# High-speed downstream jets: relevance to bow shock dynamics & evolution

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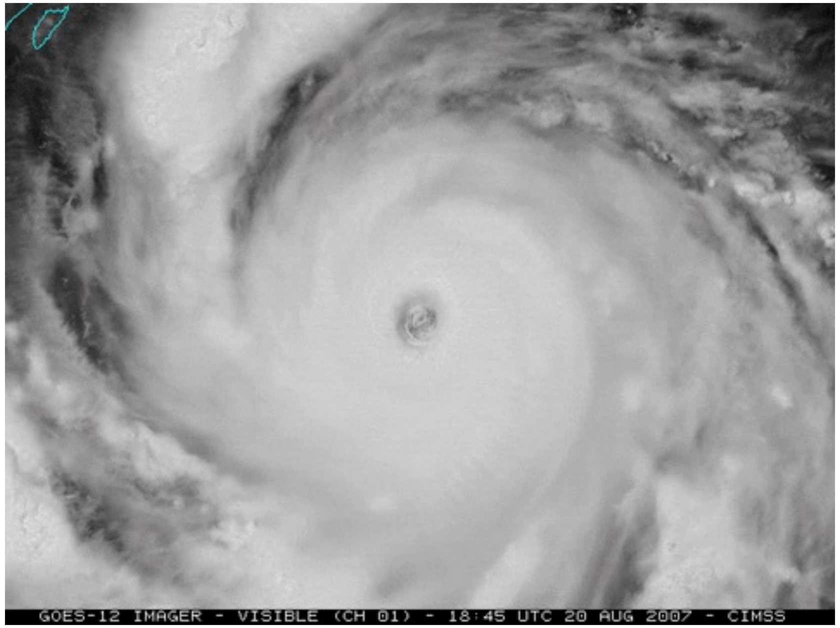
IAGA/IUGG 2023
A13: Magnetospheric Boundary Layers
13-18 July 2023

