High-speed jets at Earth's magnetosheath & more

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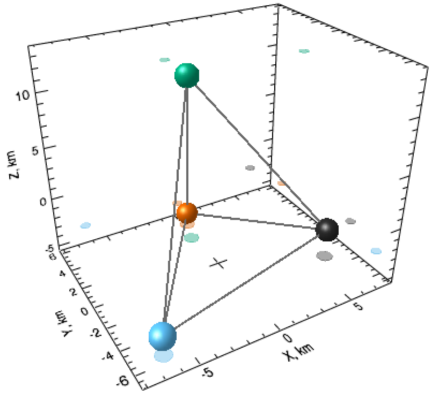
CGS weekly meetings
18/01/2023

Soon…

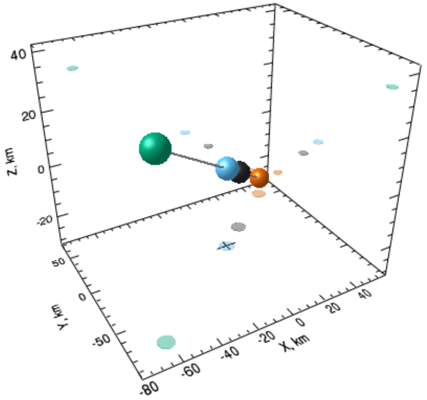
MMS mission & instrumentation

Formation

Tetrahedron

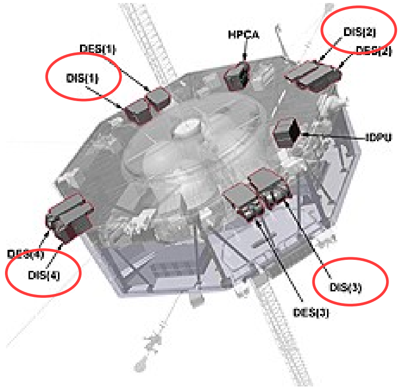


String-of-pearls

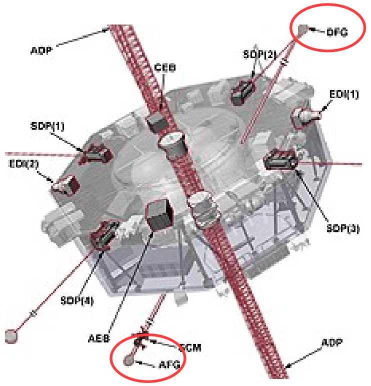


Instrumentation

FPI



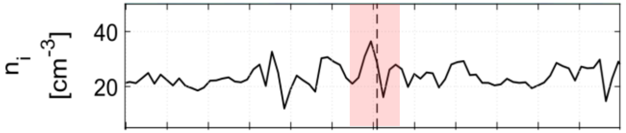
FGM



Mode

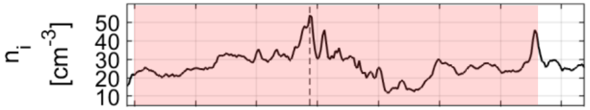
fast/srvy

FPI (ions): 4.5s
FGM: 0.0625s



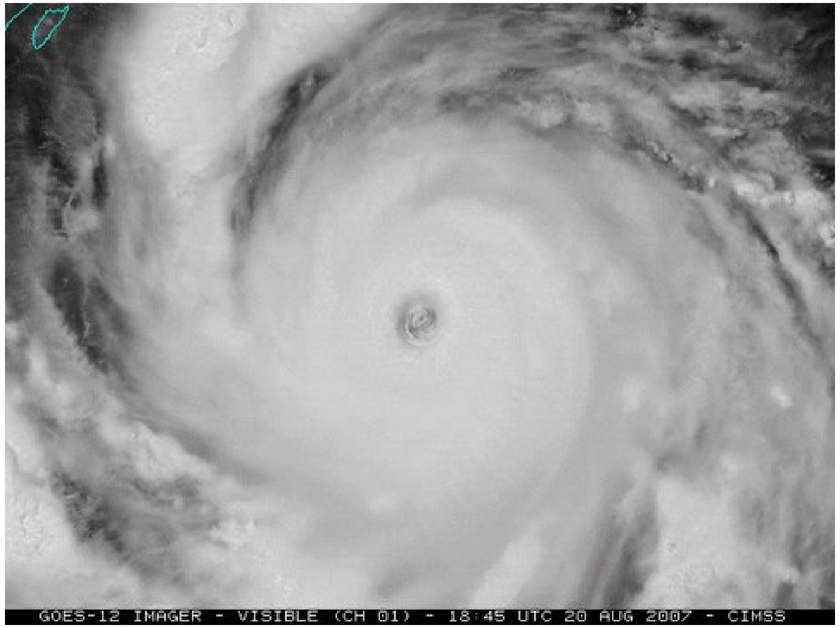
brst

FPI(ions): 0.15s
FGM: 0.0078s



Transient events – weather

Hurricanes

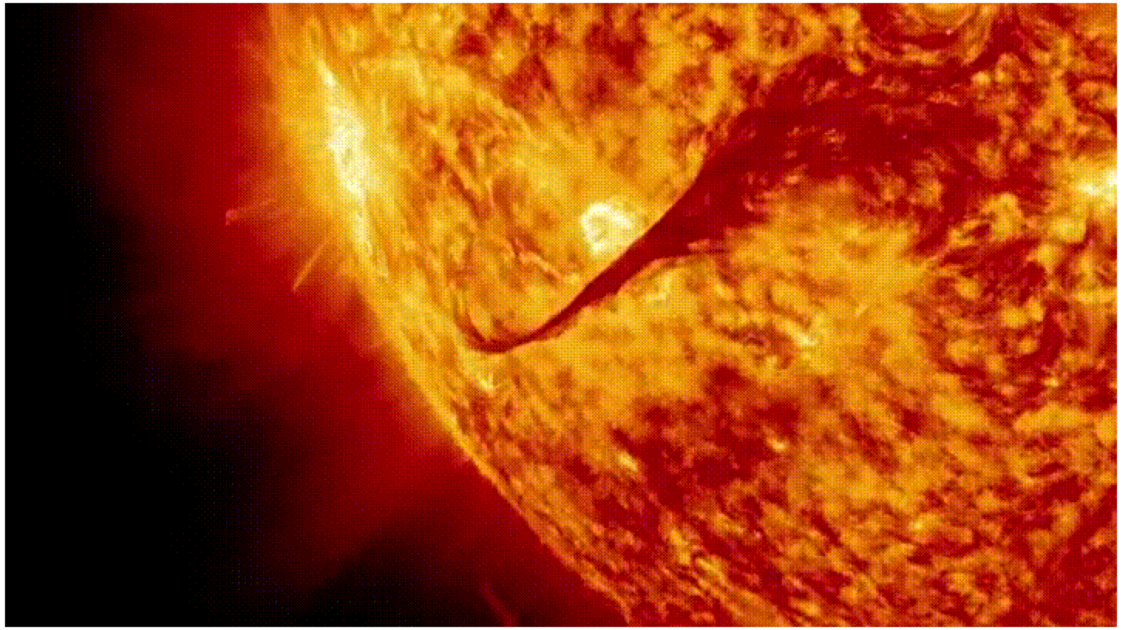


Rain

Snowstorms

Transient events – weather

CMEs/Solar Flares

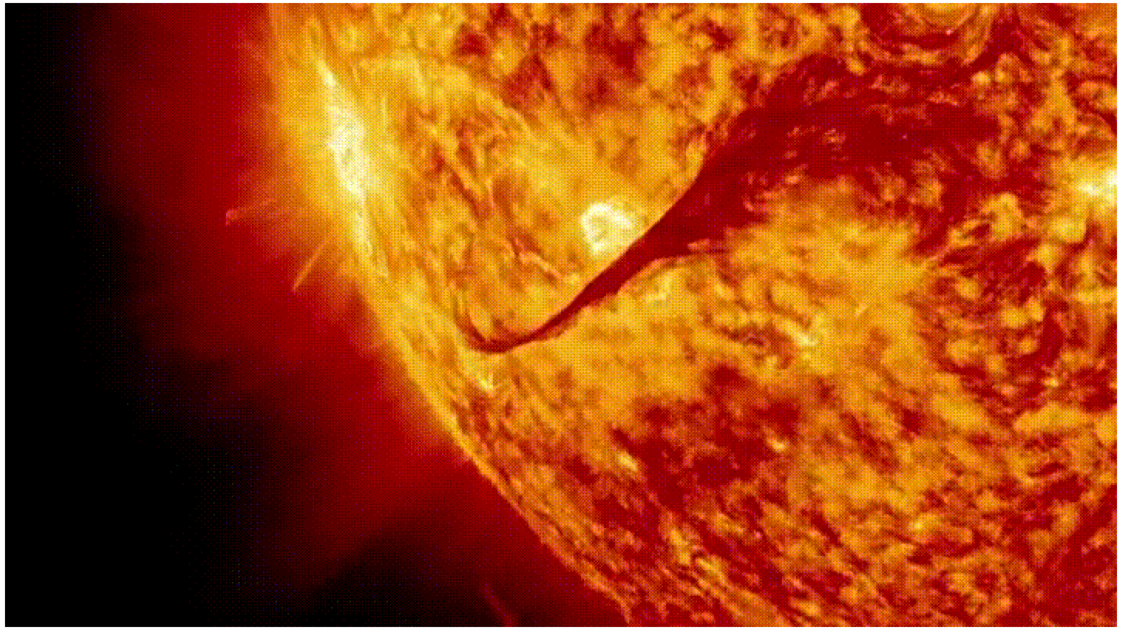


Rain

Snowstorms

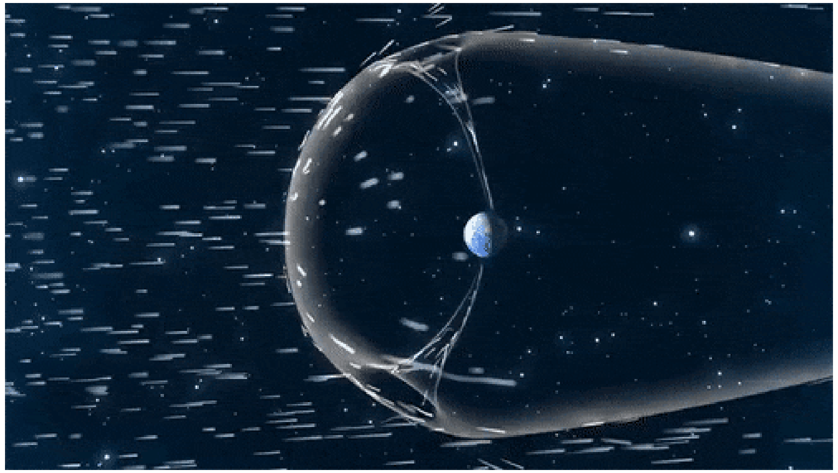
Transient events – weather

CMEs/Solar Flares



Rain

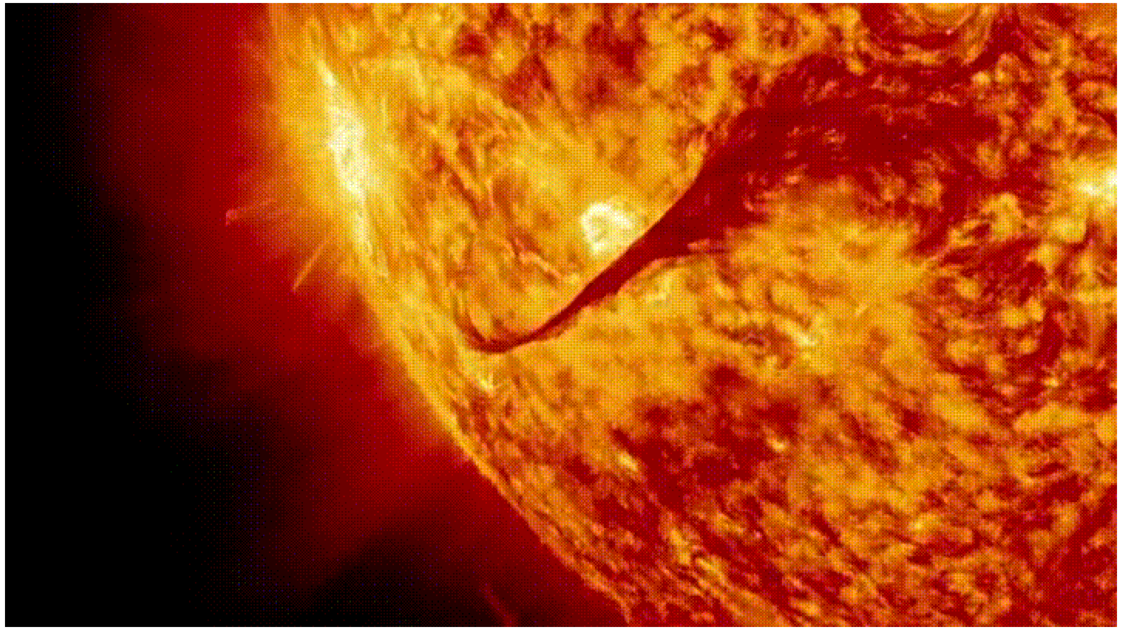
Solar cycle, streams, discontinuities



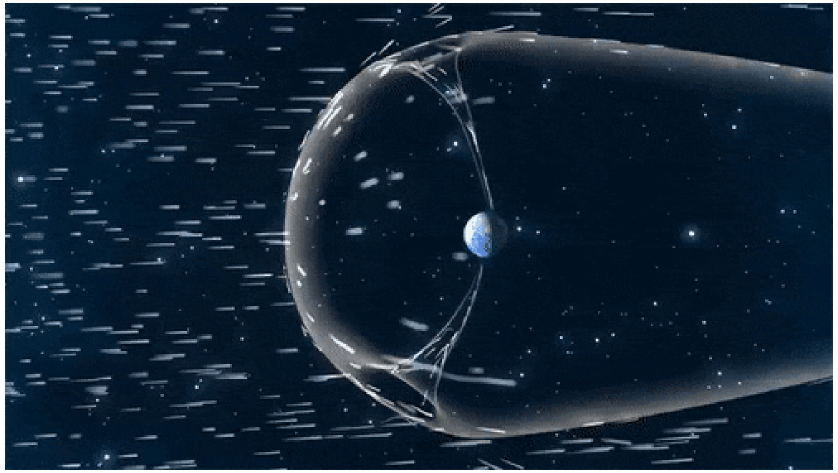
Credits : NASA

Transient events – *space* weather

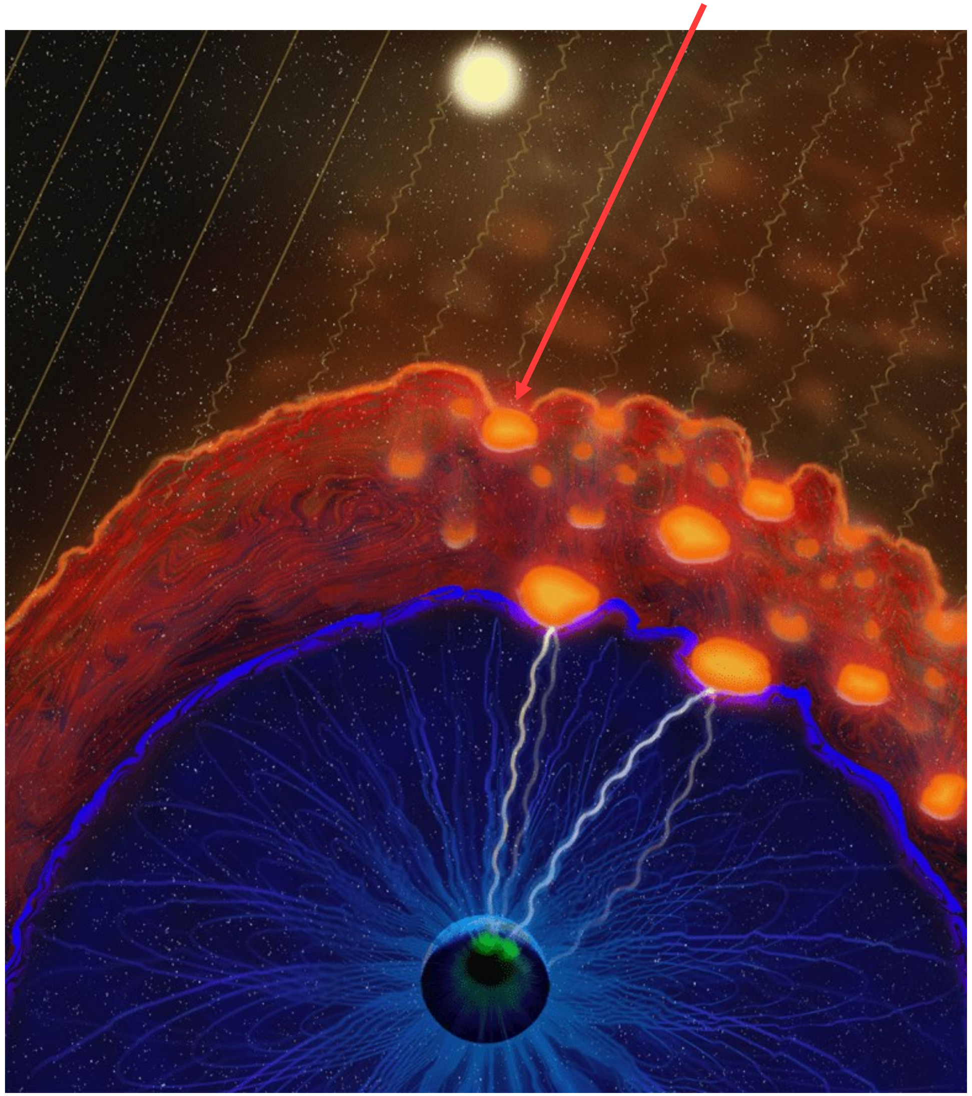
CMEs/Solar Flares



Solar cycle, streams, discontinuities



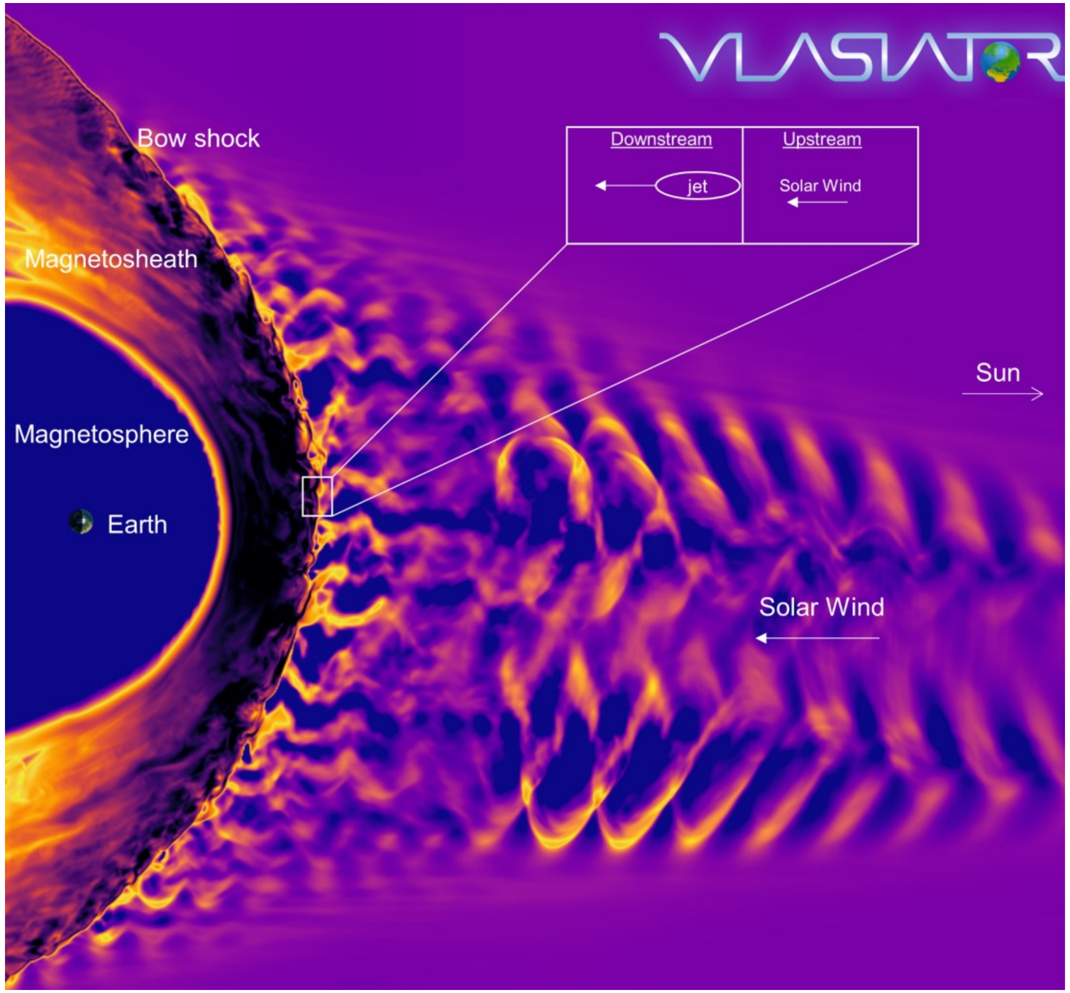
Foreshock structures & plasma jets



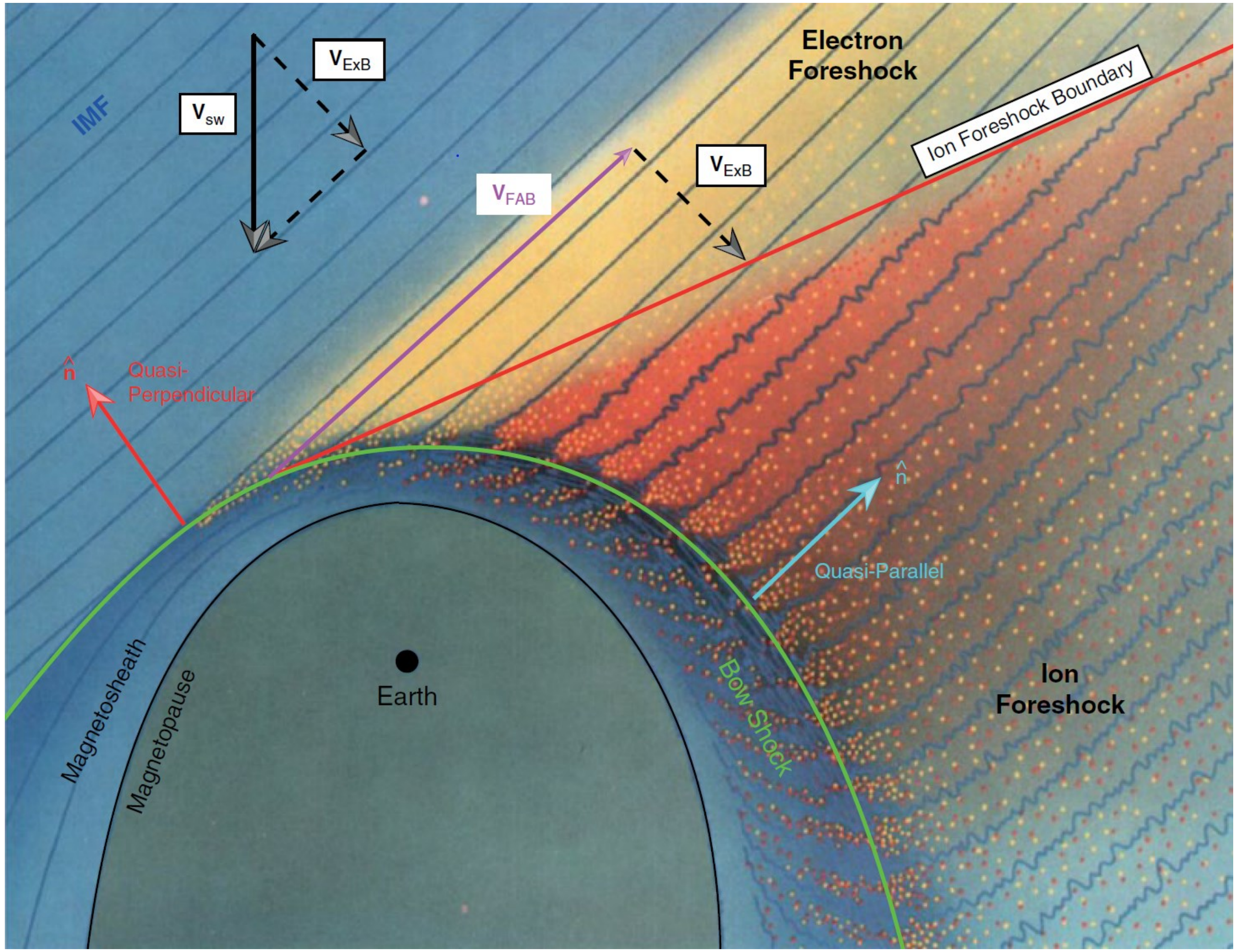
Credits : NASA

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

Earth’s magnetosphere & shock environment



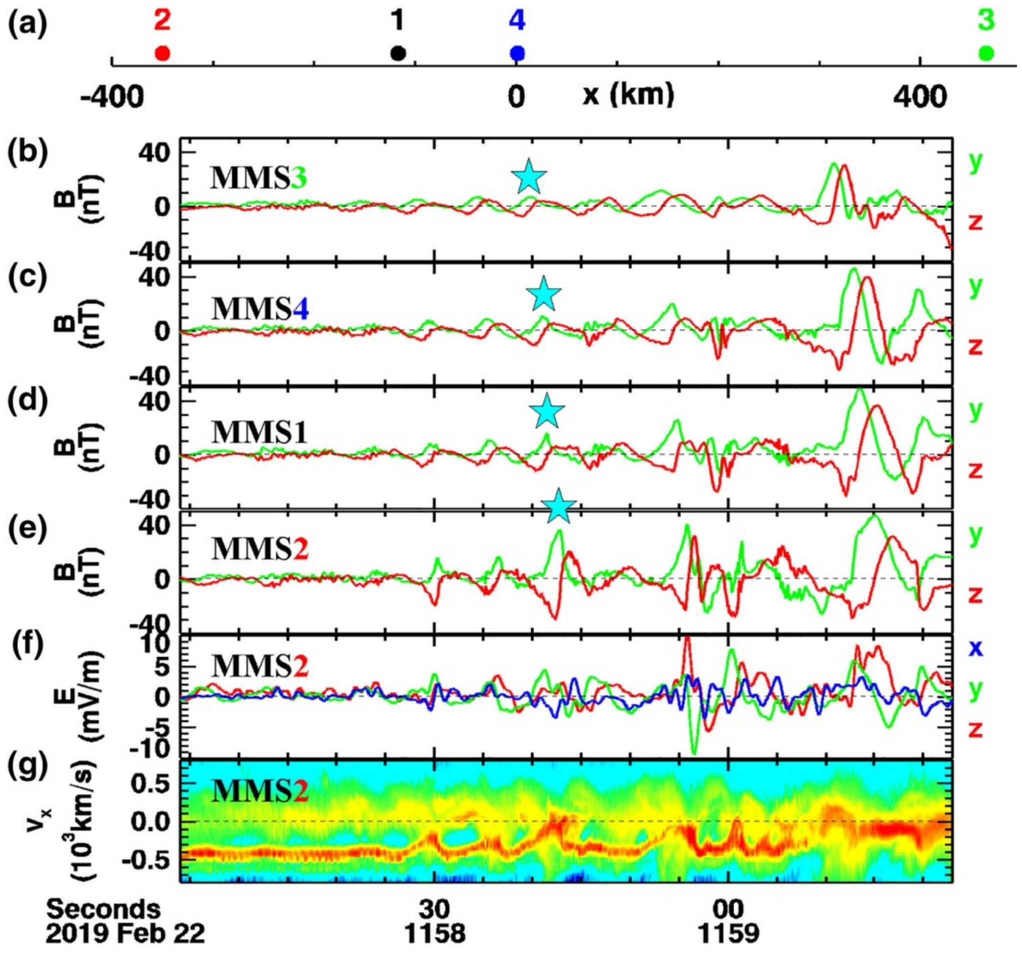
Courtesy of M. Palmroth, U Helsinki



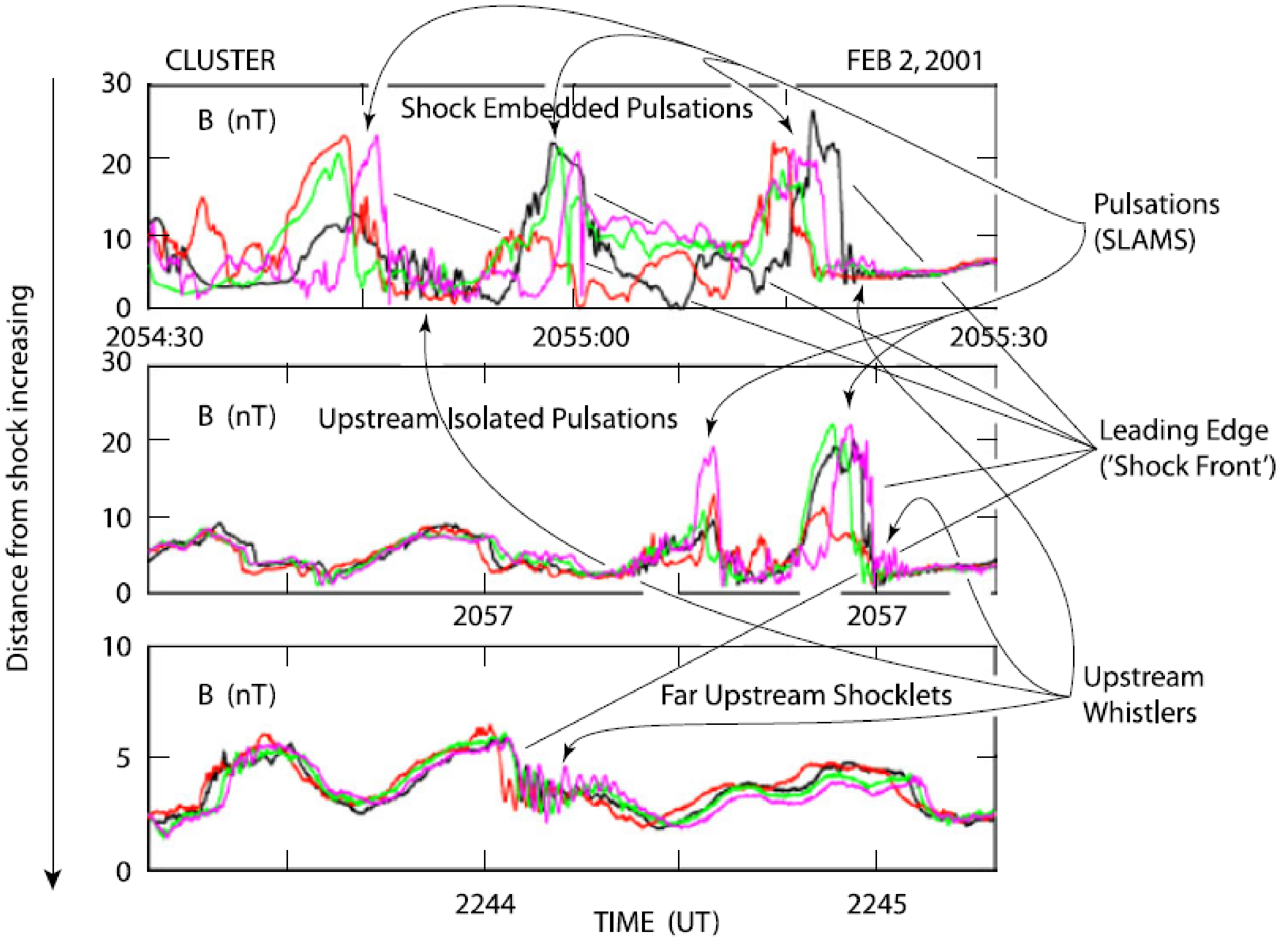
L. B. Wilson (2016)

