

Recent Advancements in Transient Processes and Particle Energization at Collisionless Shocks

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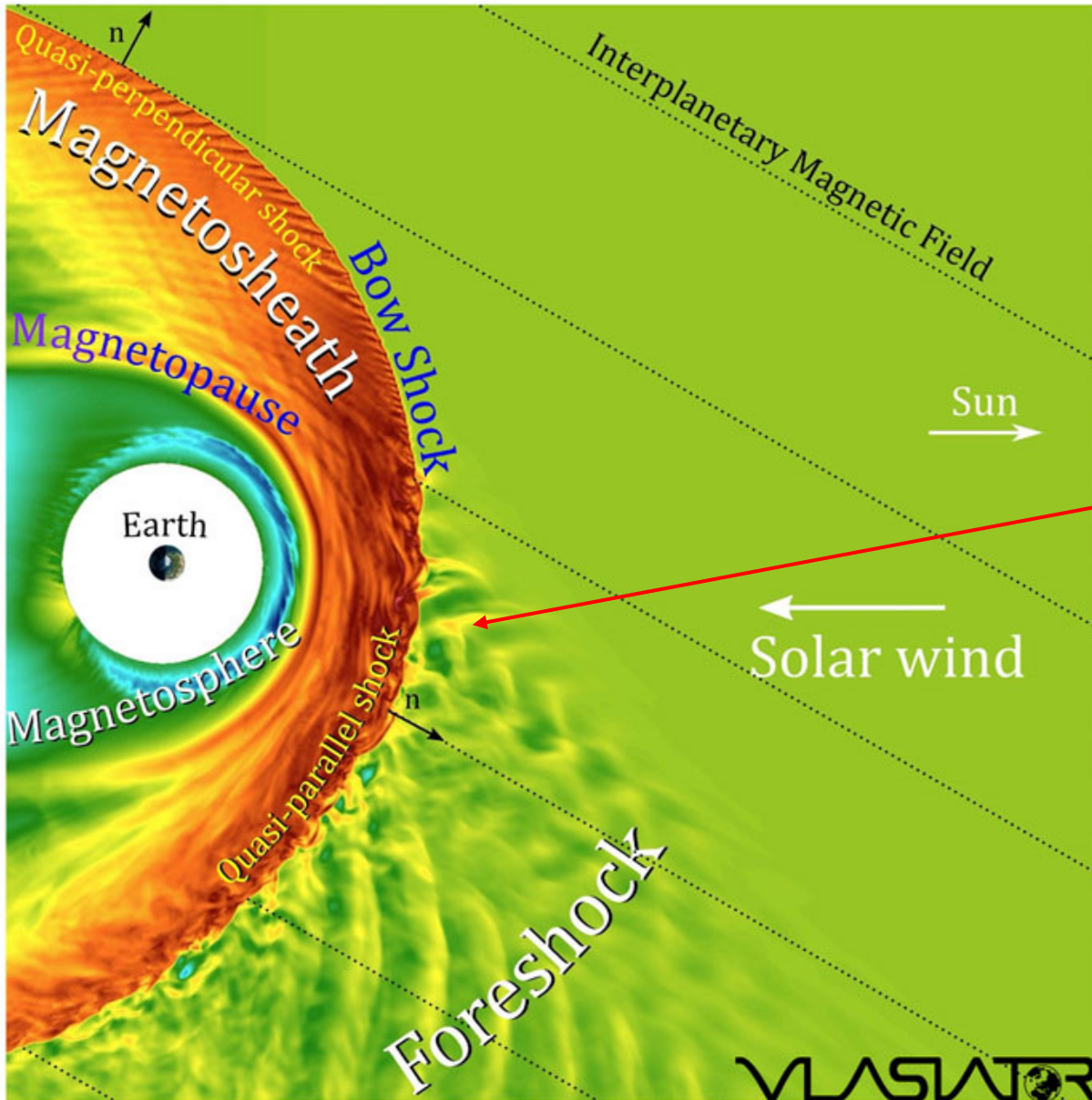
JHU/APL, Laurel, MD, USA

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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

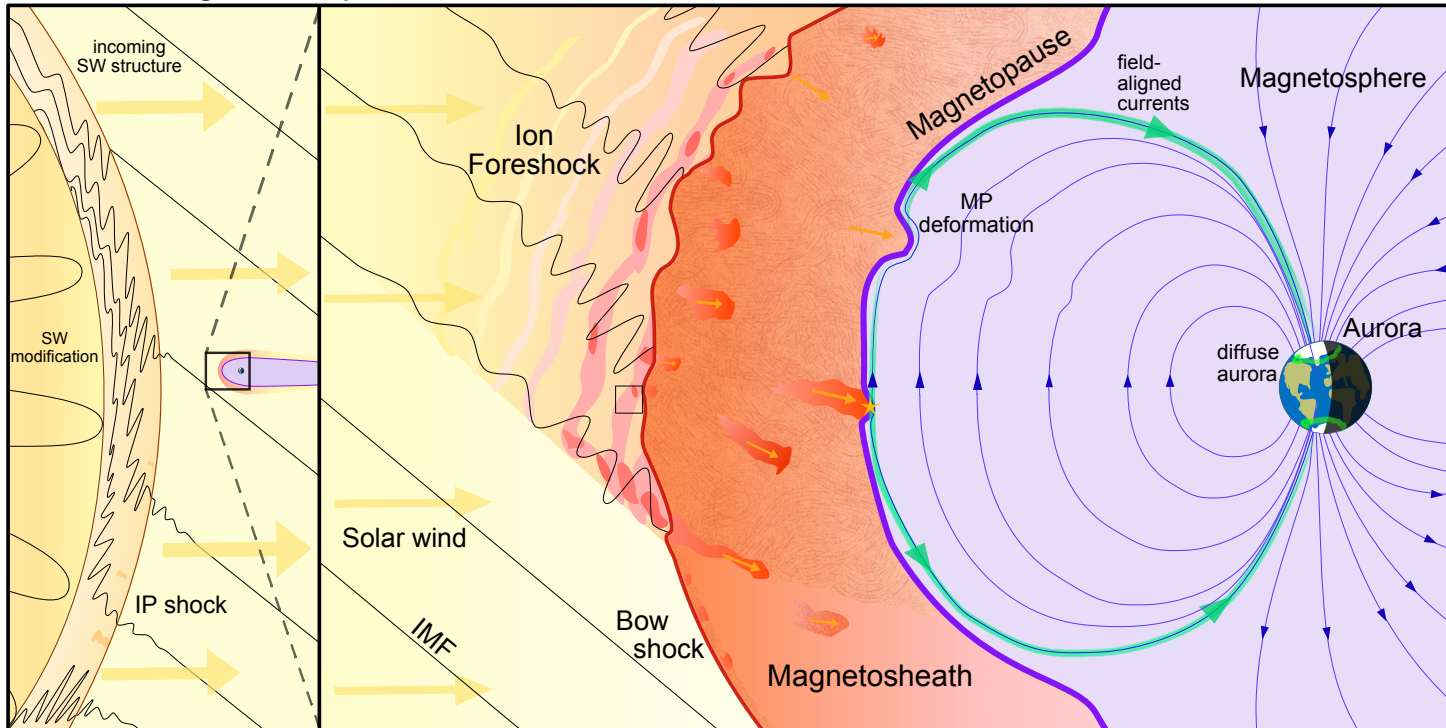
*Astro references on Qpar importance: Caprioli+2014, Giuffrida+2022, Vink+2024

What is a Dayside Transient?



← See the latest review paper about high-speed jets!

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:

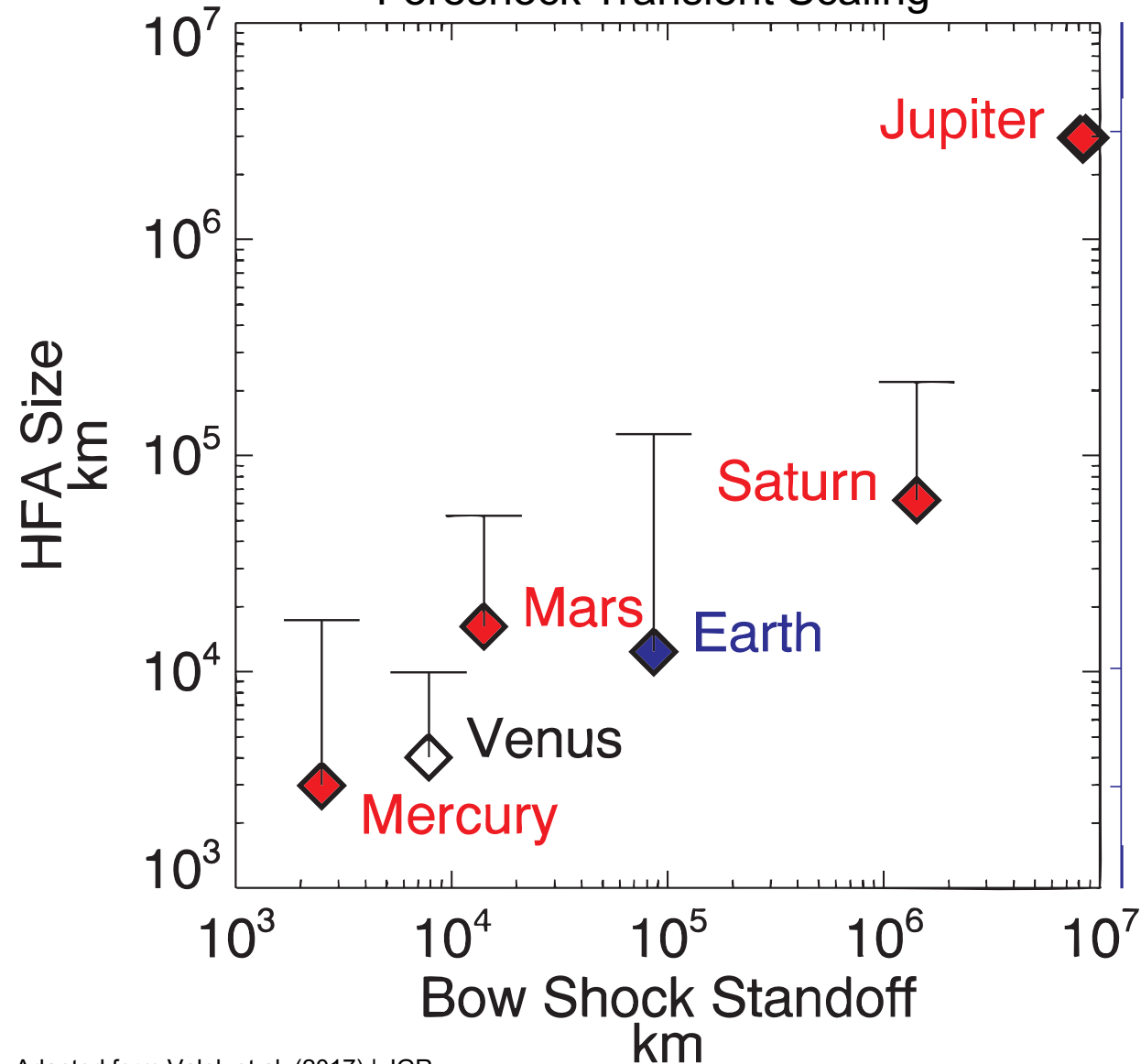
- ULF waves
- Shocklets
- SLAMS

GEM FG: Multiscale Dayside Transients and their Effect on Earth's Magnetosphere

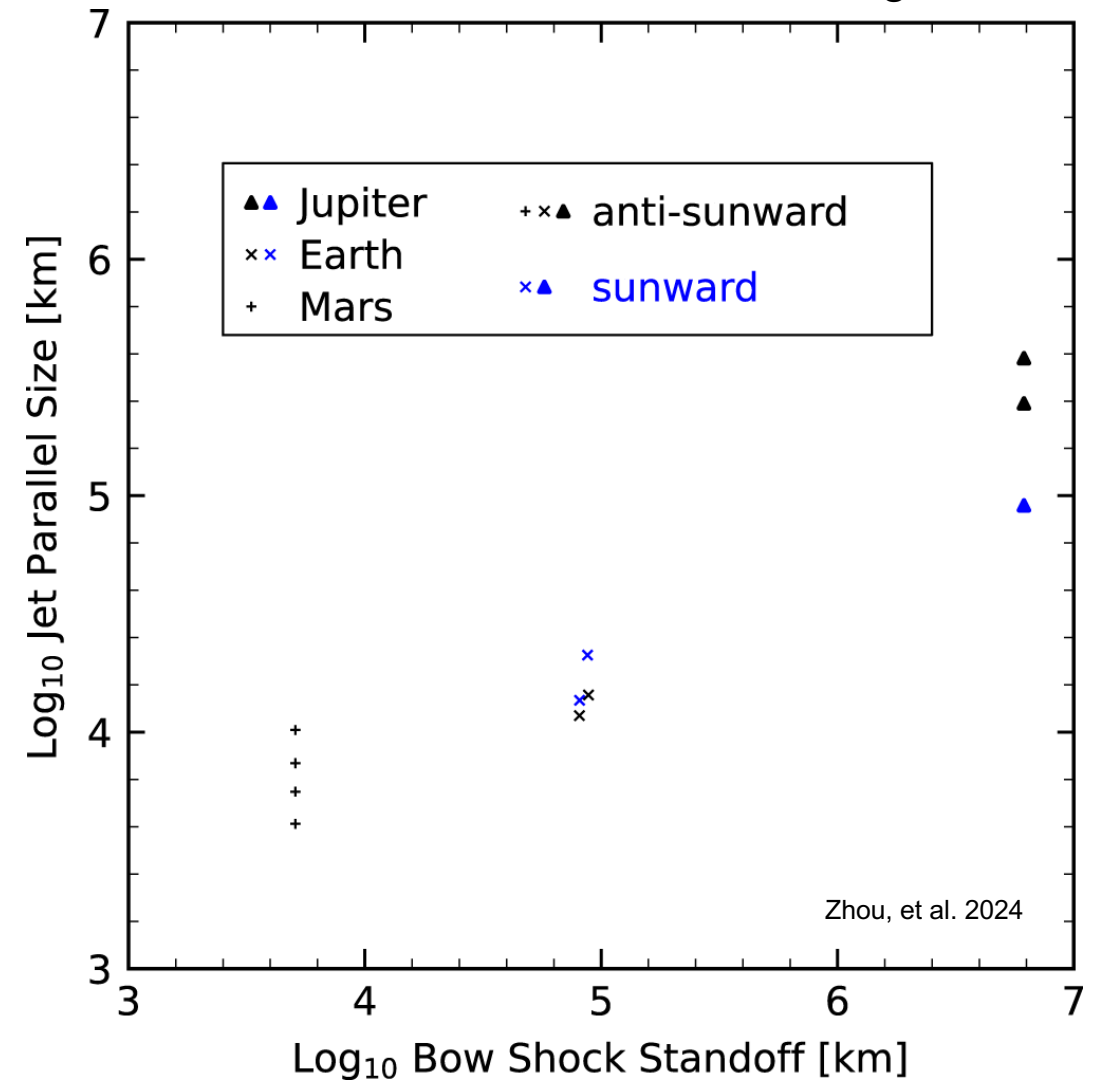
(2025 - 2029; Savvas Raptis, Ivan Vasko, Yuxi Chen, Gonzalo Cucho-Padin, Imogen Gingell, Terry Z. Liu, Ying Zou)

Transients Scaling Across Different Systems

Foreshock Transient Scaling



Downstream Jet Scaling



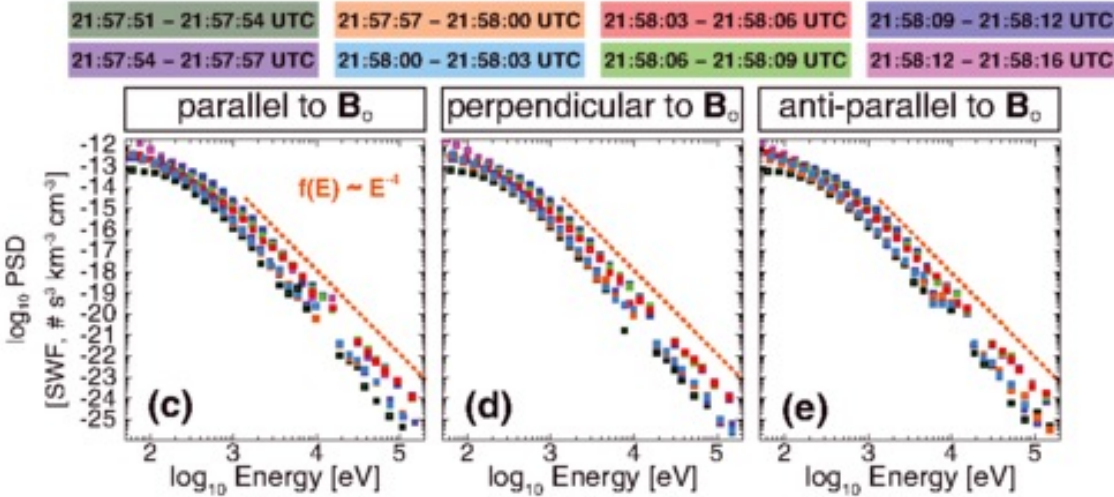
Zhou, et al. 2024

Important point to remember

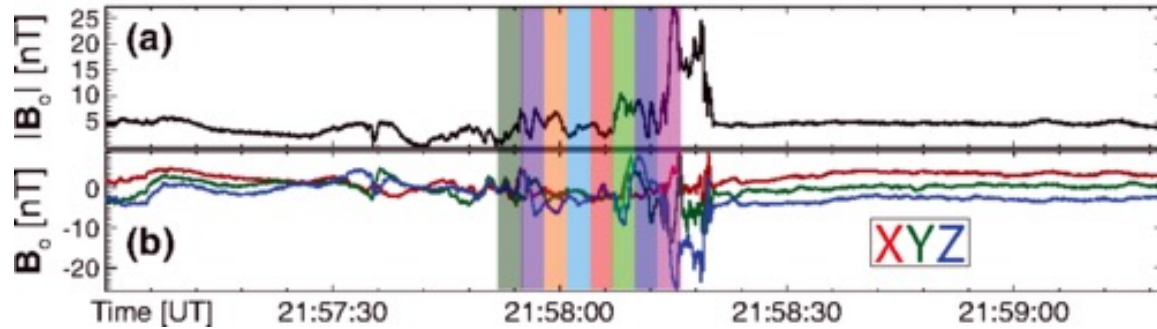
Foreshock Transients & Electron acceleration