# Transient events – weather

Hurricanes

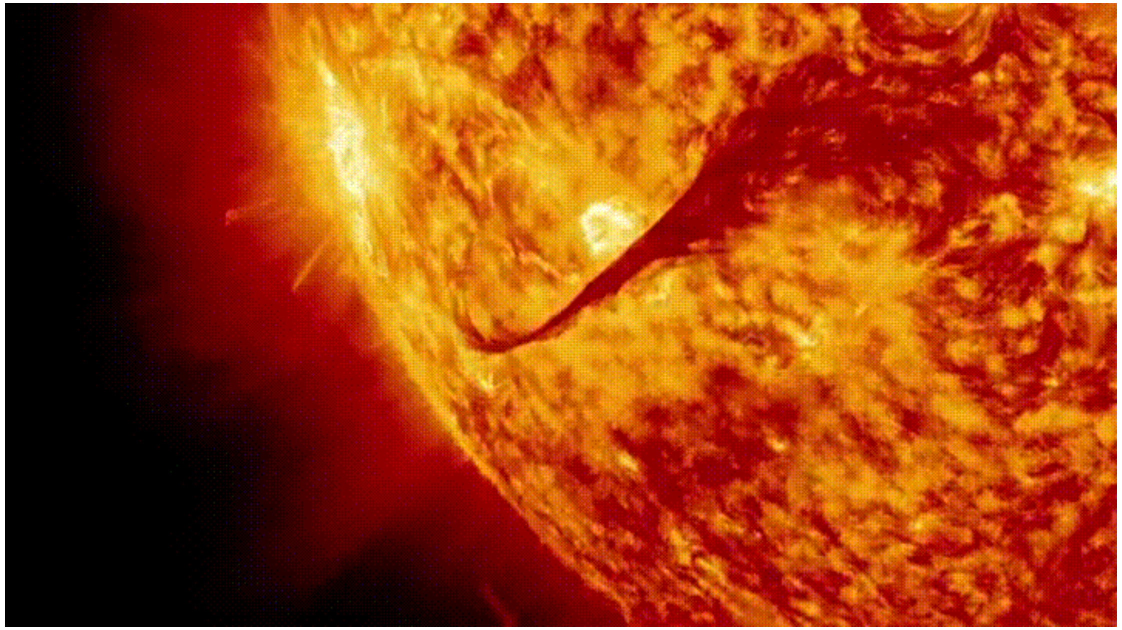



Rain

Snowstorms

# Transient events – weather

CMEs/Solar Flares

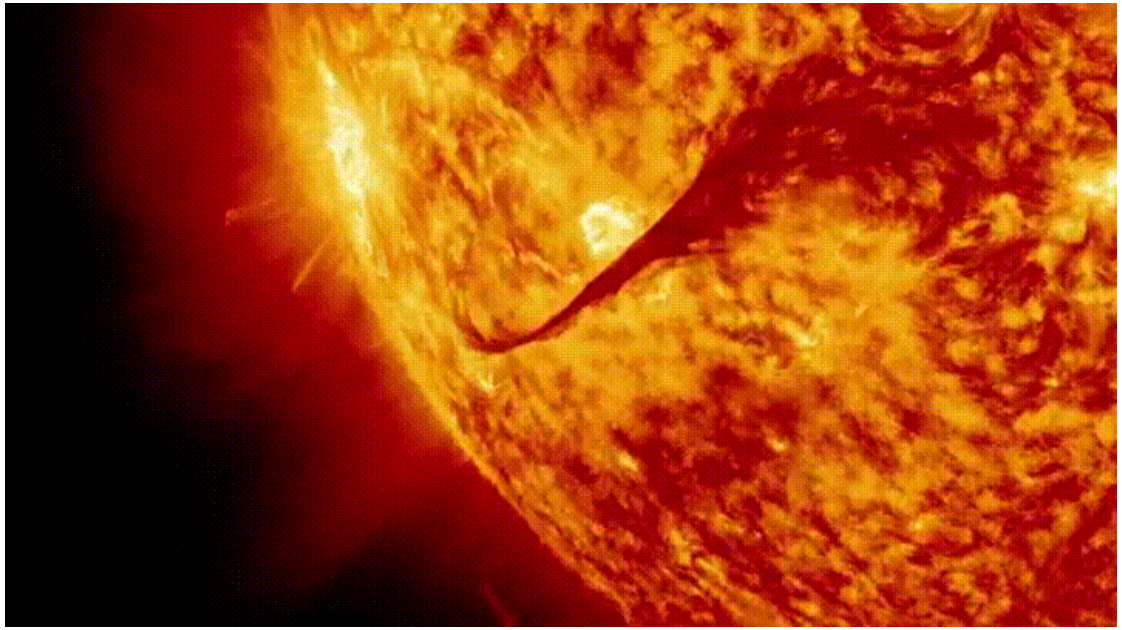


Rain

Snowstorms

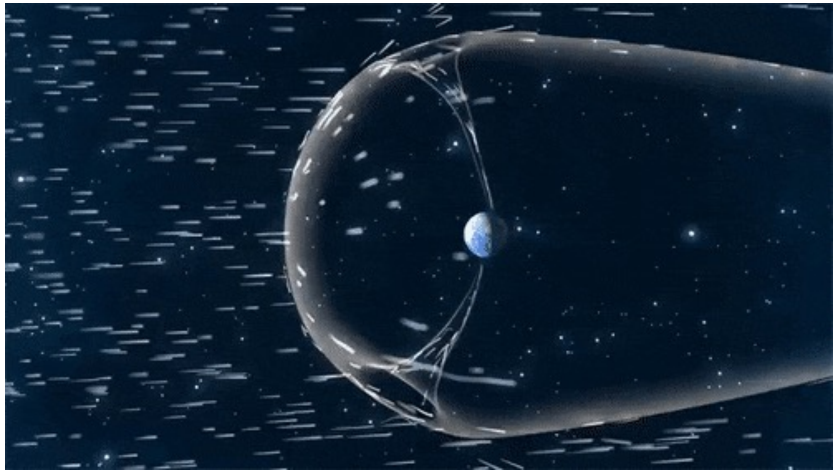
# Transient events – weather

CMEs/Solar Flares



Rain

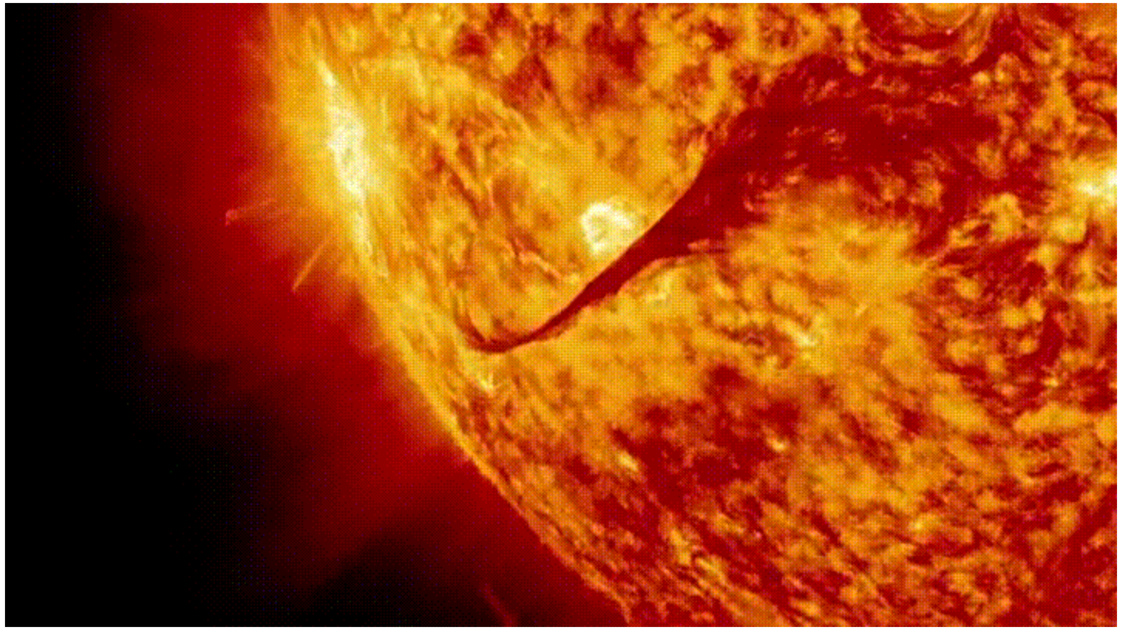
Solar cycle, streams, discontinuities



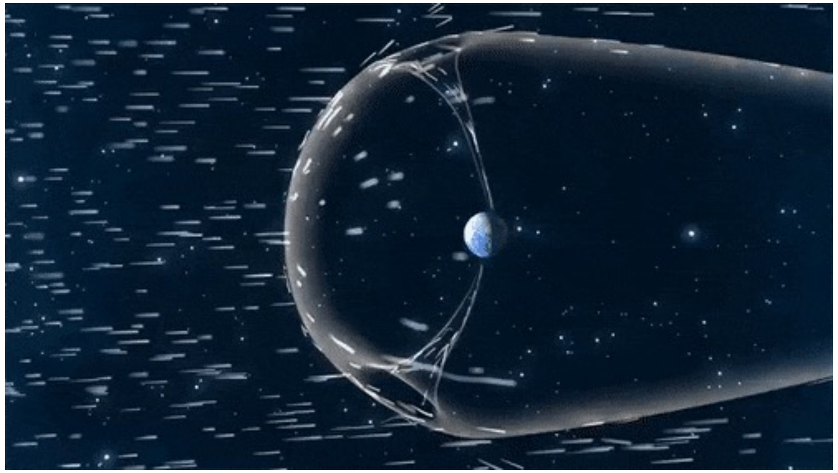
Credits : NASA

# Transient events – *space* weather

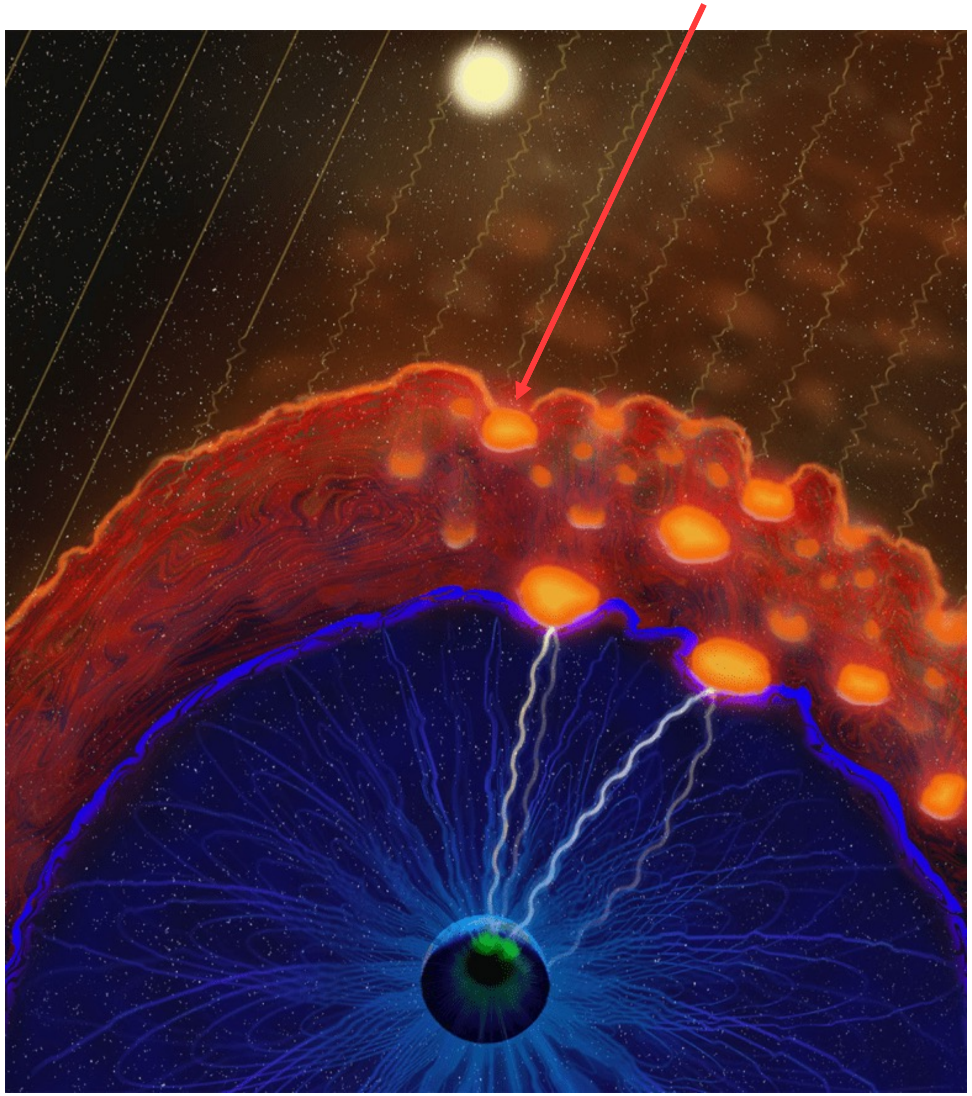
CMEs/Solar Flares



Solar cycle, streams, discontinuities



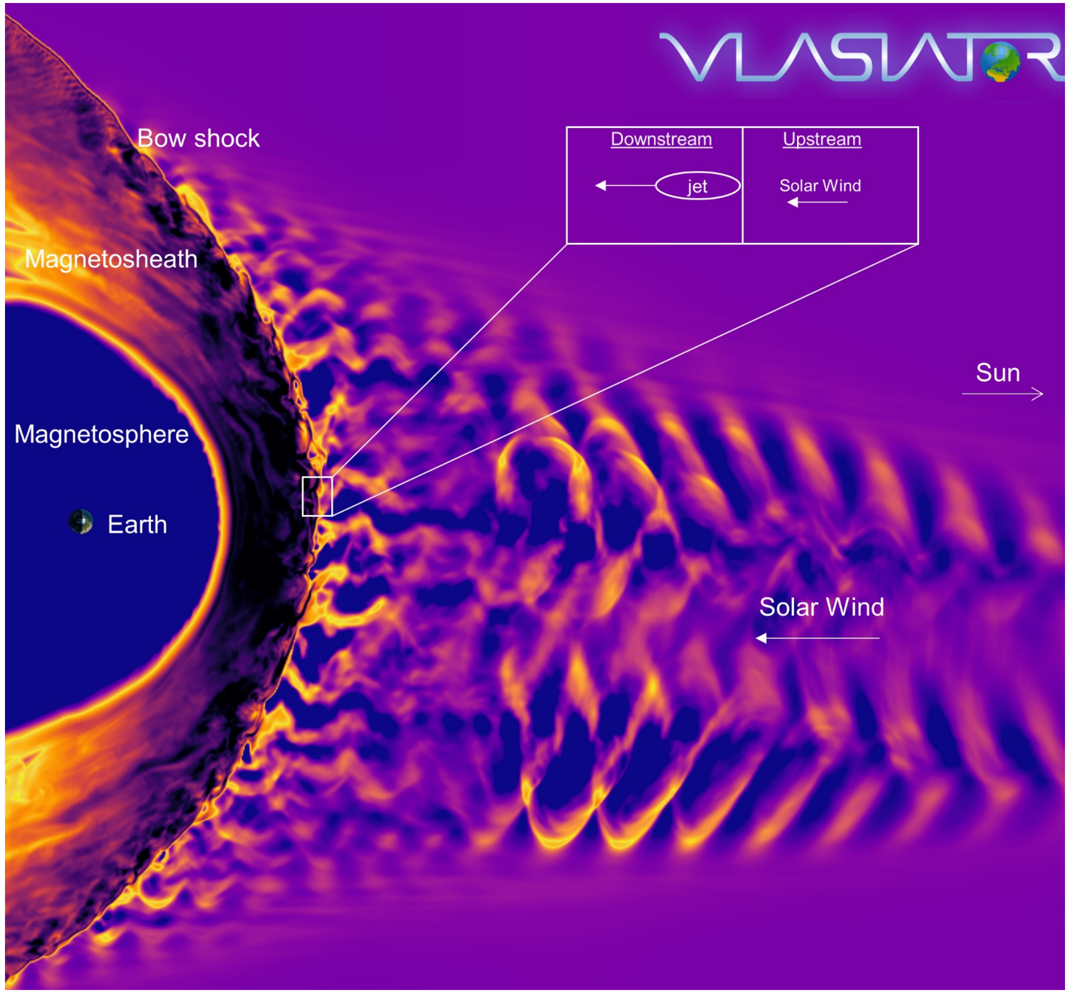
Foreshock structures & plasma jets

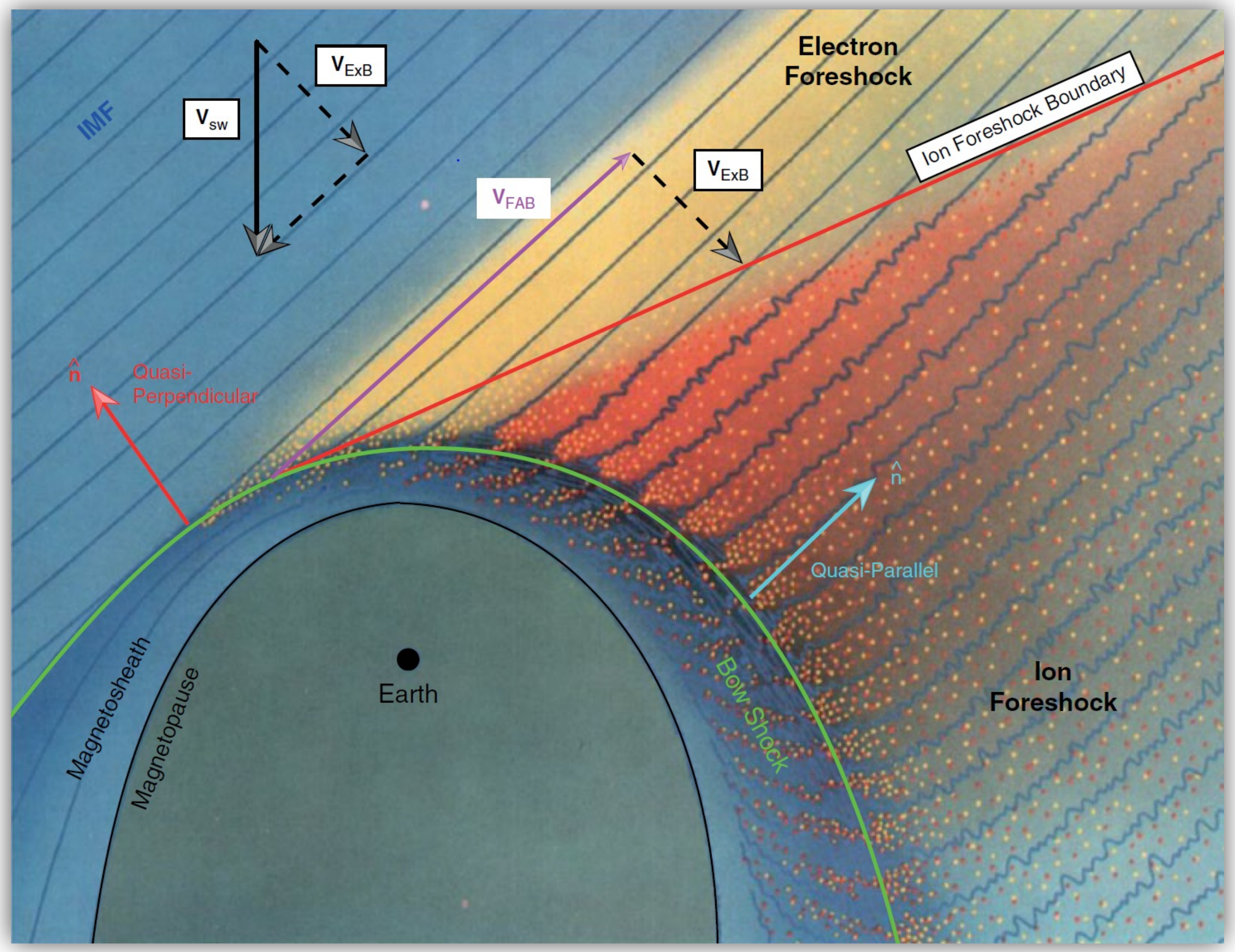


Credits : NASA

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

# Earth’s magnetosphere & shock environment



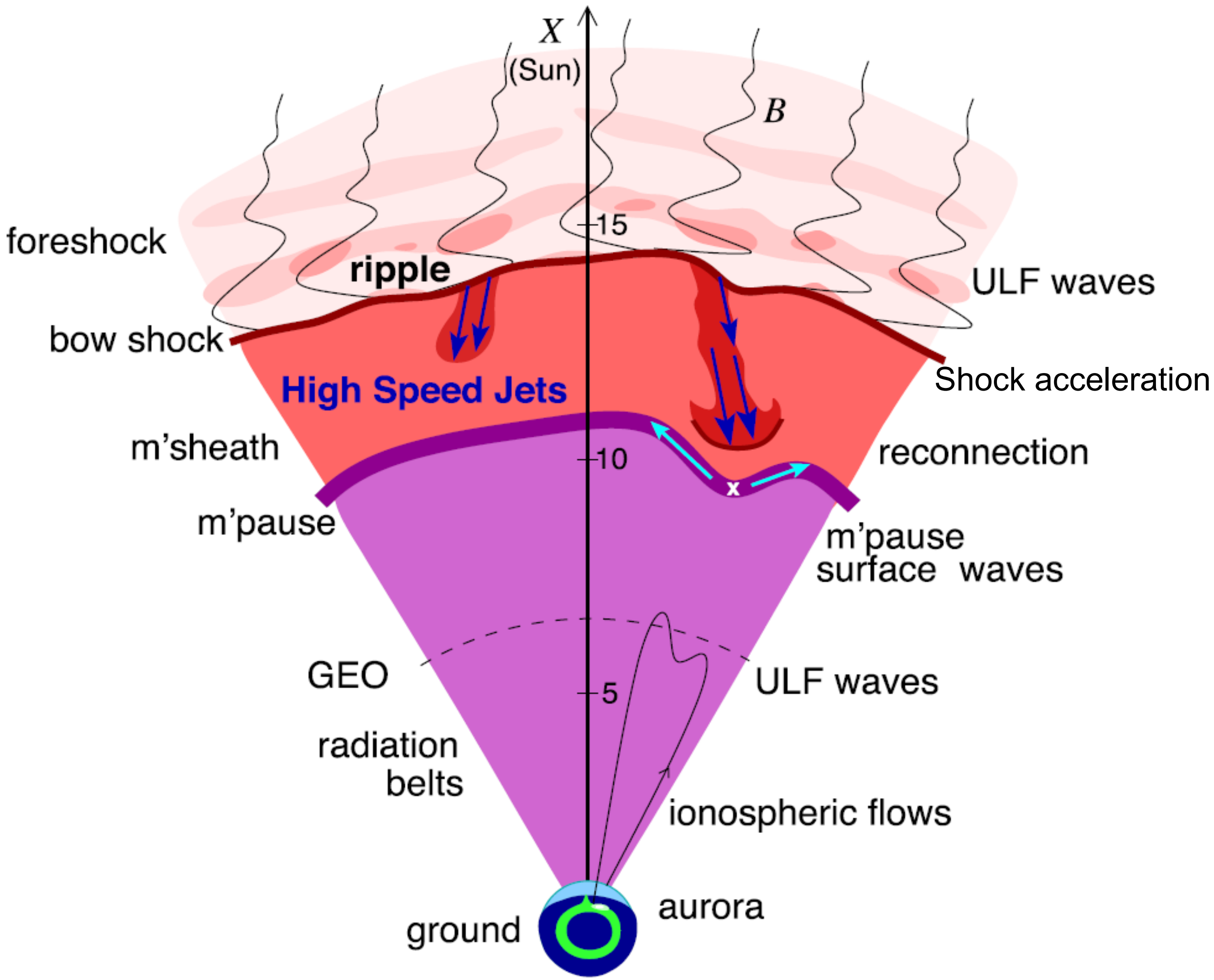




Courtesy of M. Palmroth, U Helsinki

L. B. Wilson (2016)

# Magnetosheath high-speed jets

# Magnetosheath jets




## Definition

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

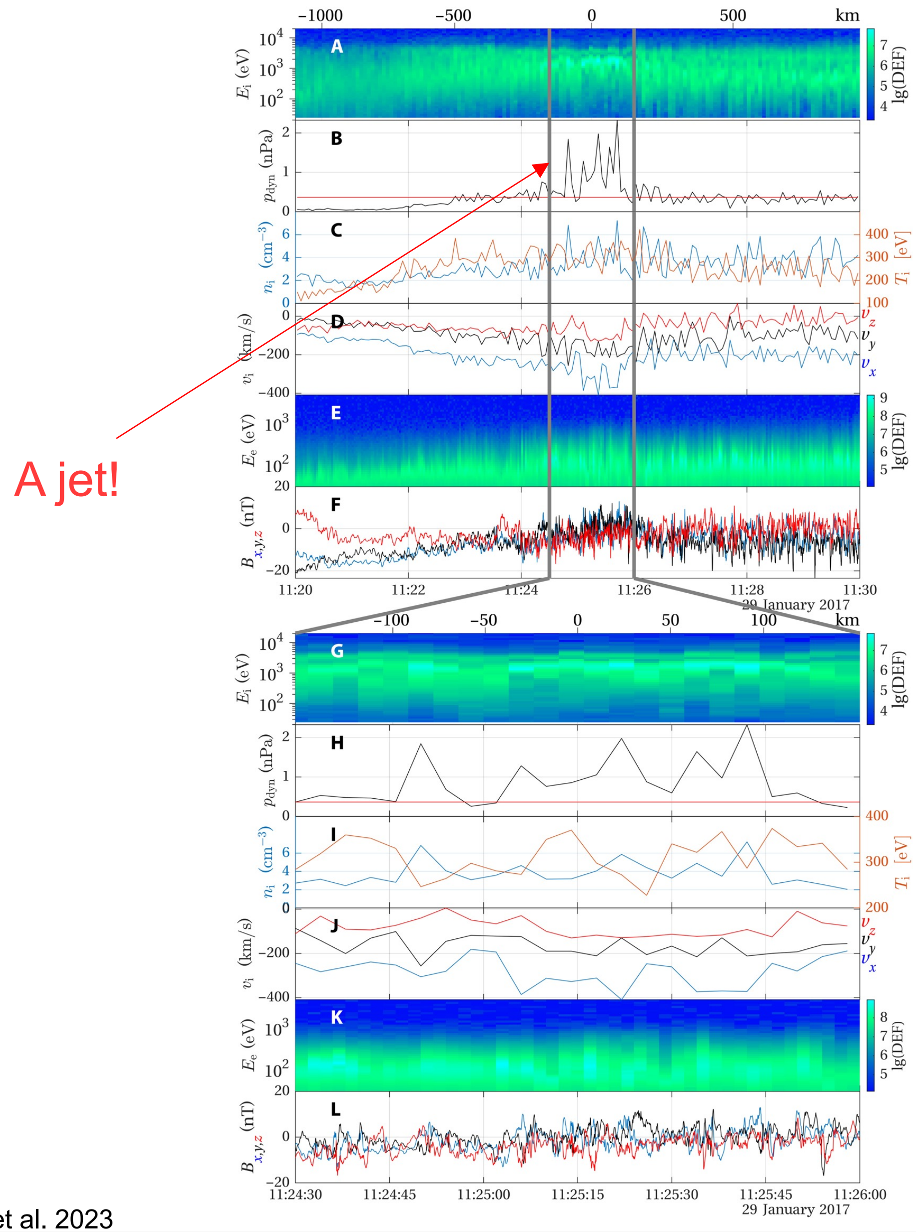
*e.g., 200% dynamic pressure enhancement compared to background magnetosheath*

