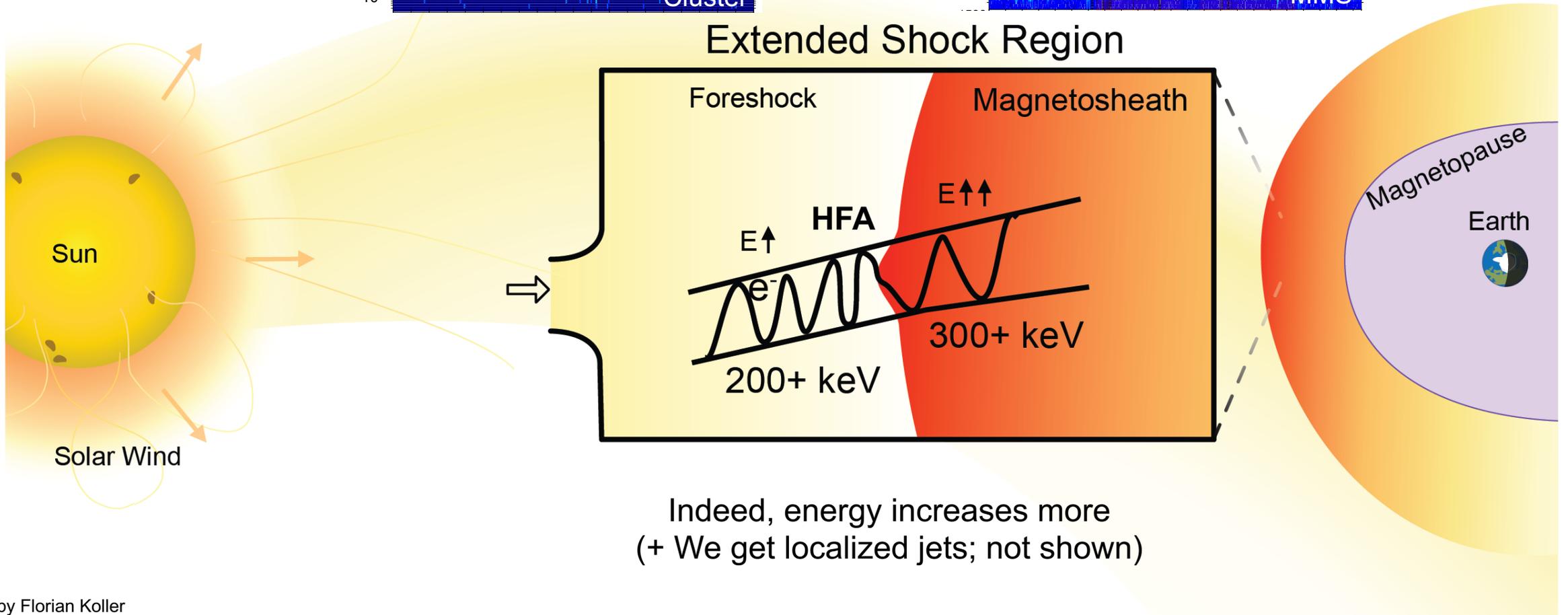
But let's ask one more question

What do we expect to see when these transient appear downstream?

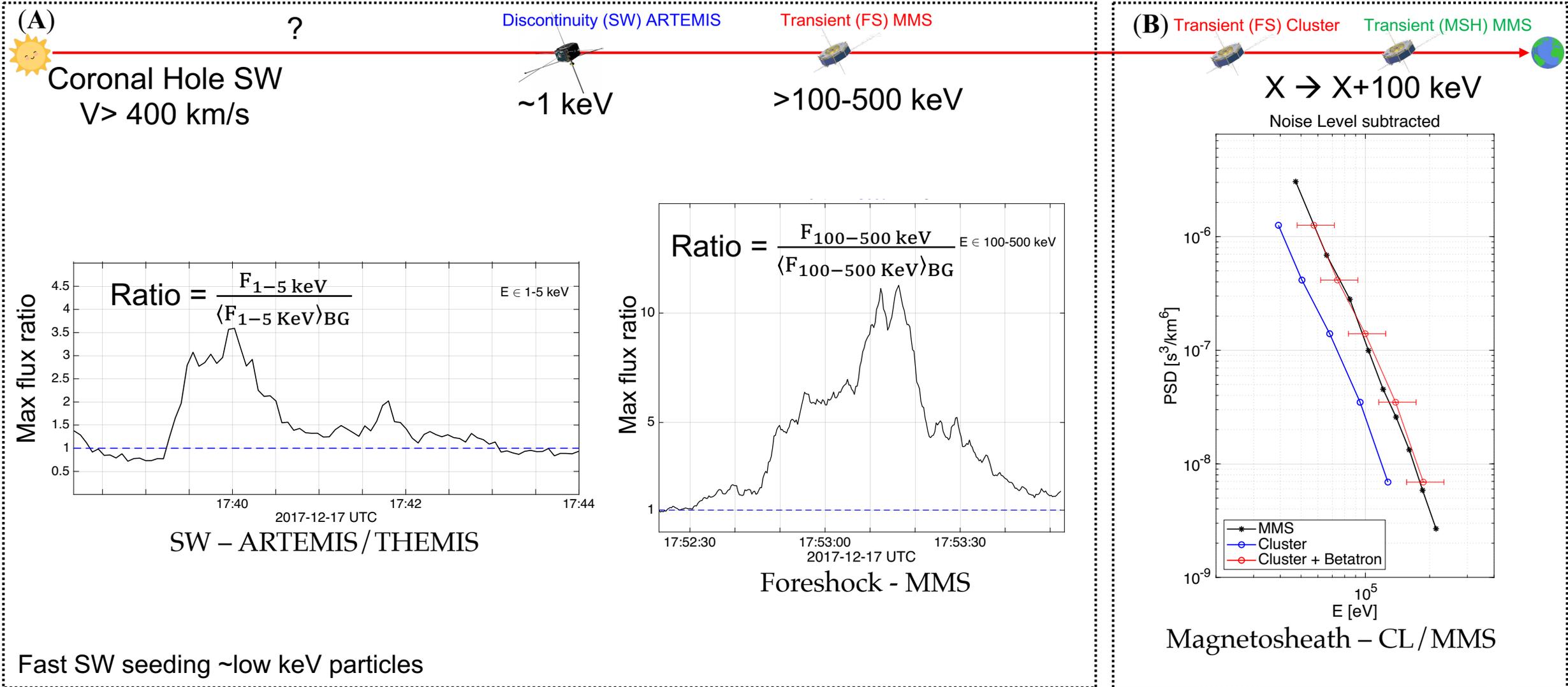


But let's ask one more question

What do we expect to see when these transient appear downstream?



Reinforced Shock Acceleration: From Sun to Earth

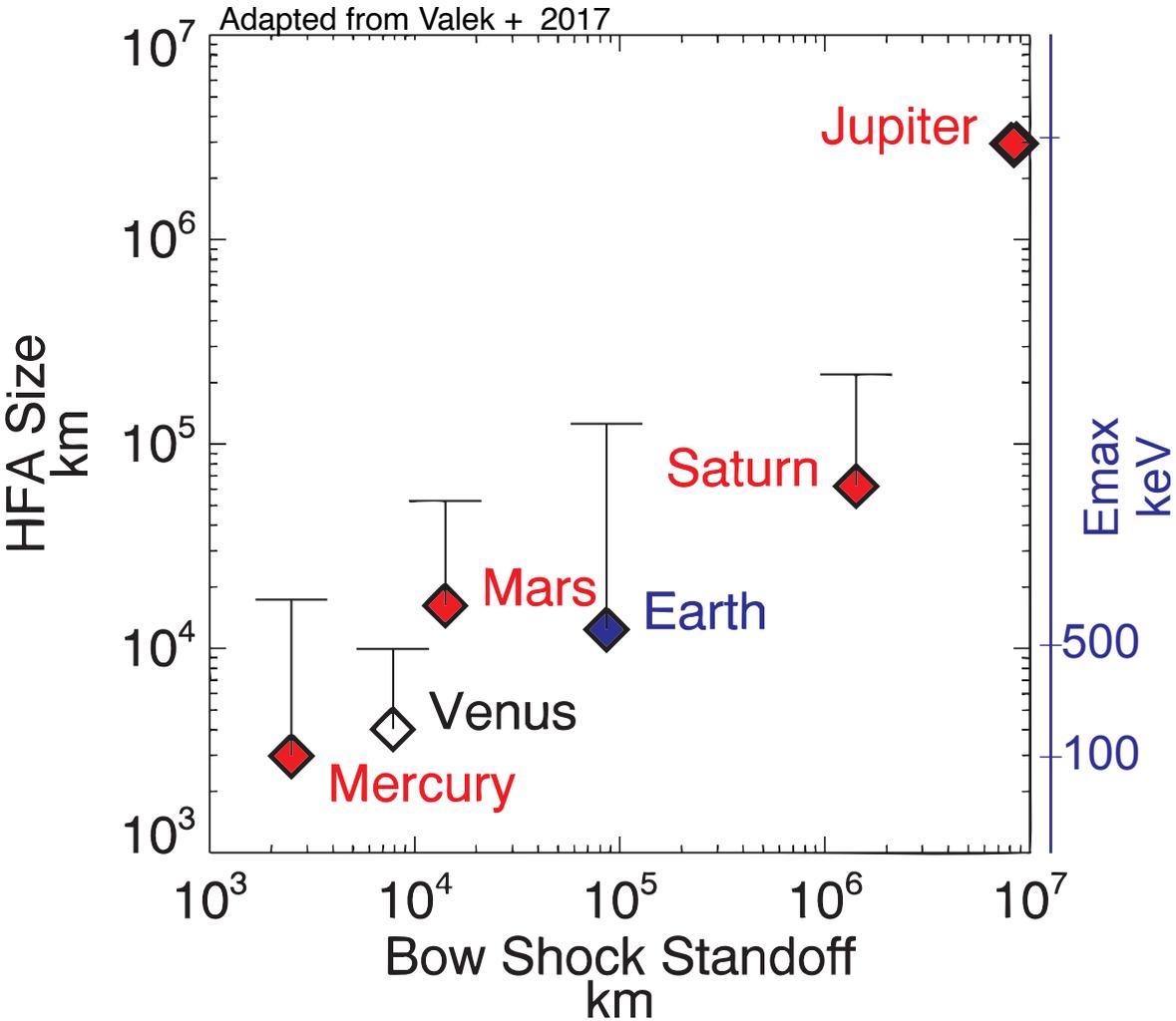


(A) : Raptis+ 2025 (NatComm) - *Revealing an Unexpectedly Low Electron Injection Threshold via Reinforced Shock Acceleration*

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

Very fresh results!

