

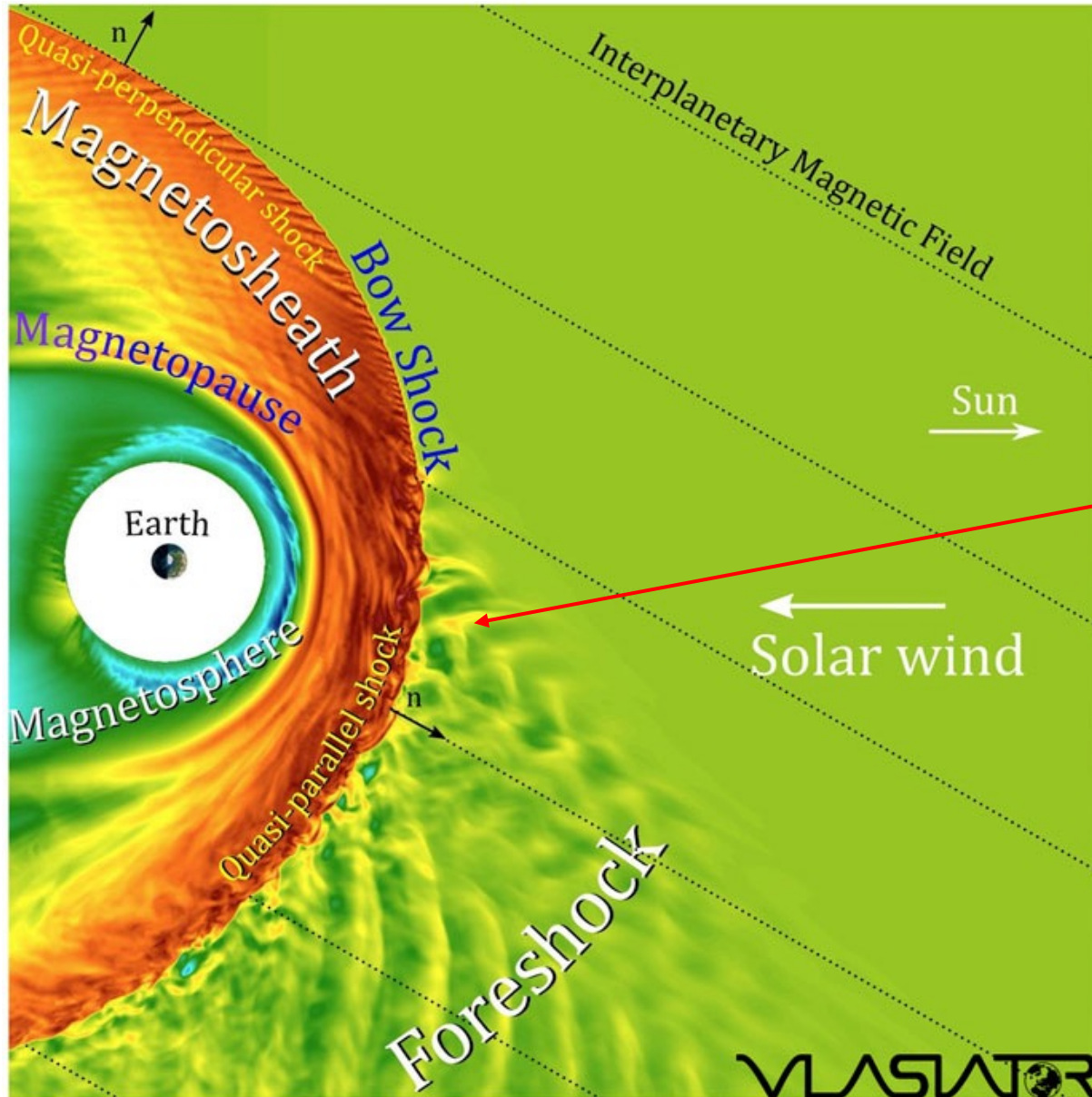
Recent Advancements in Transient Processes and Particle Energization at Planetary Bow Shocks

Savvas Raptis

JHU/APL, Laurel, MD, USA

Thanks to collaborators and friends: Drew L. Turner, Ahmad Lalti, Martin Lindberg, Damiano Caprioli, George Clark, Terry Liu, Jamey R. Szalay, Lynn Wilson III, Imogen Gingell, Ying Zou, Ivan Vasko, Colby C. Haggerty, Yufei Zhou, David Sibeck, Primoz Kajdic, Adnane Osmane, Ian Cohen, Philippe Escoubet, and more

Earth's Qpar bow shock and foreshock



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

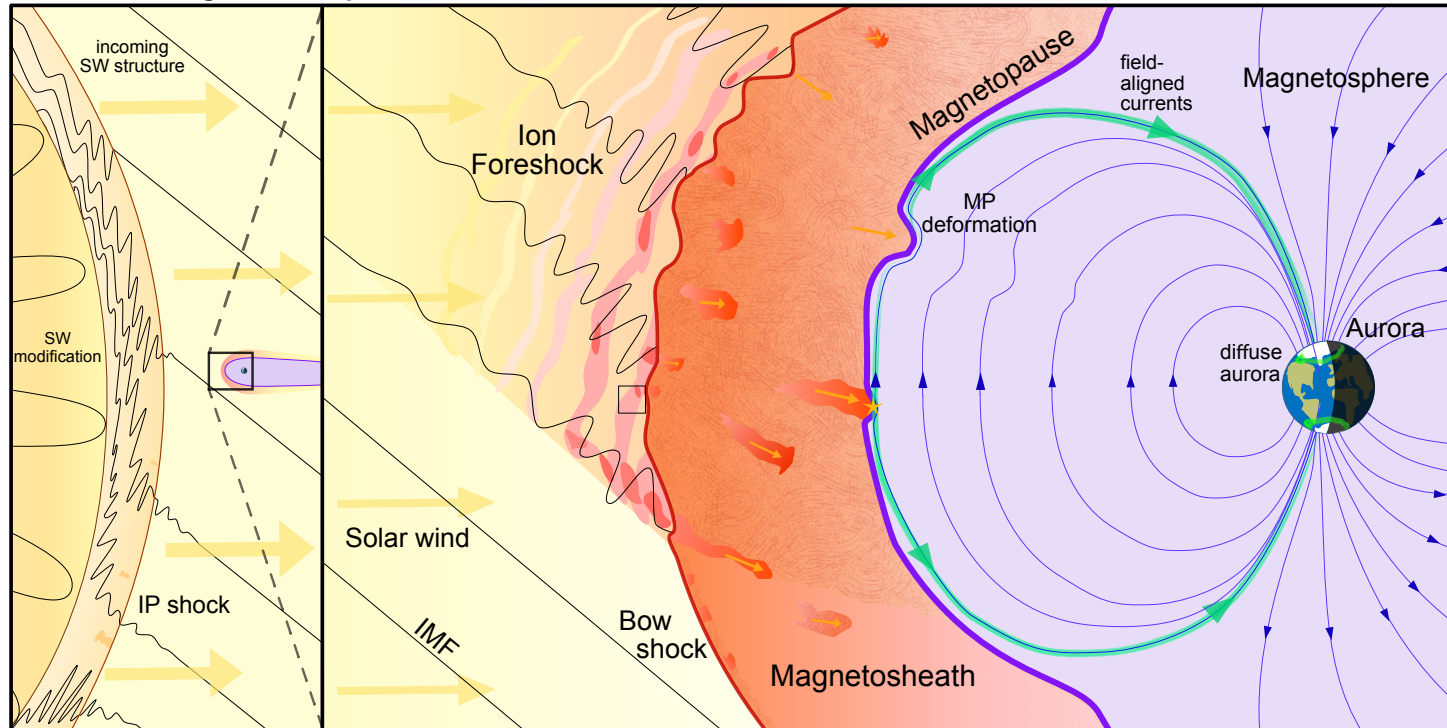
- Very **efficient particle accelerators**
- **Transient phenomena** upstream and downstream
- ULF waves upstream and downstream
- Kinetic plasma physics
- Wave particle interaction
- Turbulence
- Current sheets & reconnection

*Astro references on Qpar importance for supernovas:
Caprioli+2014, Giuffrida+2022, Vink+2024, McGinness+2026

What is a Dayside Transient?

Review of dayside transients: Zhang et al., 2022; Kajdic et al., 2024
Review of magnetosheath jets: Krämer et al., 2025

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



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

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

- 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, Yuxi Chen, Gonzalo Cucho-Padin, Imogen Gingell, Terry Z. Liu, Ying Zou)

Universality of shock-generated transients

	coronal shocks	interplanetary shocks	Mercury	Venus	Earth	Mars	Jupiter	Saturn
ULFs	?	yes	yes	yes	yes	yes	yes	yes
shocklets	?	rare	yes?	yes	yes	yes	yes	yes
SLAMS	?	no?	yes	yes	yes	yes	yes	yes
SHFAs	?	?	?	yes	yes	yes	?	* ?
HFAs	?	?	maybe?	yes	yes	yes	yes	yes
FBs	?	?	?	* ?	yes	?*	?	?
jets	?	yes	maybe?	?	yes	yes?	yes?	?

Hietala et al. ISSI 2019

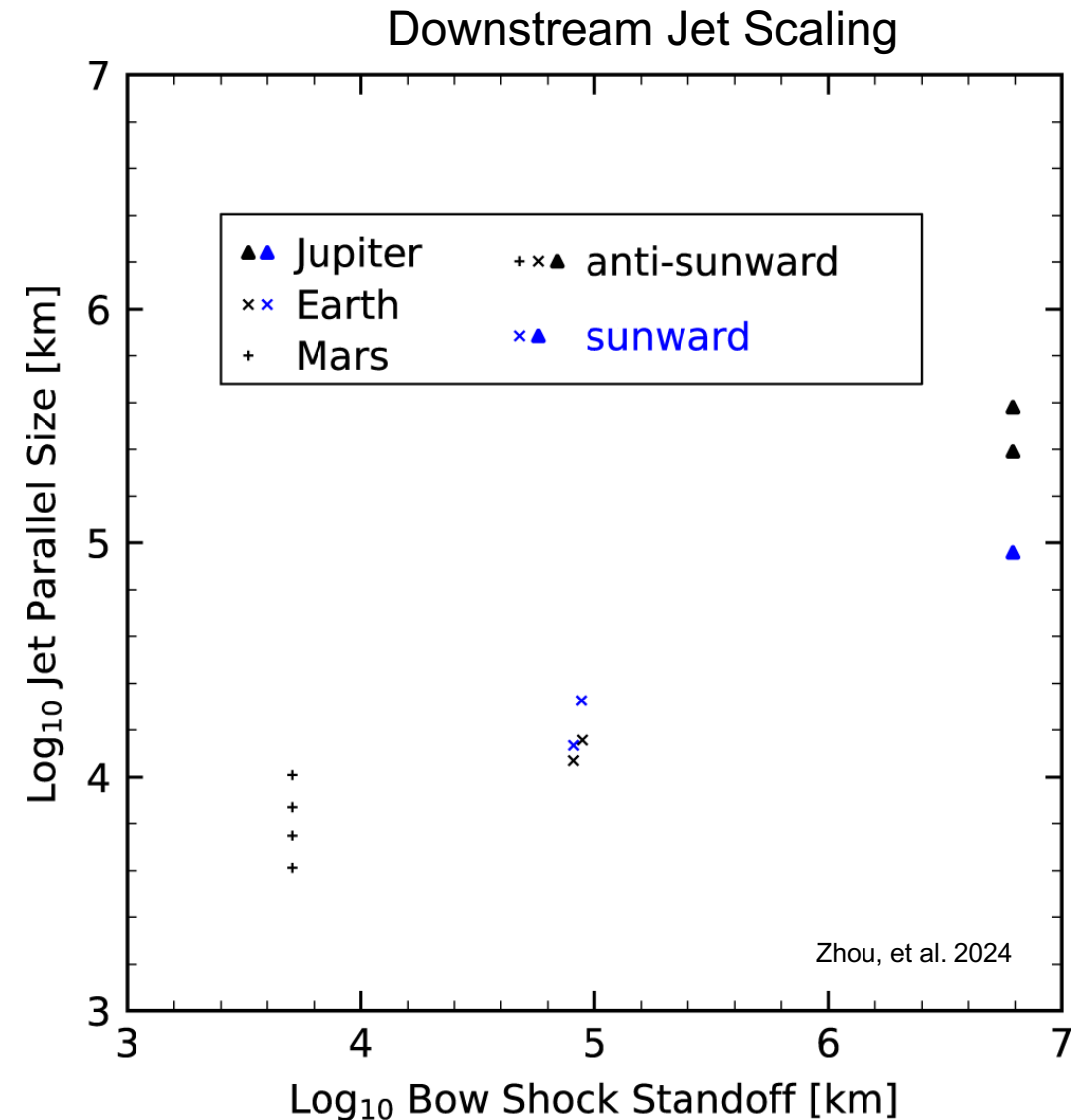
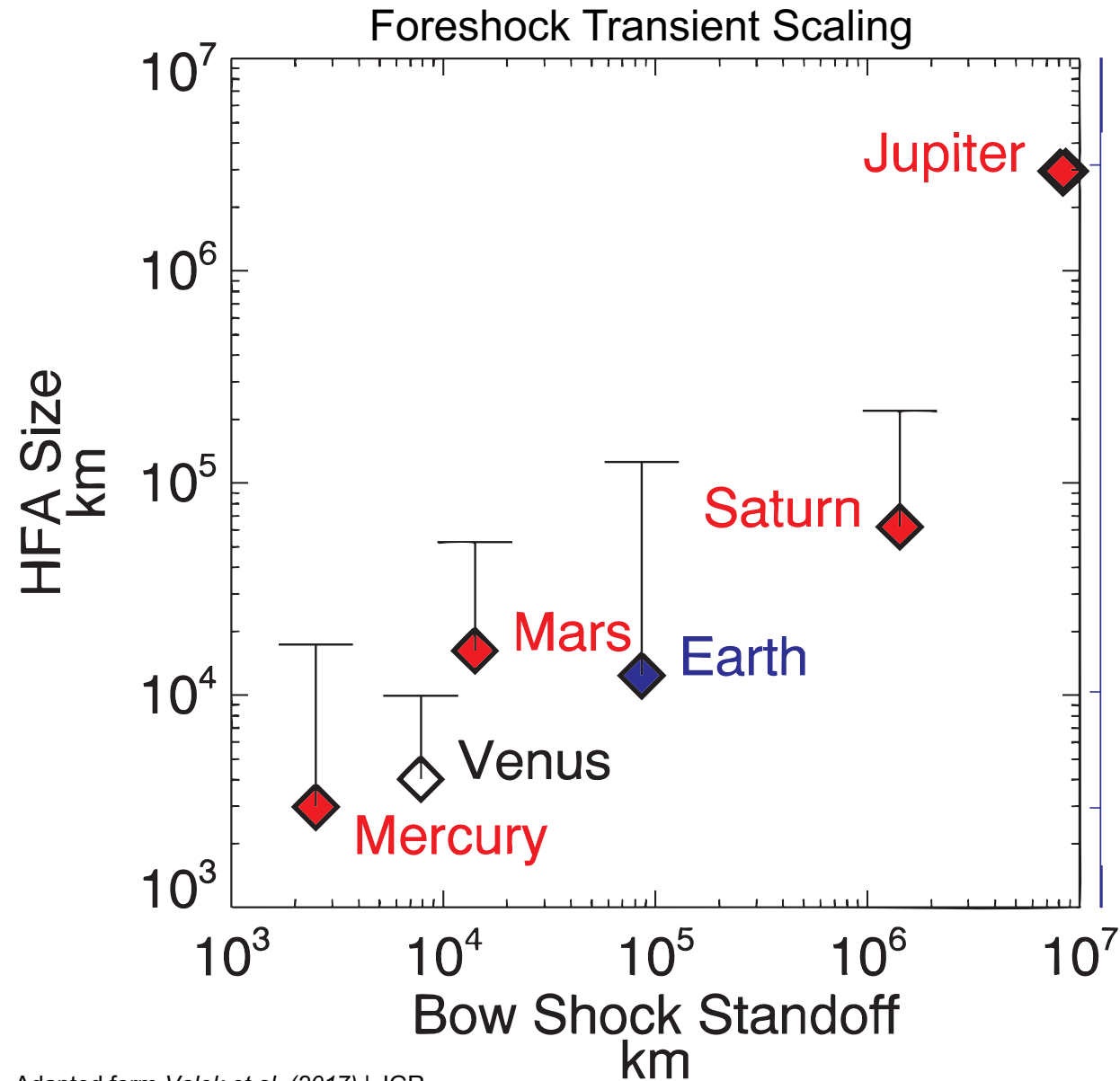
Yes!*

Yes!*

Probably*?

Maybe?

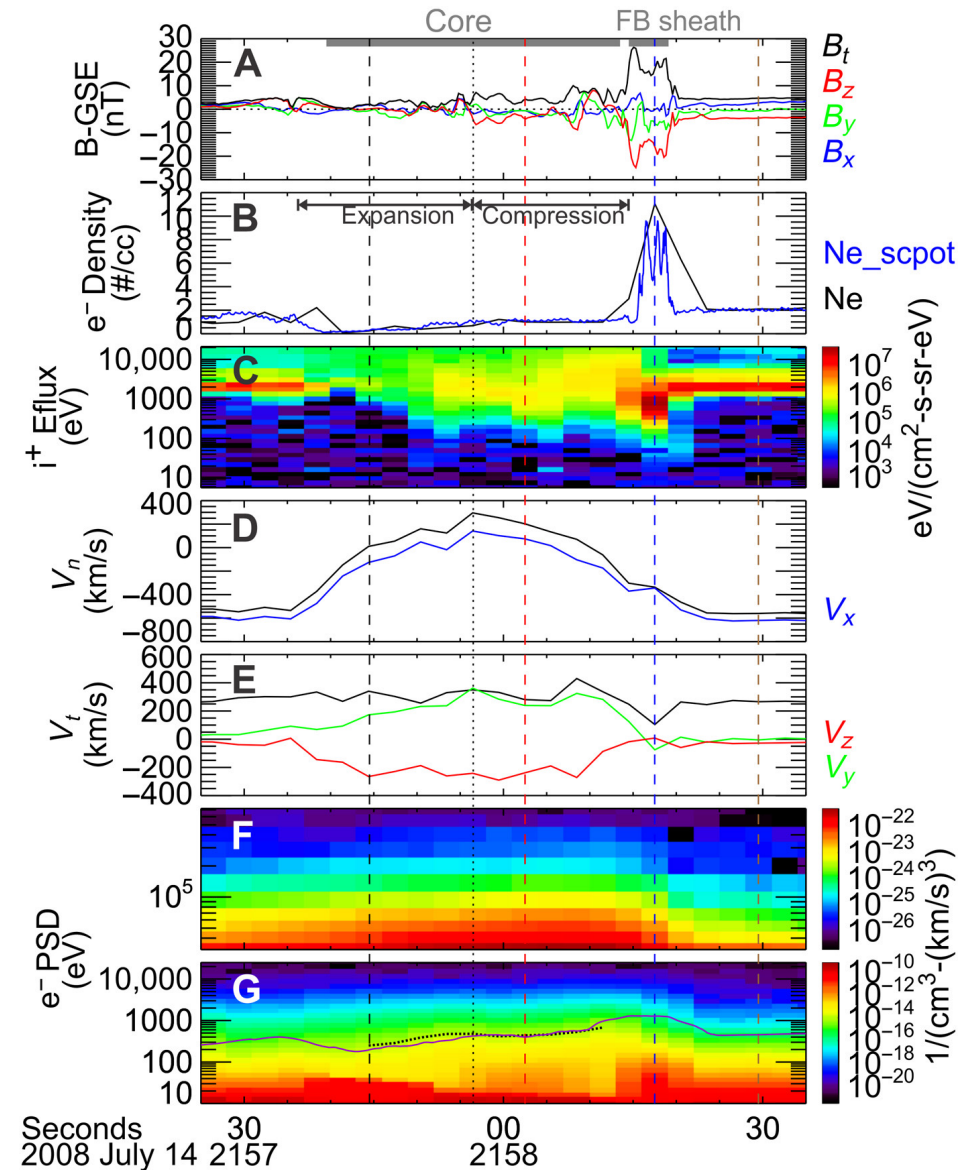
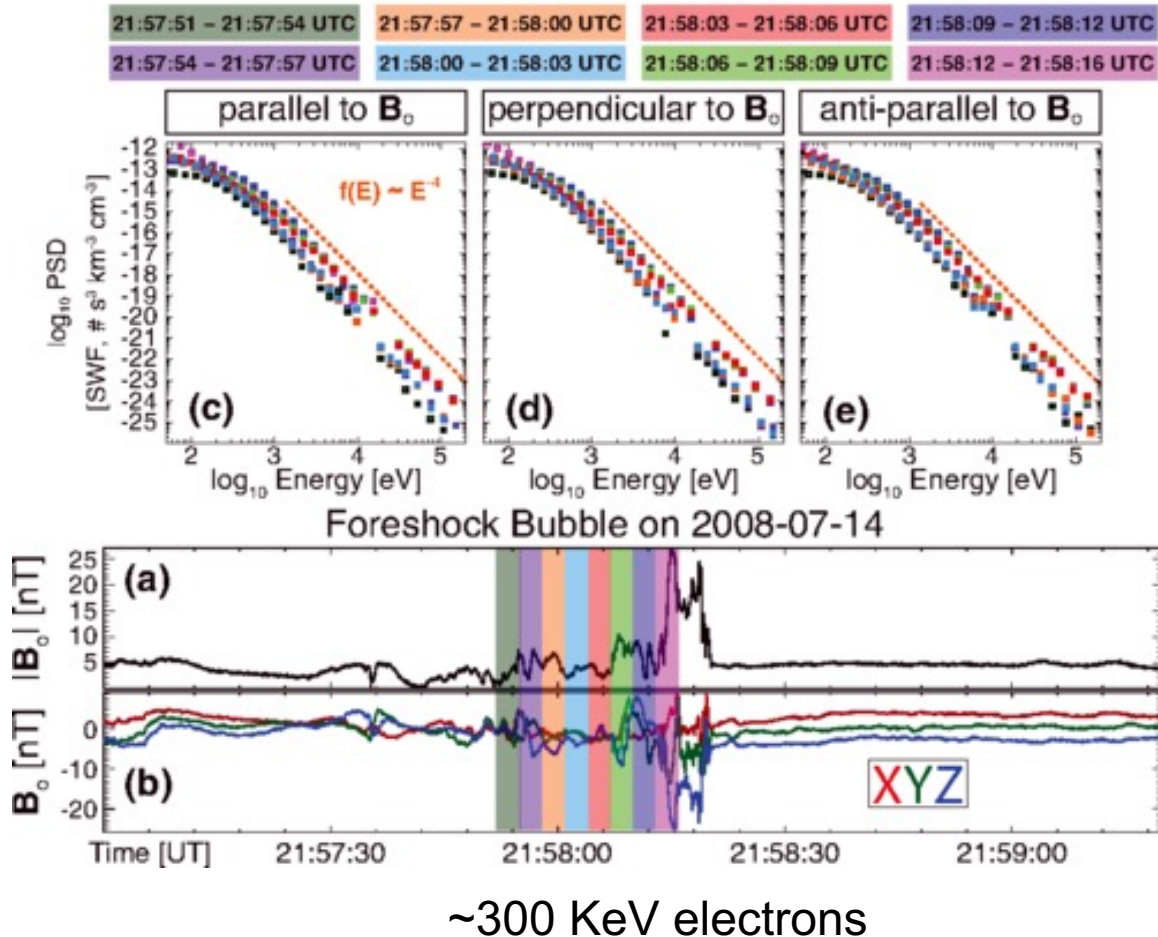
Transients Scaling Across Different Systems