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

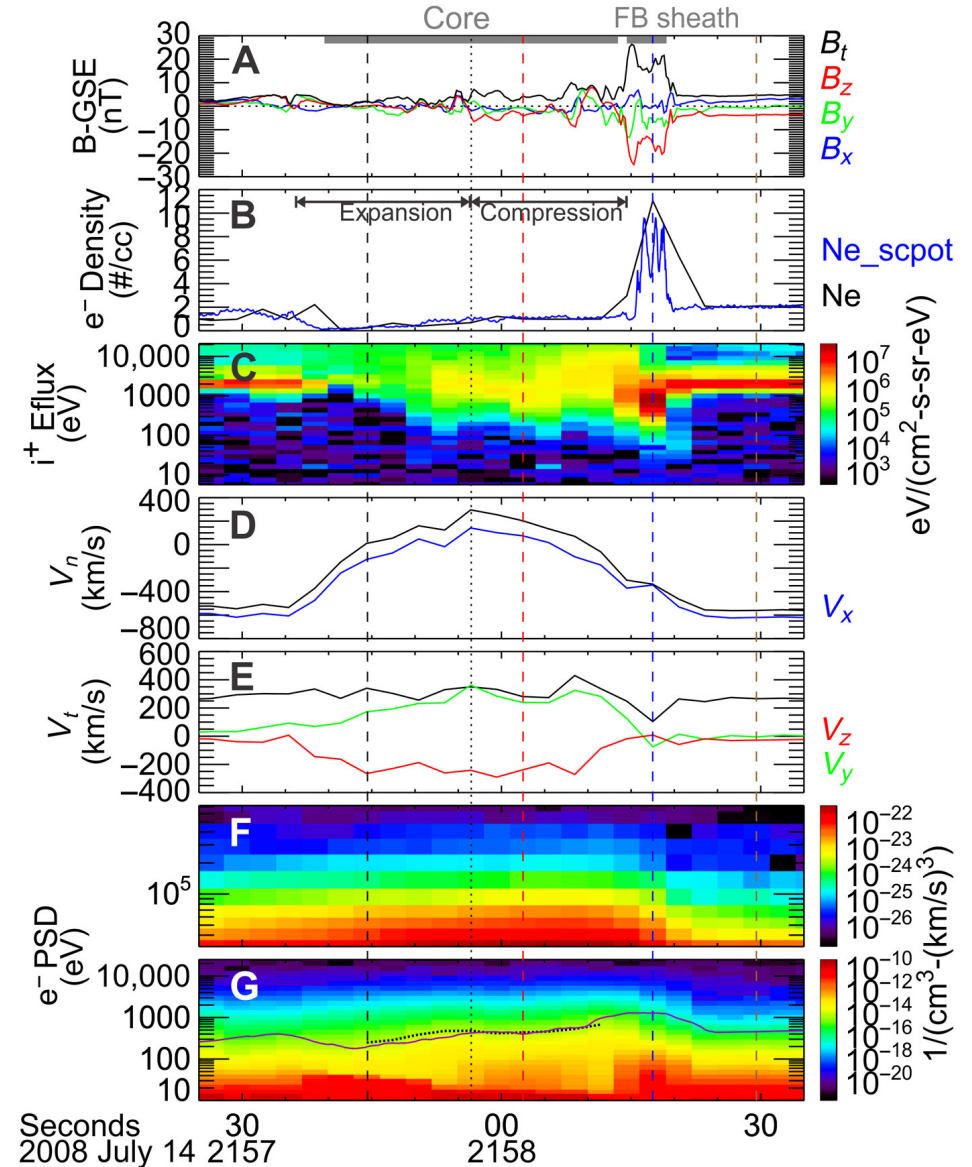
Combined low and high energy electron spectra



Foreshock Bubble on 2008-07-14



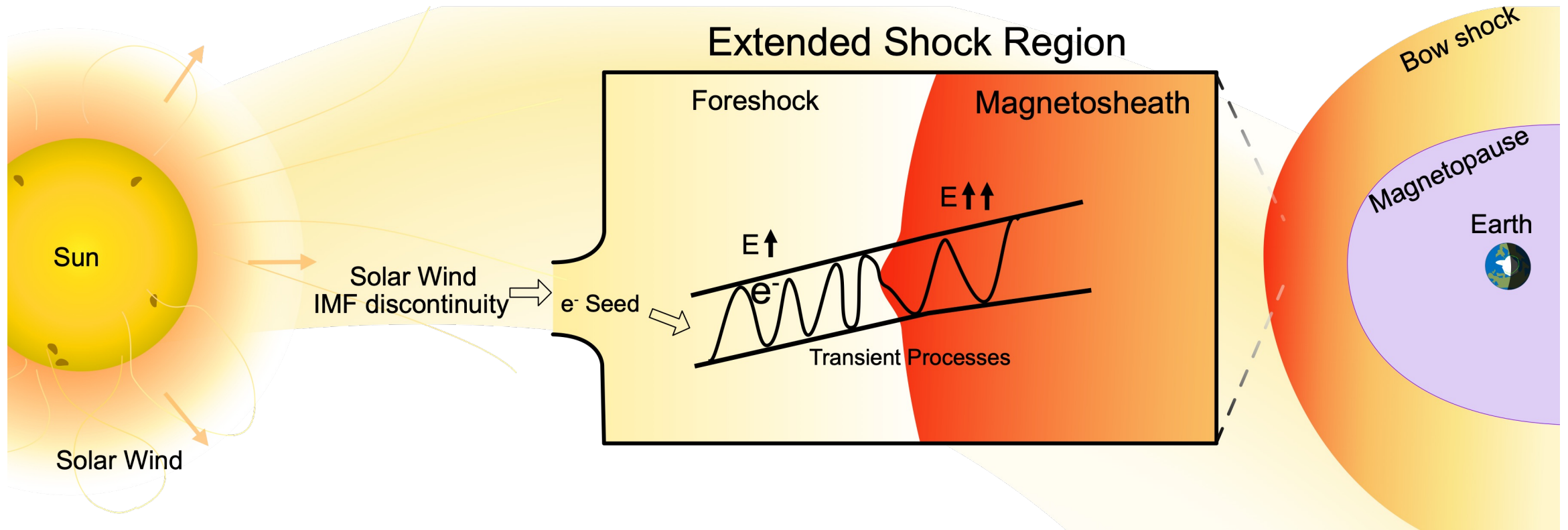
~300 KeV electrons



~200 KeV electrons

Liu T. et al. 2019 | Science Adv.