Electron Acceleration in other planets



In environments of $\Delta B \sim B$, diffusion scales can be estimated by Bohm's diffusion (Caprioli & Spitkovsky 2014).

Using the maximum energy we had (**event #1**) we obtained:

$$L \sim 10 - 100R_e \sim 5 \times 10^{4-5} [\text{km}]$$

If we **move to another planetary system**, we can take some typical size for foreshock transients to be for **Jupiter**:

$$L \sim 100 - 1000R_e \sim 5 \times 10^{5-6} [\text{km}]$$

This in turn, with a background magnetic field of $\sim 0.5 \text{ nT}$ gives:

$$E \sim 1 [\text{MeV}]$$

Juno Observations – Jovian Bow Shock Crossing

Foreshock Transient (HFA):

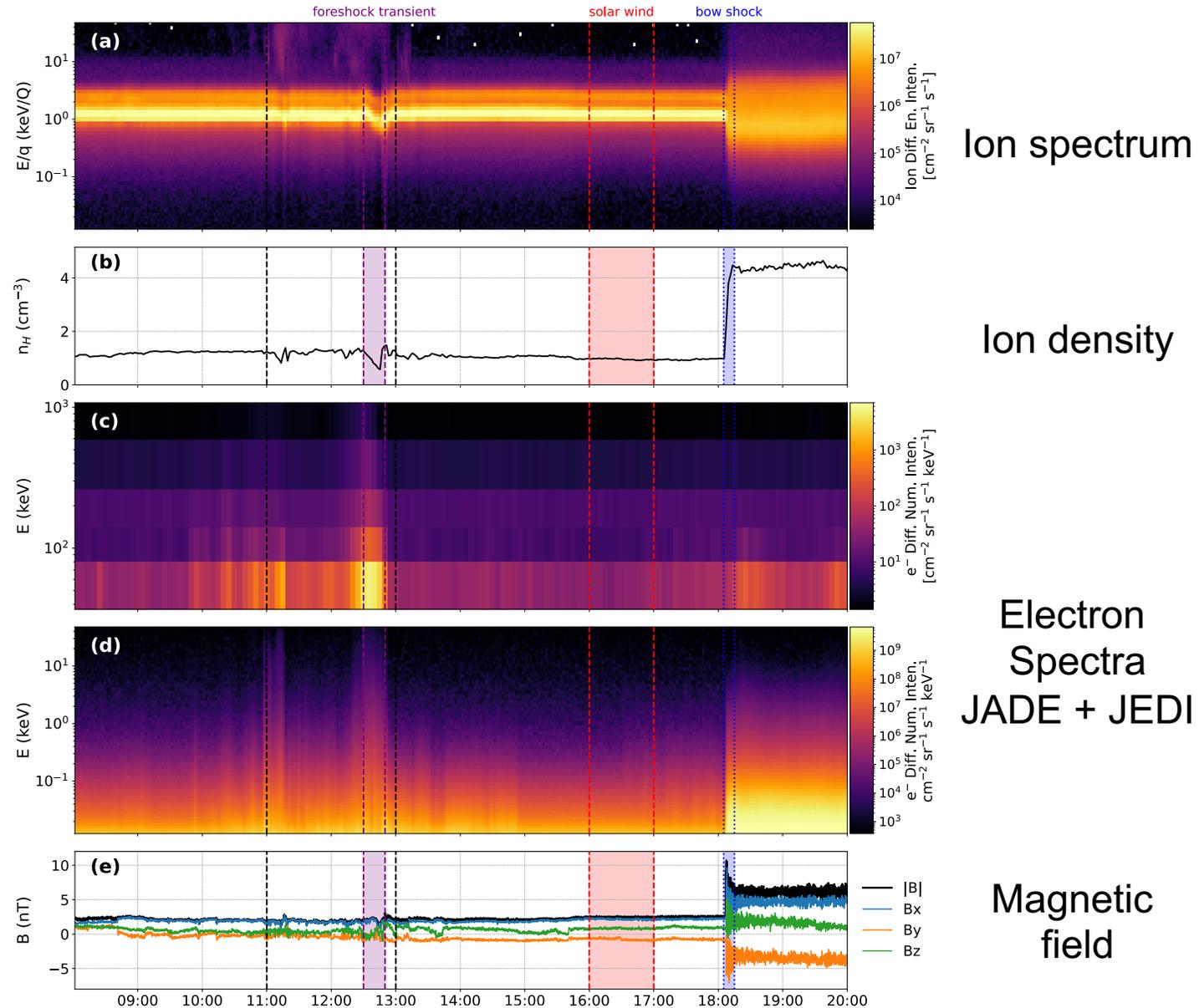
- High energy electrons **up to 1 MeV** (agreement with Raptis+2025a,b)
- Disrupted solar wind beam
- Localized depletion of n and B

Solar wind (SW):

- Typical SW: $\sim 1\text{-}2/\text{cc}$, 2.5 nT
- No energetic electrons

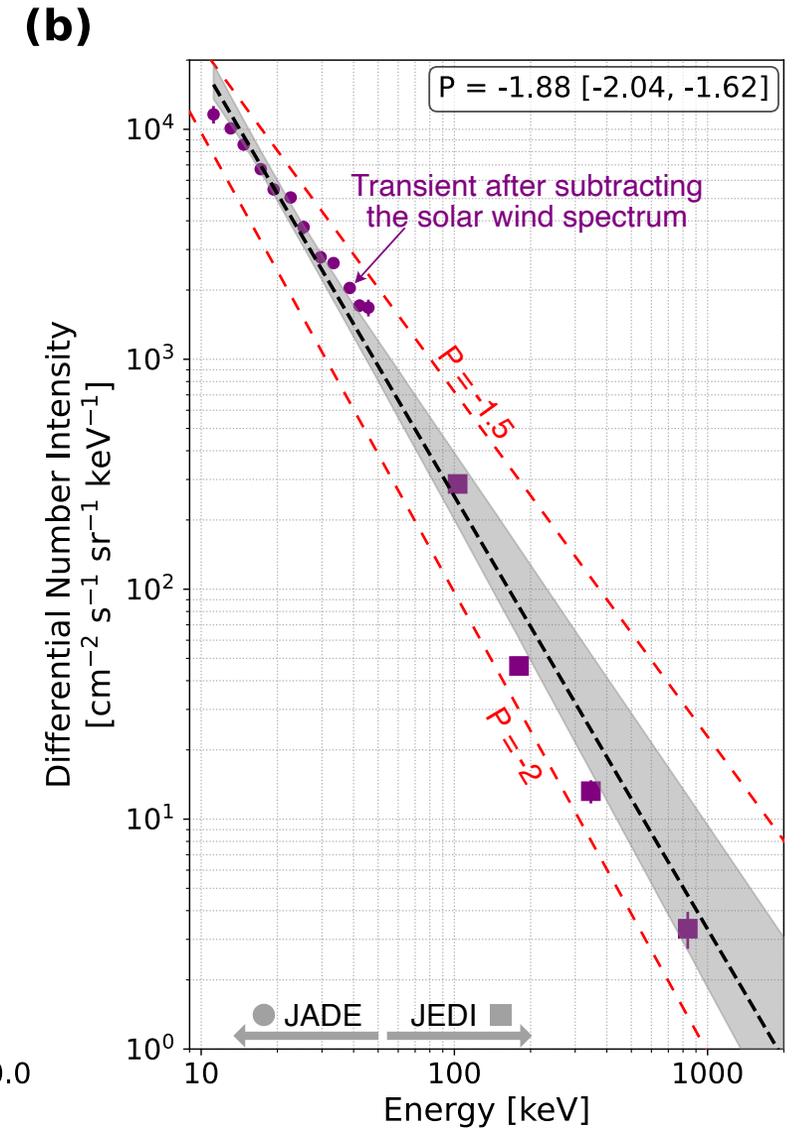
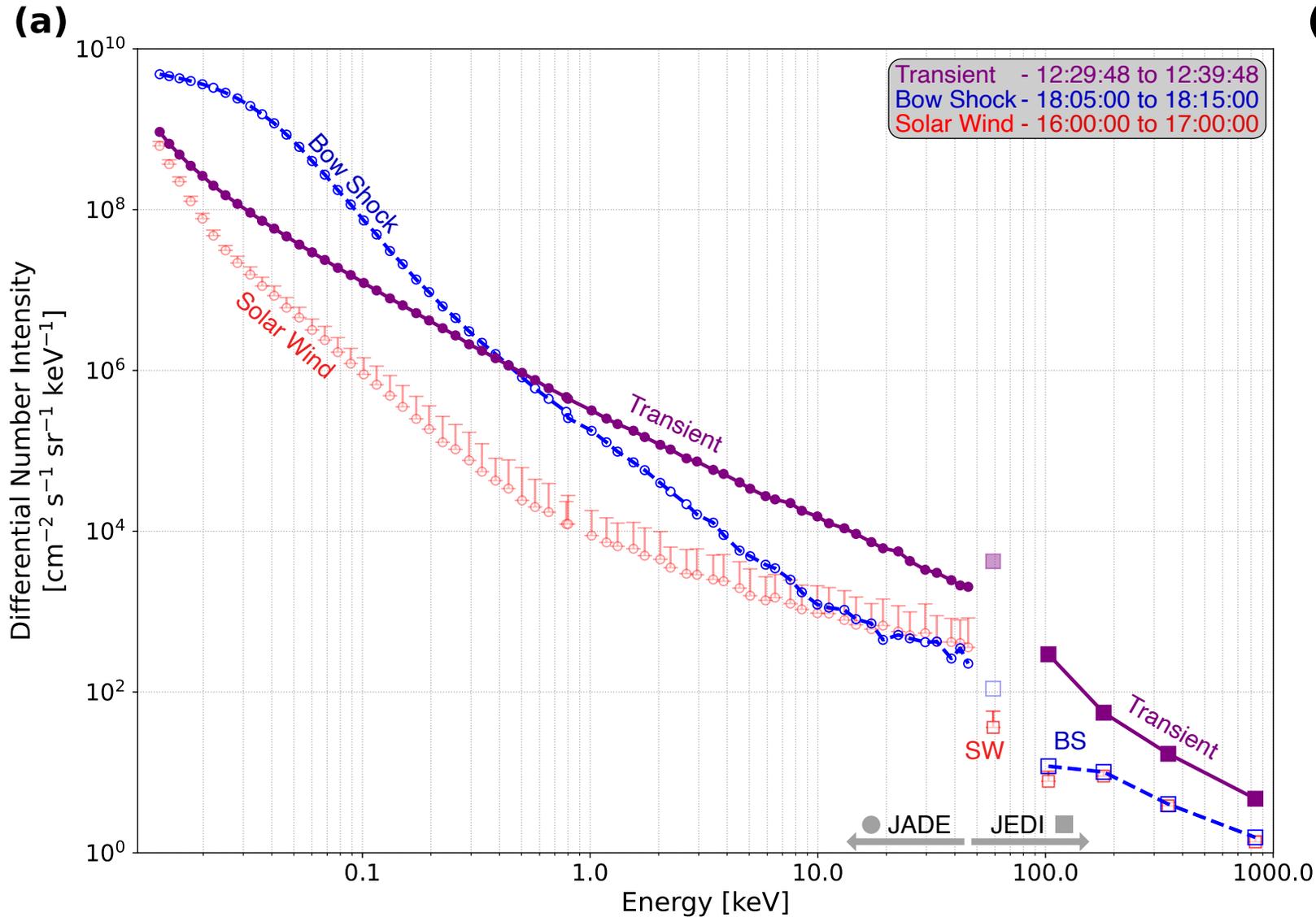
Bow shock (BS):