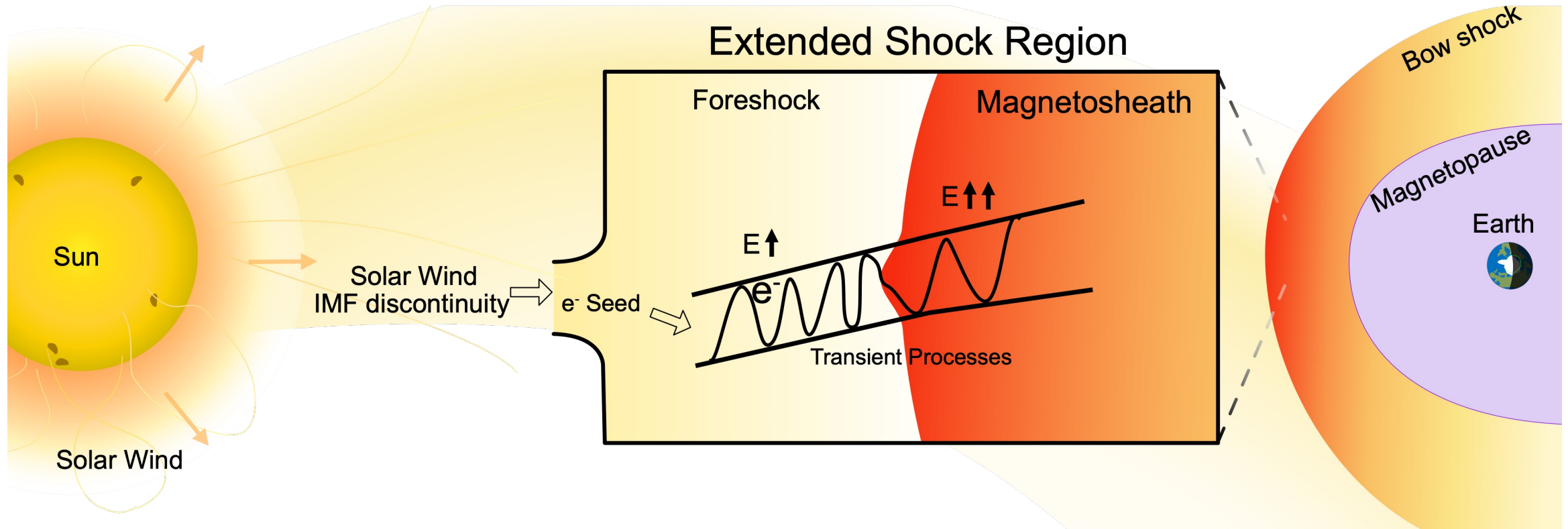
Foreshock Transients & Electron acceleration

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; Liu et al., 2026

Combined low and high energy electron spectra



Mental Picture to Keep in Mind



Qpar **Extended shock** includes the **foreshock**, the **magnetosheath** and their **transient processes**

Latest Results

Transients & Particle Acceleration

Earth



Raptis et al.2025 | NatComm

Earth



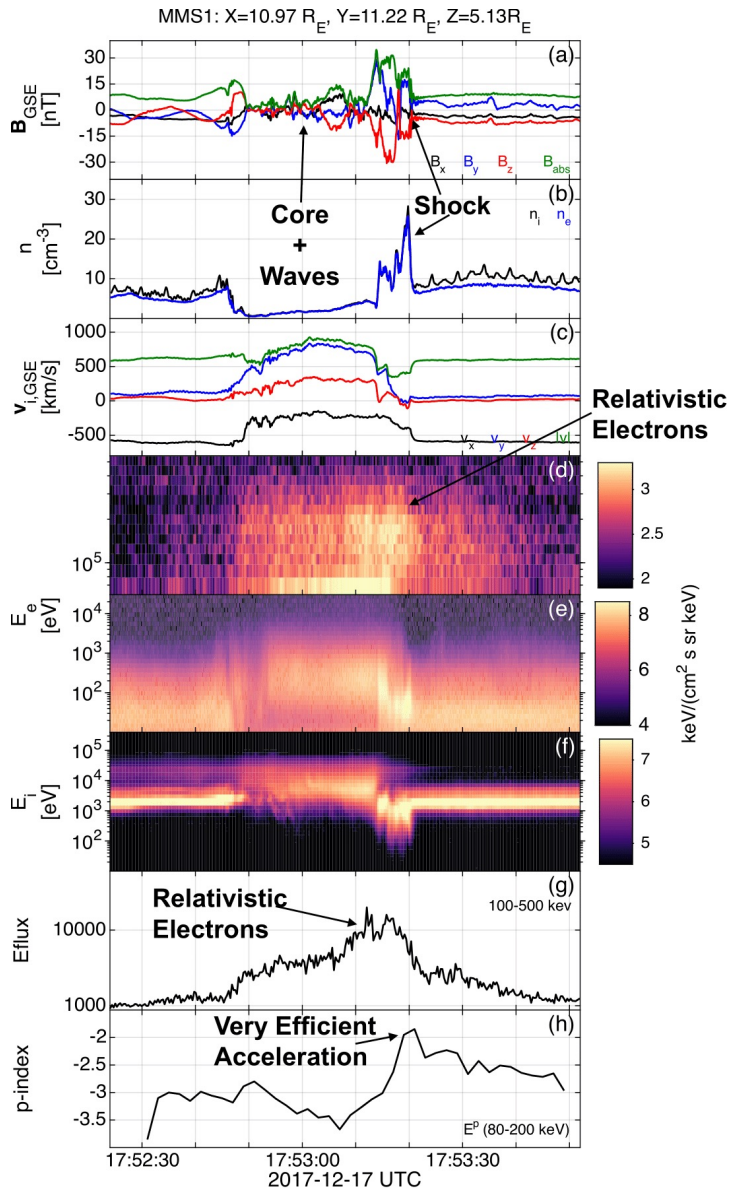
Raptis et al.2025 | ApJL

Jupiter

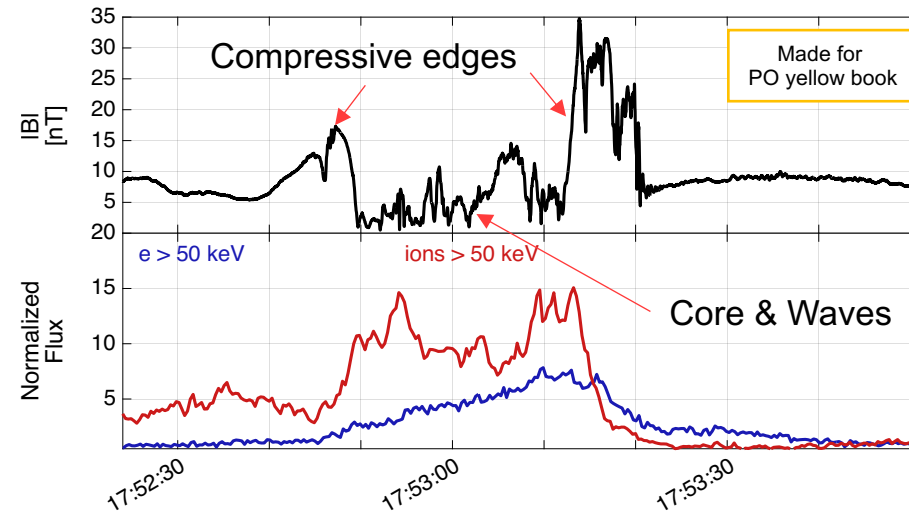


Raptis et al.2026 | Nature

Transients & Relativistic Electrons with MMS



New plot, much easier to understand!



With respect to upstream conditions
(SW/FS):

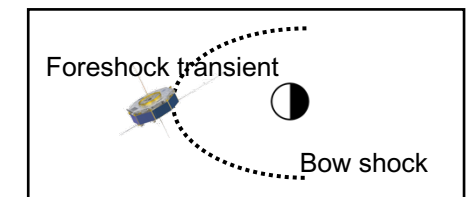
- Electron fluxes ($>50 \text{ keV}$) up to x6
- Ion fluxes ($>50 \text{ keV}$) up to x15

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)

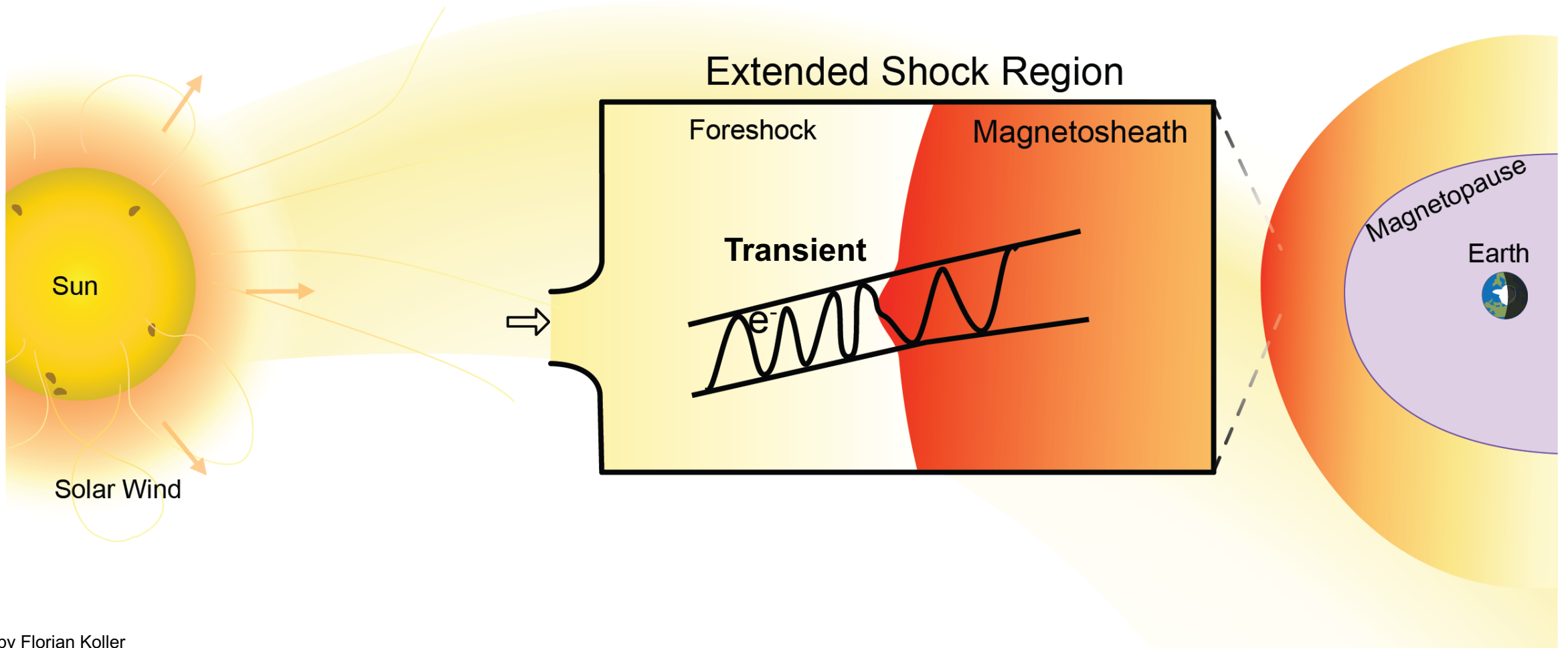
Unique property

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



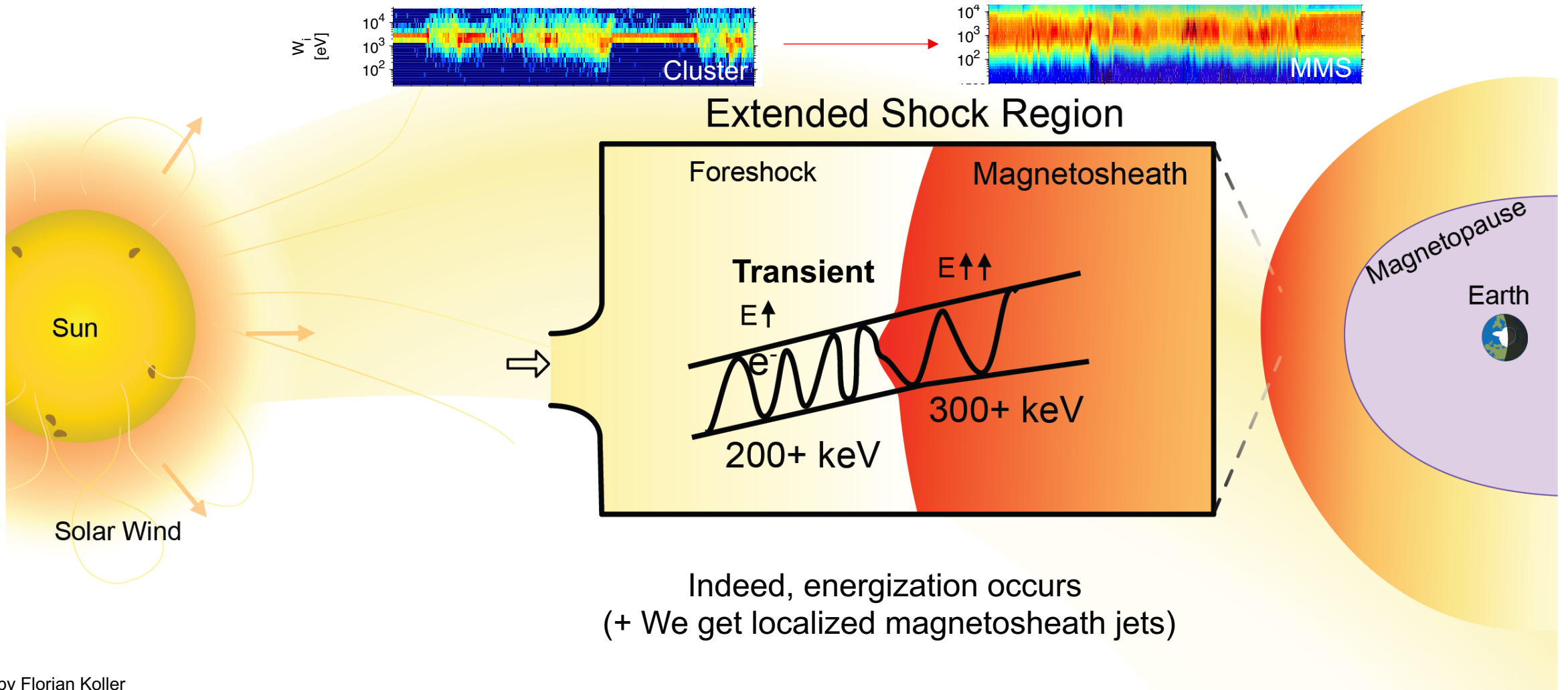
But let's ask one more question

What do we expect to see when transients cross the bow shock and go downstream?

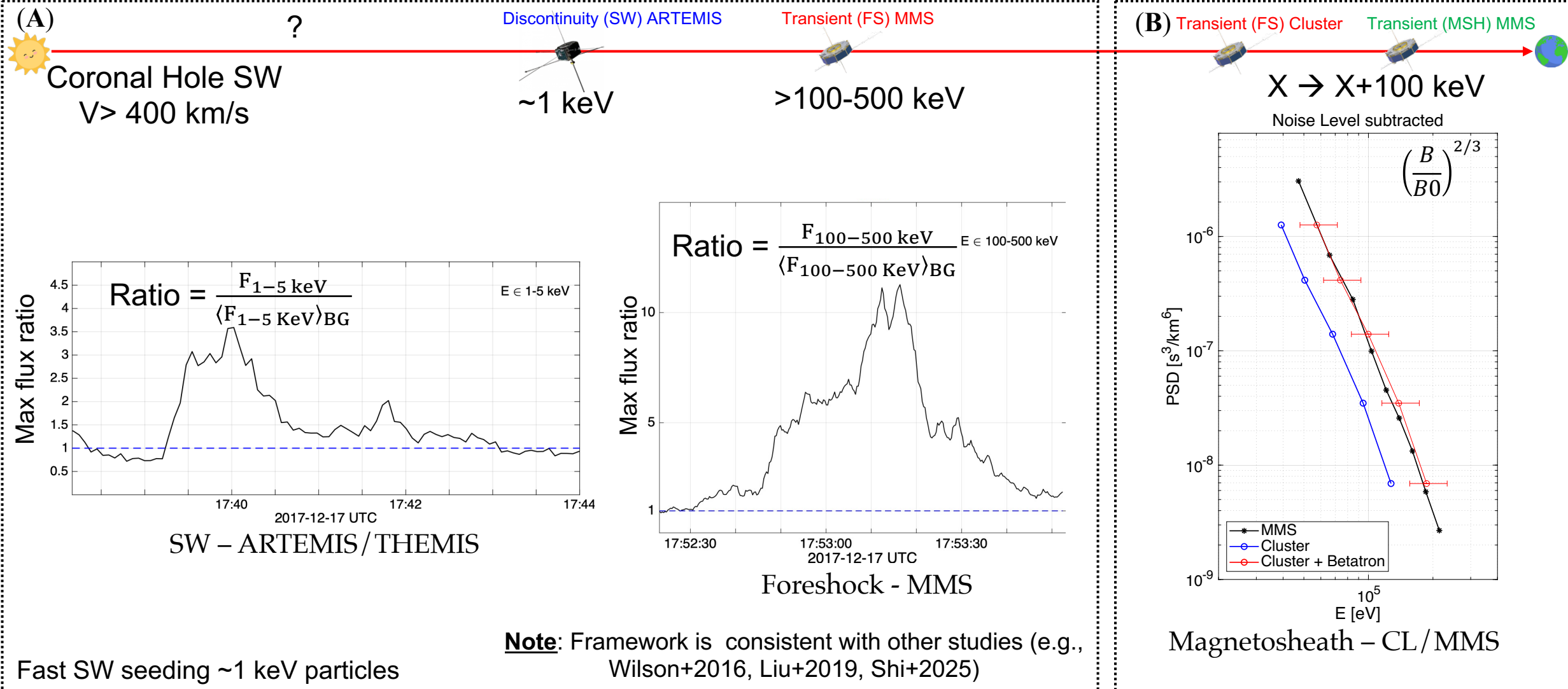


But let's ask one more question

What do we expect to see when transients cross the bow shock and go downstream?



Reinforced Shock Acceleration (RSA): 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*

The question now is:

What about other planetary shocks?



