



Compressive Structures in the Foreshock of Collisionless Shocks

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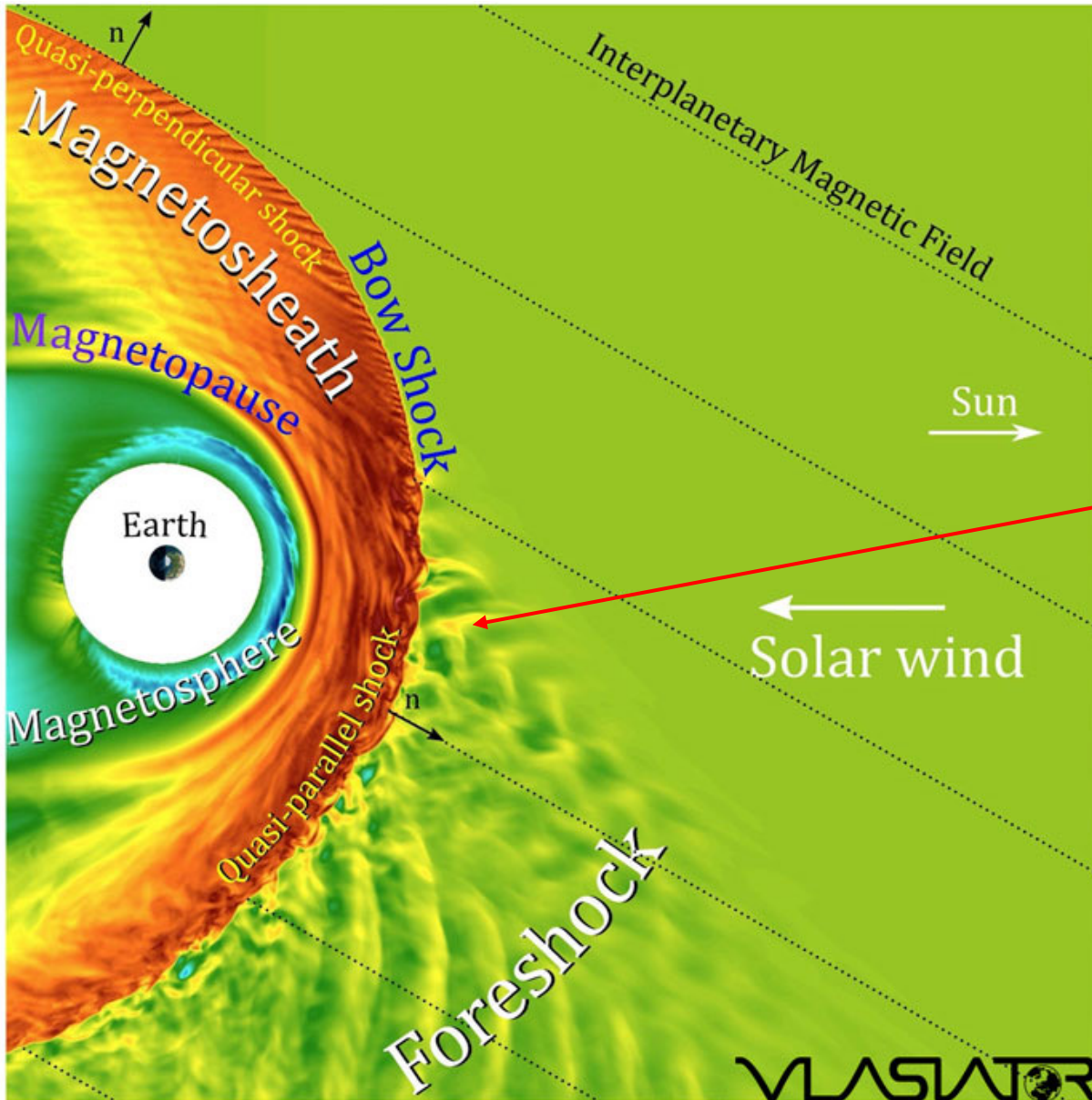
Acknowledgments:

- MMS Early Career Grant

Raptis+ 2026 (ApJL) - *Compressive Structures in the Foreshock of Collisionless Shocks*

Shocks & Transient Structures

Earth's Qpar bow shock and foreshock



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



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
- Current sheets & reconnection



See our latest work on transients & particle acceleration published today!

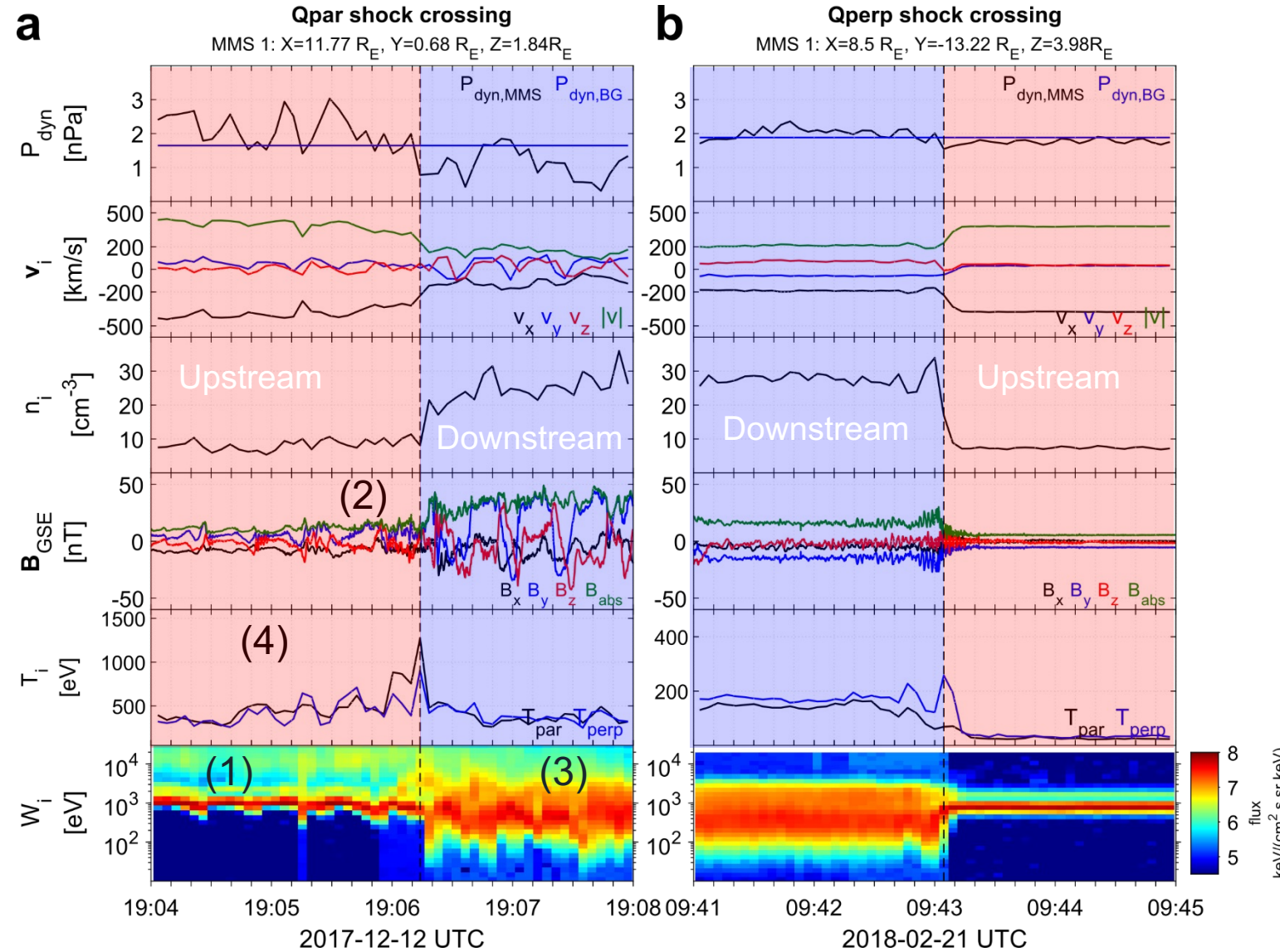
<https://www.nature.com/articles/s41586-026-10473-z>