Foreshock & evolution of ULF wavefield

MMS



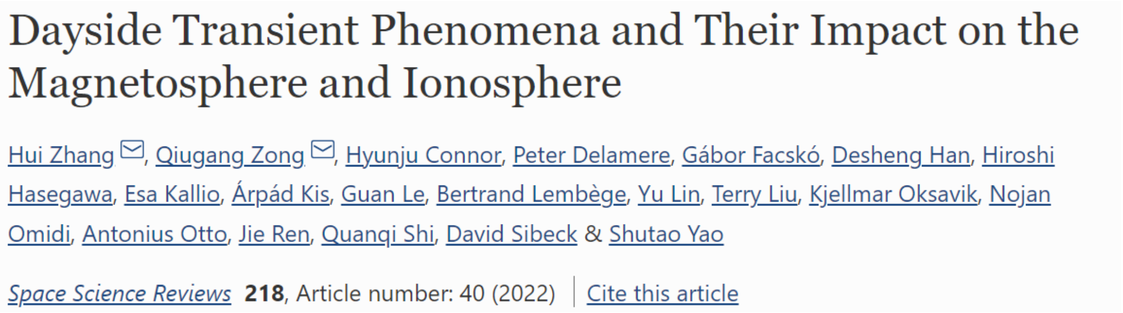
Cluster



Chen et al. 2021

Lucek et al, 2002

Why do we care? “big picture”



Dayside Transient Phenomena and Their Impact on the Magnetosphere and Ionosphere

Hui Zhang, Qiugang Zong, Hyunju Connor, Peter Delamere, Gábor Facskó, Desheng Han, Hiroshi Hasegawa, Esa Kallio, Árpád Kis, Guan Le, Bertrand Lembège, Yu Lin, Terry Liu, Kjellmar Oksavik, Nojan Omidi, Antonius Otto, Jie Ren, Quanqi Shi, David Sibeck & Shutao Yao

Space Science Reviews **218**, Article number: 40 (2022) | Cite this article

Transmission of foreshock waves through Earth’s bow shock

L. Turc, O. W. Roberts, D. Verscharen, A. P. Dimmock, P. Kajdič, M. Palmroth, Y. Pfau-Kempf, A. Johlander, M. Dubart, E. K. J. Kilpua, J. Soucek, K. Takahashi, N. Takahashi, M. Battarbee & U. Ganse

Nature Physics (2022) | Cite this article

Downstream high-speed plasma jet generation as a direct consequence of shock reformation

Savvas Raptis, Tomas Karlsson, Andris Vaivads, Craig Pollock, Ferdinand Plaschke, Andreas Johlander, Henriette Trollvik & Per-Arne Lindqvist

Nature Communications **13**, Article number: 598 (2022) | Cite this article

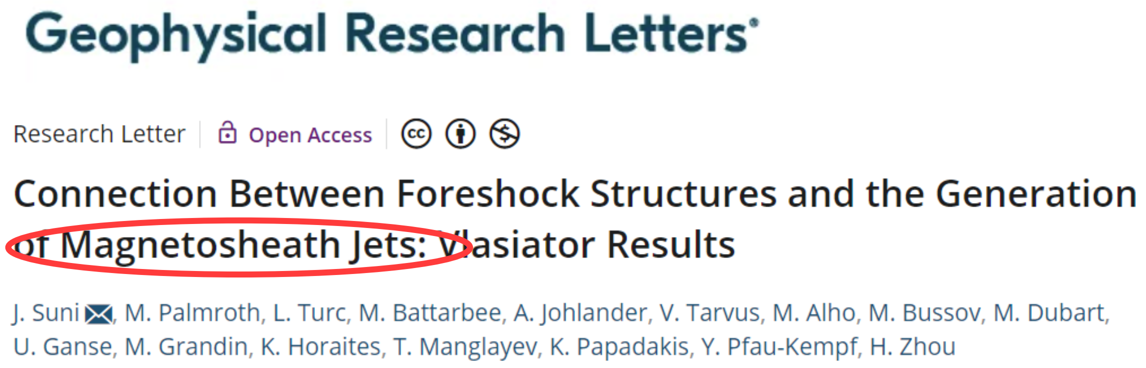
Geophysical Research Letters

Research Letter | Free Access

Investigating the Role of Magnetosheath High-Speed Jets in Triggering Dayside Ground Magnetic Ultra-Low Frequency Waves

Boyi Wang, Yukitoshi Nishimura, Heli Hietala, Vassilis Angelopoulos

First published: 07 November 2022 | https://doi.org/10.1029/2022GL099768

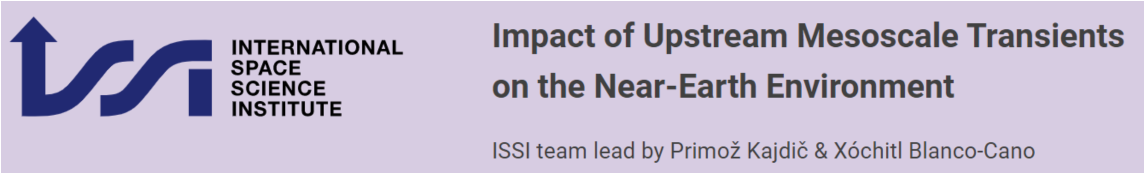


Geophysical Research Letters

Research Letter | Open Access

Connection Between Foreshock Structures and the Generation of Magnetosheath Jets: Vlasiator Results

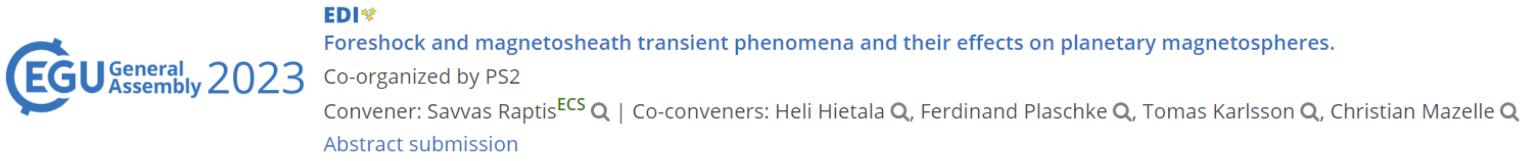
J. Suni, M. Palmroth, L. Turc, M. Battarbee, A. Johlander, V. Tarvus, M. Alho, M. Bussov, M. Dubart, U. Ganse, M. Grandin, K. Horaites, T. Manglayev, K. Papadakis, Y. Pfau-Kempf, H. Zhou



INTERNATIONAL SPACE SCIENCE INSTITUTE

Impact of Upstream Mesoscale Transients on the Near-Earth Environment

ISSI team lead by Primož Kajdič & Xóchitl Blanco-Cano



EGU General Assembly 2023

EDI

Foreshock and magnetosheath transient phenomena and their effects on planetary magnetospheres.

Co-organized by PS2

Convener: Savvas Raptis ECS | Co-conveners: Heli Hietala, Ferdinand Plaschke, Tomas Karlsson, Christian Mazelle

Abstract submission

Foreshocks Across The Heliosphere: System Specific Or Universal Physical Processes?

ISSI Team led by H. Hietala (UK) & F. Plaschke (AT)

(skipping the real scientific reason, i.e., plasma, shock physics, waves etc.)

Jets – references update (>2019)

Jets Downstream of Collisionless Shocks

Plaschke et al. (2018)

https://link.springer.com/article/10.1007/s11214-018-0516-3

Associated phenomena & effects

- **Excitation** of surface **eigenmodes** at magnetopause: Archer et al. (2019, 2021)
- **Mirror mode waves** and jets**:** Bianco-Cano et al. (2020)
- Bursty **magnetic reconnection** at the Earth's magnetopause: Ng et al. (2021)
- **Ground-based magnetometer** response: Norenius et al. (2021)
- Generation **of Pi2 pulsations**: Katsavrias et al. (2021)
- B in jets, **Bz variations near magnetopause**: Vuorinen et al. (2021)
- High-Speed Jets **Triggering Dayside Ground ULF**: Wang et al (2022)

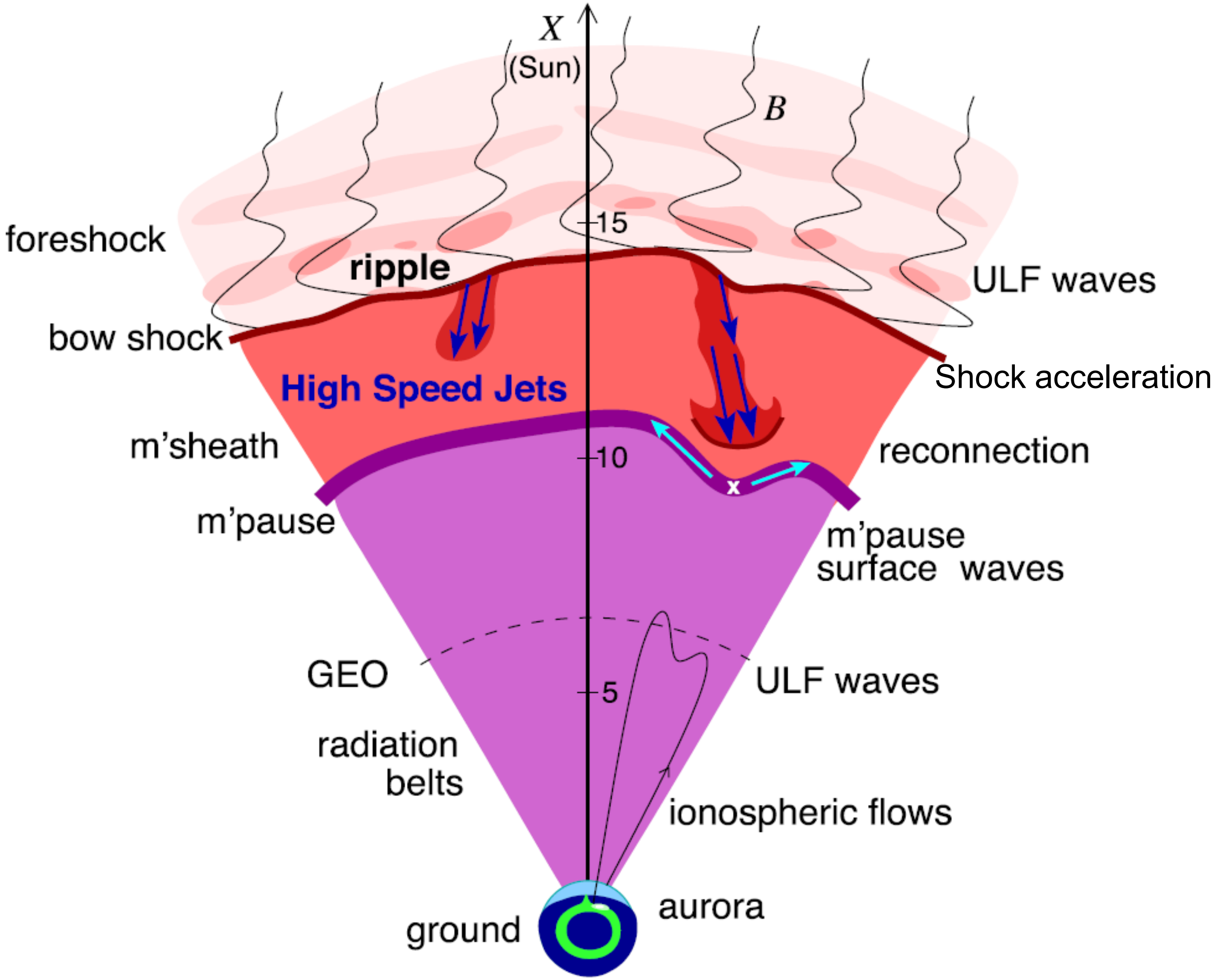
Modeling & formation

- **Velocity & magnetic field alignment** in jets**:** Plaschke et al. (2020)
- **Classification** of jets using MMS & Neural Networks: Raptis et al. (2020a,2020b)
- Comparison **MMS vs simulations**: Palmroth et al. (2021)
- **Solar wind effect** on jet formation: LaMoury et al. (2021)
- Magnetosheath Jets and **Plasmoids** - Hybrid Simulations: Preisser et al. (2020)
- **Formation** of jets in **Quasi-perpendicular magnetosheath**: Primoz et al. (2021)
- **Occurrence** in relation to **CMEs and SIRs**: Koller et al. (2022)
- **Shock reformation** and the **formation of high-speed jets**: Raptis et al. (2022a)
- **Electron acceleration** and **bow waves in** jets: Vuorinen et al. (2022)
- **Kinetic structure** of jets **and partial plasma moments**: Raptis et al. (2022b)

And more : Liu et al. (2020a,2020b), Omelchenko et al (2021), Sibeck et al. (2021), Suni et al. (2021), Tinoco-Arenas et al. (2022) … etc.

Magnetosheath high-speed jets

Magnetosheath jets effects



Plaschke F. et al. (2018); sketch by H. Hietala | Space Sci. Rev

Definition

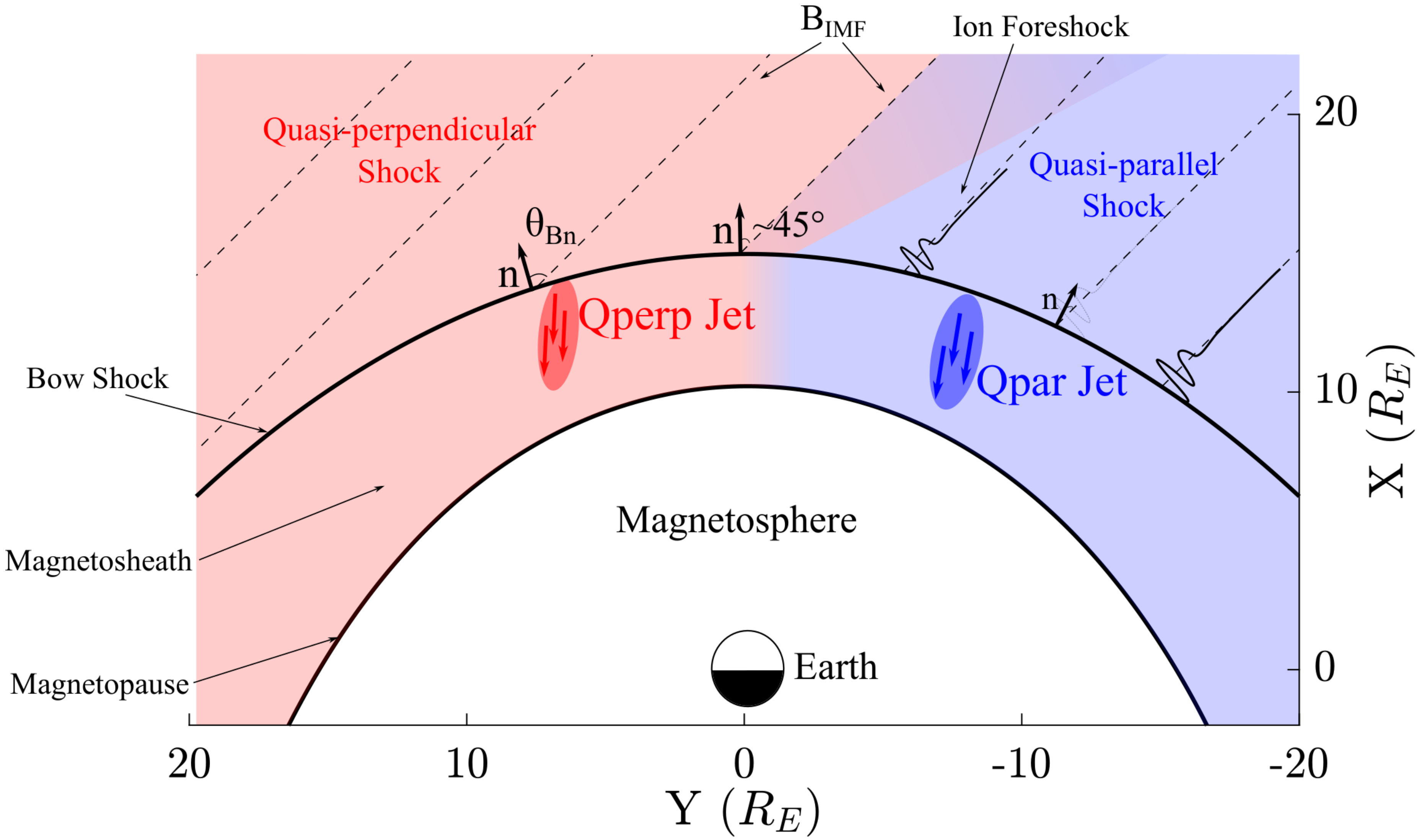
Magnetosheath jets are **transient localized enhancements** of **dynamic pressure** (density and/or velocity increase)

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

Shock, magnetosheath & jet classification

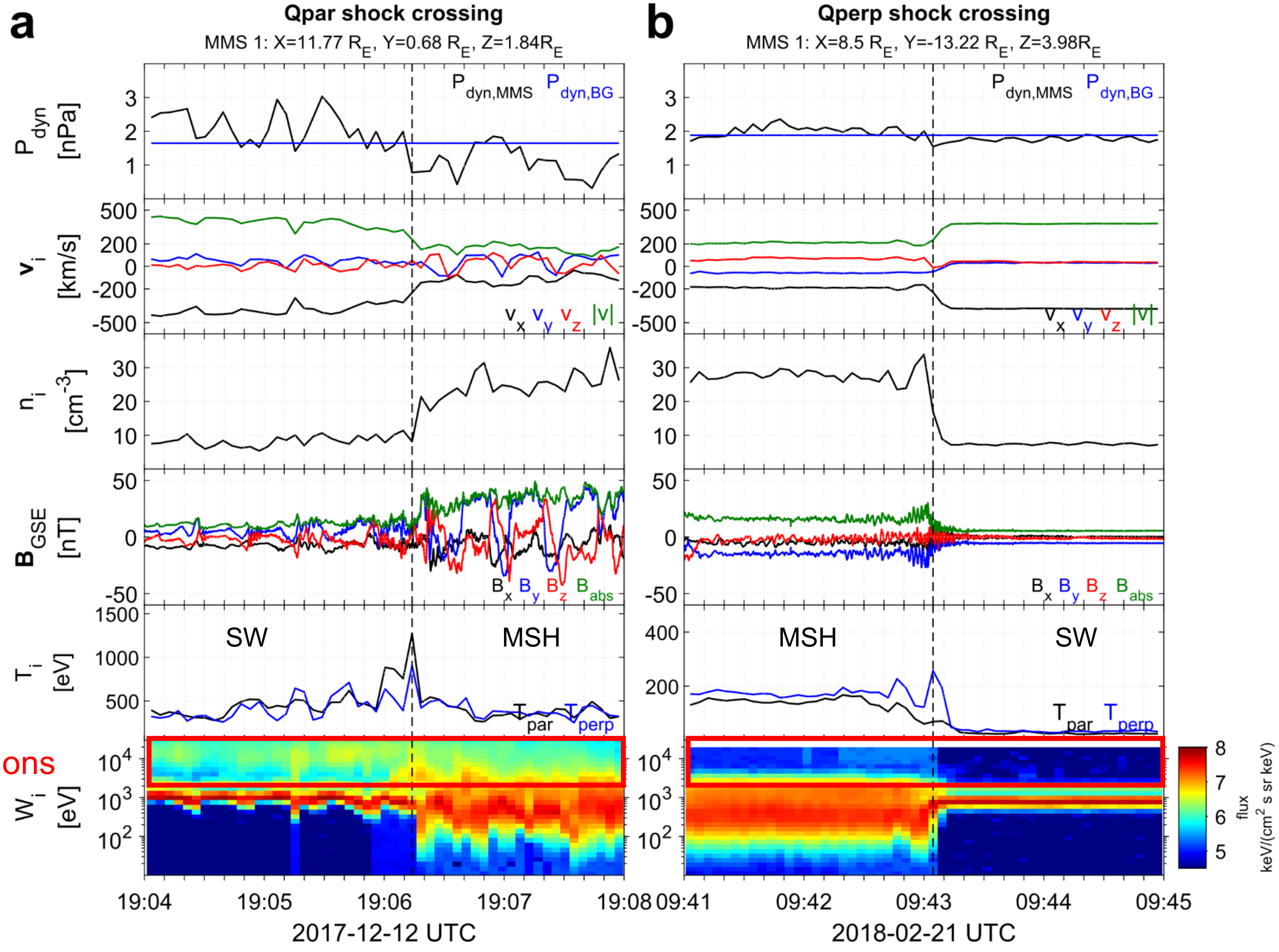


"Θ_{Bn} is the angle between the IMF and the shock's normal vector"

Qpar = $\Theta_{\text{Bn}} \lesssim 45°$
Qperp = $\Theta_{\text{Bn}} \gtrsim 45°$

Raptis, Aminalragia-Giamini et al. (2020) | Front. Astron. Space Sci

Shock transitions with MMS

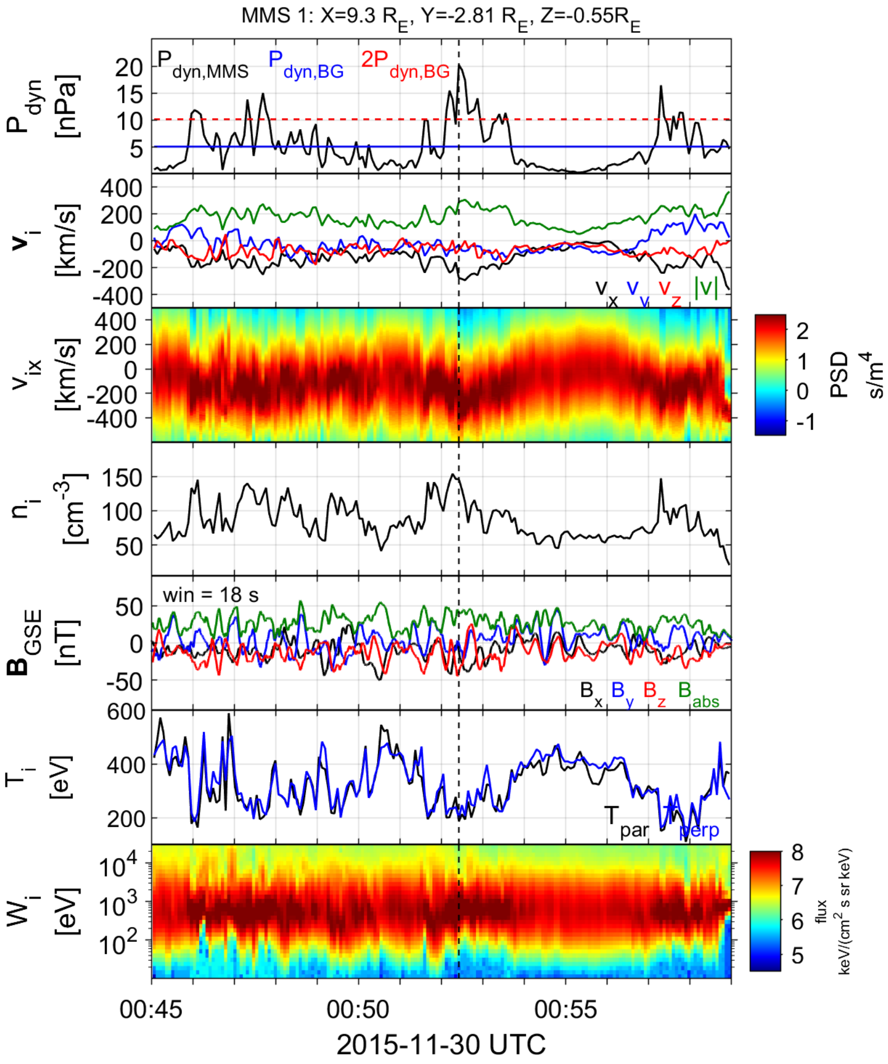


high-energy ions

Recent Results of Jets

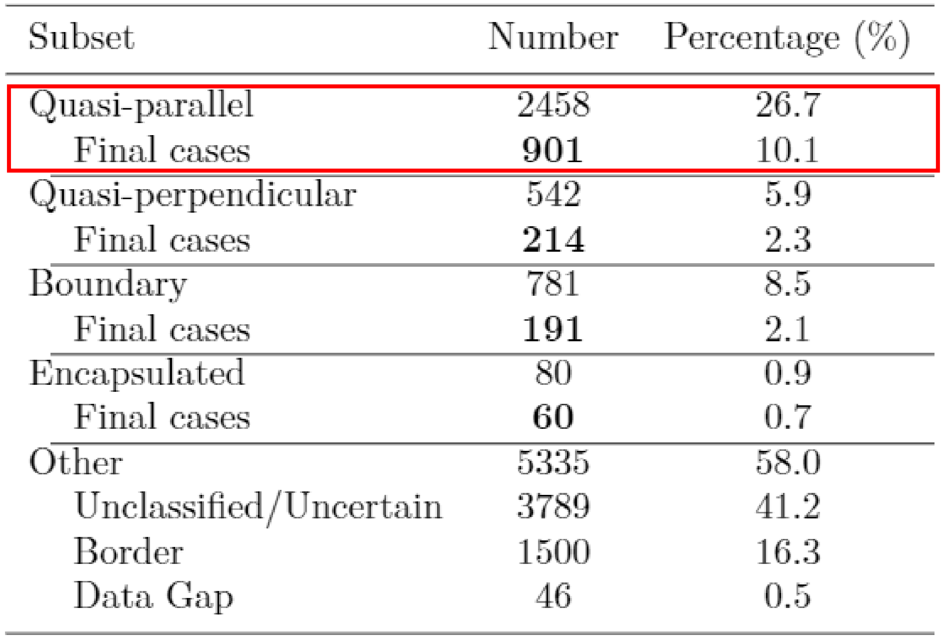
Summarized properties – Quasi parallel

- Most common
- High dynamic pressure
- Primarily Earthward
- Associated with low temperature (ΔT)
- Associated with high |B| & ΔB
- Δβ<0



Qpar Jet

Jets found in $Q_\parallel$ MSH

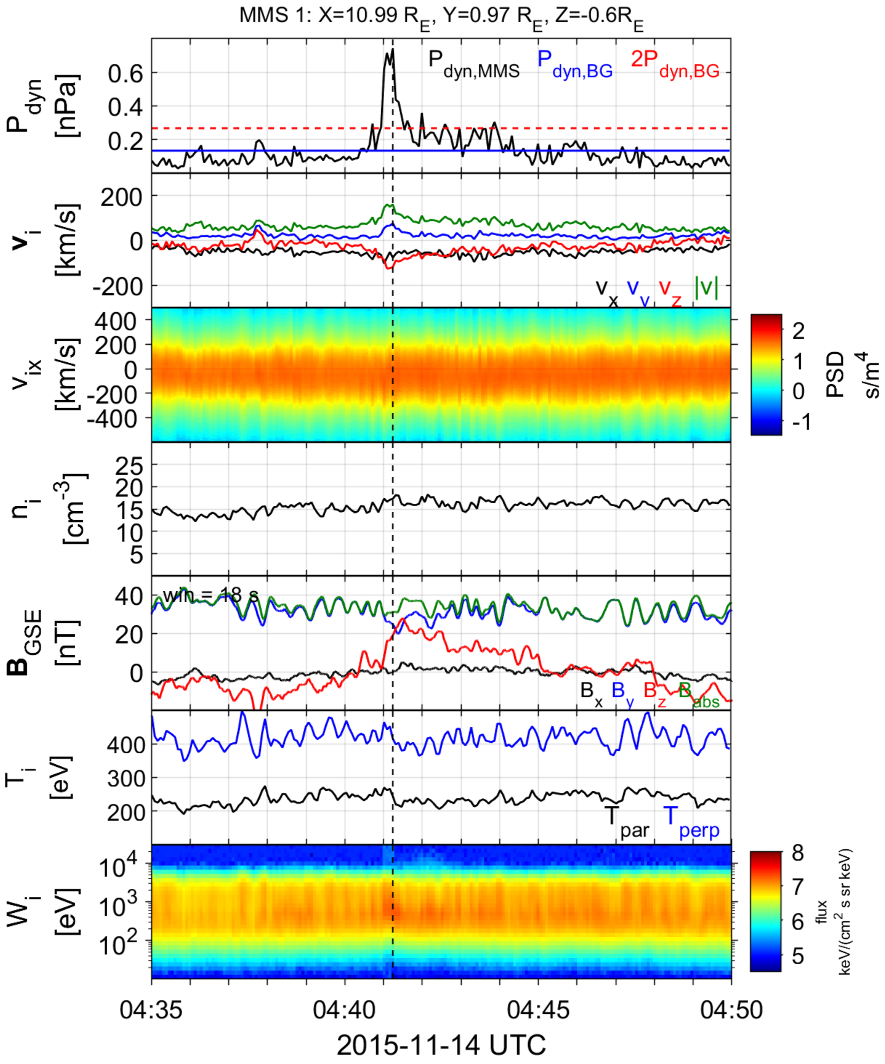


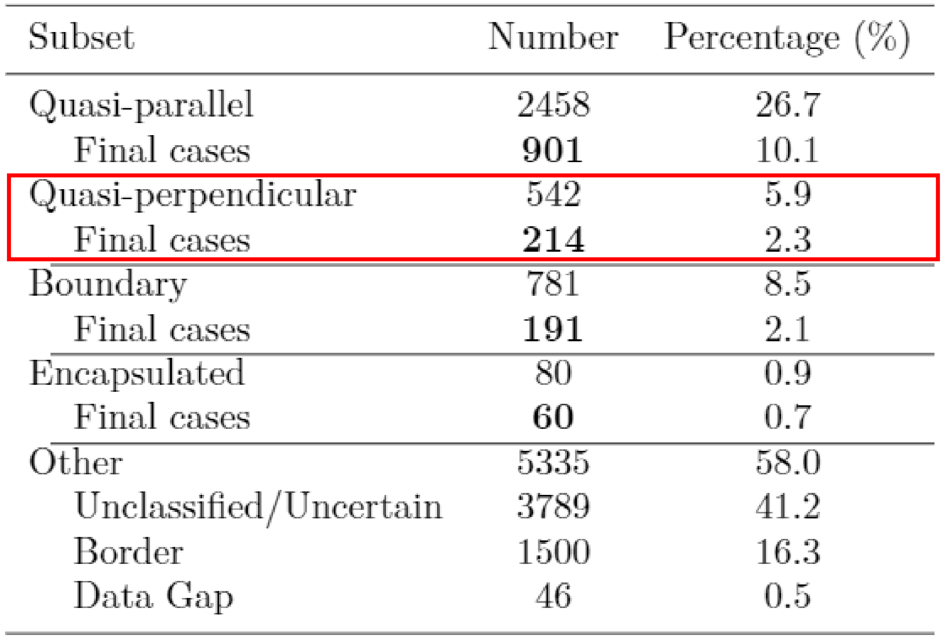
Subset	Number	Percentage (%)
Quasi-parallel	2458	26.7
Final cases	**901**	10.1
Quasi-perpendicular	542	5.9
Final cases	**214**	2.3
Boundary	781	8.5
Final cases	**191**	2.1
Encapsulated	80	0.9
Final cases	**60**	0.7
Other	5335	58.0
Unclassified/Uncertain	3789	41.2
Border	1500	16.3
Data Gap	46	0.5