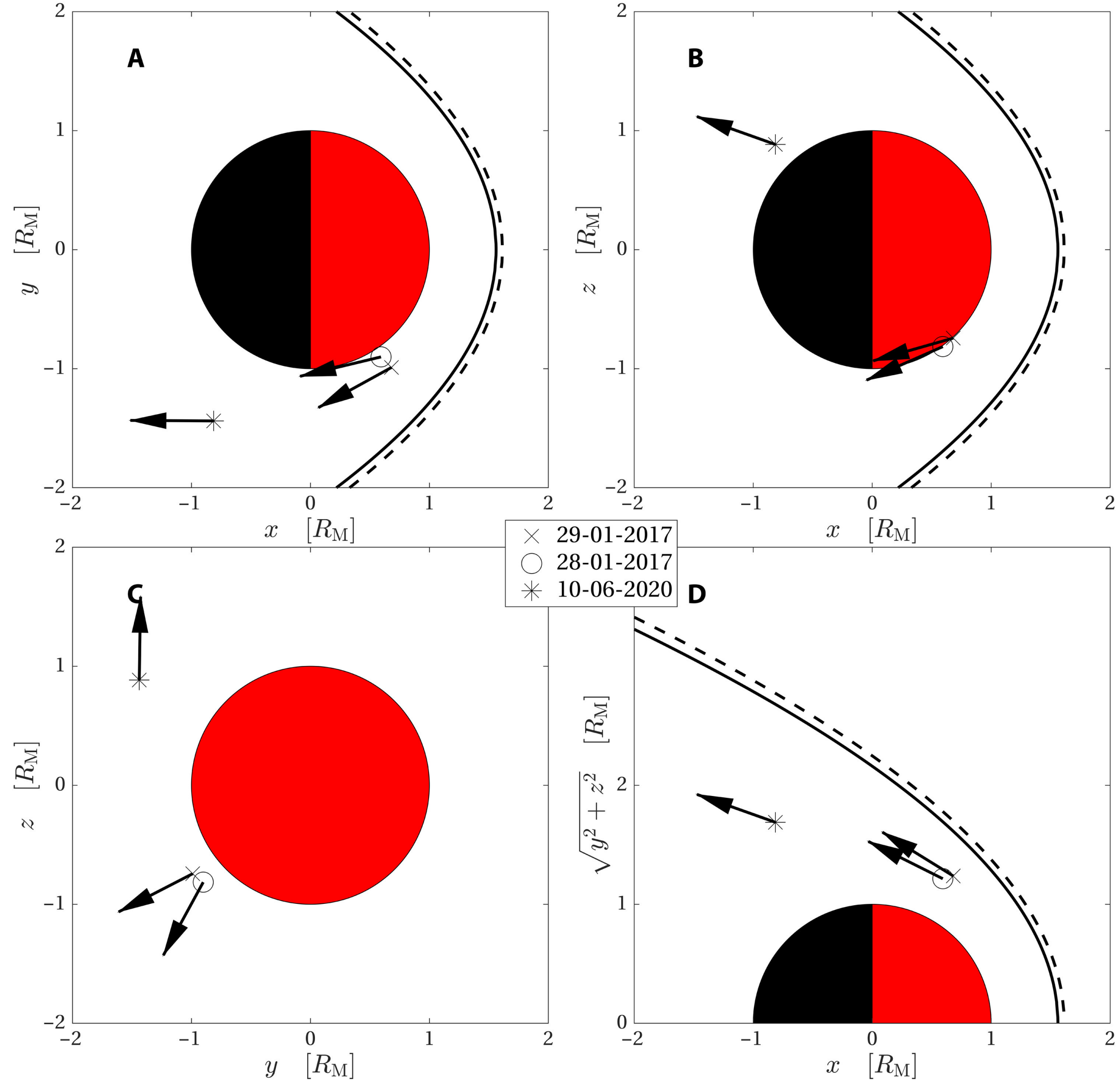
## Related phenomena

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

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

# Jets on other planets (Mars - MAVEN)




Gunell et al. 2023

# 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)
- **Waves** and **jets** using burst MMS data: Krämer et al. (2023)

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.

# Jets – references update (>2019)

Jets Downstream of Collisionless Shocks

Plaschke et al. (2018)

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

→

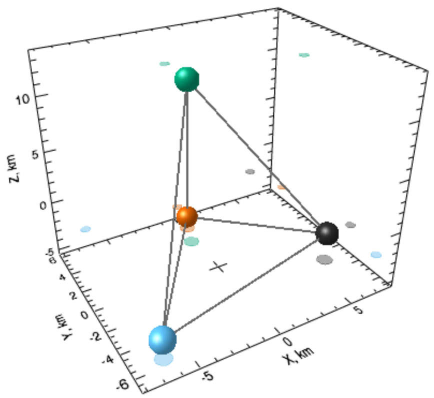
**Jets Downstream of Collisionless Shocks: The Last Five Years**

Ongoing review (TBD)

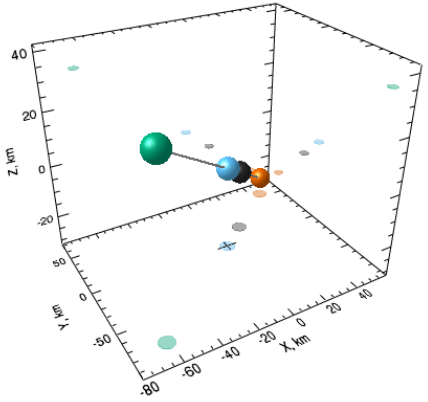
# MMS mission & instrumentation

## Formation

### Tetrahedron

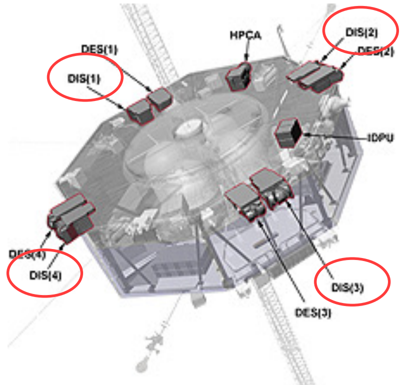


### String-of-pearls

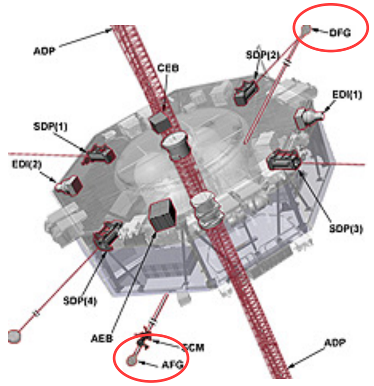


## Instrumentation

### FPI



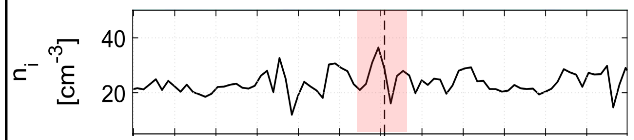

### FGM




## Mode

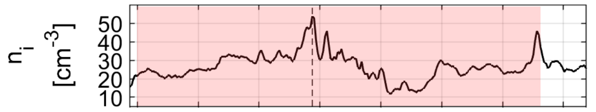
### fast/srvy

FPI (ions): 4.5s
FGM: 0.0625s

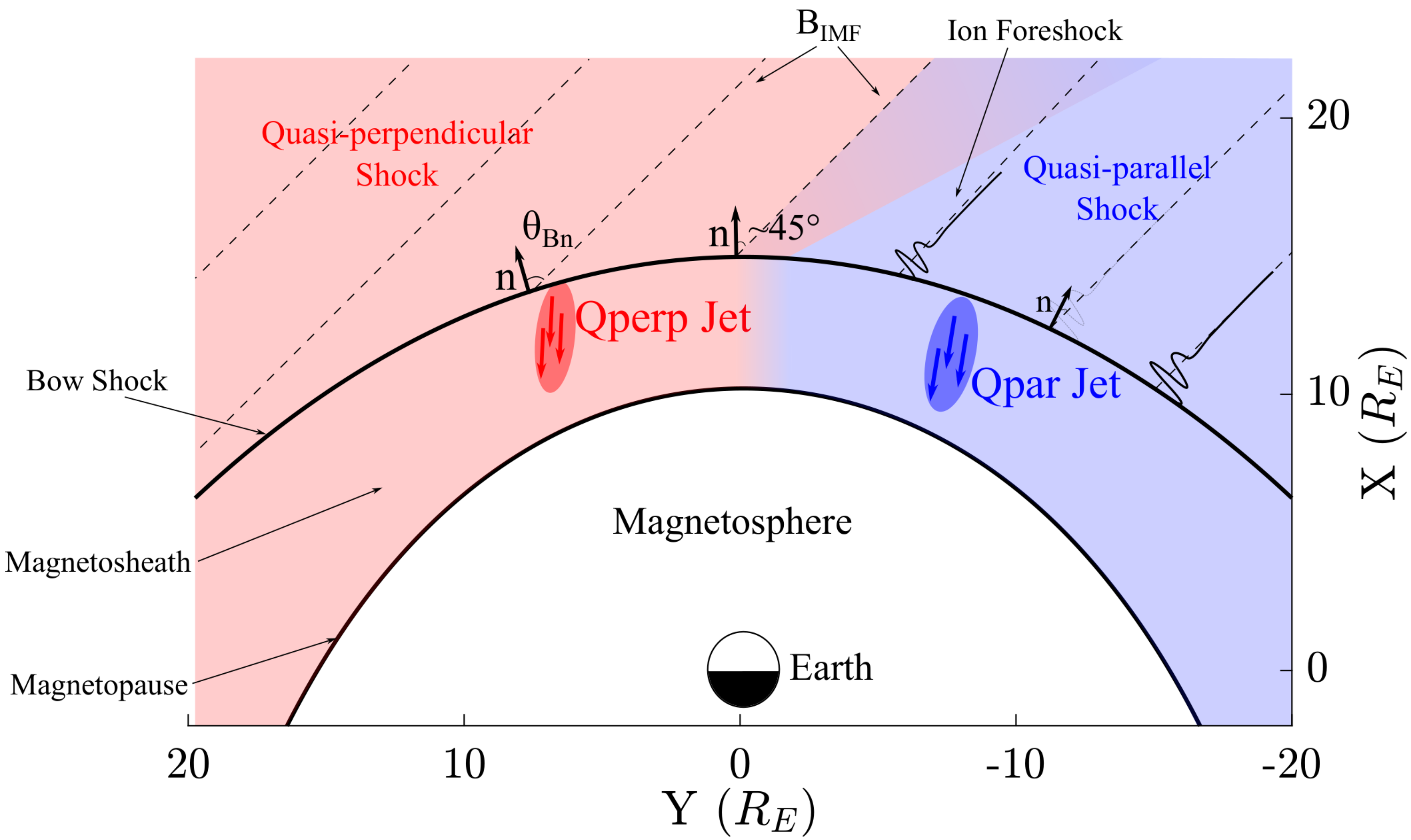


### brst

FPI(ions): 0.15s
FGM: 0.0078s



# Shock, magnetosheath & jet classification

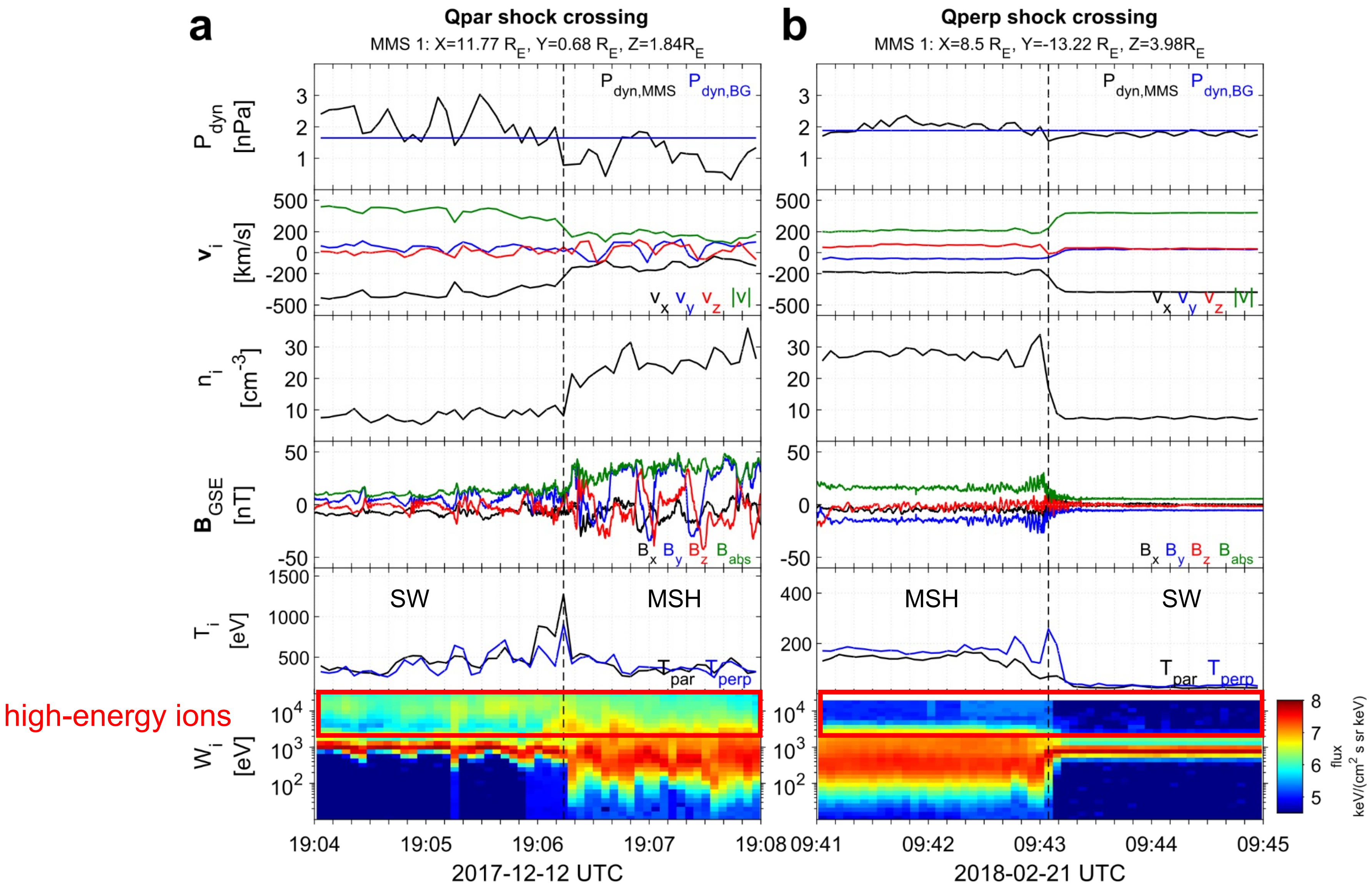



"$\Theta_{Bn}$ is the angle between the IMF and the shock's normal vector"

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

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

# Shock transitions with MMS



# MMS – Updated 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 nature communications

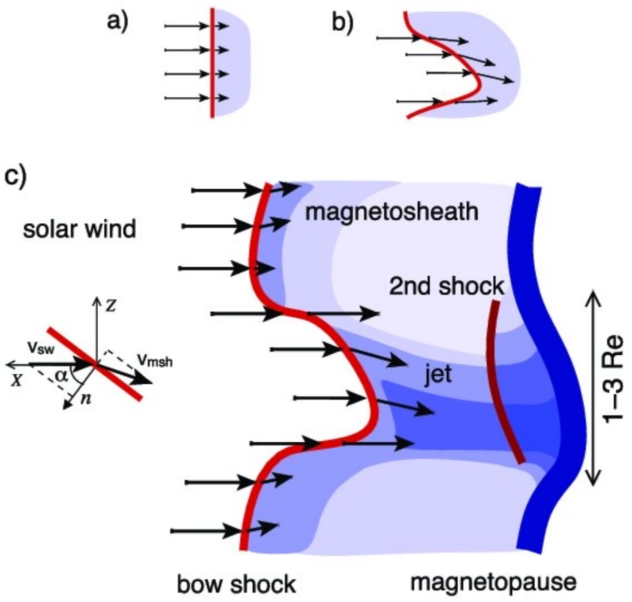
# Recent MMS results

# **Formation** of Jets

Raptis, S., Karlsson, T., Vaivads, A., Pollock, C., Plaschke, F., Johlander, A., ... & Lindqvist, P. A. (2022). Downstream high-speed plasma jet generation as a direct consequence of shock reformation. Nature communications, 13(1), 598.

