

Particle Acceleration and Transient Processes Upstream of Planetary Bow Shocks

Savvas Raptis

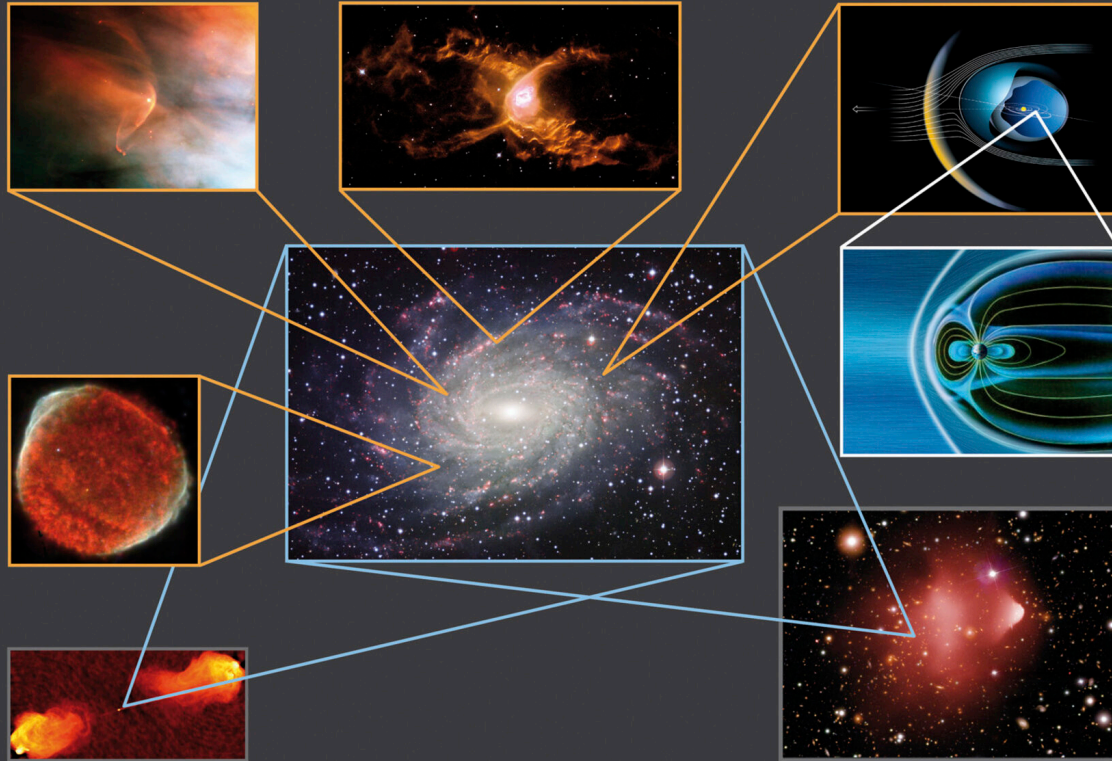
APL/JHU, Laurel, MD, USA

Acknowledgments:

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

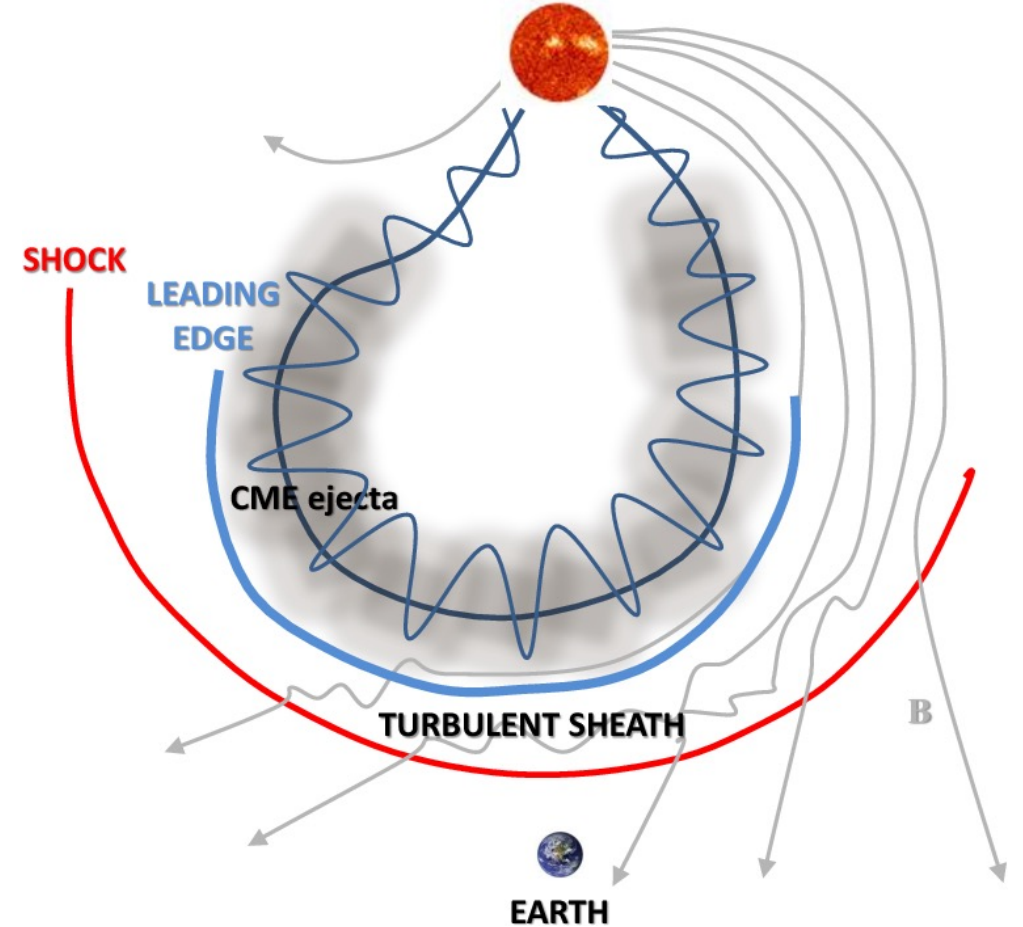
Thanks to co-authors and collaborators: Ahmad Lalti, Drew Turner, Terry Liu, Martin Lindberg, Damiano Caprioli, Lynn Wilson III, Yufei Zhou, David Sibeck, Primož Kajdič, Adnane Osmane, Ian Cohen, Philippe Escoubet, Jim Burch, George Clark, Jamey S ++ many more

Collisionless Shocks in Universe



Shock waves:

Formed when structure moves with speed above local wave speed (e.g., sound, magnetosonic)



They are everywhere!

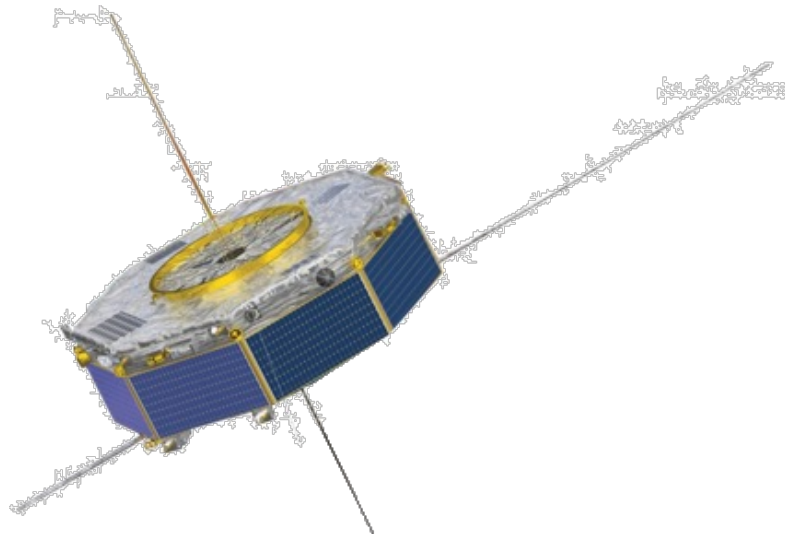
Heating, accelerating particles and converting energies

Space plasma observations & simulations

In-situ
(examples)

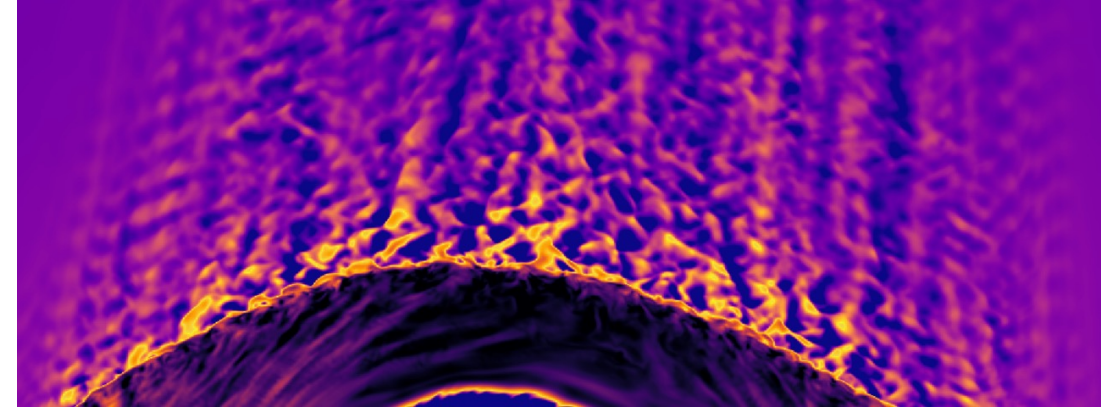
Cluster
MMS
THEMIS

Arase
ACE
WIND

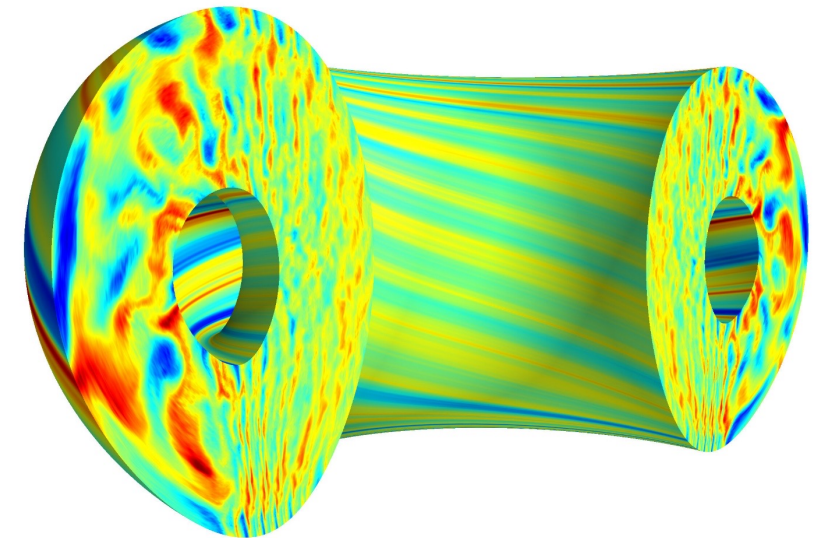


Remote Sensing
(examples)

SOHO
SDO
Solar Orbiter
PSP
SMILE



Fluid, Hybrid, PIC, Monte Carlo



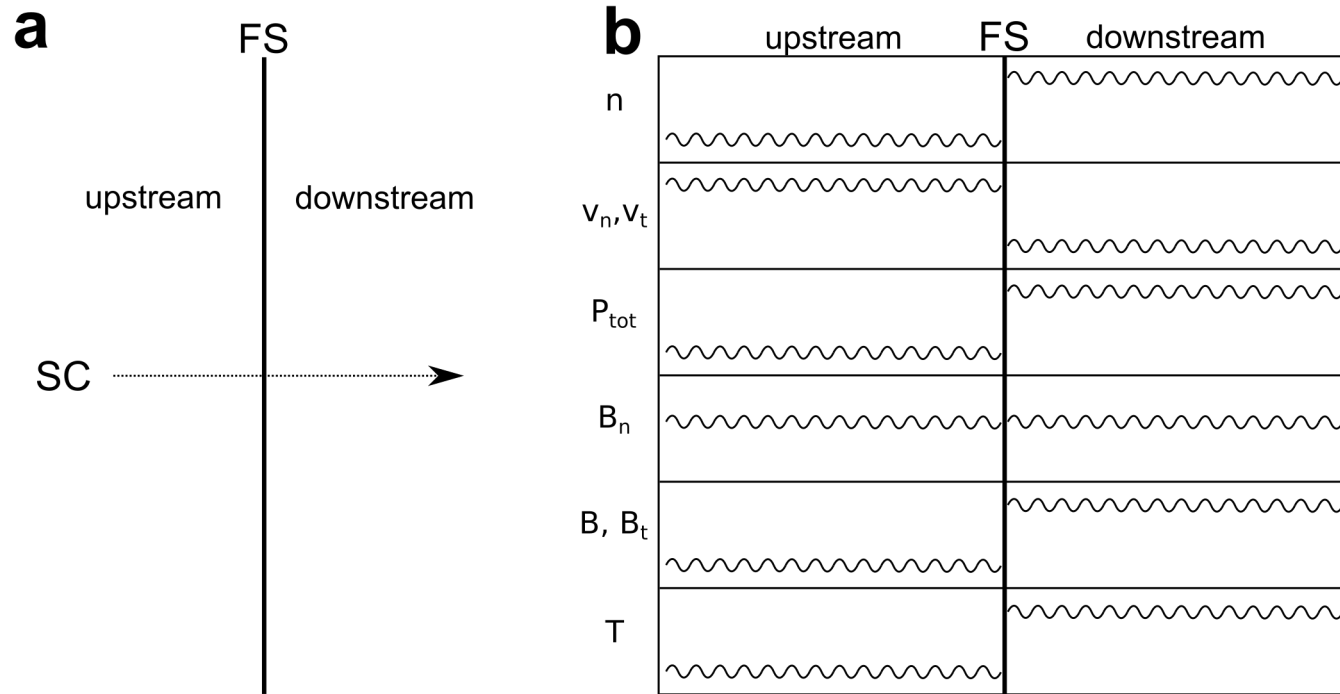
Cluster & MMS = Near shock | **THEMIS/ARTEMIS** = Moon, SW

[Top]: M. Palmroth, Vasiator
[Bottom]: Emily Belli, General Atomics

1. Shocks & Transient Phenomena
2. Particle Acceleration
3. New Results on Particle Acceleration

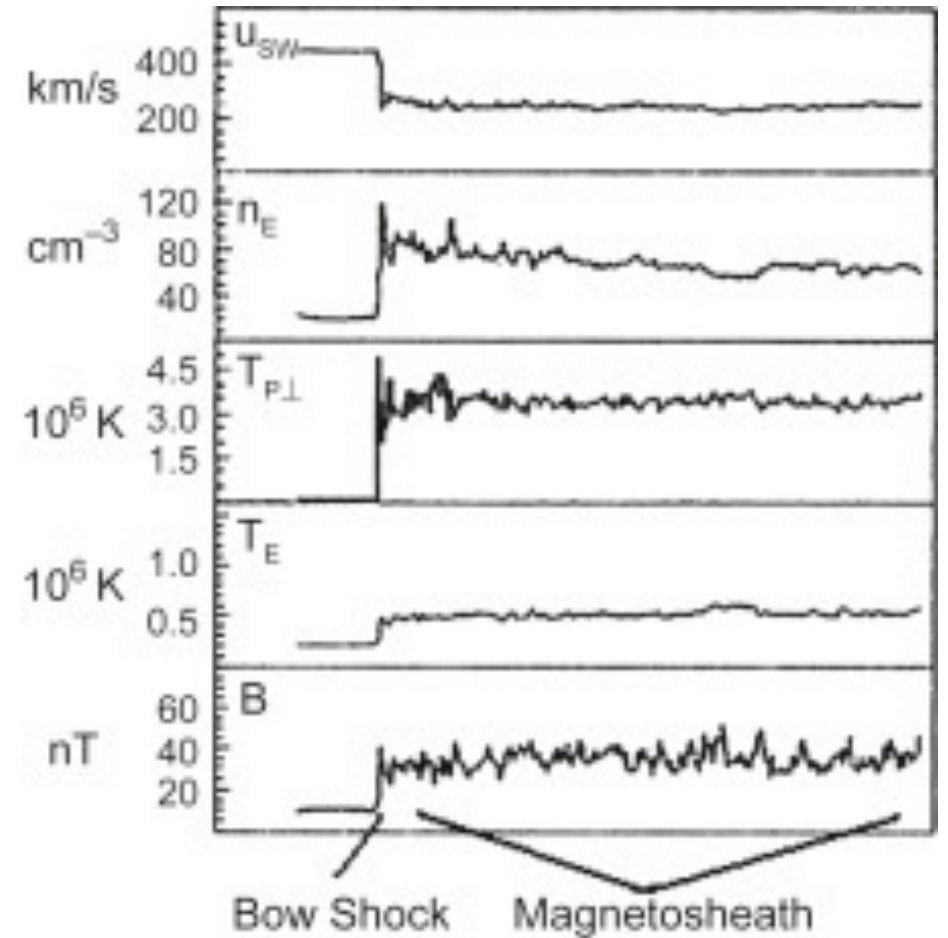
Shocks & Transient Phenomena

Fast shock transition (Theory & initial data)



Rankine Hugoniot relations / Jump Conditions

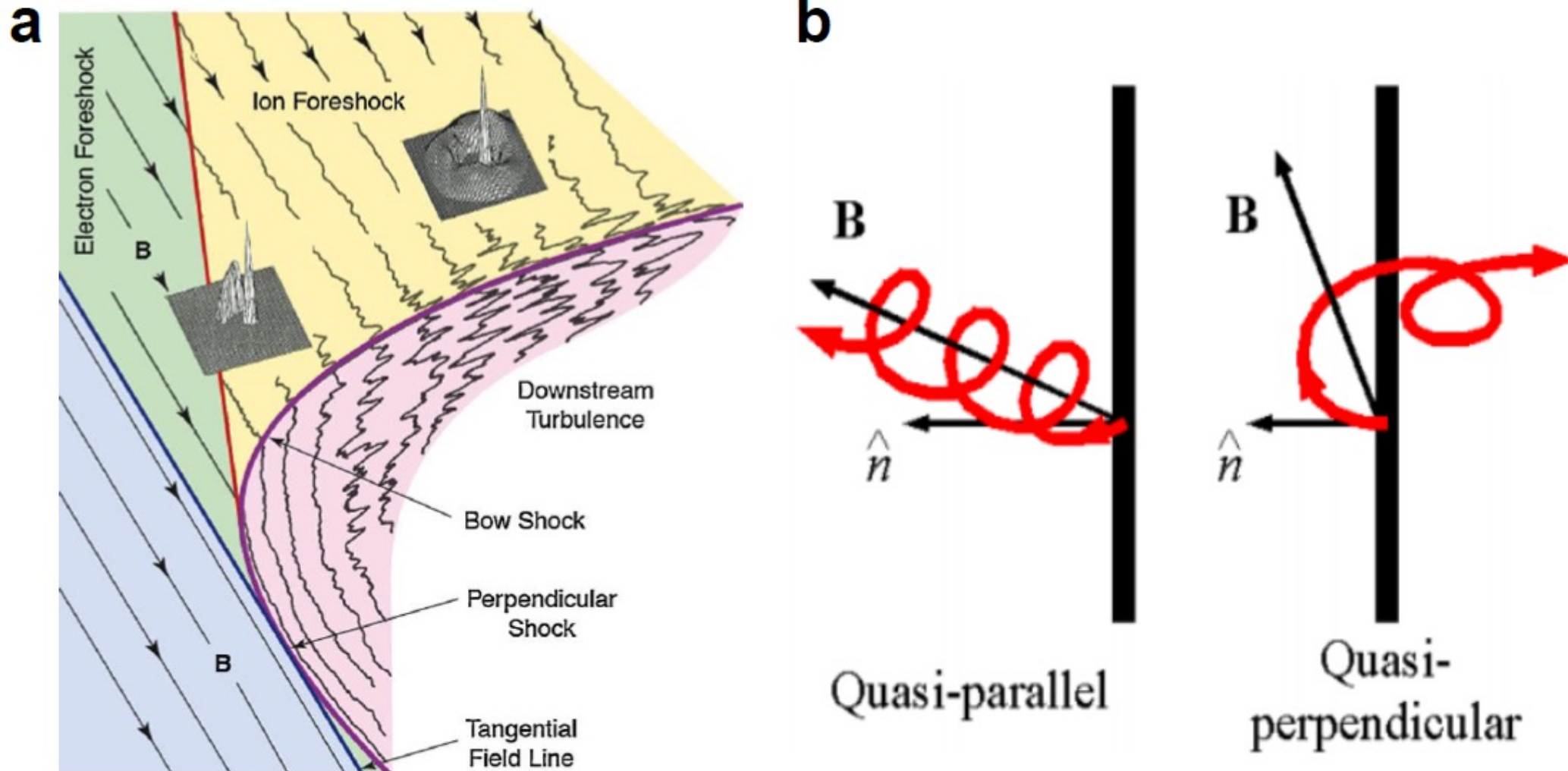
Thermalization, Compression, Breaking



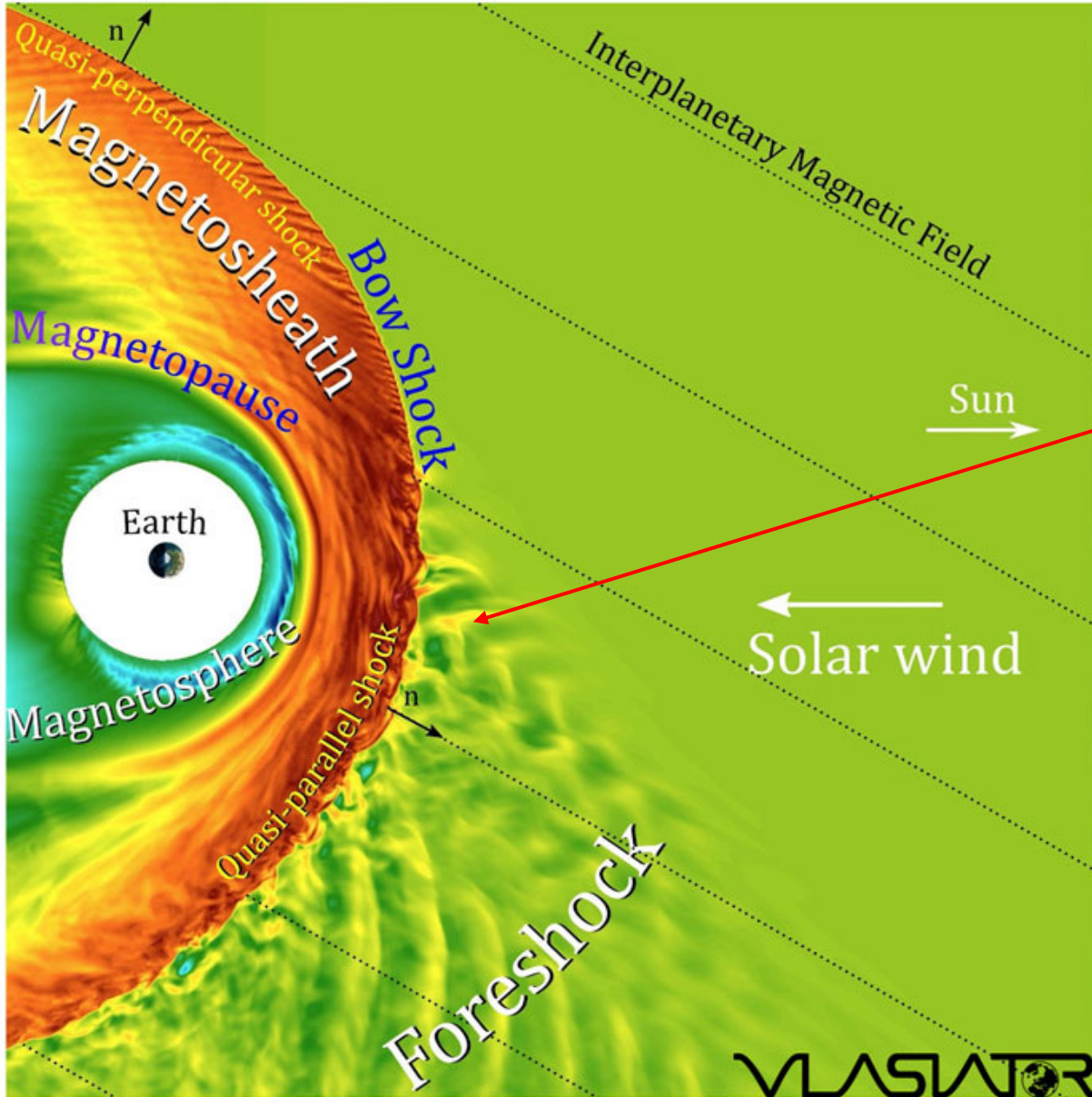
1D Isotropic and adiabatic one fluid plasma shock transitions

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

Shock & foreshock



Earth's Qpar bow shock and foreshock



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

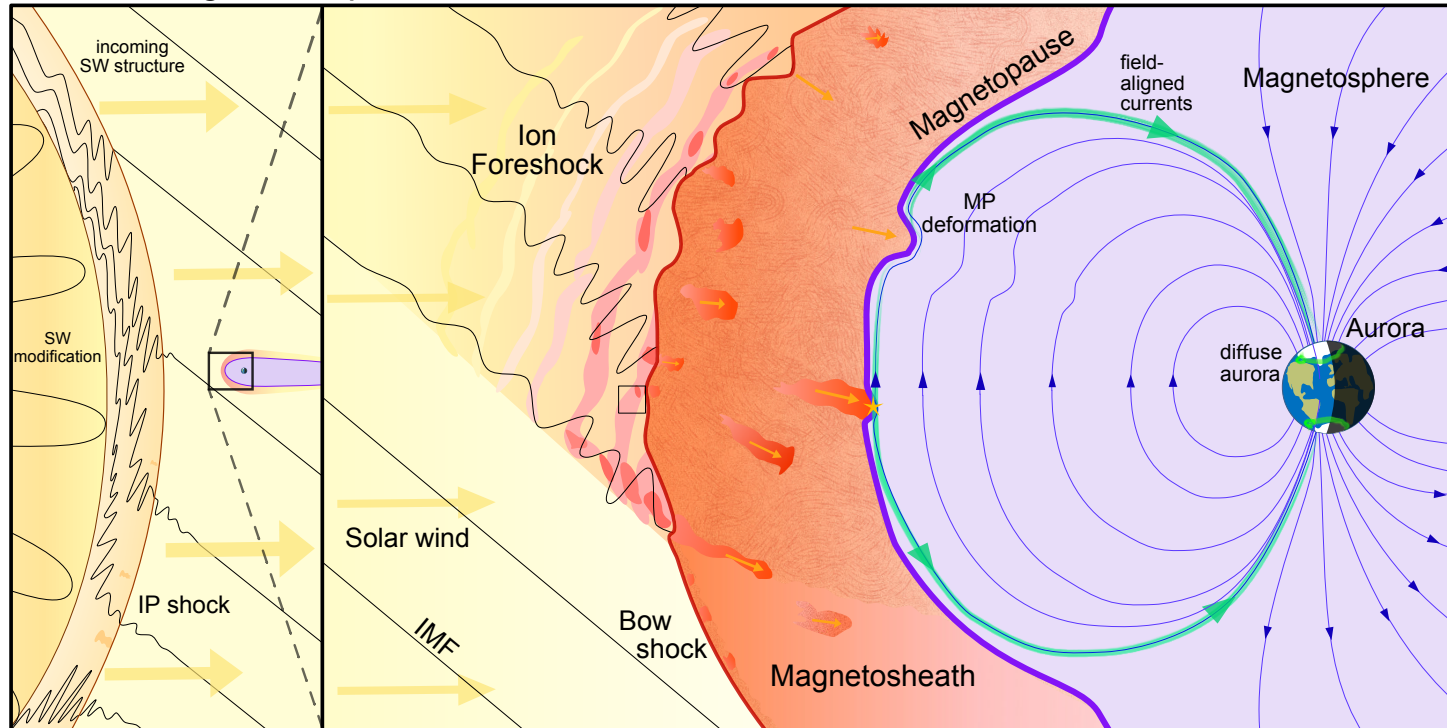
- Very **efficient particle accelerators**
- **Transient phenomena** upstream and downstream
- ULF waves upstream and downstream
- Kinetic plasma physics
- Wave particle interaction
- Turbulence
- Current sheets & reconnection

What is a Dayside Transient?



← New review paper about high-speed jets!

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



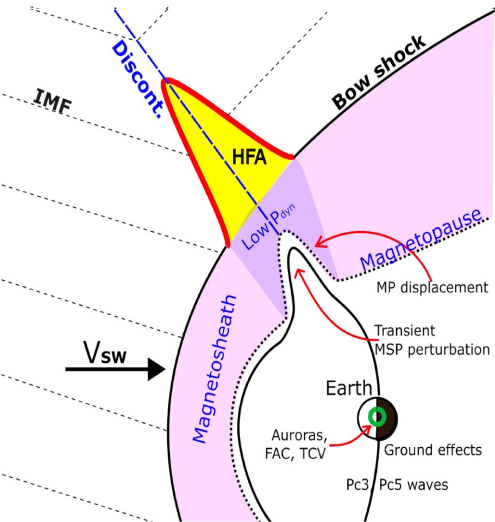
Transient phenomena are events that disrupt the steady-state plasma conditions, occurring temporarily and introducing dynamic changes to the physical system

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

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

The anatomy of an HFA

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



Hot Flow Anomalies (HFA)

Kajdič+ (2024)

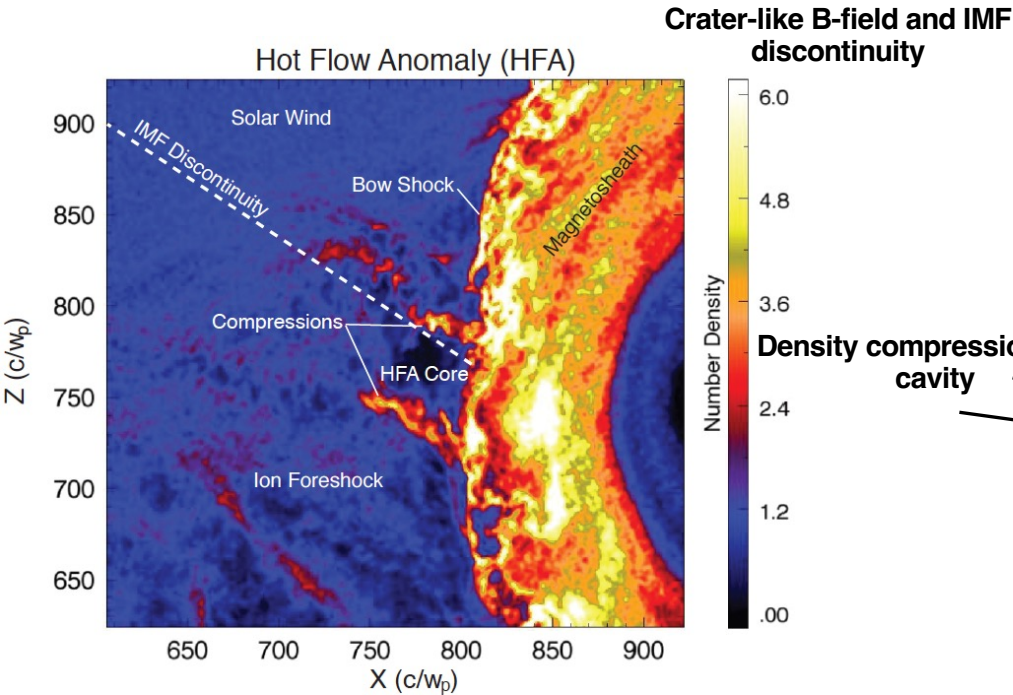


Figure by Nick Omid

How they form?

