JOHNS HOPKINS
APPLIED PHYSICS LABORATORY

Shock Generated Transients and their Effects on Earth's Magnetospheric Environment

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Acknowledgments:

- MMS Early Career Grant and APL R&D program
- ISSI Team: P. Kajdič - Impact of Upstream Mesoscale Transients on the Near-Earth Environment
- GEM Focus group: **Multiscale Dayside Transients (MDT)** and their Effect on Earth's Magnetosphere

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

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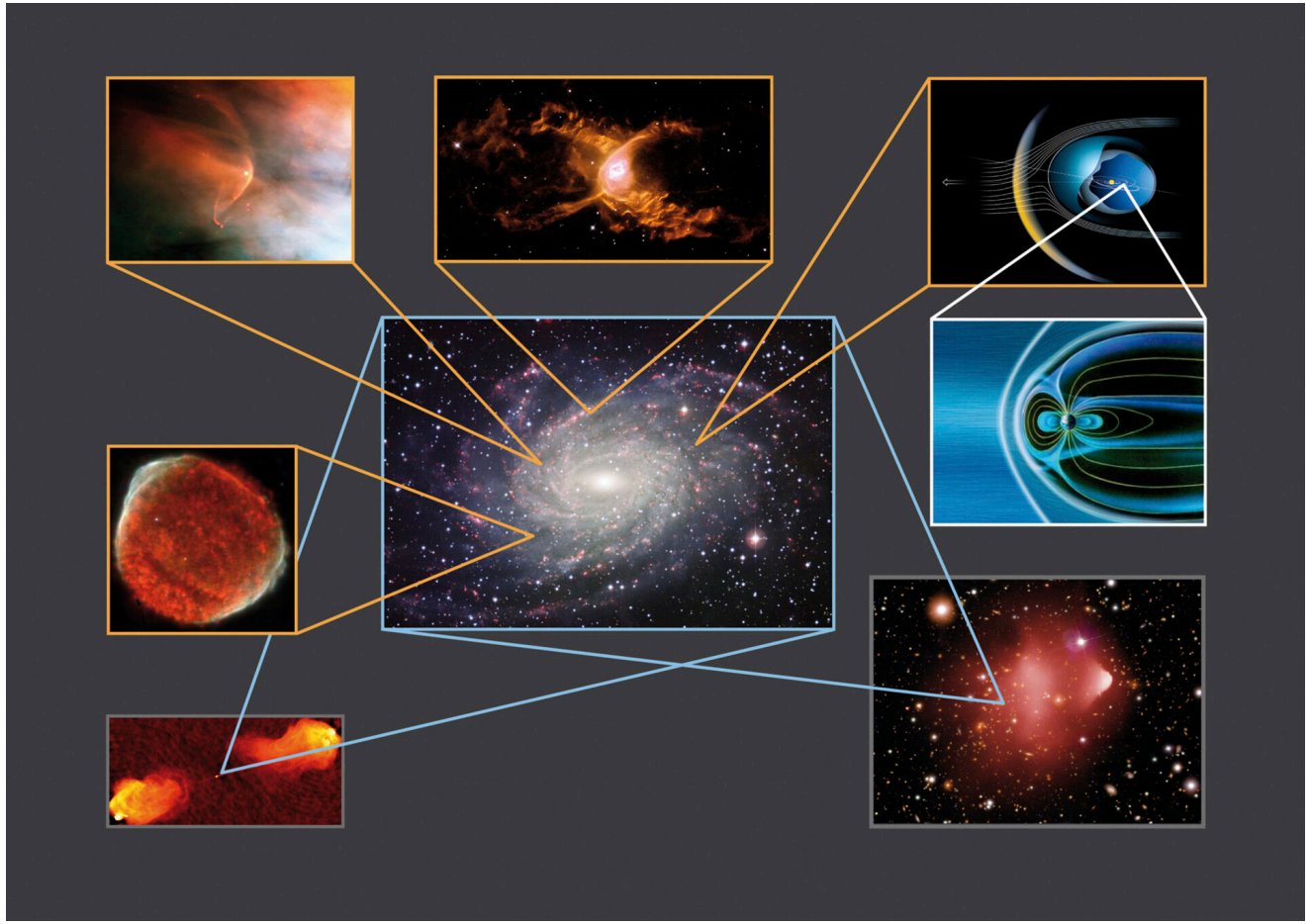
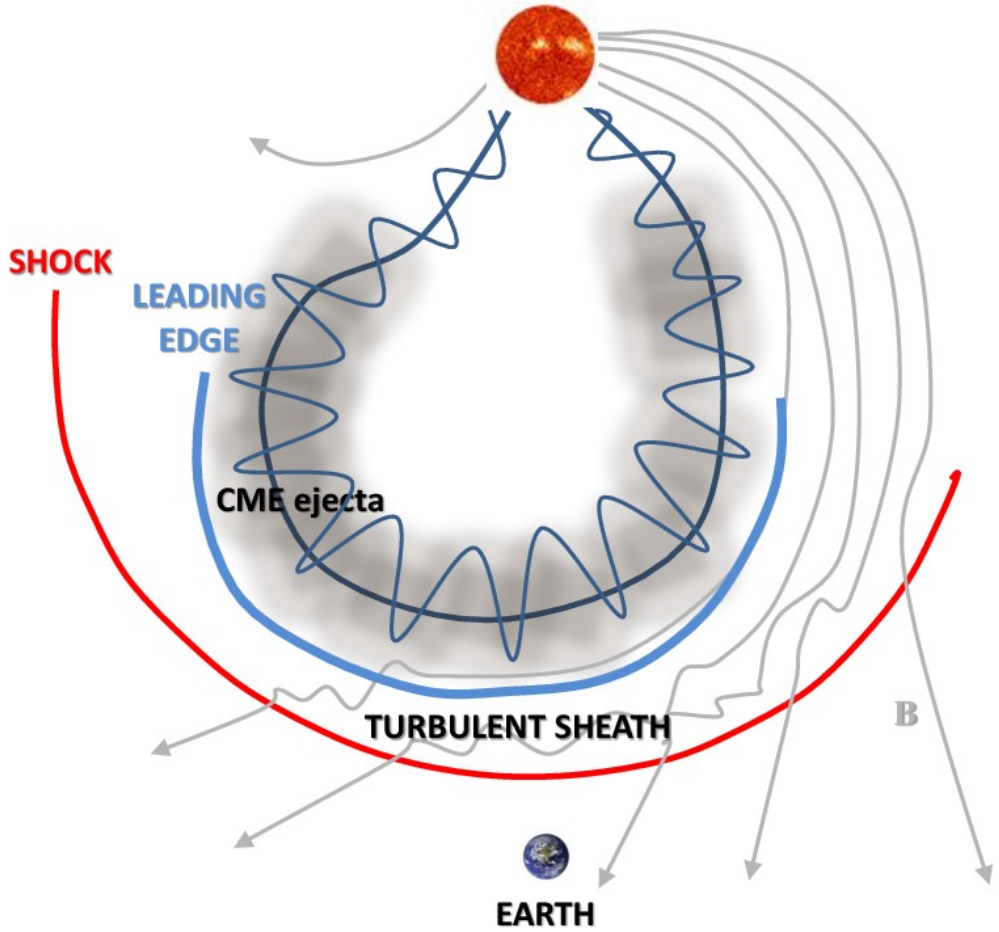
Collisionless Shocks in Universe



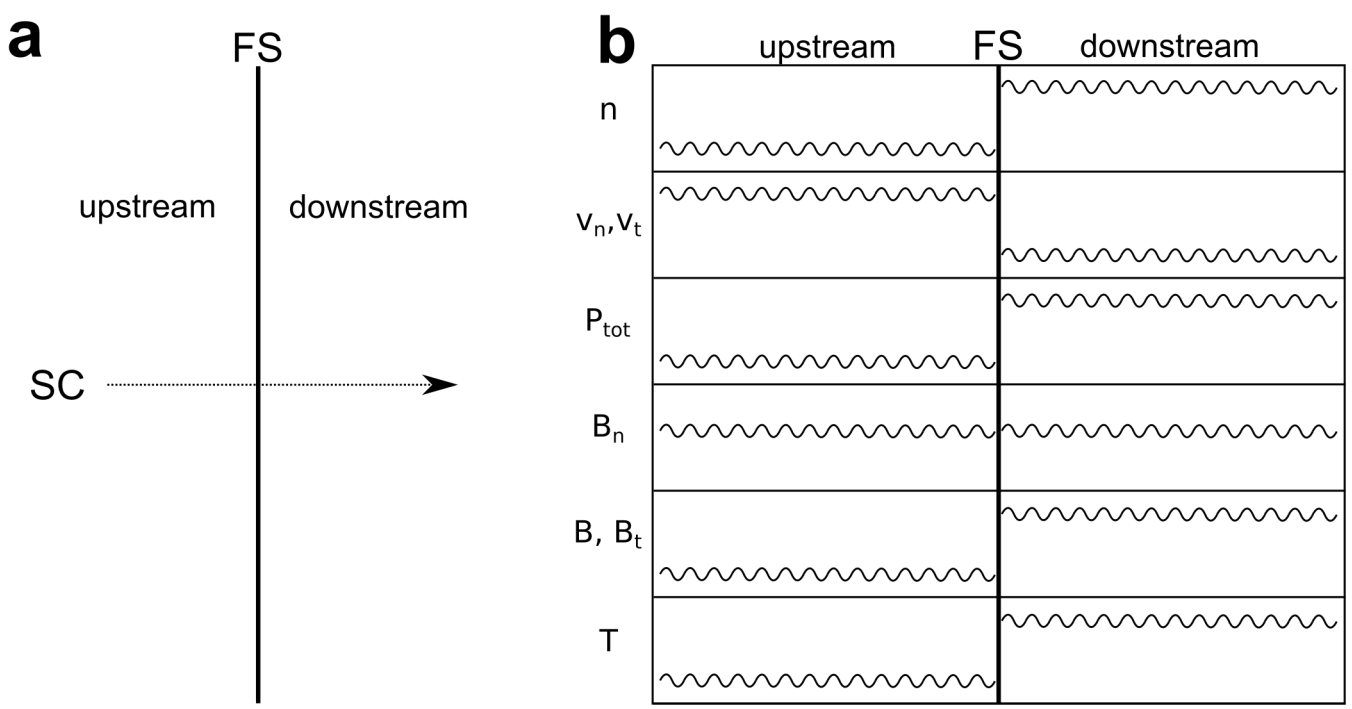


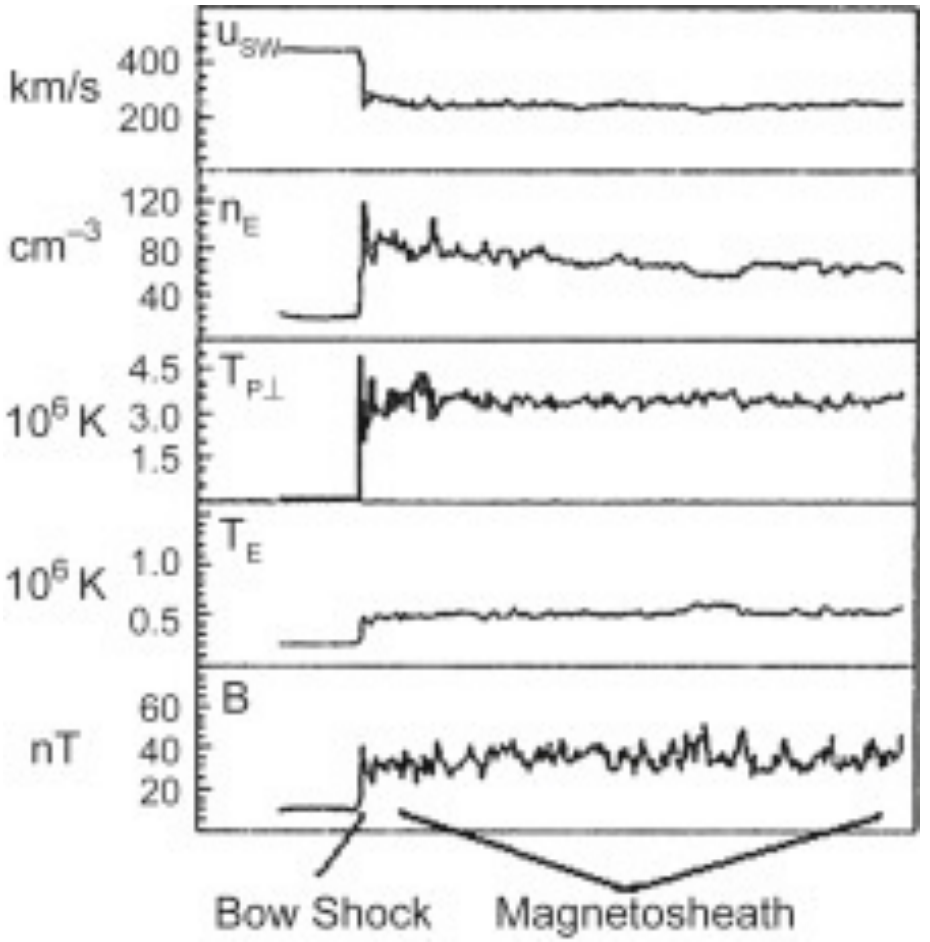
<u>Shock waves:</u>
Formed when structure moves with speed above local wave speed (e.g., sound, magnetosonic)

They are everywhere!