Particle Acceleration: Hilas Criterion and Scales

- General geometrical criterion: Hilas Limit (Hilas+ 1984)

$$E_{\max} \approx qBLV$$

A particle cannot exceed an energy higher than the total magnetic potential drop across a system

We require the diffusion length (L_D) to be smaller than the system size where acceleration takes place (L), and under Bohm's Diffusion (strong scattering), $D \approx 1/3 v r_g$,

This results in a maximum obtainable energy using $r_g = p/(qB)$ of :

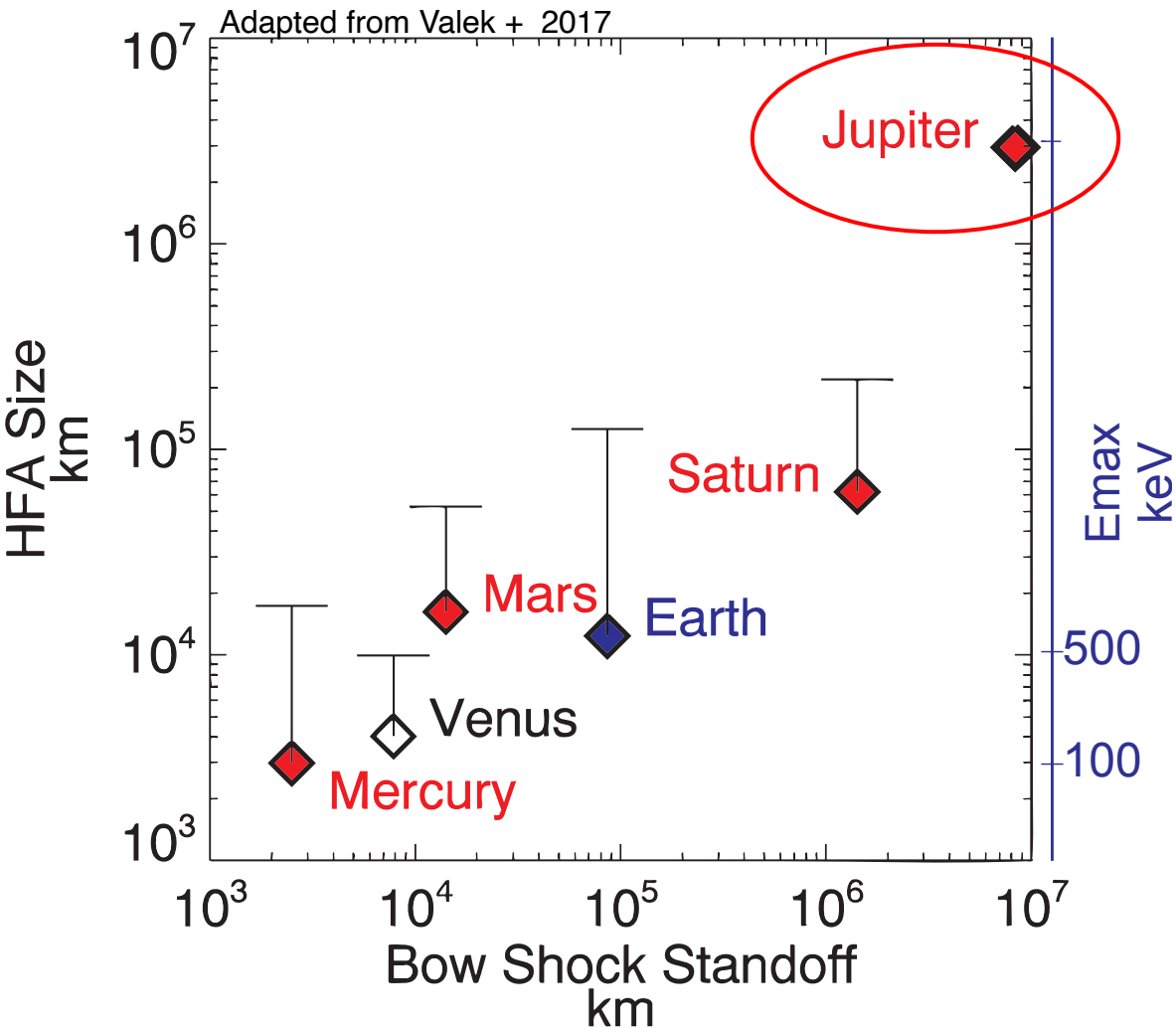
$$E_{\max}^2 - (3qBLV)E_{\max} - (mc^2)^2 = 0$$

For simplicity in the relativistic limit this results to :

$$E_{\max} \approx \alpha L, \quad \alpha \approx 3qBV_{sh}$$

Or in simple words, as long as we can constrain these 3 variables, we can constrain $E_{\max}$

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:

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

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

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

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

$$E \sim 1 - 2 [\text{MeV}]$$

Juno Observations – Jovian Bow Shock Crossing

Foreshock Transient (HFA):

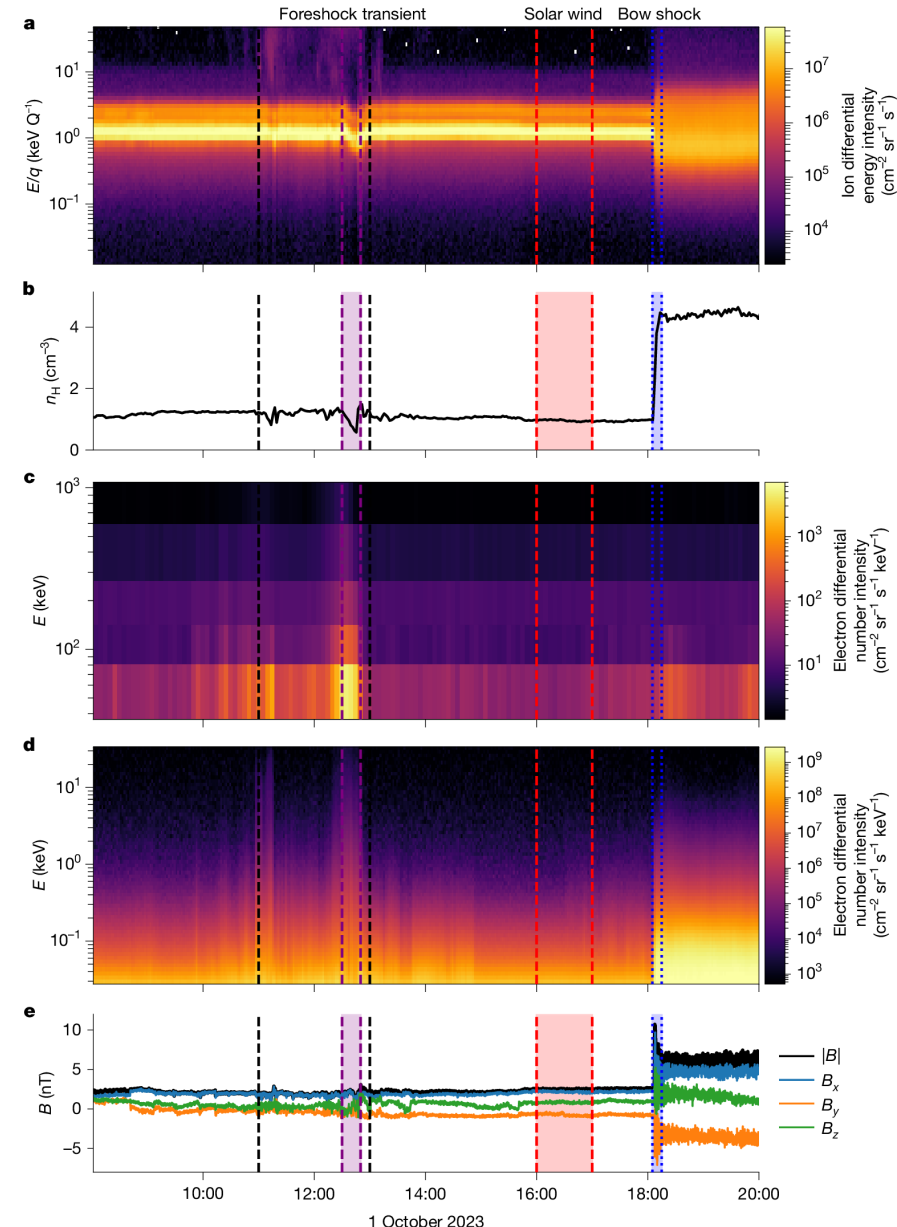
- Energetic electrons **up to 1 MeV**
- Disrupted solar wind beam
- Localized depletion of n and B

Solar wind (SW):

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

Bow shock (BS):

- Duskward Flanks Crossing [+12.9, +60.5, -59.3] R_j)
- Typical compression of ~ 2 for B and n
- suprathermal electrons present but minimal energetic electrons **only up to 10ish KeV**



Ion spectrum

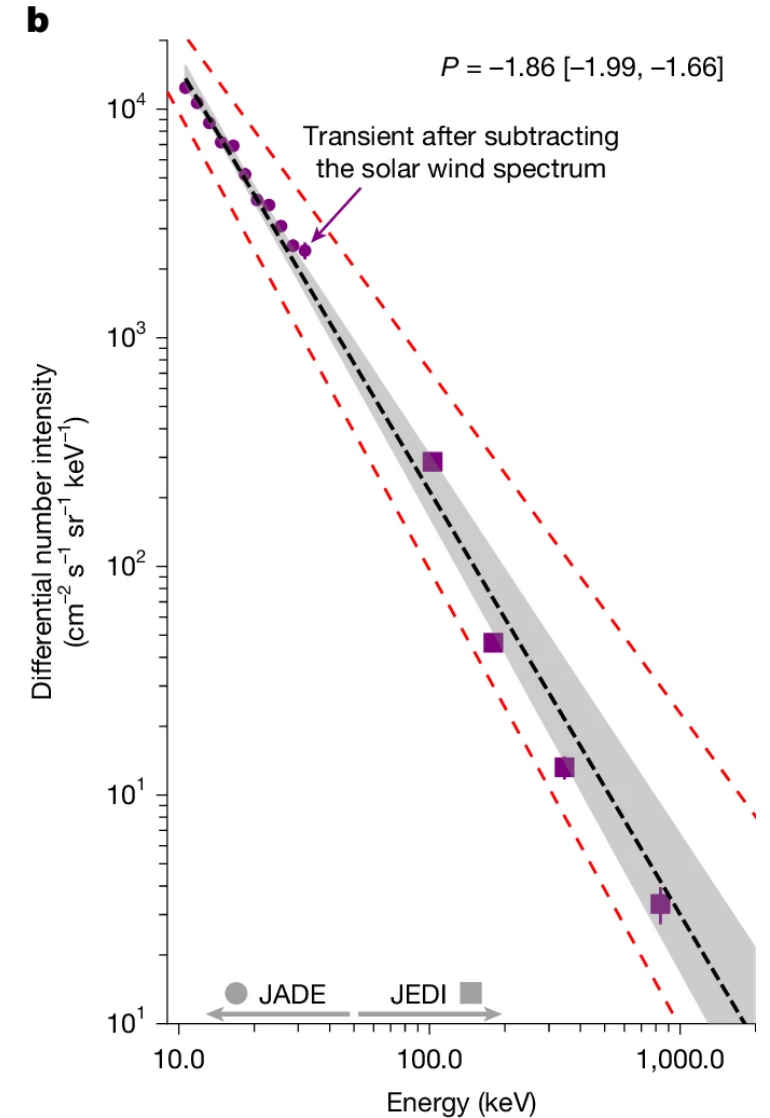
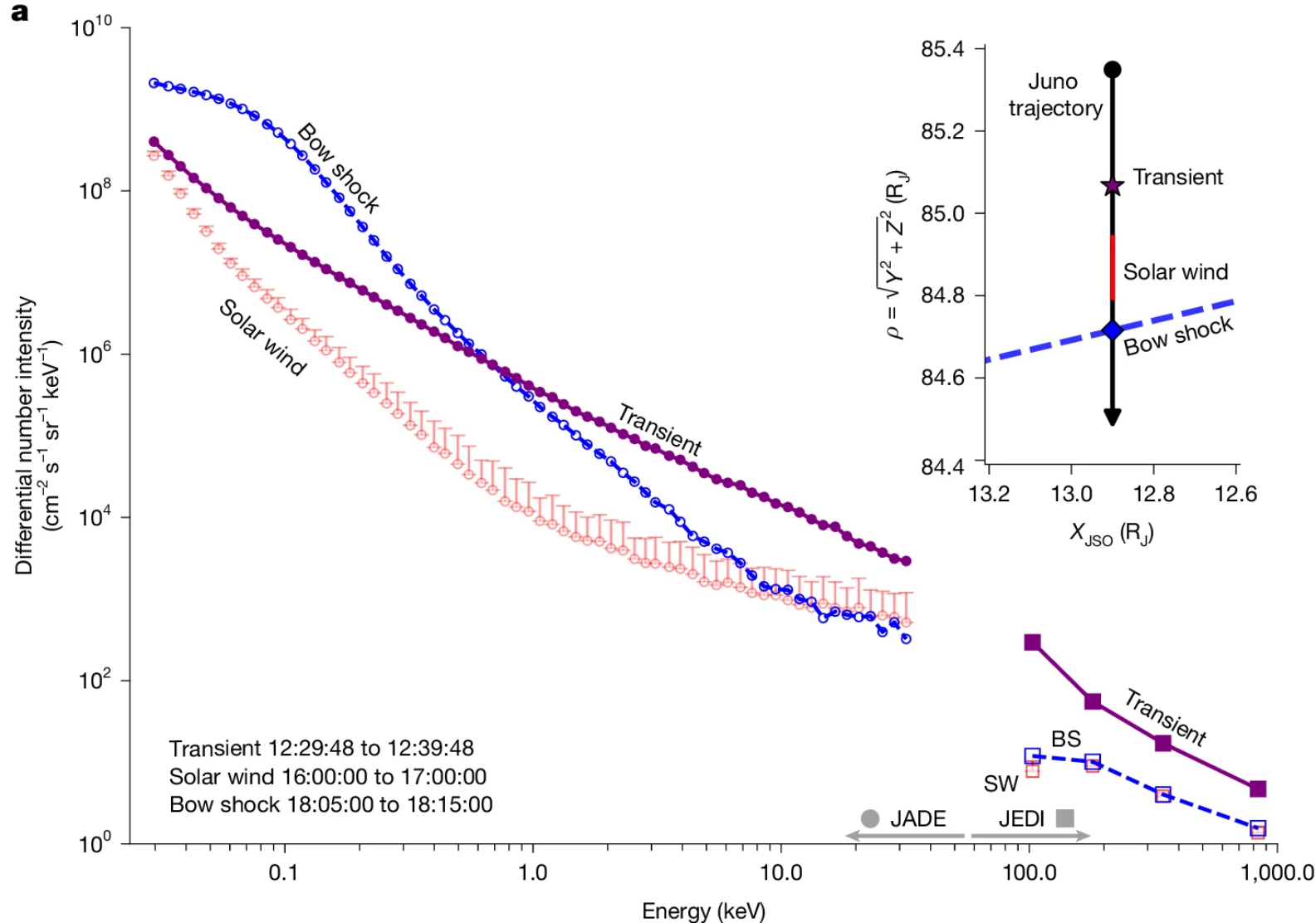
Ion density

Electron
Spectra
JADE + JEDI

Magnetic
field

Reinforced Shock Acceleration at Jupiter

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



Most efficient acceleration happens at the foreshock. The bow shock crossing only up to <10 keV

Can we extrapolate to astrophysical shocks?

$$E_{\max} \sim BV_{\text{sh}}L$$

Inputs: in situ planetary data

Extended Data Table II. Approximate scale sizes of foreshock transients.

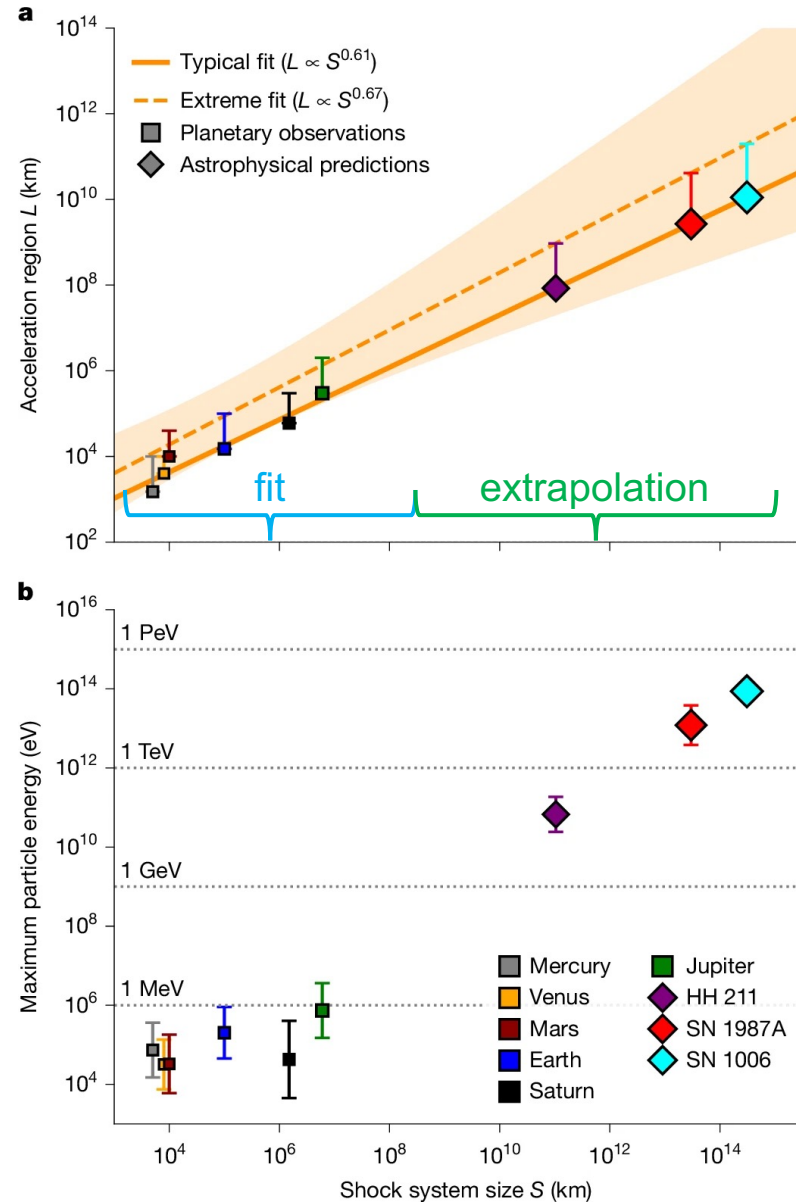
Planet	L_{typ} (km)	L_{ext} (km)
Mercury	1.5×10^3	1.0×10^4
Venus	4.0×10^3	1.0×10^4
Mars	1.0×10^4	4.0×10^4
Earth	1.5×10^4	1.0×10^5
Saturn	6.0×10^4	3.0×10^5
Jupiter	3.0×10^5	2.0×10^6

Extended Data Table III. Parameter ranges used for obtaining the the maximum particle energy range.

Object	S (km)	V_{sh} (km s ⁻¹)	B (nT)
Mercury	5.0×10^3	[100, 600]	[10, 40]
Venus	8.0×10^3	[100, 600]	[5, 15]
Earth	1.0×10^5	[100, 600]	[3, 10]
Mars	1.0×10^4	[100, 600]	[1, 5]
Jupiter	6.0×10^6	[100, 600]	[0.5, 2.0]
Saturn	1.5×10^6	[100, 600]	[0.1, 1.5]
HH211	$\sim 1.05 \times 10^{11}$	[50, 150]	[4, 10]
SN 1987A	$\sim 3.0 \times 10^{13}$	[2000, 4000]	[0.1, 0.5]
SN 1006	$\sim 3.0 \times 10^{14}$	[3500, 4500]	[0.1, 0.2]

From three observables to $E_{\max}$

1. B and V_{sh} : taken from each system (tables above).
2. L : fit planetary data to a power law linking transient size to shock standoff distance S .
3. **Extrapolate**: apply the upper prediction interval of the fit to HH 211, SN 1987A and SN 1006.
4. **Bound**: the Hillas limit turns each L into a maximum energy.



Caveats & Assumptions:

- ❖ An extrapolation beyond any in situ test
- ❖ Assumes quasi-parallel geometry and transient formation at these shocks
- ❖ Bohm diffusion ($dB/B_0 \gg 1$) is conservative: these are lower bounds (*Malkov & Diamond 2005*)
- ❖ Upstream field coherence may cap L in some systems

Why trust it:

- The $L(S)$ scaling is anchored in decades of in situ planetary data and produce reasonable values
- The SN 1006 prediction ($\lesssim 100$ TeV) matches independently observed maximum (*Giuffrida et al., 2022*)
- At Earth and Jupiter, the transient outperforms the shock front itself and the limits match observations made from in-situ missions