Plan to discuss this more at SWT meeting ☺

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 ↓

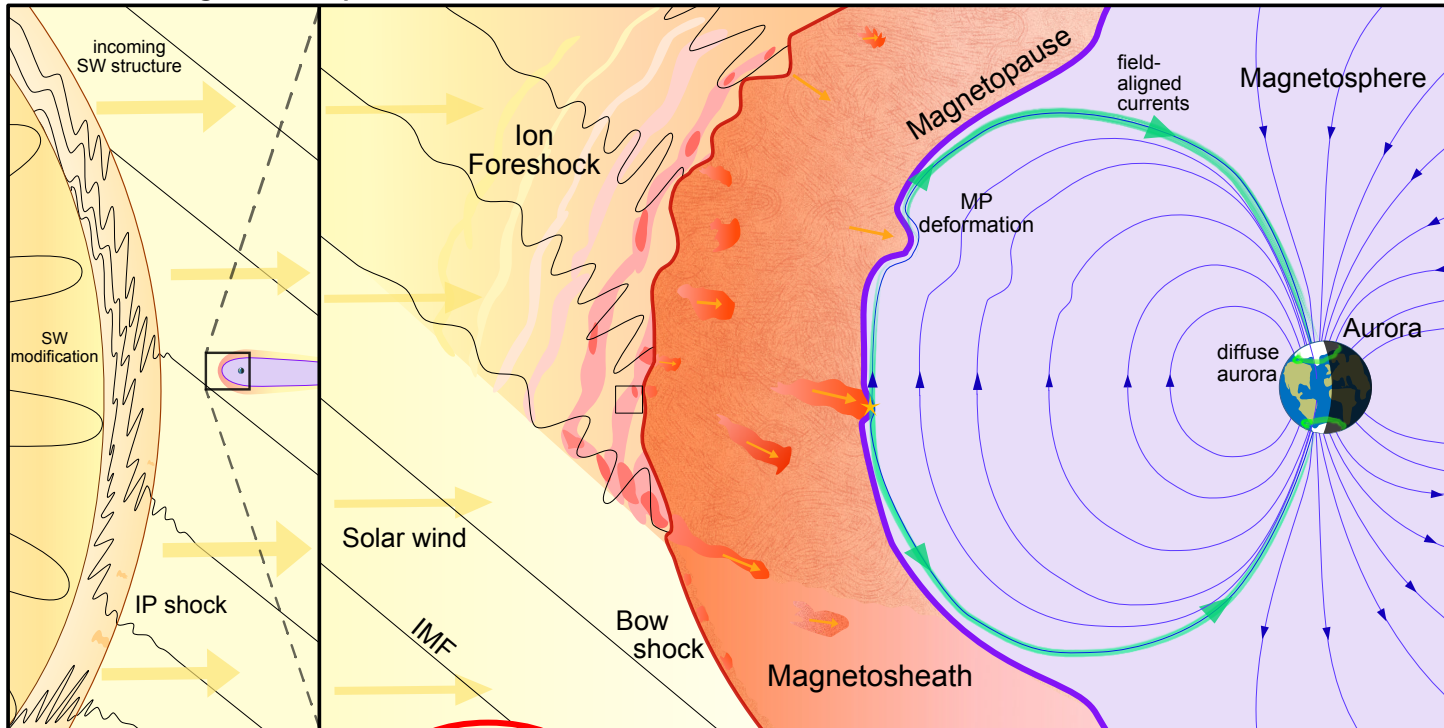


What is a Dayside Transient?



← 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

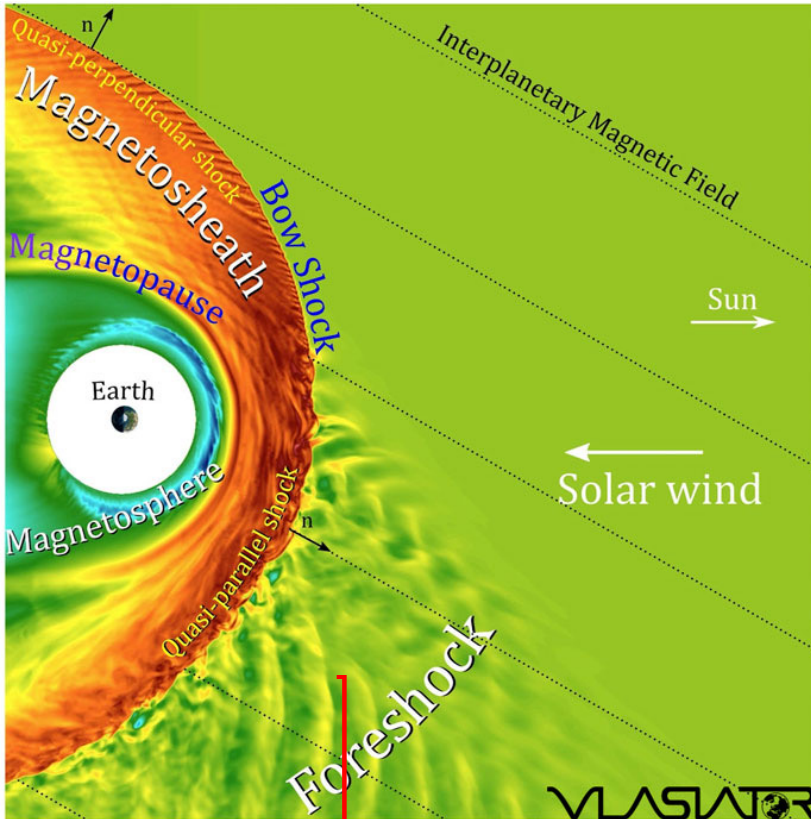
- Global (Solar):
 - Coronal Mass Ejection (CME)
 - High-Speed Stream (HSS)
 - Pressure Pulse / IP Shocks
- Fluid scale:
 - Flux Transfer Event (FTE)
 - Magnetopause (bursty) Reconnection
- Mesoscale:
 - Hot Flow Anomalies (HFAs)
 - Foreshock Bubbles (FBs)
 - Magnetosheath High Speed Jets (HSJs)
- Kinetic:
 - ULF waves
 - Shocklets
 - SLAMS