Heating, accelerating particles and converting energies

Fast shock transition (Theory & initial data)





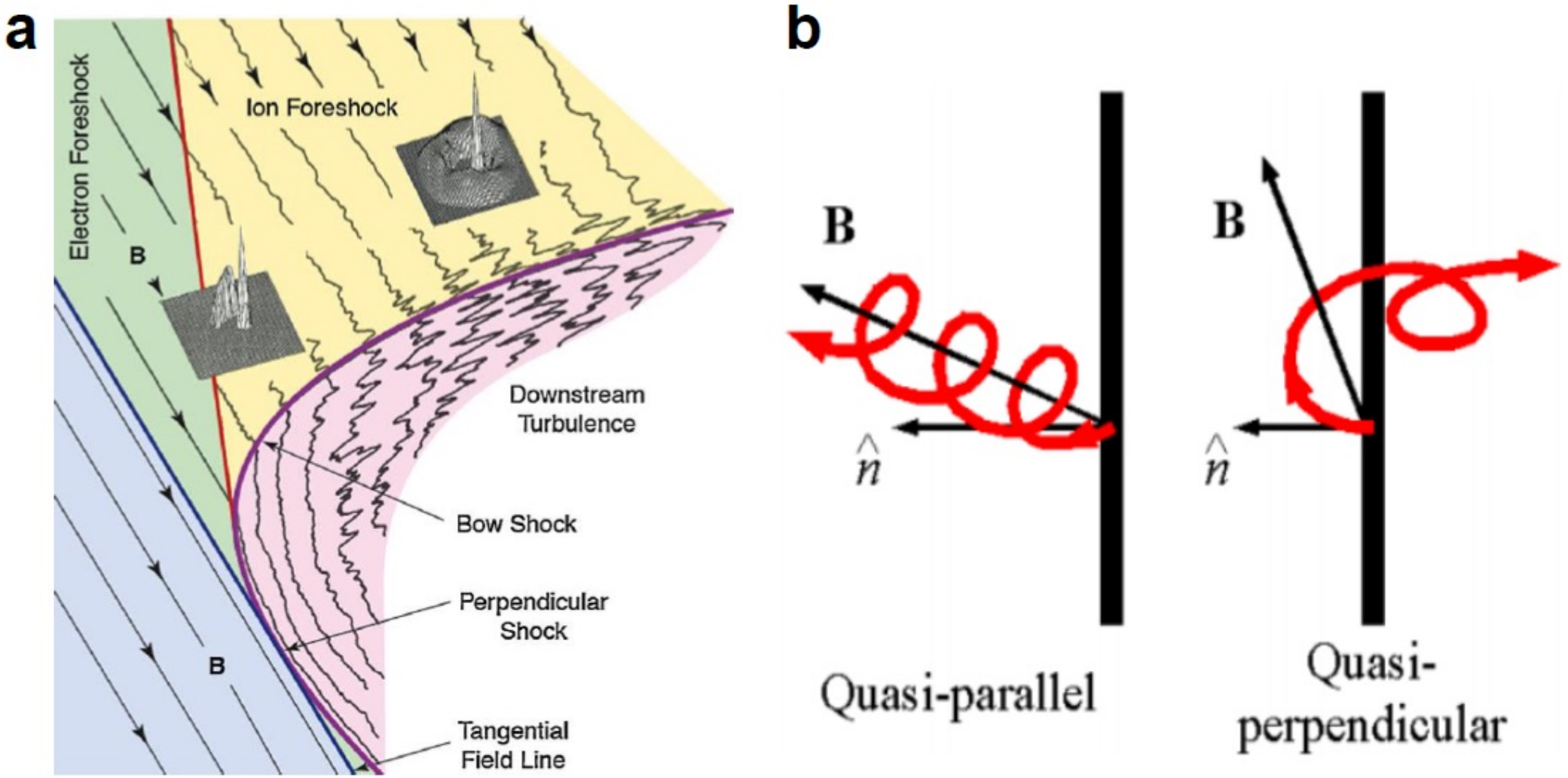
Rankine Hugoniot relations / Jump Conditions

Thermalization, Compression, Breaking

1D Isotropic and adiabatic one fluid plasma shock transitions

1964. Initial results of IMP-1 magnetic field experiment.

The Supercritical Bow Shock & foreshock

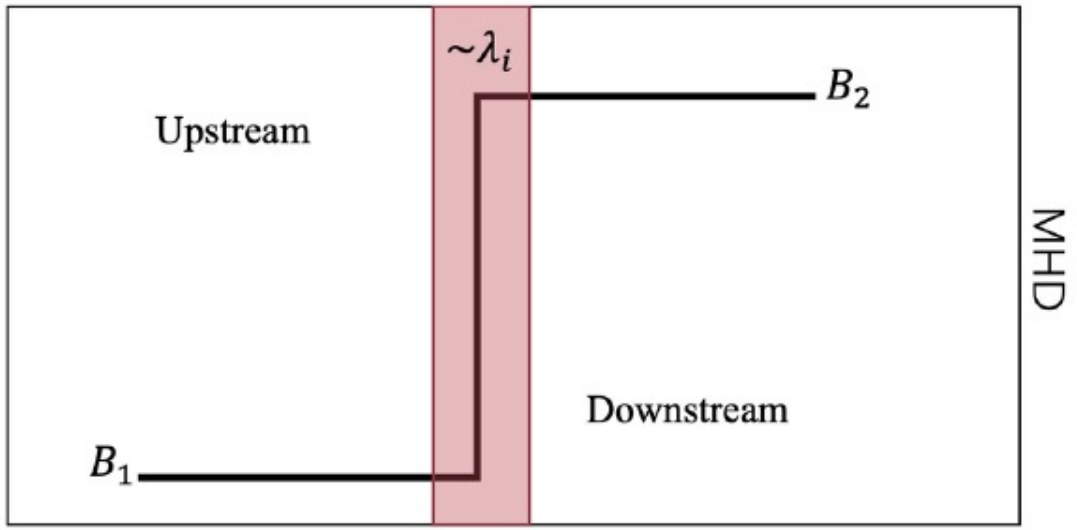


Reproduced from [Balogh and Treumann, 2013].

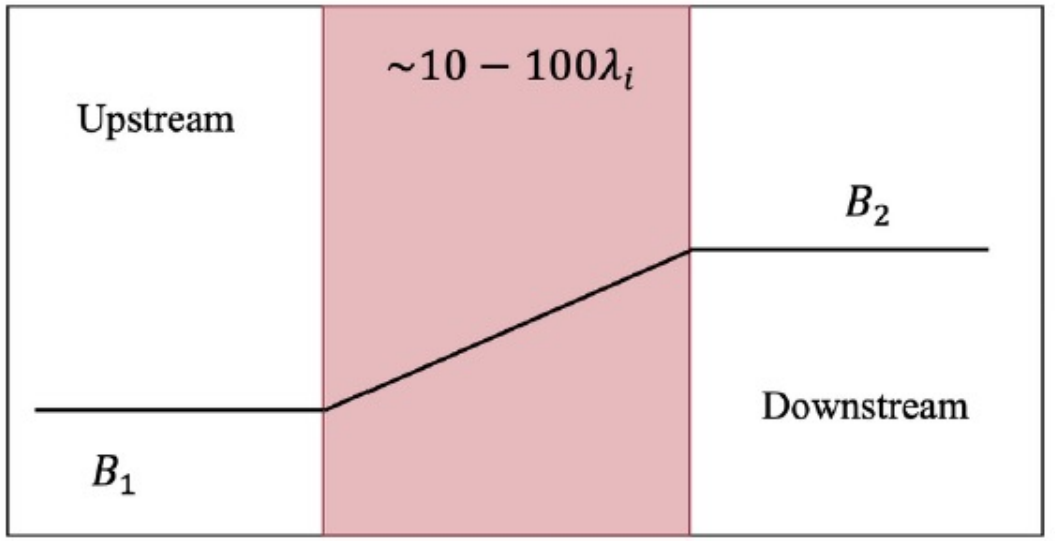
Assuming Specular Reflection

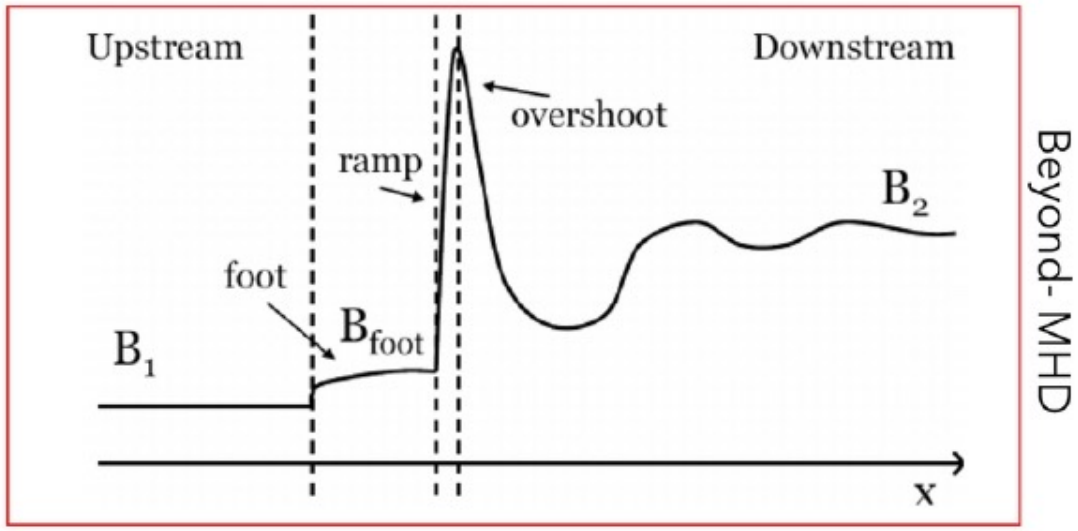
Quasi-parallel and Quasi-perpendicular shocks

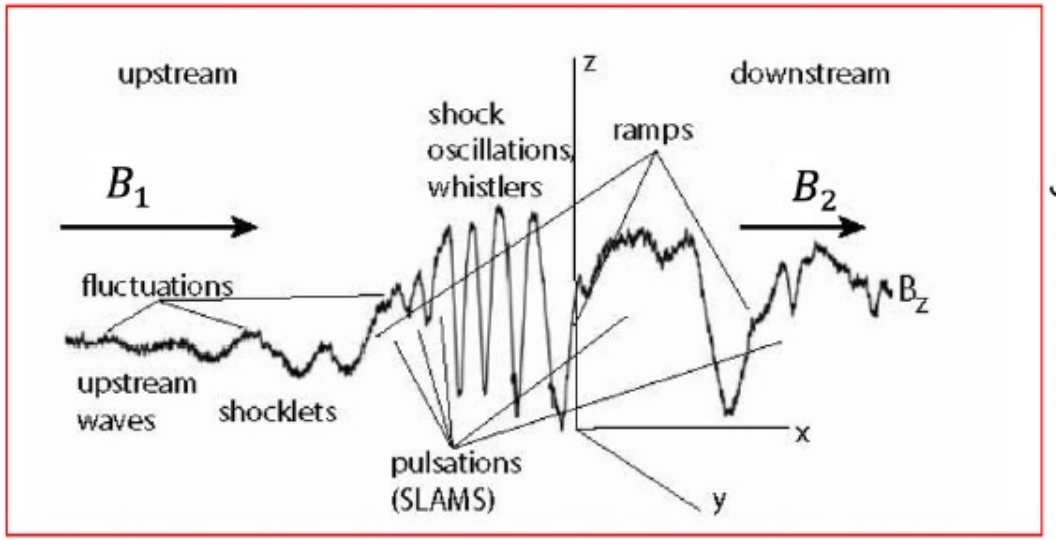
Qperp transition



Qpar transition





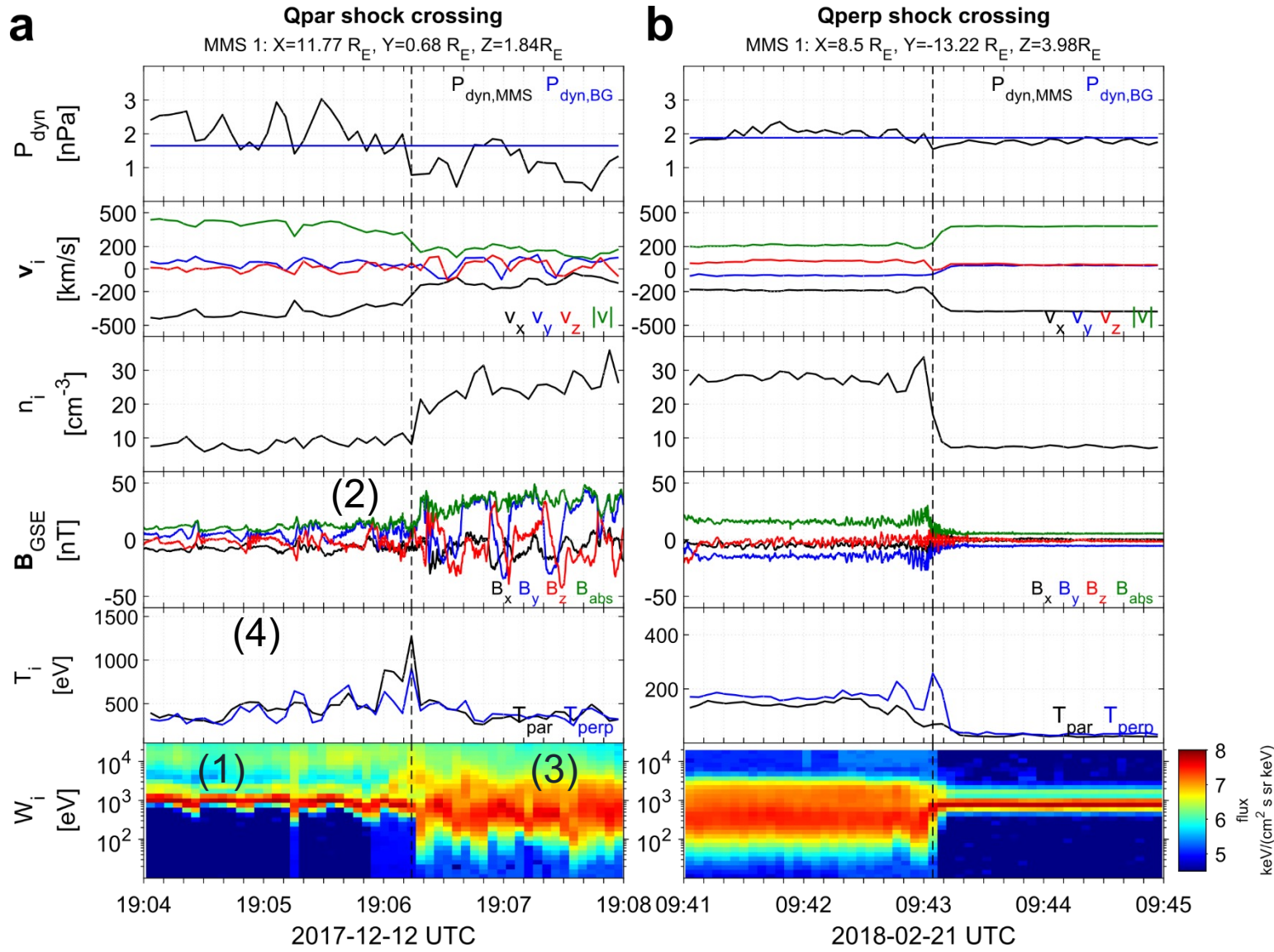


Slide from Immanuel Jebaraj

Community Reminder: Qpar – Qperp crossings

Qpar shocks and downstream plasma:

1) Presence of foreshock
2) Magnetic field fluctuations ↑
3) High energy ions ↑
4) Downstream temperature anisotropy ↓

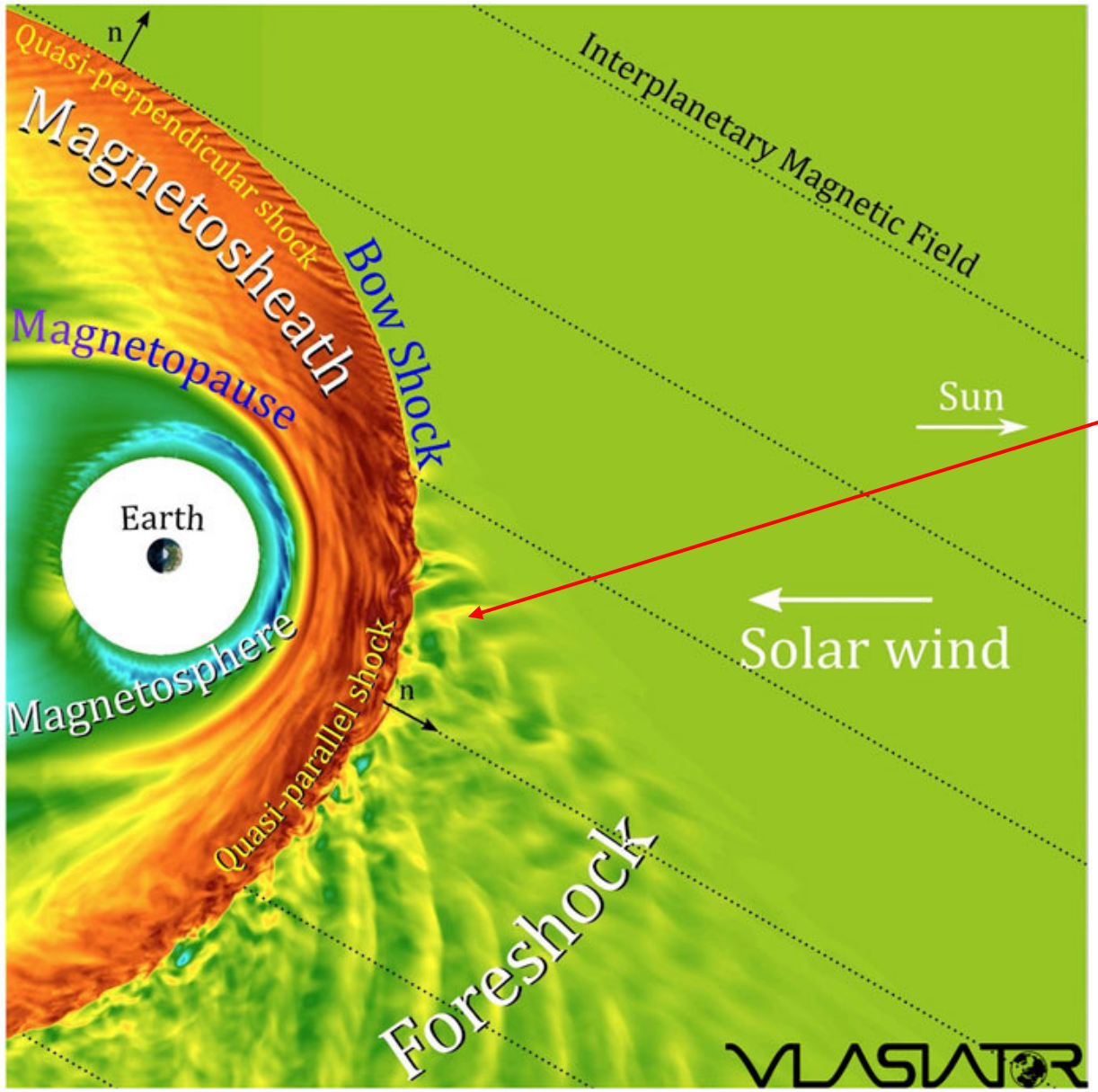


MMS, Cluster, THEMIS, MMS

Raptis+(2020a,2020b), Karlsson+(2021), Koller+(2024,2025), Svenningsson+(2024)