Mental Picture to Keep in Mind



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

Latest Results

Transients & Particle Acceleration



Raptis et al.2025 | NatComm

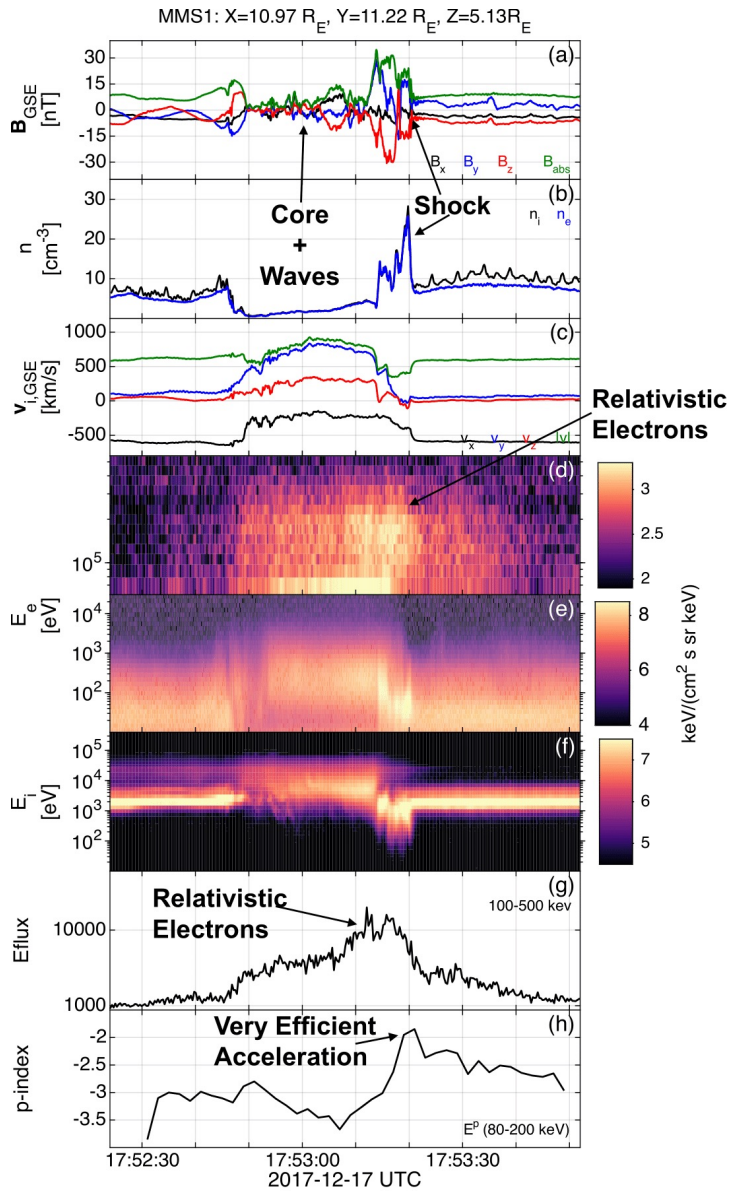


Raptis et al.2025 | ApJL

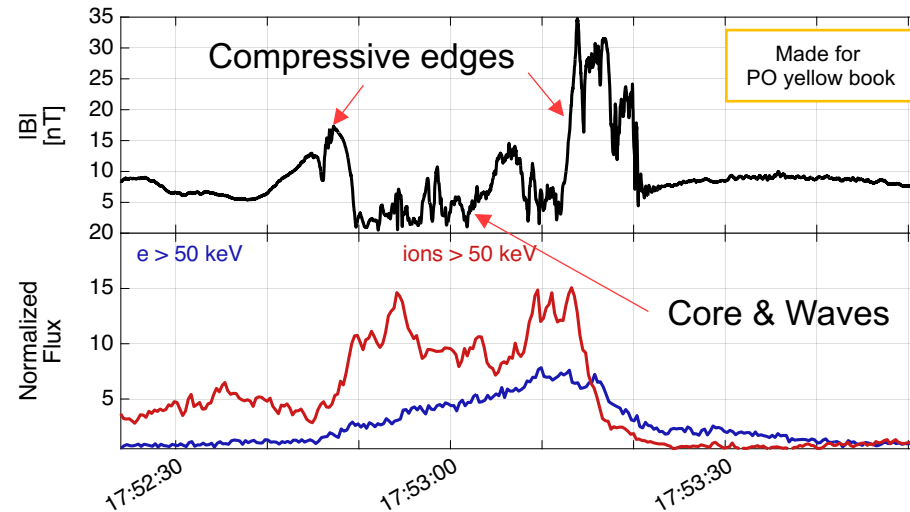


Raptis et al.2026 | Nature

Transients & Relativistic Electrons with MMS



New plot, much easier to understand!



With respect to upstream conditions (SW/FS):

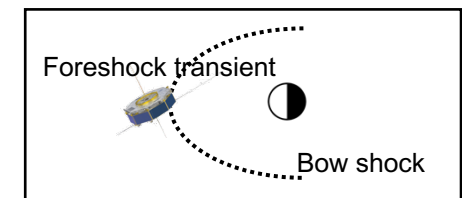
- Electron fluxes ($>50 \text{ keV}$) up to x6
- Ion fluxes ($>50 \text{ keV}$) up to x15

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)