# How are these jets created (Qpar) ?

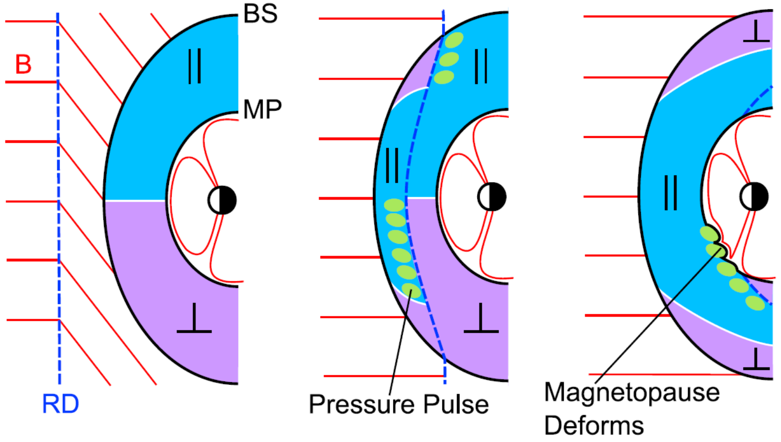
## Shock ripples




SW → locally inclined part of the bow shock → less deceleration and heating

Hietala et al. (2009,2012)

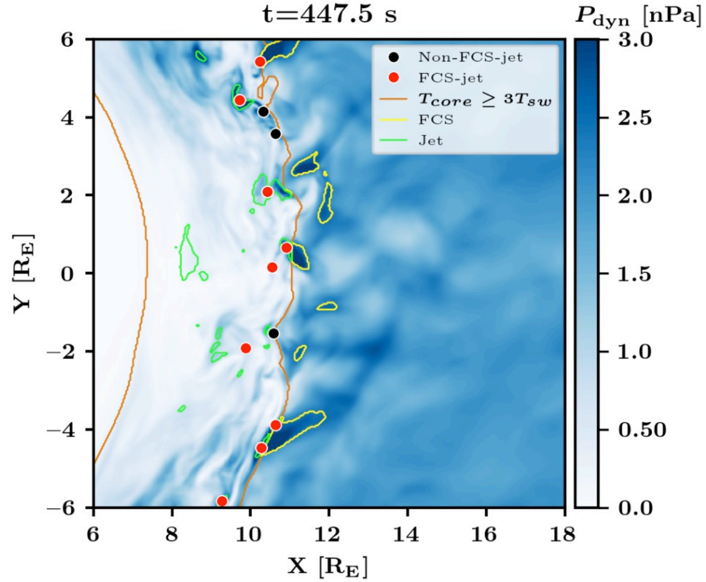
## SW discontinuities




RD → Change in Foreshock position → Pressure pulses

Archer et al. (2012), Zhou et al. (2023)

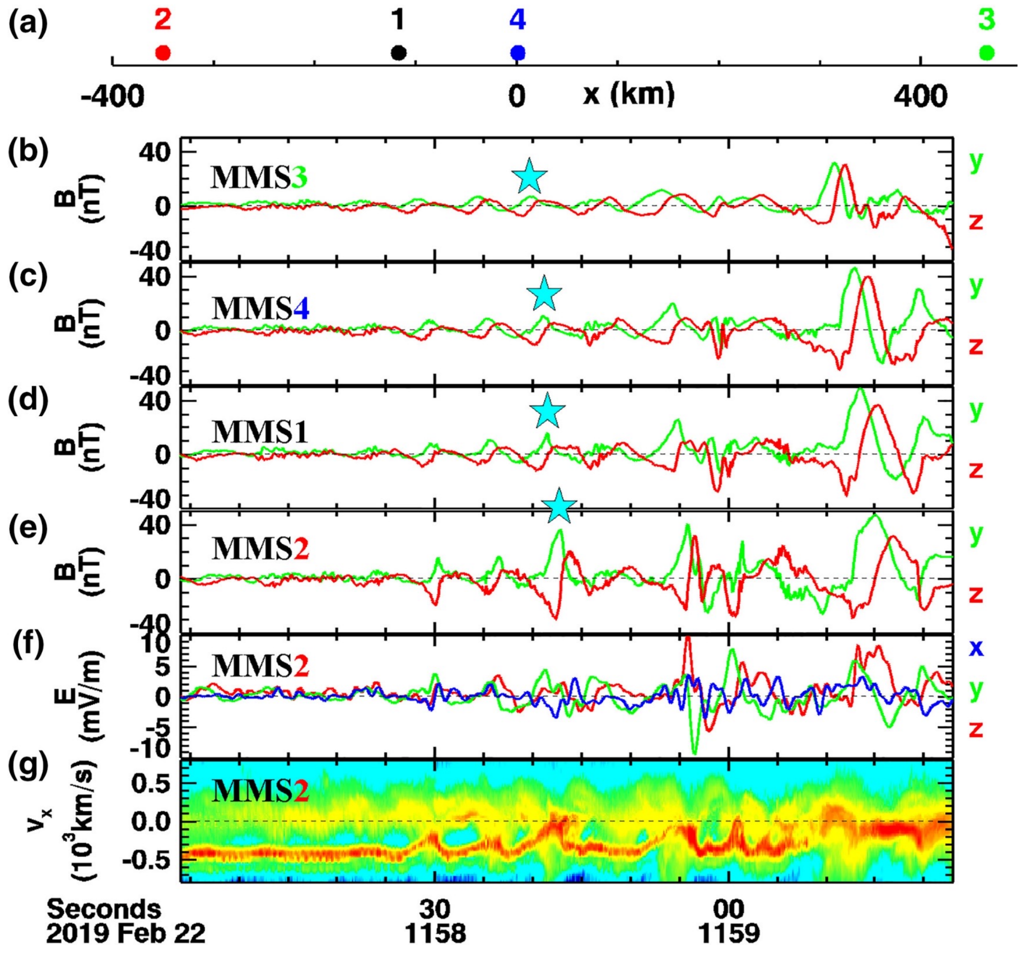
## Foreshock Structures & Reformation



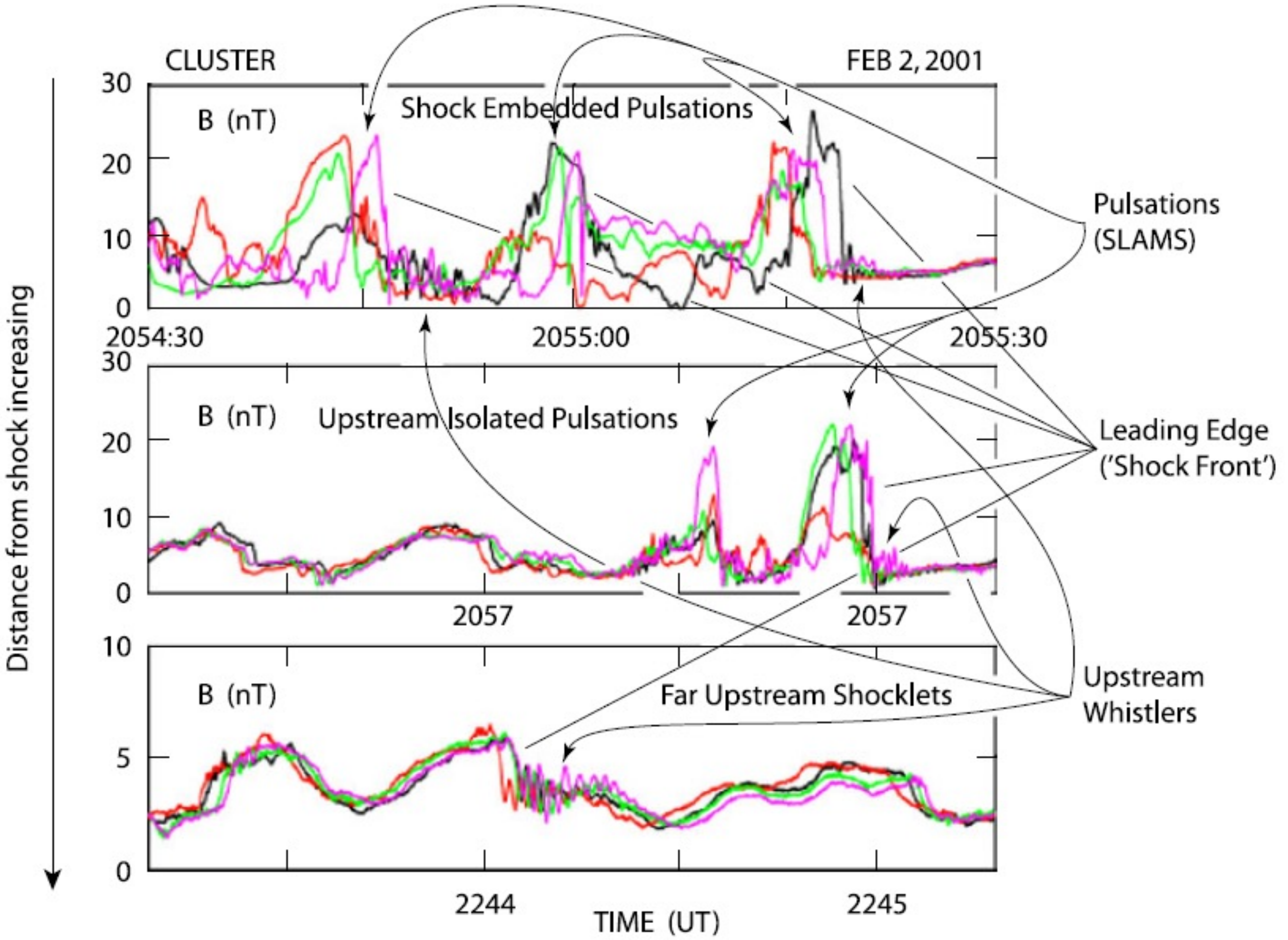

Karlsson et al.(2015), Suni et al. (2021), Omelchenko et al. (2021), **Raptis** et al. (2022a)

# Foreshock & evolution of ULF wavefield

MMS




Cluster



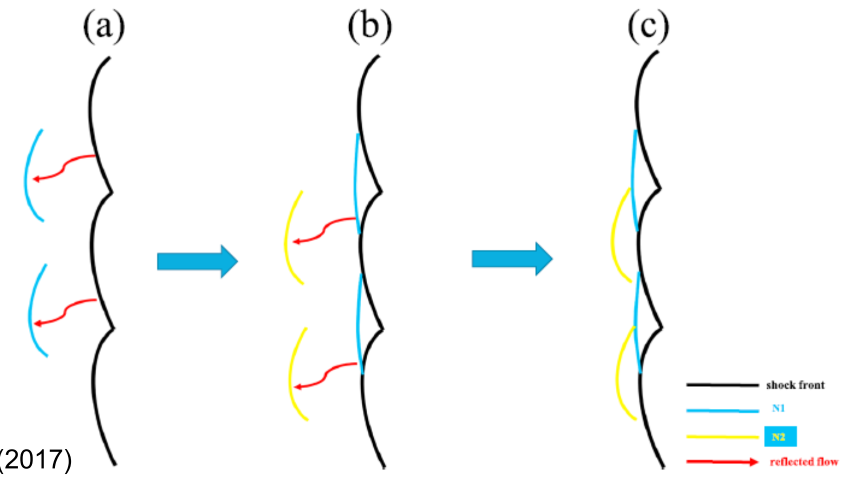

Chen et al. 2021

Lucek et al, 2002

# Quasi-parallel shock reformation

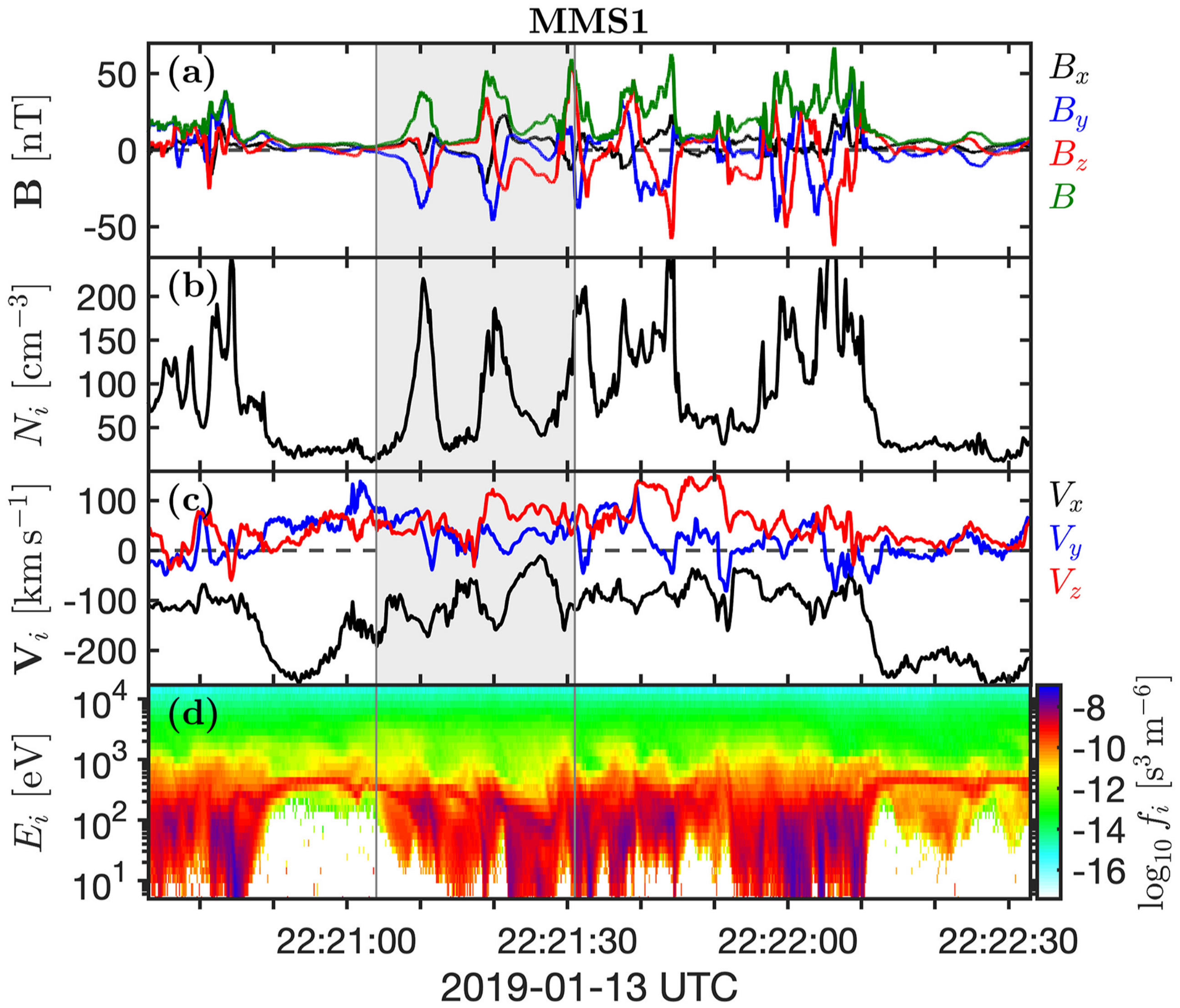
Shock Reformation

*Burgess (1989)*: "the shock exhibits a cyclic behavior ….. cyclic shock reformation;"




Hao et al. (2017)

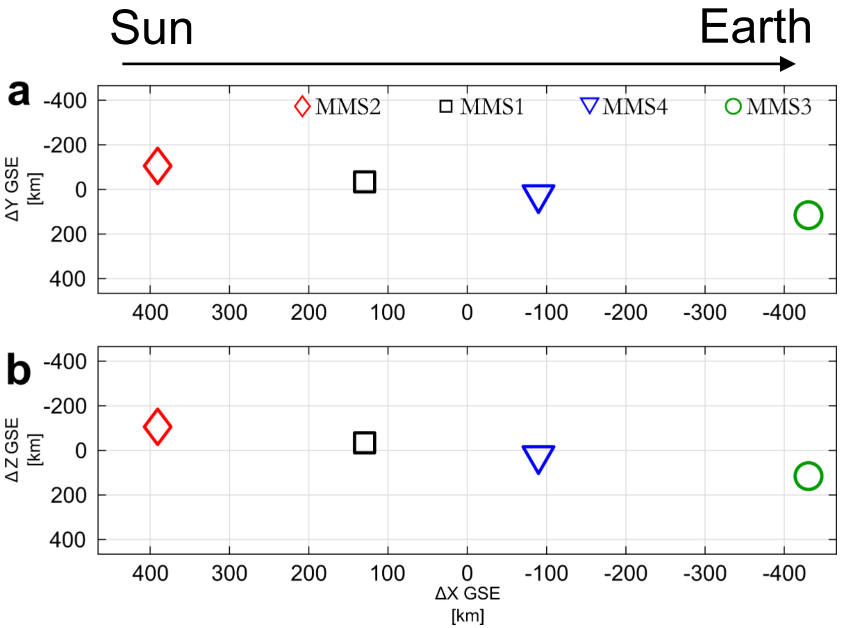
**Figure 11.** The sketch for evolution of shock front. (a) A rippled shock front, (b) a plane shock front, and (c) a rippled shock front. Solid lines and red arrows denote shock front and reflected beams, and N1 and N2 indicate new shock fronts.