Figure taken from PhD Thesis (Raptis 2022)

Earth's Qpar bow shock and foreshock



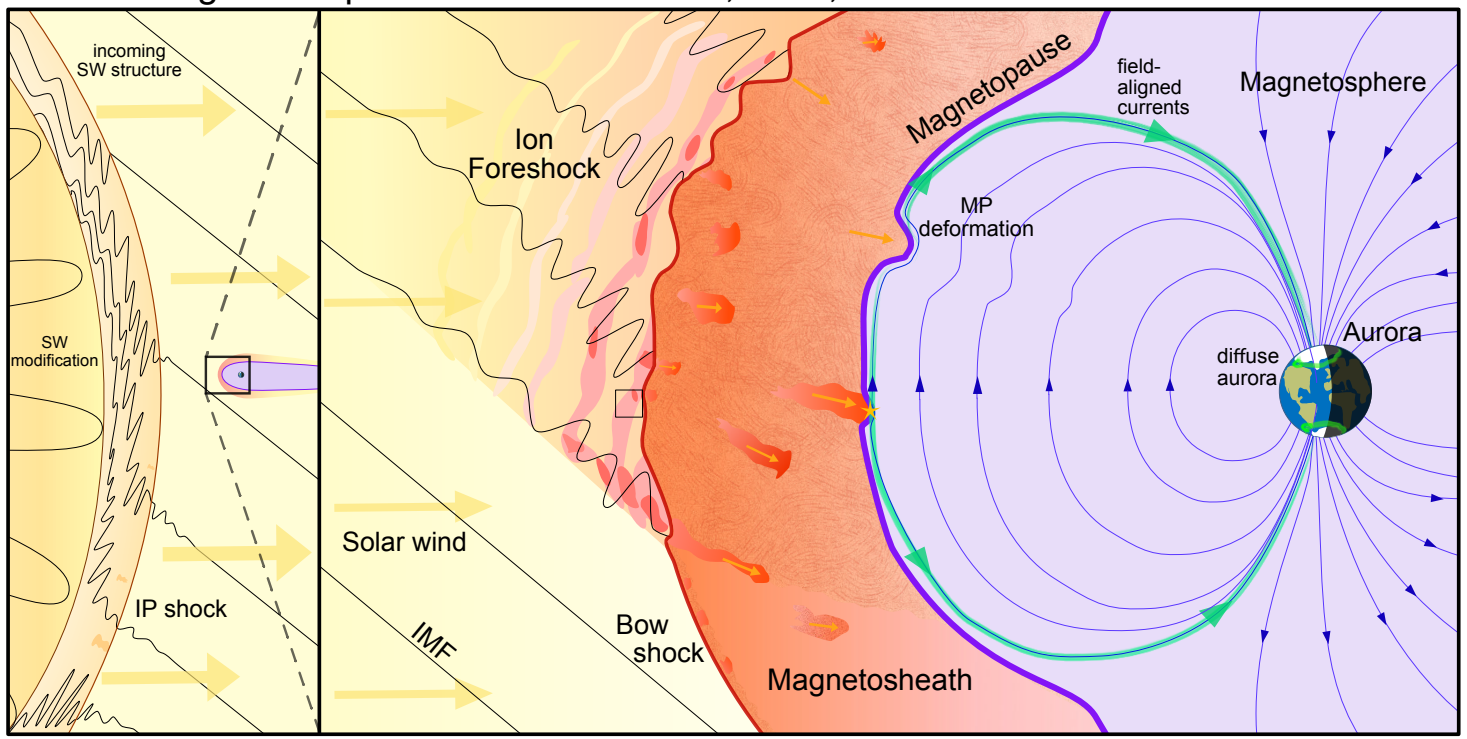
Qpar shocks ($\theta_{Bn} < \sim 45^\circ$)

- Very efficient particle accelerators
- **First boundary of SW & magnetosphere coupling**
- **Transient phenomena** upstream and downstream
- ULF waves upstream and downstream
- Kinetic plasma physics
- Wave particle interaction
- Turbulence
- Current sheets & reconnection

What is a Dayside Transient?

←New review paper about high-speed jets!

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



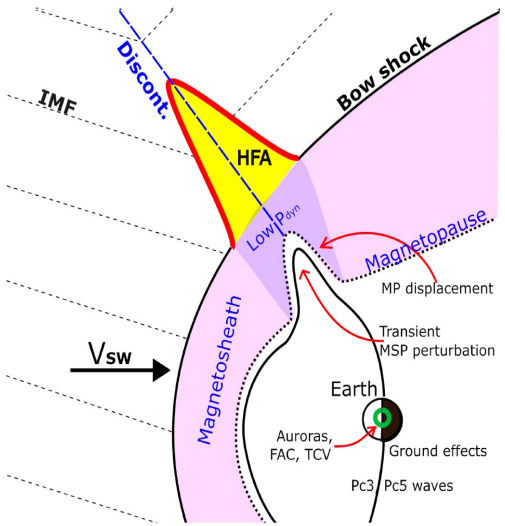
Transient phenomena are events that disrupt the steady-state plasma conditions, occurring temporarily and introducing dynamic changes to the physical system

- 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, 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)

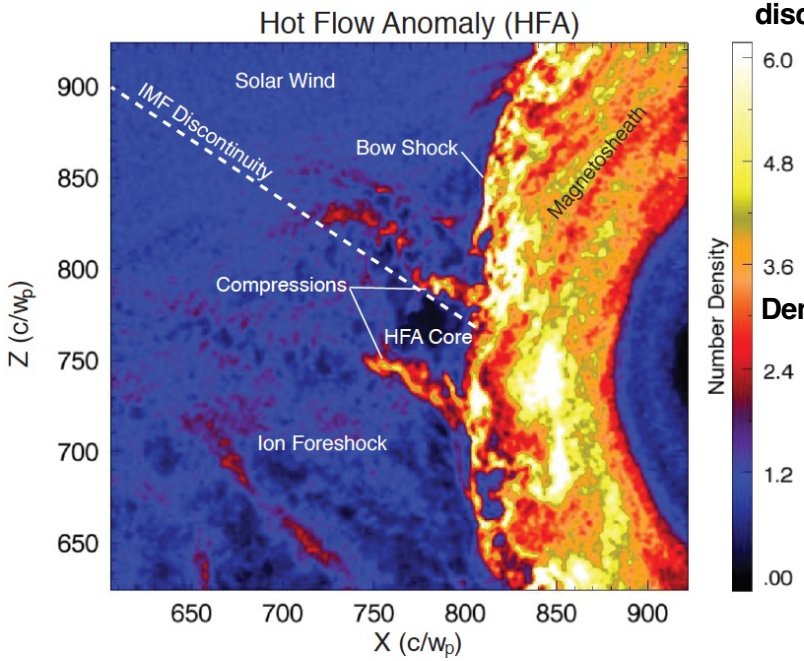


Figure by Nick Omidi

Crater-like B-field and IMF discontinuity

Density compressions and cavity

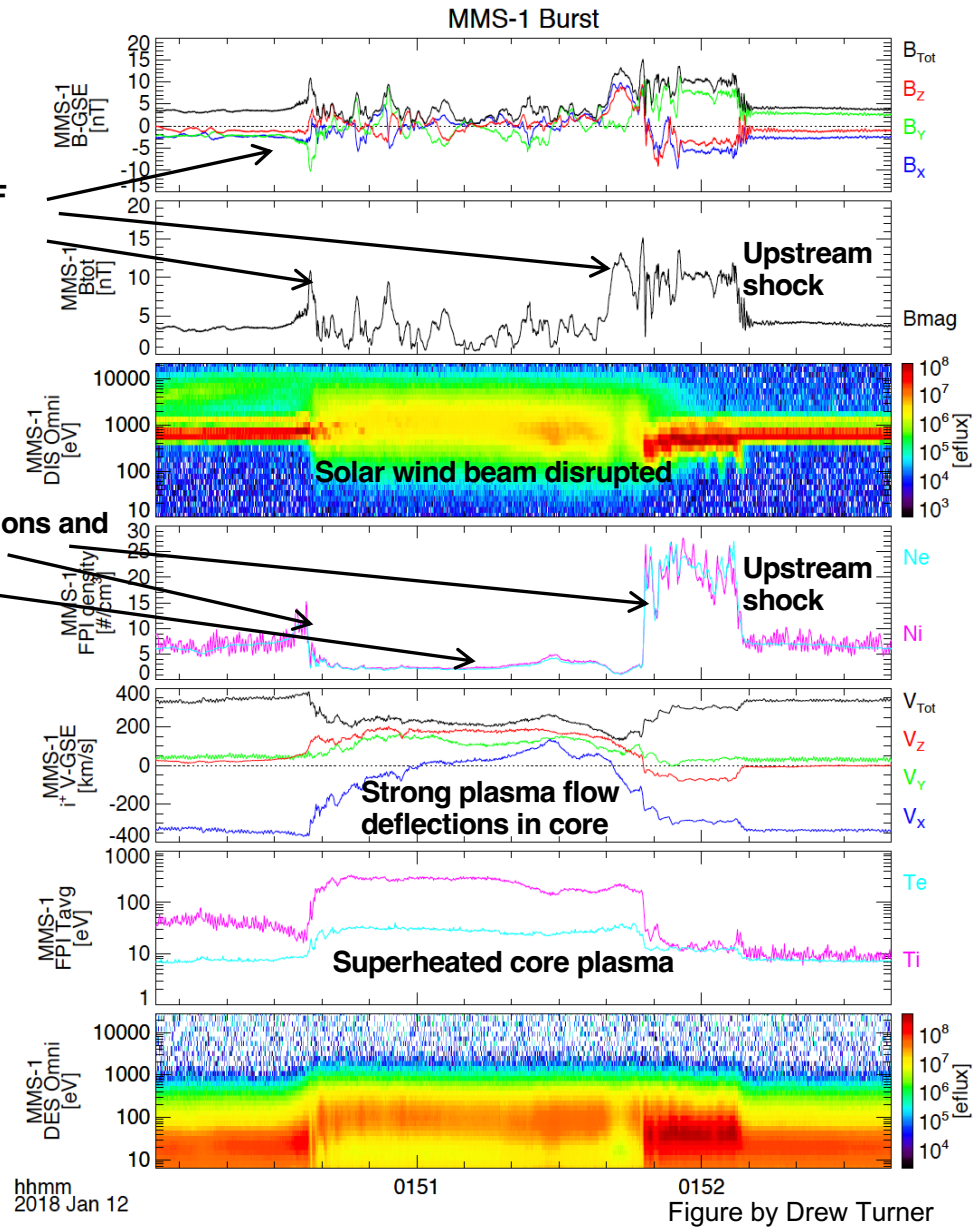
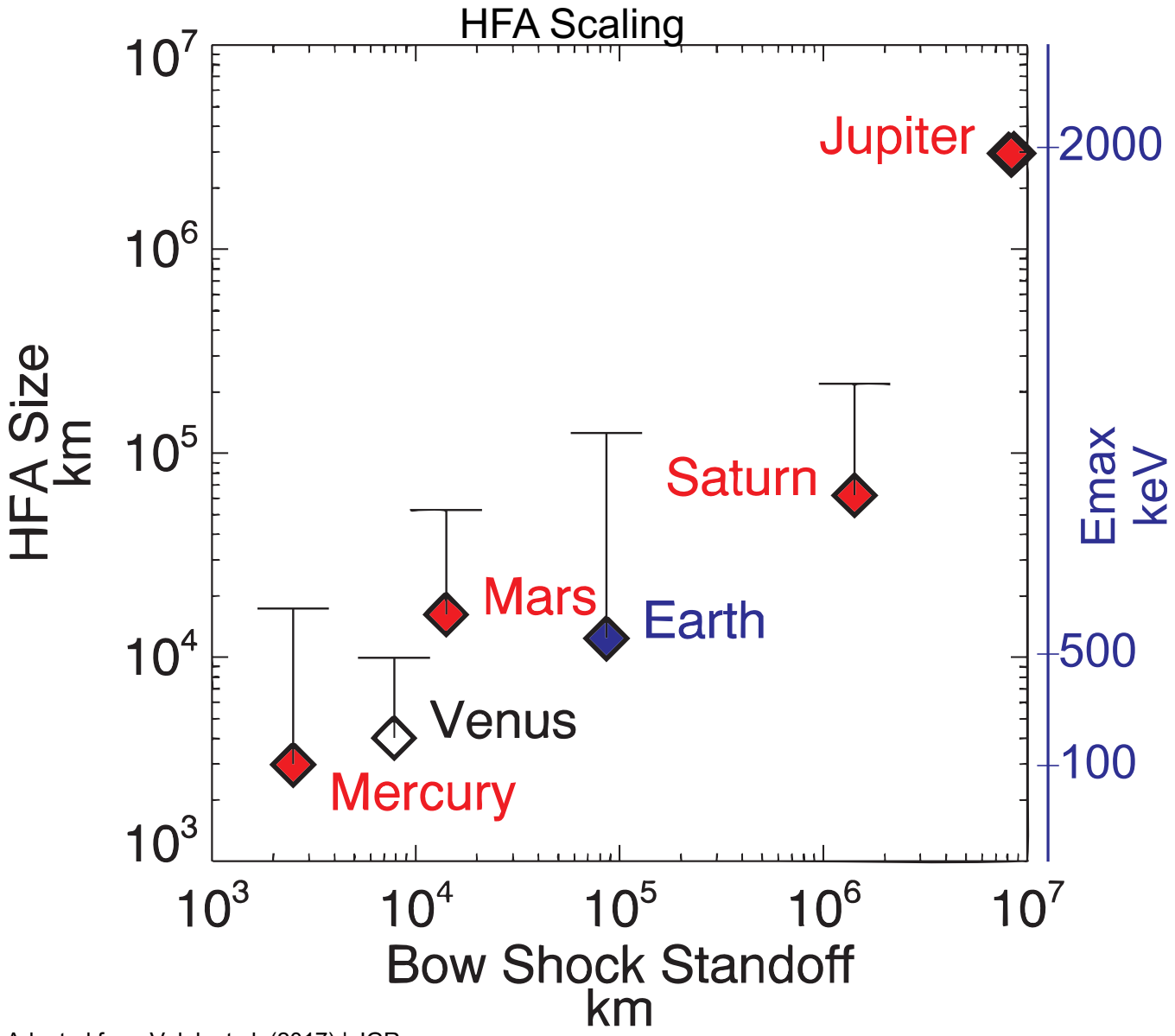