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

Crater-like B-field and IMF discontinuity

Density compressions and cavity

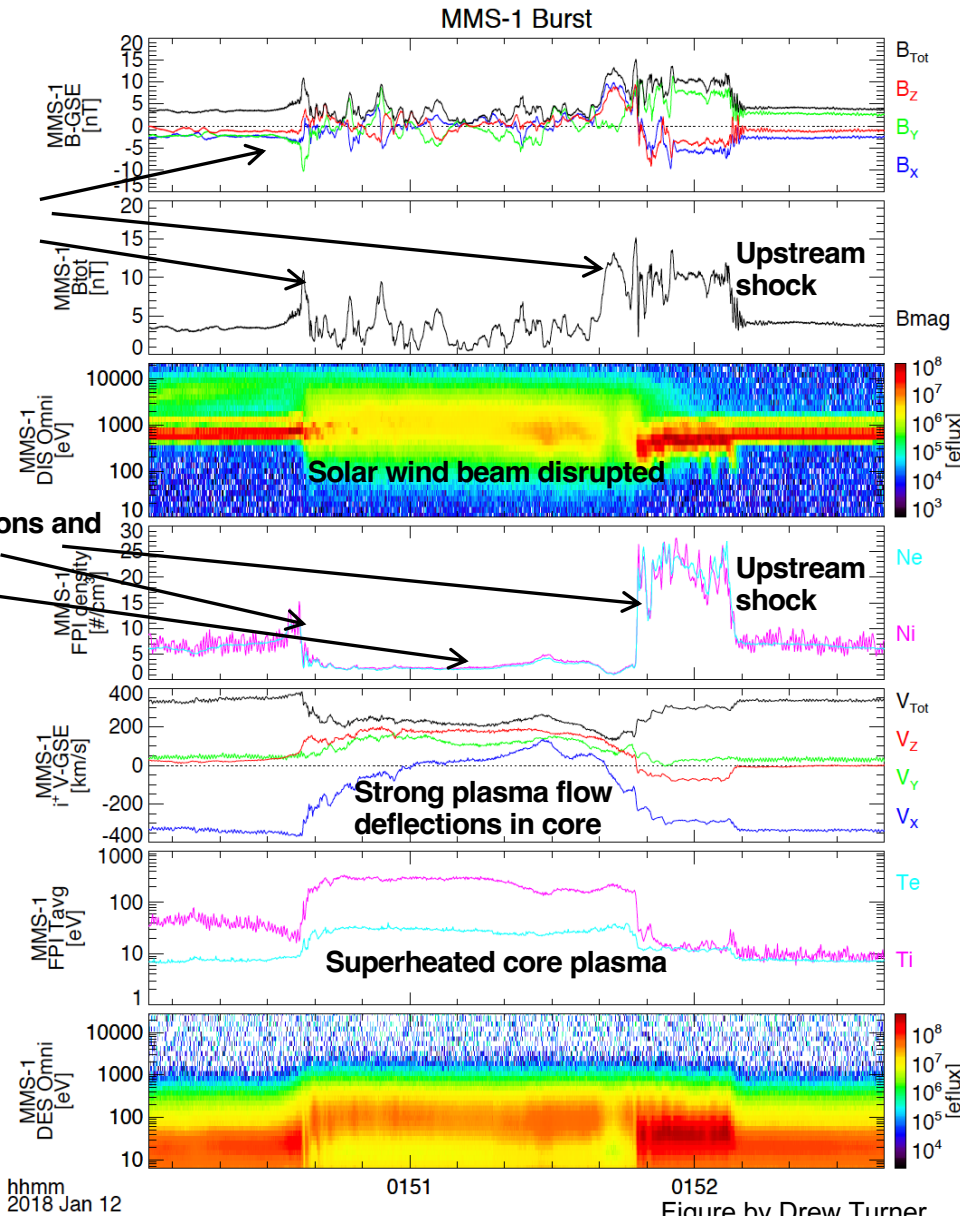
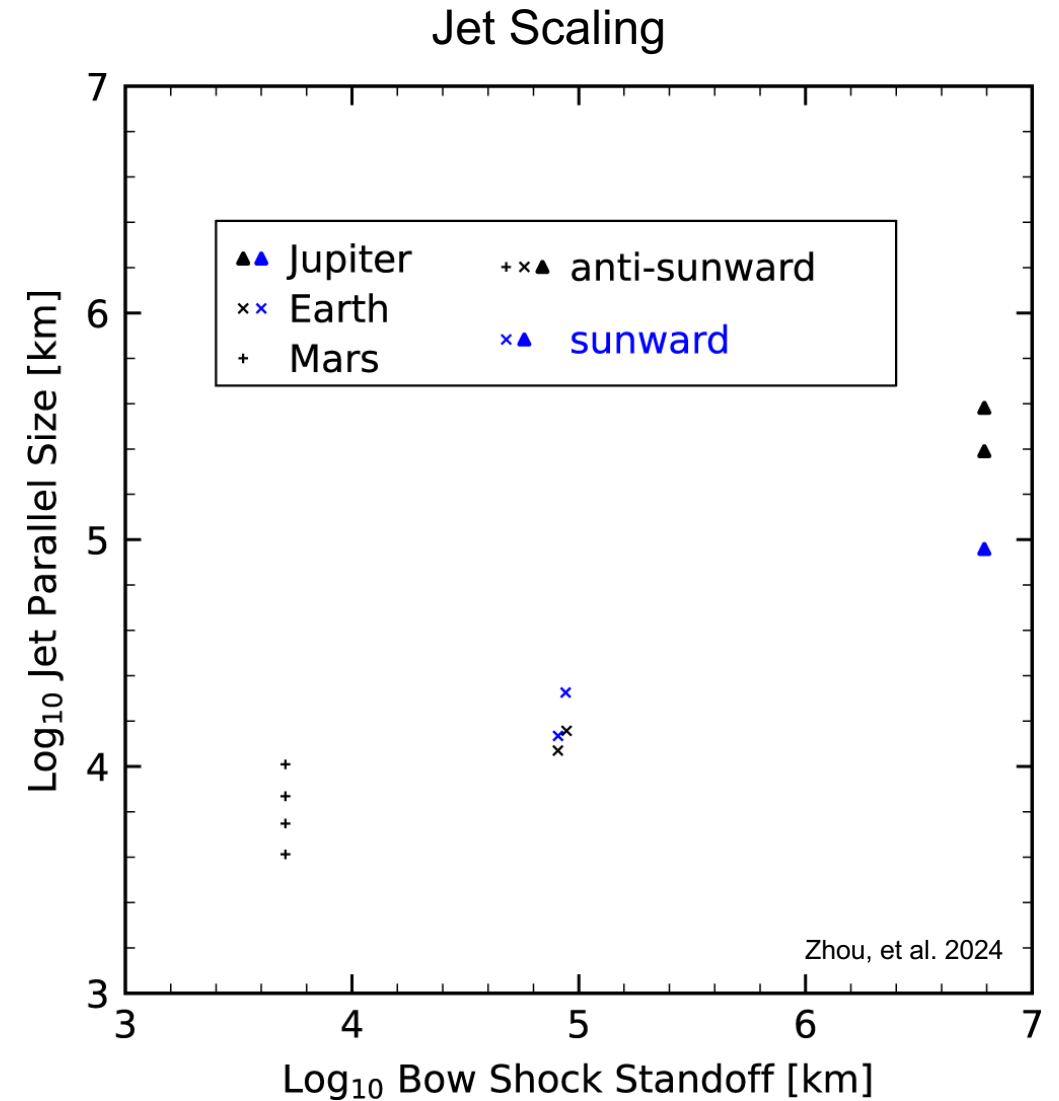
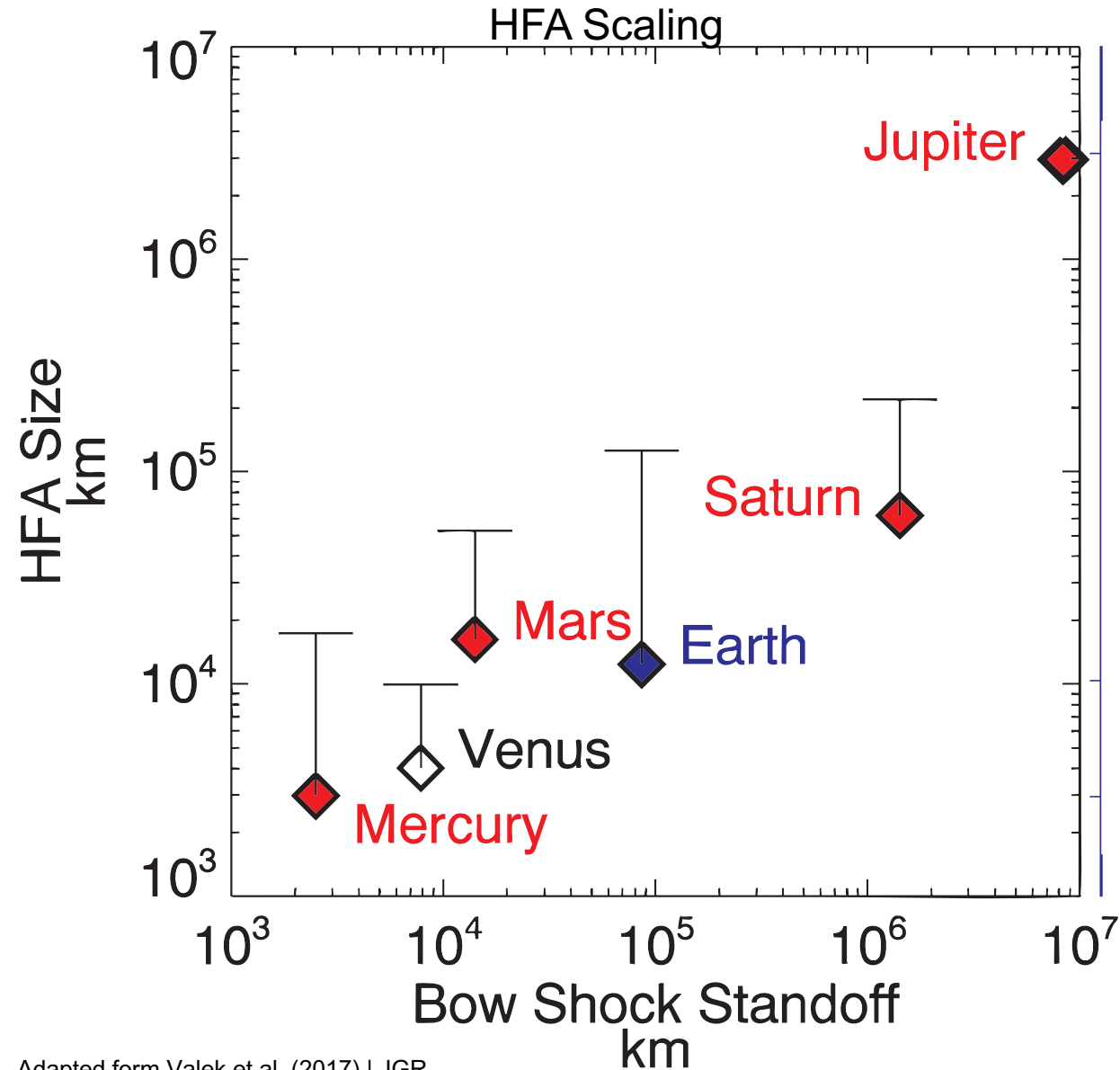


Figure by Drew Turner

Transients Scaling Across Different Systems



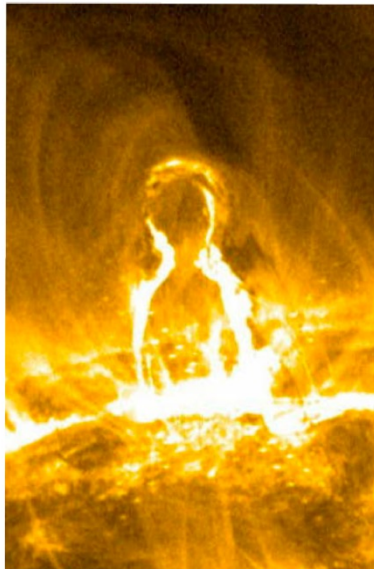
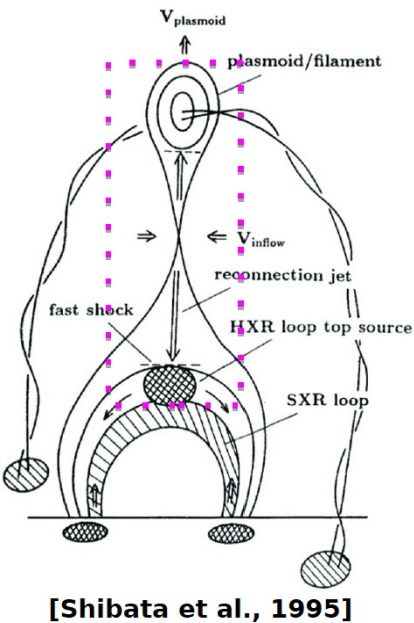
Please remember that, very important!

1. Shocks & Transient Phenomena
2. Particle Acceleration
3. New Results on Particle Acceleration

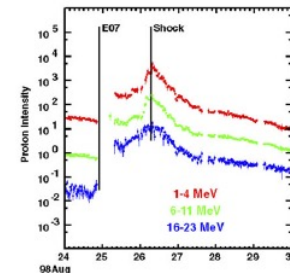
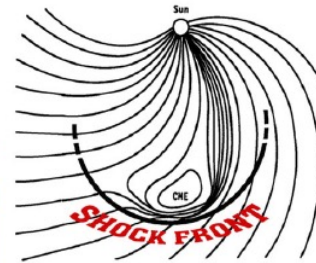
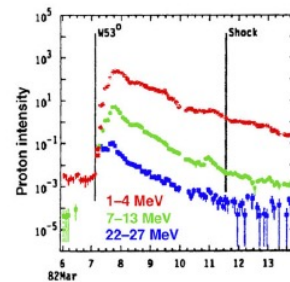
Particle Acceleration

Shocks as particle accelerators

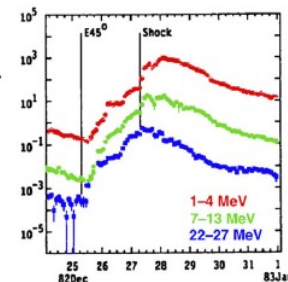
- Different shock geometries and particles have different acceleration mechanisms invoked but all can accelerate particles
- **Astrophysics:** Supernova remnants, cosmic rays
- **Solar Physics:** SEP acceleration, fast shock at reconnection



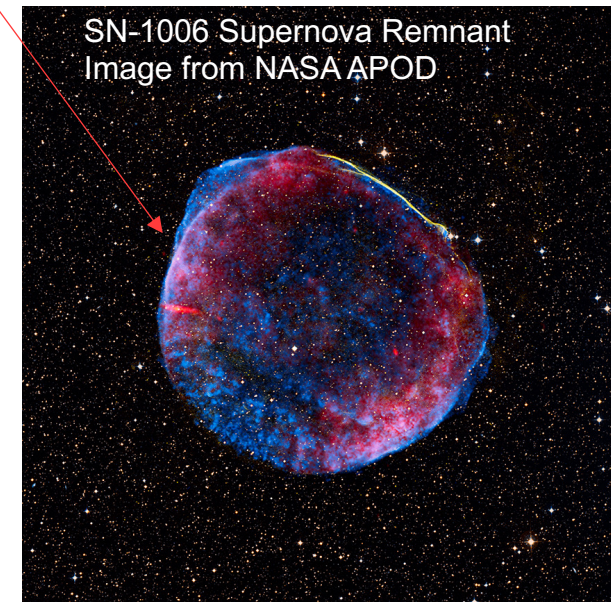
Courtesy of Li-Jen Chen, GSFC



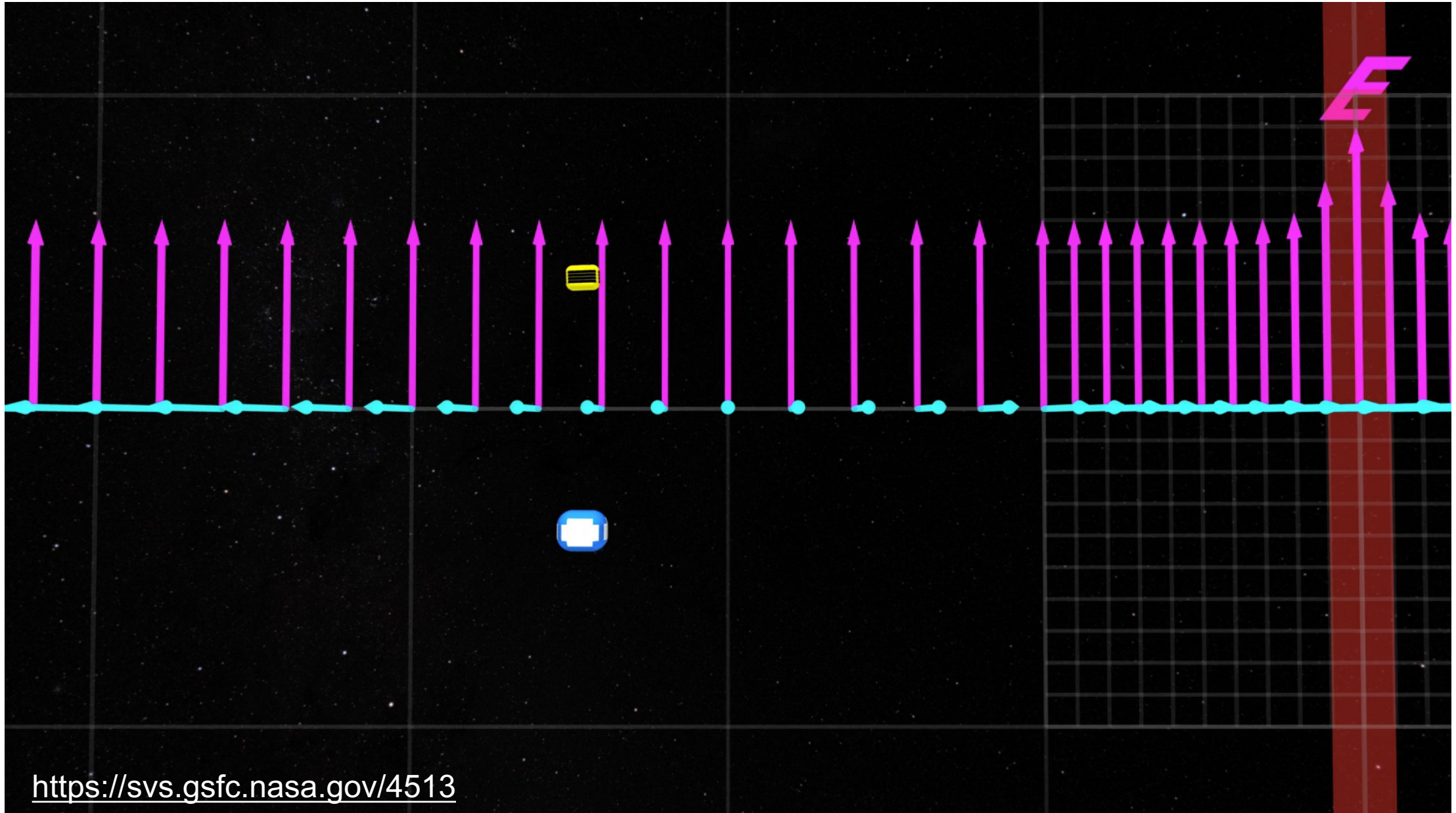
Desai & Giacalone (2016)



Shock wave

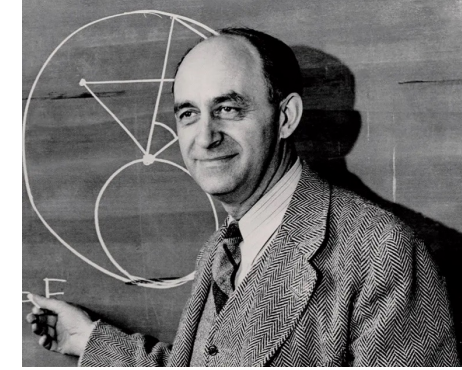


Shock Drift Acceleration (SDA)



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

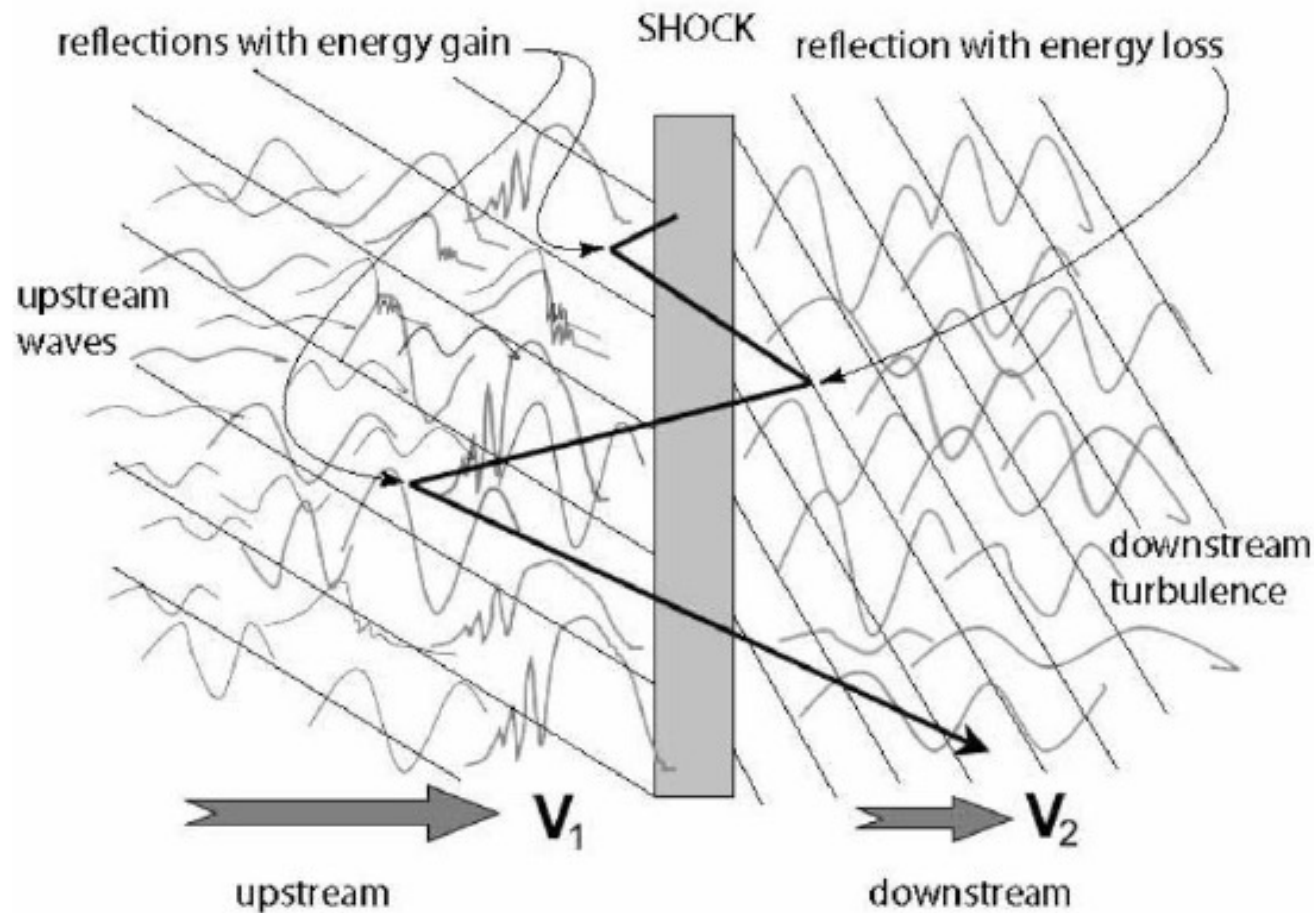
Diffusive Shock Acceleration (DSA)



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

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

$$\langle \Delta E/E \rangle \sim 4/3 \beta$$



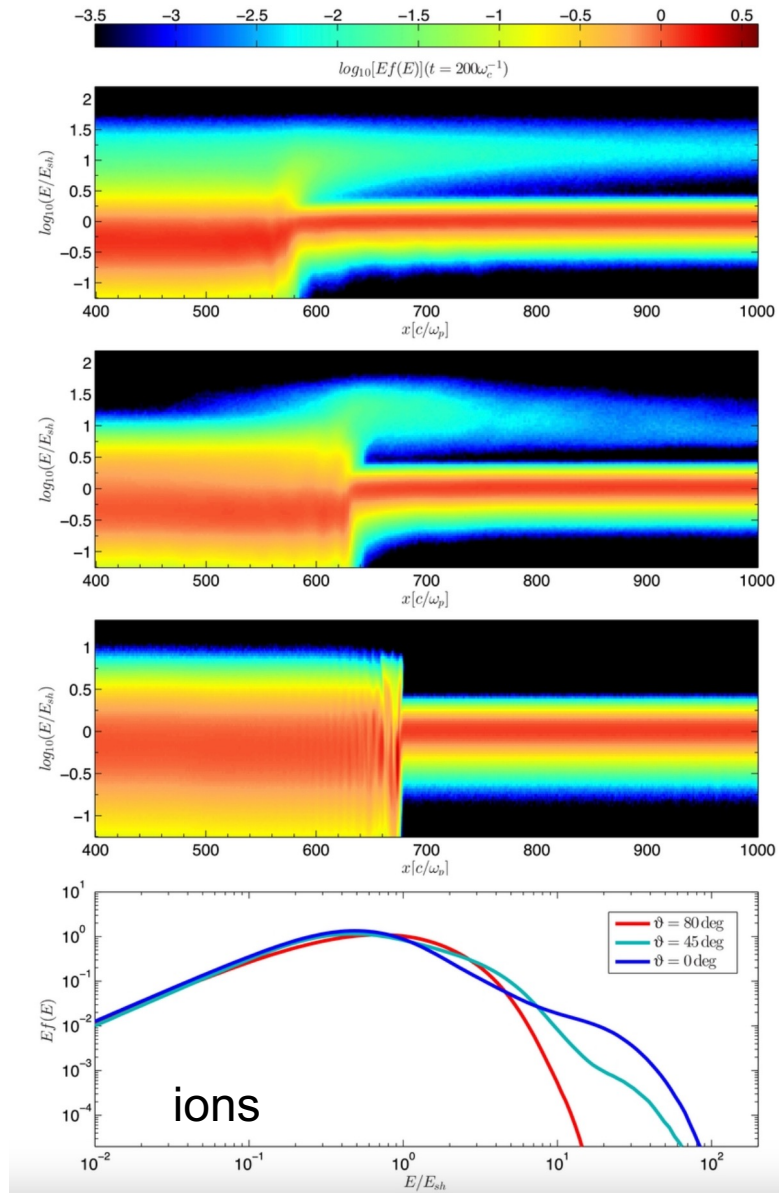
Simplified explanation

- 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?

