

Collisionless Shocks in the Heliosphere: Transient Processes and Particle Energization

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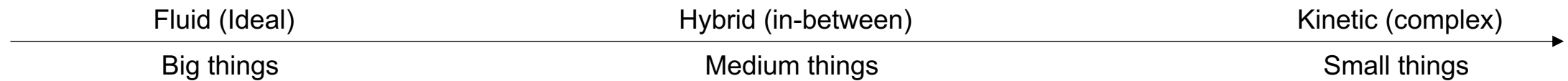
Acknowledgments:

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

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

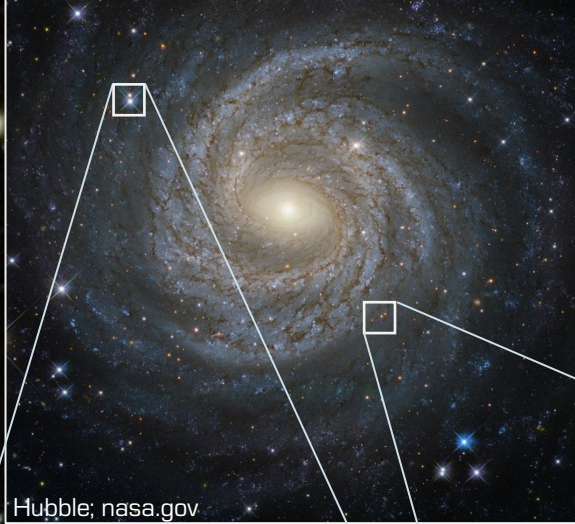
1. High level intro
2. Shocks (Geometry)
3. Shocks (Acceleration)
4. Transient phenomena
5. New Results on Particle Acceleration

General Intro



Intergalactic Medium

Galactic and Interstellar Media



Hubble; nasa.gov

Astrospheres



LL Orionis; nasa.gov

Astrospheres



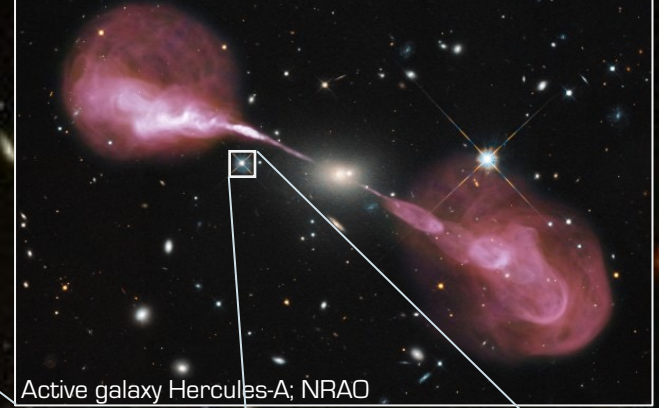
Eta Carinae; nasa.gov

Interstellar Media and Stellar Interactions



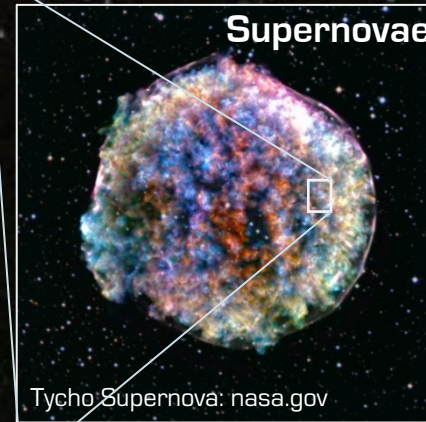
Zeta Ophiuchi; nasa.gov

Galactic Jets



Active galaxy Hercules-A; NRAO

Supernovae



Tycho Supernova; nasa.gov

Shock Waves

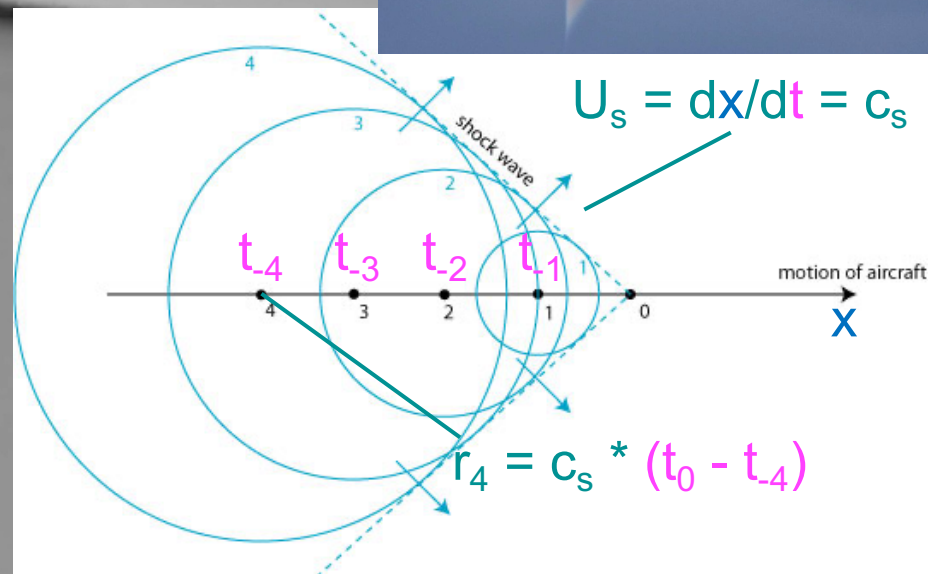
Collisional shock: NO UPSTREAM INFORMATION!

Collisional shock(s): Downstream information flow causes complexity (additional compressions and rarefactions; additional shocks)

Dissipation comes from collisions.

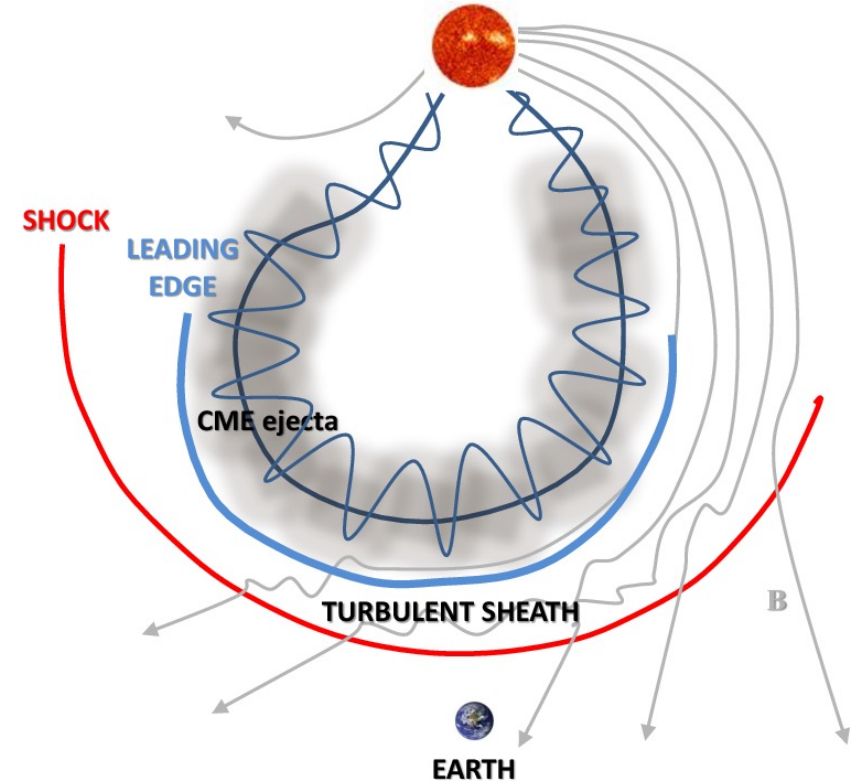
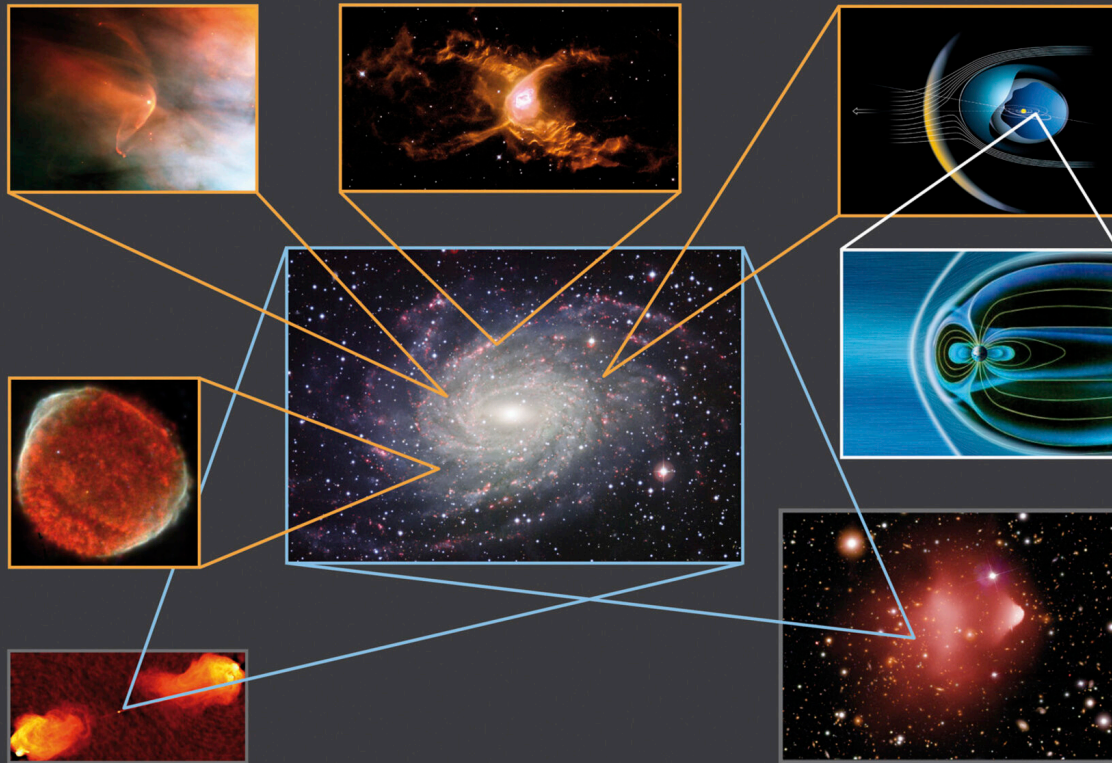


Collisional shocks are mediated by pressure waves (sound speed)



Collisionless Shocks in Universe

mediated by **electromagnetic fields**, and **wave particle interactions**



Shock are found everywhere!

Heating, accelerating particles and converting energies

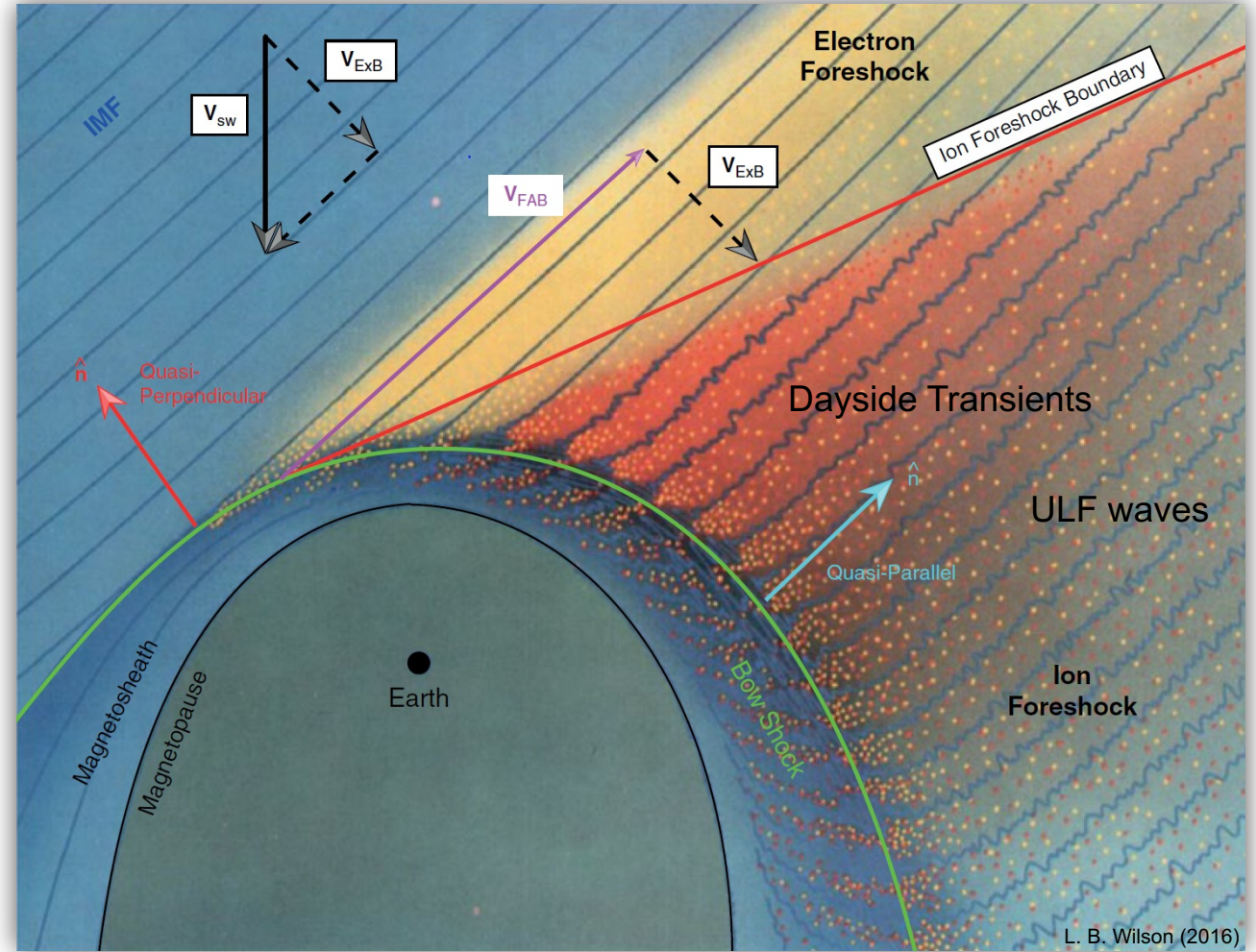
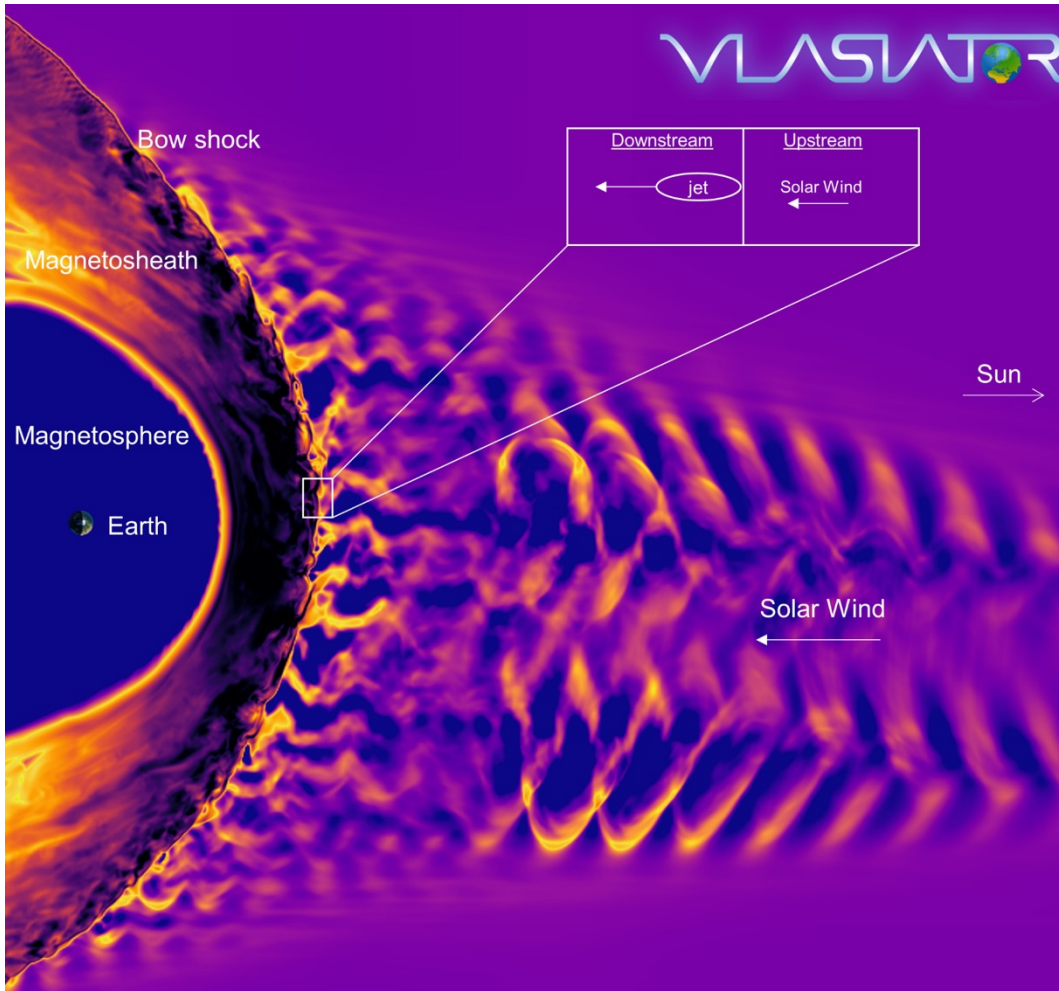
Shock waves:

Formed when structure moves with speed above local information transfer speed
(In our case, fast magnetosonic waves)

$$v_{ms}^2(\theta) = \frac{v_A^2 + c_s^2}{2} \pm \sqrt{\frac{(v_A^2 + c_s^2)^2}{4} - v_A^2 c_s^2 \cos^2 \theta},$$

Earth's magnetosphere & shock environment

Raptis+2022 Nat.Com; Courtesy of M. Palmroth, U Helsinki



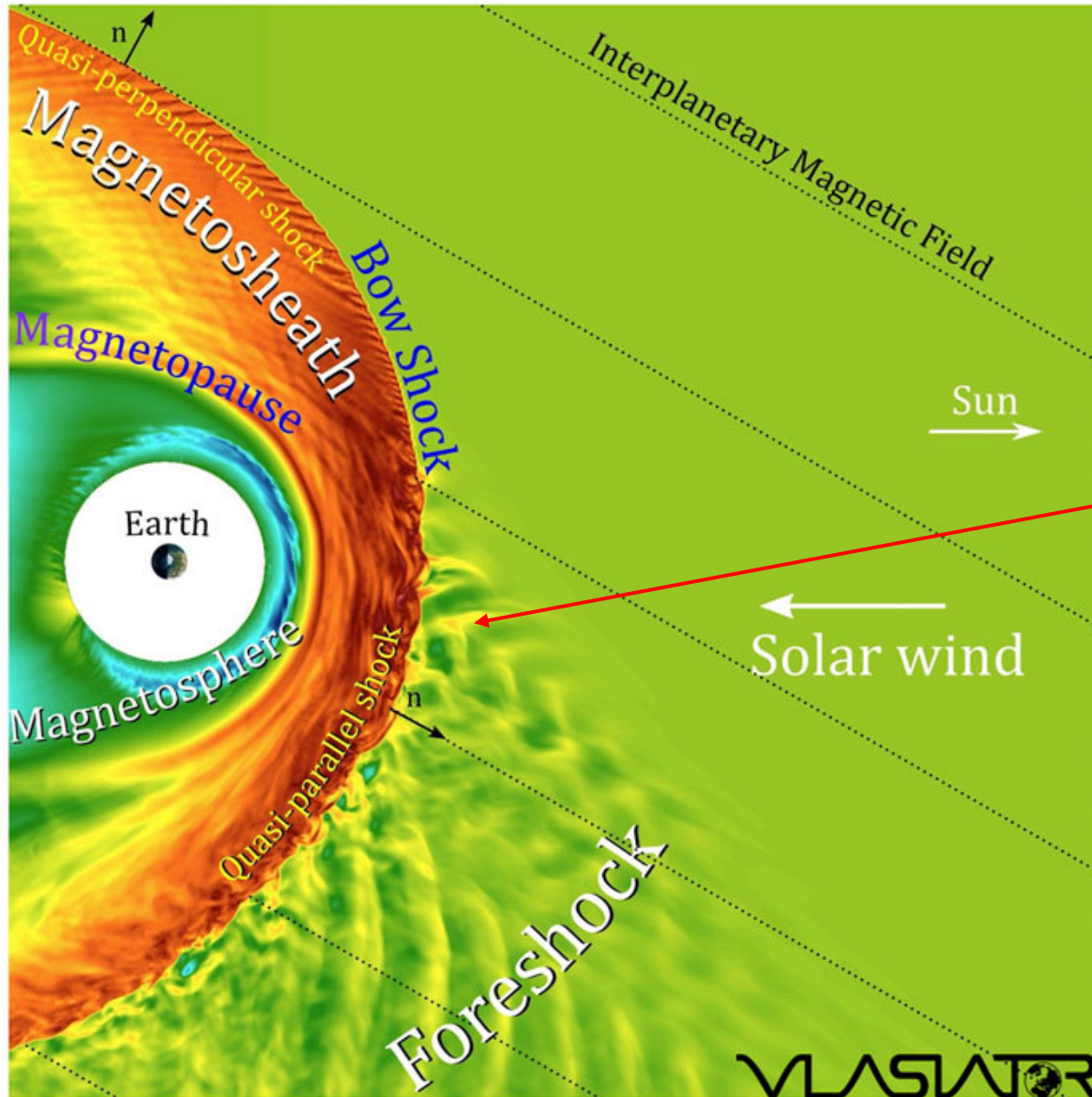
Quasi-parallel ($\theta_{Bn} < \sim 45$ deg)
Quasi-perpendicular ($\theta_{Bn} > \sim 45$ deg)

Supercritical shocks: $M_{fast} \geq M_c$, ($M_c \sim 1-2$) resistivity alone is not sufficient: shock “foot”, foreshock, overshoot, and reflected particles.

fast magnetosonic shock wave

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

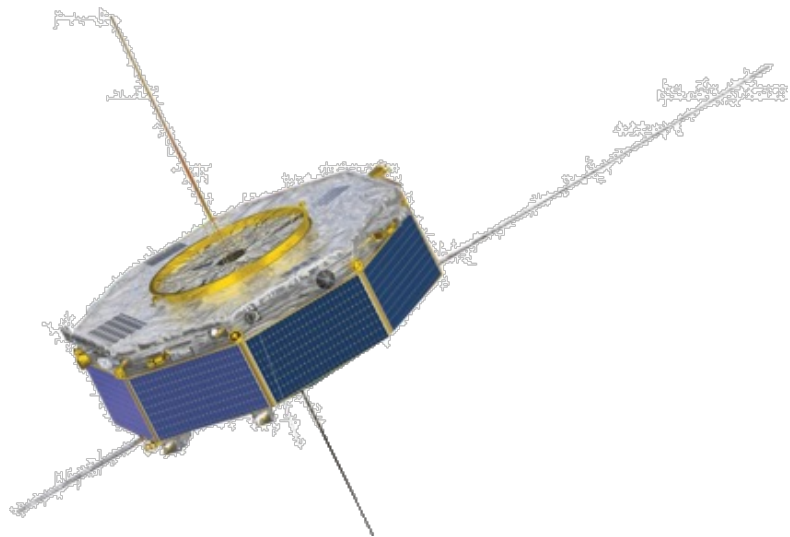
*Some Astro references on Qpar importance: Caprioli+2014, Giuffrida+2022, Vink+2024

Space plasma observations & simulations

In-situ
(examples)

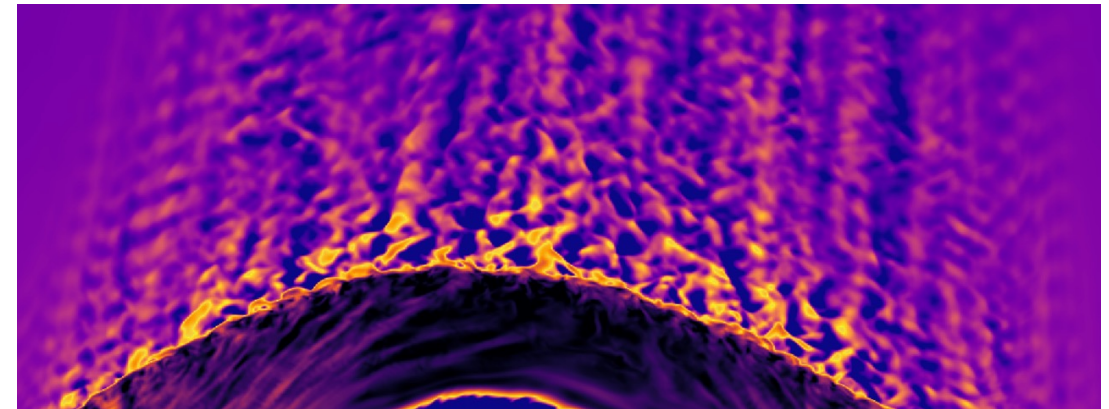
Cluster
MMS
THEMIS

Arase
ACE
WIND

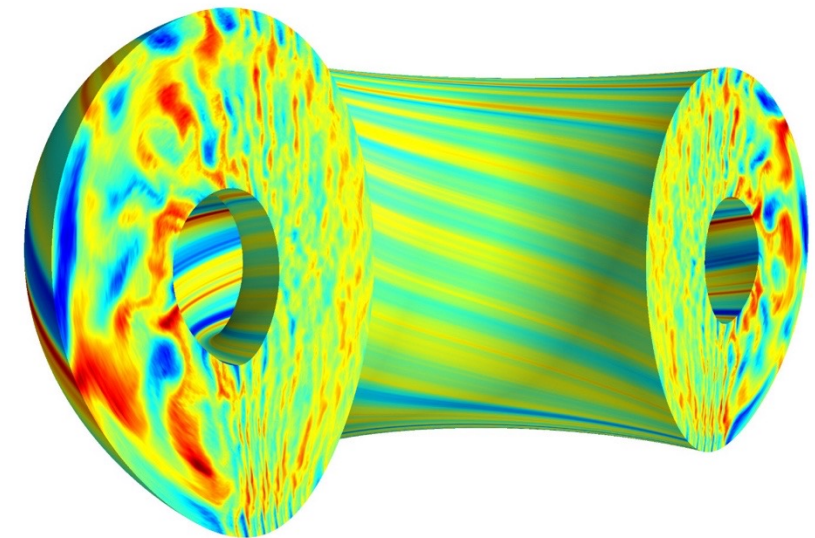


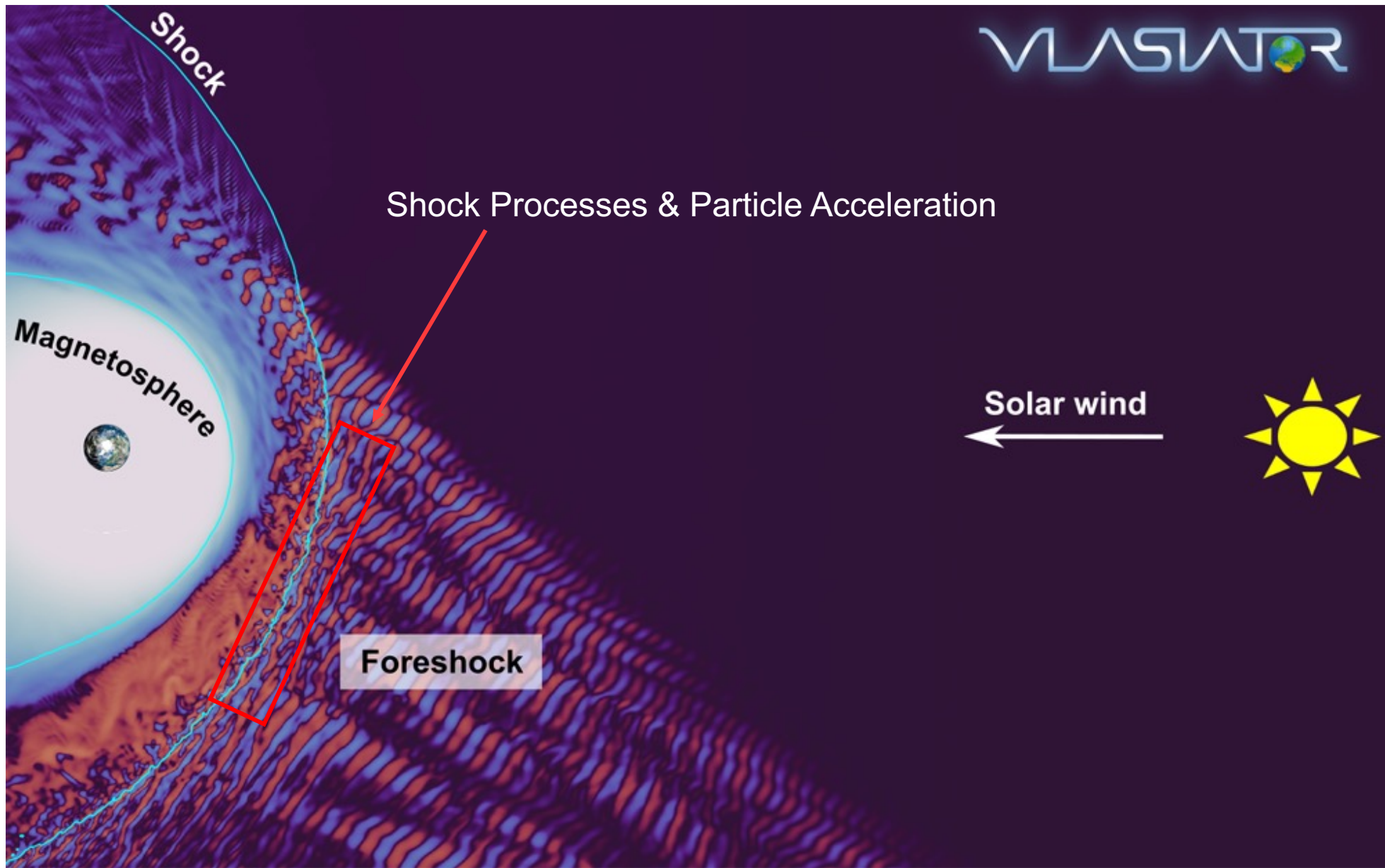
Remote Sensing
(examples)

SOHO
SDO
Solar Orbiter
PSP
SMILE



Fluid, Hybrid, PIC, Monte Carlo





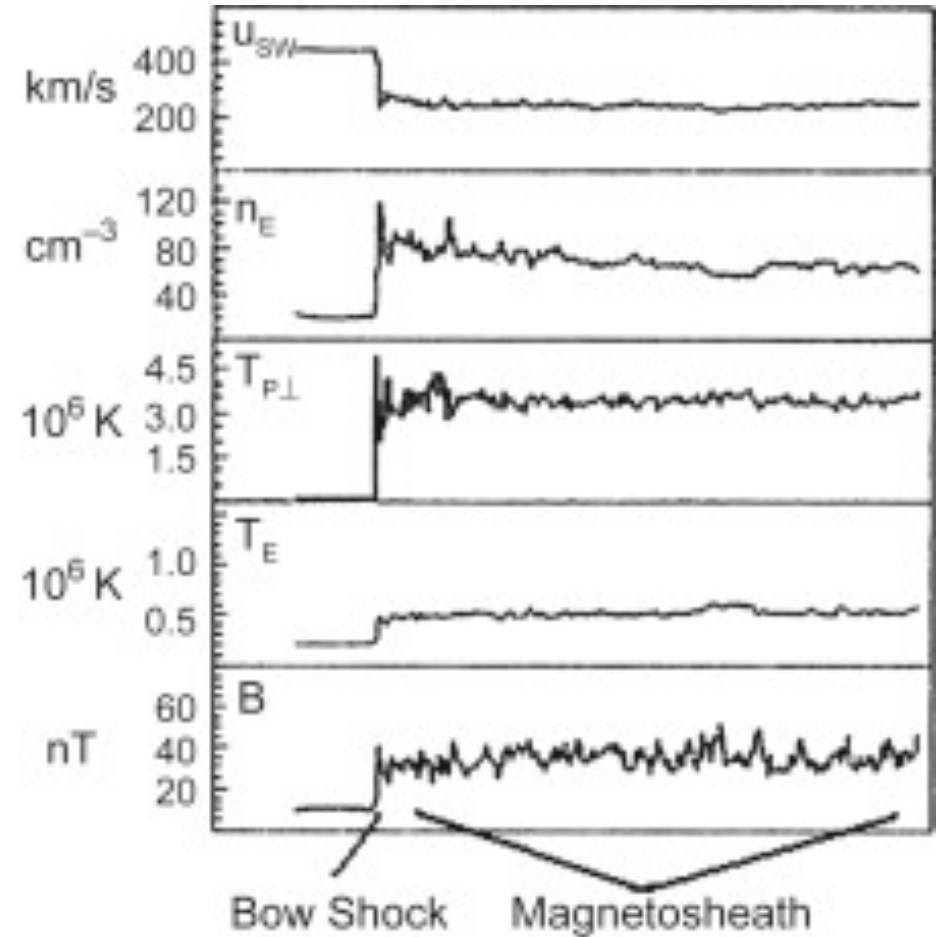
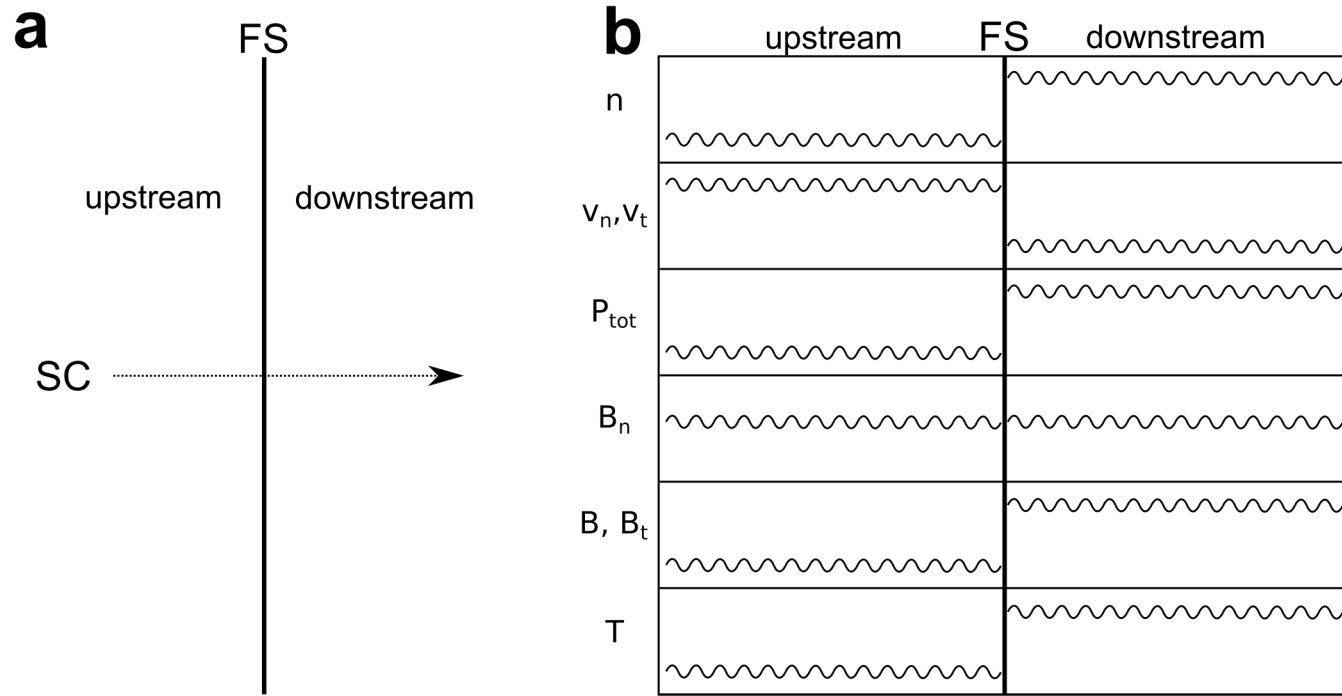
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Shocks

Structure & Geometry

For more in-depth information see
Magnetosphere Seminars (e.g., from Heli Hietala):
<https://www.youtube.com/watch?v=pls75HVm2Bk>

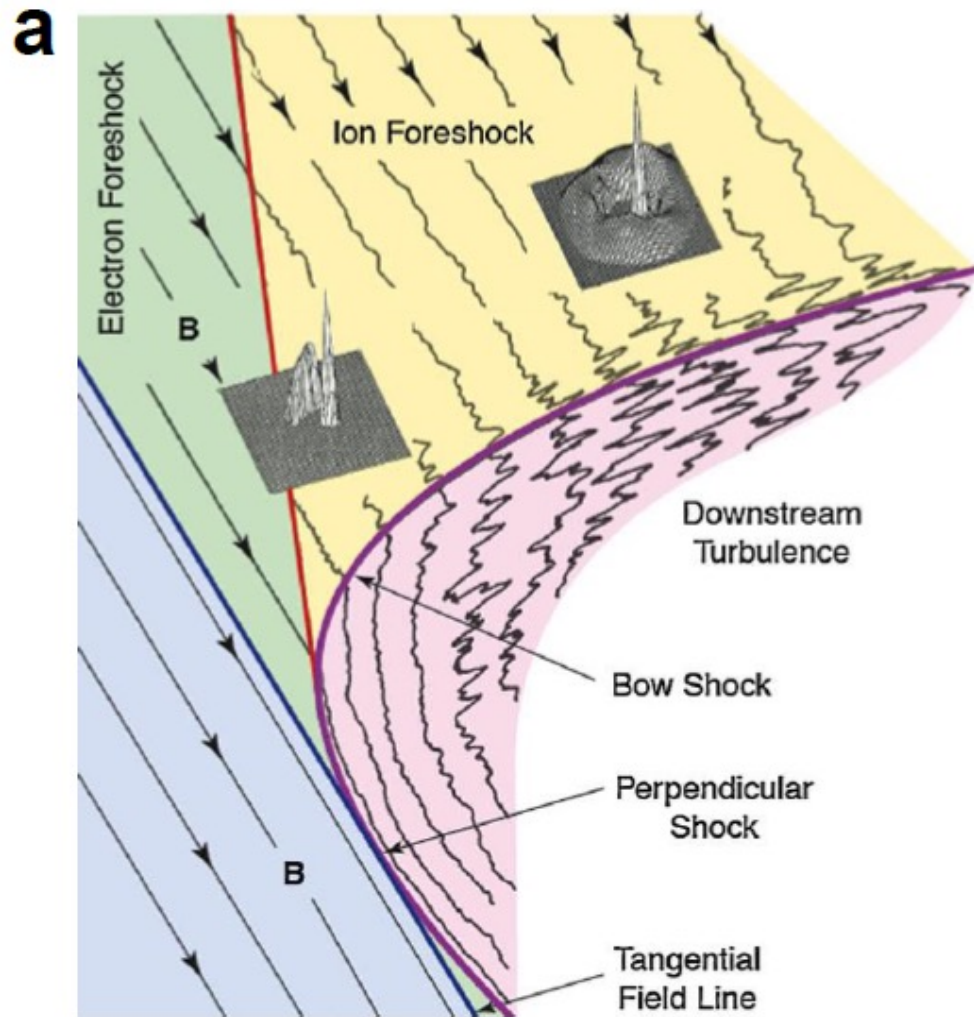
Fast shock transition (Theory & initial data)



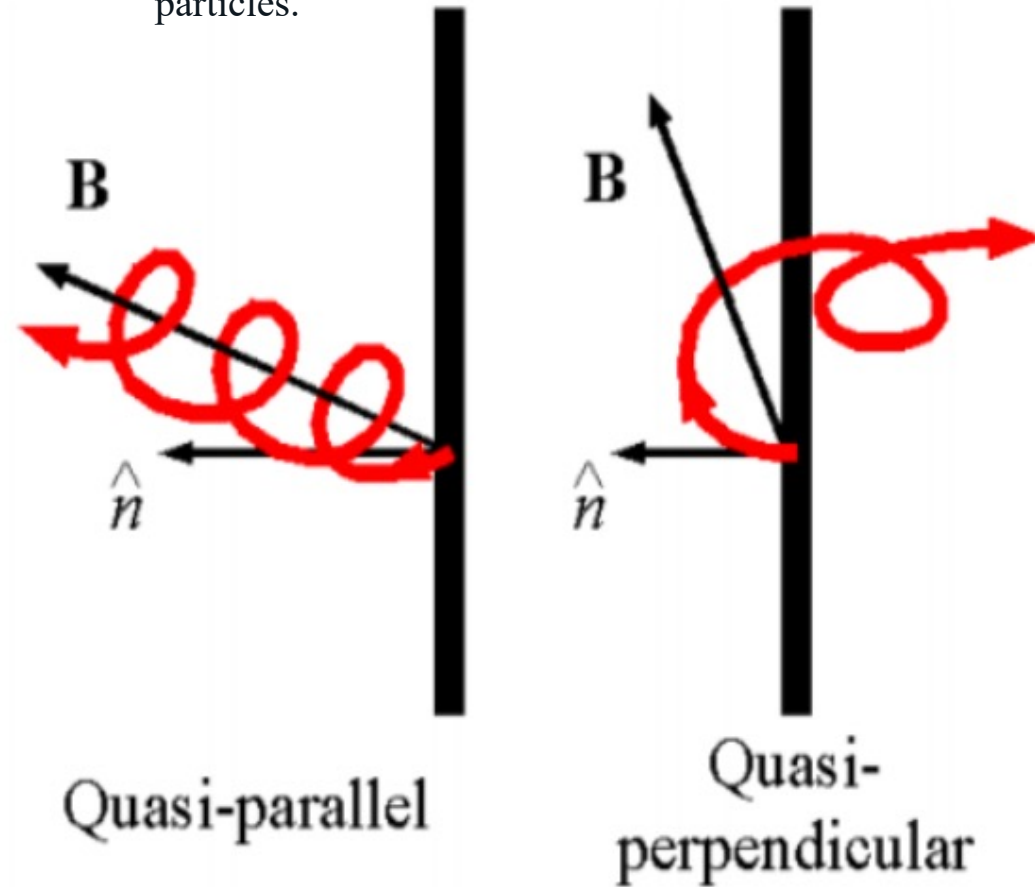
Rankine Hugoniot relations / Jump Conditions

Thermalization, Compression, Breaking

Shock & foreshock

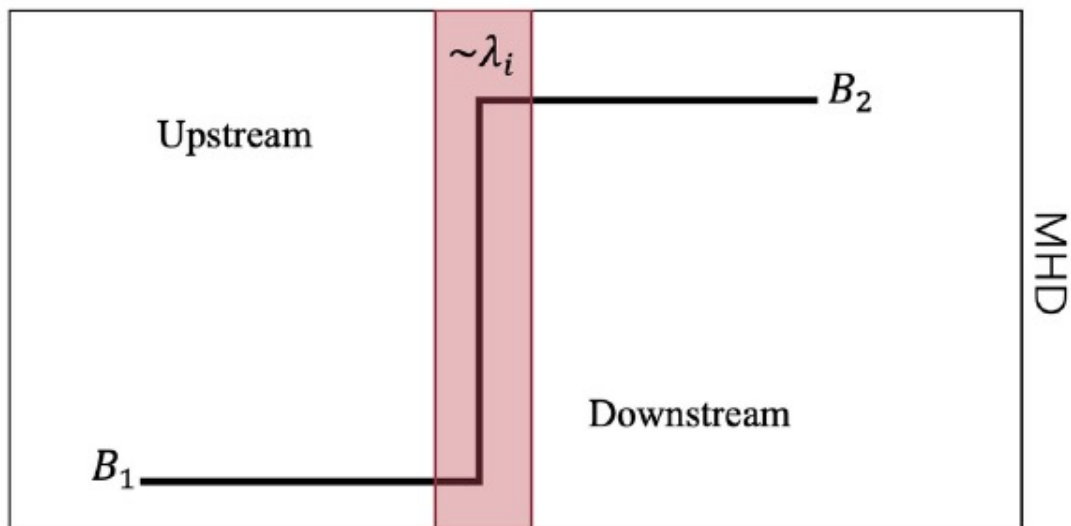


b *Supercritical shocks:* $M_{\text{fast}} \geq M_c$, ($M_c \sim 1-2$) resistivity alone is not sufficient: shock “foot”, foreshock, overshoot, and reflected particles.