Figure by Drew Turner

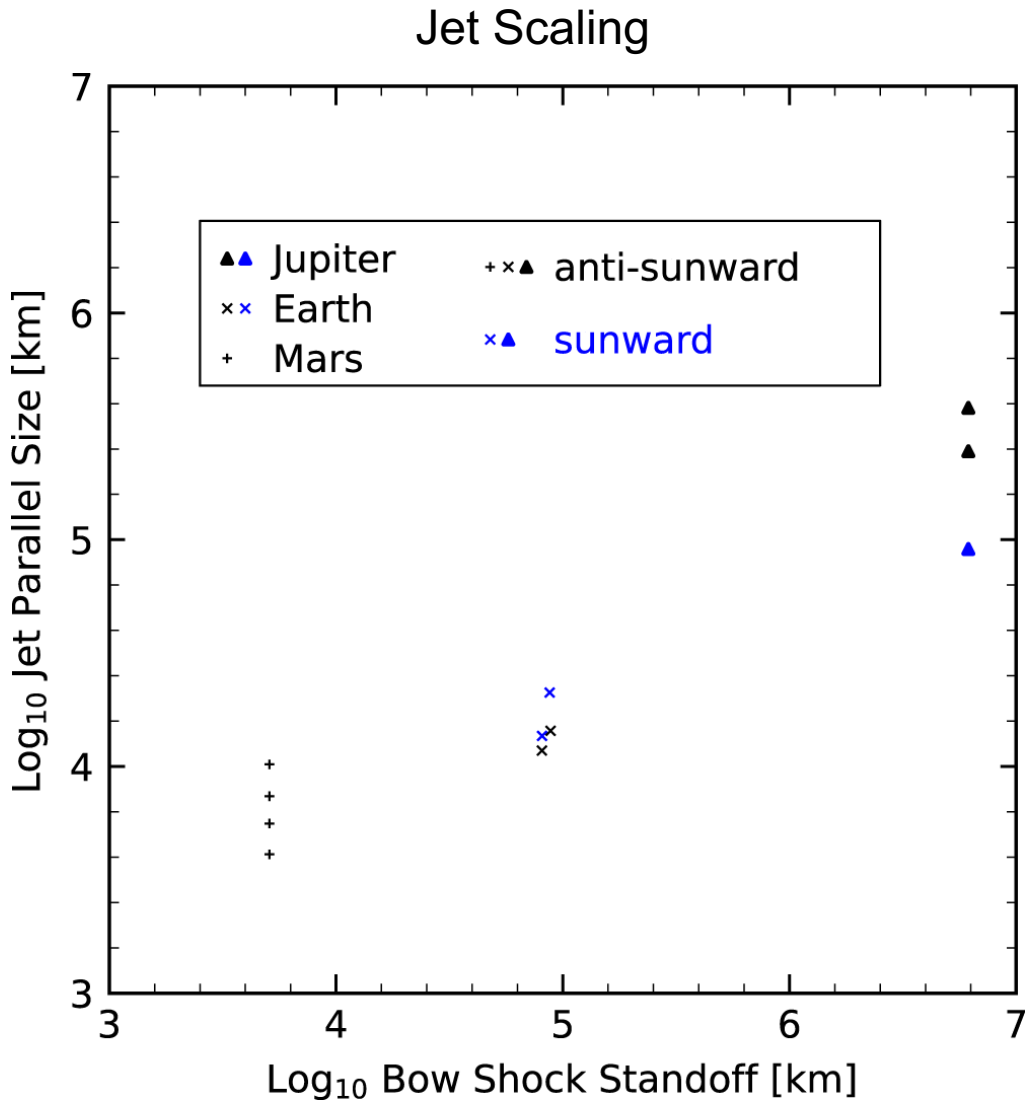
How do they form?

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

Transients Scaling Across Systems



Adapted form Valek et al. (2017) | JGR



Zhou, et al. 2024

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

Maybe?! – See more at AGU25 ;)

Yes!*

Yes!*

*Gunell+ 2023, Zhou+ 2024, Mohammed-Amin+ 2025

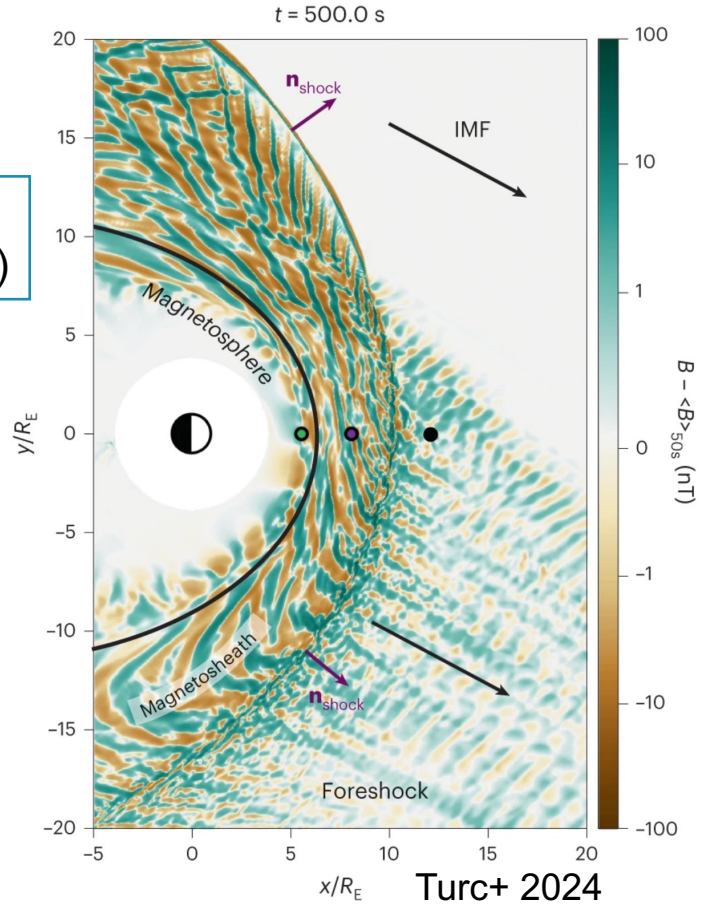
Effects of Transients to Magnetosphere

Transient and Wave transmission

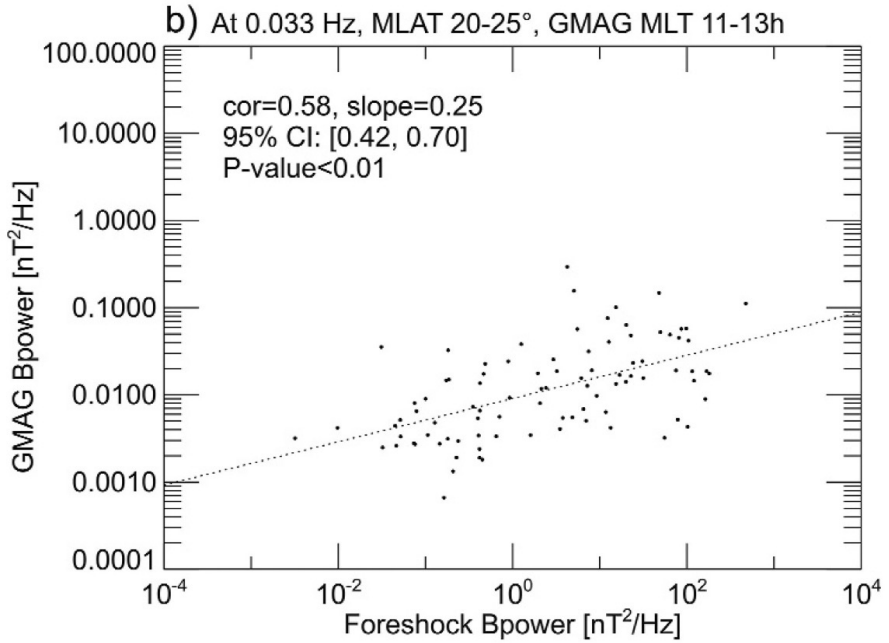
Pi2 Pulsations transmitted associated to jets/foreshock transients (Katsavrias+ 2021)

Evidence of Pc3 waves generated by a large HFA (Zhao+ 2017)

Foreshock transients driving Pc5 waves (Hartinger+ 2013)



Turc+ 2024



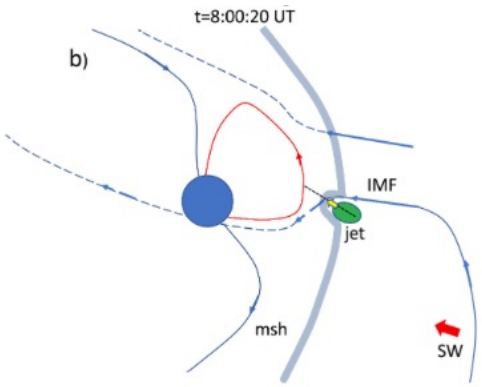
Liu+ 2025

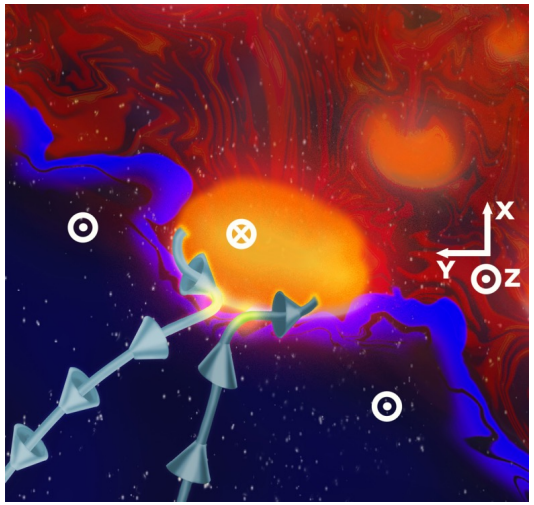
GMAG correlation with foreshock waves

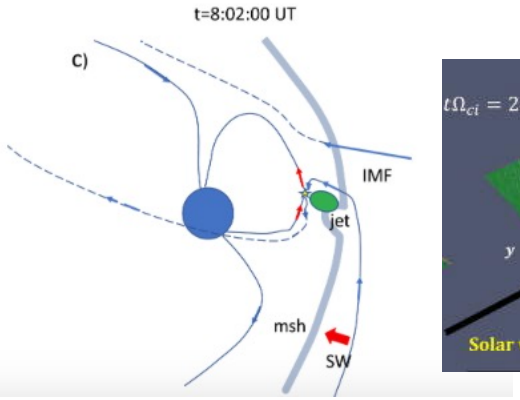
How are the ULF waves transmitted from the magnetosheath to magnetosphere?

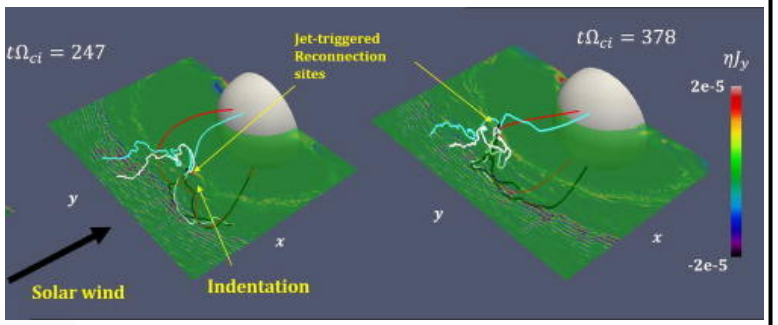
Global hybrid simulations & in-situ conjunctions are needed.

Magnetopause Reconnection and Displacement









Ng+2021

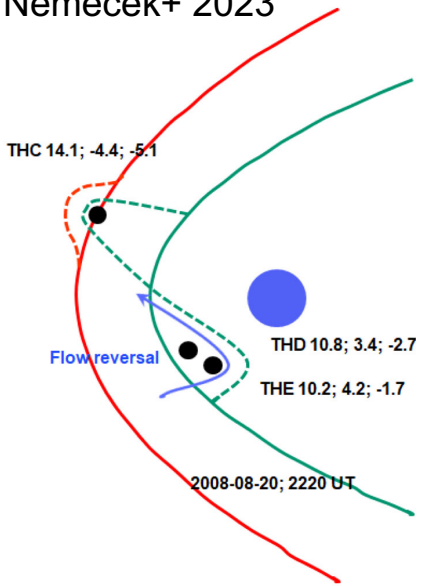
Transient localized processes drive and adapt MP bursty reconnection

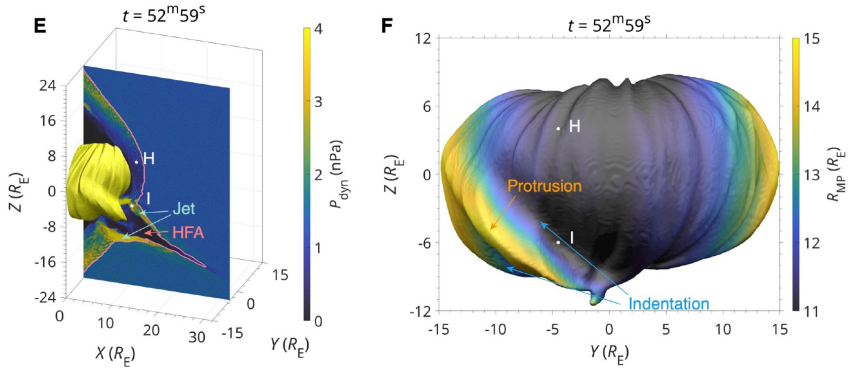
Hietala+ 2018, Escoubet+ 2020, Vuorinen+ 2021

"Jets can have bursts of southward Bz"

Open question: Is this sufficient? Is it large enough? For long enough time?