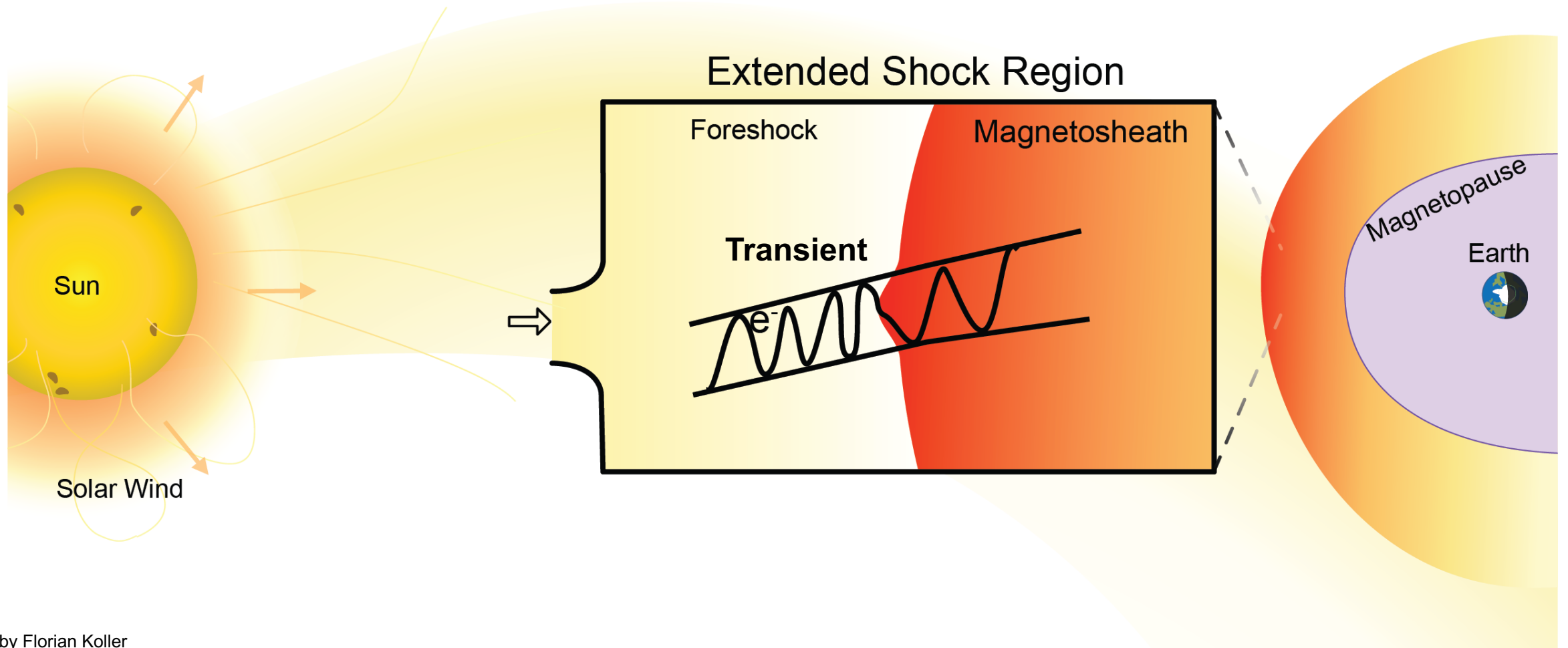
Unique property

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



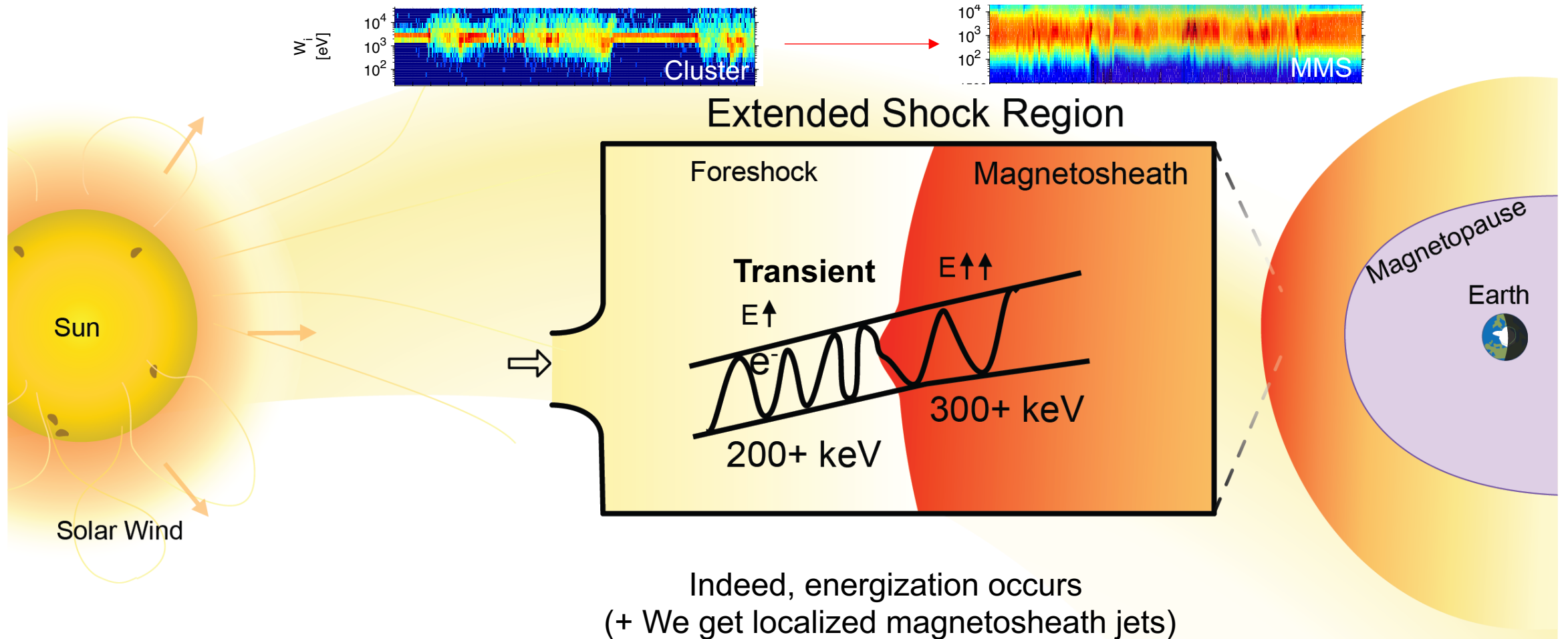
But let's ask one more question

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

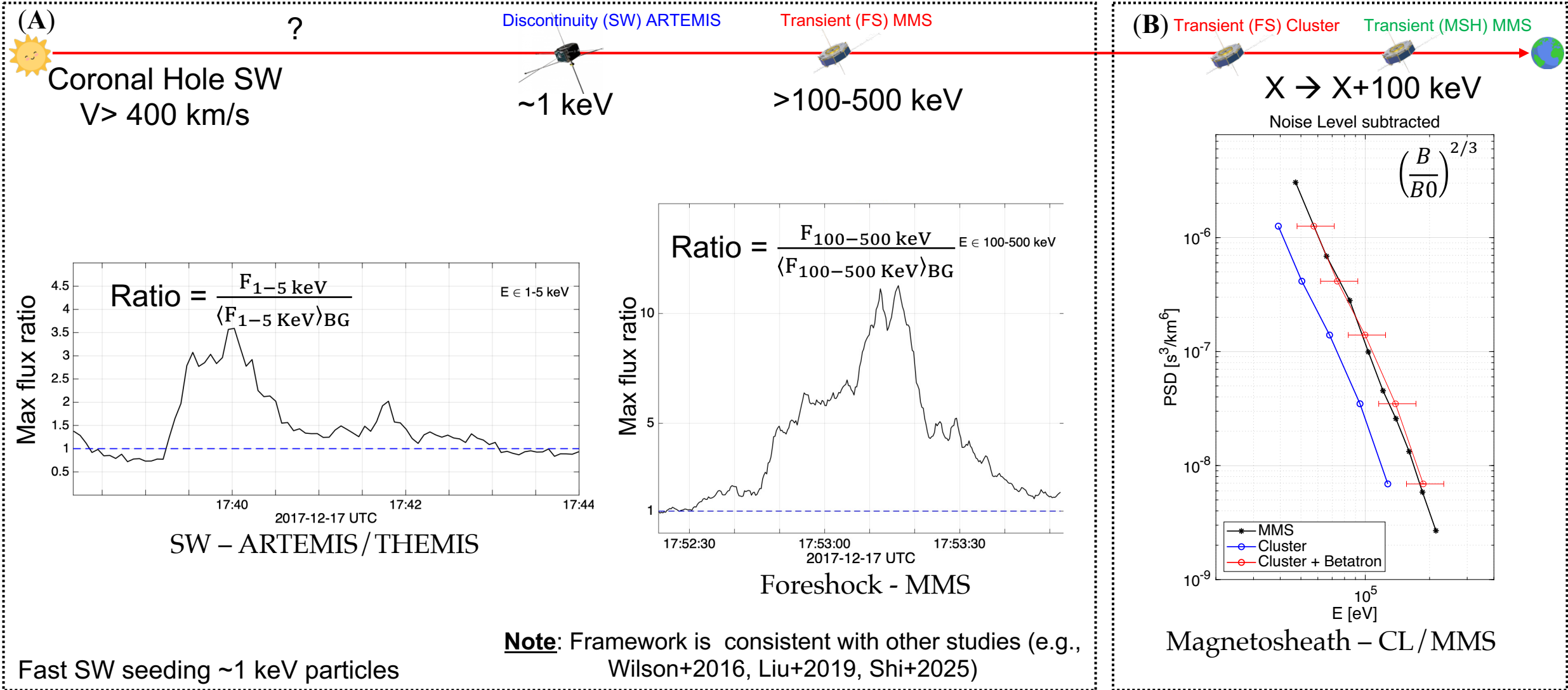


But let's ask one more question

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: Hillas Criterion and Scales

General geometrical criterion: Hillas Limit (Hillas+ 1984)

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

For Bohm diffusion ($\Delta B \sim B$), $D \simeq vr_g/3$, and requiring $D/V_{sh} \lesssim L$ gives an escape-limited maximum energy

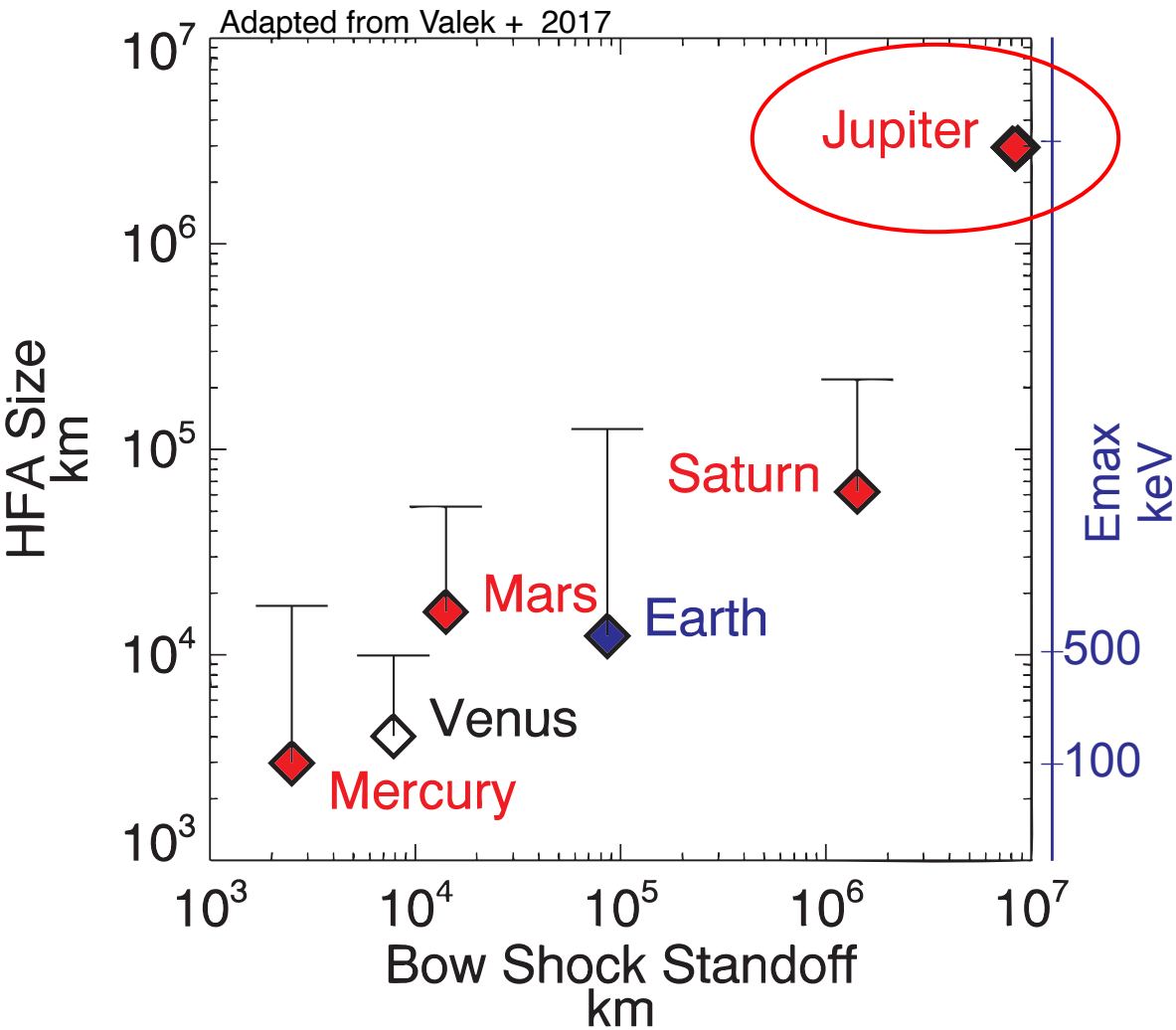
$$E_{max}^2 - (3qBLV)E_{max} - (mc^2)^2 = 0$$

For simplicity in the ultra relativistic regime this reduces to :

$$E_{max} \approx 3qBLV_{sh}$$

Or in simple words, as long as we can constrain these 3 variables, we can have an upper bound for 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:

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

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 ~ 0.5 nT gives:

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

Juno Observations – Jovian Bow Shock Crossing

Foreshock Transient (HFA):

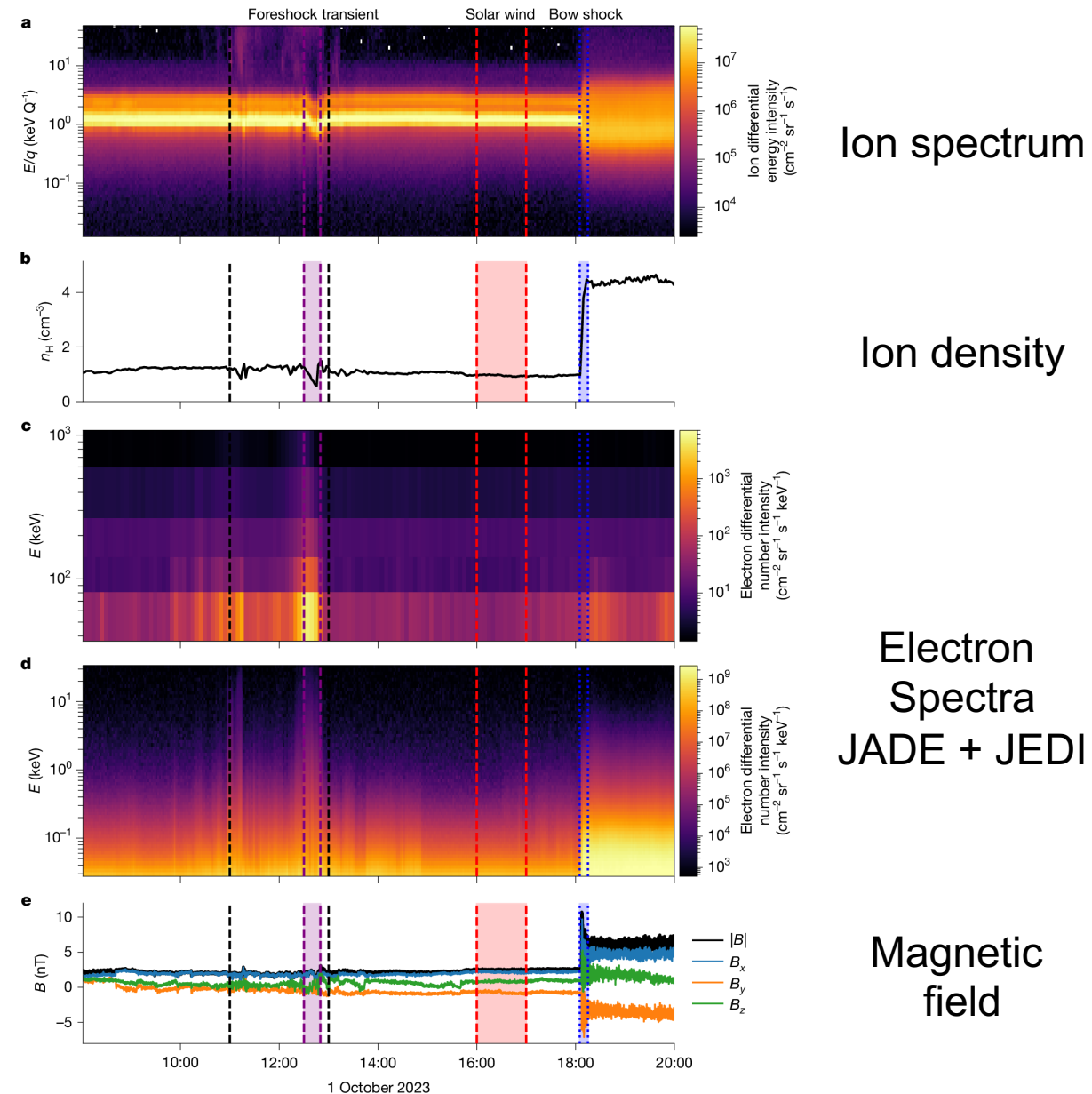
- Energetic electrons **up to 1 MeV**
- Disrupted solar wind beam
- Localized depletion of n and B