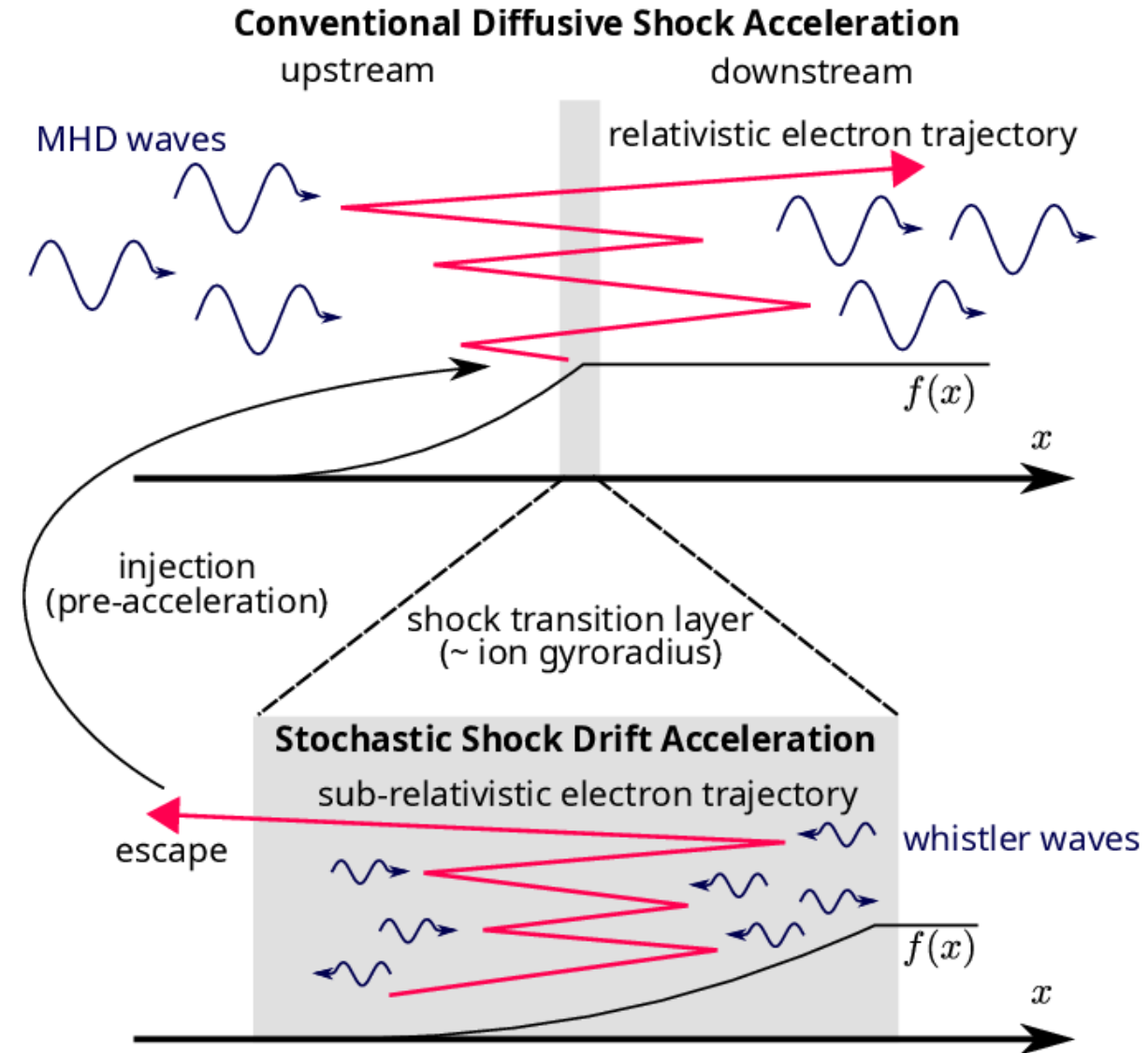
Acceleration at Qpar and Qperp shocks



Qpar shock (DSA)

Oblique shock

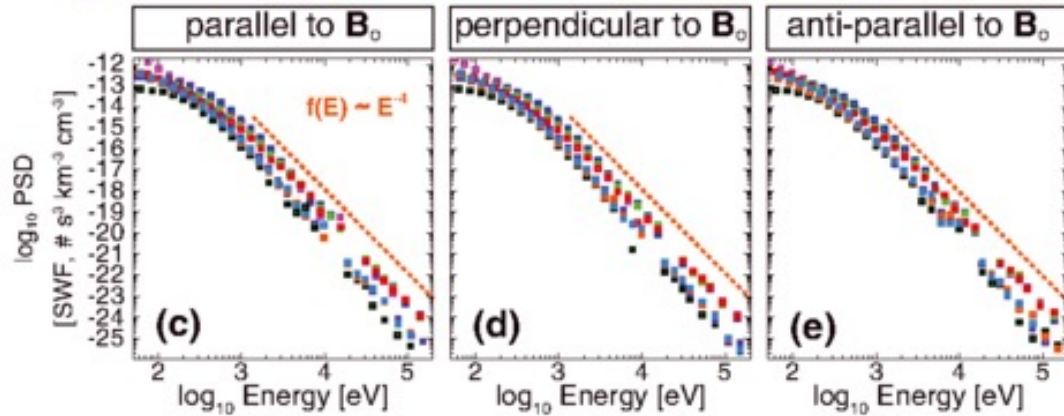
Qperp shock (SDA/SSDA)



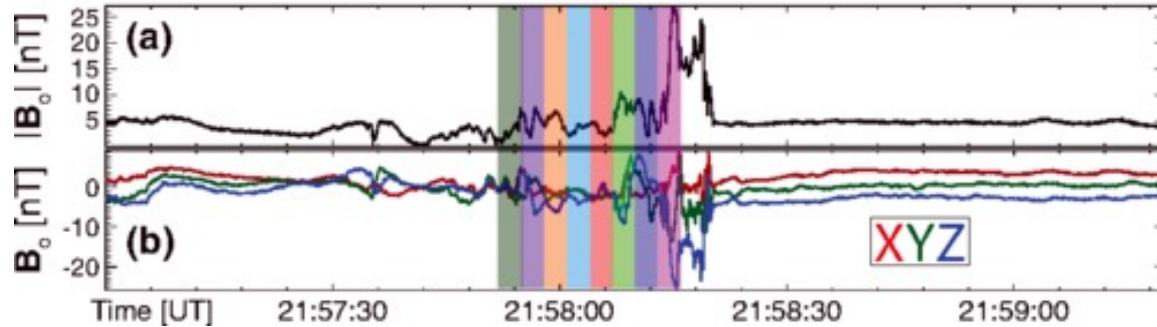
Foreshock Transients & Electron acceleration

Combined low and high energy electron spectra

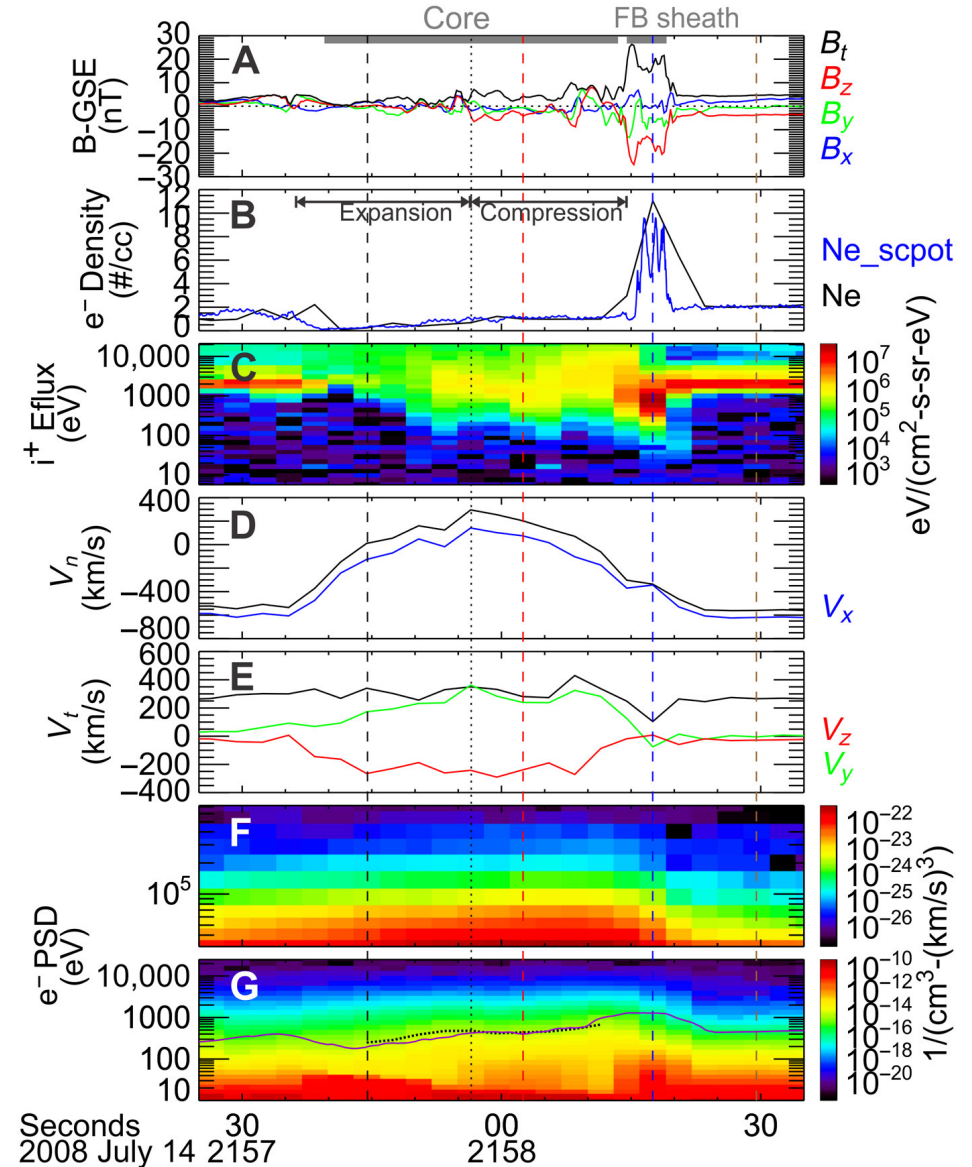
21:57:51 – 21:57:54 UTC 21:57:57 – 21:58:00 UTC 21:58:03 – 21:58:06 UTC 21:58:09 – 21:58:12 UTC
 21:57:54 – 21:57:57 UTC 21:58:00 – 21:58:03 UTC 21:58:06 – 21:58:09 UTC 21:58:12 – 21:58:16 UTC



Foreshock Bubble on 2008-07-14



~300 KeV electrons



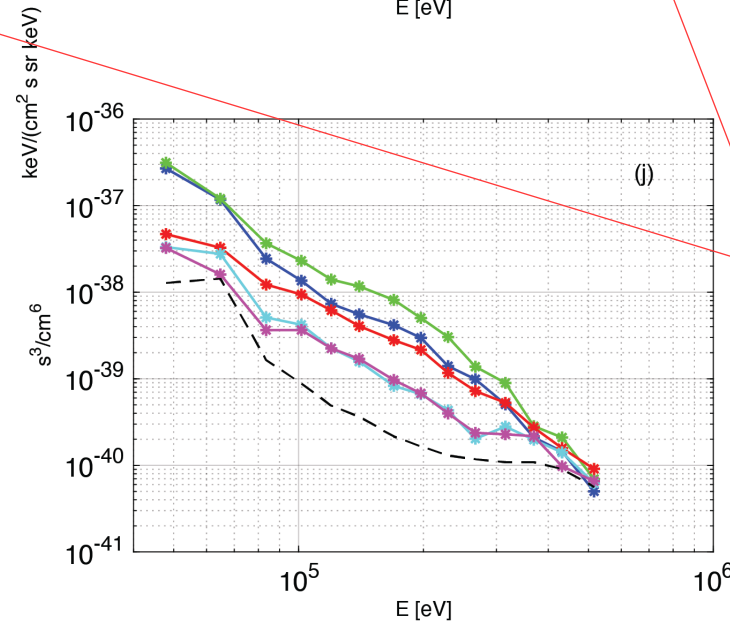
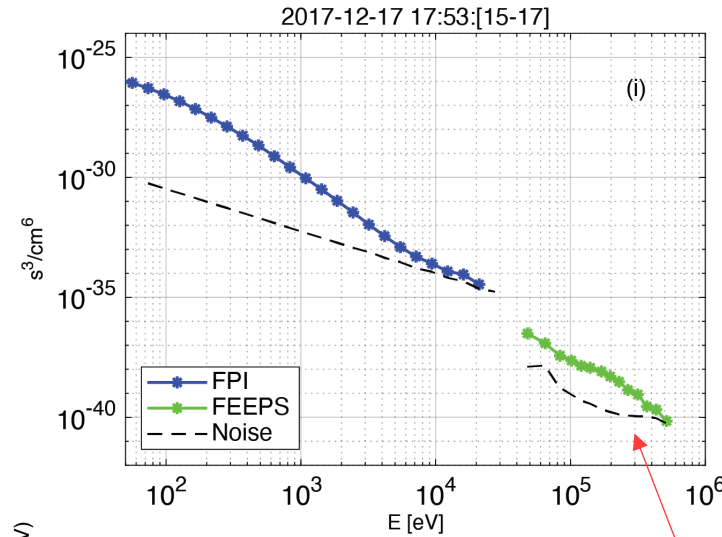
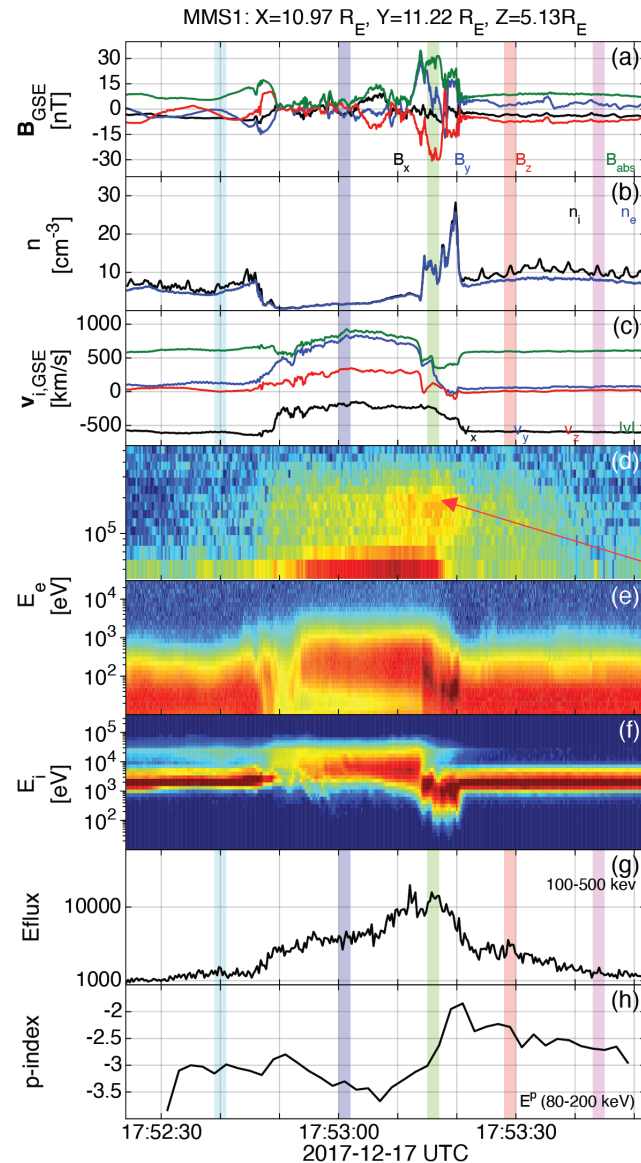
~200 KeV electrons

Liu T. et al. 2019 | Science Adv.

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New Results

Relativistic Electrons with MMS

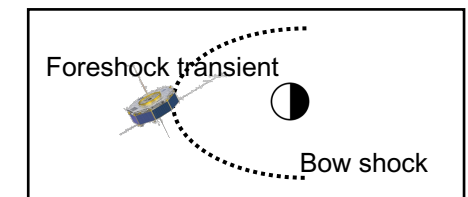


Typical properties of transient:

- 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)

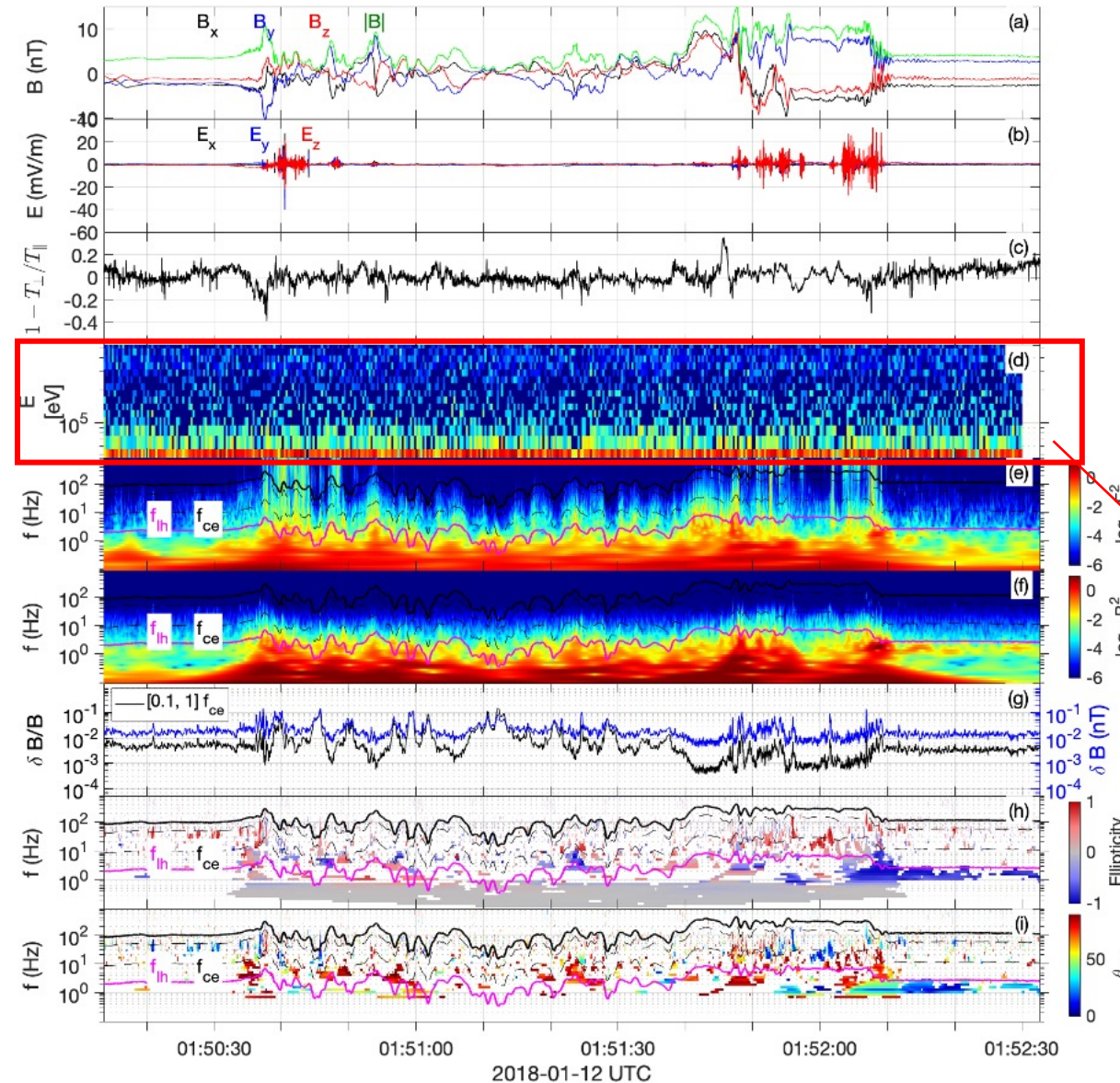
Unique property

>500 keV electrons throughout the core and shock region



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

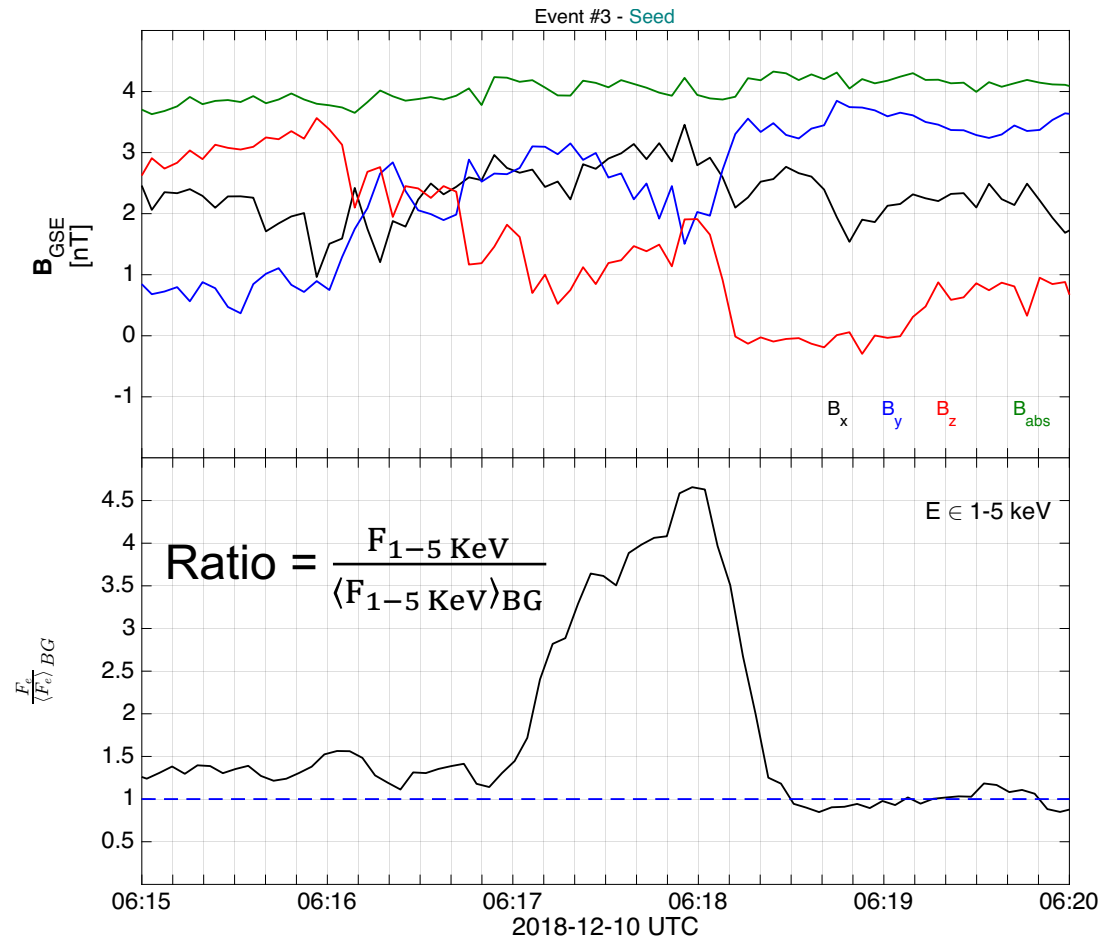
So why not always relativistic electrons?



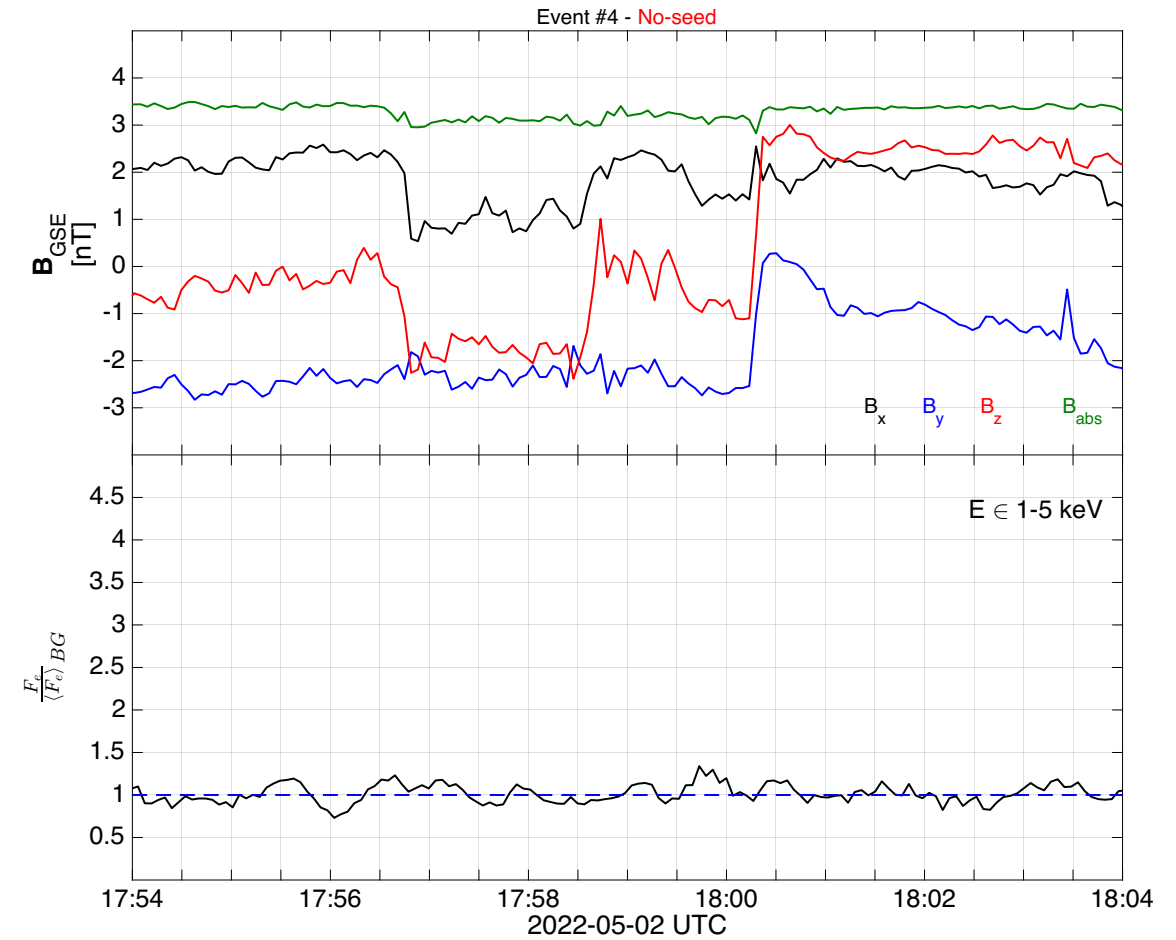
- Waves are there
- Shock is there,
- All the stuff are there.

FEEPS = no signal

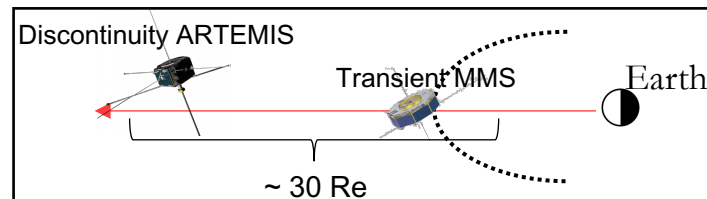
Upstream conditions for two event - ARTEMIS



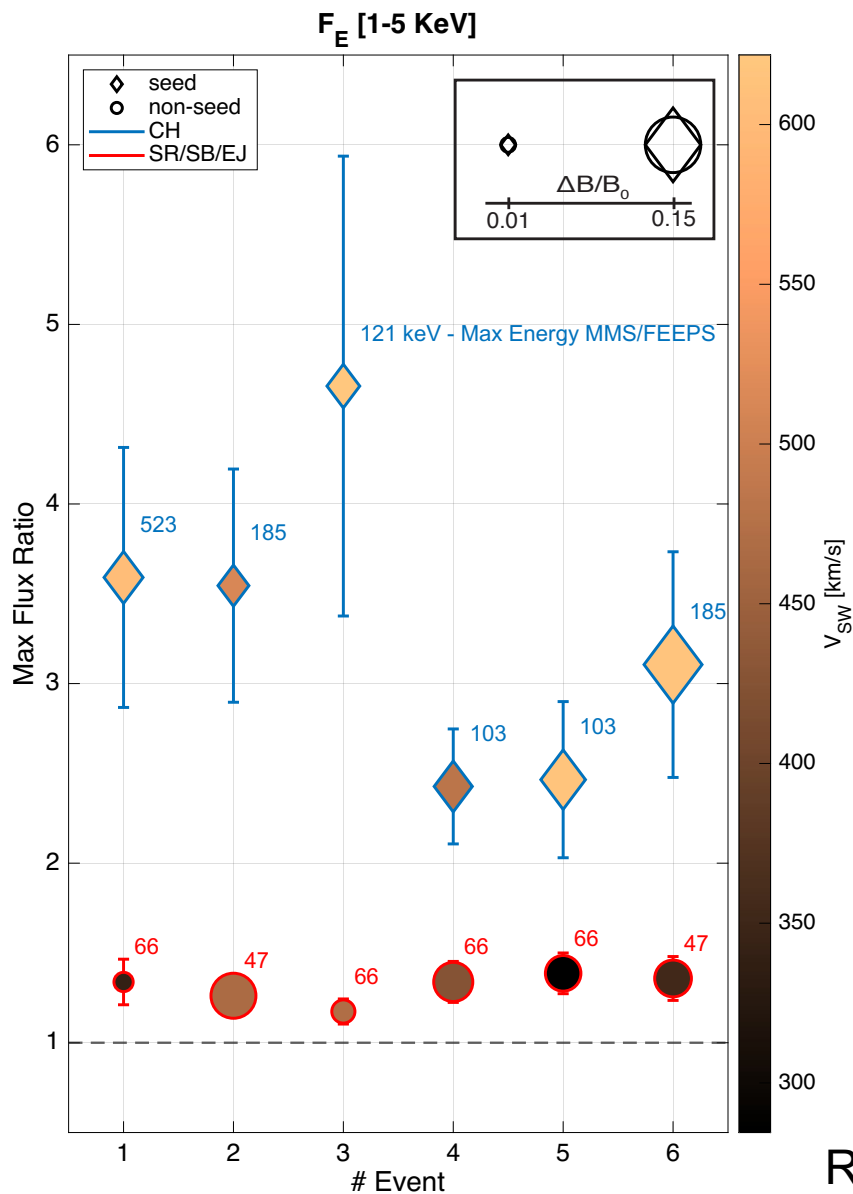
FEEPS: 100+ KeV



No Signal at FEEPS



Statistics for seed and acceleration



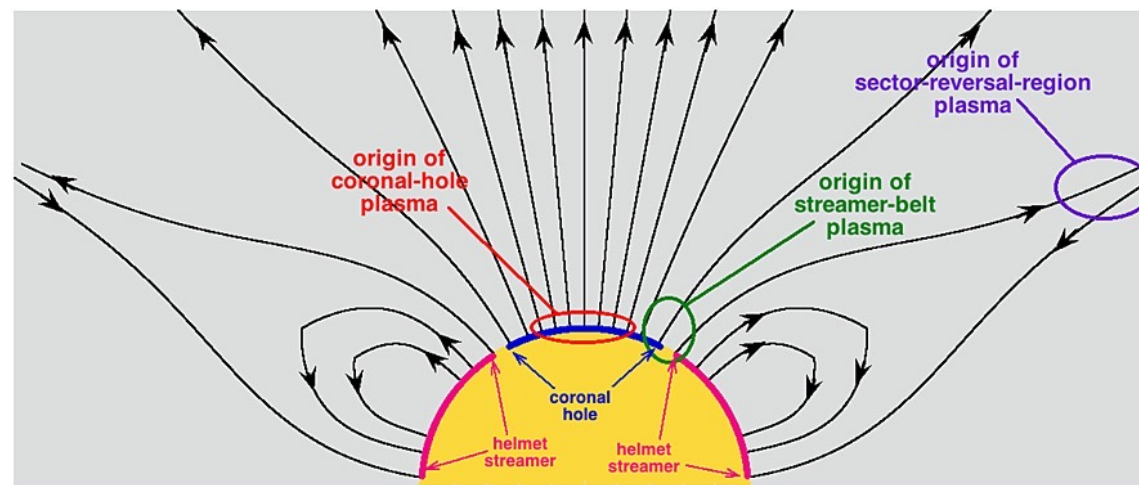
Seed events (FEEPS > 100 KeV)