Němeček+ 2023

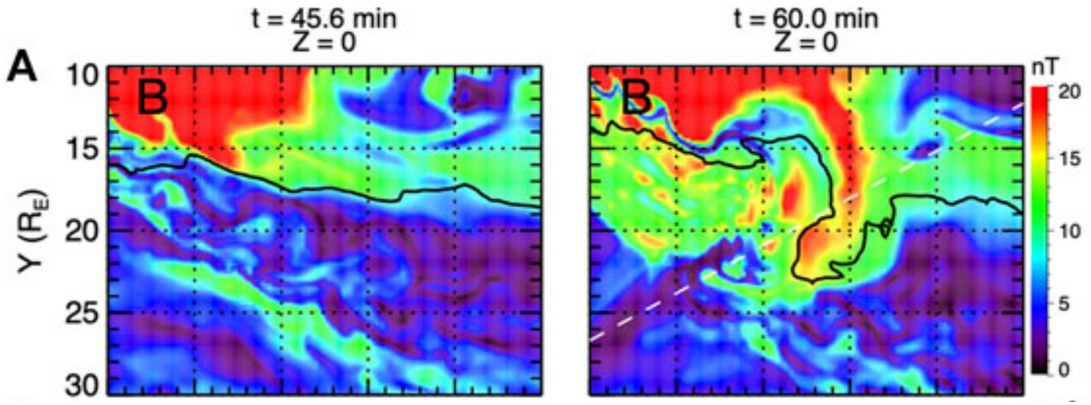




Zhou+ 2025 (under review)

Jets ~ 4Re localized
HFAs ~6Re over the whole MSH

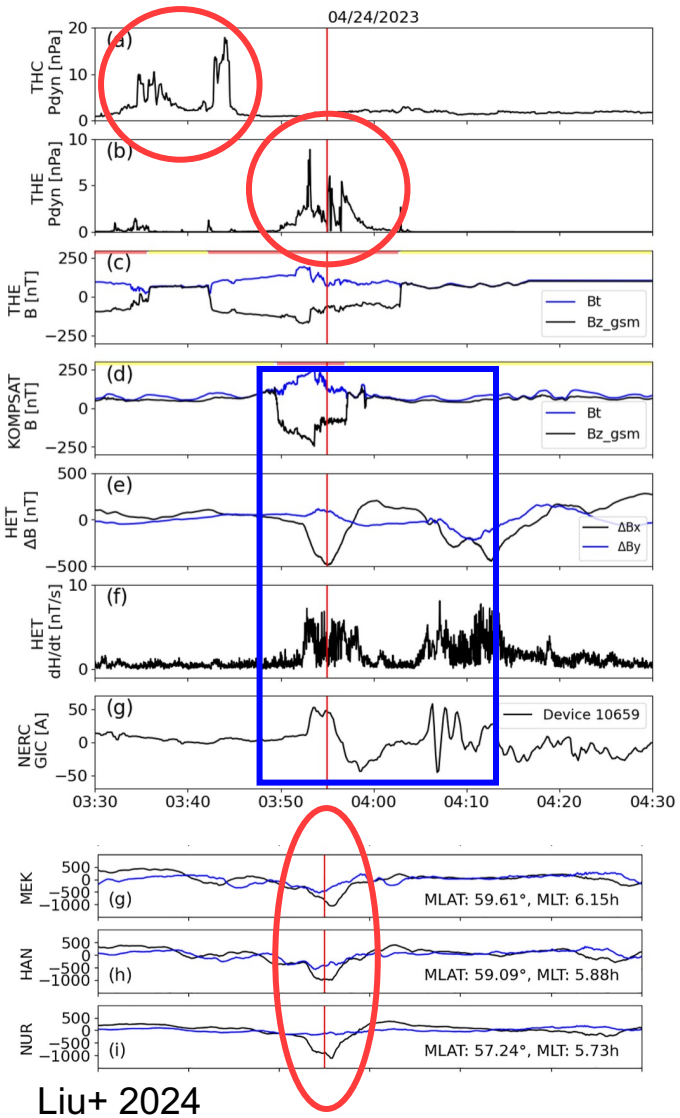
Open question: How "important" is this for preconditioning the magnetosphere?



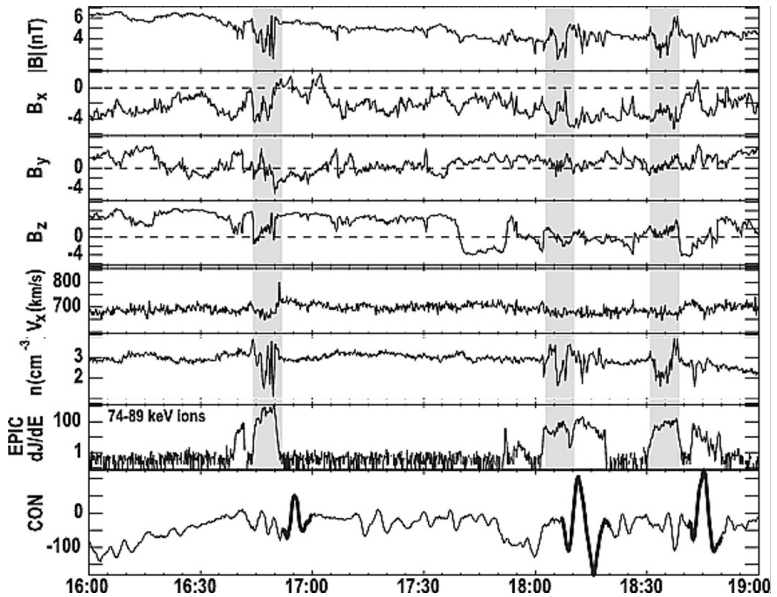
Wang+ 2021

Yang+2023, Guo+ 2023, Sibeck+2025

Inner magnetosphere and Ionosphere effects



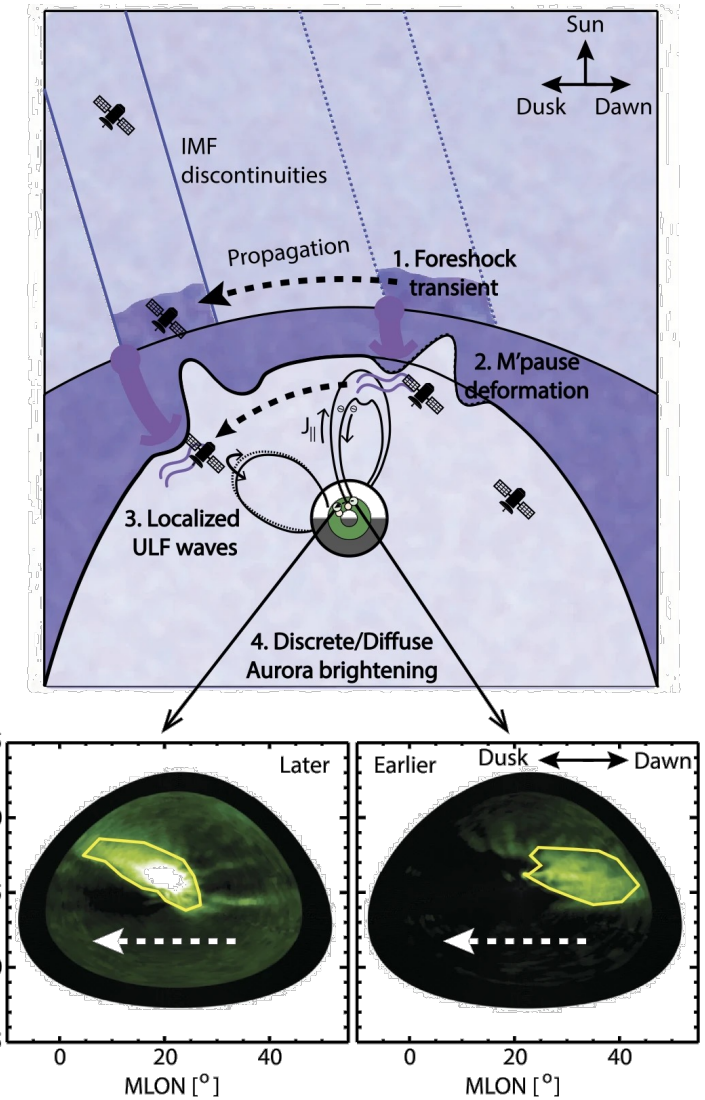
Liu+ 2024



Murr+ 2003

Which shock-generated transients cause ground perturbations?

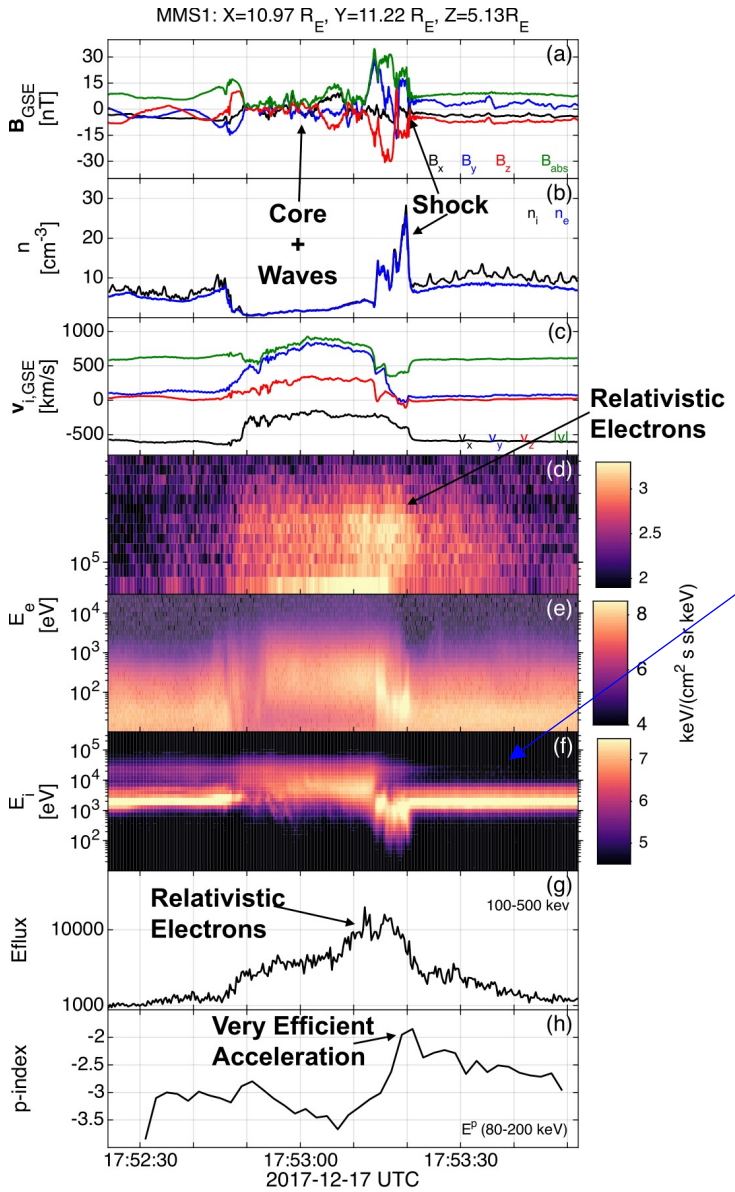
How do shock-generated transients drive localized aurora brightening?



Shen+2018, Wang+ 2018,2025, Xu+ 2024

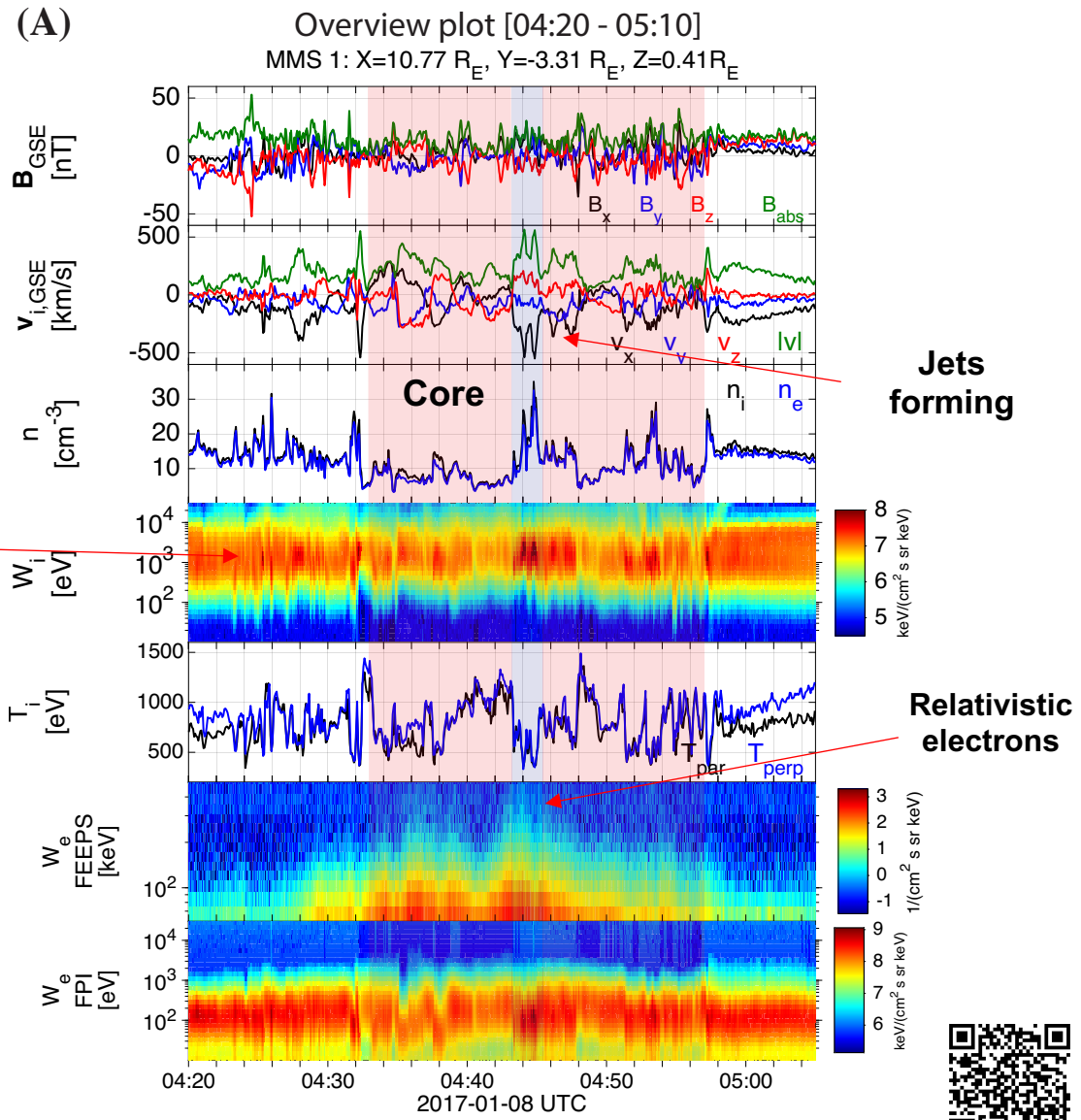
Recent Results

HFAs and FBs are amazing particle accelerators



Solar wind

Magnetosheath



Raptis et al.2025 NatComm

Raptis et al.2025 ApJL

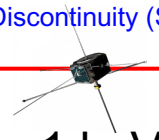
Reinforced Shock Acceleration: From Sun to Earth

(A)

Coronal Hole SW
V> 500 km/s

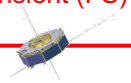
?