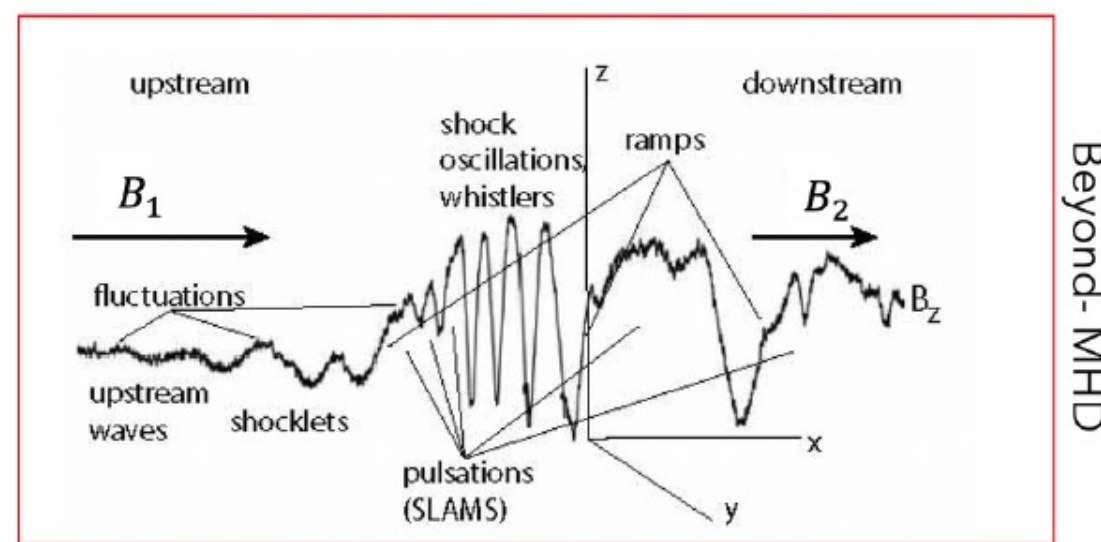
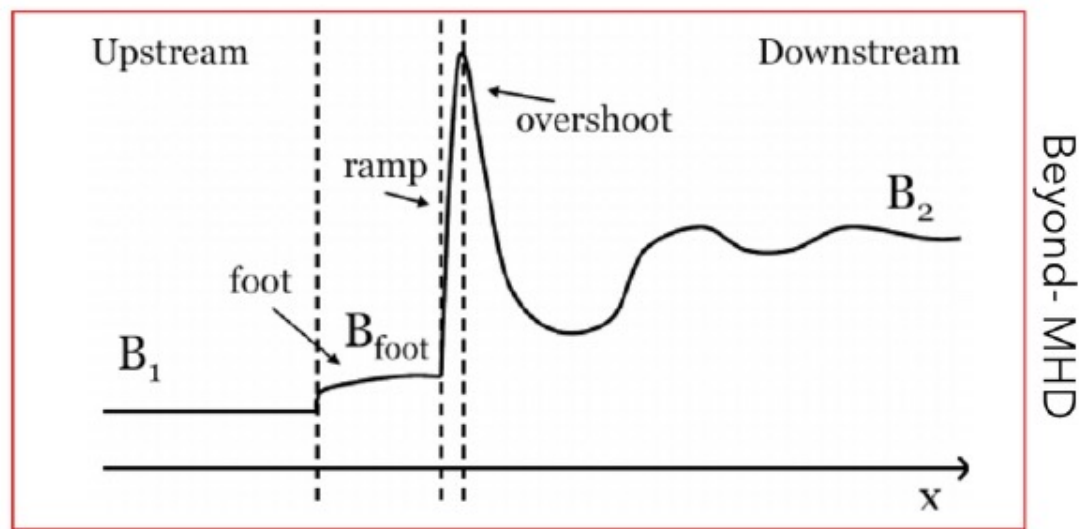
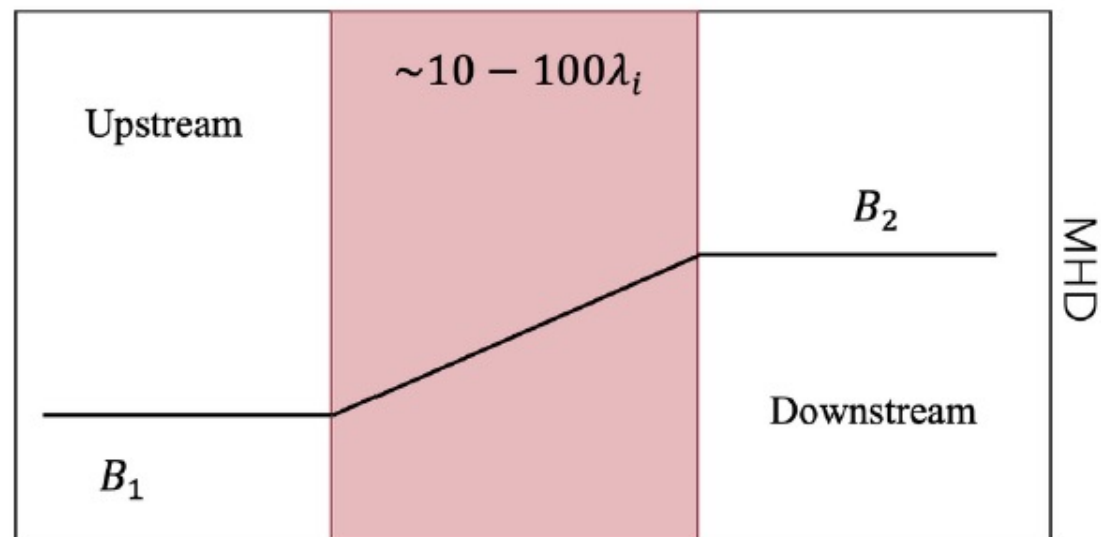


Quasi-parallel and Quasi-perpendicular shocks

Qperp transition



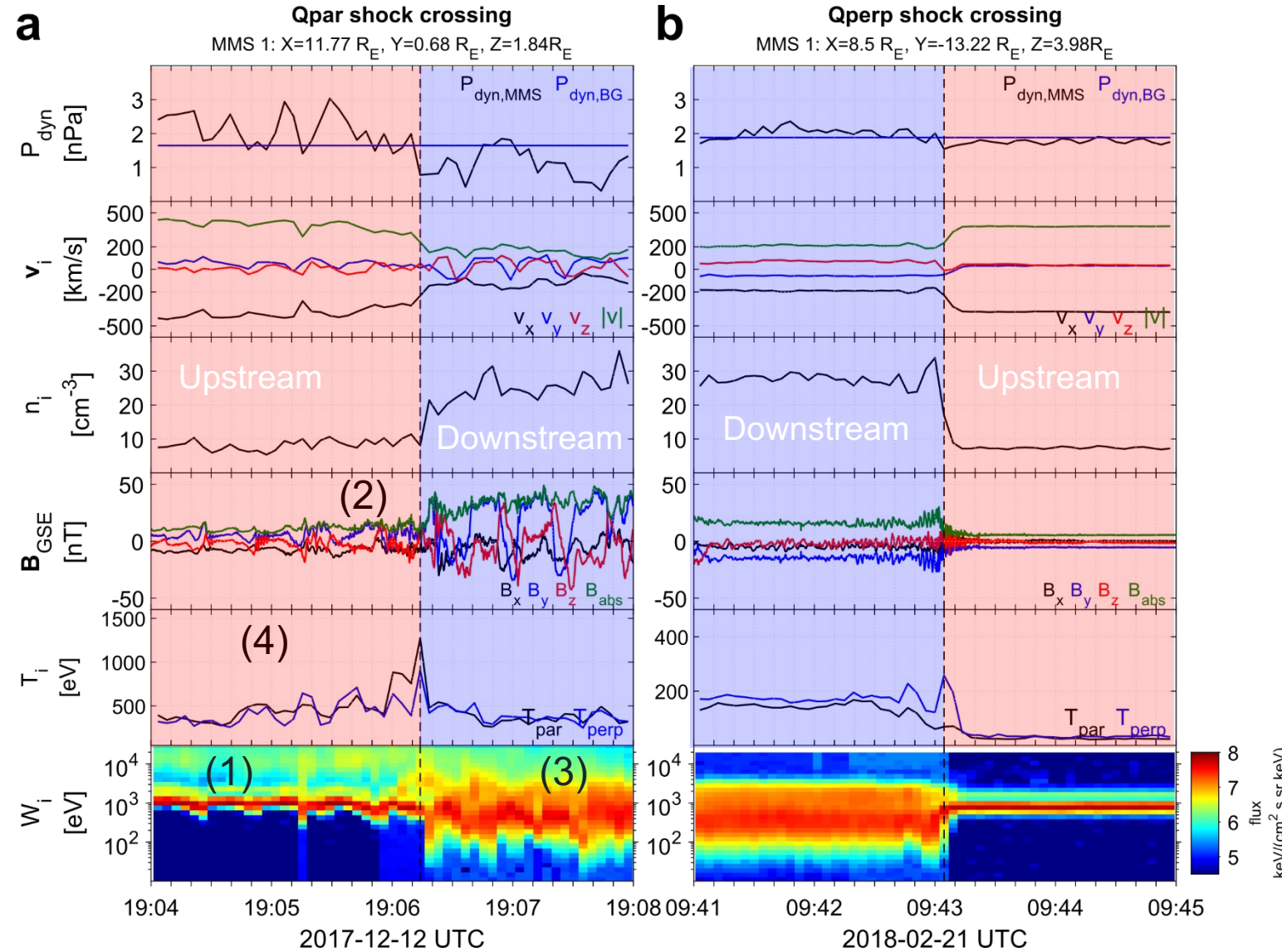
Qpar transition



Qpar – Qperp crossings

Qpar shocks and downstream plasma:

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



Shock Reformation & SLAMS

Shock Reformation

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

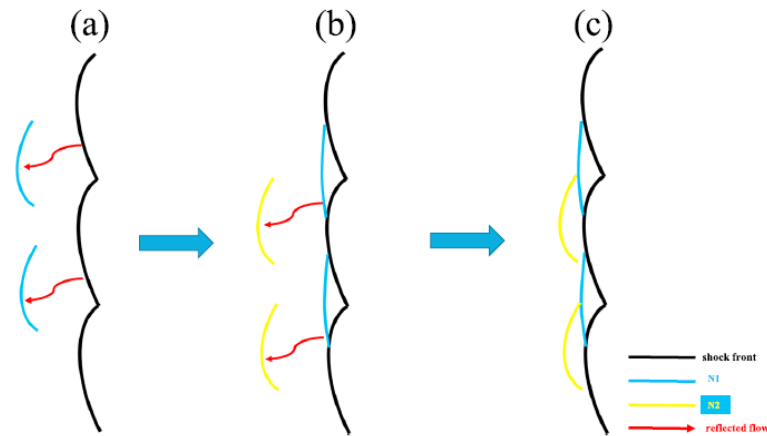


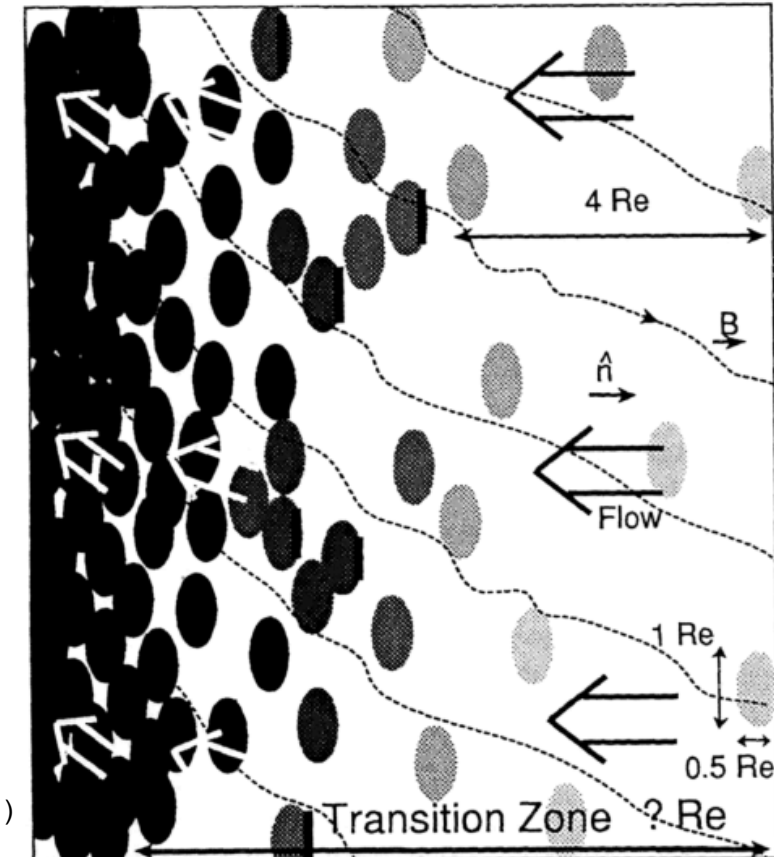
Figure 11. The sketch for evolution of shock front. (a) A rippled shock front, (b) a plane shock front, and (c) a rippled shock front. Solid lines and red arrows denote shock front and reflected beams, and N1 and N2 indicate new shock fronts.

Hao et al. (2017)

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

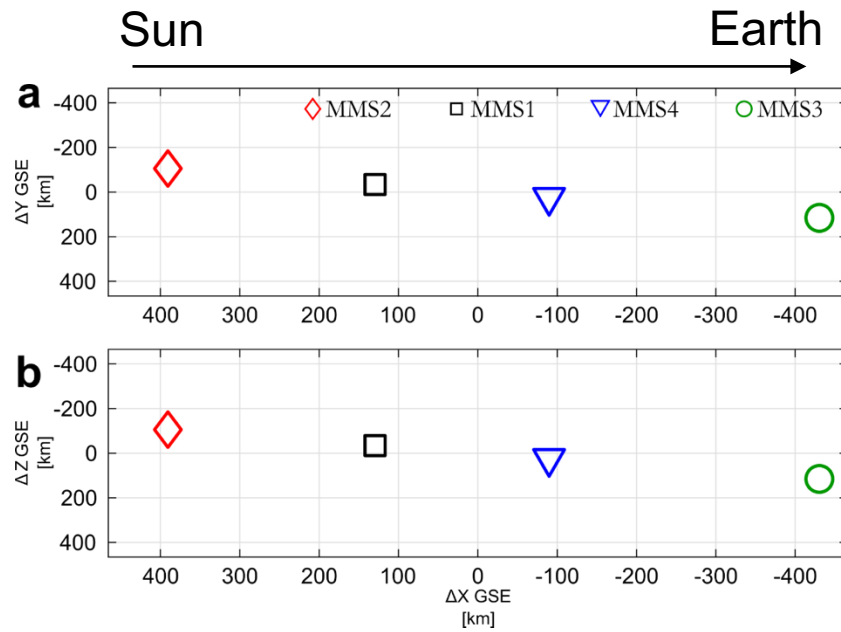
ULF non-linear evolution = SLAMS

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



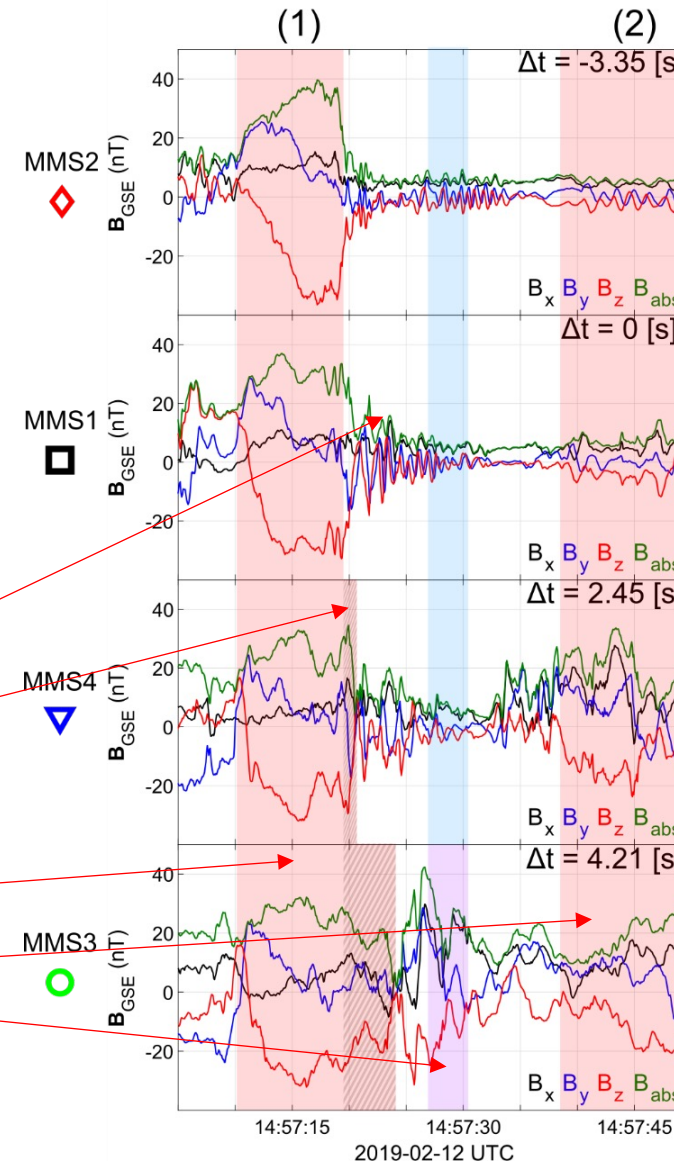
Schwartz, (1991)

Jets, Waves and Shock reformation



Evolution of SLAMS/Reformation

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



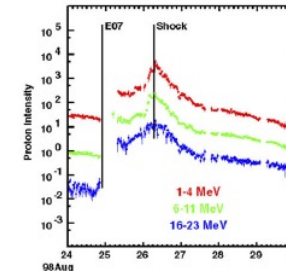
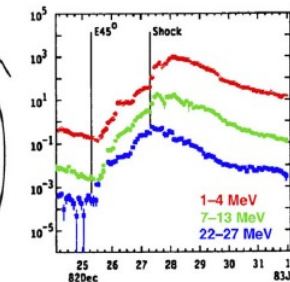
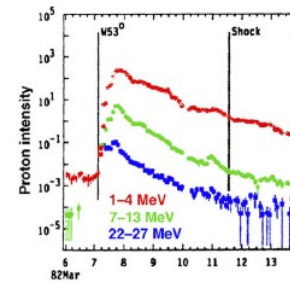
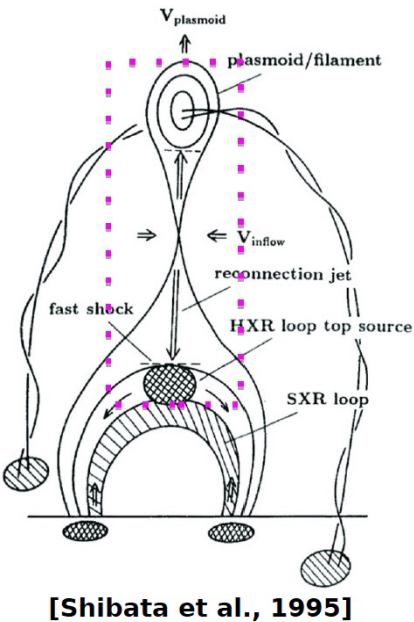
Sun
 ↓
 ~1000 km
 ~ 10 λ_i
 ↓
 Earth

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

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

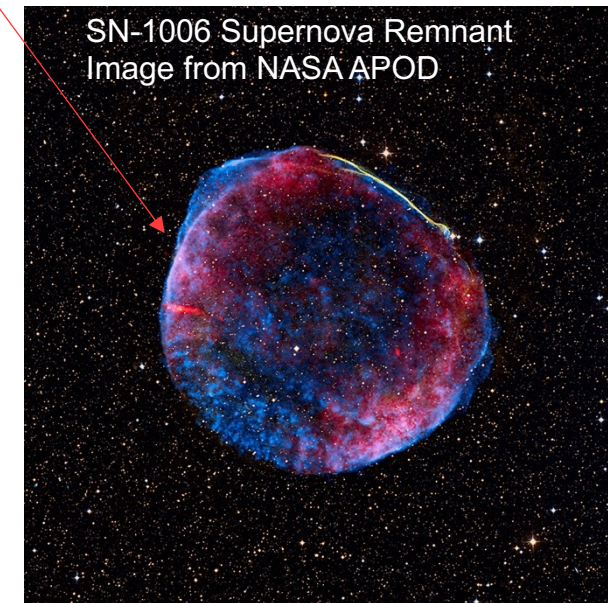
Shocks as particle accelerators

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



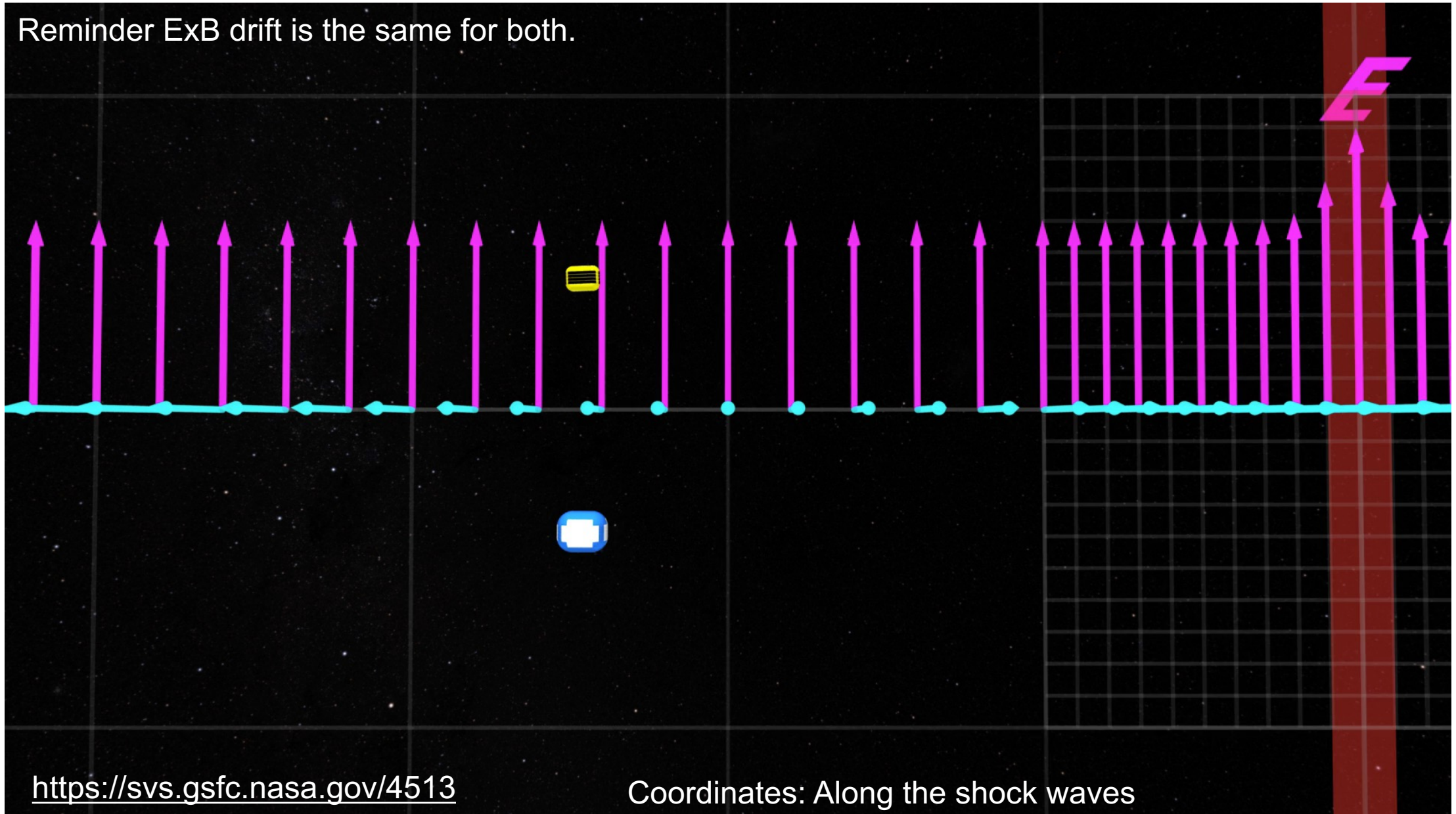
Desai & Giacalone (2016)

Shock wave



Shock Drift Acceleration (SDA)

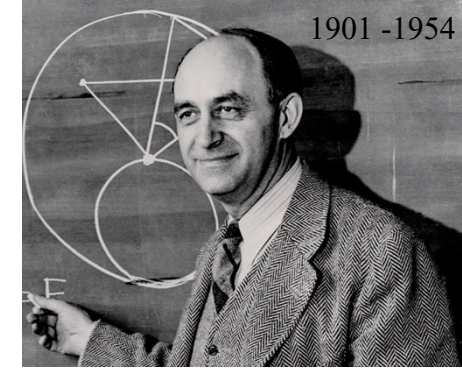
Reminder ExB drift is the same for both.



<https://svs.gsfc.nasa.gov/4513>

Coordinates: Along the shock waves

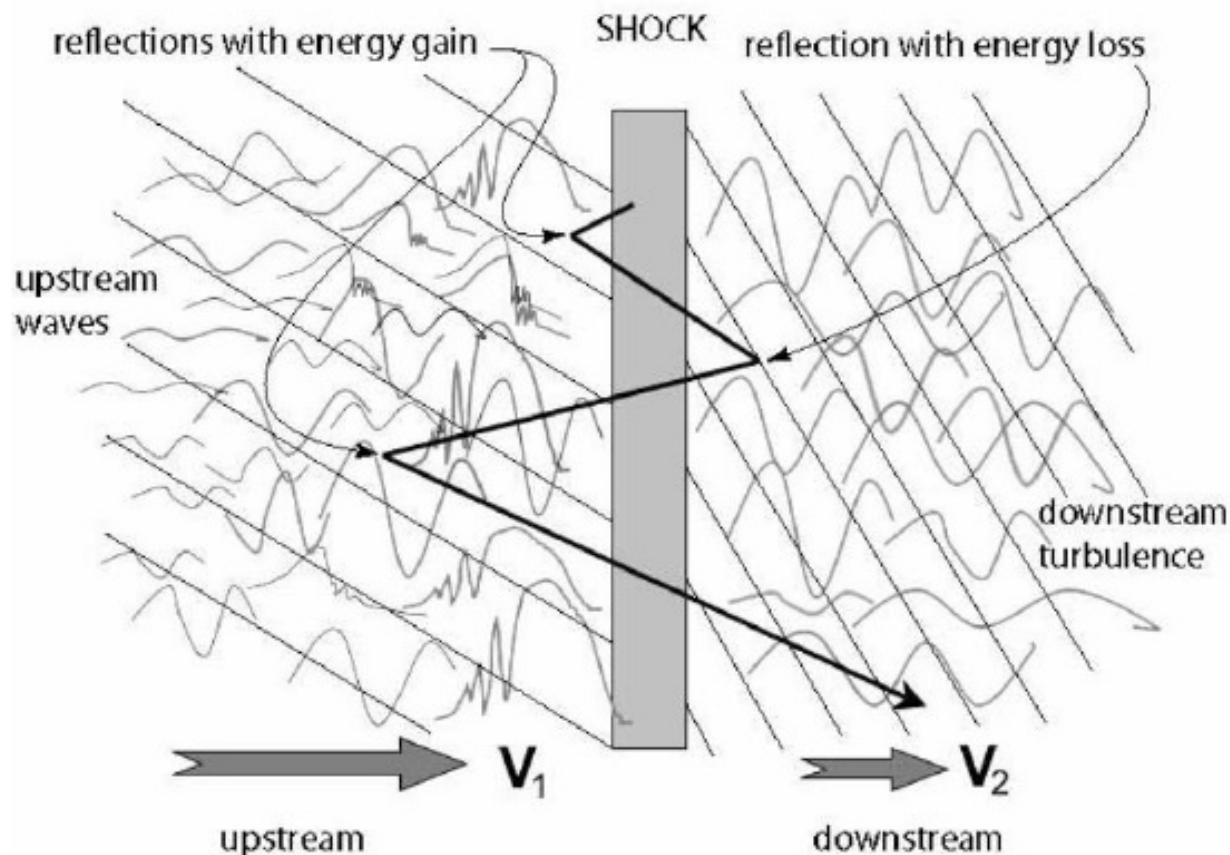
Diffusive Shock Acceleration (DSA)



$$\beta = V_s/c < 1$$

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

$$\langle \Delta E/E \rangle \sim 4/3 (V_1 - V_2)/c$$



Simplified explanation

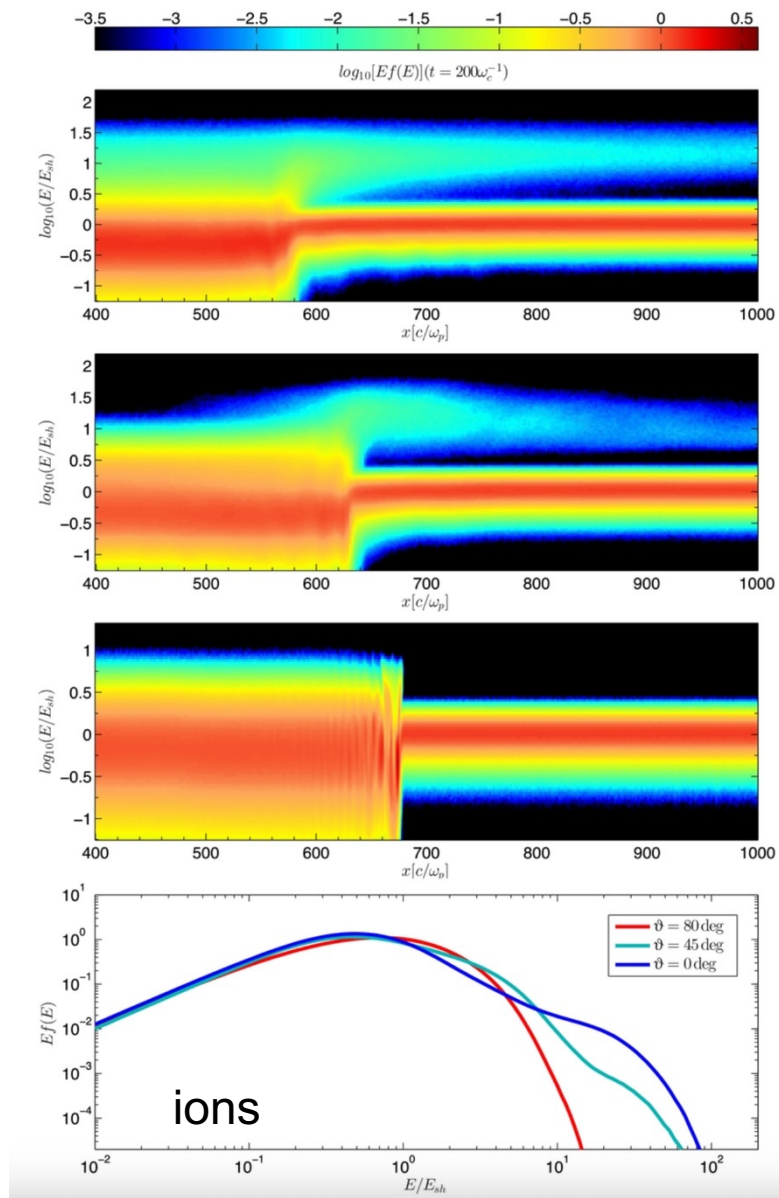
- Waves + turbulence downstream = Scatter particles back to the shock
- Some of the particles get to very high energies.

Injection Problem

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

Reminder: In the shock frame, upstream and downstream flows move toward each other.

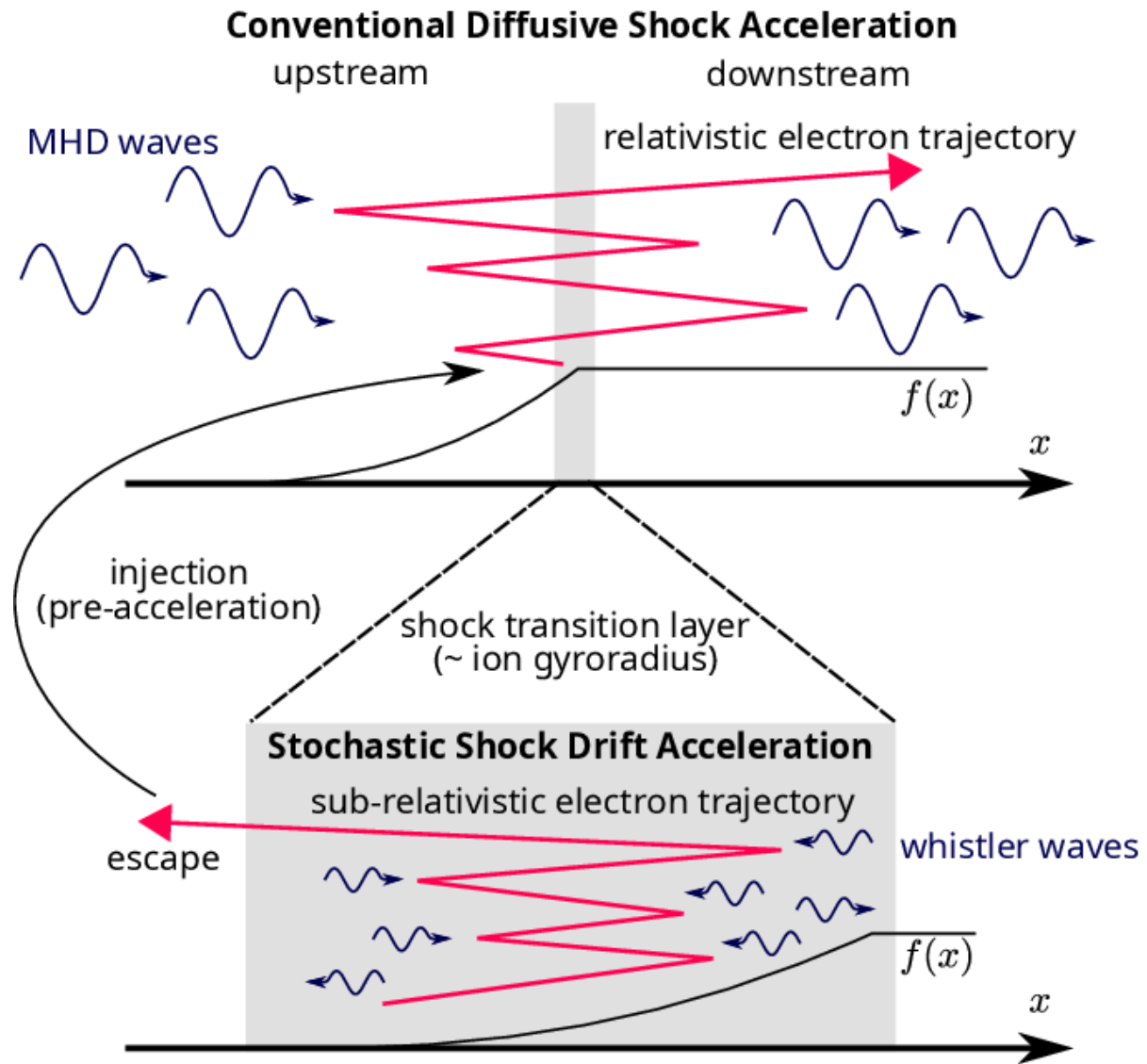
Acceleration at Qpar and Qperp shocks



Qpar shock (DSA)

Oblique shock

Qperp shock (SDA/SSDA)



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

So we (kind of) know shocks, and acceleration!

Let's go to transients!

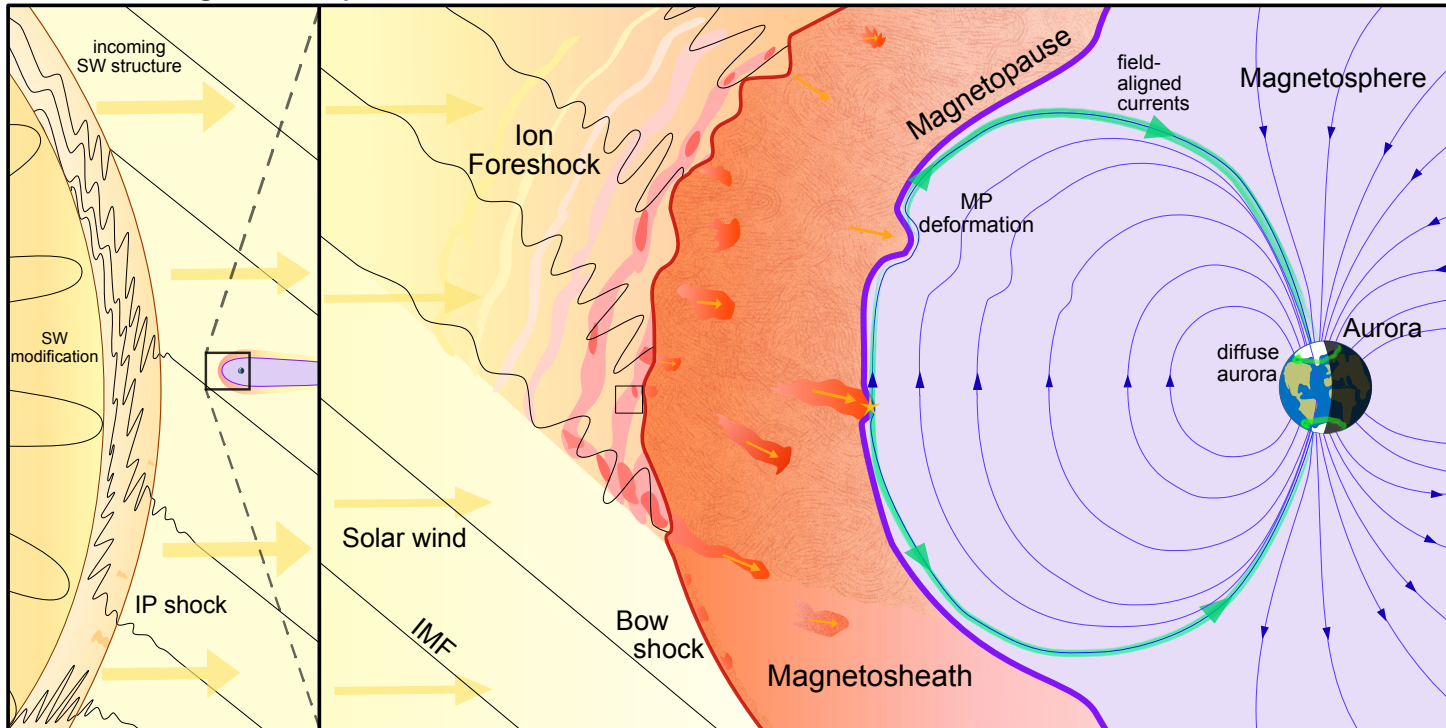
What is a Dayside Transient?



← New review paper about high-speed jets!

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



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

- **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

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)

Foreshock Transients

Driven transients with most notable impact

How many: ~several per day!

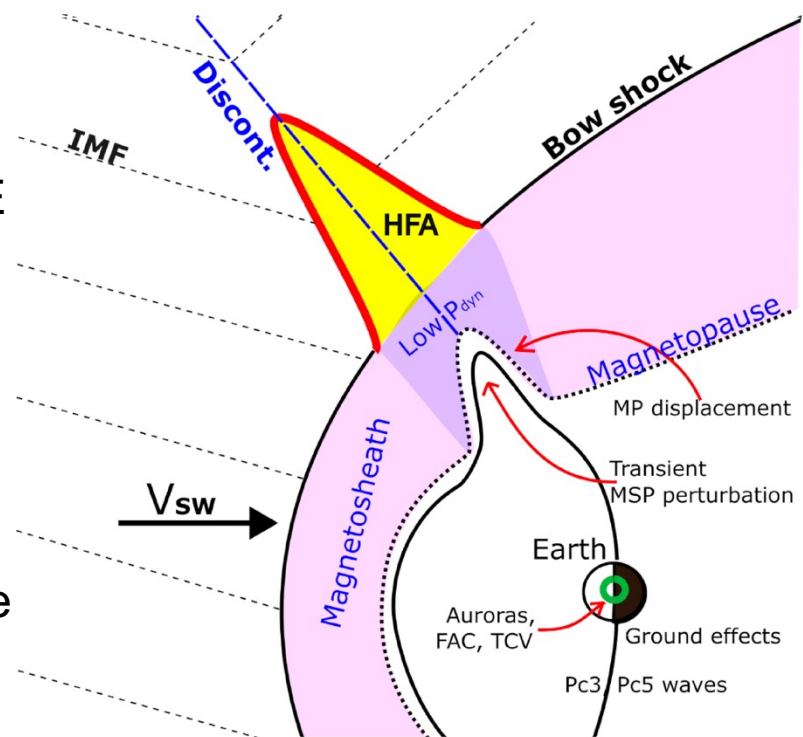
How big: ~10s of Re

HFAs

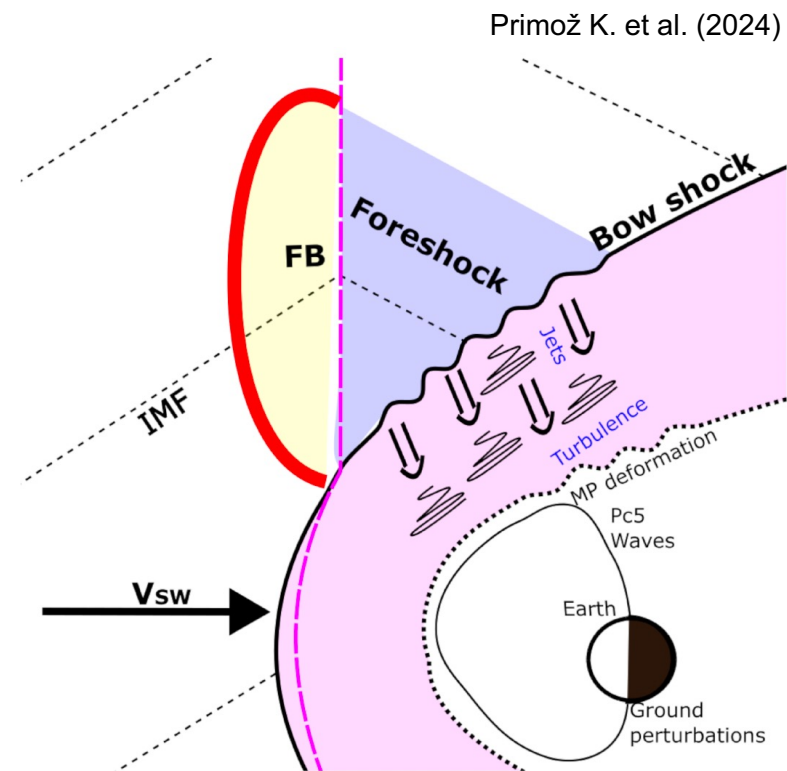
Discontinuities intersects BS and E
 ($-V \times B$) points towards the sheet,
 ions pile up and thermalized

FBs

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



Hot Flow Anomalies (HFAs)



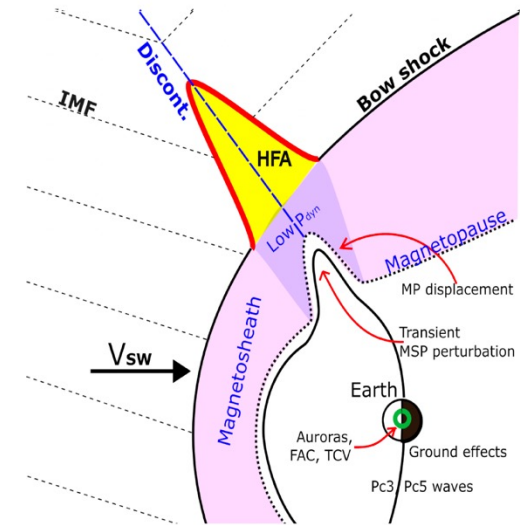
Foreshock Bubbles (FBs)

Primož K. et al. (2024)

Foreshock Transients, Shock-Generated Transients, TUMS (**T**ransient **U**pstream **M**esoscale **S**tructures)

The anatomy of an HFA

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



Hot Flow Anomalies (HFA)

Kajdič+ (2024)

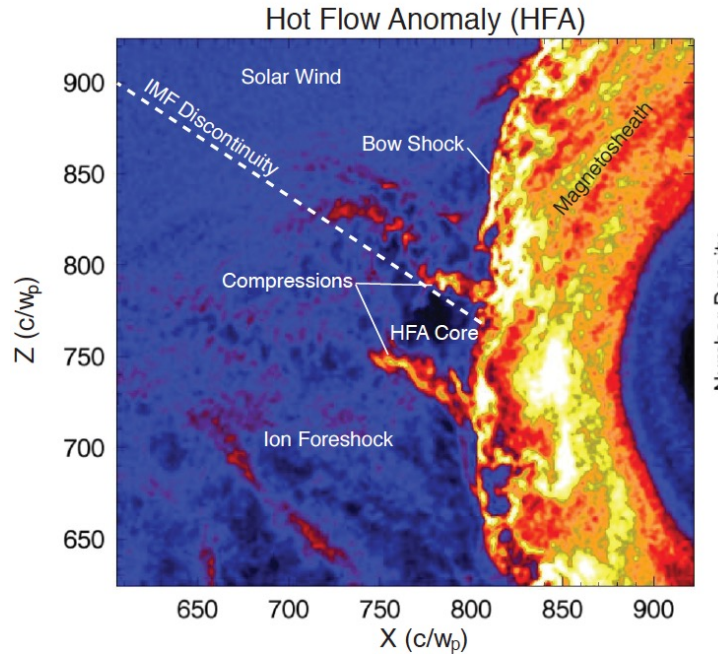


Figure by Nick Omidi

Crater-like B-field and IMF discontinuity

Density compressions and cavity

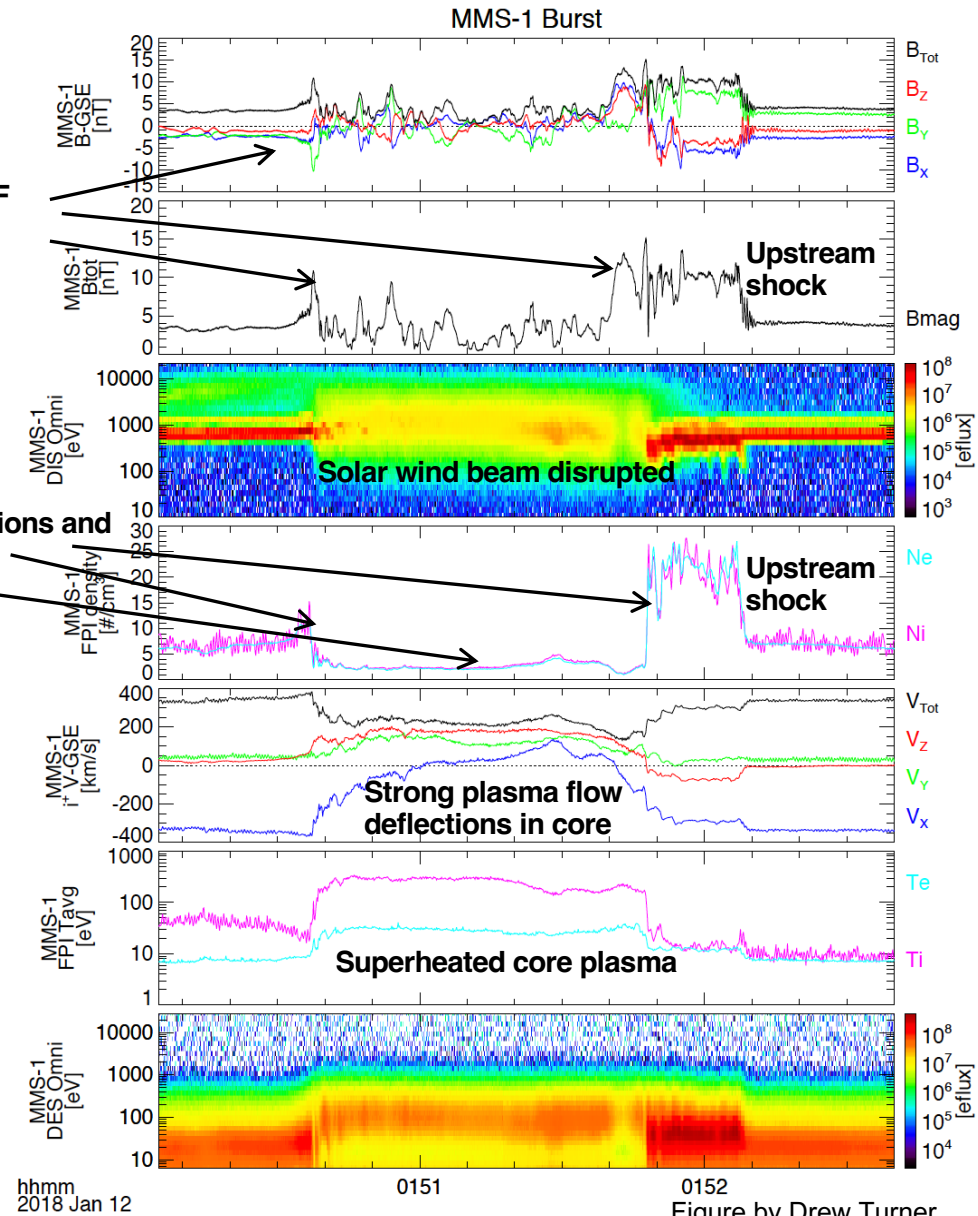


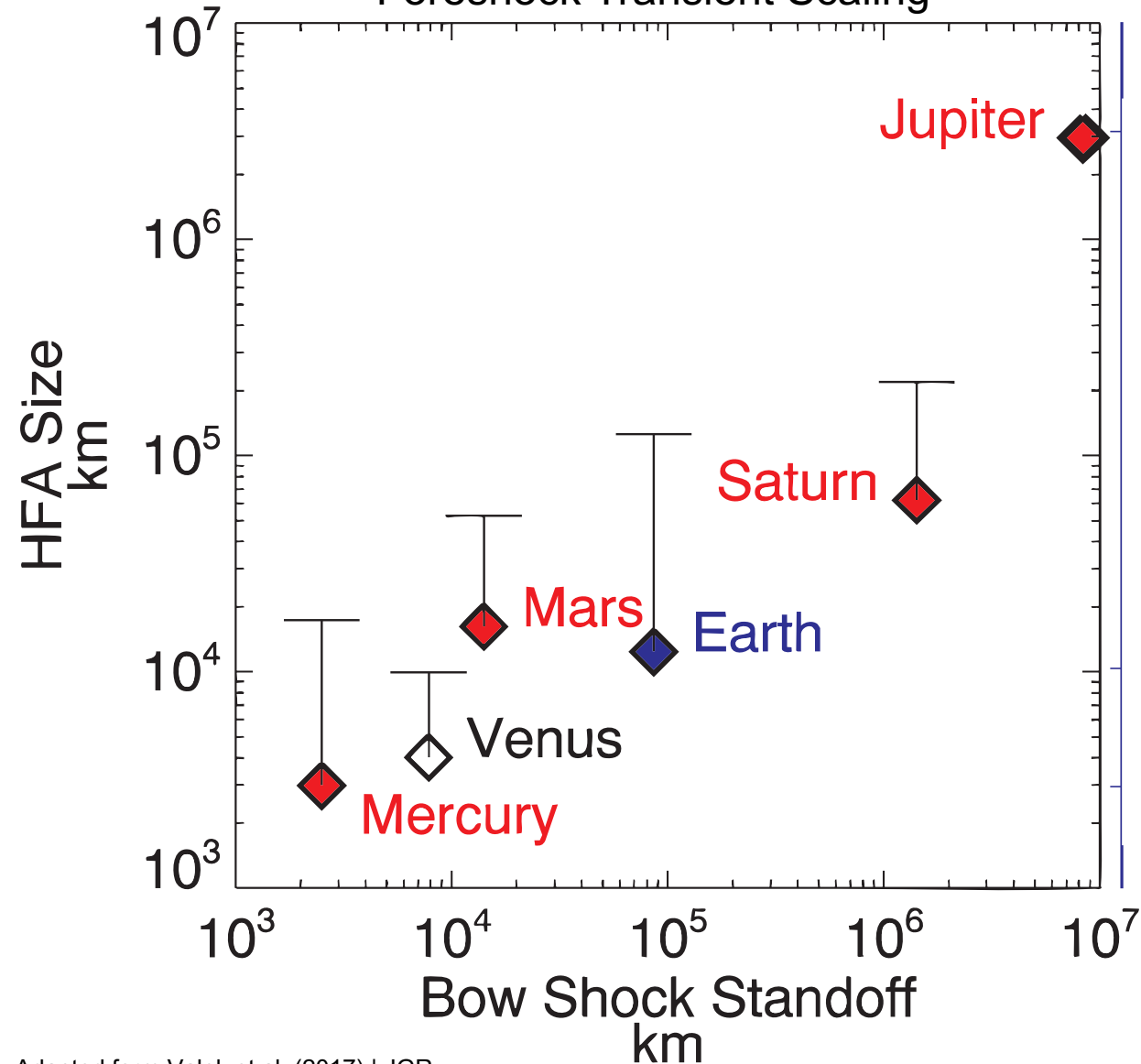
Figure by Drew Turner

How do they form?