Illustration of the process in an arbitrary planet

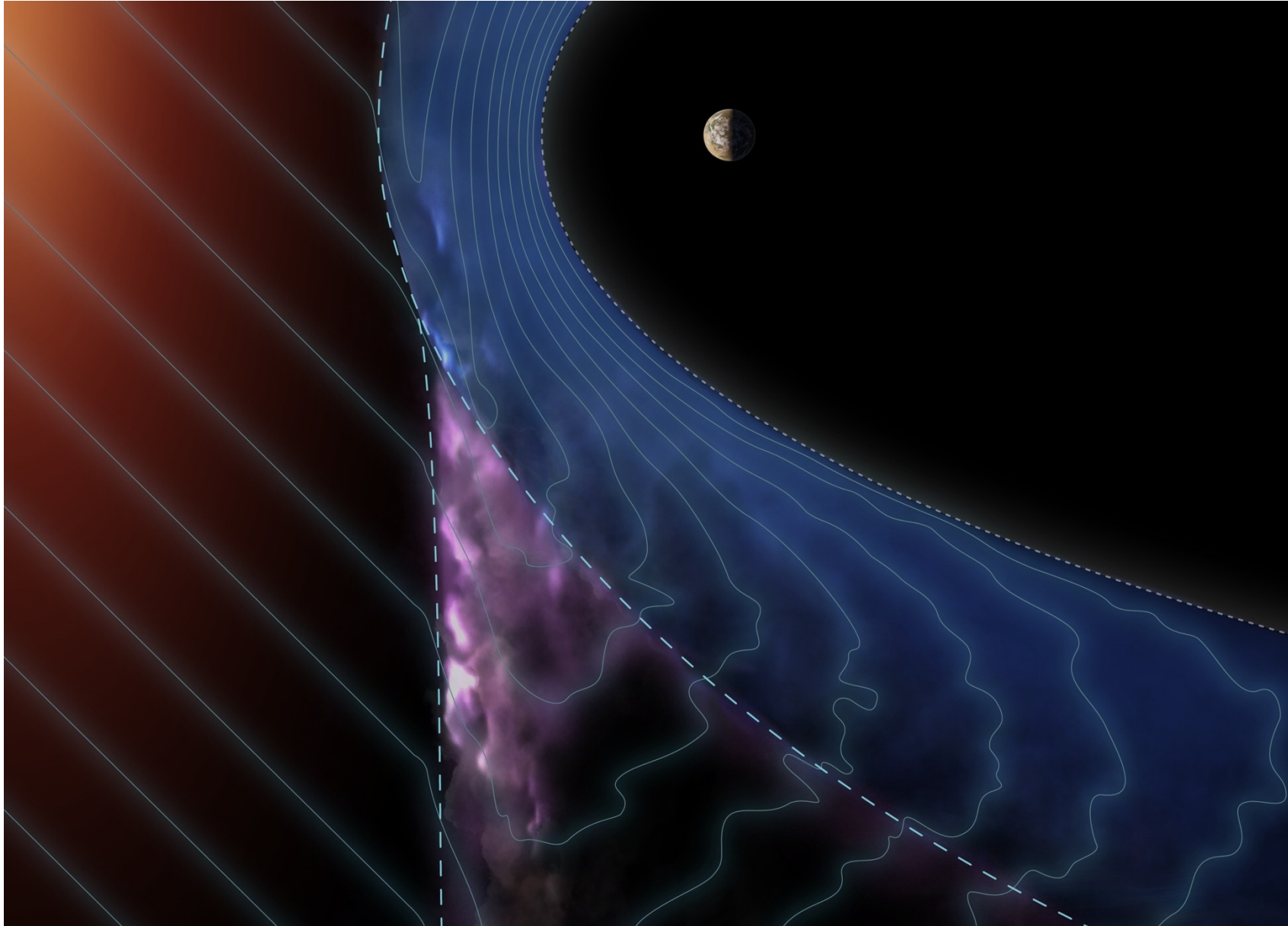


Illustration of the process in an arbitrary planet

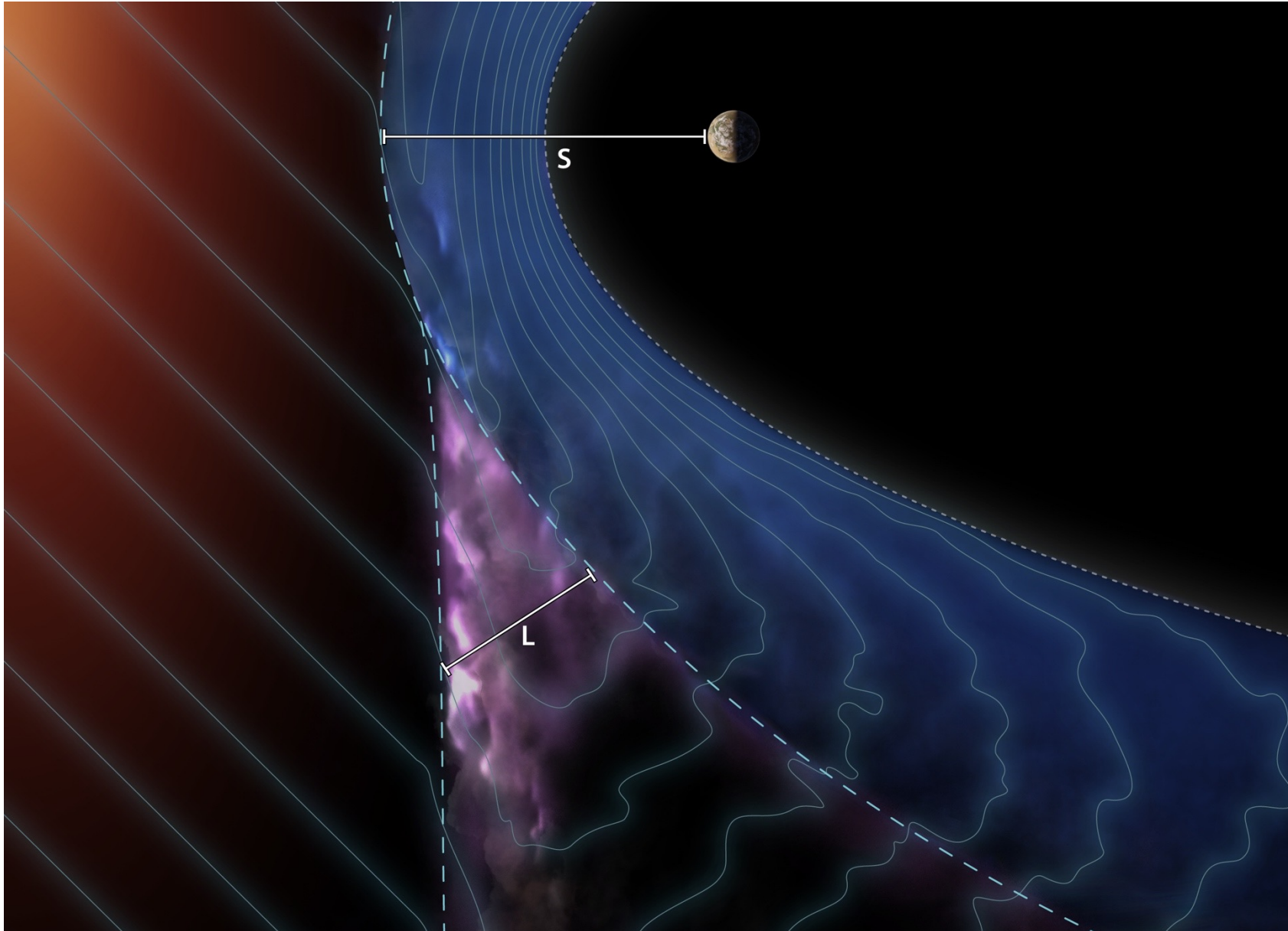


Illustration of the process in an arbitrary planet

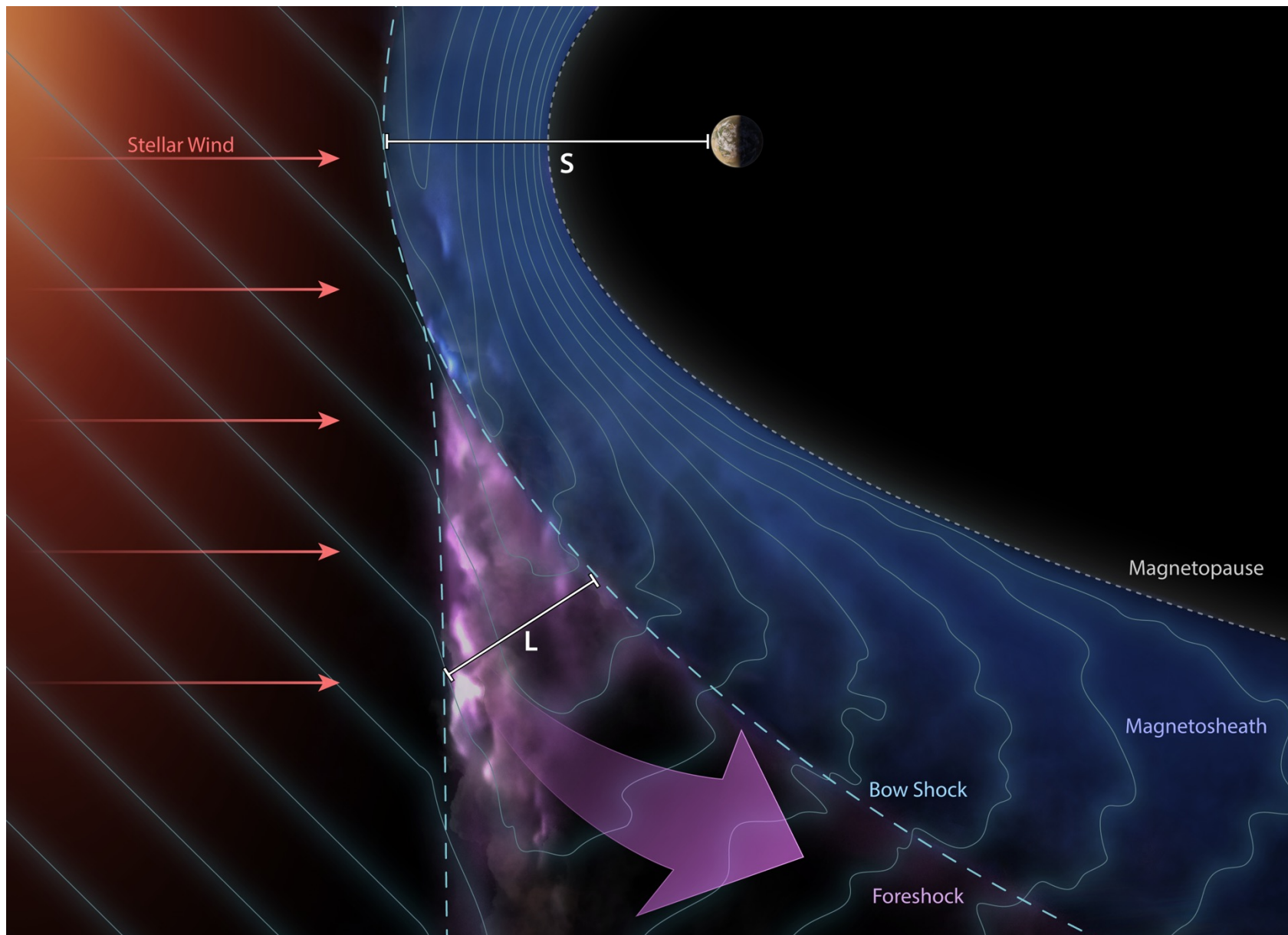
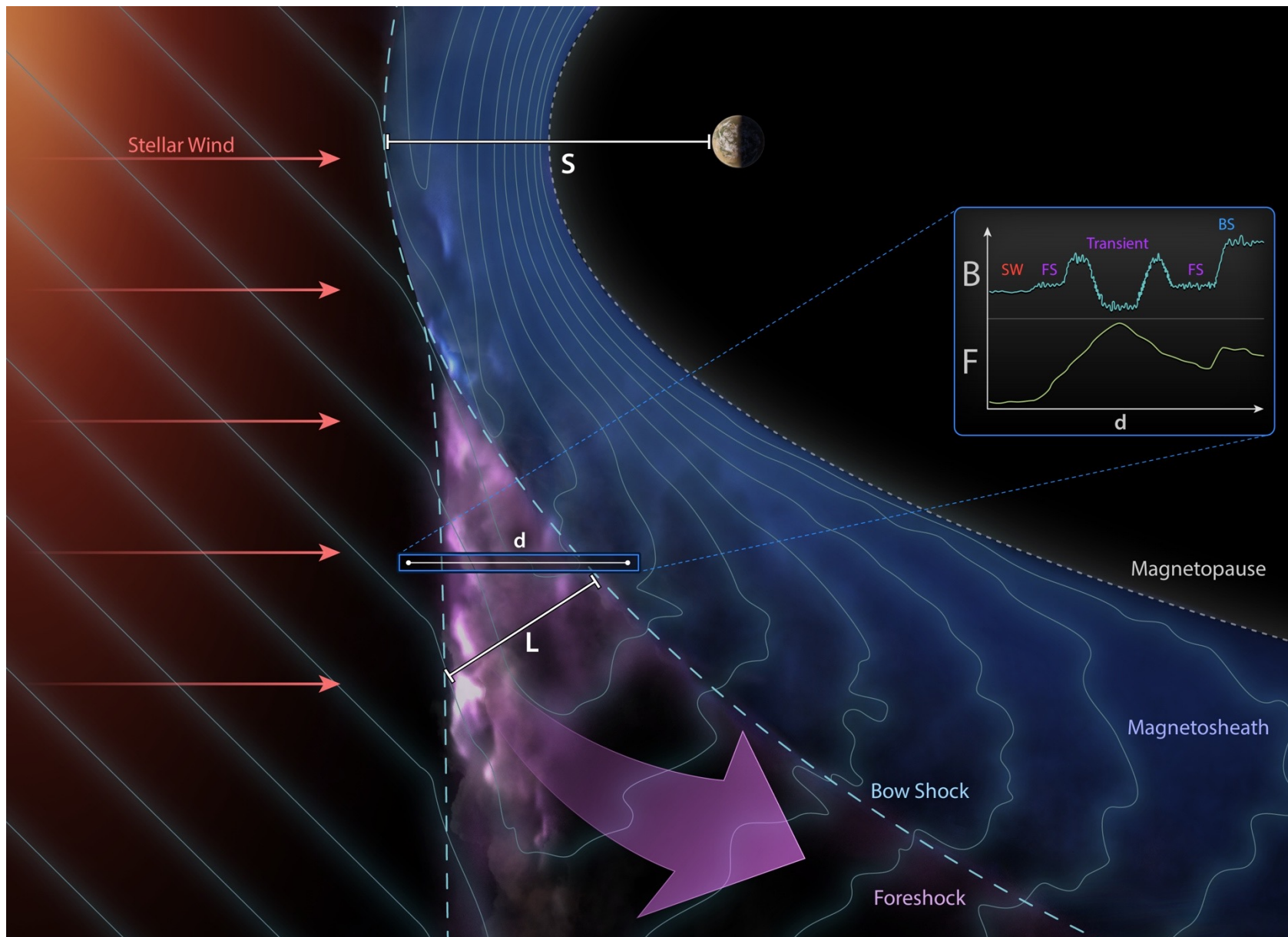


Illustration of the process in an arbitrary planet



Summary & Future Work

Transient Processes at Quasi-Parallel shocks may be more important than previously realized! **relativistic particles, localized compressive edges/shocks** operating multiple temporal and spatial scales all interacting with each other.

Recent results:

- ❖ **Seeding and Max Energy:** Identified **a systematic suprathermal seeding (~1–5 keV) intrinsic to fast solar wind**. **Localized transients act as the primary driver** to energize these electrons to high energies (**100s of keV**). (Raptis et al., 2025a)
- ❖ **A Two-Step Mechanism:** **Particles get more energized when larger transients (i.e., HFAs/FBs) cross the bow shock**. For energetic particles, **additional acceleration can be modeled by 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 ~10-100 TeV particles in in supernova shocks (e.g., SN 1006) consistent with cosmic ray observations**. (Raptis et al., 2026)

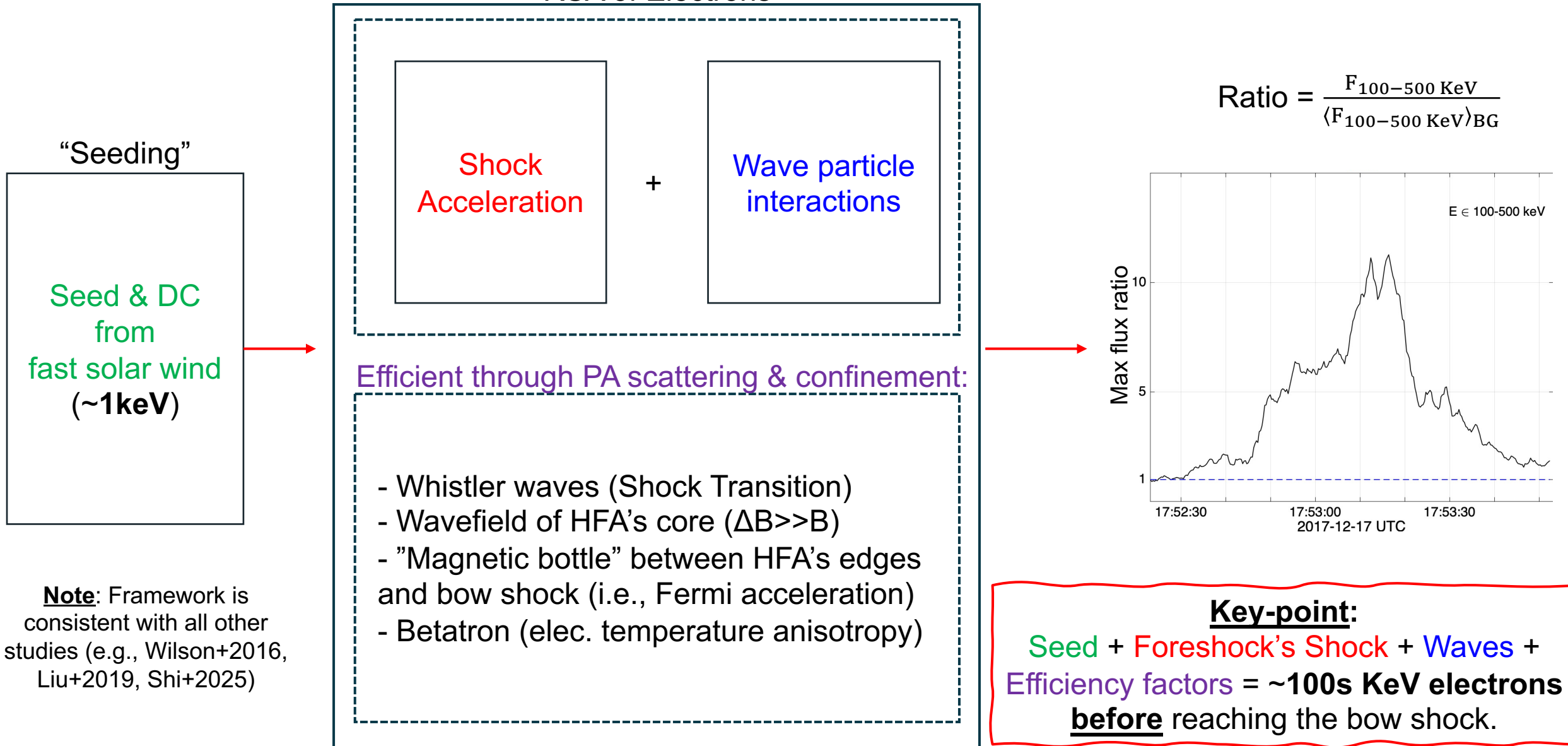
Future steps:

- **Formulate a physical first-principle model:** We know foreshock transients form, but we are not sure about the details, so extrapolation to other systems is speculative and needs to be grounded.
- **Energy transfer & wave particle interaction** is still unclear. We need to look at electron scales for formulating the connection from thermal to suprathermal energies and to uncover the processes of pre-seeding

Appendix

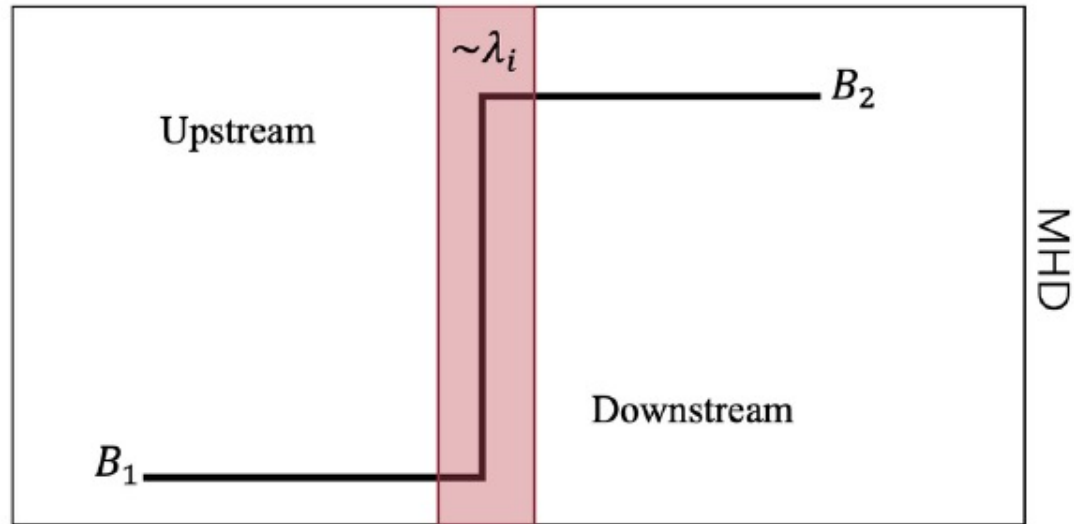
Reinforced Shock Acceleration of Electrons

RSA of Electrons

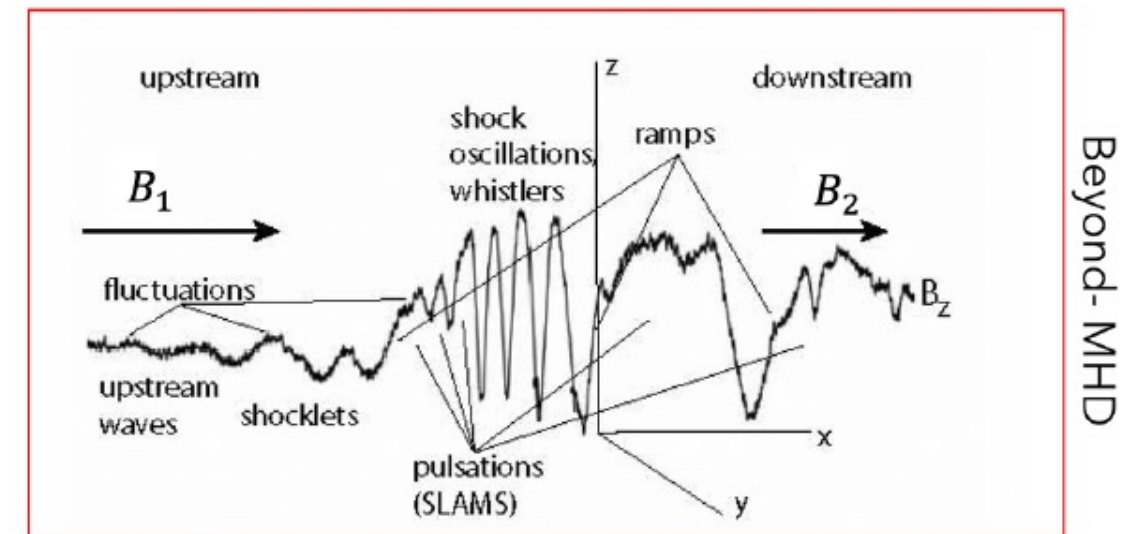
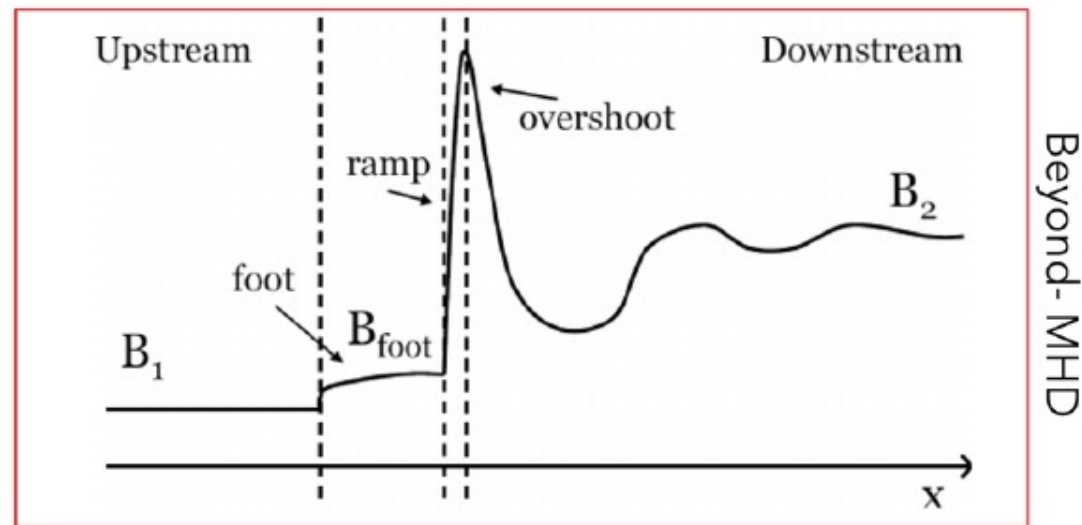
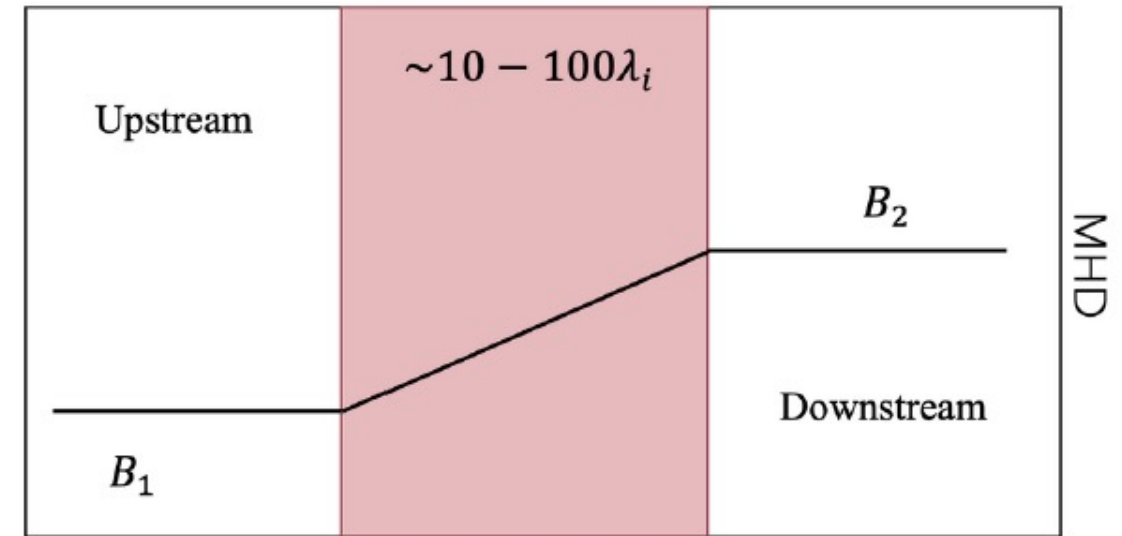