Raptis S., Karlsson T., et al. (2020) | JGR

Summarized properties – Quasi perpendicular

- Less common
- Less Energetic
- Mainly velocity driven
- Very small duration (~4 sec)
- Could be connected to MSH reconnection, mirror mode waves or FTEs





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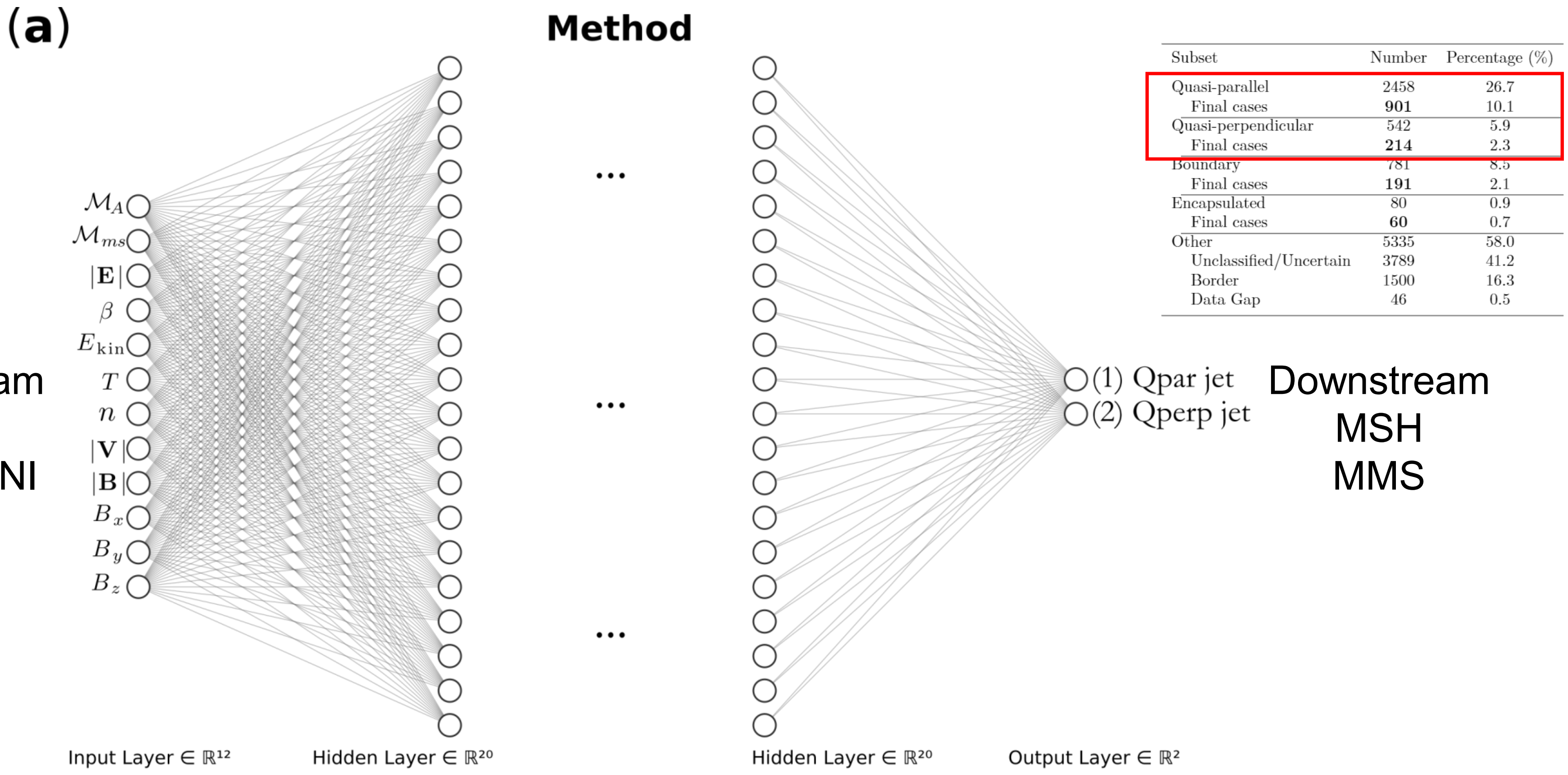
Qperp Jet

Jets found in $Q_\perp$MSH

Raptis S., Karlsson T., et al. (2020) | JGR

Classifying jets with Neural Networks



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Data Gap	46	0.5

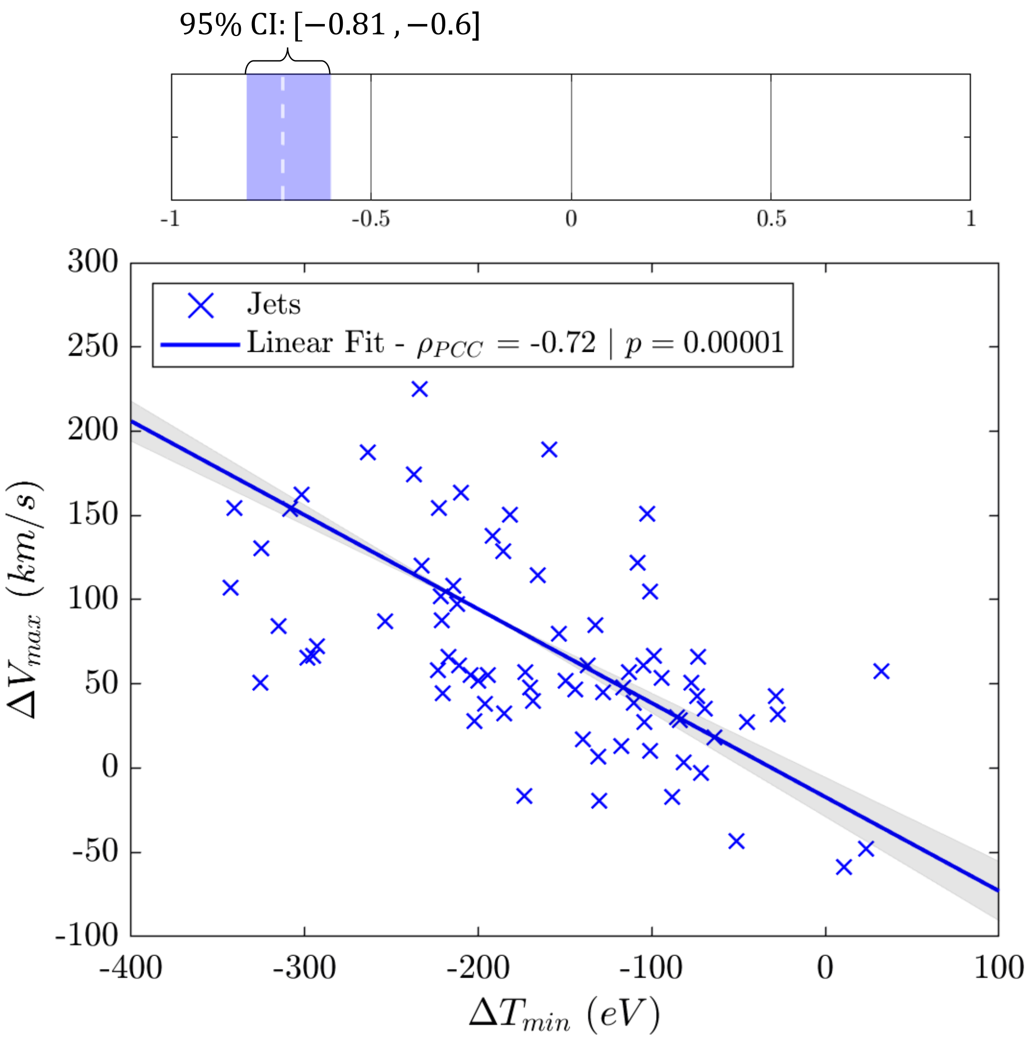
Upstream
SW
L1 OMNI

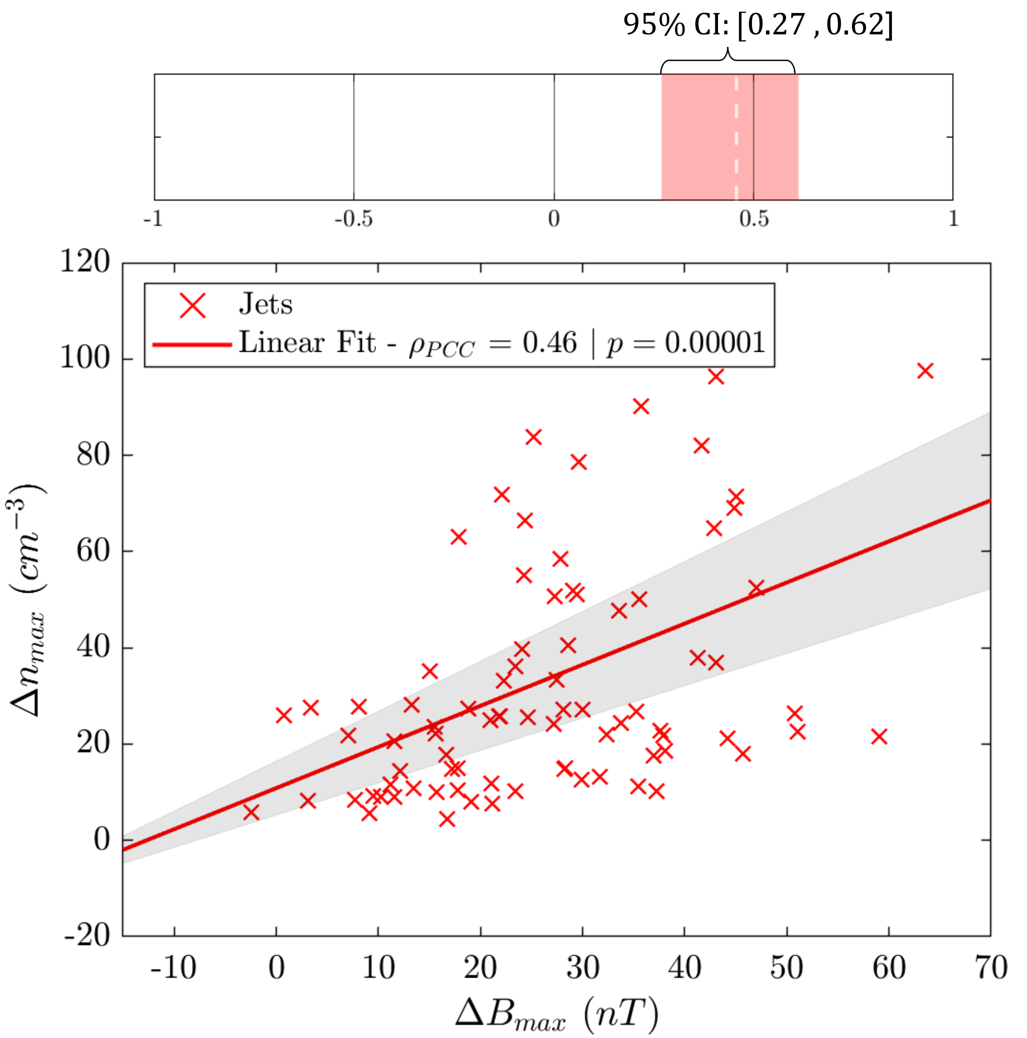
Downstream
MSH
MMS

Raptis, Aminalragia-Giamini et al. (2020) | Front. Astron. Space Sci

Example: statistics of subset close to bow shock

$n = 90$





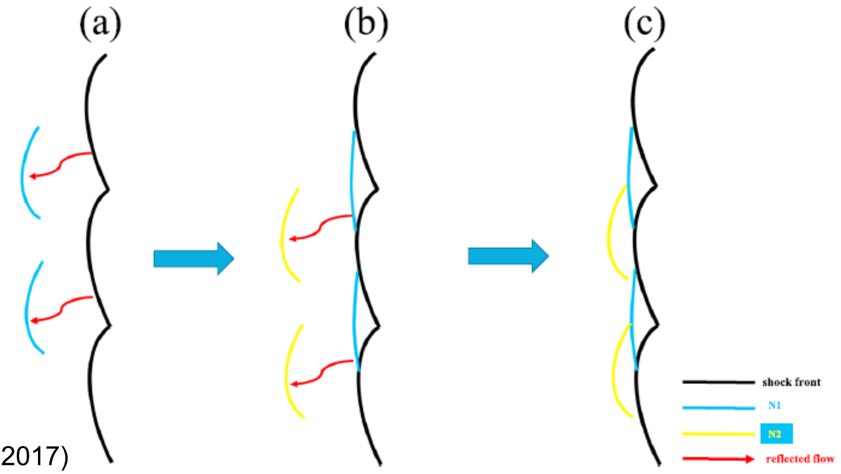
(unpublished data – Ongoing work)

Burst data of MMS

Shock global reformation

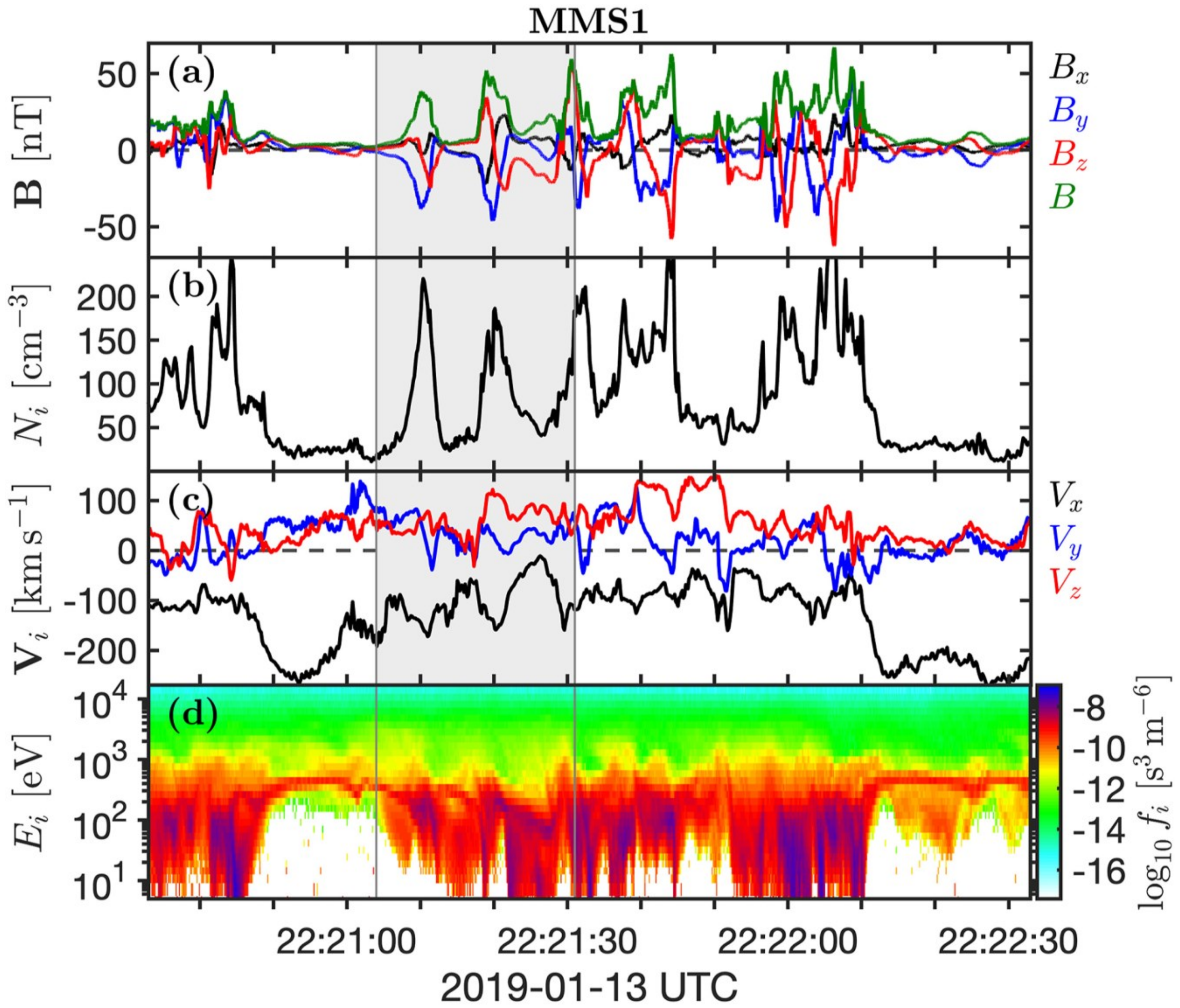
Shock Reformation

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



Hao et al. (2017)

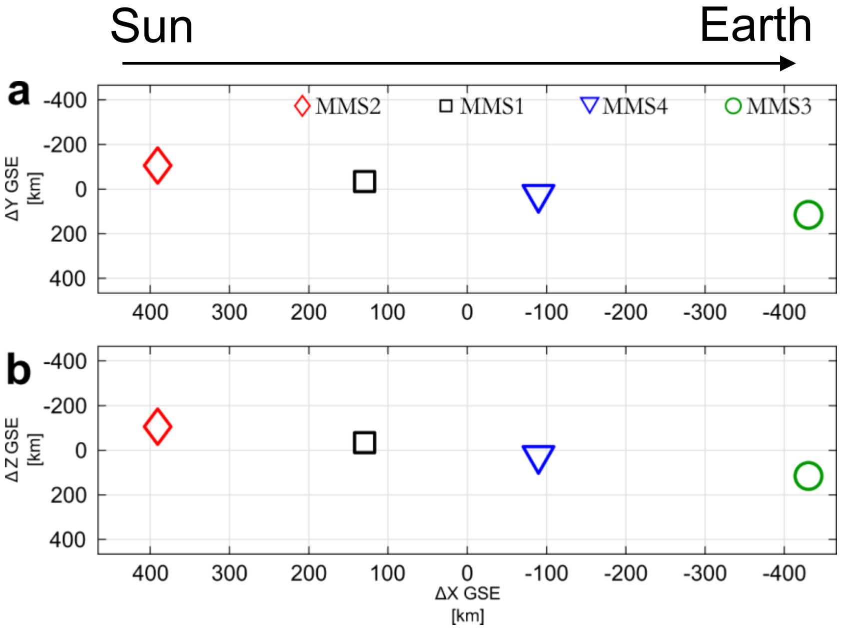
Figure 11. The sketch for evolution of shock front. (a) A rippled shock front, (b) a plane shock front, and (c) a rippled shock front. Solid lines and red arrows denote shock front and reflected beams, and N1 and N2 indicate new shock fronts.

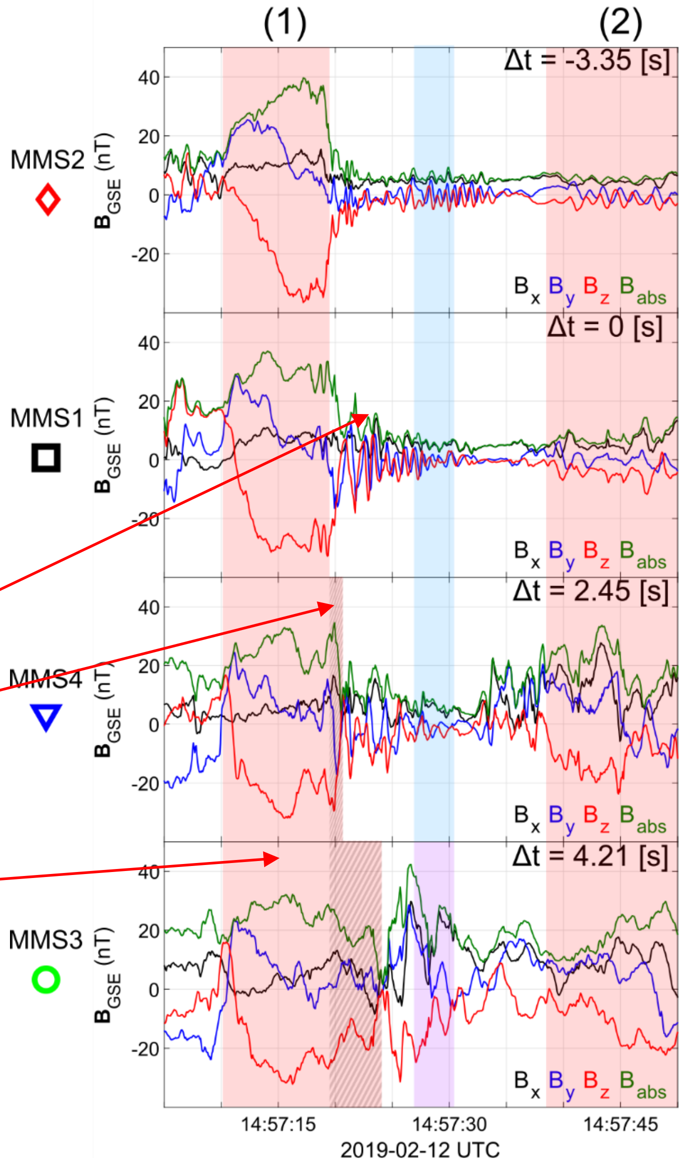


Similar definitions : Hao et al. (2016,2017), Liu et al. (2021), Johlander et al. (2022), Raptis et al. (2022a)

Johlander et al. (2022)

SLAMS – wave activity and reformation





Evolution of SLAMS

- Interaction with upstream whistler
- New peak /evolution*
- Formation of *downstream density enhancement***

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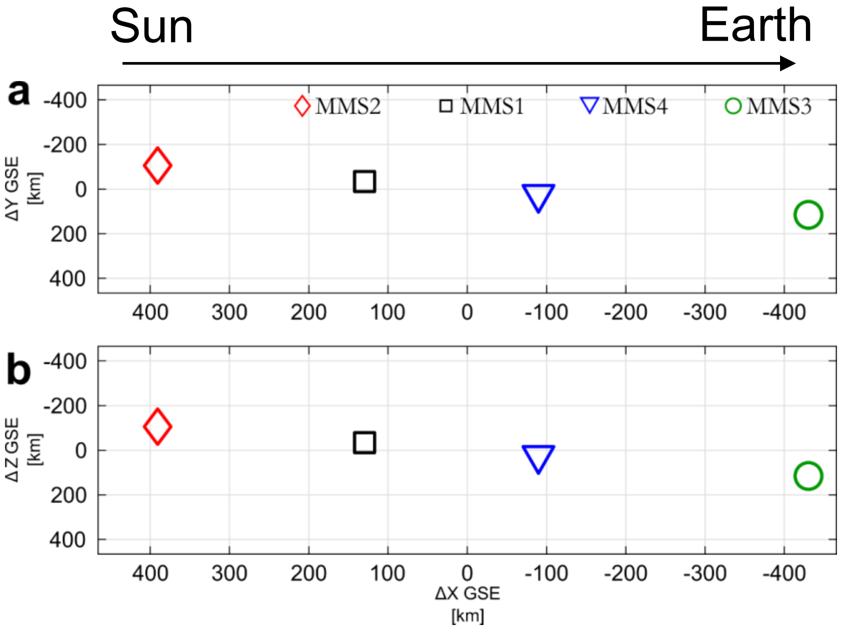
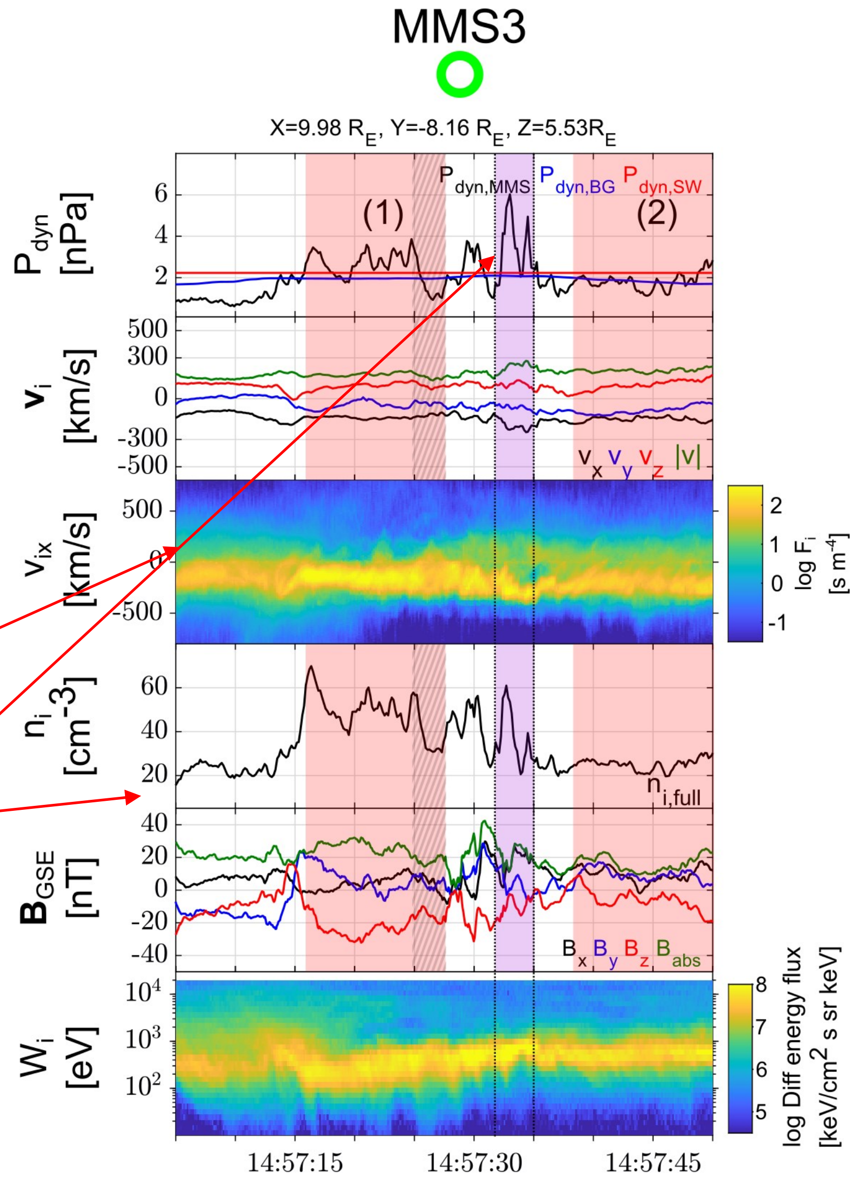
* See similar examples by Turner et al. (2021), Chen et al. (2021) | *(Self-) reformation*