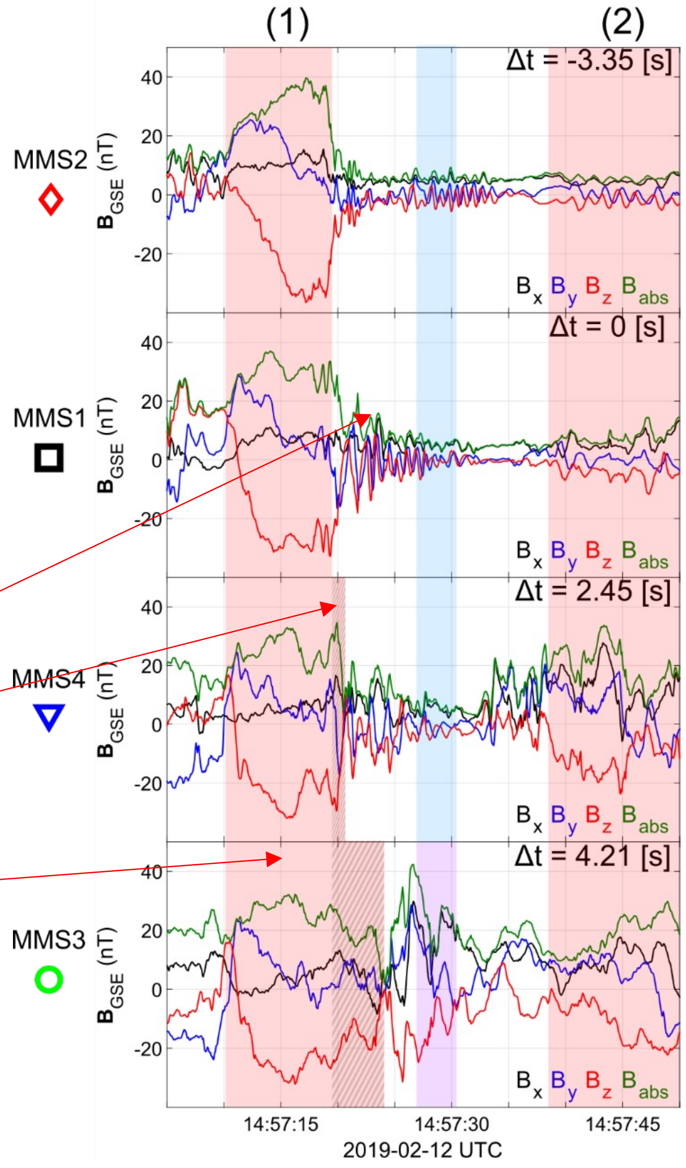



Similar definitions : Hao et al. (2016,2017), Liu et al. (2021), Johlander et al. (2022), Raptis et al. (2022a)

Johlander et al. (2022)

# SLAMS – wave activity and reformation



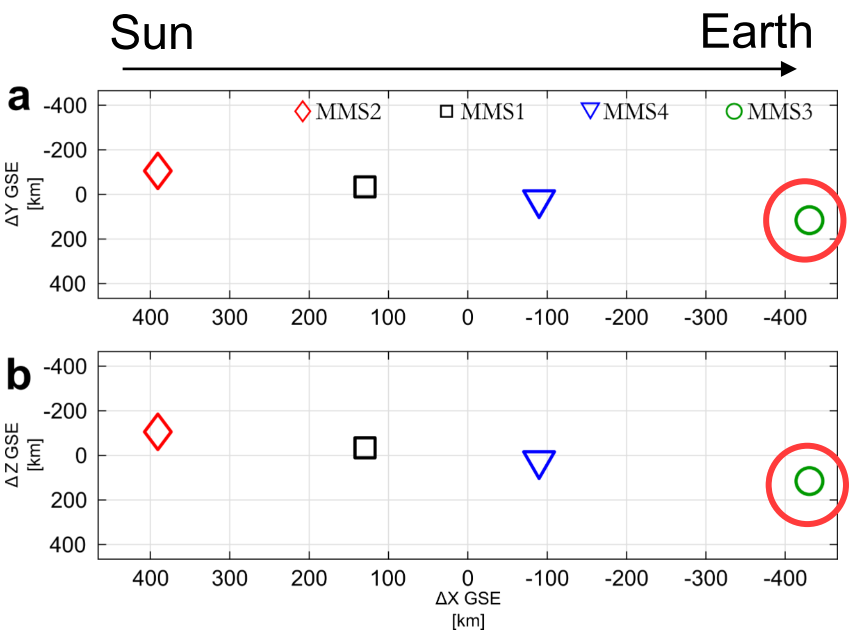

Evolution of SLAMS

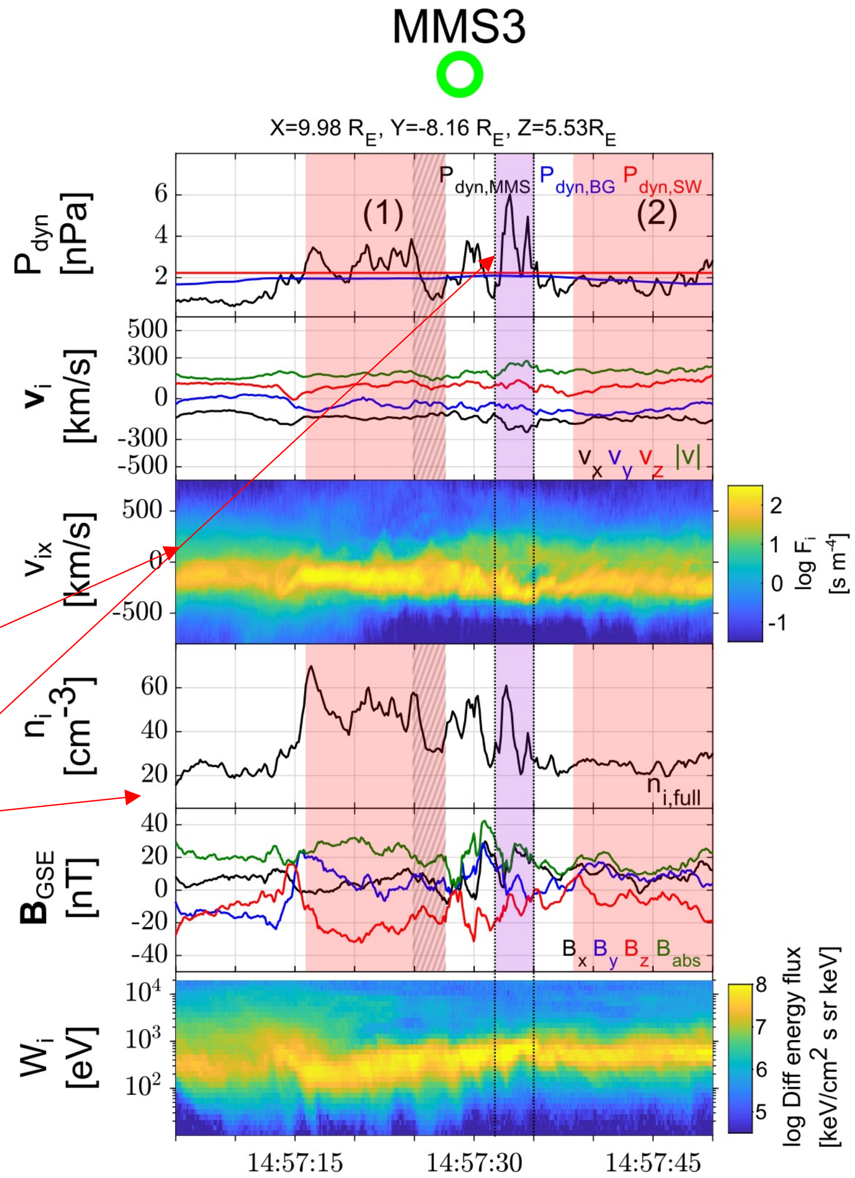
- Interaction with upstream whistler
- New peak /evolution*
- Formation of *downstream density enhancement***

* 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*

# Jet “slipping through” the reformation cycle



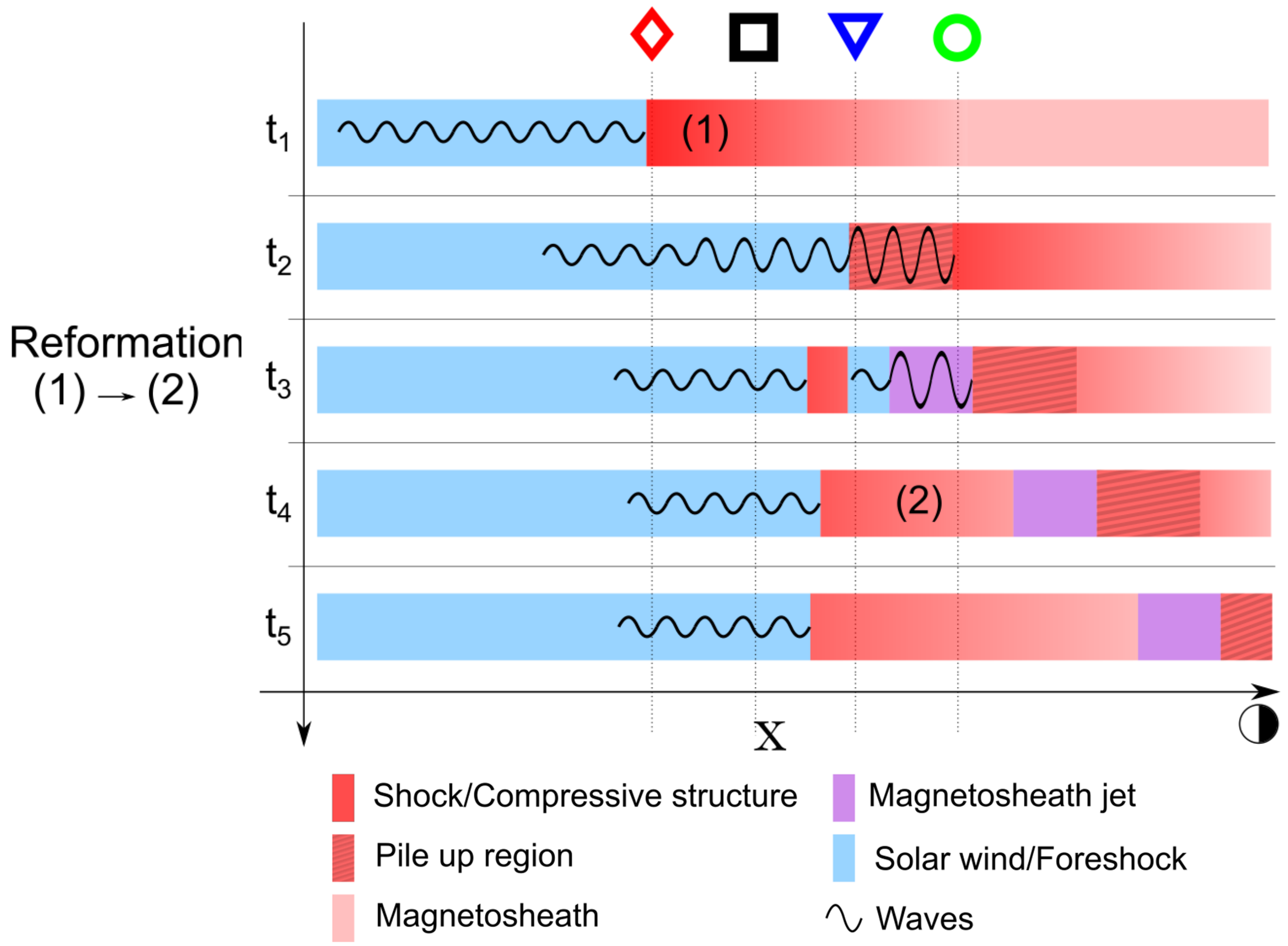



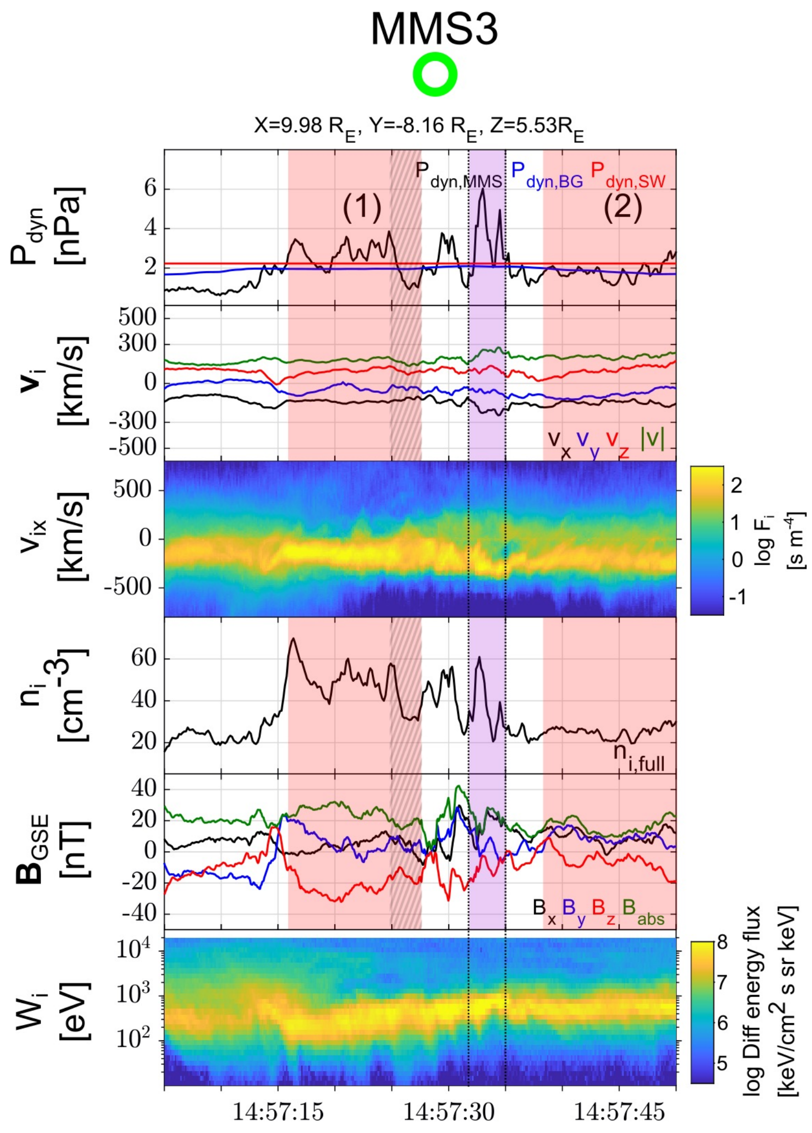

## Properties

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

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

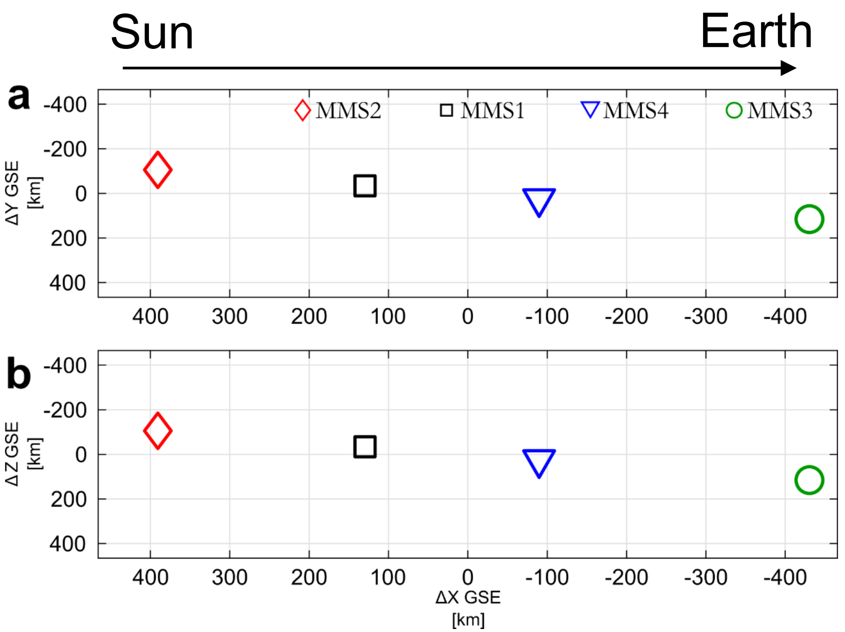
# Shock reformation & magnetosheath jets