Discontinuity (SW) ARTEMIS

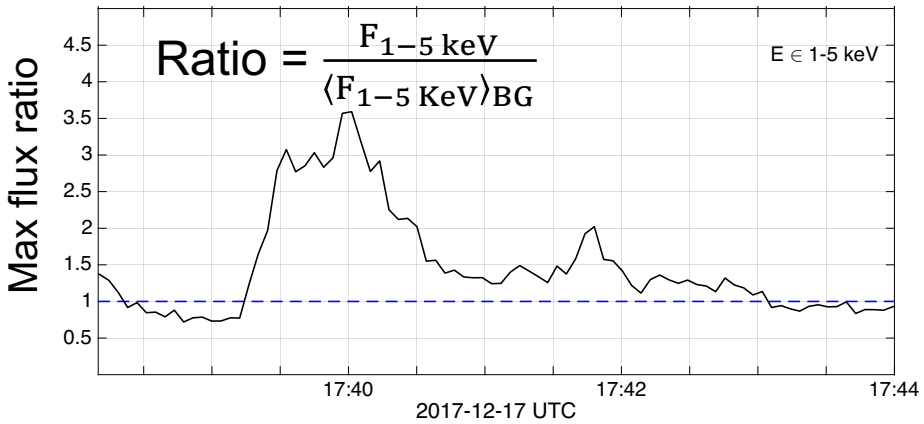


~1 keV

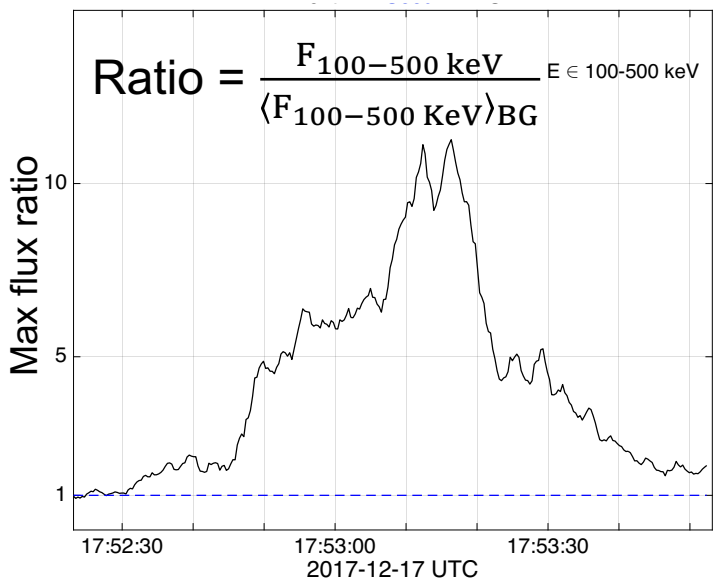
Transient (FS) MMS



>100-500 keV



SW – ARTEMIS / THEMIS



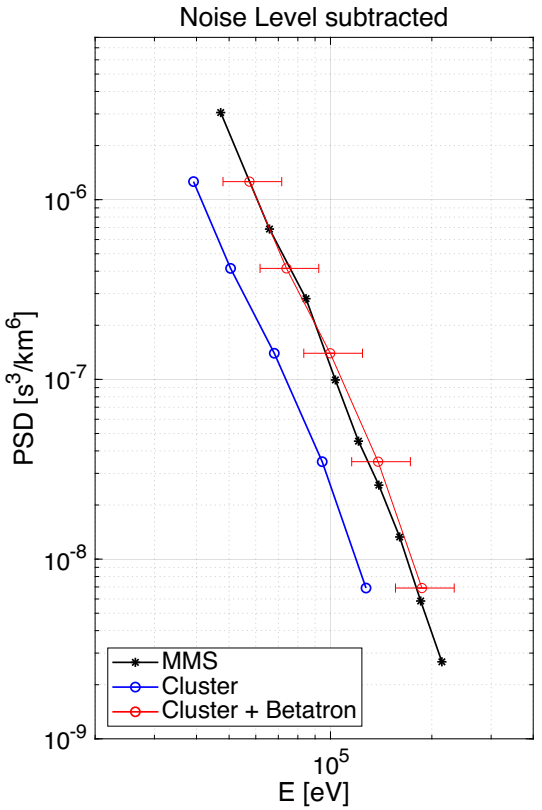
Foreshock - MMS

Fast SW seeding ~low keV particles

(B) Transient (FS) Cluster

Transient (MSH) MMS

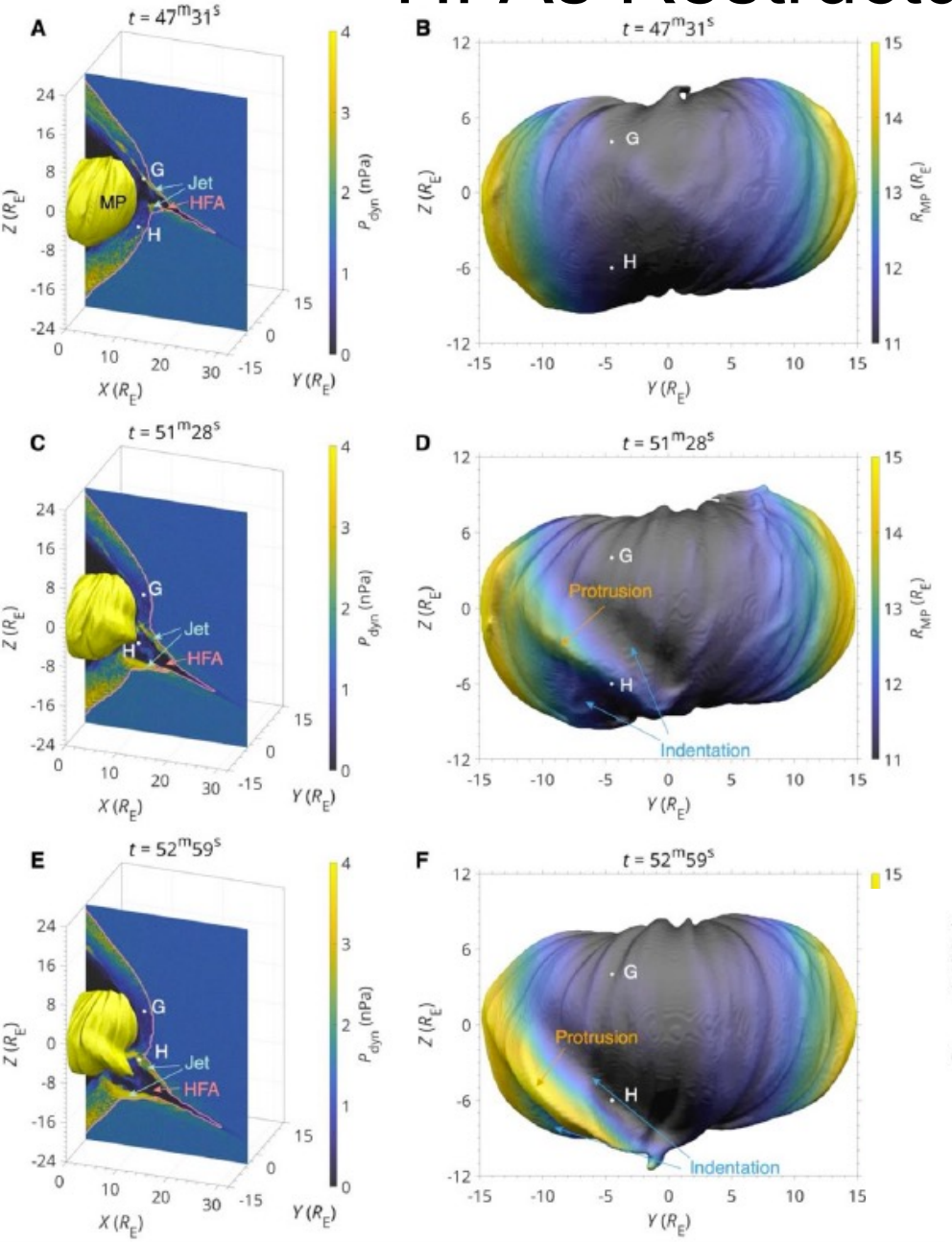
X → X+100 keV



Magnetosheath – CL / MMS

(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*

HFAs Restructuring the Entire Magnetosheath

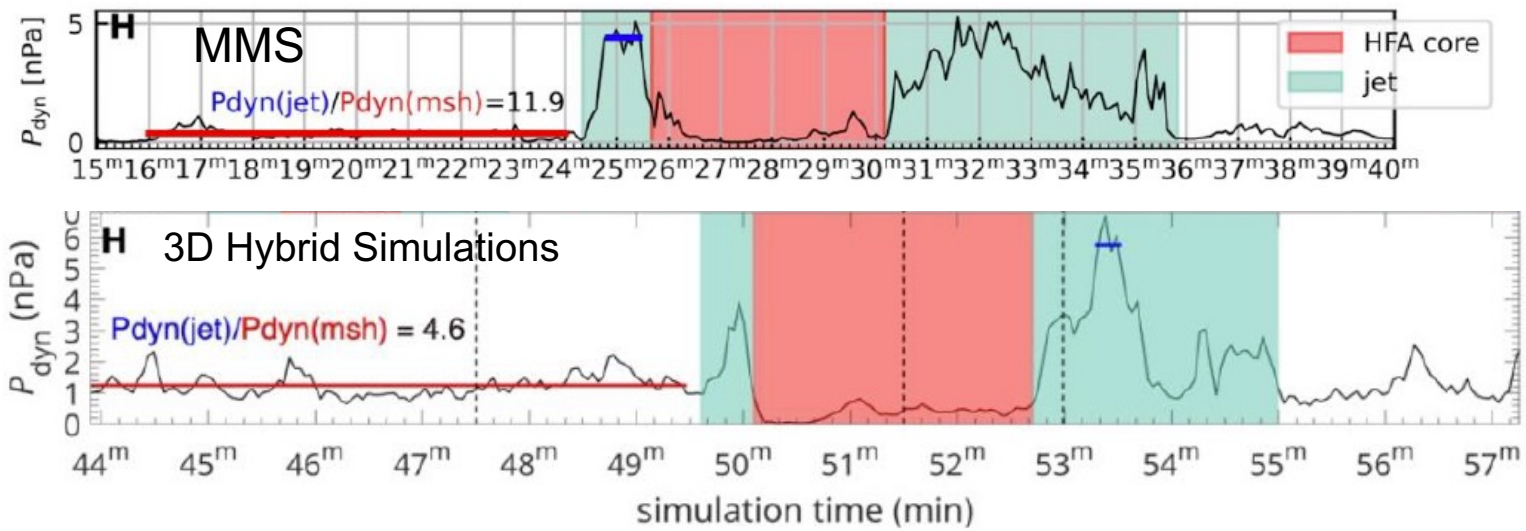


Localized dynamic enhancements (jets) at the edges
(stuff move inwards)

Core density depletion effects
(stuff move outwards)

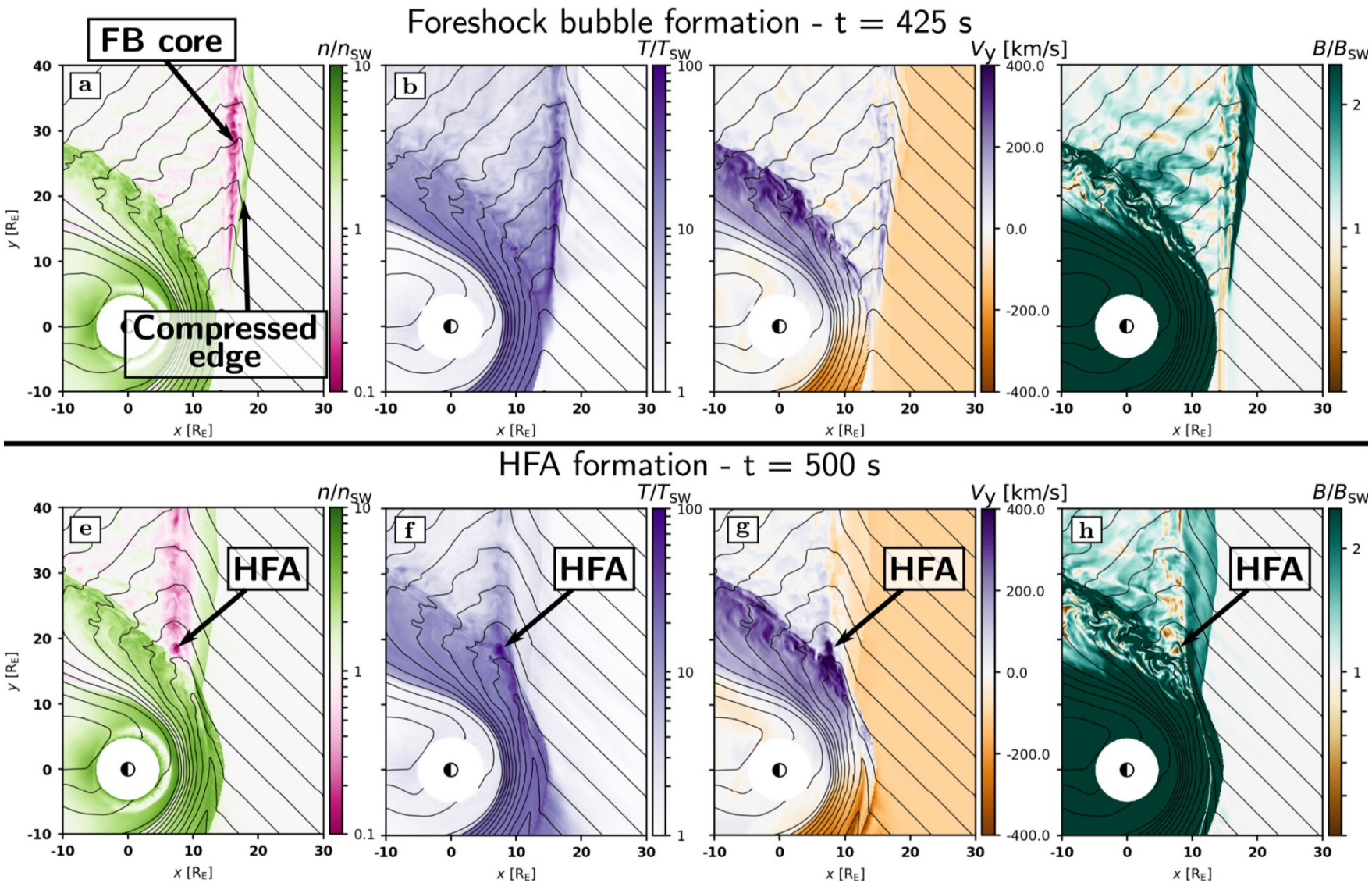
<u>Leads to magnetosheath restructuring</u>

- <u>Spatial extent</u>: ~10s of Re
- <u>Duration</u>: ~10s of minutes



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

Interplay between FBs and HFAs

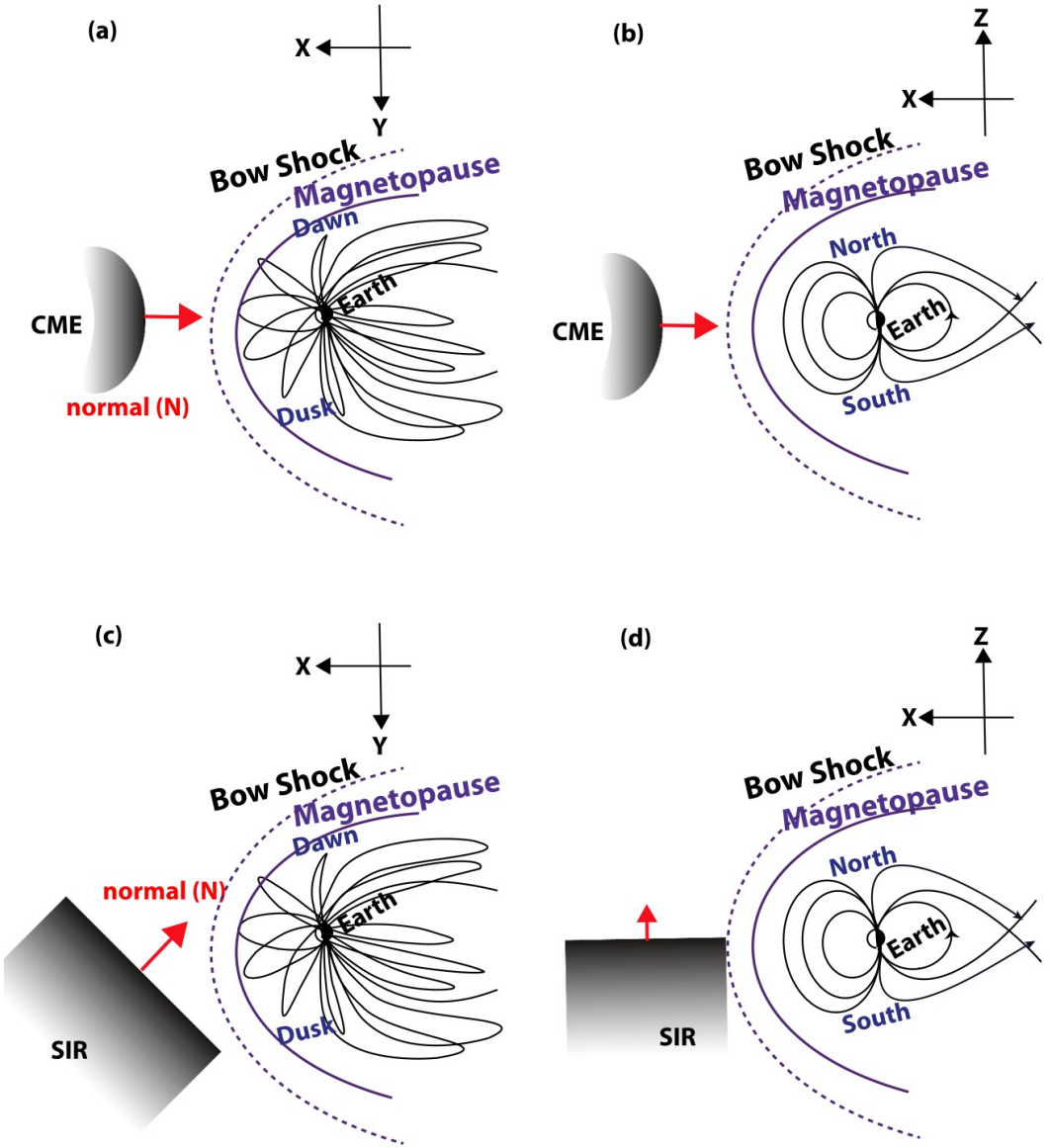


Turc et al., 2025

Key findings

- Directional discontinuity generate several types of foreshock transients
- FBs can modulate the conditions causing HFAs to form
- Similar to other studies, bow shock deformations are associated to parameters at the core of the transients

