JOHNS HOPKINS
APPLIED PHYSICS LABORATORY

Transient Phenomena at Collisionless Shocks and Their Effect on Particle Acceleration

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- JHU/APL R&D fund
- ISSI Team: P. Kajdič - Foreshocks Across The Heliosphere: System Specific Or Universal Physical Processes?

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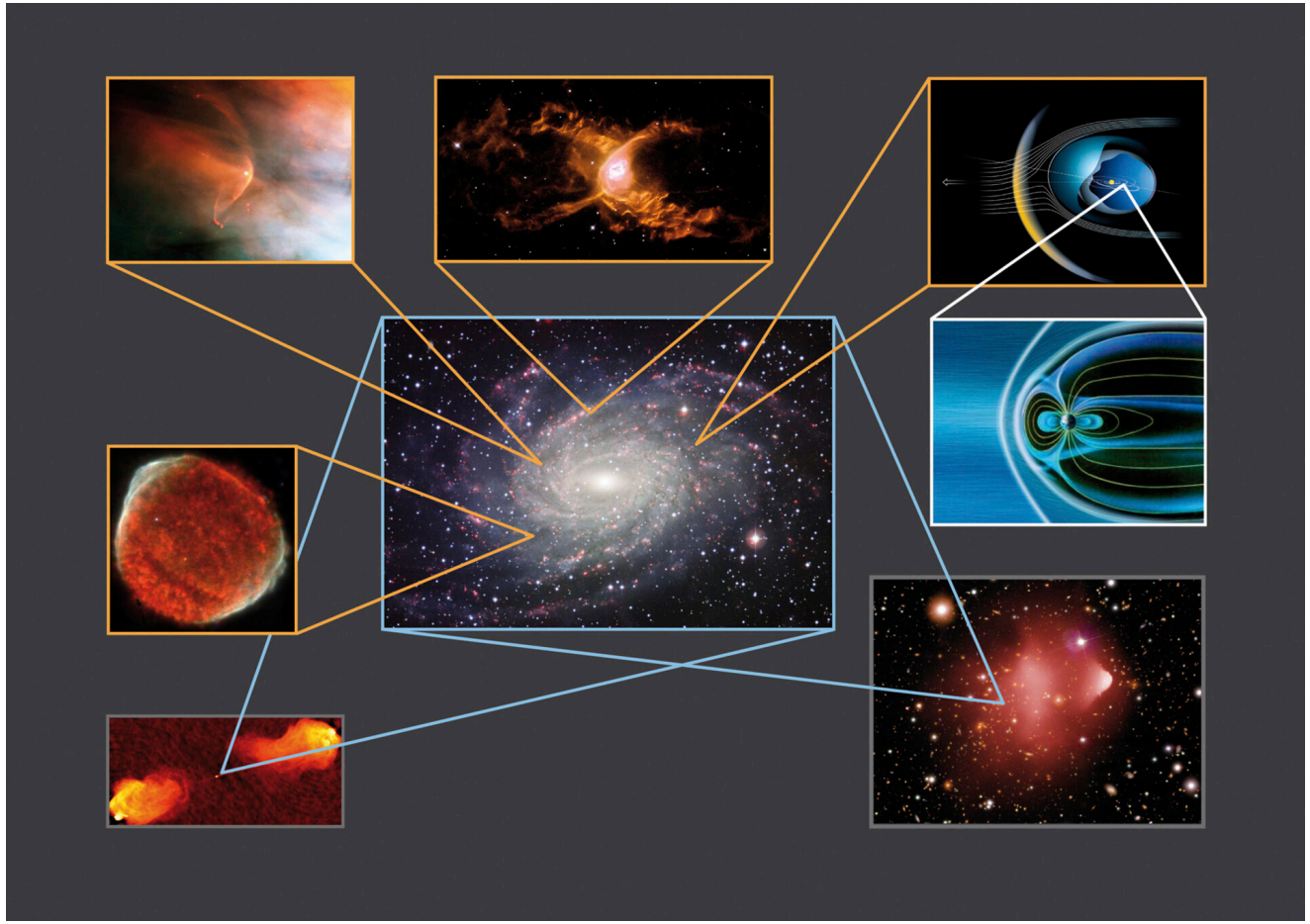
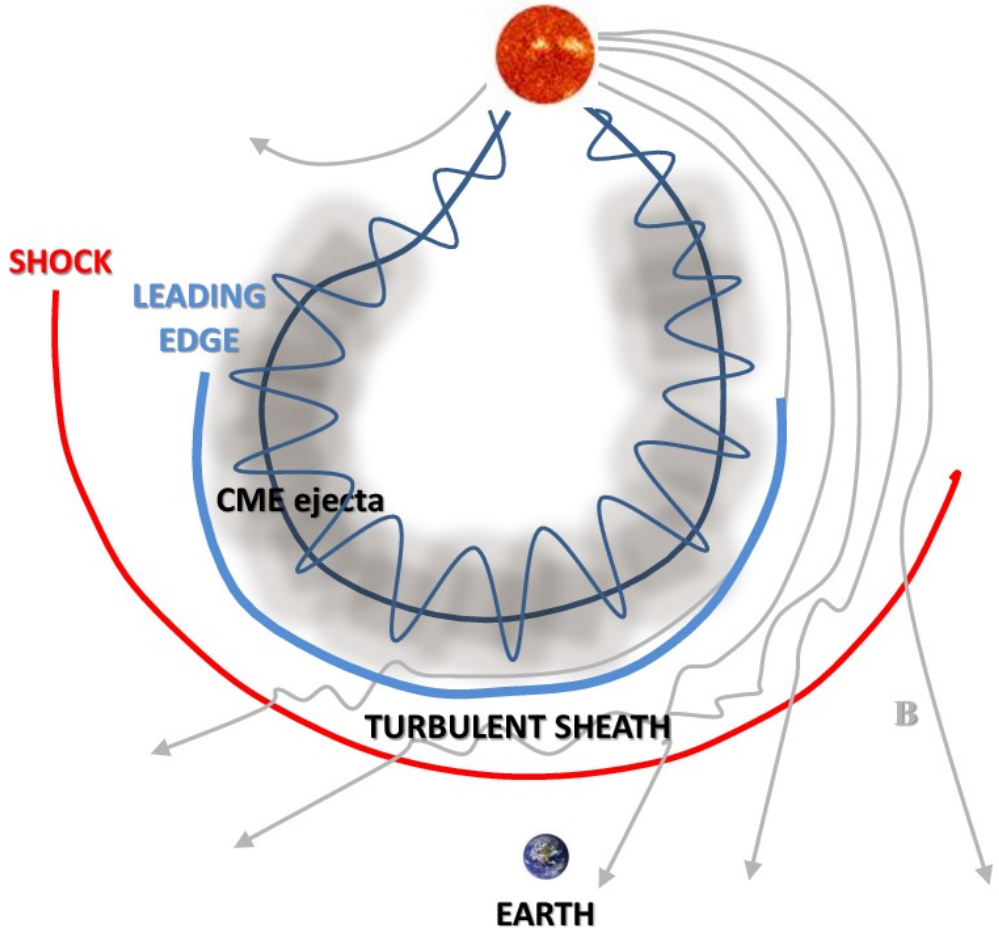
1. High level intro
2. Shocks (Geometry)
3. Shocks (Acceleration)
4. Transient phenomena
5. New Results on Particle Acceleration

General Intro

Collisionless Shocks in Universe



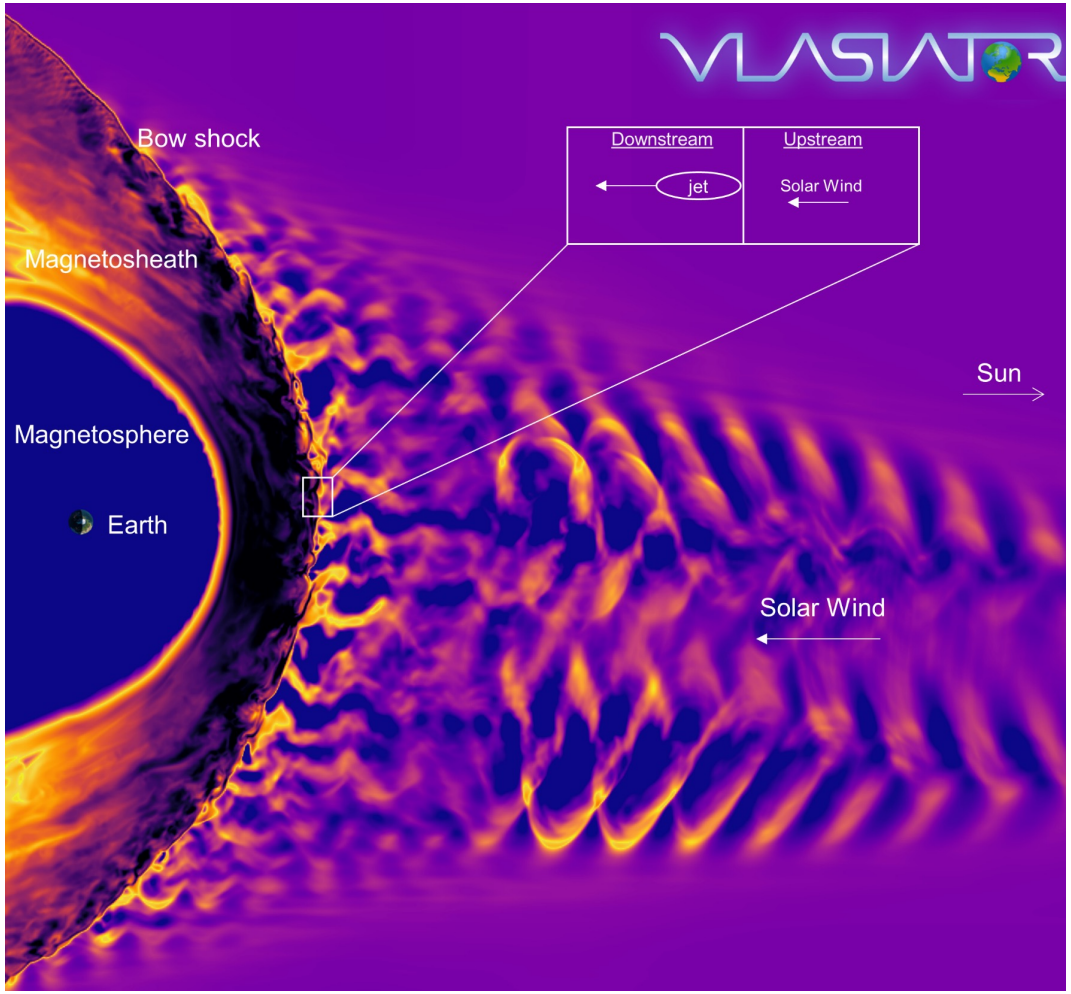


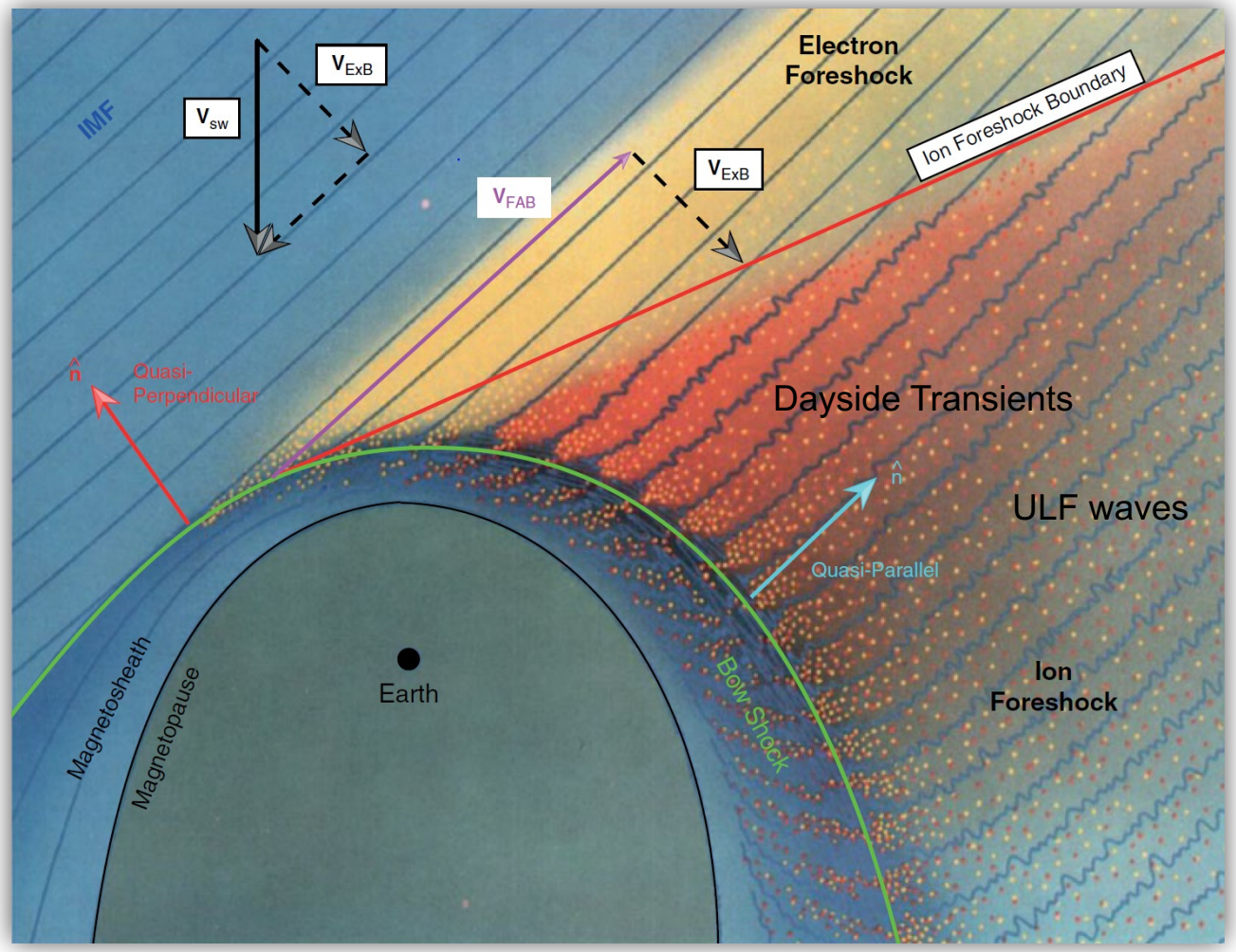
<u>Shock waves:</u>
Formed when structure moves with speed above local wave speed (e.g., sound, magnetosonic)

They are everywhere!

Heating, accelerating particles and converting energies

Earth's magnetosphere & shock environment

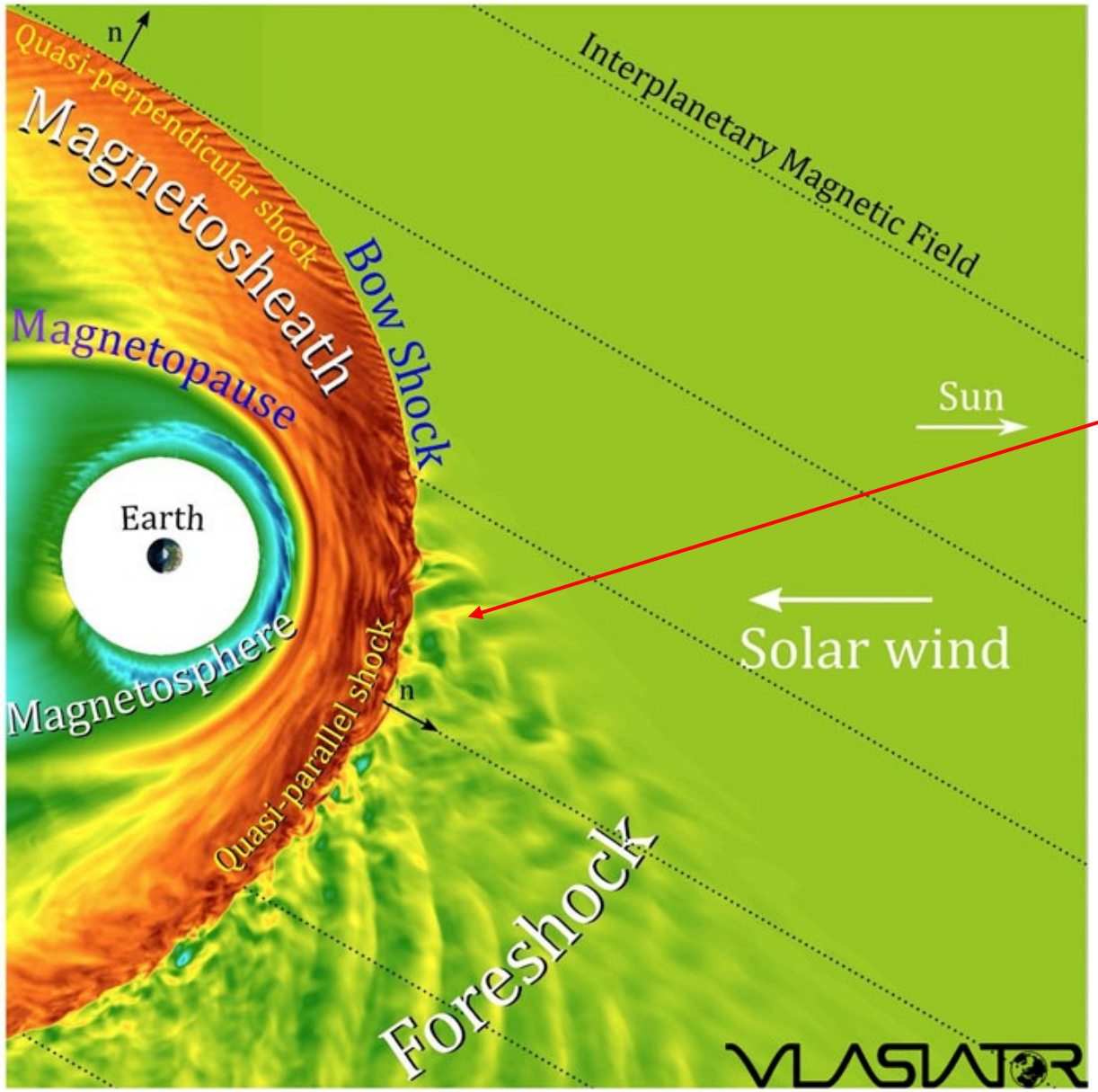




Courtesy of M. Palmroth, U Helsinki

L. B. Wilson (2016)

Earth's Qpar bow shock and foreshock

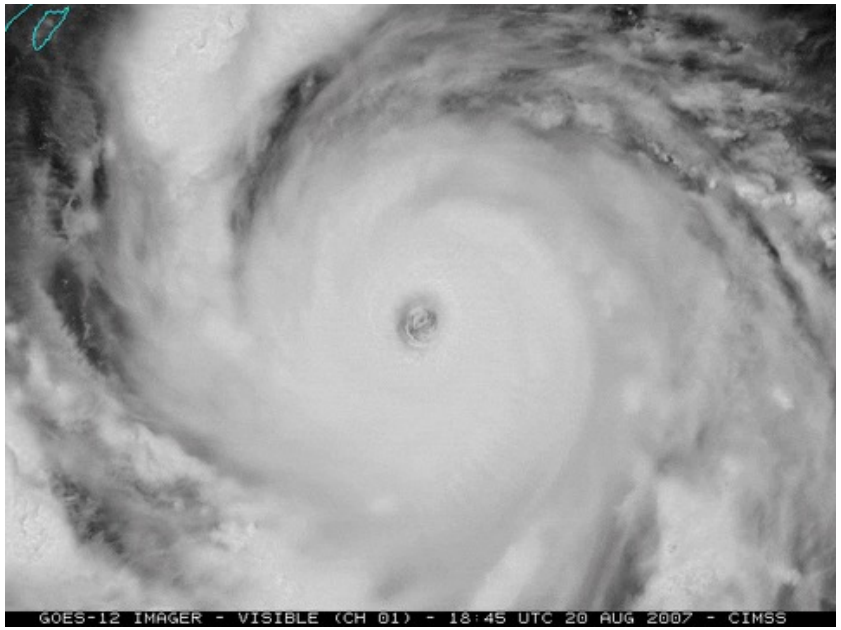


Qpar shocks ($\theta_{Bn} < \sim 45^\circ$)

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

Transient events – weather

Hurricanes

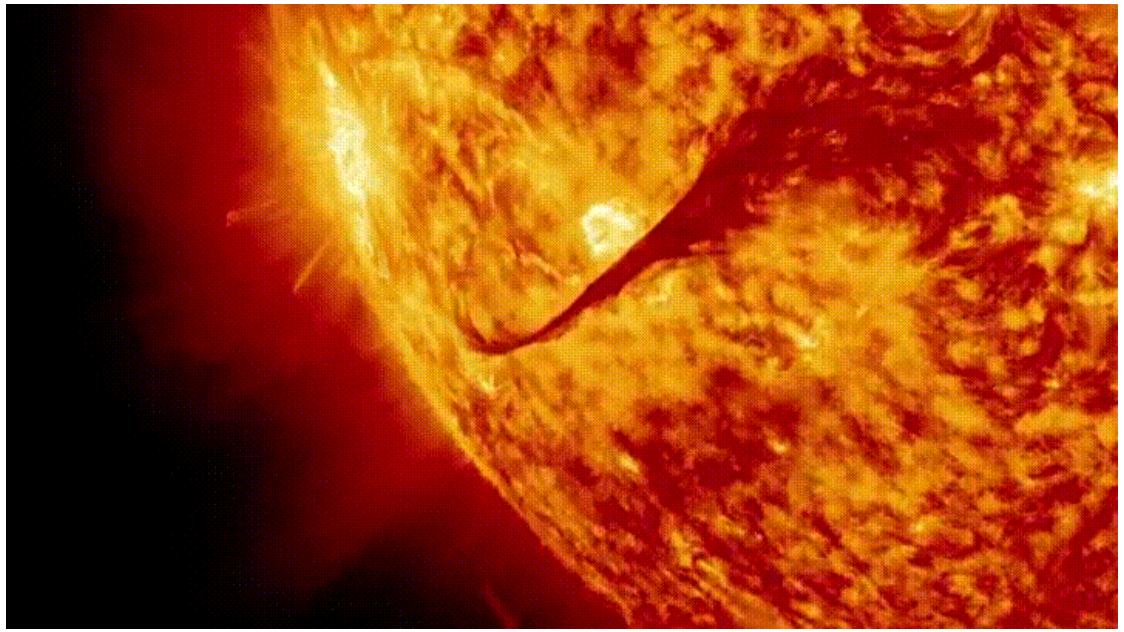


Rain

Snowstorms

Transient events – weather

CMEs



Rain

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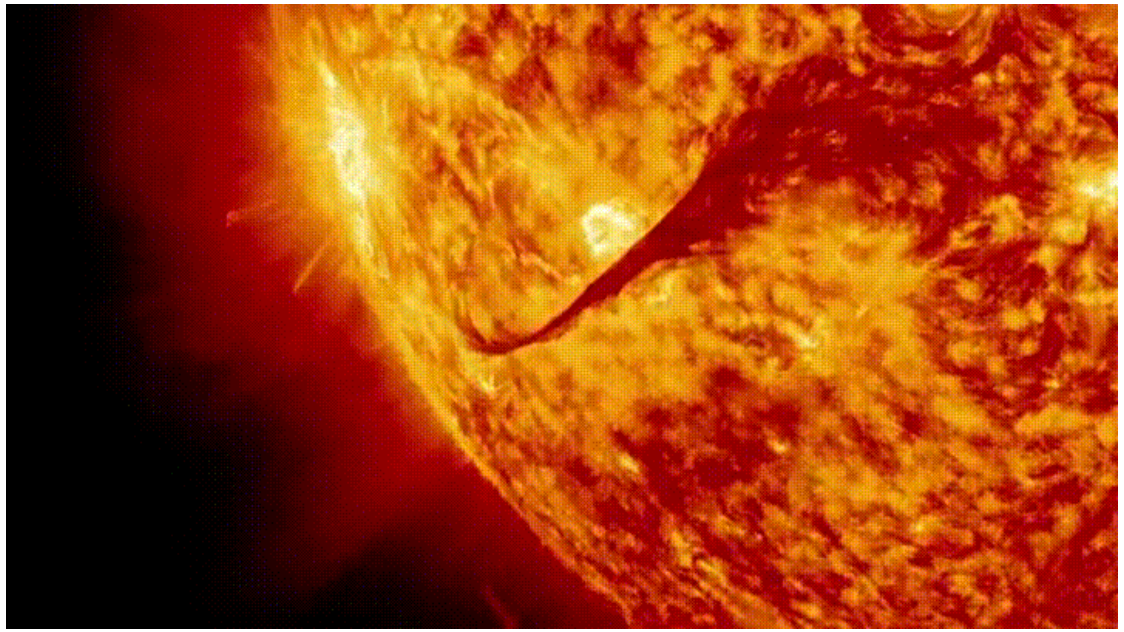
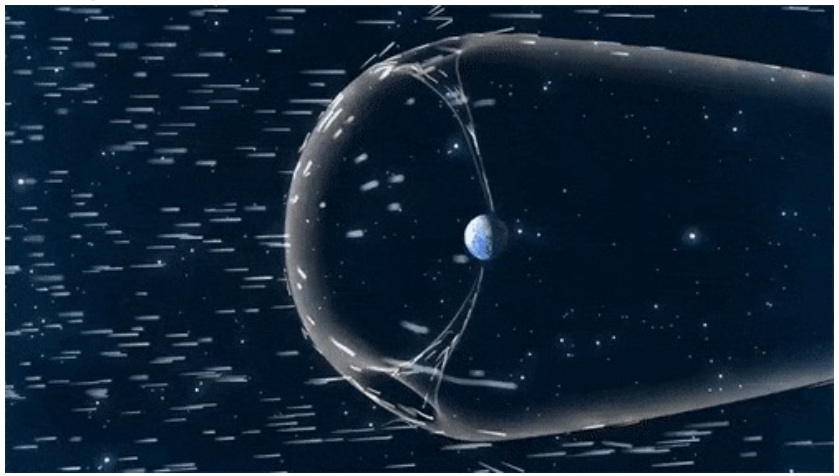
Transient events – weather

CMEs



Rain

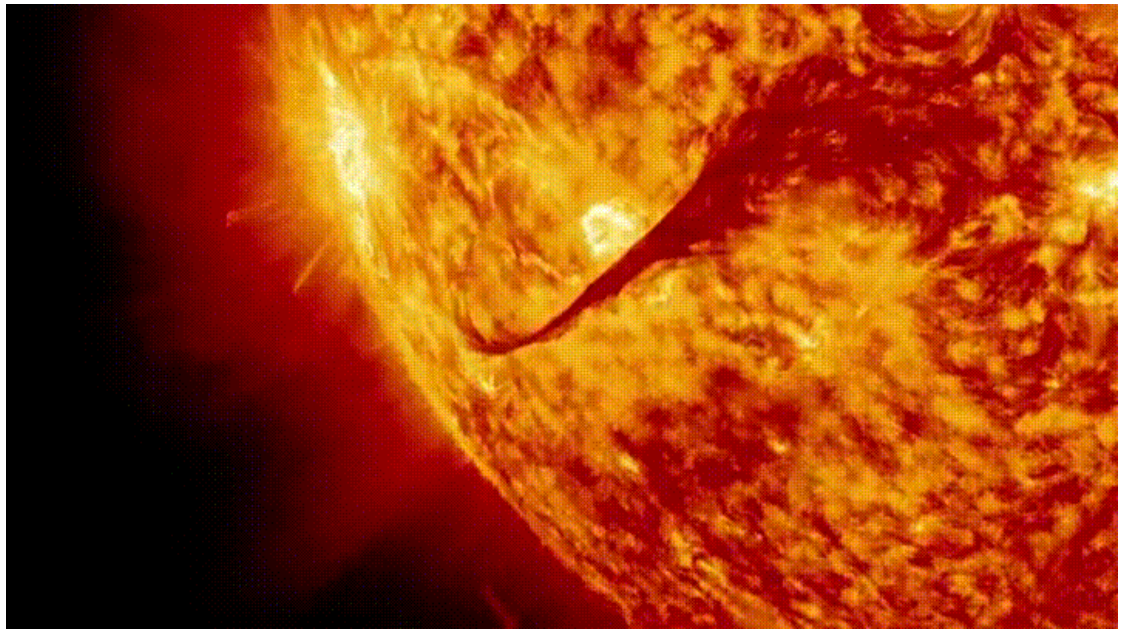
High speed streams, discontinuities



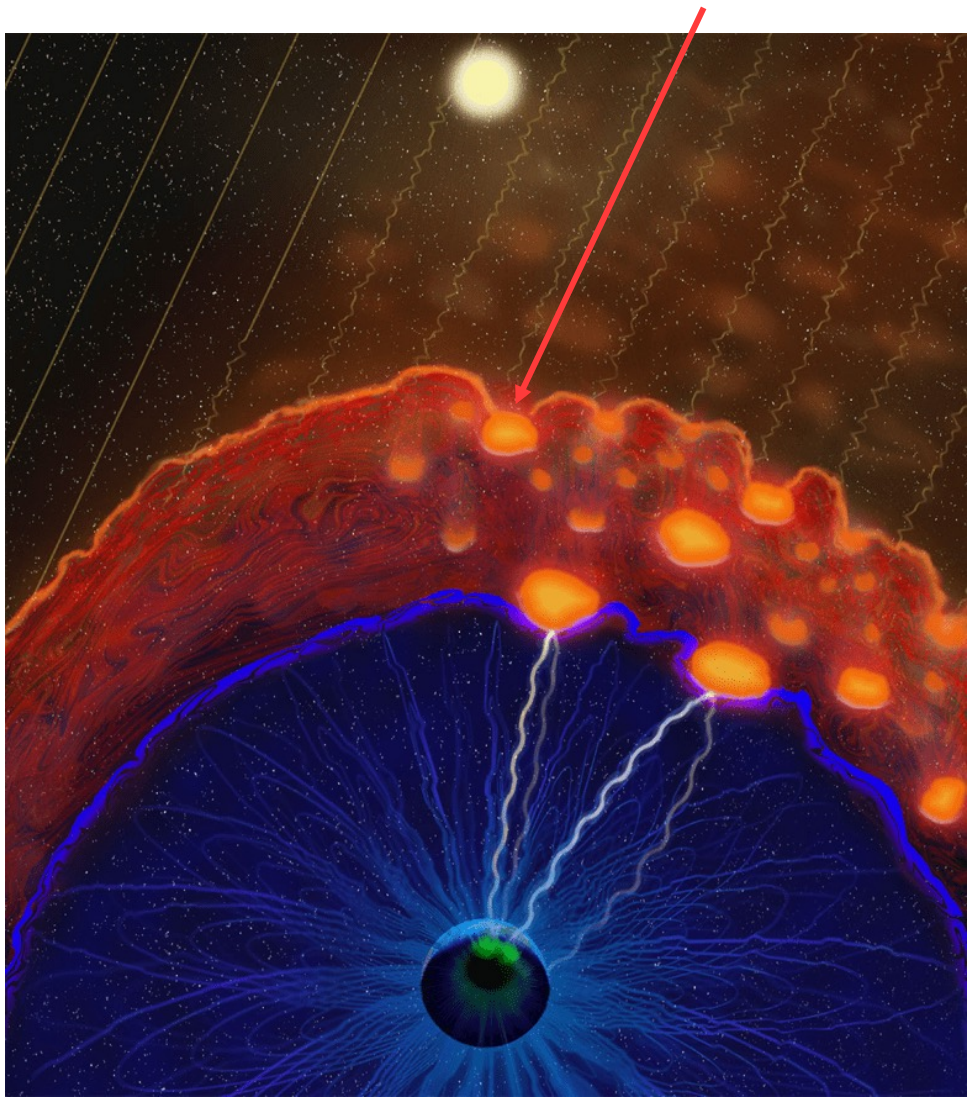
Credits : NASA

Transient events – *space* weather

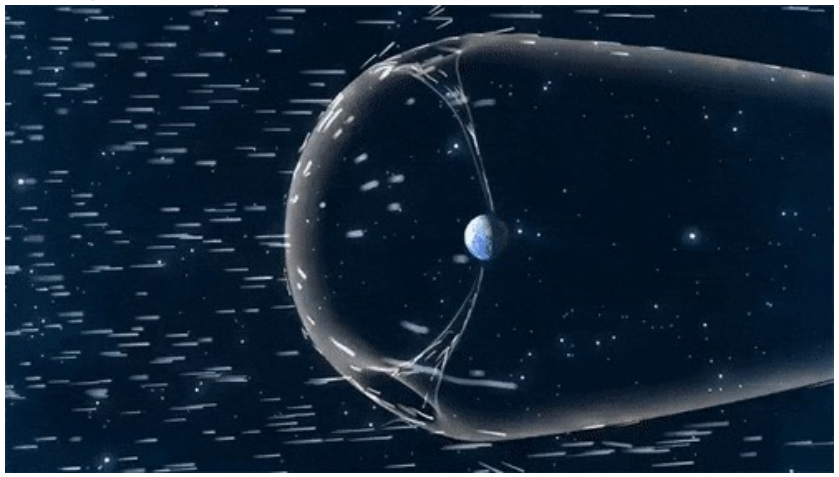
CMEs



Foreshock transients & plasma jets



High speed streams, discontinuities

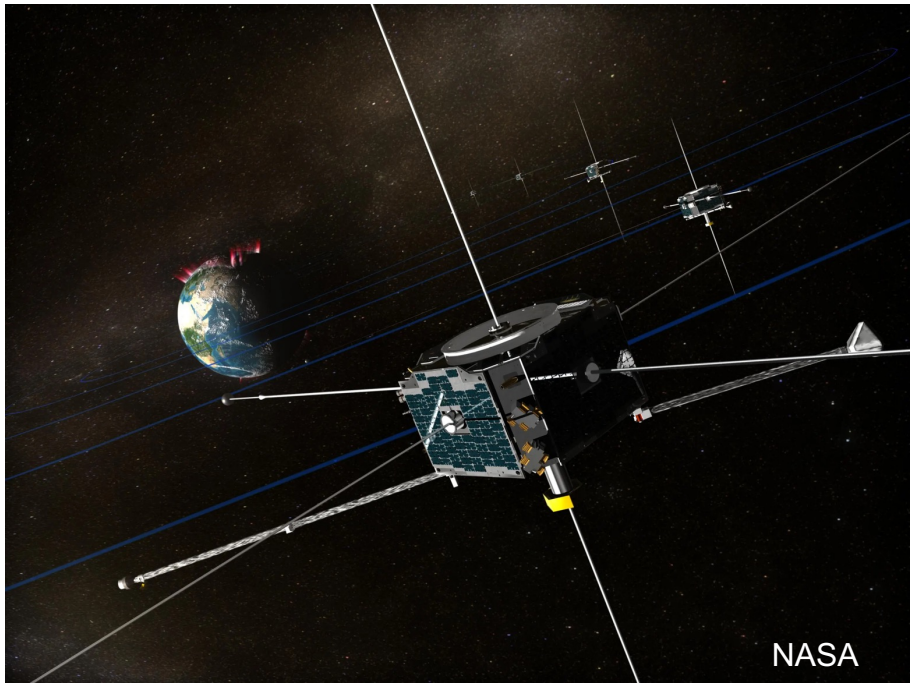


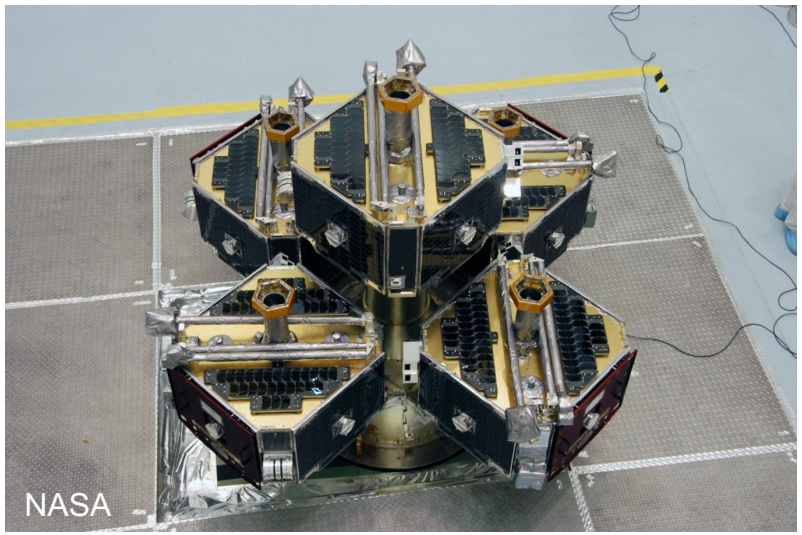
Credits : NASA

Credits: Vuorinen et al. (2022) https://eos.org/features/space-raindrops-splashing-on-earths-magnetic-umbrella

In-situ observations

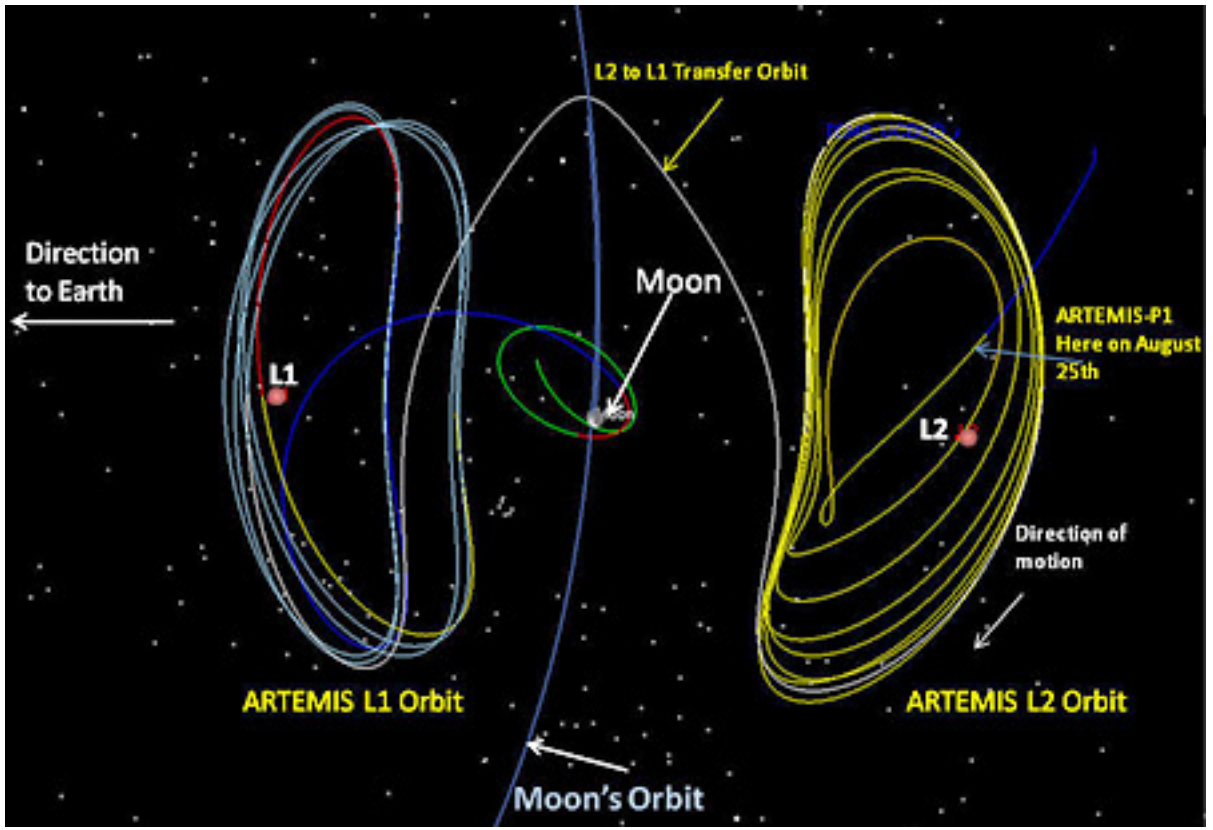
THEMIS/ARTEMIS mission



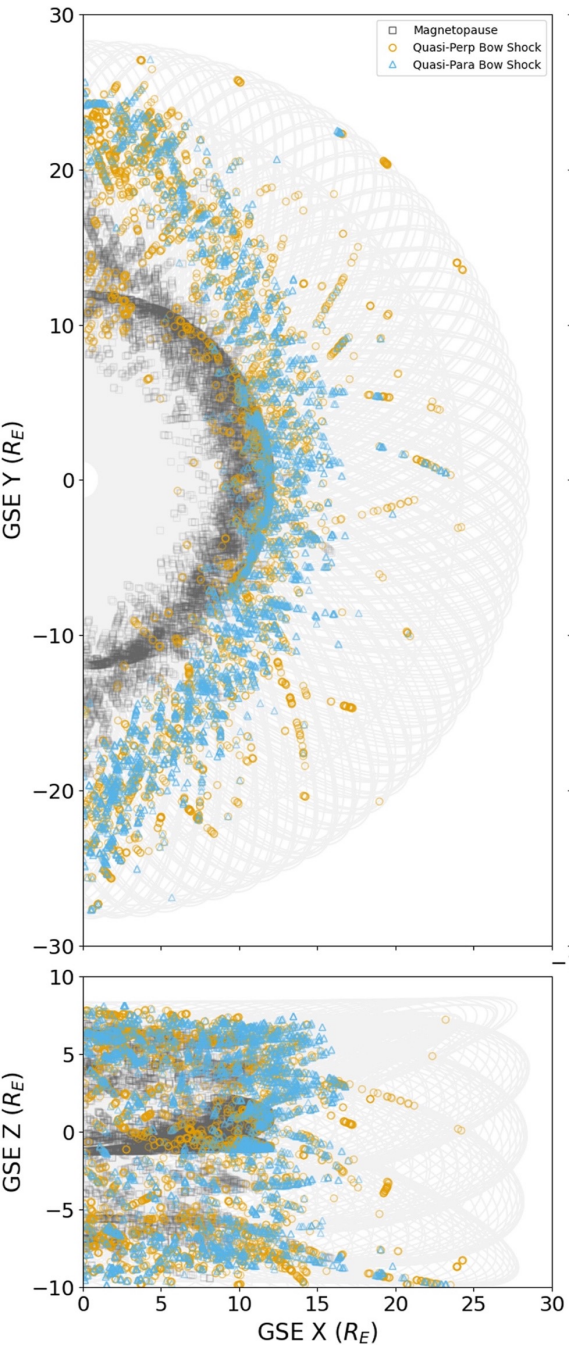


Feb. 17, 2007: Launch → 5 SC, magnetotail reconnection objectives
Jan. 1, 2009: THEMIS-P1 and P2 are Reassigned, Renamed and Redirected to the Moon → ARTEMIS