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

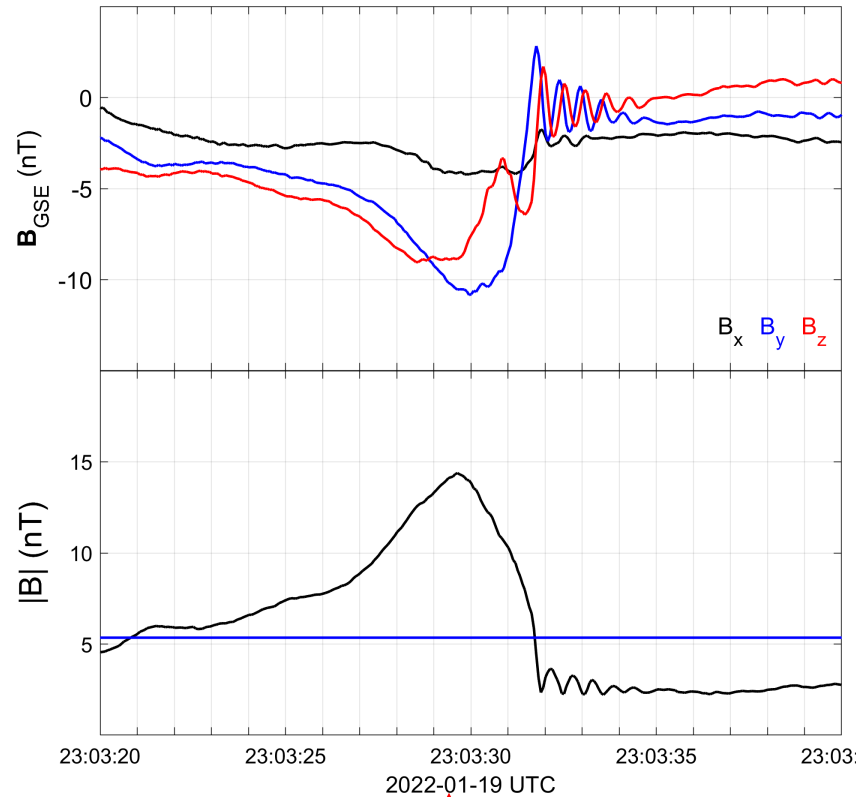
(2025 - 2029; Savvas Raptis, Ivan Vasko, Yuxi Chen, Gonzalo Cucho-Padin, Imogen Gingell, Terry Z. Liu, Ying Zou)

ULF Waves, Shocklets & SLAMS

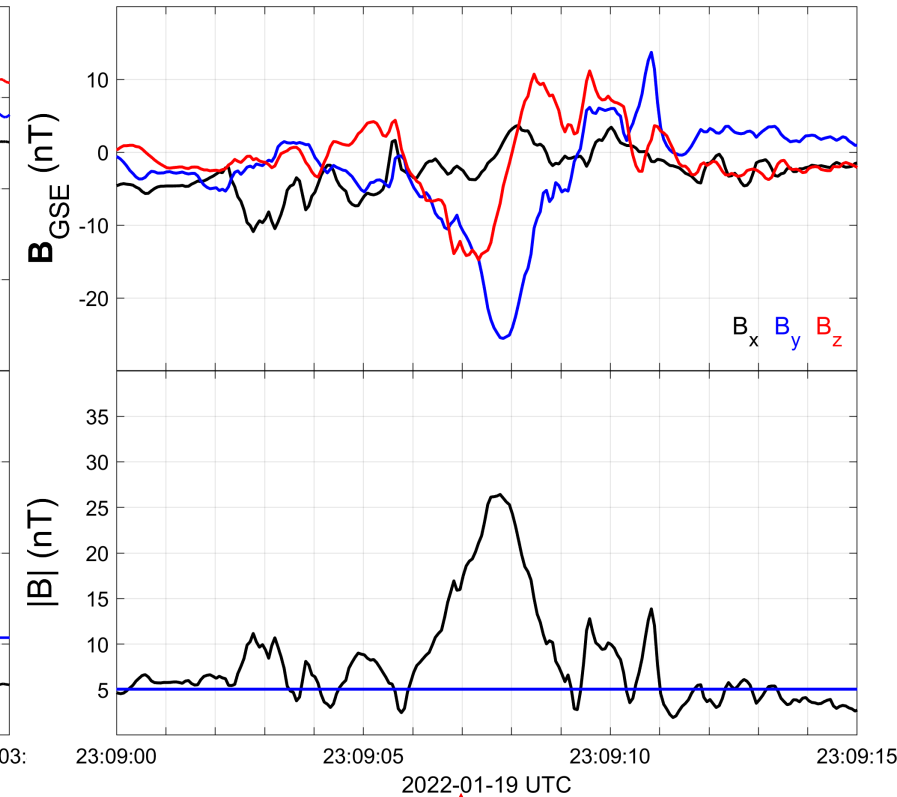
Foreshock Compressive Structures (FCS)



Shocklets



SLAMS



- $\Delta B/B_0 > 2$
- Act like local shock fronts
- Dispersive whistler wave train

- Shocklets = non-linear, steepened
- SLAMS = More monolithic (?)

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!*

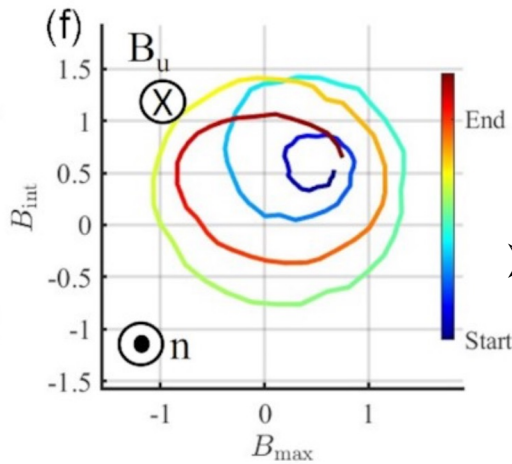
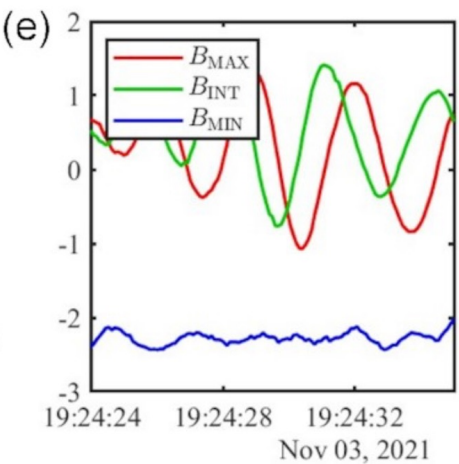
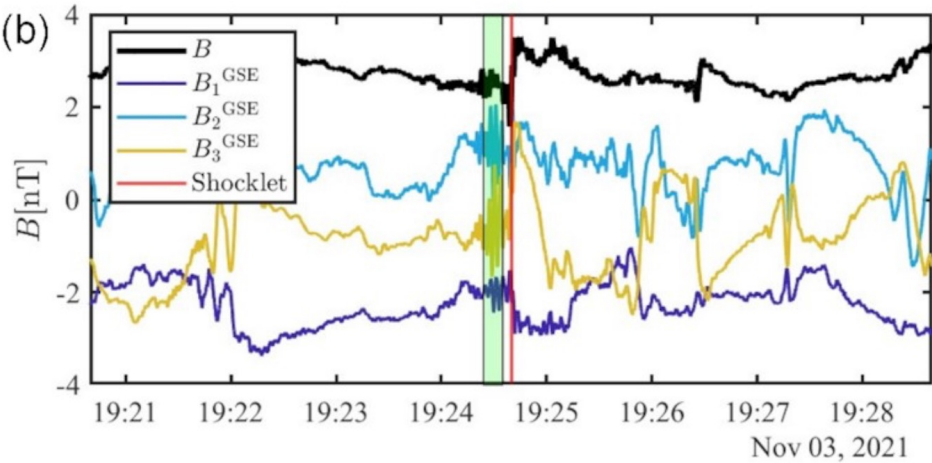
Yes!*

Maybe? (Let's discuss it today!)