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 Borovsky 2014, Camporeale+ 2017] methodology



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

Reinforced Shock Acceleration of Relativistic Electrons

Electron acceleration at Foreshock Transient

Injection Threshold
“Seeding”

Seed from
CH plasma
(1-5 keV)

Shock
Acceleration
(SDA/DSA)

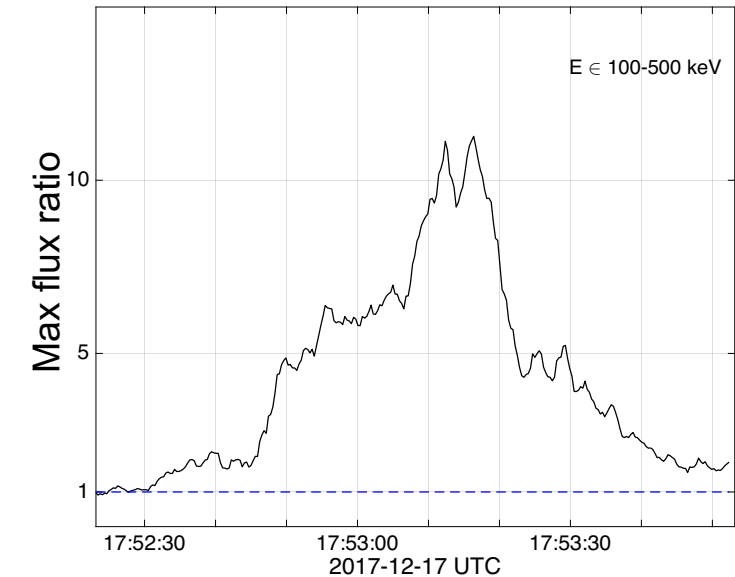
+

Wave particle
interactions

Efficient through PA scattering & confinement:

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

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

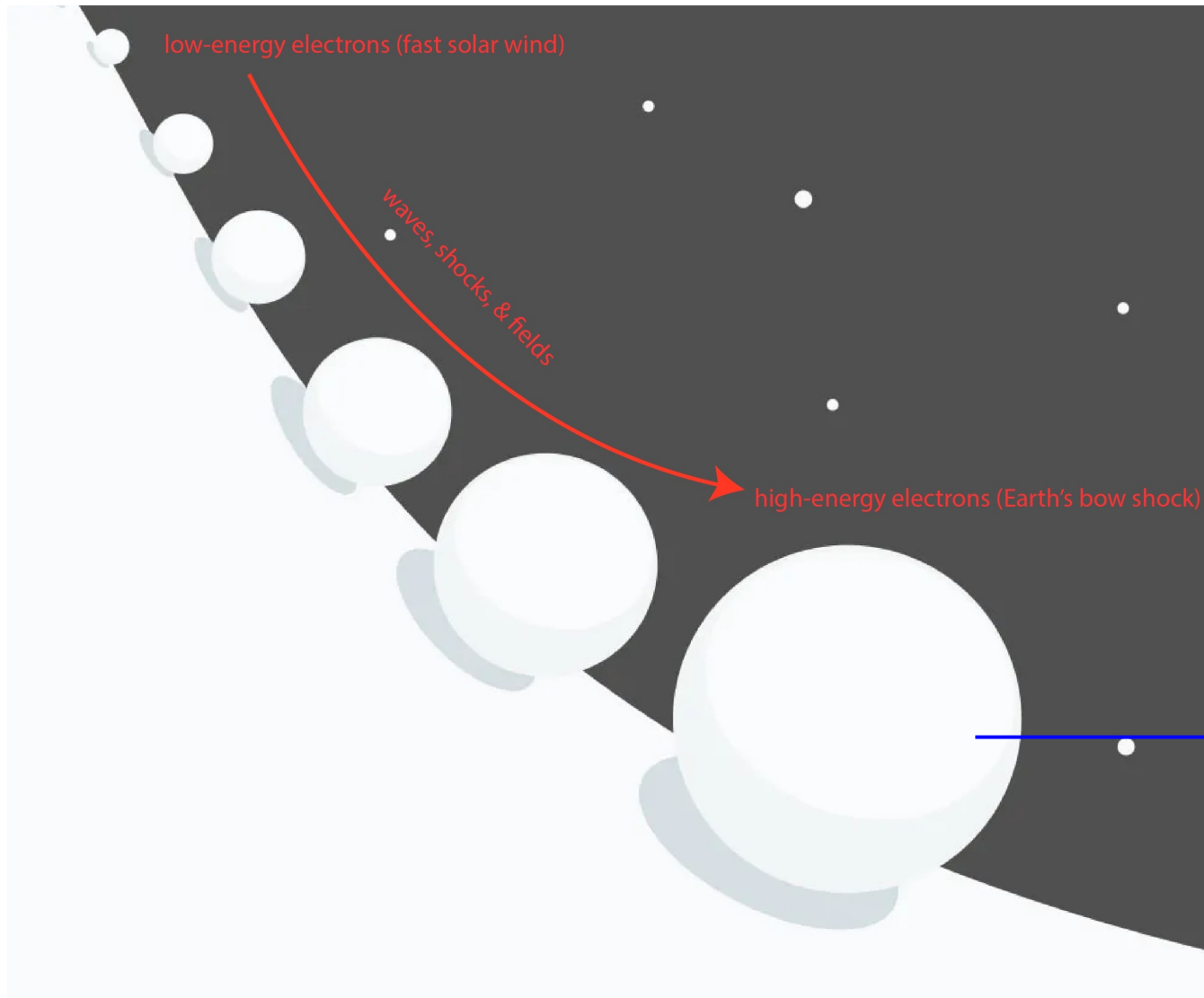


Key-point:

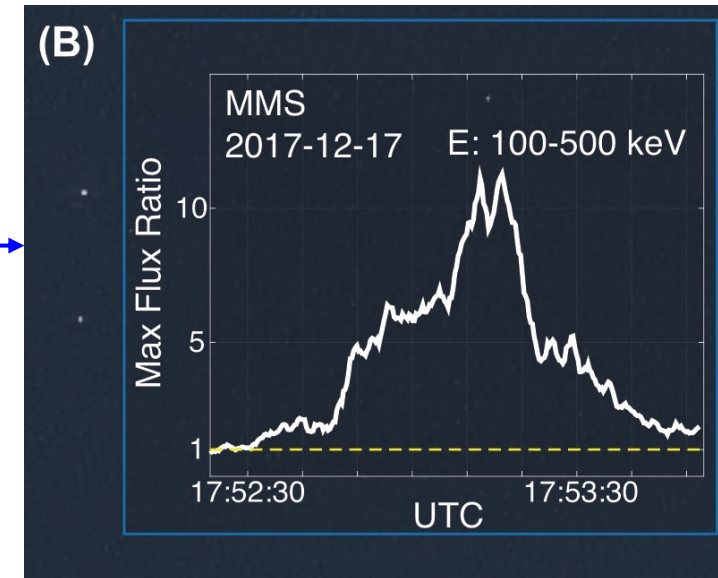
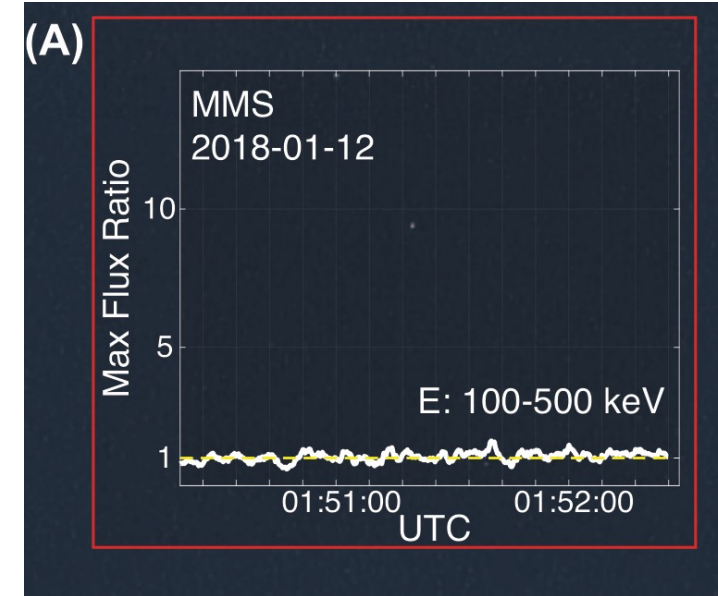
Seed + Foreshock's Shock + Waves +
Efficiency factors = ~MeV electrons
before reaching the bow shock.

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

Simplistic Picture to remember

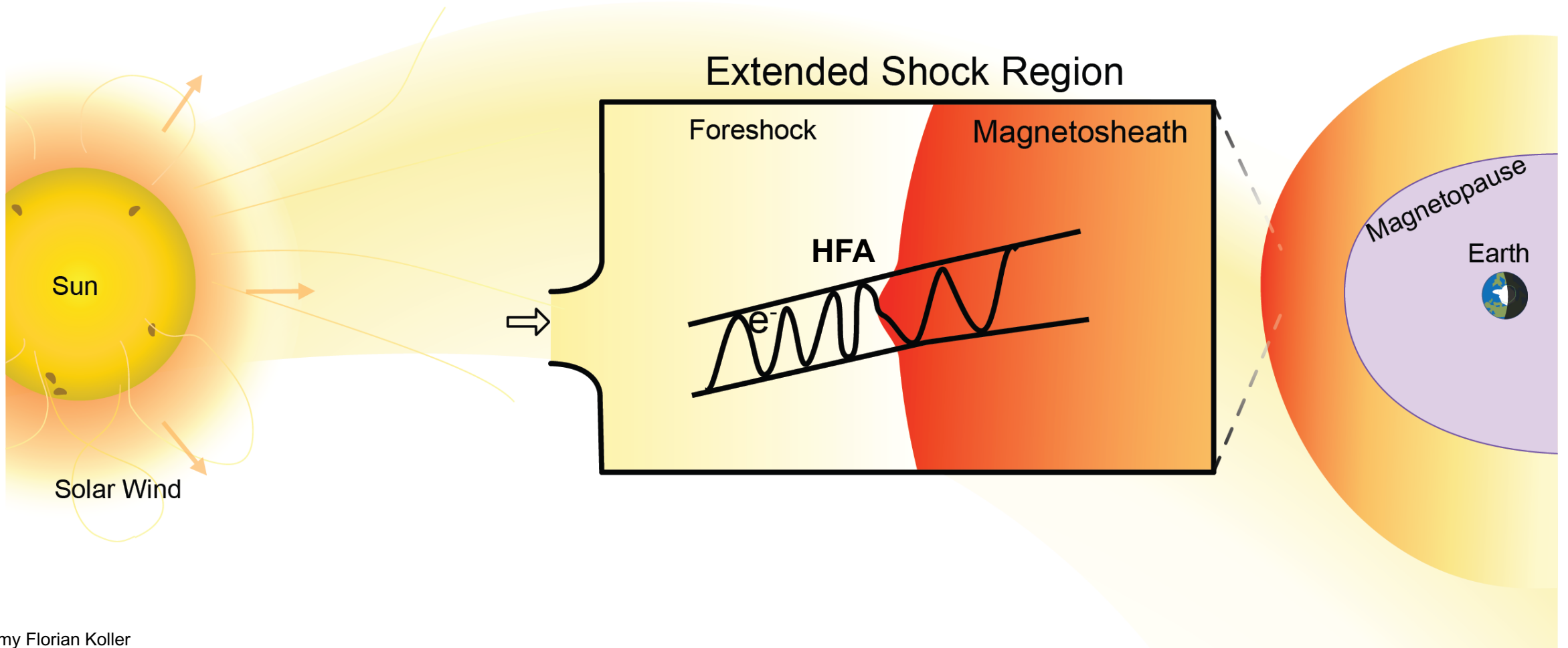


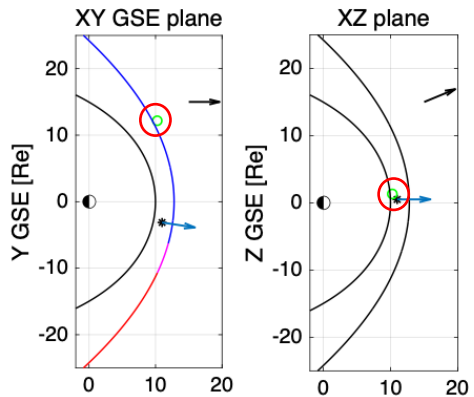
✗



But let's ask one more question

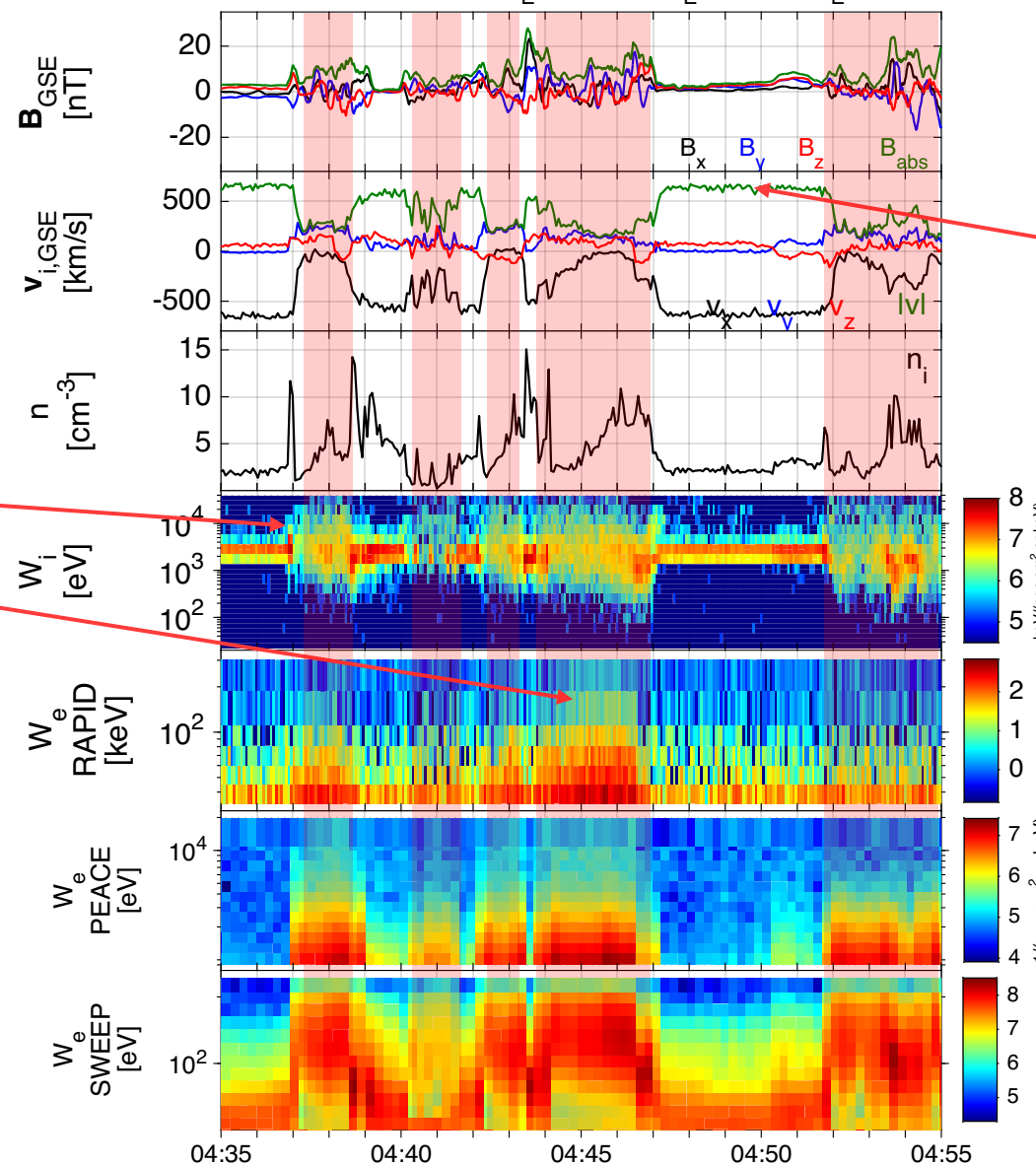
What do we expect to see when these transient appear downstream?





Cluster: Upstream showing HFAs

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



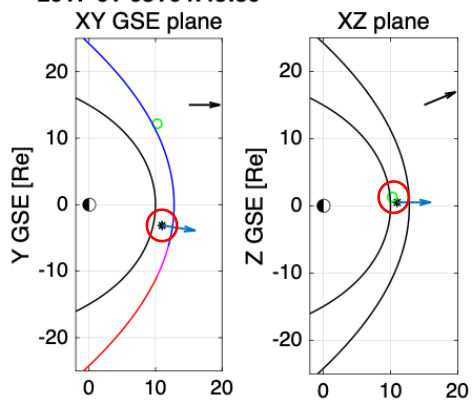
700 km/s Solar Wind!

Fast coronal hole plasma consistent with our previous work ✓

Typical properties:

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

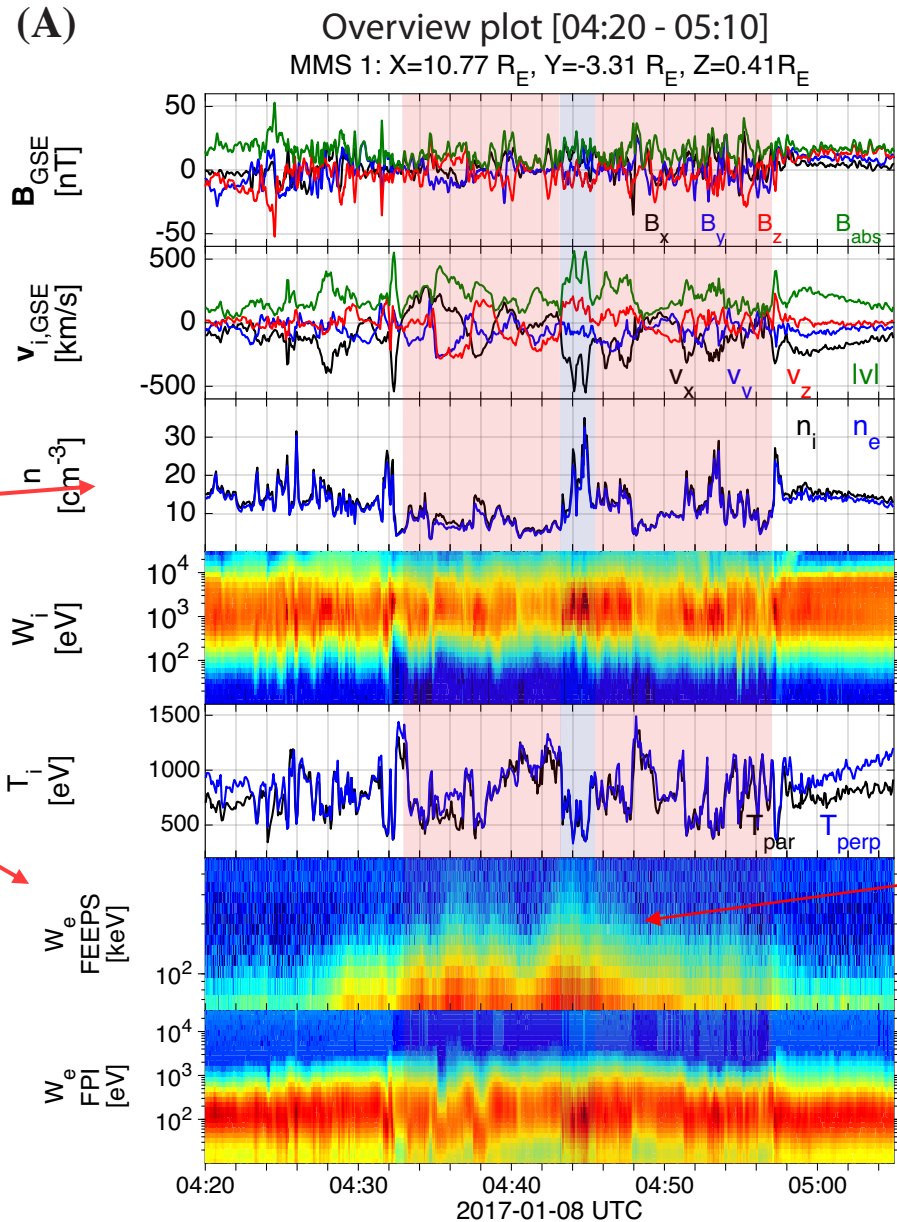
2017-01-08T04:45:30



MMS: Downstream HFAs and jets

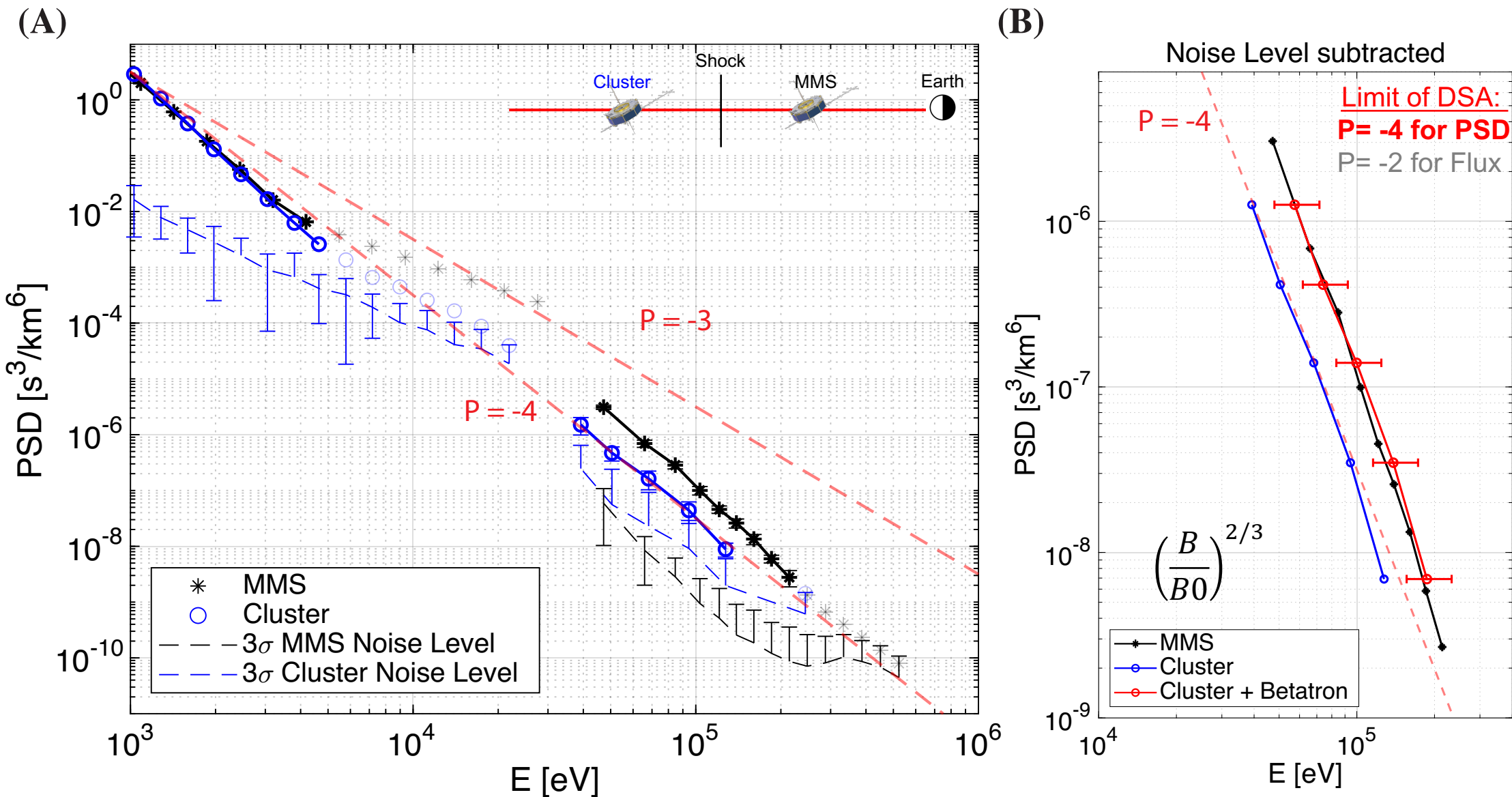
- Hot Flow Anomalies
- Localized compressions
- ~300 keV electrons

(A)



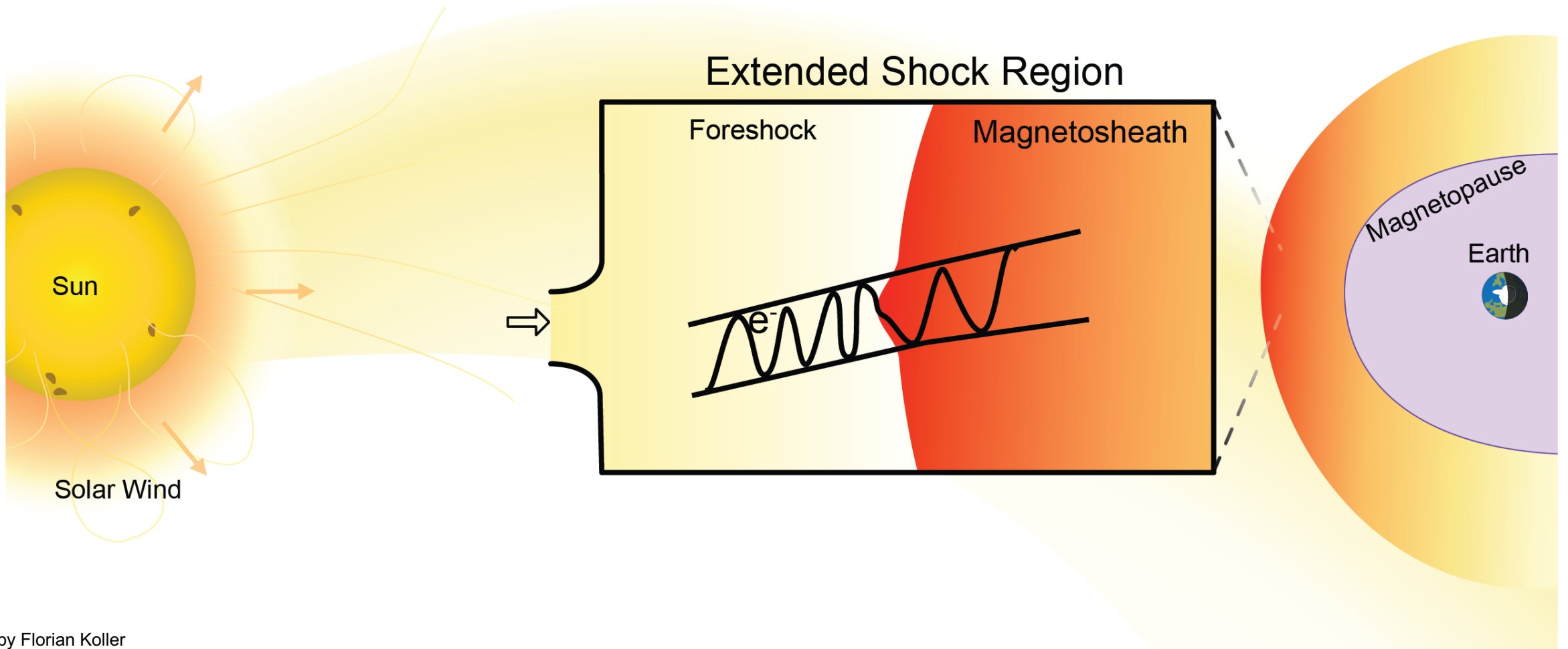
- 20+min interval!

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



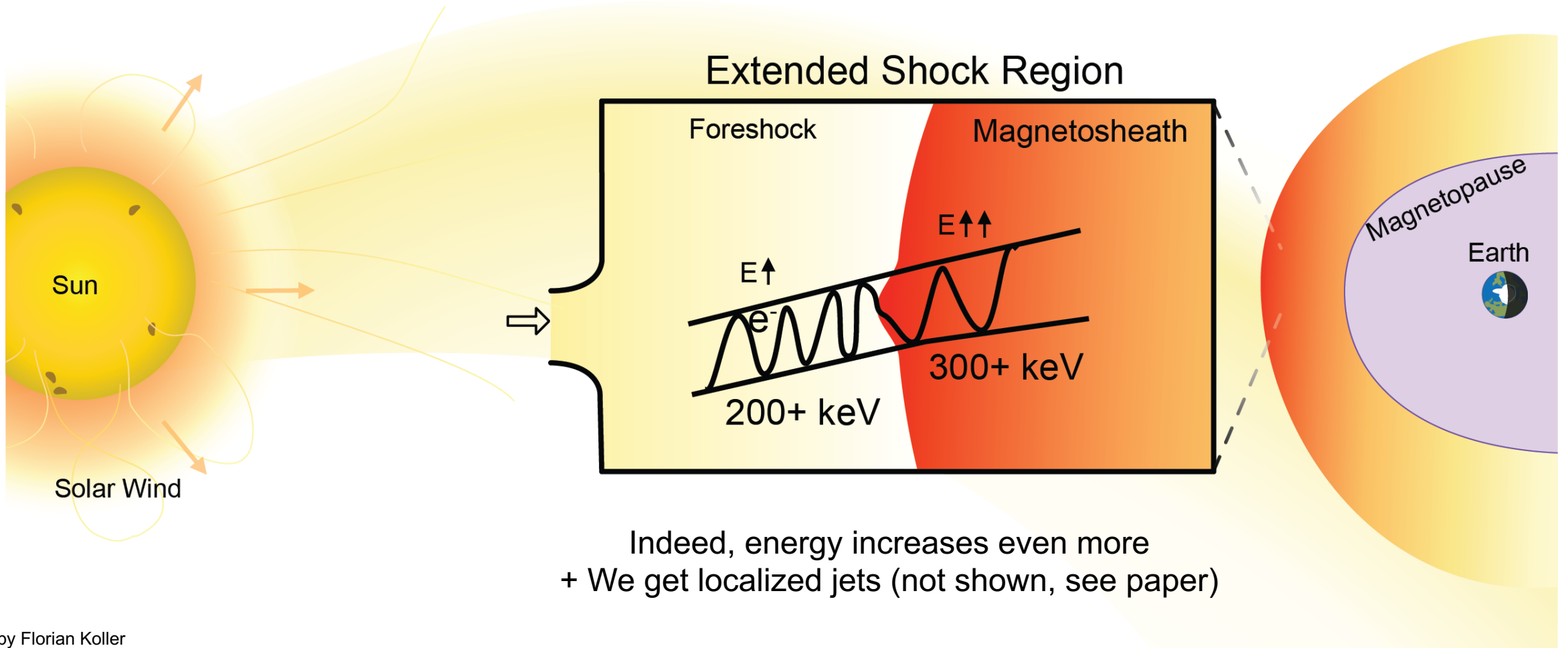
But let's ask one more question

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?