Orbiting the moon it can (sometimes) provide close to Earth in-situ observations of upstream conditions (when moon is on the dayside)

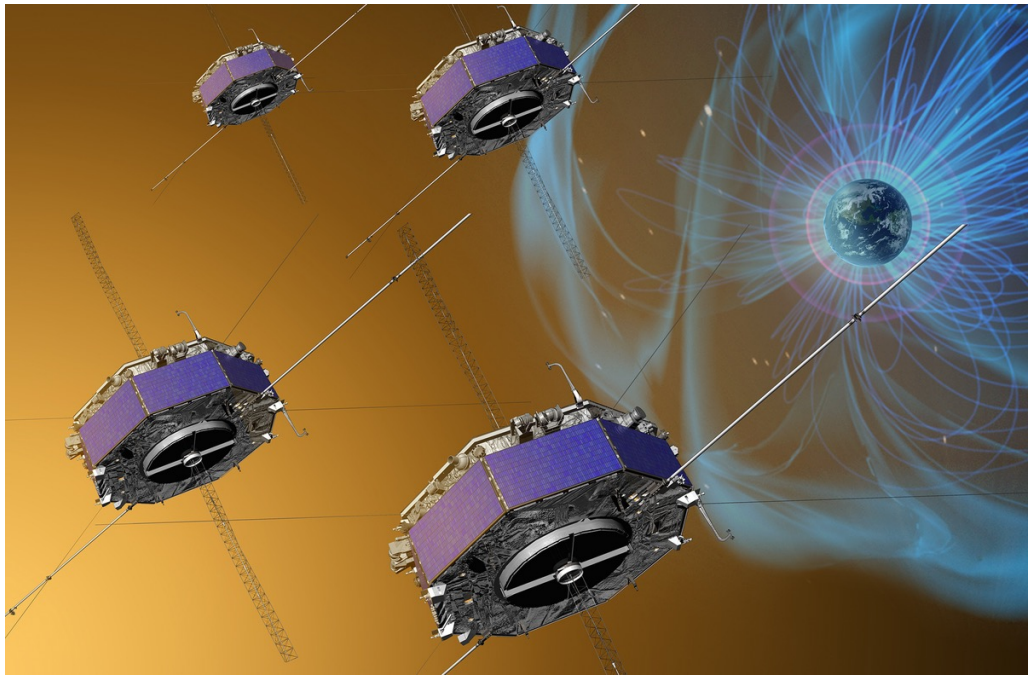


MMS mission

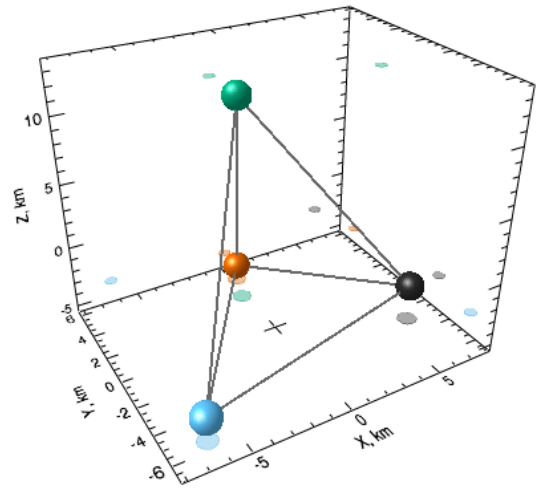


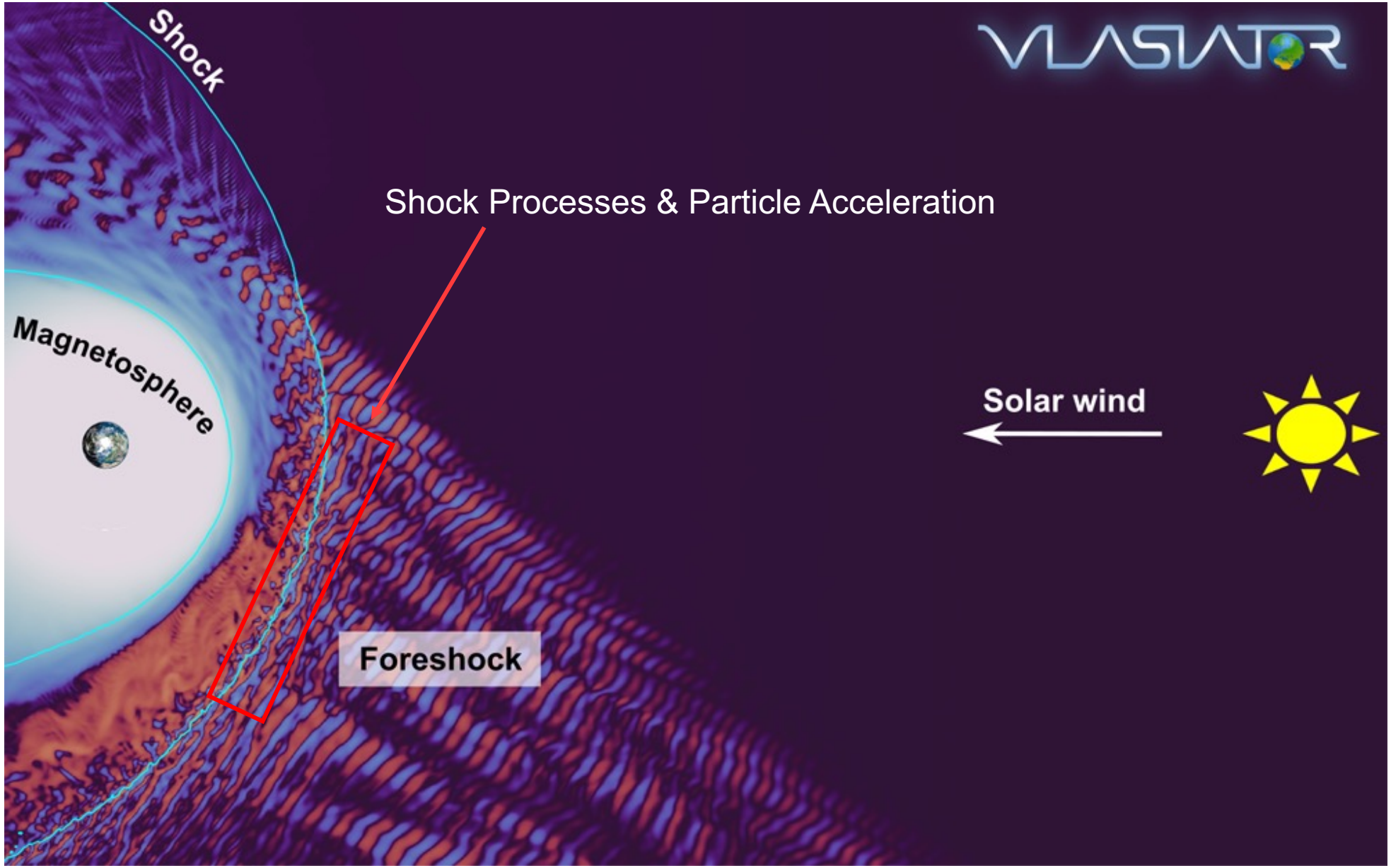
Toy-Edens+ (2024)

- Launched March 2015
- 4 identical s/c (10s to 100s km separation)
- Equatorial HEO, w/ apogee: ~12 RE (2015-2018); ~28 RE (2018-present



- Several thousands of shock crossings Lalti+ (2023), Toy-Edens+ (2024)
- In-situ observations of plasma moments, fields, and distributions.





Credits: Lucille Turc / Vlasiator team

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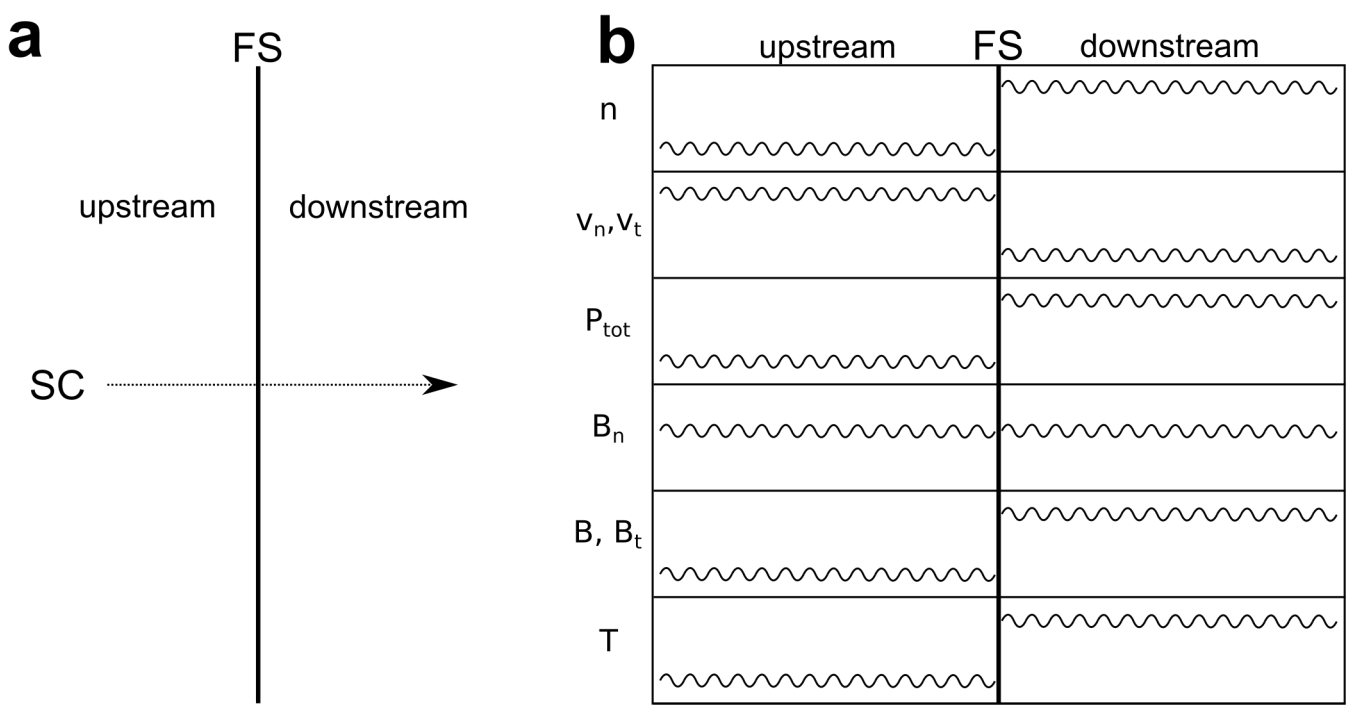
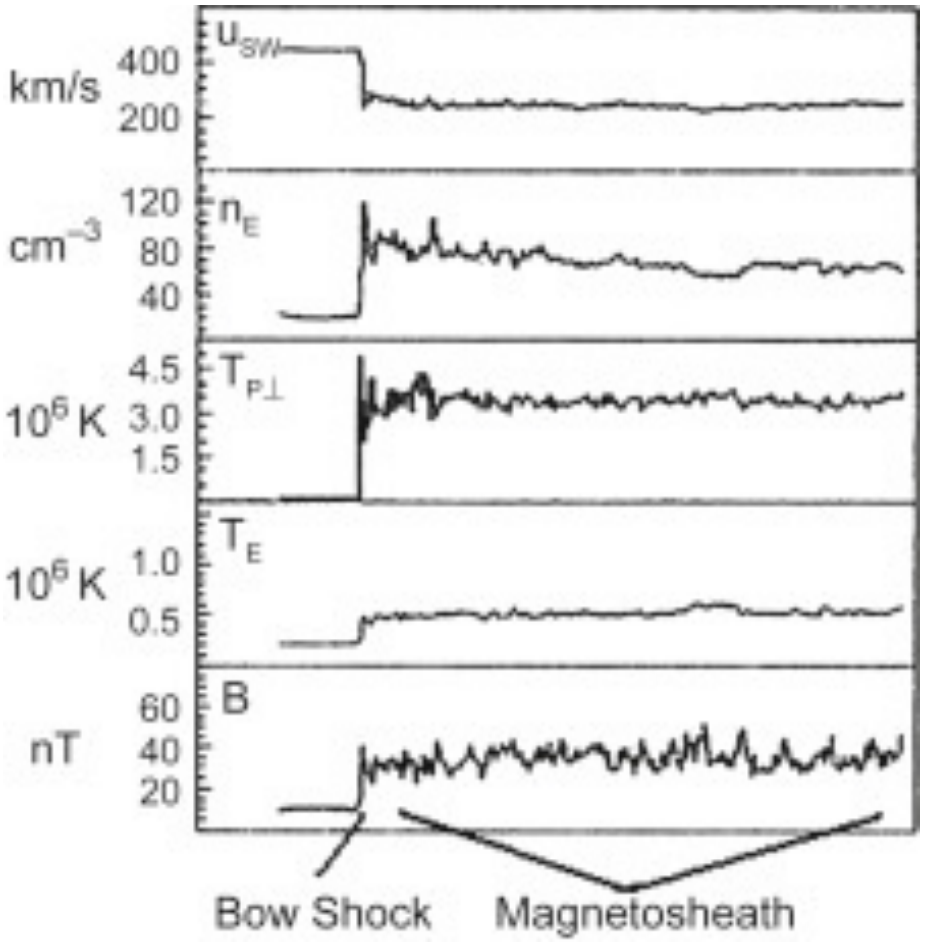
Shocks

Structure & Geometry

Fast shock transition (Theory & initial data)





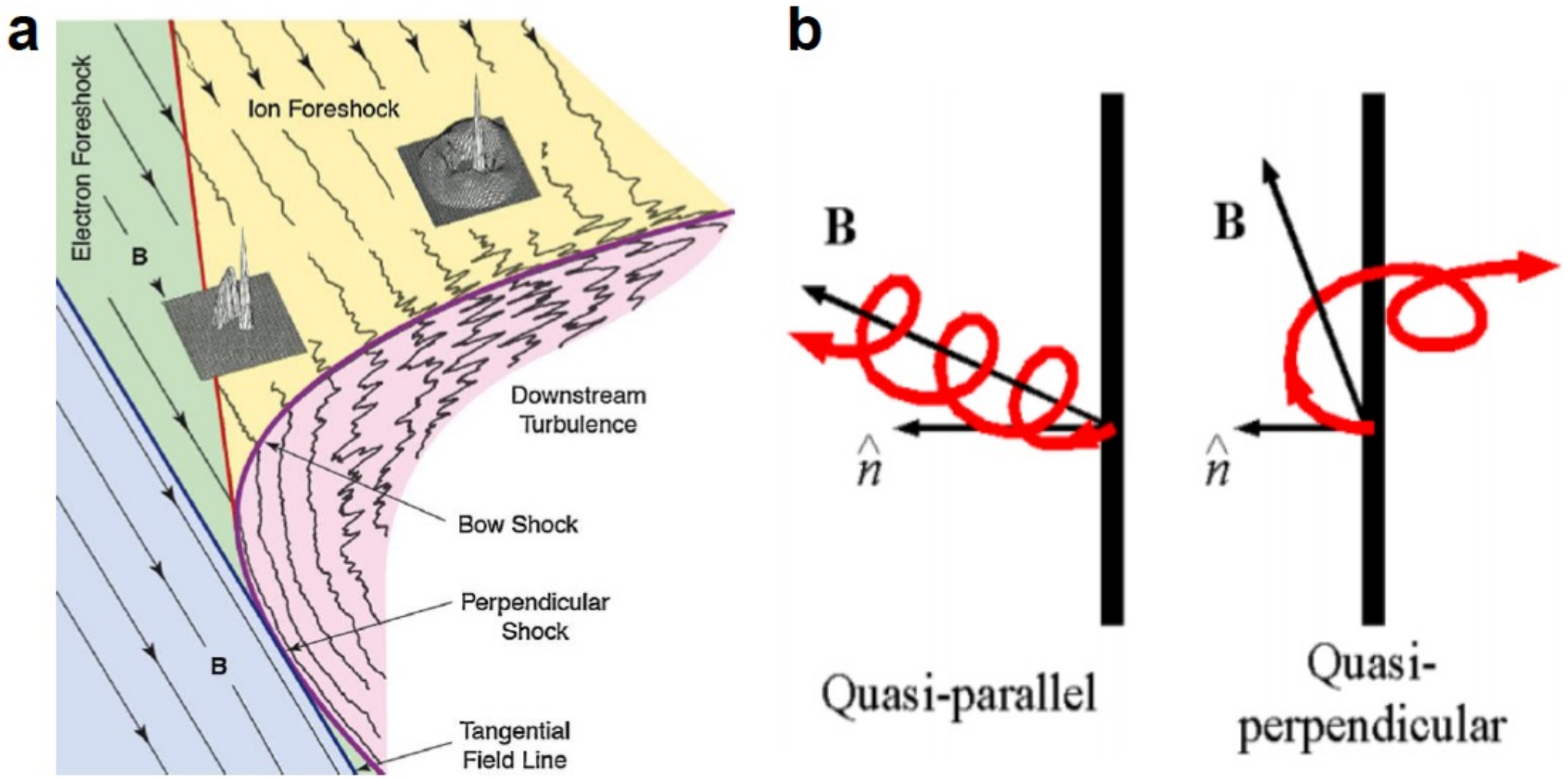
Rankine Hugoniot relations / Jump Conditions

Thermalization, Compression, Breaking

1D Isotropic and adiabatic one fluid plasma shock transitions

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

Shock & foreshock

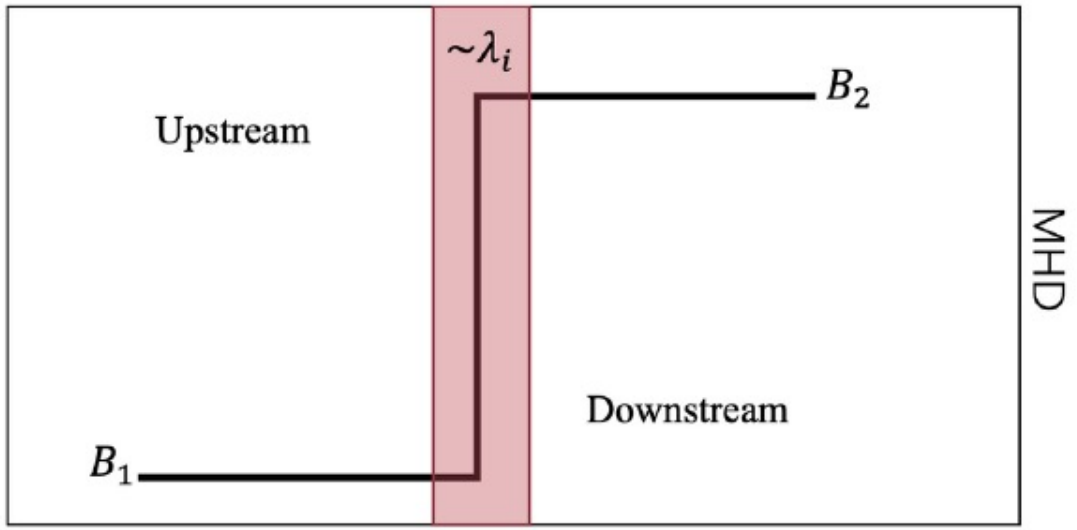


Reproduced from [Balogh and Treumann, 2013].

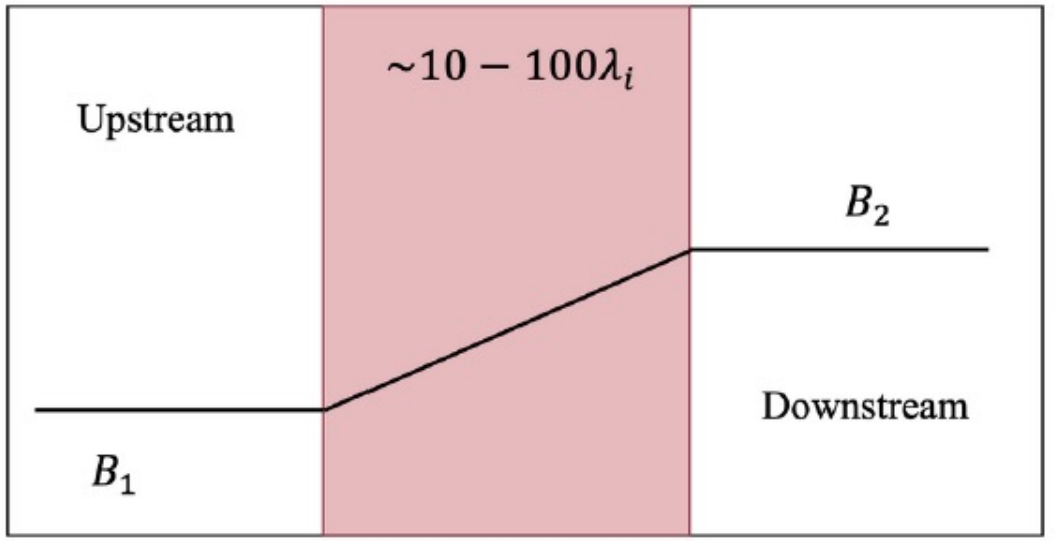
Assuming Specular Reflection

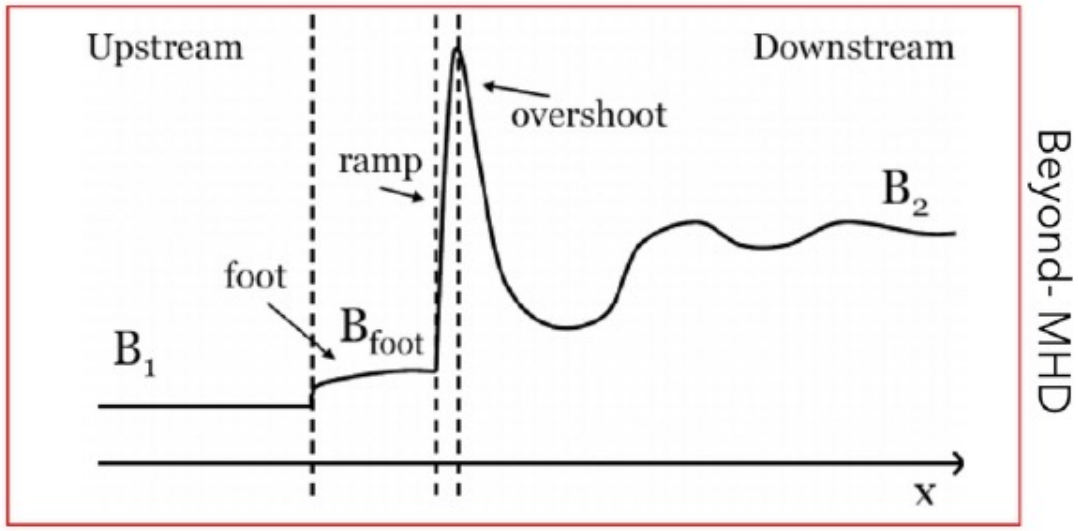
Quasi-parallel and Quasi-perpendicular shocks

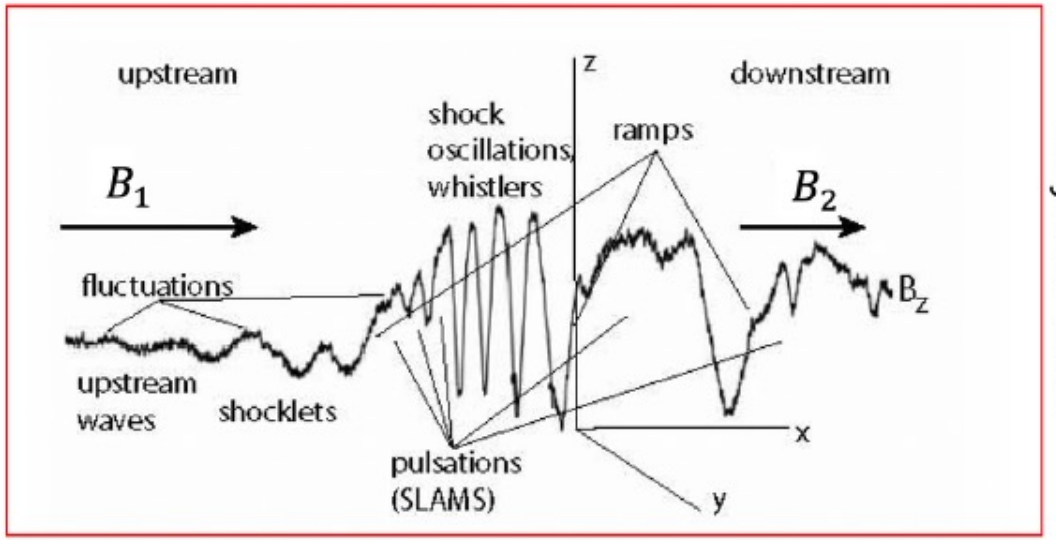
Qperp transition



Qpar transition



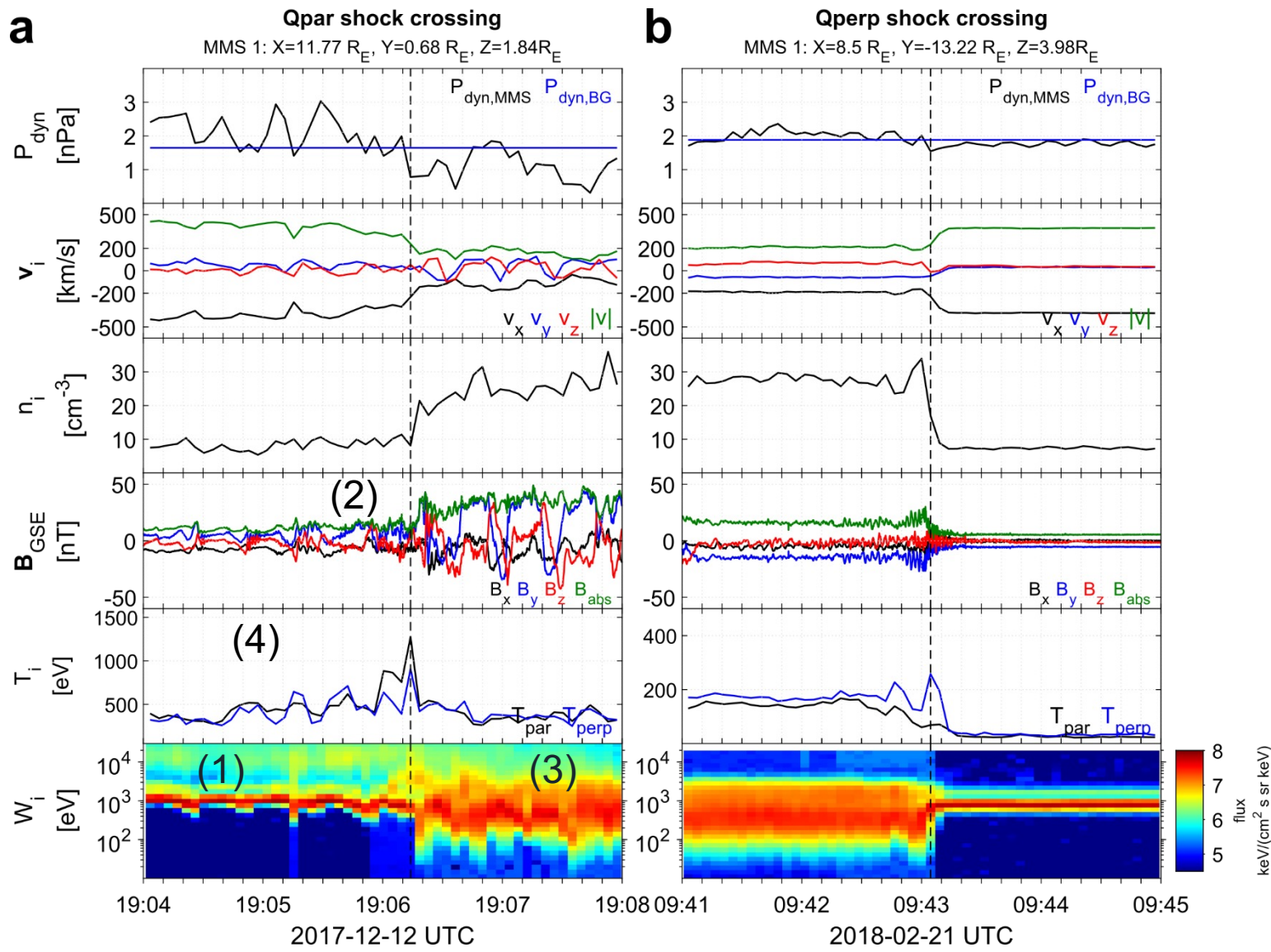




Qpar – Qperp crossings

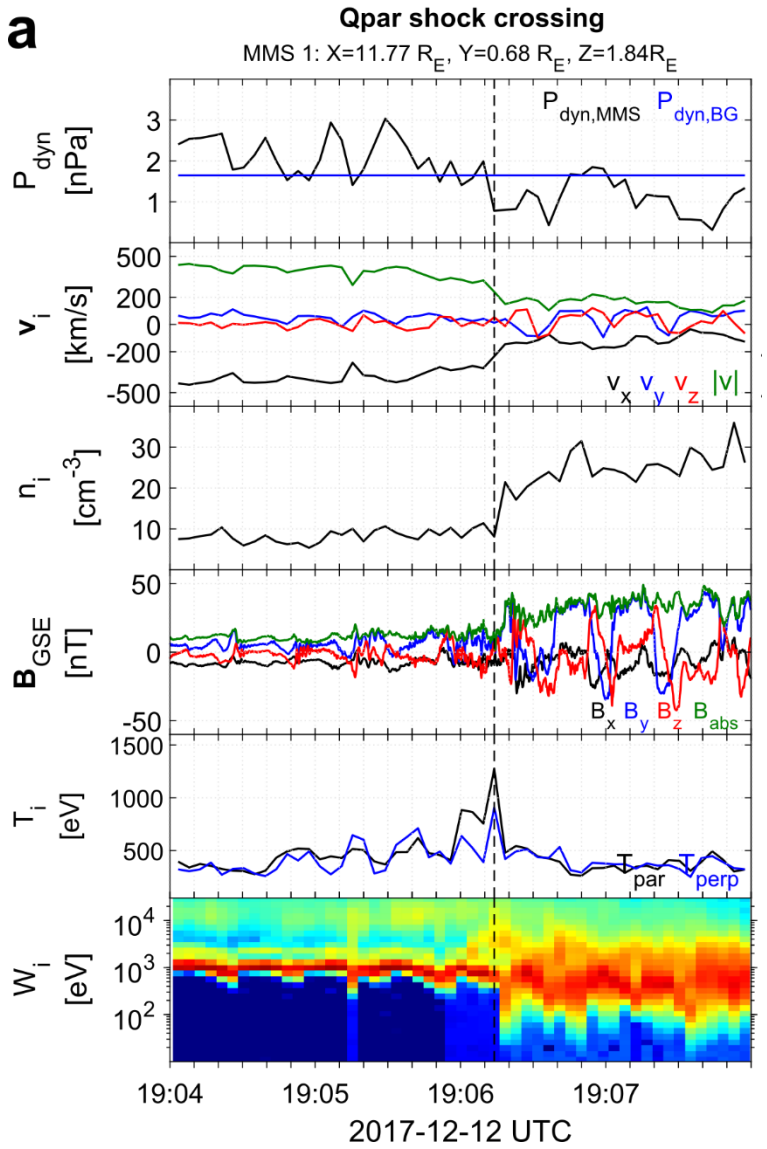
Qpar shocks and downstream plasma:

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



Raptis+ (2020), Karlsson+ (2021), Koller+ (2024)

Qpar shocks have different flavors



The nice/smooth ones

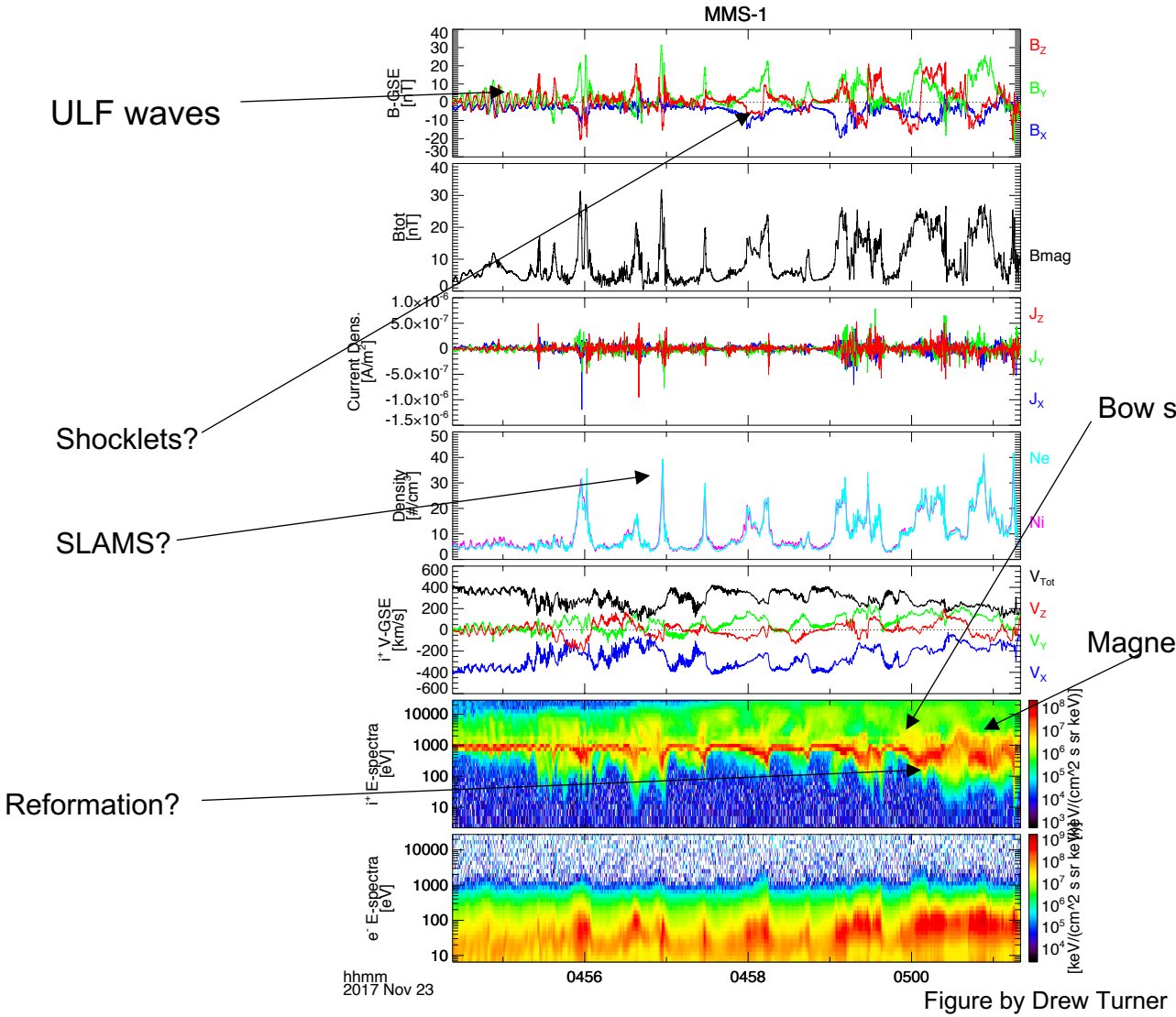


Figure by Drew Turner

The complicated, exotic ones

Shock Reformation & SLAMS

Shock Reformation

Burgess (1989): “the shock exhibits a cyclic behavior ….. cyclic shock reformation;”

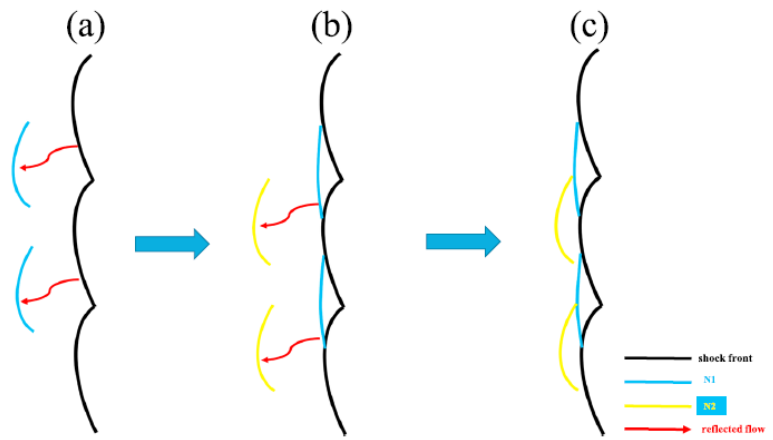


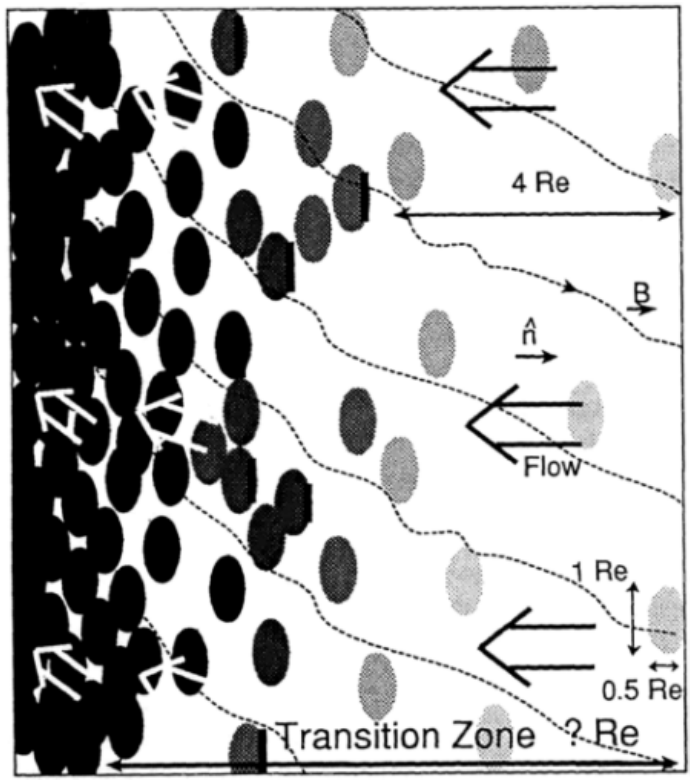
Figure 11. The sketch for evolution of shock front. (a) A rippled shock front, (b) a plane shock front, and (c) a rippled shock front. Solid lines and red arrows denote shock front and reflected beams, and N1 and N2 indicate new shock fronts.