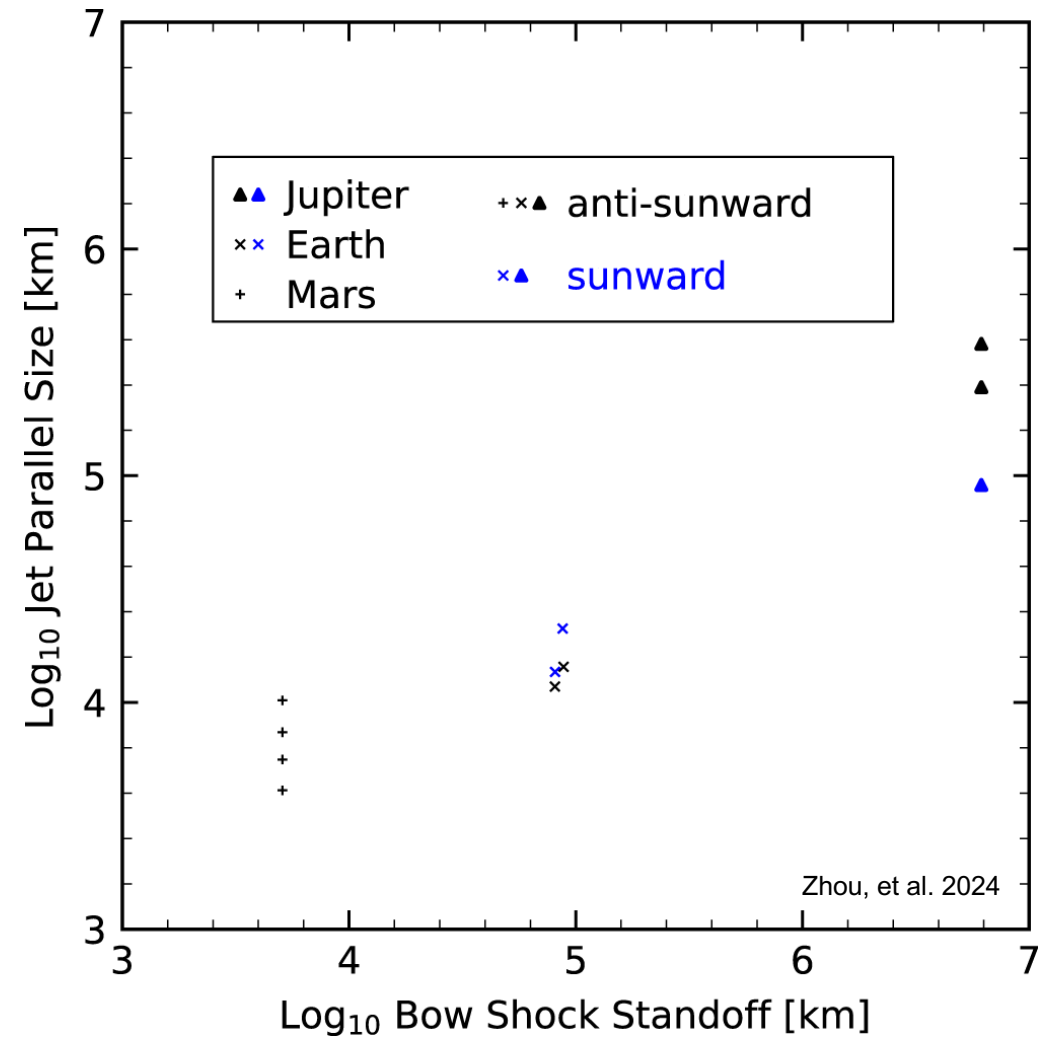
Discontinuity intersects the bow shock and the convection electric field ($-V \times B$) points towards the sheet on at least one side.

Transients Scaling Across Different Systems

Foreshock Transient Scaling



Downstream Jet Scaling



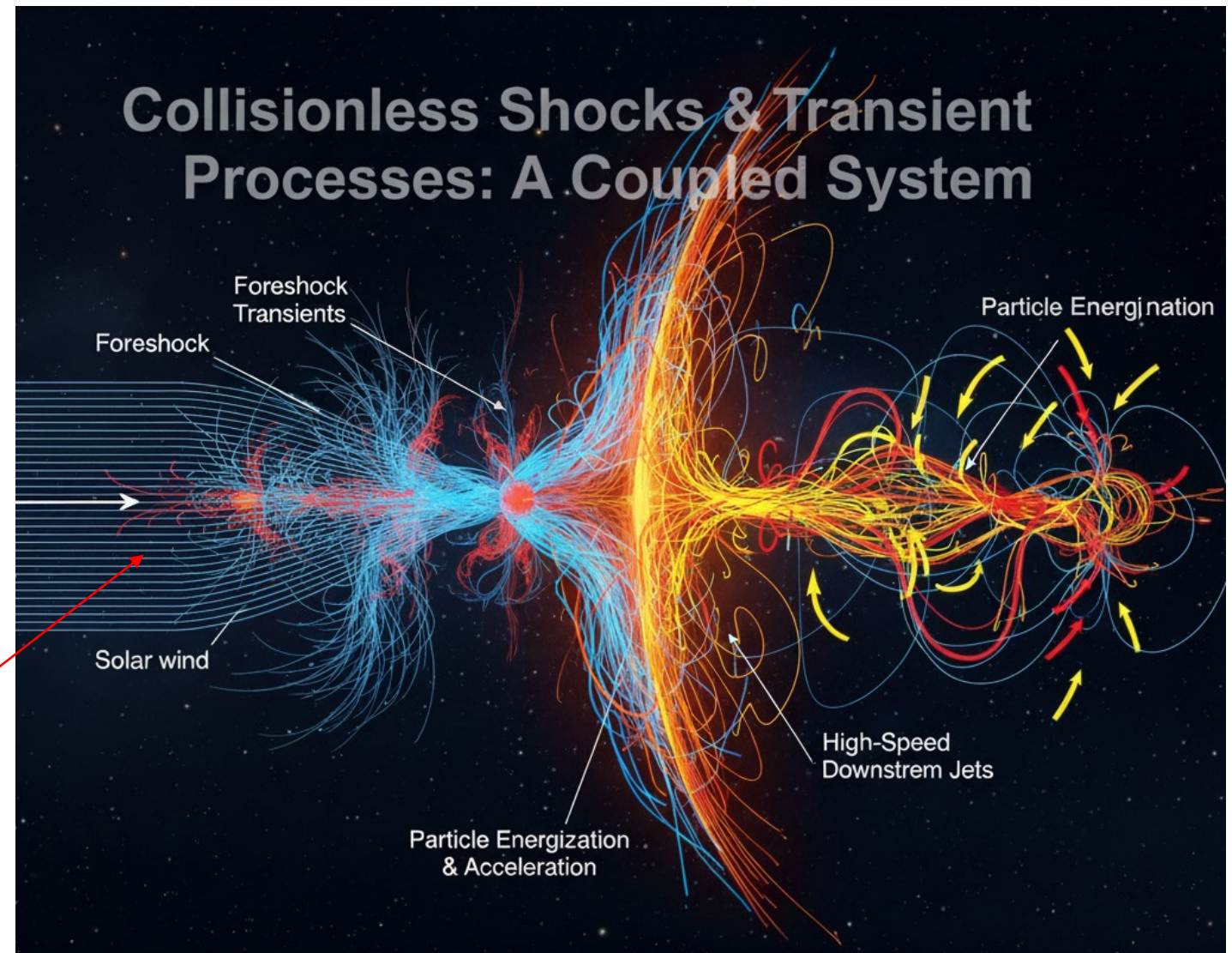
Zhou, et al. 2024

Shocks and upstream/downstream environments

Studying localized processes as individual components is problematic.

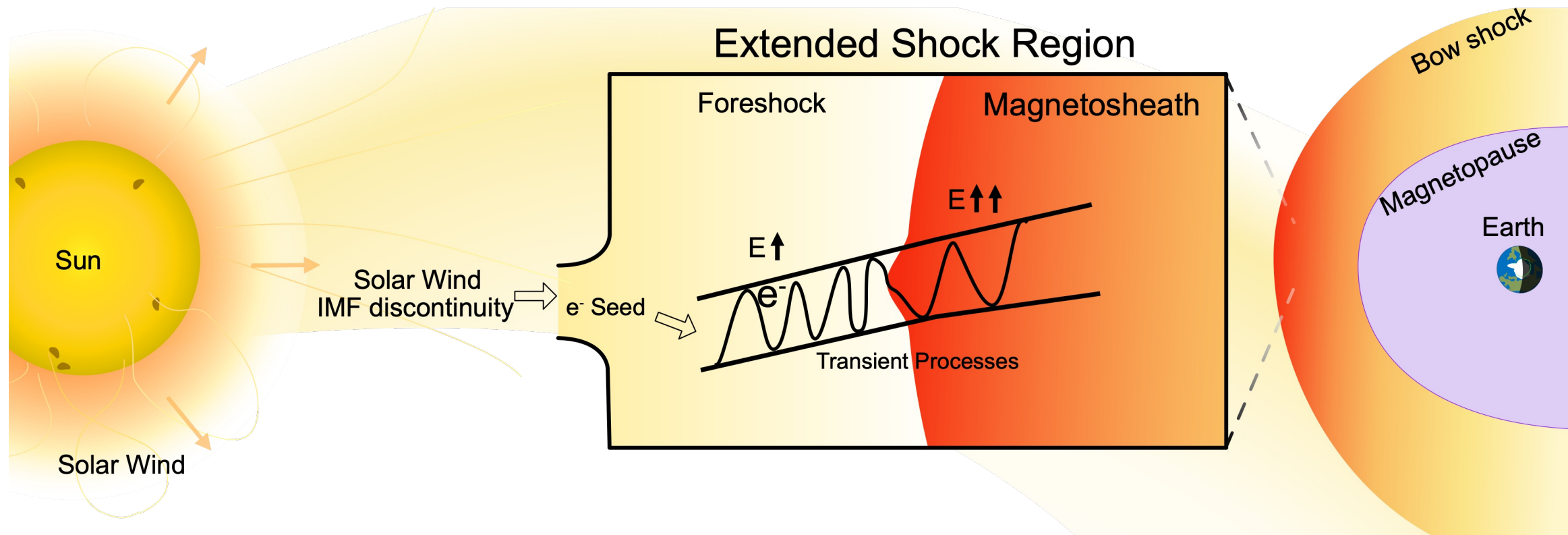
- **The bow shock decide** what the foreshock and magnetosheath are doing.
- Whether we see transients or not is also **controlled by the shock.**
- **Transients** both upstream and downstream **are connected**

Poor Gemini trying to illustrate this.



Credits: Google's Gemini (can AI really generate anything?)

Mental Picture to Keep in Mind



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5. New Results on Particle Acceleration

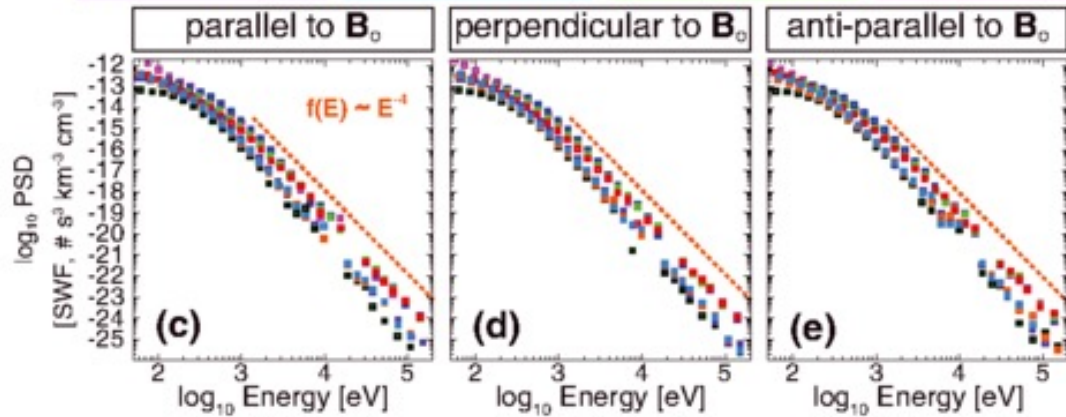
Particle Acceleration Recent Results*

...and why transients can make Q_{par} shocks super accelerators

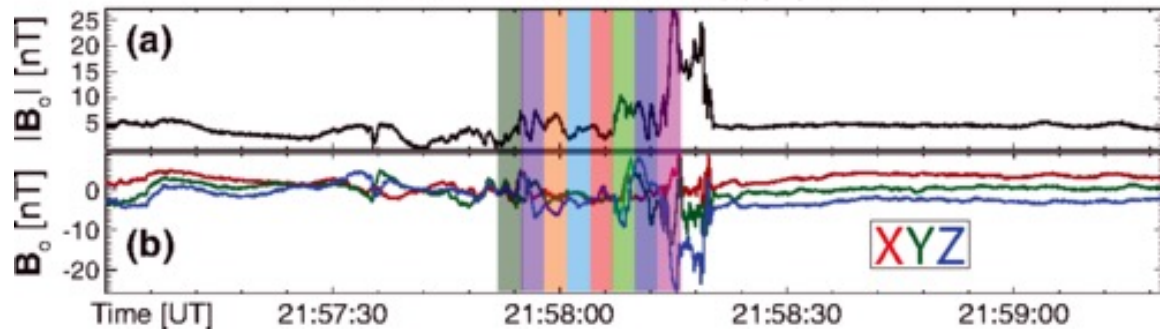
*See also: Wilson III L. et al. 2016; Turner et al. 2018; Liu et al. 2019; Shi et al. 2025 ; Tonoian et al. 2023; Kamaletdinov et al. 2024; Li et al. 2025

Foreshock Transients & Electron acceleration

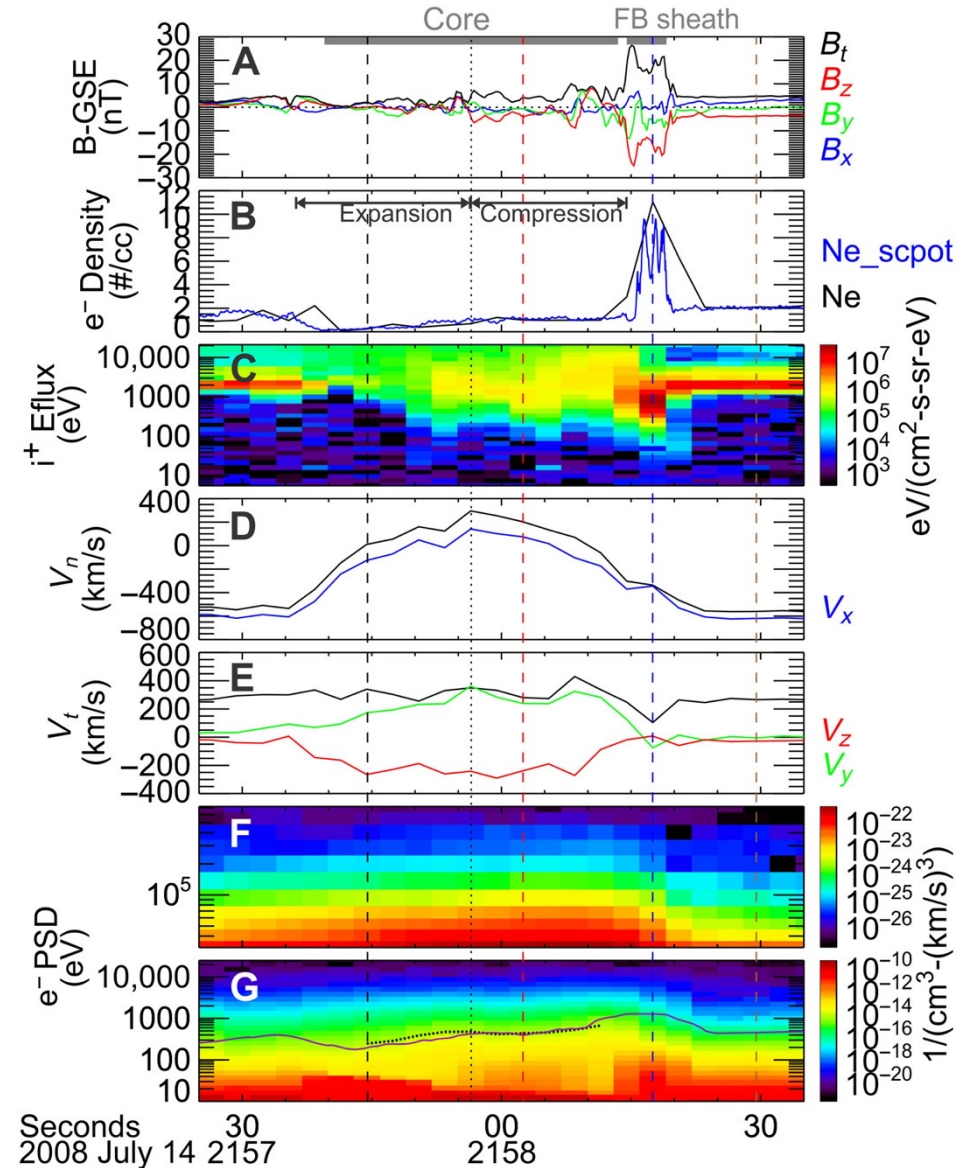
Combined low and high energy electron spectra



Foreshock Bubble on 2008-07-14

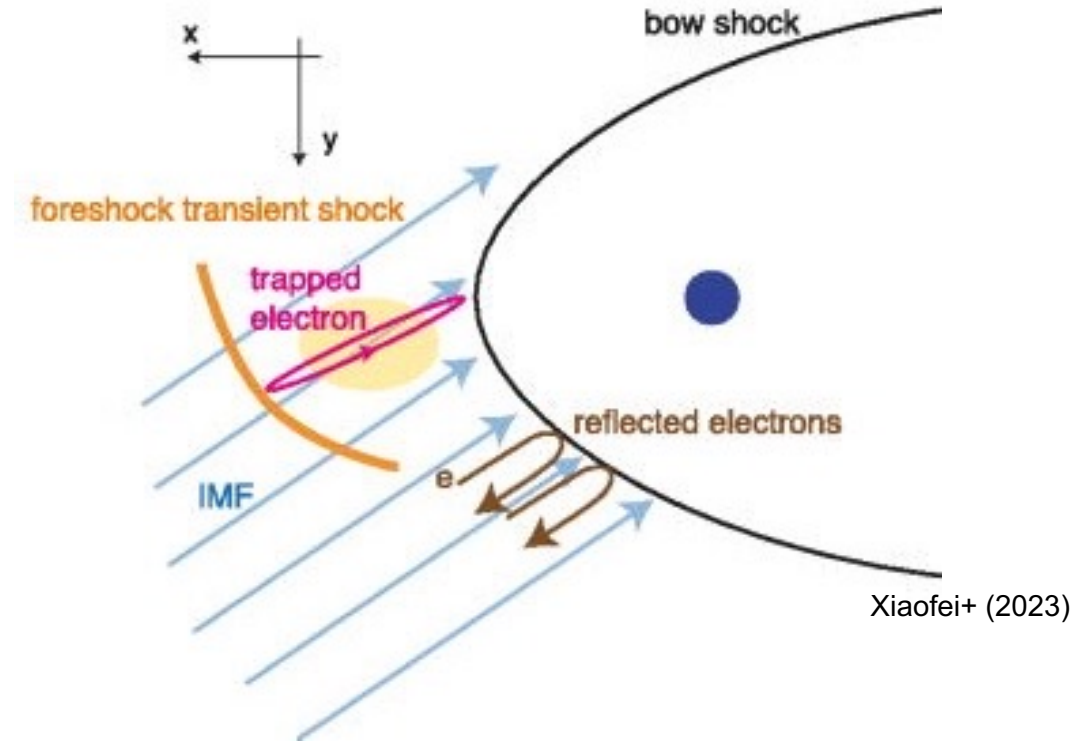
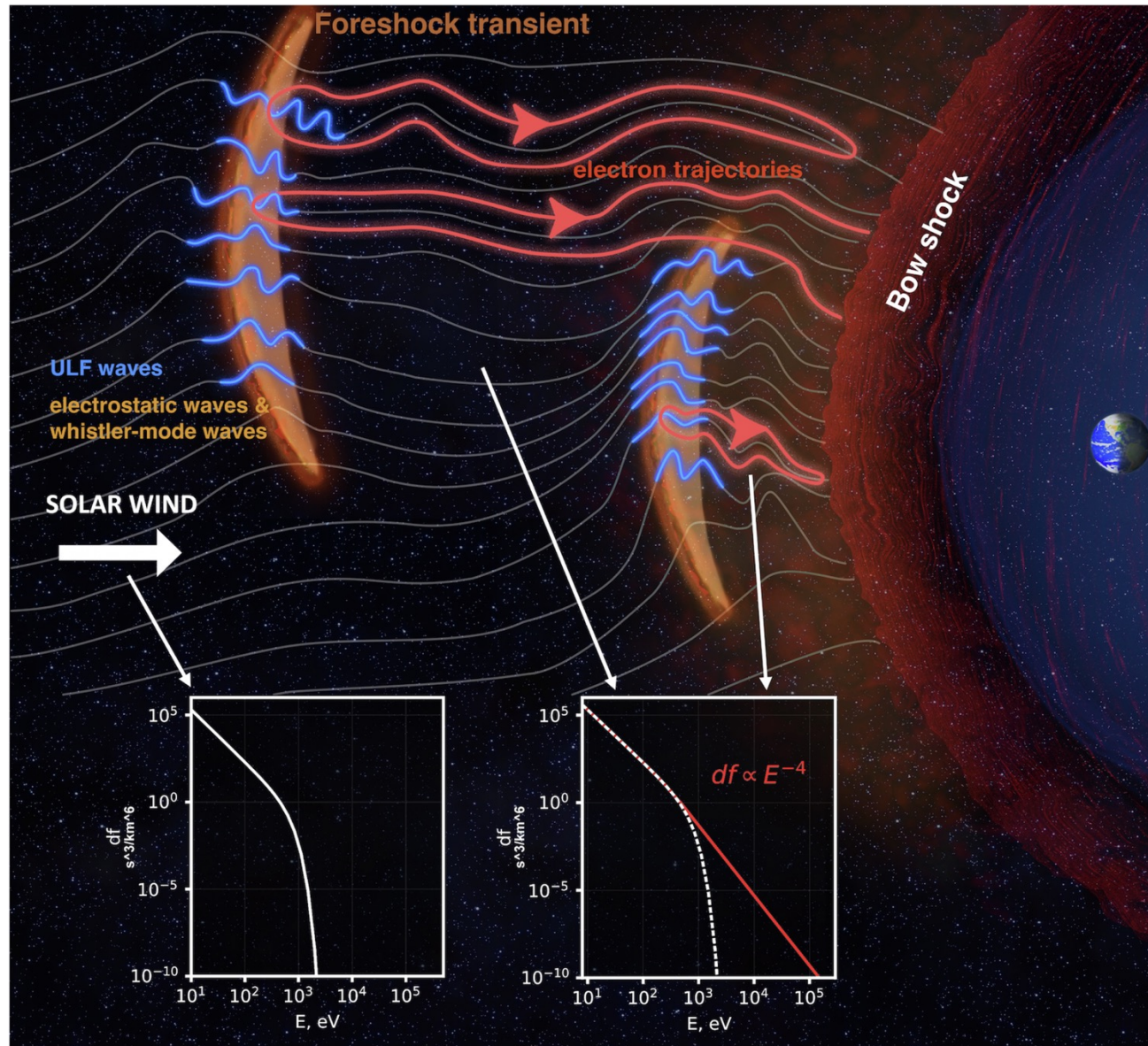


~300 KeV electrons



~200 KeV electrons

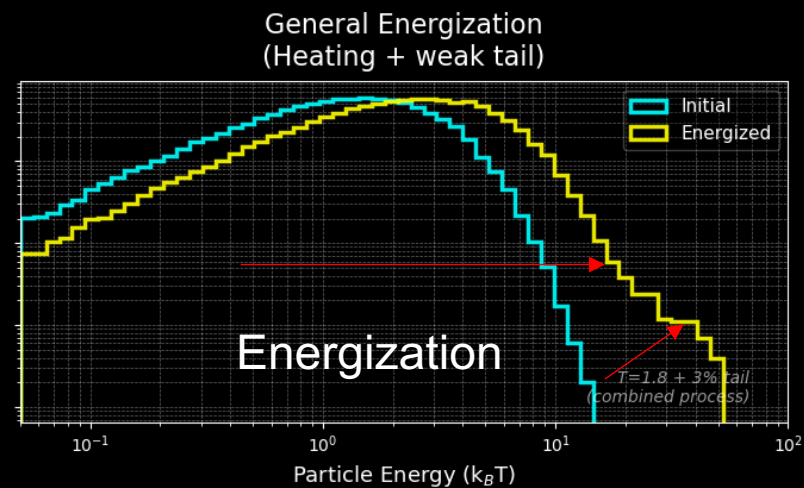
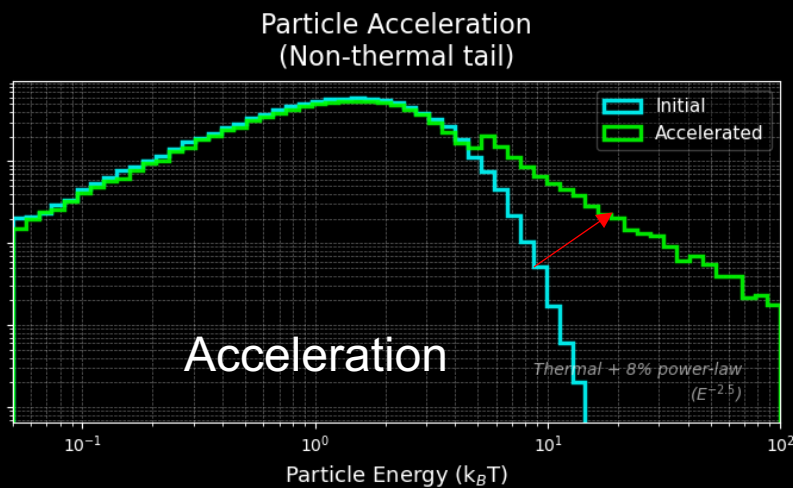
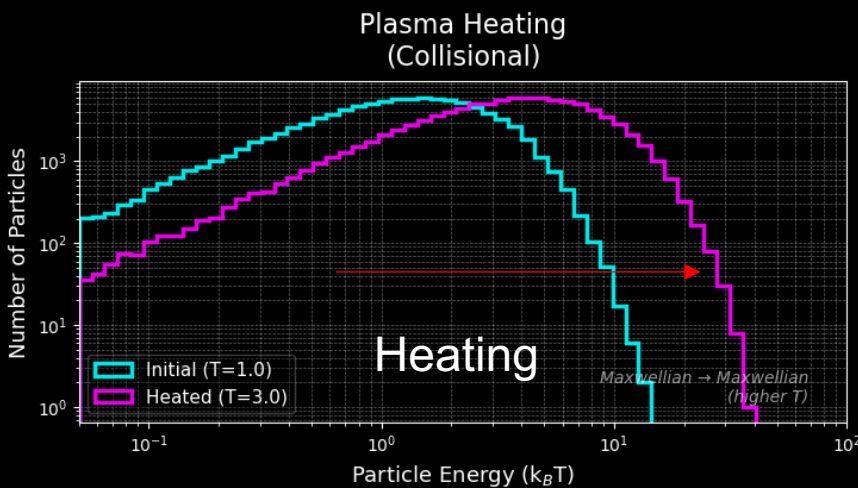
Recent advancements – Wave Particle Interactions



- Adiabatic heating
- Temperature Anisotropy
- High frequency whistlers
- non-adiabatic energization

Electron acceleration + pitch angle scattering

Plasma Energy Distribution Evolution



New Results on Electron Acceleration

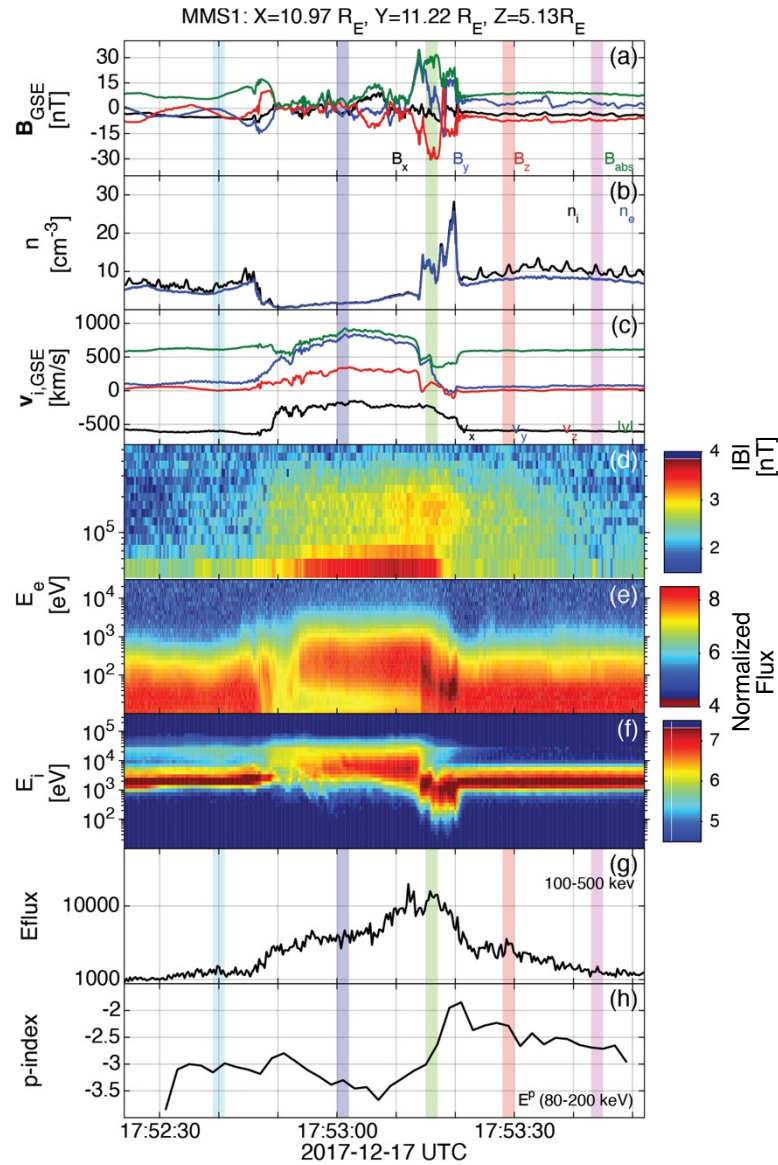
Reminder 1: So far we have use acceleration and energization interchangeably; there are differences though.

Reminder 2: **Non-adiabatic processes**: scales \sim gyroradius/gyroperiod, or when wave-particle interaction

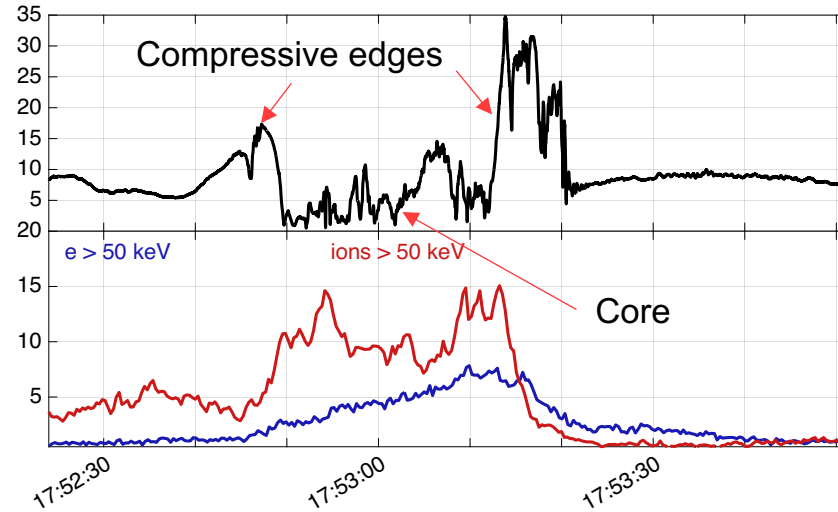
Reminder 3: **Qpar Shocks include the foreshock, the magnetosheath and their transient processes**



Relativistic Electrons with MMS



New plot, much easier to understand!



With respect to upstream conditions (SW/FS):

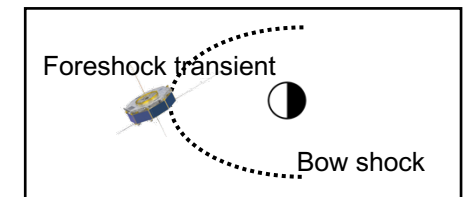
- Electron fluxes (>50 keV) up to x6
- Ion fluxes (>50 keV) up to x15

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)

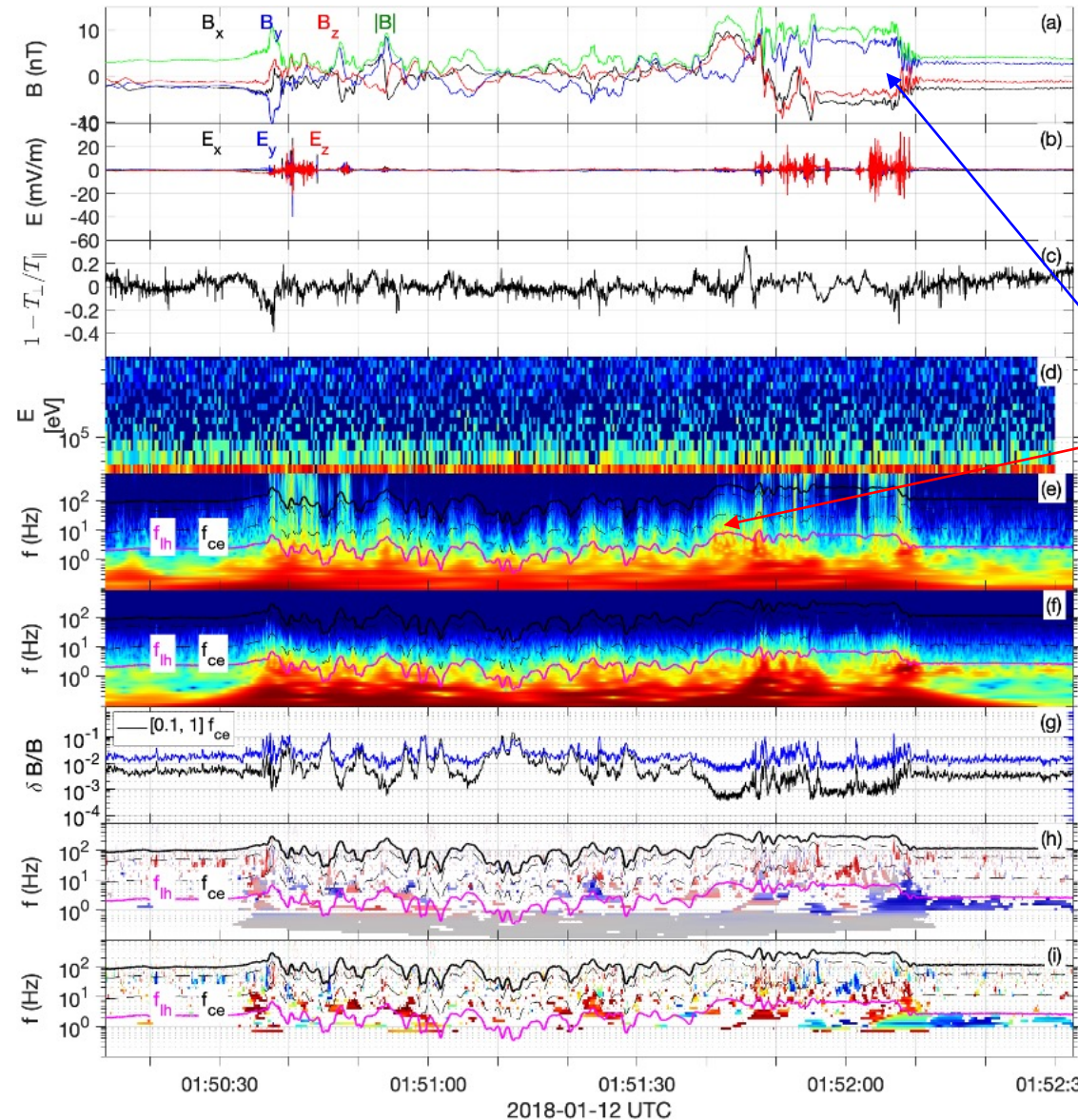
Unique property

>500 keV electrons throughout the core and shock region



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

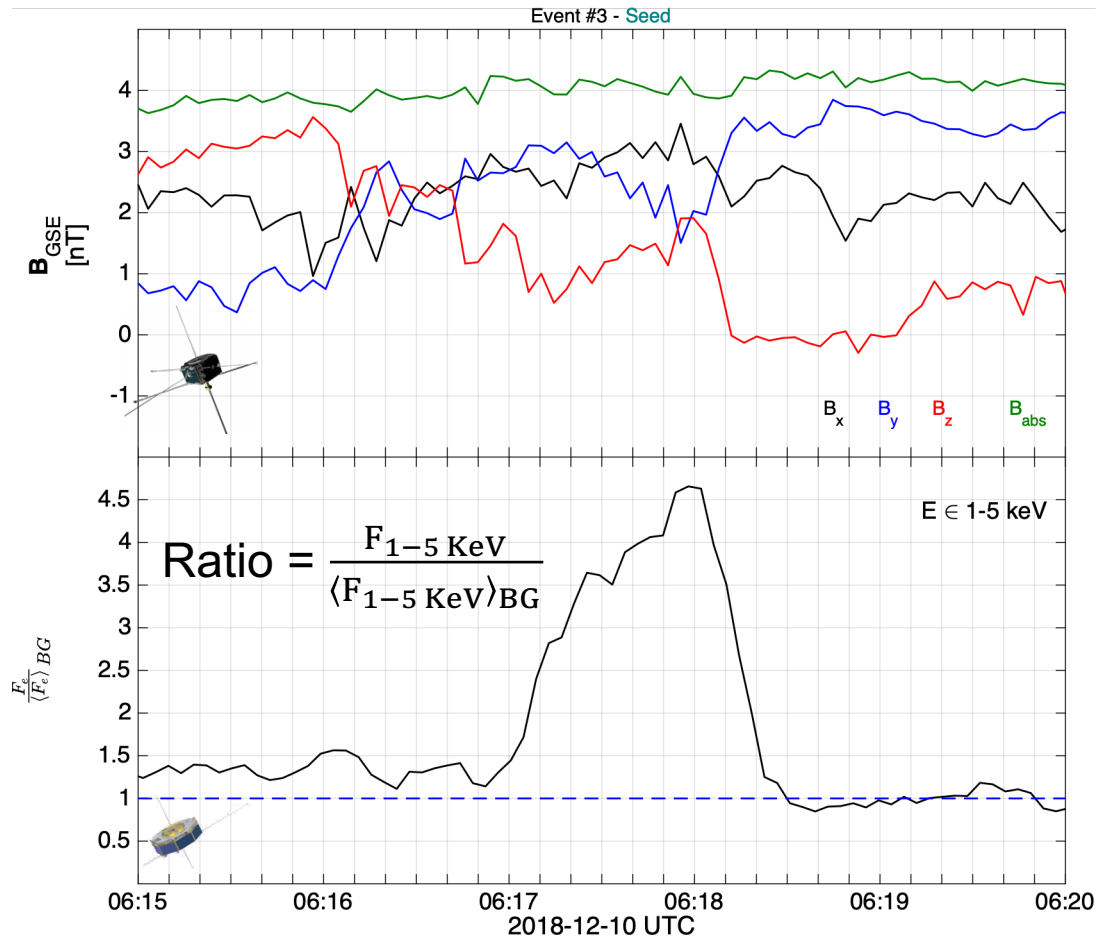
So why there are not always energetic electrons?



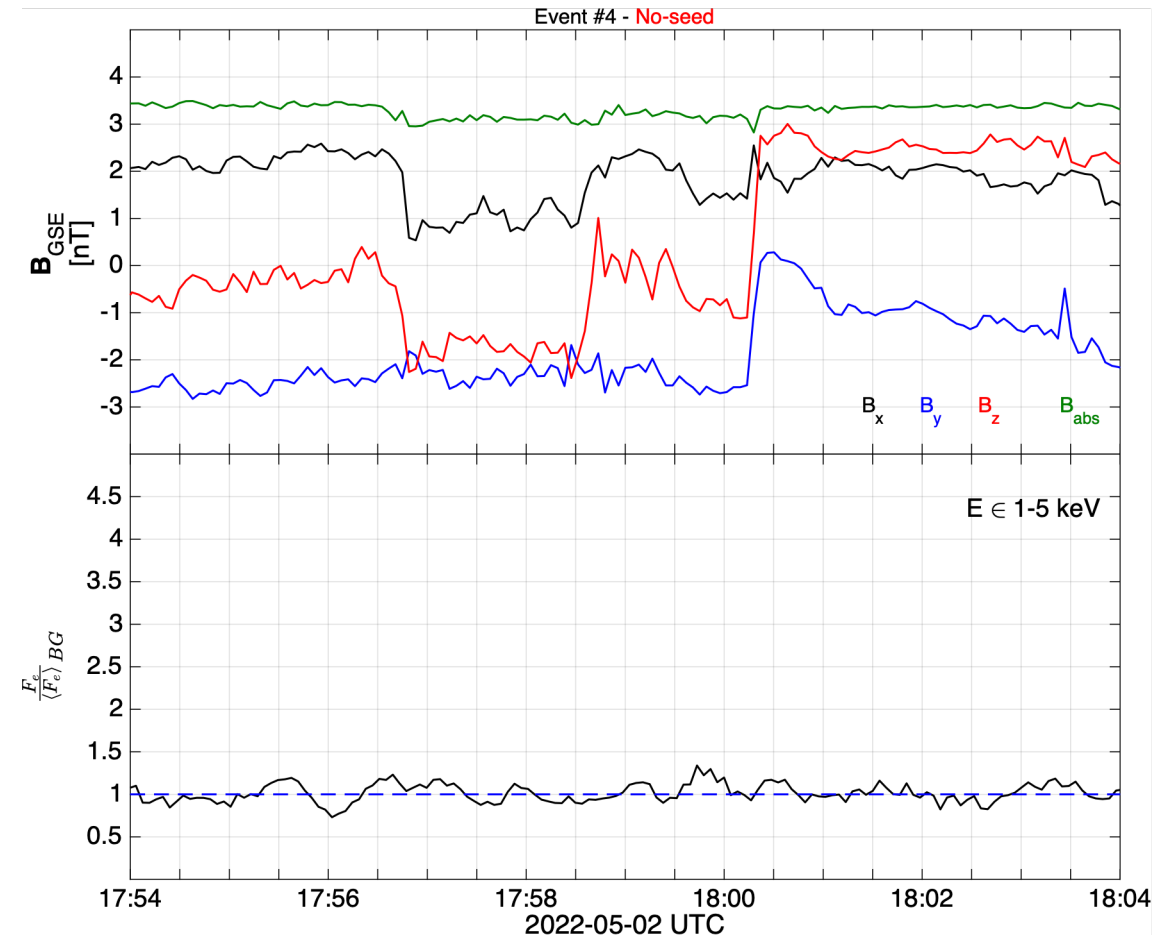
- Waves are there
- Localized shock is there
- All the stuff are there.