Reinforced Shock Acceleration: Sun to magnetosheath

(A)

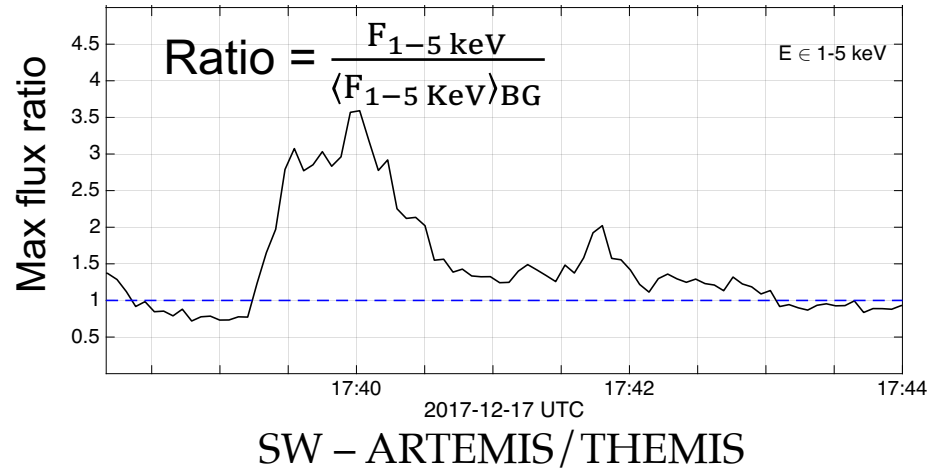
Discontinuity (SW) ARTEMIS

Transient (FS) MMS

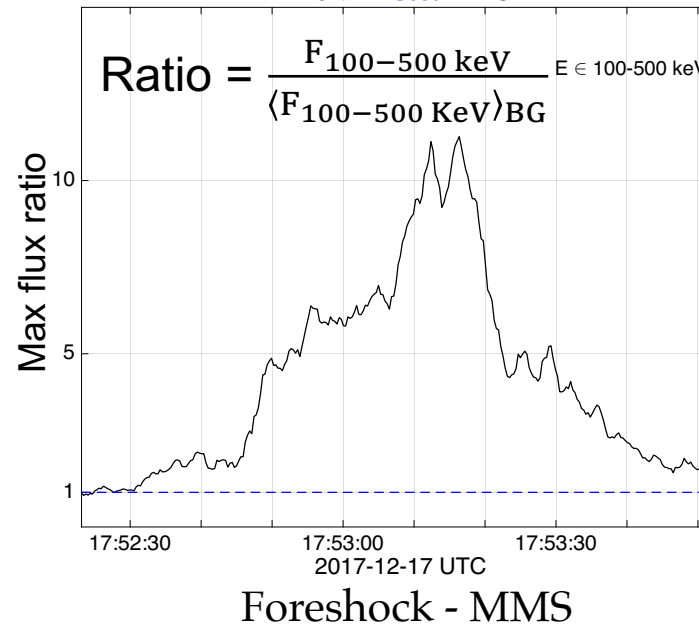
Coronal Hole SW
 $V > 500$ km/s

~ 1 keV

> 100 -500 keV



Fast SW seeding $\sim$ low keV particles



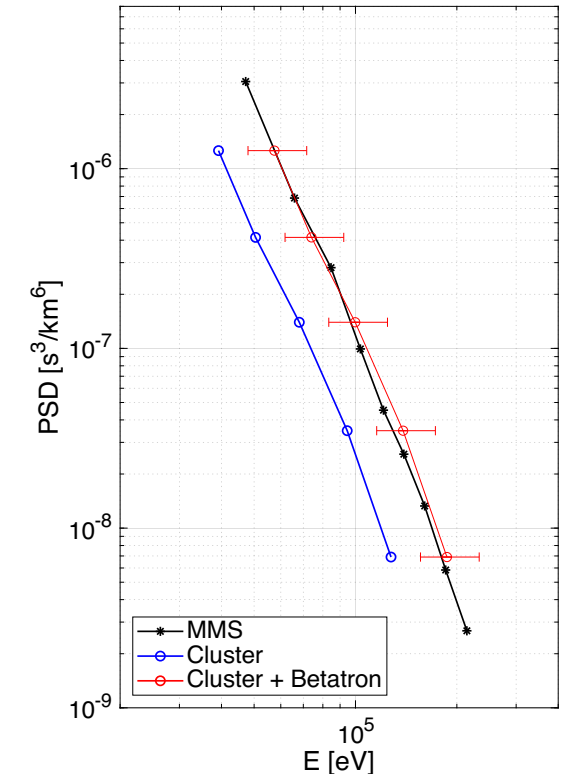
(B)

Transient (FS) Cluster

Transient (MSH) MMS

200 $\rightarrow$ 300 keV

Noise Level subtracted



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

Foreshock Transients at Quasi-Parallel shocks are amazing! Relativistic particles, localized compressive edges/shocks on multiple temporal and spatial scales, forming high-speed jert, all interacting with each other.

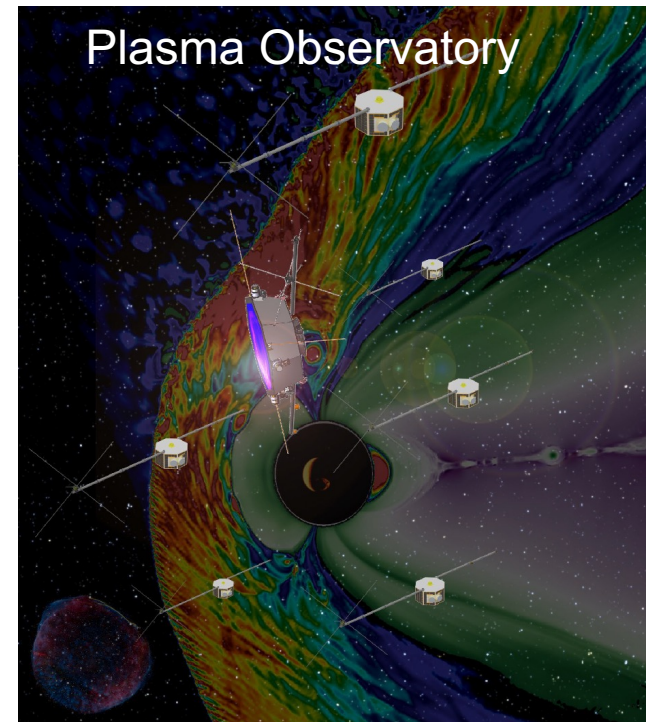
Recent results:

❖ **Revealed** that the **electron injection threshold at Earth** to be at the **suprathermal range of $\sim 1\text{-}5$ 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.*

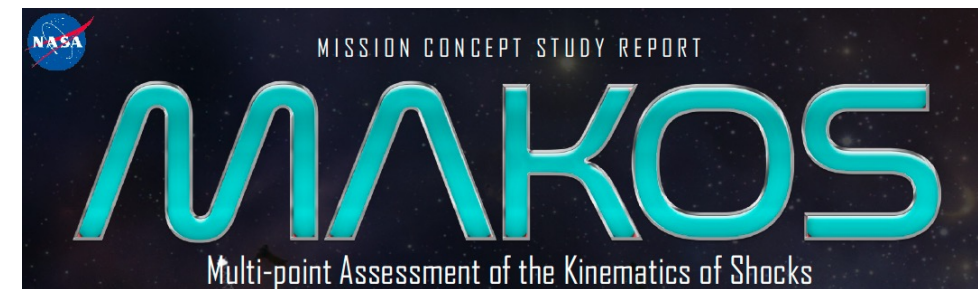
GEM FG: **(MDT) Multiscale Dayside Transients and their Effect on Earth's Magnetosphere (2025 – 2029)**
Savvas Raptis, Ivan Vansko, Imogen Gingell, Terry Z. Liu, Ying Zou, Runyi Liu, David Tonoian



Retino+ 2021 | Ex. Astro.

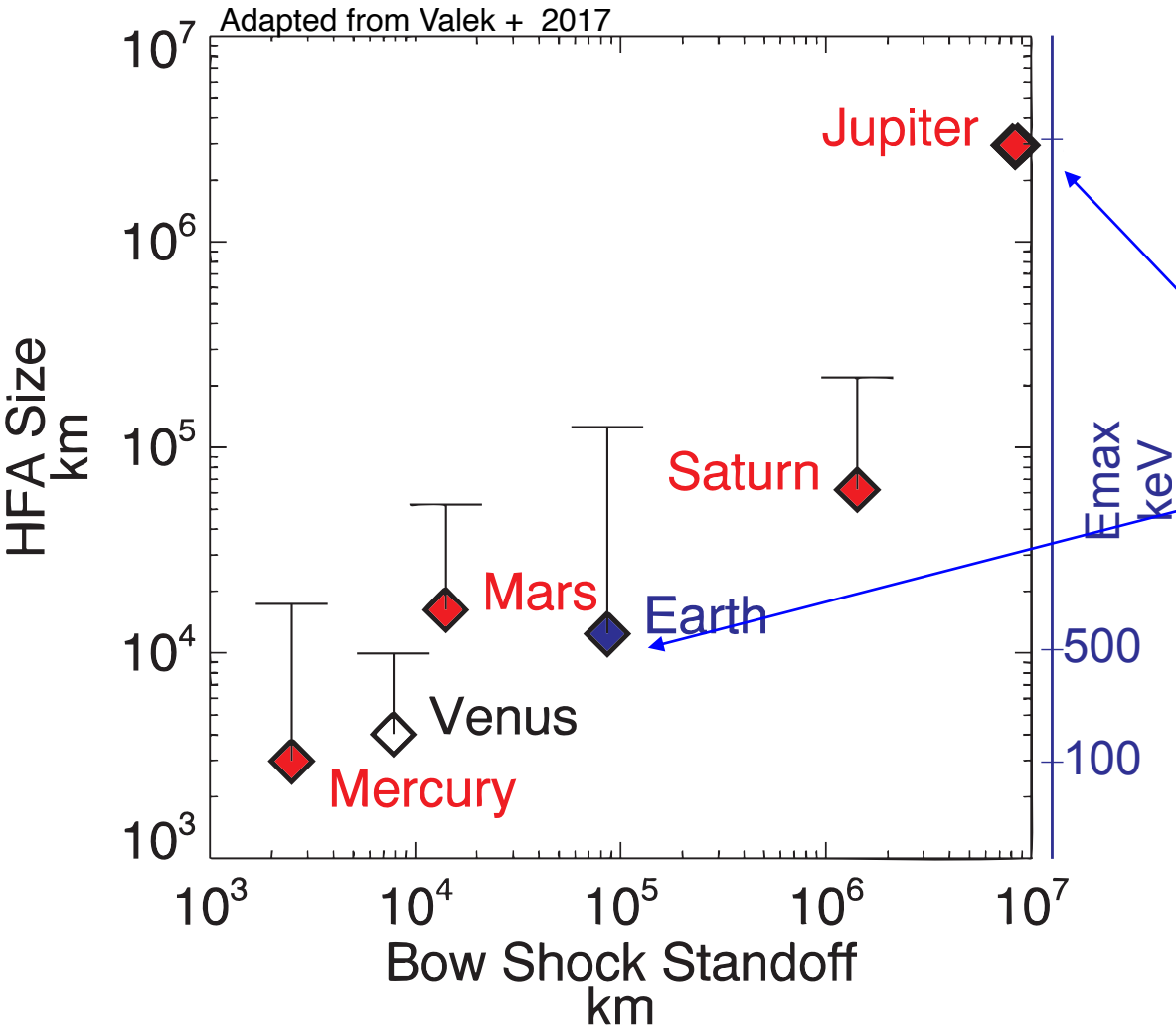


Goodrich+ 2023



New Ongoing Results?

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:

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

If we **move to another planetary system**, we can take some typical size for foreshock transients to be for **Jupiter**:

$$L \sim 100 - 1000 R_e \sim 5 \times 10^{5-6} [\text{km}]$$

This in turn, with a background magnetic field of $\sim 0.5 \text{ nT}$ gives:

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

Juno Observations – Jovian Bow Shock Crossing

Foreshock Transient (HFA):

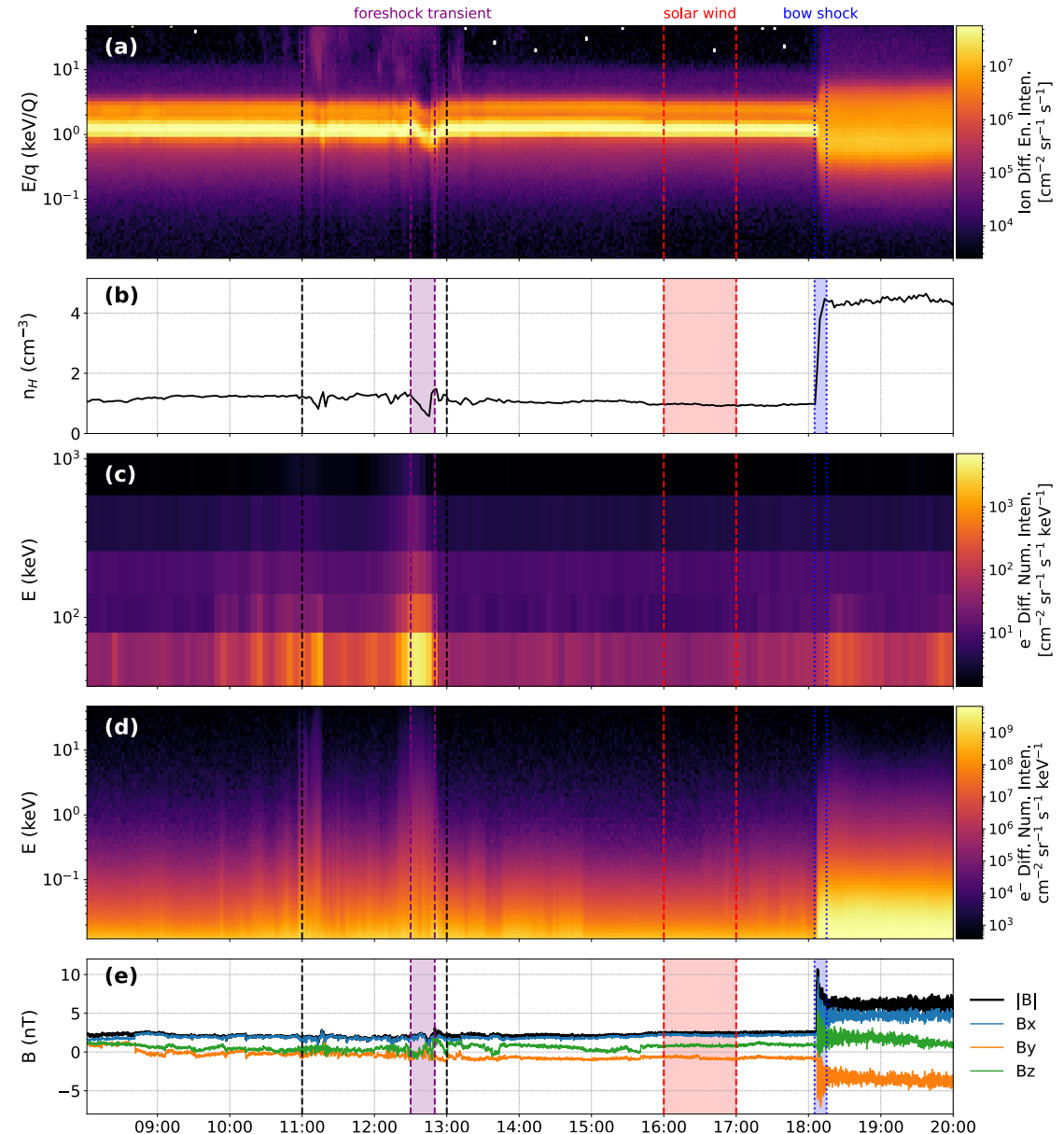
- High energy electrons up to 1 MeV (*agreement with Raptis+2025*)
- Disrupted solar wind beam
- Localized depletion of n and B

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



Ion spectrum

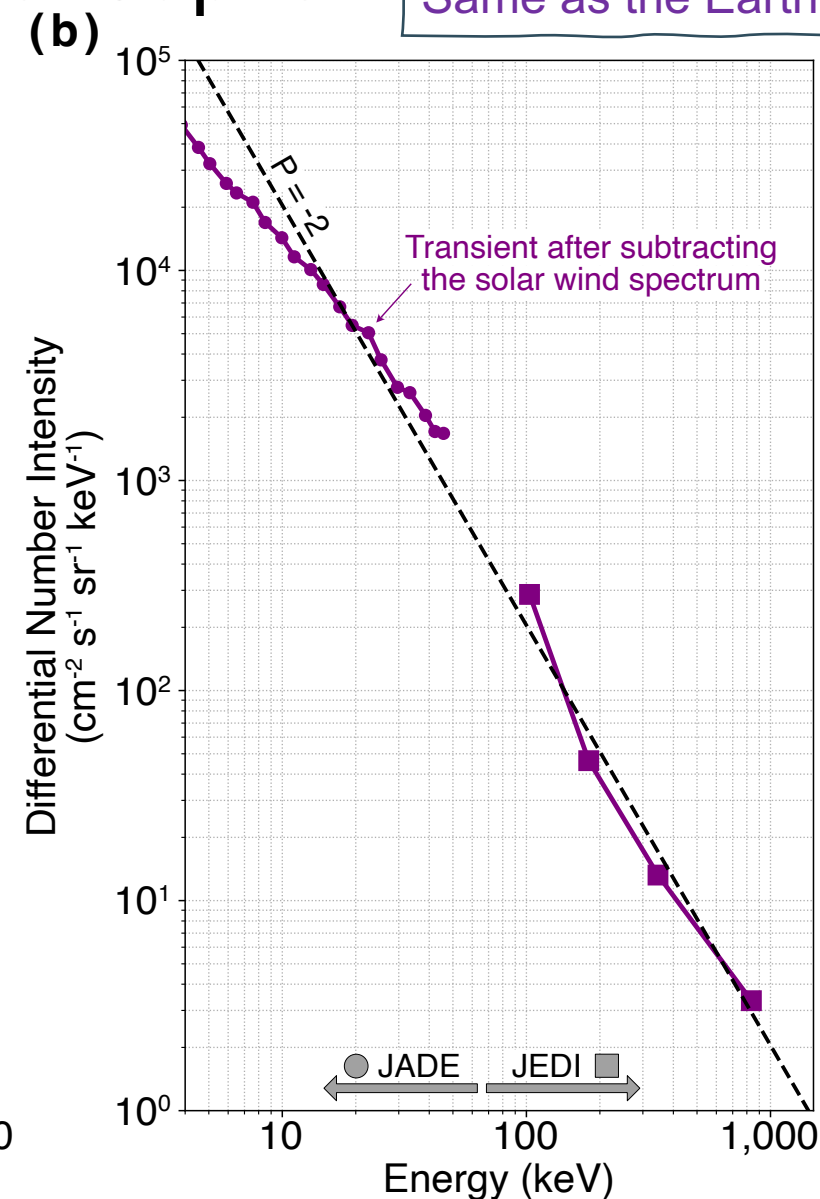
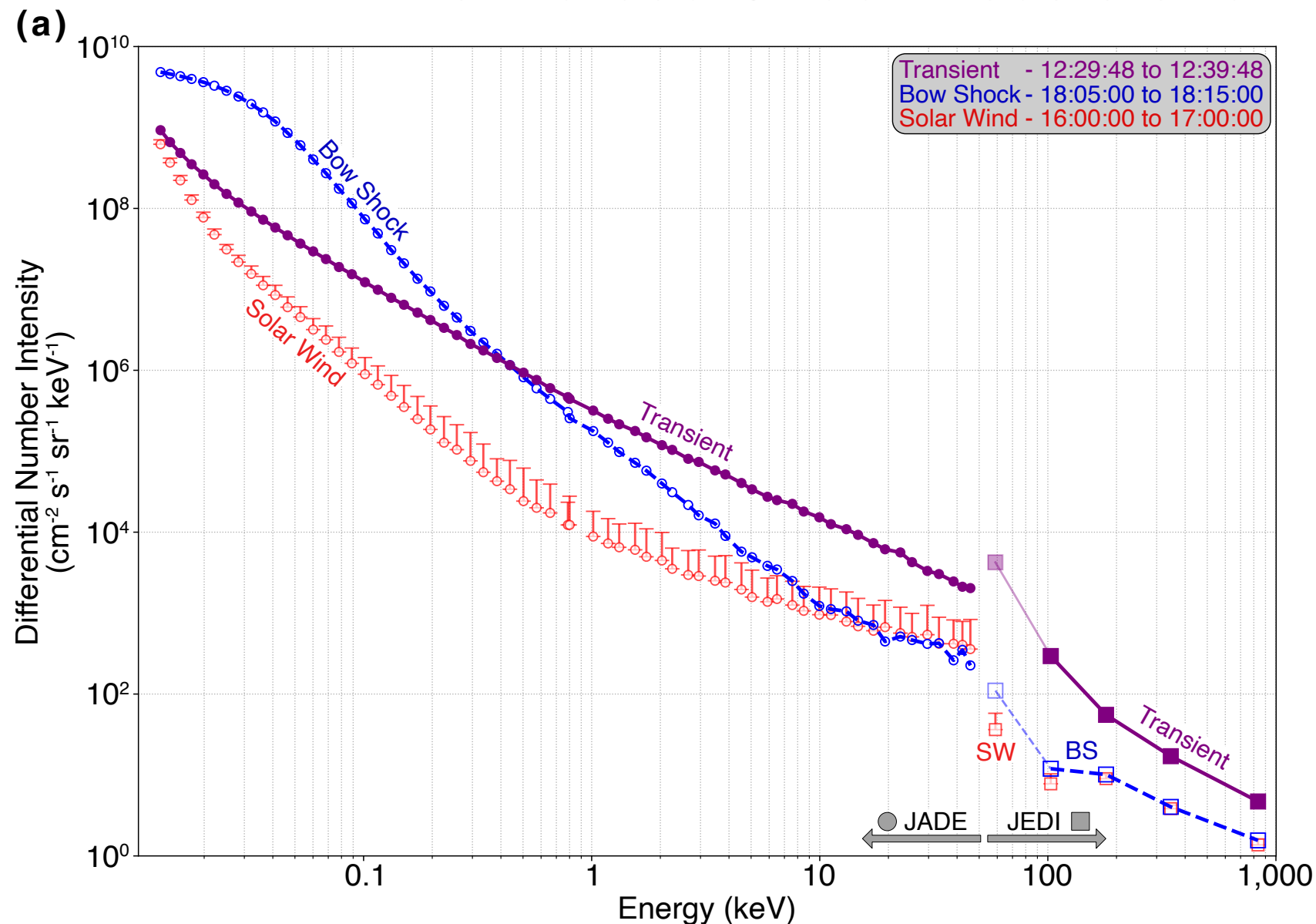
Ion density

Electron Spectra

Magnetic field

Reinforced Shock Acceleration at Jupiter

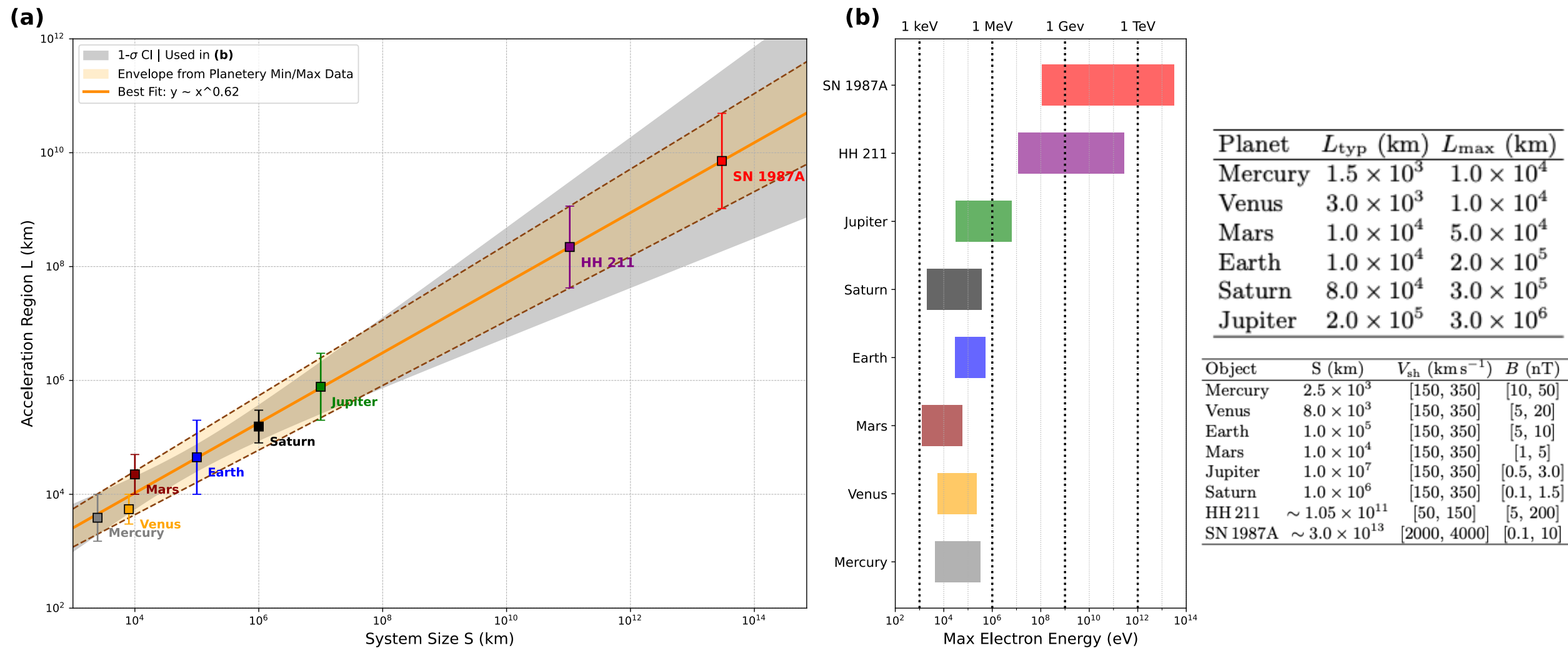
Reaching DSA limit
Same as the Earth!