Maybe? (we'll discuss it another day 😊)

Disclaimer: Shocklets at IP shocks & Differences to Intrinsic FCS

IP Shock
Shocklet 2

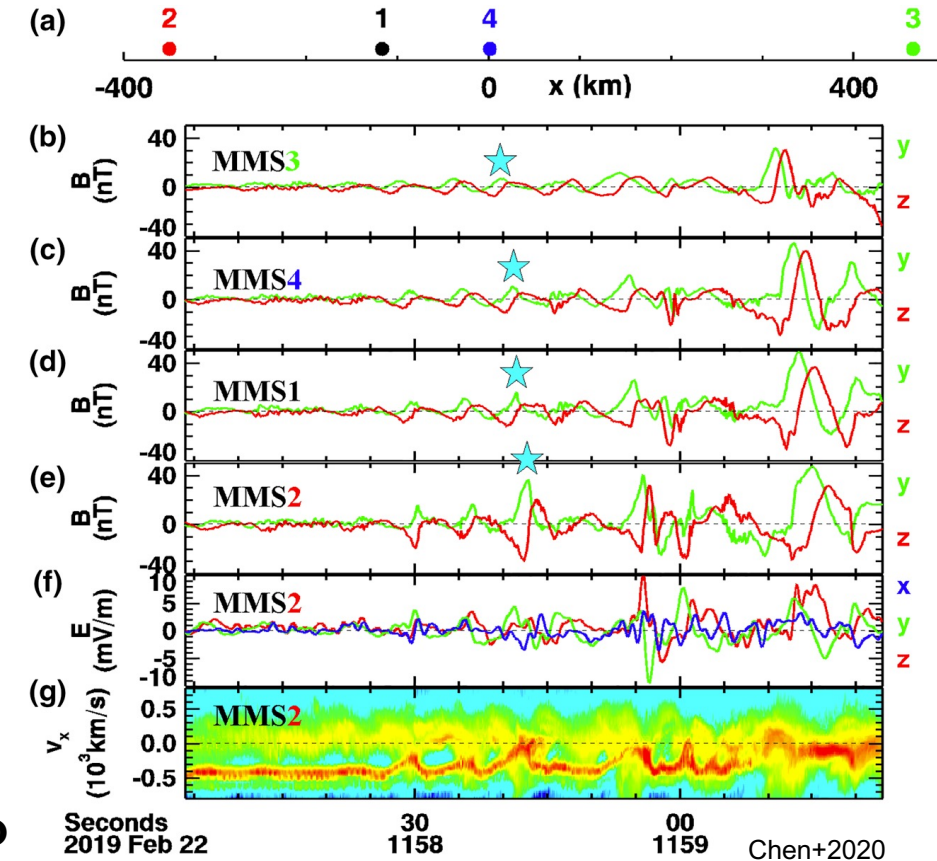


➤ Formation of **Shocklets at IP Shocks** originates from **Alfvenic Structures pre-existing** at the solar wind

➤ **At Earth** compressive structures form from **intrinsic wavefield of the foreshock**, rather than large scale alfvenic fluctuations

➤ Interestingly, **several high Mach IP shocks appear to lack such structures** (e.g., Jebaraj+2024)

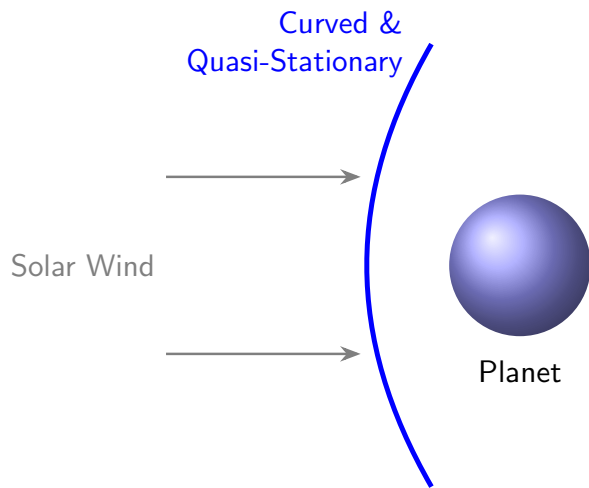
Earth's Bow shock



Our Goal & Challenges

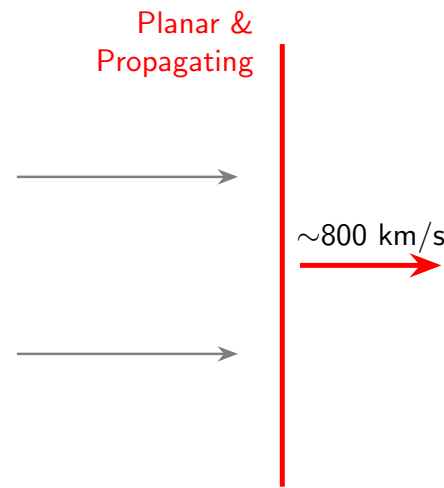
- We compare two shocks of similar Mach numbers to evaluate their foreshock structures (1) **Earth's Bow Shock with MMS during latest campaign** and (2) **an IP Shock using Solar Orbiter**.

Planetary Bow Shock



- "Cross-talk" from Q_{\perp}
- Hours of observations

Interplanetary (IP) Shock



- Restricted foreshock
- Limited observation time

Planetary Bow Shocks: A **curved**, quasi-stationary obstacle. Reflected ions are **magnetically connected for long durations**, allowing observations to be **taken** showing waves to grow and steepen into complex structures.

IP Shocks: A "planar" and **propagating** structure **moving rapidly** (~ 800 km/s) through the solar wind, potentially **restricting the foreshock development and limiting our observation capabilities**.

Case Study
MMS String of Pearl Campaign

Bow shock
MMS
2025/02/27

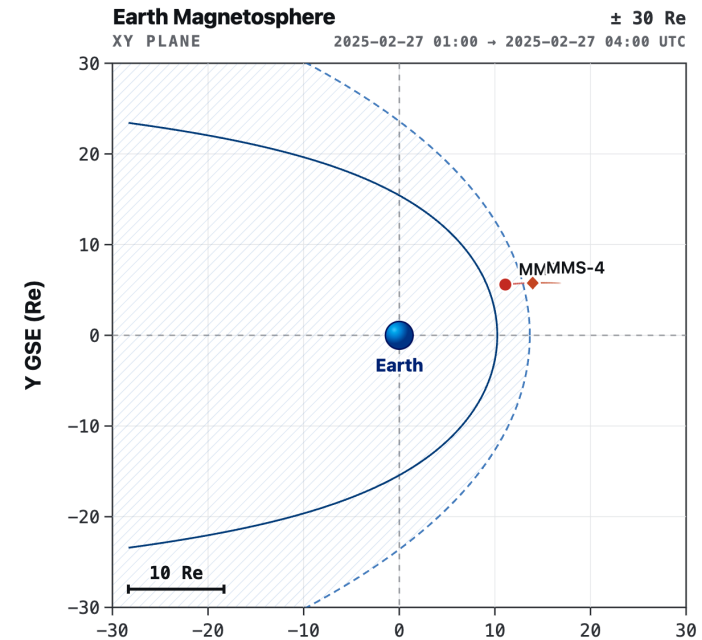
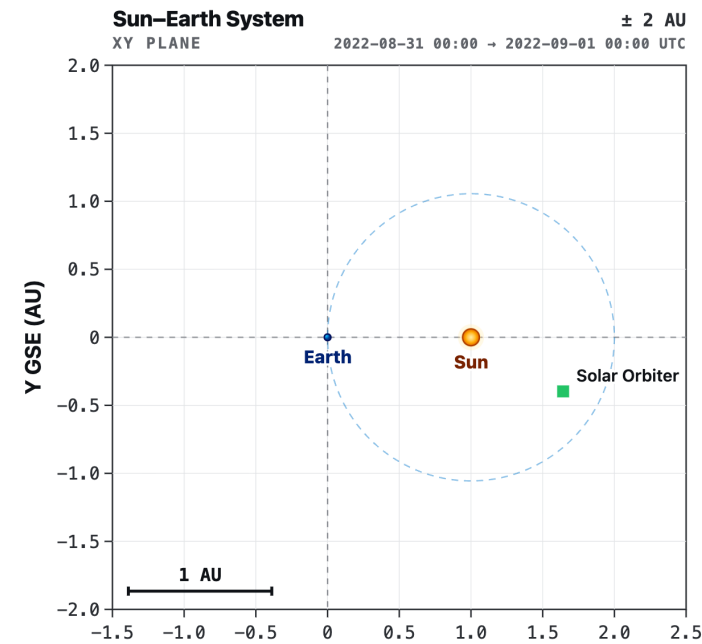
IP Shock
Solar Orbiter
2022/08/31