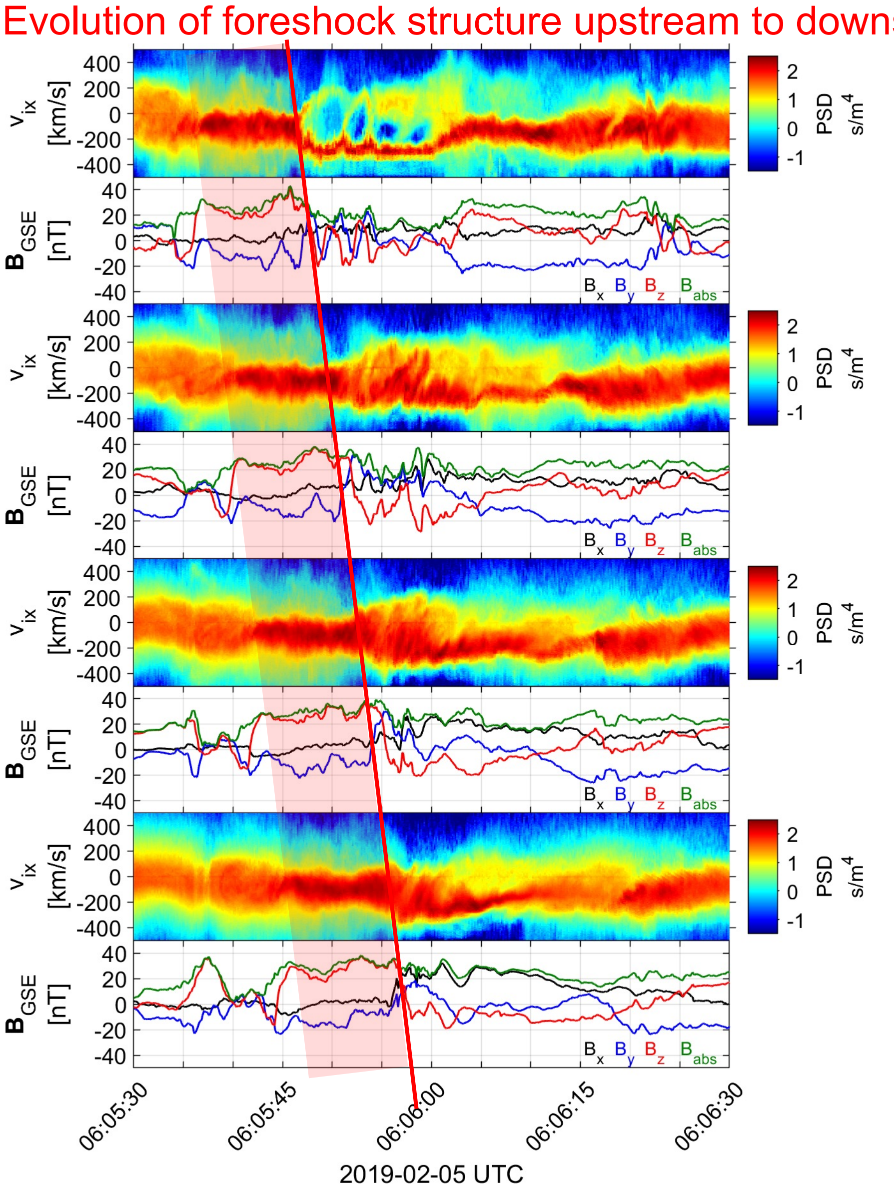



**Raptis S.**, et al. 2022a | Nat. Commun.

# More events ( MMS 1 – 4)

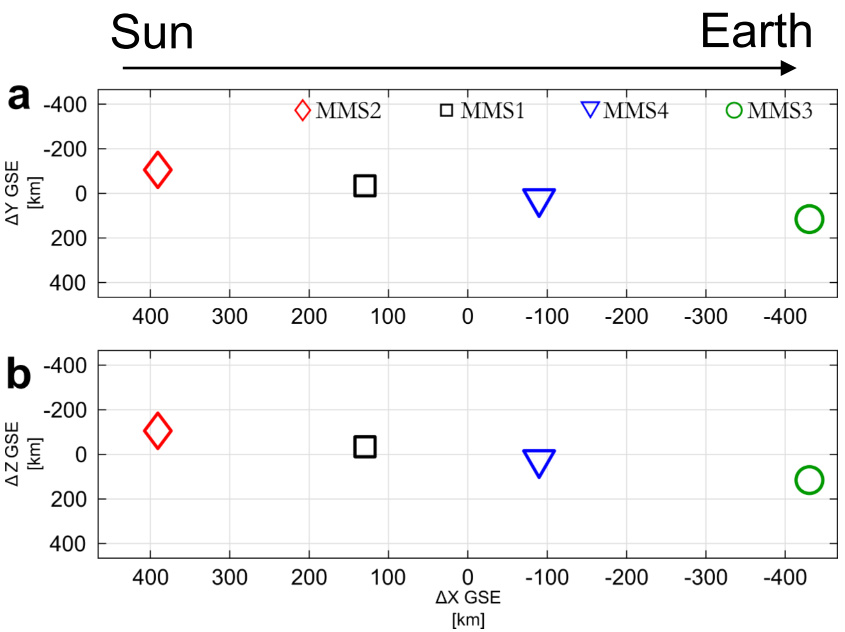


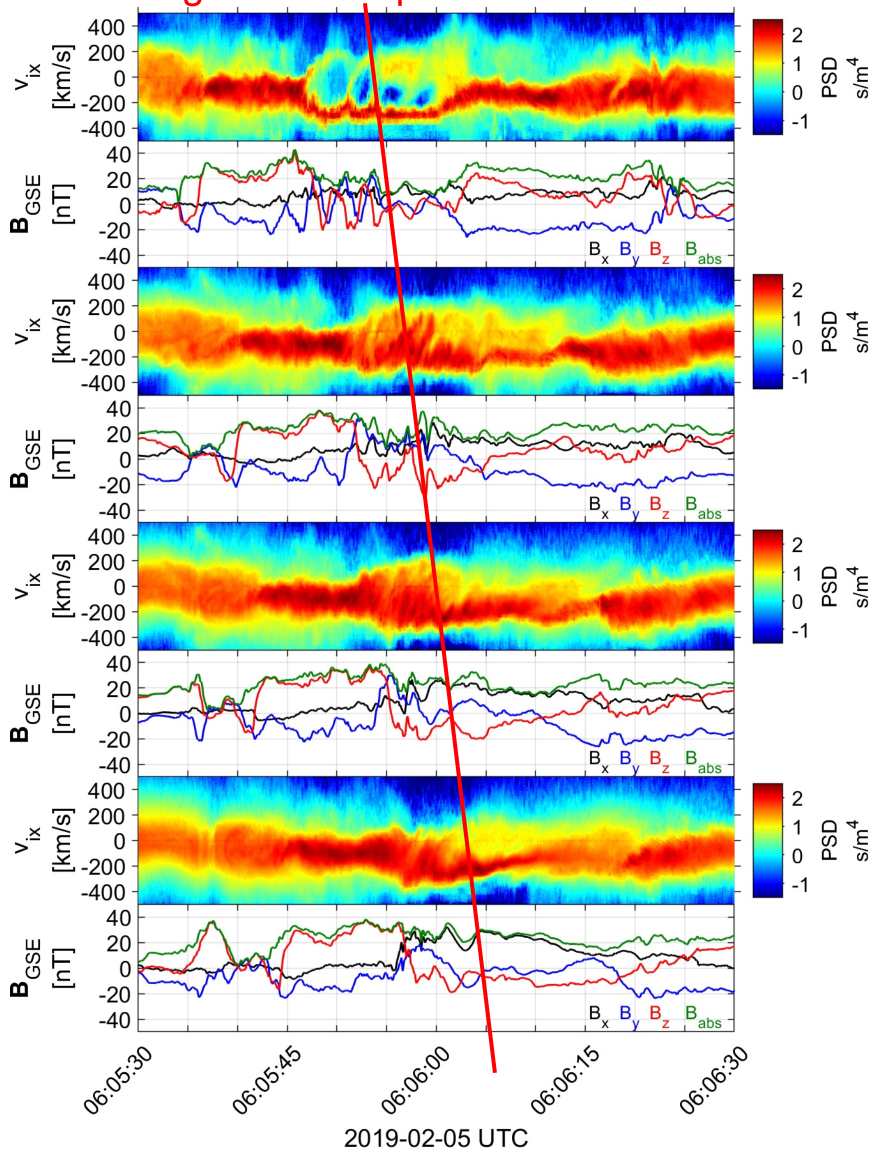

Raptis+ 2023 (Ongoing)

+Very promising comparison results with VLASIATOR Hybrid simulations (soon….)

# More events ( MMS 1 – 4)




Jet forming from the upstream wave field & the reformation




Raptis+ 2023 (Ongoing)

+Very promising comparison results with VLASIATOR Hybrid simulations (soon….)

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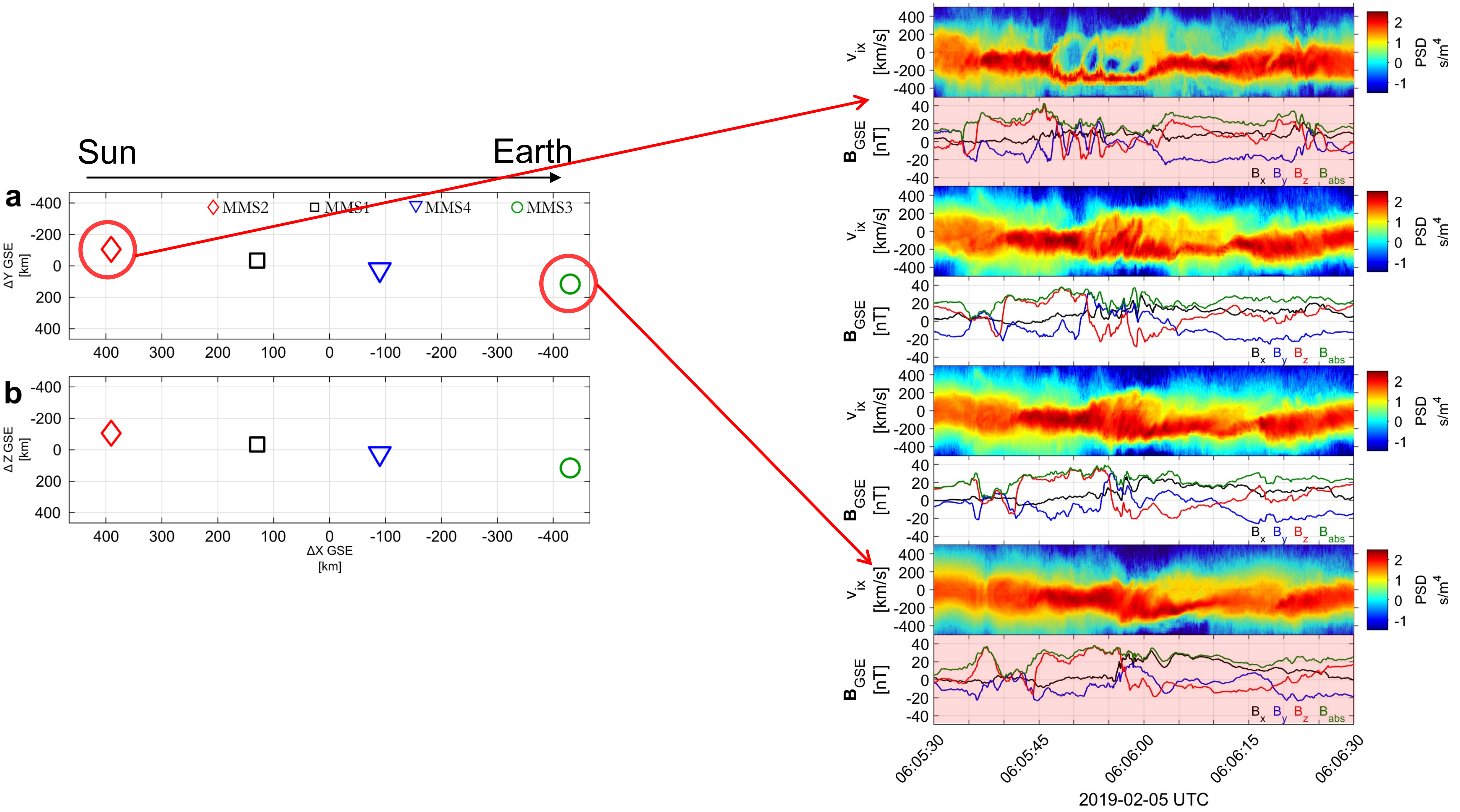
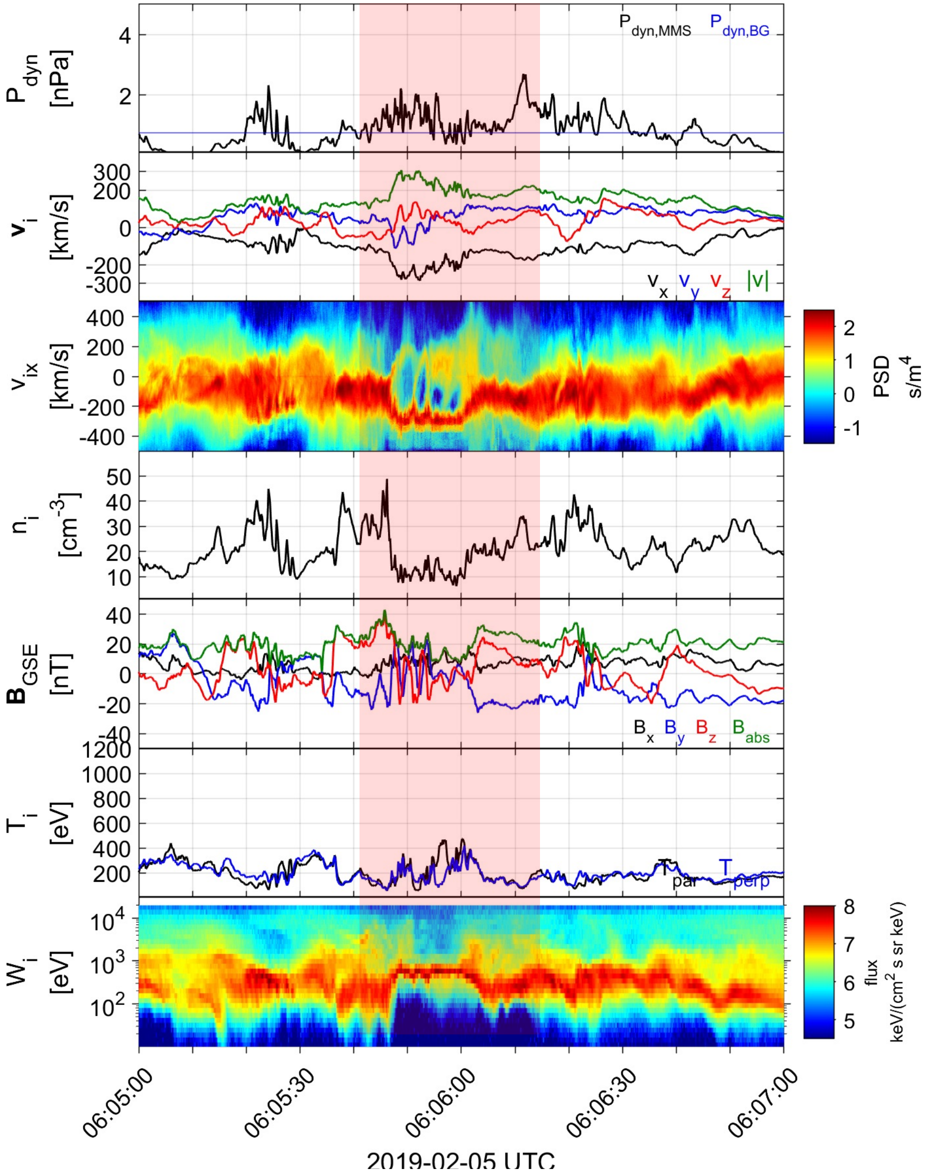