** See similar example by Liu et al. (2021) | *(Global) reformation*

Jet “slipping through” the reformation cycle



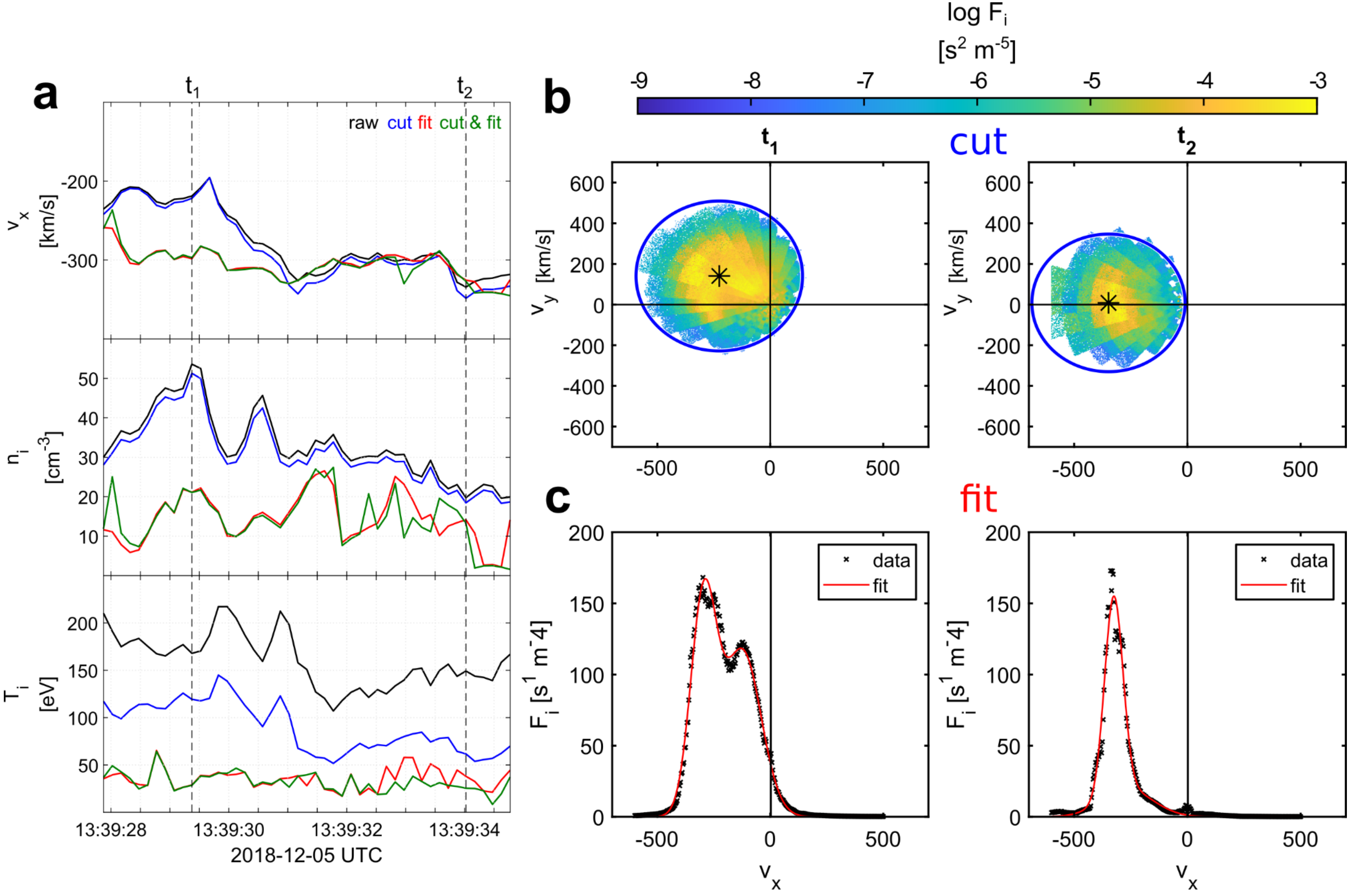


Properties

- Thermalized distribution
- Compression
- Dynamic pressure increase (i.e., increase in velocity and density)

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

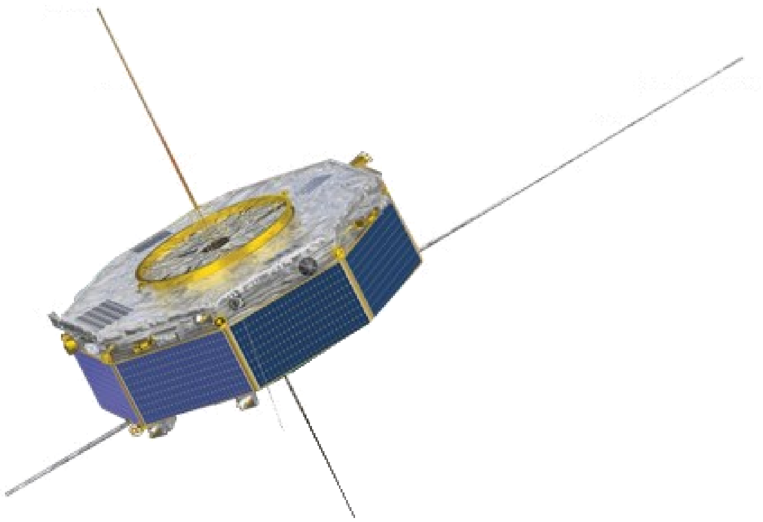
Partial moment derivation



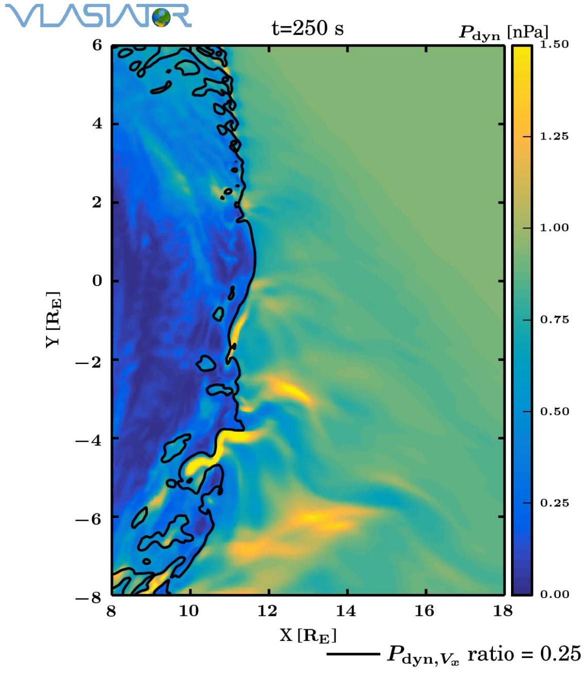
Methods:

- Cut : $1v_{th}$ sphere in 3D VDF around bulk velocity
- Fit : Fit 2 Maxwellians in 1D reduced VDFs

Raptis S, et al,. 2022b | GRL

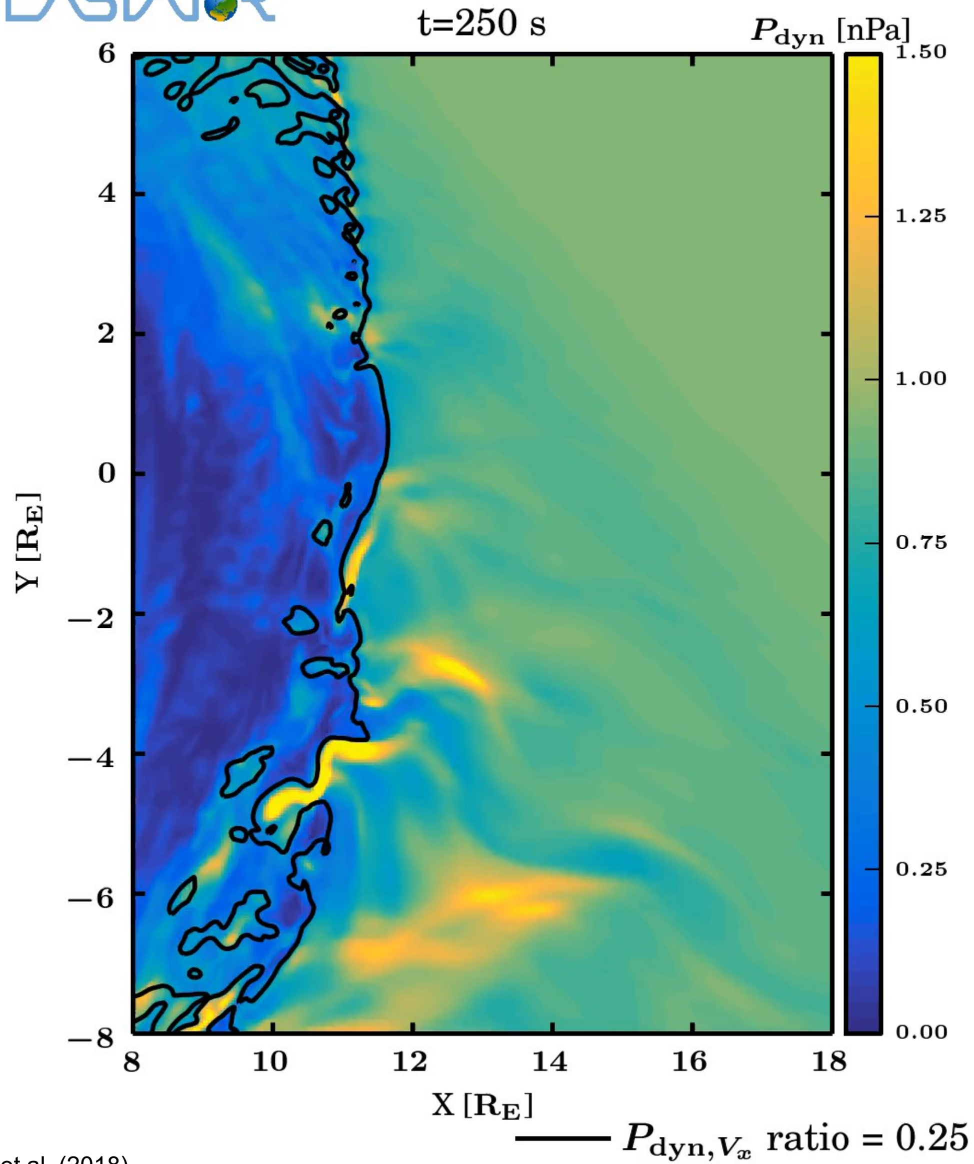


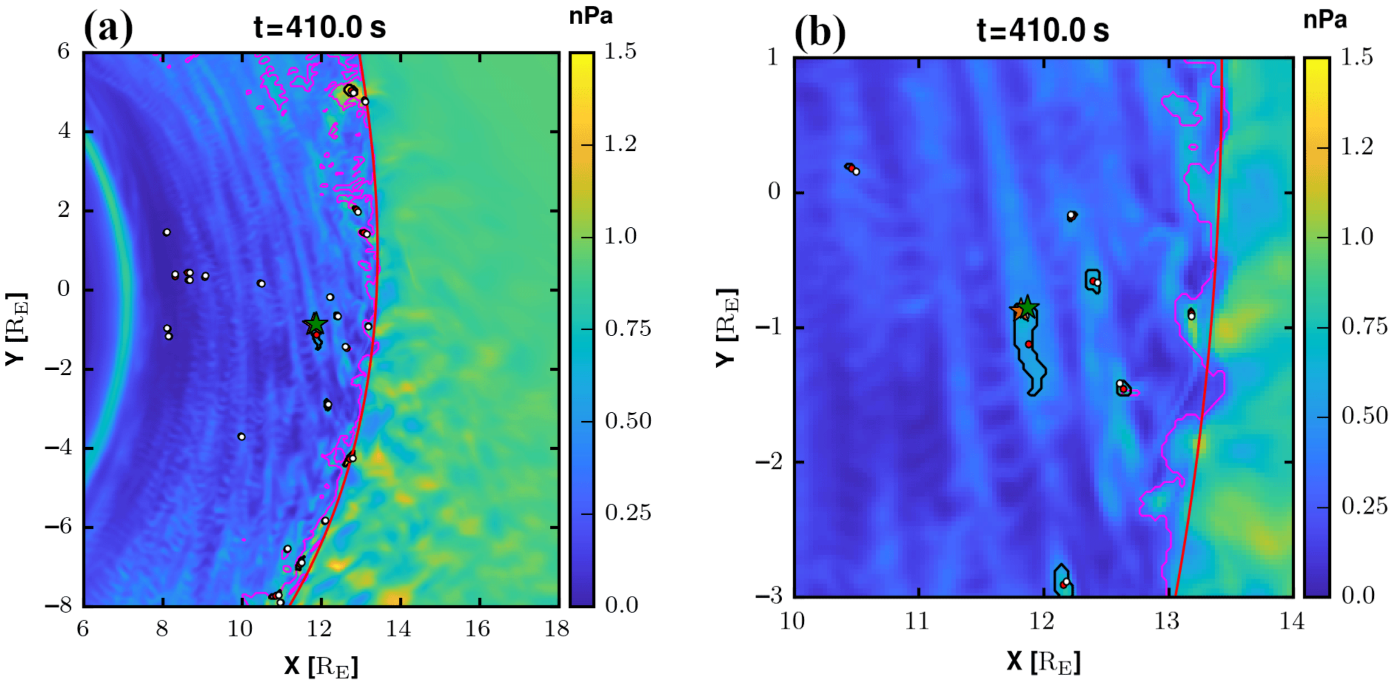
Comparison
MMS **vs** Vlasiator



Palmroth, M., **Raptis, S.,** et al. (2021). Magnetosheath jet evolution as a function of lifetime: global hybrid-Vlasov simulations compared to MMS observations, Ann. Geophys., 39, 289–308, doi:10.5194/angeo-39-289-2021

Jets in simulations





Palmroth, et al. (2018)
Palmroth, **Raptis** et al. (2021)

Case Comparison

Dynamic Pressure

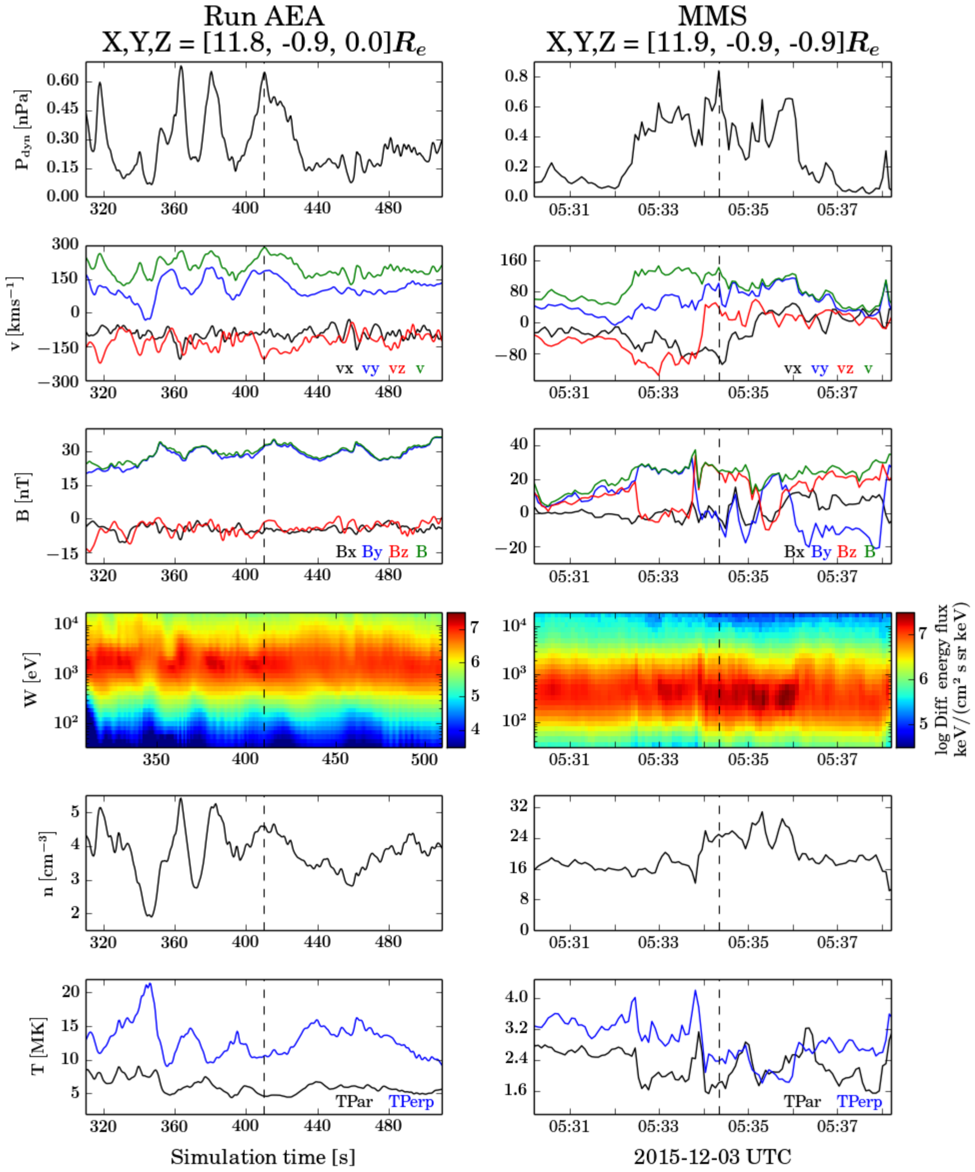
Velocity

Magnetic Field

Ion Energy Spectrum

Density

Temperature

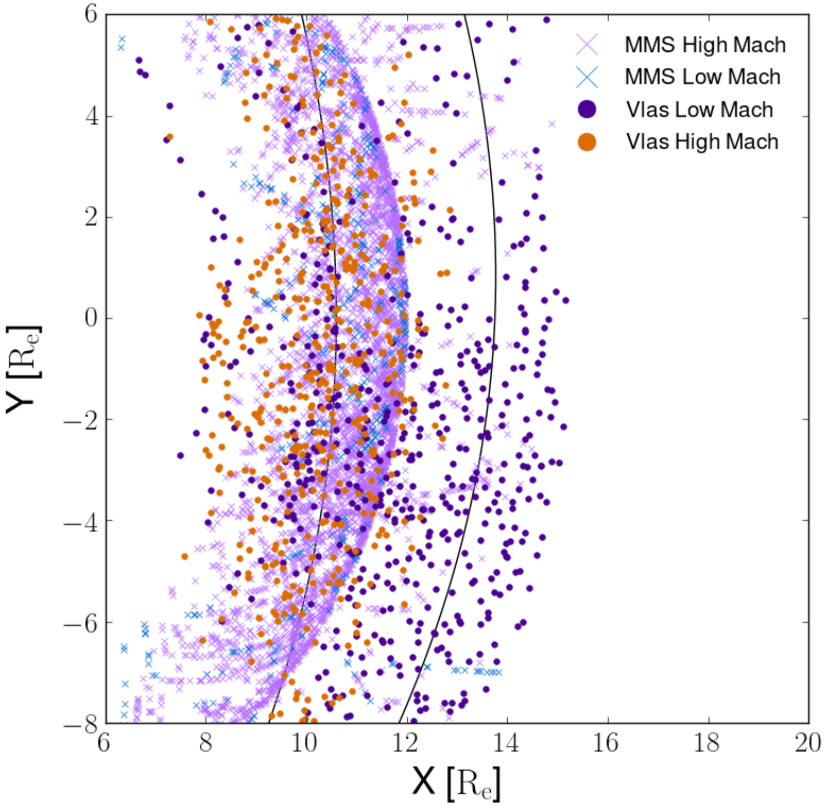


Palmroth M., **Raptis S.**, et al. (2021) | Annales

Run Details

	Jet search start [s]	Jet search stop [s]	Number of jets
Run HM30	290	419.5	144
Run HM05	290	589.5	293
Run LM30	290	669.5	368
Run LM05	290	439.5	119

	IMF [nT]	|IMF|	n [cm^{-3}]	v [km s^{-1}]	Cone [°]	M_A
HM30	(−4.3, 2.5, 0.0)	5	1	(−750, 0, 0)	30	6.9
HM05	(−5.0, 0.4, 0.0)	5	3.3	(−600, 0, 0)	5	10
LM30	(−8.7, 5.0, 0.0)	10	1	(−750, 0, 0)	30	3.4
LM05	(−10.0, 0.9, 0.0)	10	3.3	(−600, 0, 0)	5	5

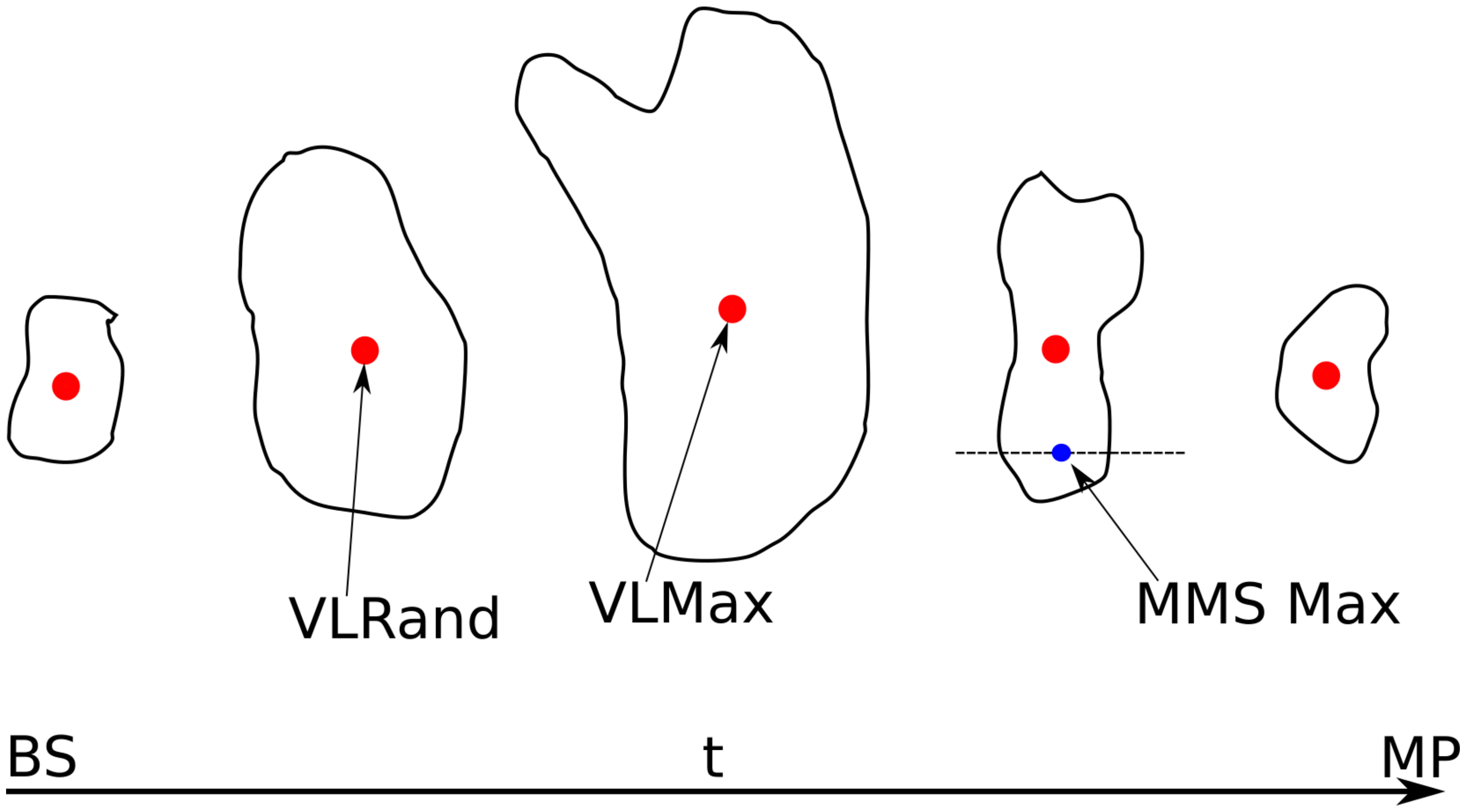


Palmroth M., **Raptis S.**, et al. (2021) | Annales

Limitations & some details

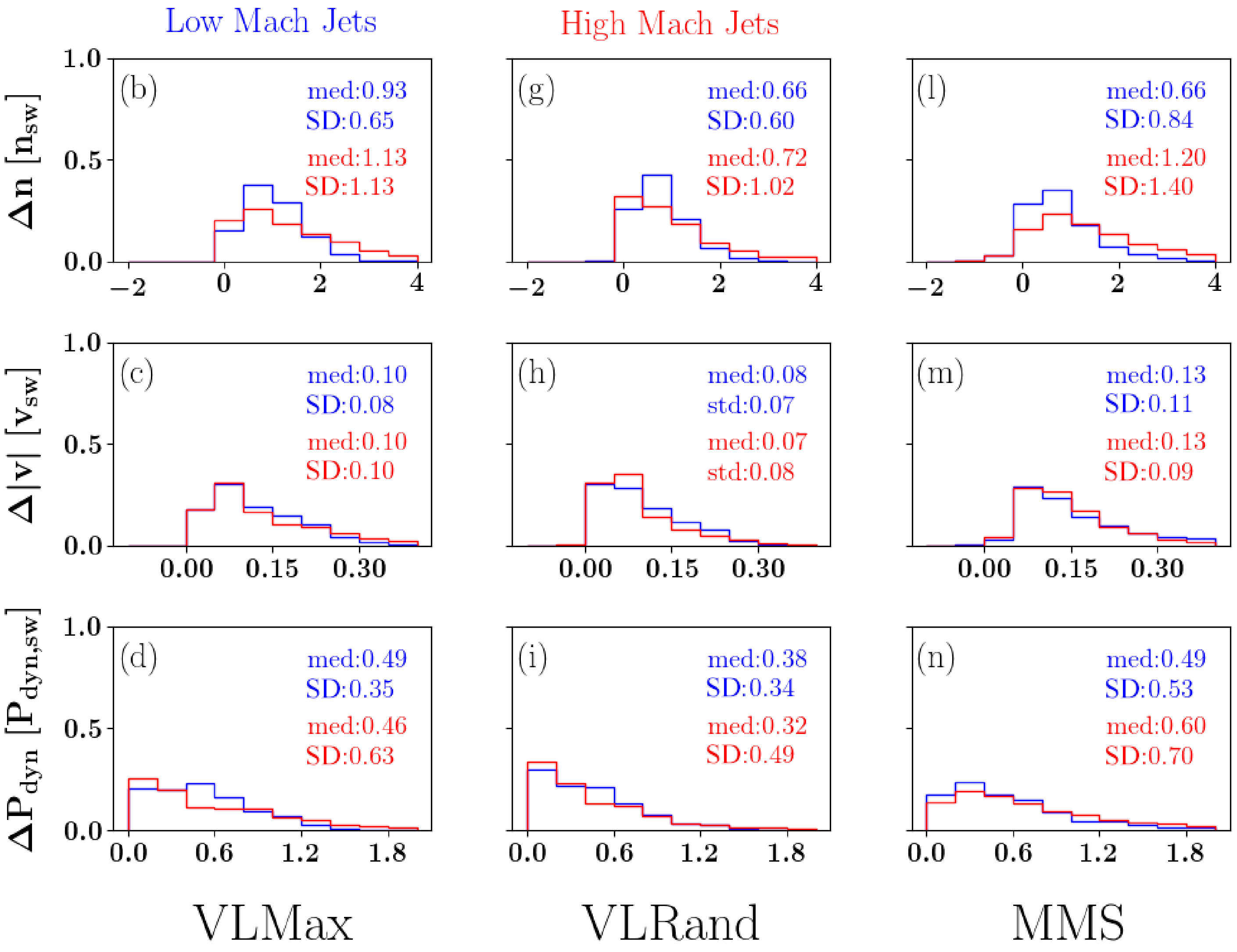
- BS position = Core population heated 3 times compared to SW
- 2D runs
- Electrons are massless charge-neutralizing fluid
- Temperature varies a lot during jets
- Jet is regarded the same if 50% of cells are the same during previous time step.
- Grid size: 30 km/s and 227 km

Main differences between MMS & Vlasiator



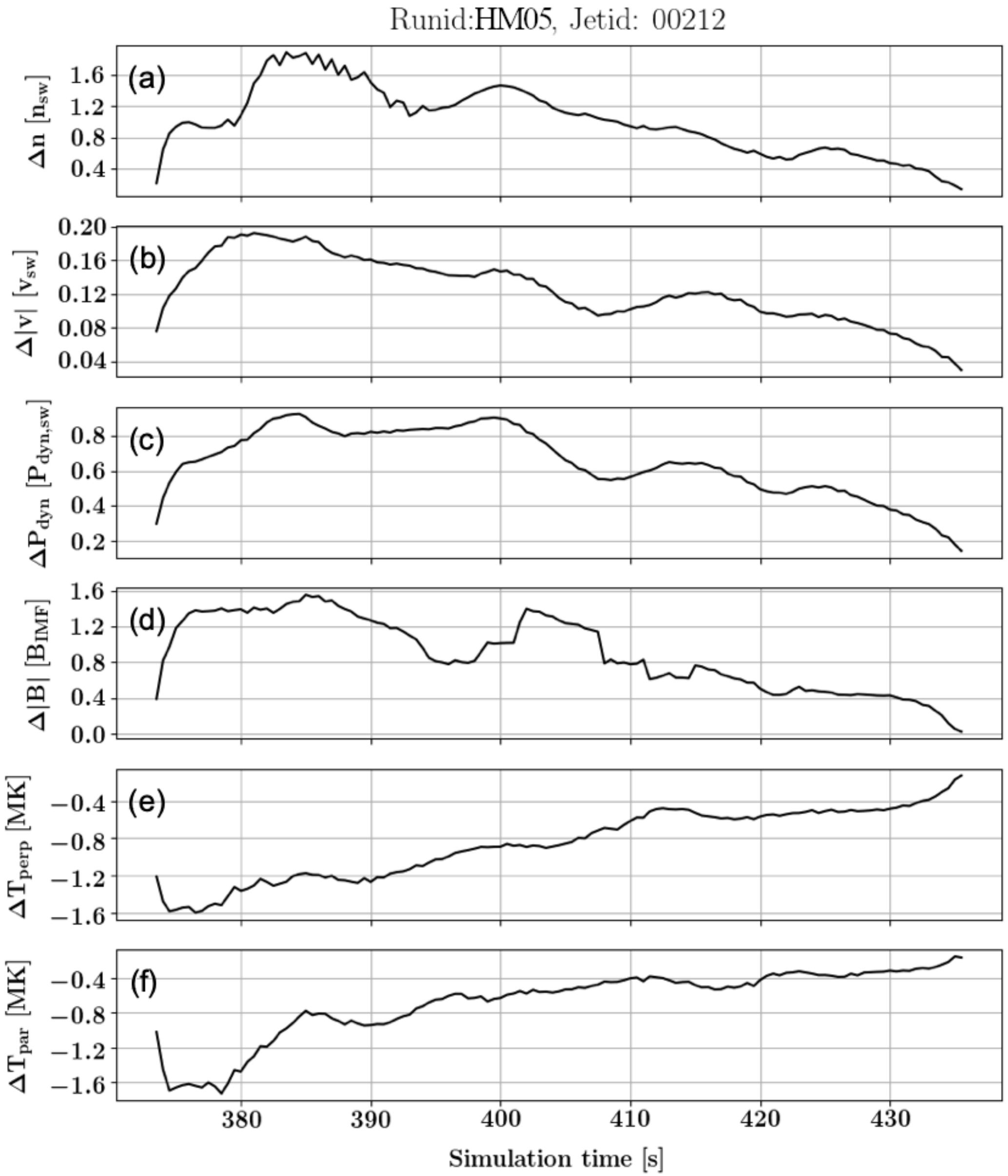
Palmroth M., **Raptis S.**, et al. (2021) | Annales