**FEEPS (panel d):
no signal?!**

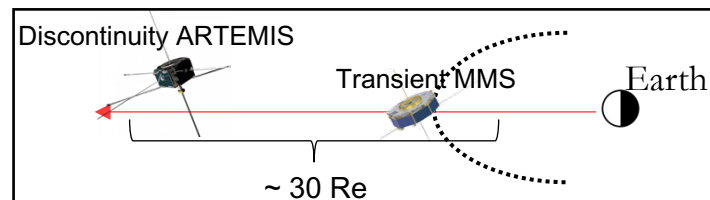
Upstream conditions for two events - ARTEMIS



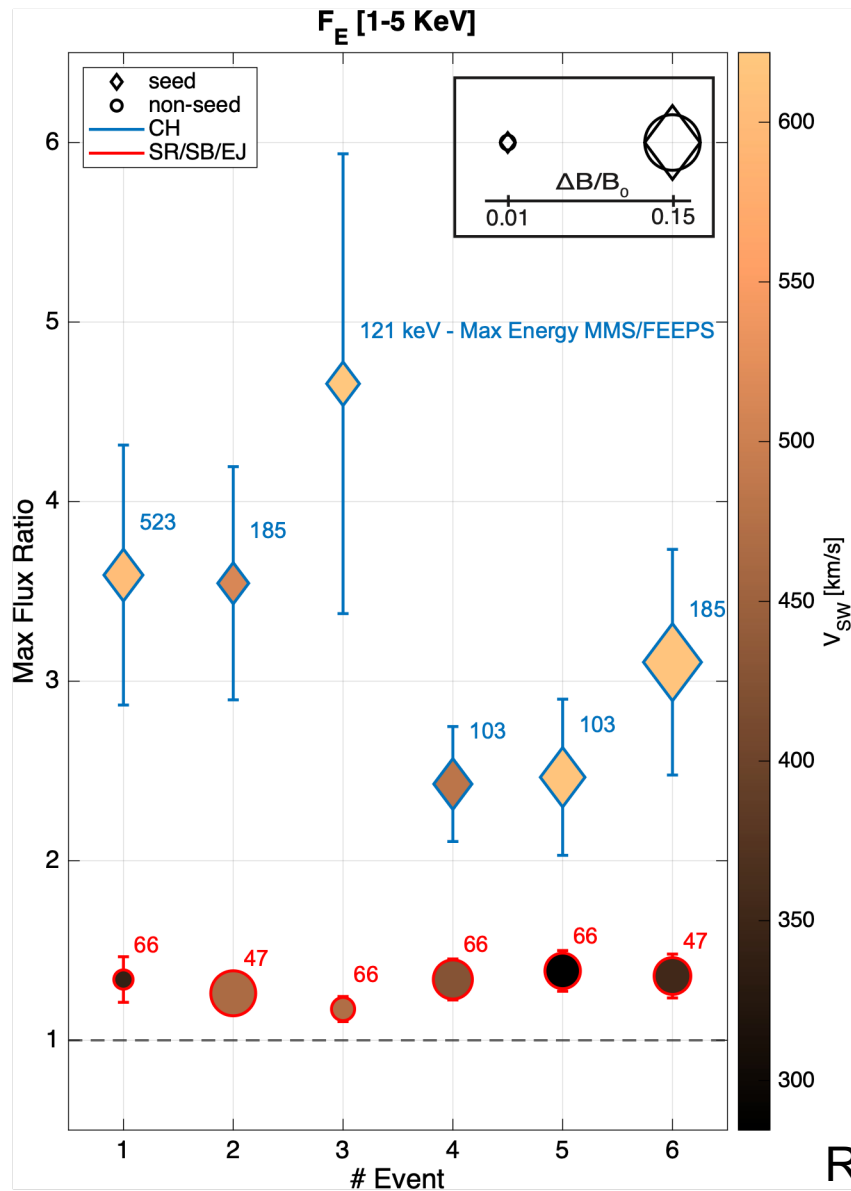
FEEPS: 100+ KeV



No Signal at FEEPS



Seeding and particle acceleration



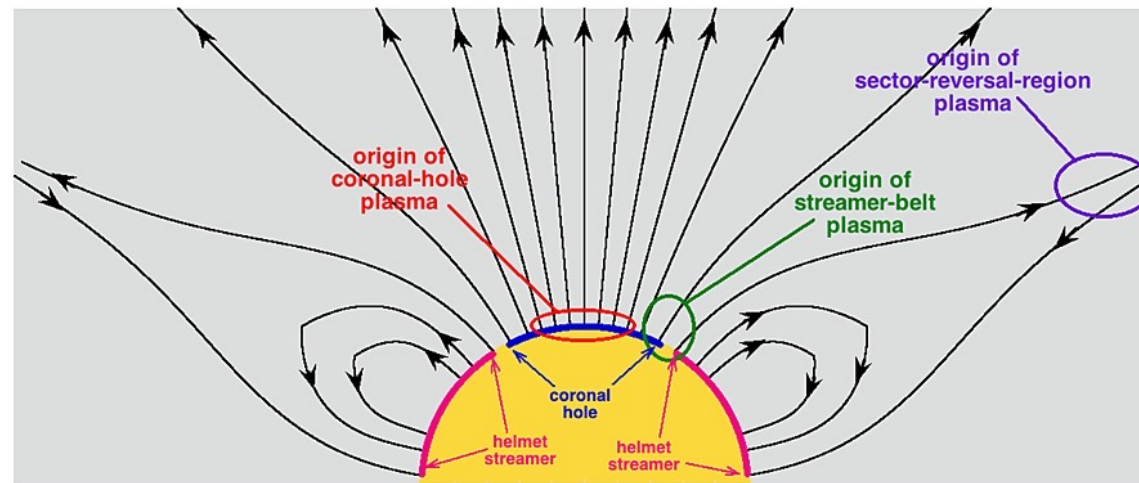
Seed events (FEEPS > 100 KeV)

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

No-seed (FEEPS = Noise)

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

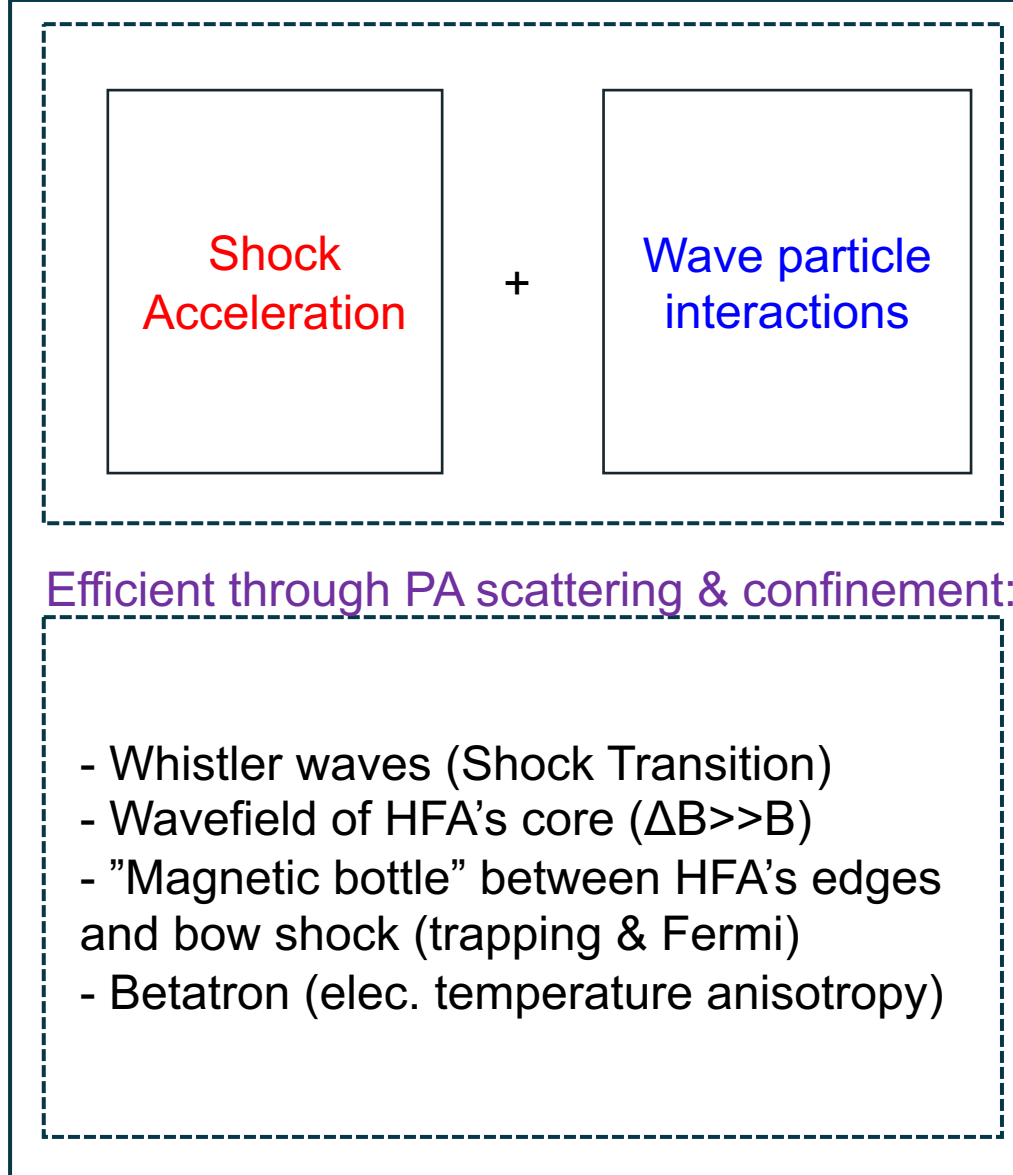
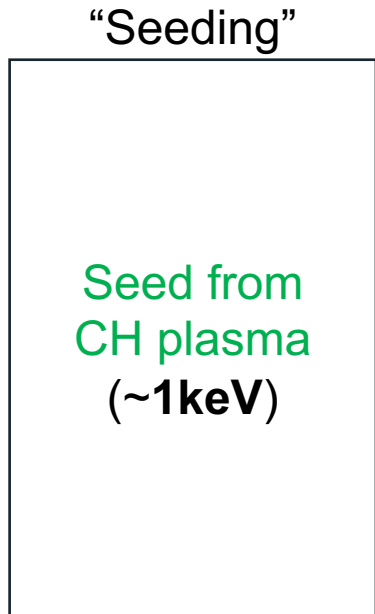
Using: [Xu and Borosvky 2014, Camporeale+ 2017] methodology



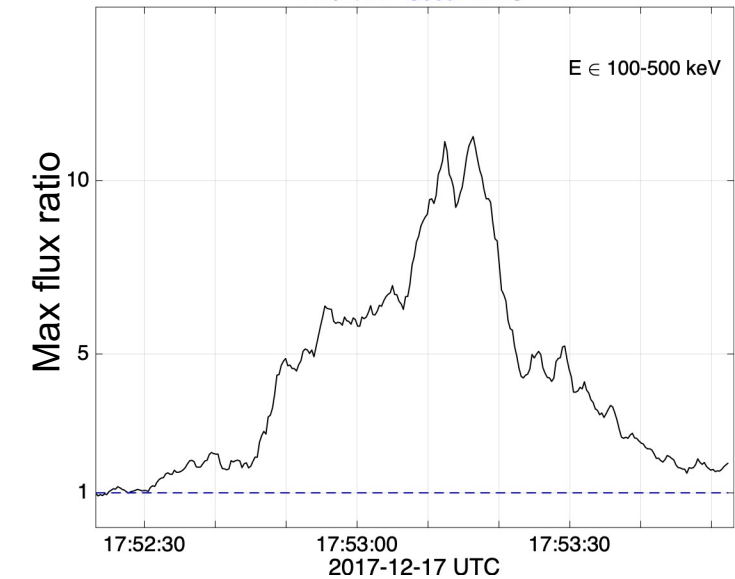
$$\text{Ratio} = \frac{F_{1-5 \text{ KeV}}}{\langle F_{1-5 \text{ KeV}} \rangle_{\text{BG}}}$$

Reinforced Shock Acceleration

Electron acceleration at Foreshock Transient



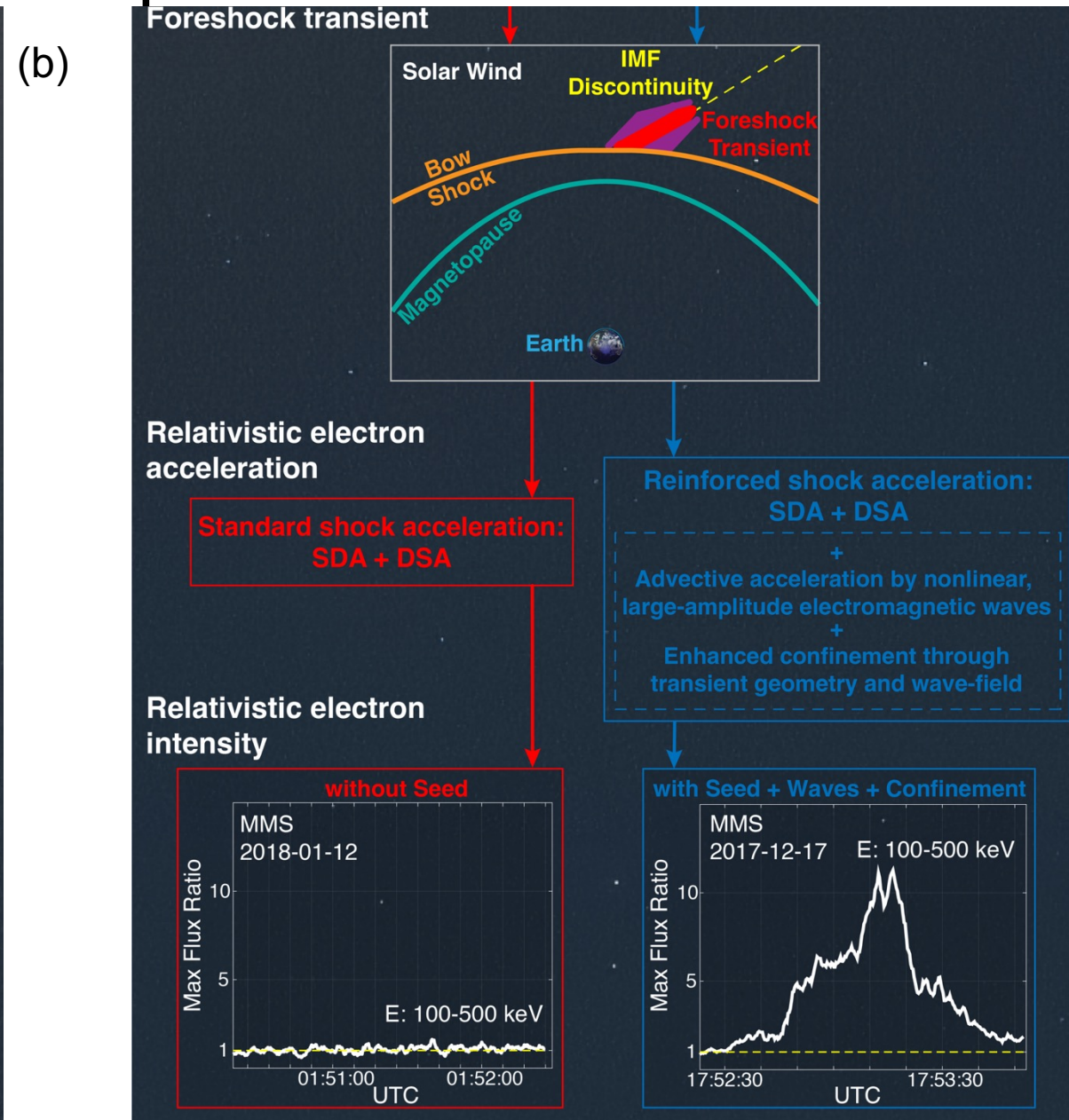
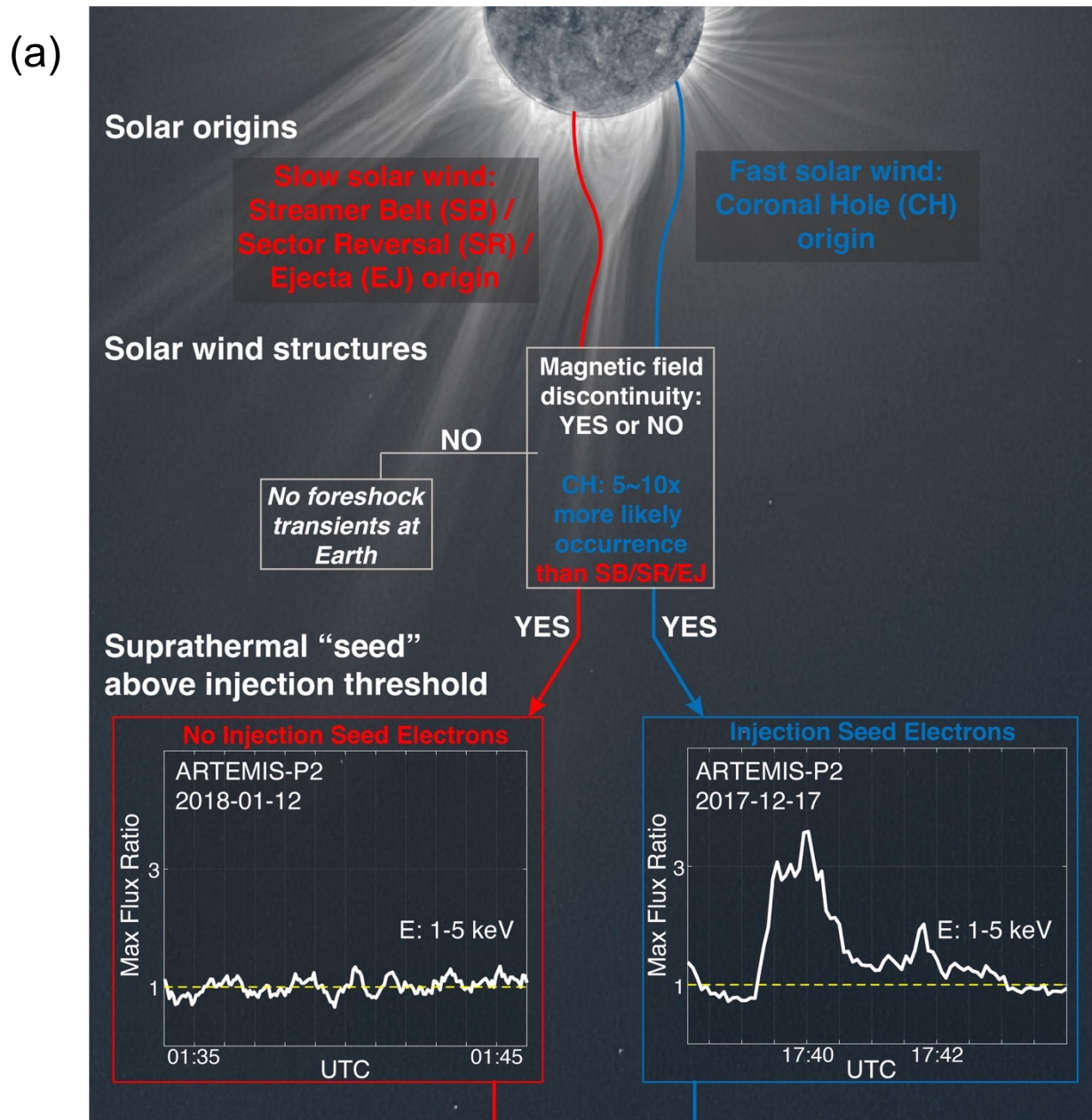
$$\text{Ratio} = \frac{F_{100-500 \text{ KeV}}}{\langle F_{100-500 \text{ KeV}} \rangle_{\text{BG}}}$$



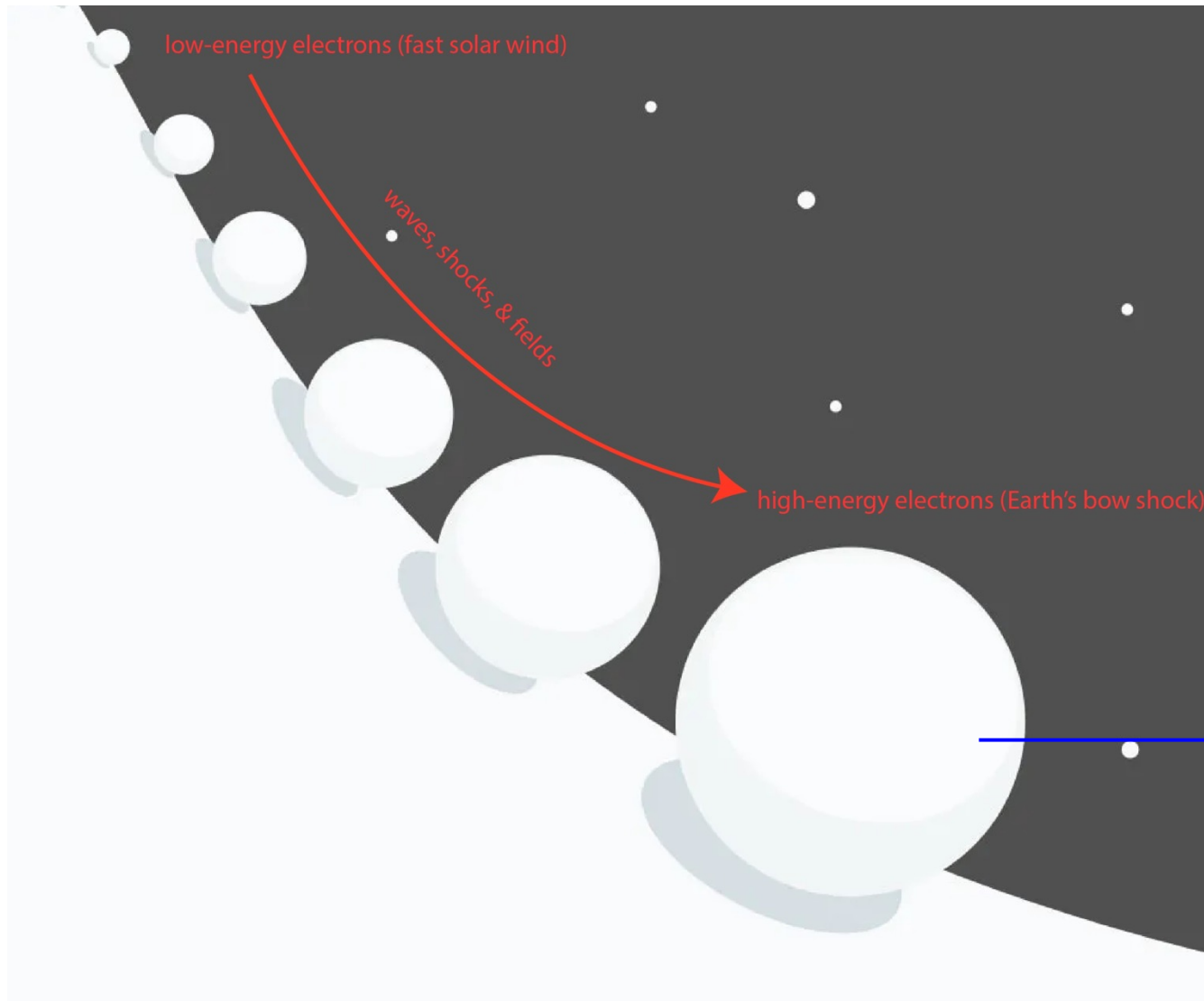
Note: Framework is consistent with all other studies (e.g., Wilson+2016, Liu+2019, Shi+2025)

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

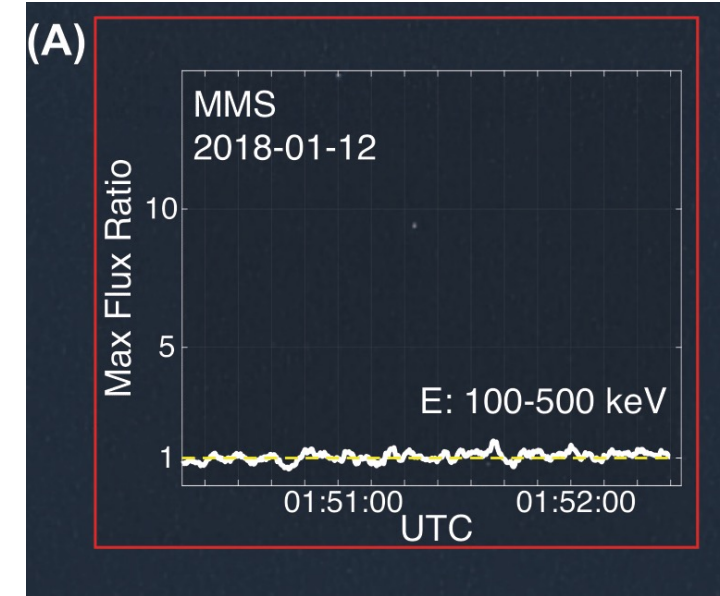
Schematic of the process



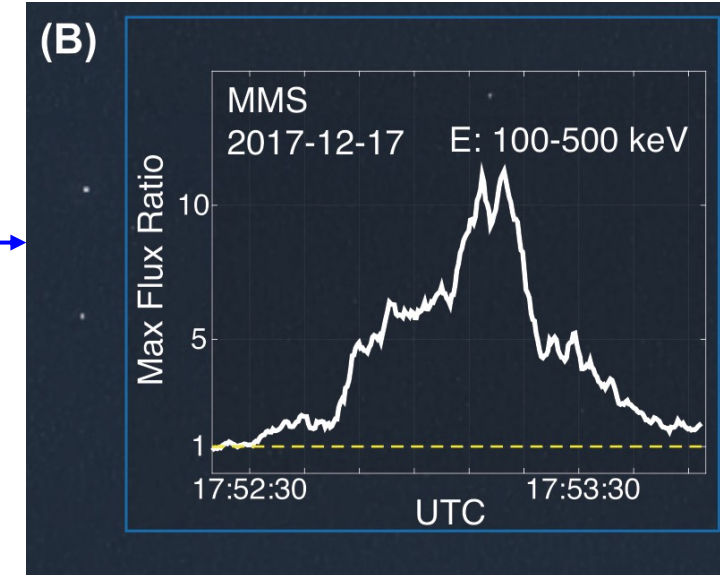
Simple Simplistic Picture to remember



✗

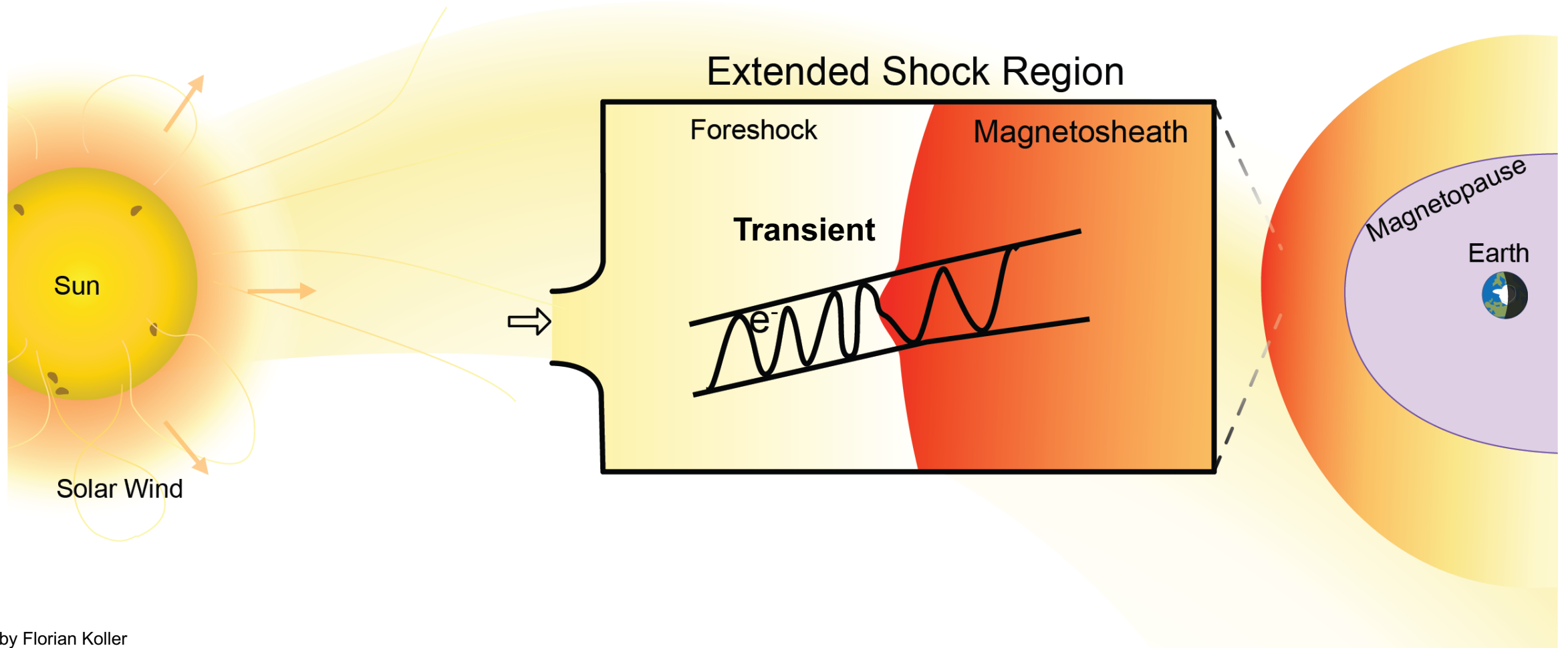


✓



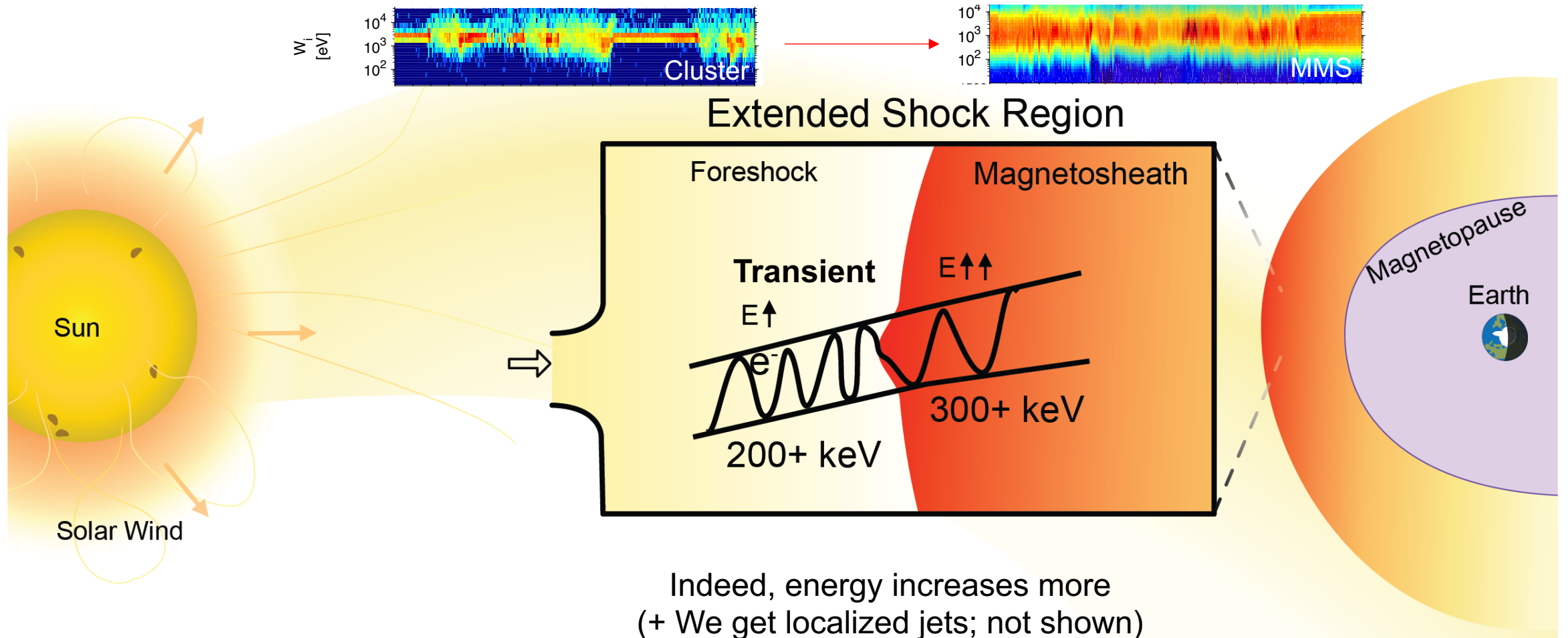
But let's ask one more question

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

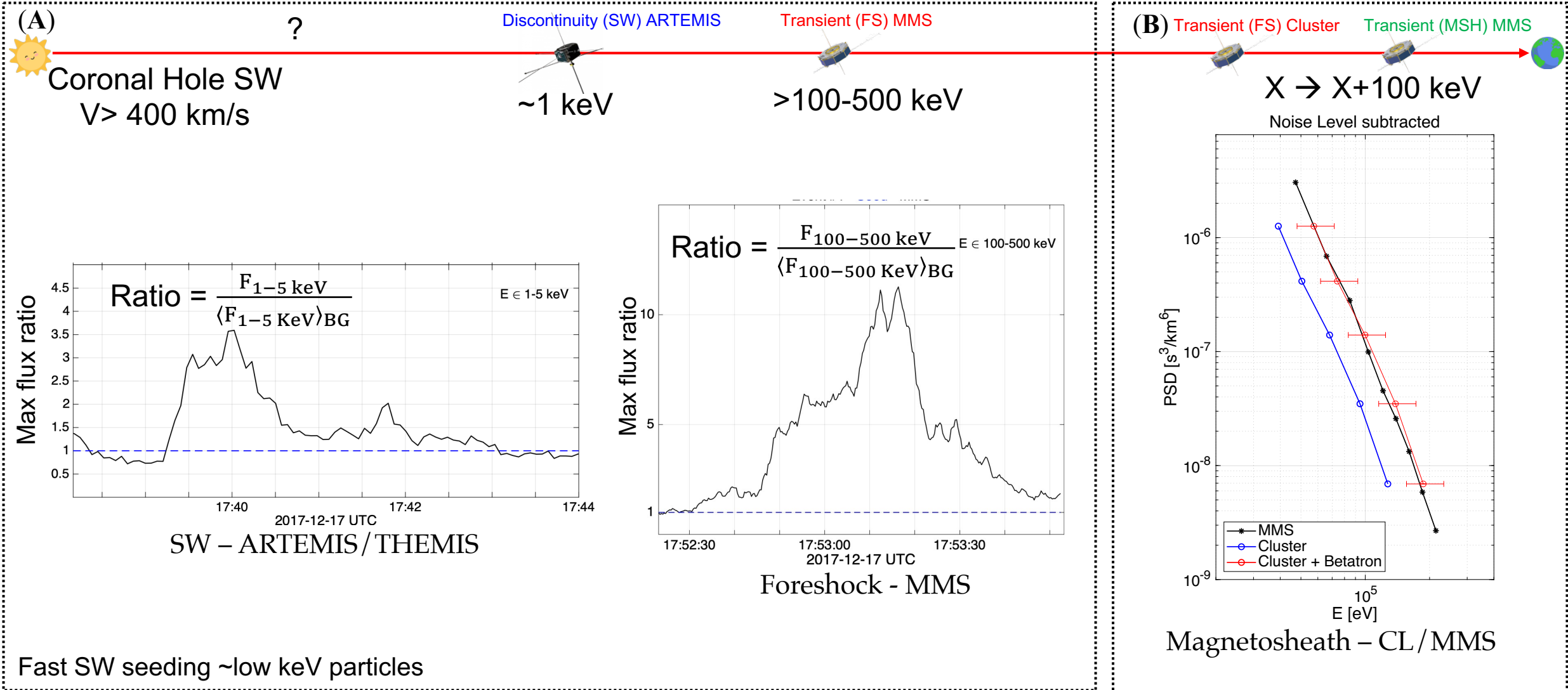


But let's ask one more question

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



Reinforced Shock Acceleration: 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*

Even fresher results!

The question now is:

What about other planets?

Particle Acceleration: Hillas Criterion and Scales

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

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

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

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

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

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

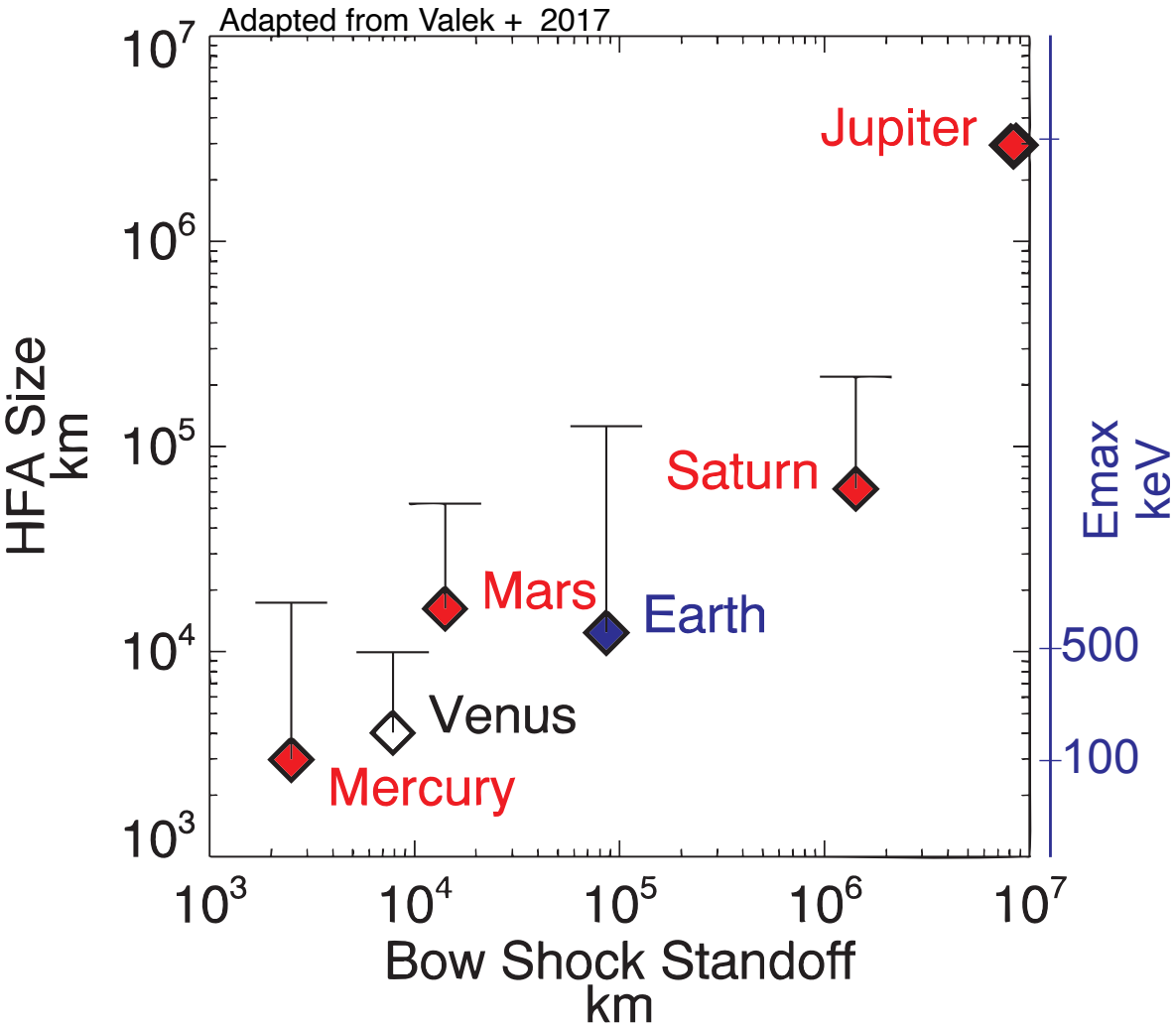
For simplicity in the ultra relativistic regime (not in our solar system) this results :

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

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

See also recent work of Oka+ 2025

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):

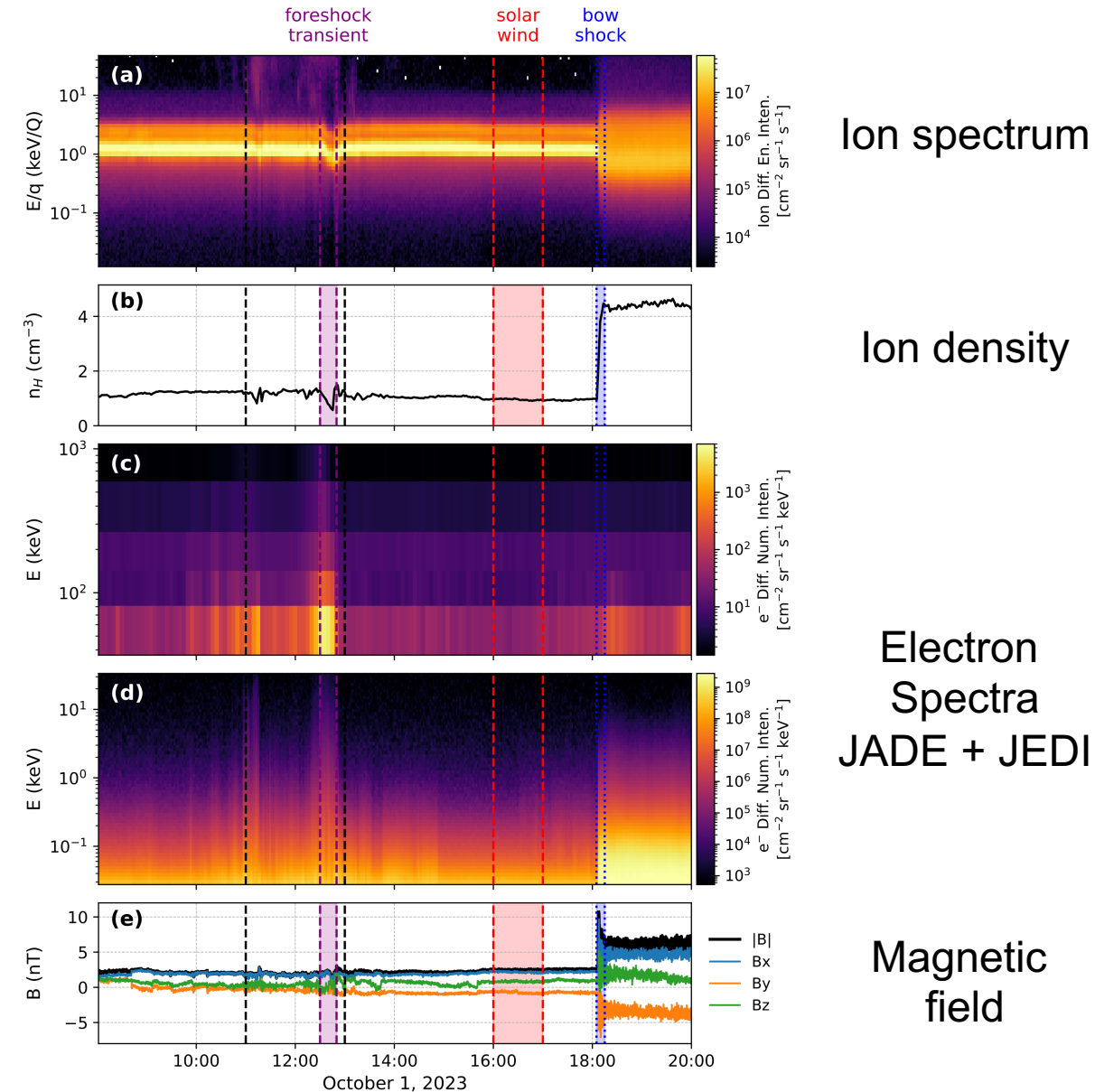
- Energetic electrons **up to 1 MeV** (*agreement with Raptis+2025a,b, Shi+2025*)
- Disrupted solar wind beam
- Localized depletion of n and B

Solar wind (SW):

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

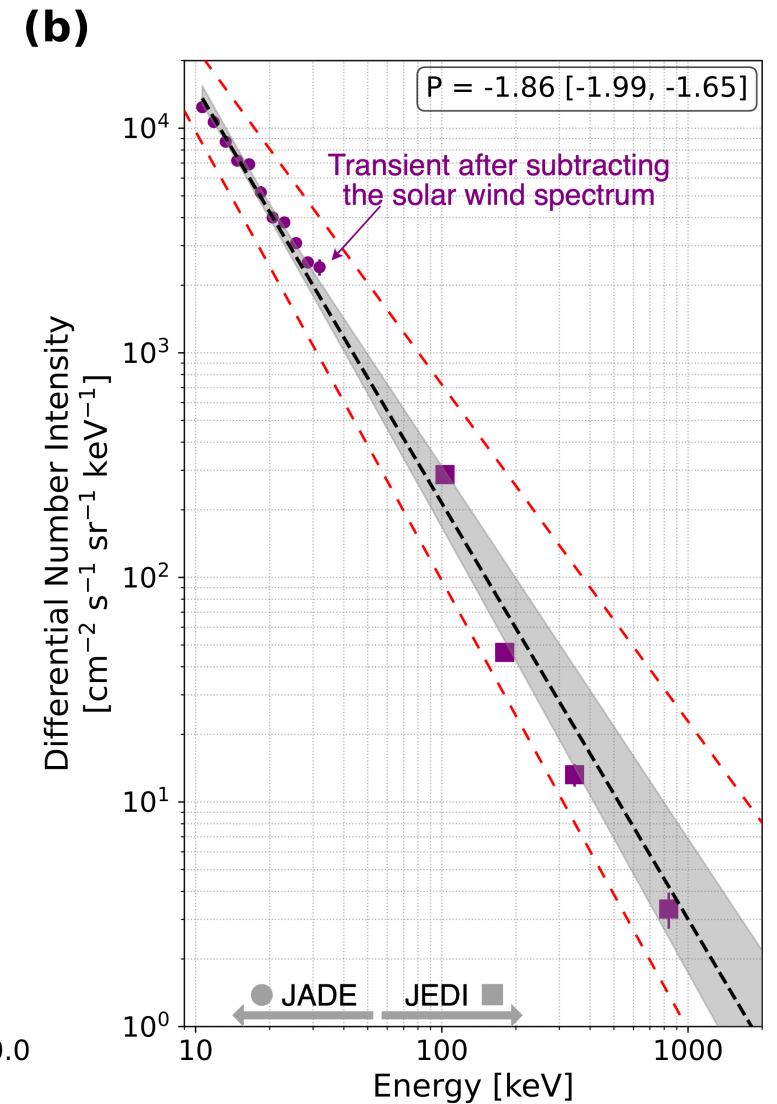
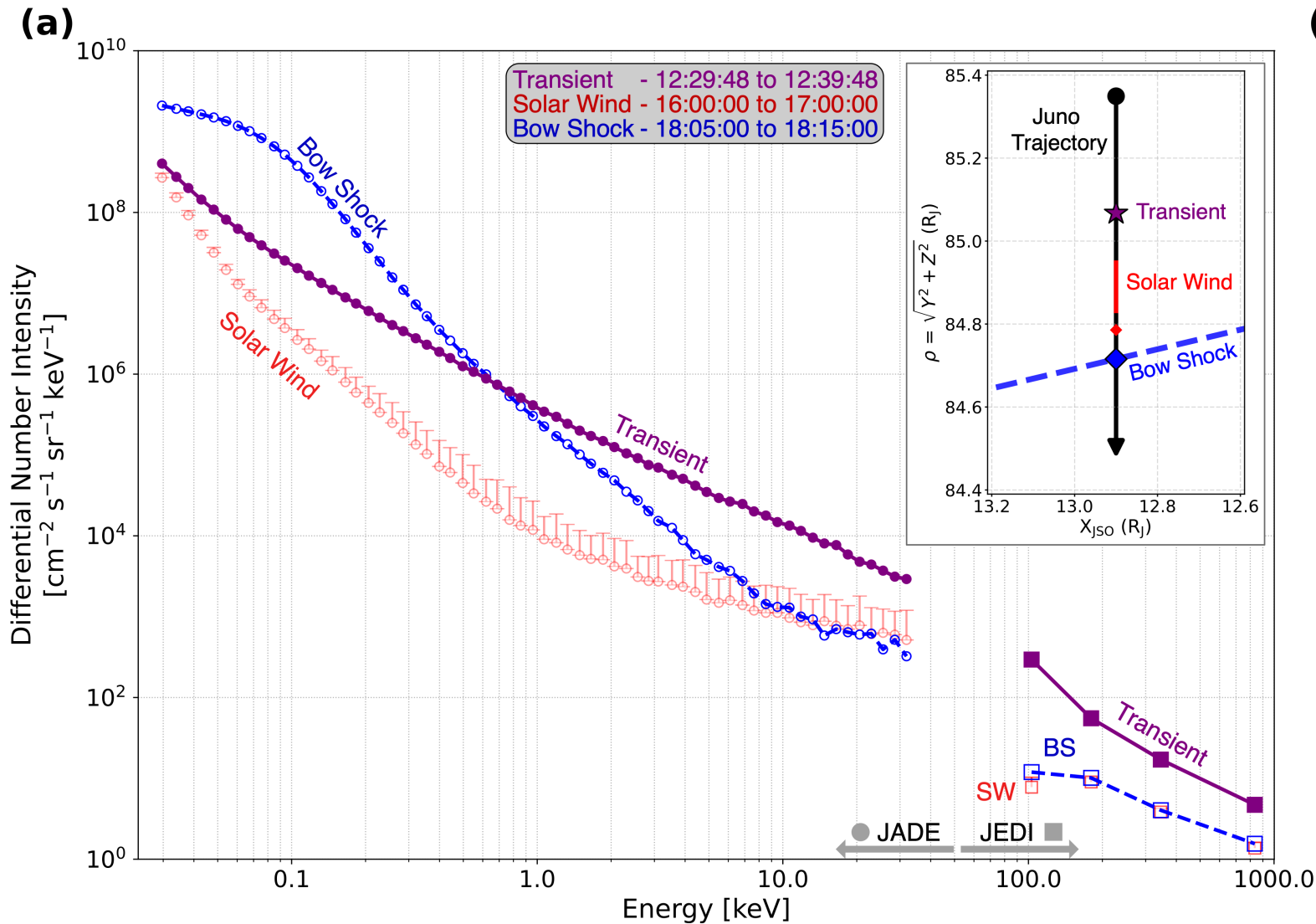
Bow shock (BS):