Solar Orbiter Nugget



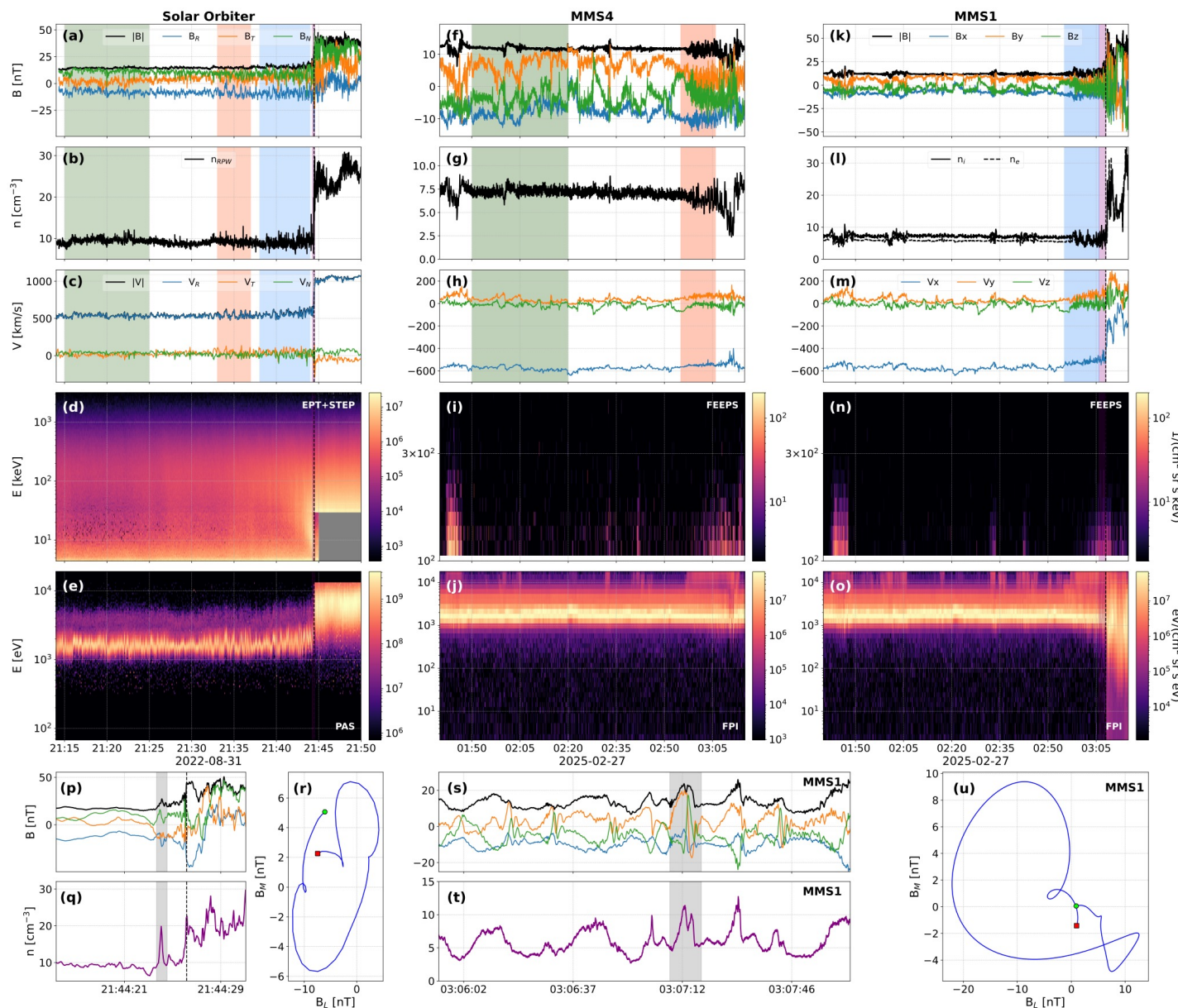
Results

Article



MMS1-4 separation >2 Re

Overview observations



High-Level takeaways

- Solar Orbiter observes an IP shock with elliptically polarized structure just 3 seconds upstream. Saturation of STEP on Solar Orbiter
- MMS-4 observes foreshock, but limited non-linear evolution
- MMS-1 observes distinct polarized compressive structure upstream of the bow shock (a few minutes)

Green = Solar Wind
 Red = Far Upstream Foreshock
 Blue = Near Shock Foreshock

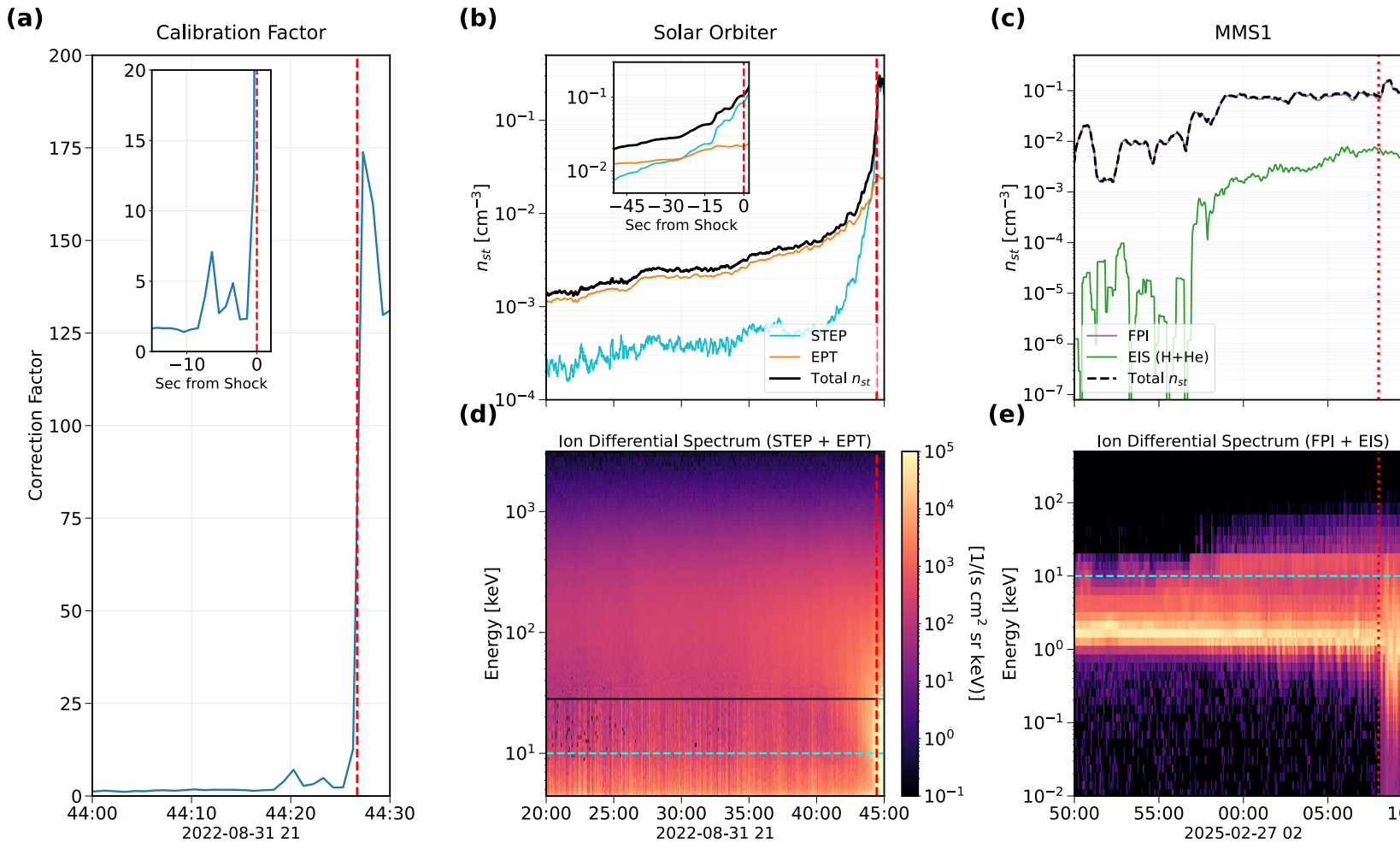
Some questions we follow up:

- Is the foreshock different?
- Are these structures of similar origin?
- Do they happen at relatively similar distances?

Methodology & Assumptions

$$S = \frac{V_{sh} \cdot (t - t_0)}{d_i}$$

$$n_{st} = 4\pi \int_{E_{min}}^{E_{max}} \frac{j(E)}{v} dE$$



- **Panel (a)**: STEP had dead-time saturation. Calibration factor of STEP against EPT in overlapping range (~60–80 keV)

- **Panels (b) and (c)**: Suprathermal density > Energetic density for Earth, not for IP shocks (more on this later)

- $E_{min} = 10$ keV

- Normalized density: n_{st}/n_{sw}

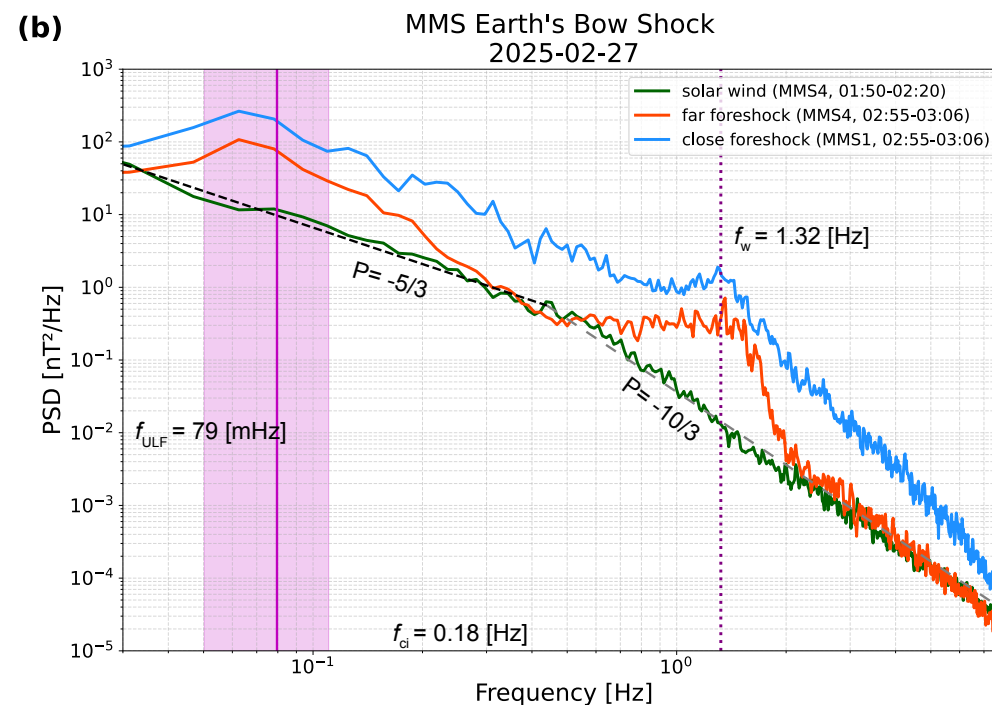
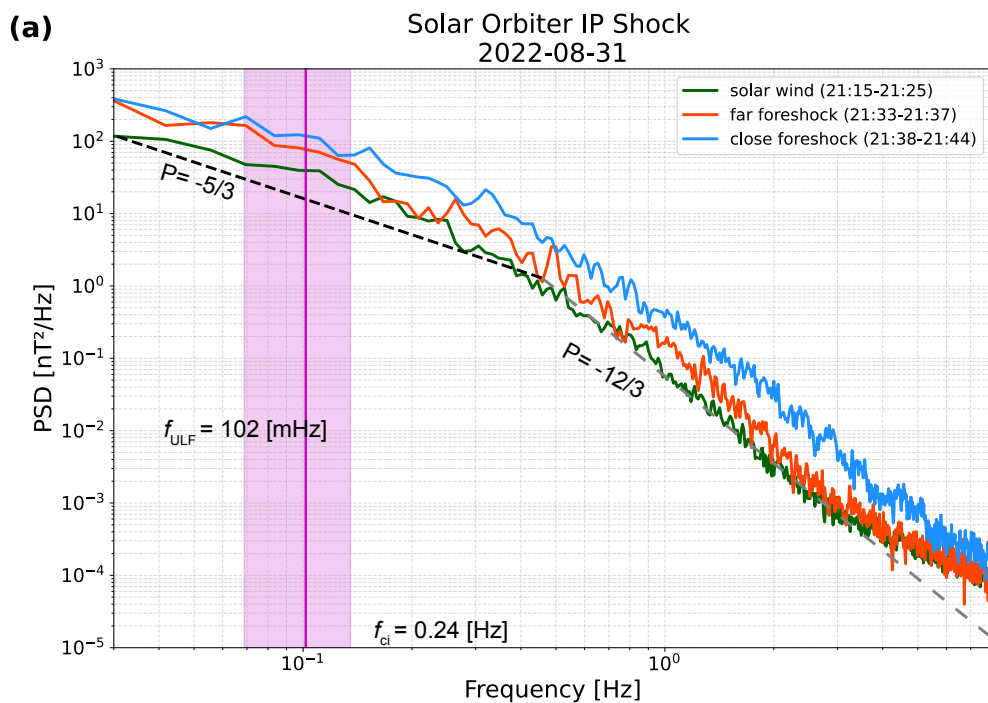
Some reminders: $Ma \sim v\sqrt{n}/B$, $d_i \sim 1/\sqrt{n}$,

\hat{n} & θ_{Bn} : can be estimated with several methods. All of them can be seriously misleading (we can discuss this).