Comparison MMS & Vlasiator



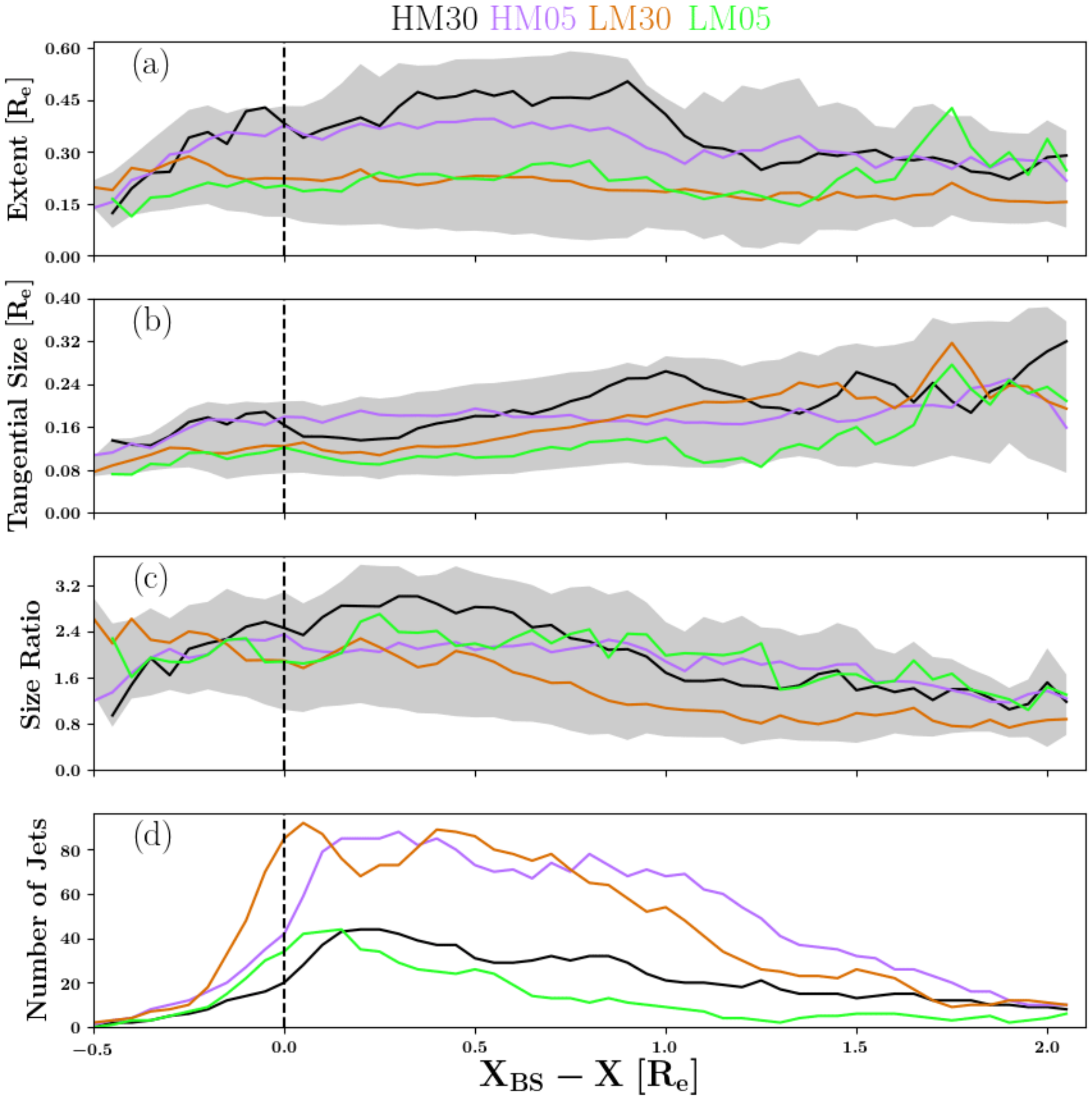
Palmroth M., **Raptis S.**, et al. (2021) | Annales

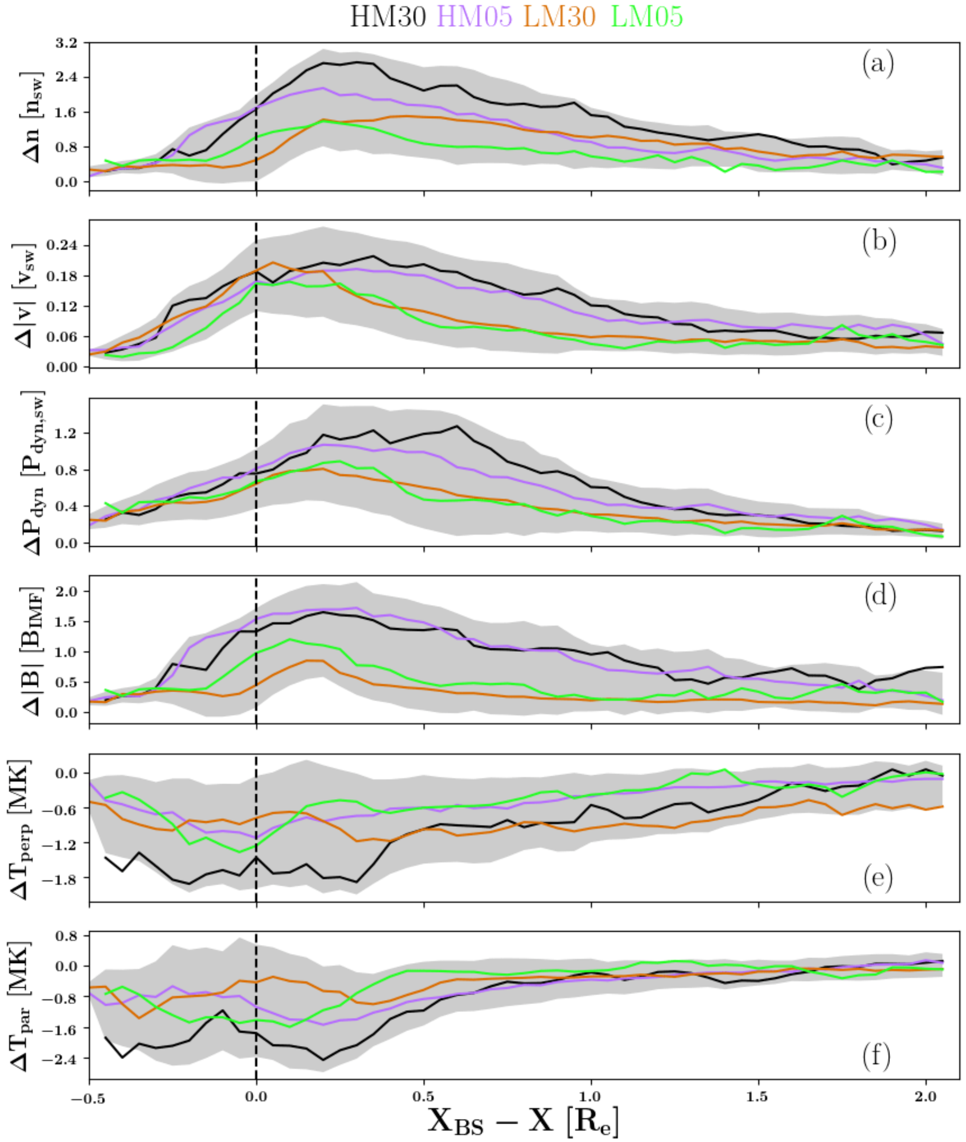
An evolution of a jet using Vlasiator



Palmroth M., **Raptis S**., et al. (2021) | Annales

Superposed Epoch Analysis Vlasiator





Palmroth M., **Raptis S.**, et al. (2021) | Annales

MMS – Finalized Jet Database

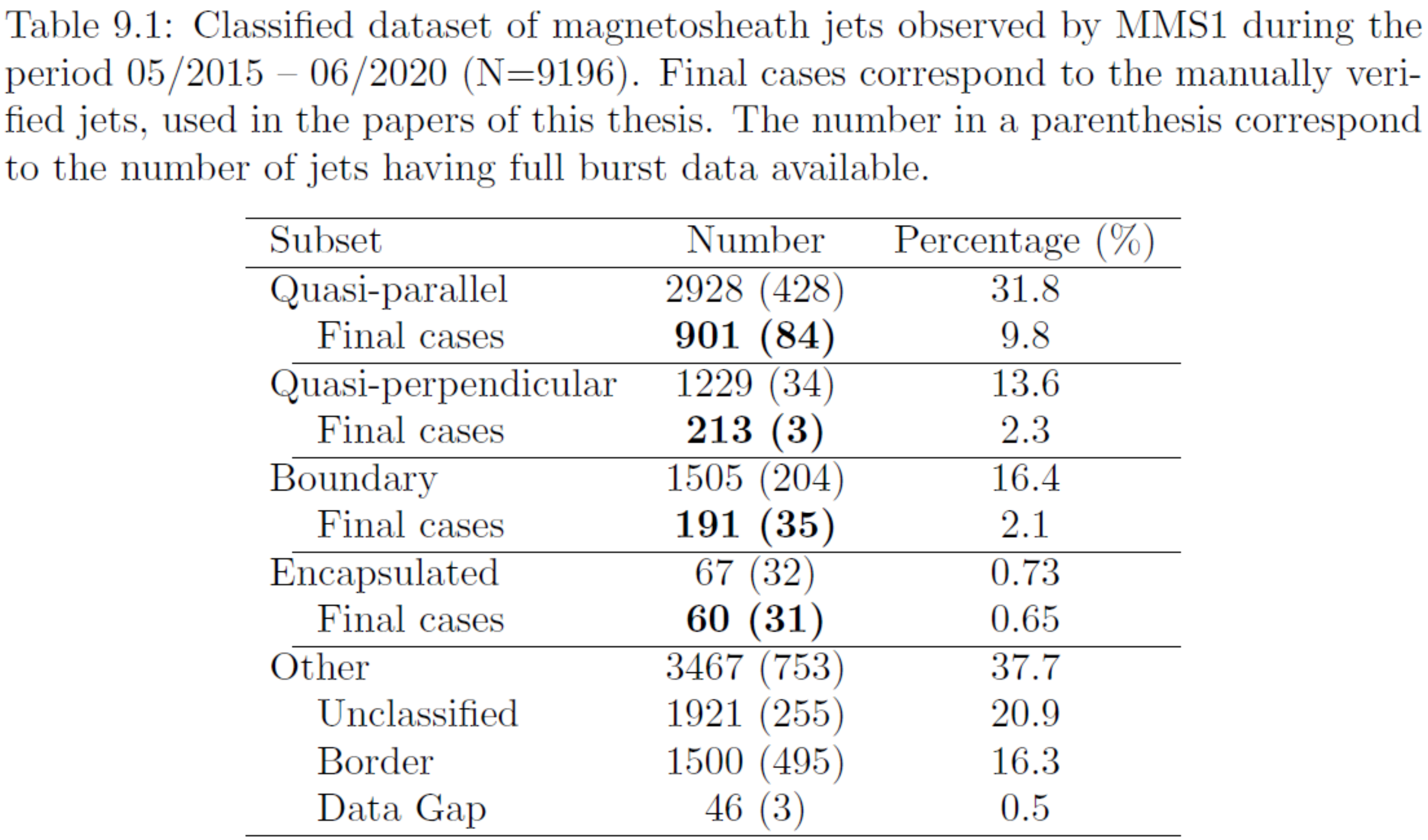


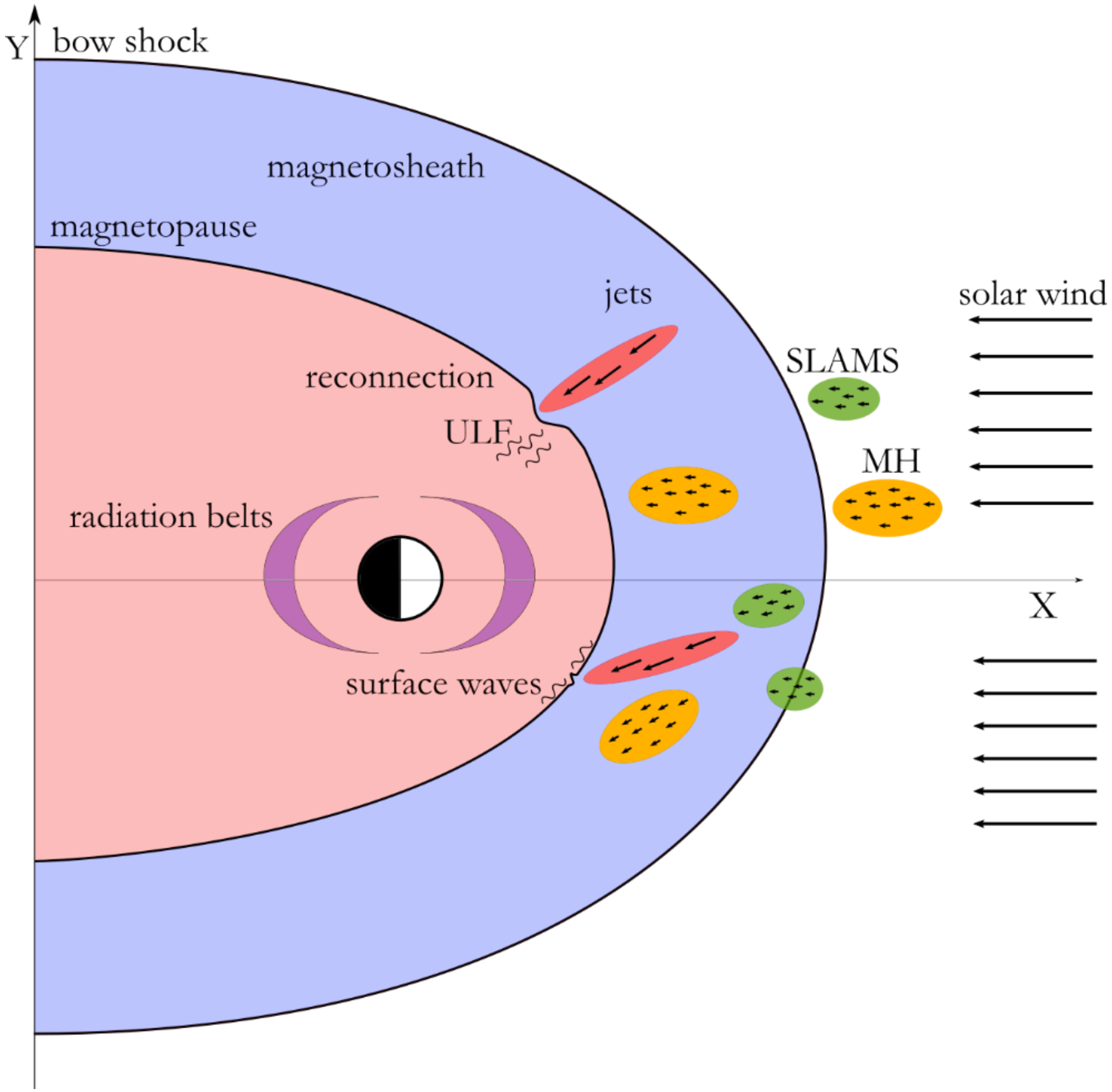
Table 9.1: Classified dataset of magnetosheath jets observed by MMS1 during the period 05/2015 – 06/2020 (N=9196). Final cases correspond to the manually verified jets, used in the papers of this thesis. The number in a parenthesis correspond to the number of jets having full burst data available.

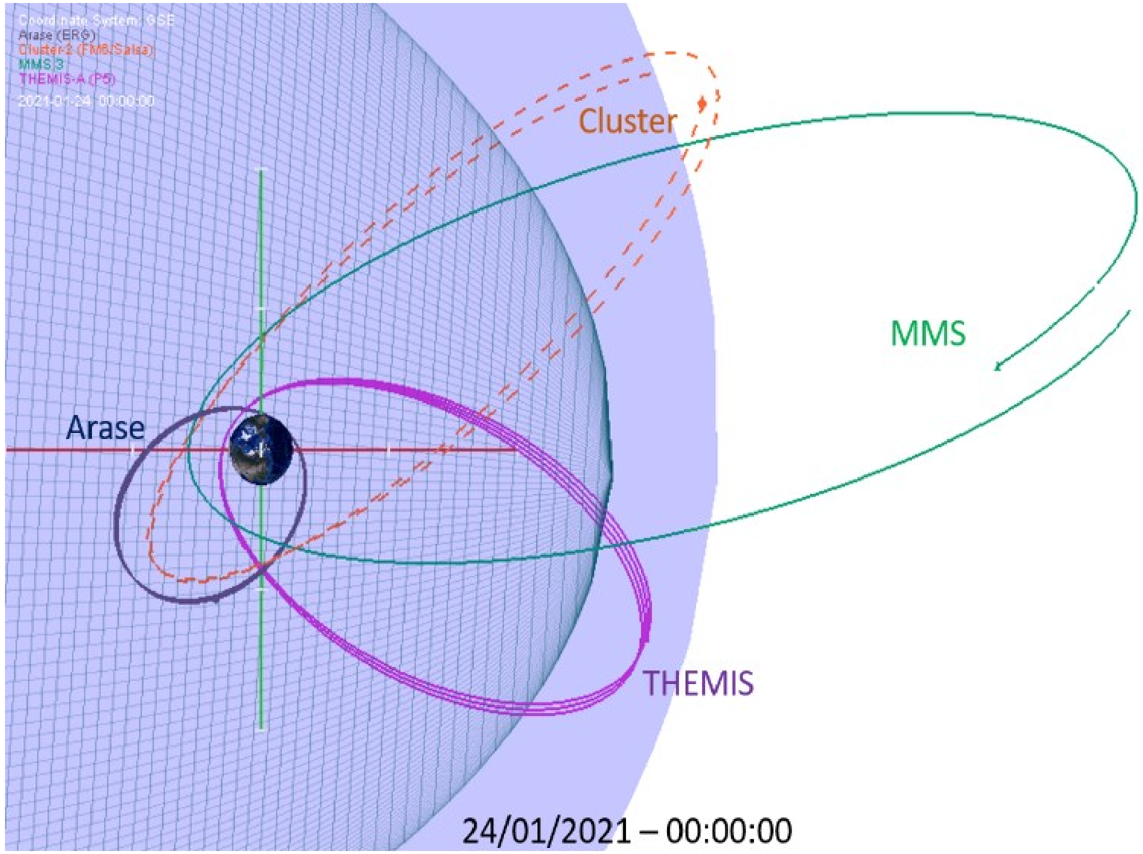
Subset	Number	Percentage (%)
Quasi-parallel	2928 (428)	31.8
Final cases	**901 (84)**	9.8
Quasi-perpendicular	1229 (34)	13.6
Final cases	**213 (3)**	2.3
Boundary	1505 (204)	16.4
Final cases	**191 (35)**	2.1
Encapsulated	67 (32)	0.73
Final cases	**60 (31)**	0.65
Other	3467 (753)	37.7
Unclassified	1921 (255)	20.9
Border	1500 (495)	16.3
Data Gap	46 (3)	0.5

https://zenodo.org/record/7085778

Thesis: High-speed jets and related phenomena at Earth's bow shock and magnetosheath

A lot of data are not fully used (conjunction example)

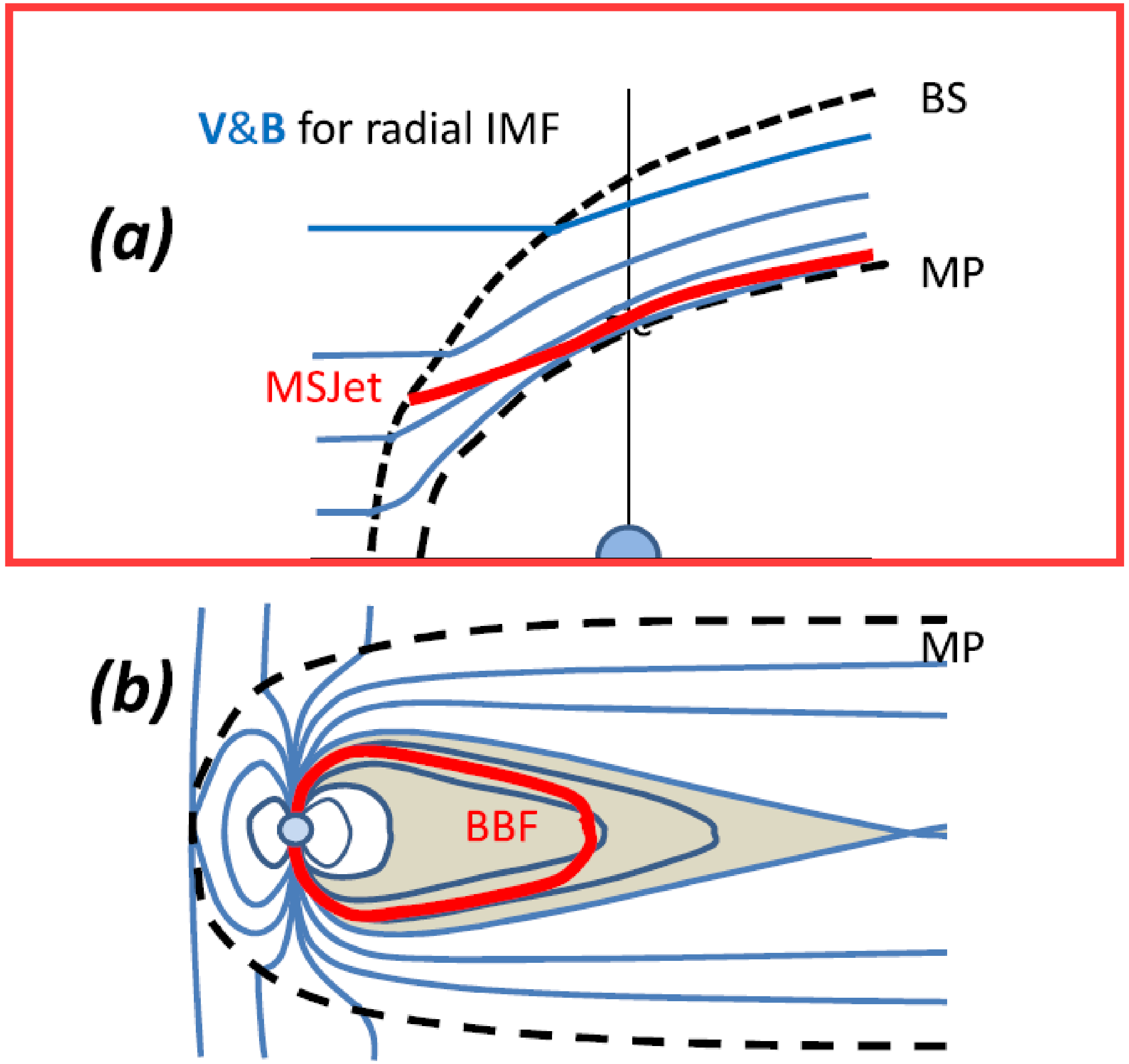


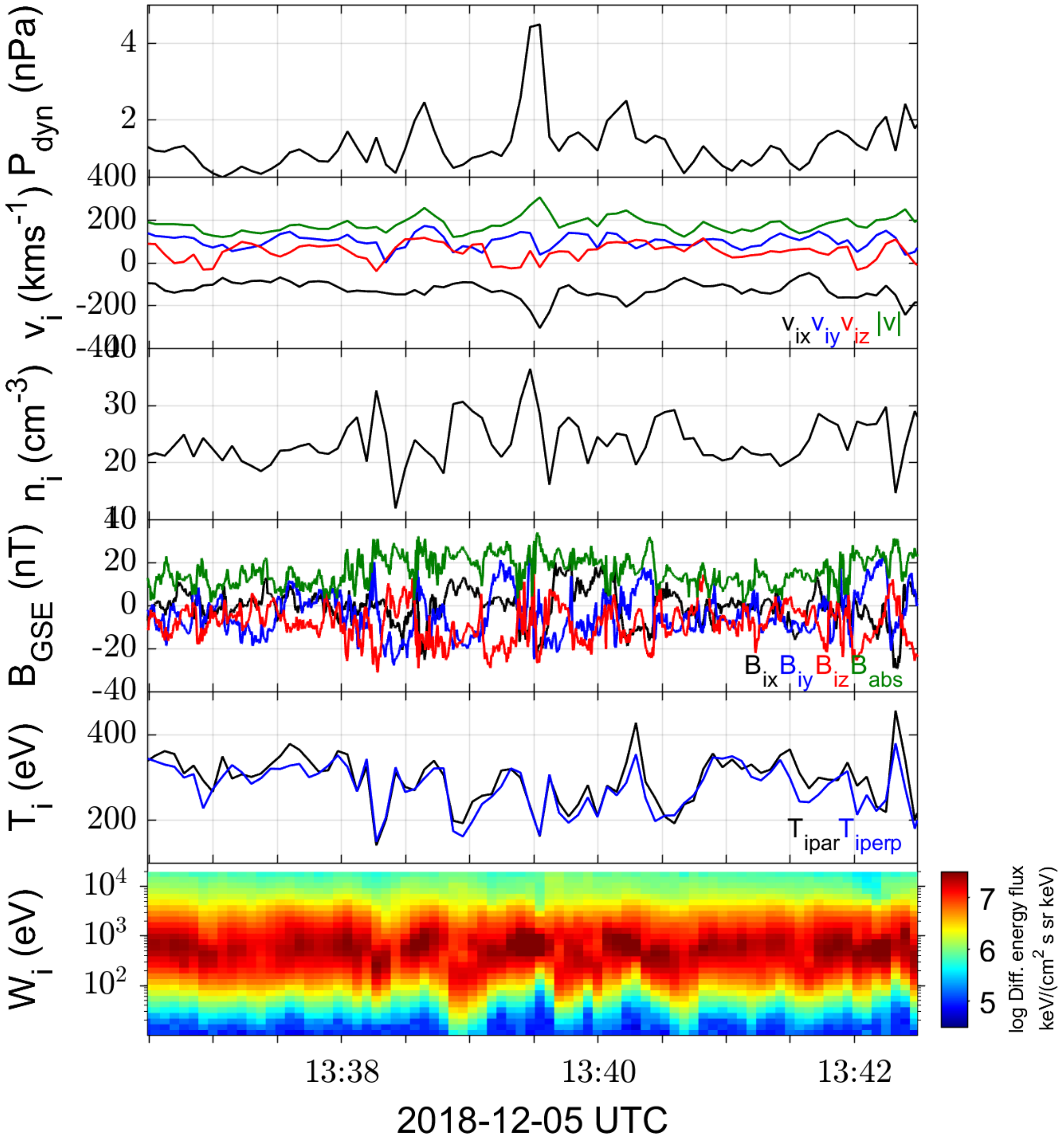


Currently, visitor at ESA/ESTEC working on conjunction list for multi-mission events

Bursty Bulk Flows
(nightside plasma jets)
A possible analogy

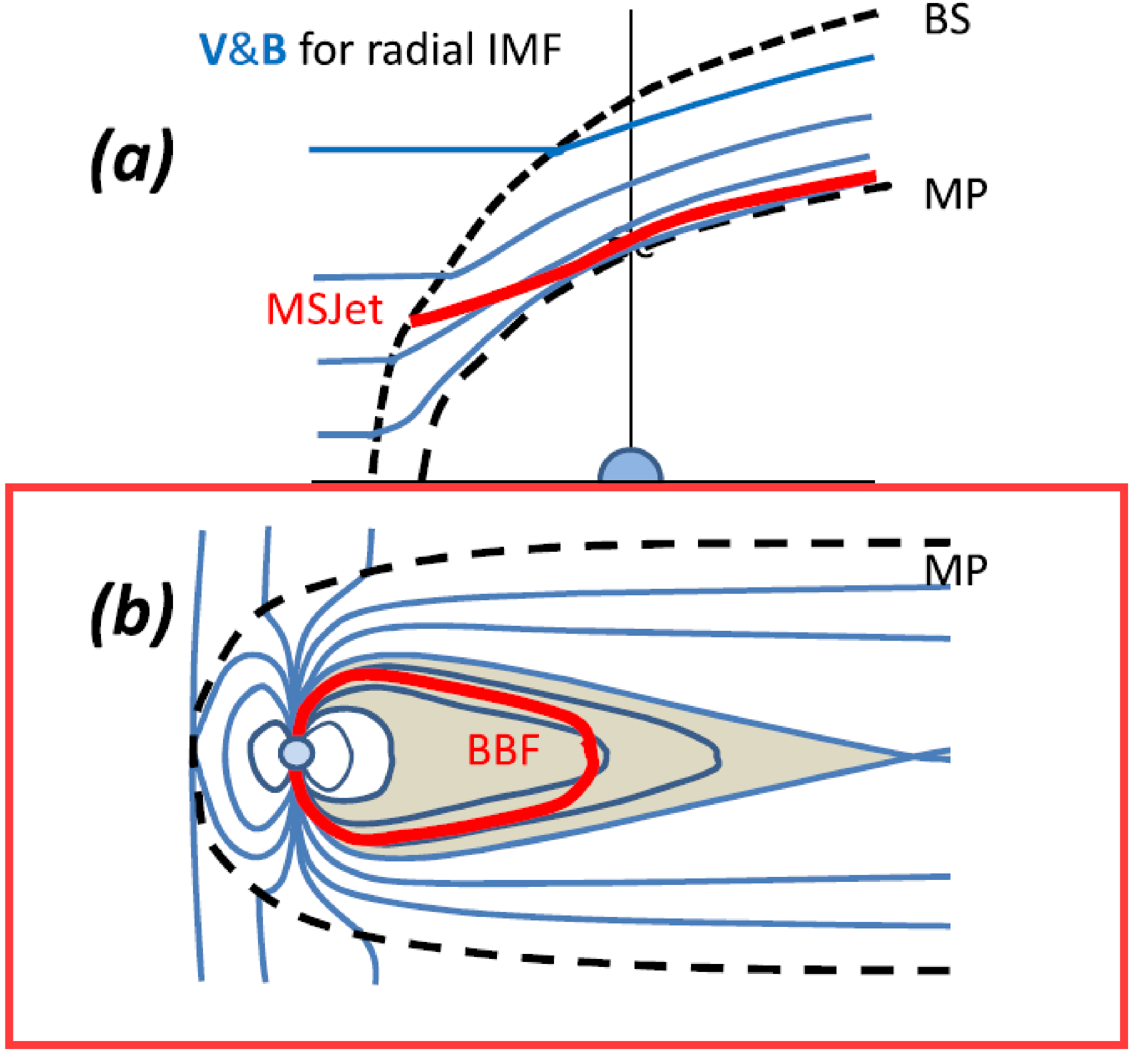
A dayside plasma jet

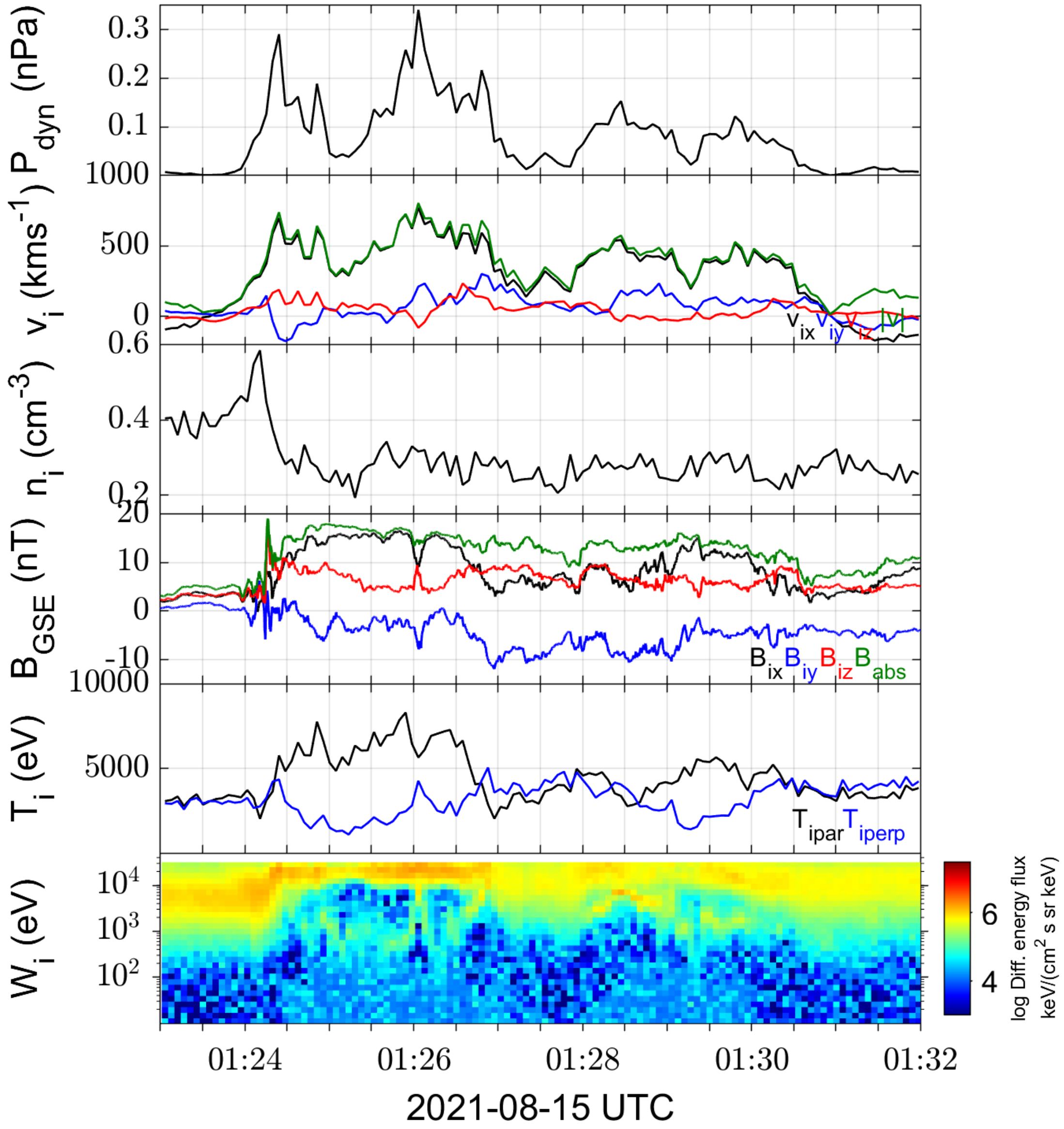




Plaschke F. et al. (2018) | Space Sci. Rev

A nightside plasma jet





Plaschke F. et al. (2018) | Space Sci. Rev

Some similarities & differences

✓

Similarities

- Transient events
- High-speed plasma flows
- Both interact with surrounding plasma
- Flow breaking / diversion process (?)