The DSA-like acceleration happens at the transient, bow shock only up to <10 keV

Appendix

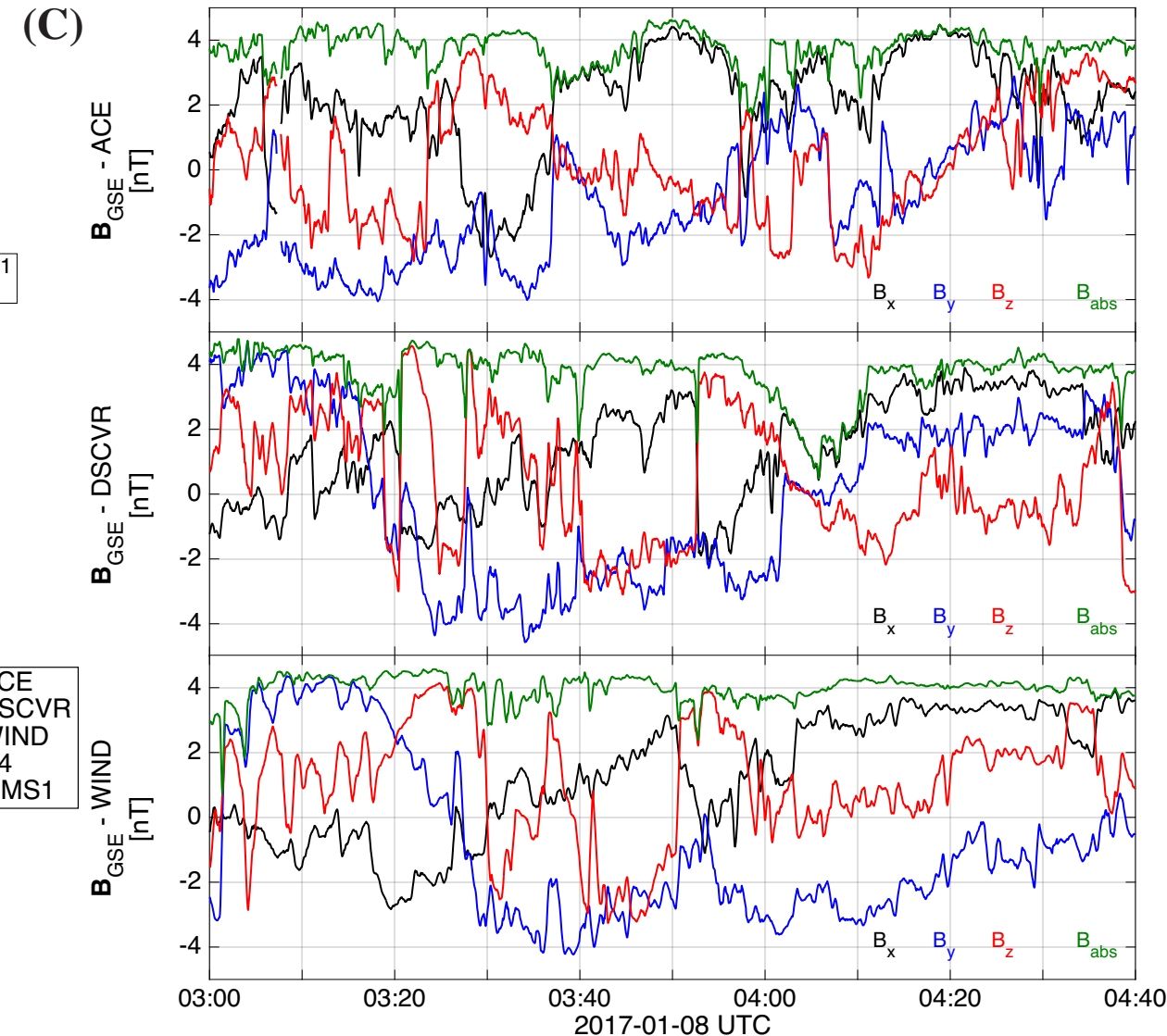
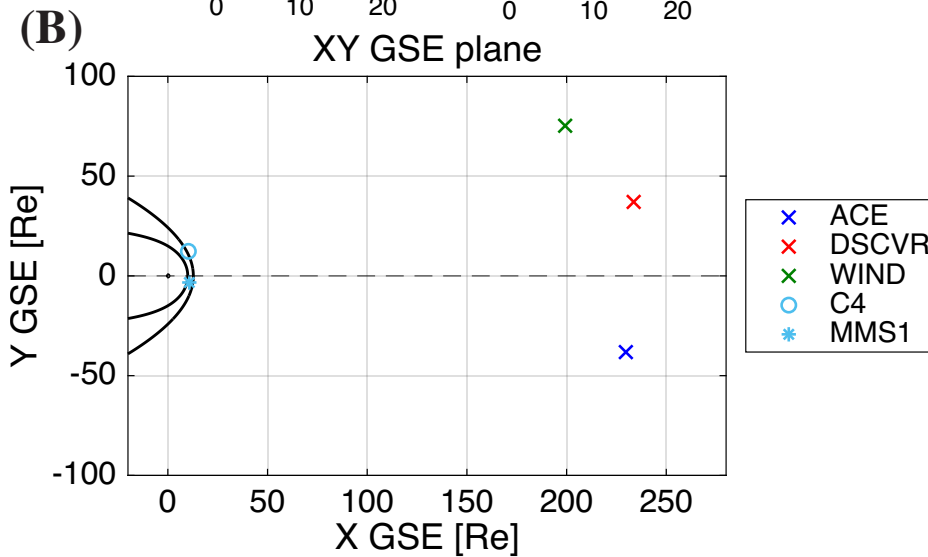
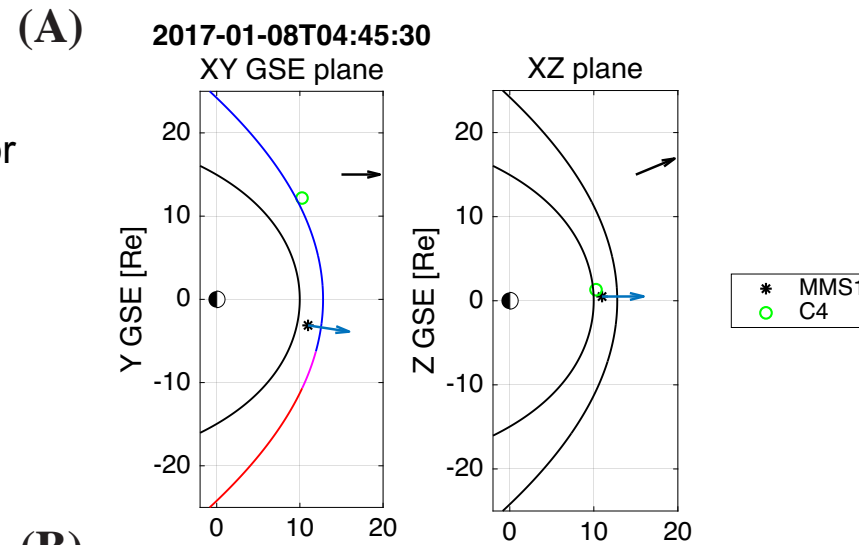
Generalized framework?



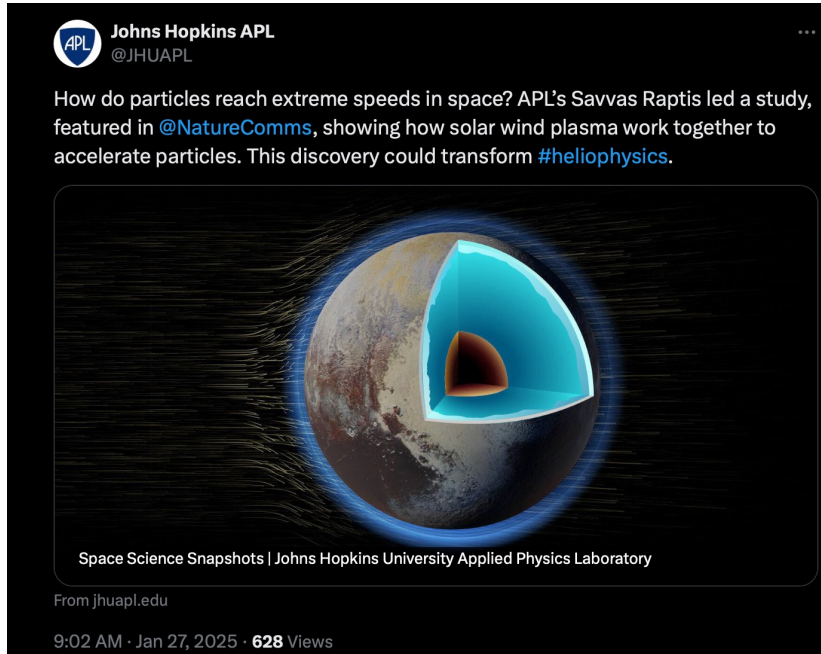
Conjunctions between MMS - CL

Notes

1. Great conjunction for HFAs (remember how they form)
2. Fast solar wind = Reinforced Shock Acceleration + Conductive of Jets and HFAs



Online Attention



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...

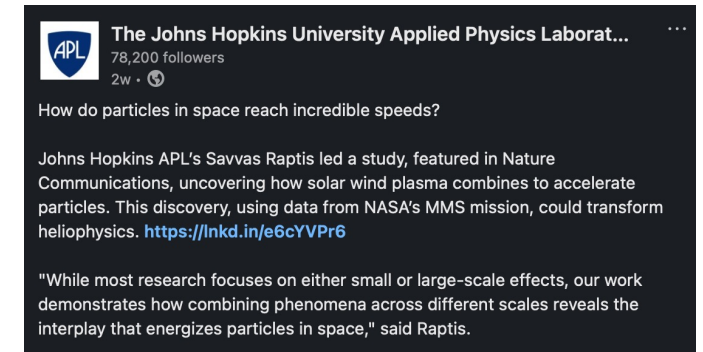
Read the popular science version of the paper:



Read the actual paper:

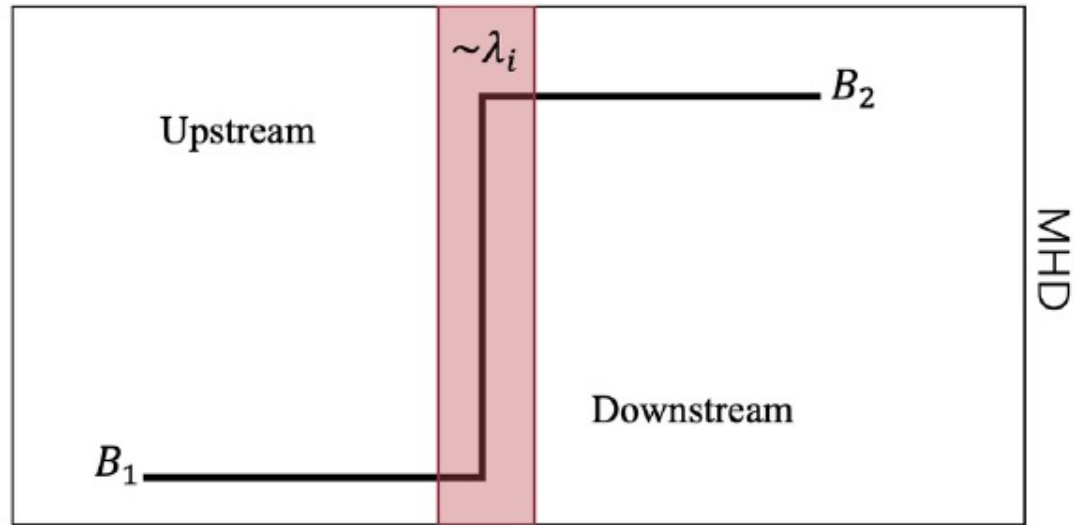


Read the “science nugget” from ARTEMIS mission:

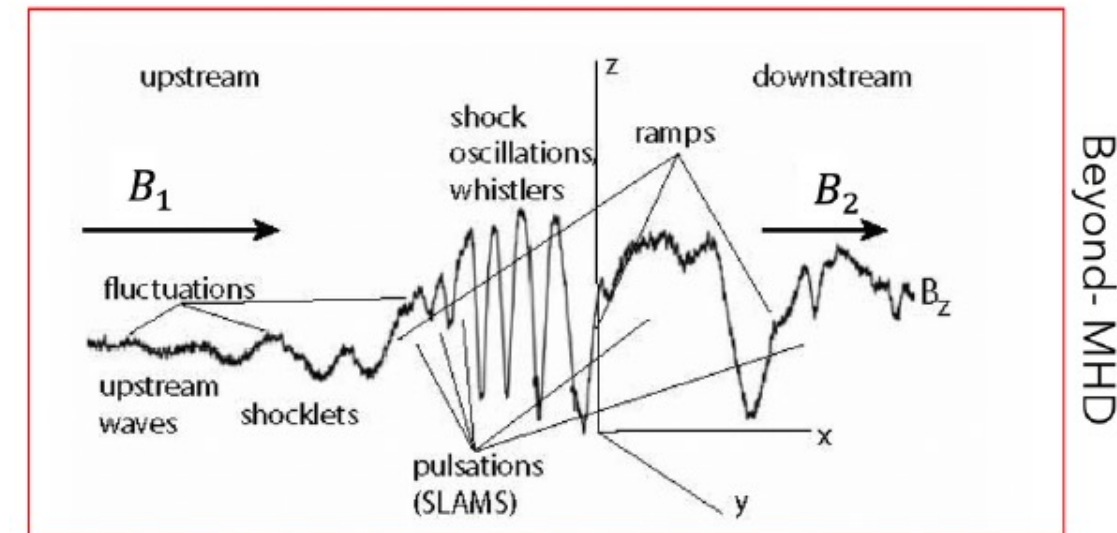
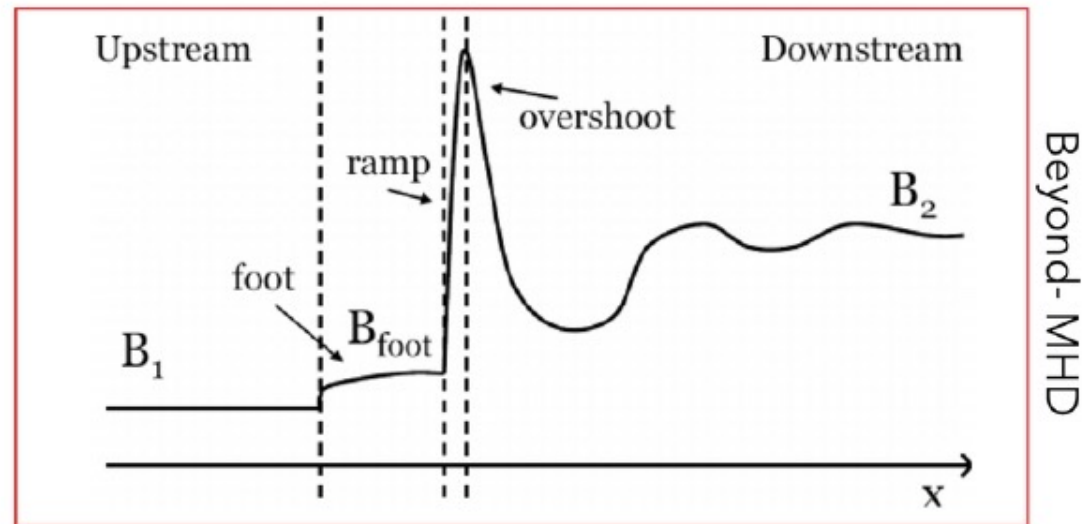
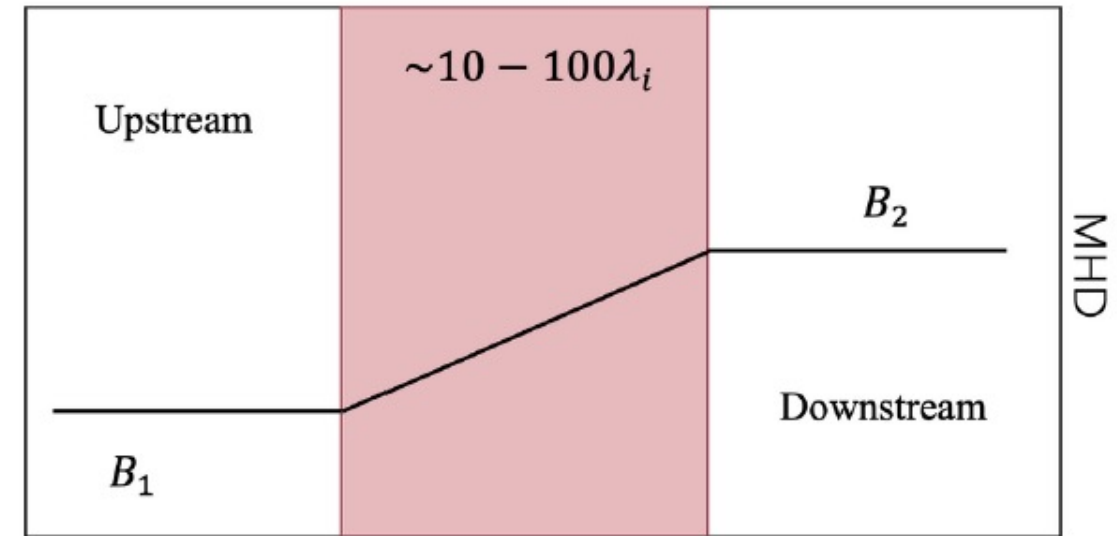


Quasi-parallel and Quasi-perpendicular shocks

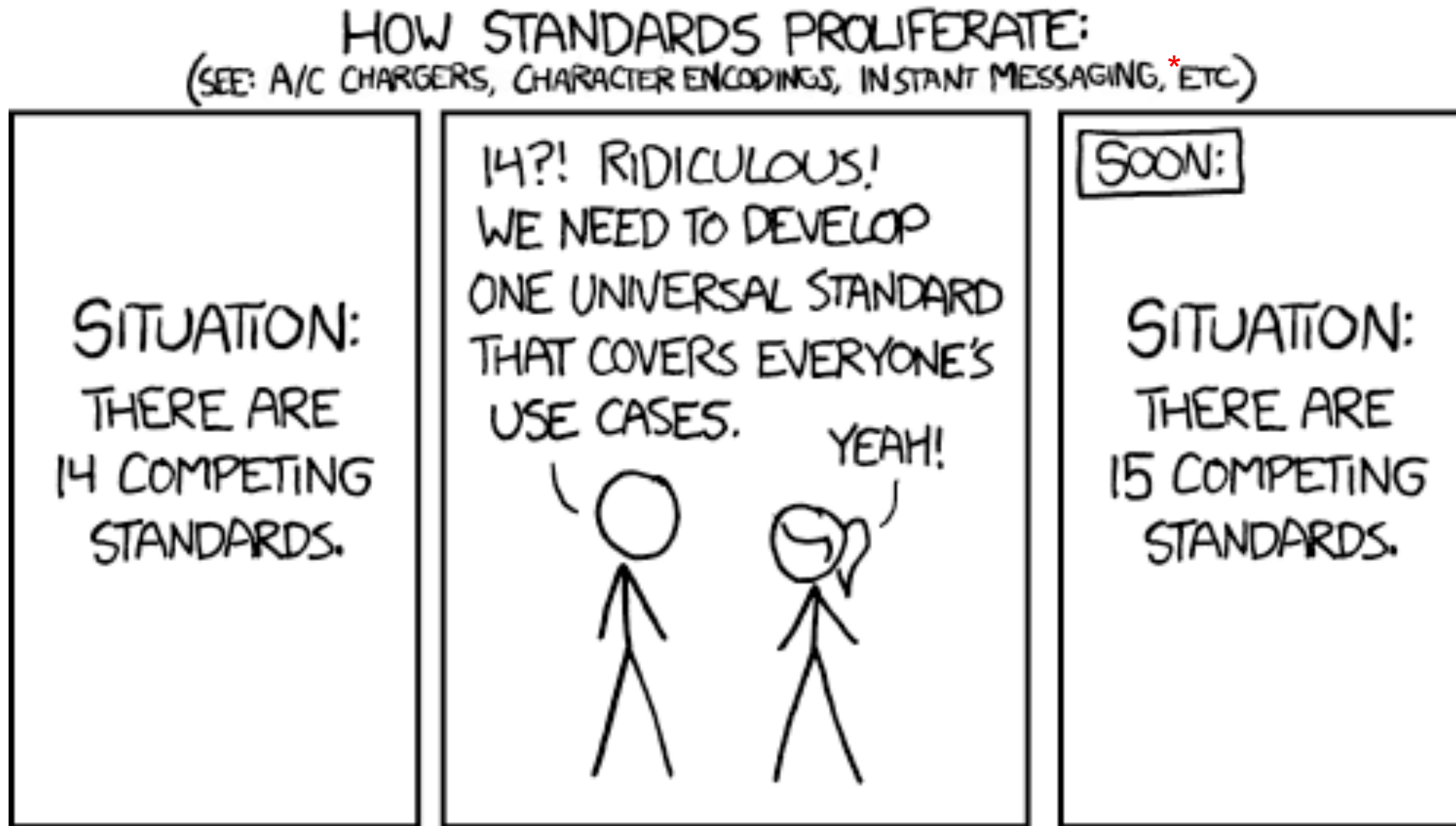
Qperp transition



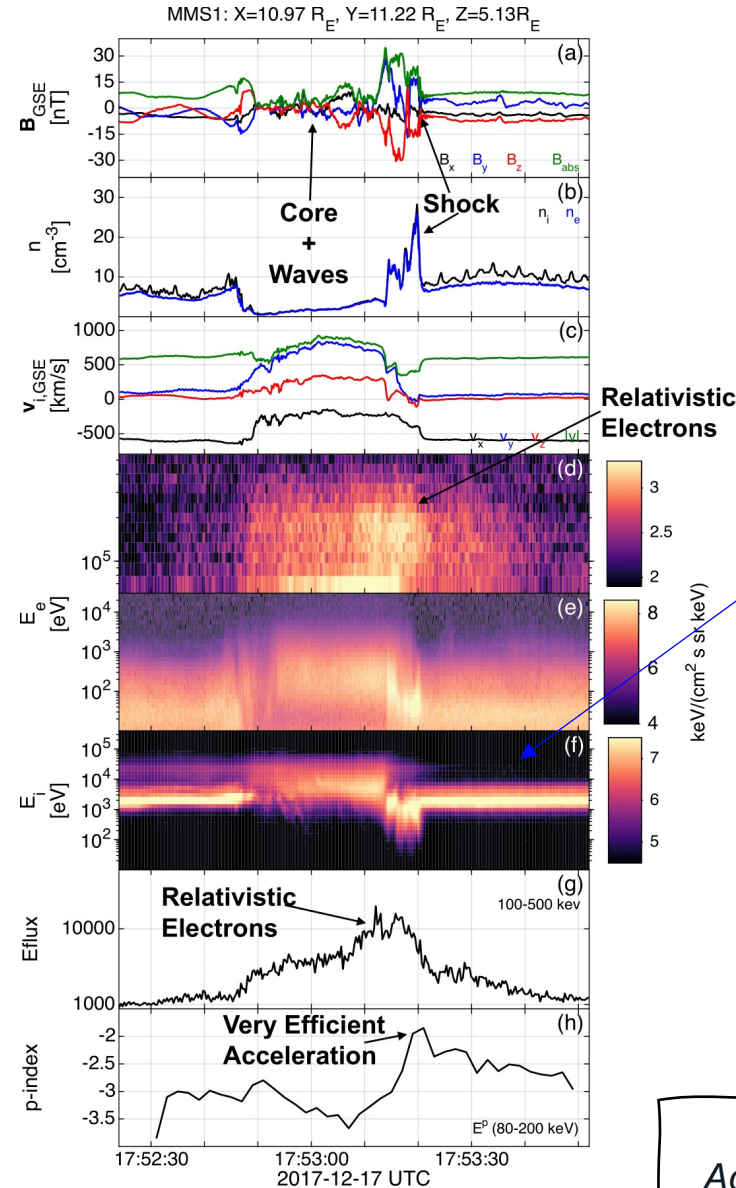
Qpar transition



Discussing new models

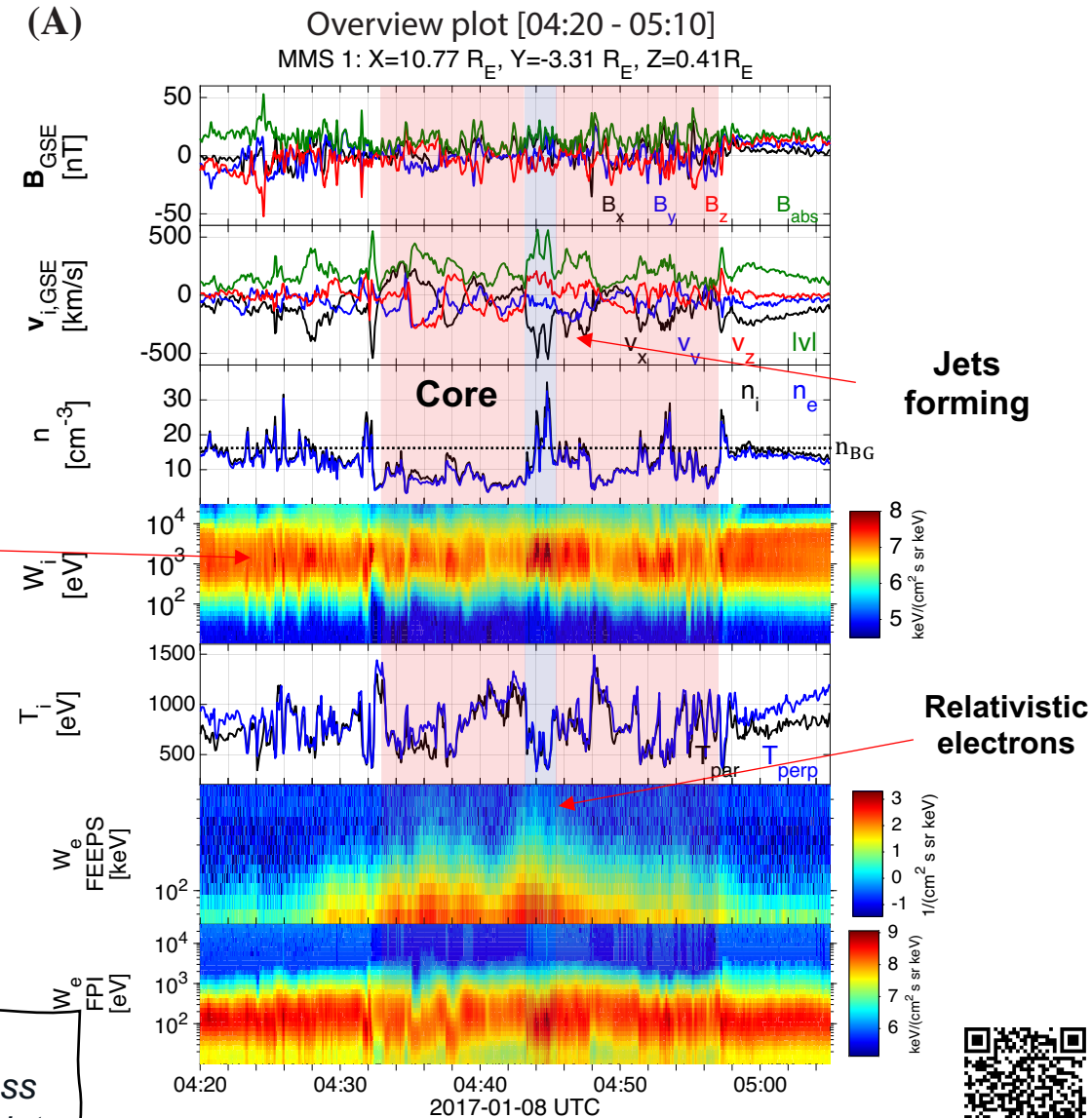


Foreshock transients are amazing particle accelerators



Raptis et al.2025 NatComm

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



Raptis et al.2025 ApJL

Transients with most notable impact

How many: ~several per day!

How big: up to ~10s of Re

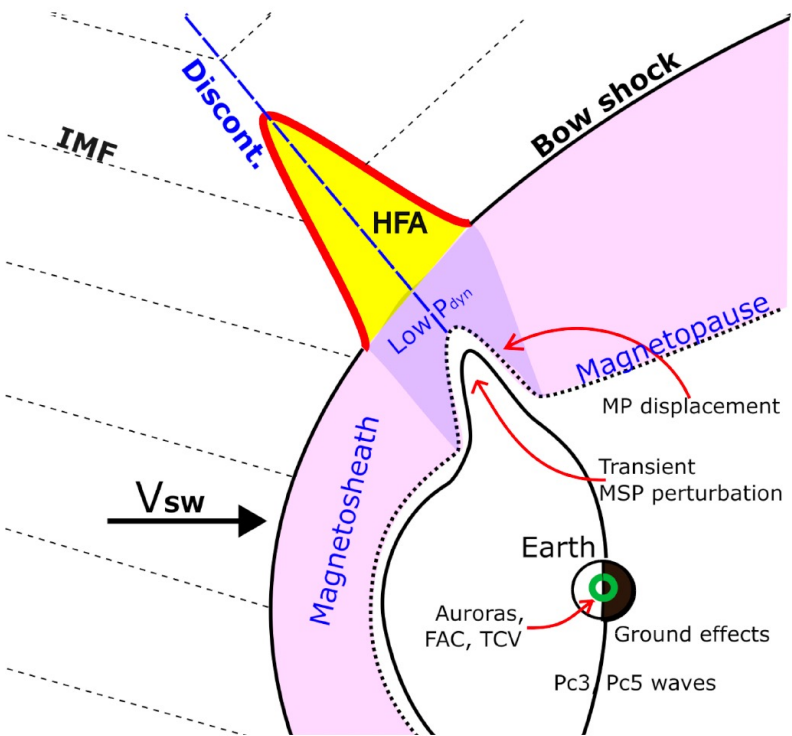
HFAs

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

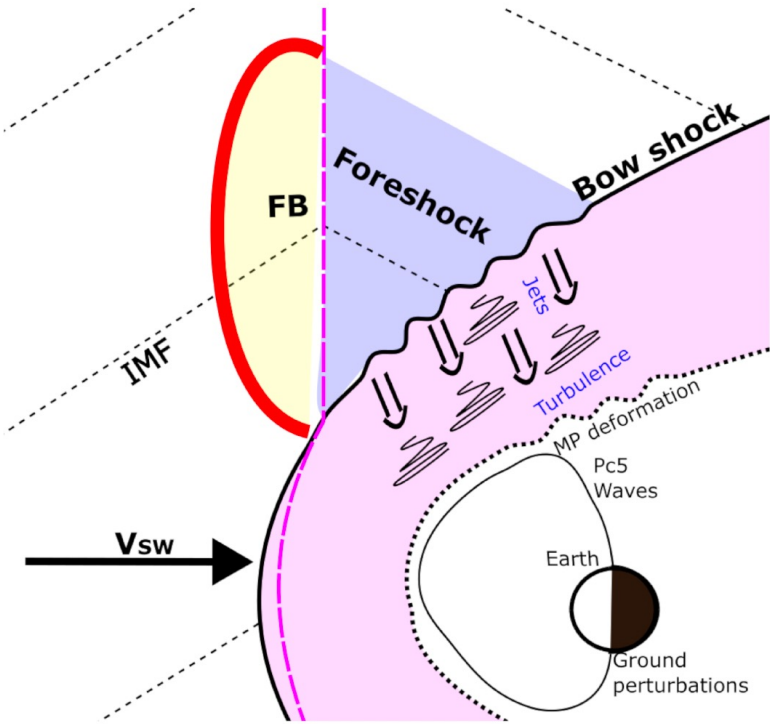
FBs

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

Zhang et al., (2022)



Hot Flow Anomalies (HFAs)



Foreshock Bubbles (FBs)

Universality of shock-generated transients

	coronal shocks	interplanetary shocks	Mercury	Venus	Earth	Mars	Jupiter	Saturn
ULFs	?	yes	yes	yes	yes	yes	yes	yes
shocklets	?	rare	yes?	yes	yes	yes	yes	yes
SLAMS	?	no?	yes	yes	yes	yes	yes	yes
SHFAs	?	?	?	yes	yes	yes	?	?
HFAs	?	?	maybe?	yes	yes	yes	yes	yes
FBs	?	?	?	?	yes	?	?	?
jets	?	yes	maybe?	?	yes	yes?	yes?	?