Hao et al. (2017)

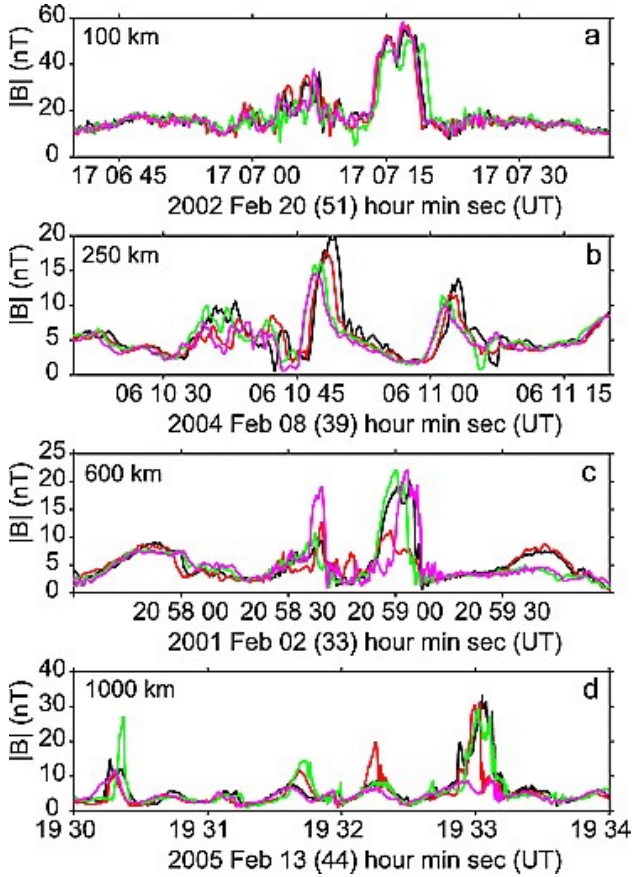
*«The **shock is the first and largest** amplitude upstream magnetic **pulsation**»*

ULF non-linear evolution = SLAMS

Chen et al. (2020): “…ULF waves can arise at the foreshock and evolve into SLAMS …”



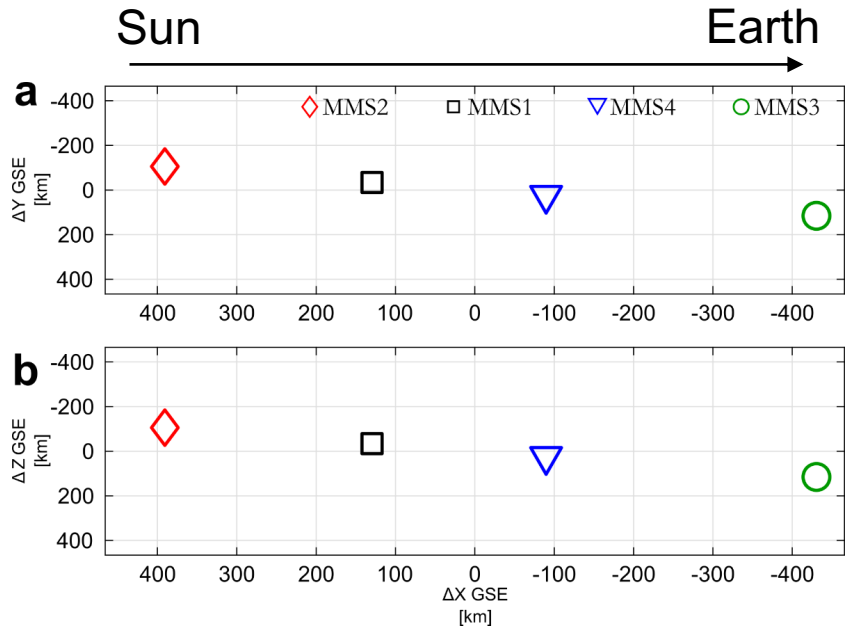
Schwartz, (1991)

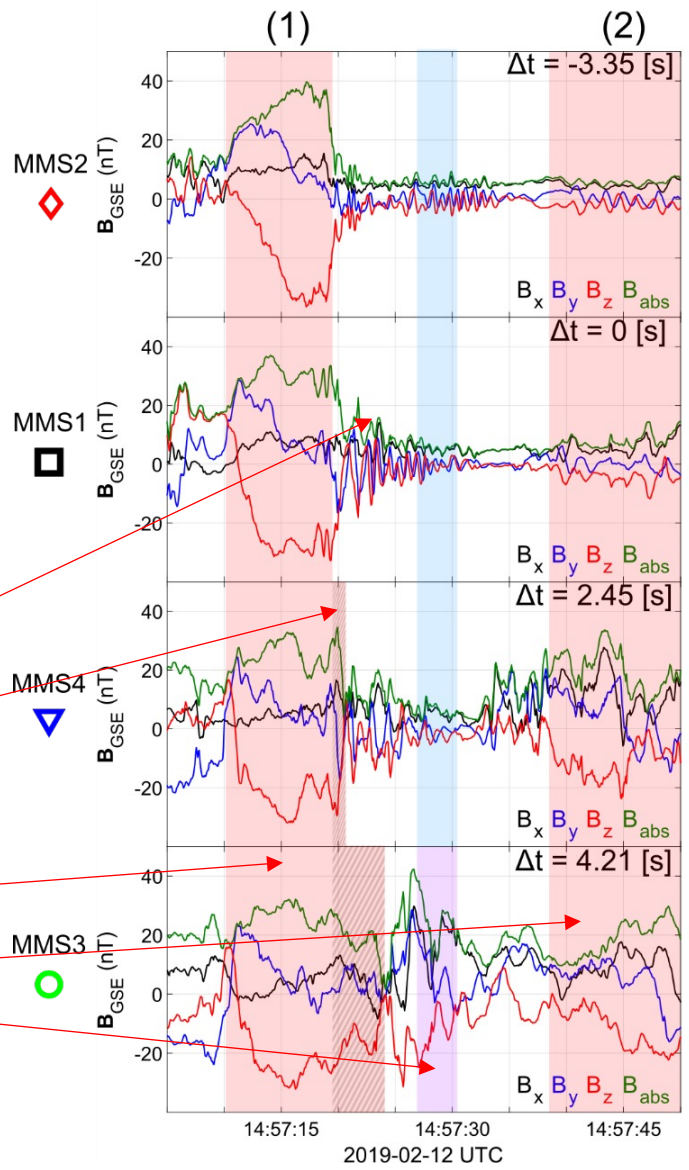


Lucek, (2008)

Similar definitions : Hao et al. (2016,2017), Liu et al. (2021), Johlander et al. (2022), Raptis et al. (2022a)

SLAMS – wave activity and reformation





Sun

~1000 km
~ 10 λi

Earth

Evolution of SLAMS/Reformation

- Interaction with upstream whistler
- New peak /evolution*
- Formation of *downstream density enhancement***
- Reformation cycle → jet and new front

* See similar examples by Turner et al. (2021), Chen et al. (2021) | "*(Self-) reformation/evolution/ripples*"

** See similar example by Liu et al. (2021), Johlander et al. (2022) | *(Qpar) reformation*

Raptis S., et al. 2022a | Nat. Commun.

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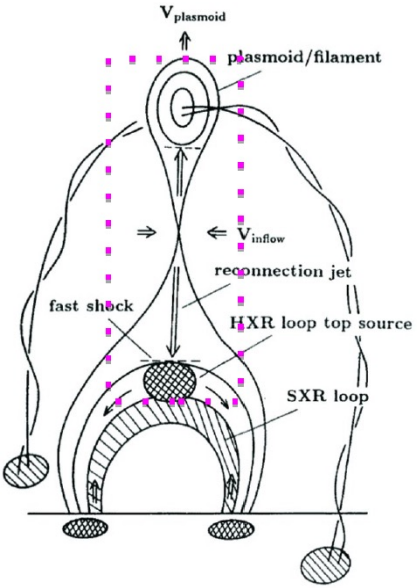
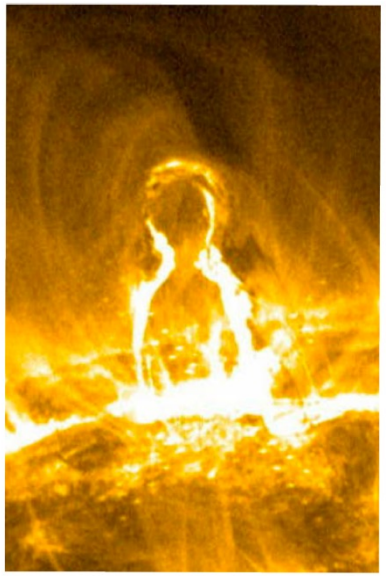
Shocks & Acceleration

Shocks as particle accelerators

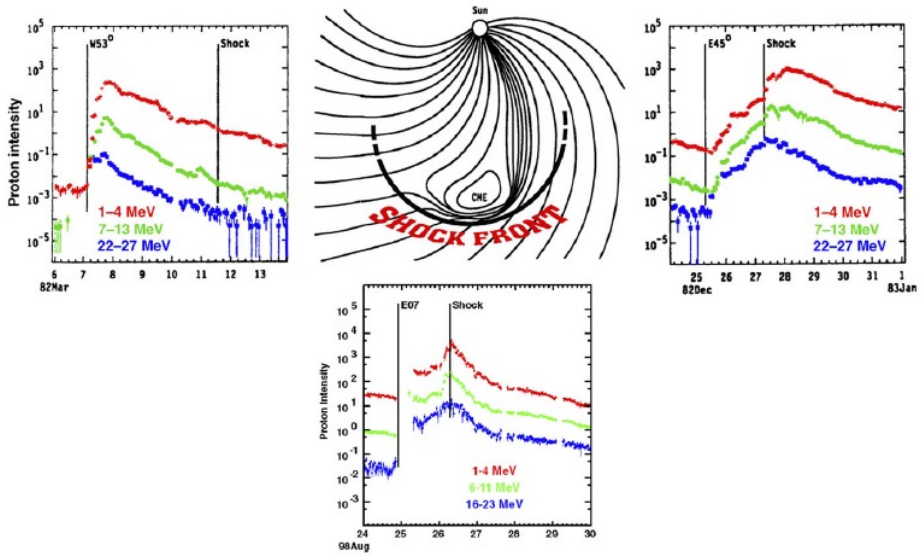
- Different shock geometries and particles have different acceleration mechanisms invoked but all can accelerate particles
- Astrophysics: Supernova remnants, cosmic rays
- Solar Physics: SEP acceleration, fast shock at reconnection



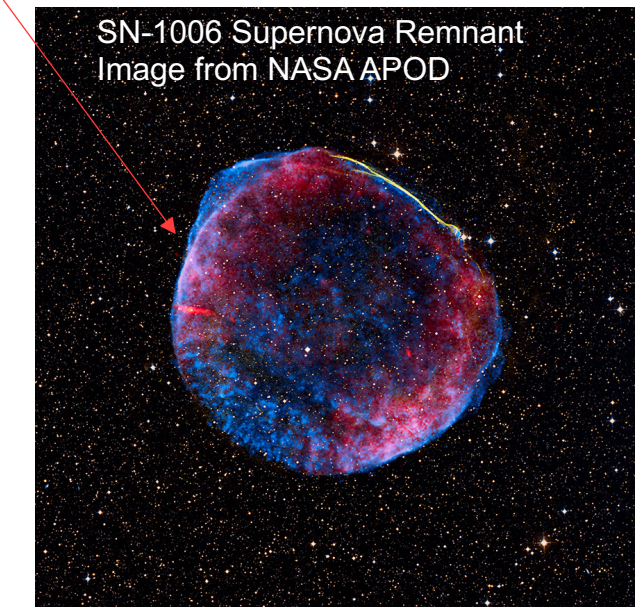
[Shibata et al., 1995]



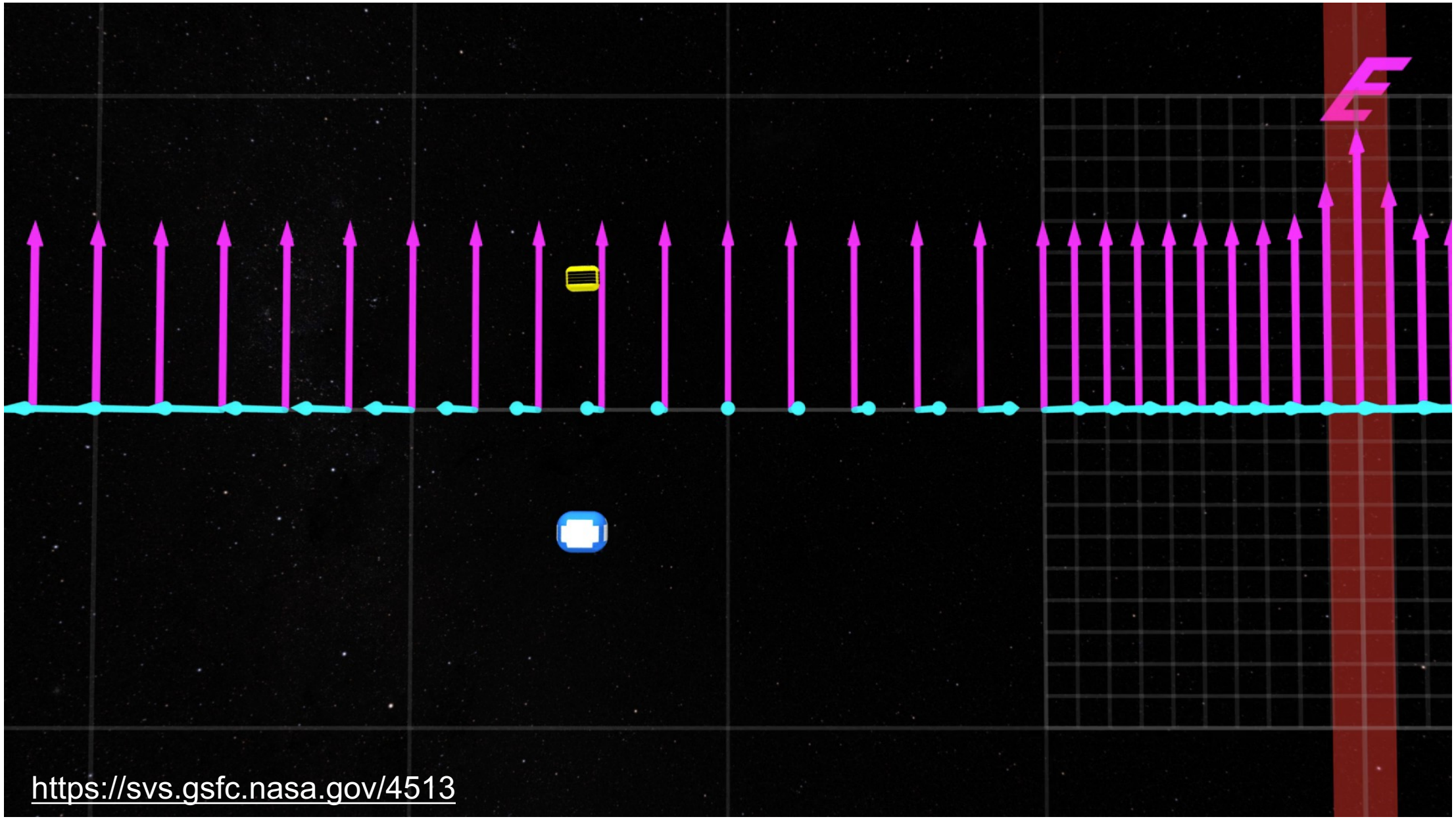
Courtesy of Li-Jen Chen, GSFC



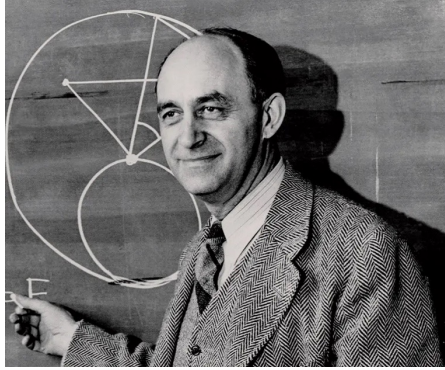
Desai & Giacalone (2016)



Shock Drift Acceleration (SDA)

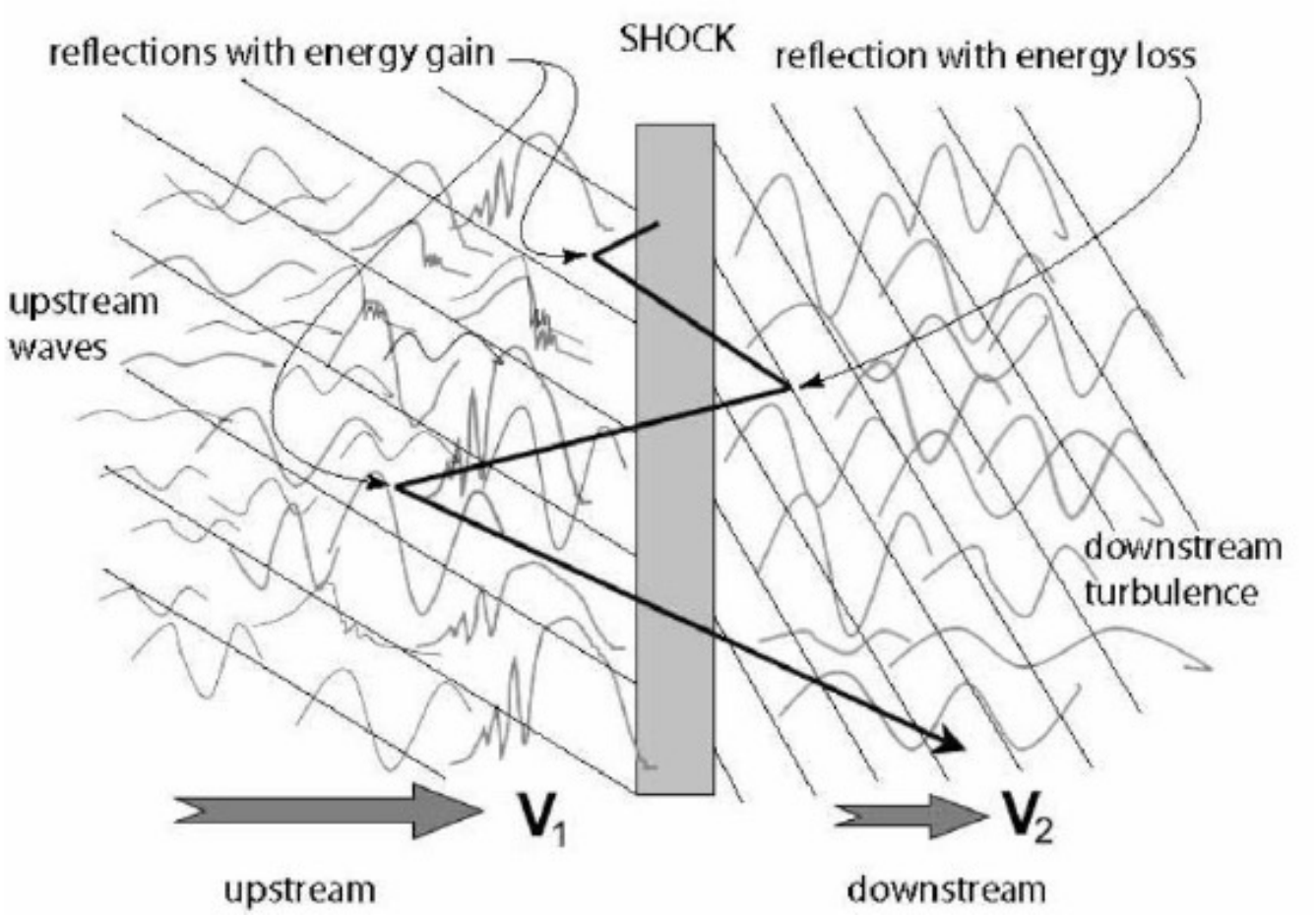


Diffusive Shock Acceleration (DSA)



1st Order Fermi, head-on collisions guaranteed
(quasi-para shocks):
$<\Delta E/E> \sim 4/3\ \beta$

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



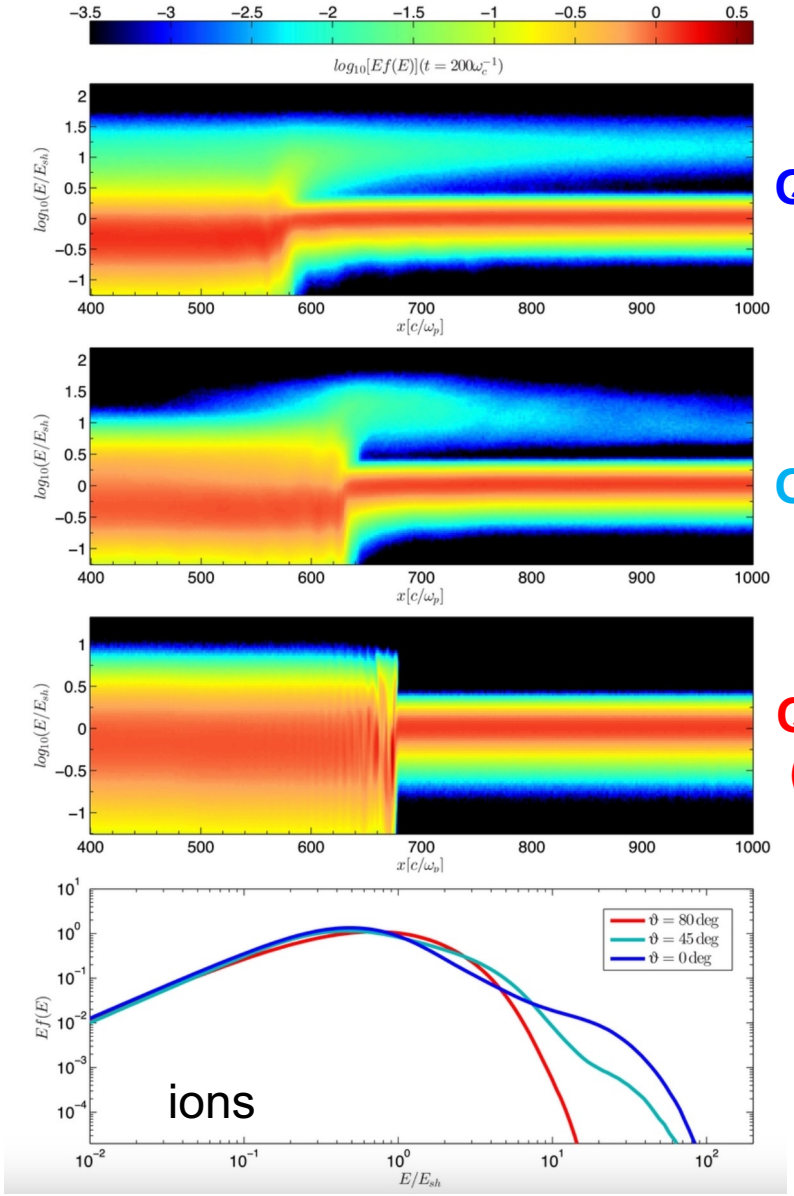
Simplified explanation

- 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?

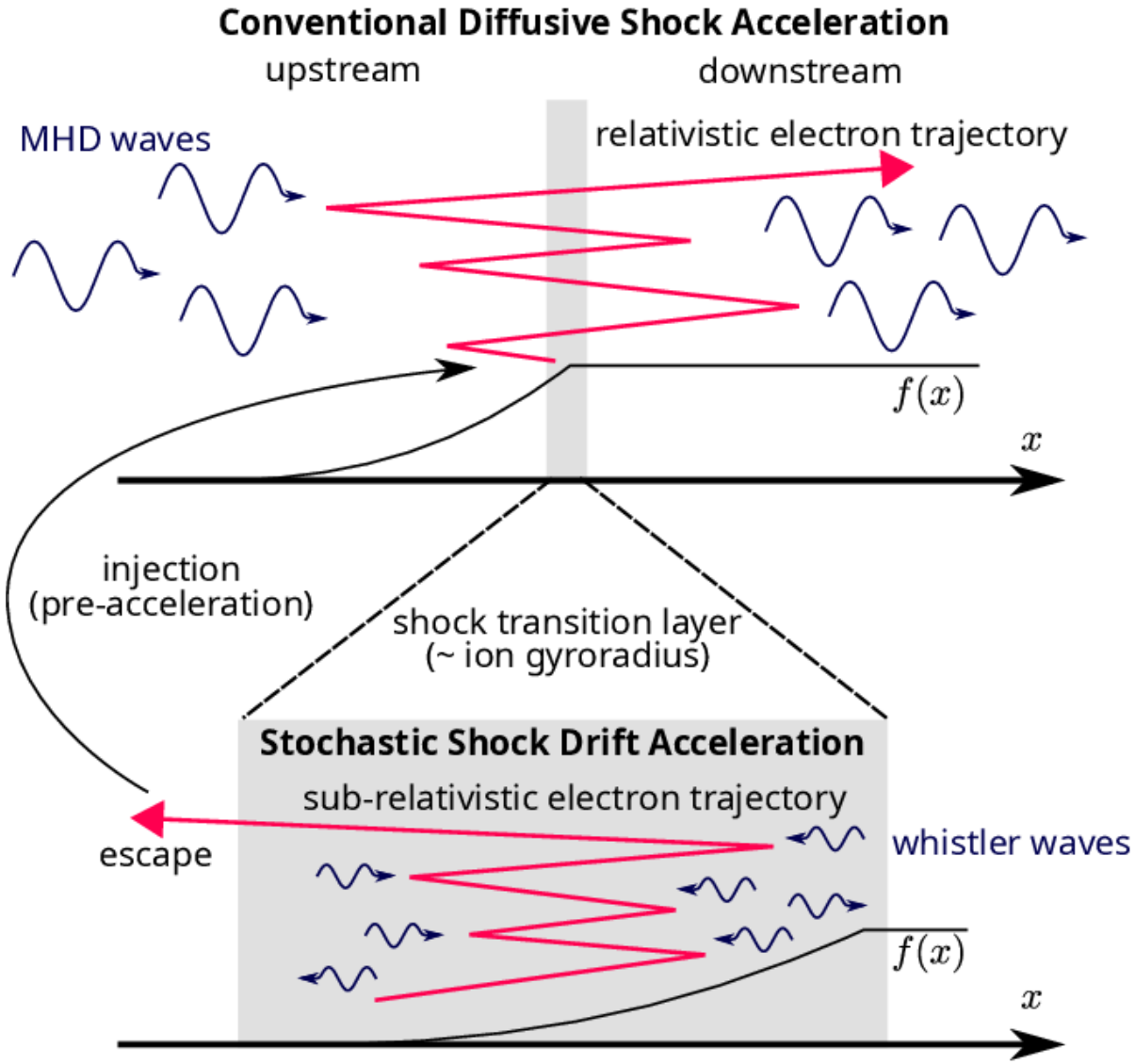
Acceleration at Qpar and Qperp shocks



Qpar shock (DSA)

Oblique shock

Qperp shock (SDA/SSDA)

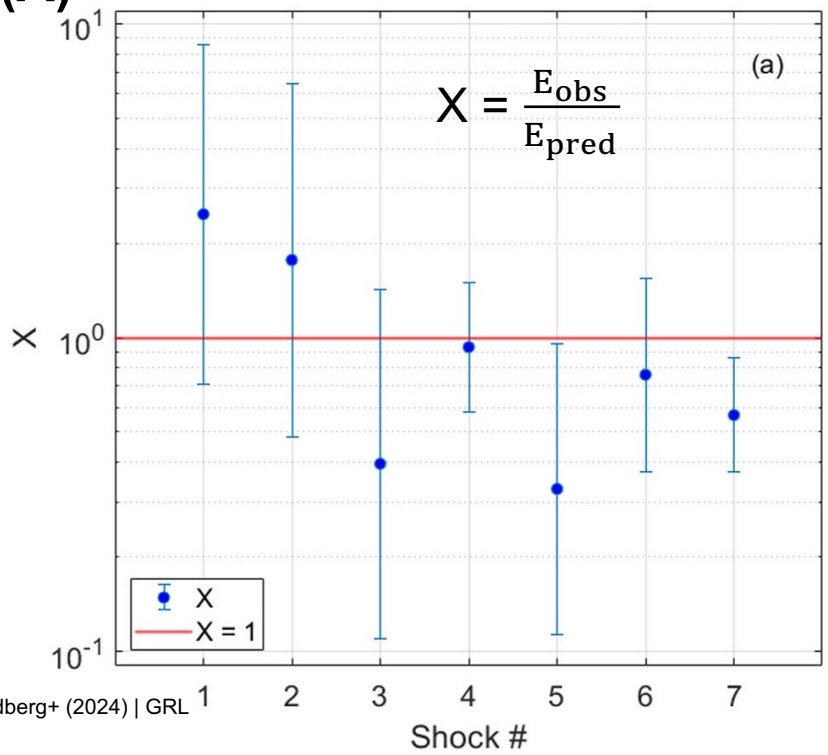


Caprioli and Spitkovsky 2014

Amano et al. 2020 | PRL

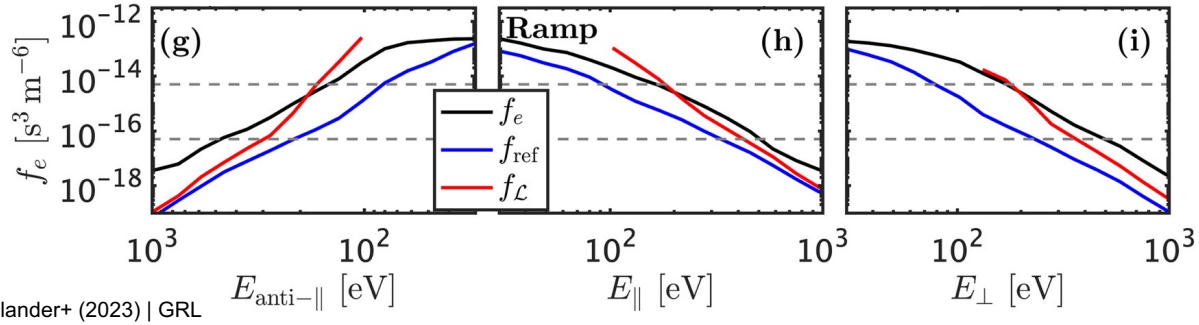
Recent results by MMS on Electron Acceleration

(A)



Lindberg+ (2024) | GRL

(B)



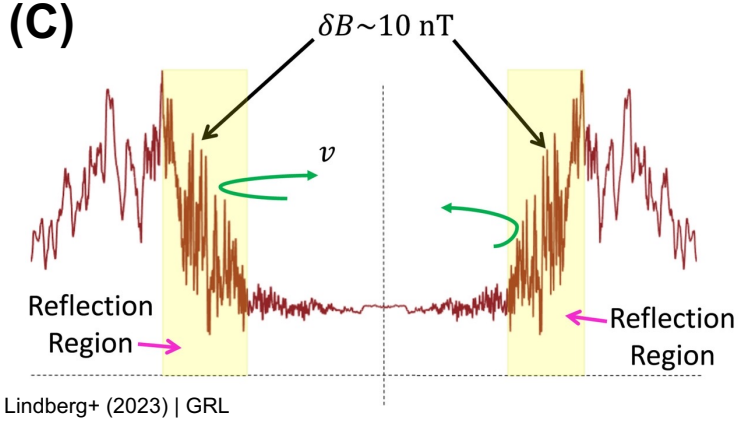
Johlander+ (2023) | GRL

(A) Qperp shocks consistent with SSDA predictions (X=1 is theoretical prediction)

(B) Non-adiabatic heating observed (Red: Model | Black: Observations)

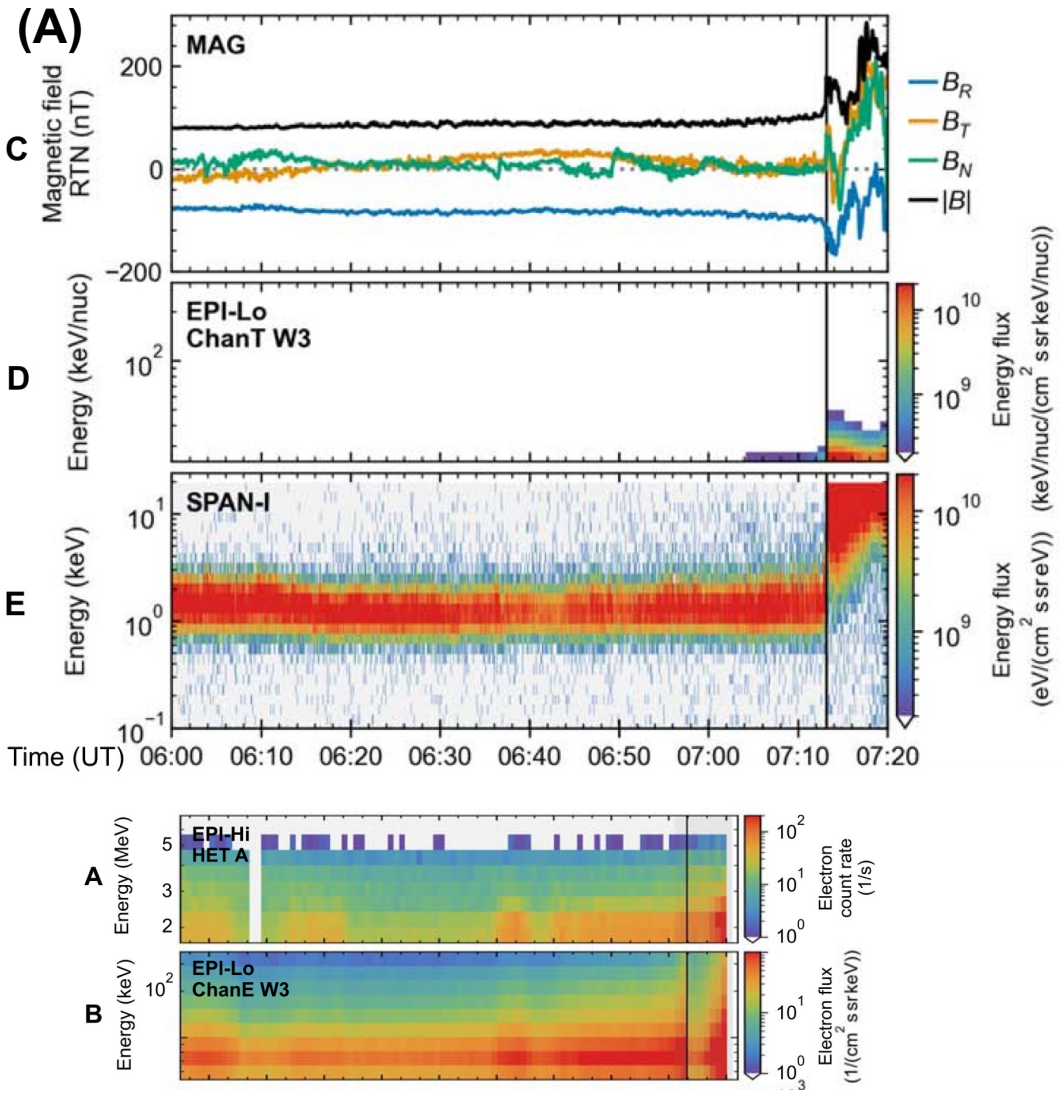
(C) Collapsing bottle + PA scattering + adiabatic reflection

(C)

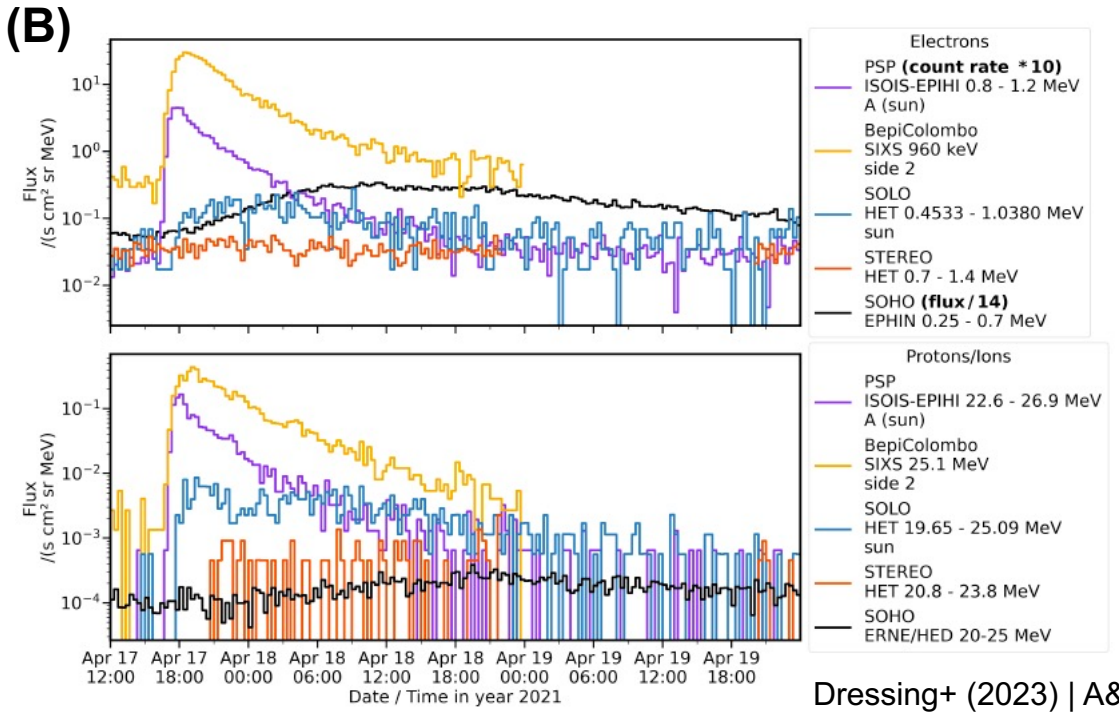


Lindberg+ (2023) | GRL

Recent Results from PSP and SolO



Jebaraj+ (2024) | ApJL



Dressing+ (2023) | A&A

(A) PSP data showing up to 6 MeV electrons at an IP shock!