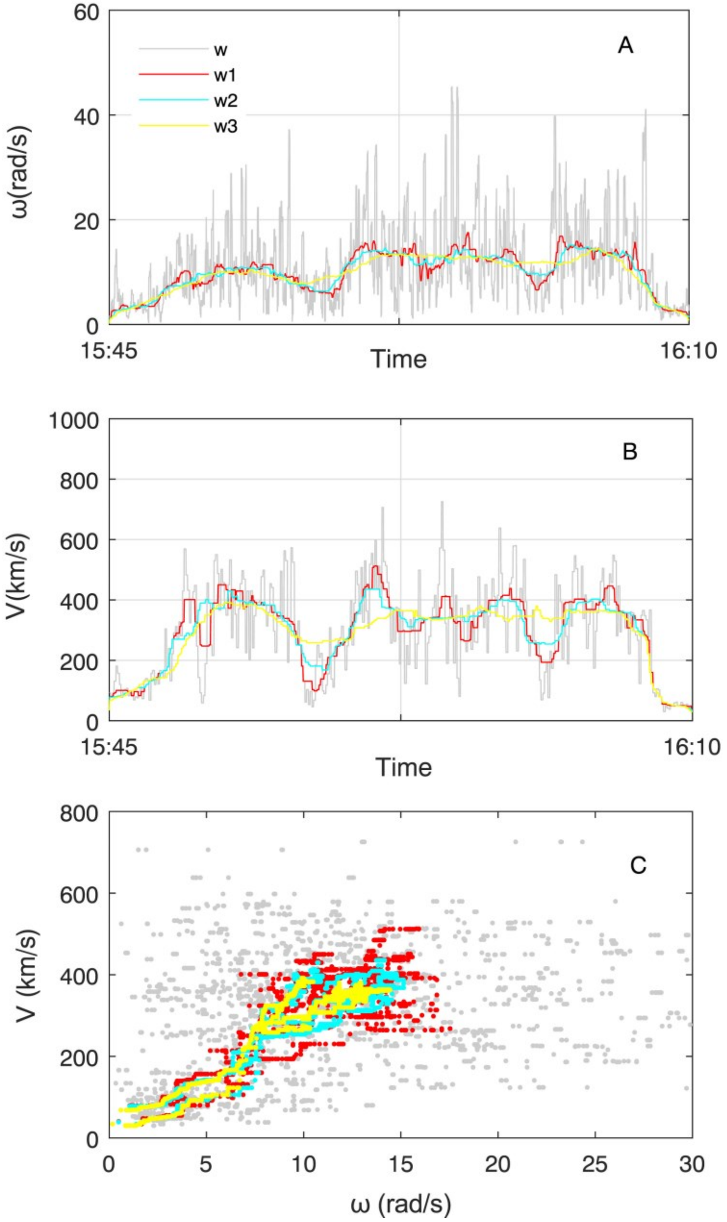
✗

Differences

- BBFs studied for more years
- Vastly different criteria in literature
- BBFs are typically longer and faster
- Different origin (reconnection)
- Different plasma environments (n, T)
- MSH (kinetic) vs magnetotail (magnetic)
- Open vs closed field lines

TLDR : different environment, scales, observational/modeling limitations…

Some recent results – Observations (MMS)



Zhang et al. (2019) | GRL

Enhancements of vorticity is associated with the high-speed flow and high-energy ion flux (above 10 keV)

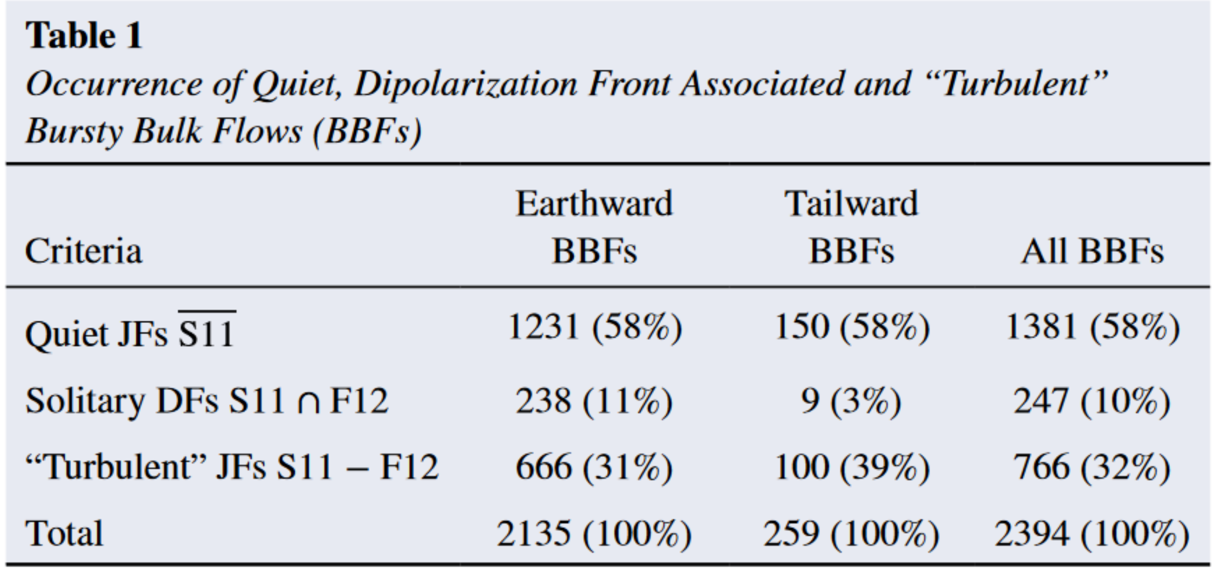


Table 1

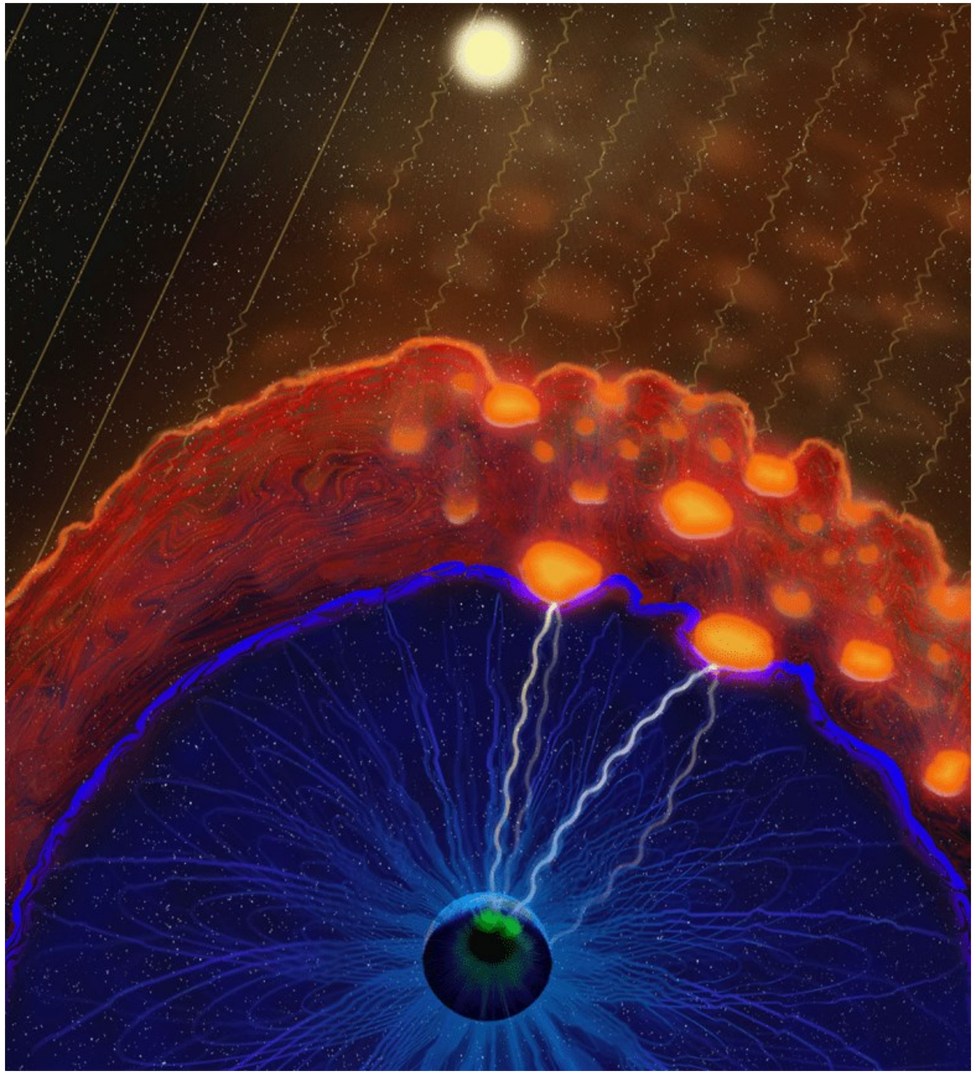
Occurrence of Quiet, Dipolarization Front Associated and "Turbulent" Bursty Bulk Flows (BBFs)

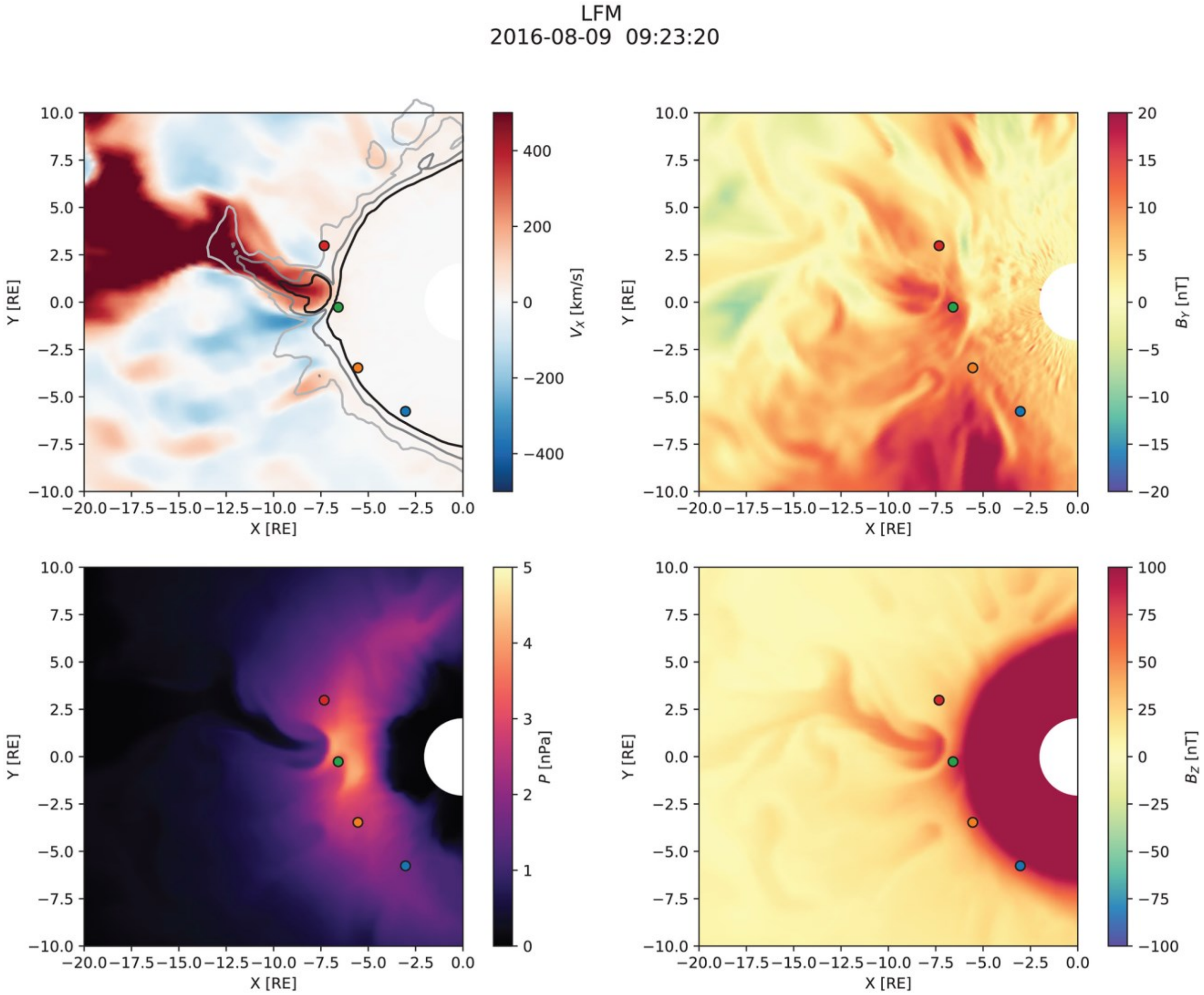
Criteria	Earthward BBFs	Tailward BBFs	All BBFs
Quiet JFs $\overline{S11}$	1231 (58%)	150 (58%)	1381 (58%)
Solitary DFs $S11 \cap F12$	238 (11%)	9 (3%)	247 (10%)
"Turbulent" JFs $S11 - F12$	666 (31%)	100 (39%)	766 (32%)
Total	2135 (100%)	259 (100%)	2394 (100%)

We find that only 10% are associated solitary sharp and strong dipolarization of the magnetic field

https://zenodo.org/record/7009706 Richard et al. (2022) | GRL

Conclusion





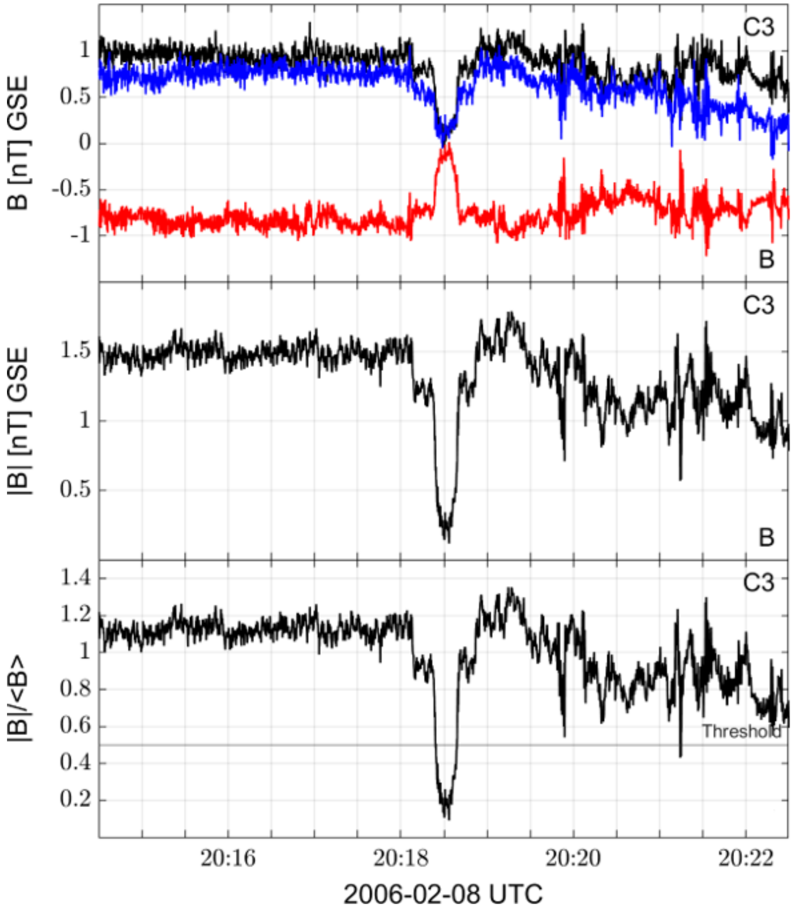
Vuorinen et al. (2022)

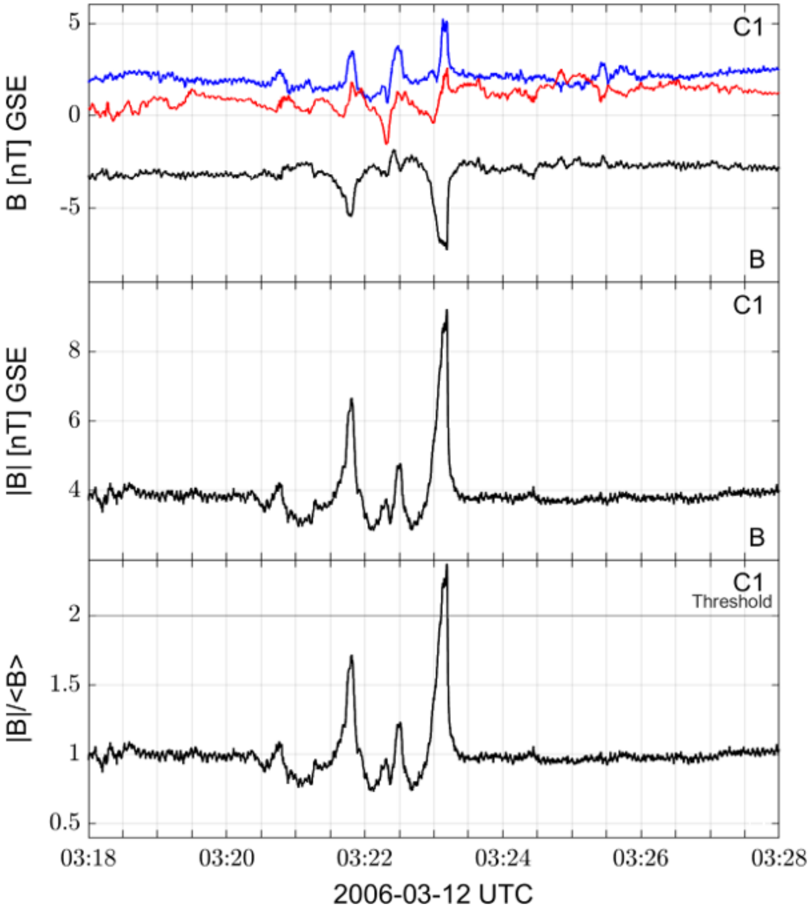
Thank you for listening ☺

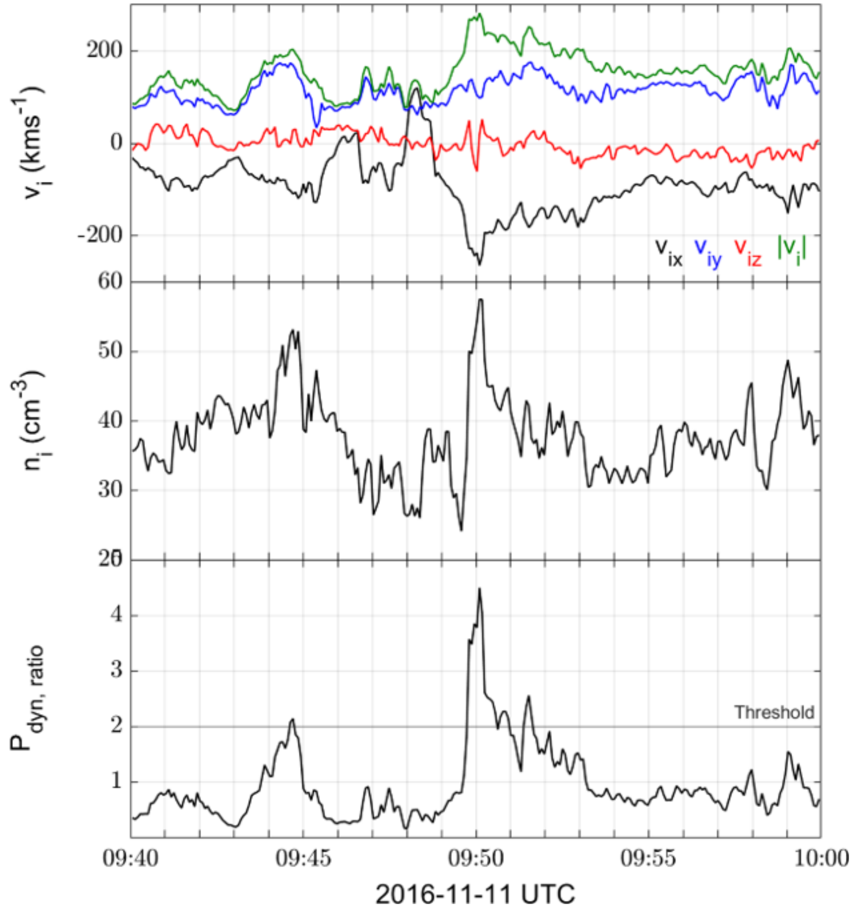
Merkin et al. (2019)

Extras

Dayside Transient Phenomena

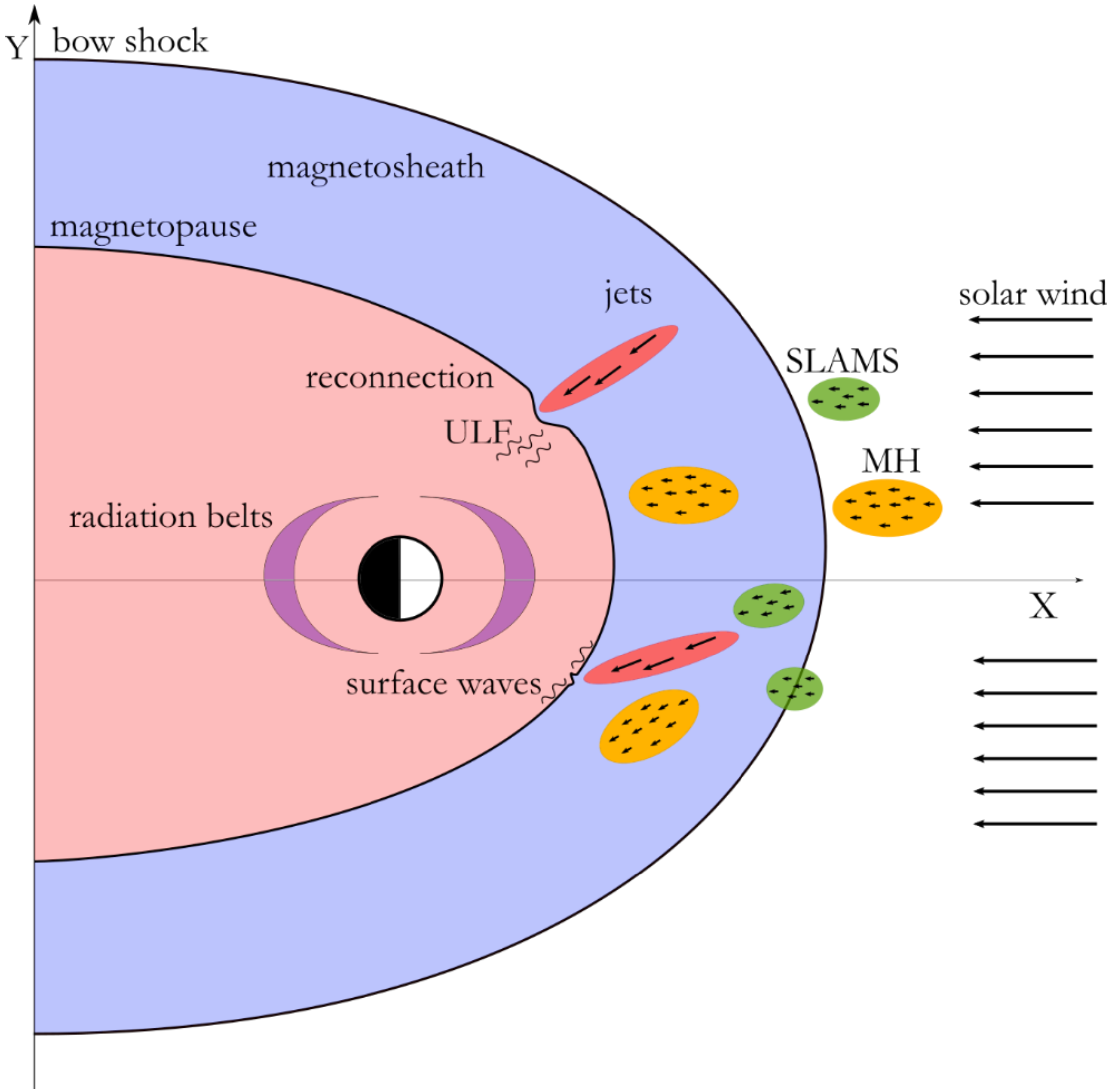

Magnetic Hole

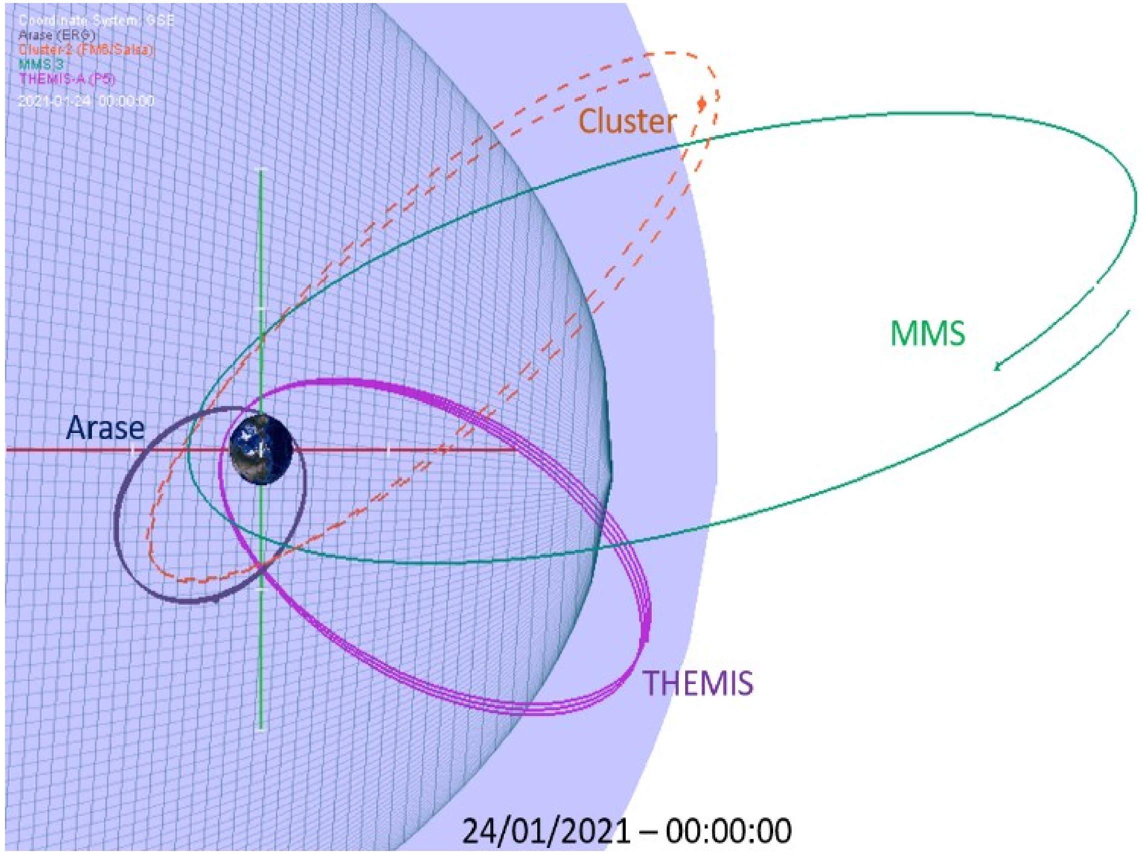

SLAMS


Magnetosheath Jet

(unpublished data – Ongoing work)