Quasi-parallel and Quasi-perpendicular shocks

Qperp
transition



Qpar
transition



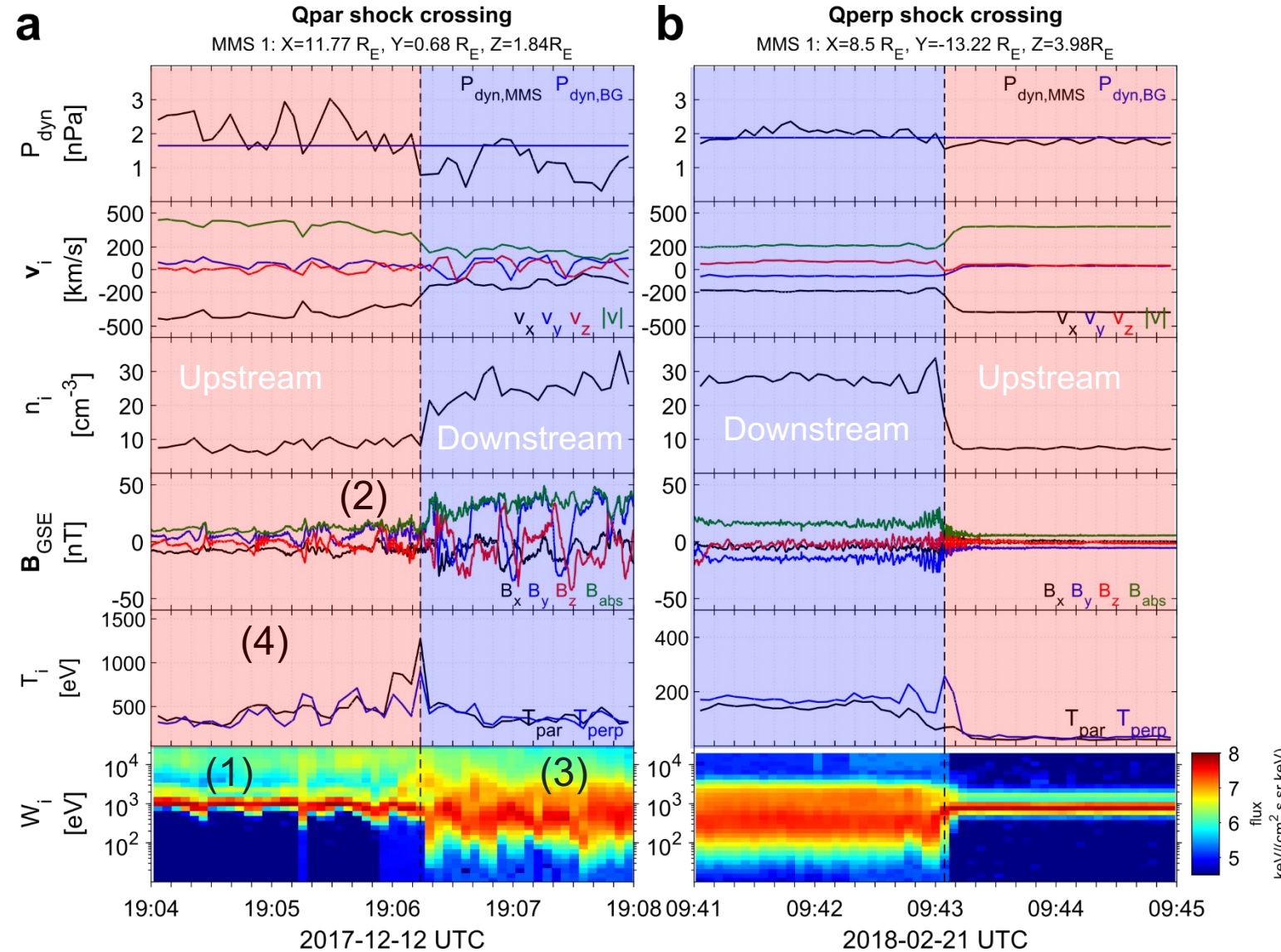
Community Reminder: Qpar – Qperp Shocks

Qpar shocks and downstream plasma:

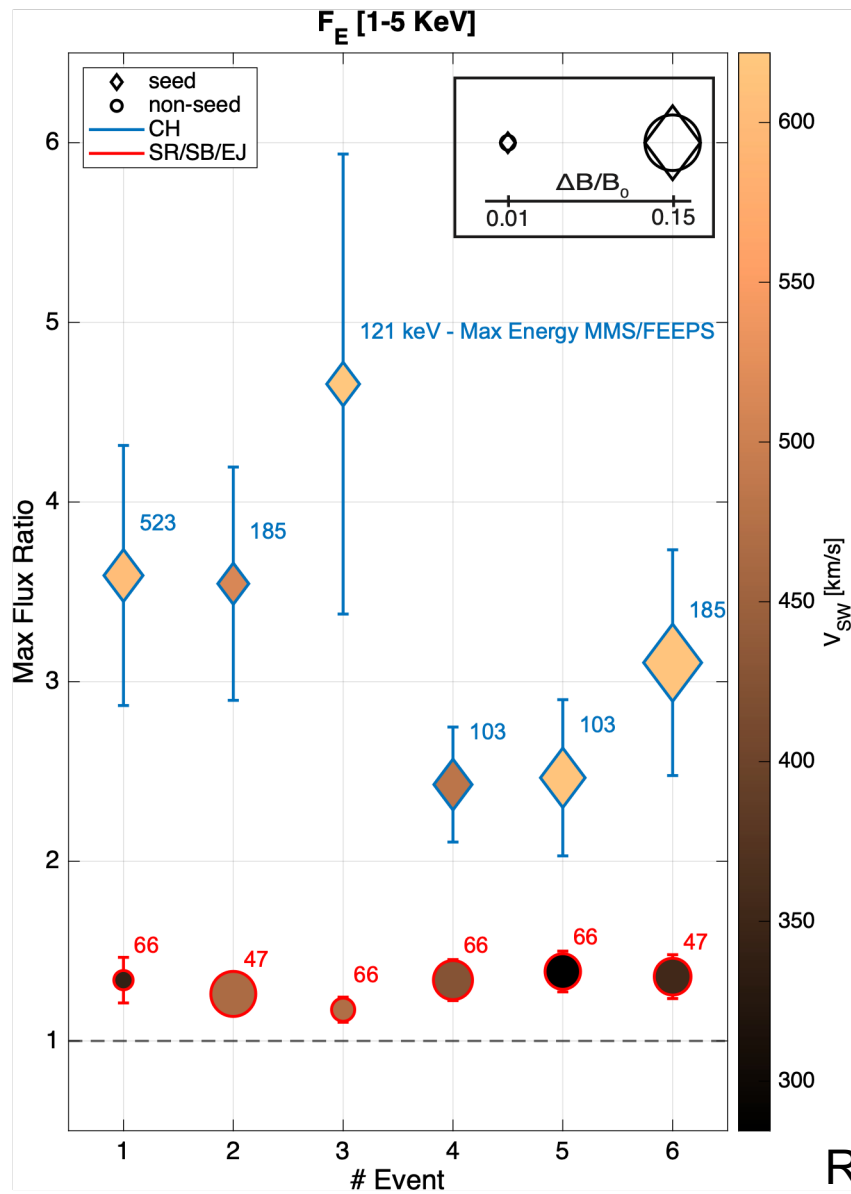
- 1) Presence of foreshock ✓
- 2) Magnetic field fluctuations ↑
- 3) High energy ions ↑
- 4) Temperature anisotropy ↓

See our new MMS citizen science project:
“Shock Detectives”:

<https://www.zooniverse.org/projects/vickitoye/dens/shock-detectives>



Seeding and particle acceleration

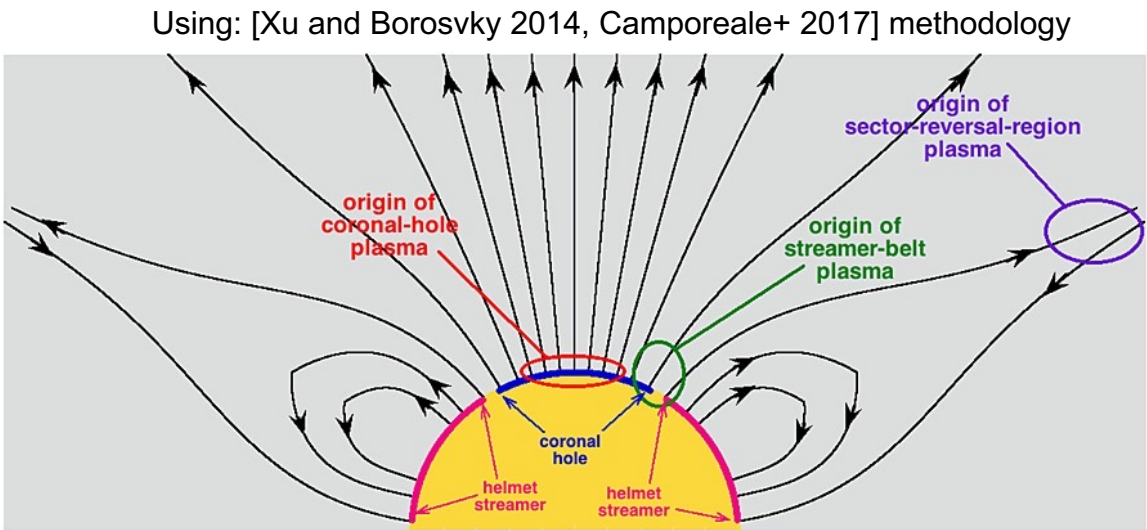


Seed events (FEEPS > 100 KeV)

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

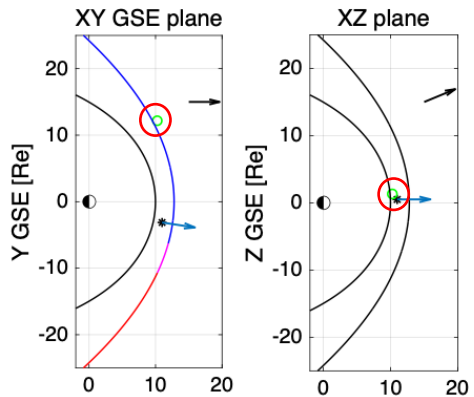
No-seed (FEEPS = Noise)

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



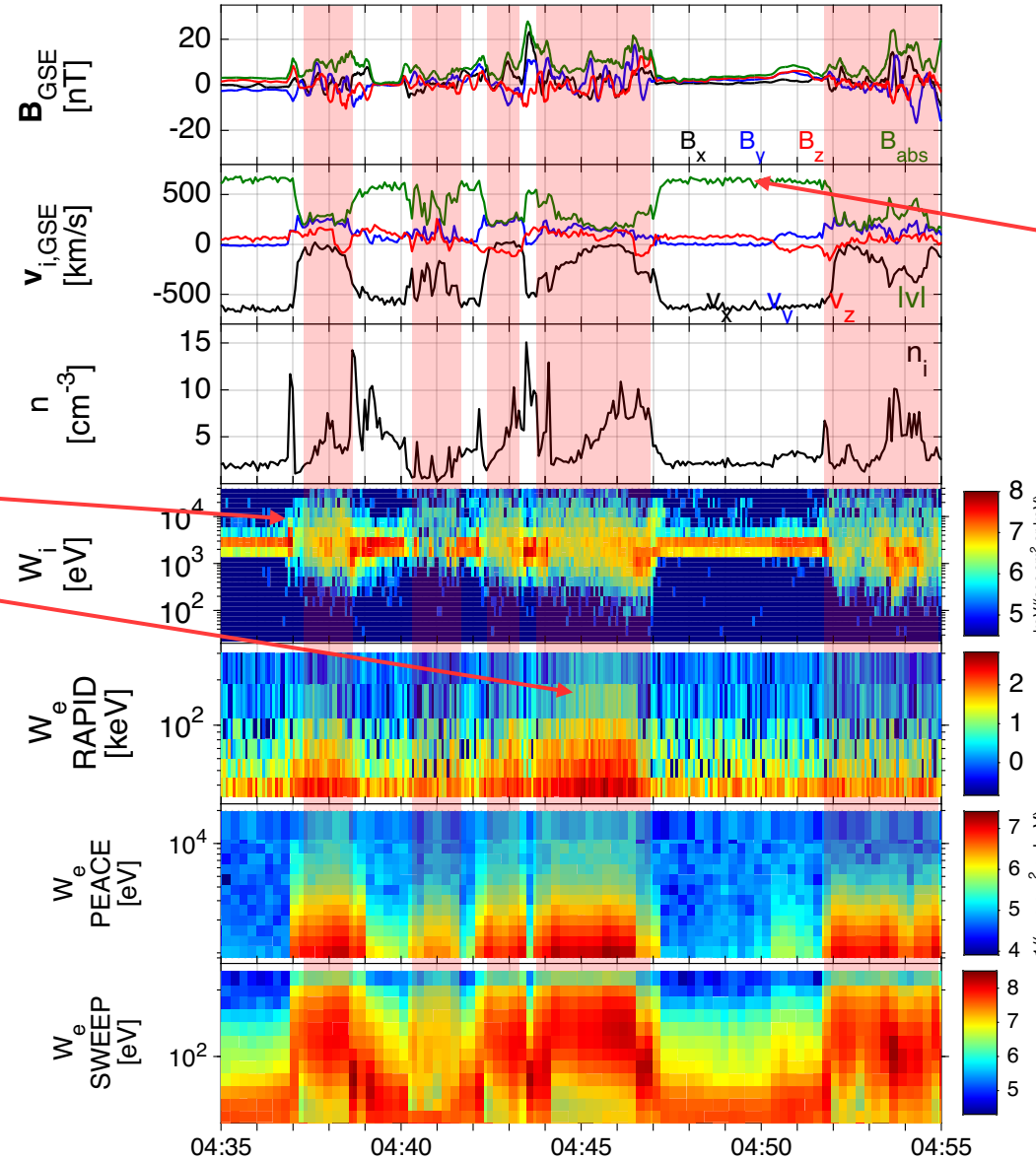
$$\text{Ratio} = \frac{F_{1-5 \text{ KeV}}}{\langle F_{1-5 \text{ KeV}} \rangle_{BG}}$$

2017-01-08T04:45:30



Cluster: Upstream showing HFAs

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



700 km/s Solar Wind!

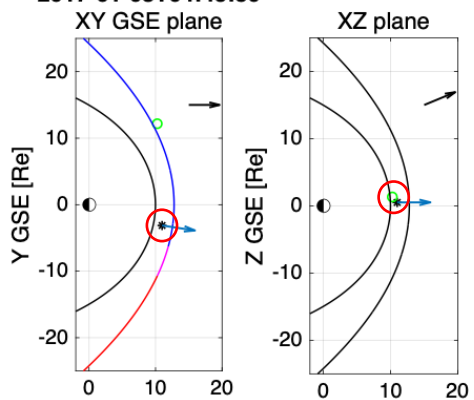
Fast coronal hole plasma consistent with our previous work ✓

Typical properties:

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

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

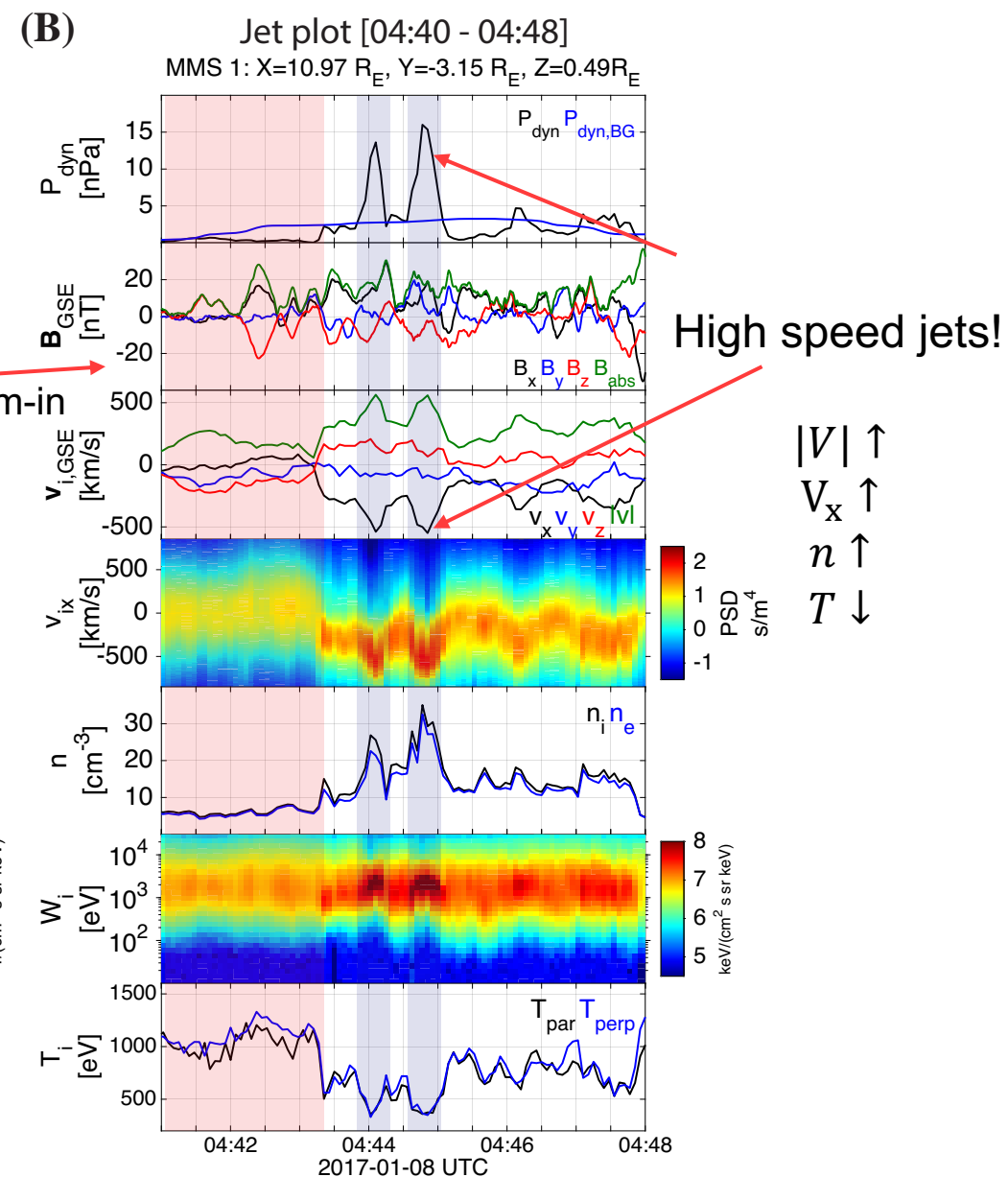
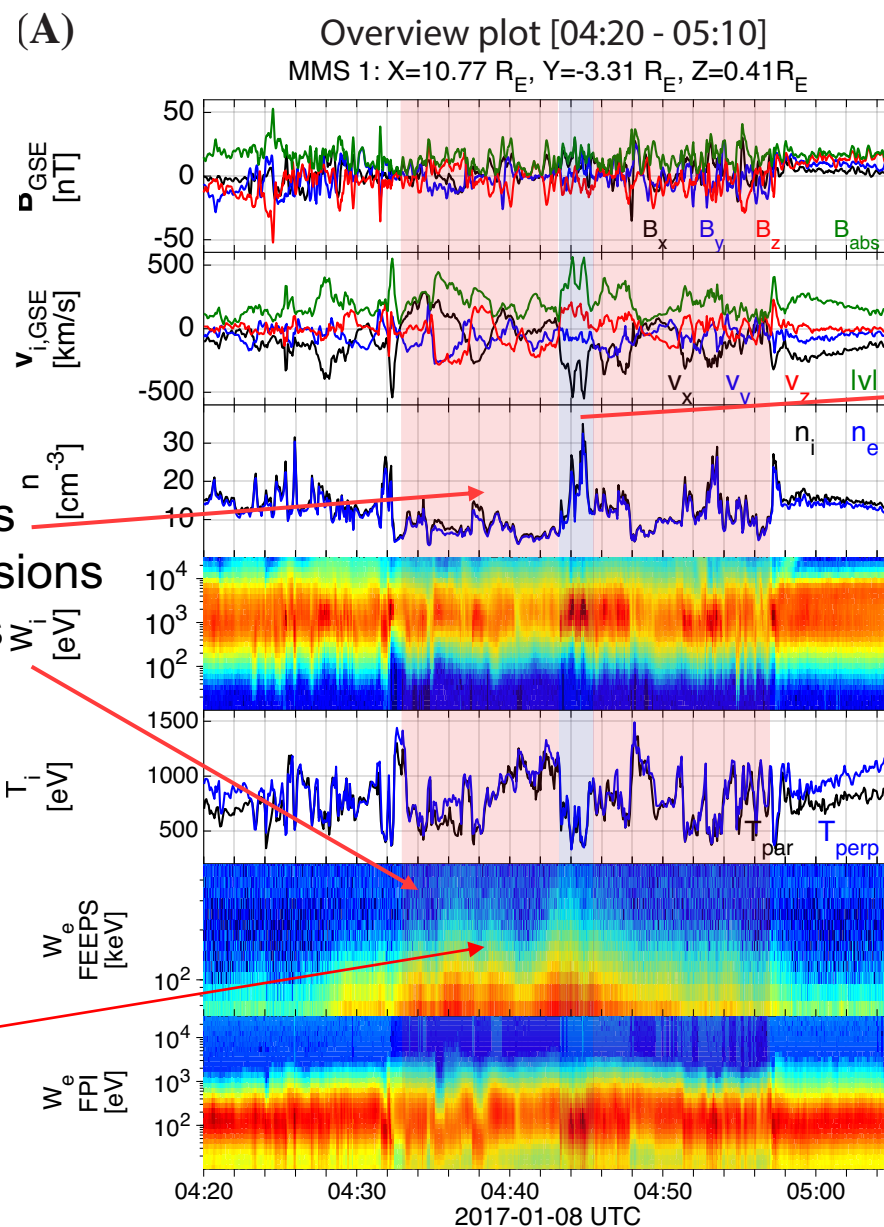
2017-01-08T04:45:30