(B) Relativistic ~(MeV) electrons at an SEP associated to a CME shock

Hundreds of shocks observed by SolO (Trotta+ 2025) https://serpentine-h2020.eu

1. High level intro
2. Shocks (Geometry)
3. Shocks (Acceleration)
4. Transient phenomena
5. New Results on Particle Acceleration

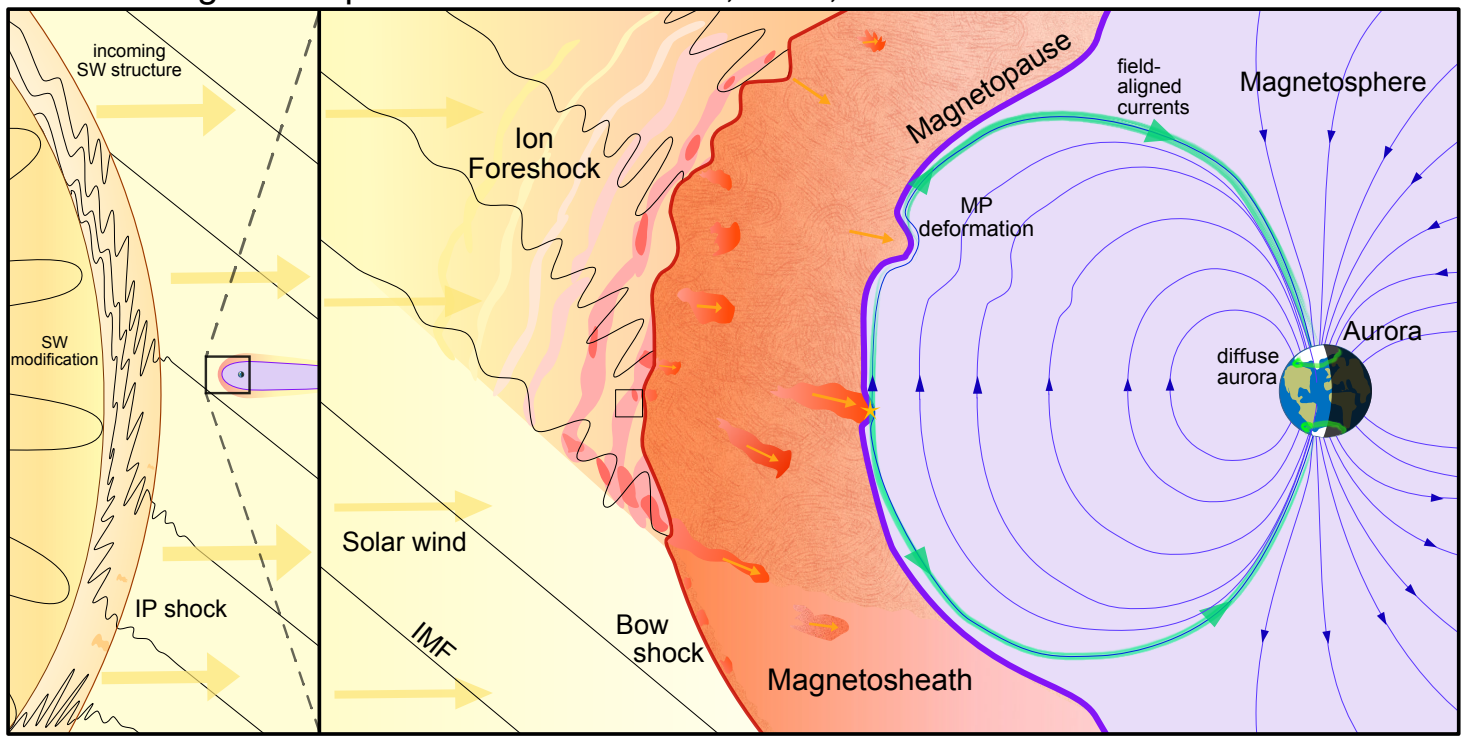
So we know shocks, and we know acceleration!

Let’s go back to Transients!

What is a Dayside Transient?

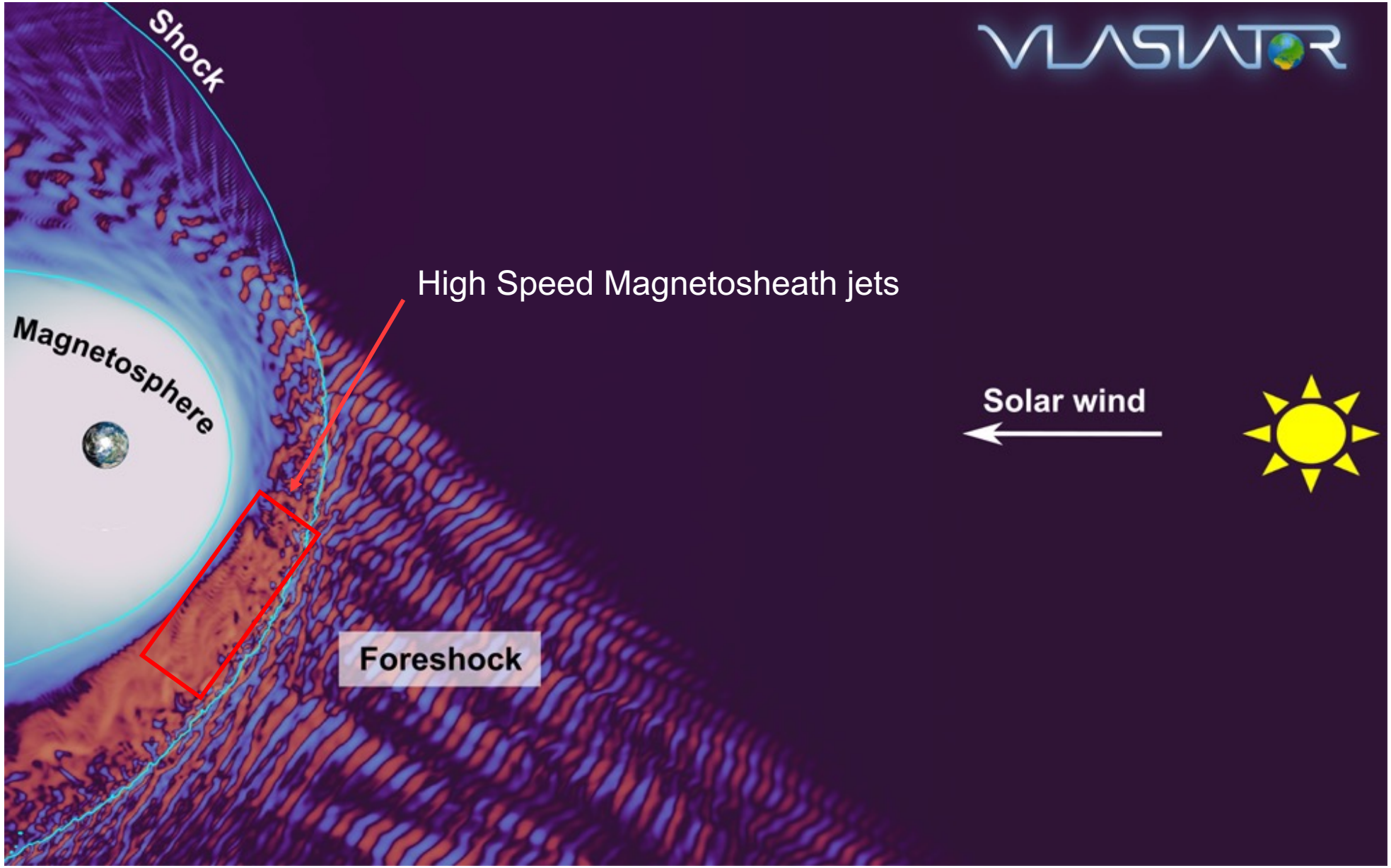
Transient phenomena are events that disrupt the steady-state plasma conditions, occurring temporarily and introducing dynamic changes to the physical system

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



- Global (Solar):
  - Coronal Mass Ejection (CME)
  - High-Speed Stream (HSS)
  - Pressure Pulse
- 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

←New review paper about high-speed jets!



Credits: Lucille Turc / Vlasiator team

Magnetosheath jets

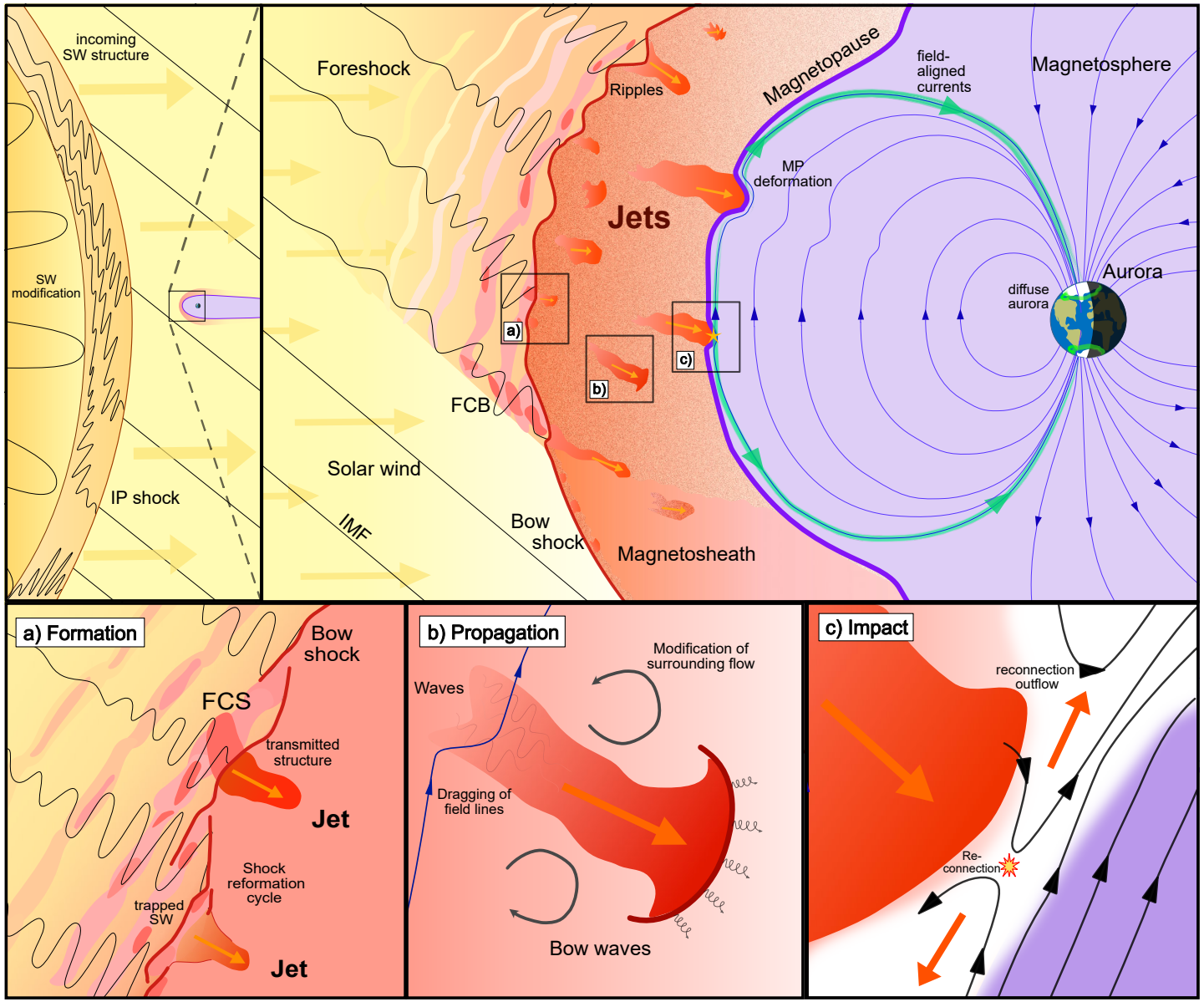


Figure adapted from Krämer et al., 2025, Credits: Florian Koller

Definition

Magnetosheath jets are **transient localized enhancements** of **dynamic pressure** (density and/or velocity increase)

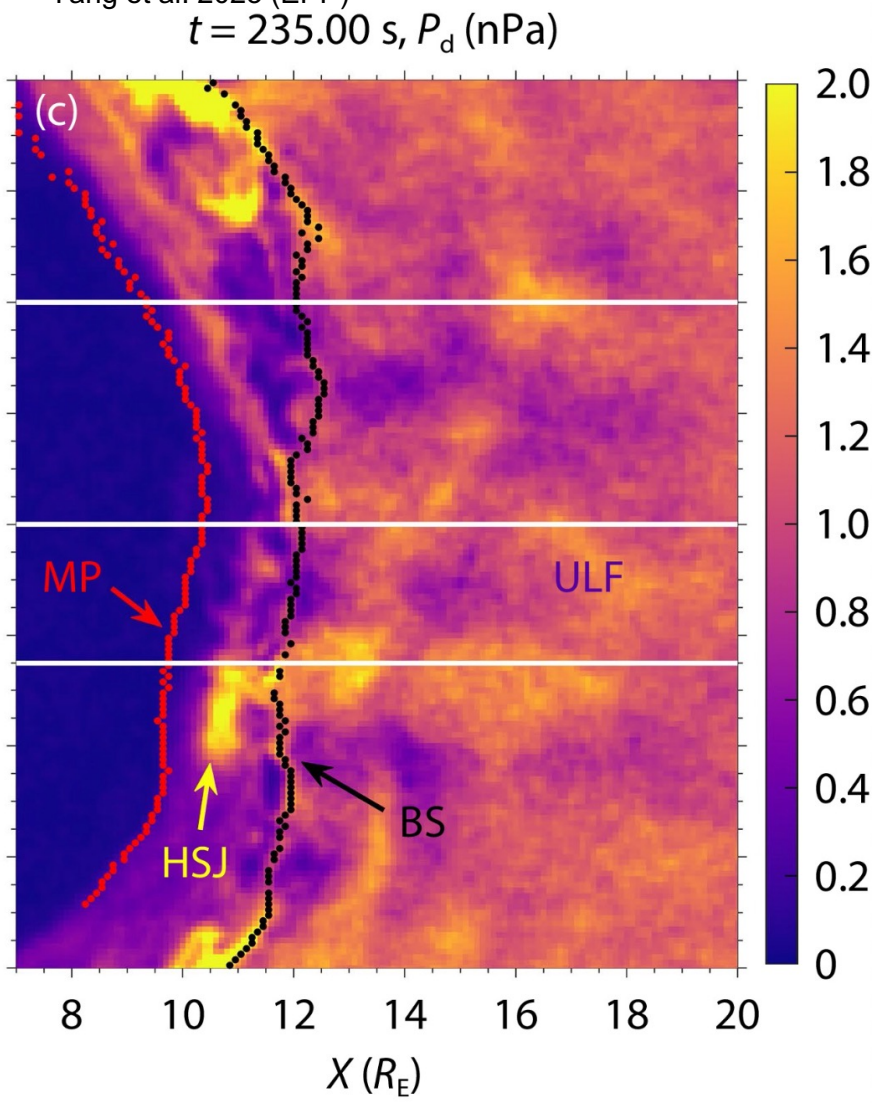
e.g., 200% dynamic pressure enhancement compared to background magnetosheath

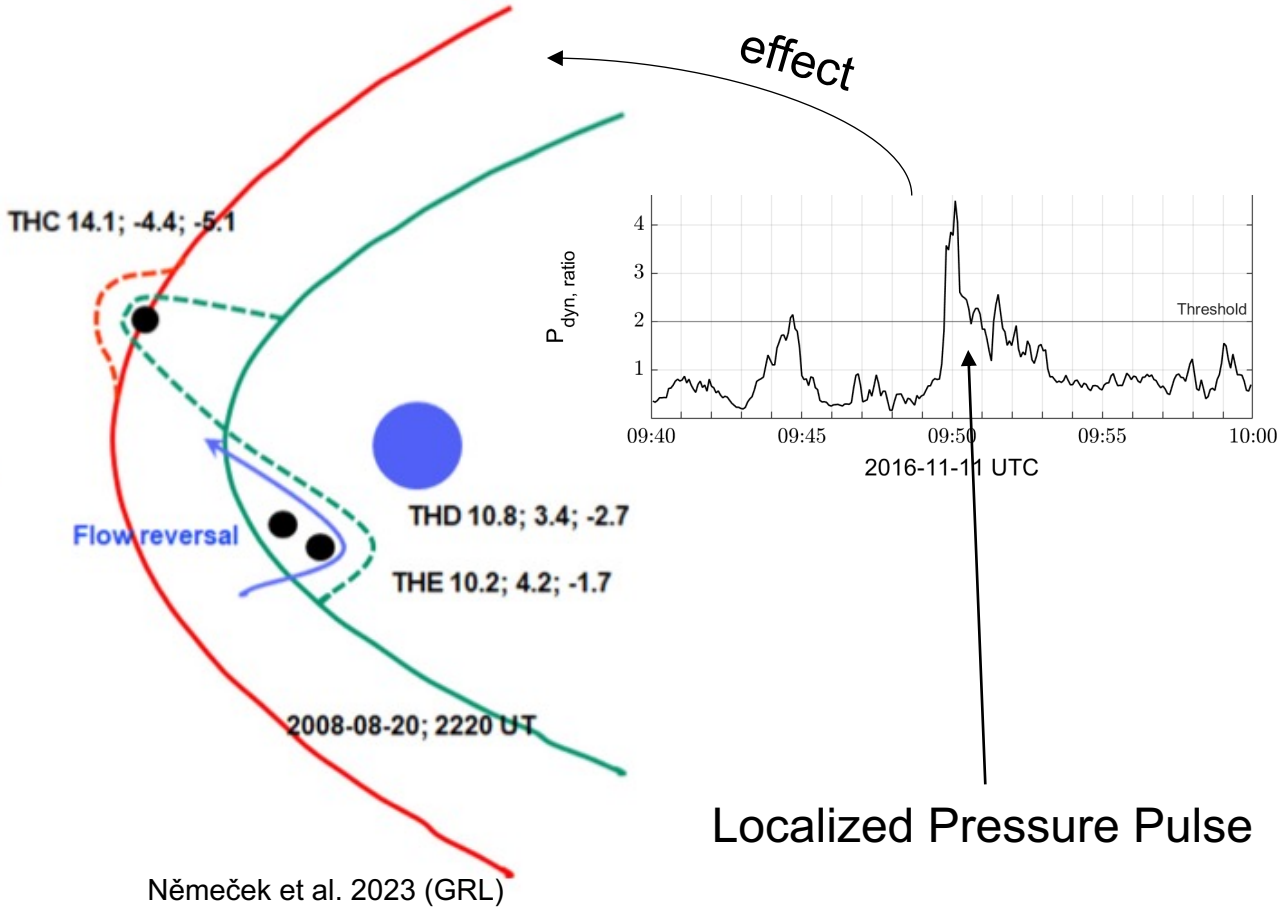
Related phenomena

Radiation belts
Throat aurora
Magnetopause reconnection
Magnetopause penetration
Shock acceleration
Magnetopause surface eigenmodes
ULF waves
Substorms
Ground magnetometer detection

Jets & Magnetosphere Effects

Yang et al. 2023 (EPP)





Němeček et al. 2023 (GRL)

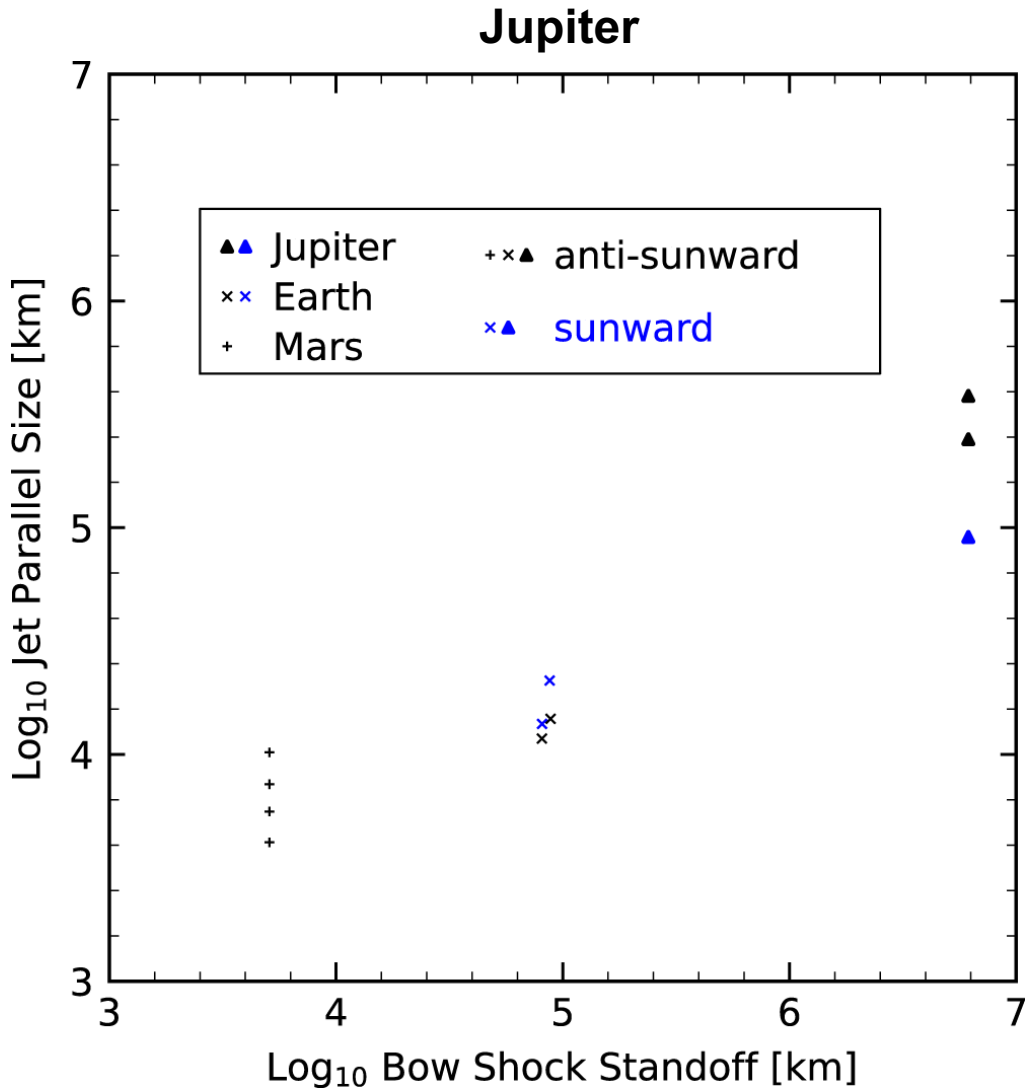
Ng et al., (2023 - GRL), Yang et al. (2023 - EPP), Guo et al. (2023 - EPP)

Reconnection: Hietala et al. (2018), Nykiri et al. (2019), Escoubet et al. (2020), Vuorinen et al. (2021), Ng et al. (2021)

Jets: A universal Phenomenon

- Jets exist in other planets & IP Shocks
  - ❖ Mars : Gunnel et al., 2023
  - ❖ Jupiter: Zhou et al., 2024
  - ❖ IP shocks: Hietala et al., 2024
  - ❖ Mercury (?): Karlsson et al., 2016

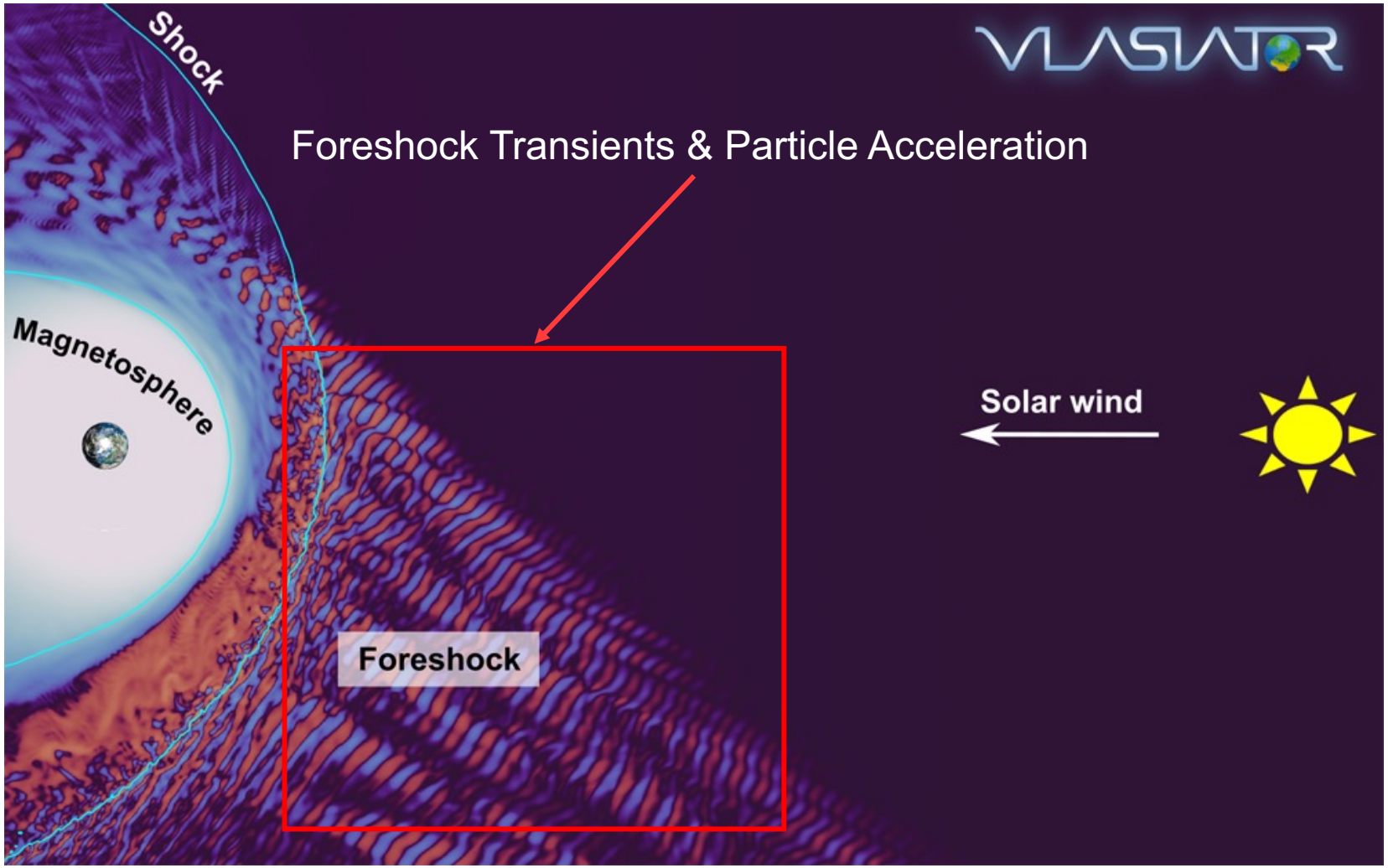
Q: Are jets a universal phenomenon across shocks?
A: **Probably**!



Zhou, **Raptis**, et al. 2024 | Nat. Commun.

Things we know:

- Shocks (Geometry)
- Shock Acceleration (DSA/SDA)
- Downstream transients (Jets)
- Let’s go upstream!



Credits: Lucille Turc / Vlasiator team

Foreshock Transients

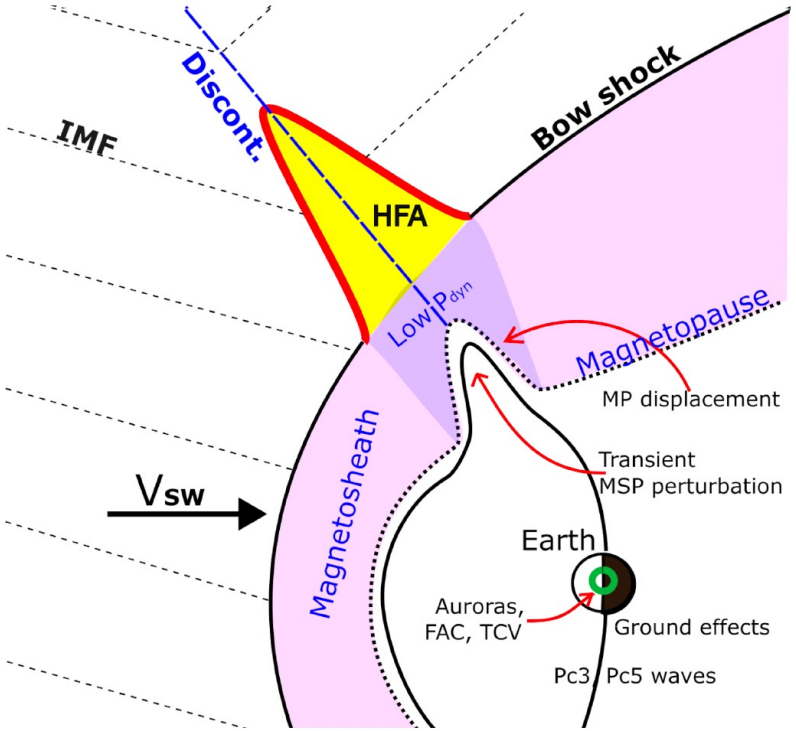
Transients with most notable impact

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

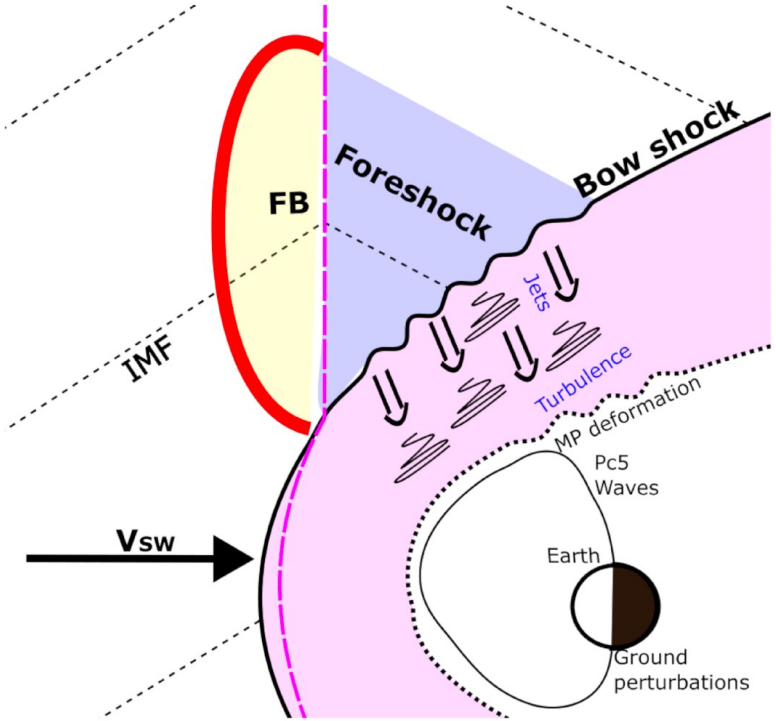
HFAs
Discontinuities intersects BS and E (-V X B) points towards the sheet, ions pile up and thermalized

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

Zhang et al., (2022)



Hot Flow Anomalies (HFAs)



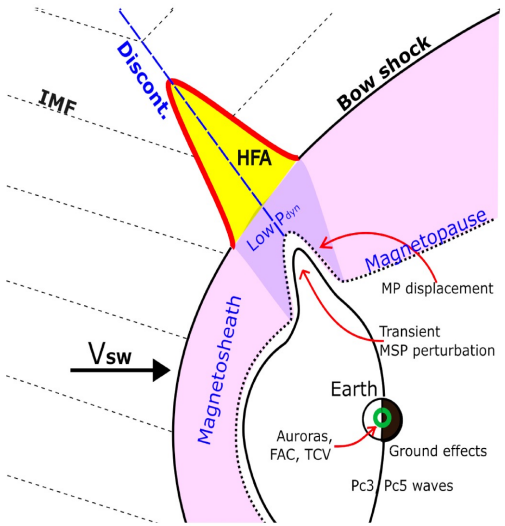
Foreshock Bubbles(FBs)

Primož K. et al. (2024)

TUMS (Transient Upstream Mesoscale Structures)

The anatomy of an HFA

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



Hot Flow Anomalies (HFA)

Kajdič+ (2024)

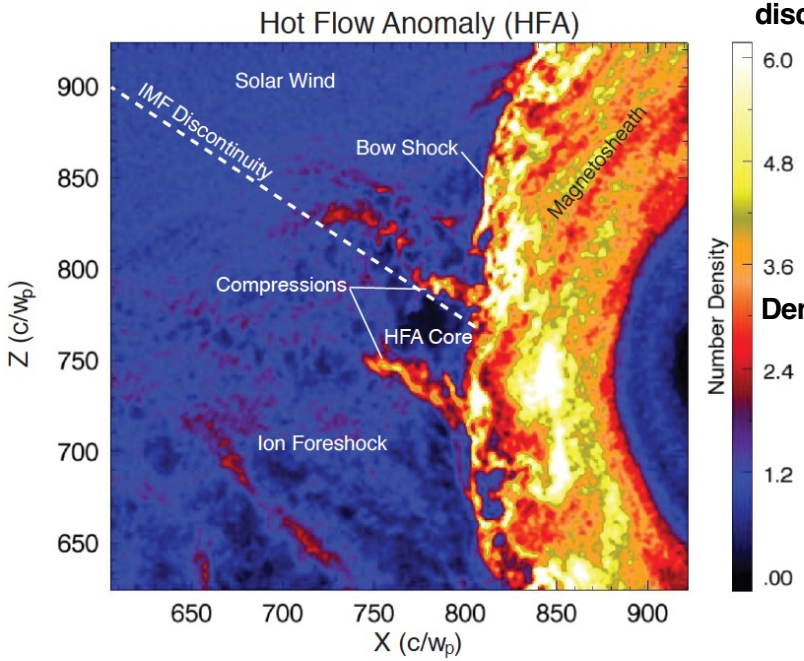


Figure by Nick Omidi

Crater-like B-field and IMF discontinuity

Density compressions and cavity

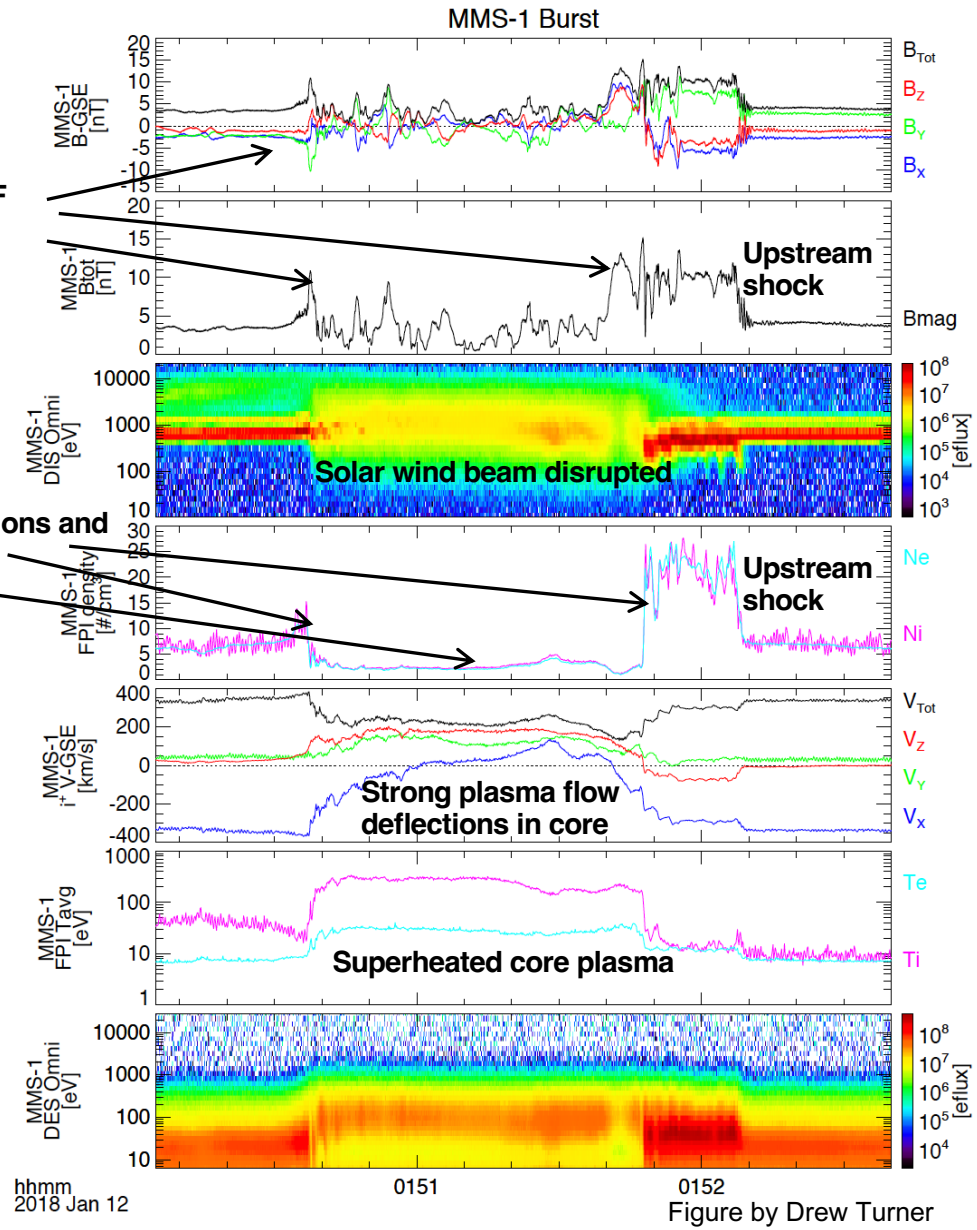


Figure by Drew Turner

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

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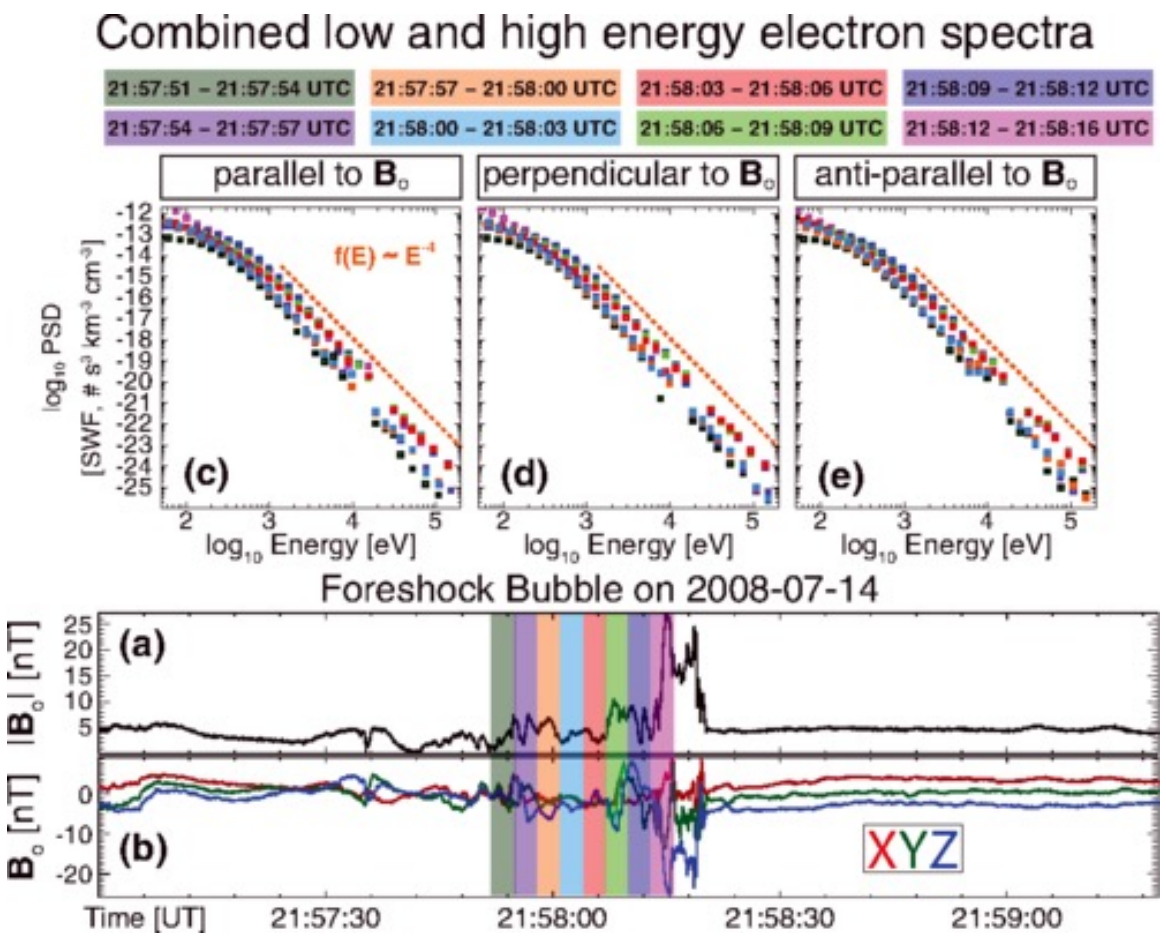
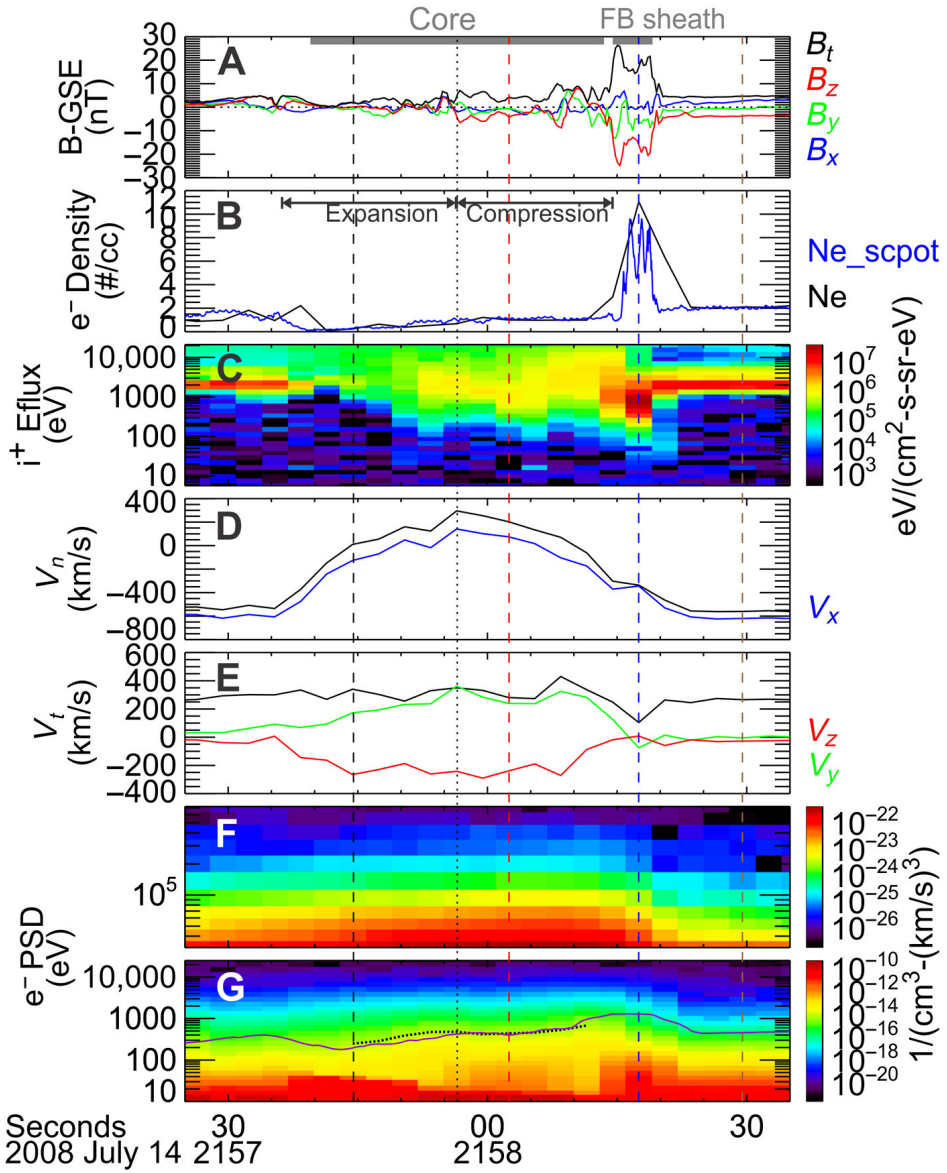
Foreshock/Dayside/Shock-generated Transients…