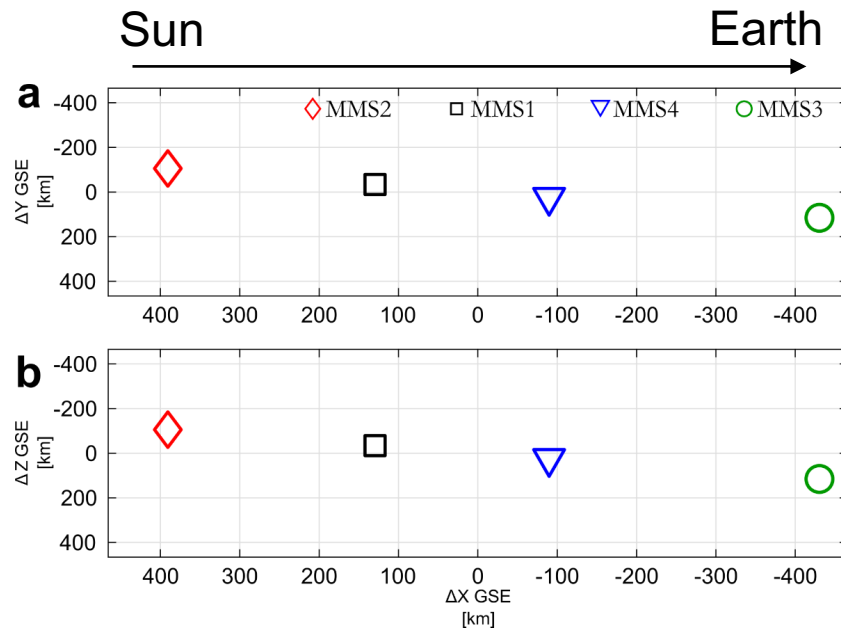
Hietala et al. ISSI 2019

Yes!*

Yes!*

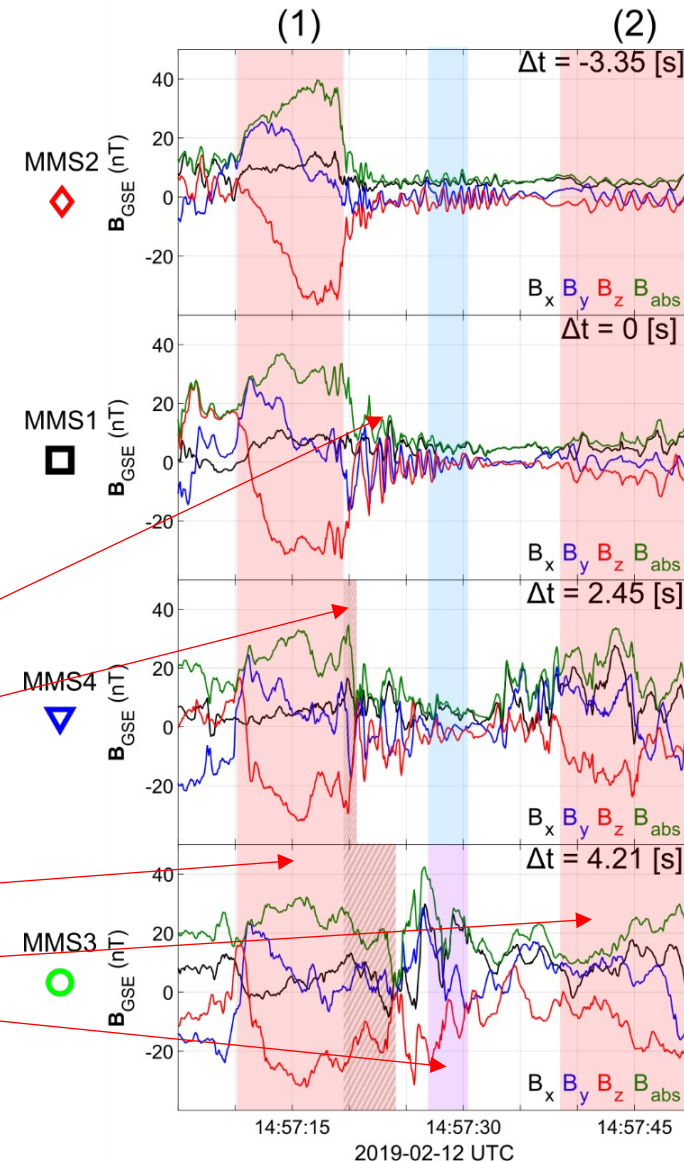
Maybe? (see more at AGU ☺)

SLAMS – wave activity and 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

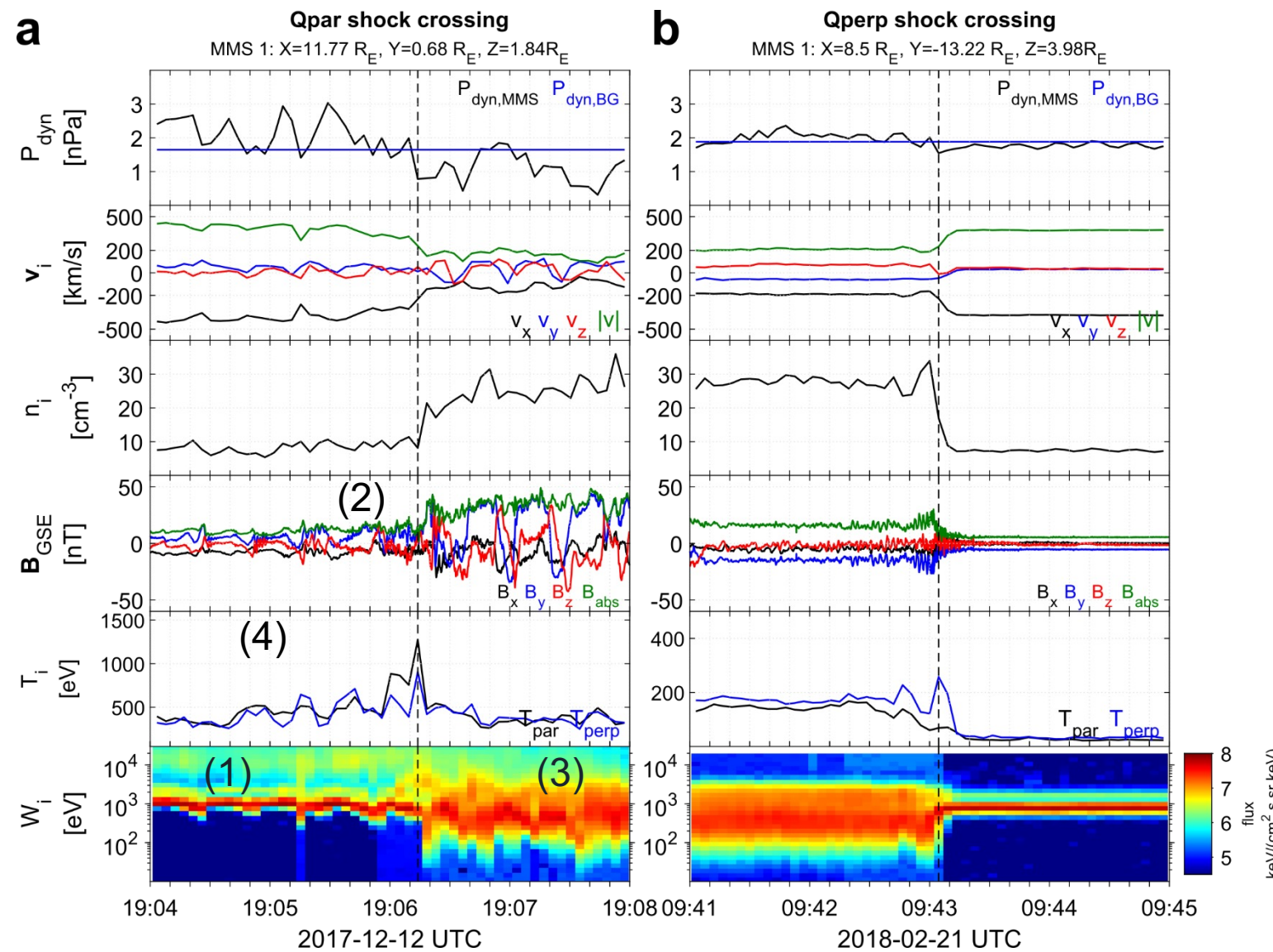
* See similar examples by Turner et al. (2021), Chen et al. (2021) | “(Self-) reformation/evolution/ripples”

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

Community Reminder: Qpar – Qperp crossings

Qpar shocks and downstream plasma:

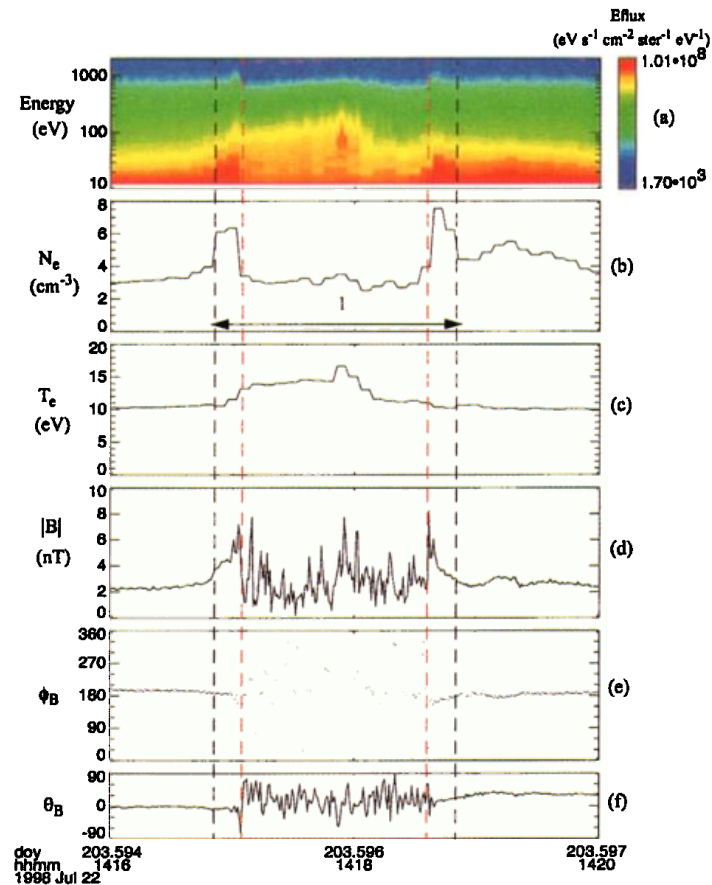
- 1) Presence of foreshock
- 2) Magnetic field fluctuations $\uparrow$
- 3) High energy ions $\uparrow$
- 4) Downstream temperature anisotropy $\downarrow$



Hot Flow Anomalies at other Planetary Systems

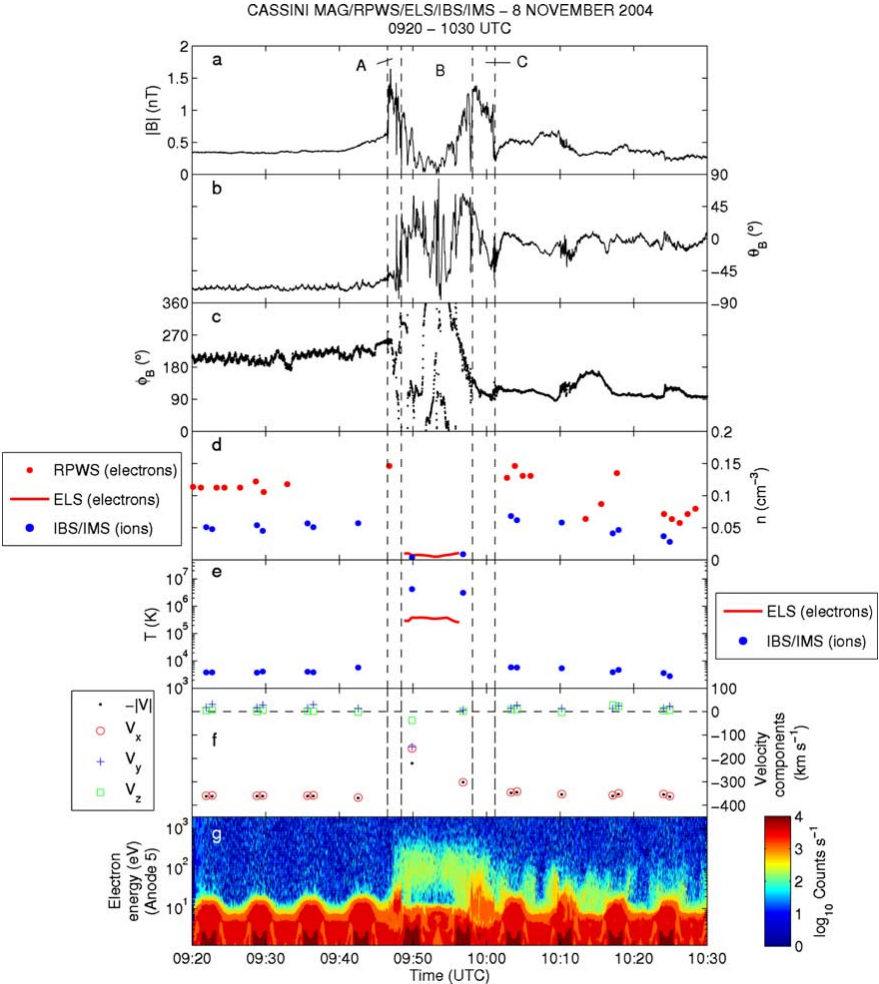
HFAs have been observed throughout the solar system

Mars: Øieroset et al. [GRL 2001] with MGS



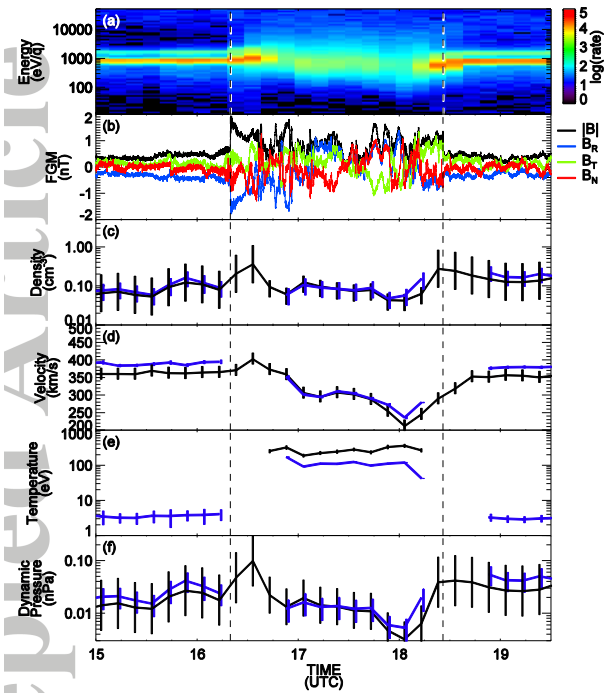
From Øieroset et al. [GRL 2001]

Saturn: Masters et al. [JGR 2009] with Cassini

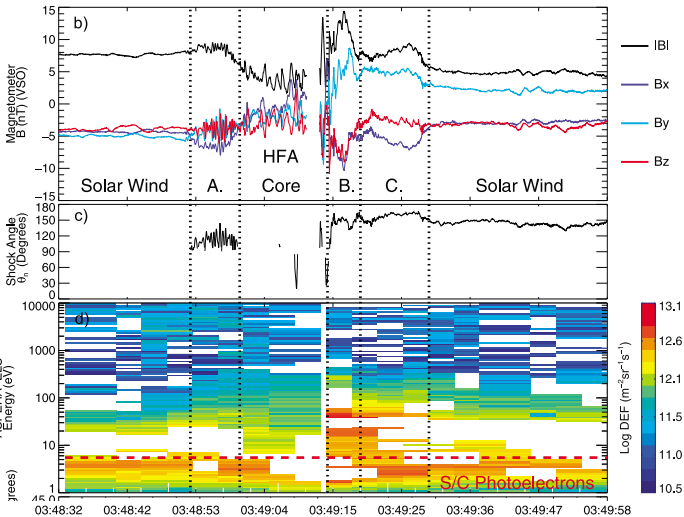


From Masters et al. [JGR 2009]

Jupiter: Valek et al. [GRL 2017]
with Juno



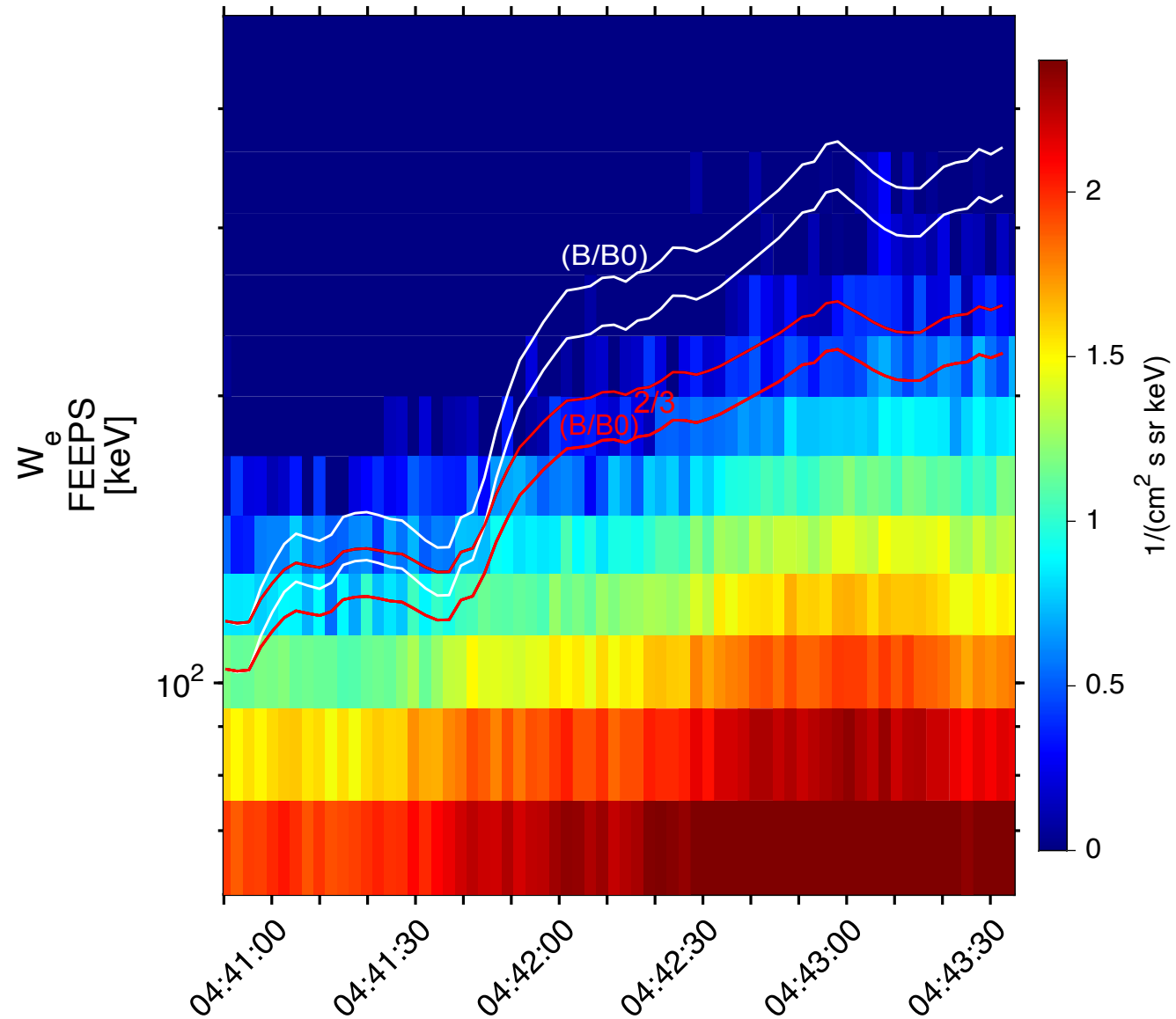
Venus: Collinson et al. [JGR 2012]
with Venus Express



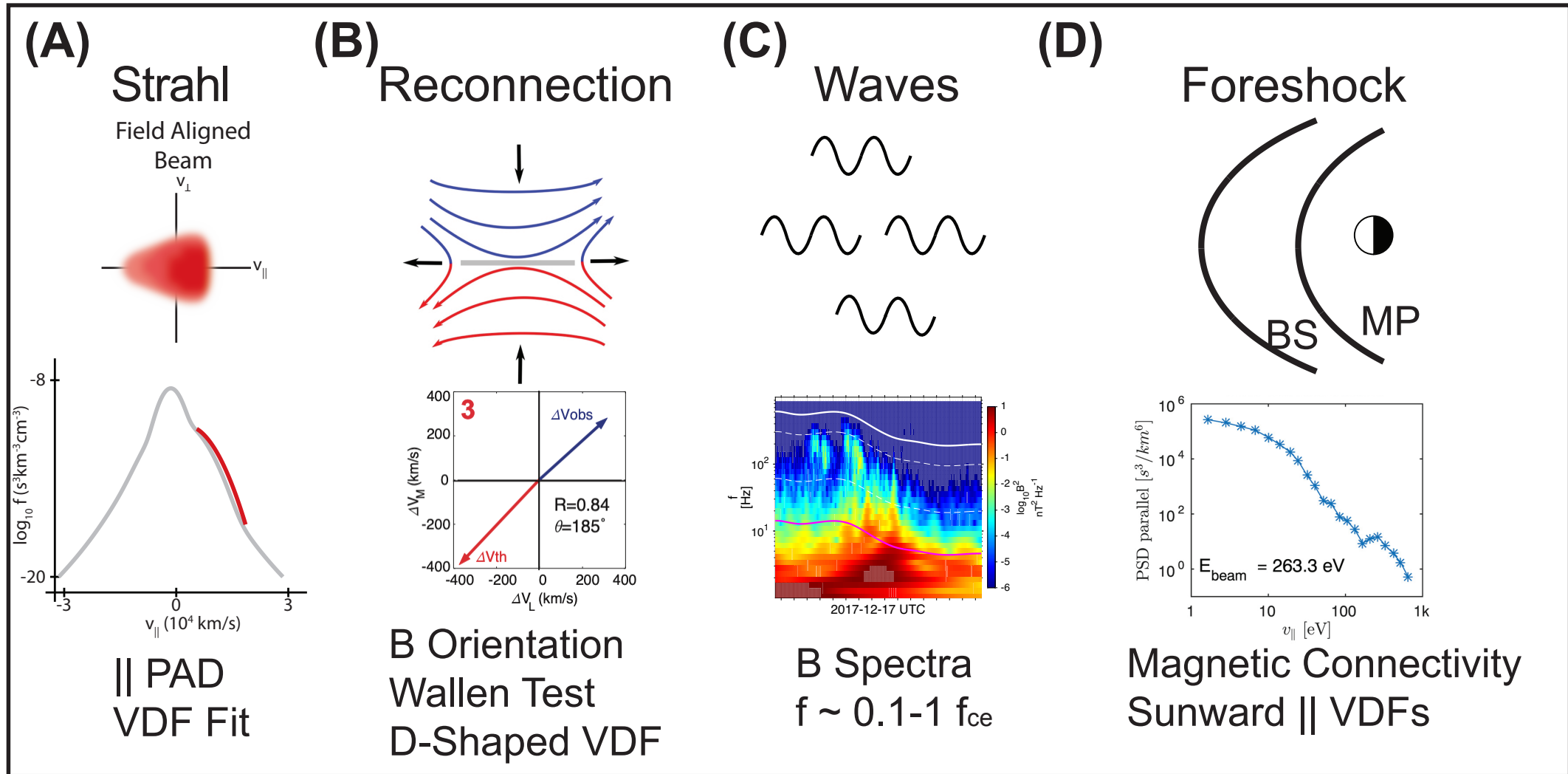
From Collinson et al. [JGR 2012]

HFAs are ubiquitous at collisionless astrophysical shocks

Why Stochastic Betatron Acceleration? Better agreement



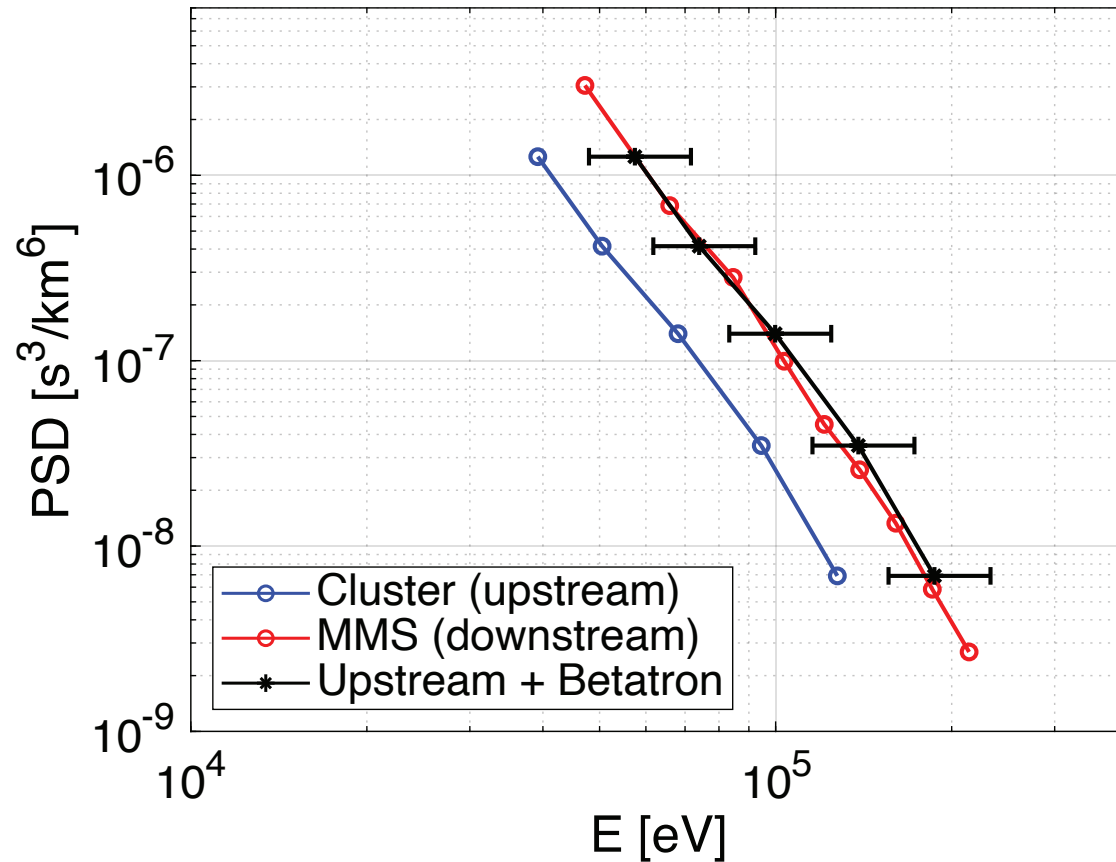
Some Ideas about the Seed Population



Preliminary Comparison (Data vs Simulations)

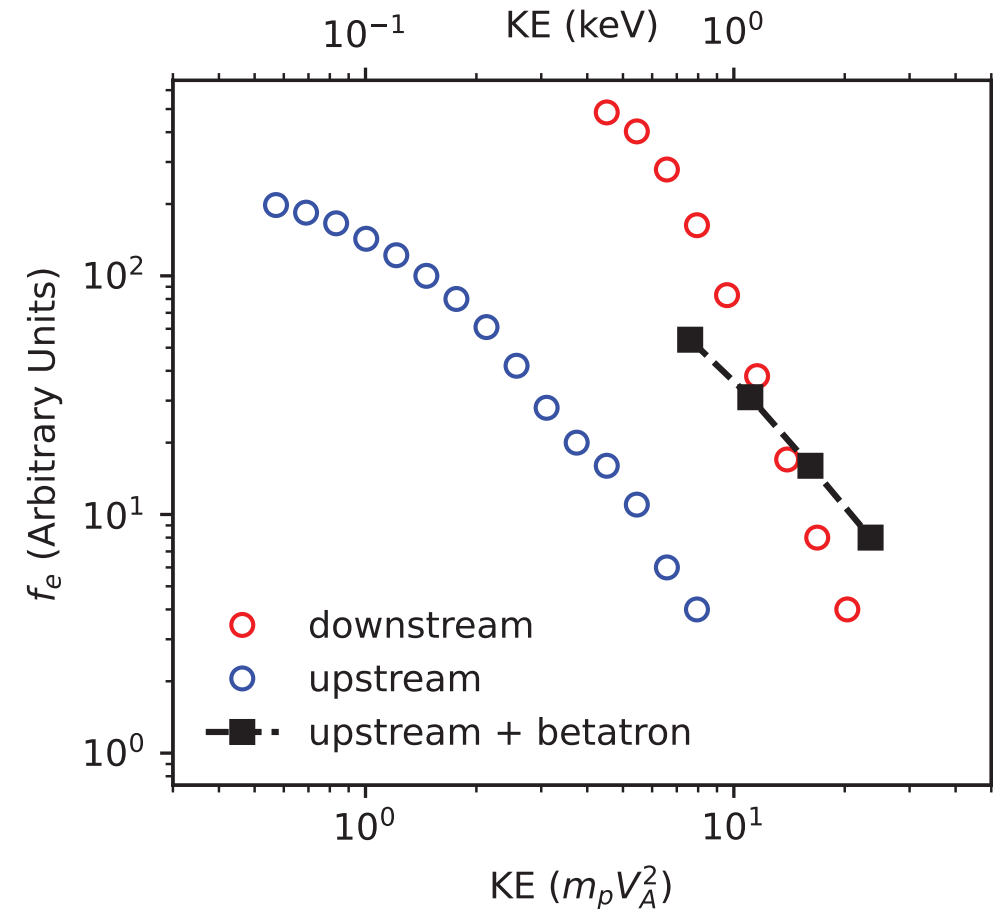
(A)

In-situ Observations

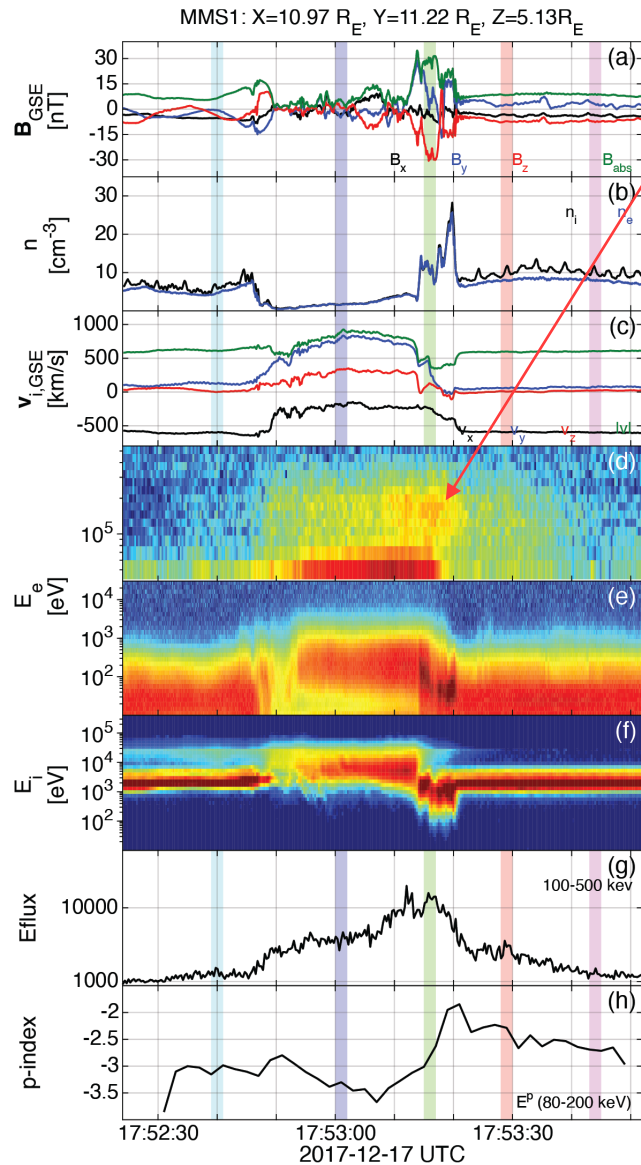


(B)

Hybrid Simulations

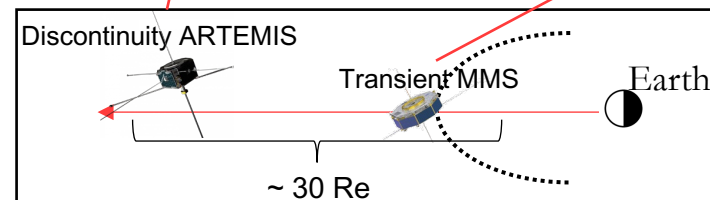
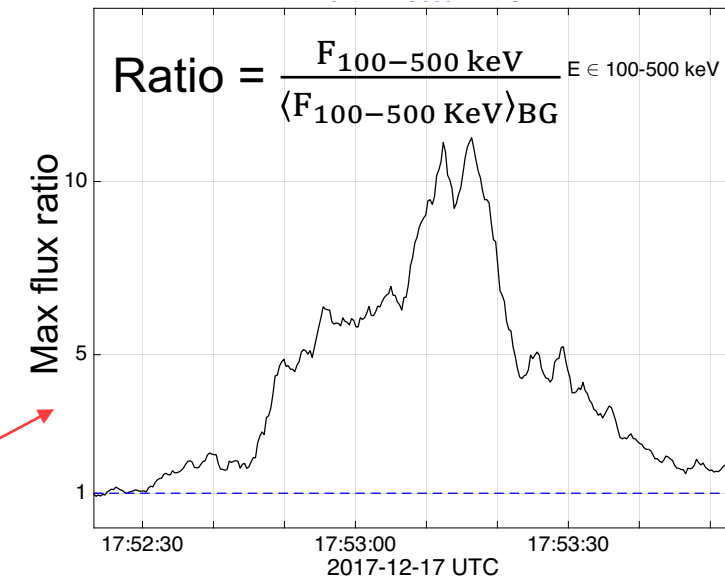
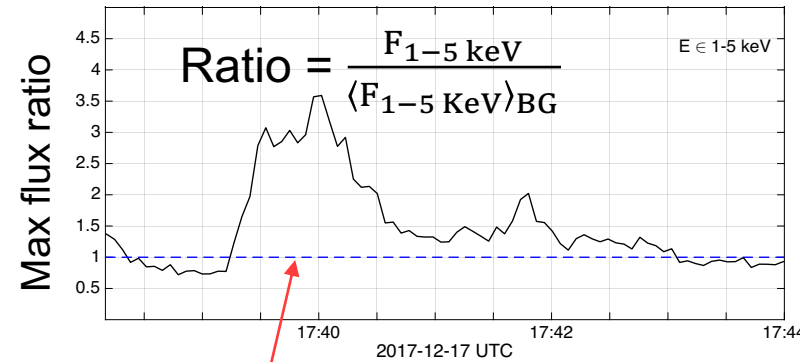


Reinforced Shock Acceleration of Relativistic Electrons



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.