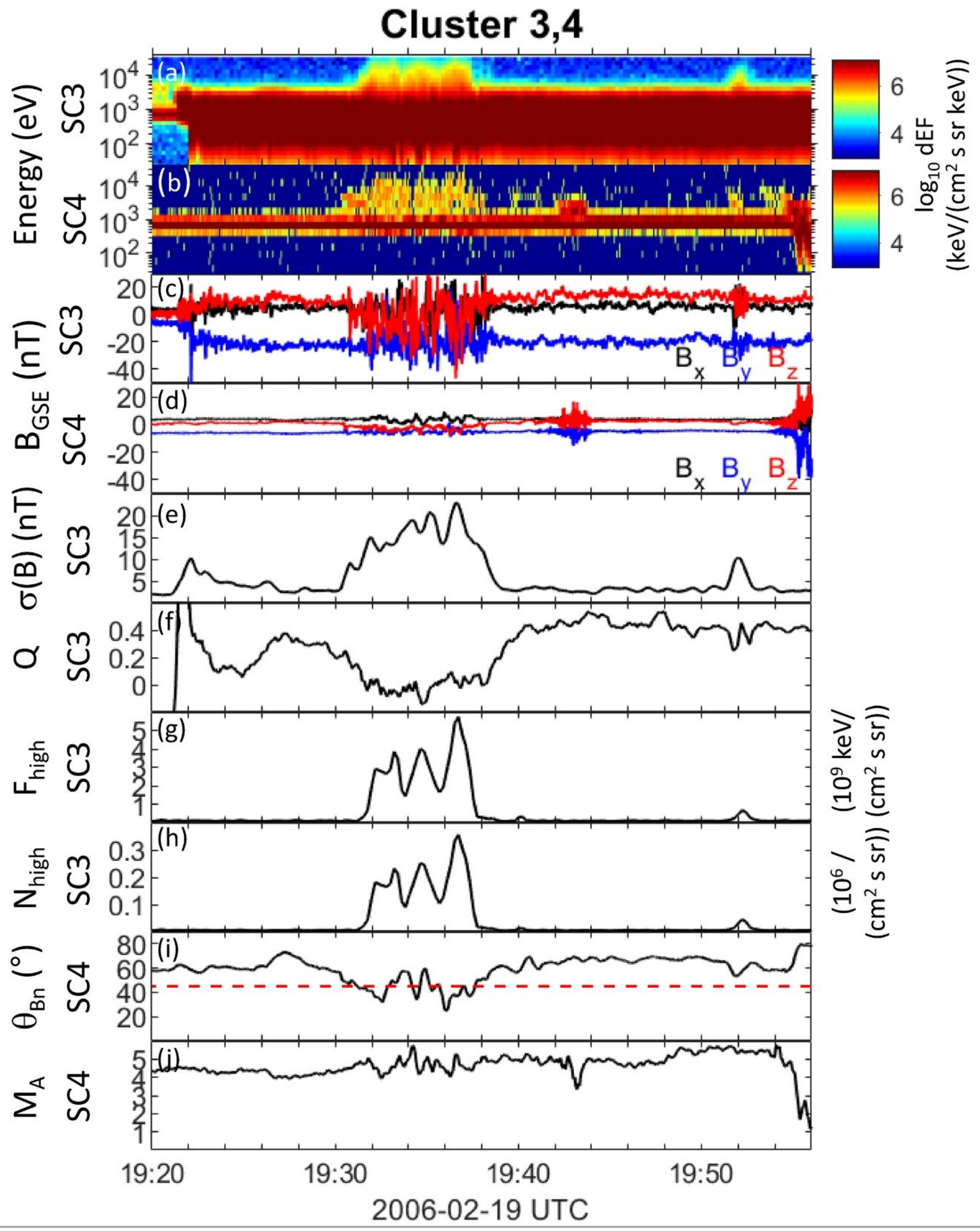
A lot of data are not fully used (conjunction example)





Currently, at ESA ESTEC working on conjunction lists for bow shock & MSH

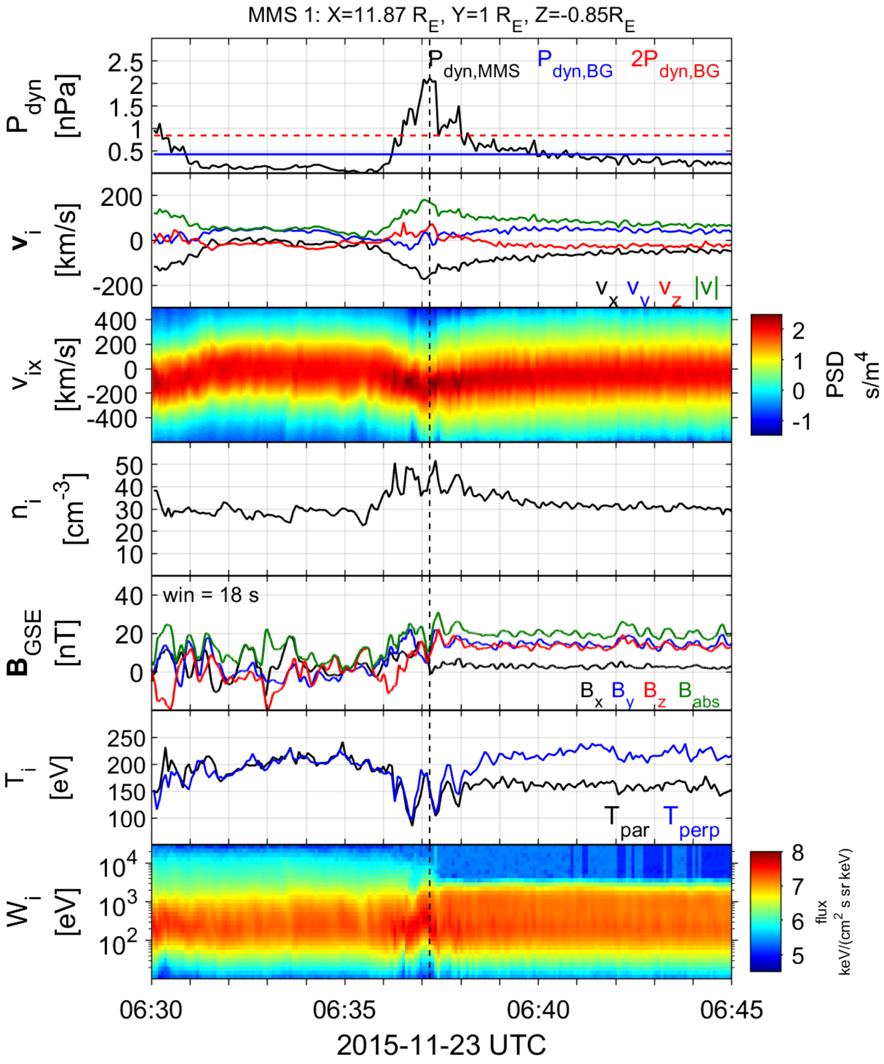
Classification Cluster

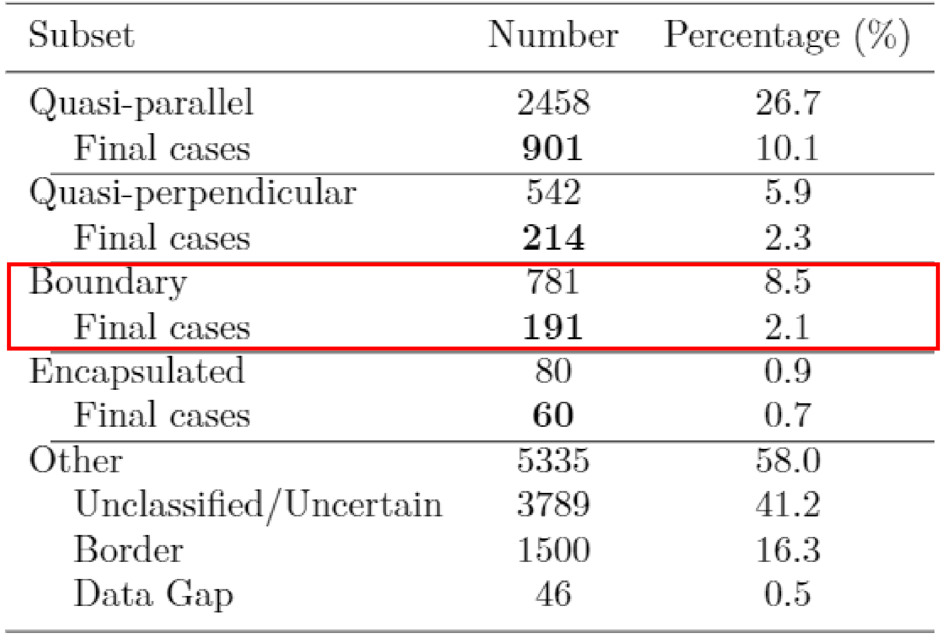


Karlsson T., **Raptis S.,** et al. (2021) | JGR

Summarized properties – Boundary

- Hard to estimate their occurrence rate
- Quite energetic and long duration
- Similar properties to Qpar jets
- Maybe associated to pressure pulses of SW [Archer et al. 2012]





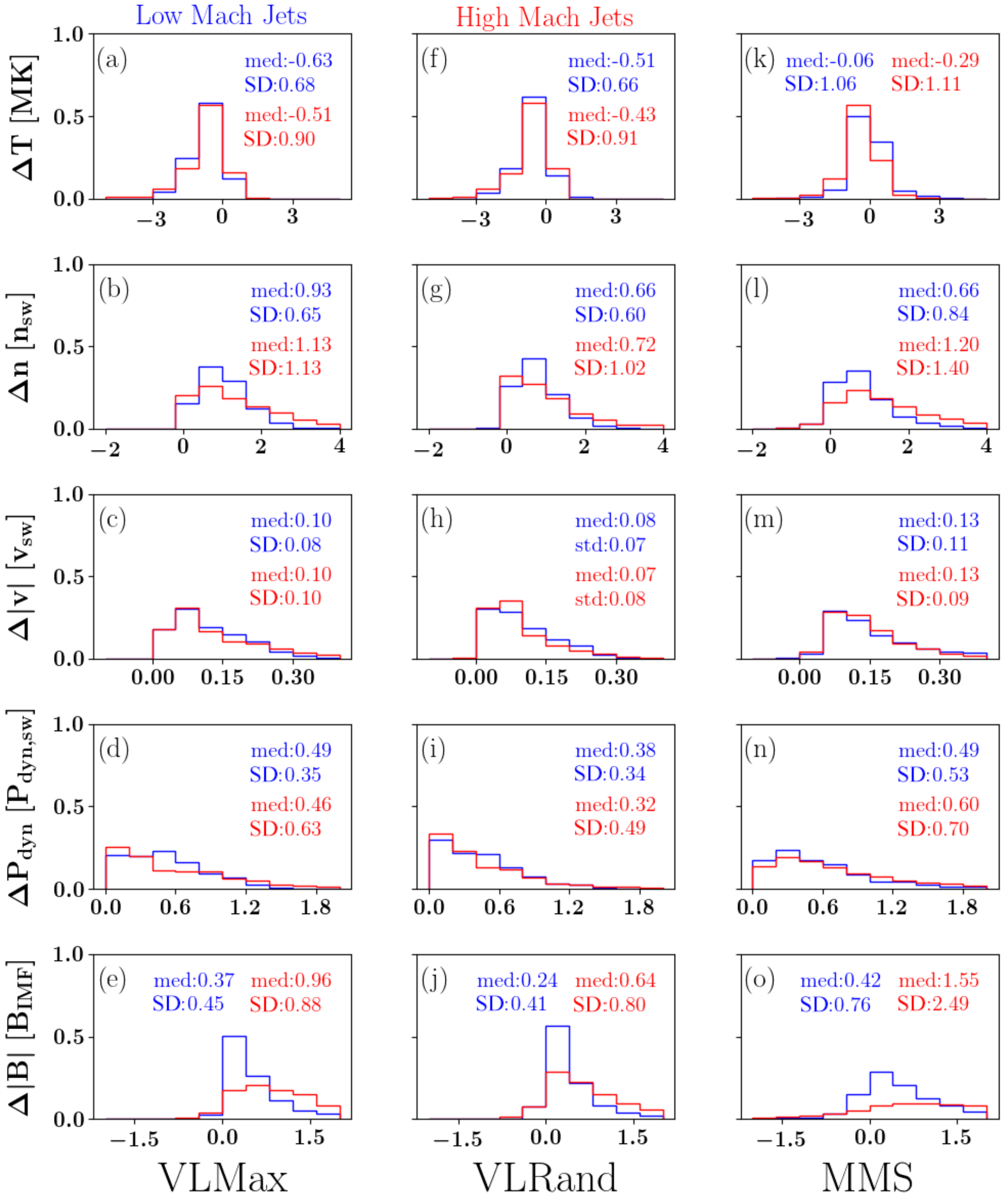
Subset	Number	Percentage (%)
Quasi-parallel	2458	26.7
Final cases	**901**	10.1
Quasi-perpendicular	542	5.9
Final cases	**214**	2.3
Boundary	781	8.5
Final cases	**191**	2.1
Encapsulated	80	0.9
Final cases	**60**	0.7
Other	5335	58.0
Unclassified/Uncertain	3789	41.2
Border	1500	16.3
Data Gap	46	0.5

Boundary Jet

Jets found in the boundary between $Q_{\parallel}$ and $Q_{\perp}$ MSH

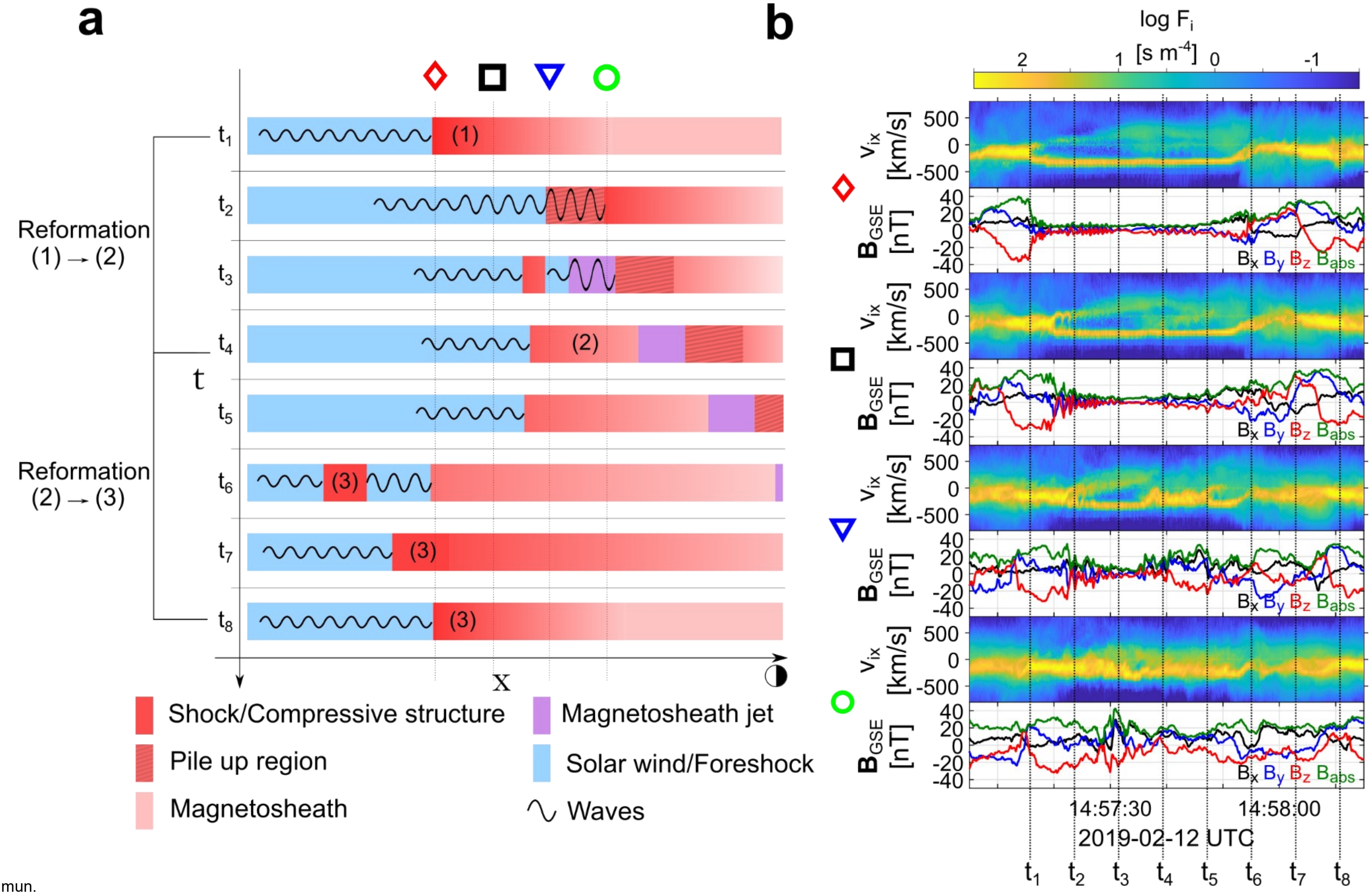
Raptis S., Karlsson T., et al. (2020) | JGR

Comparison MMS & Vlasiator



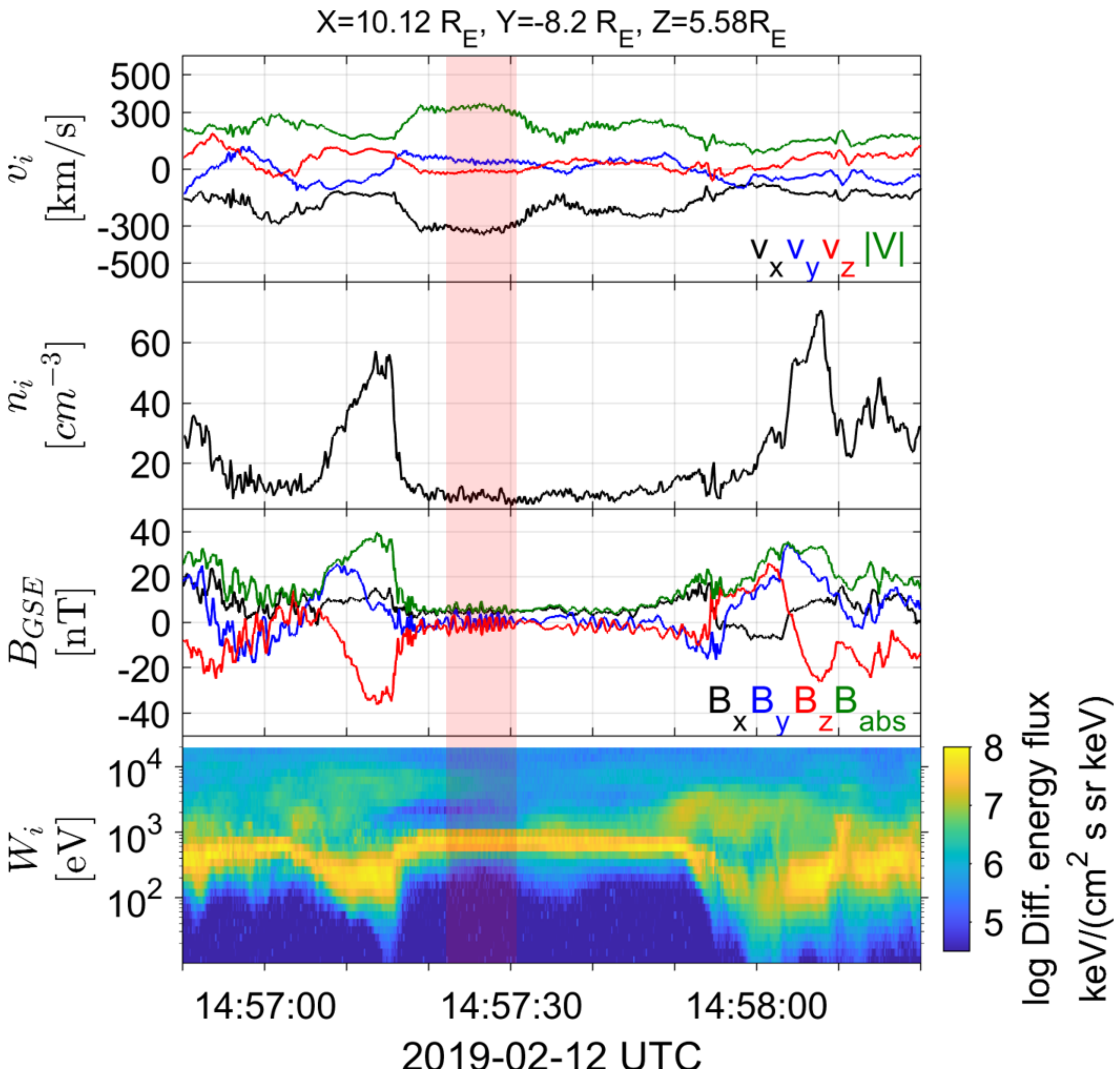
Palmroth M., **Raptis S.**, et al. (2021) | Annales

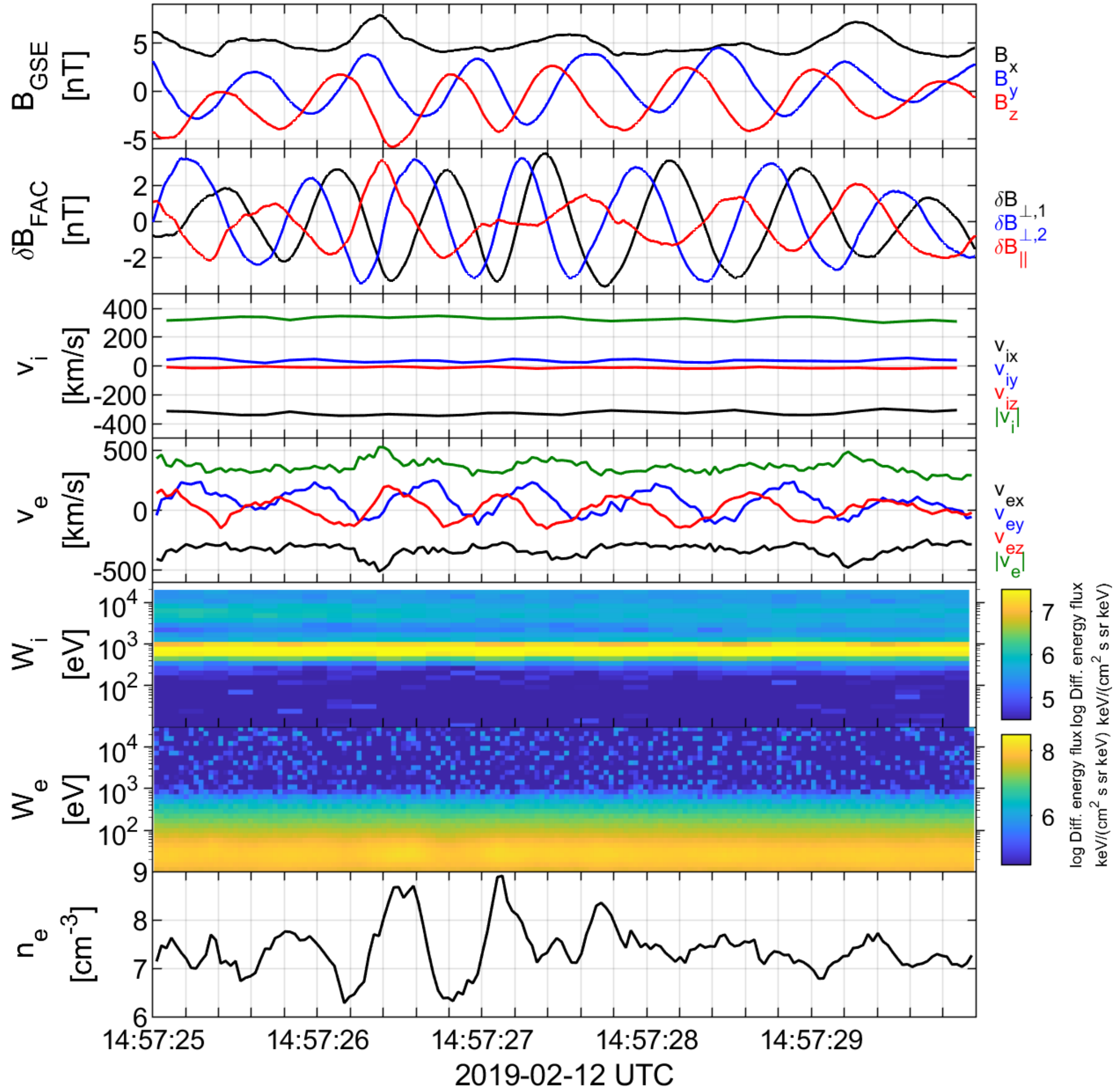
Global Shock Reformation Picture



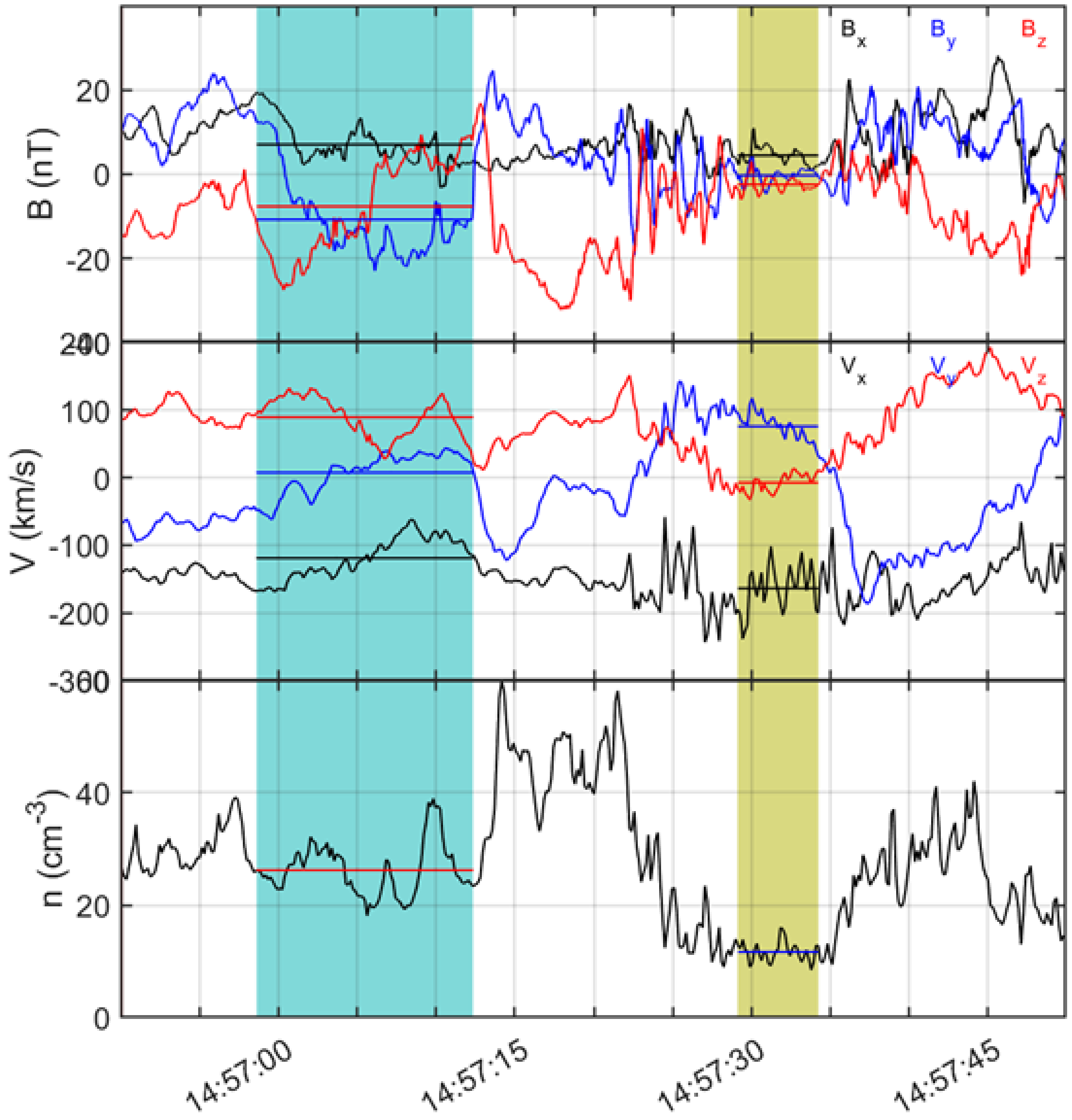
Raptis S., et al. (2022a) | Nat. Commun.

Upstream whistlers paper V





Local & Global Shock properties



Local Measurements (e.g., MMS4)

$\theta_{Bn} \approx 65-80°$ (large variations)

Global (OMNI) + BS model (e.g., Farris et al.)