IMF Discontinuities & Transients



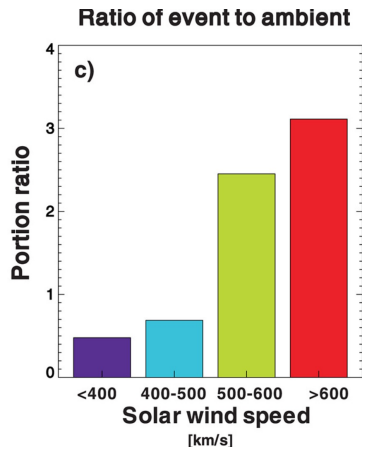
Lee et al., 2024, 2025

Magnetosheath high-speed jets are measured more frequently during fast SW (Raptis+2020, Koller+2023)

Solar wind speed has the highest **positive correlation with particle energization** (Liu+2017a)

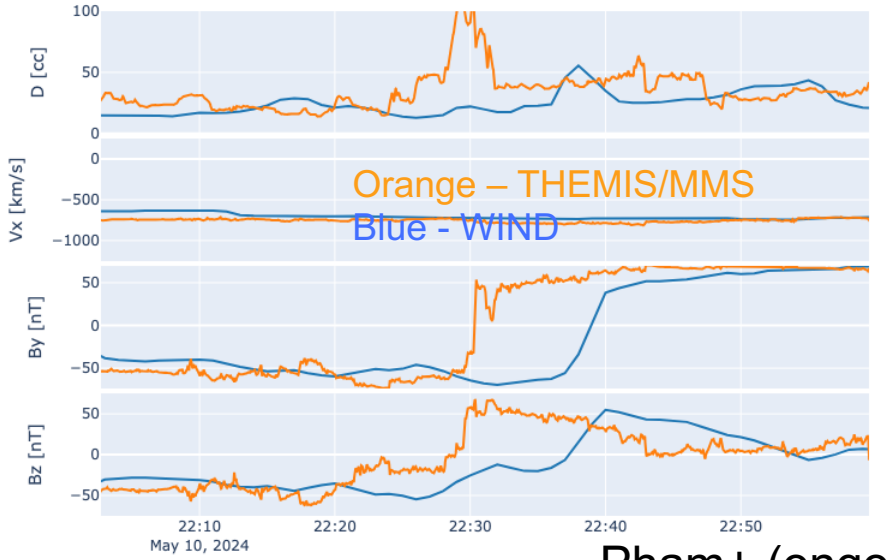
Distinct **seeding of suprathermal particles allowing HFAs to accelerate electrons to 100s of keV** during fast SW (Raptis+2025a)

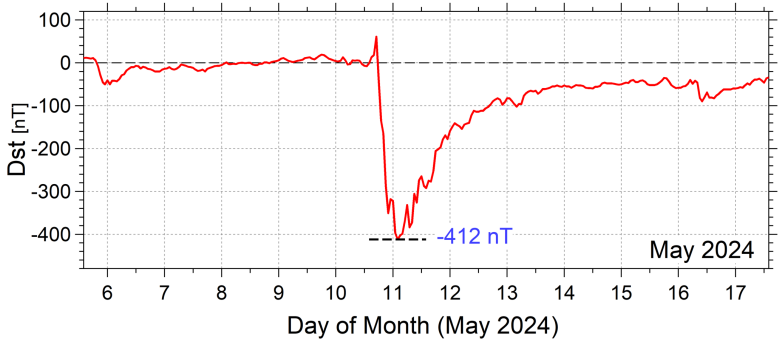
Series of HFAs found both **upstream and with equivalent downstream** measurements during fast SW (Raptis+2025b)



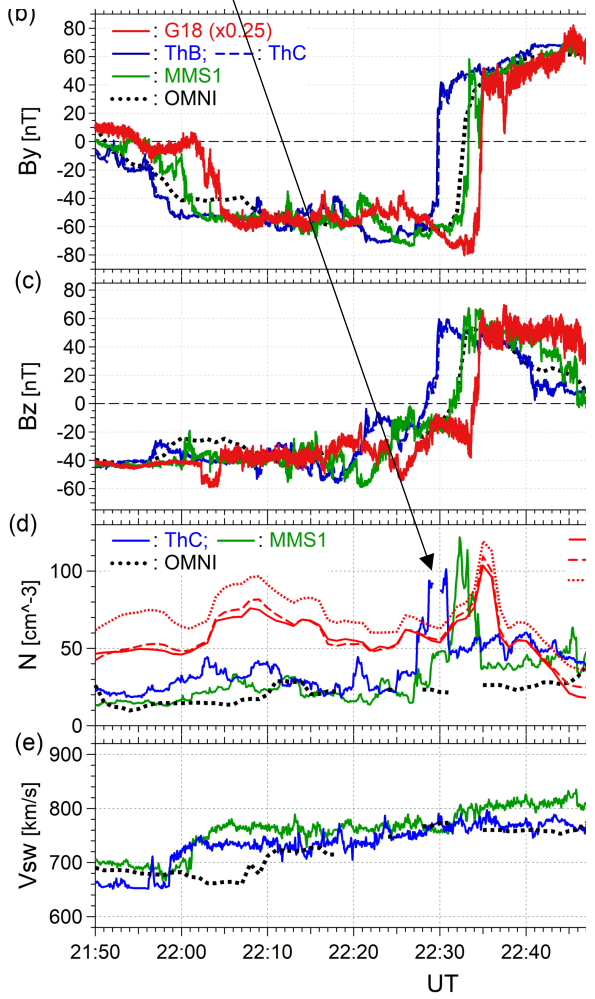
Liu et al., 2017b

Upstream Variability & Gannon Storm Success



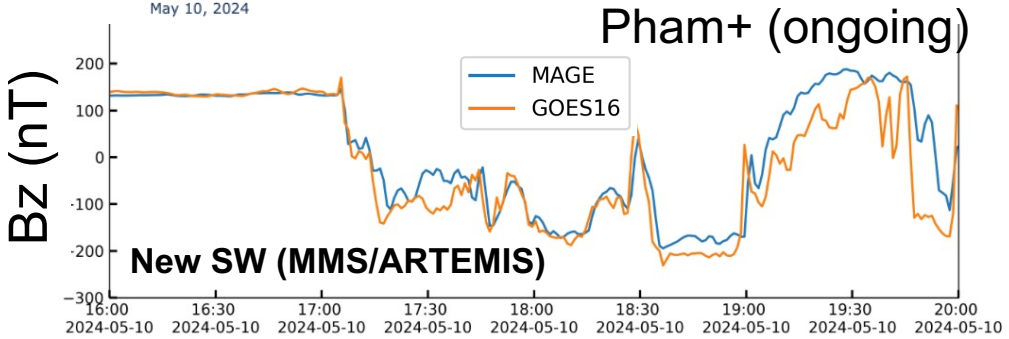


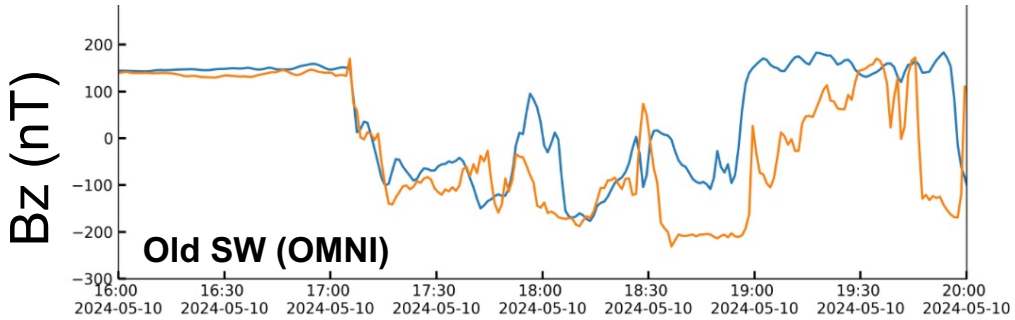
This density enhancement may play a crucial role



Ohtani+ (2025)

Pham+ (ongoing)





- ✓ Introduced local upstream (~10 min) transient variability from local *in-situ* observations
- ➢ Data–model agreement increased drastically
- ➢ Physical interpretation of ground data changed significantly

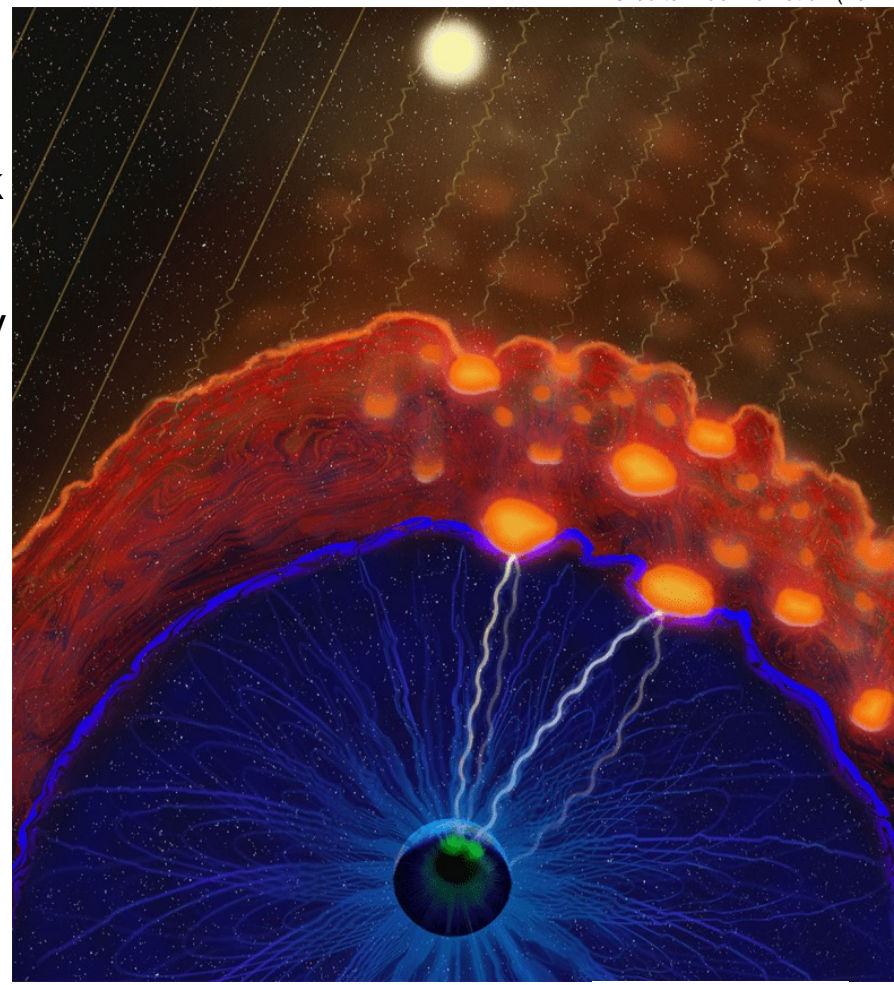
Final Words

Evaluating the global picture of these cross-scale processes is the next step

- **Global Magnetospheric Impact**: Can we observe the global effects of large-scale transients across the entire magnetosphere? How does the lack or inclusion of these in simulations affect the outcome?
- **Transients & Preconditioning:** Simulations show that solar wind variability affects the magnetosphere, but results for single transients are mixed. The effect of a realistic inclusion of transients on system preconditioning and evolution remains a key unknown.
- **Counteract reporting bias:** We can gain critical insights by studying transients that cause large magnetopause displacements but produce no ionospheric or ground response; these "null events" have the most to teach us.

Reminder: Our models of BS/MP can have disagreements of 5+ Re with data

Credits: Vuorinen et al. (2022



People interested in presenting at Mini-GEM please let us know + Ideas for GEM Challenge.