- Typical compression of ~ 2 for B and n
- suprathermal electrons present but minimal energetic electrons **only up to 10ish KeV**



Reinforced Shock Acceleration at Jupiter

DSA (rel) ~ 2
 DSA (non-rel) ~ 1.5



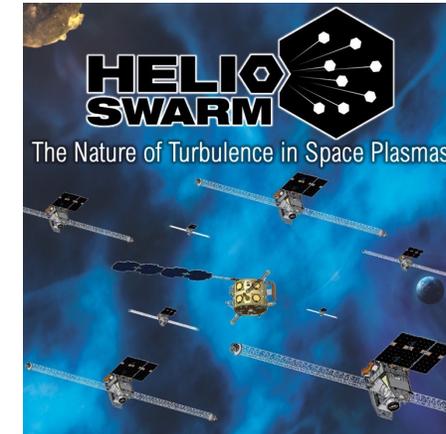
This “DSA-like” acceleration happens at the transient, bow shock only up to <10 keV

Concluding Words

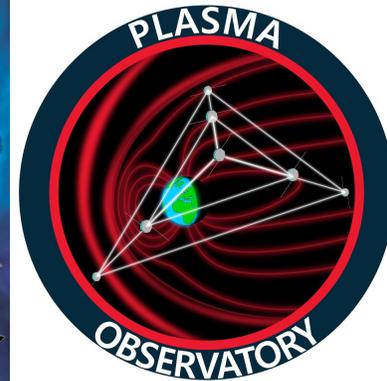
Foreshock Transients at Quasi-Parallel shocks are amazing! Relativistic particles, localized compressive edges/shocks on multiple temporal and spatial scales, forming high-speed jets, all interacting with each other.

Recent results:

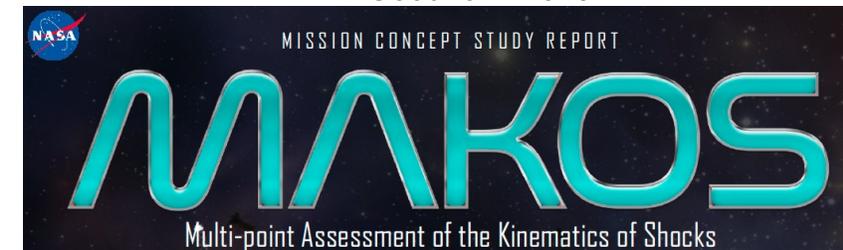
- ❖ **Seeding and Max Energy:** Identified a systematic suprathermal seeding ($\sim 1\text{--}5$ keV) intrinsic to fast solar wind. Localized transients act as the primary driver to boost these electrons to high energies (100s of keV). (Raptis et al., 2025a)
- ❖ **A Two-Step Mechanism:** Particles get energized when larger transients (i.e., HFAs/FBs) cross the bow shock. For energetic particles, additional acceleration can be modeled by adiabatic compression (betatron) and strong scattering. (Raptis et al., 2025b)
- ❖ **Broader Implications:** We expanded this model to test its universality at other planetary boundaries (e.g., Jupiter – 1 MeV electrons) and fundamental astrophysical shocks. This model predicts up to 100 TeV particles in in supernova shocks (e.g., SN 1006) in agreement with cosmic ray observations. (Raptis et al., 2026, under review)



Retino+ 2021 | Ex. Astro.



Goodrich+ 2023

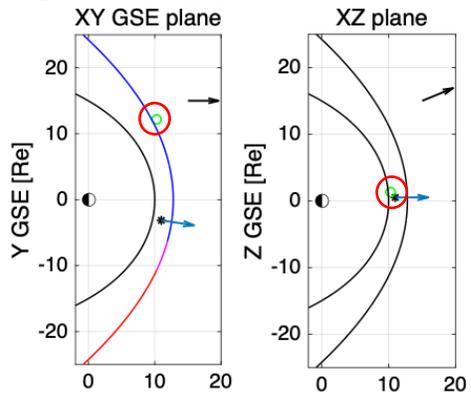


GEM FG: (MDT) Multiscale Dayside Transients and their Effect on Earth's Magnetosphere (2025 – 2029)

Savvas Raptis, Ivan Vasko, Imogen Gingell, Terry Z. Liu, Ying Zou, Runyi Liu, David Tonoian

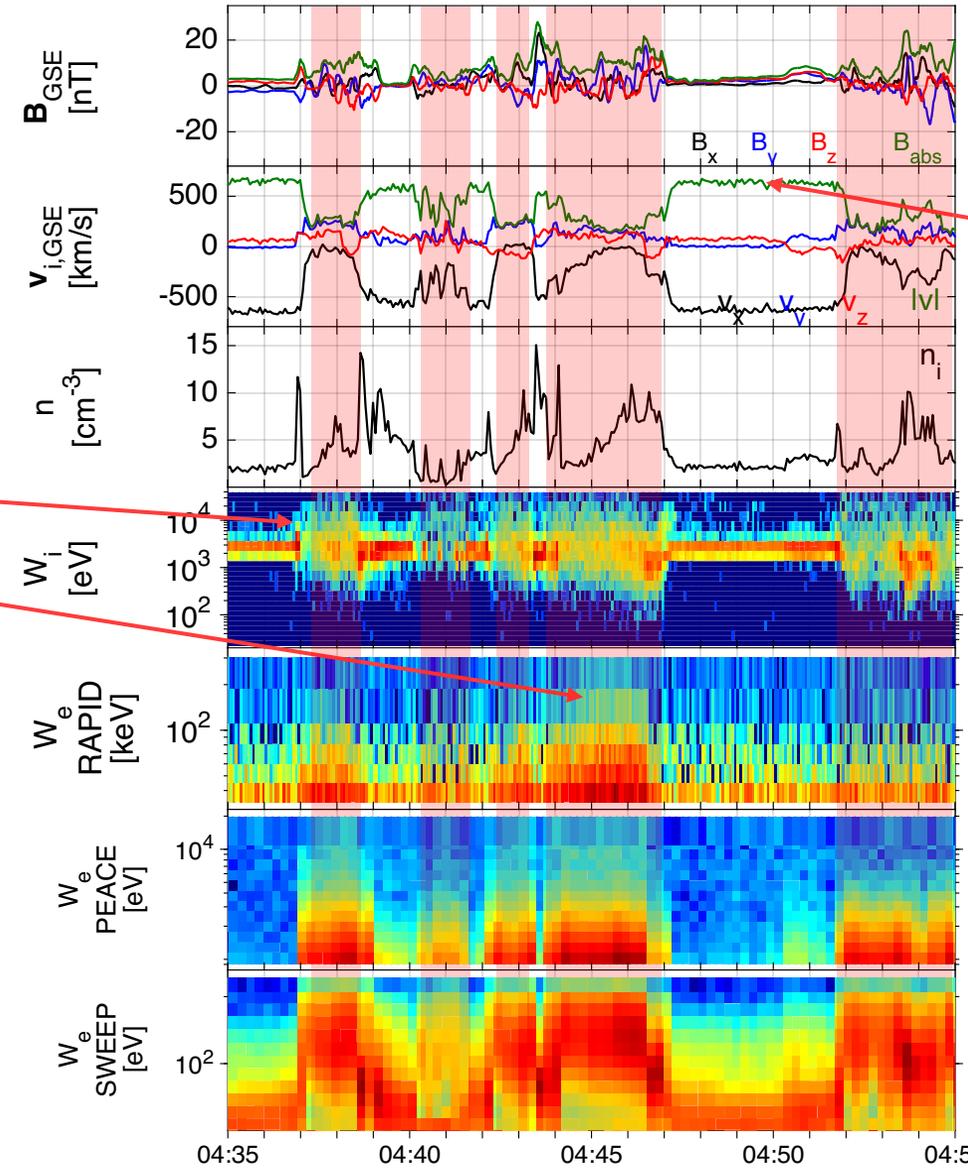
Appendix

2017-01-08T04:45:30



Cluster: Upstream showing HFAs

CL 4: X=10.27 R_E, Y=12.25 R_E, Z=-0.45R_E



- Hot Flow Anomalies
- Disturbed SW beam
- ~200 keV electrons

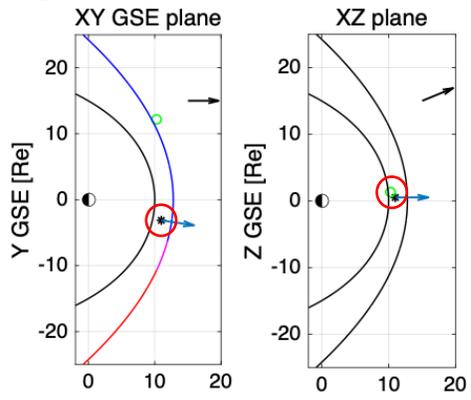
700 km/s Solar Wind!