Solar wind (SW):

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

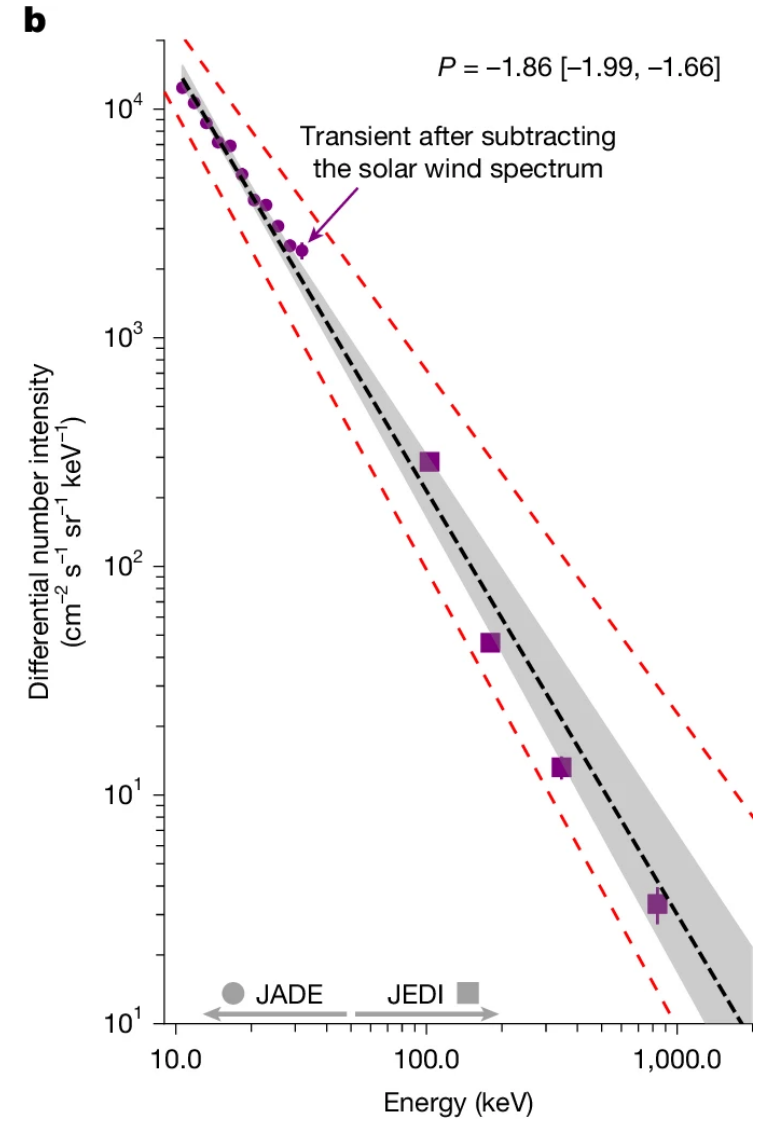
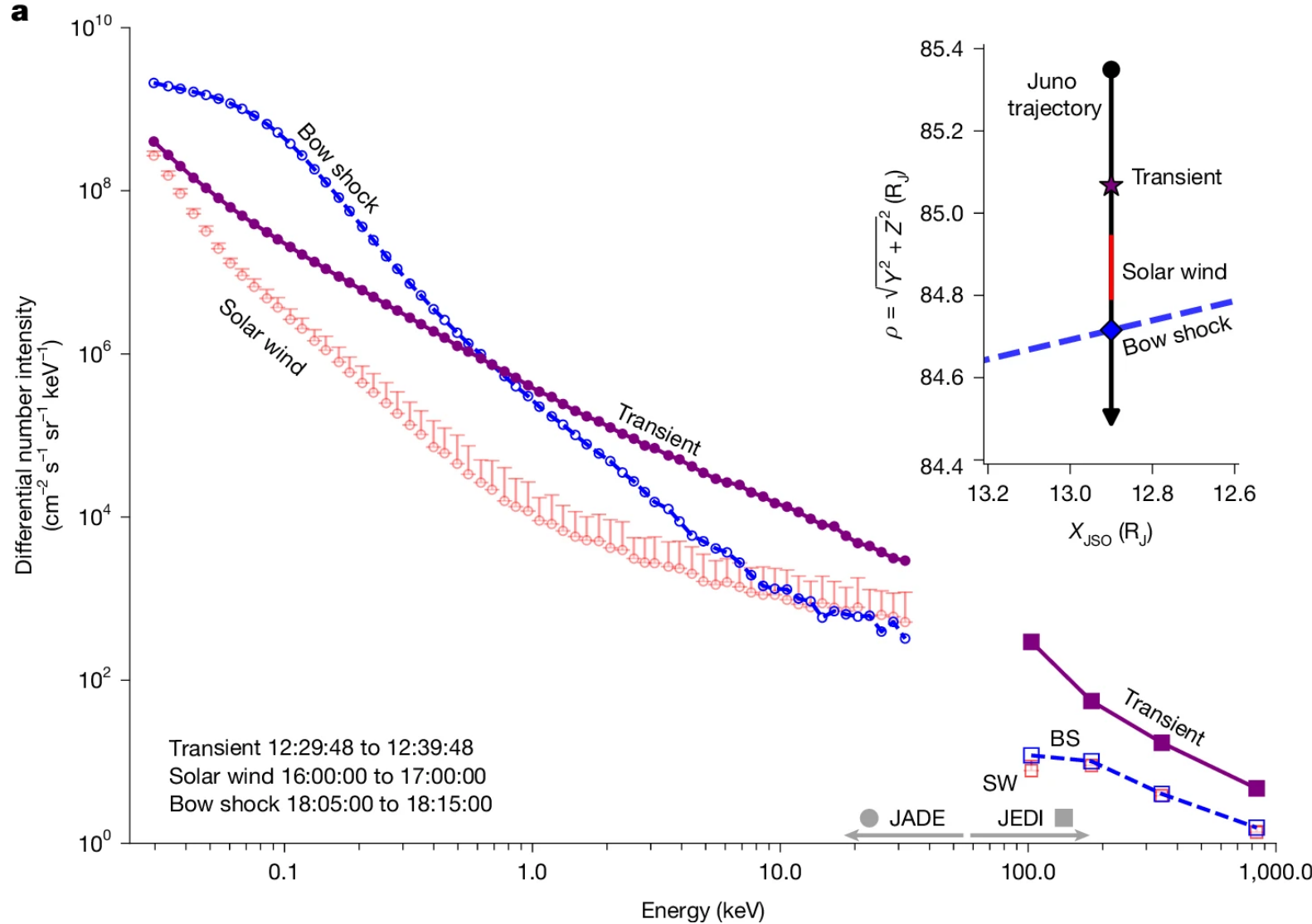
Bow shock (BS):

- 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



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

Can we extrapolate to astrophysical shocks?