Raptis+ 2023 (Ongoing)

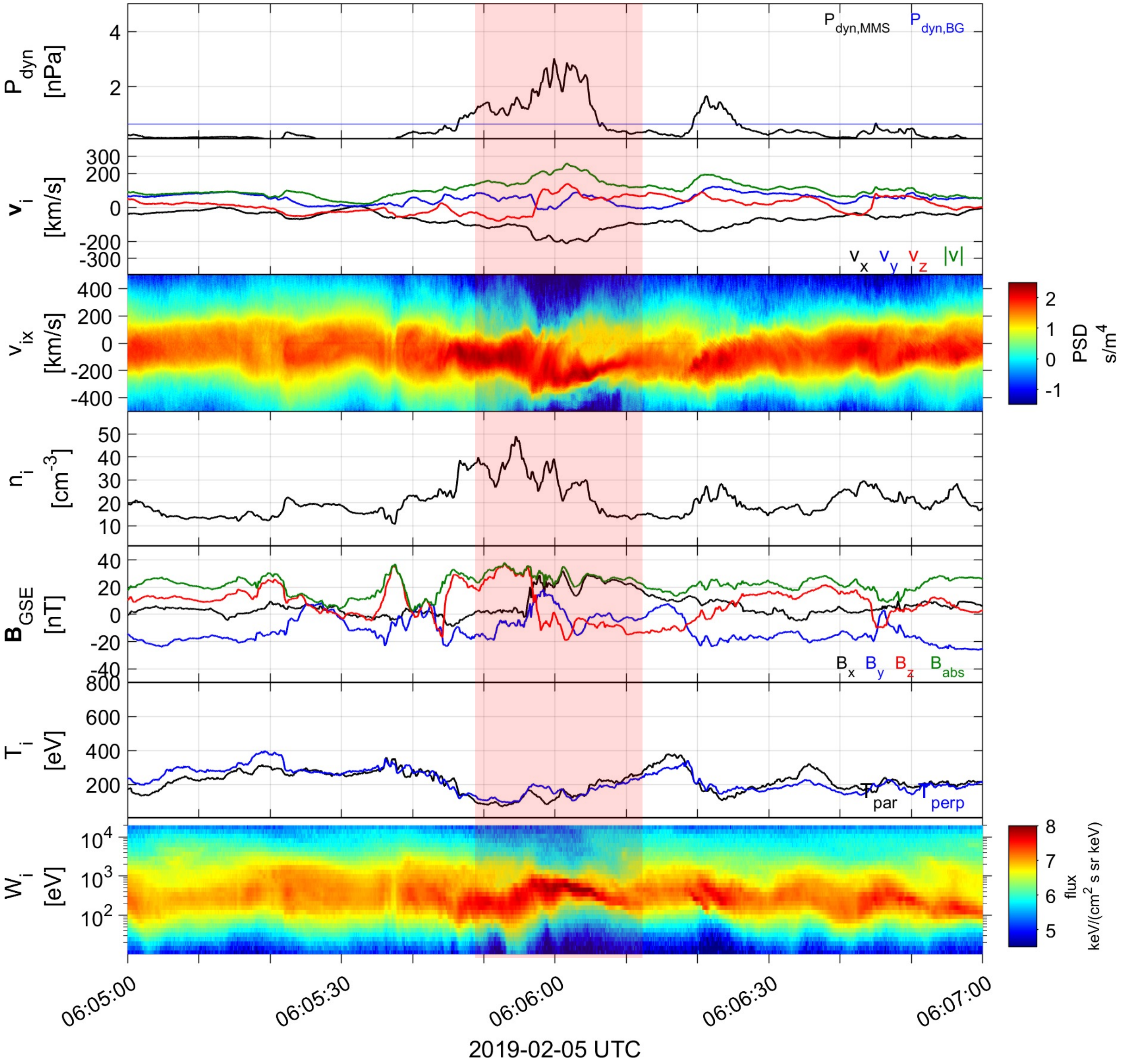
+Promising comparison results with VLASIATOR Hybrid simulations….

# More events ( MMS 2 & 3)




Upstream

Downstream




+Promising comparison results with VLASIATOR Hybrid simulations….

Raptis+ 2023 (Ongoing)

# Recent MMS results

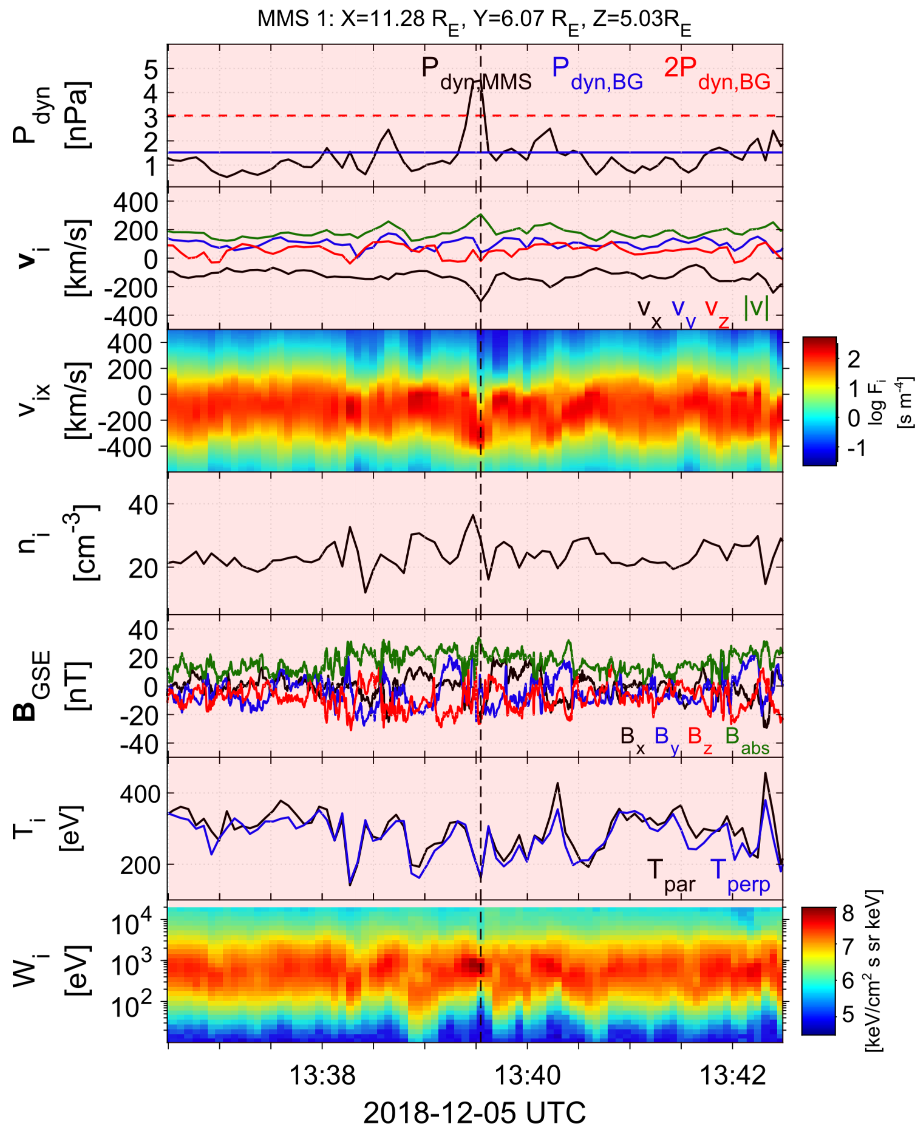
# **Evolution & Properties** of Jets

Raptis, S., Karlsson, T., Vaivads, A., Lindberg, M., Johlander, A., & Trollvik, H. (2022). On magnetosheath jet kinetic structure and plasma properties. Geophysical Research Letters, 49(21), e2022GL100678.