...and why they make Qpar shocks super accelerators

Foreshock Transients & Electron acceleration



~300 KeV electrons

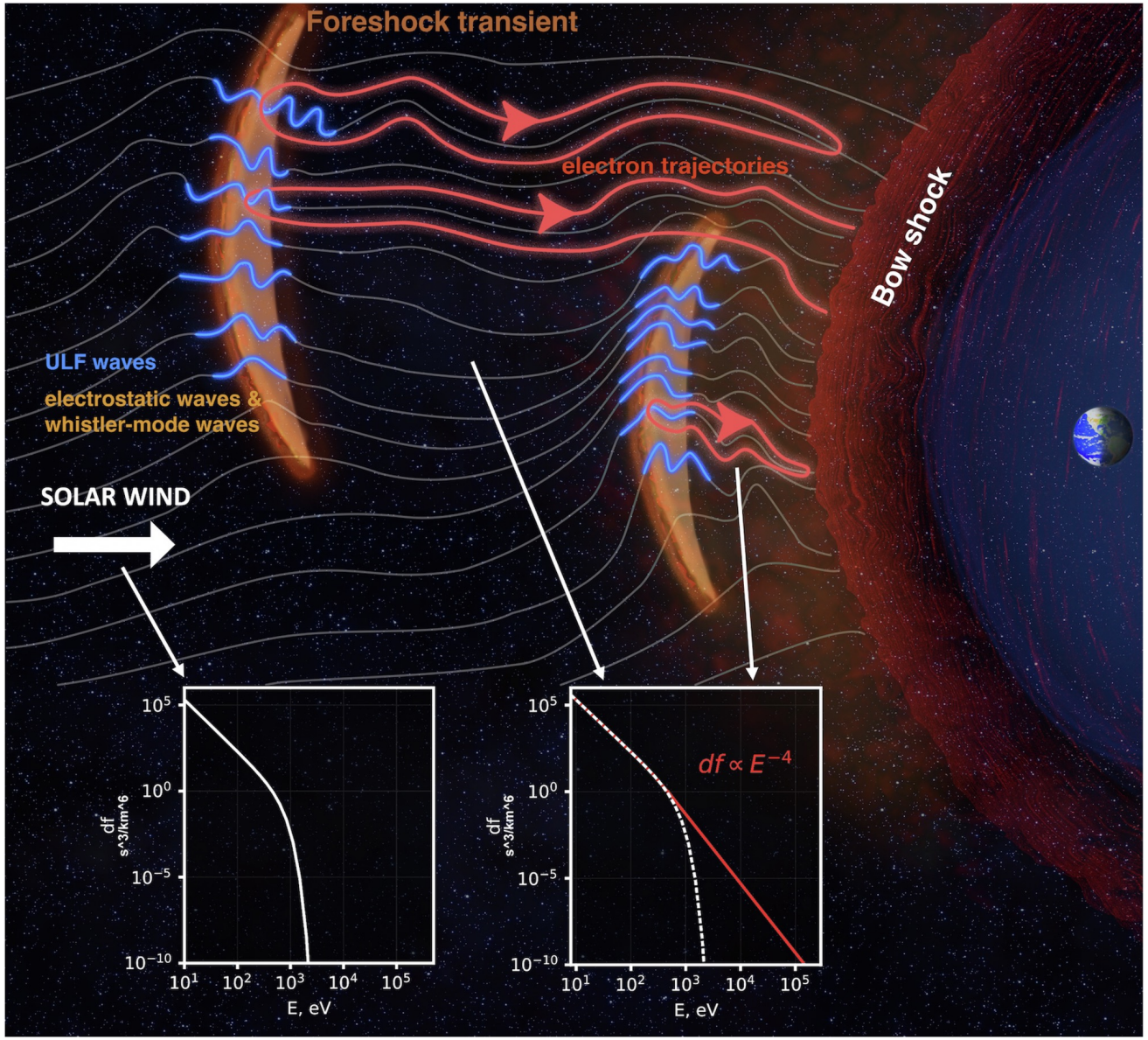


~200 KeV electrons

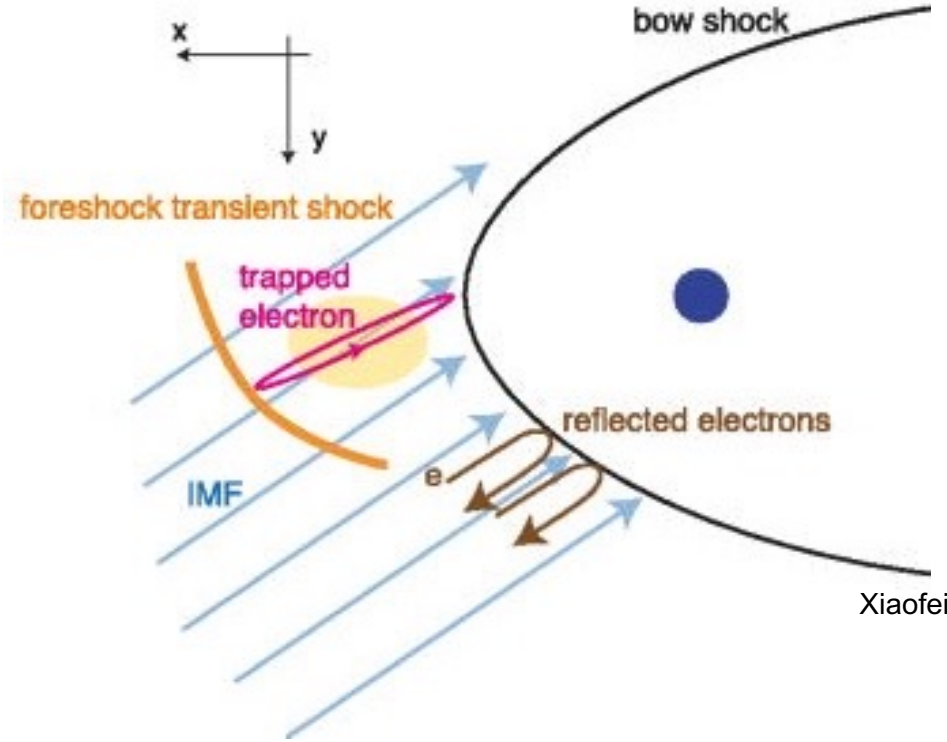
Wilson III L. et al. 2016 | PRL

Liu T. et al. 2019 | Science Adv.

Recent updates – Wave Particle Interactions



Shi+ 2025 Nat.Com



Xiaofei+ (2023)

- Adiabatic heating
- Temperature Anisotropy
- High frequency whistlers

Electron acceleration + pitch angle scattering

See Artemyev+, Xiaofei+, Vargas + Tonoian+ (2022 – 2025)

New Results on Electron Acceleration

Reminder:

Qpar shocks → DSA is efficient, but how do we solve the injection problem?
Qperp shocks → (S)SDA is fine, but not sufficient to drive relativistic energies.

Reminder: Qpar shocks include the foreshock and its transients

Raptis et al.2025 NatComm

Raptis et al.2025 ApJL

Online Attention

ScienceDaily

New study unveils breakthrough in understanding cosmic particle accelerators

Science Daily, 13 Jan 2025

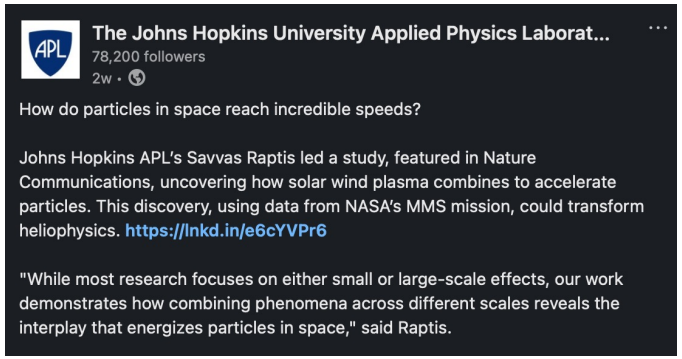
Scientists have come a step closer to understanding how collisionless shock waves -- found throughout the universe -- are able...

PHYS.ORG

Cosmic shock waves: Unraveling the mystery of electron acceleration

Phys.org, 13 Jan 2025

Scientists have come a step closer to understanding how collisionless shock waves—found throughout the universe—are able to...

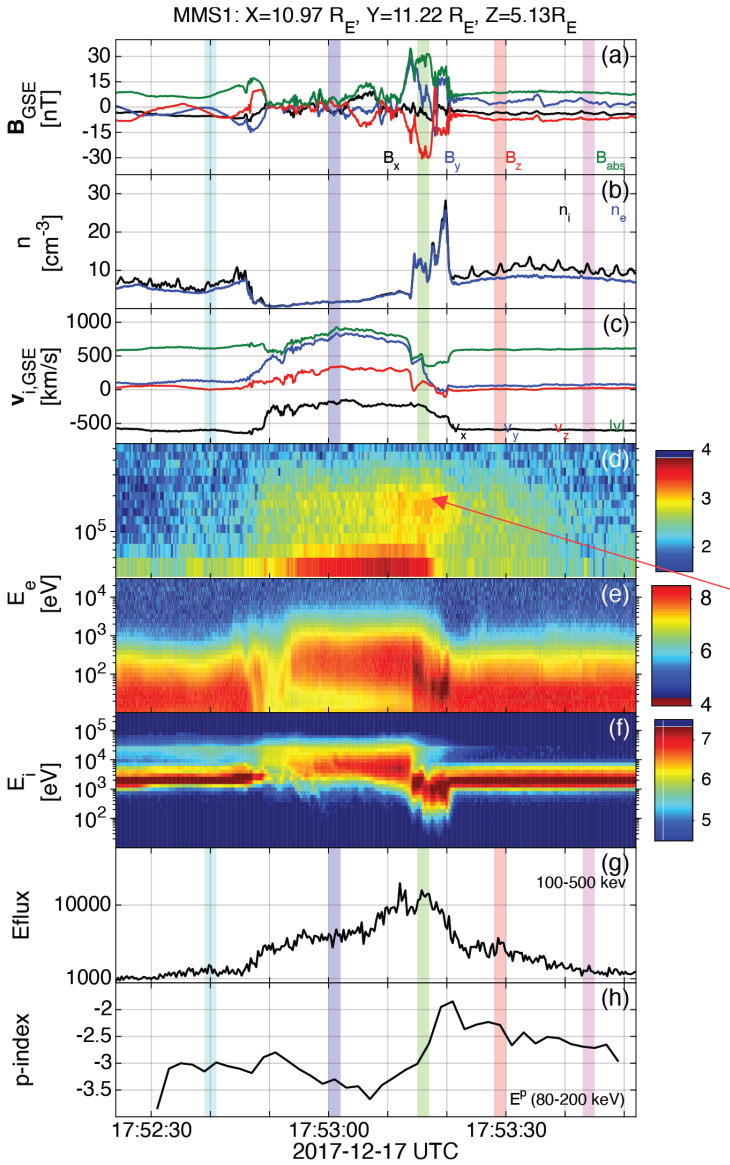


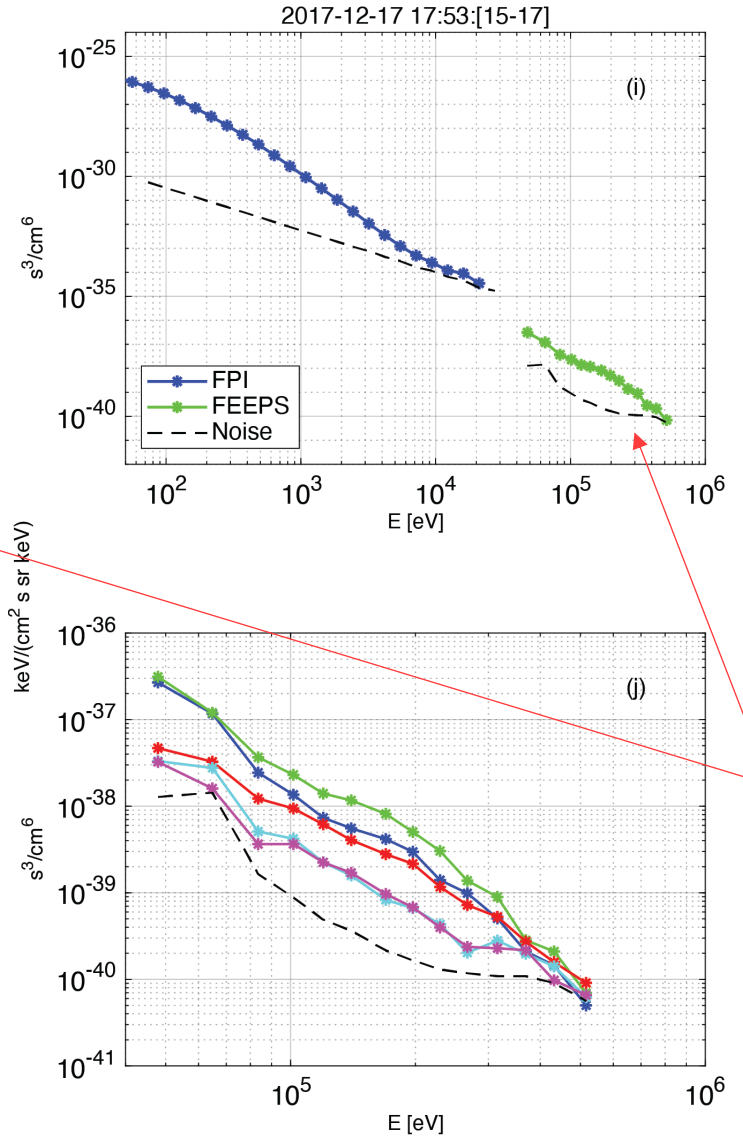
Read the popular science version of the paper:

Read the actual paper:

Read the “science nugget” from ARTEMIS mission:

Relativistic Electrons with MMS



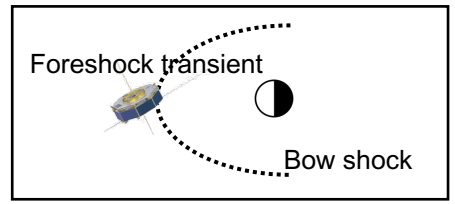


Typical properties of transient:

- Depleted Core (low B, n)
- Mature HFA (ΔB/B0 ~ 1-4)
- SW beam disrupted
- Strong density and magnetic field compressive boundaries
- Formation of a Qperp “shock”
- Flow anomaly (velocity decreasing)

Unique property

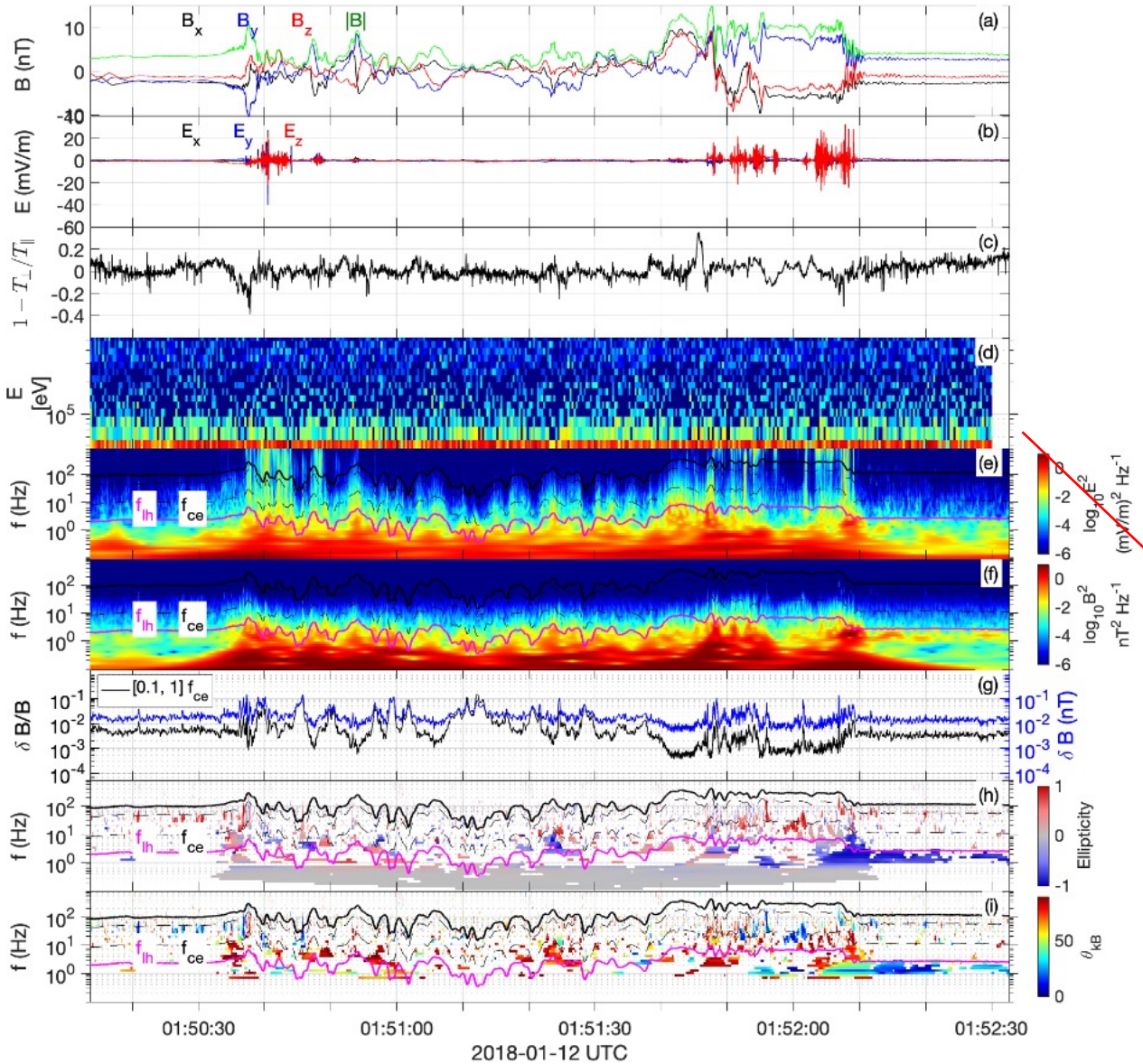
>500 keV electrons throughout the core and shock region



Raptis et al.2025 NatComm

Missing piece of the puzzle? – Let's look at another event

So why there are not always relativistic electrons?

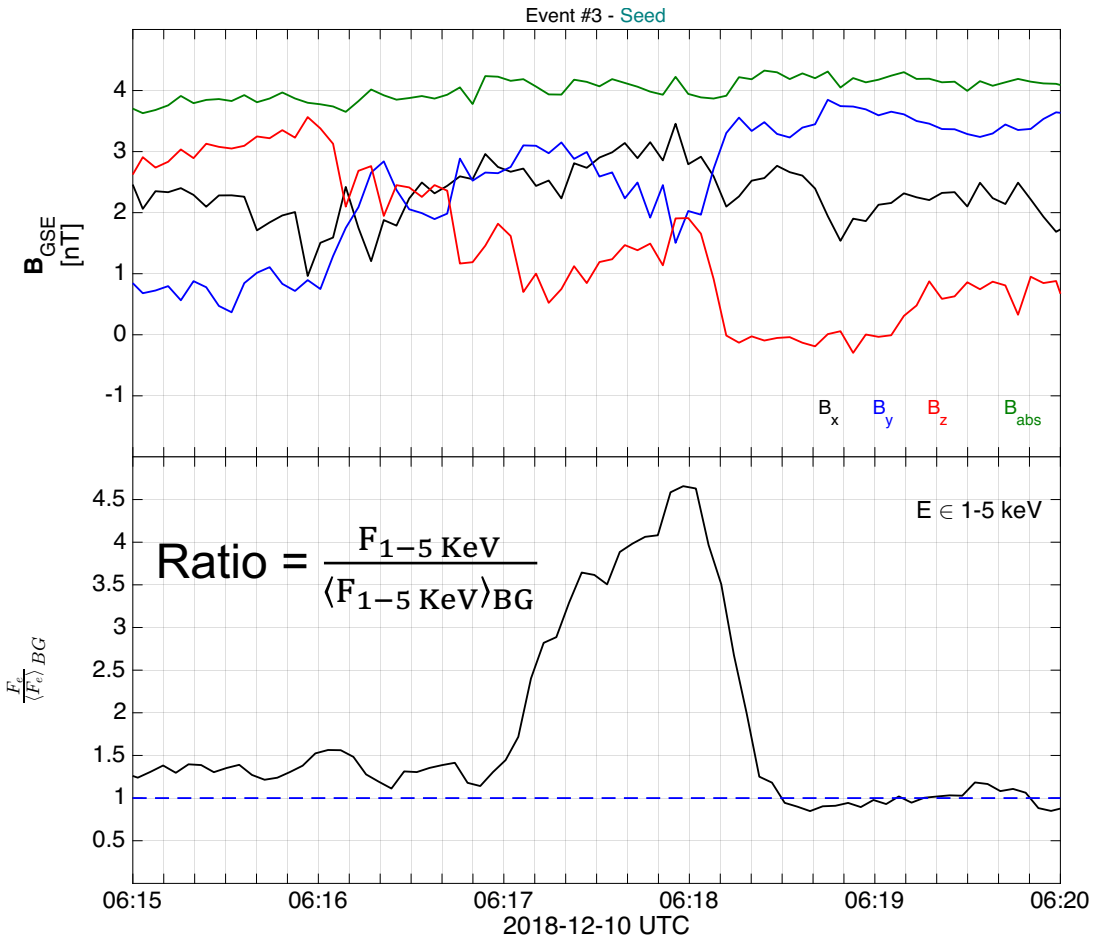


- Waves are there
- Shock is there,
- All the stuff are there.

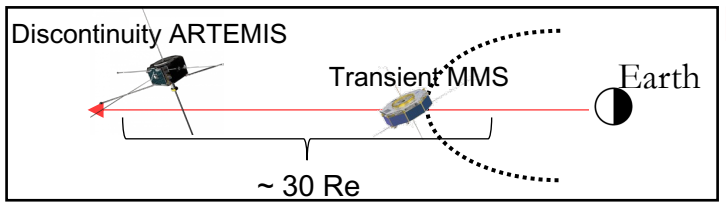
FEEPS = no signal

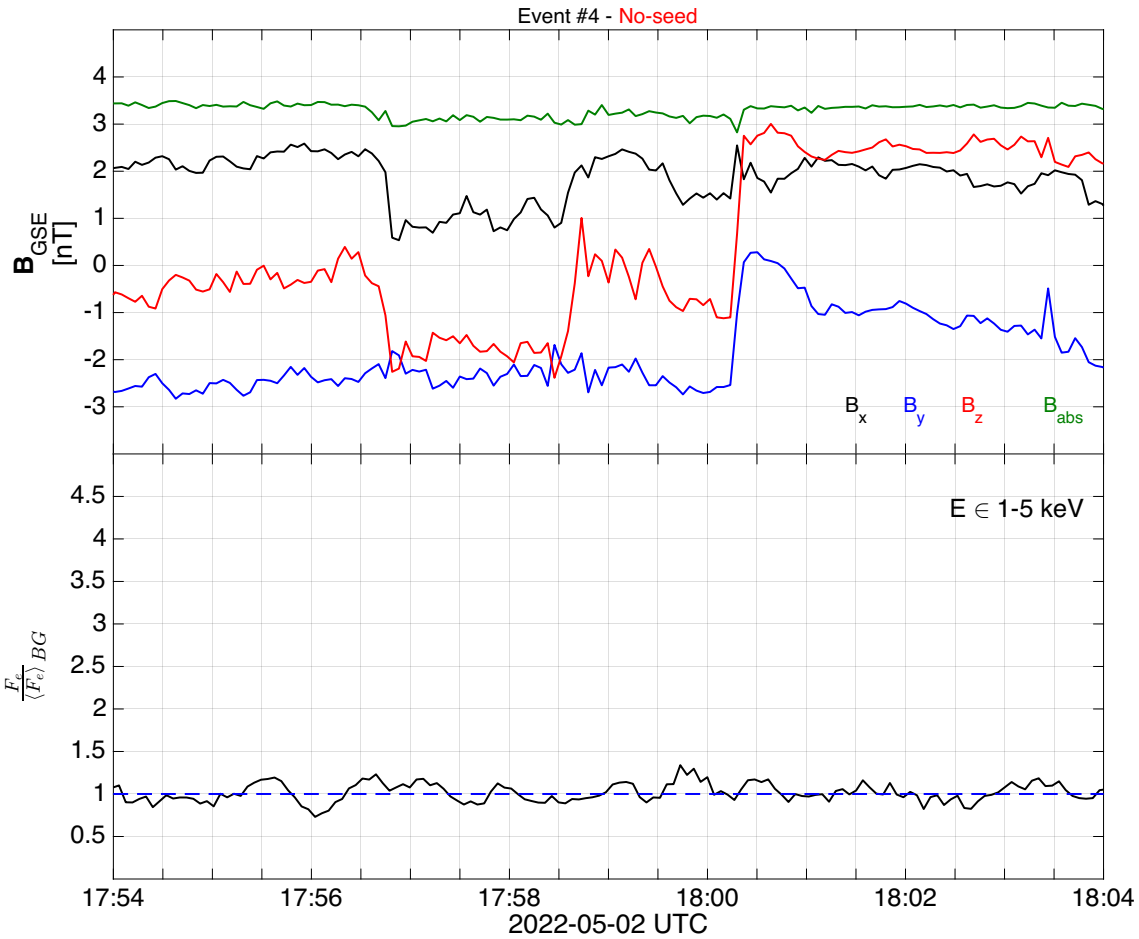
Raptis et al.2025 NatComm

Upstream conditions for two event - ARTEMIS



FEEPS: 100+ KeV

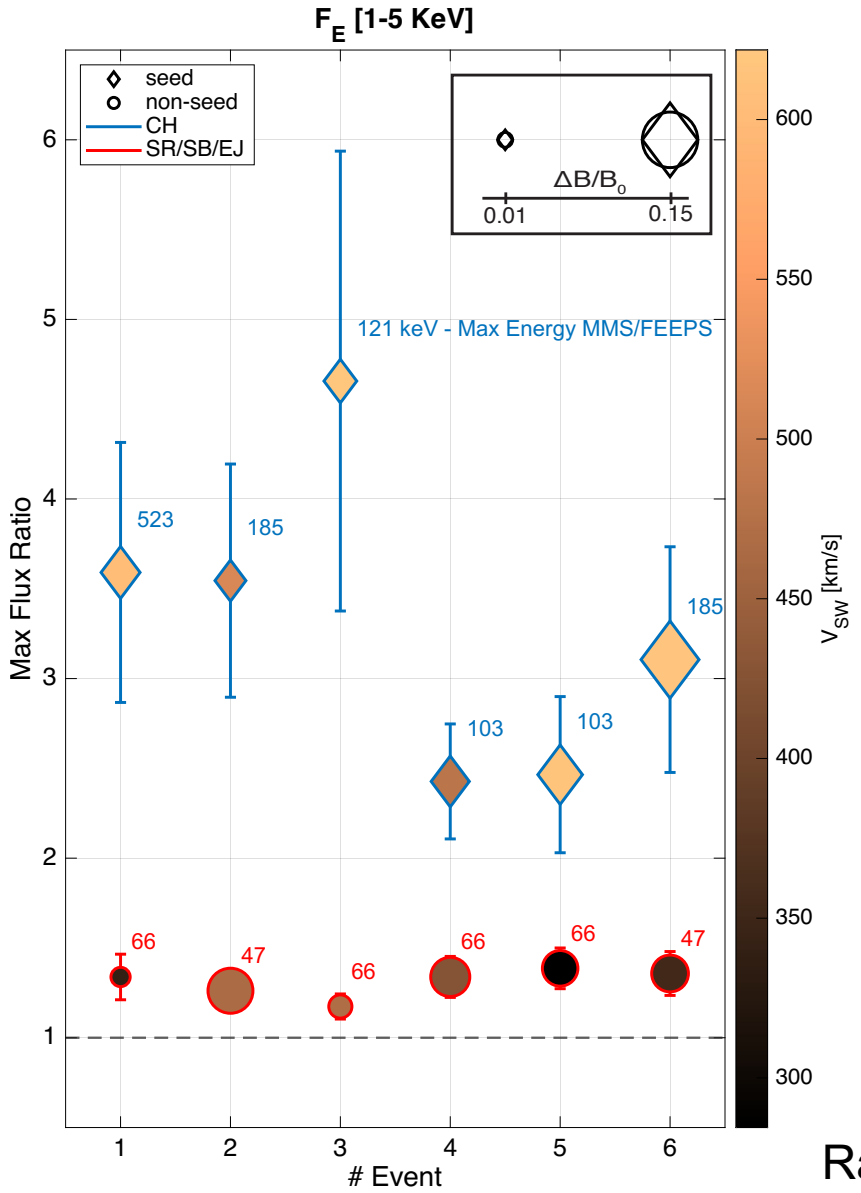




No Signal at FEEPS

Raptis et al.2025 NatComm

Statistics for seed and acceleration



Raptis et al.2025 NatComm

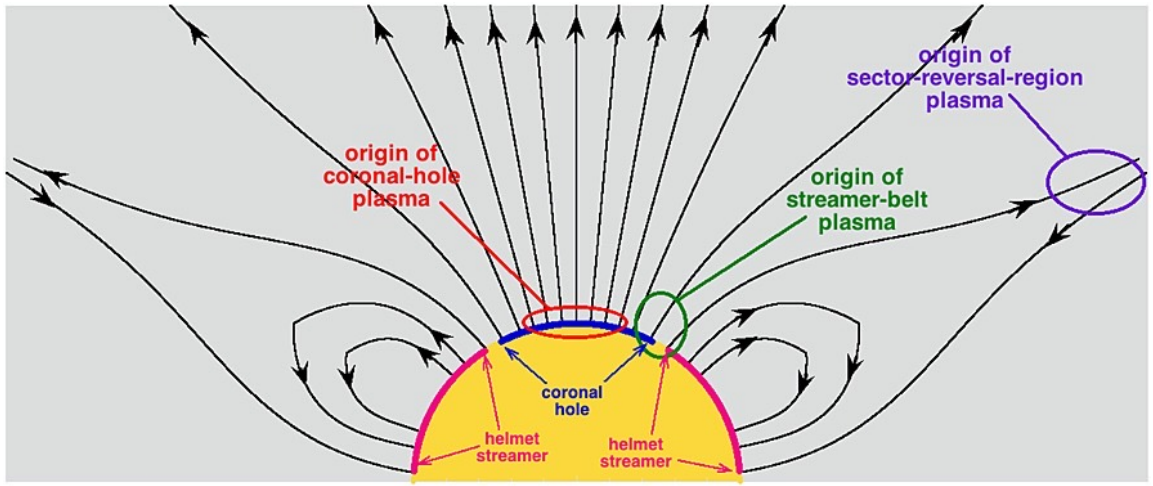
Seed events (FEEPS > 100 KeV)

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%)

Using: [Xu and Borosvky 2014, Camporeale+ 2017] methodology



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

Terry Liu+ (2017) noticed similar trends

Reinforced Shock Acceleration of Relativistic Electrons

Injection Threshold "Seeding"

Seed from CH plasma (**1-5 keV**)

Note: Other works results are fully consistent with our description: Wilson+2016, Liu+2019, Xiaofei+2025

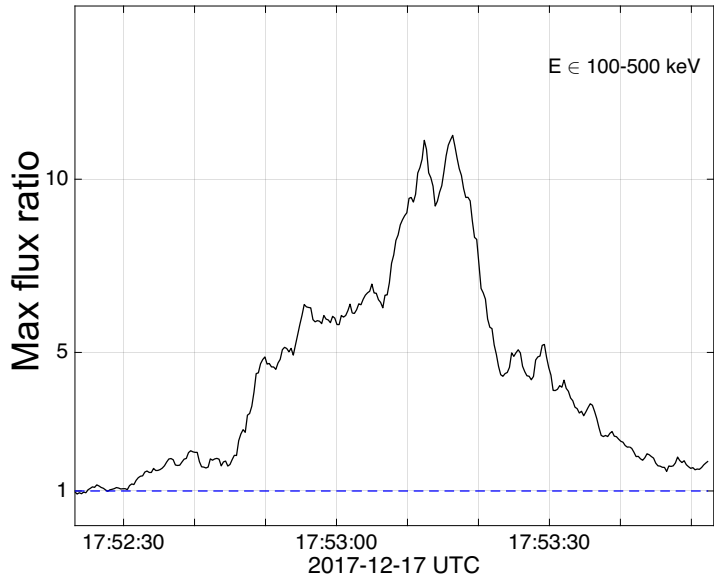
Electron acceleration at Foreshock Transient

Shock Acceleration (SDA/DSA) + Wave particle interactions

Efficient through PA scattering & confinement:

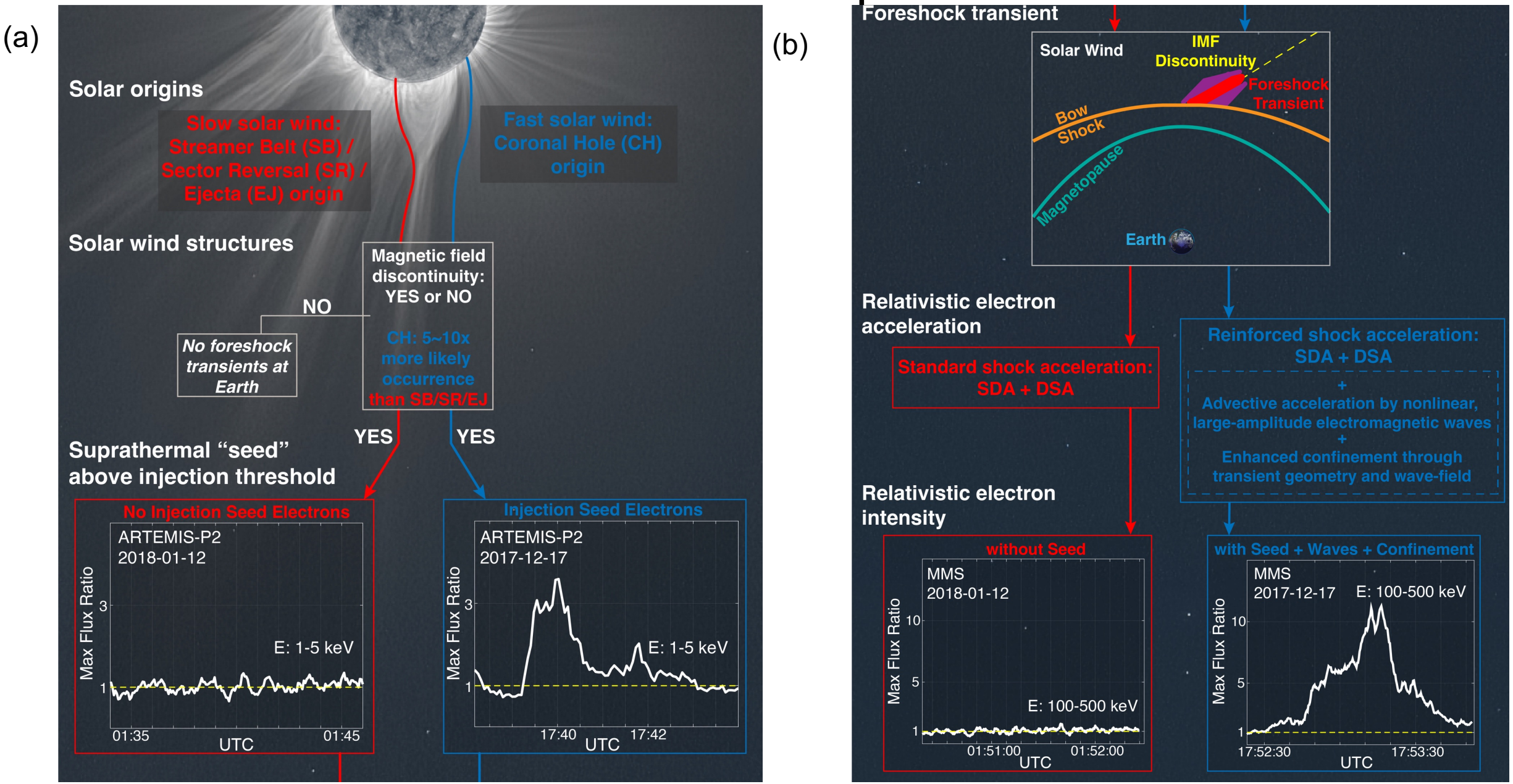
- LF whistler waves (Shock Transition)
- Wavefield of HFA's core (ΔB>>B)
- "Magnetic bottle" between edges of HFA and Earth's bow shock (geometry)
- Betatron (electron acceleration temperature anisotropy)

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



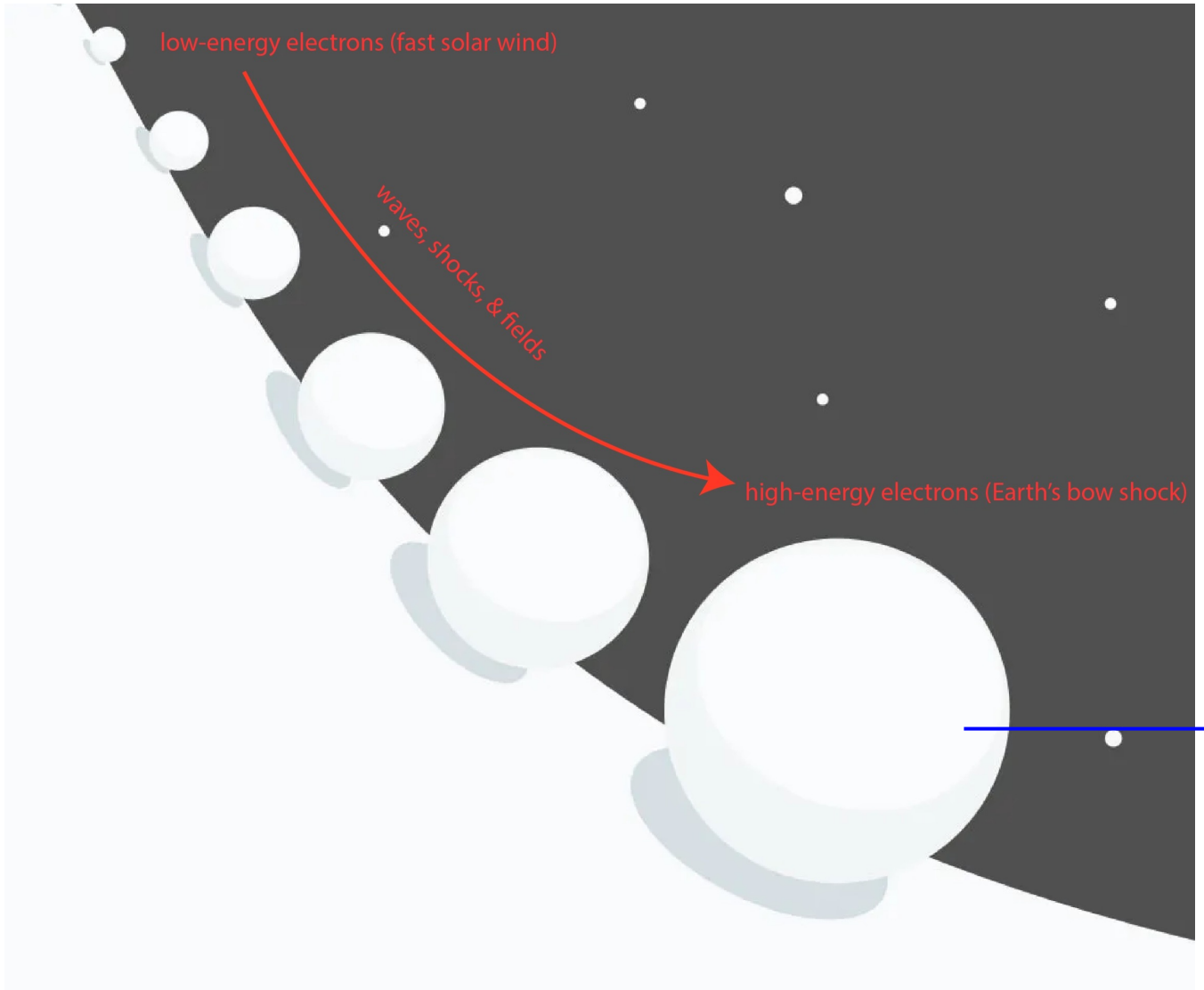
Key-point:
Seed + Foreshock's Shock + Waves + Efficiency factors = **~MeV electrons before** reaching the bow shock.