Assumptions & Methods

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

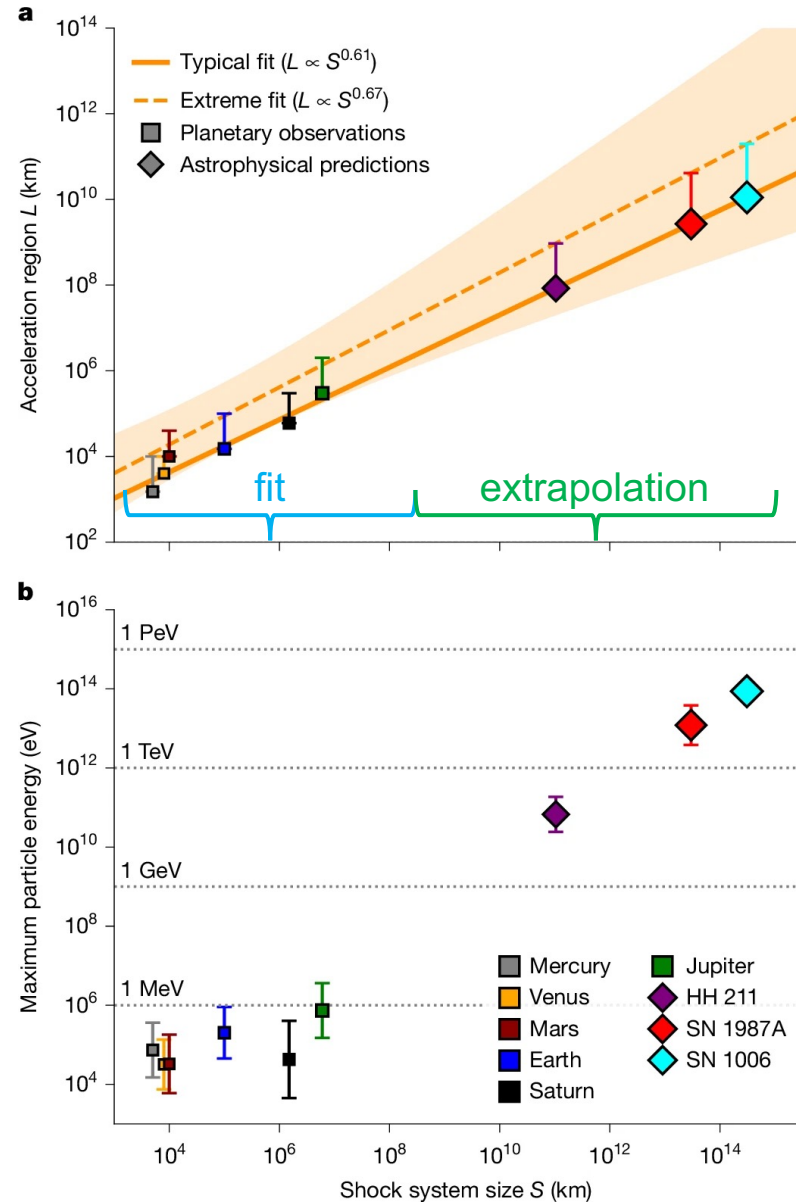
Planet	L_{typ} (km)	L_{ext} (km)
Mercury	1.5×10^3	1.0×10^4
Venus	4.0×10^3	1.0×10^4
Mars	1.0×10^4	4.0×10^4
Earth	1.5×10^4	1.0×10^5
Saturn	6.0×10^4	3.0×10^5
Jupiter	3.0×10^5	2.0×10^6

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]
HH 211	$\sim 1.05 \times 10^{11}$	[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]

Steps:

1. Hillas criterion through diffusive confinement
2. Assumed Bohm limit for strong scattering ($dB/B_0 \gg 1$).
3. Fit *planetary* data to a power-law linking acceleration scale (L) to shock standoff distance (S).
4. Apply upper prediction interval to estimate acceleration scales for distant astrophysical objects.



Caveats & Assumptions:

- ❖ An impossible to verify extrapolation
- ❖ Geometric limitations
- ❖ Magnetic coherence can vary strongly in each system

Broader Discussion:

- Jupiter and Earth show most efficient acceleration during a large scale transient rather than at the shock transition.
- Predicted max energies ~ observations at SN1006