MMS: Downstream HFAs and jets

- Hot Flow Anomalies
- Localized compressions
- ~300 keV electrons

- 20+min interval



Zoomed-in timeseries of Transient

Foreshock Transient (HFA):

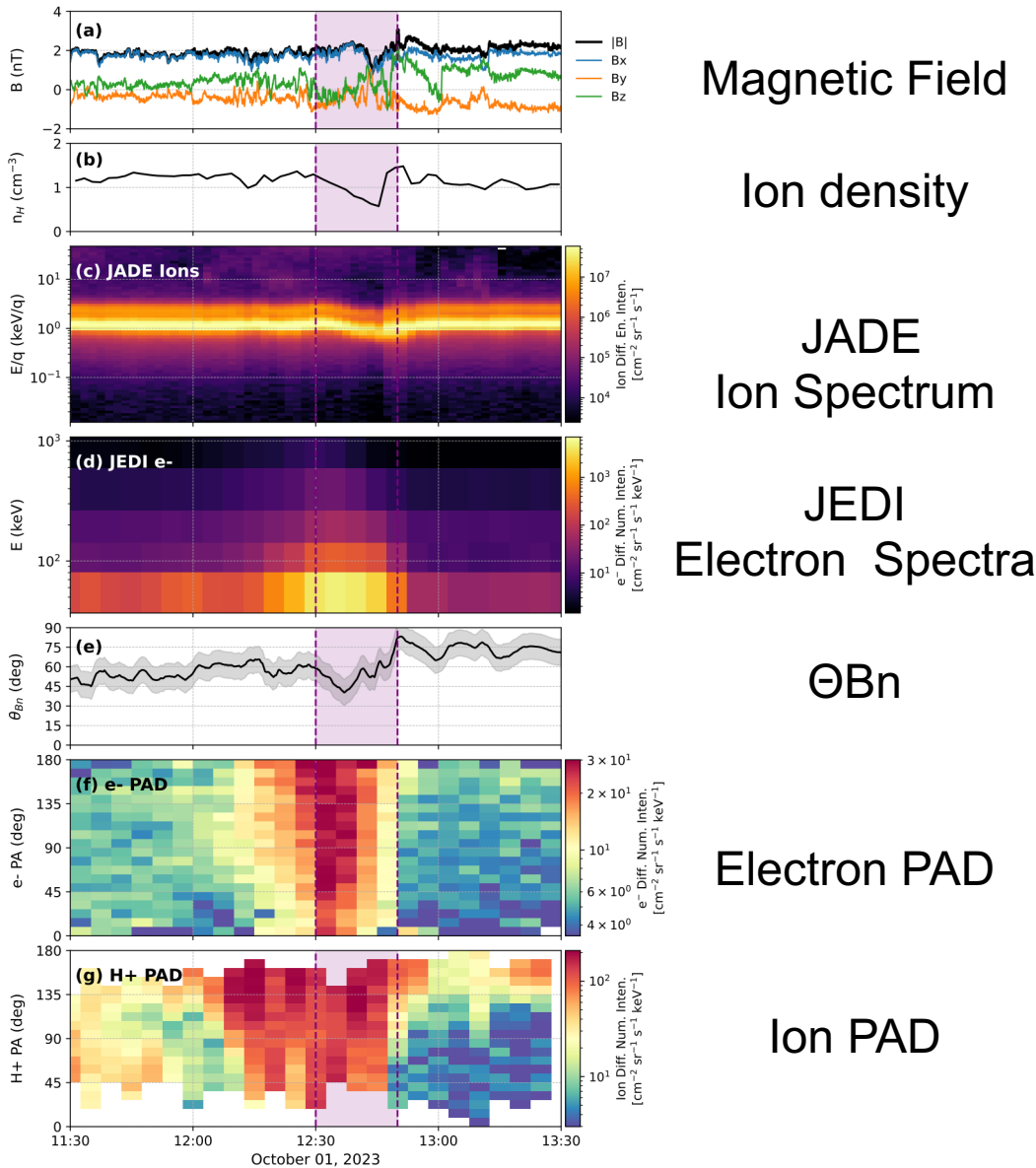
- High energy electrons **up to 1 MeV** (agreement with *Raptis+2025a,b*)
 - Disrupted solar wind beam
 - Localized depletion of n and B
- Using bow shock model (Joy+ 2002), local angle changes from ~40 to ~75 degrees

Global Geometry:

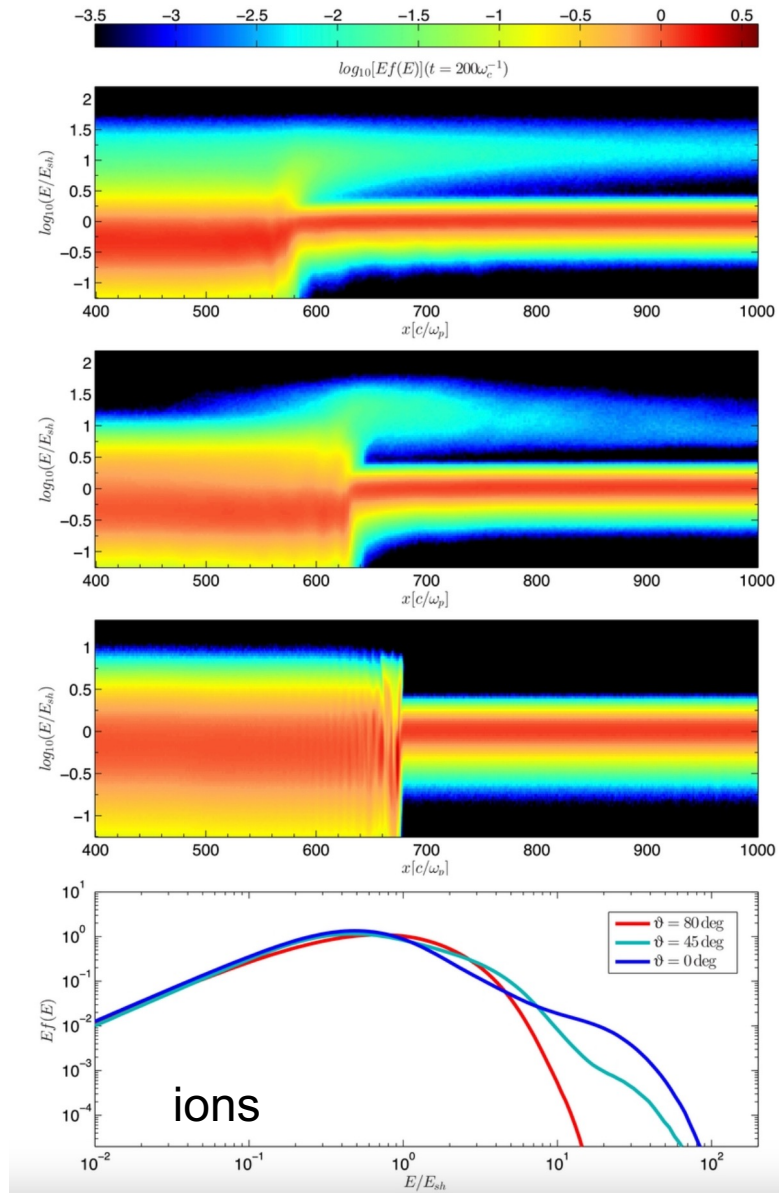
- Pitch Angle Distributions (PADs):
- ✓ Isotropic distribution, strong scattering
 - ✓ No trapped population
 - ✓ Localized within the ~15min interval

Extended Data Table I. Properties of the foreshock transient observed by Juno.

Parameter	Symbol	Value
Interval Duration	Δt	≈ 900 s (15 min)
Solar Wind Speed (X-JSO)	v_{sw}	400 km/s
MVA Quality Ratio	$\lambda_{int}/\lambda_{min}$	5.82
Boundary Normal (JSO)	$\mathbf{n}_{MVA}$	[0.80, -0.58, 0.17]
Effective Speed	v_{eff}	≈ 318 km/s
Transient Scale Size	L	2.86×10^5 km



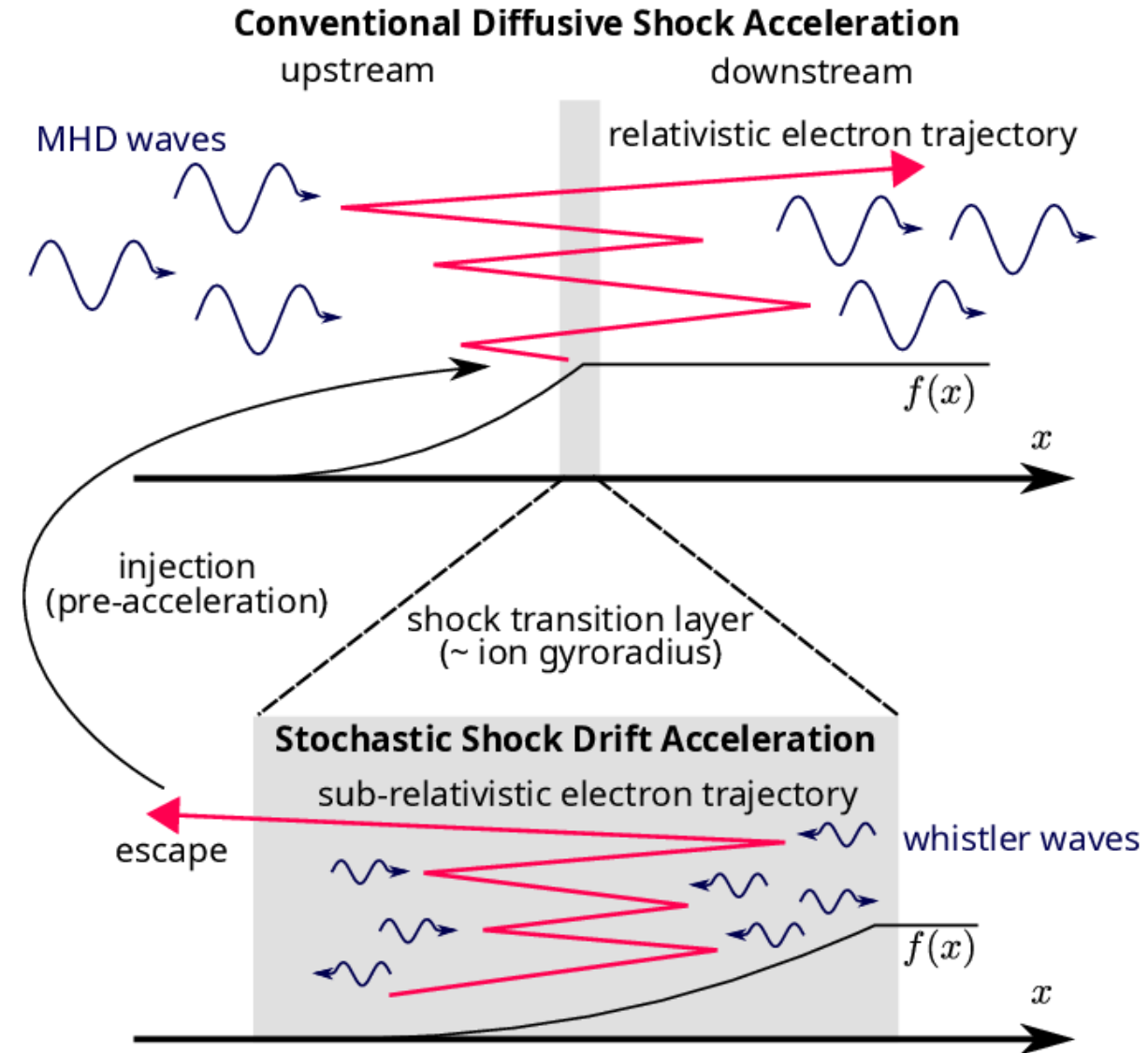
Acceleration at Qpar and Qperp shocks



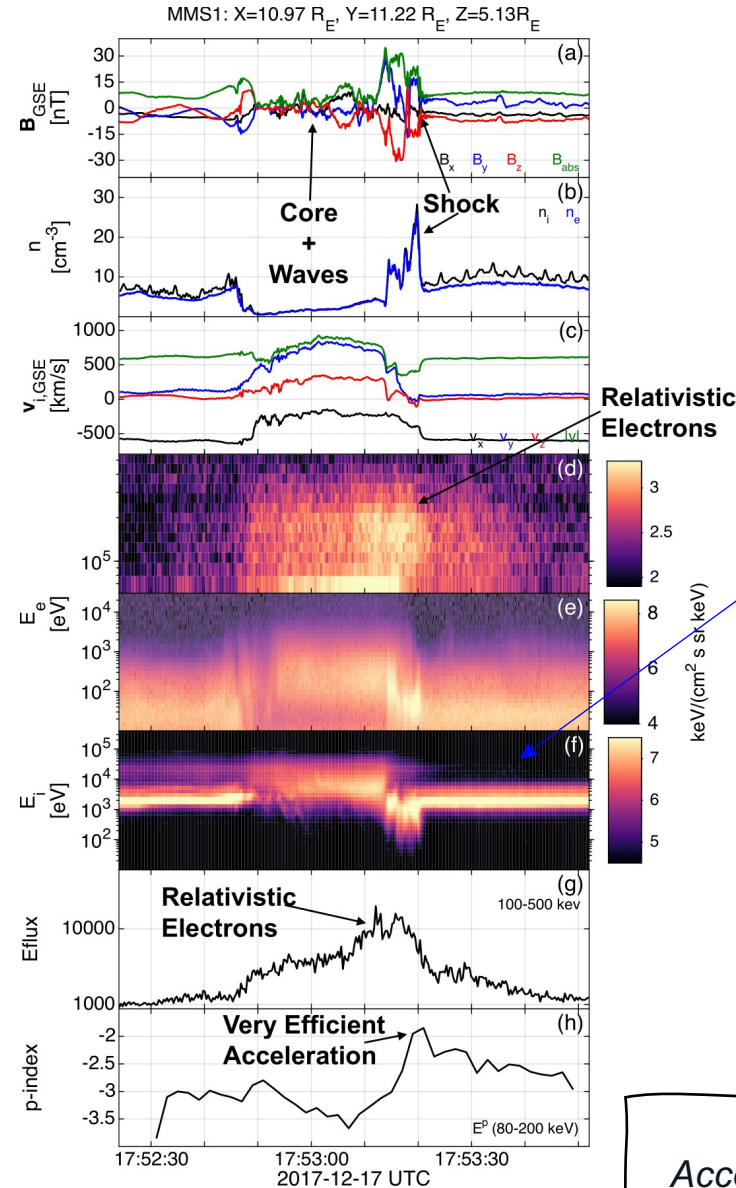
Qpar shock (DSA)

Oblique shock

Qperp shock (SDA/SSDA)



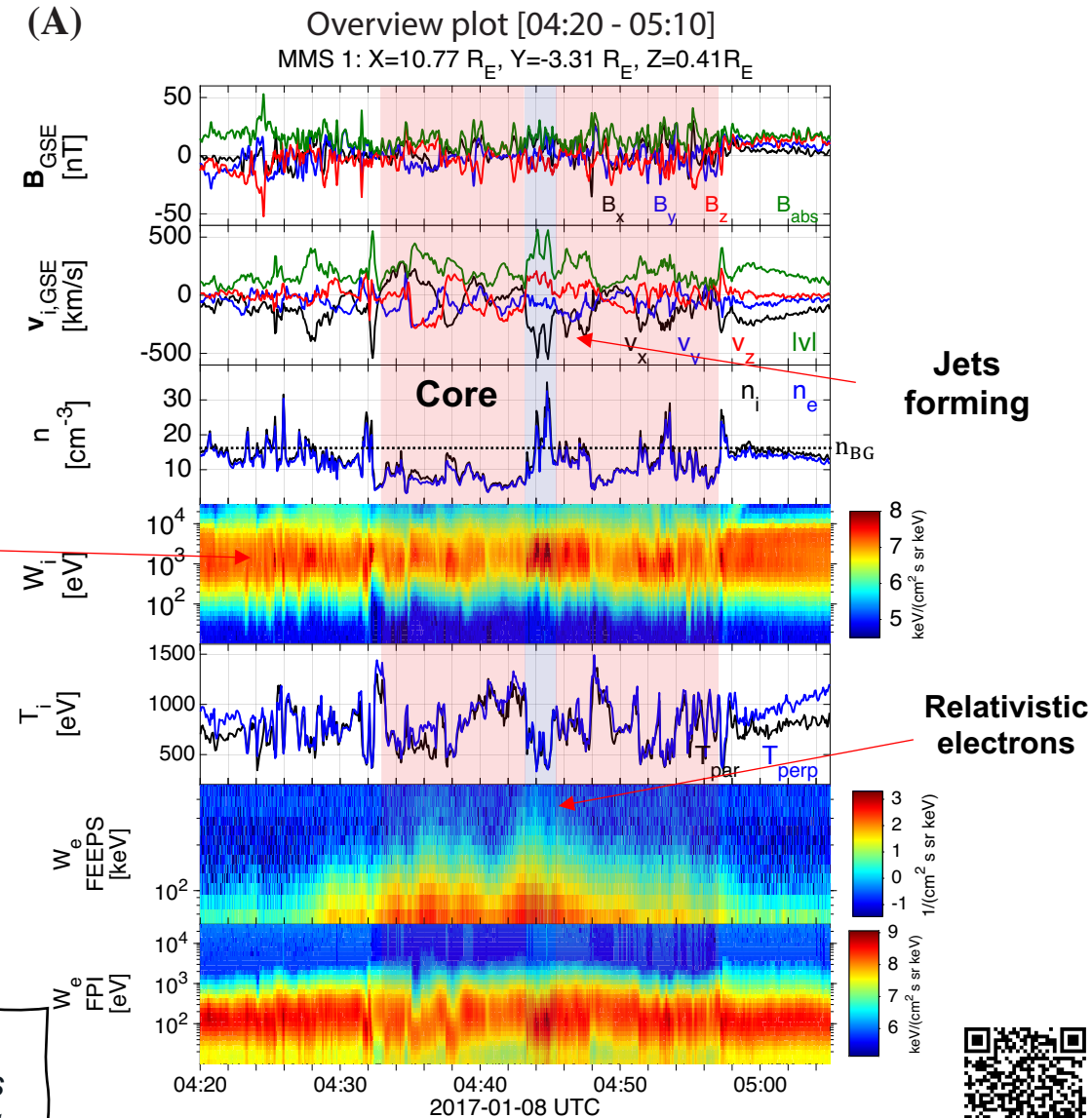
Shock-generated transients are amazing particle accelerators



Solar wind

Magnetosheath

Transients get transmitted
Accelerating particles in the process
restructuring the sheath & forming jets



Transients with most notable impact

How many: ~several per day!