- 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



This “DSA-like” acceleration happens at the transient, bow shock crossing only up to <10 keV

Illustration of the process in an arbitrary planet

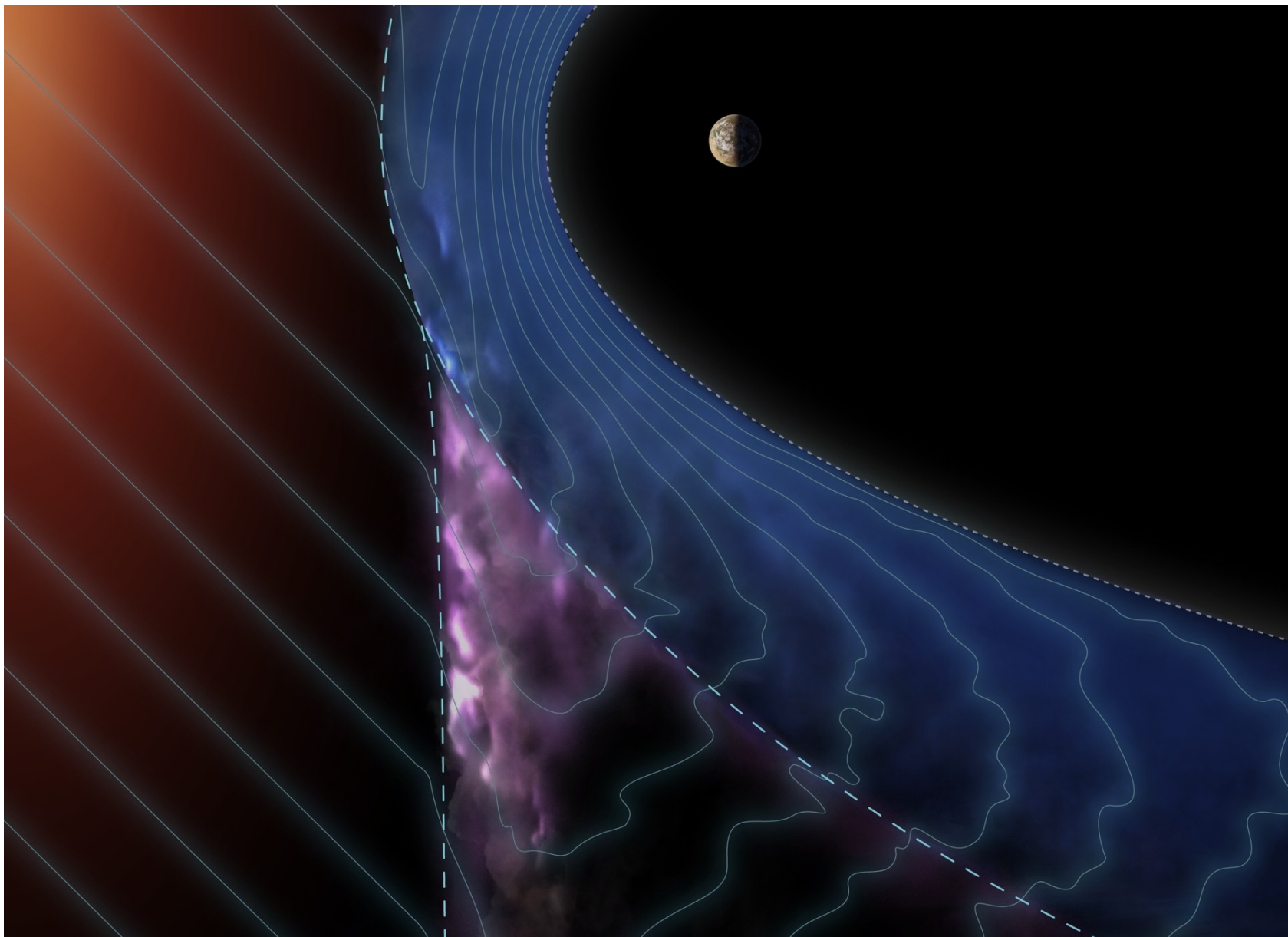


Illustration of the process in an arbitrary planet

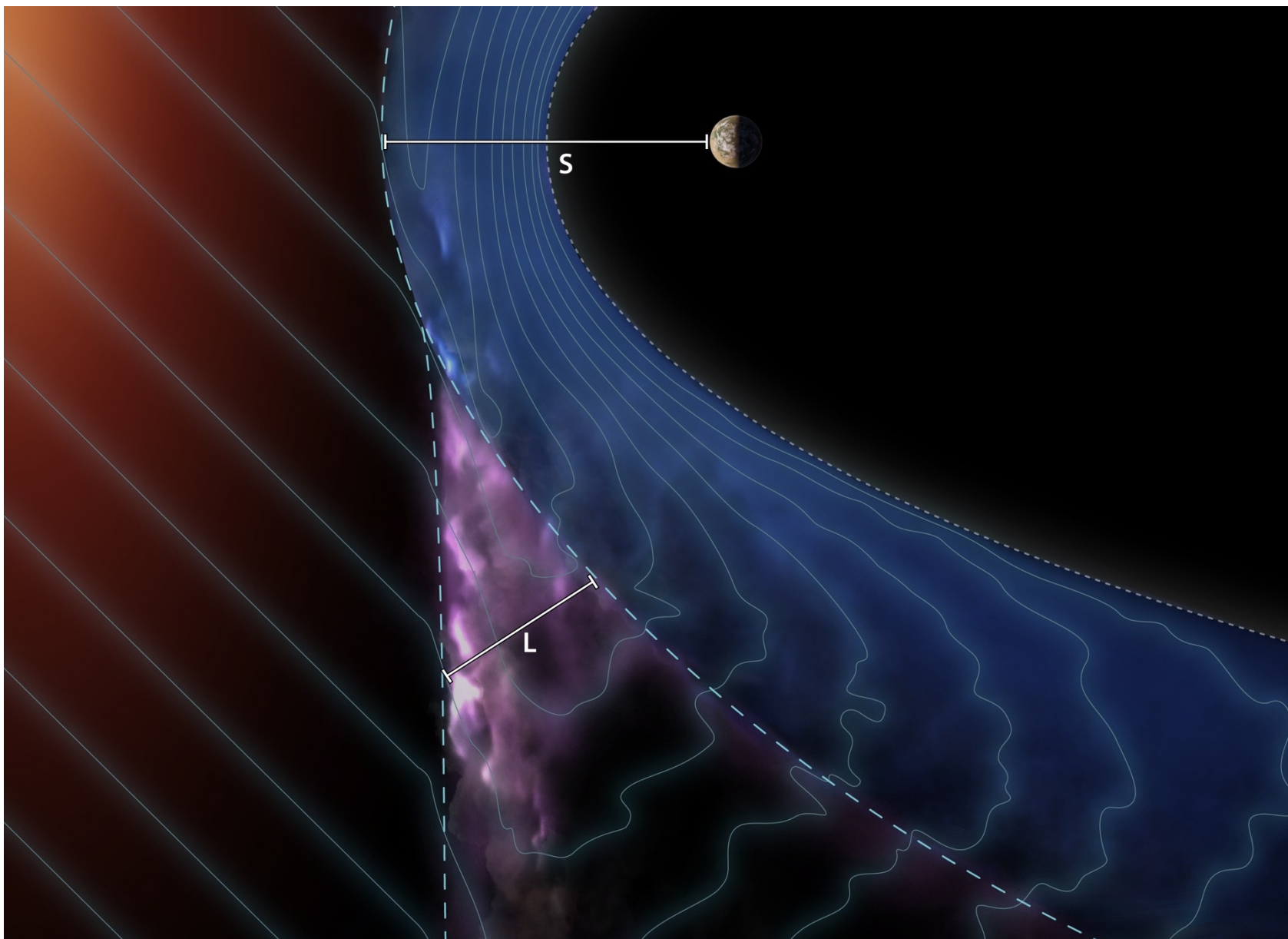


Illustration of the process in an arbitrary planet

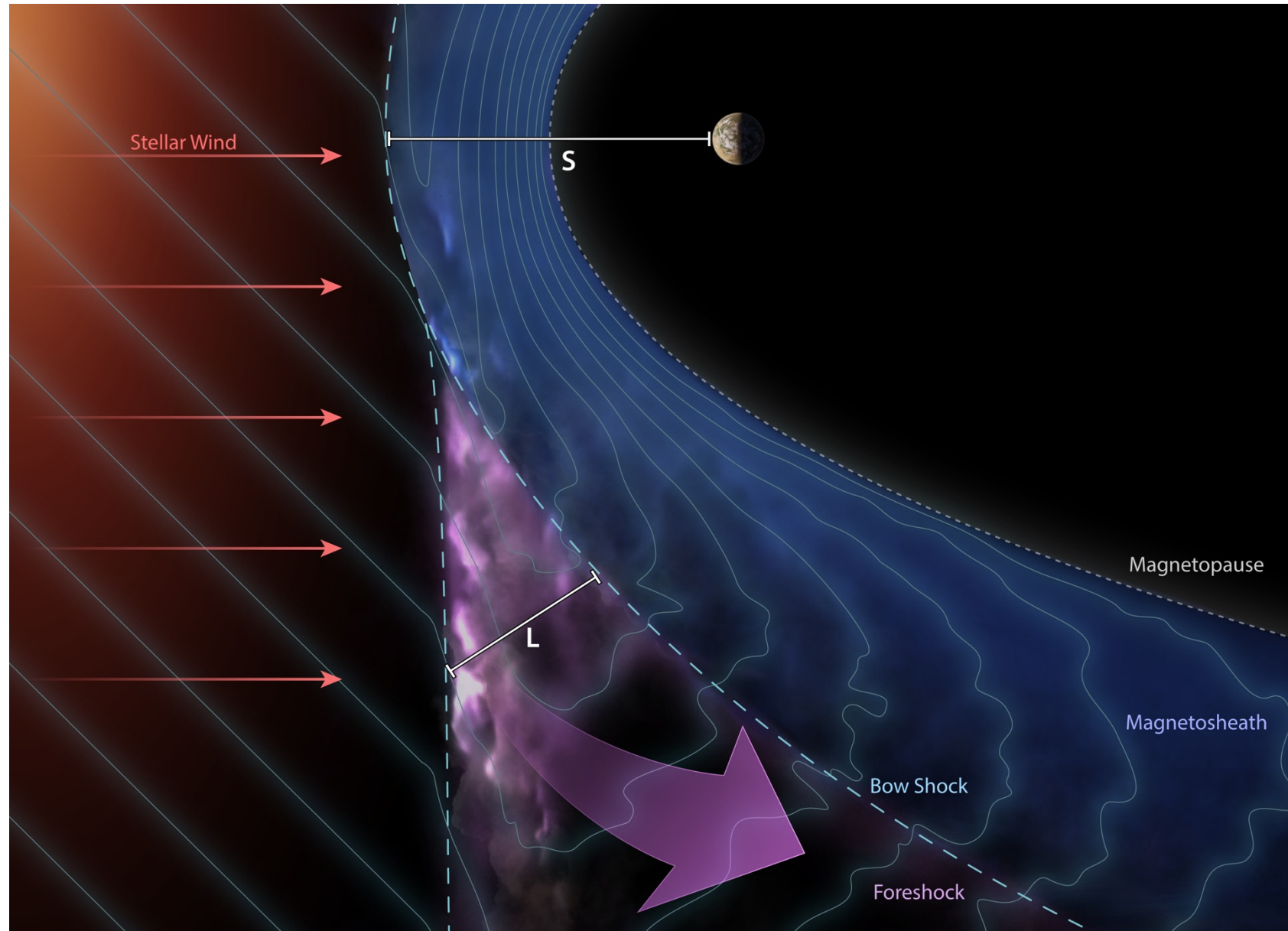
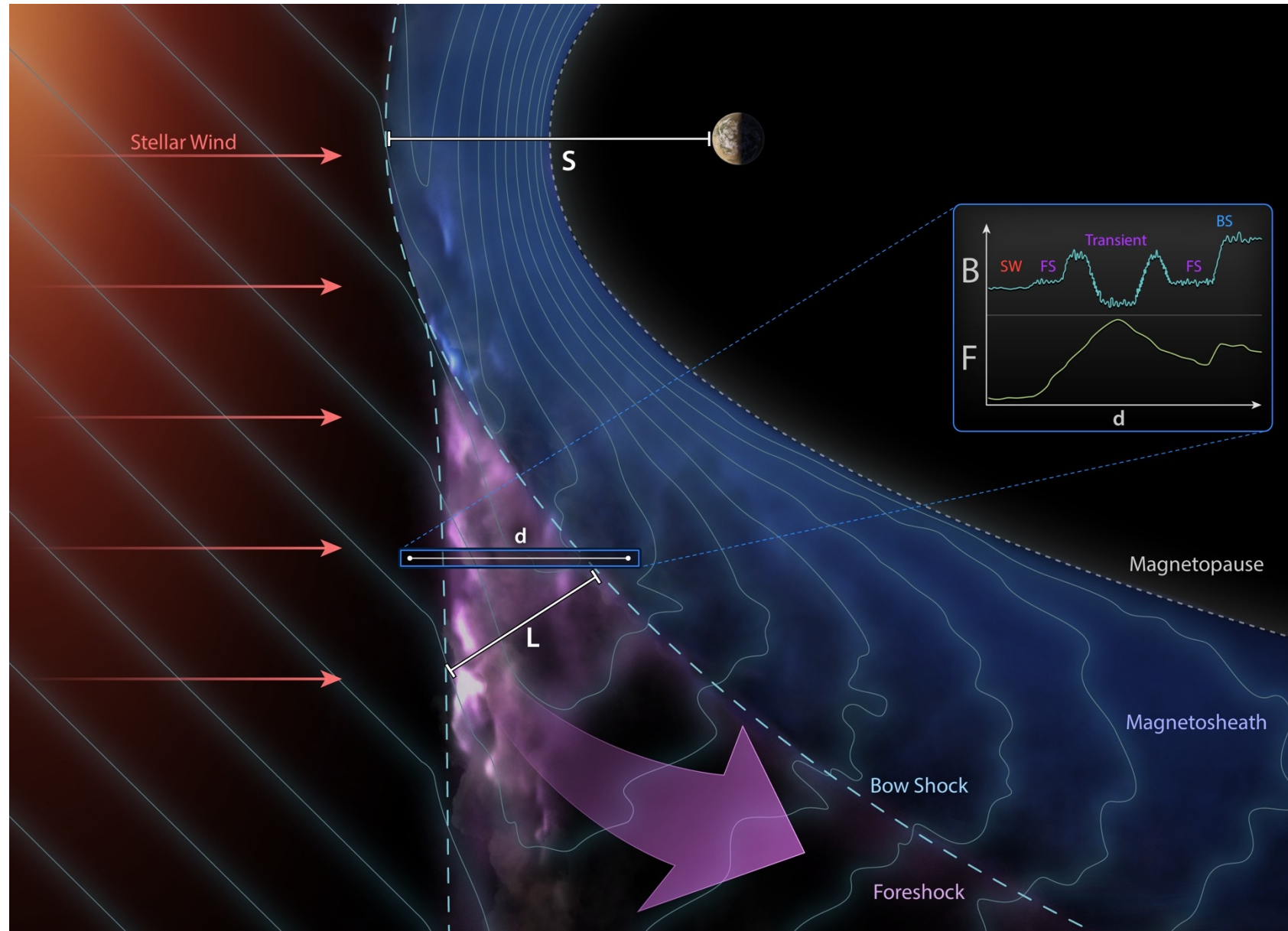


Illustration of the process in an arbitrary planet



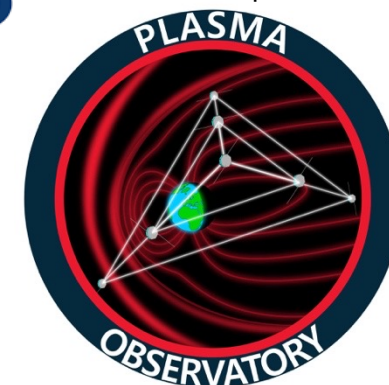
Summary & Concluding Words



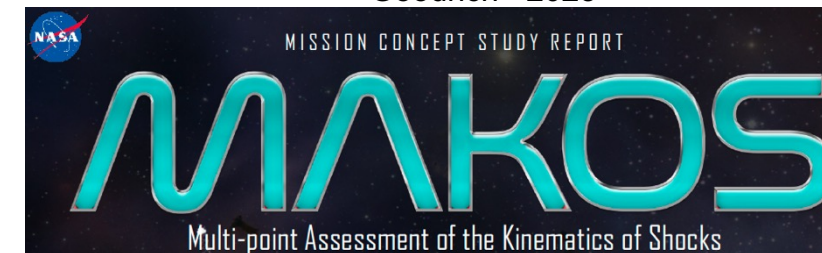
McComas+ 2025

IMAP

Retino+ 2021 | Ex. Astro.



Goodrich+ 2023



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 ($\sim 1\text{--}5$ keV) intrinsic to fast solar wind. Localized transients act as the primary driver to boost these electrons to high energies (100s of keV). (Raptis et al., 2025a | NatComm)
- ❖ **A Two-Step Mechanism:** Particles get energized when larger transients (i.e., HFAs/FBs) cross the bow shock. For energetic particles, additional acceleration can be modeled by “adiabatic” compression (betatron) and strong scattering. (Raptis et al., 2025b | ApJL)
- ❖ **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 up to 100 TeV particles in in supernova shocks (e.g., SN 1006) in agreement with cosmic ray observations. (Raptis et al., 2026 | under review)

NSF GEM FG: (MDT) Multiscale Dayside Transients and their Effect on Earth's Magnetosphere (2025 – 2029)

Savvas Raptis, Ivan Vasko, Imogen Gingell, Terry Z. Liu, Ying Zou, Runyi Liu, David Tonoian

Extras

Zoomed-in timeseries of Transient

Foreshock Transient (HFA):

- High energy electrons **up to 1 MeV** (agreement with *Raptis+2025a,b*)
- Disrupted solar wind beam
- Localized depletion of n and B

Global Geometry:

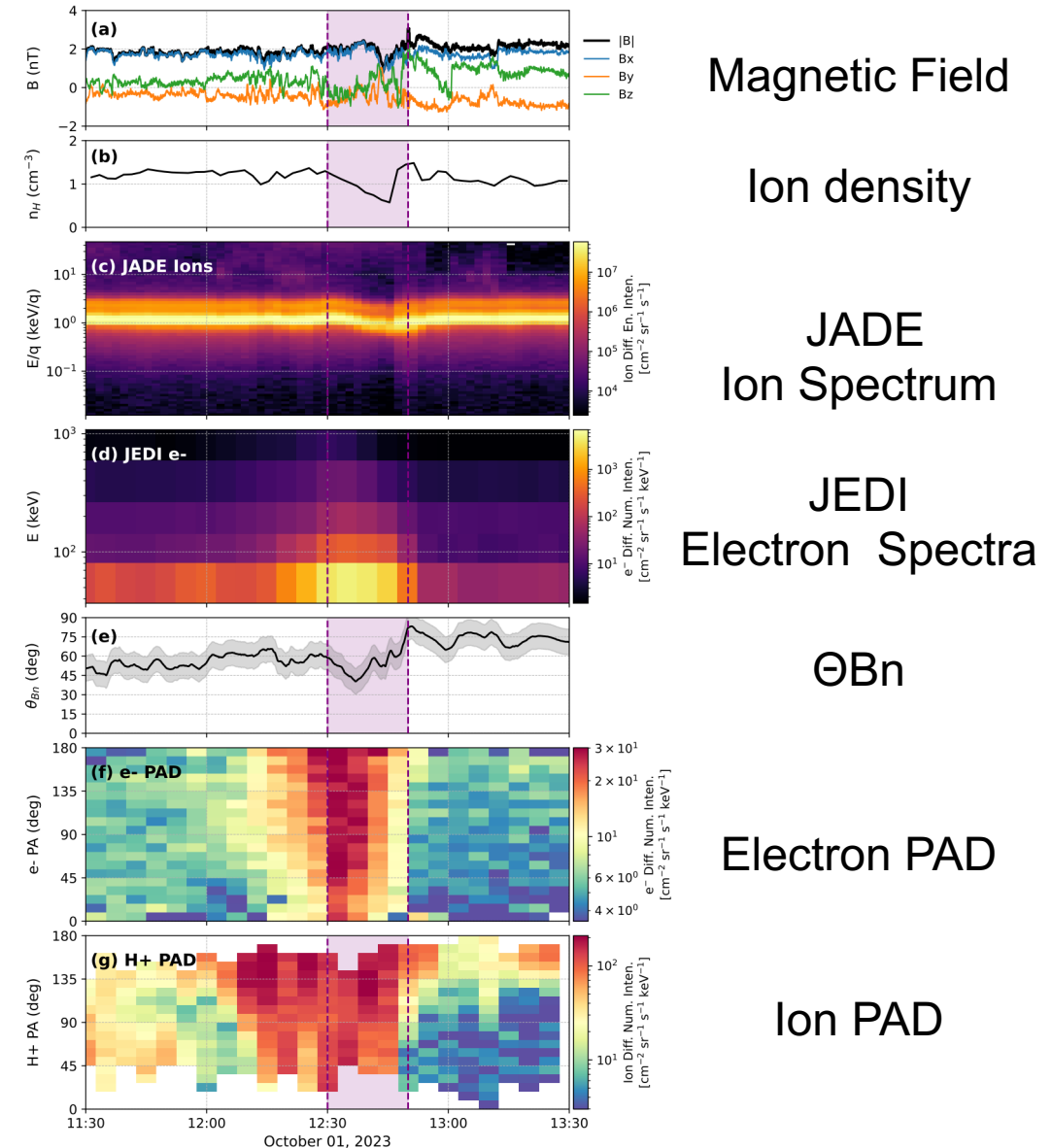
- Using bow shock model (Joy+ 2002), local angle changes from ~ 40 to ~ 75 degrees

Pitch Angle Distributions (PADs):

- ✓ Isotropic distribution, strong scattering
- ✓ No trapped population
- ✓ Localized within the ~ 15 min interval

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

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



Can we extrapolate to astrophysical bow shocks?

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

Assumptions & Methods

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

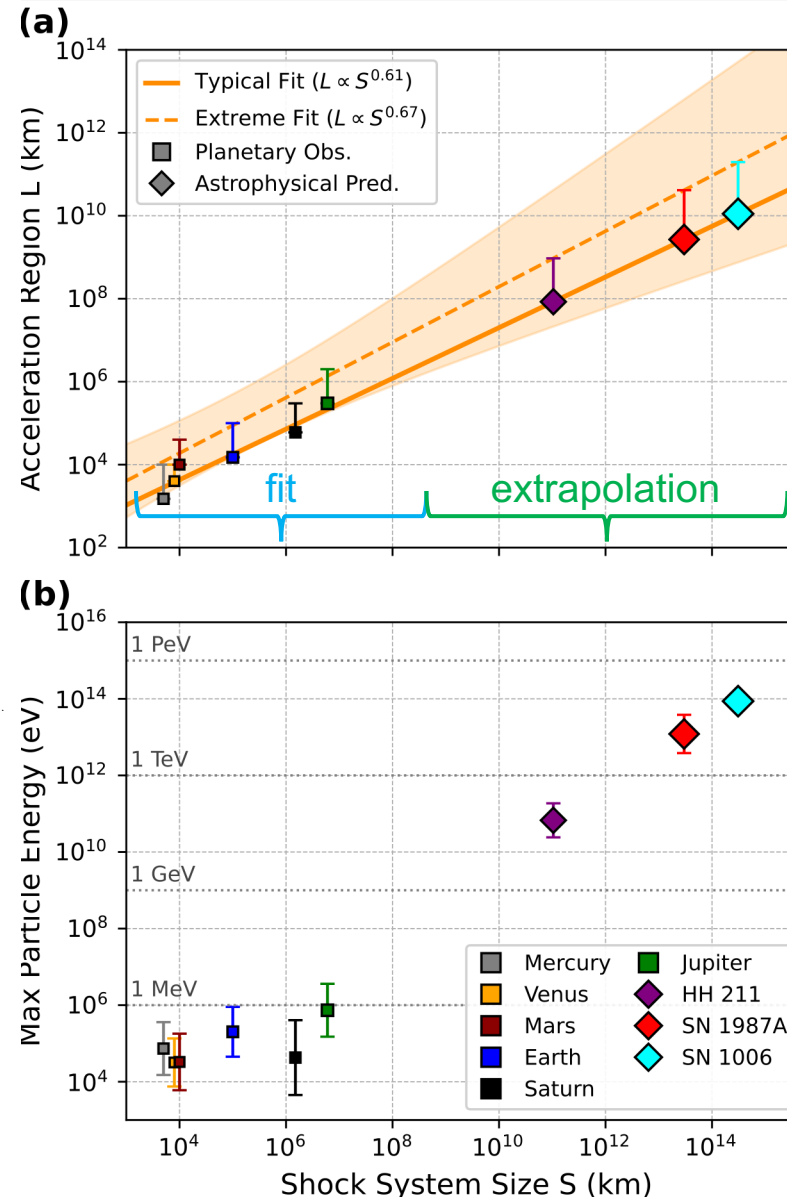
Planet	L_{typ} (km)	L_{ext} (km)
Mercury	1.5×10^3	1.0×10^4
Venus	4.0×10^3	1.0×10^4
Mars	1.0×10^4	4.0×10^4
Earth	1.5×10^4	1.0×10^5
Saturn	6.0×10^4	3.0×10^5
Jupiter	3.0×10^5	2.0×10^6

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]
HH211	$\sim 1.05 \times 10^{11}$	[50, 150]	[4, 10]
SN 1987A	$\sim 3.0 \times 10^{13}$	[2000, 4000]	[0.1, 0.5]
SN 1006	$\sim 3.0 \times 10^{14}$	[3500, 4500]	[0.1, 0.2]

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 size (L) to shock standoff distance (S).
4. Applied the upper prediction interval to estimate unobservable scales for distant astrophysical objects.



Caveats & Assumptions:

- ❖ Impossible to verify extrapolation
- ❖ Geometric limits
- ❖ Conservative estimates
- ❖ Magnetic coherence can vary strongly in each system

Discussion:

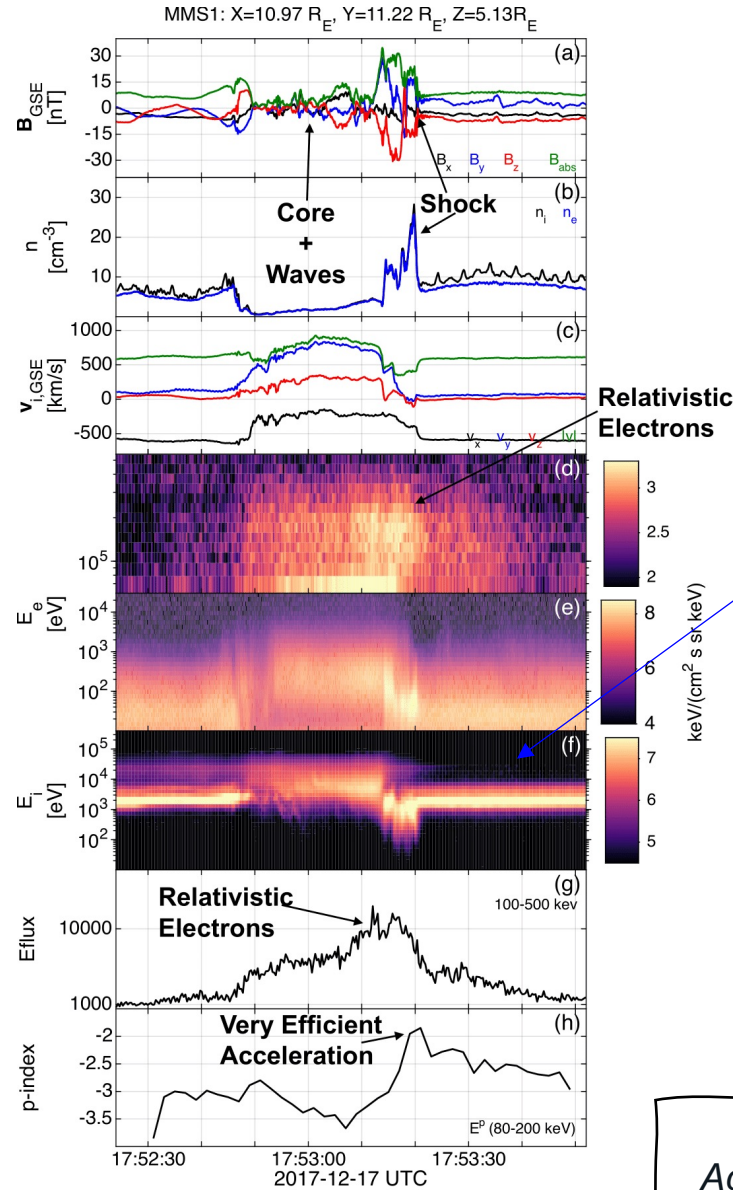
- DSA paradigm impact: Jupiter and Earth show acceleration during transient not at the shock!
- Predicted max energies ~ observations at SN1006

Discussing new models

^{*}
~~HOW STANDARDS PROLIFERATE:~~
(SEE: A/C CHARGERS, CHARACTER ENCODINGS, INSTANT MESSAGING, ^{*}ETC)

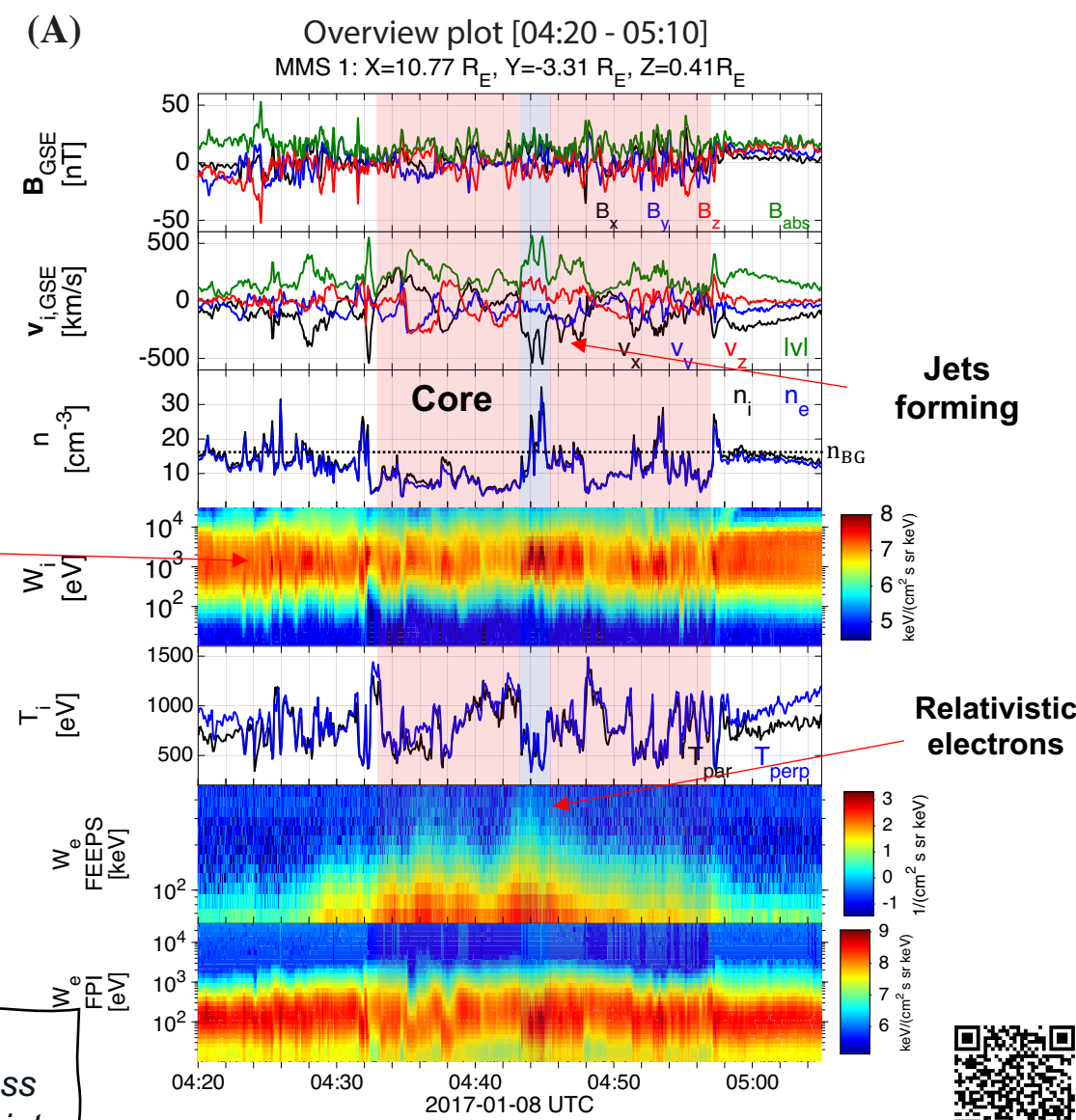


HFAs and FBs are amazing particle accelerators



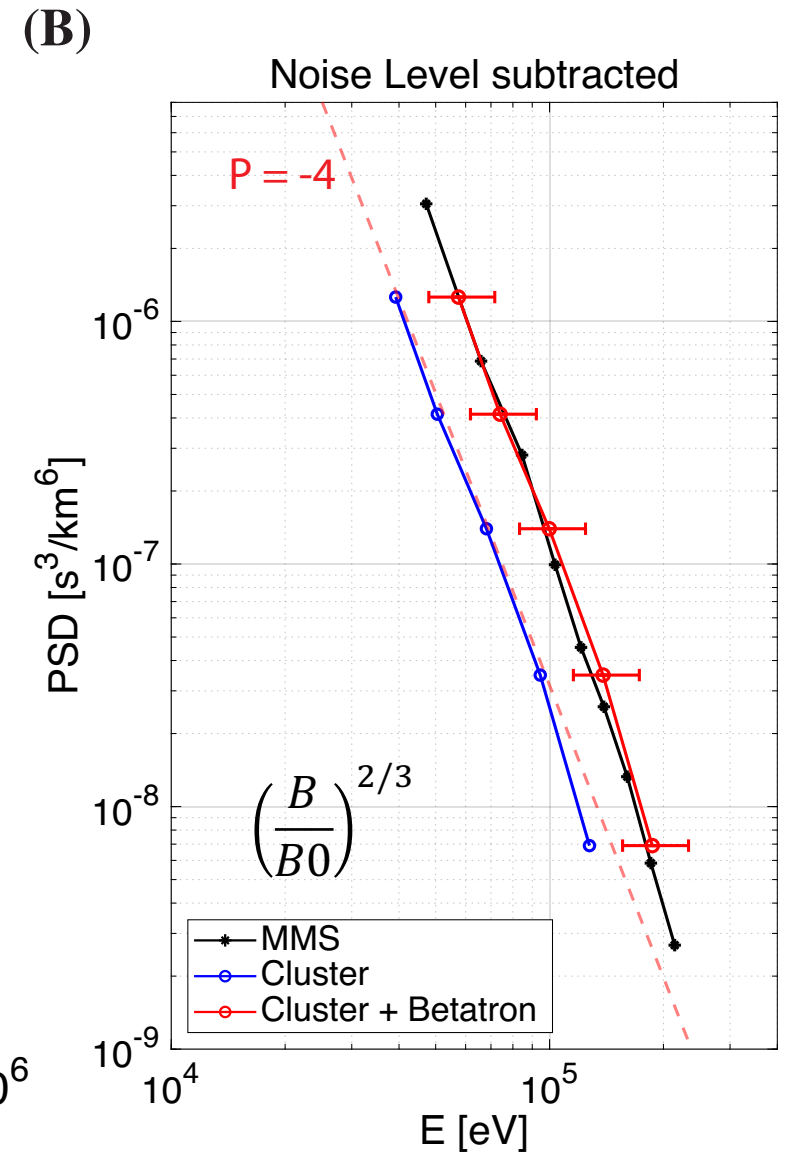
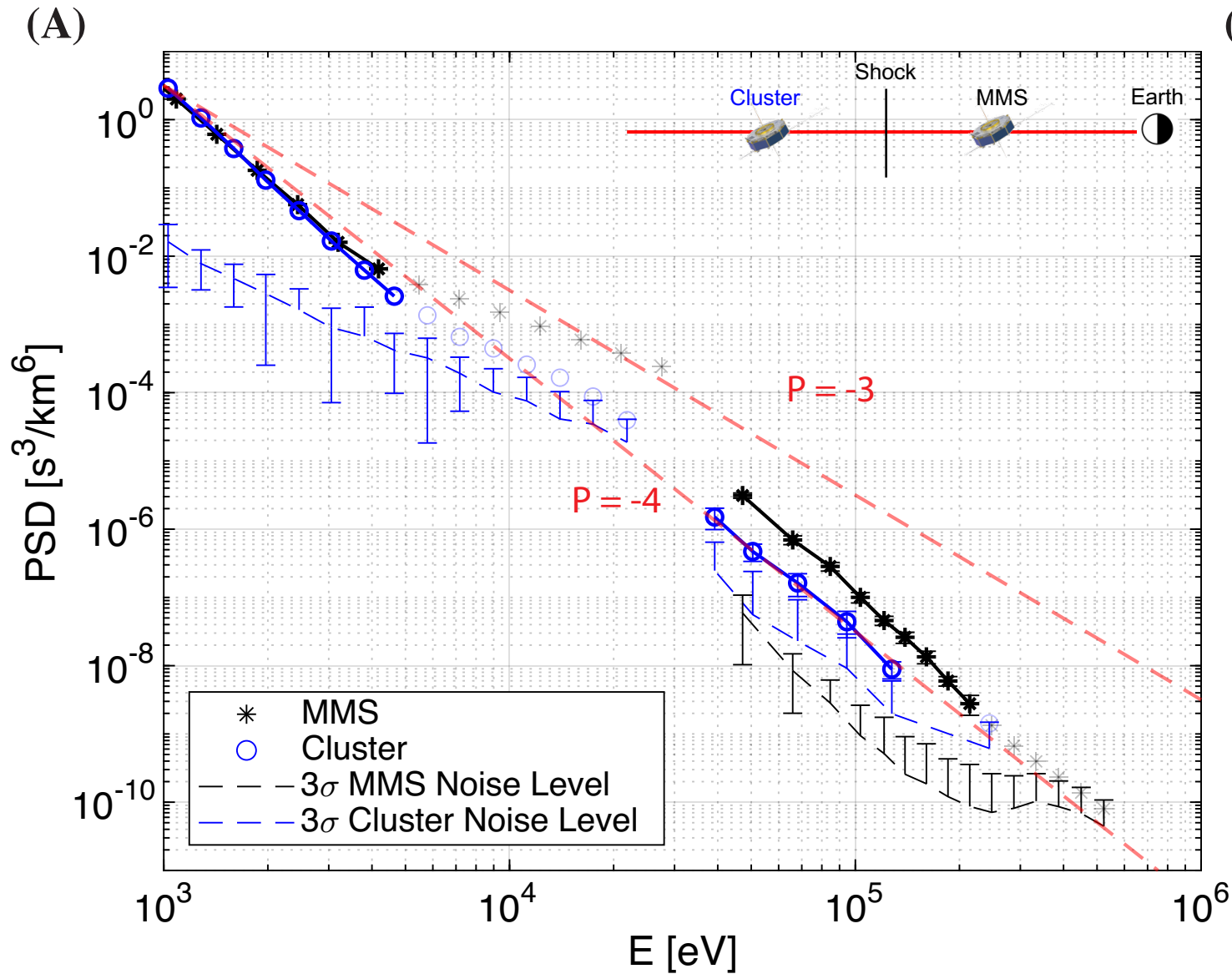
Solar wind

Magnetosheath



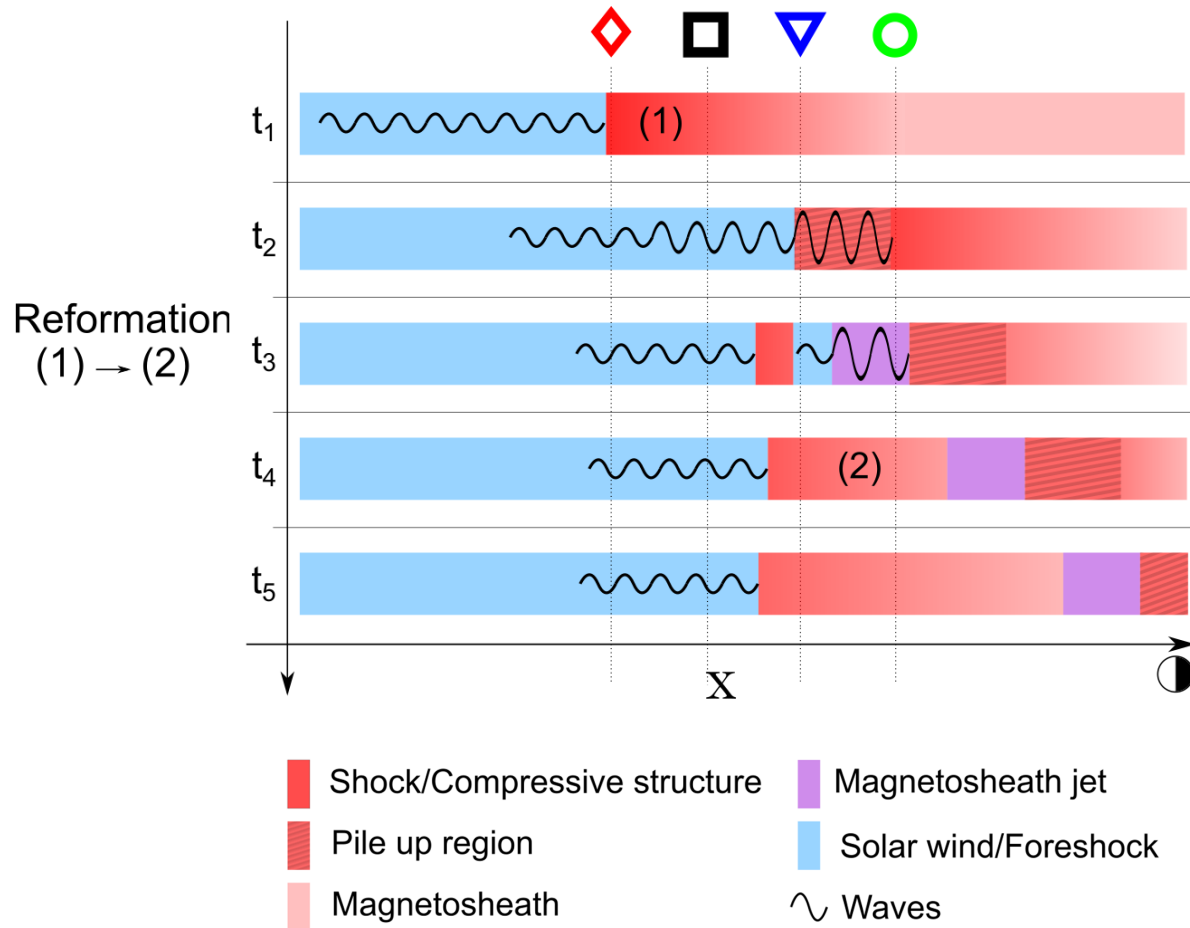
Transients get transmitted
Accelerating particles in the process
Restructuring the sheath & forming jets

Electron Acceleration: From Cluster (Upstream) to MMS (Downstream)

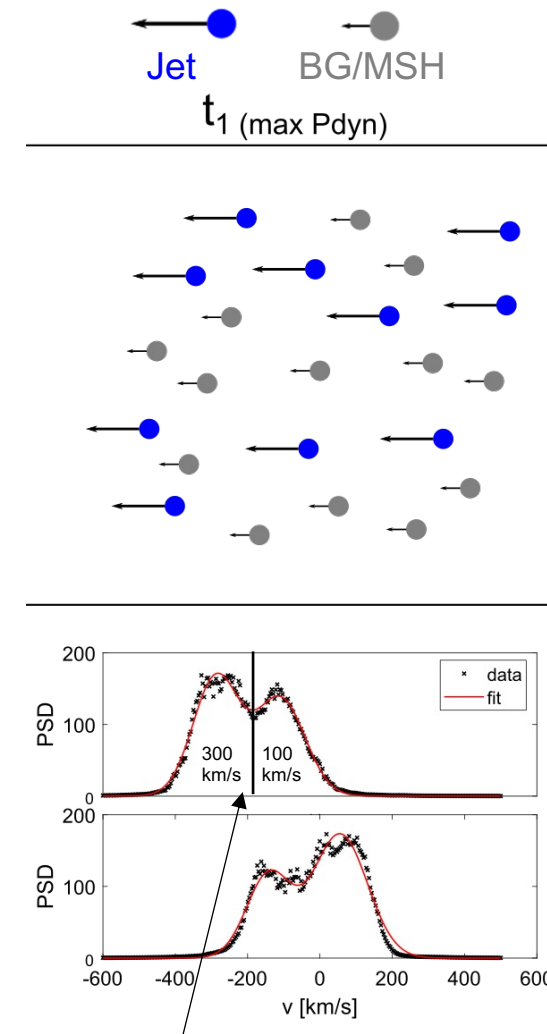


Jets & Kinetic Plasma Processes

Jets forming from shock's fundamental non-stationarity process



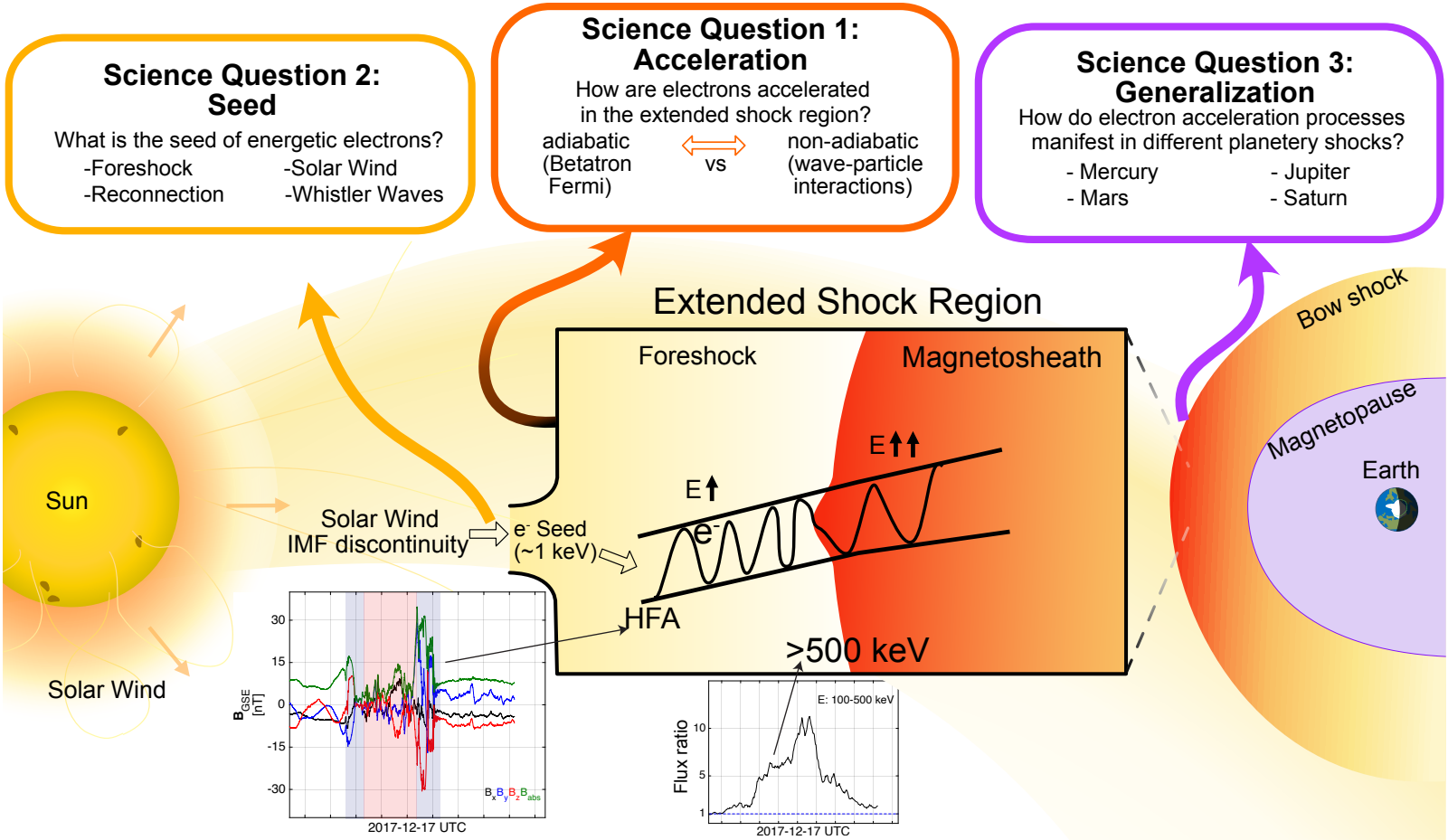
Jets exhibiting 2+ populations = partial moments needed



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?