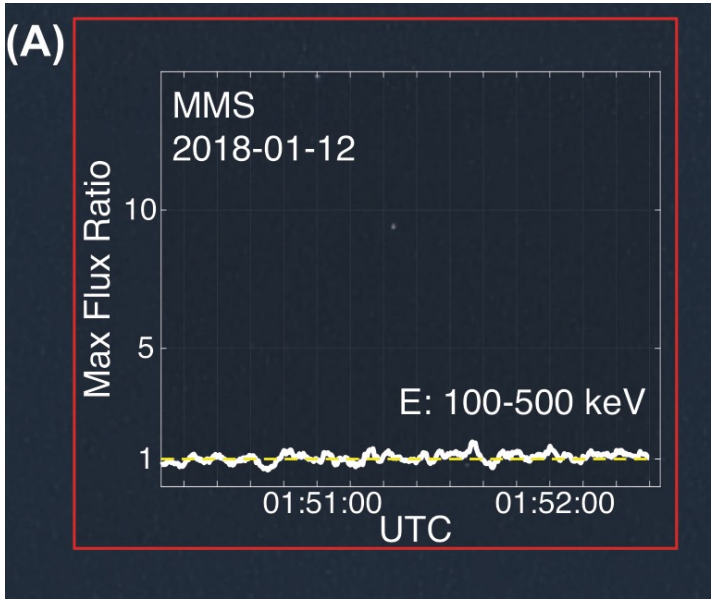
Schematic of the process

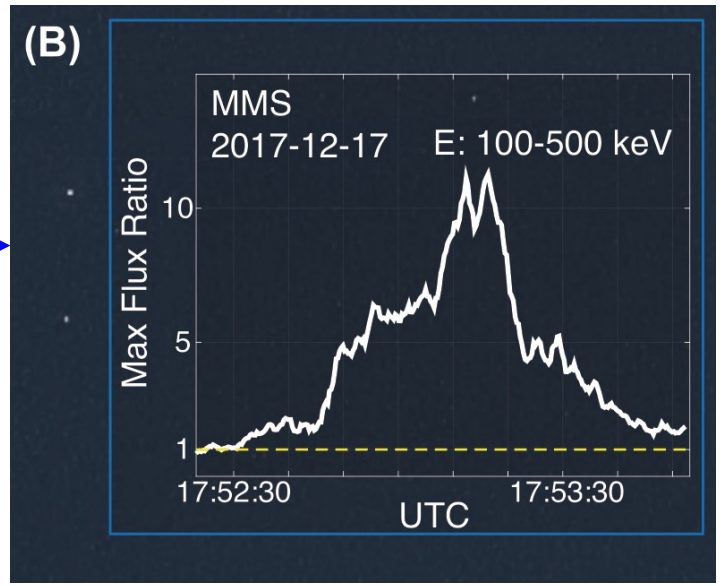


Raptis et al.2025 NatComm

Simplistic Picture to remember



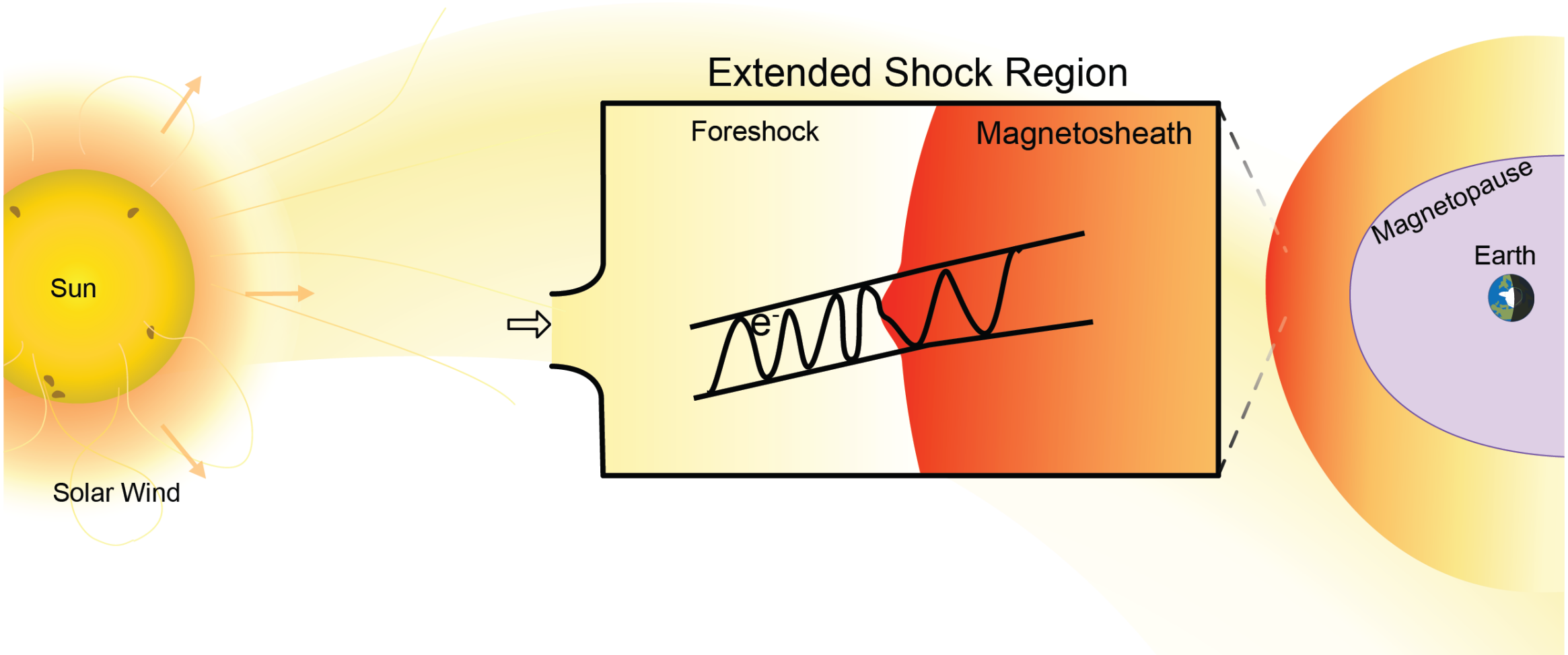




How do relativistic electrons form at shocks? "Behind The paper" https://communities.springernature.com/posts/shocks-acceleration-electrons-from-sun-to-earth

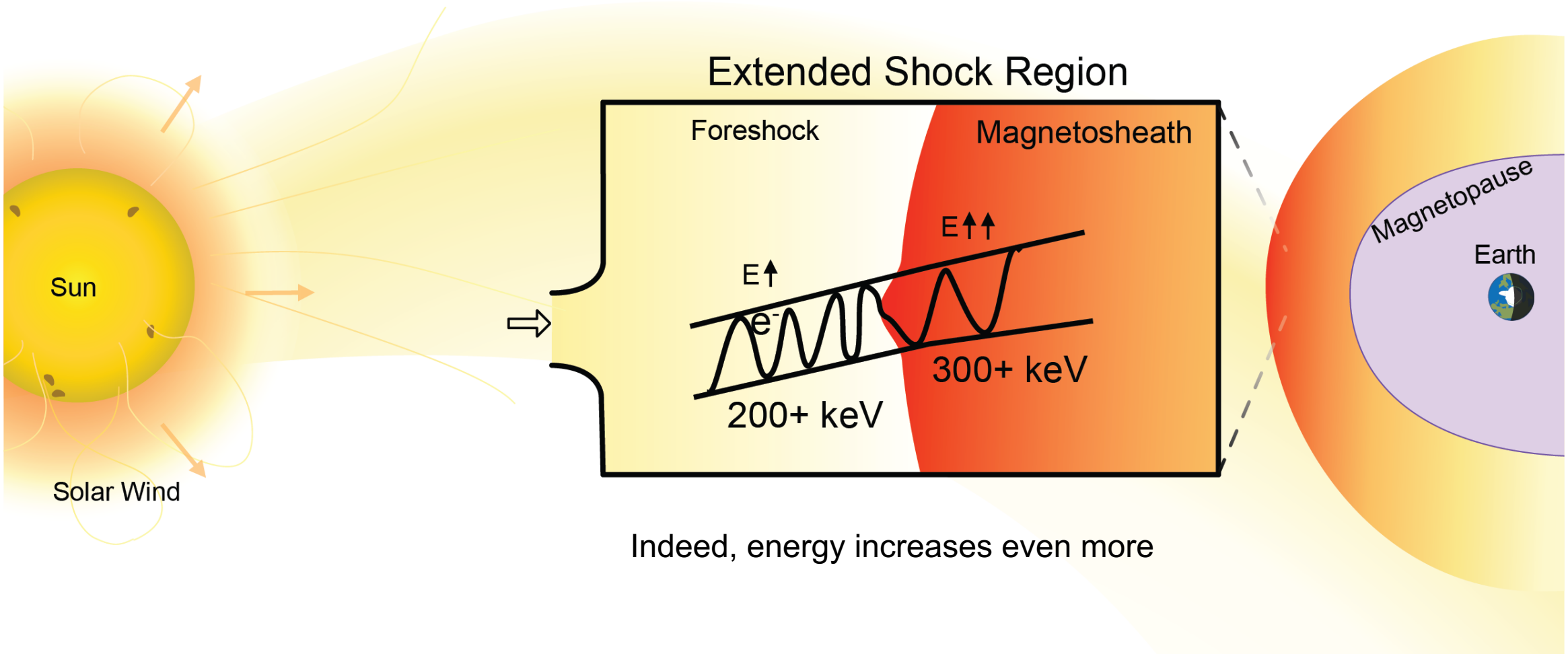
But let's ask one more question

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



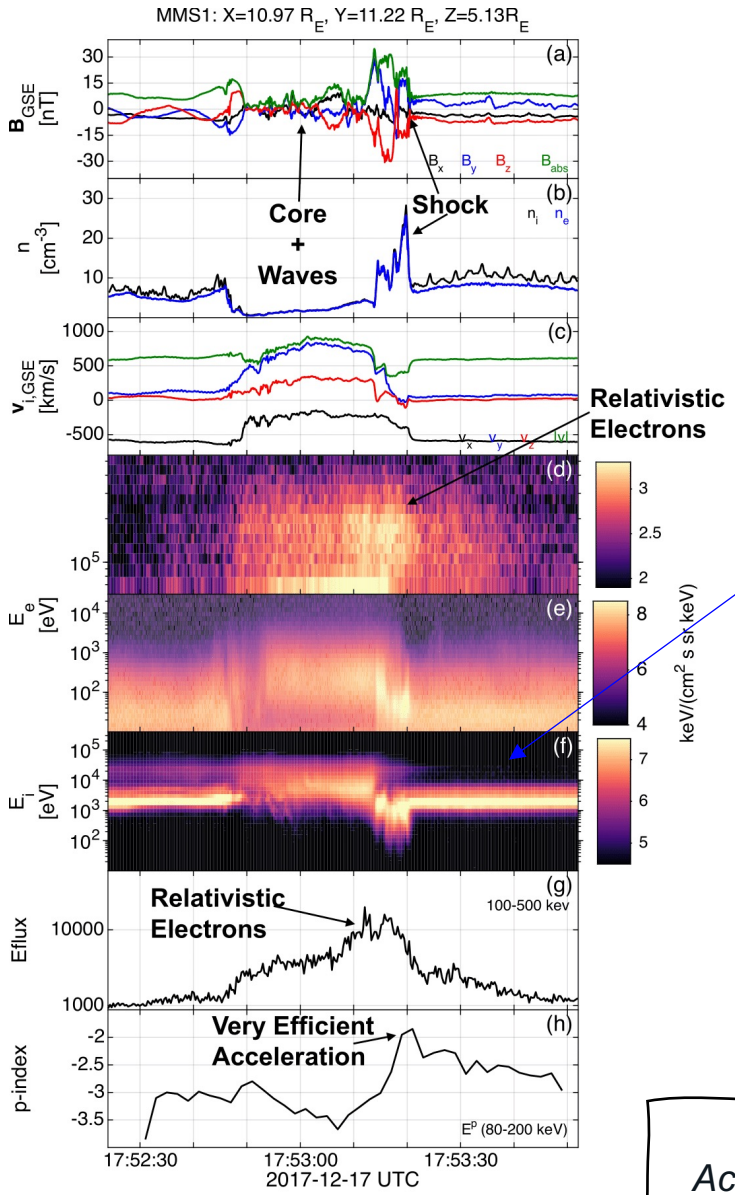
But let's ask one more question

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



Indeed, energy increases even more

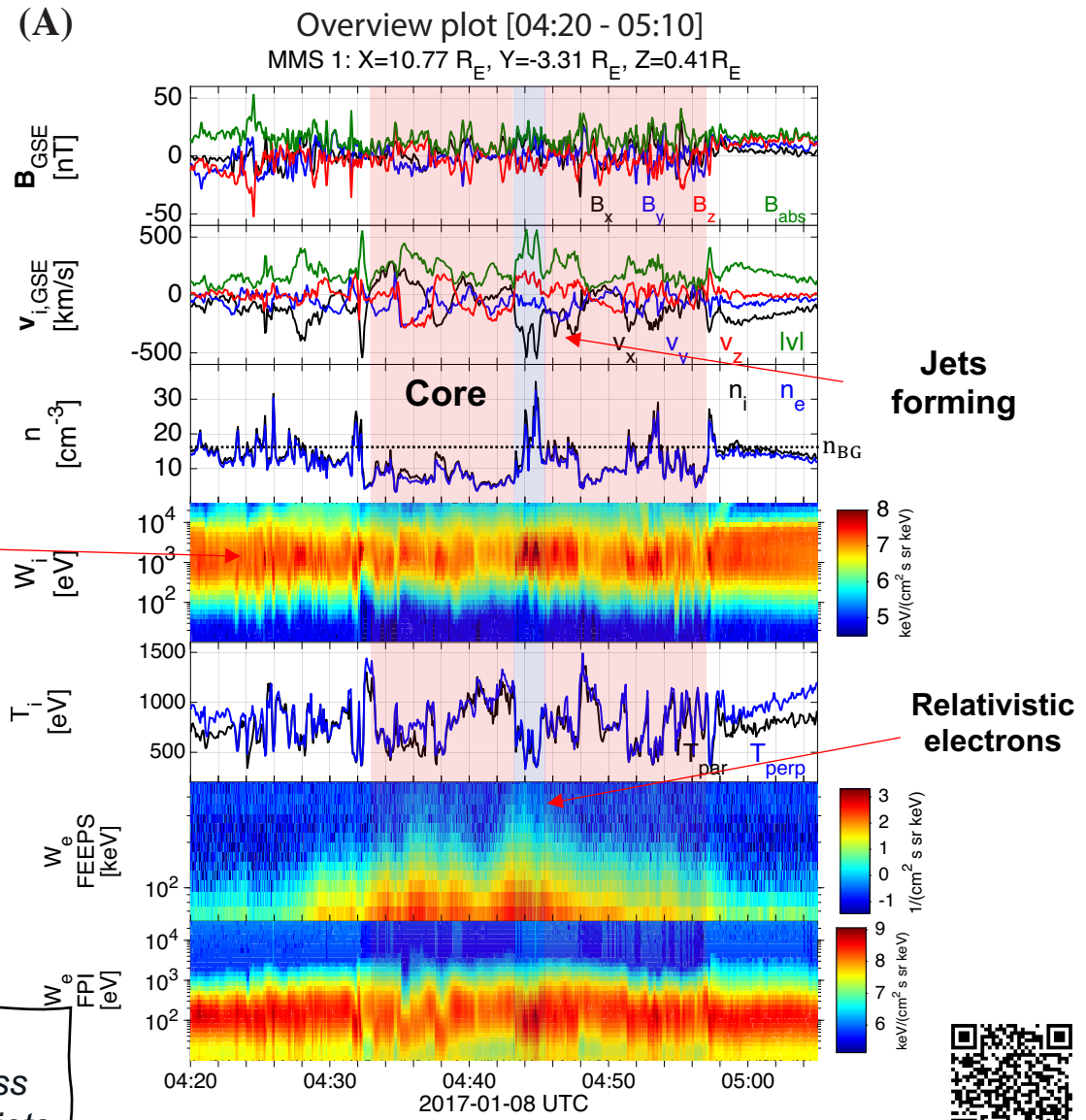
HFAs and FBs are amazing particle accelerators



Raptis et al.2025 NatComm

Solar wind

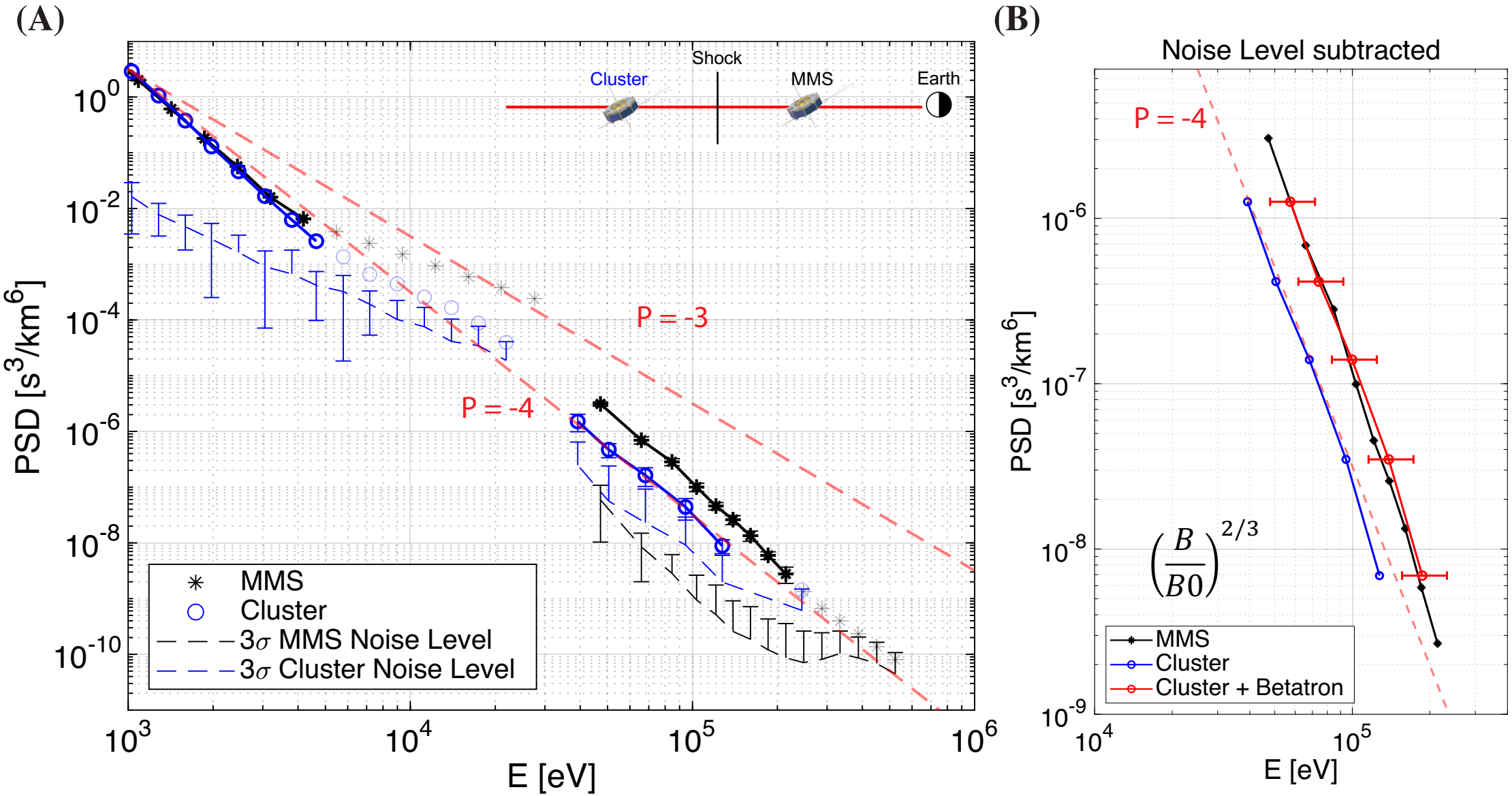
Magnetosheath



Raptis et al.2025 ApJL

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

Betatron Across Shock Cluster and MMS



Raptis et al.2025 ApJL

Transients & Reinforced Shock Acceleration

(A)

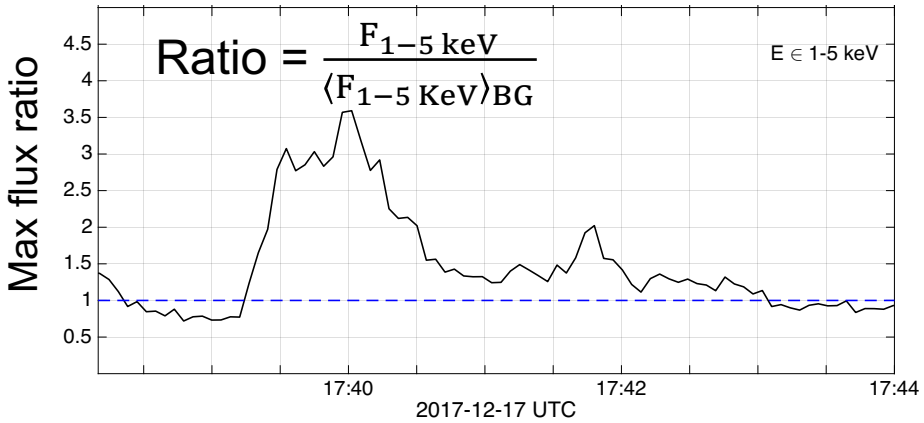
Discontinuity (SW) ARTEMIS

Transient (FS) MMS

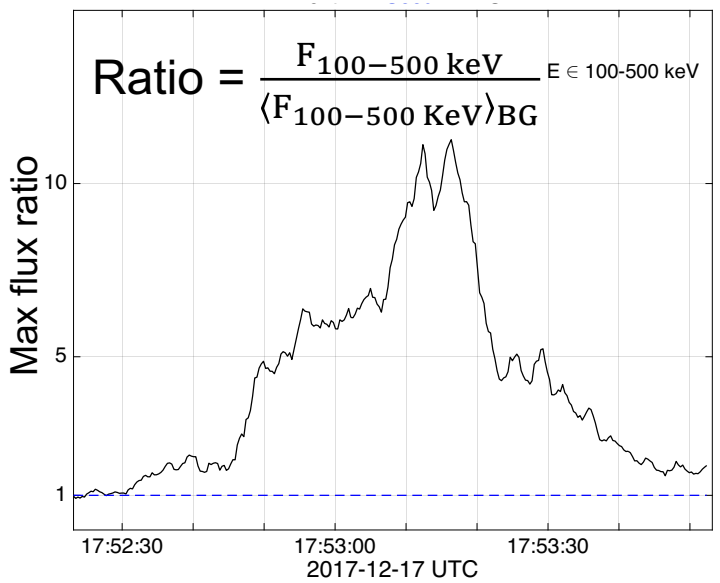
Coronal Hole SW
V> 500 km/s

~1 keV

>500 keV



SW – ARTEMIS / THEMIS



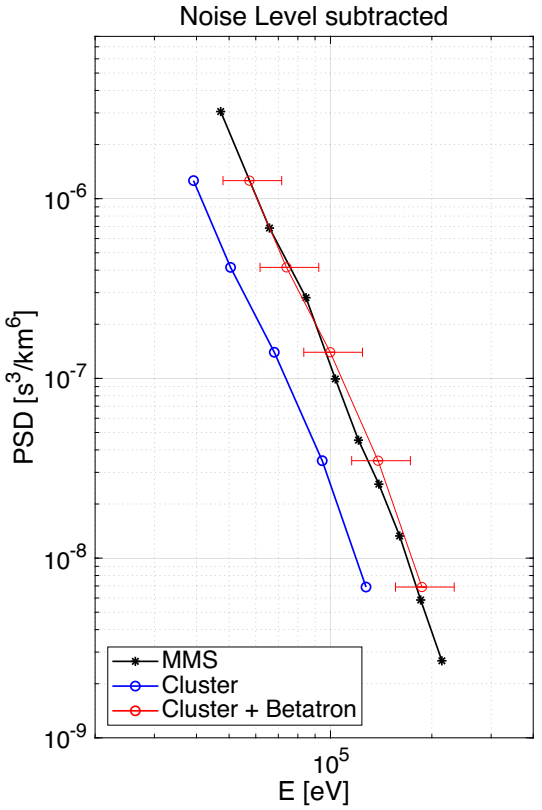
Foreshock - MMS

Fast SW seeding ~keV particles

(B) Transient (FS) Cluster

Transient (MSH) MMS

200 → 300 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*

Concluding Words

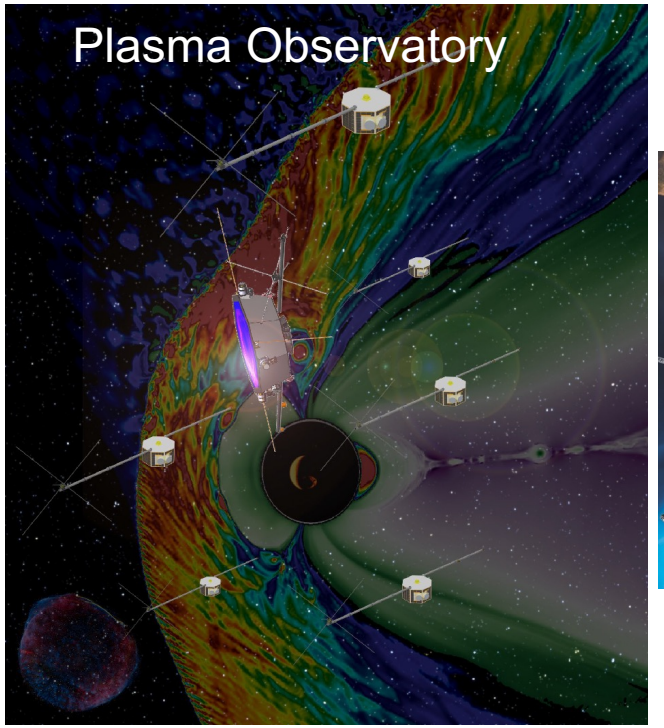
Quasi-Parallel shocks are amazing! Relativistic particles, **non-stationary** shocks on multiple temporal and spatial scales, **high-speed jets**, **foreshock transients** all interacting with each other.

Recent results:

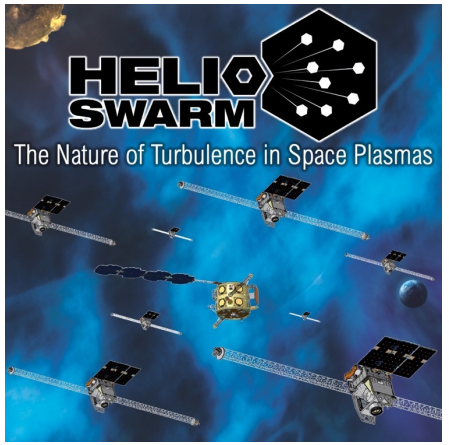
- **Revealed** that the **electron injection threshold at Earth** to be at the **suprathermal range of ~1-5 KeV** as a systematic **feature of the fast solar wind/coronal hole plasma.**

Discussion: *What happens in other planets and systems? What processes cause seeding? Which is the dominant mechanism?*

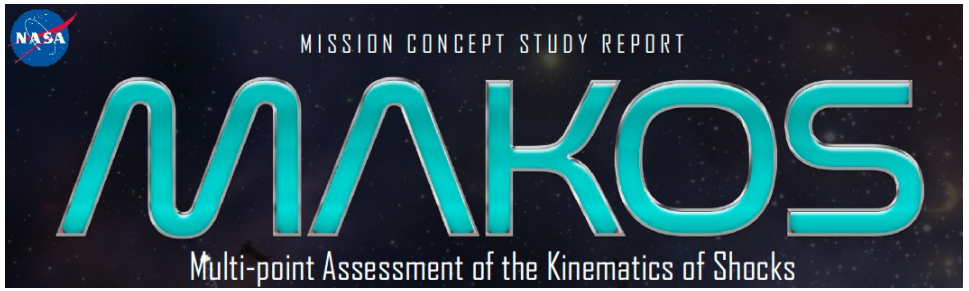
EGU/AGU session: *Collisionless Shocks in Heliospheric and Astrophysical Plasmas and their Effects on Planetary Magnetospheres.*



Retino+ 2021 | Ex. Astro.



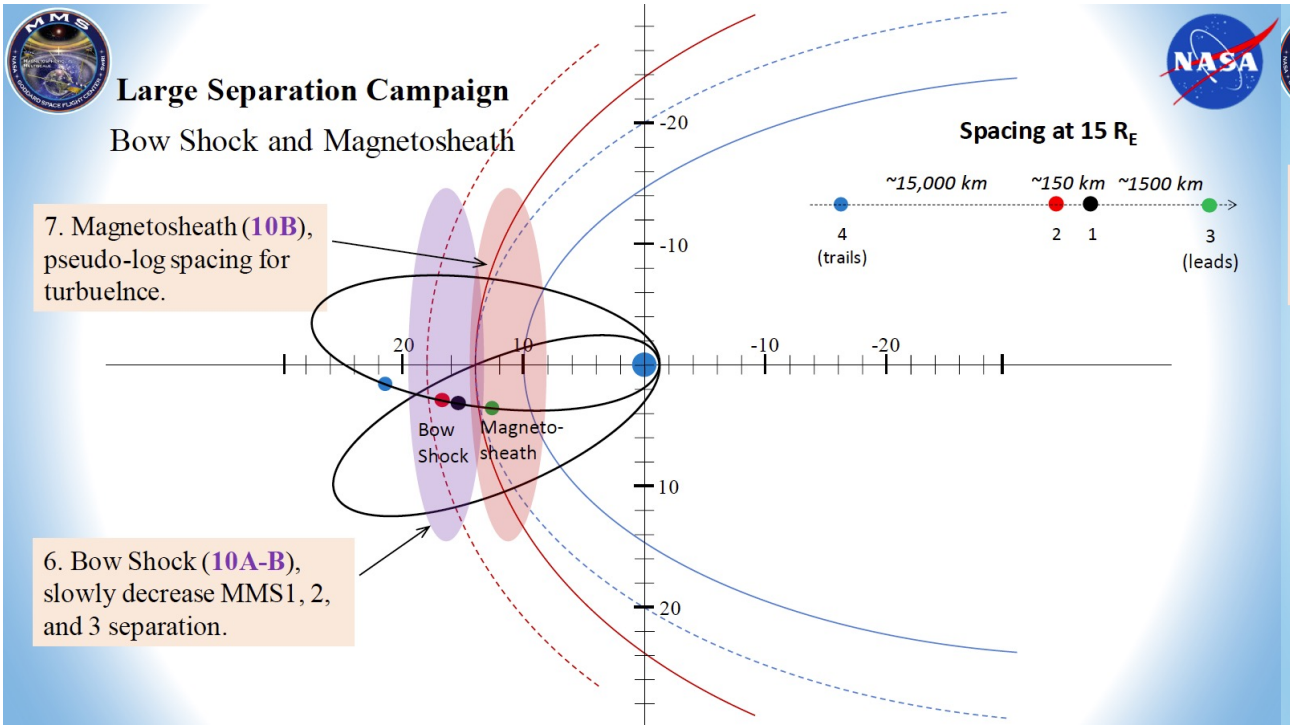
Goodrich+ 2023

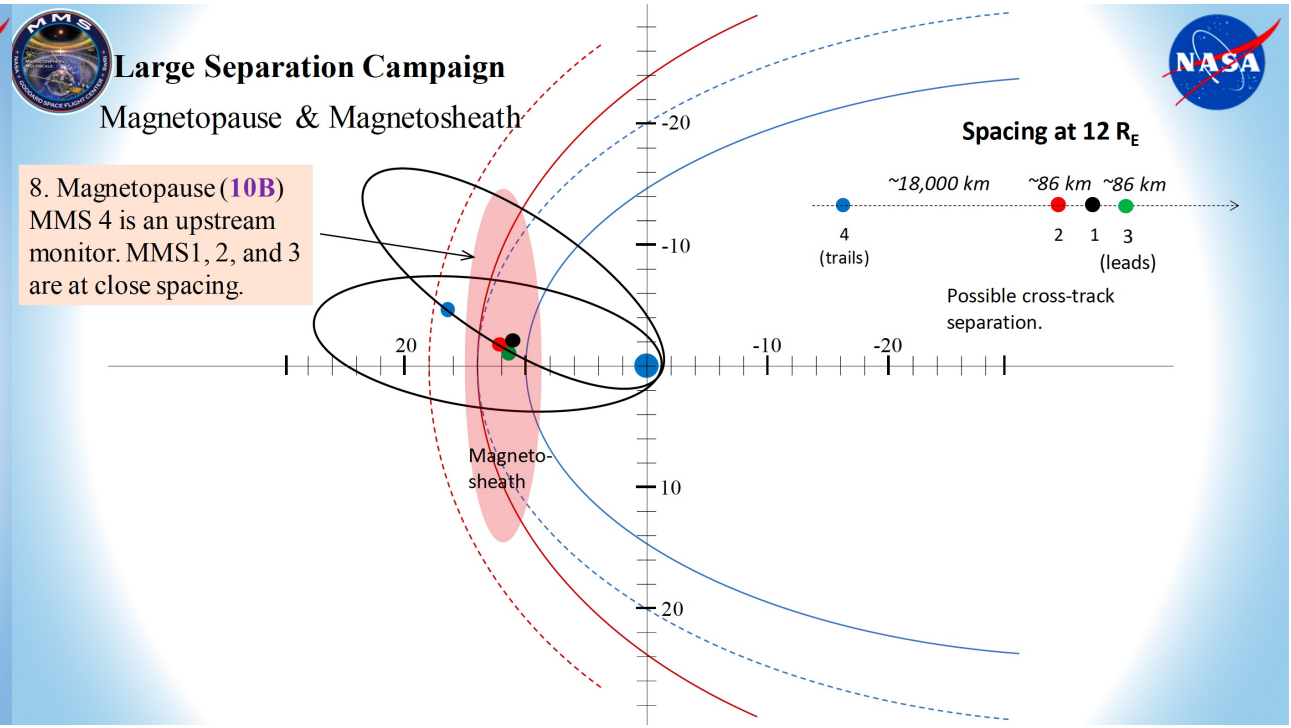


GEM FG: (**MDT**) **M**ultiscale **D**ayside Transients and their Effect on Earth's Magnetosphere (2025 – 2029)
Savvas Raptis, Ivan Vansko, Imogen Gingell, Terry Z. Liu, Ying Zou, Runyi Liu, David Tonoian

Extras

Timeliness (Ongoing MMS Campaigns)





String-of-pearls campaigns with **variable separation (cross-scale)**:

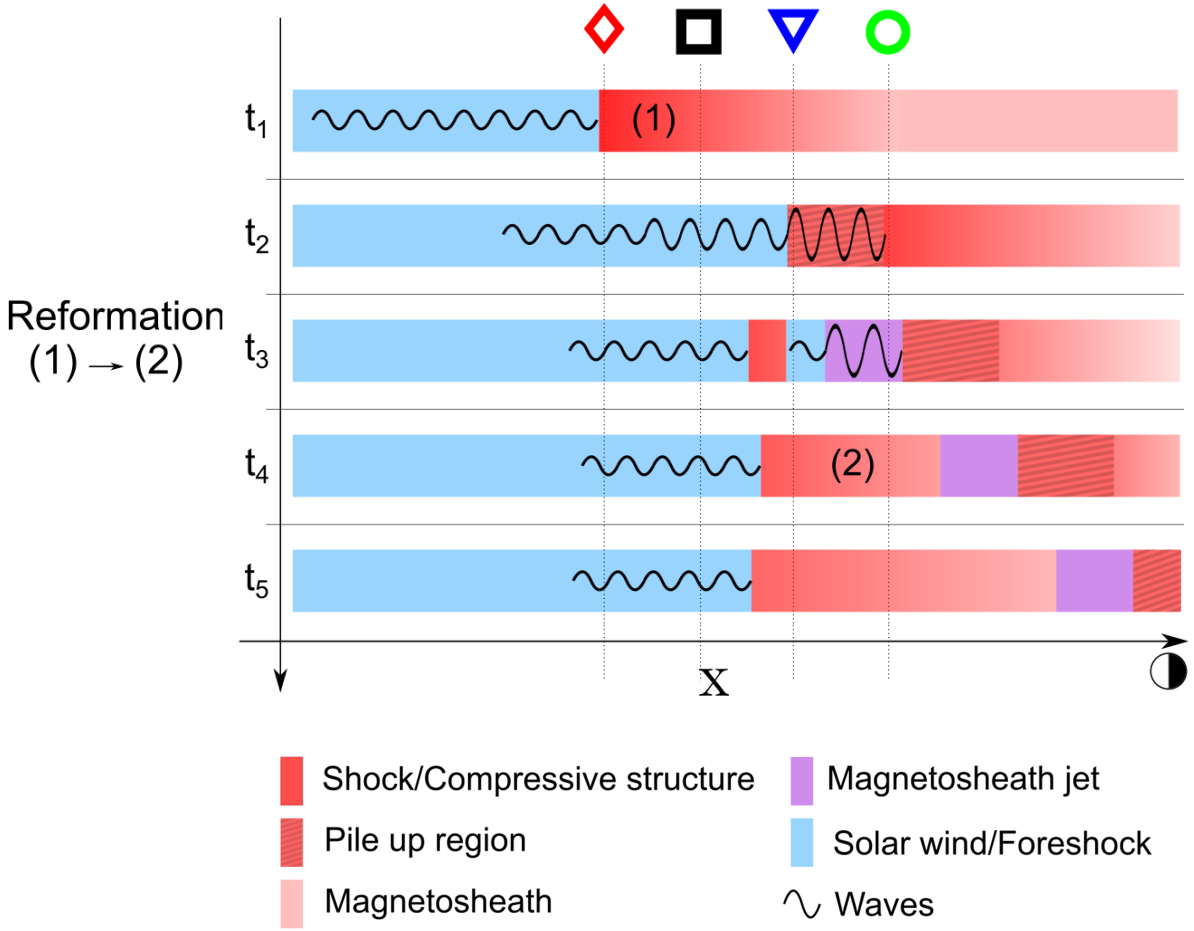
(a) 1000s kms showing effects of dayside transients on the magnetosphere

(b) ~1-2 satellites upstream and ~1-2 downstream to evaluate the transmission

(c) Magnetopause response (1000s km separation) to upstream SW/foreshock data (several Re)

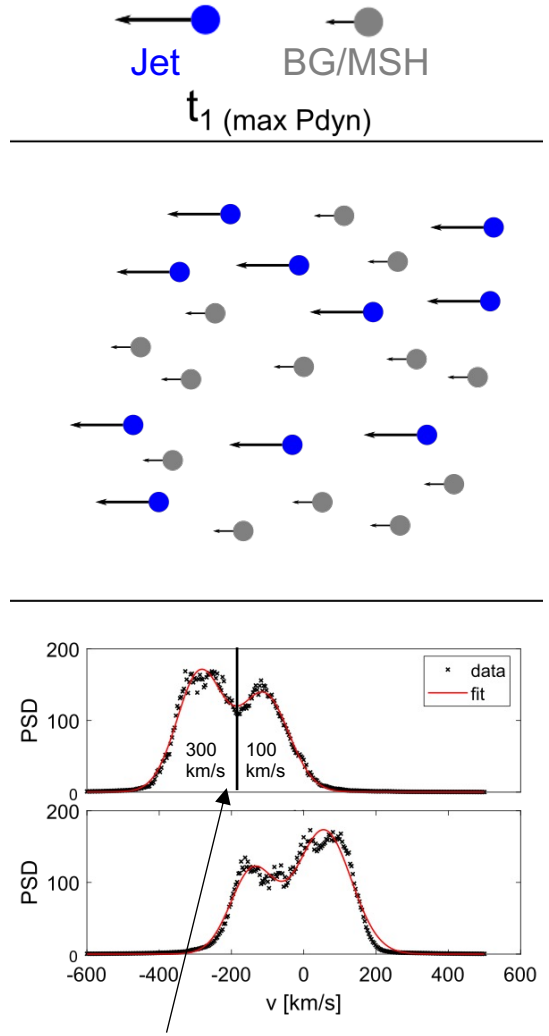
Jets & Kinetic Plasma Processes

Jets forming from shock's fundamental non-stationarity process



Raptis S., et al. 2022a | Nat. Commun.