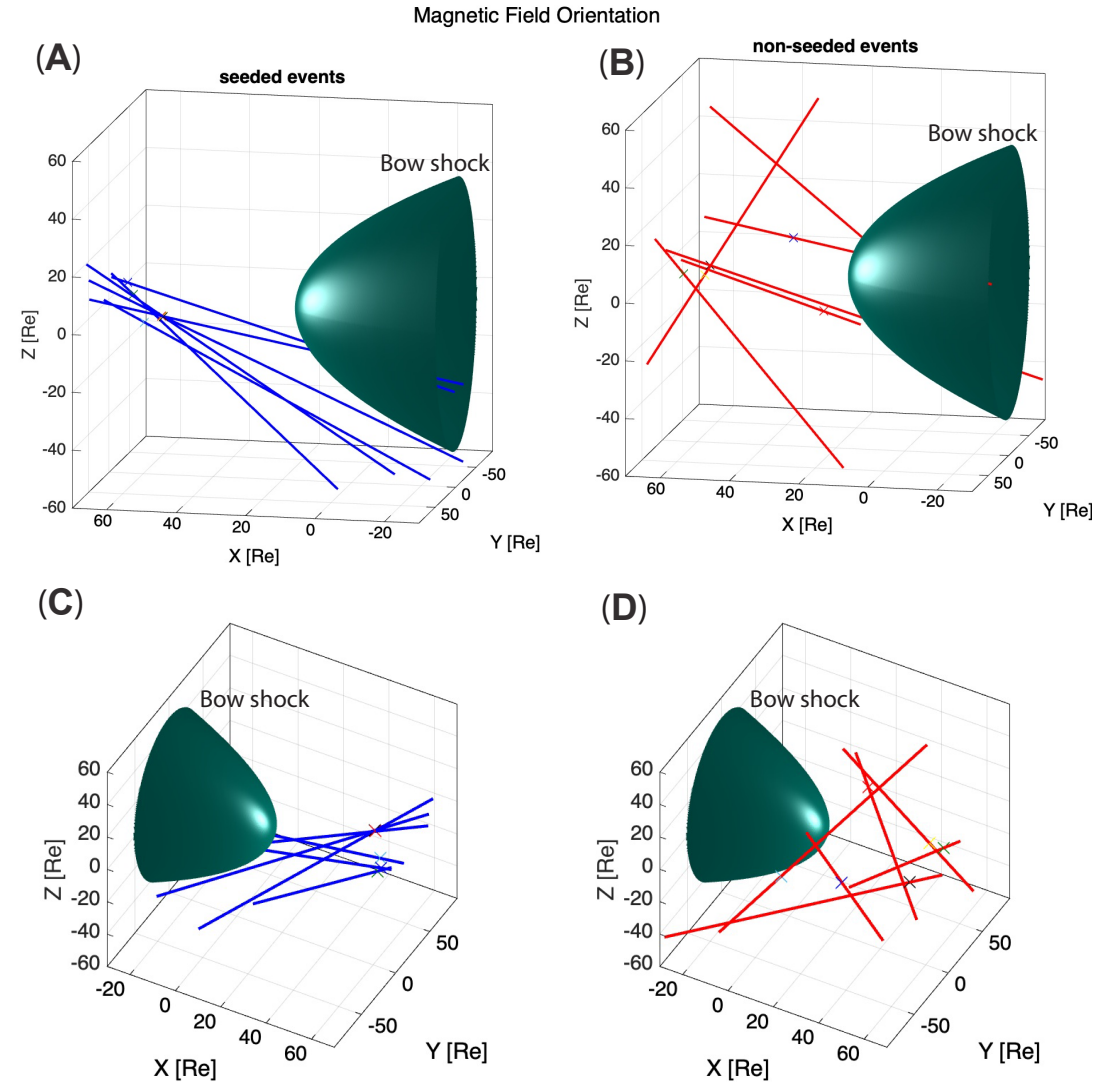
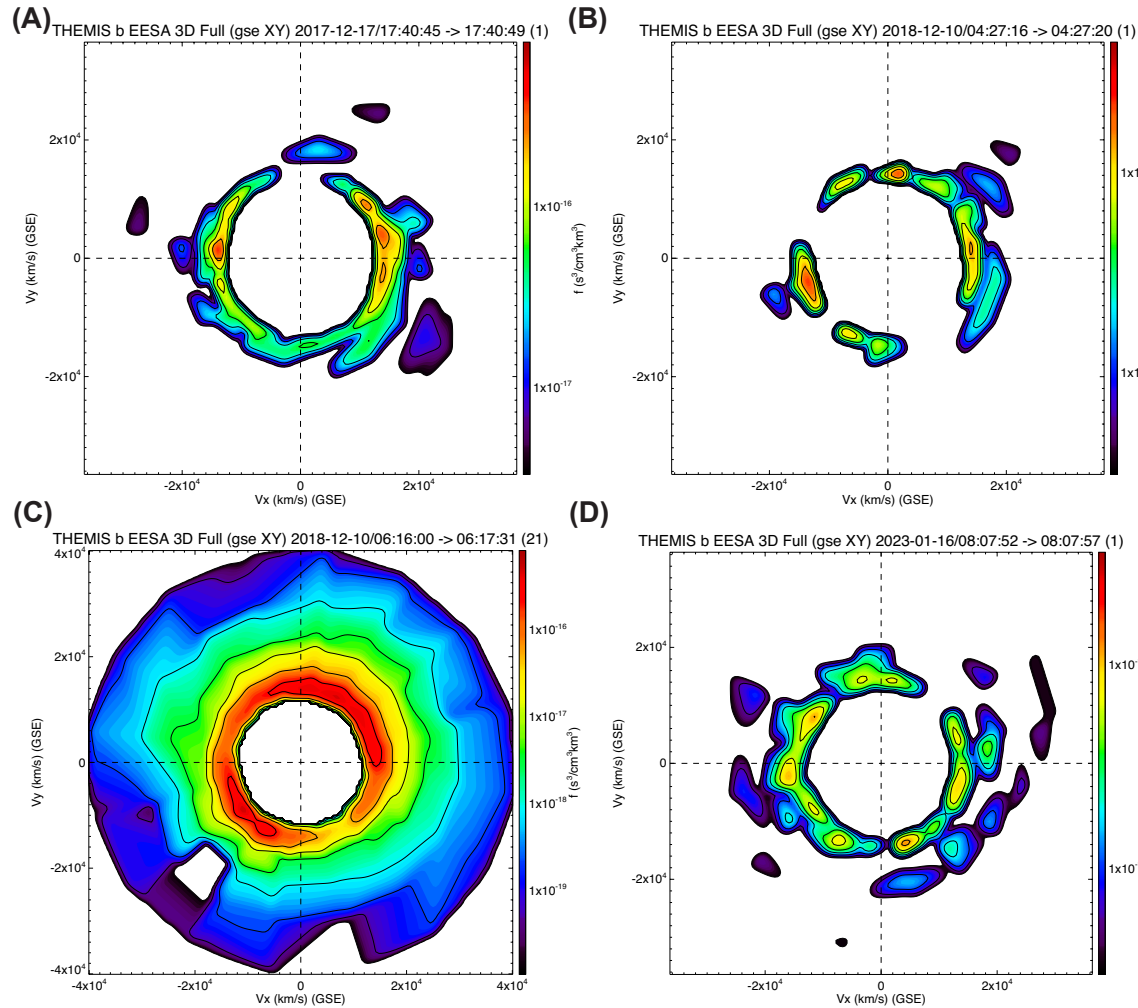
Is seed from the foreshock? – Maybe partially

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

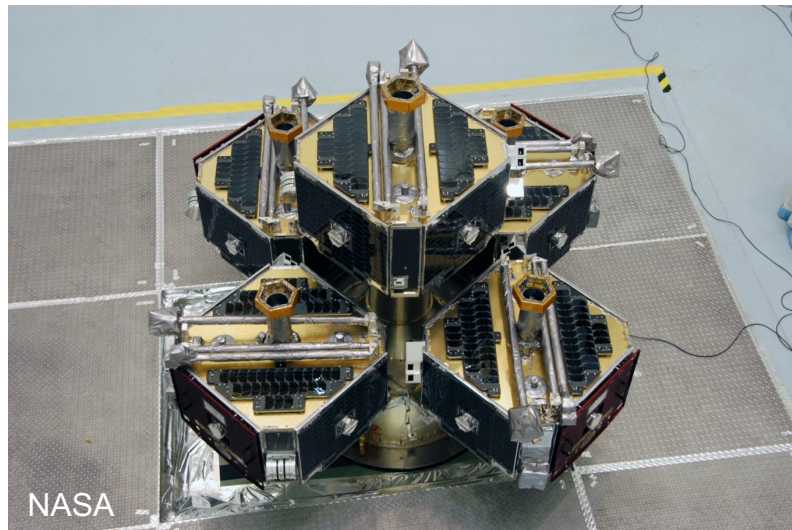
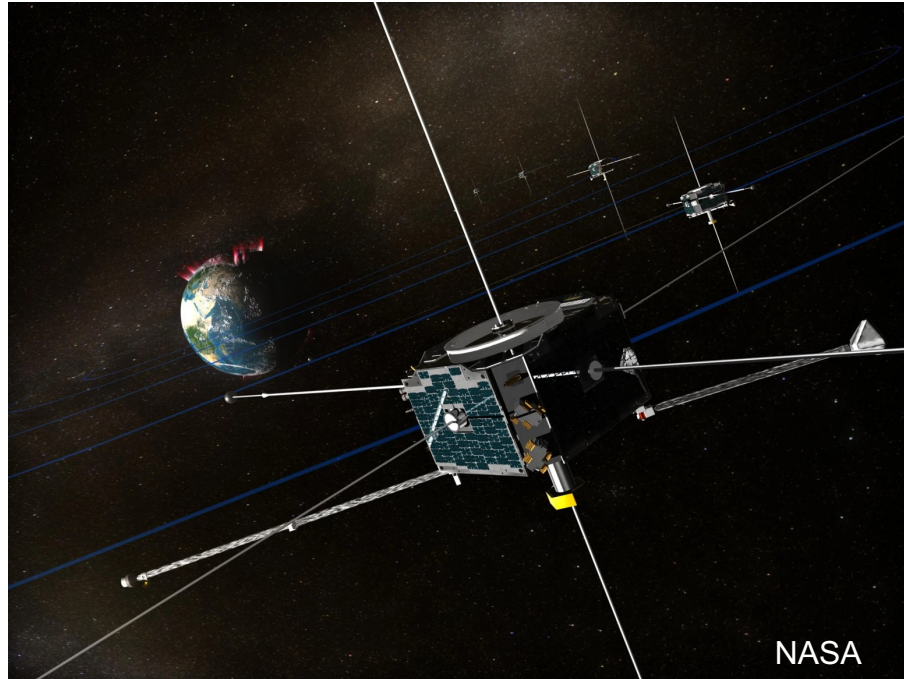
(C) → Seeded event full mode

(D) → Non-seeded event – partial mode

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

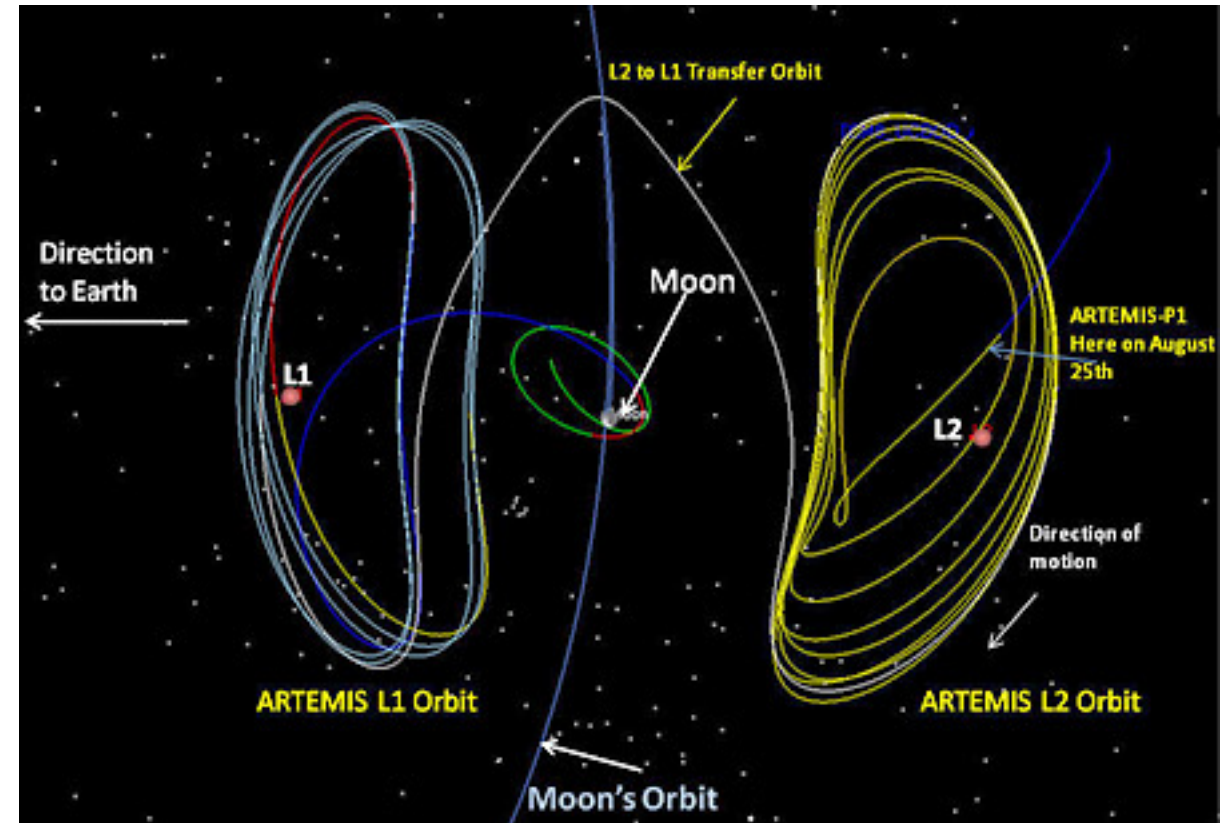


THEMIS/ARTEMIS mission

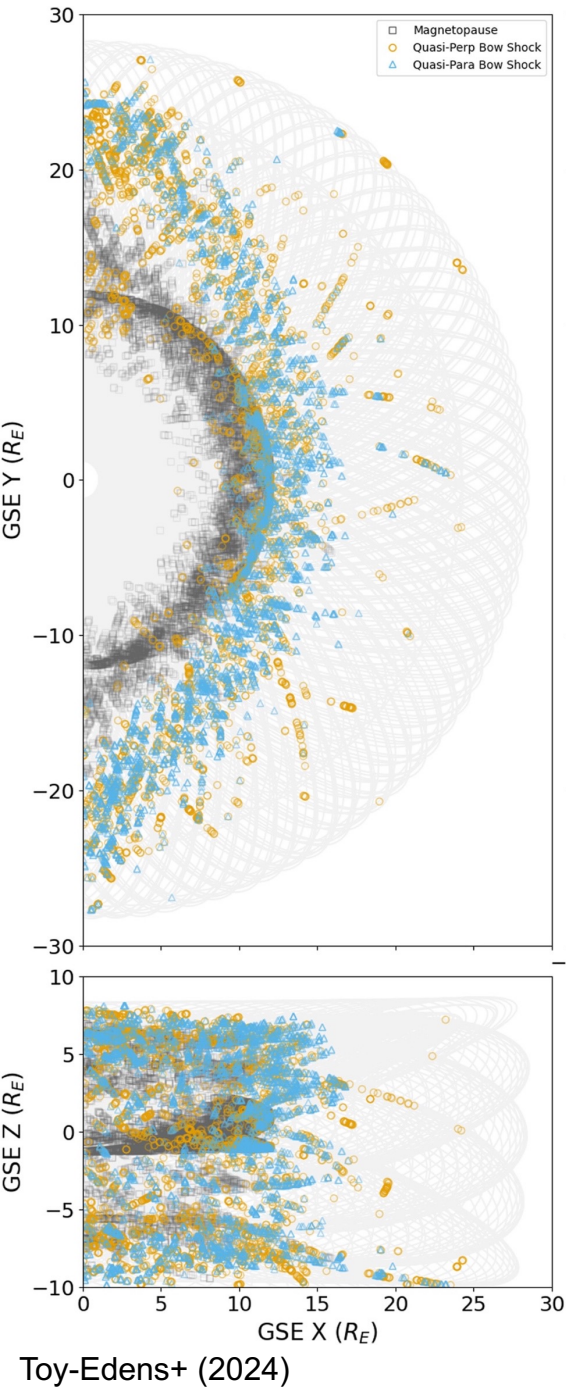


Feb. 17, 2007: Launch → 5 SC, magnetotail reconnection objectives
Jan. 1, 2009: THEMIS-P1 and P2 are Reassigned, Renamed and Redirected to the Moon → ARTEMIS

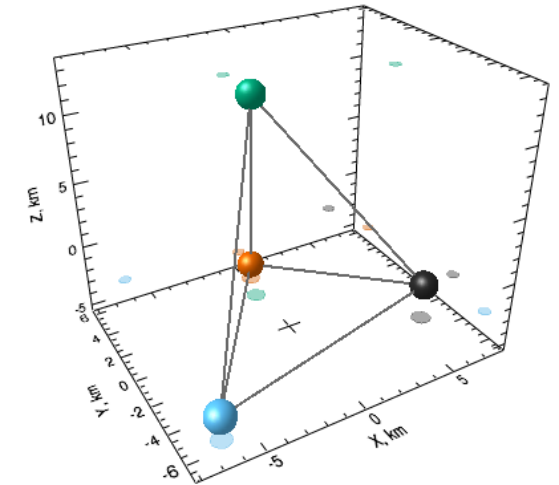
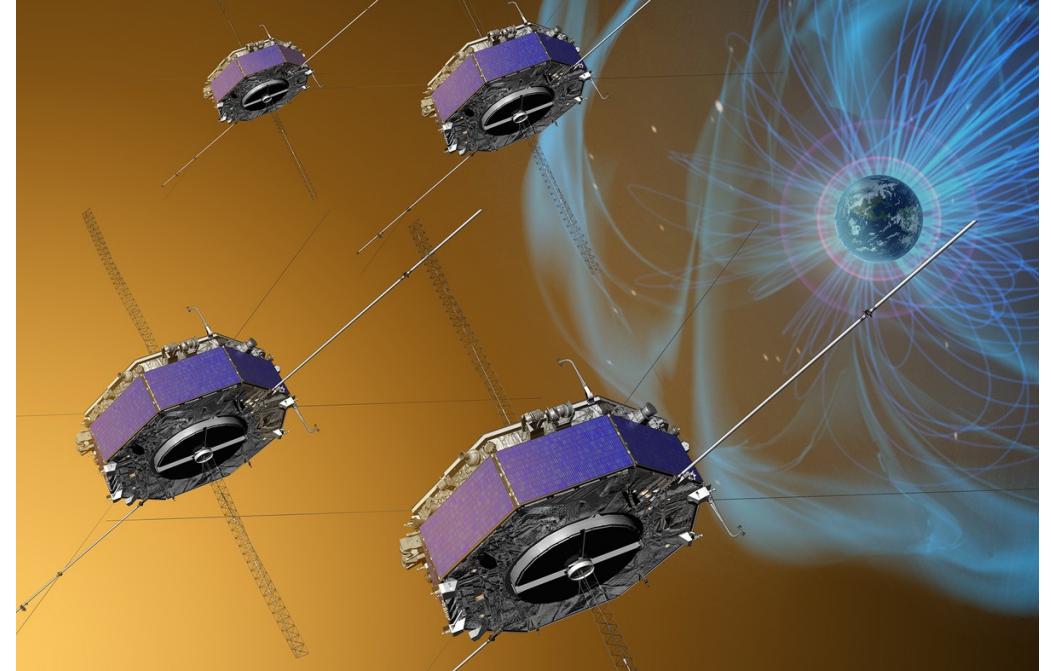
Orbiting the moon it can (sometimes) provide close to Earth in-situ observations of upstream conditions (when moon is on the dayside)



MMS mission



- Launched March 2015
- 4 identical s/c (10s to 100s km separation)
- Equatorial HEO, w/ apogee: $\sim 12 R_E$ (2015-2018); $\sim 28 R_E$ (2018-present)
- Several thousands of shock crossings Lalti+ (2023), Toy-Edens+ (2024)
- In-situ observations of plasma moments, fields, and distributions.



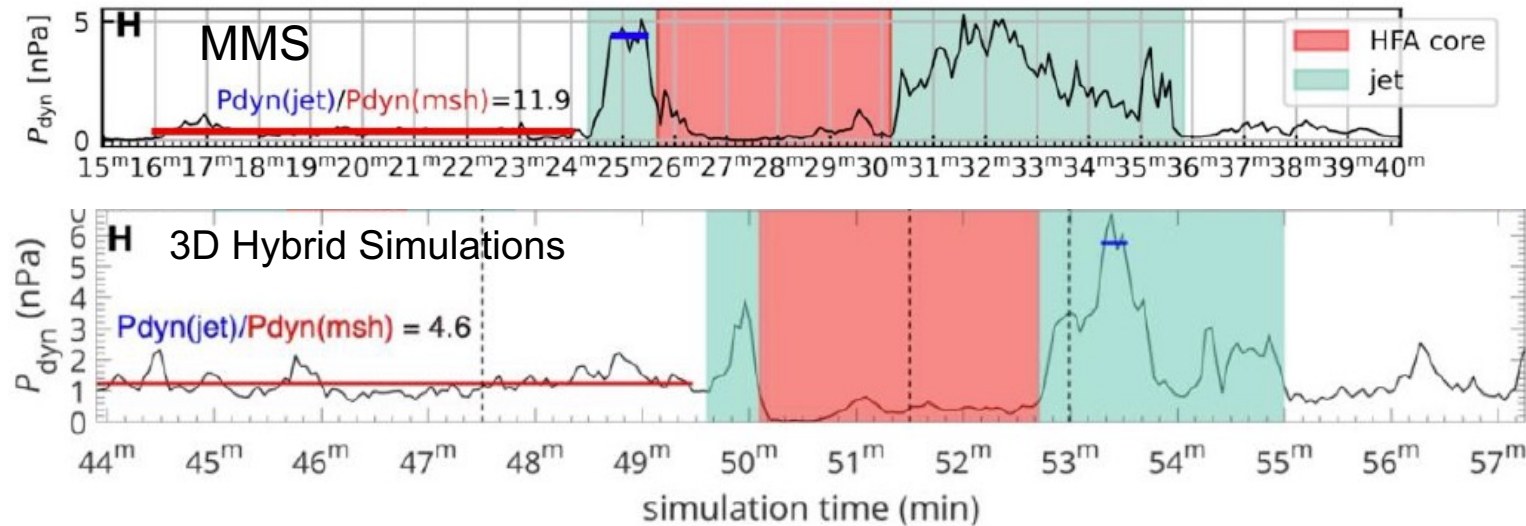
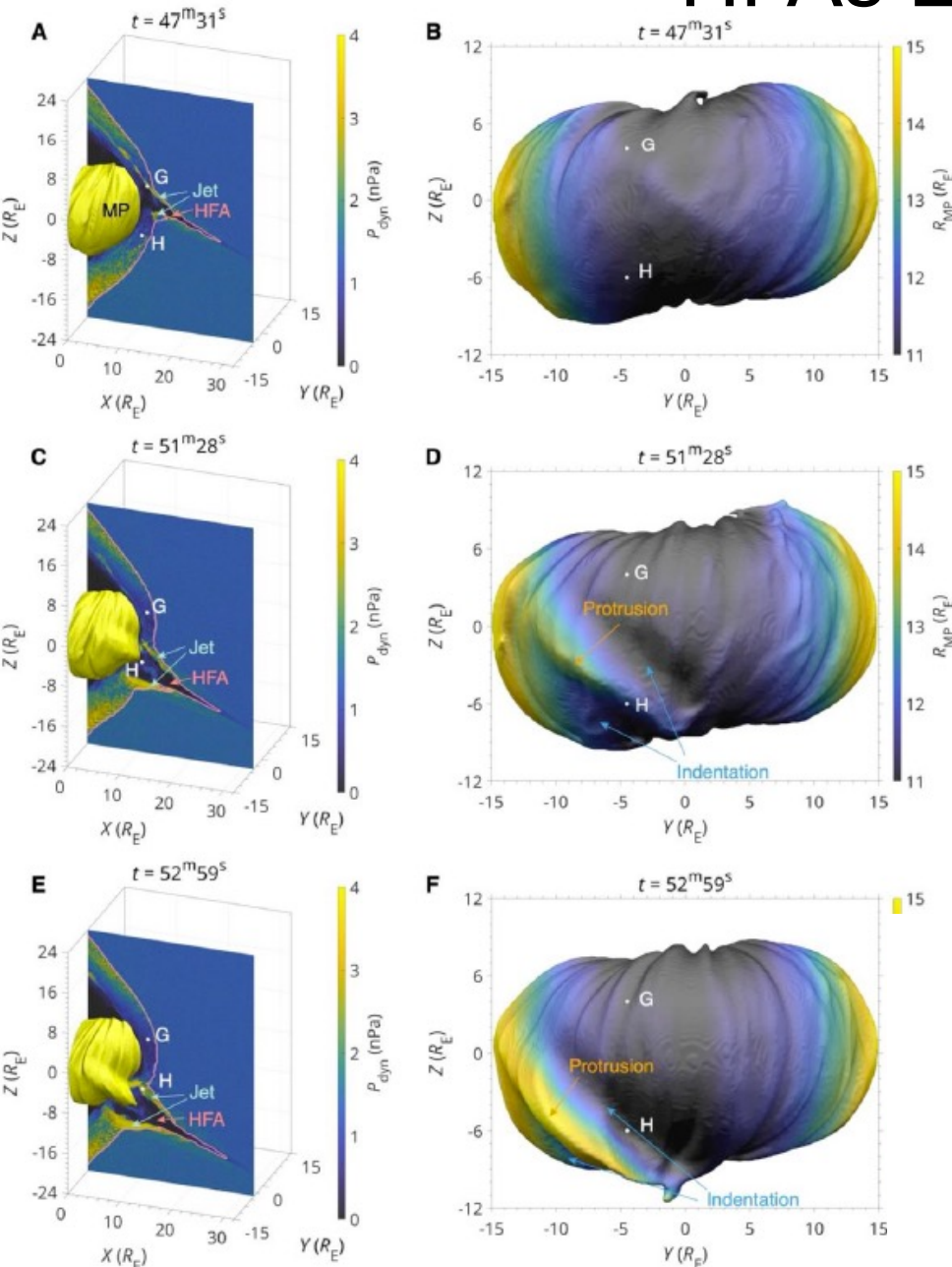
HFAs Effect on Magnetosheath

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

Core density depletion effects
(stuff move outwards)

Leads to magnetosheath restructuring

- Spatial extent: ~10s of R_E
- Duration: ~10s of minutes



HFAs associated to jets (Archer+2014, Zhou+ 2023)

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