Planetary and astro people: Can we generalize ?

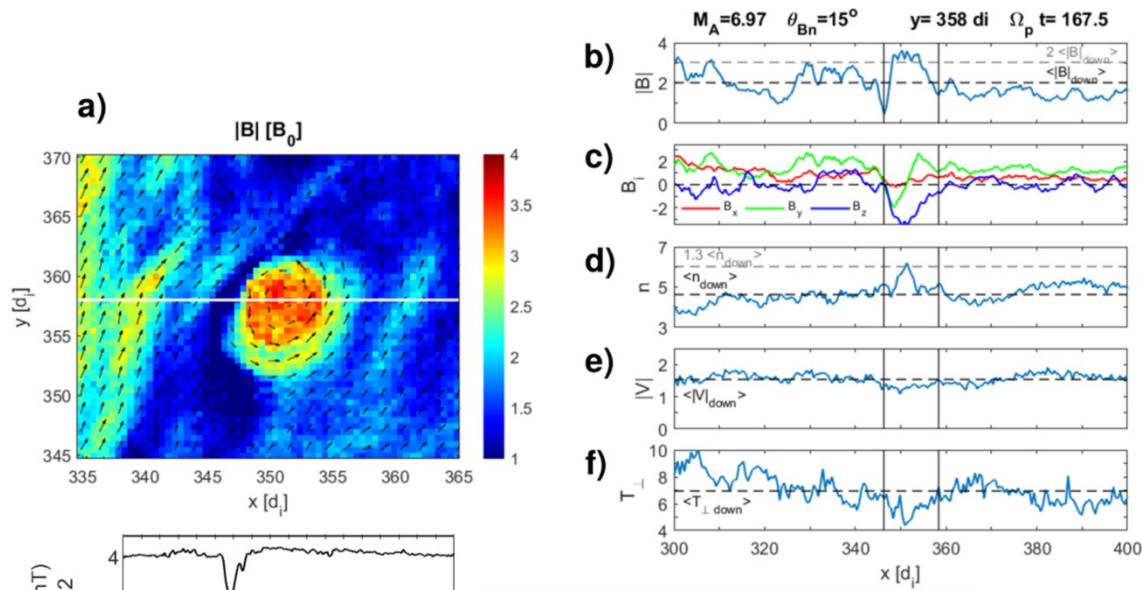
- What is the system size and local conditions?
- Do we observe energetic electrons upstream?
- Do we have datasets/examples available?

Method and data people:

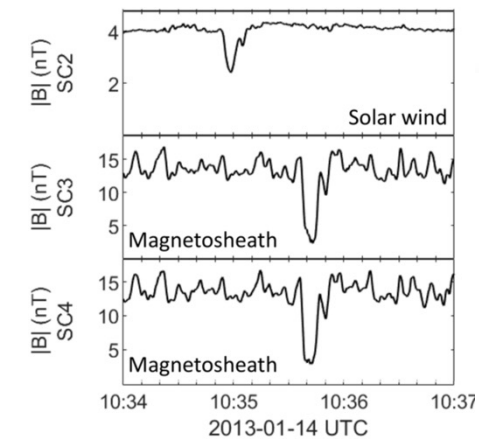
- How can we establish an automatic finder?
- How to associate DCs with transients?
- How to quantify each acceleration process

Transmission of Foreshock Transients

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

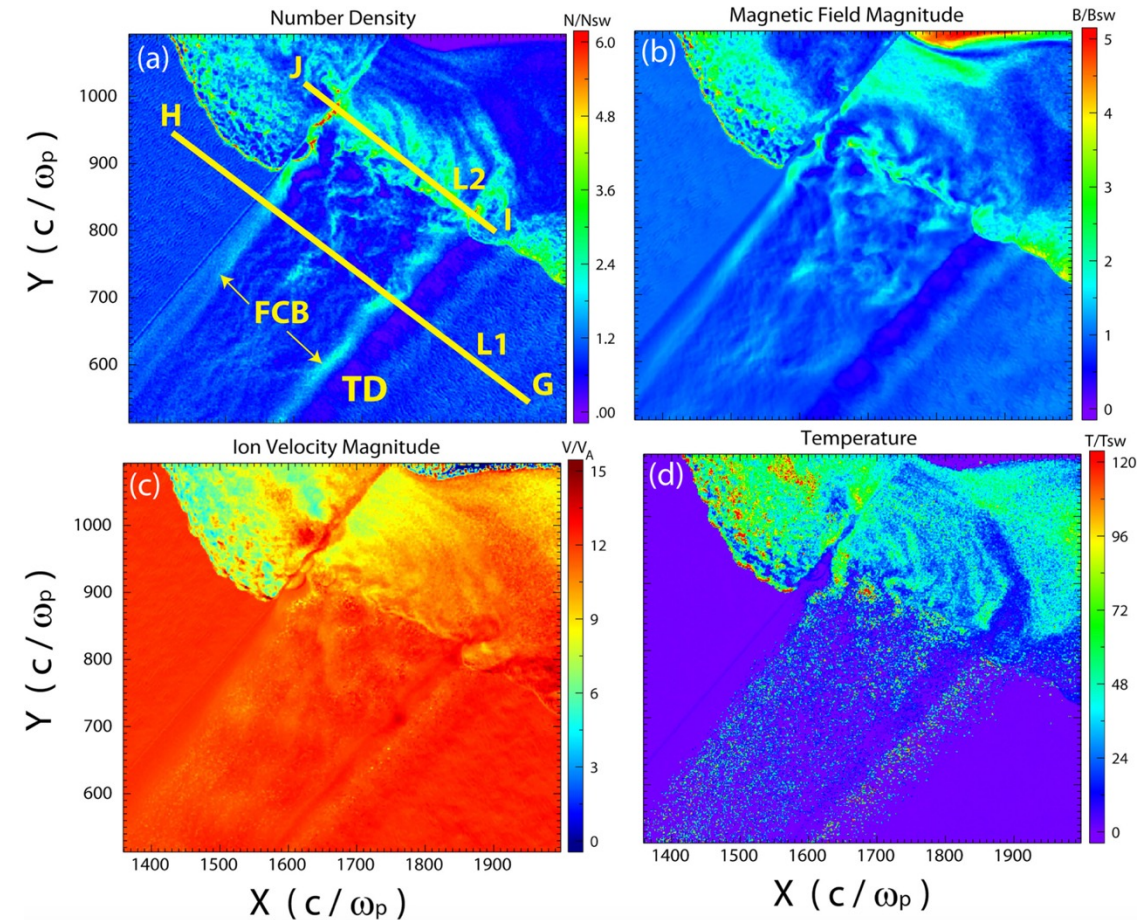


Preisser L., et al. 2020 | ApJL



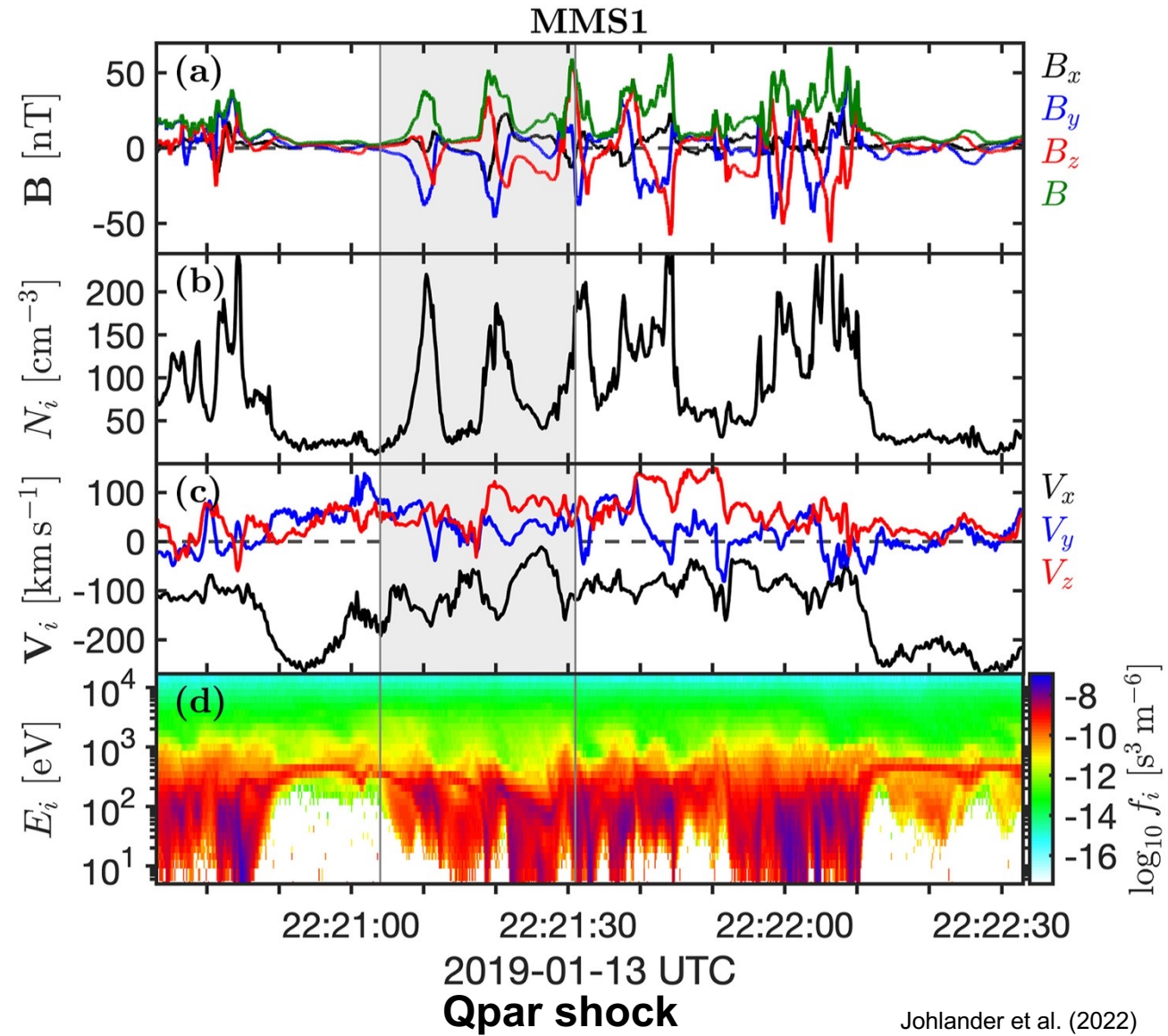
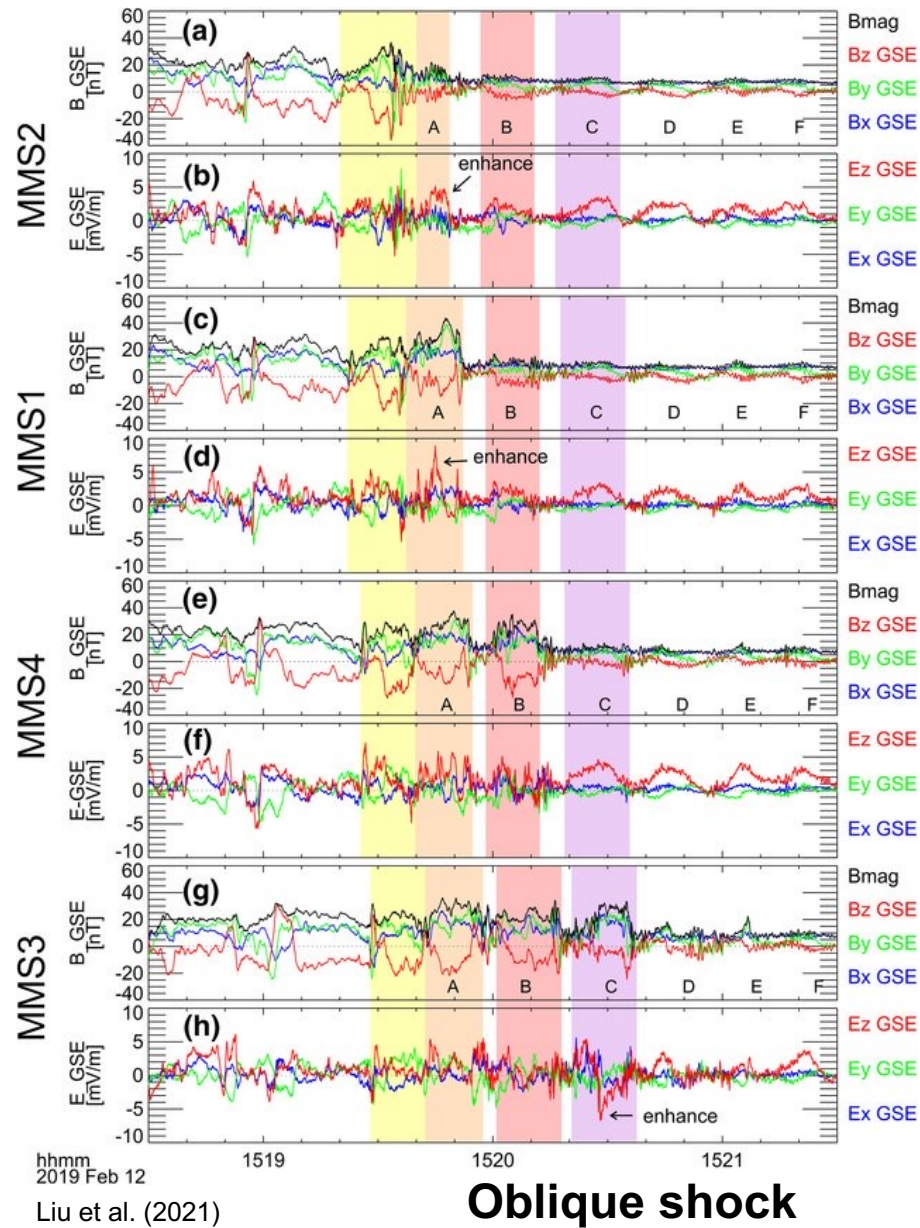
Karlsson T., et al. 2022 | ANGE0

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

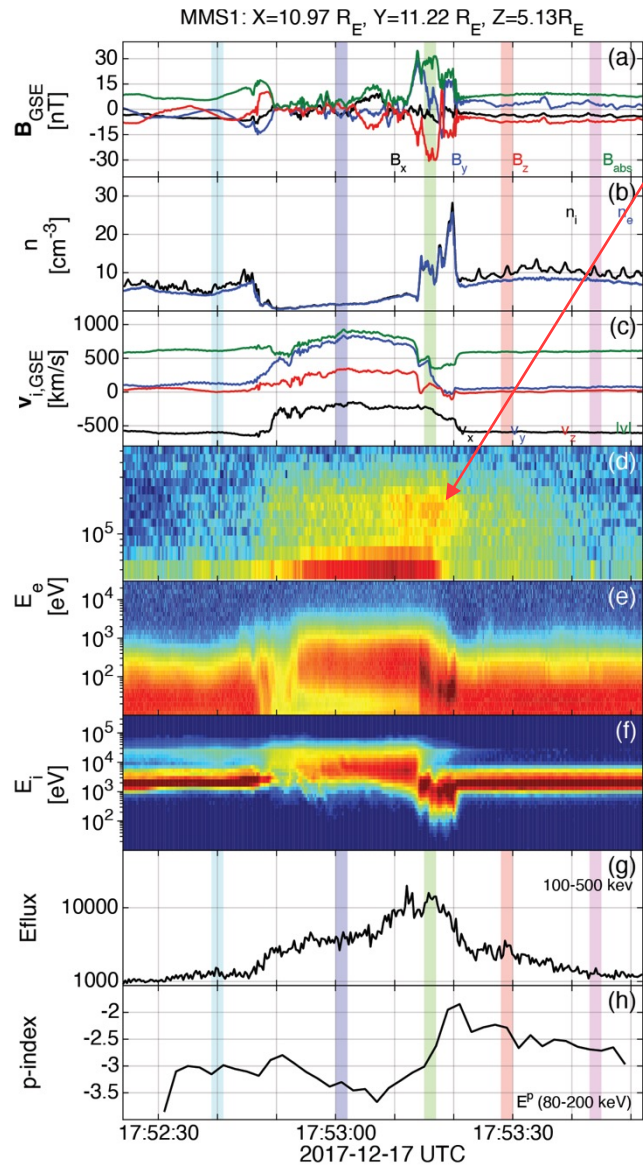


Sibeck D., et al. 2021 | JGR

Shock Reformation – MMS Results

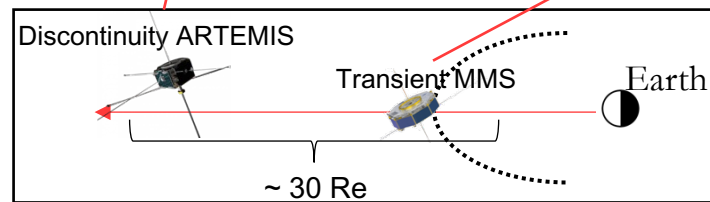
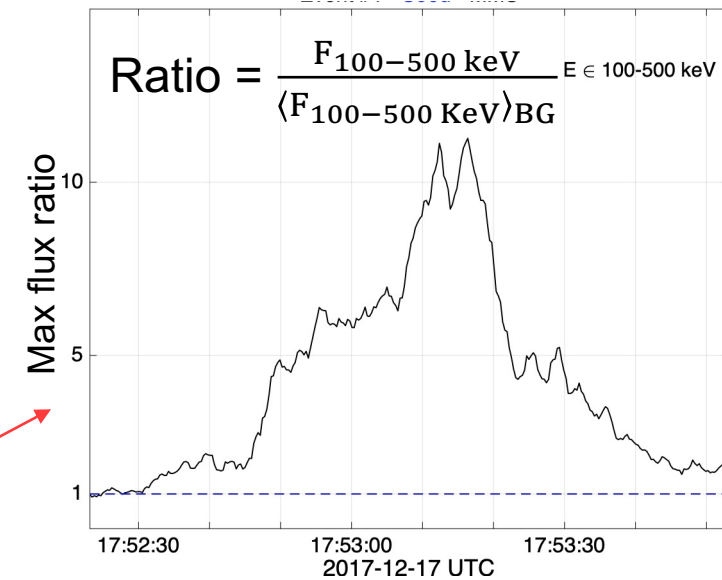
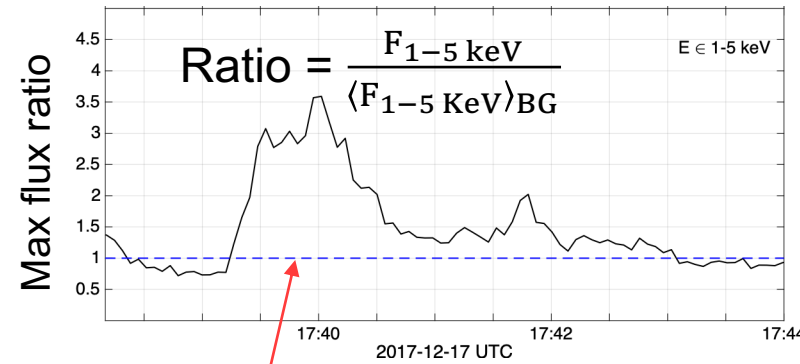


Reinforced Shock Acceleration of Relativistic Electrons



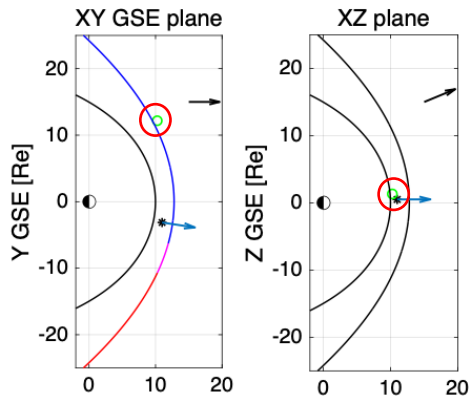
Most energetic electrons observed (**500+keV**) at foreshock observed by MMS obtained by:

- (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)

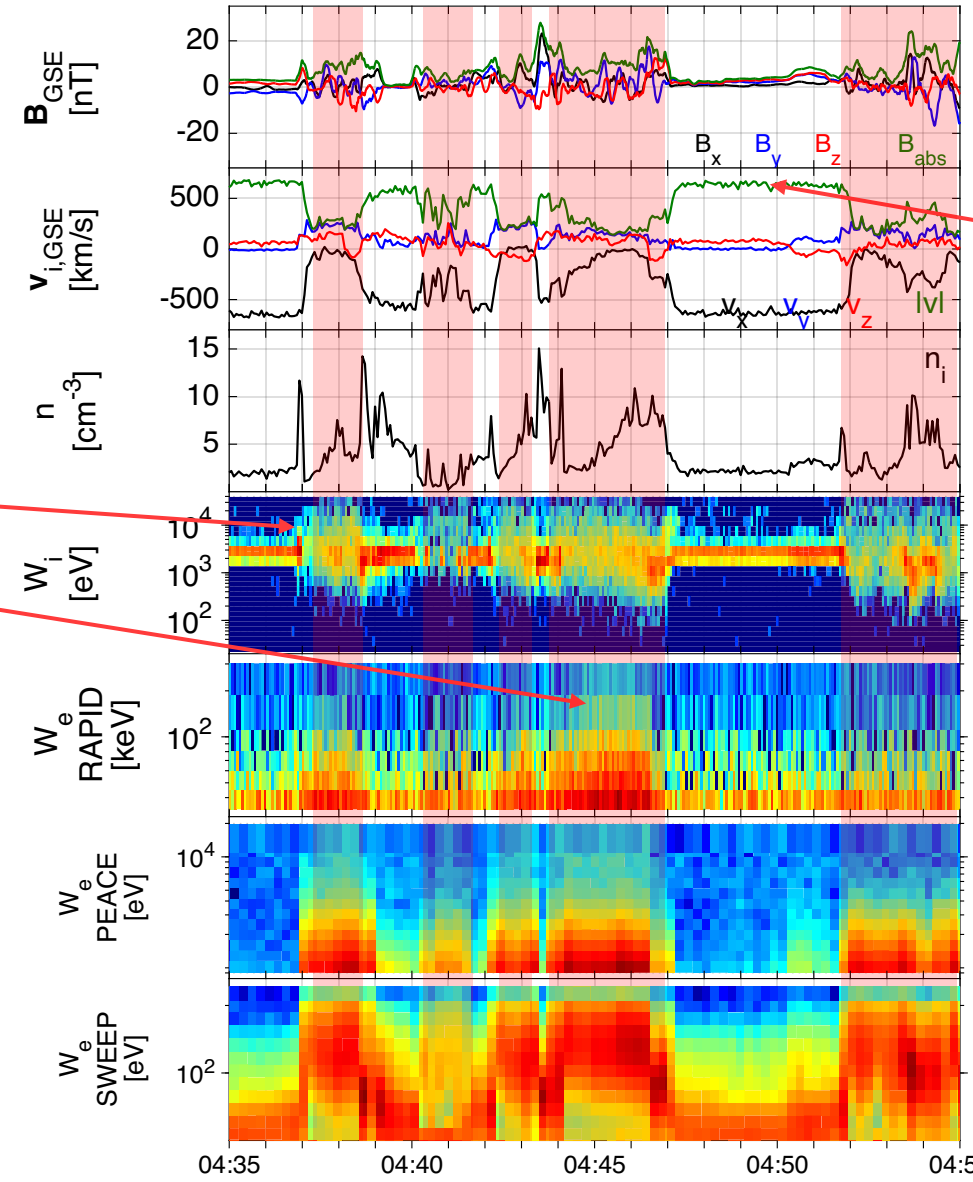


Key-point:
Seed + Foreshock's Shock + Waves + Efficiency factors = ~MeV electrons before reaching the bow shock.

Cluster: Upstream showing HFAs



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



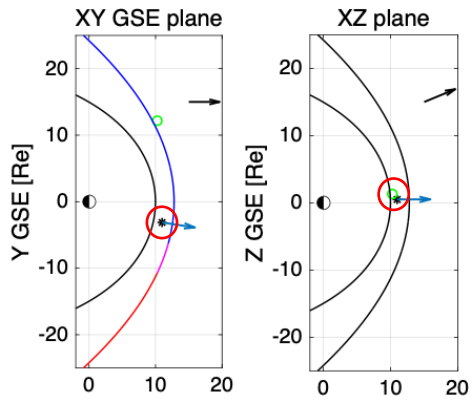
700 km/s Solar Wind!

Fast coronal hole plasma consistent with our previous work ✓

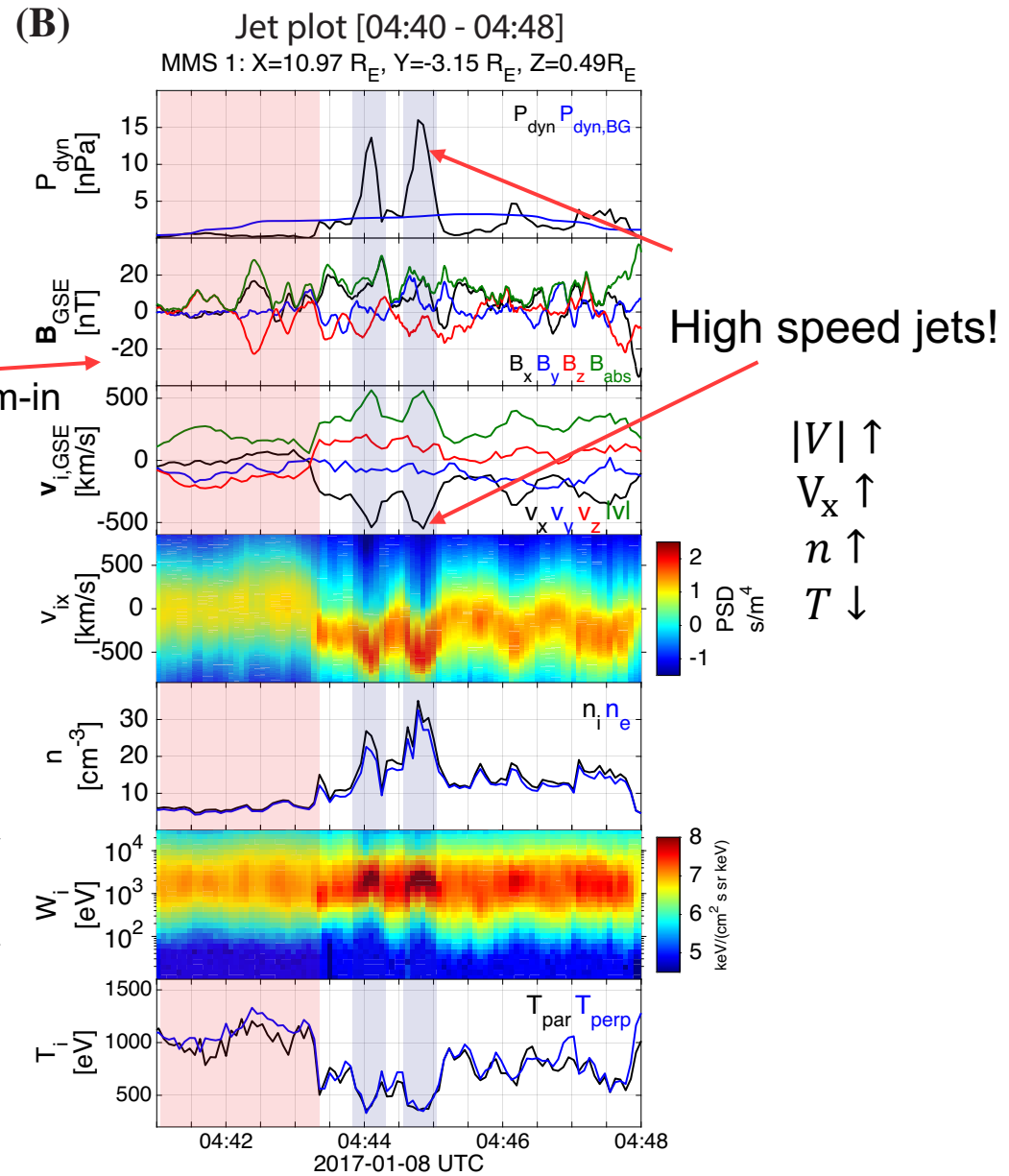
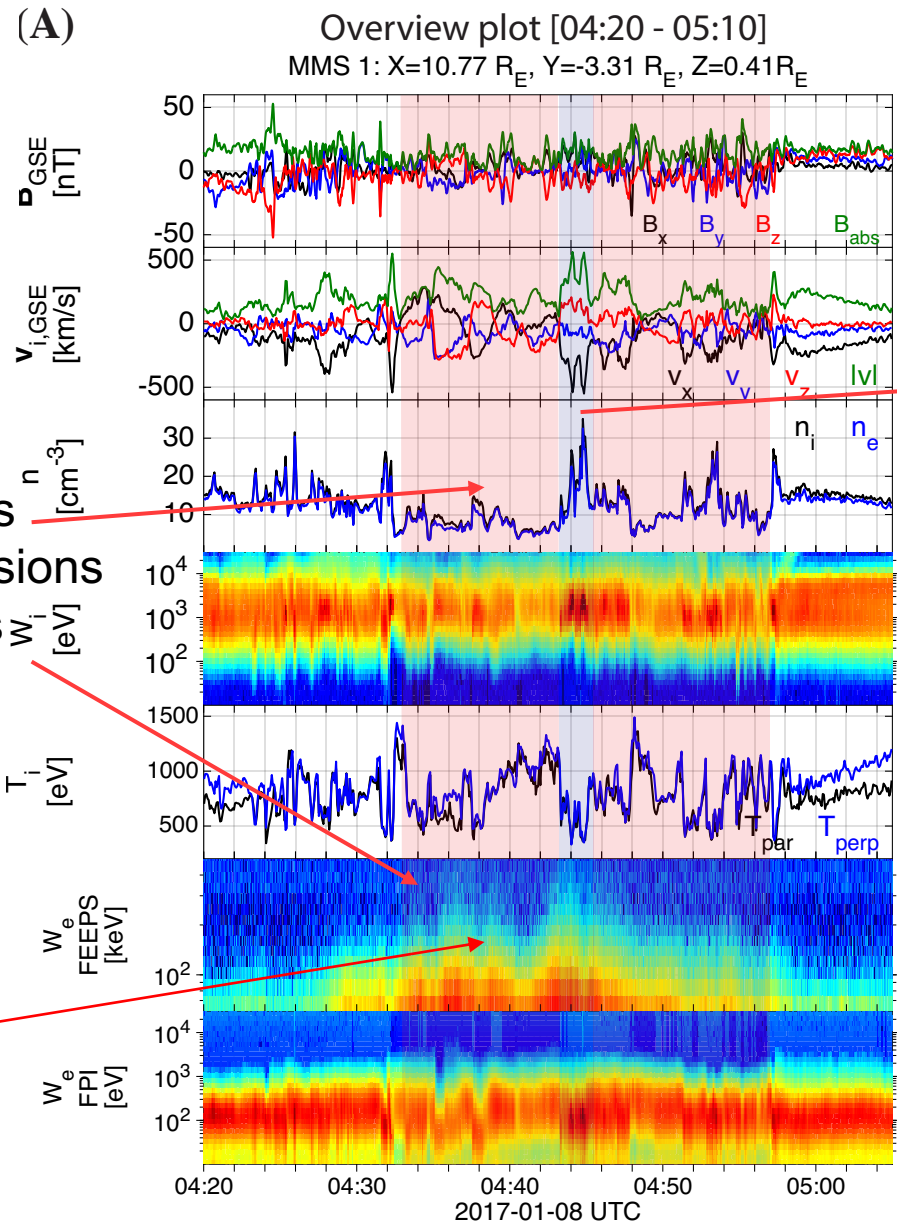
Typical properties:

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

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



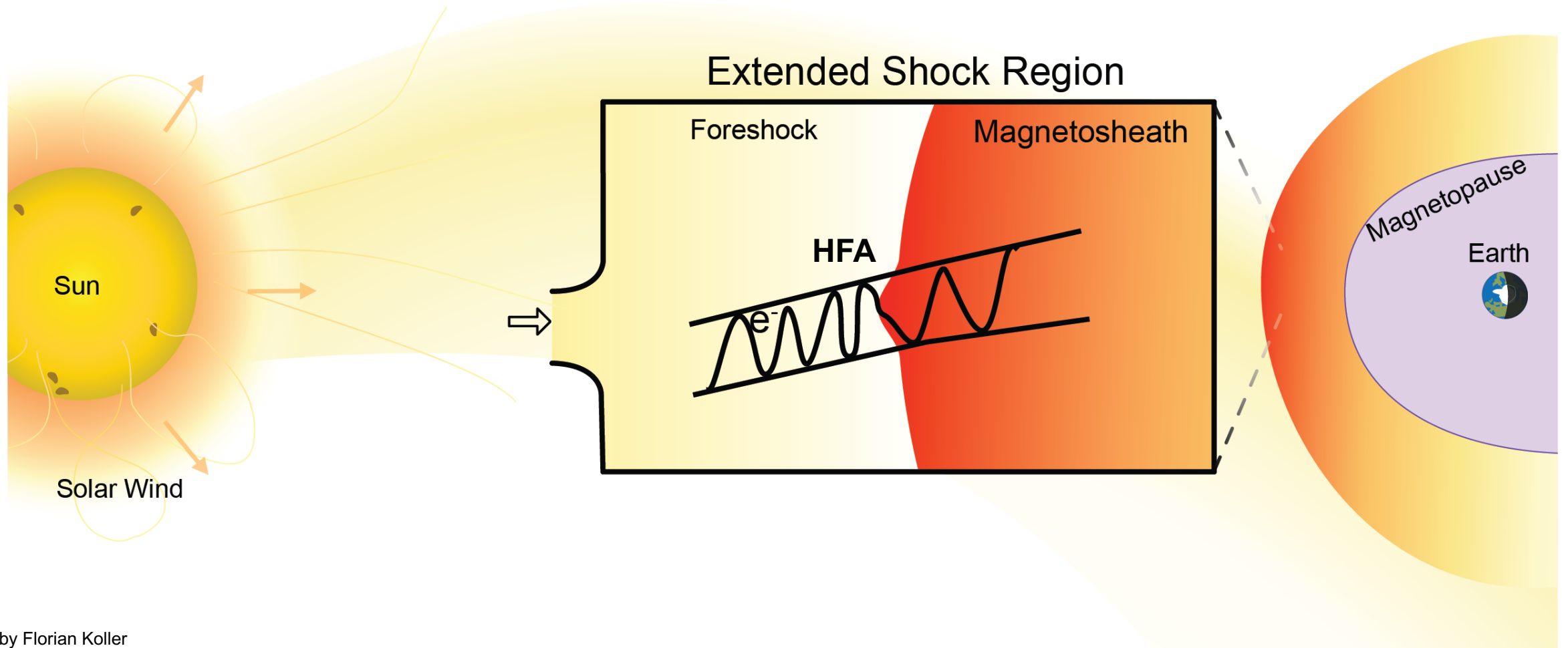
MMS: Downstream HFAs and jets



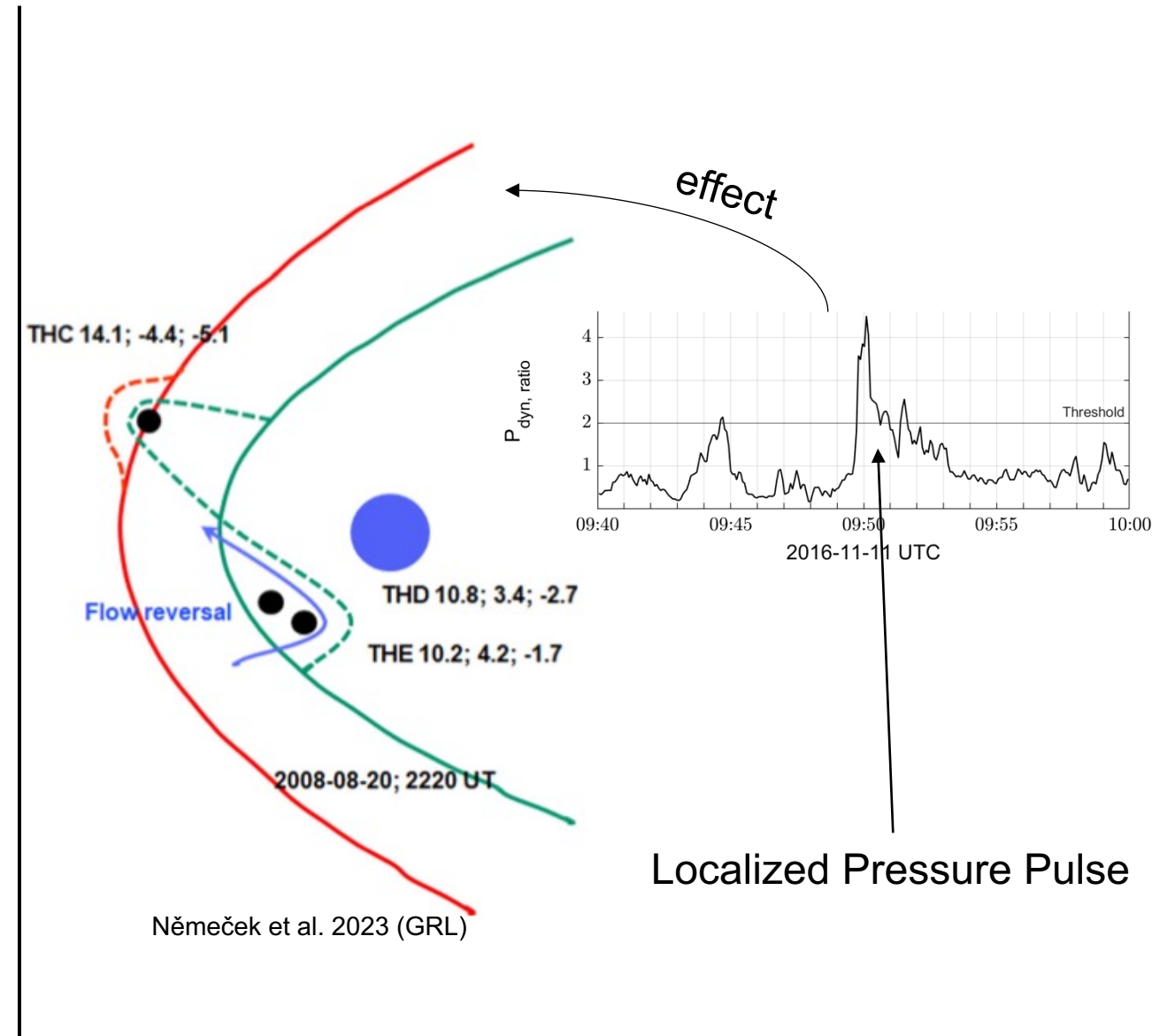
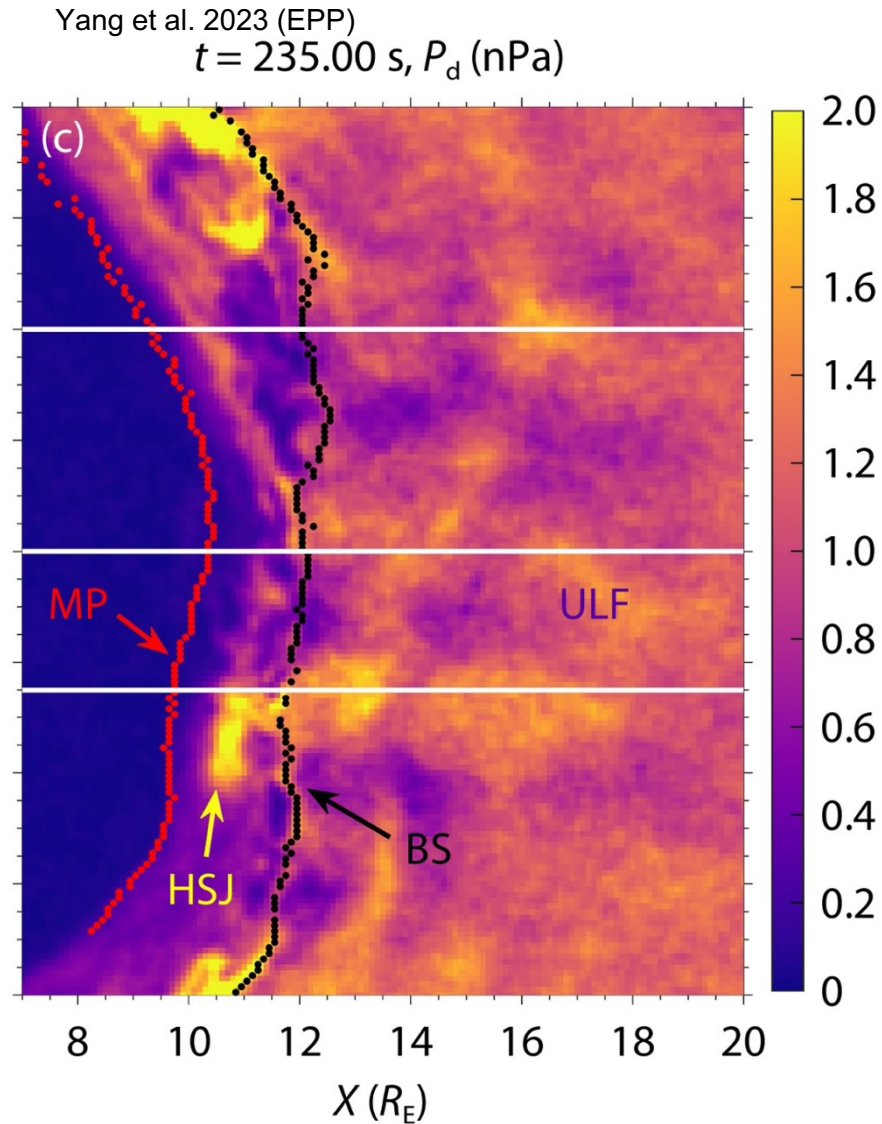
- Hot Flow Anomalies
- Localized compressions
- ~300 keV electrons
- 20+min interval

But let's ask one more question

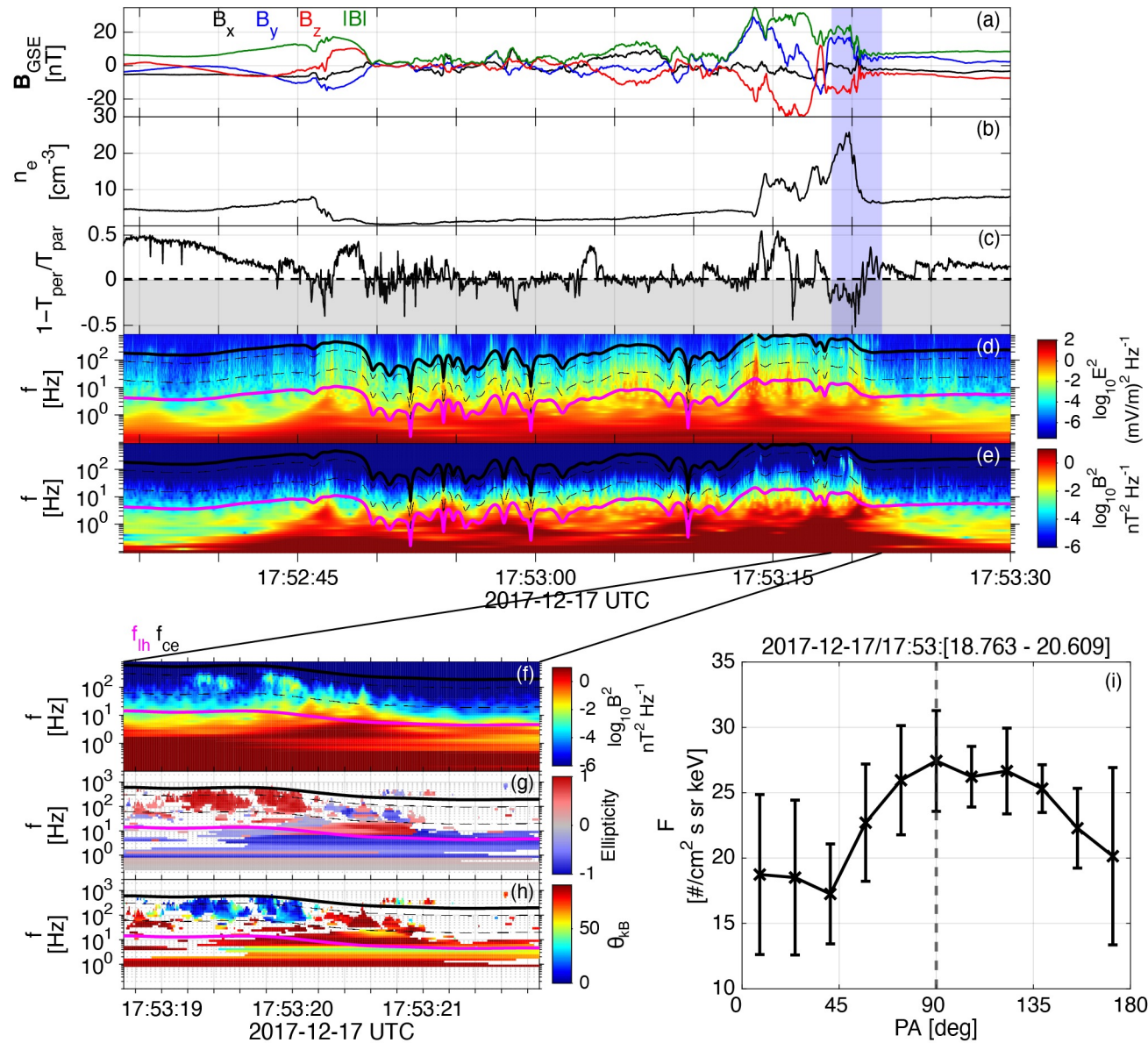
What do we expect to see when transients cross the bow shock and go downstream?