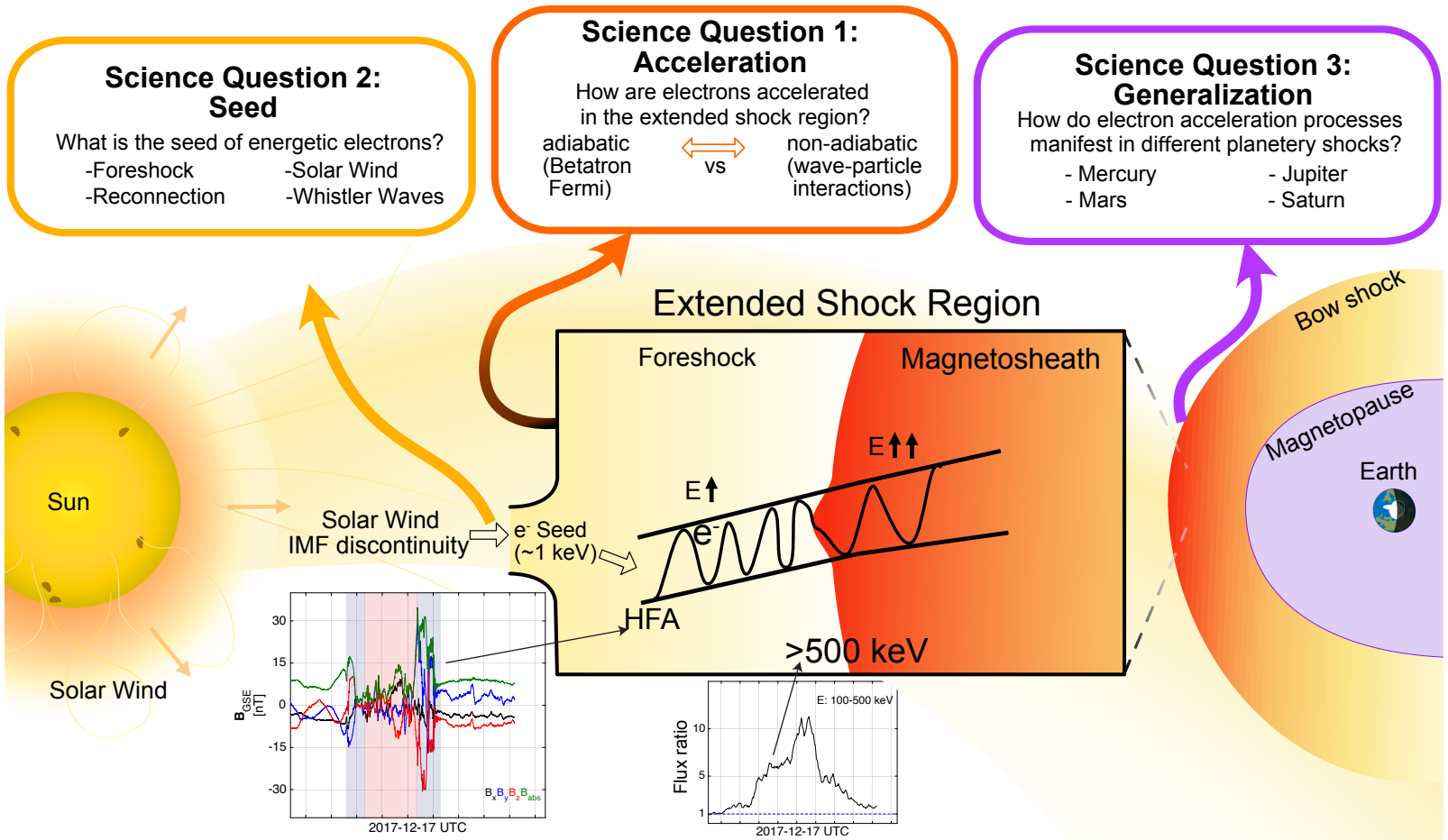
Jets exhibiting 2+ populations = partial moments needed



This velocity describes neither populations

Raptis S, et al,. 2022b | GRL

Some potential future work



Solar people: What is causing the seed?

- Solar Wind reconnection ?
- Wave-particle interactions?
- Strahl population?

Planetery and astro people: Can we generalize ?

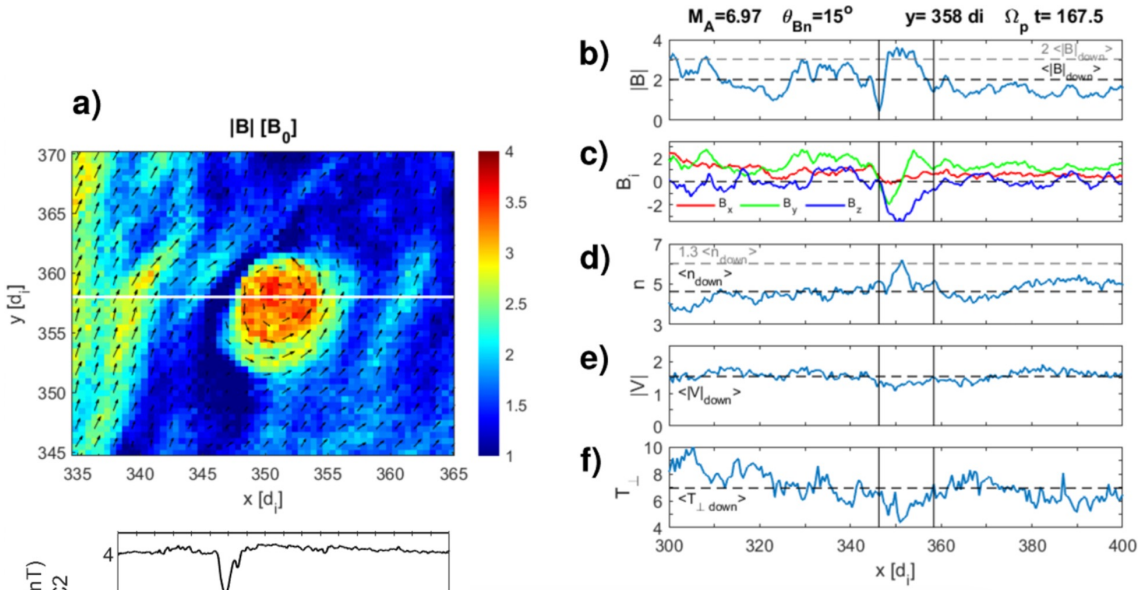
- What is the system size and local conditions?
- Do we observe energetic electrons upstream?
- Do we have datasets/examples available?

Method and data people:

- How can we establish an automatic finder?
- How to associate DCs with transients?
- How to quantify each acceleration process

Transmission of Foreshock Transients

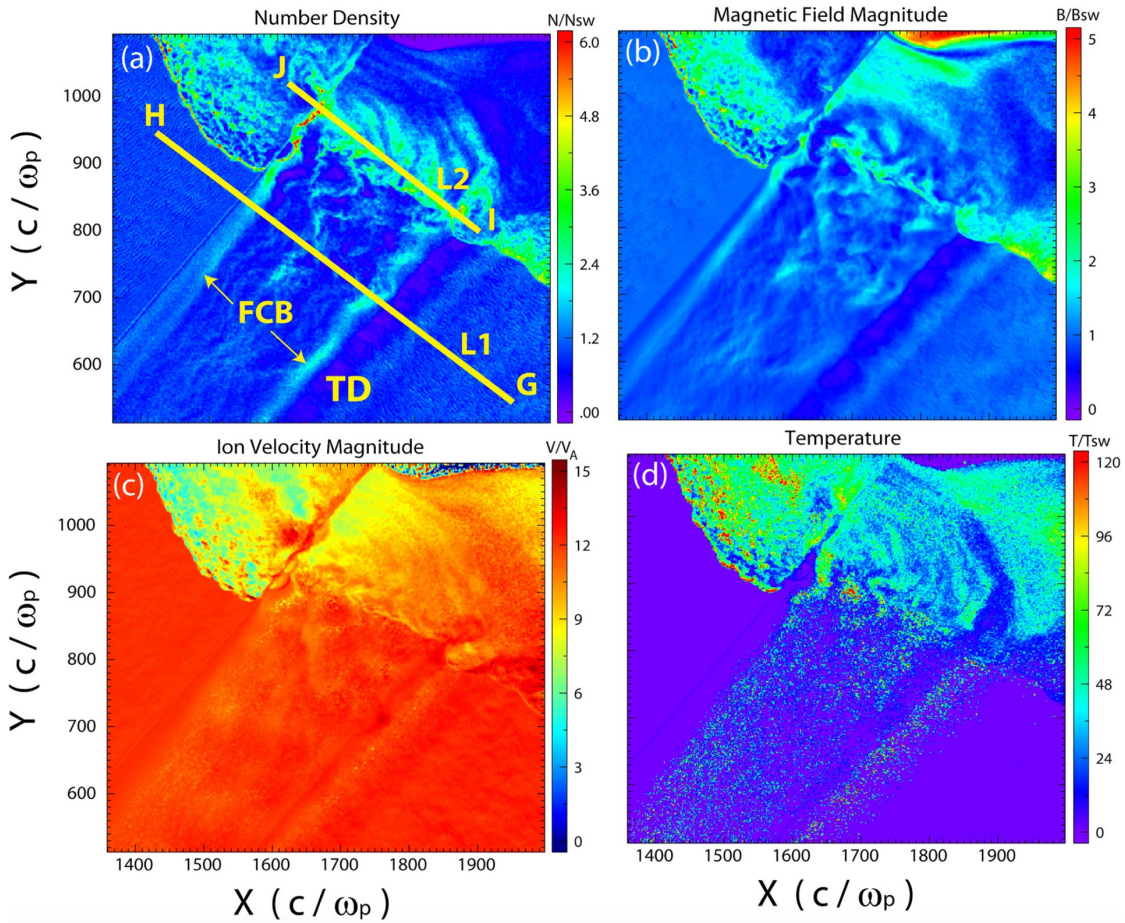
ULF waves are transmitted and so are the non-linear associated phenomena (Shocklets, SLAMS, etc.)



Karlsson T., et al. 2022 | ANGEO

Preisser L., et al. 2020 | ApJL

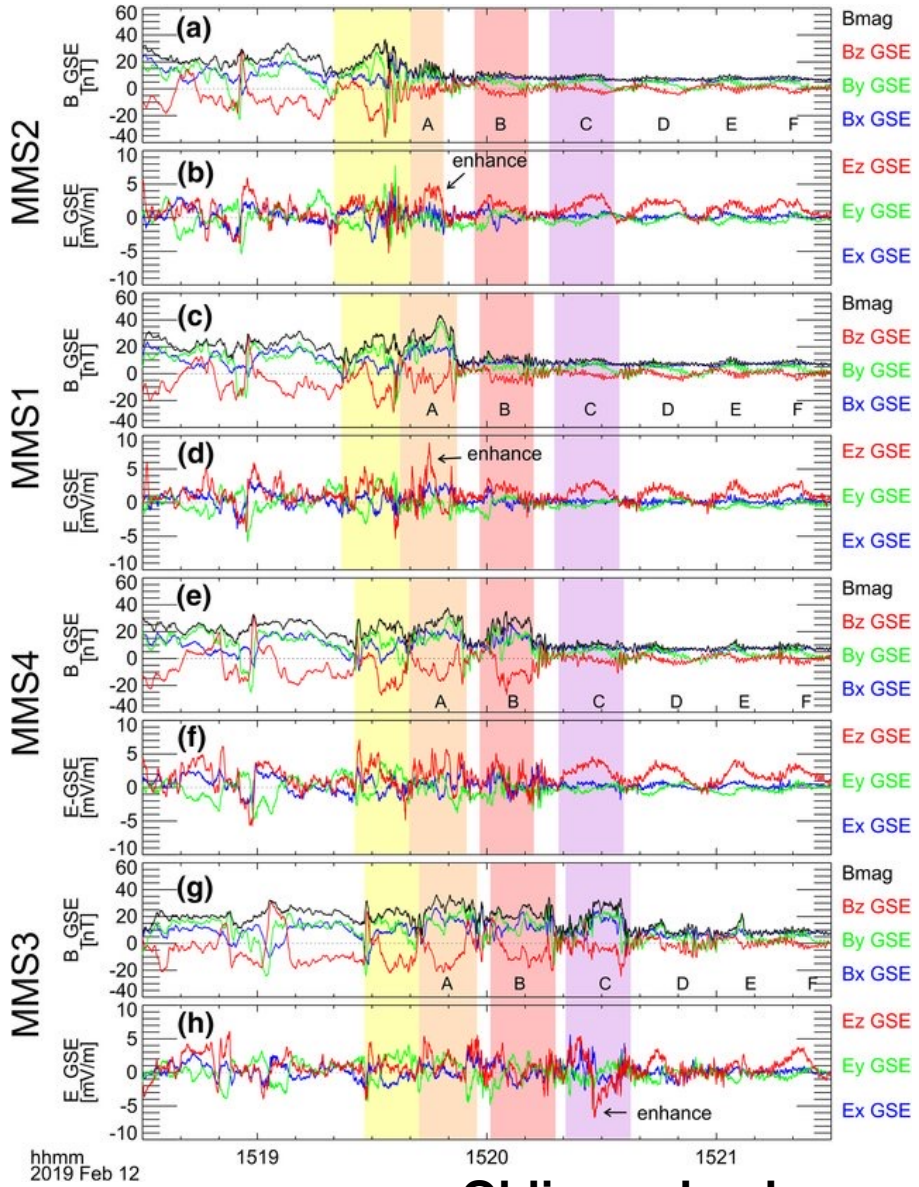
Transmission of FCB, FBs, HFAs, etc. has been shown in simulation and observations.



Sibeck D., et al. 2021 | JGR

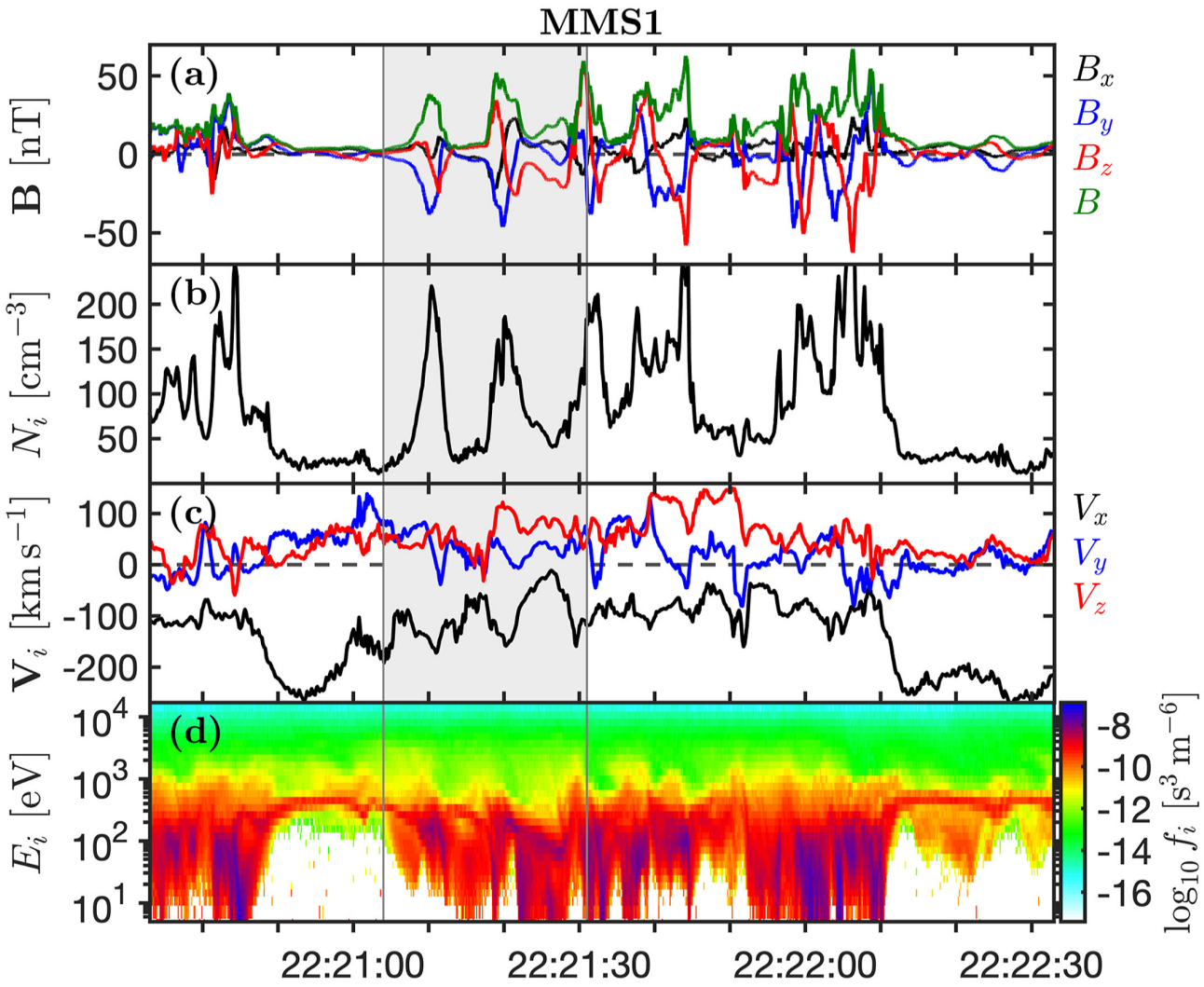
Turc L., et al. 2023 | Nat. Physics **Raptis S.**, et al. 2022a | Nat. Commun **Kajdic P.**, et al. 2022 | JGR **Wang C-P.**, et al. 2023 | Frontiers **Eastwood J.P.**, et al. 2008 | JGR **Zhou Y.**, et al. 2023 | GRL

Shock Reformation – MMS Results



Liu et al. (2021)

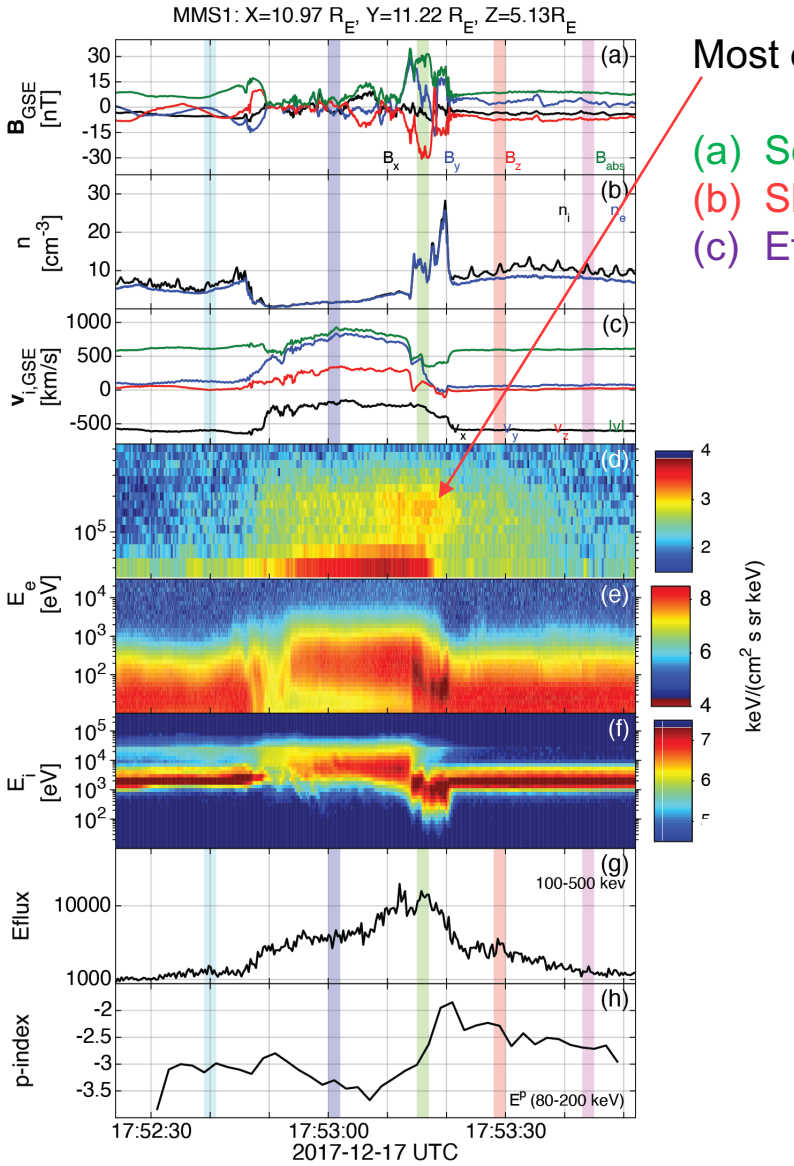
Oblique shock



Qpar shock

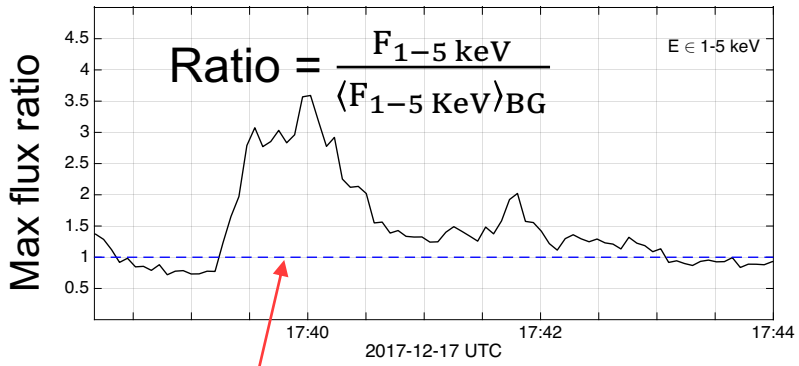
Johlander et al. (2022)

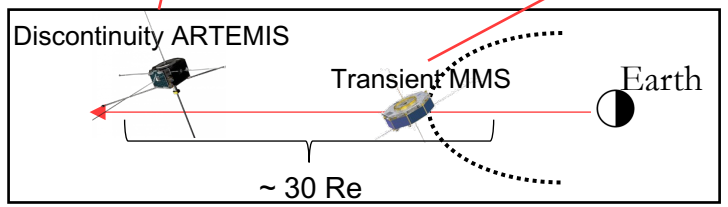
Reinforced Shock Acceleration of Relativistic Electrons

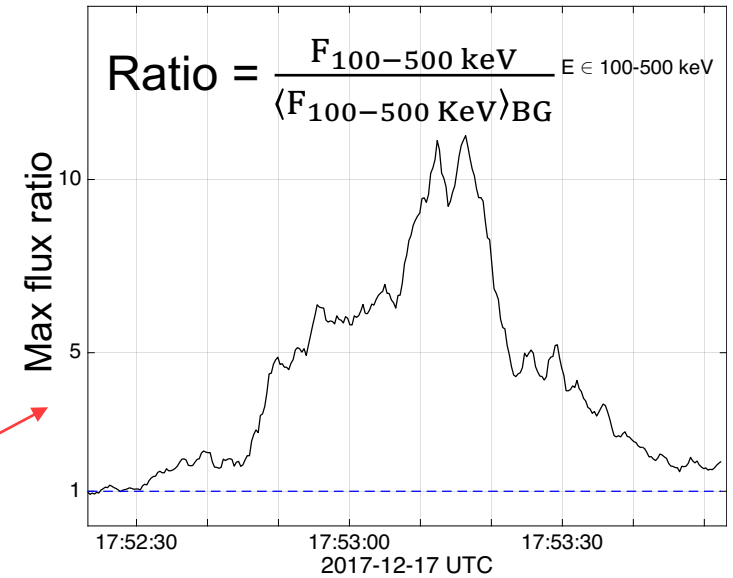


Most energetic electrons observed **(500+keV)** at foreshock observed by MMS obtained by:

(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)



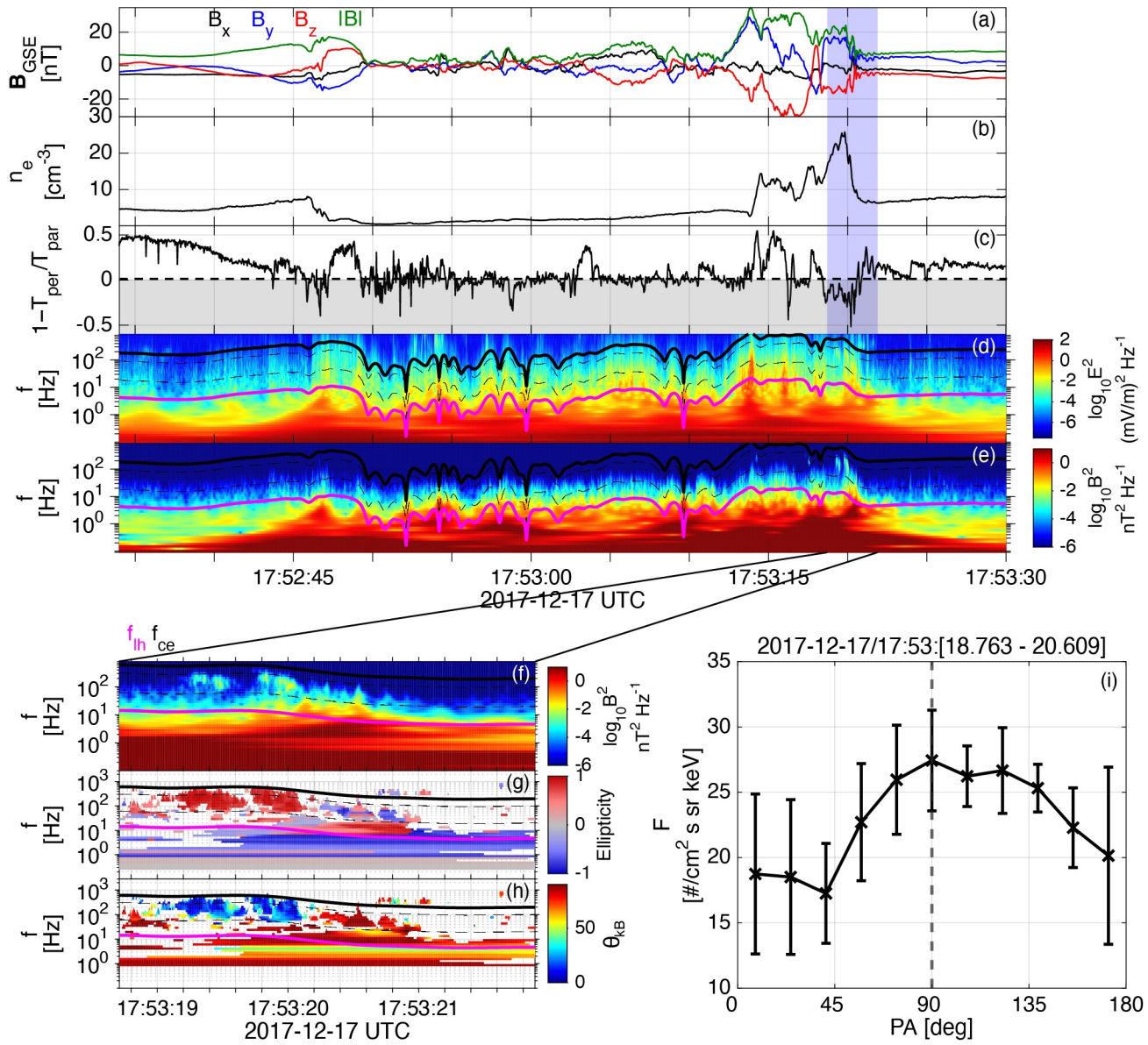




Key-point:
Seed + Foreshock's Shock + Waves + Efficiency factors = **~MeV electrons before** reaching the bow shock.

Raptis+ 2025 Nat.Comm

Wave analysis of event



Acceleration:

- Shock Acceleration
- Betatron → Temperature anisotropy
- High amplitude electron whistler waves (Chorus) resonance

Scattering & Trapping:

- LF whistler waves (Shock)
- Wavefield of HFA's core
- Geometry of HFA. i.e., "Magnetic bottle" between edges of HFA and the Earth's bow shock

Particularly efficient acceleration:

$$\frac{U_E}{U_I} = \frac{\text{Energy density suprathermal electrons}}{\text{Energy density Solar Wind}} \sim 5\ \%$$

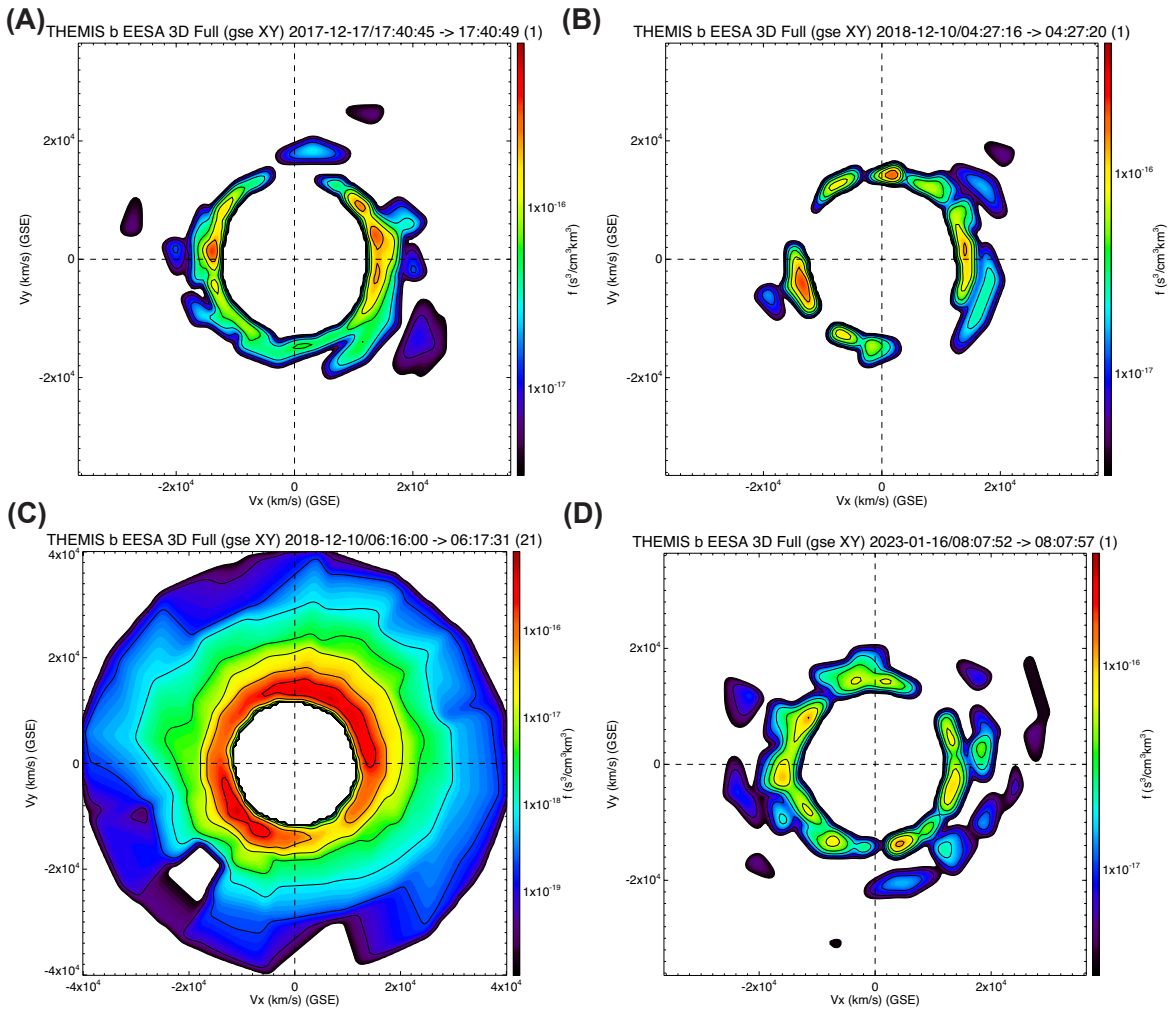
Raptis+ 2025 Nat.Comm

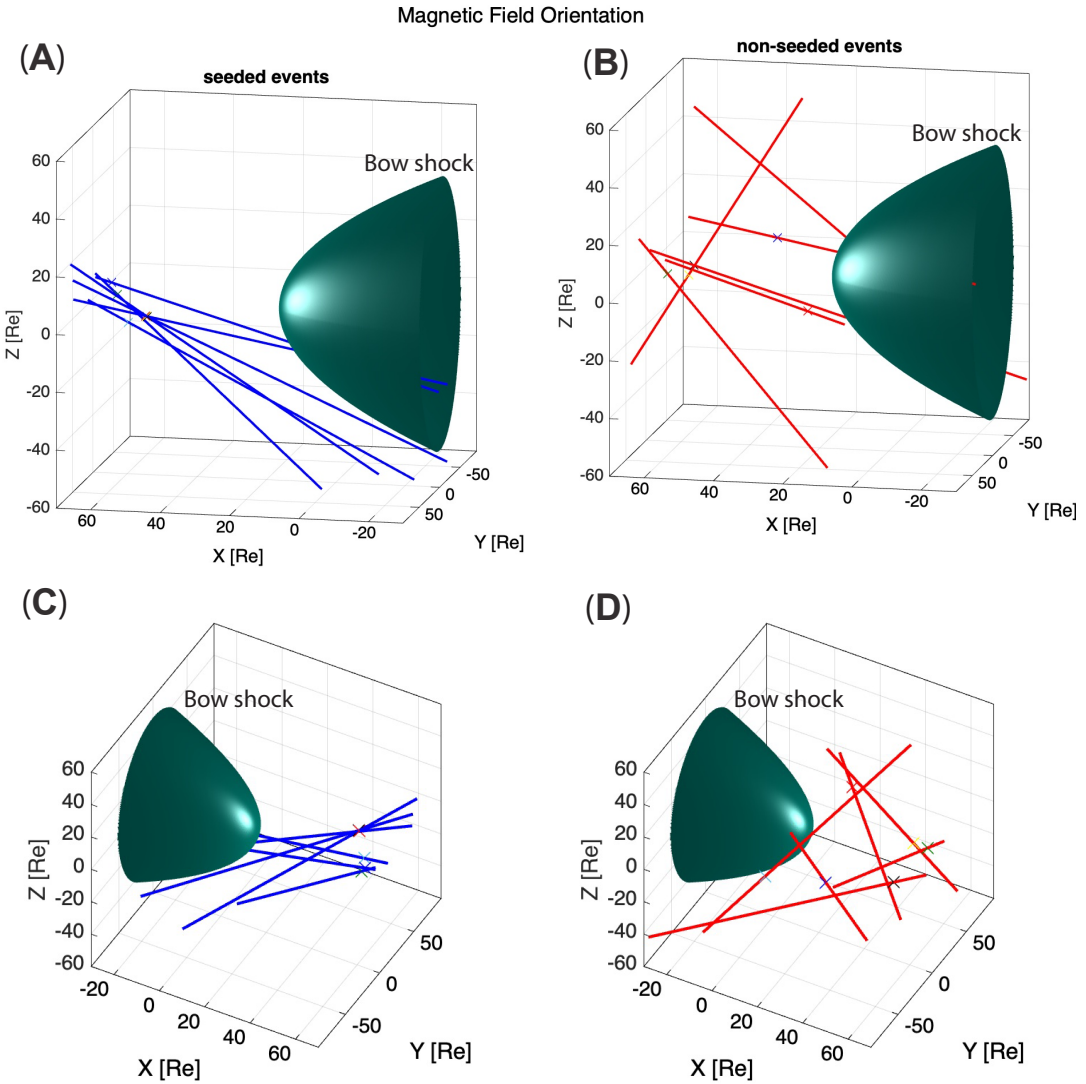
See Artemyev+, Xiaofei+, Vargas + Tonoian+ (2022 – 2024)