Fast coronal hole plasma consistent with our previous work ✓

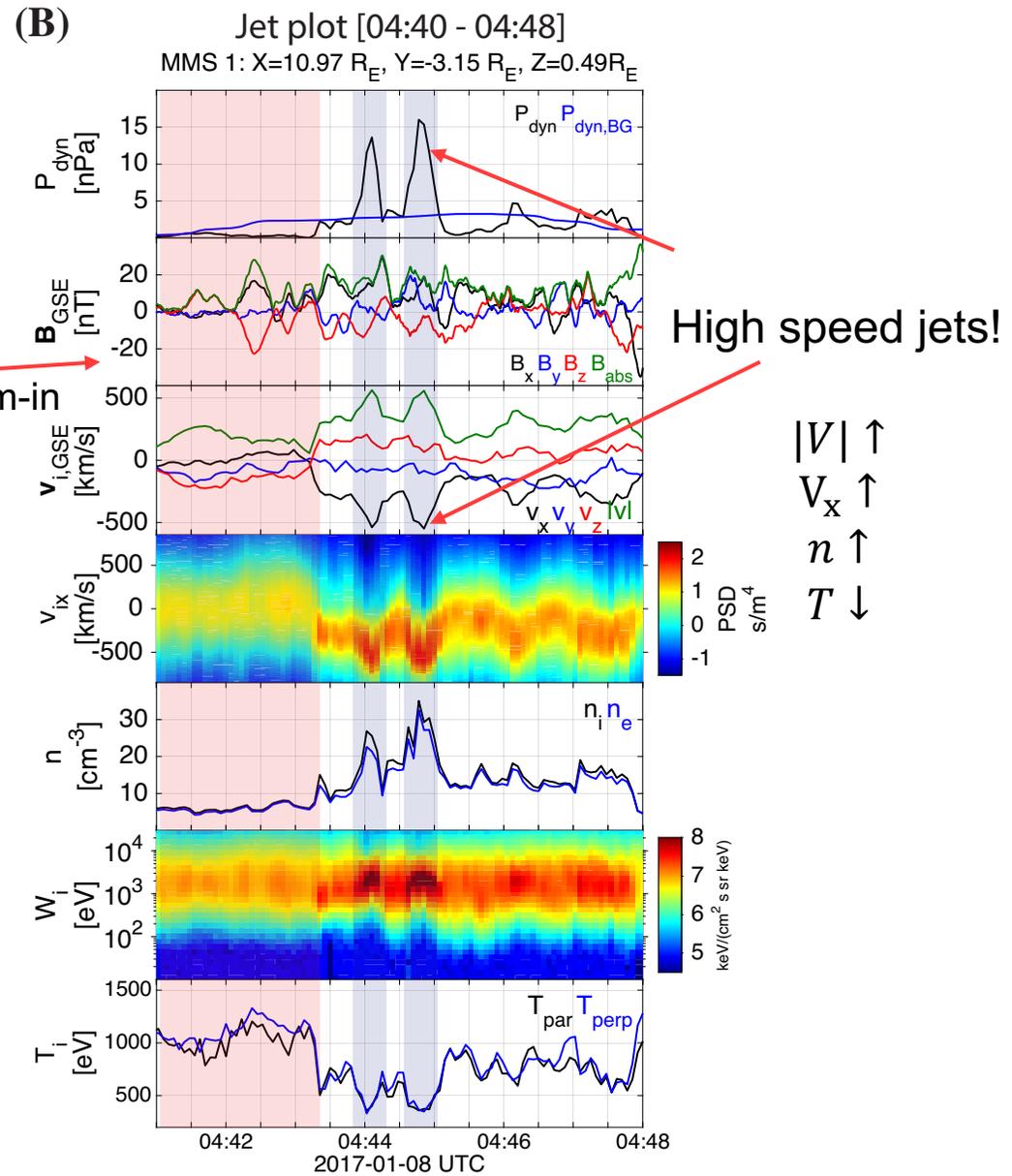
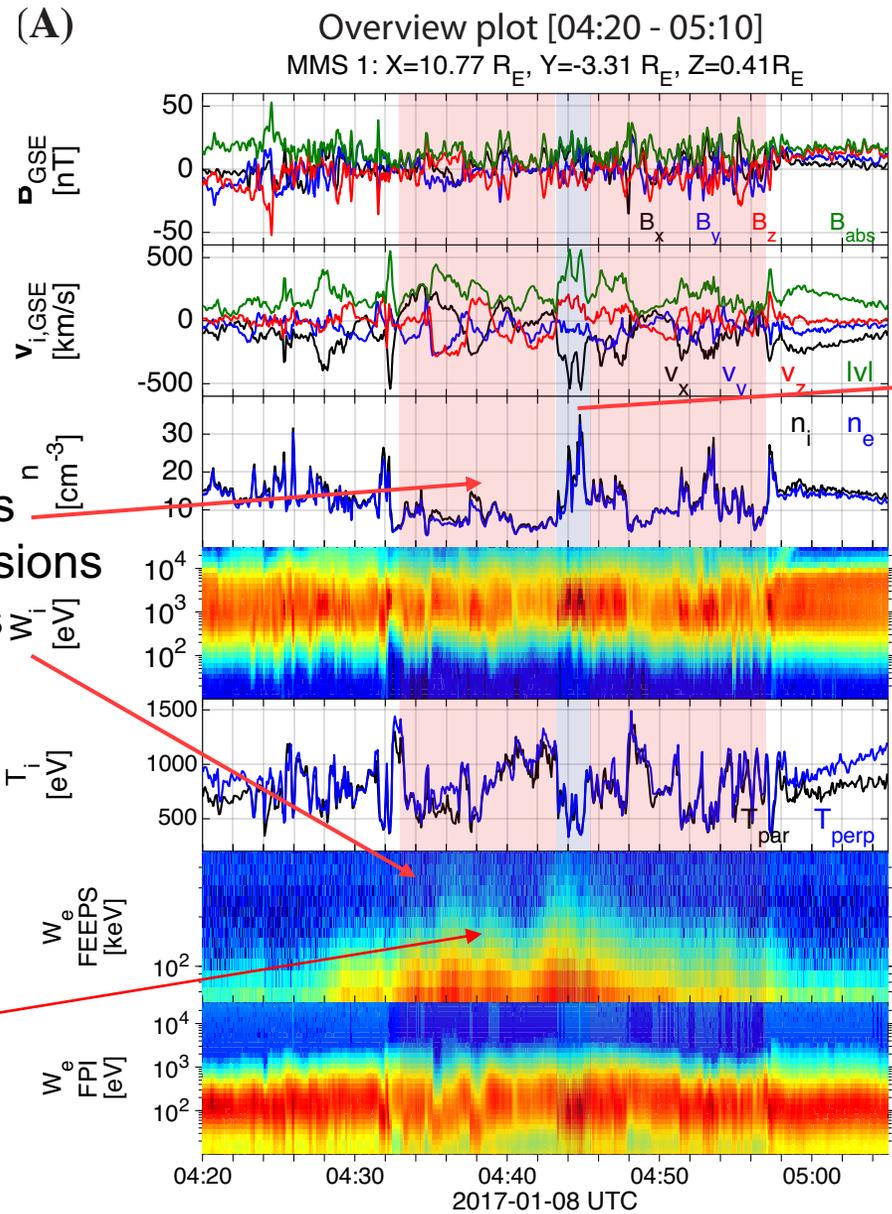
Typical properties:

- Compressive edges ✓
- Flow anomaly ✓
- Hot core ✓
- Particle energization ✓

2017-01-08T04:45:30



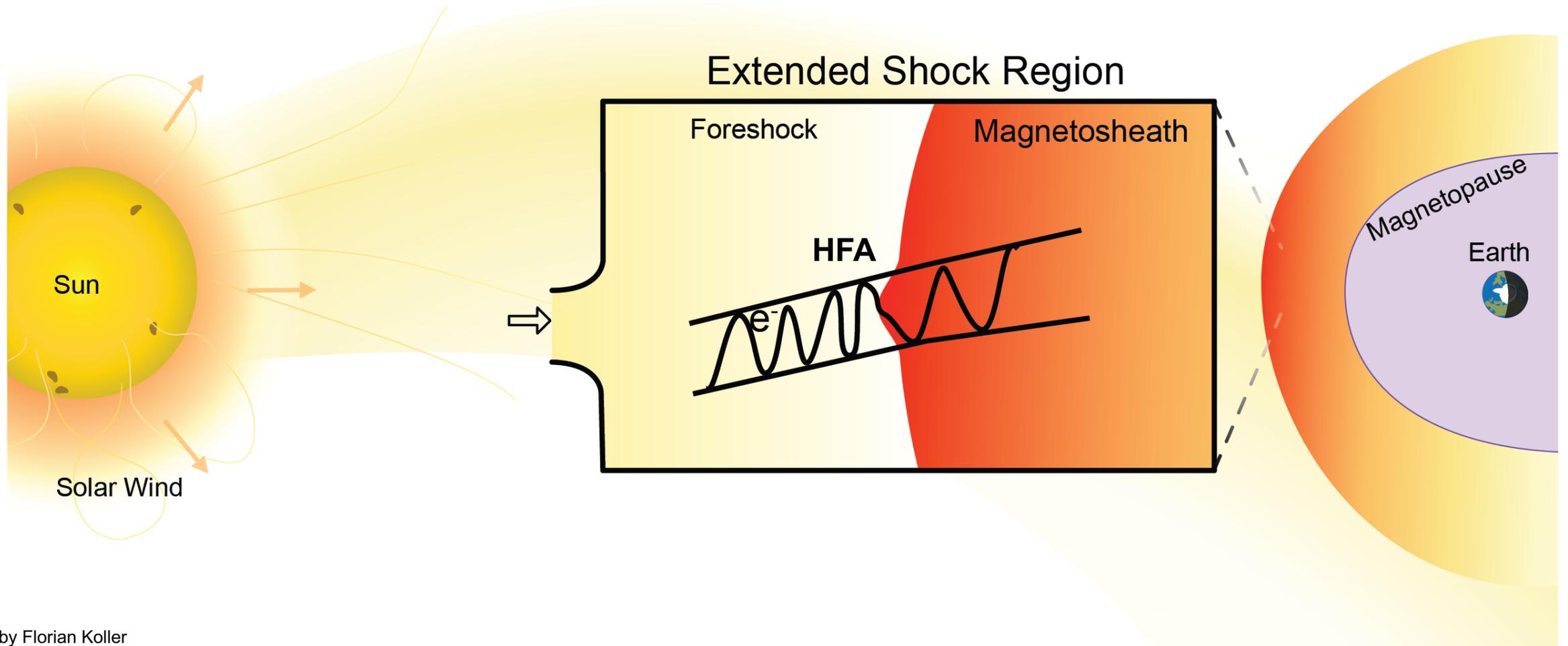
MMS: Downstream HFAs and jets



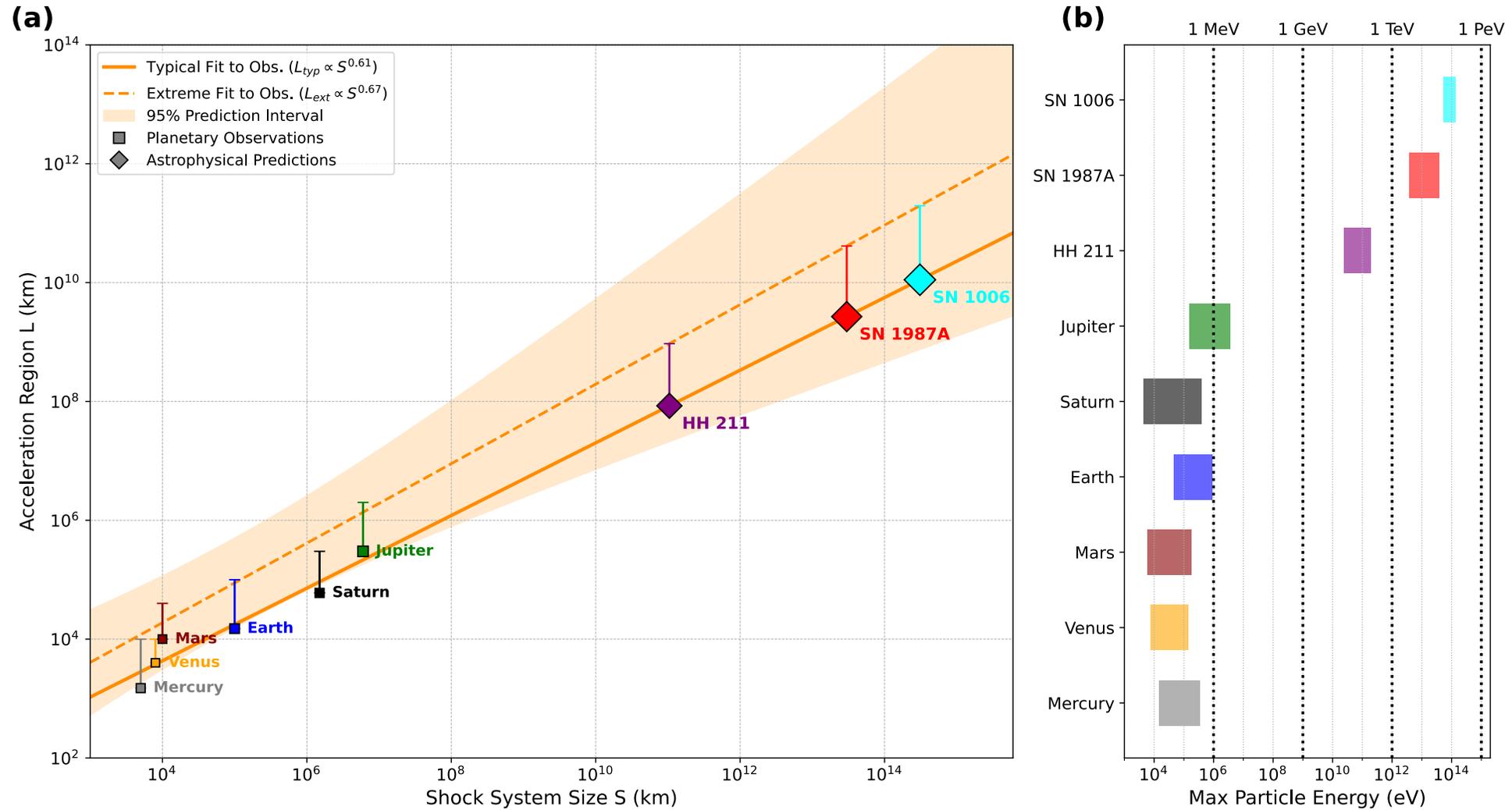
- Hot Flow Anomalies
- Localized compressions
- ~300 keV electrons
- 20+min interval

But let's ask one more question

What do we expect to see when these transient appear downstream?



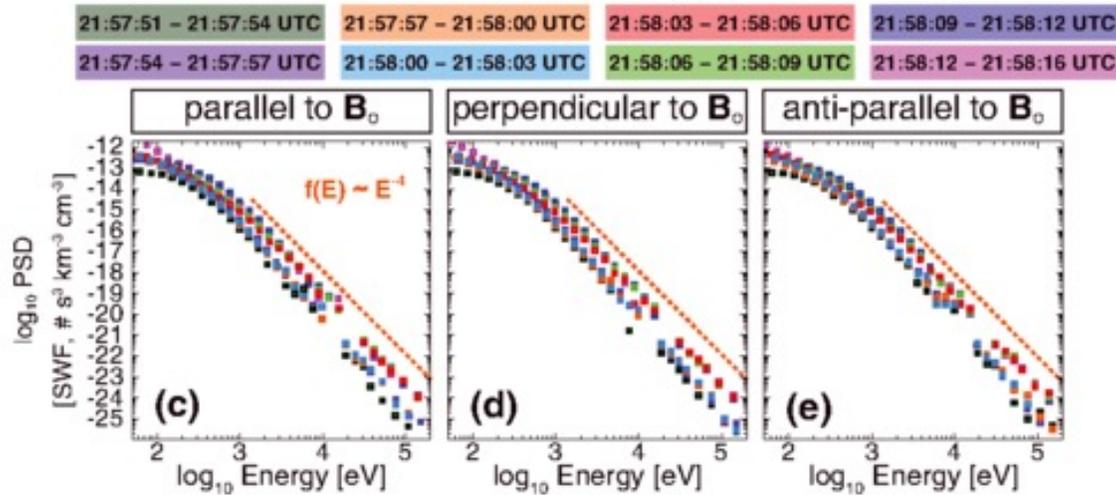
Adapted Hillas Limit to Transient Structures



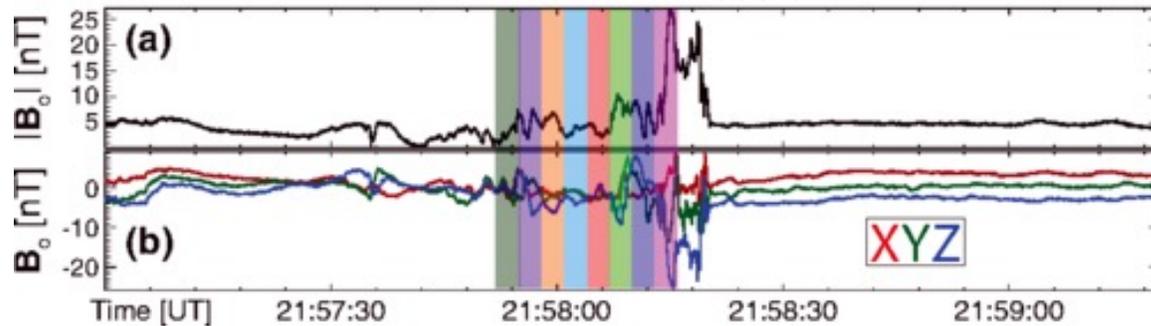
Foreshock Transients & Electron acceleration

See also: Turner et al. 2018; Liu et al. 2019; Shi et al. 2023,2025 ; Tonoian et al. 2023; Kamaletdinov et al. 2024; Li et al. 2025; Oka et al. 2025

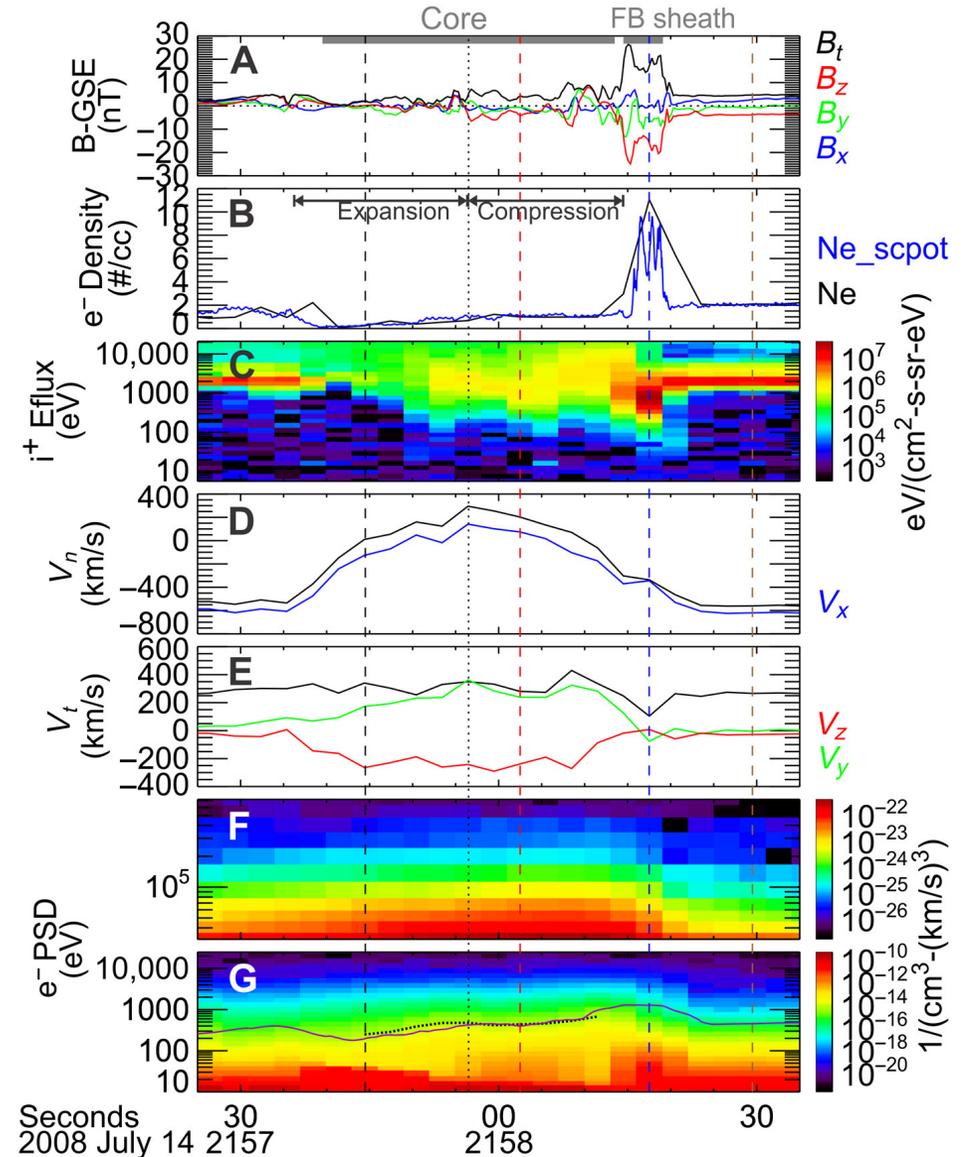
Combined low and high energy electron spectra