How big: up to ~10s of Re

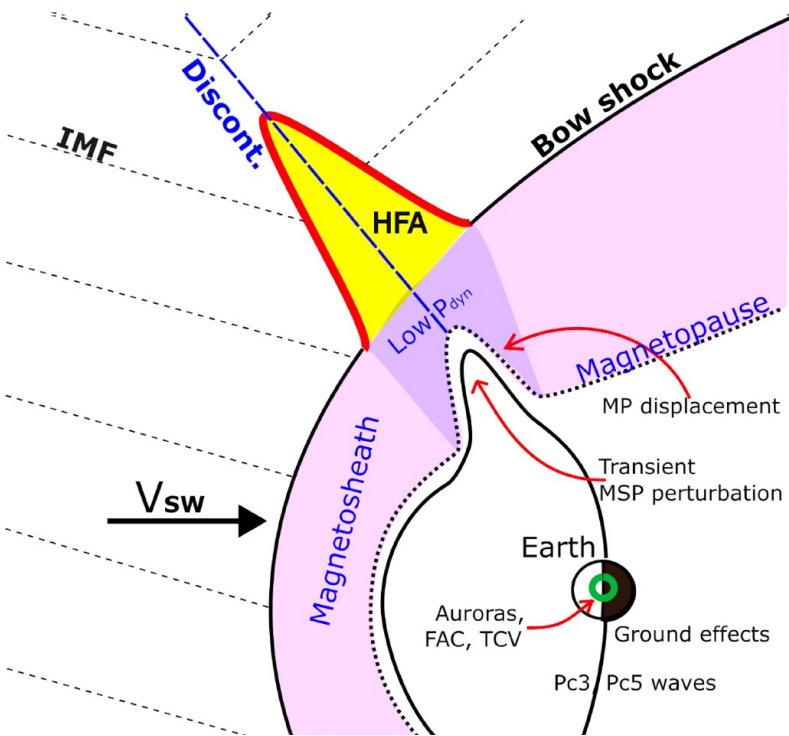
HFAs

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

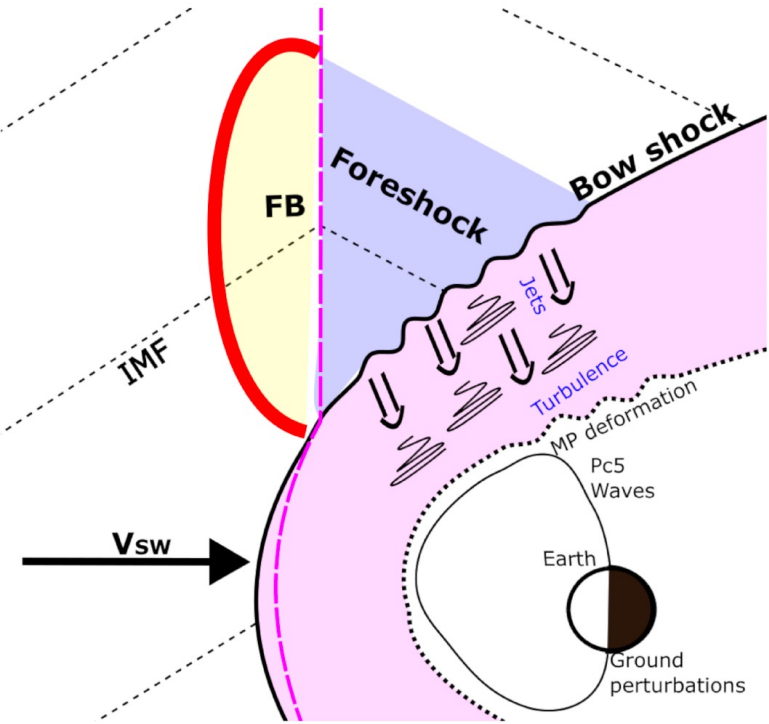
FBs

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)

The anatomy of an HFA

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

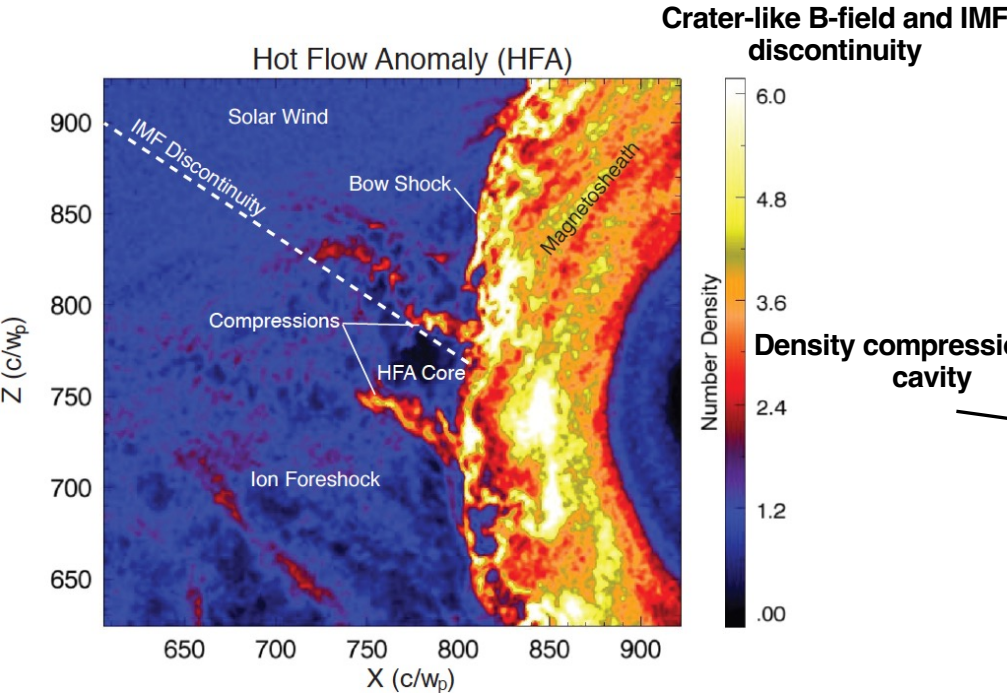
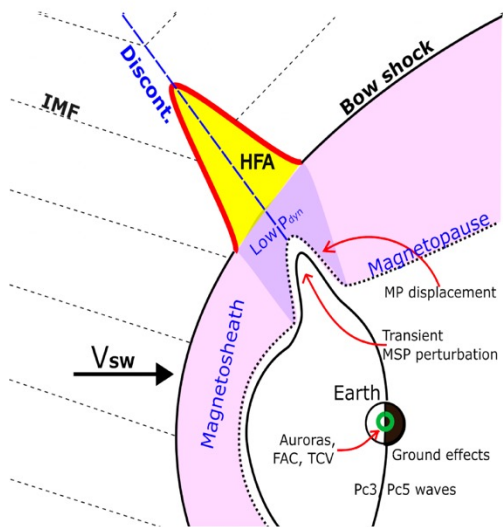


Figure by Nick Omid

Hot Flow Anomalies (HFA)

Kajdič+ (2024)

How do they form?

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

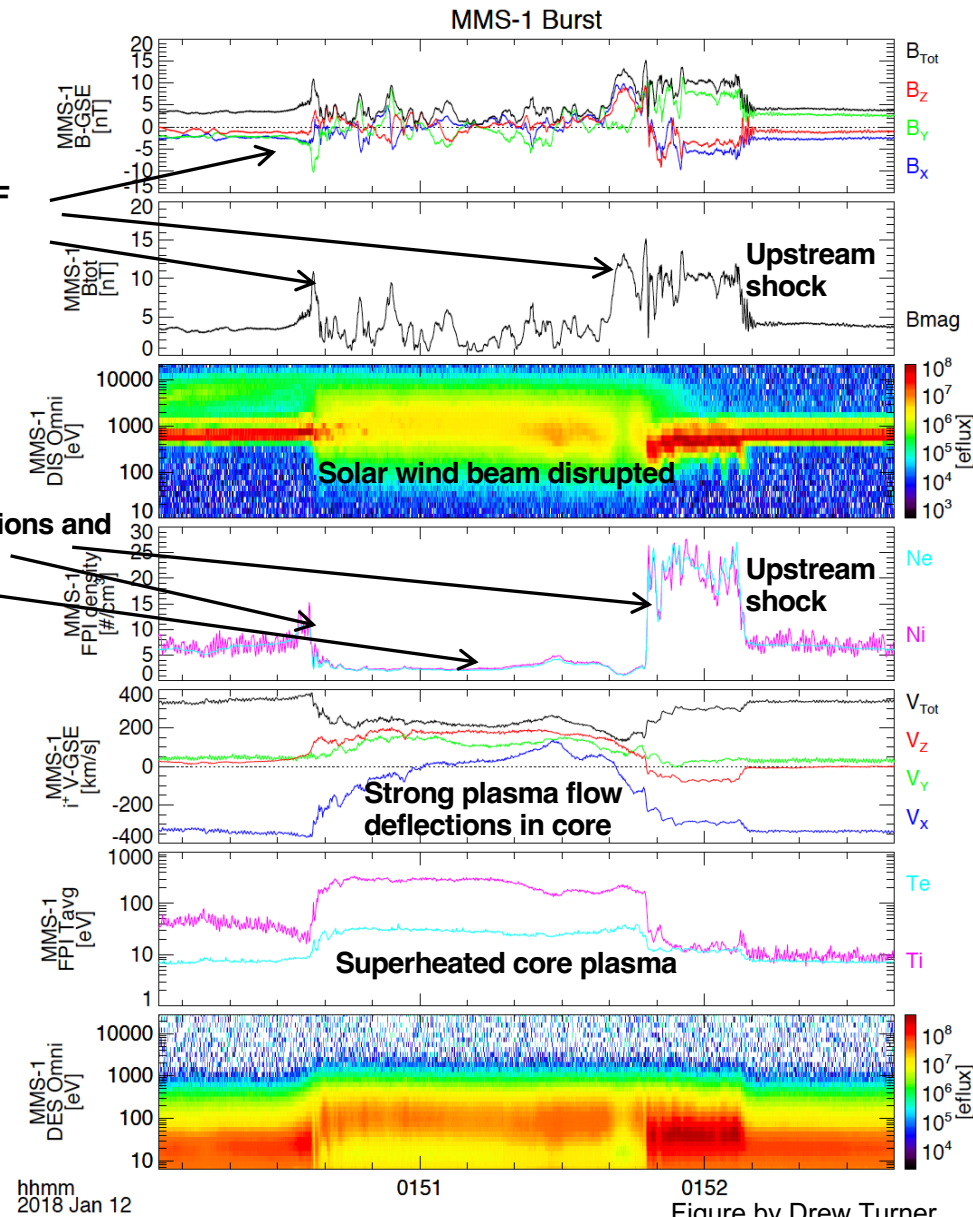
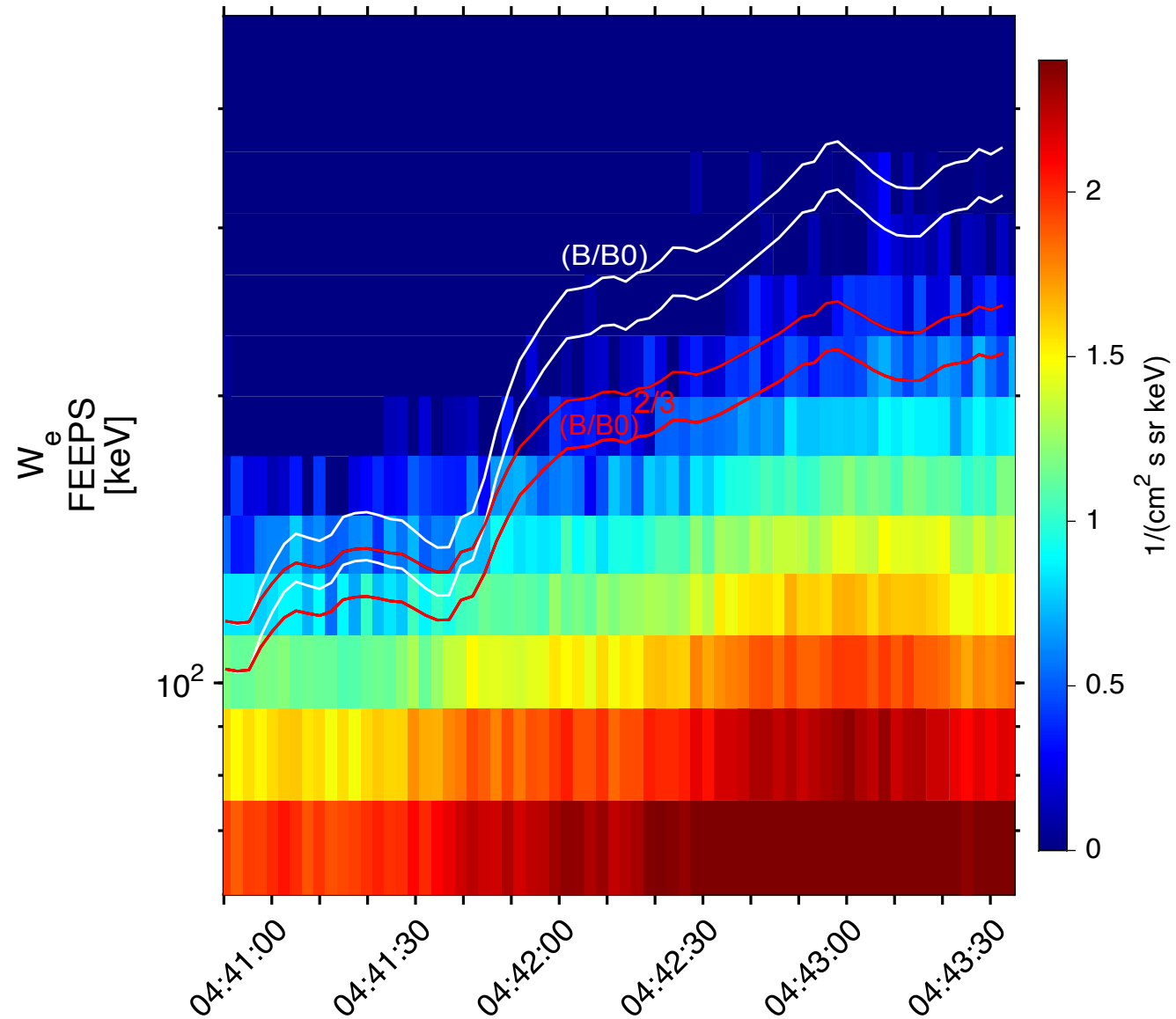
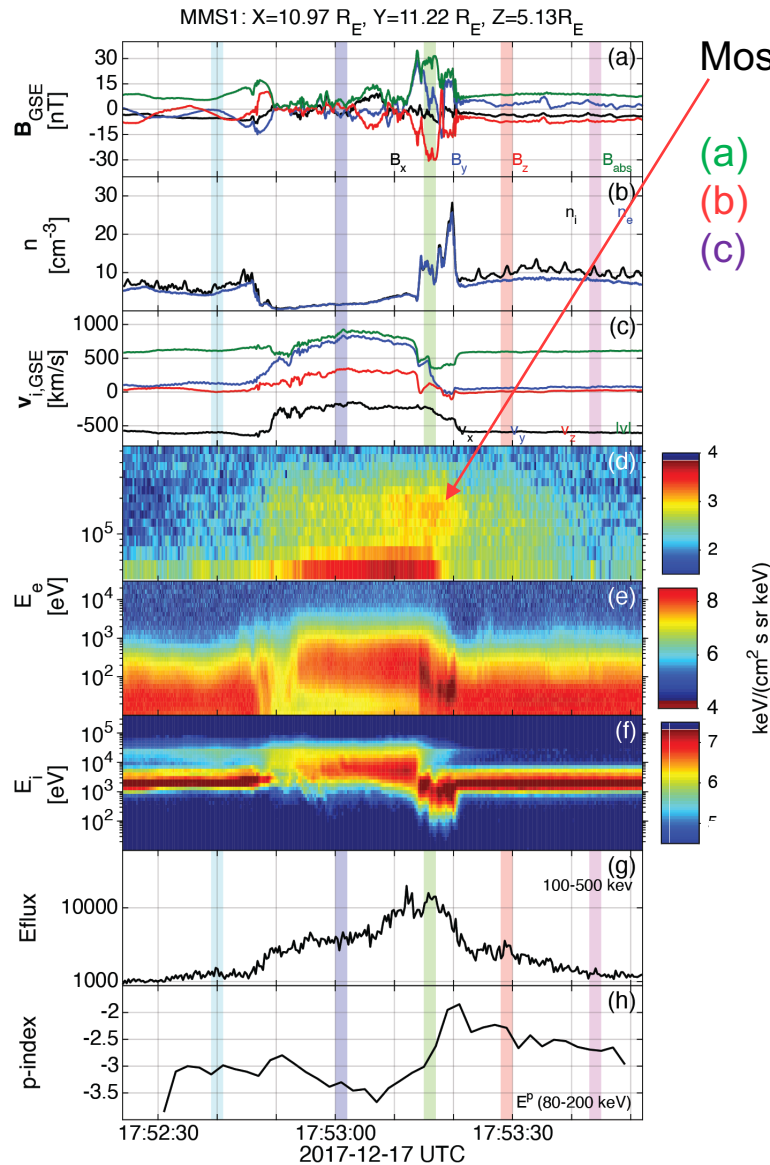


Figure by Drew Turner

Why Stochastic Betatron Acceleration? Better agreement

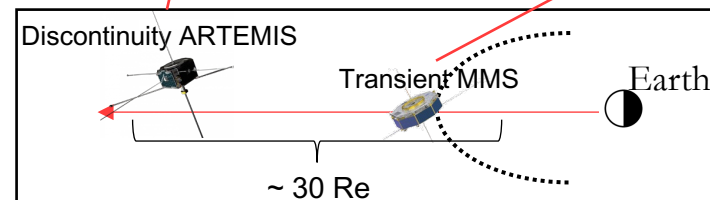
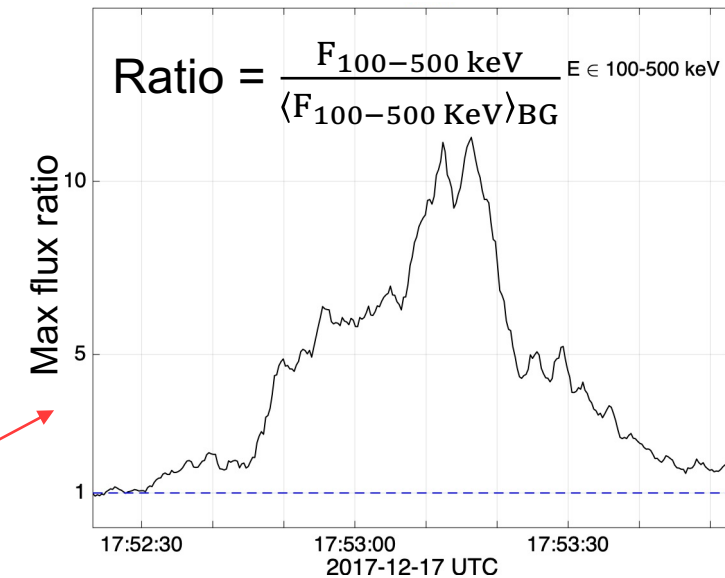
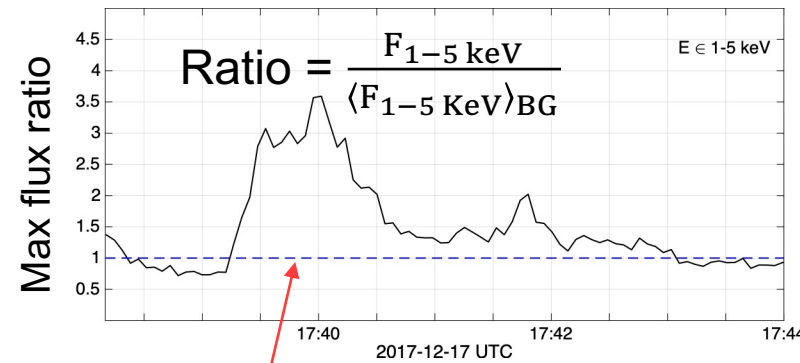


Reinforced Shock Acceleration of Relativistic Electrons



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

- (a) Seed population from fast coronal hole solar wind at suprathermal energy range (~1-5 KeV)
- (b) Shock acceleration (SDA/Betatron/Fermi) + Wave particle interaction
- (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.

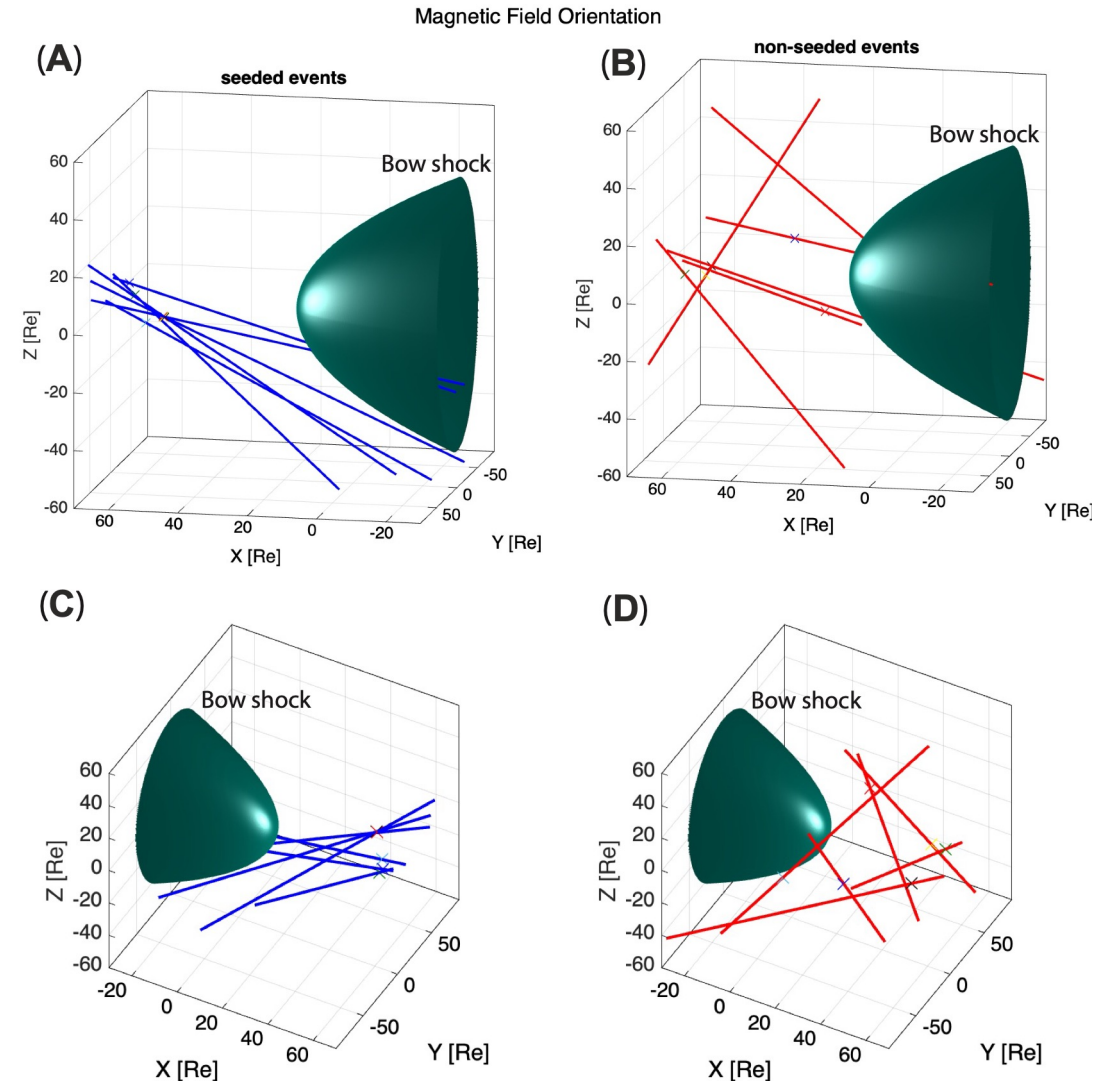
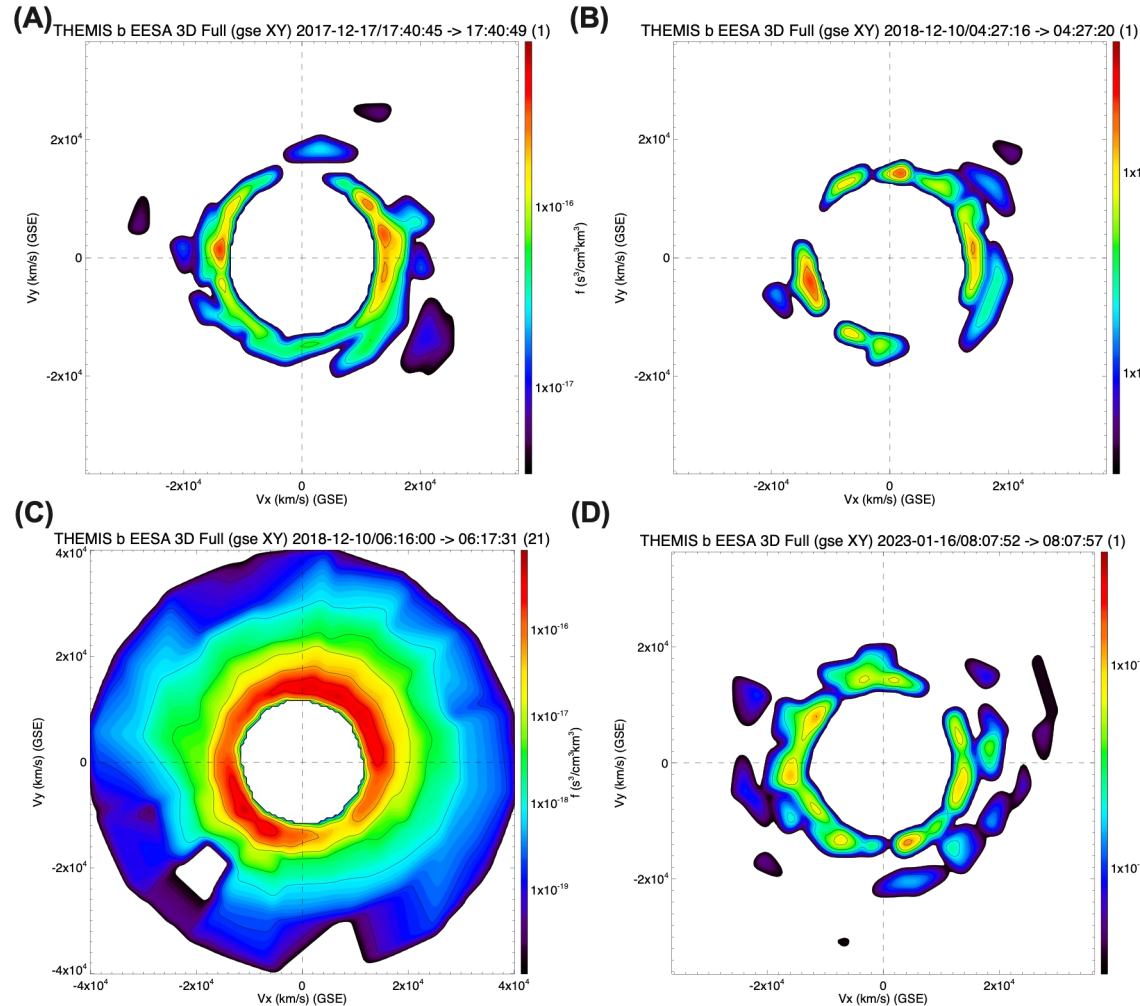
Is seed from the foreshock? – Maybe partially