Is seed from the foreshock? – Maybe partially

(A), (B) → Seeded events – partial mode
(C) → Seeded event full mode
(D) → Non-seeded event – partial mode

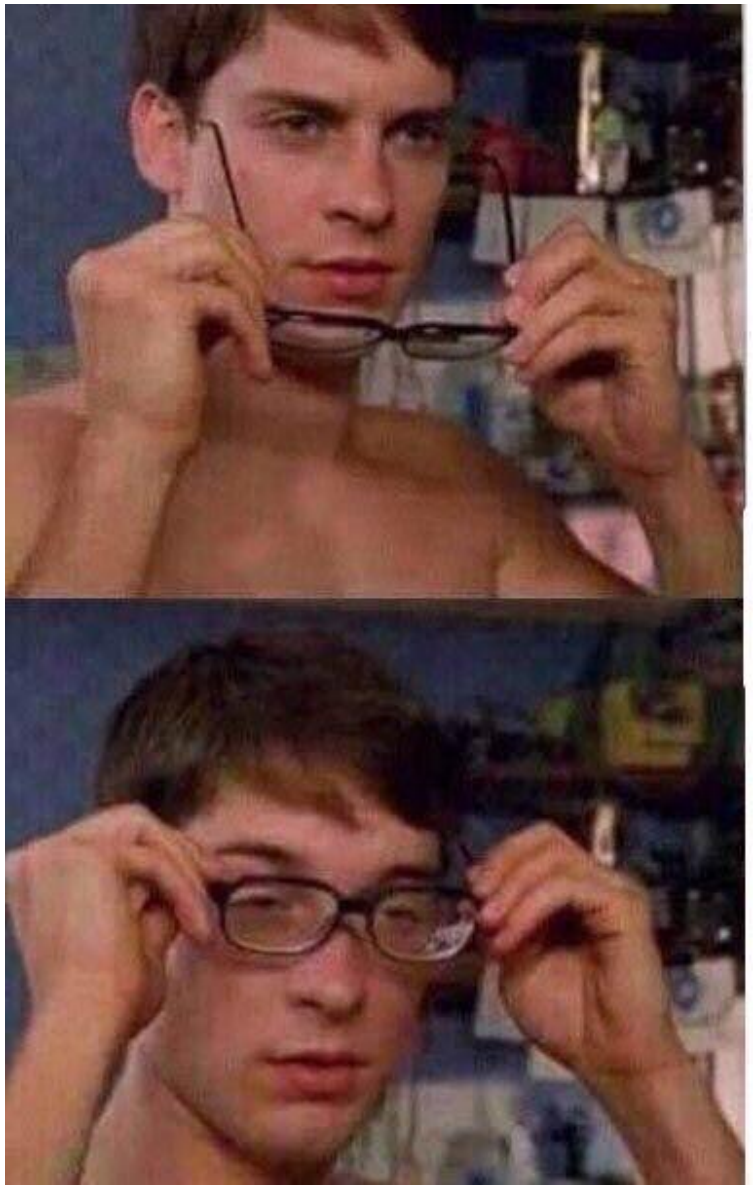
3/6 seeded and 2/6 non seeded connected to foreshock

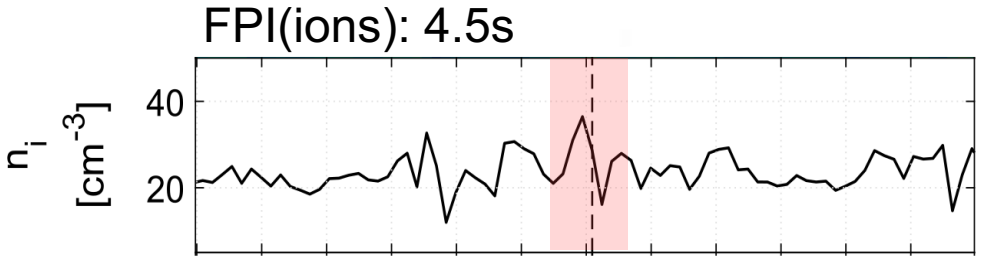


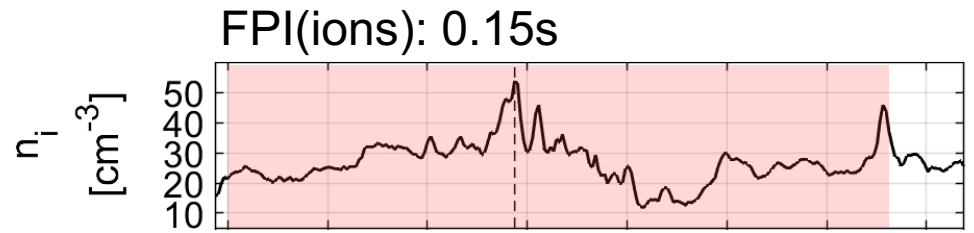


Raptis+ 2025 Nat.Comm

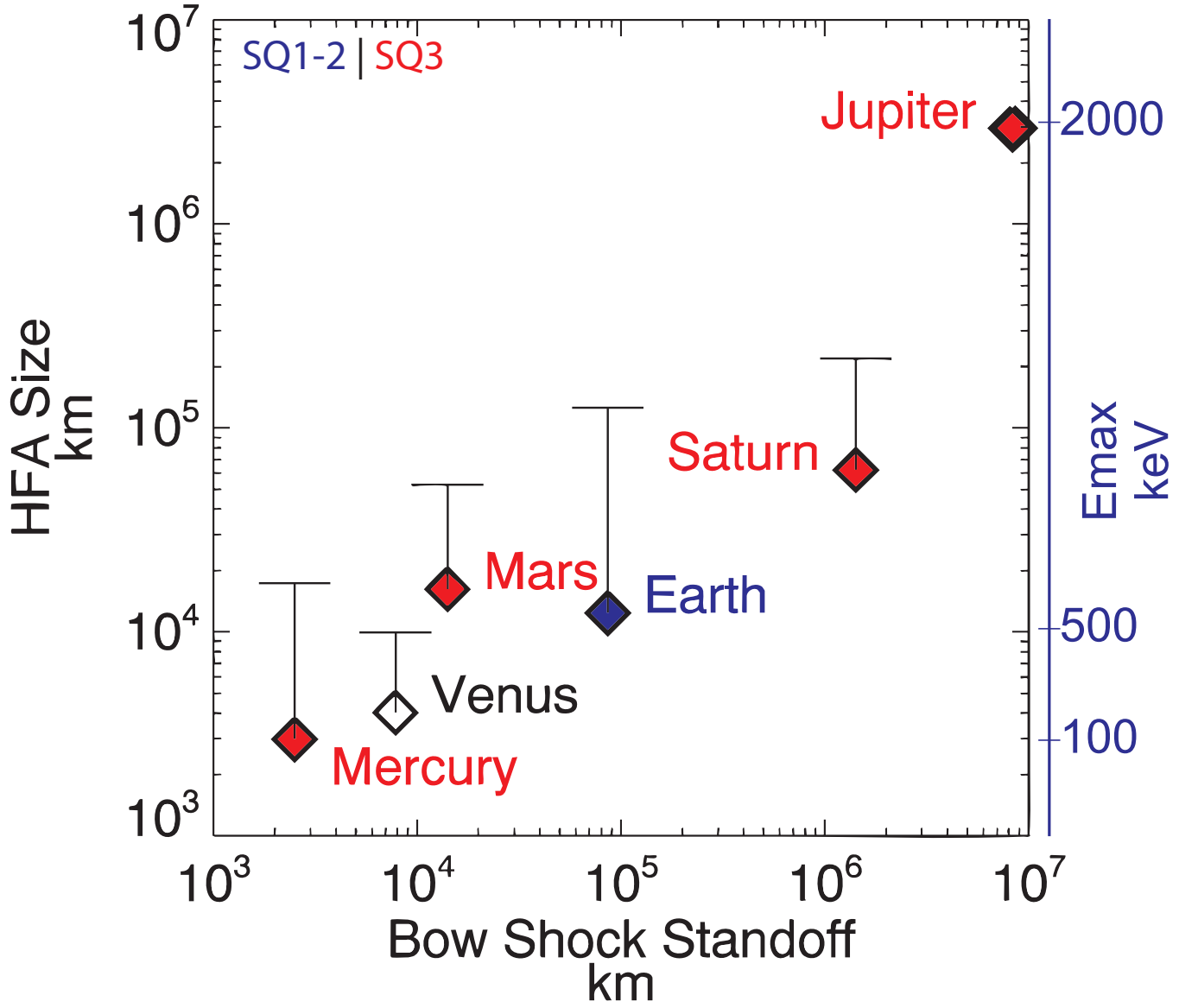
Why MMS burst data?





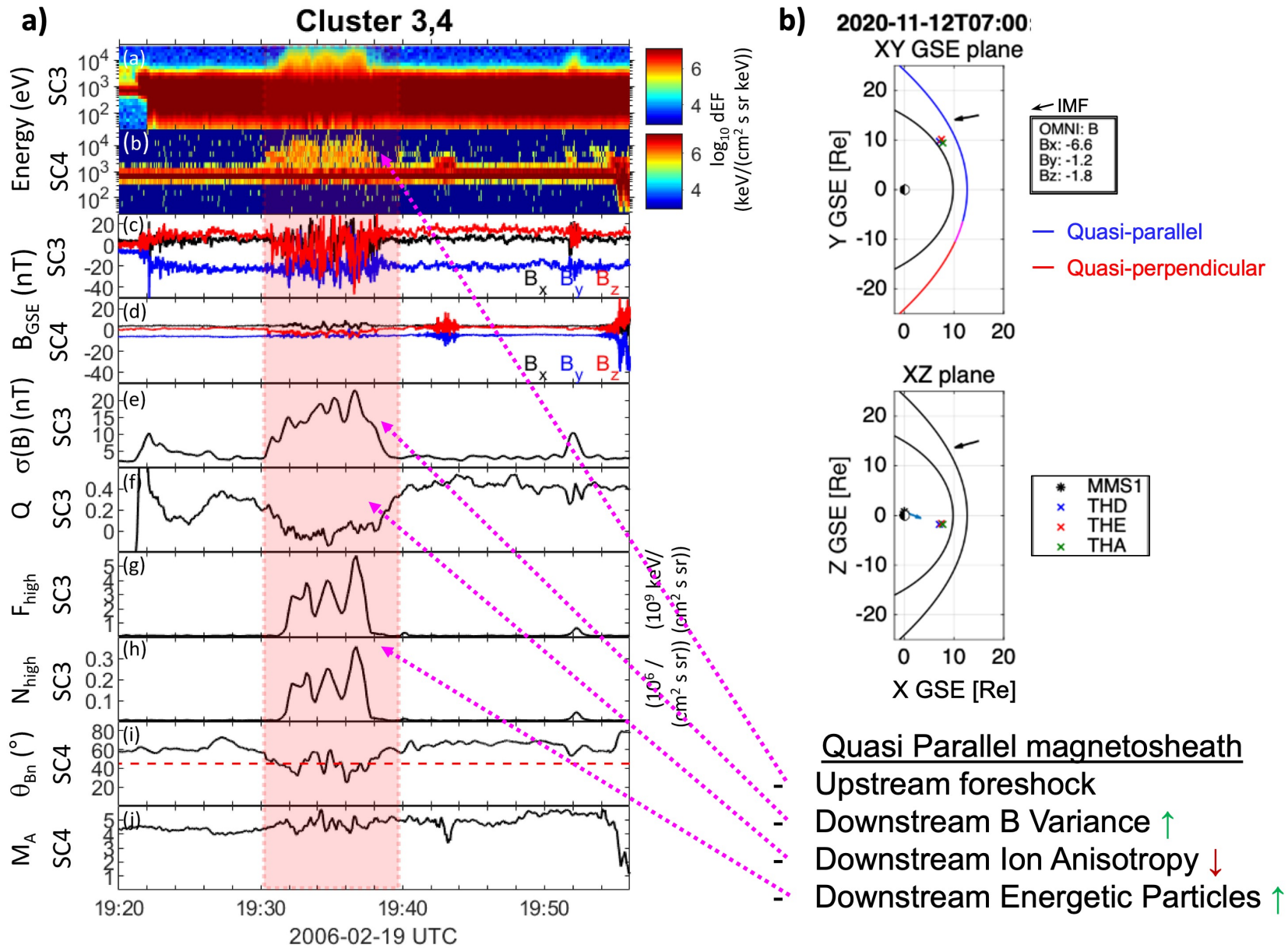


Foreshock transients at other planets & Electrons



Adapted form Valek et al. (2017) | JGR

In-situ classification of the Quasi-parallel magnetosheath



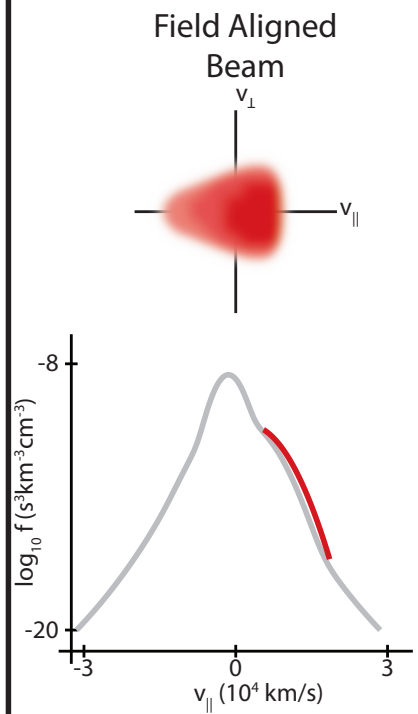
Quasi Parallel magnetosheath

- Upstream foreshock
- Downstream B Variance ↑
- Downstream Ion Anisotropy ↓
- Downstream Energetic Particles ↑

Karlsson+ 2022

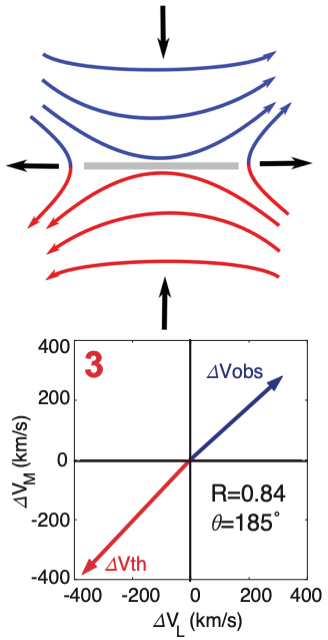
Some Ideas about the Seed Population

(A) Strahl



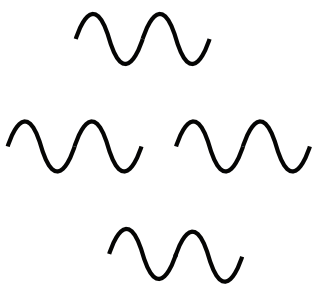
|| PAD
VDF Fit

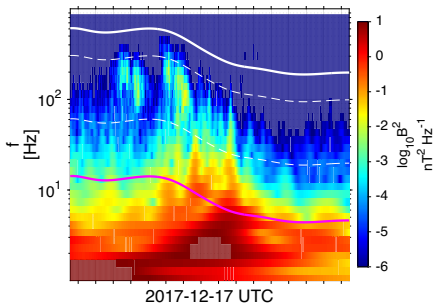
(B) Reconnection



B Orientation
Wallen Test
D-Shaped VDF

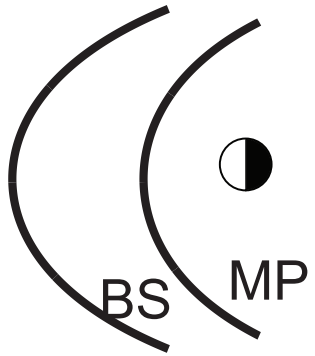
(C) Waves

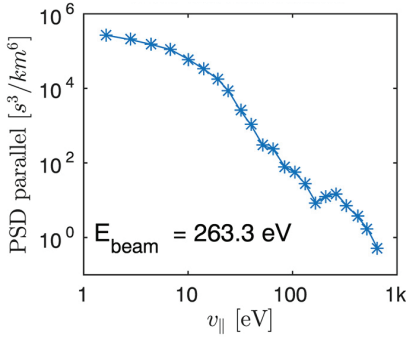




B Spectra
f ~ 0.1-1 f_{ce}

(D) Foreshock

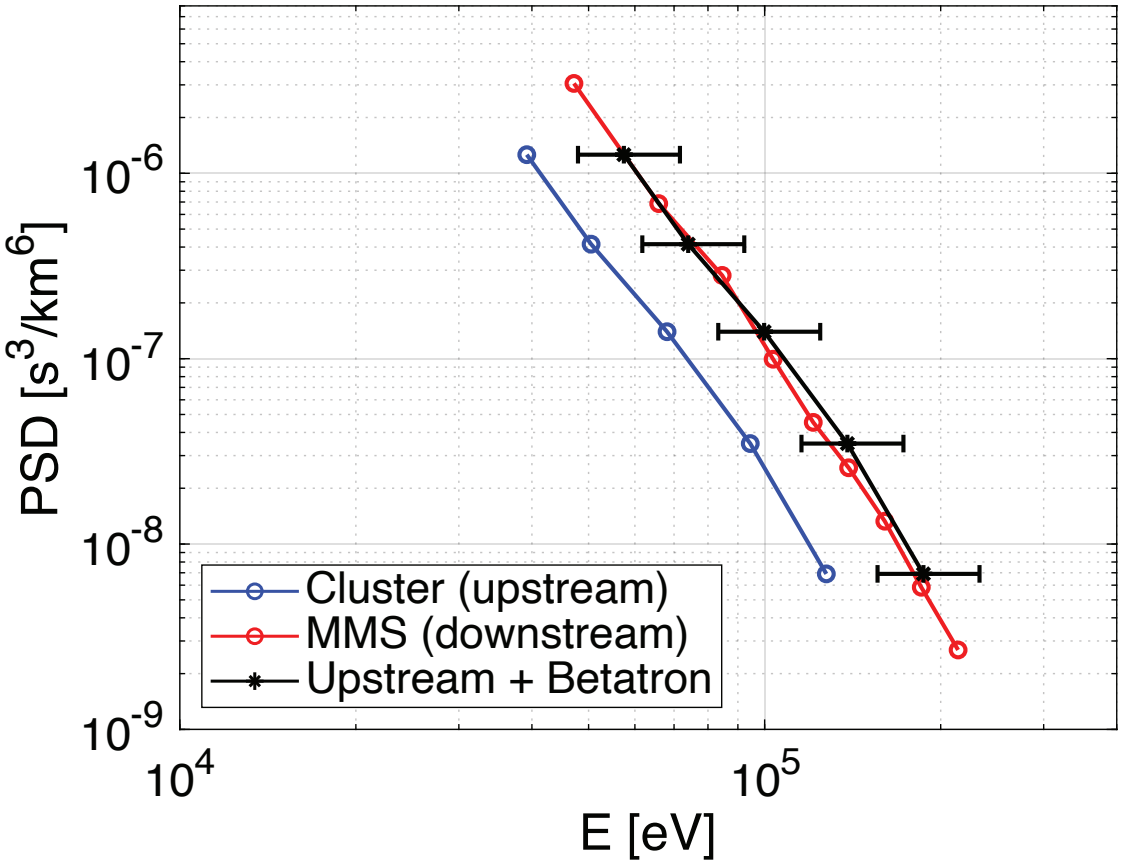




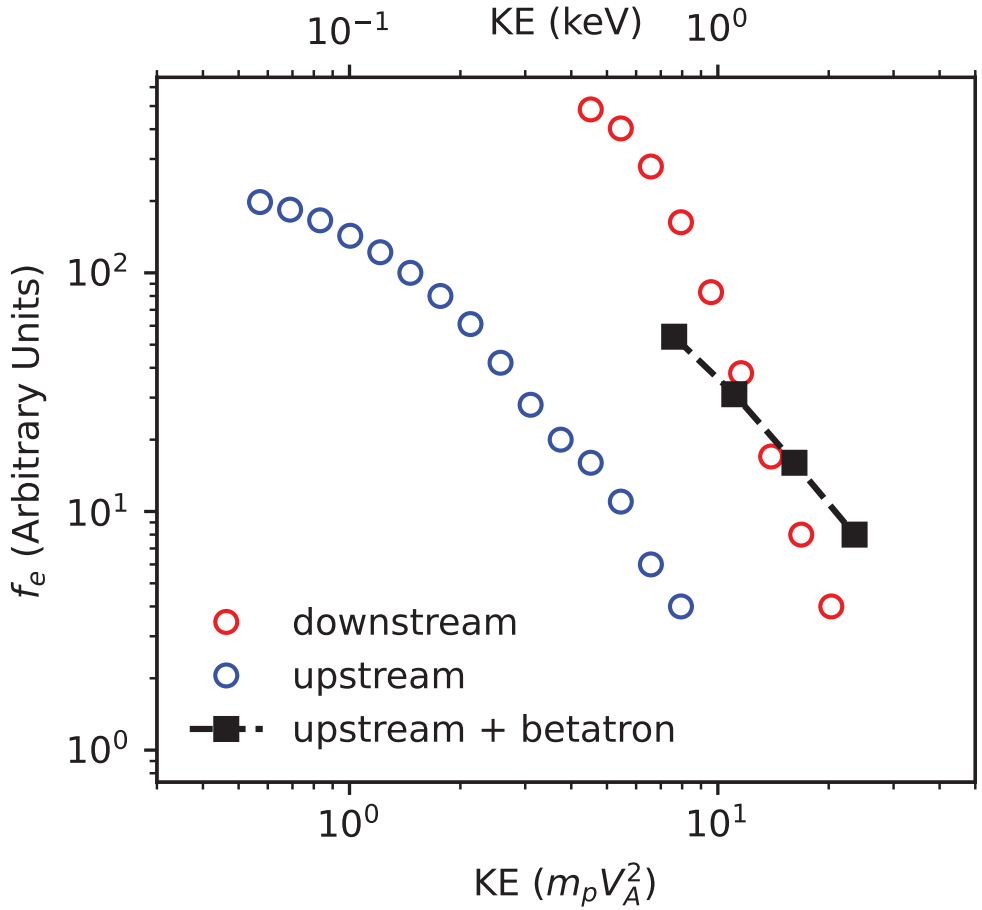
Magnetic Connectivity
Sunward || VDFs

Preliminary Comparison (Data vs Simulations)

(A) *In-situ* Observations



(B) Hybrid Simulations

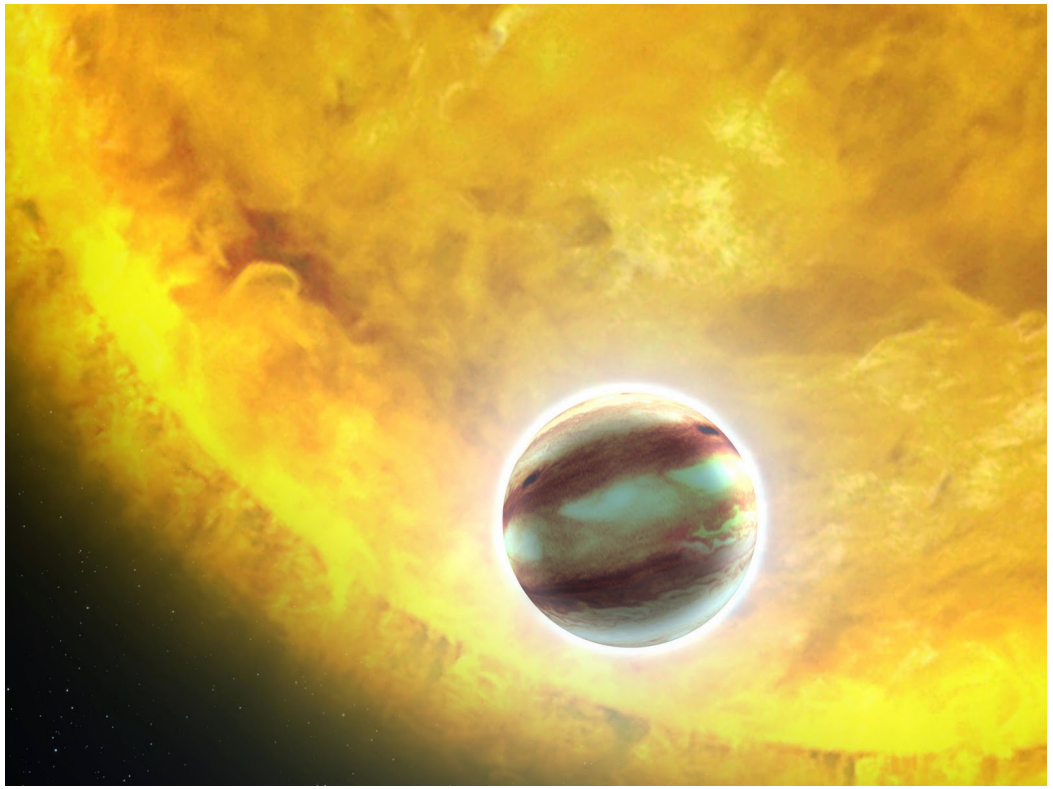


Electron Acceleration in astrophysics

Taking an **exoplanet, ultra-hot Jupiter**, assuming shock and foreshock transient exist (big assumption):

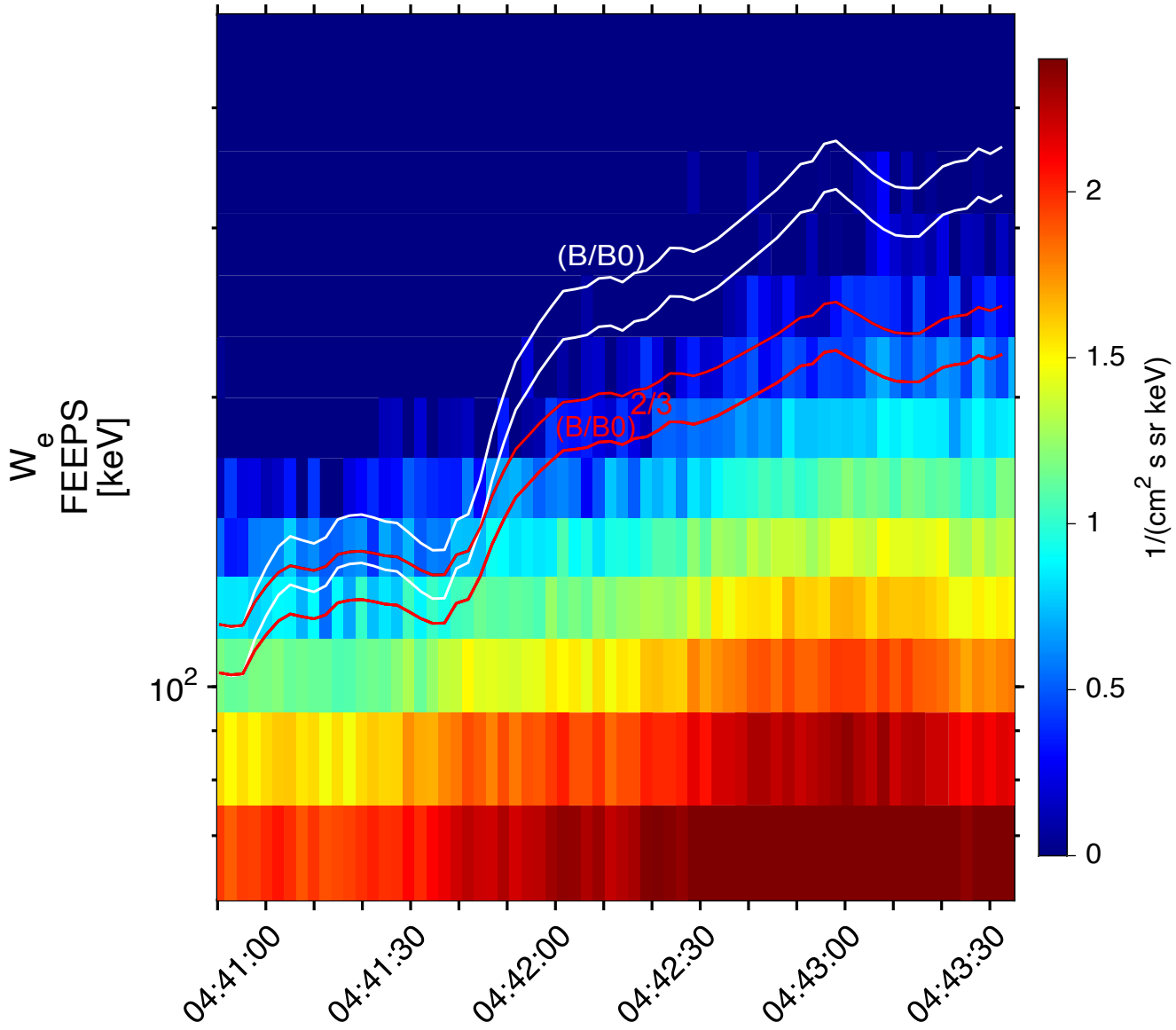
One can estimate the magnetic field of the stellar wind near their orbit to be $\mathrm{B} \sim 0.01 - 1\mathrm{G} \sim 10^{3-5}\,\mathrm{nT}$

James webb showing bow shock waves from newborn stars moving with ~100 km/s in the interstellar medium

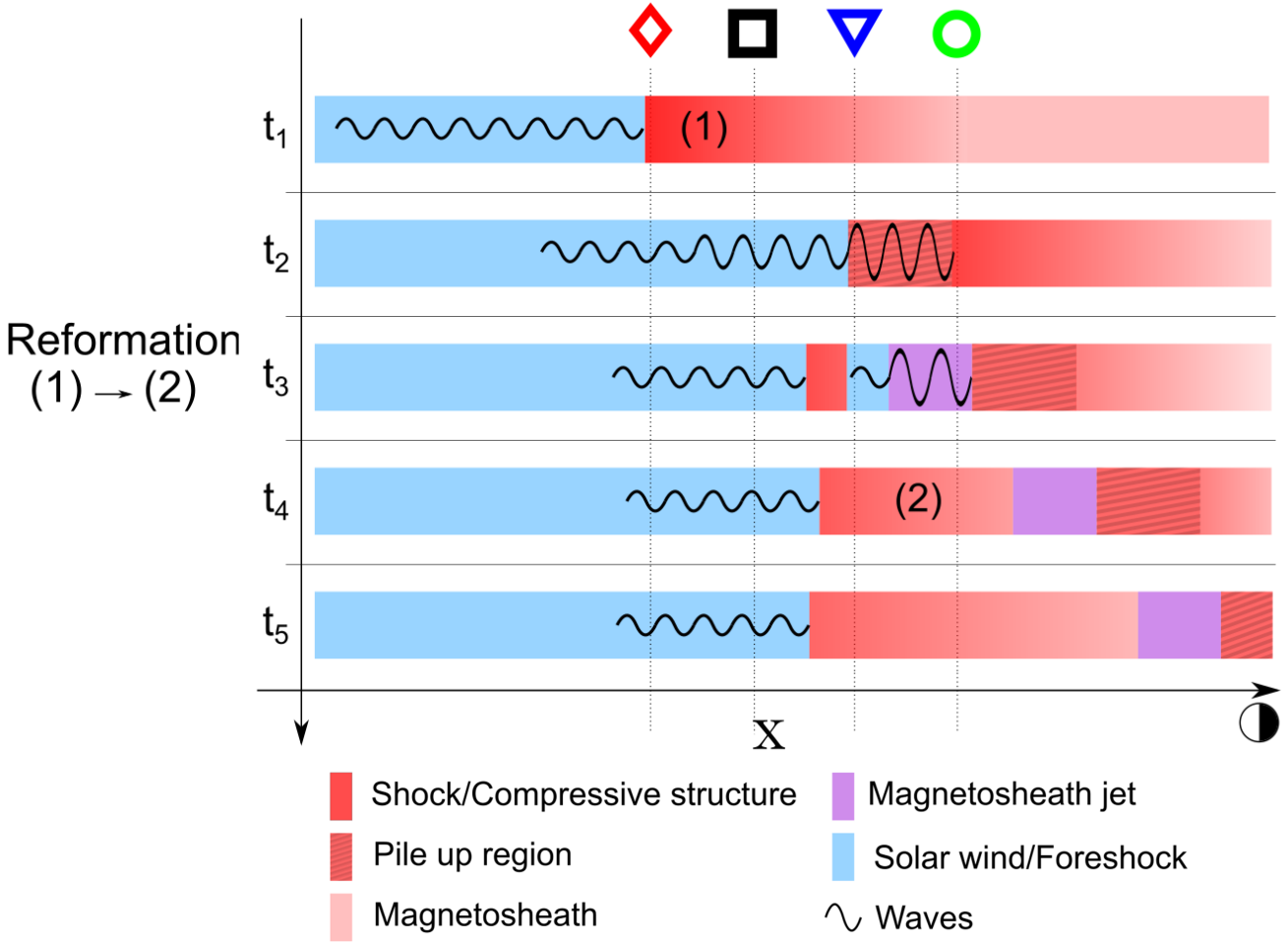


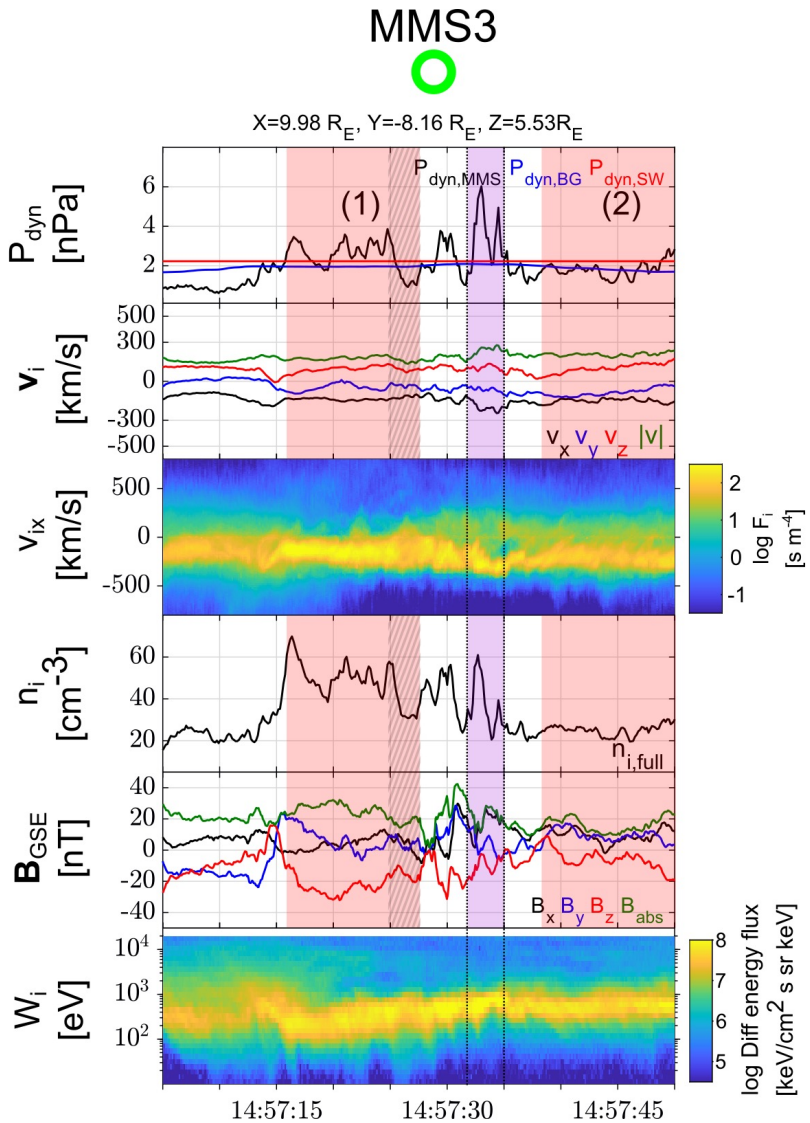
ASP 18 b, a hot Super-Jupiter that orbits its star in less than one day. Image Credit: NASA, ESA, and G. Bacon

Why Stochastic Betatron Acceleration?



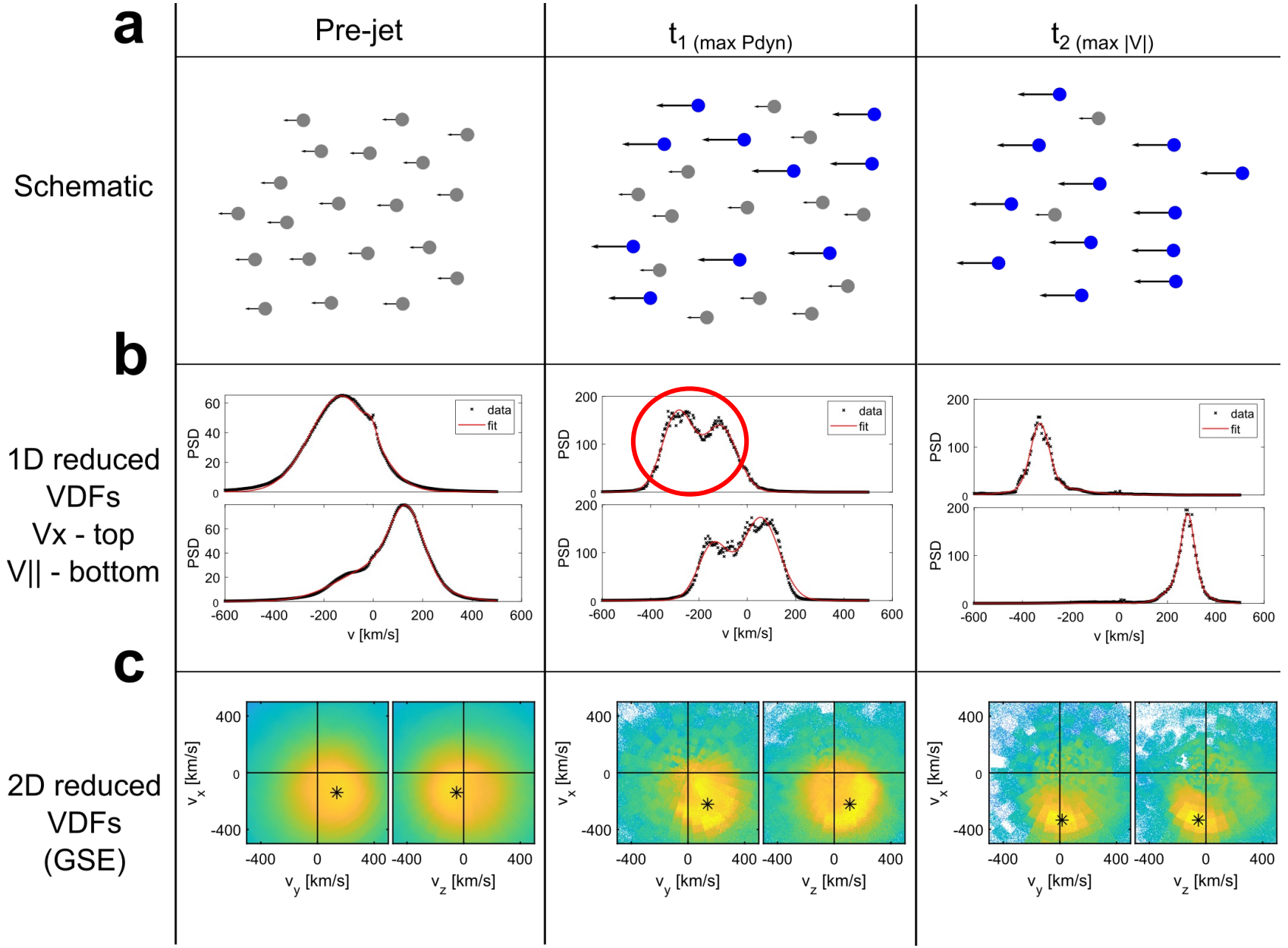
Shock reformation & magnetosheath jets





Raptis S., et al. 2022a | Nat. Commun.

Jet evolution in Qpar magnetosheath



Raptis S, et al,. 2022b | GRL