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

Upcoming Actions from our GEM FG

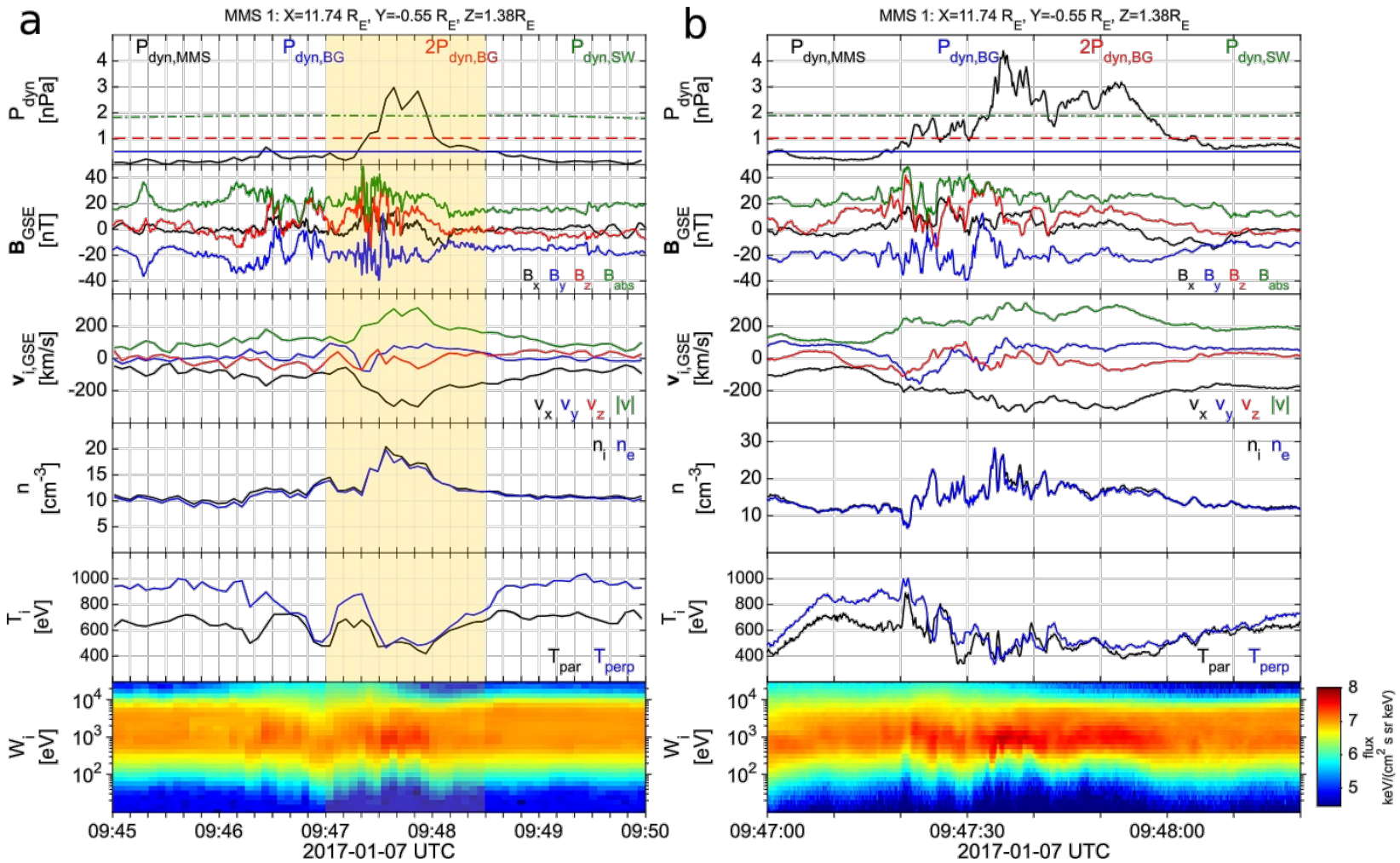
- Wiki Page: https://gem.epss.ucla.edu/mediawiki/index.php/FG:_Multiscale_Dayside_Transients_and_their_Effect_on_Earth%27s_Magnetosphere

Join our Google Group to (at some point…) get updates and information for our telecons and meetings: https://groups.google.com/g/helio-day-research

Extra Backup Slides

Example of a Transient Event (High-speed jet)

Example of High-Speed jet (MMS Data)



Krämer+ (2025)

MMS helped bridging fluid to ion/electron scales

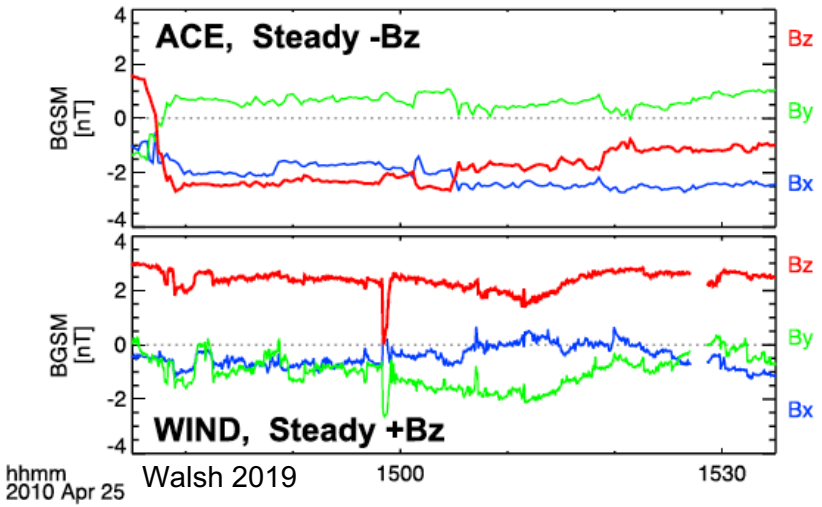
Clarified transient processes:

- Formation
- Particle acceleration
- Propagation
- Distribution-function evolution

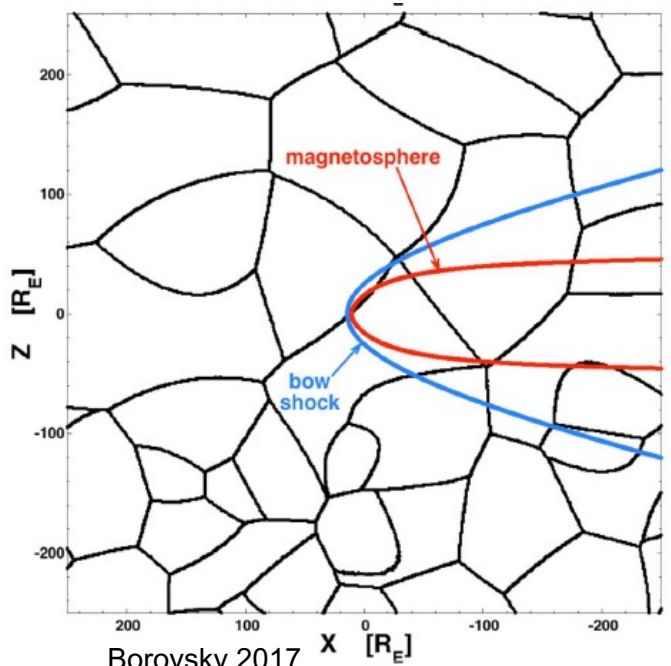
Remaining challenge: co-existing phenomena (HFAs, jets, SLAMS) are interconnected and need deeper investigation

We need more than 4-point measurements and in various scales

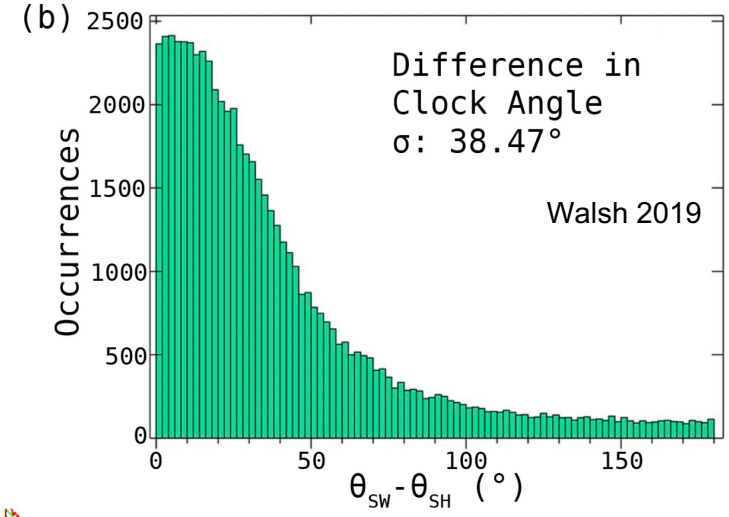
Spatial and Temporal Solar Wind Variability

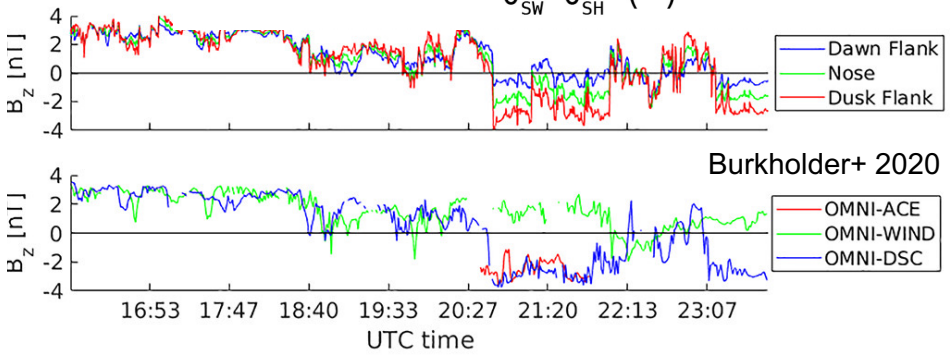


Walsh 2019

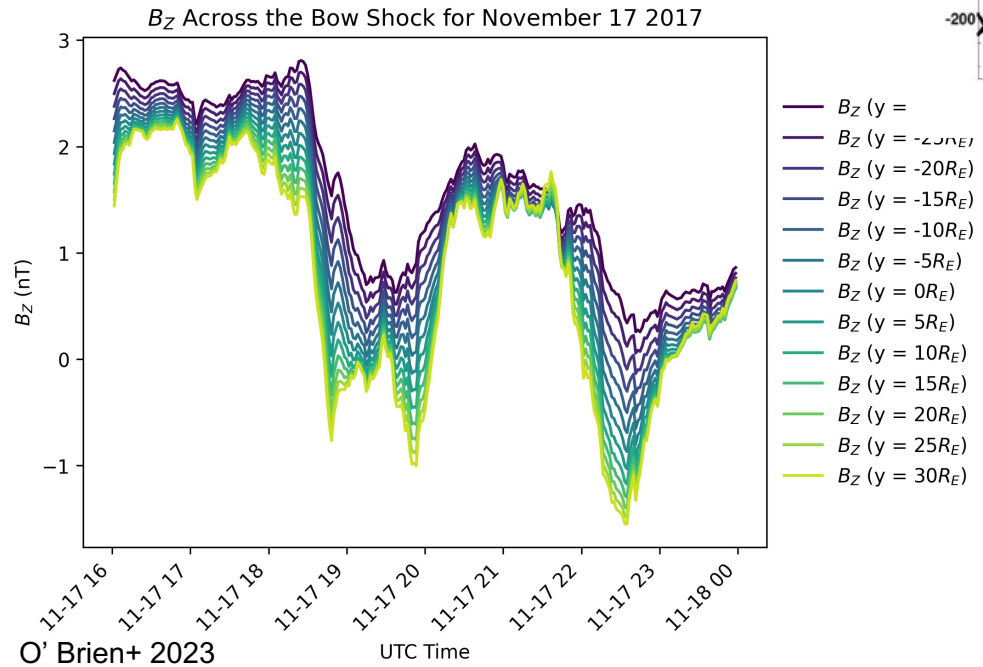


Borovsky 2017

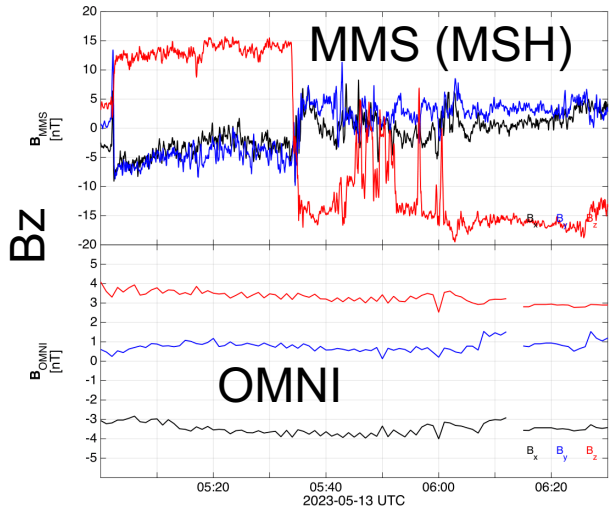


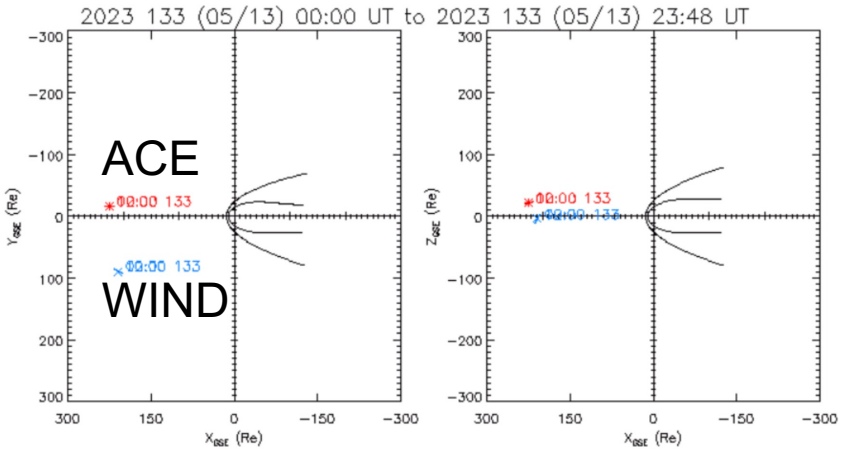


Burkholder+ 2020

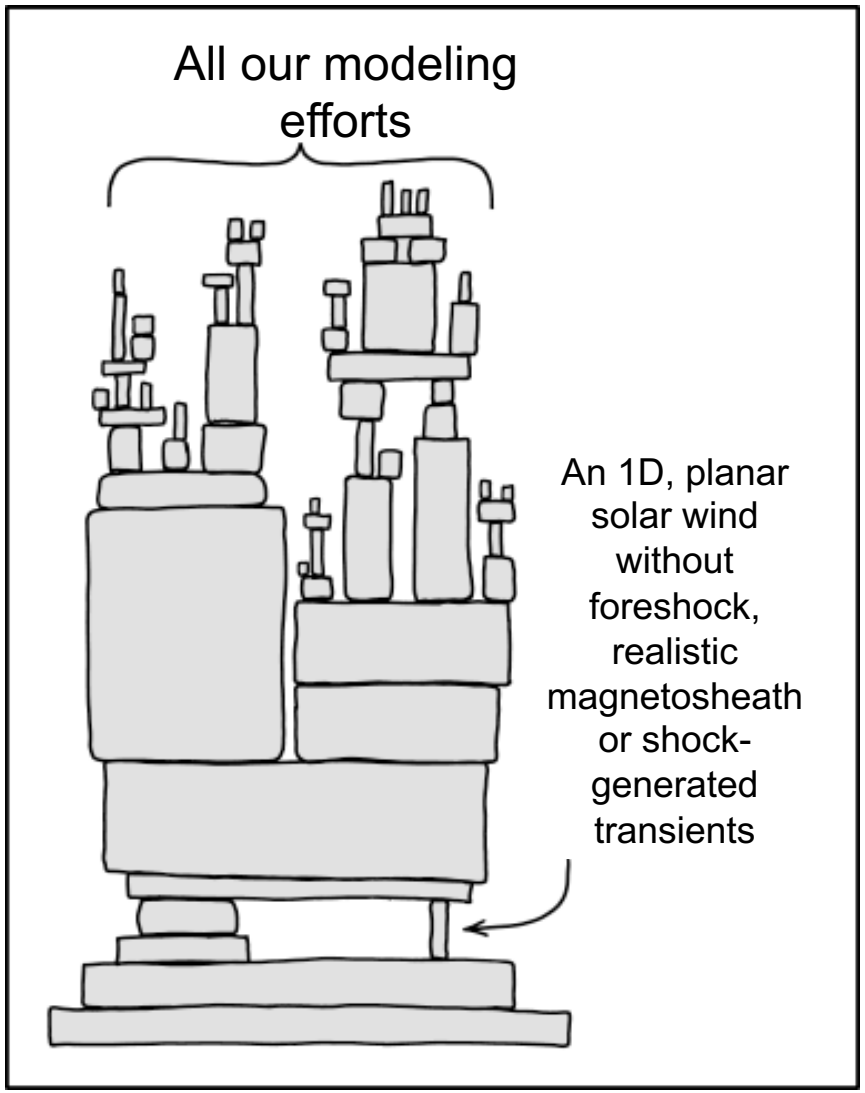


O' Brien+ 2023





What are we dealing with?



Two challenges:

Solar wind information limitations:

- Reality has complex 3D structure and spatial variability.
- It is easier to rely on simple 1D picture that is available than do the extra effort.

Neglected foreshock and magnetosheath transients:

- These transients can affect magnetopause reconnection, and more.
- They are often omitted because they are difficult to include.