Illustration of the process in an arbitrary planet

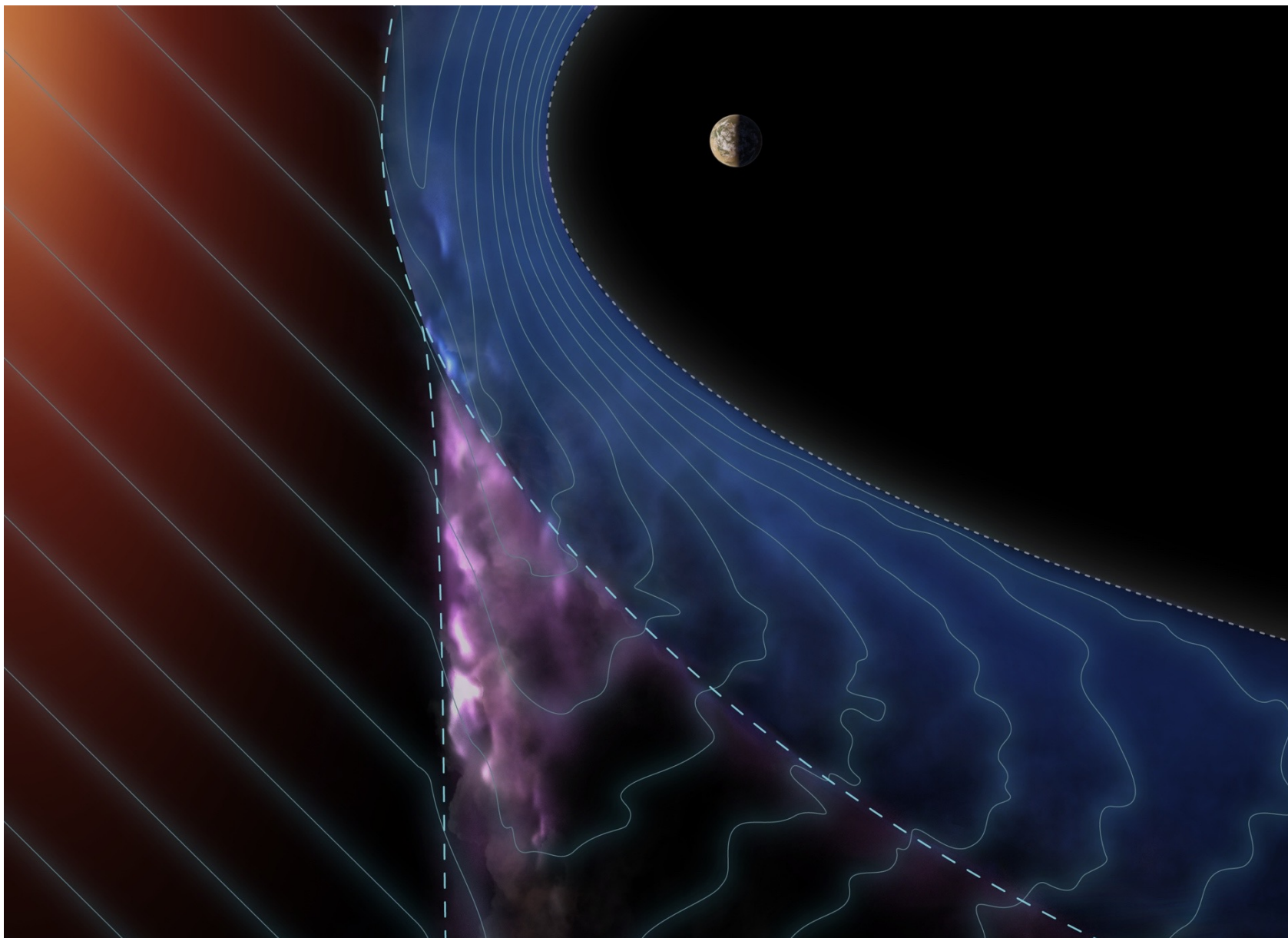


Illustration of the process in an arbitrary planet

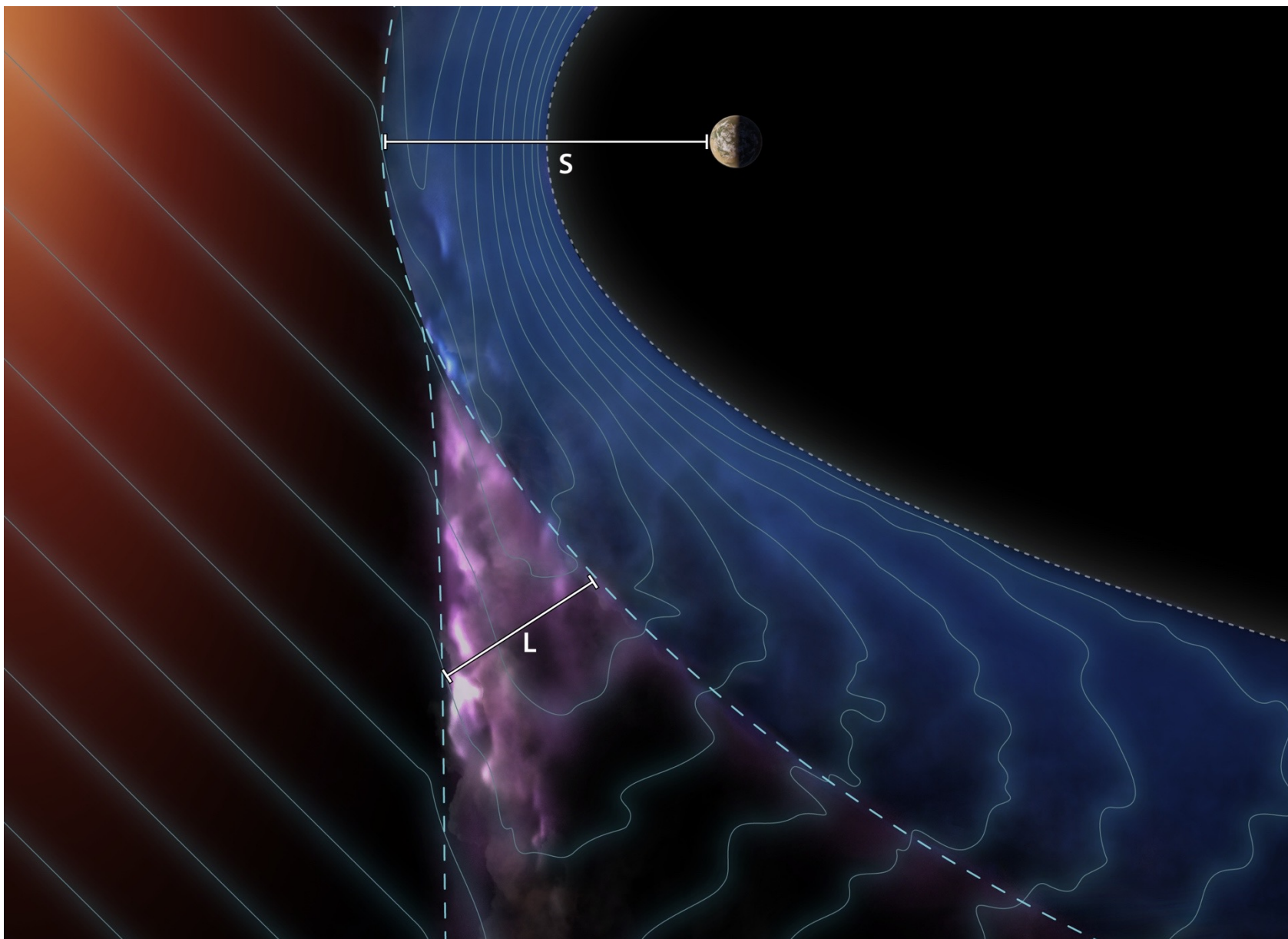


Illustration of the process in an arbitrary planet

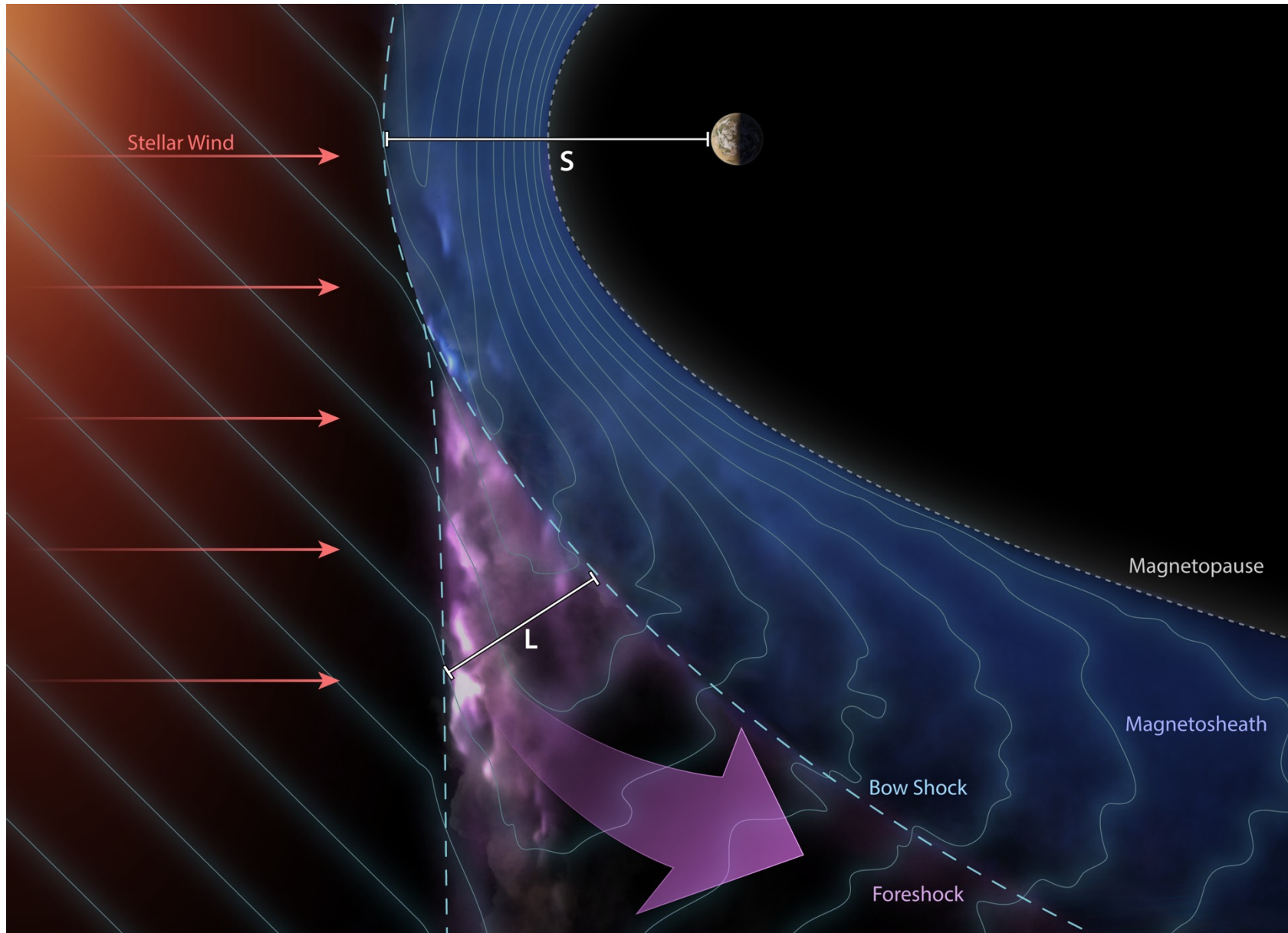
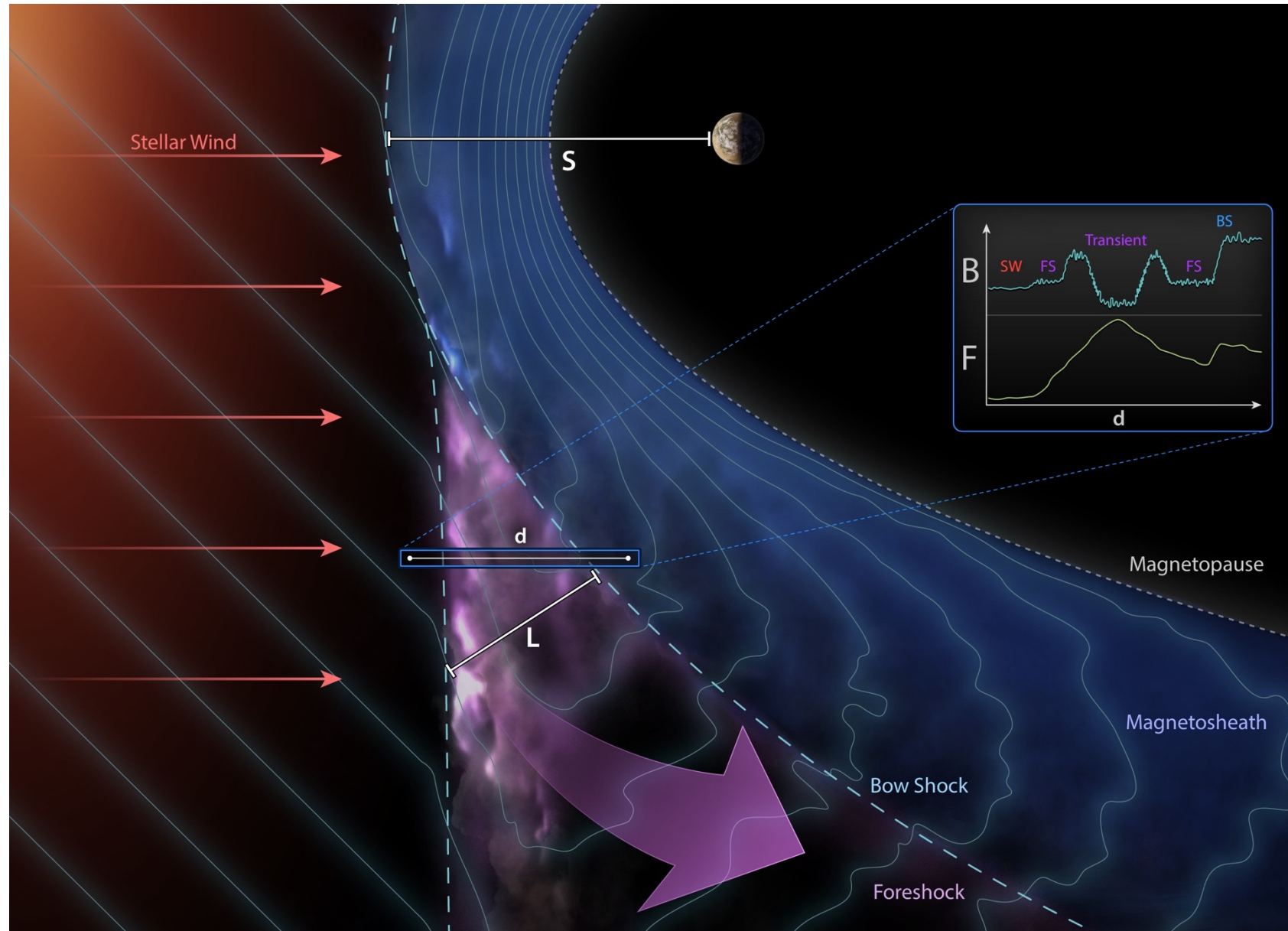


Illustration of the process in an arbitrary planet



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 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:

MMS can tackle the following outstanding questions:

- **String-of-pearl-campaign:** Connection of transient processes upstream to downstream (origin & energization)
- **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