High Speed Jets & Magnetosphere Effects



Wave analysis of event



Acceleration:

- Shock Acceleration
- Betatron \rightarrow 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:

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

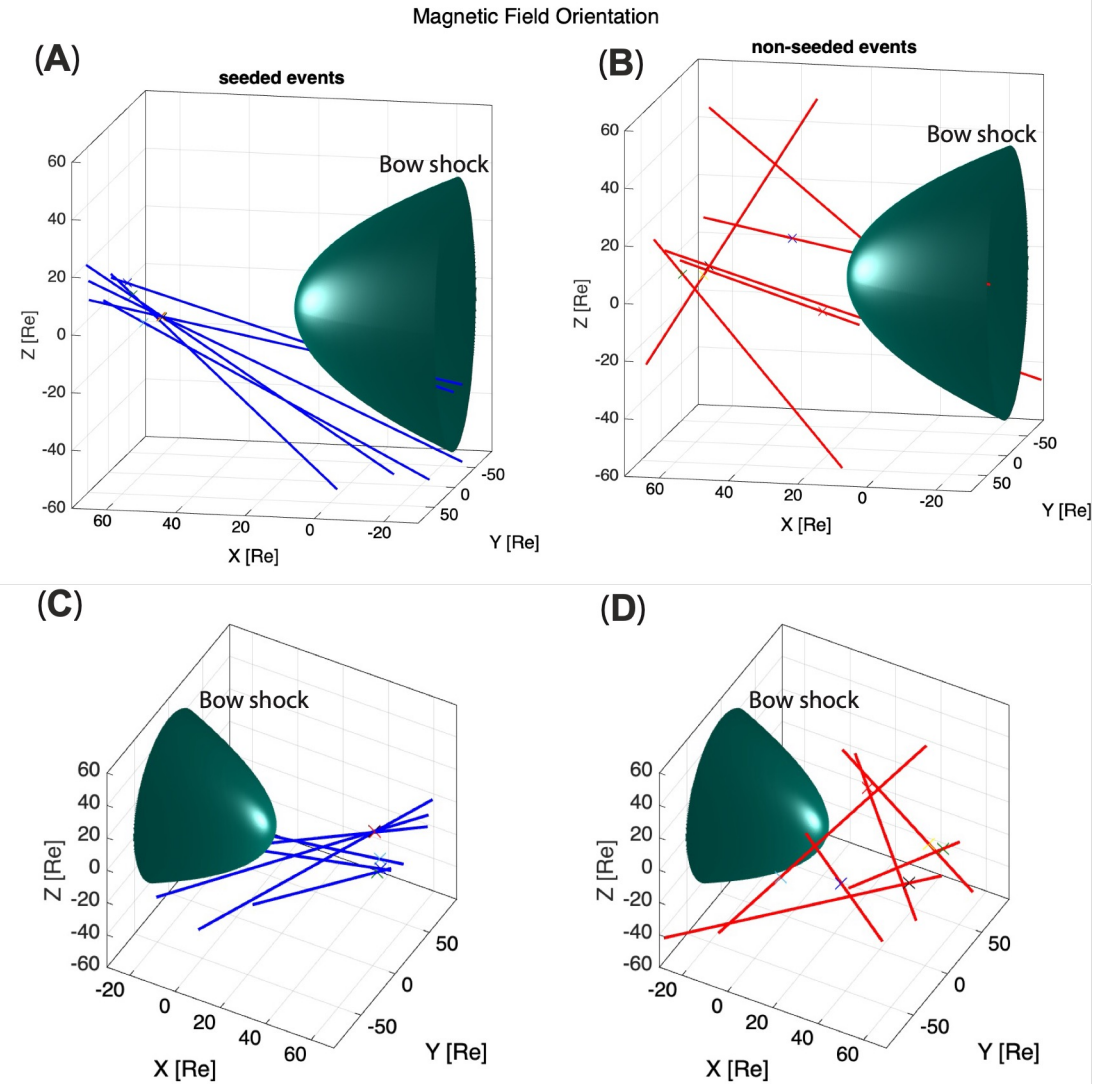
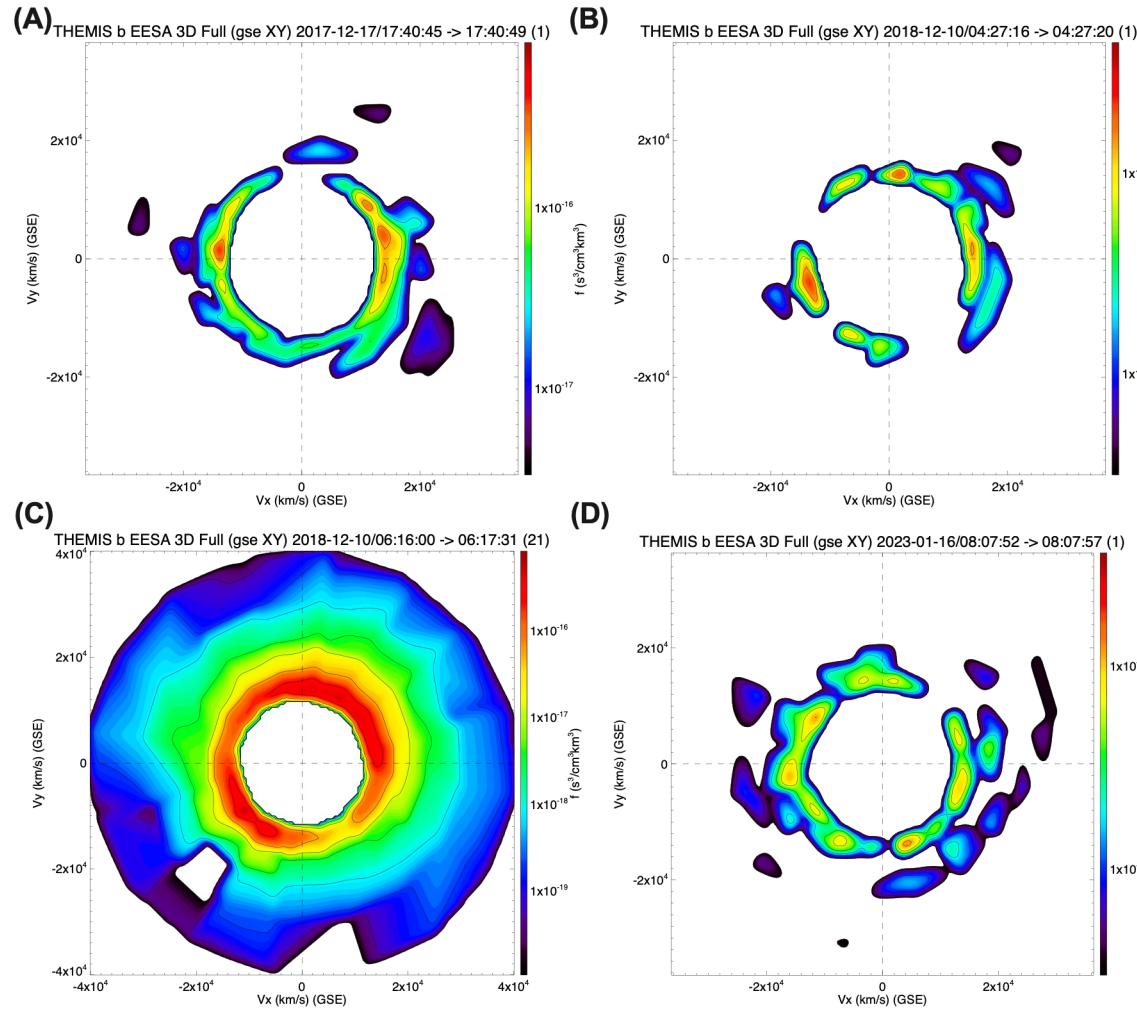
Is seed from the foreshock? – Maybe partially

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

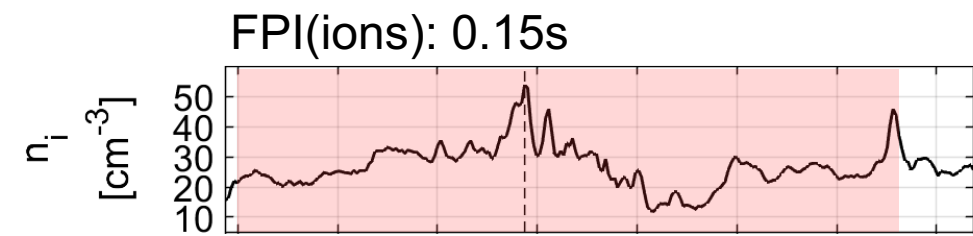
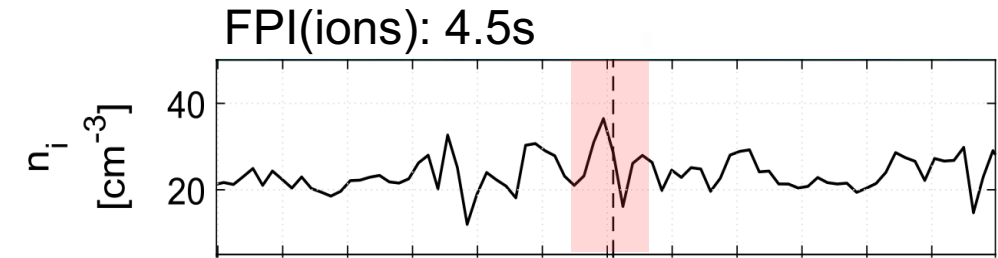
(C) → Seeded event full mode

(D) → Non-seeded event – partial mode

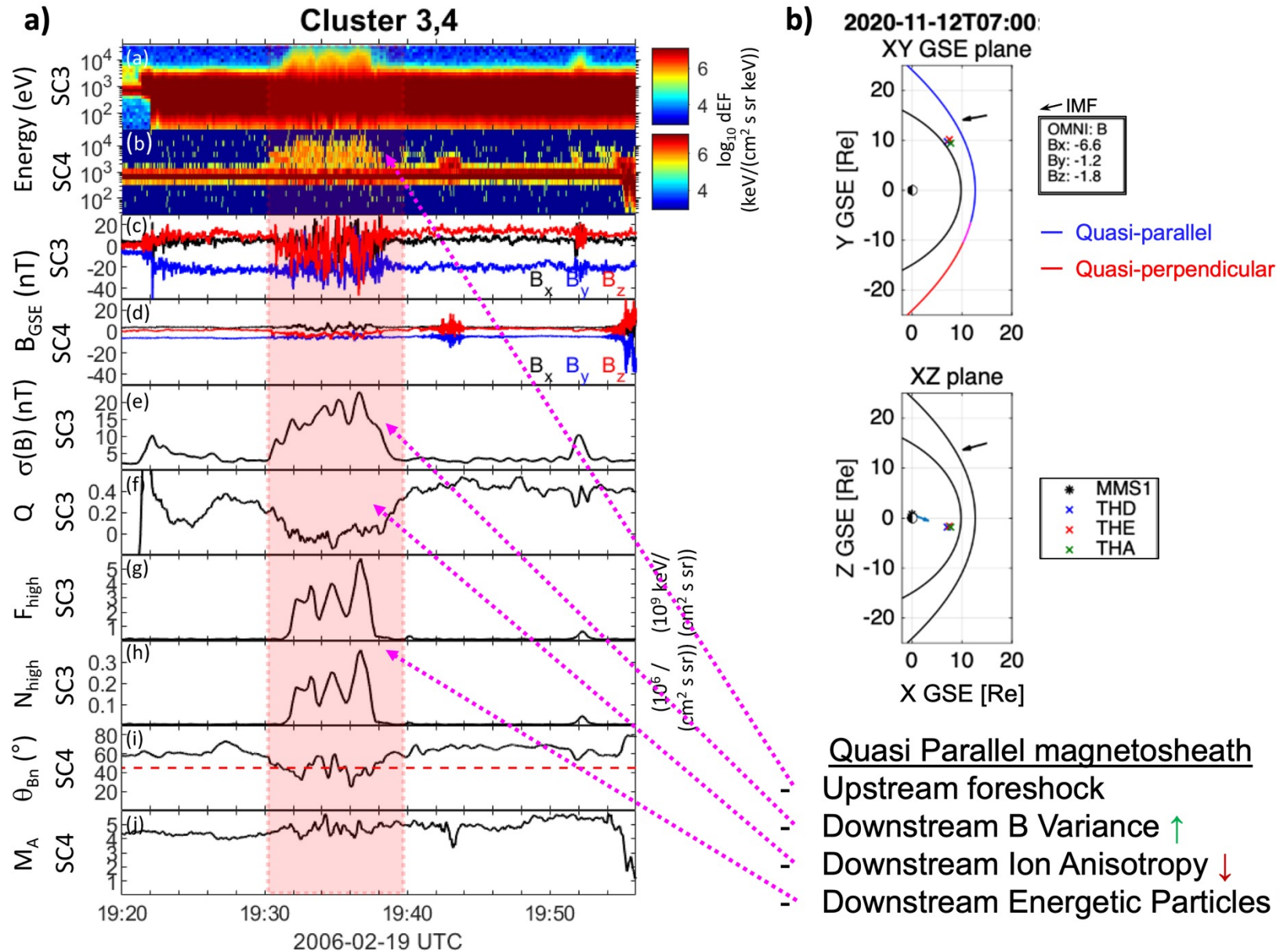
3/6 seeded and 2/6 non seeded connected to foreshock



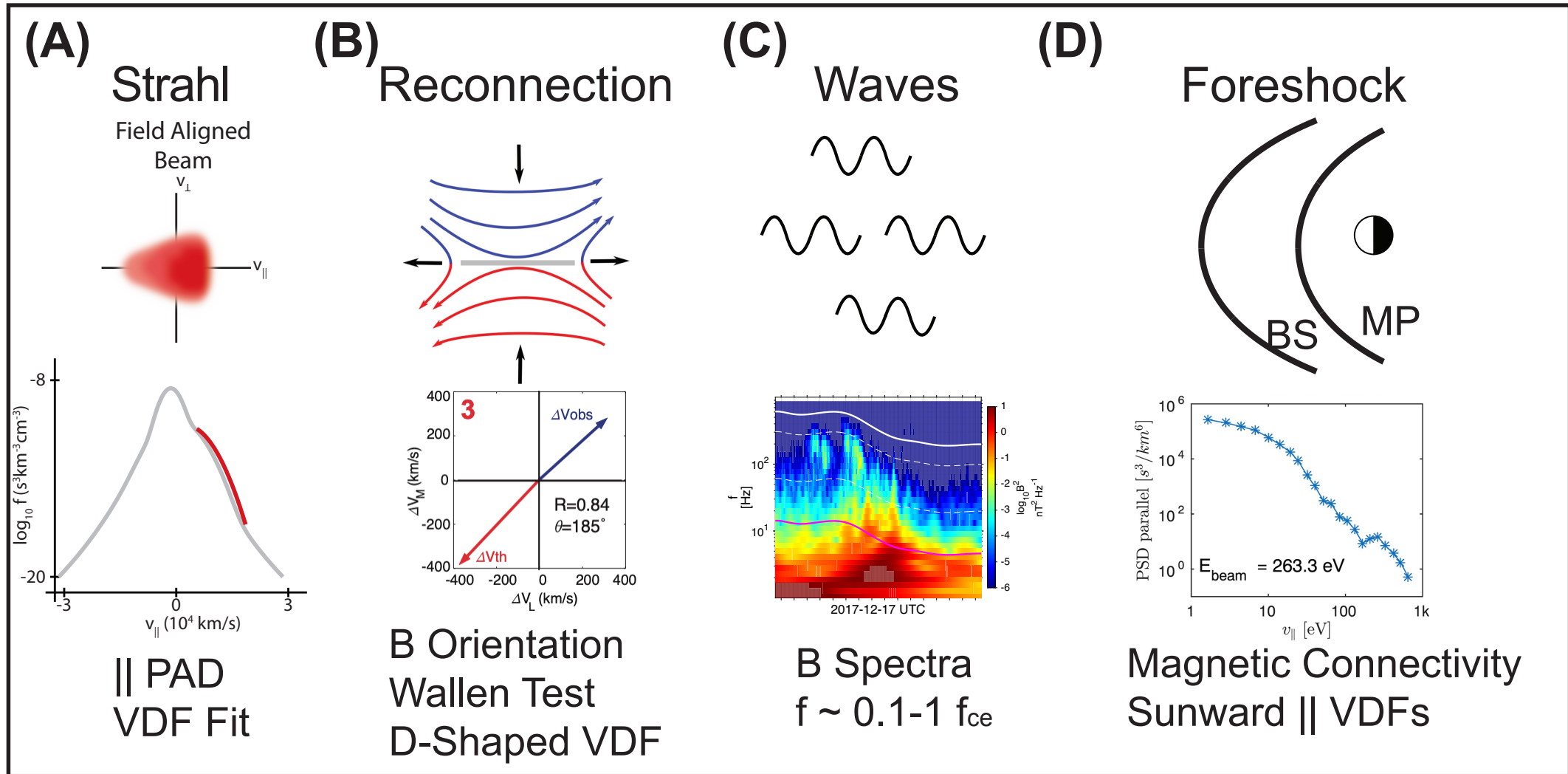
Why MMS burst data?



In-situ classification of the Quasi-parallel magnetosheath



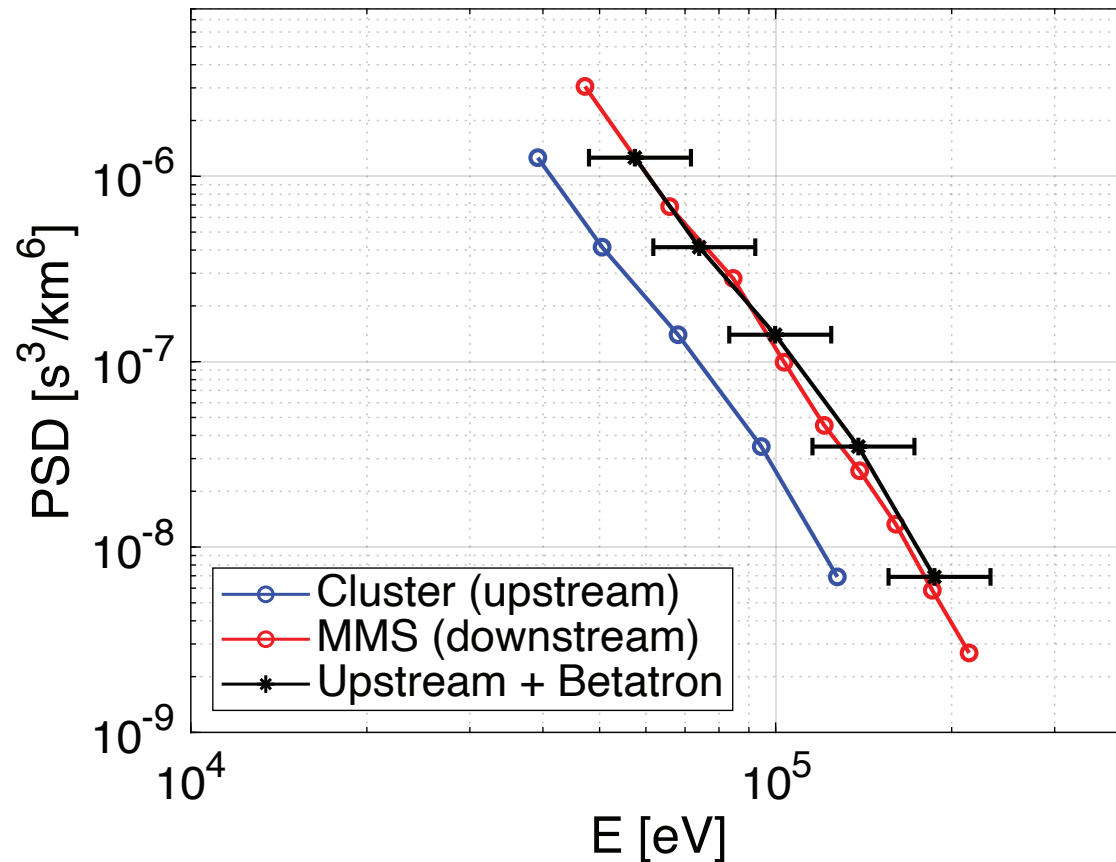
Some Ideas about the Seed Population



Preliminary Comparison (Data vs Simulations)

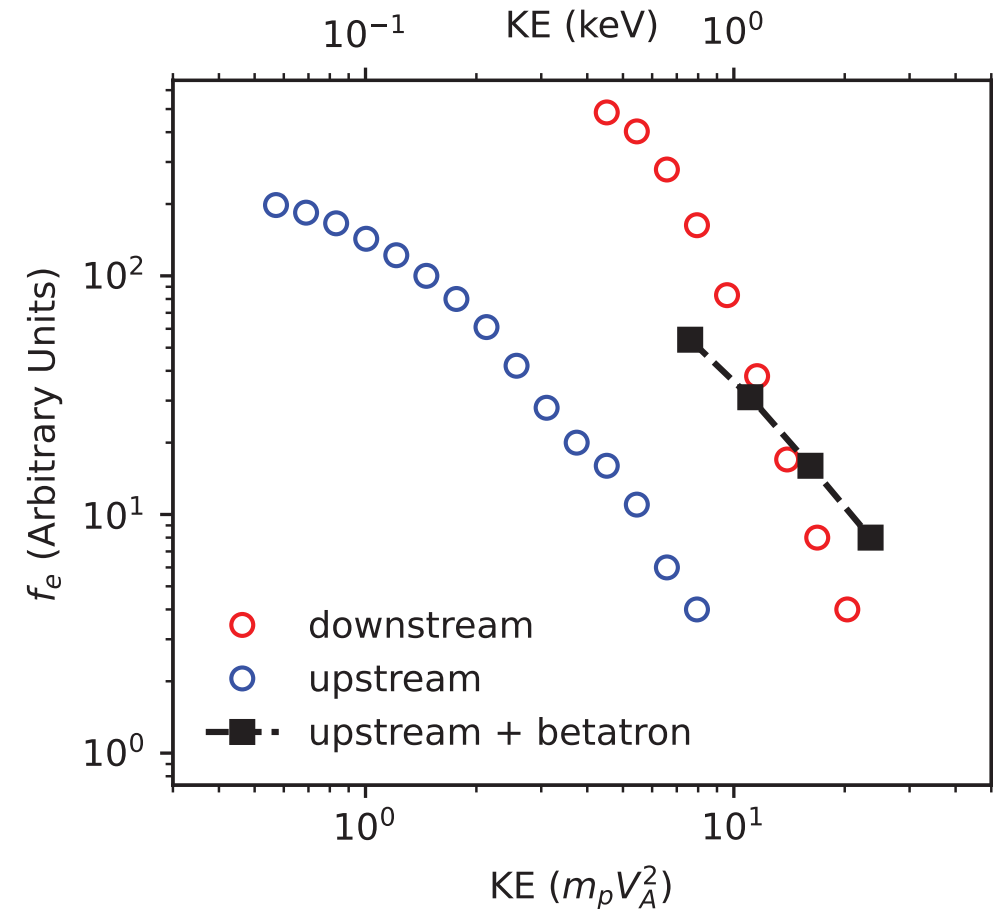
(A)

In-situ Observations



(B)

Hybrid Simulations



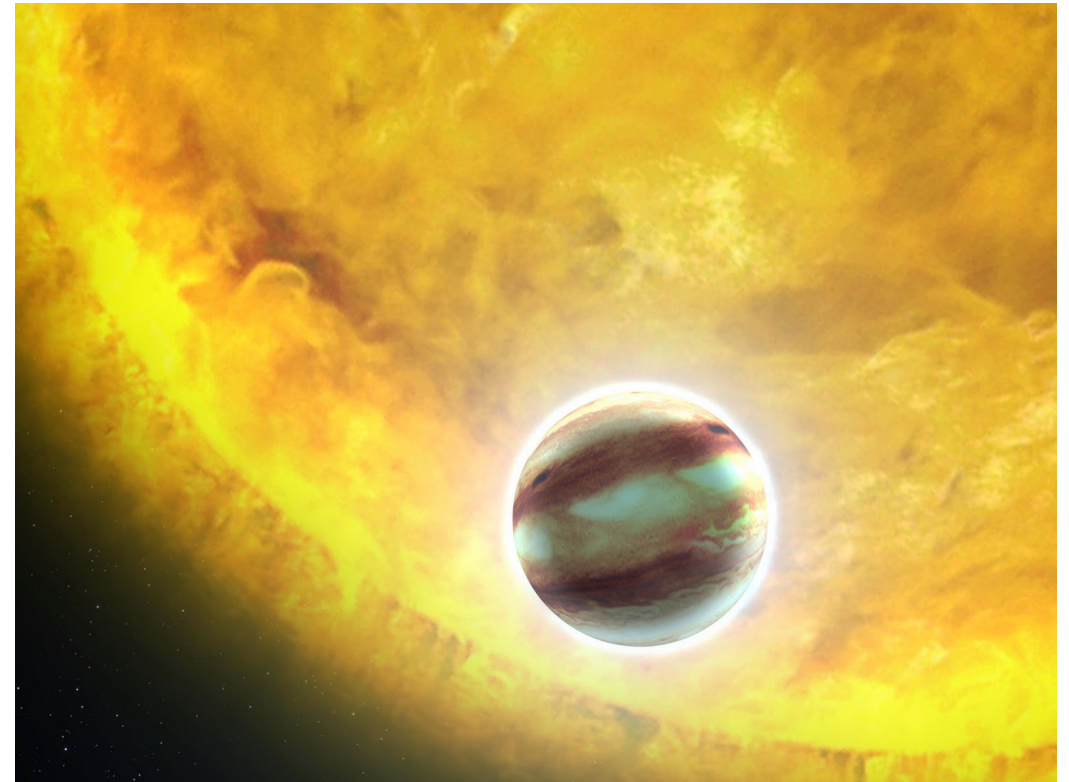
Electron Acceleration in astrophysics

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 $B \sim 0.01 - 1\text{G} \sim 10^3 - 5 \text{ nT}$

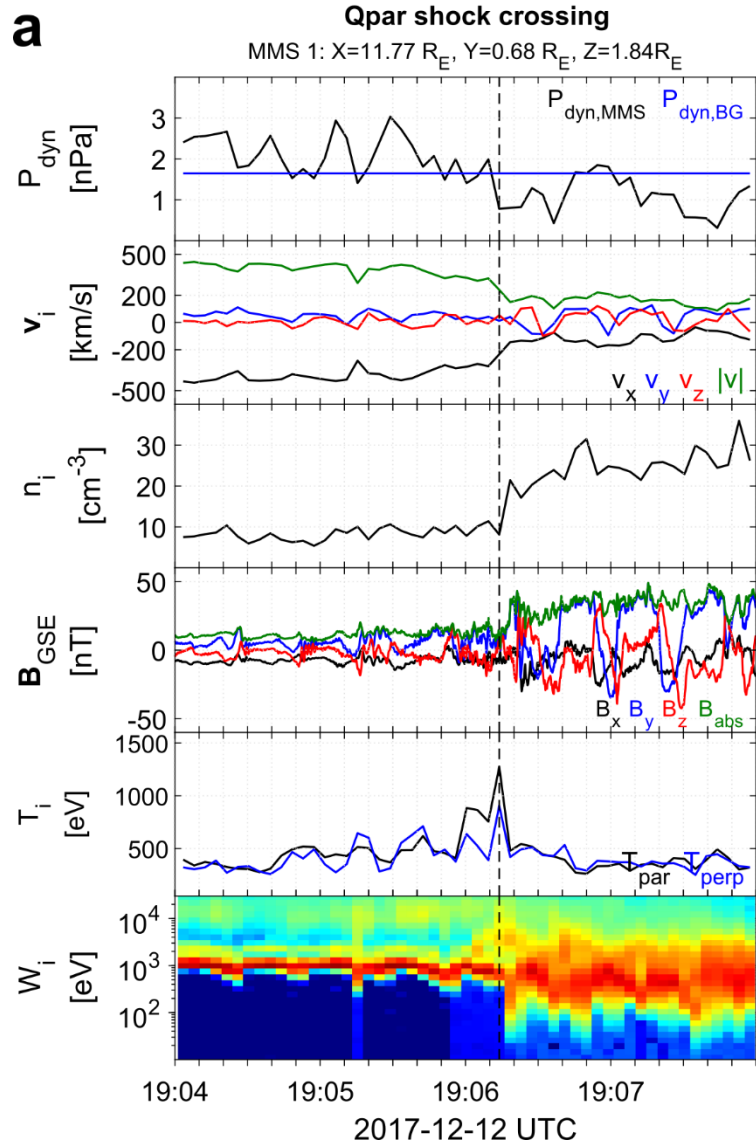


James webb showing bow shock waves from newborn stars moving with ~ 100 km/s in the interstellar medium



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

Qpar shocks have different flavors



The nice/smooth ones

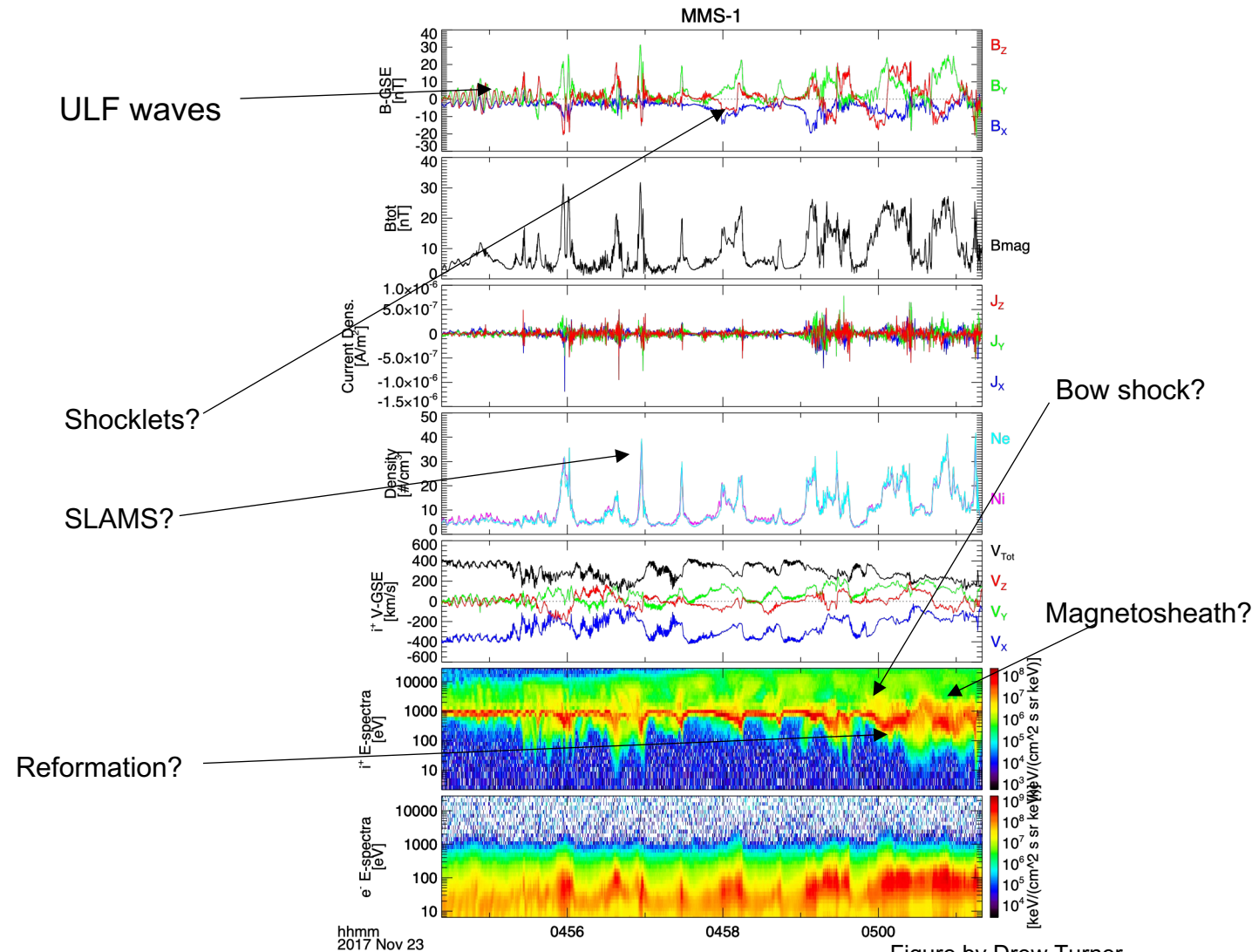
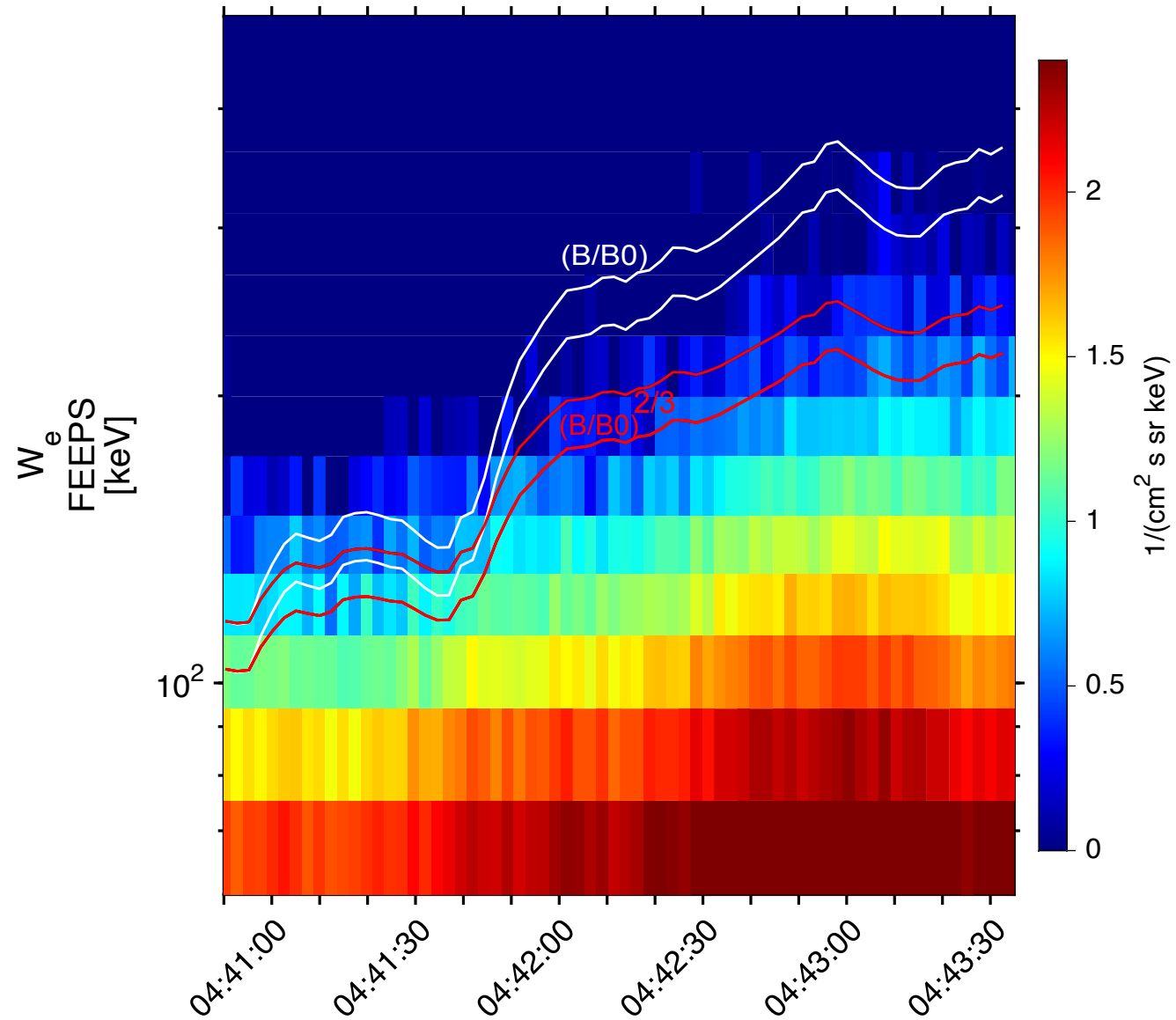


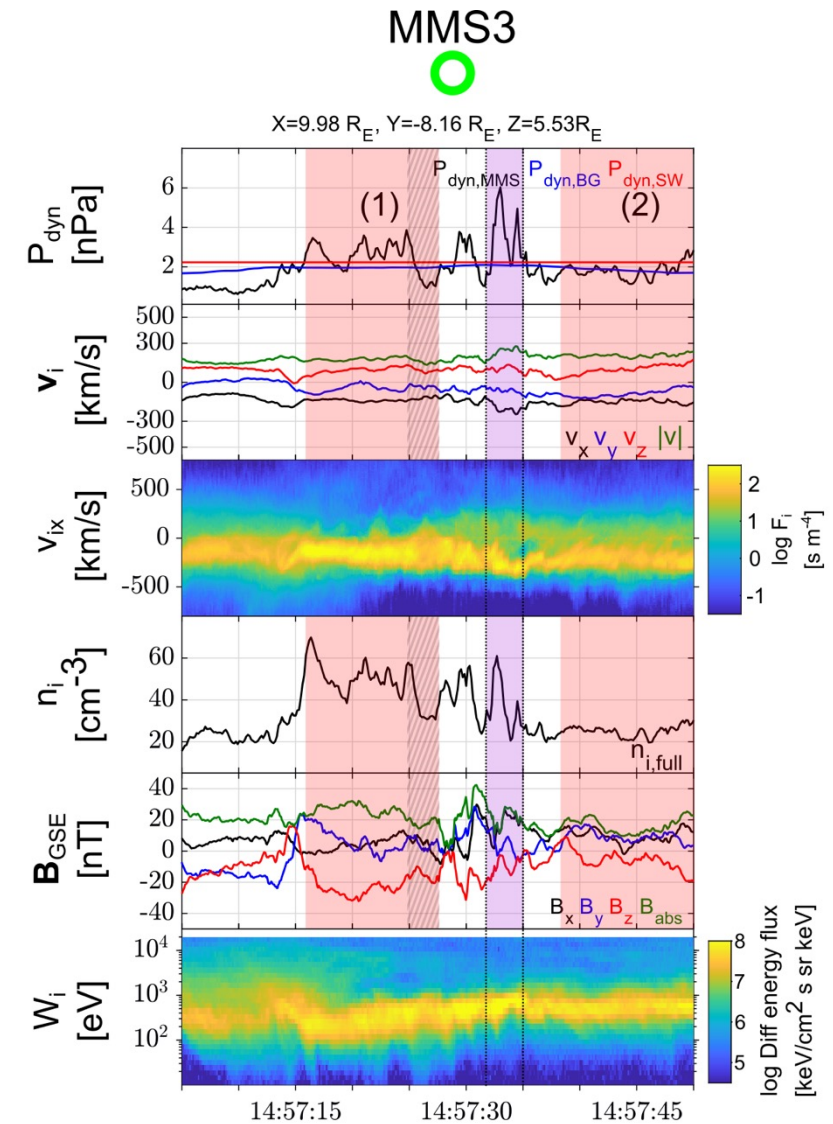
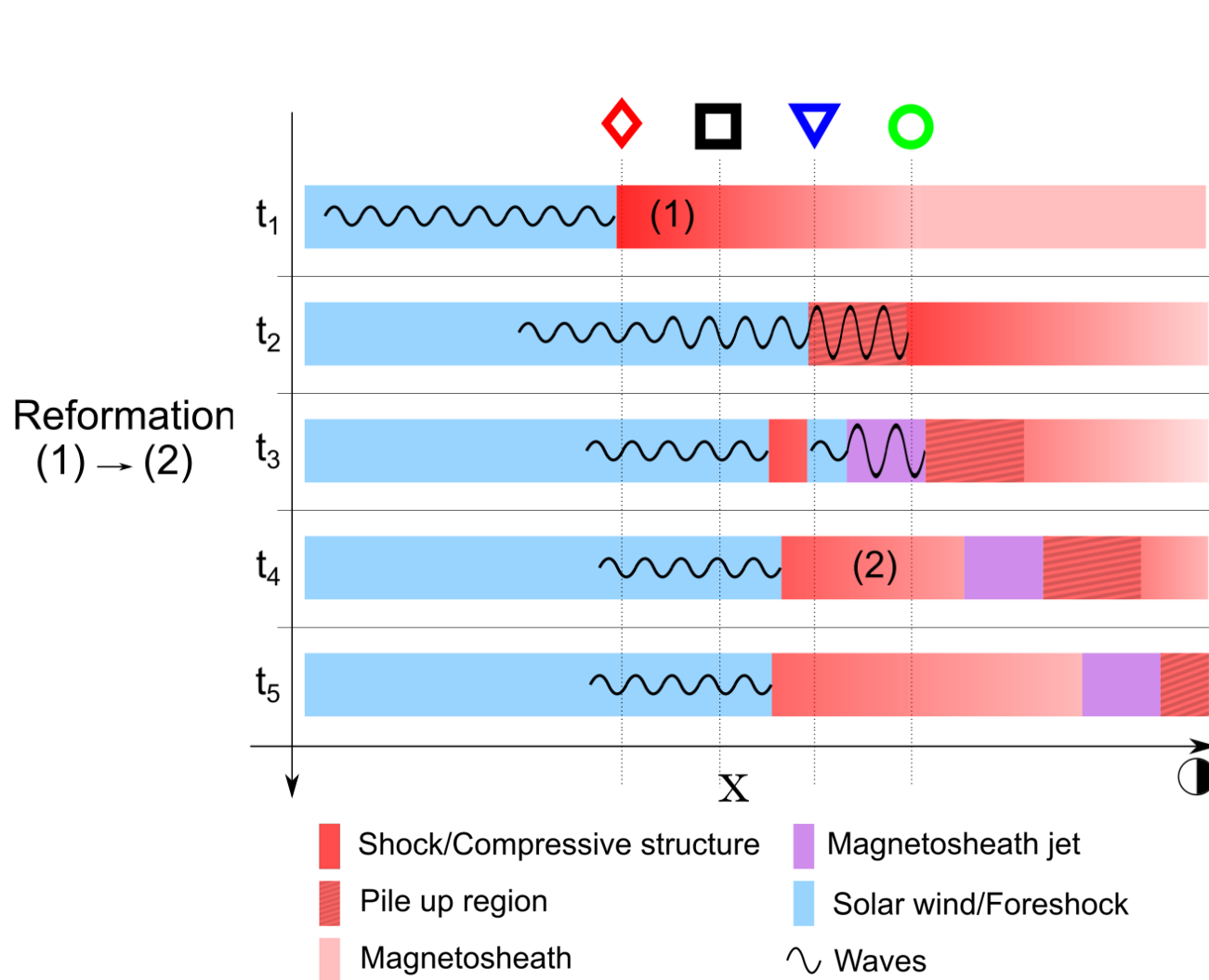
Figure by Drew Turner

The complicated, exotic ones

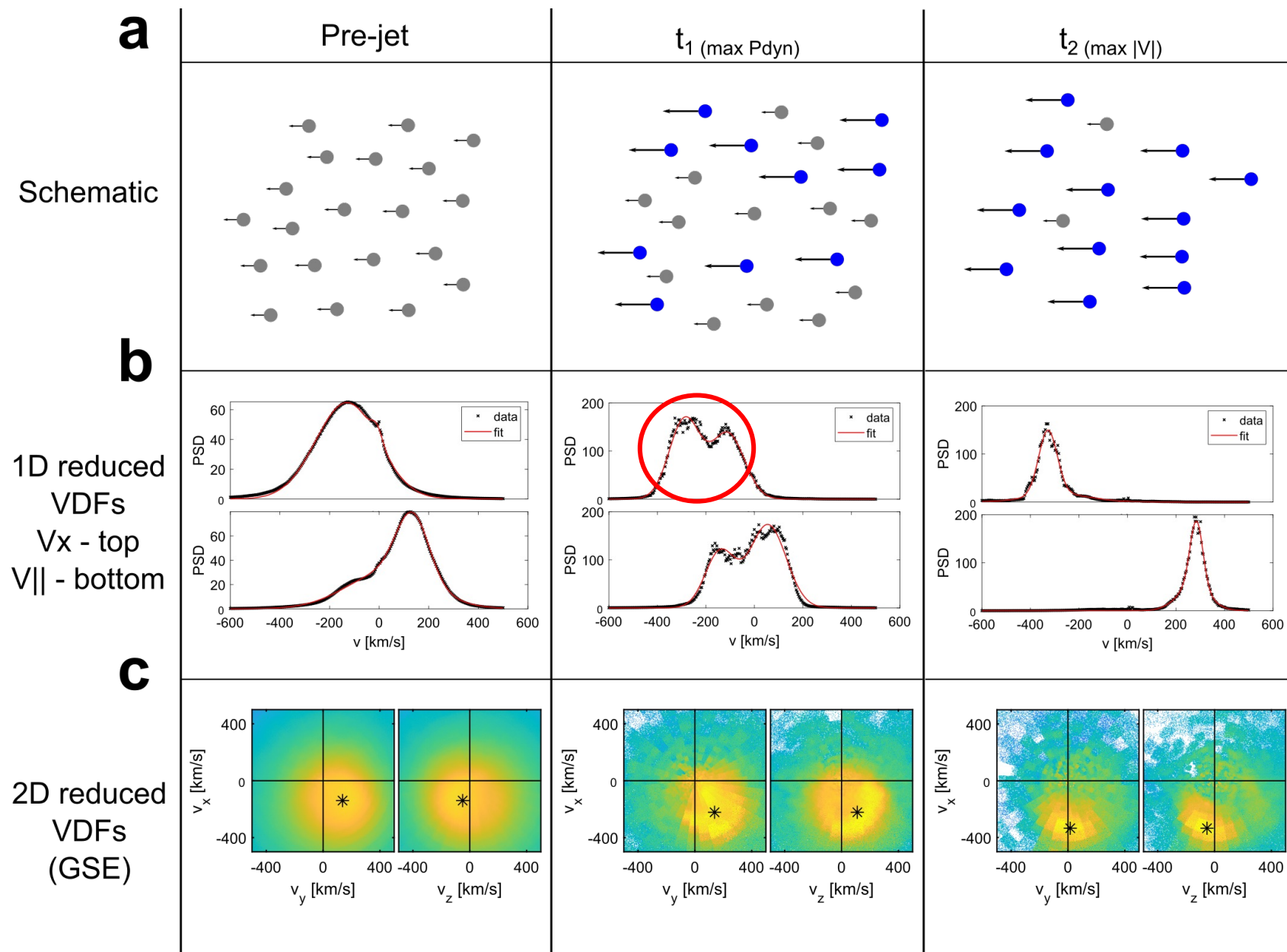
Why Stochastic Betatron Acceleration?