(A), (B) → Seeded events – partial mode

(C) → Seeded event full mode

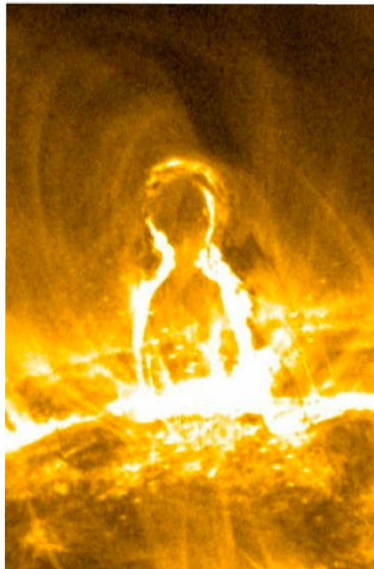
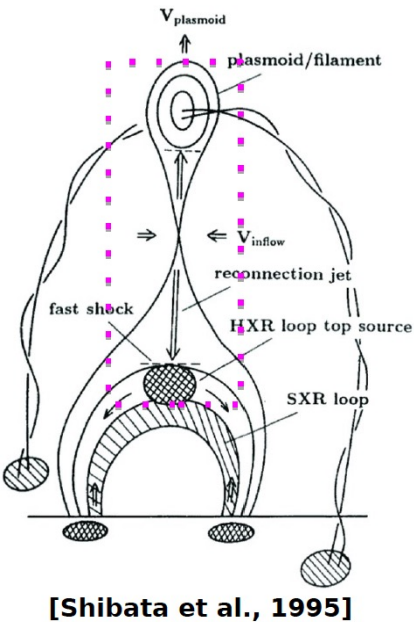
(D) → Non-seeded event – partial mode

3/6 seeded and 2/6 non seeded connected to foreshock

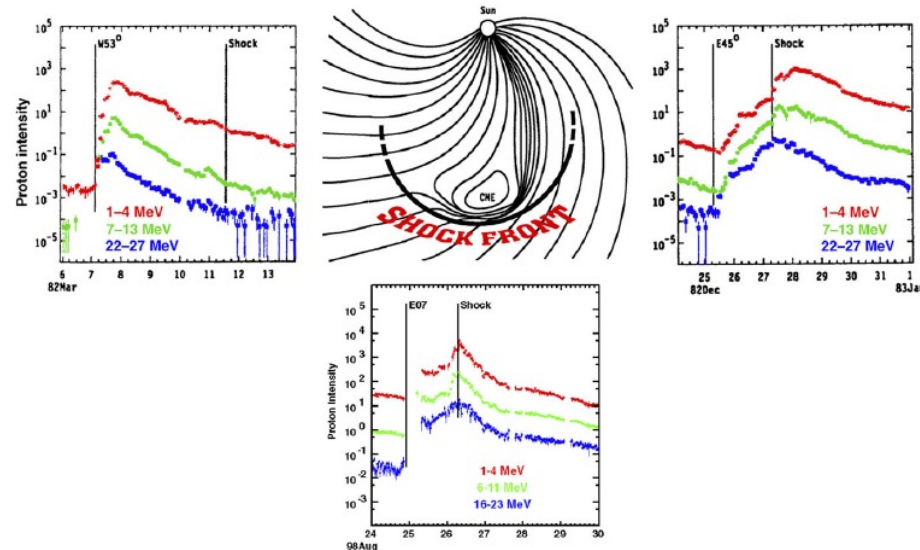


Shocks as particle accelerators

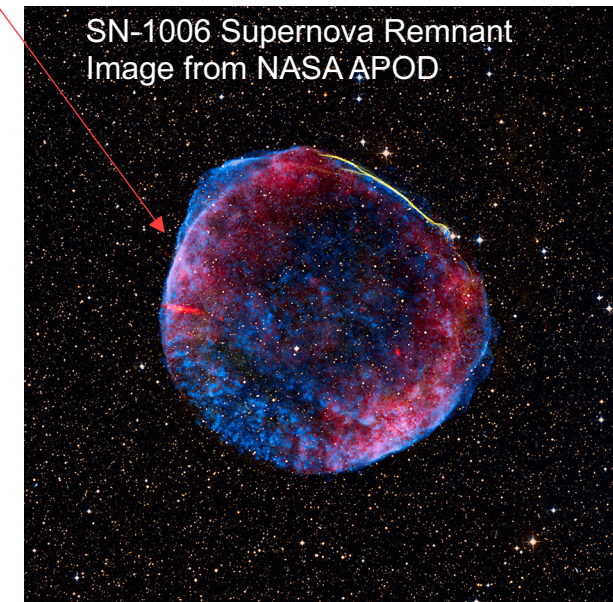
- Different shock geometries and particles have different acceleration mechanisms invoked but all can accelerate particles
- **Astrophysics:** Supernova remnants, cosmic rays
- **Solar Physics:** SEP acceleration, fast shock at reconnection



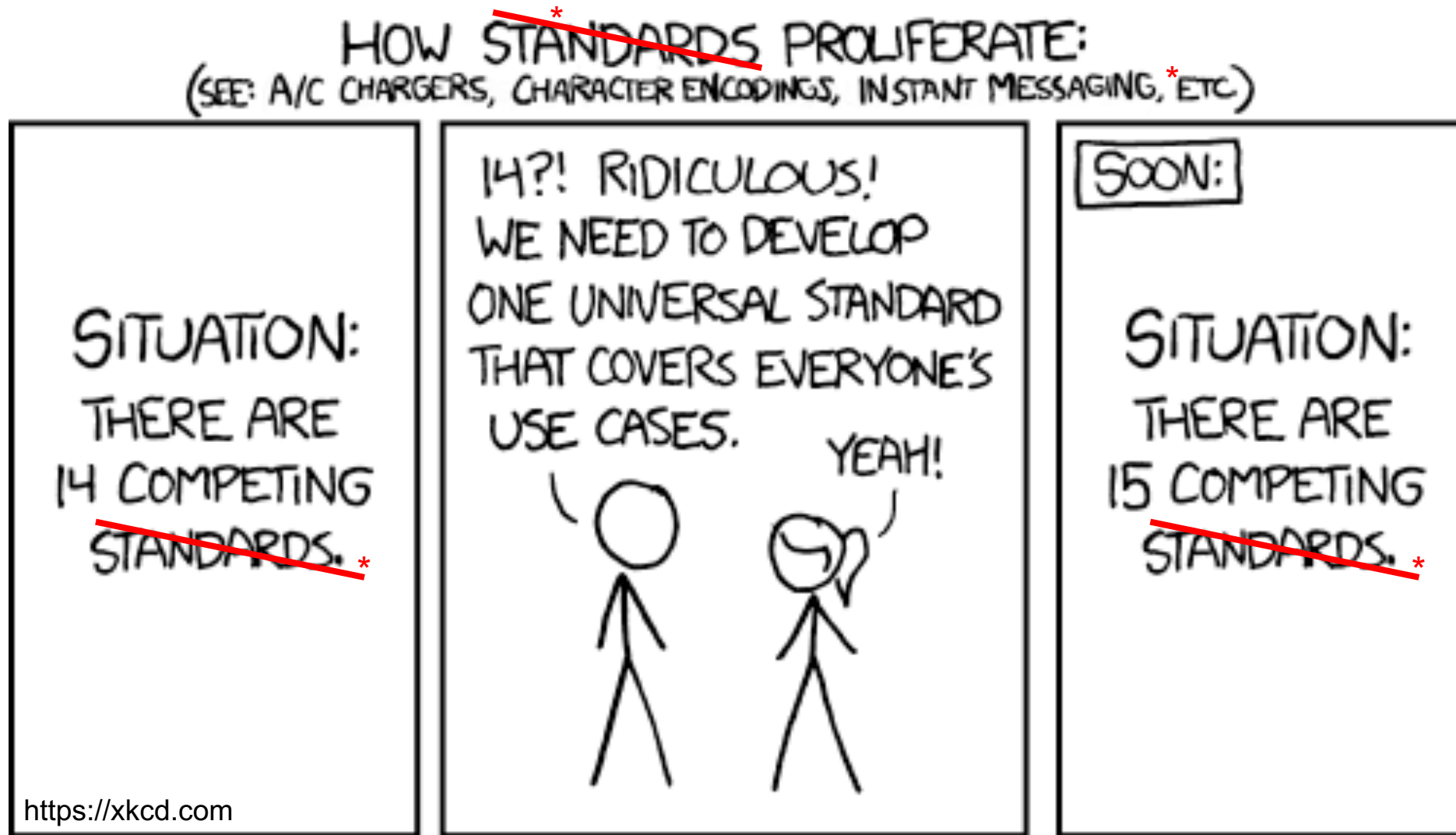
Courtesy of Li-Jen Chen, GSFC



Shock wave

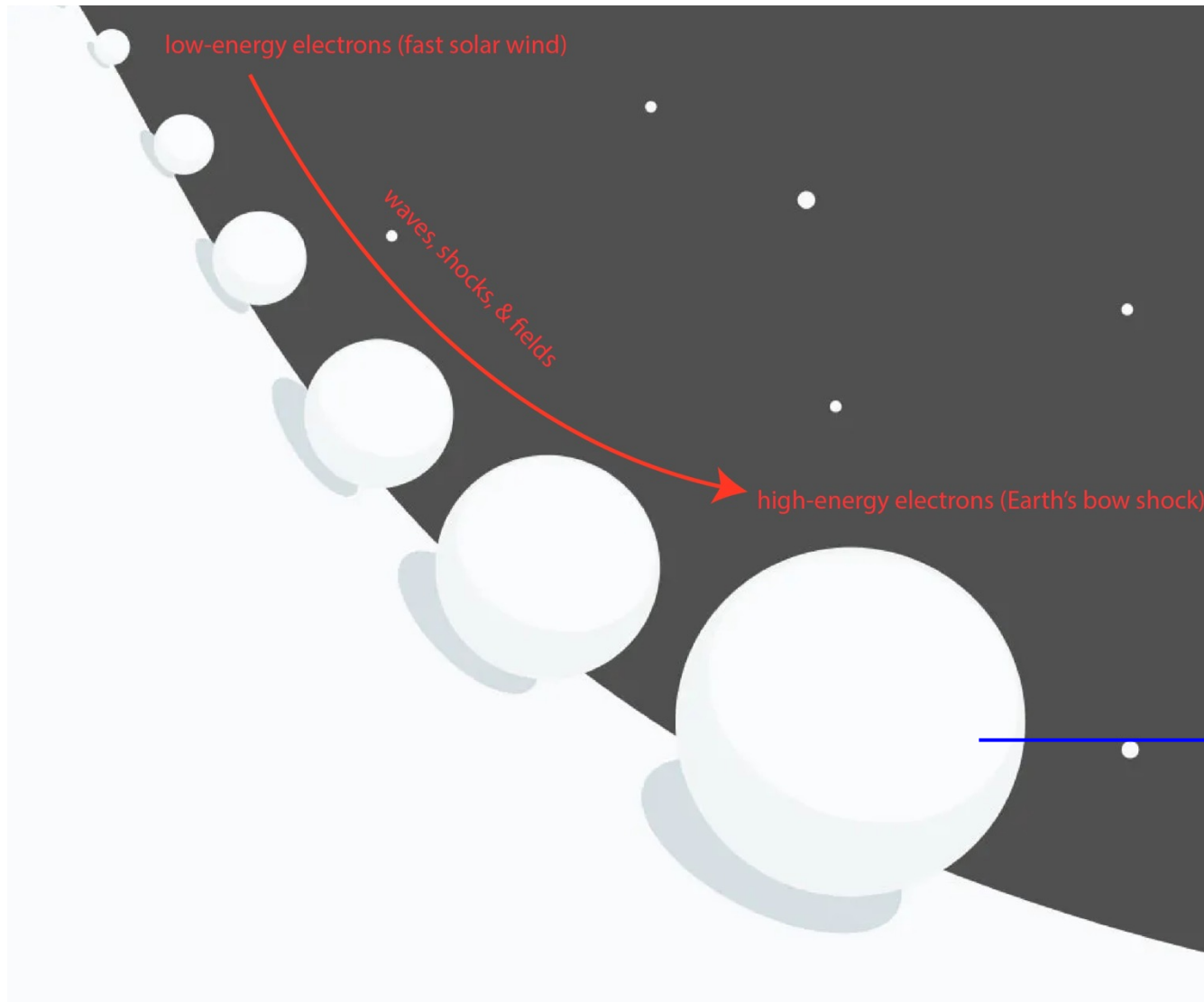


Expectation & Reality

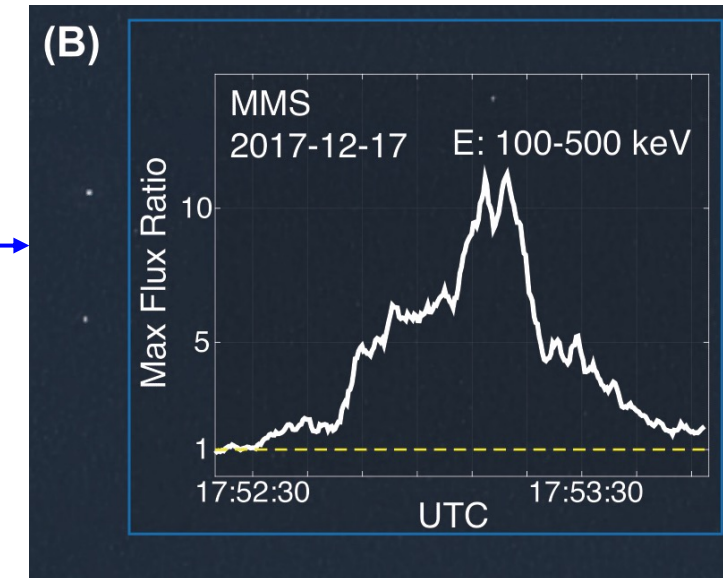
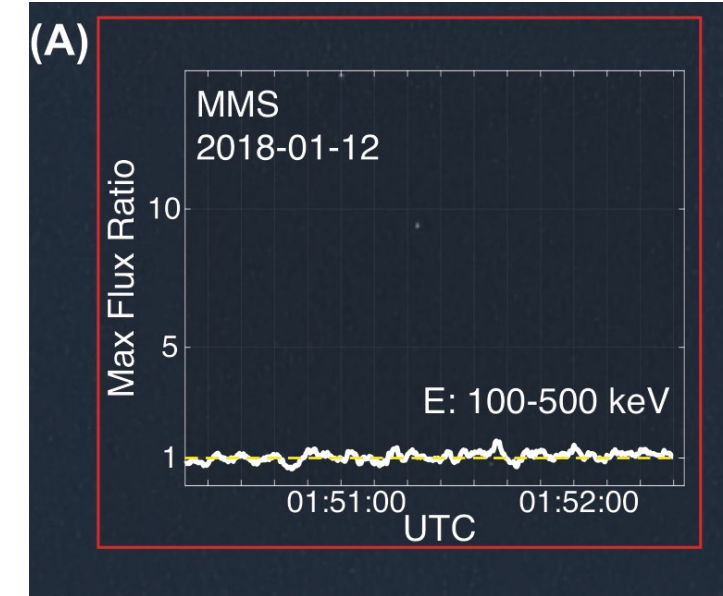


*In our case typically it is models, mechanisms, frameworks etc.

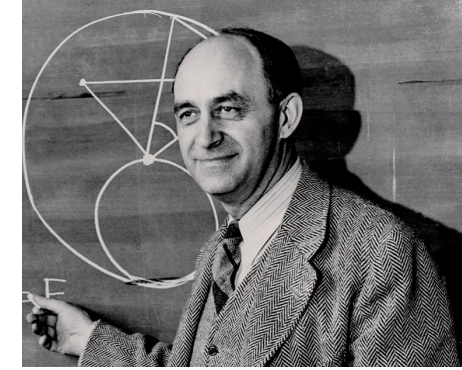
Simple Simplistic Picture to remember



✗



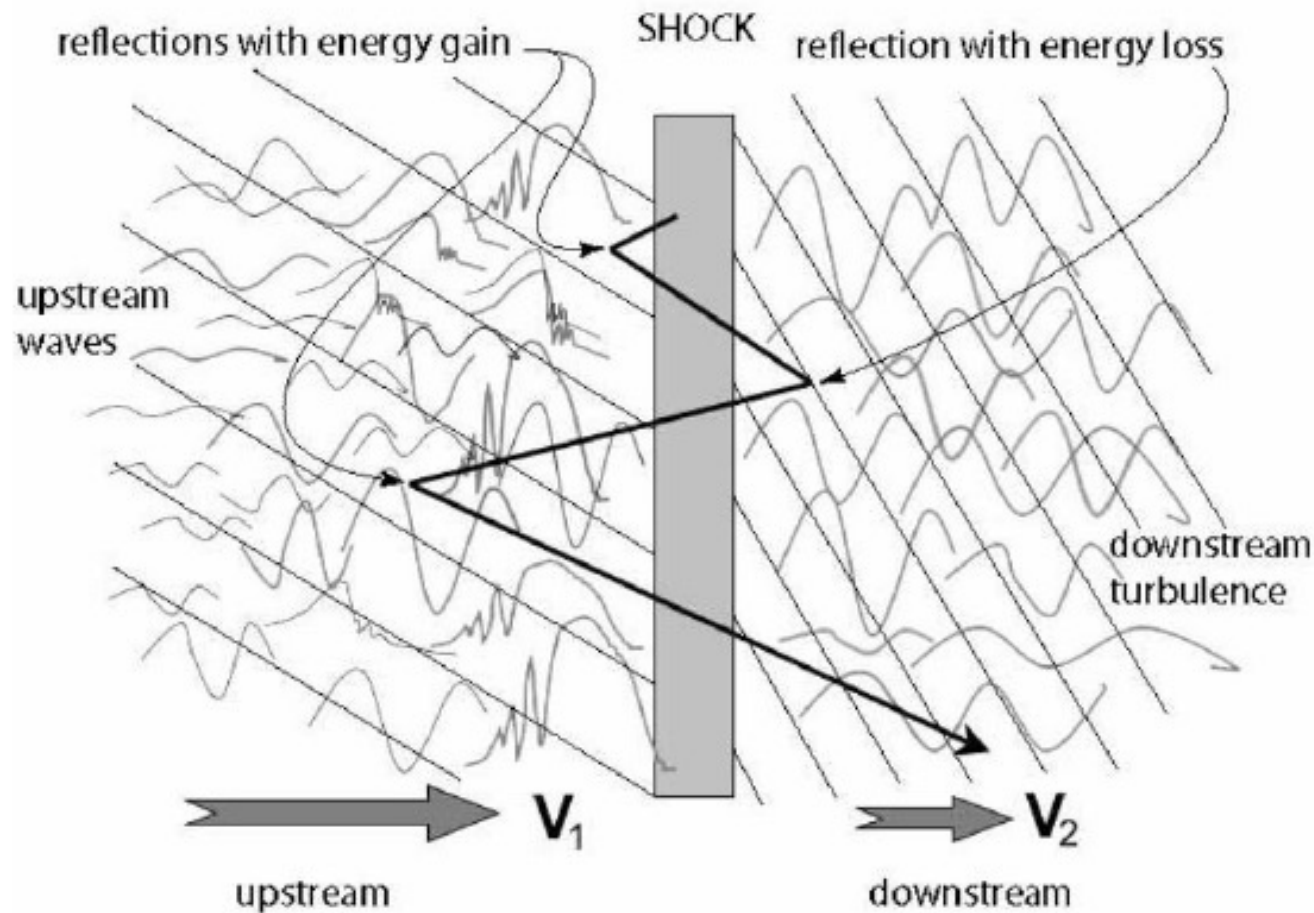
Diffusive Shock Acceleration (DSA)



$$\beta = V_{c-s}/c < 1$$

1st Order Fermi, head-on collisions guaranteed
(quasi-para shocks):

$$\langle \Delta E/E \rangle \sim 4/3 \beta$$



Simplified explanation

- Waves + turbulence downstream = Scatter particles back to the shock
- Some of the particles get to very high energies.

Injection Problem

What is the energy threshold needed to kick start this process and how do we reach that?