Foreshock Bubble on 2008-07-14



~300 KeV electrons



~200 KeV electrons

Liu T. et al. 2019 | Science Adv.

Transients with most notable impact

How many: ~several per day!

How big: up to ~10s of Re

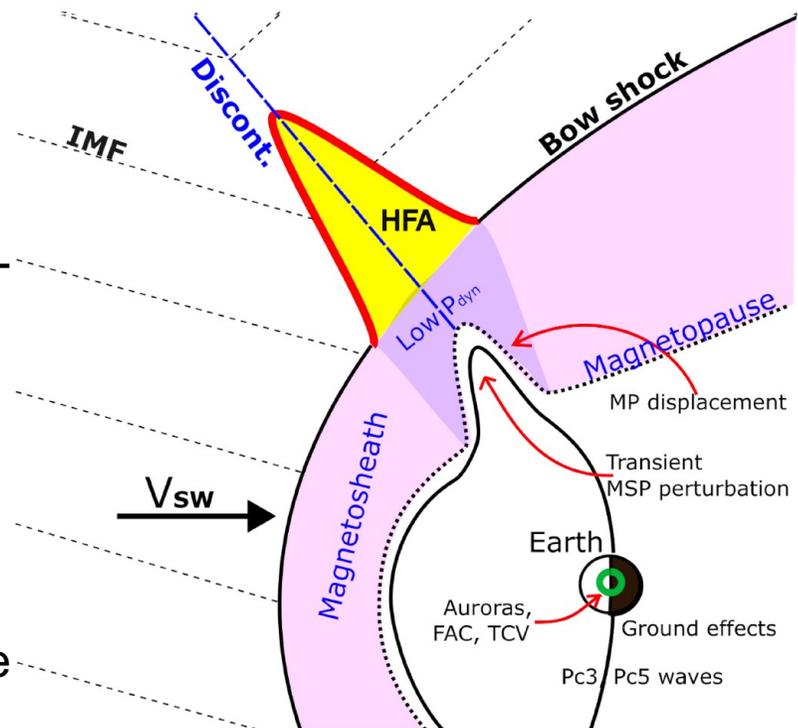
HFAs

Discontinuities intersects BS and E ($-V \times B$) points towards the sheet, ions pile up and thermalized

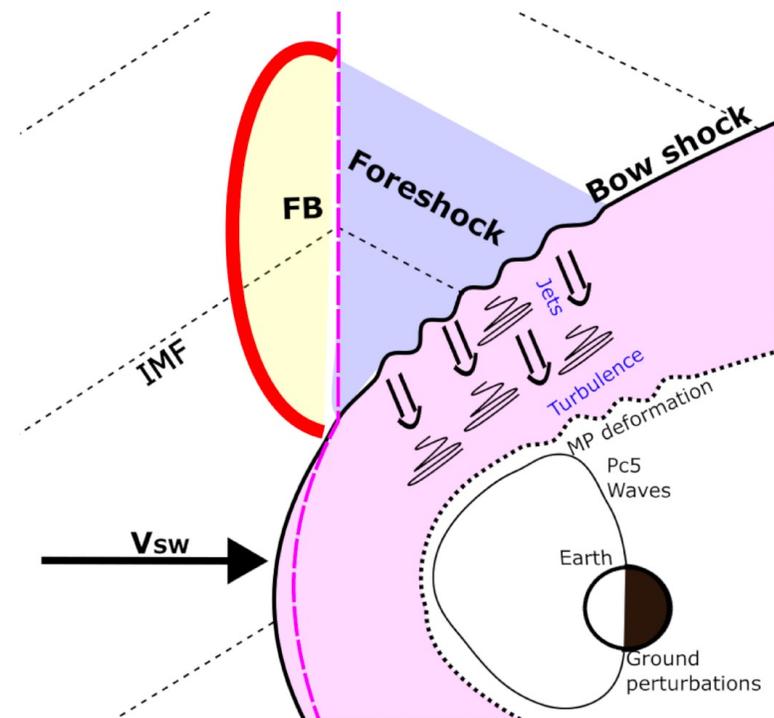
FBs

Discontinuity & foreshock backstream ions concentrate and create a bubble that expands into the SW

Zhang et al., (2022)



Hot Flow Anomalies (HFAs)



Foreshock Bubbles (FBs)

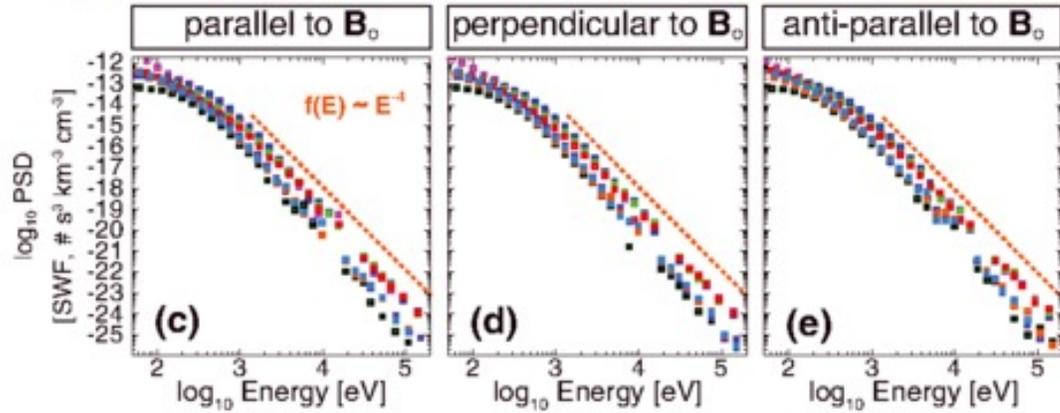
TUMS (Transient Upstream Mesoscale Structures)

Primož K. et al. (2024)

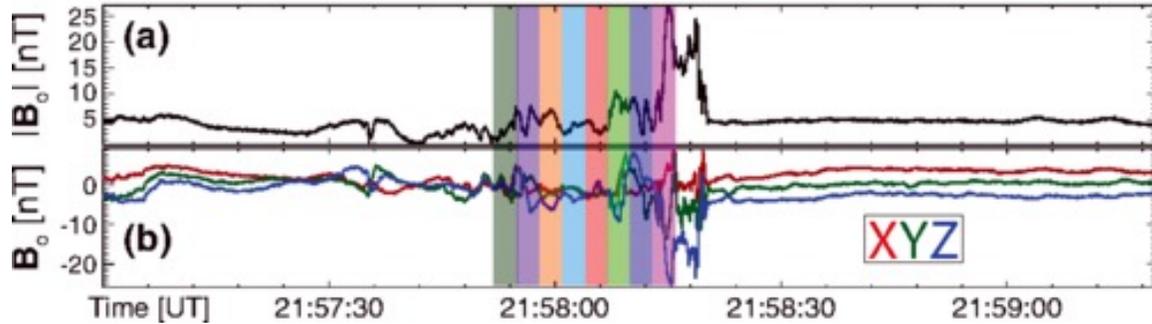
Foreshock Transients & Electron acceleration

See also: Turner et al. 2018; Liu et al. 2019; Shi et al. 2023,2025 ; Tonoian et al. 2023; Kamaletdinov et al. 2024; Li et al. 2025