Global Shock & Foreshock Properties

Parameter [unit]	Solar Orbiter	MMS
Upstream ion plasma beta (β)	0.3 - 0.5	2.0-3.0 (OMNI: \sim 1)
Shock's Normal (\hat{n})	[0.80, -0.52, -0.29]	[0.939, 0.10, 0.321]
Modeled Shock's Normal (\hat{n})	-	[0.88, 0.45, 0.11]
Shock angle ($\theta_{B\hat{n}}$) [$^\circ$]	22	39
Shock speed along \hat{n} (V_{sh}) [km/s]	880	50
Alfvén Mach number (M_A)	5.4	5.6
Ion inertial length (d_i) [km]	65	90

- High Mach number shocks, but some differences in plasma beta, and shock speed
- Slopes of SW look fine, the more we approach the shock, the more shock-driven processes dominate.



- **IP Shock:** Broadband increase as we approach the shock
- **Earth:** Peaks in ULF waves, and \sim 1Hz

ULF frequency expectation:

$$f_{fw} \text{ (mHz)} = 7.6 B_l \text{ (nT)} \cos^2 \theta_{xB}$$

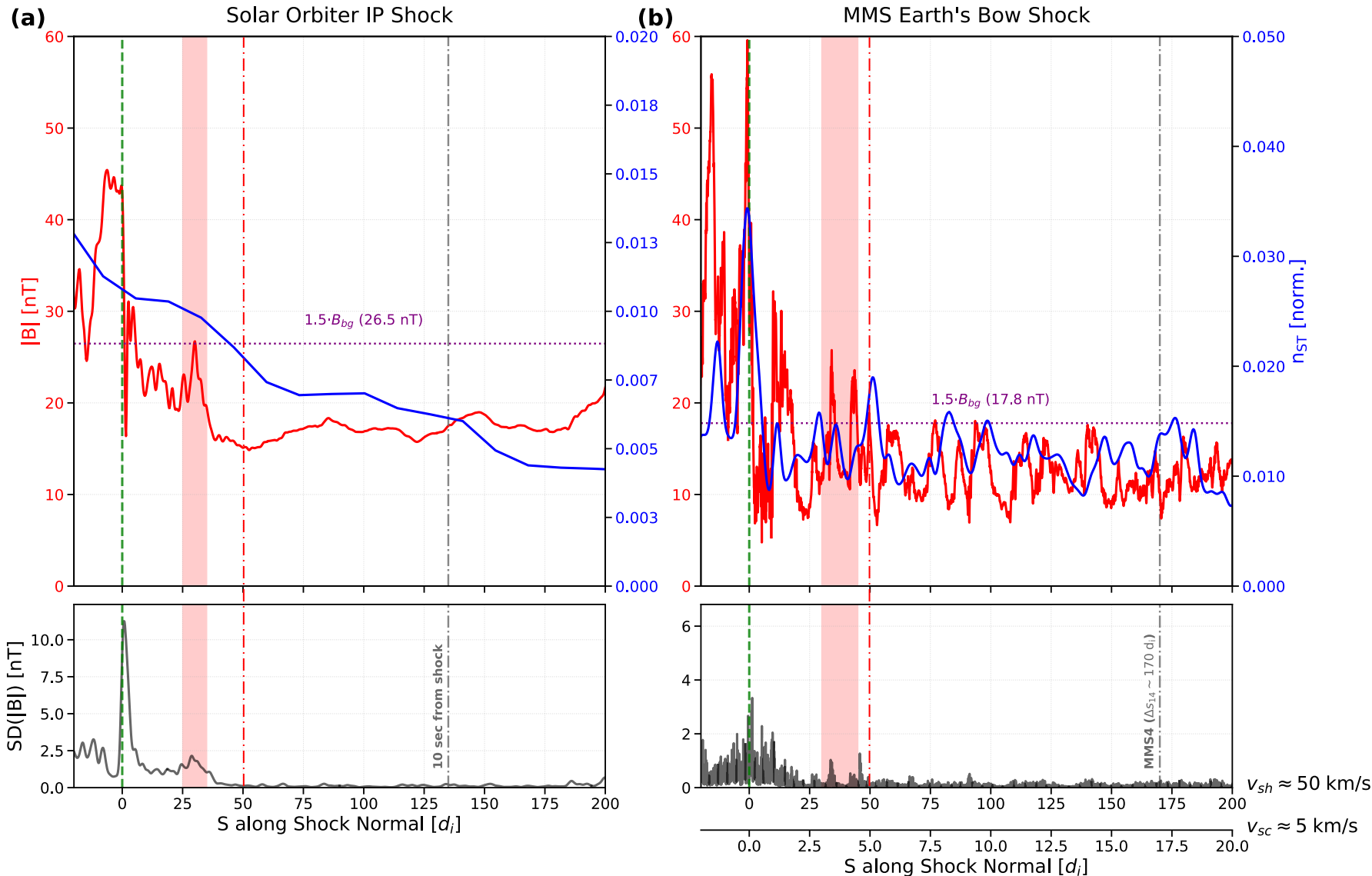
Compressive Structures

$$S = \frac{V_{sh} \cdot (t - t_0)}{d_i}$$

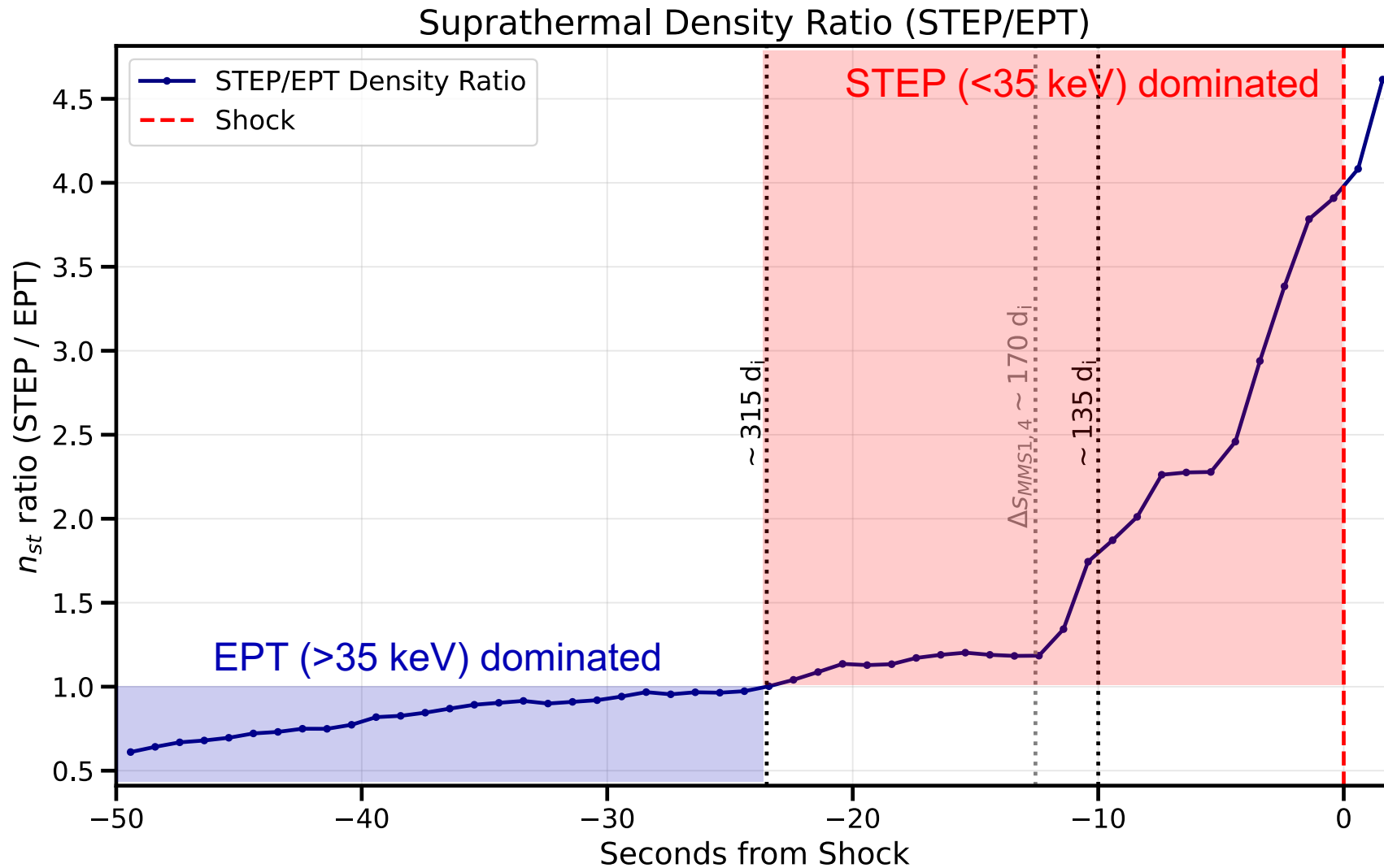
Keypoints:

- Compressive structures **develop at distances < 50 d_i** from the shock front.
- ~1% of density** is associated with suprathermals and energetic particles (>10 keV) **when significant steepening occurs.**
- This only occurs at a very narrow time window for **Solar Orbiter (~10s)**, while being up to **several hours for MMS.**

Note: We don't really know the speed of the shock at Earth, so we have an upper and lower limit.



MMS Separation & Effective Comparisons of Shocks



Keypoints:

Ratio of unity: 35+ keV deliver as much suprathermal density as 8-35 keV

STEP dominates very close to the shock at ~315di (23s), with sharpest gradient at ~135di (10s) from the shock.

➤ **At Earth**, we are **always** in the **<35 keV** regime.

➤ **At IP shock** we may only be in the **<35 KeV** regime for 10s of seconds

Summary & Discussion

Key Findings

- **Intrinsic** foreshock compressive structures (**FCSs**) form upstream at **similar normalized distances** ($\lesssim 50$ di) when the **suprathermal** (>10 keV) ion density exceeds $\sim 1\%$ of the total.
- the **“growth zone”** capable of sustaining these structures is **spatially limited** (~ 135 di), which, due to the high speed of the propagating IP shock, corresponds to a **brief observational window of ~ 10 s**.
- Other physical processes that may inhibit are **the different geometry** (curved vs “planar”) resulting in a **lack of “Cross-talk” between neighboring regions of the shock**. Statistically difficult to evaluate since **only a few high-Mach Qpar IP shocks**.

Discussion points:

A potential threshold? At both shocks, steepened foreshock compressive structures fully form when the suprathermal ion density reaches $\sim 1\%$ of the background solar wind density. Is this what is required? Can this be supplied by different processes?

Observational biases: The perceived difference in foreshock compressive structure occurrence is largely observational. **For IP shocks, missions traverse the shock rapidly, providing only a brief “spatial cut” that misleadingly suggests structures are rare or absent. In contrast, planetary observations provide long “time histories”, which misleadingly suggests an overabundance and extended range.**

Solar Orbiter Nugget



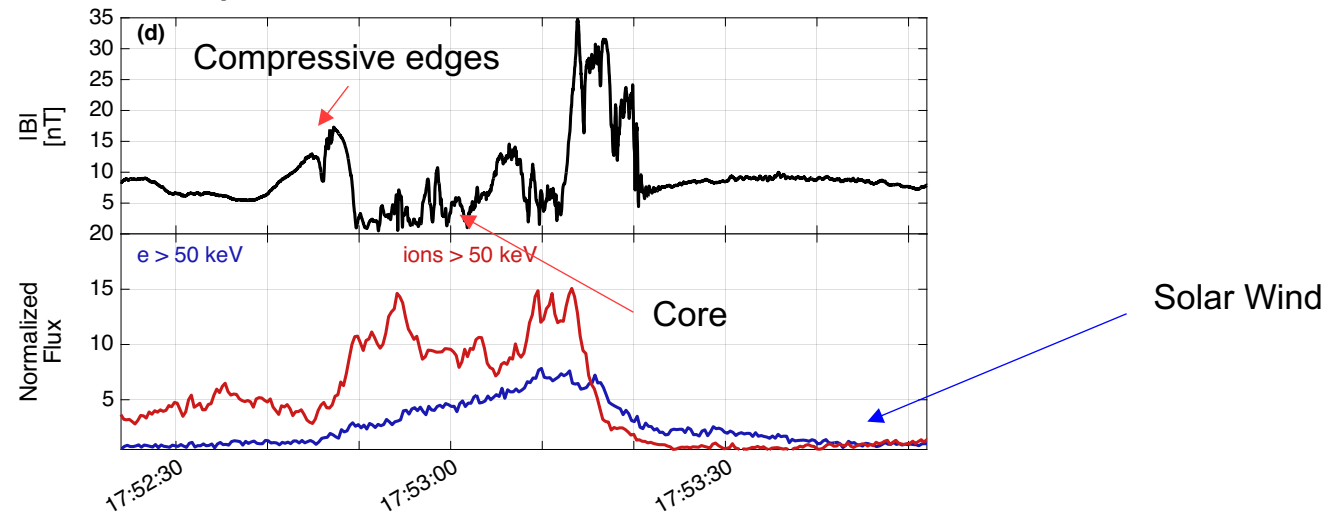
Article



Appendix

Shock-generated Transients & Particle Acceleration

New plot, much easier to understand!



With respect to upstream conditions (SW/FS):

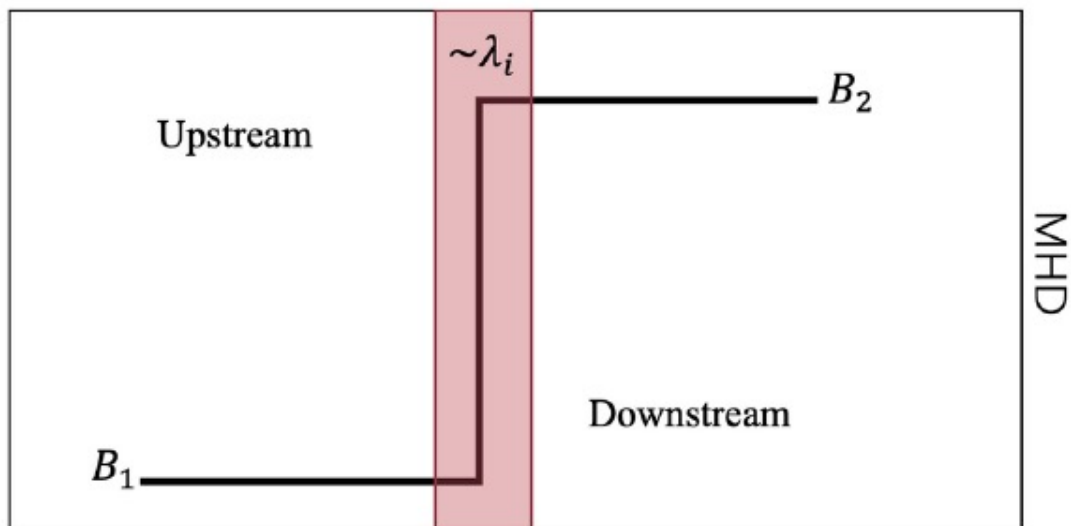
- Electron fluxes ($>50 \text{ keV}$) up to x6
- Ion fluxes ($>50 \text{ keV}$) up to x15

(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*

Quasi-parallel and Quasi-perpendicular shocks

Qperp transition



Qpar transition