$\theta_{Bn} \approx 25°$

Consistent with FCS (i.e., SLAMS) acting locally as Qperp shocks

Turner et al. 2021 (HFA):
38.5 (global)
80.3 (local)

Scale comparison (e.g., Turner et al. 2021)

Hot Flow Anomaly (HFA) self-reformation

n = [- 0.540, 0.379, 0.737]

$$\mathrm{v}_{SH} = -62.1\,\frac{km}{s}$$

New Shock ramp ~5 sec

~1Li and then growing to ~2Li

$$L_e = \sim 2\ km$$
$$L_i = \sim 90\ km$$
$$L_d = \sim 13\ m$$

SLAMS self-reformation

MC: [0.9026, 0.0987, -0.4191]
MVA: [-0.97, 0.16, -0.19]

$$\mathrm{v}_{SH} = \sim 60\,\frac{km}{s}$$

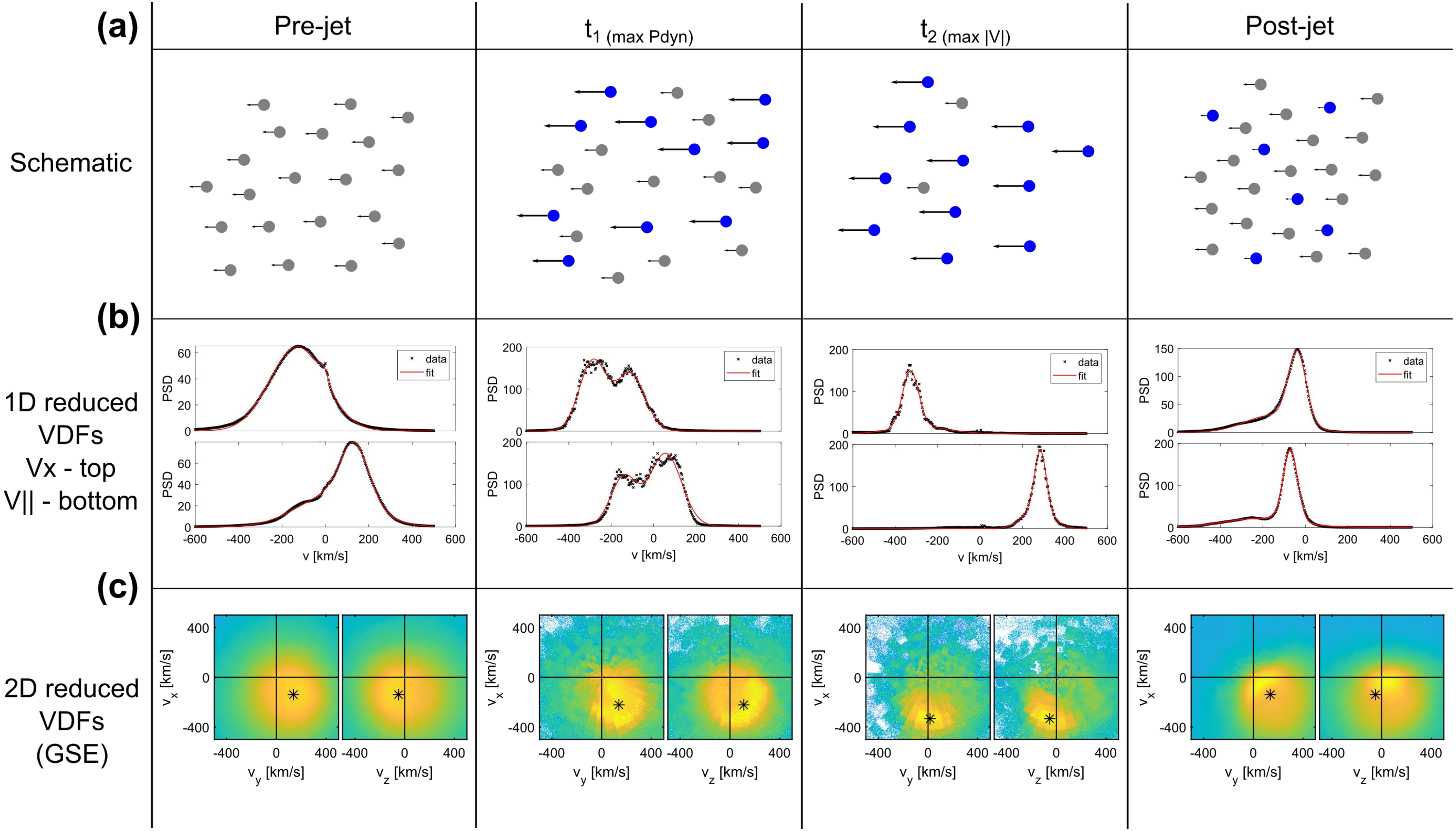
New Shock ramp ~3-5 sec

New ramp ~150km ~2 L_i

$$L_e = \sim 2\ km$$
$$L_i = \sim 80\ km$$
$$L_d = \sim 10\ m$$

"very" rough comparison

Jet evolution in Qpar Magnetosheath

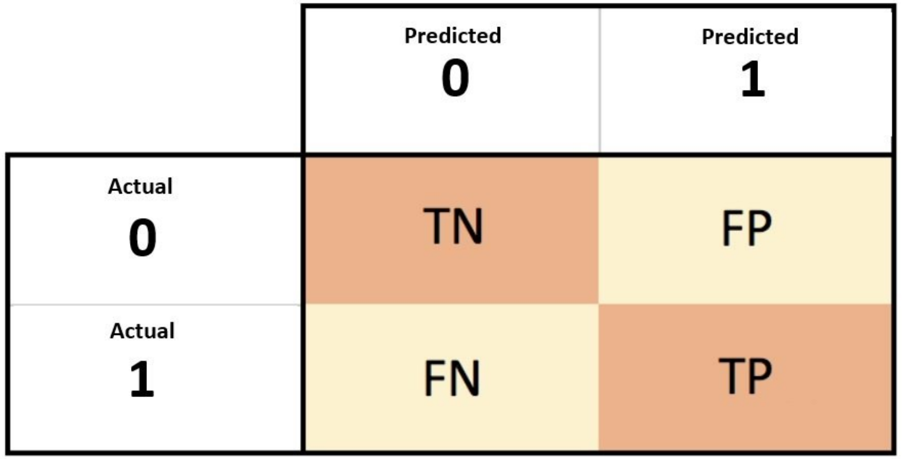


Raptis S, et al,. 2022b | GRL

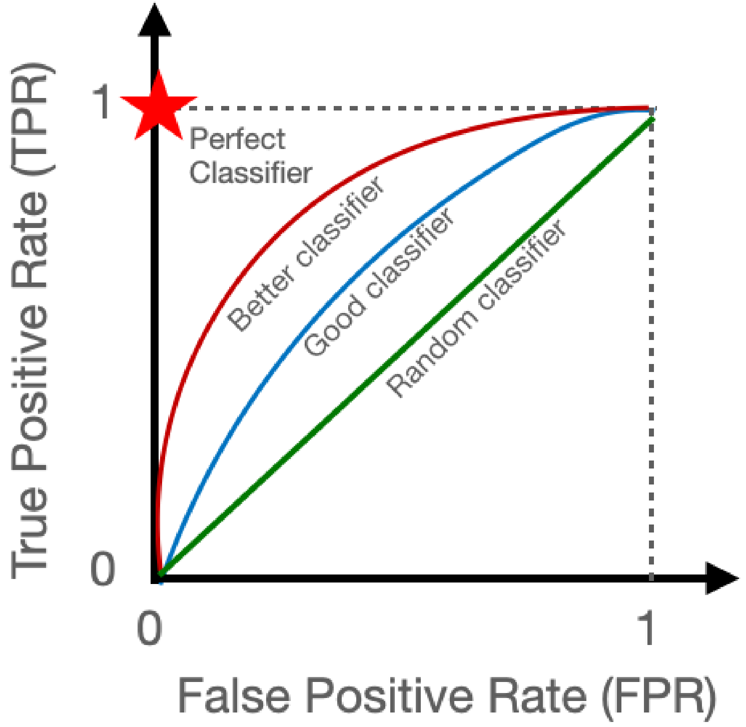
Extras

Neural Networks

Evaluation Metrics (Classification)



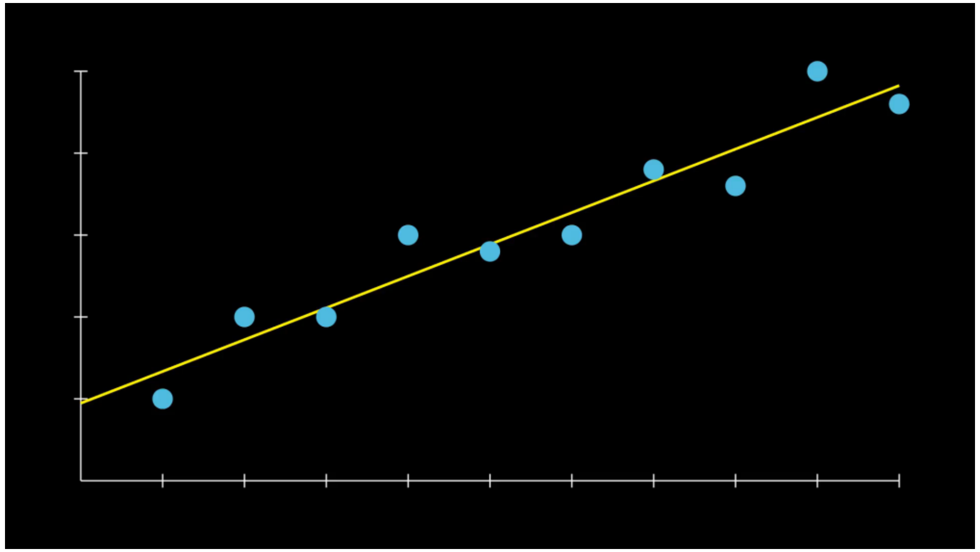
	Predicted 0	Predicted 1
Actual 0	TN	FP
Actual 1	FN	TP

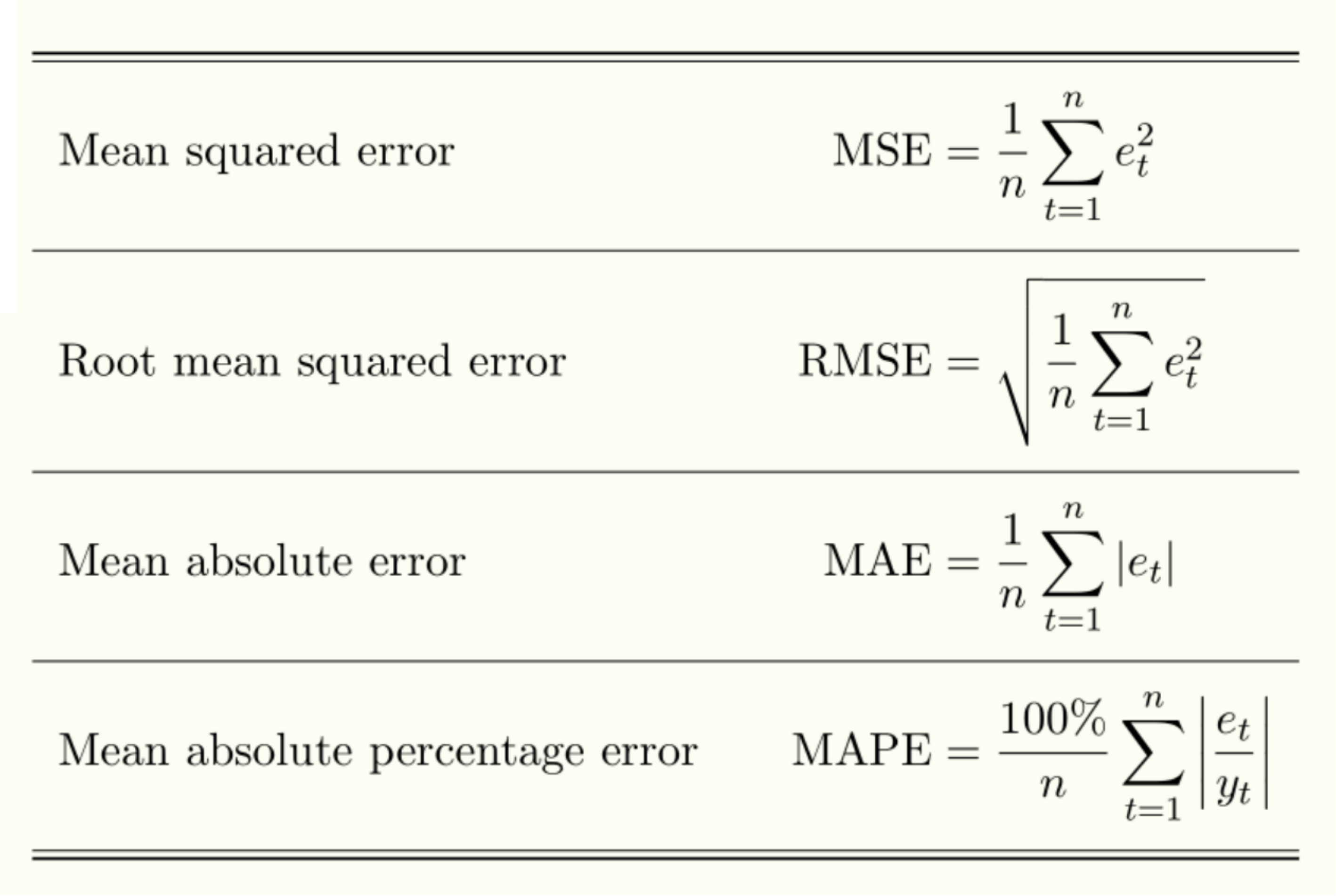


Metric	Formula
True positive rate, recall	$\frac{\mathrm{TP}}{\mathrm{TP+FN}}$
False positive rate	$\frac{\mathrm{FP}}{\mathrm{FP+TN}}$
Precision	$\frac{\mathrm{TP}}{\mathrm{TP+FP}}$
Accuracy	$\frac{\mathrm{TP+TN}}{\mathrm{TP+TN+FP+FN}}$
F-measure	$\frac{2 \cdot \mathrm{precision} \cdot \mathrm{recall}}{\mathrm{precision} + \mathrm{recall}}$

Evaluation Metrics (Regression)

$$MSE = \frac{1}{n} \Sigma \underbrace{\left(y - \widehat{y} \right)^2}_{\text{The square of the difference between actual and predicted}}$$

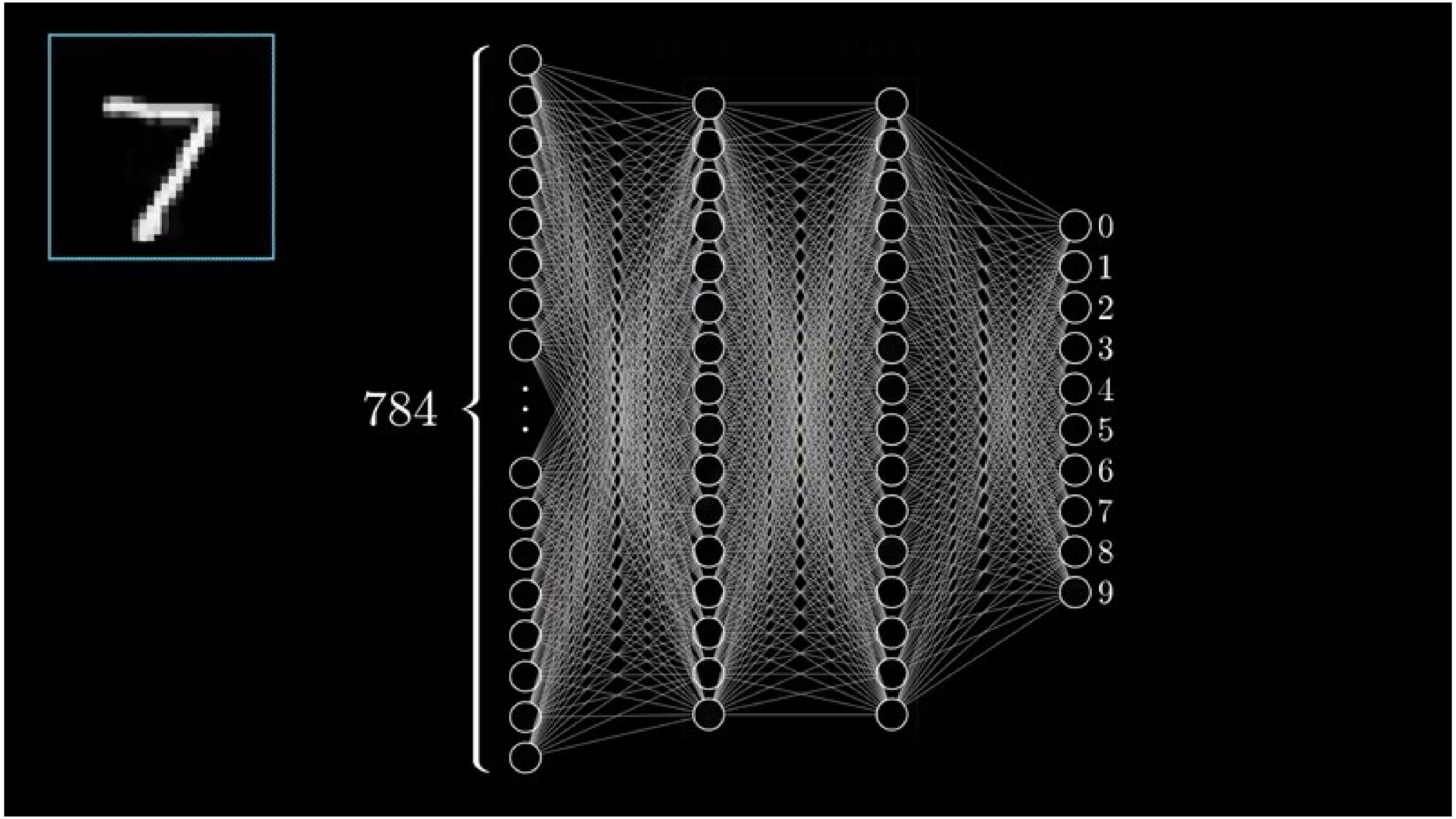




Mean squared error	$\mathrm{MSE} = \frac{1}{n} \sum_{t=1}^{n} e_t^2$
Root mean squared error	$\mathrm{RMSE} = \sqrt{\frac{1}{n} \sum_{t=1}^{n} e_t^2}$
Mean absolute error	$\mathrm{MAE} = \frac{1}{n} \sum_{t=1}^{n} \lvert e_t \rvert$
Mean absolute percentage error	$\mathrm{MAPE} = \frac{100\%}{n} \sum_{t=1}^{n} \left\lvert \frac{e_t}{y_t} \right\rvert$

Source: https://gist.github.com/thomasnield

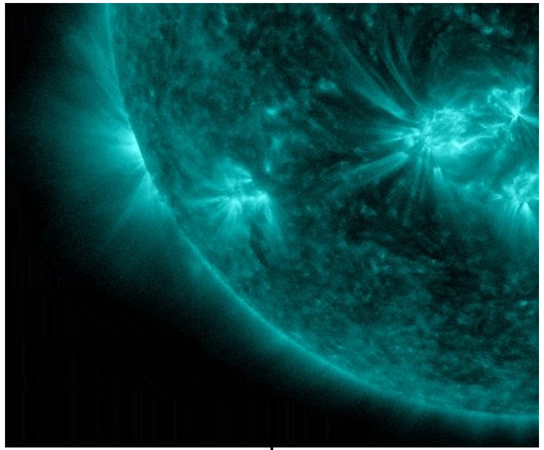
Neural Networks



*Video Courtesy**: 3Blue1Brown** (Check his YouTube page. It's great!)

Application on forescasting SEPs

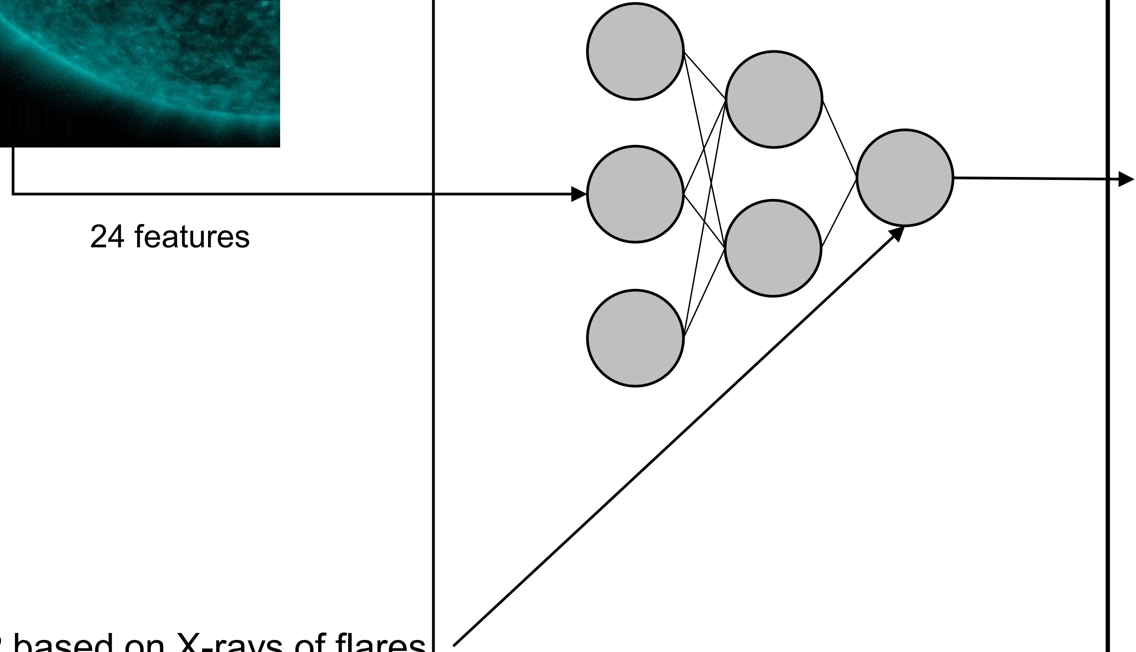
Problem description



24 features

Occurrence of SEP based on X-rays of flares

Modeling



Validation & Results

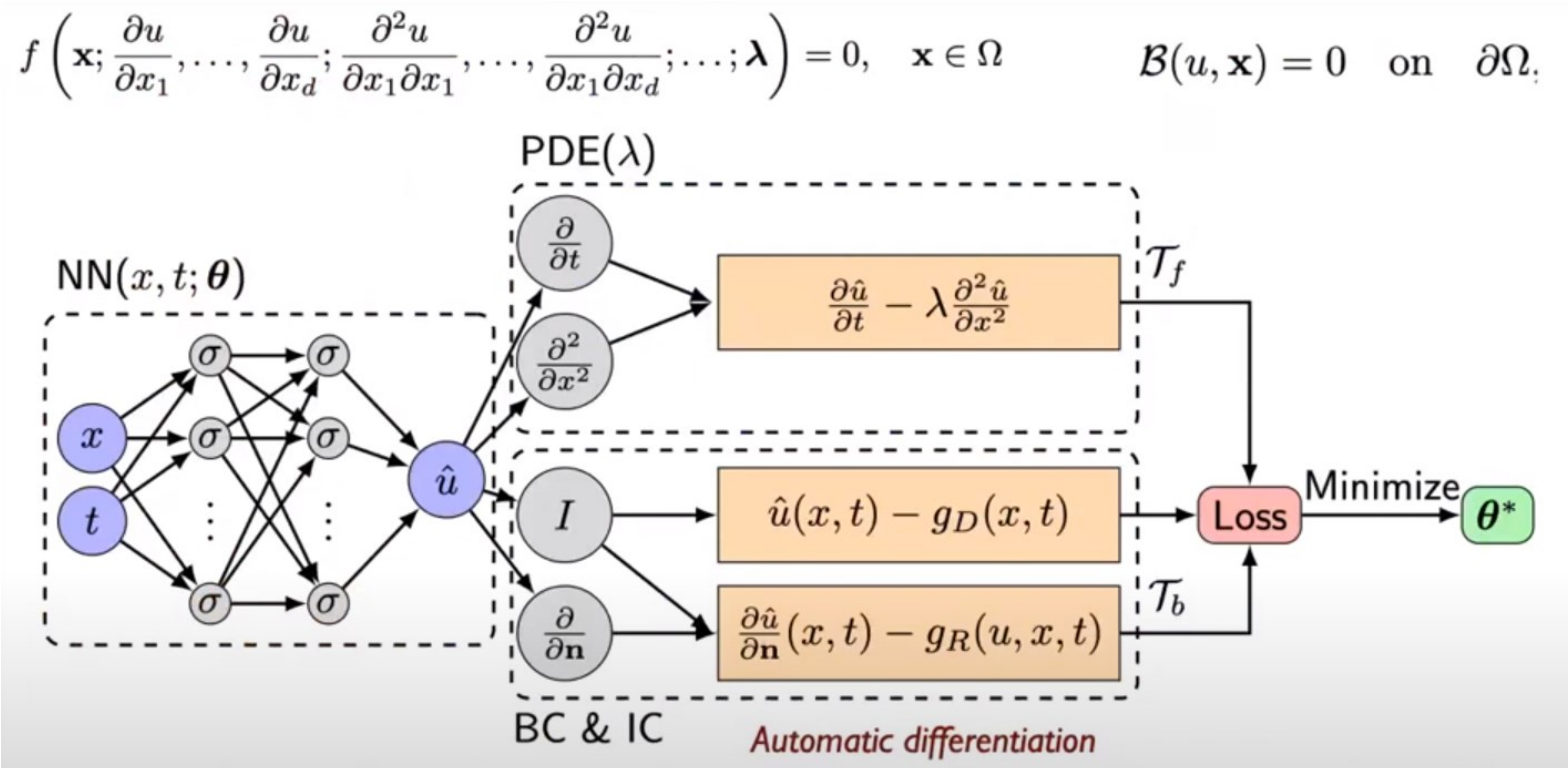
	SEP predicted always YES	SEP predicted always NO
SEP occurred YES	191/220 [86.81 %]	19/220 [8.63%]
SEP occurred NO	[7.77 %]	[92.23%]

Comparisons to other models recently published

Review of Solar Energetic Particle Models (Advances in Space Research)

Aminalragia-Giamini, **Raptis** et al. (2021) | J. Space Weather Space Clim

What exactly is a PINN then ?

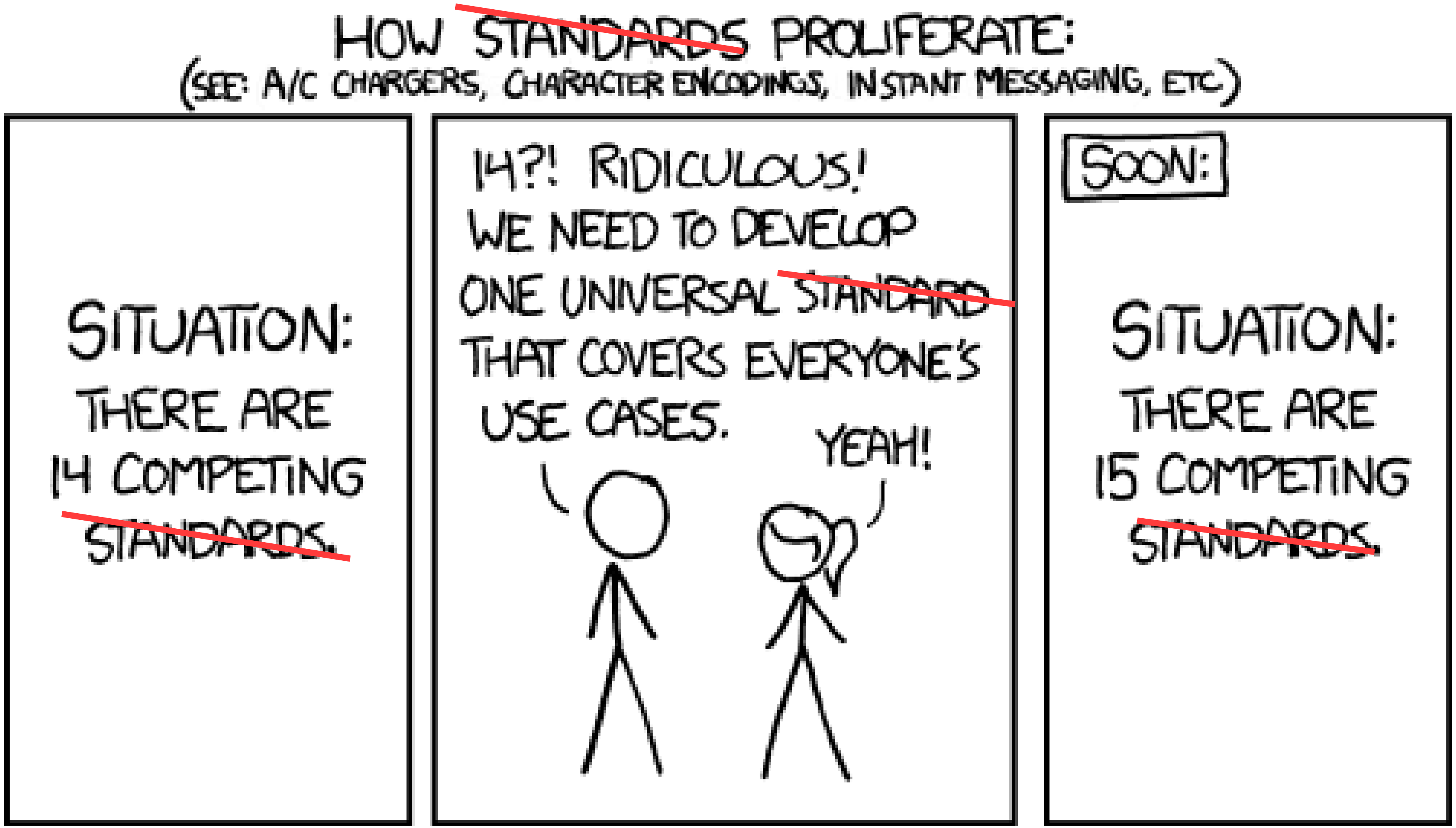


$$f\left(\mathbf{x}; \frac{\partial u}{\partial x_1}, \ldots, \frac{\partial u}{\partial x_d}; \frac{\partial^2 u}{\partial x_1 \partial x_1}, \ldots, \frac{\partial^2 u}{\partial x_1 \partial x_d}; \ldots; \boldsymbol{\lambda}\right) = 0, \quad \mathbf{x} \in \Omega \qquad \mathcal{B}(u, \mathbf{x}) = 0 \quad \text{on} \quad \partial\Omega,$$

$$loss = data\ fit + PDE\ residual + ICs\ fit + BCs\ fit$$

Idea = If output is a differentiable quantity with respect to an input = can compute PDEs = combined loss functions

Proposing a new model



*Where, standards = models, mechanisms etc.