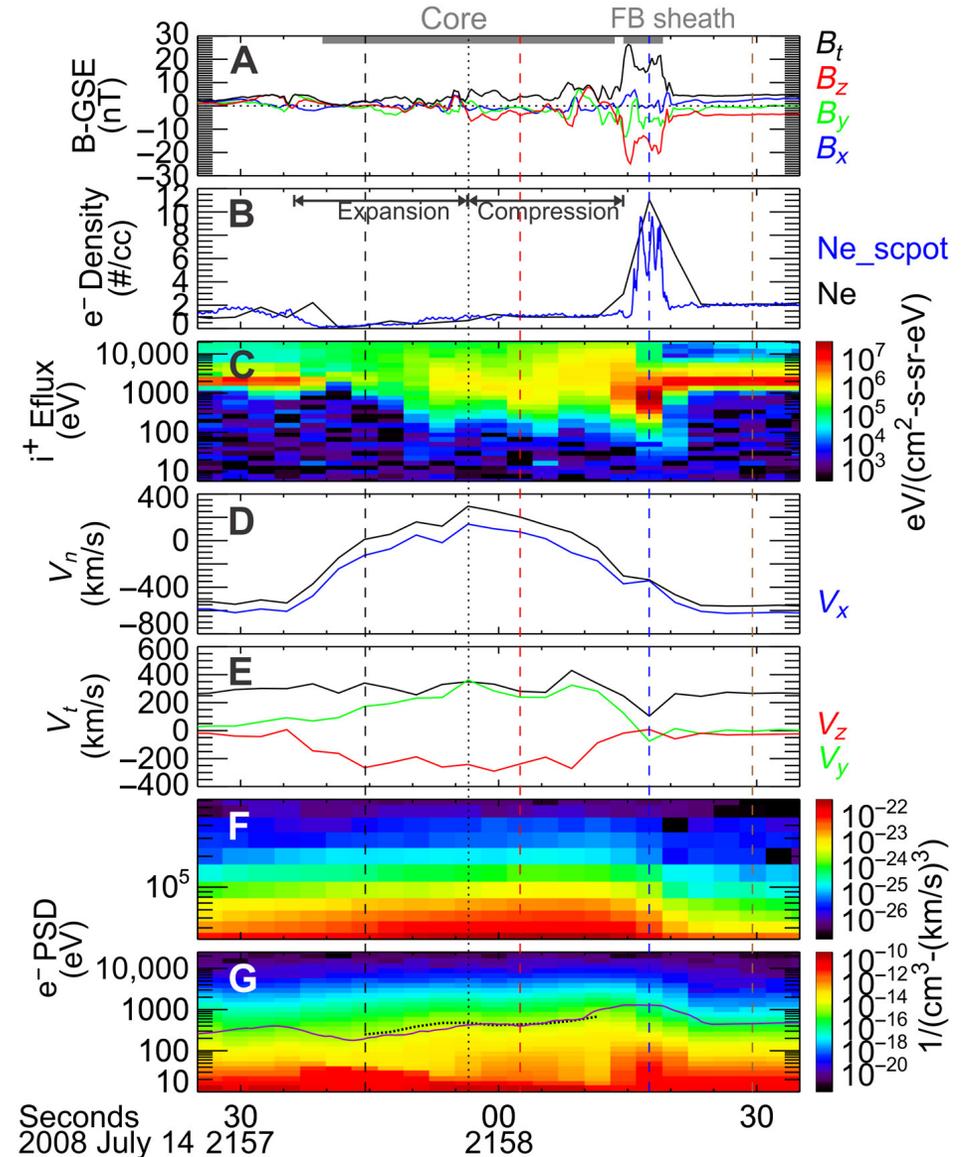
Combined low and high energy electron spectra



Foreshock Bubble on 2008-07-14



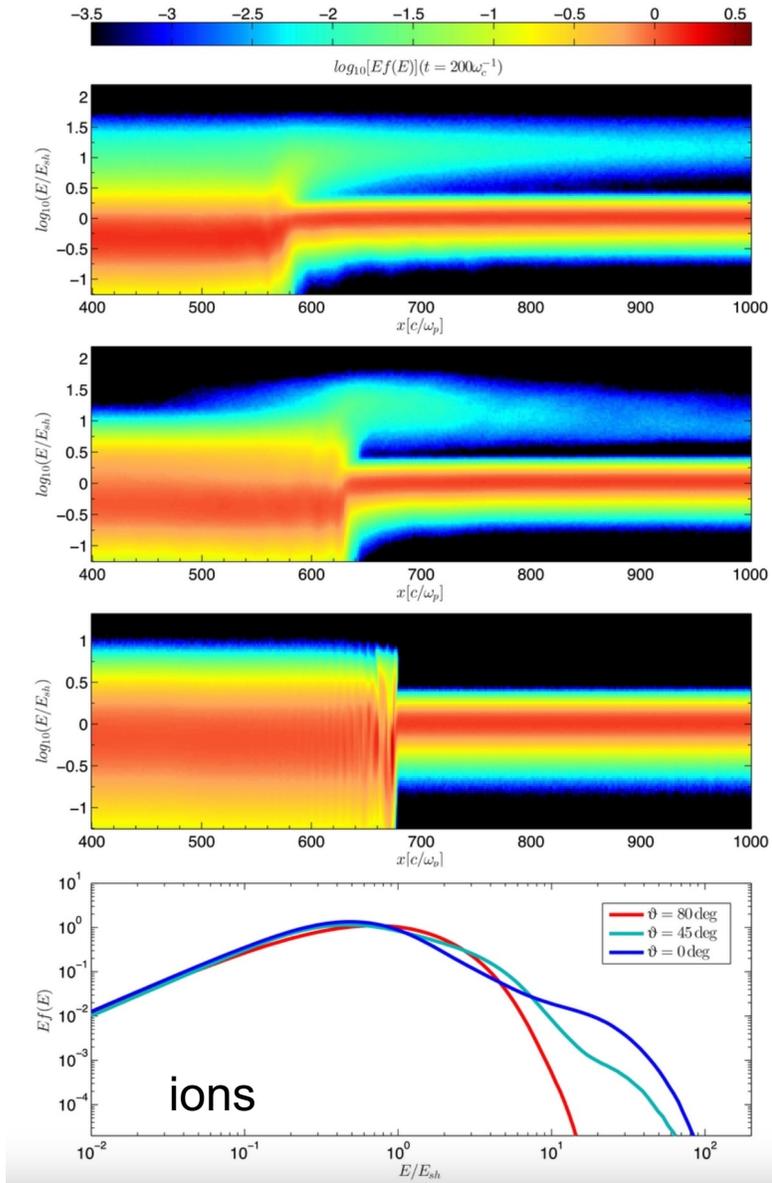
~300 KeV electrons



~200 KeV electrons

Liu T. et al. 2019 | Science Adv.

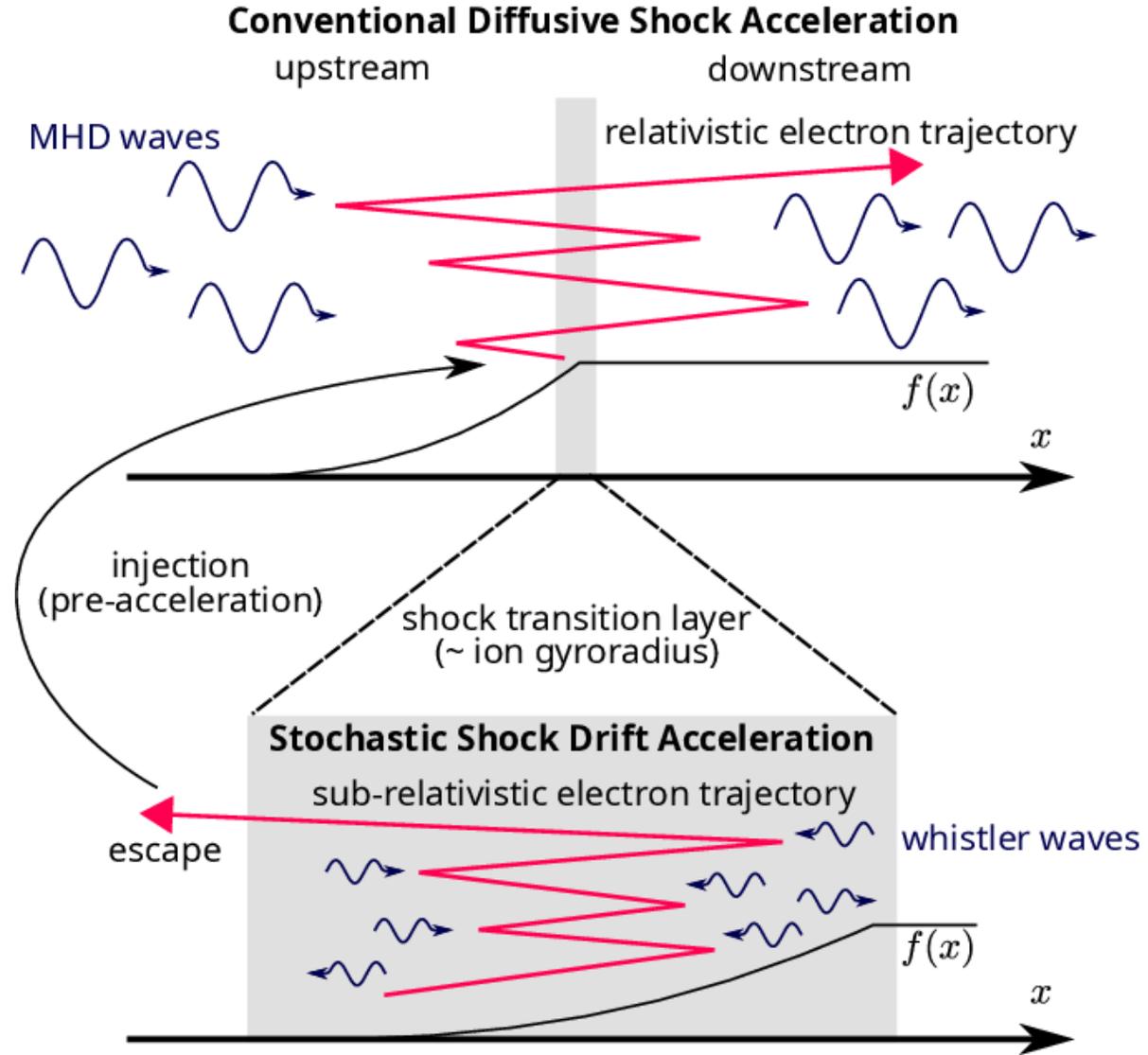
Acceleration at Qpar and Qperp shocks



Qpar shock (DSA)