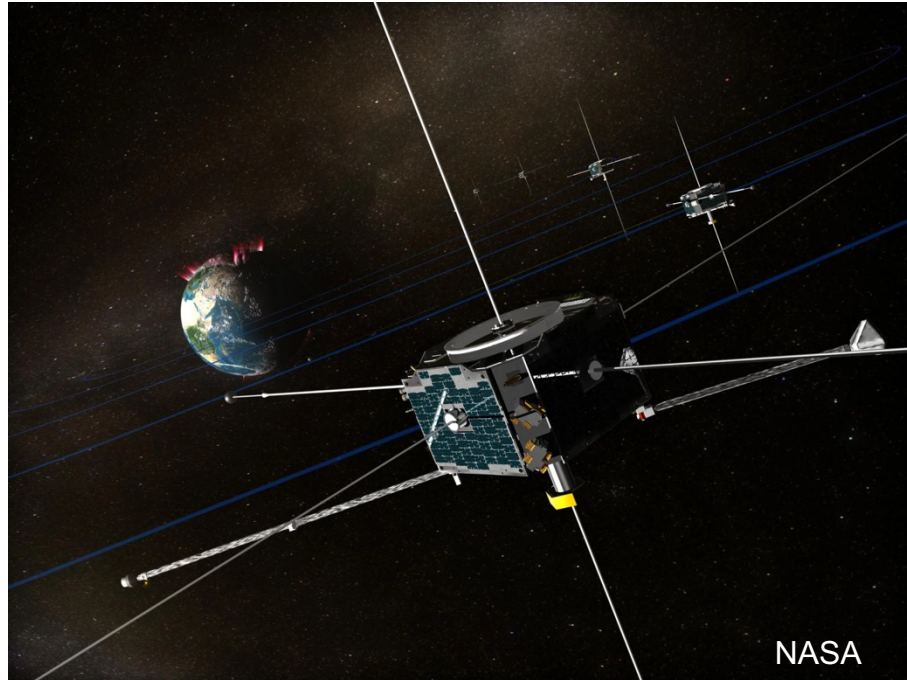
Shock reformation & magnetosheath jets



Jet evolution in Qpar magnetosheath

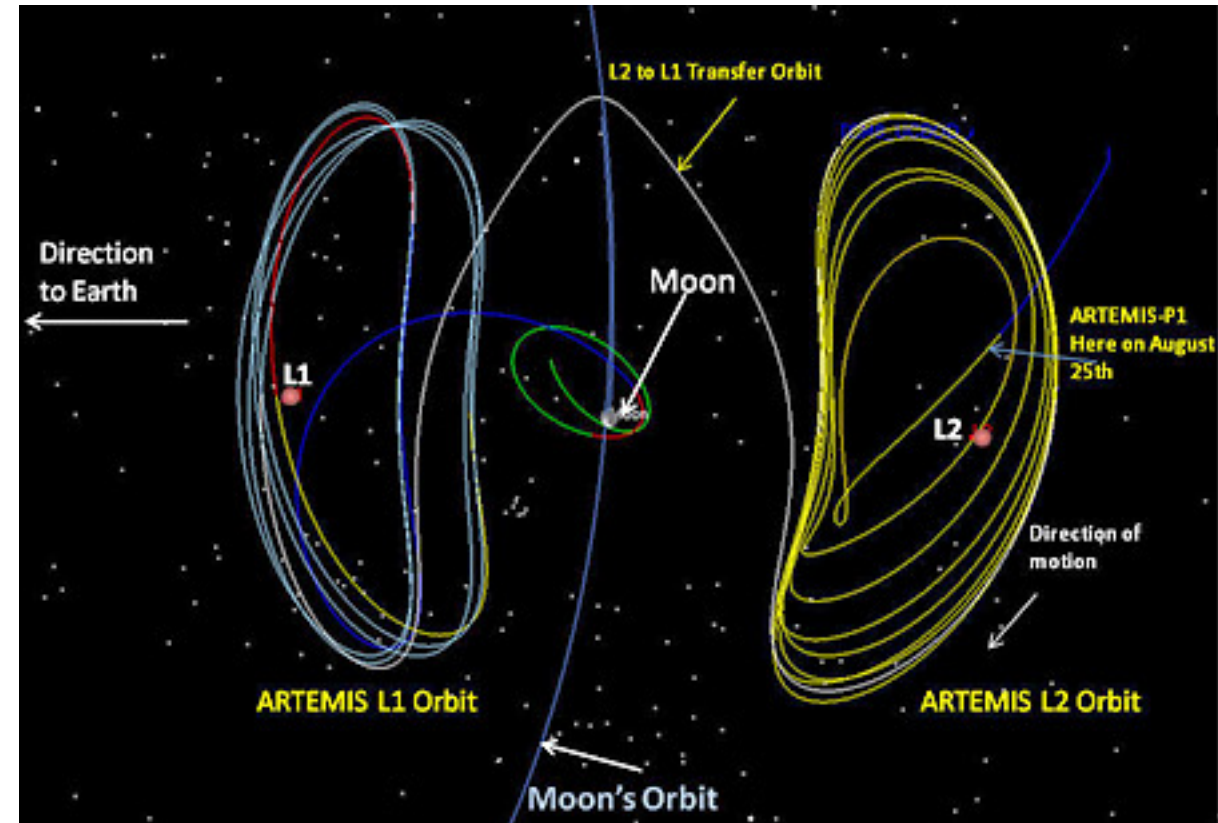
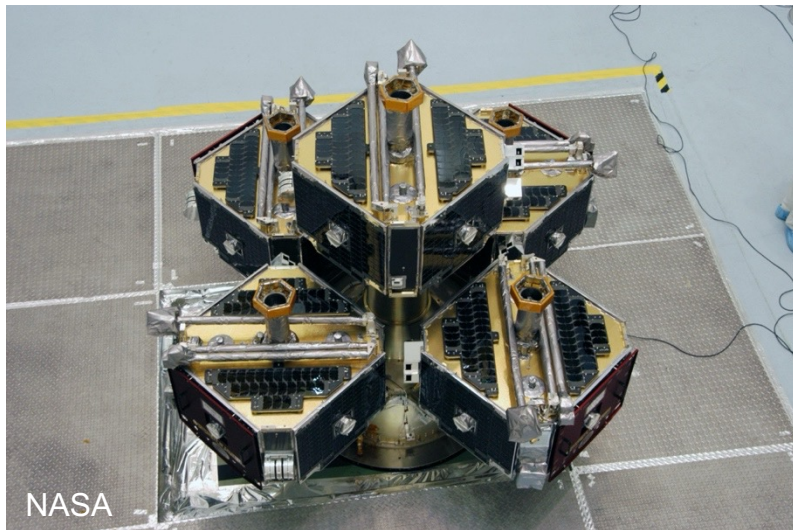


THEMIS/ARTEMIS mission

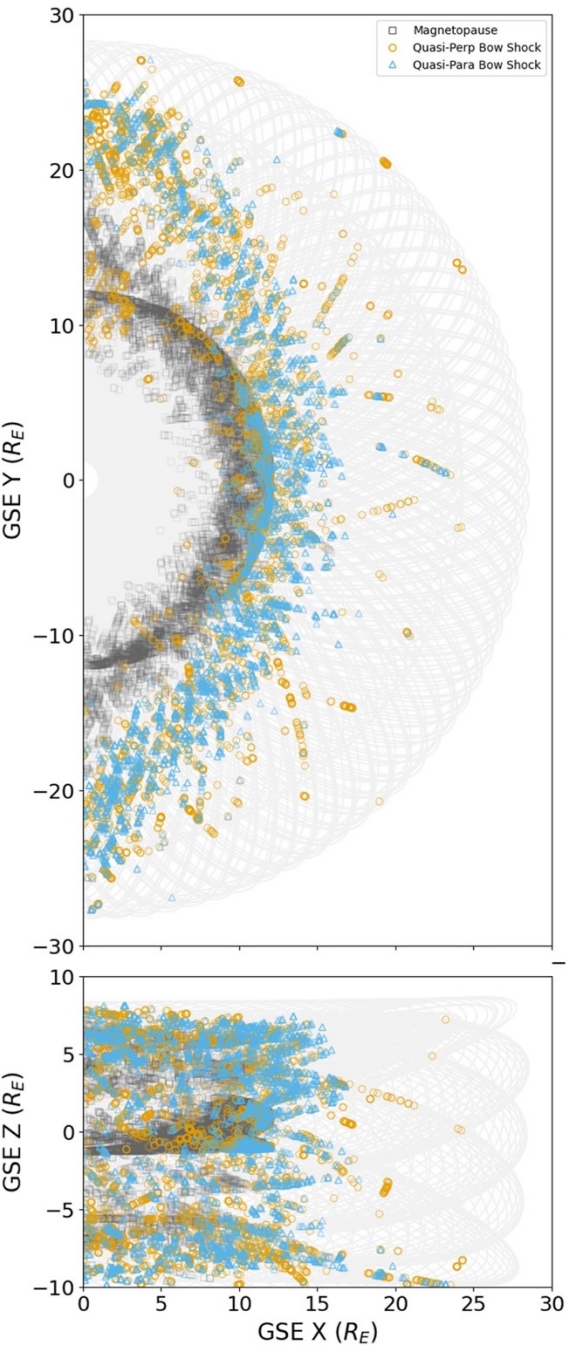


Feb. 17, 2007: Launch → 5 SC, magnetotail reconnection objectives
Jan. 1, 2009: THEMIS-P1 and P2 are Reassigned, Renamed and Redirected to the Moon → ARTEMIS

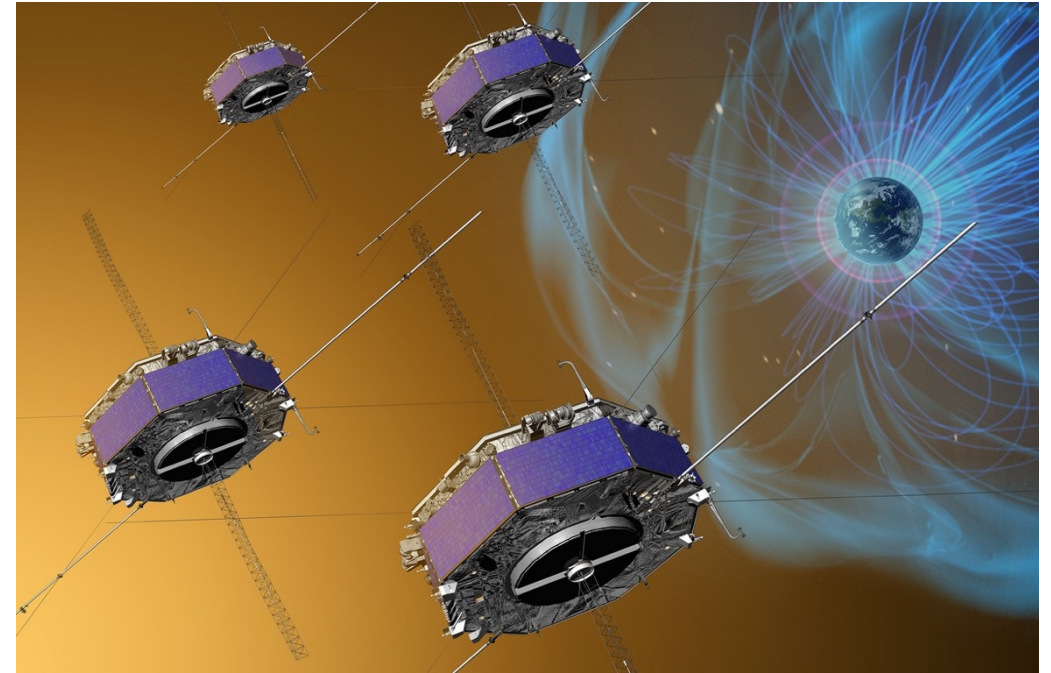
Orbiting the moon it can (sometimes) provide close to Earth in-situ observations of upstream conditions (when moon is on the dayside)



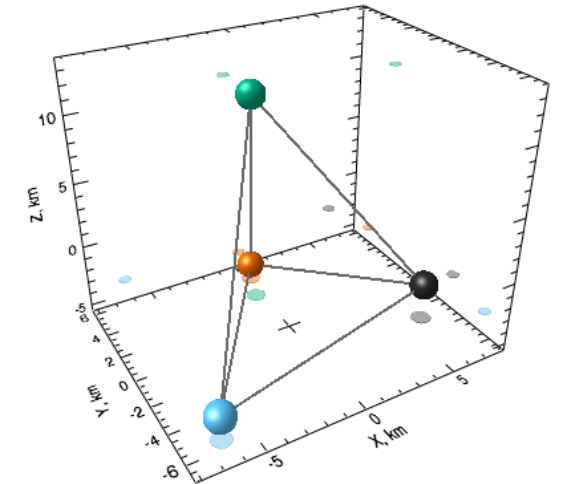
MMS mission



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

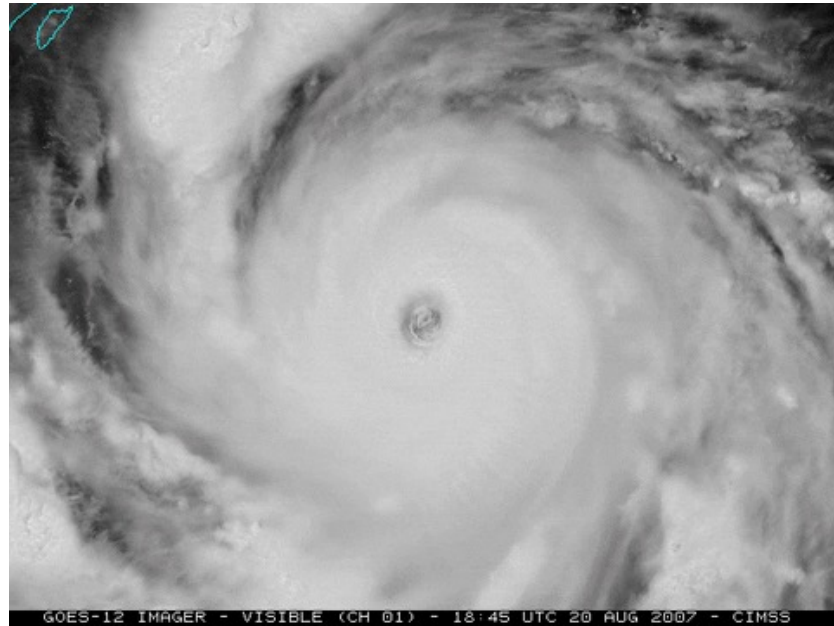


- Several thousands of shock crossings Lalti+ (2023), Toy-Edens+ (2024)
- In-situ observations of plasma moments, fields, and distributions.



Transient events – weather

Hurricanes



Rain

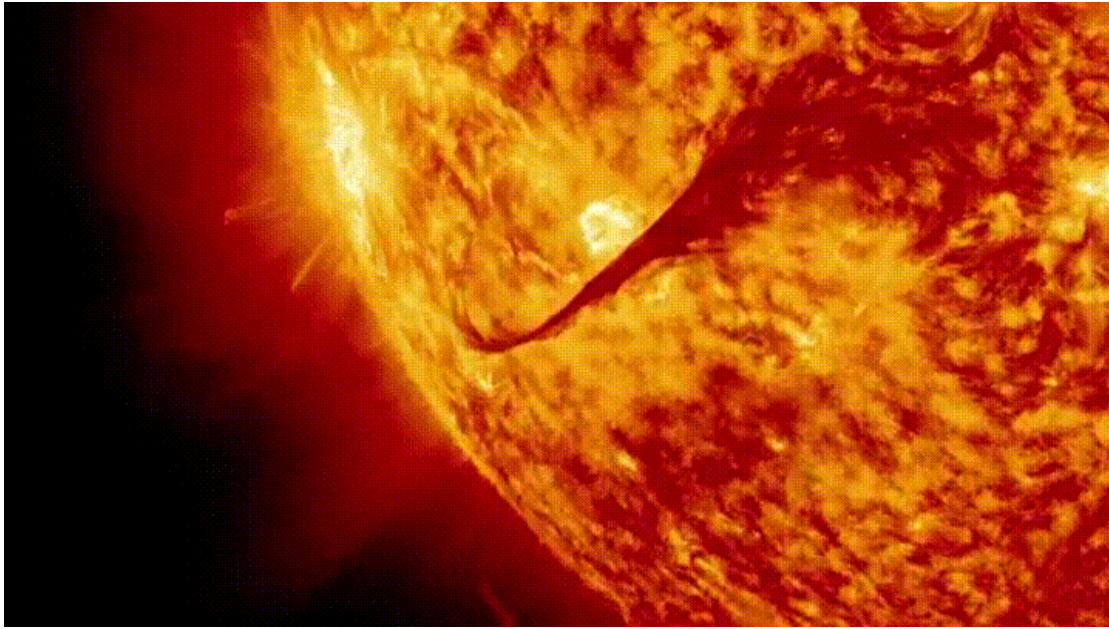


Snowstorms



Transient events – weather

CMEs



Rain

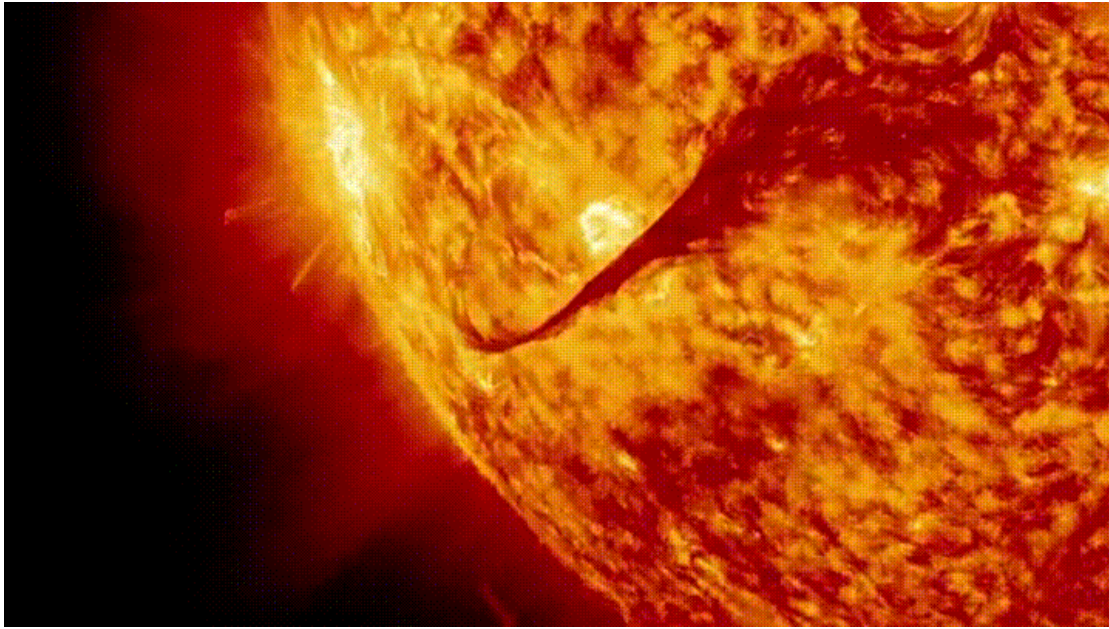


Snowstorms



Transient events – weather

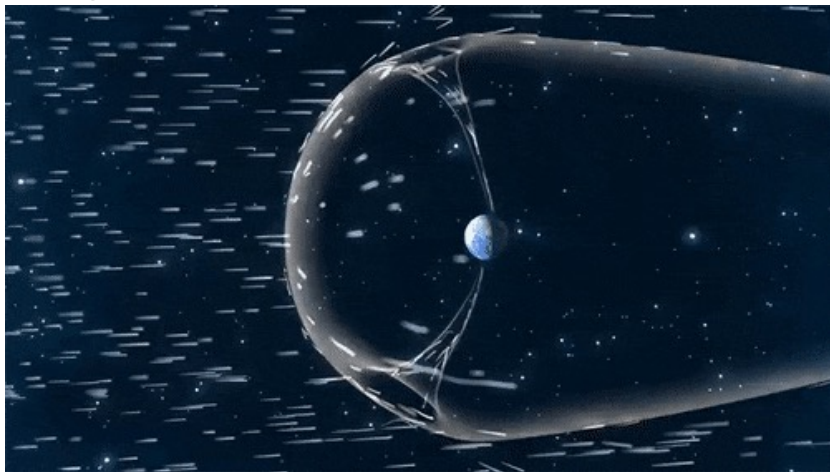
CMEs



Rain

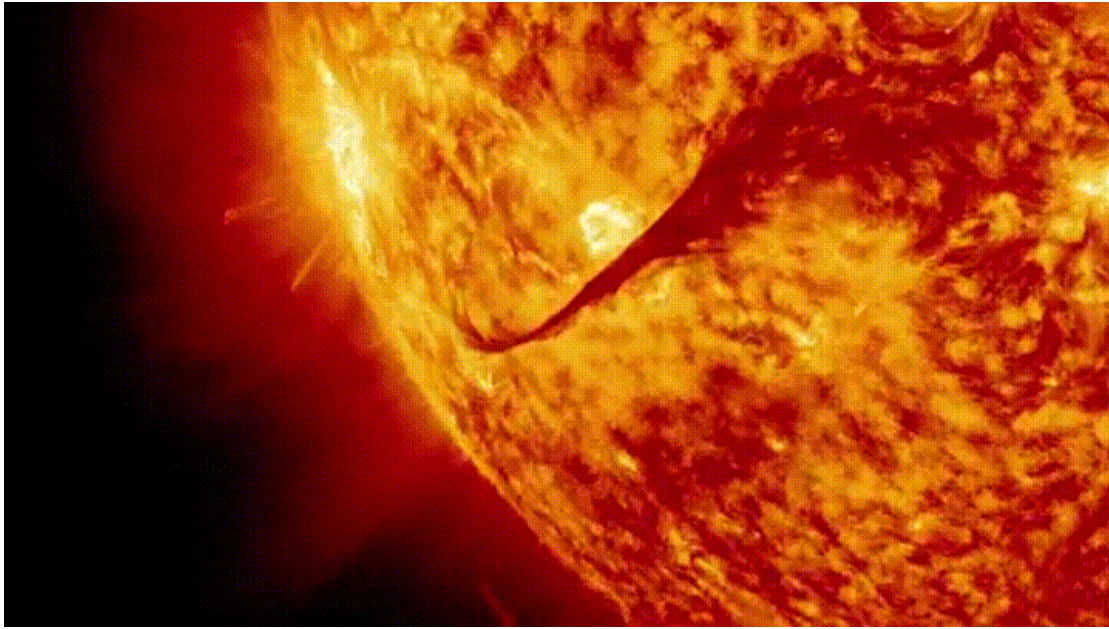


High speed streams, discontinuities

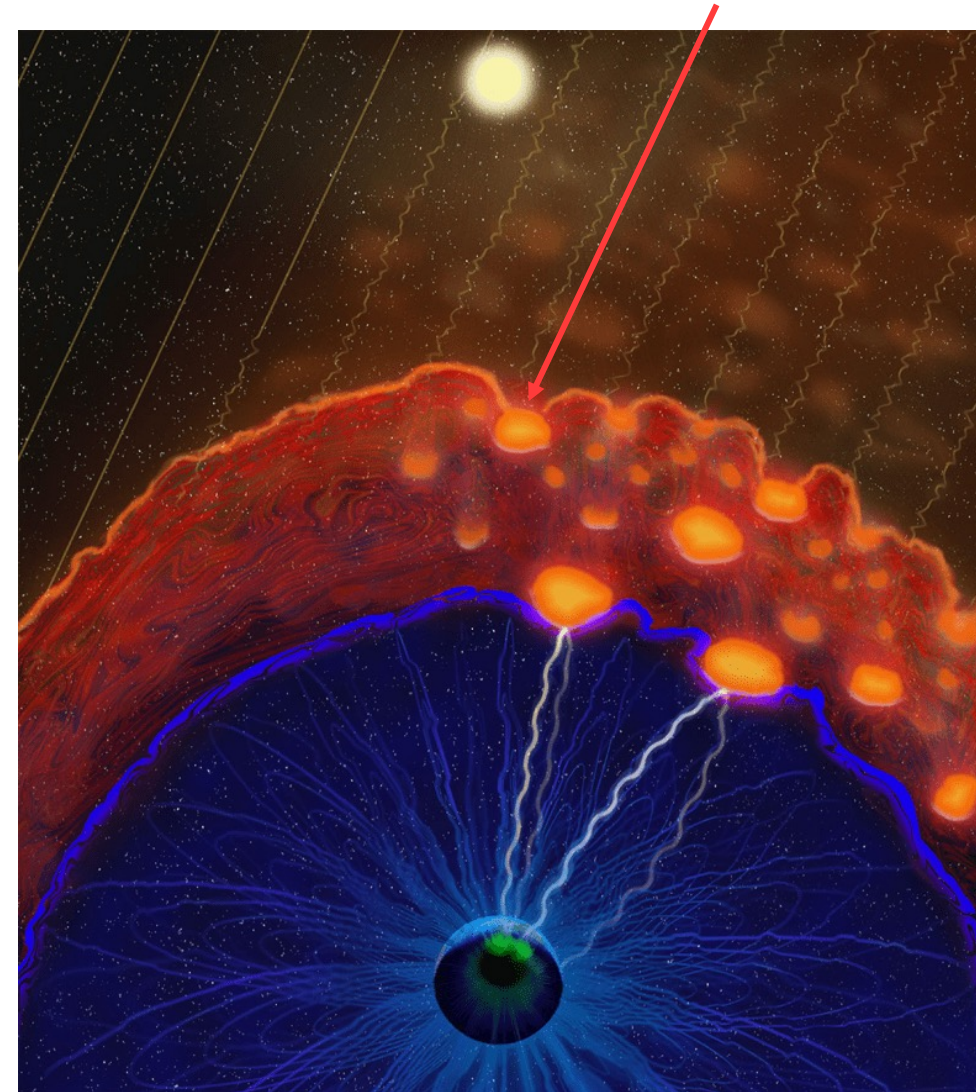


Transient events – *space weather*

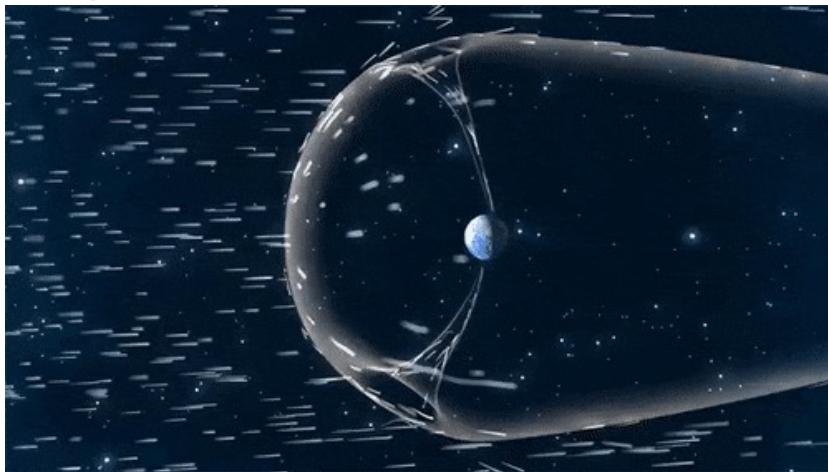
CMEs



Foreshock transients & plasma jets



High speed streams, discontinuities



Our latest published work



Johns Hopkins APL @JHUAPL

How do particles reach extreme speeds in space? APL's Savvas Raptis led a study, featured in @NatureComms, showing how solar wind plasma work together to accelerate particles. This discovery could transform #heliophysics.



Space Science Snapshots | Johns Hopkins University Applied Physics Laboratory

From jhuapl.edu

9:02 AM · Jan 27, 2025 · 628 Views



Southwest Research Institute @SwRI · Jan 15

Using data from two NASA missions including the SwRI-led Magnetospheric MultiScale (MMS), scientists created a new model that may help explain how electron cosmic rays accelerate in space.

nature.com/articles/s4146...



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...



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...

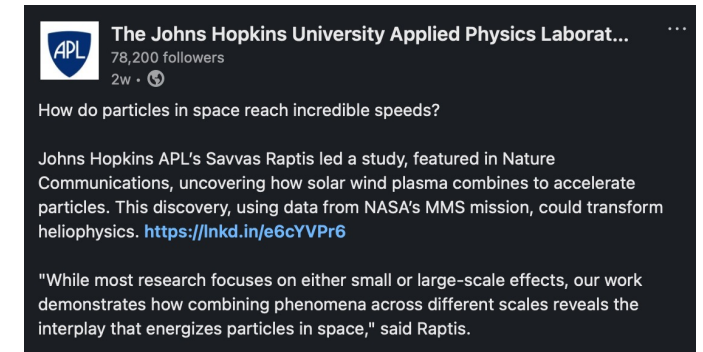
Read the popular science version of the paper:



Read the actual paper:



Read the “science nugget” from ARTEMIS mission:



The Johns Hopkins University Applied Physics Laborat...

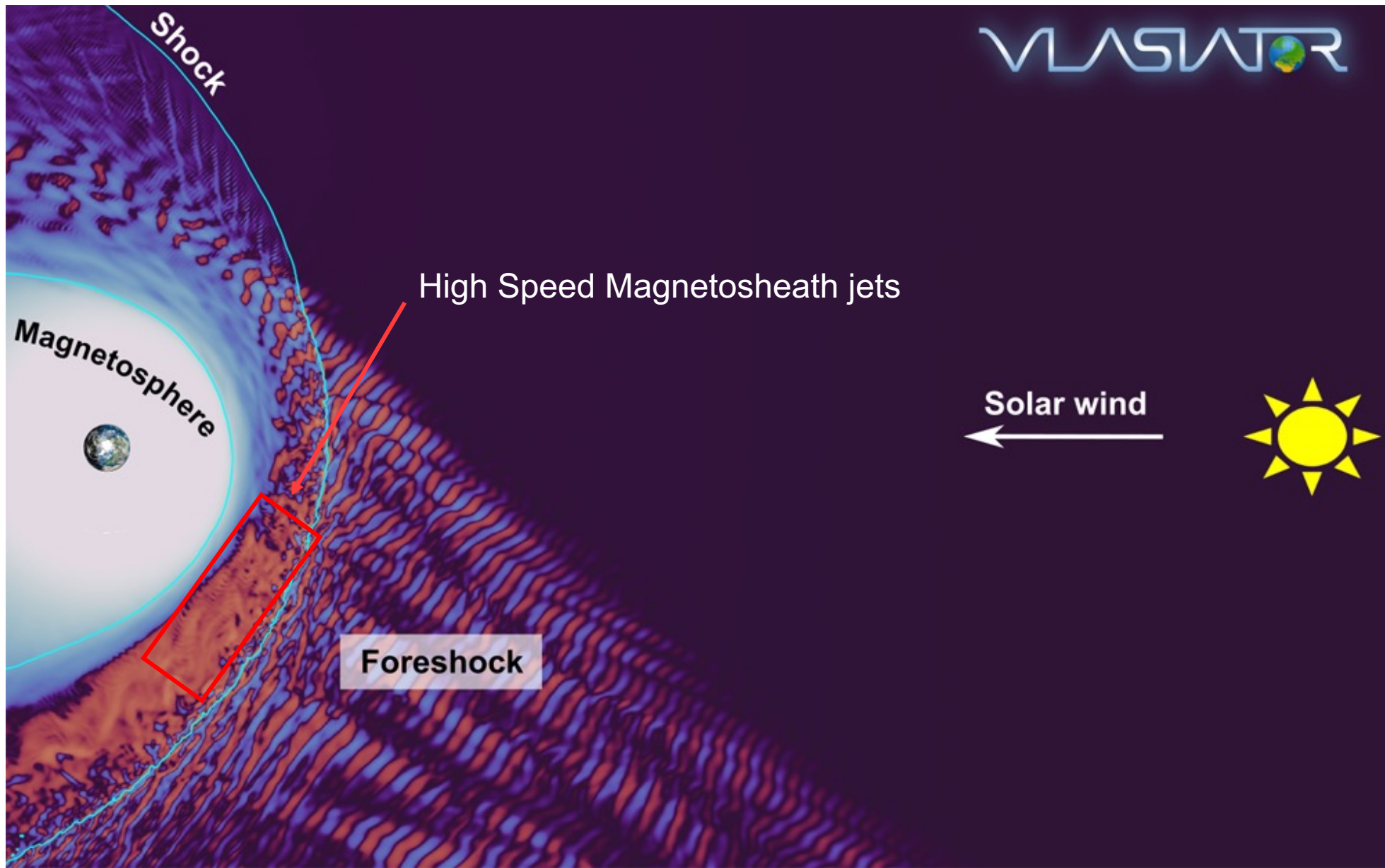
78,200 followers

2w · 🌐

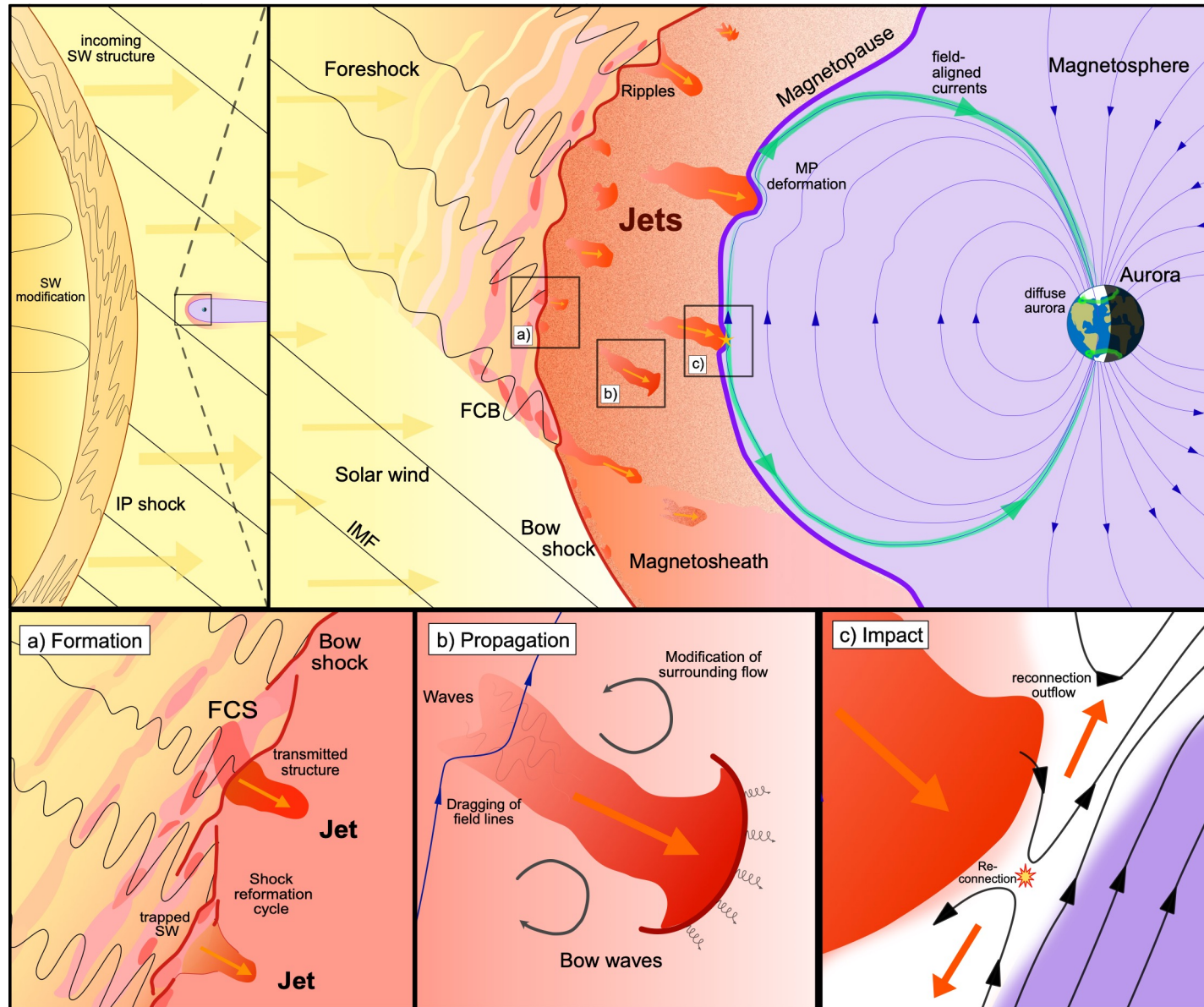
How do particles in space reach incredible speeds?

Johns Hopkins APL's Savvas Raptis led a study, featured in Nature Communications, uncovering how solar wind plasma combines to accelerate particles. This discovery, using data from NASA's MMS mission, could transform heliophysics. <https://lnkd.in/e6cYVPr6>

"While most research focuses on either small or large-scale effects, our work demonstrates how combining phenomena across different scales reveals the interplay that energizes particles in space," said Raptis.



Magnetosheath jets



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*
- Magnetopause reconnection*
- Shock acceleration*
- Magnetopause surface eigenmodes*
- ULF waves*
- Substorms*
- Ground magnetometer detection*

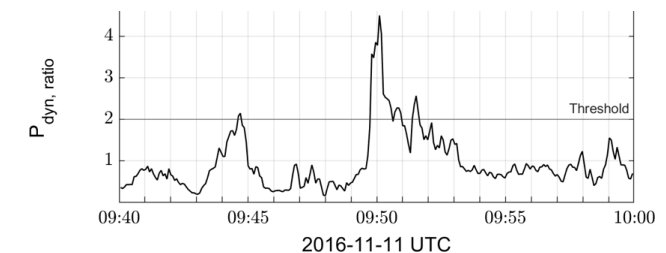


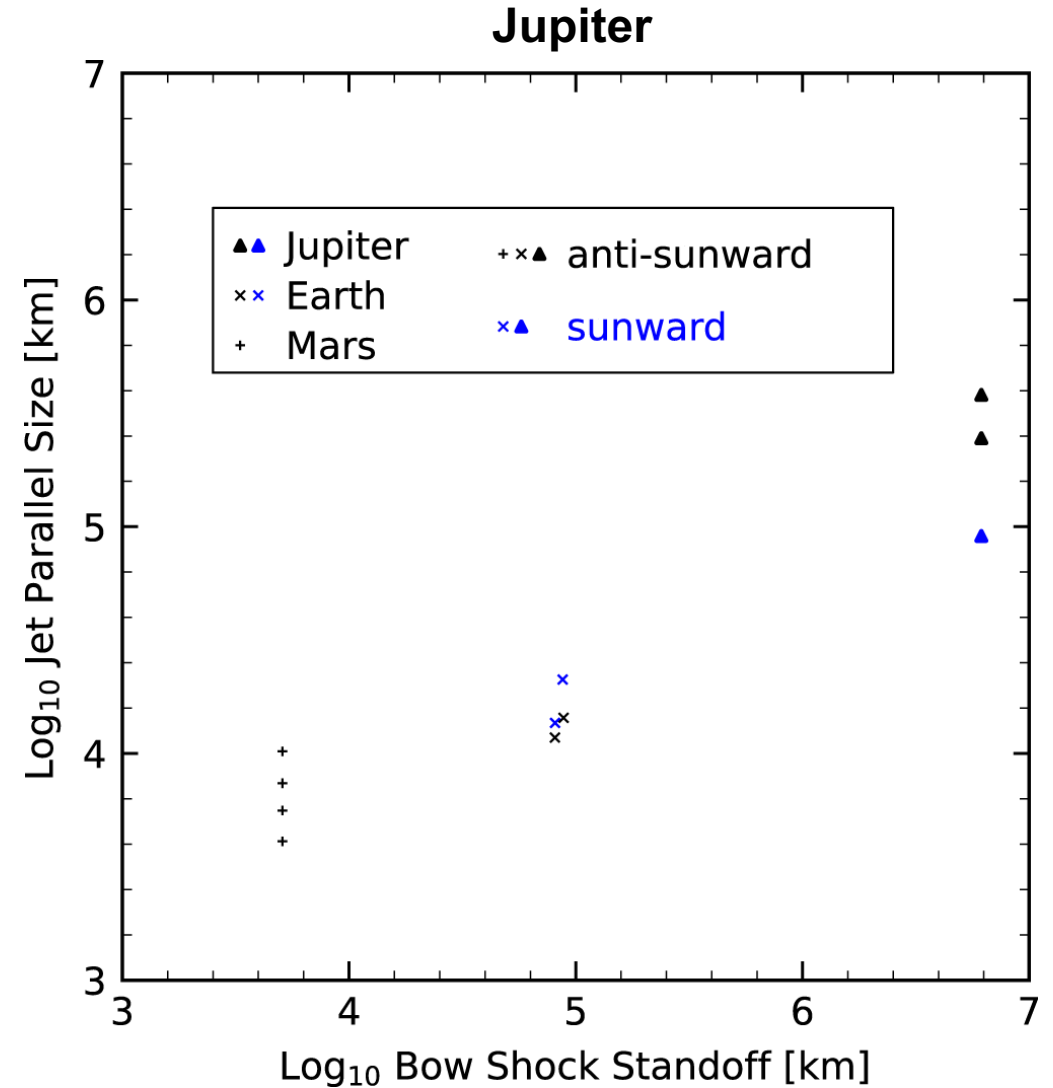
Figure adapted from Krämer et al., 2025, Credits: Florian Koller

Jets: A universal Phenomenon

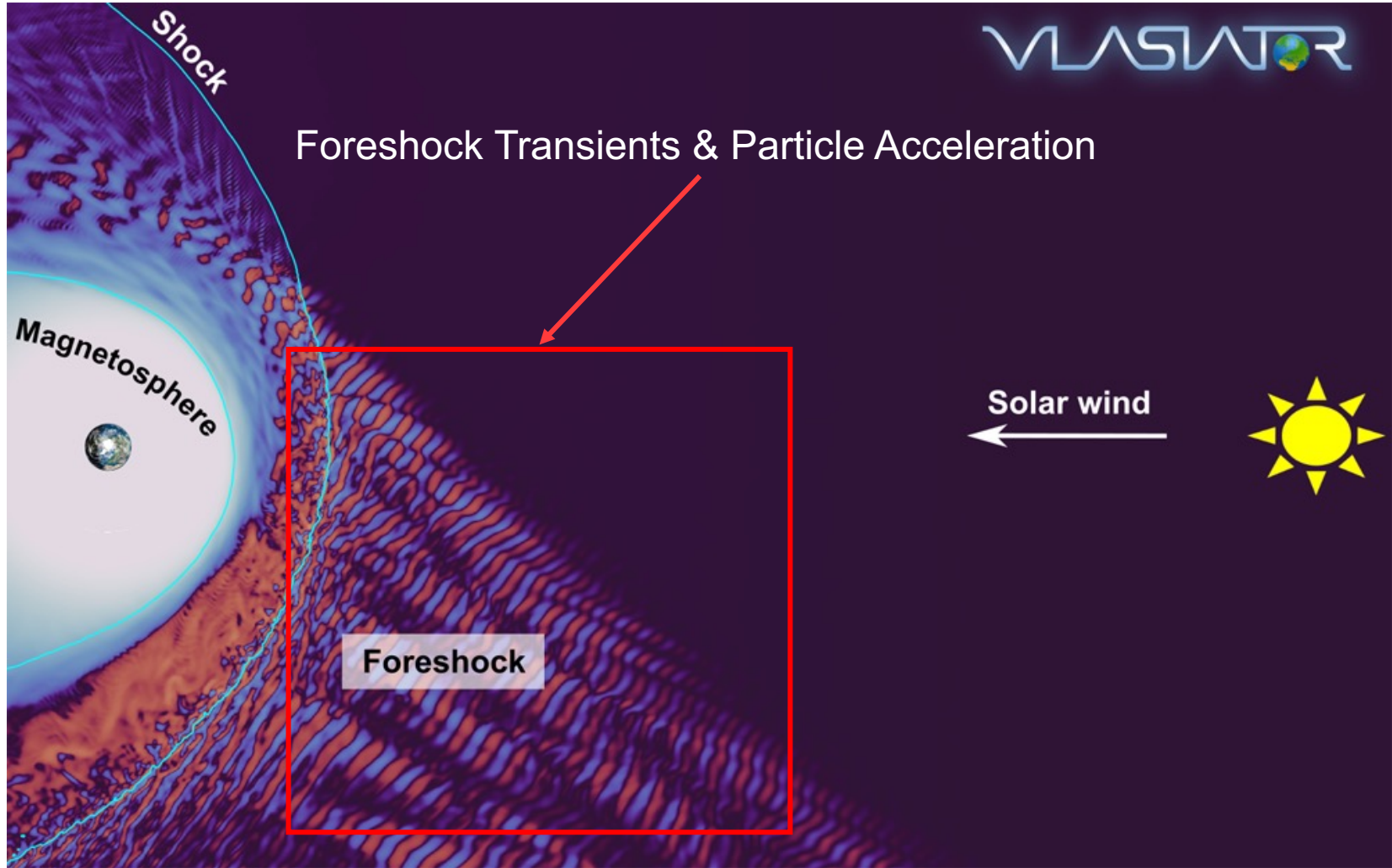
- Jets exist in other planets & IP Shocks
 - ❖ Mars : Gunnel et al., 2023, Mohammed-Amin+2024, Östman+ 2025
 - ❖ Jupiter: Zhou et al., 2024
 - ❖ IP shocks: Hietala et al., 2024
 - ❖ Mercury (TBC): Karlsson et al., 2016
 - ❖ Earth: Latest review from Krämer+ 2025

Q: Are jets a universal phenomenon across shocks?

A: **Probably!**



Foreshock Transients & Particle Acceleration



Things we know:

- Shocks (Geometry)
- Shock Acceleration (DSA/SDA)
- Let's go upstream!