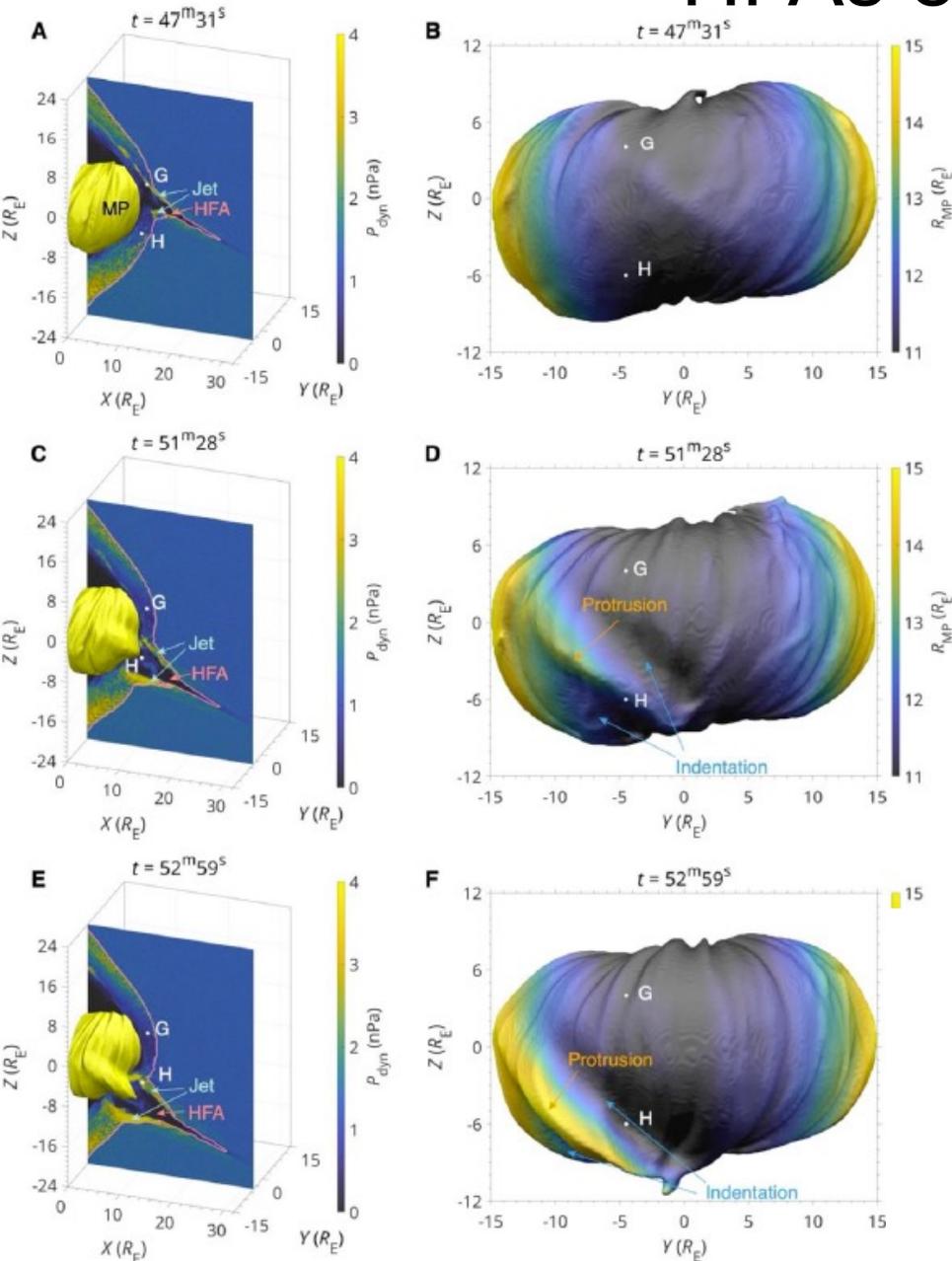
Oblique shock

Qperp shock (SDA/SSDA)



HFAs effect on Magnetosphere

See also: Shen+2018, Wang+2021, Yang+2023, Guo+ 2023, Xu+ 2024, Sibeck+2025

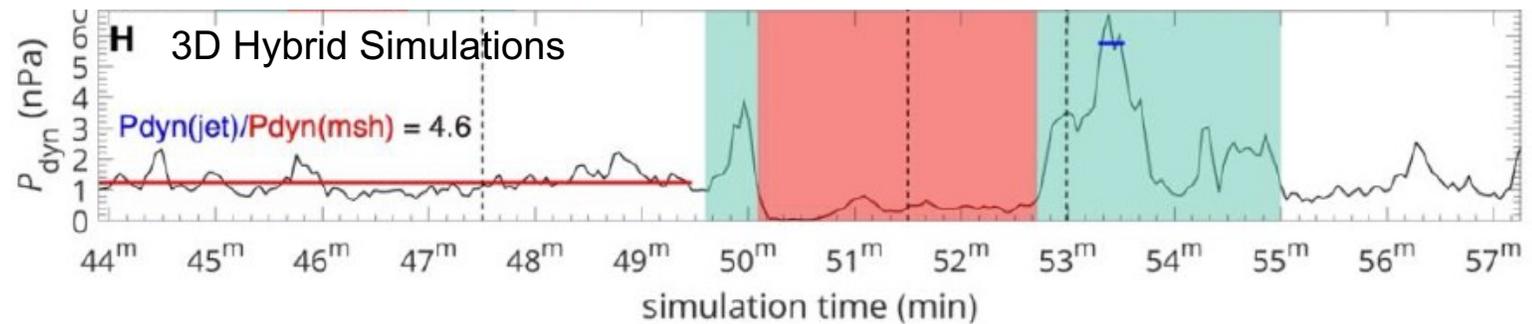
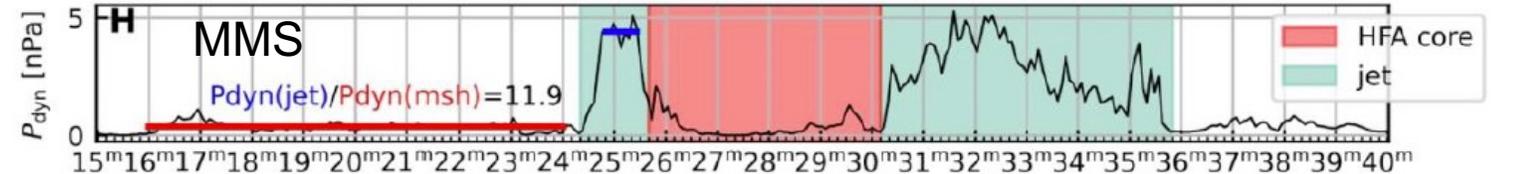


Localized dynamic enhancements (jets) at the edges
(stuff move inwards)

Core density depletion effects
(stuff move outwards)

Leads to magnetosheath restructuring

- Spatial extent: ~10s of Re
- Duration: ~10s of minutes



HFAs associated to jets (Archer+2014, Zhou+ 2023, Raptis+ 2025)

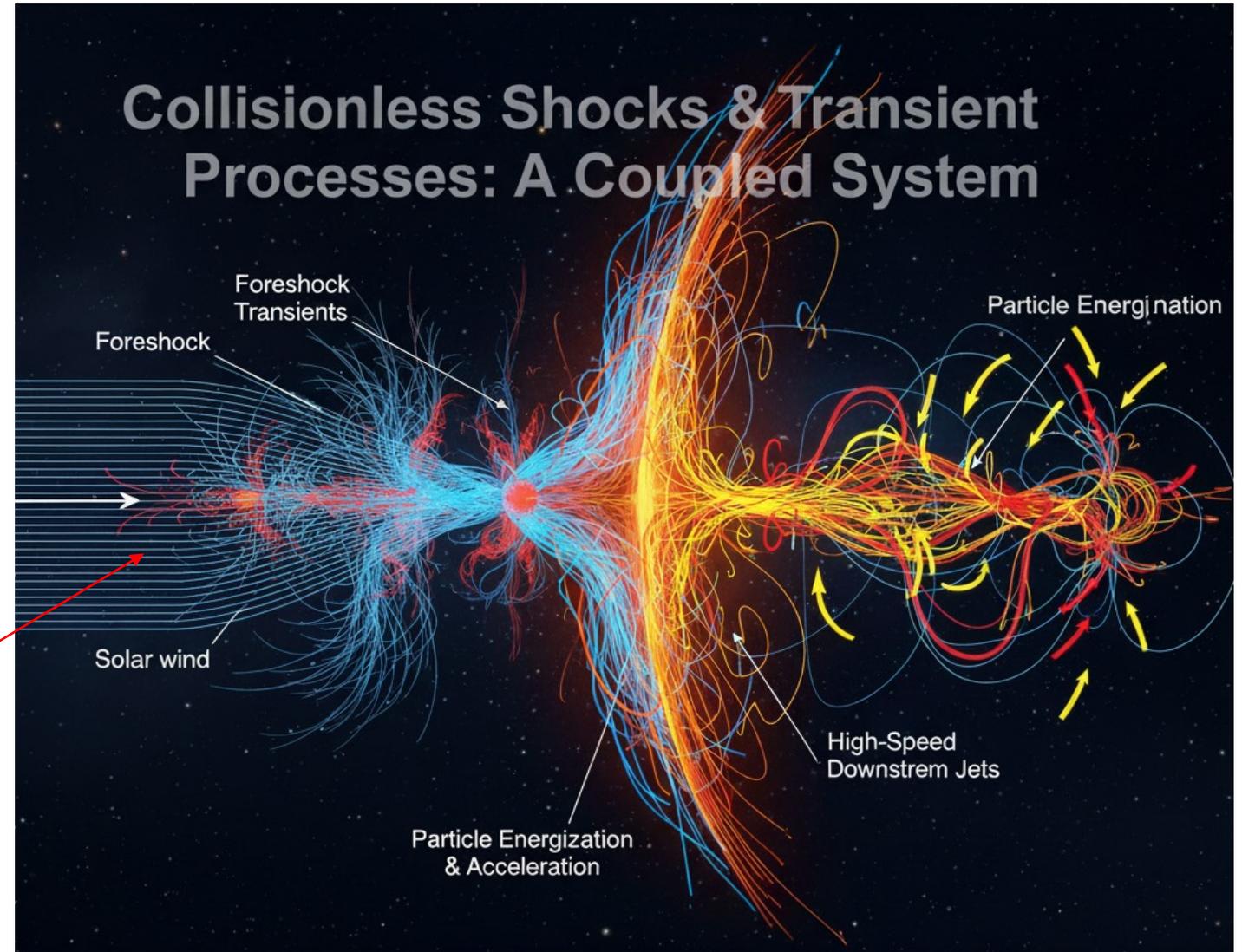
Zhou Y, et al., 2025 (Under Review)

Shocks and upstream/downstream environments

Studying transients as individual components can be problematic.

- **The bow shock decide** what the foreshock and magnetosheath are doing.
- Whether we see transients or not is also **controlled by the shock.**
- **Transients** both upstream and downstream **are connected**

Gemini trying to illustrate this.



Credits: Google's Gemini (Still not as good as Florian's sketch...)

Transients Scaling Across Different Systems