# Qpar magnetosheath jet – *fast* data

<u>Qpar magnetosheath:</u>

- High energy ions
- Low temperature anisotropy
- High **B** Variance




<u>Magnetosheath jet</u>

$|V| \uparrow$

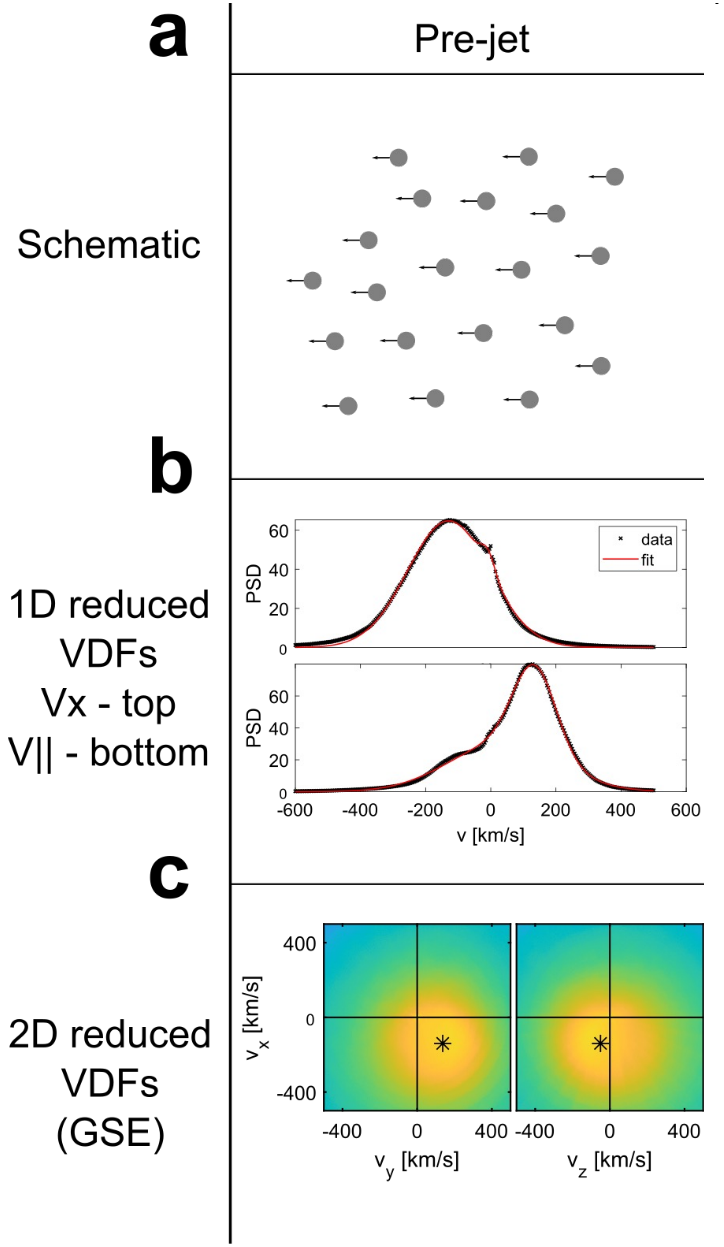
$V_x \uparrow$

$n \uparrow$

$$P_{dyn} > 2\ P_{dyn,BG}$$

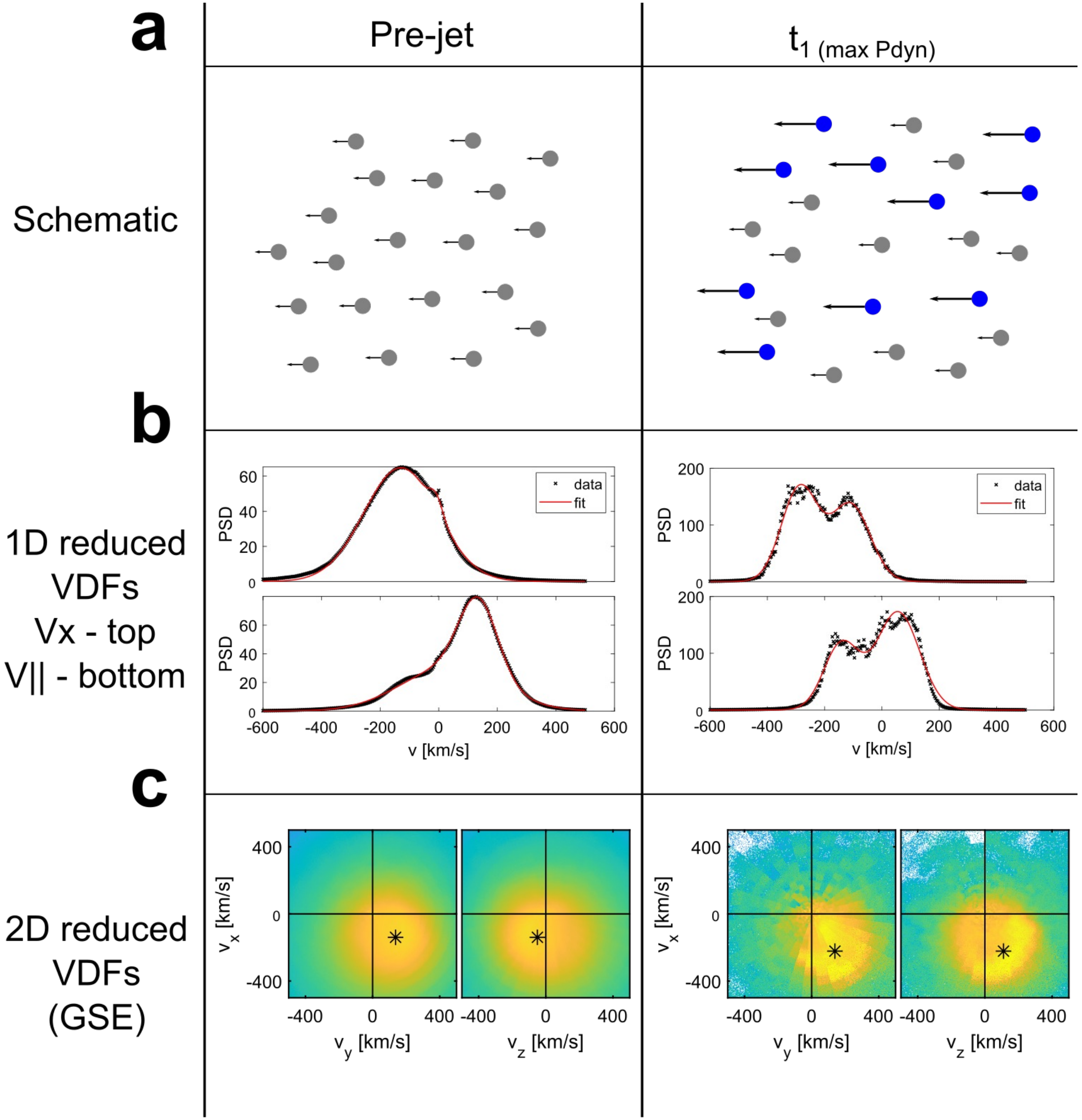
**Raptis** S, et al,. 2022b | GRL

# Jet evolution in Qpar magnetosheath



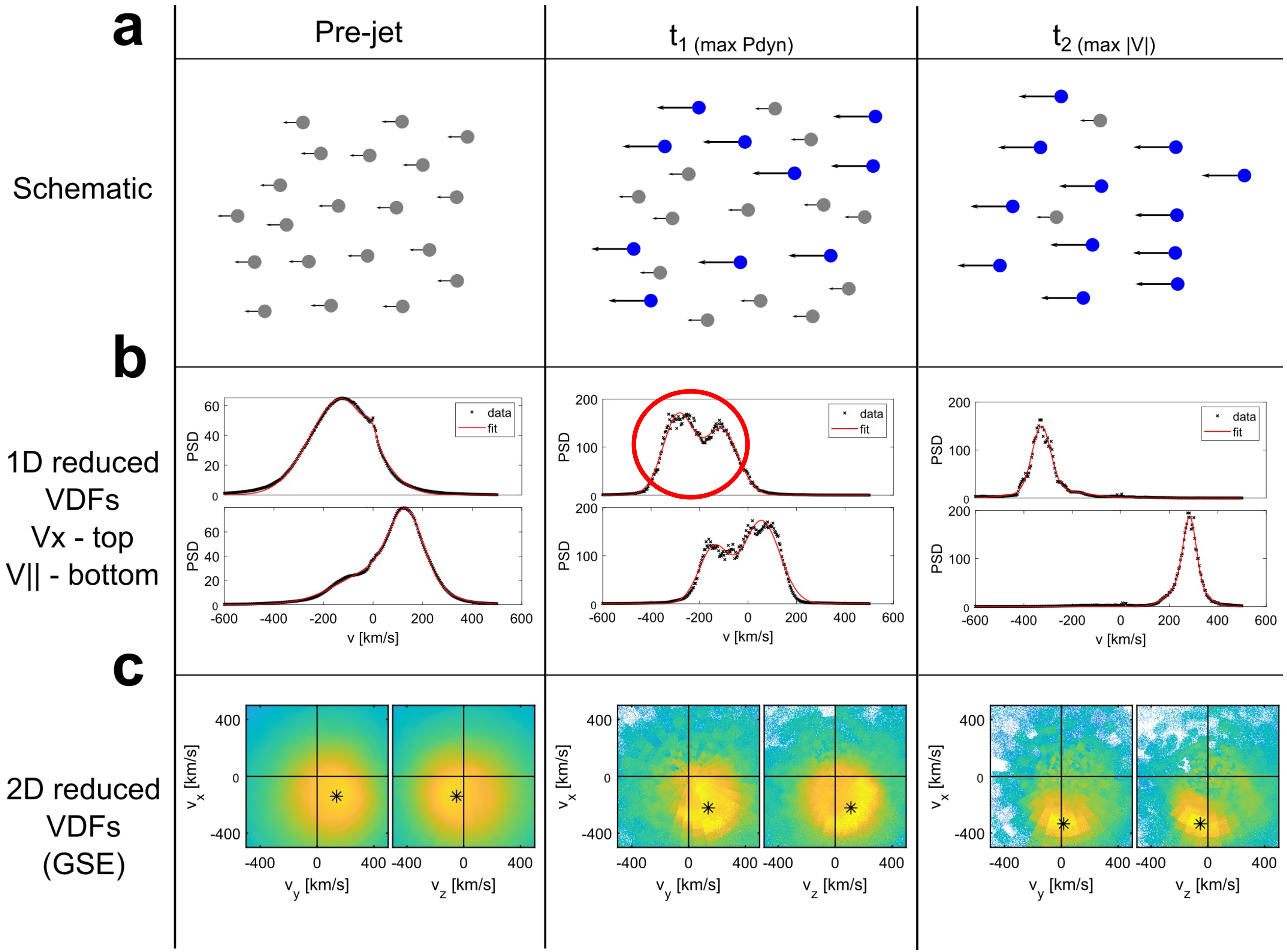

**Raptis** S, et al,. 2022b | GRL

# Jet evolution in Qpar magnetosheath




**Raptis** S, et al,. 2022b | GRL

# Jet evolution in Qpar magnetosheath

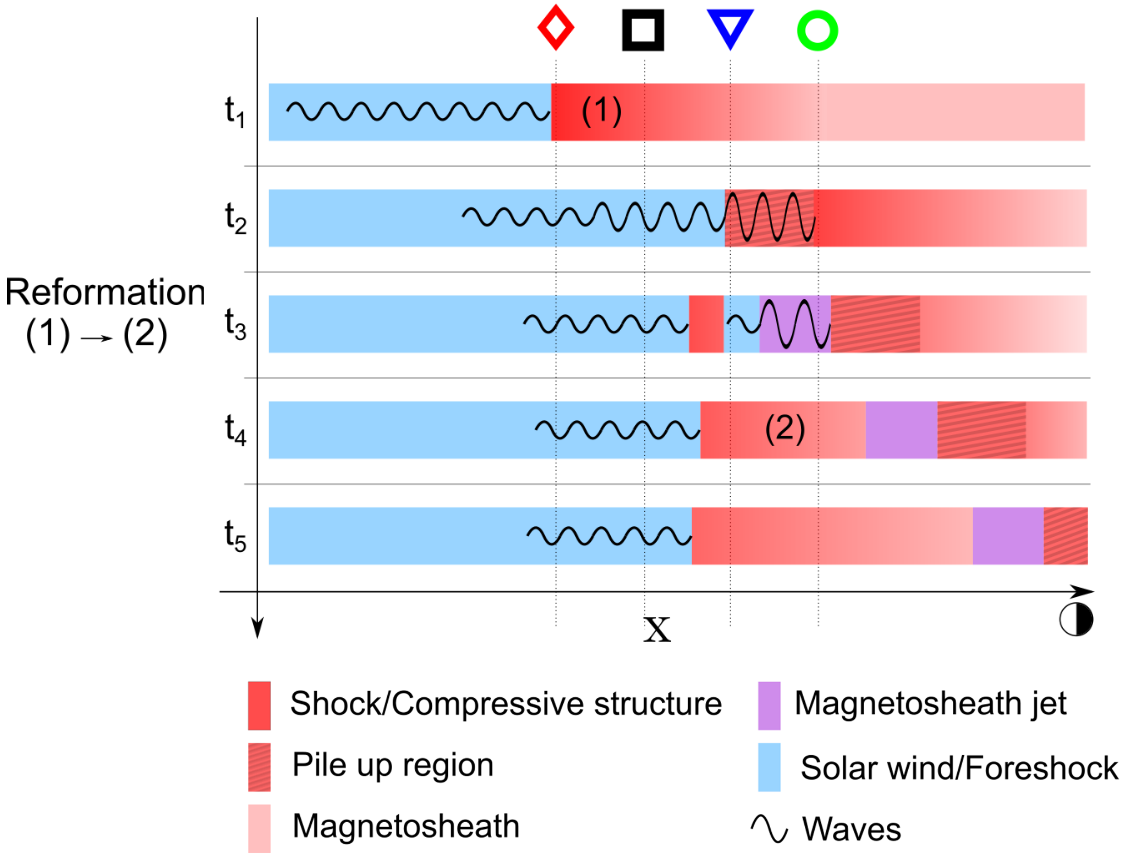



**Raptis** S, et al,. 2022b | GRL

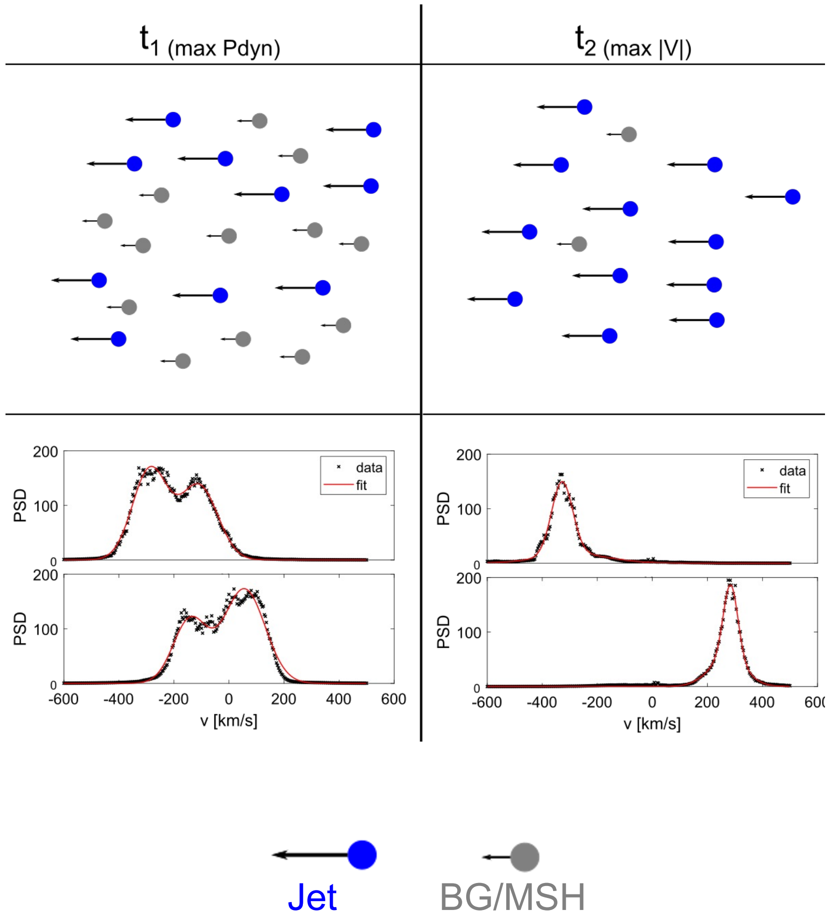
# Summary & Future

# Summary

*Jets forming from shock's fundamental non-stationarity*

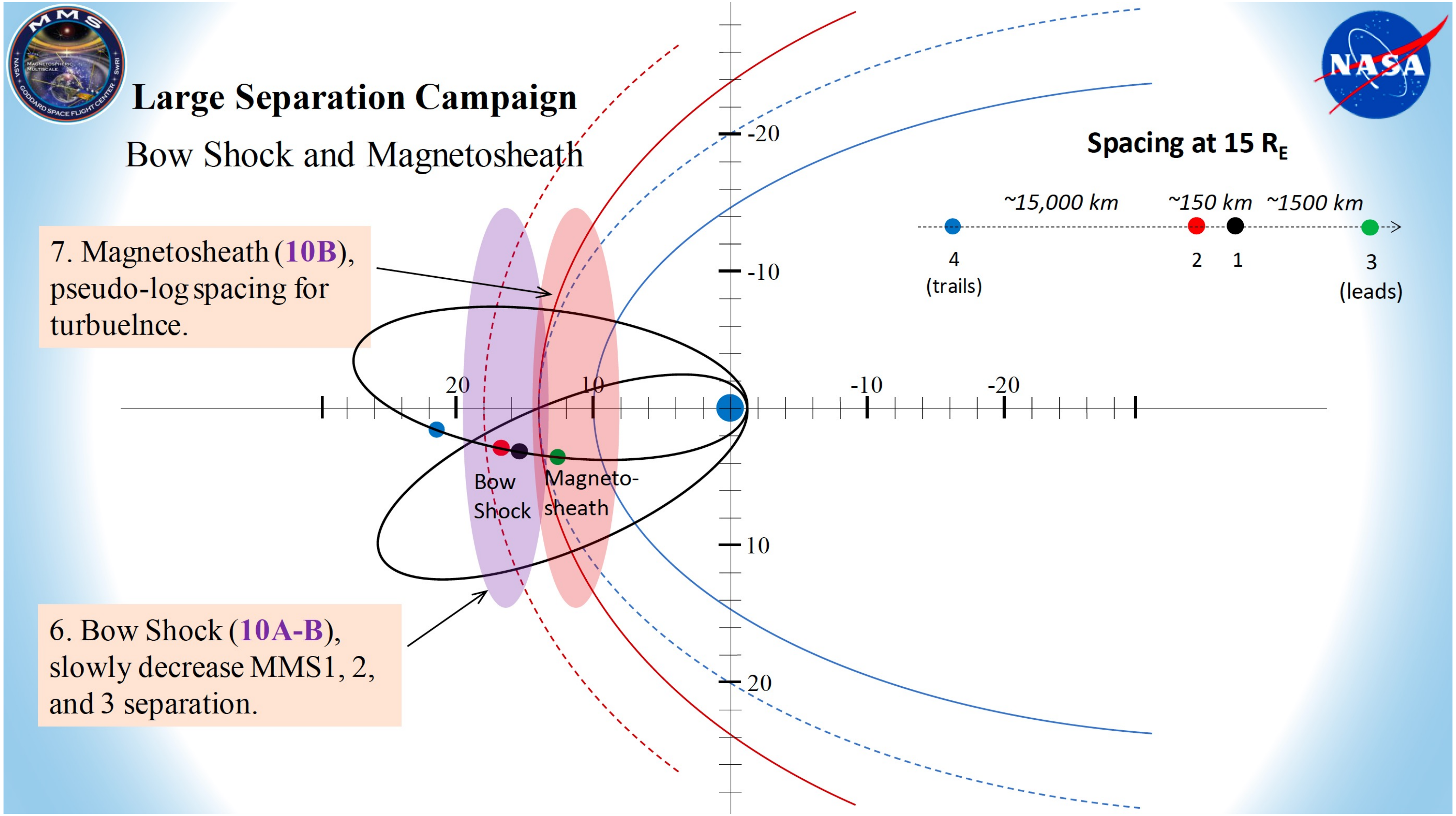



*Jets exhibiting 2+ populations = Partial moments needed = Very similar to upstream SW*

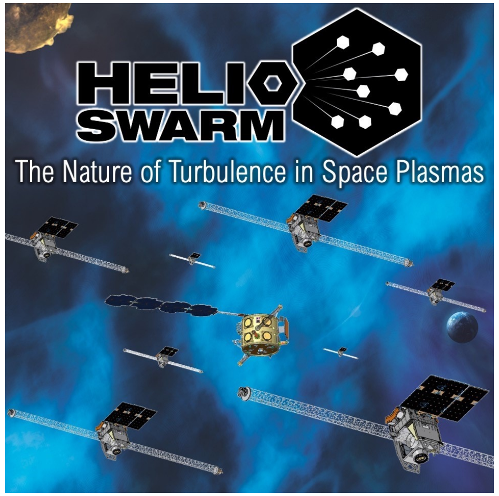


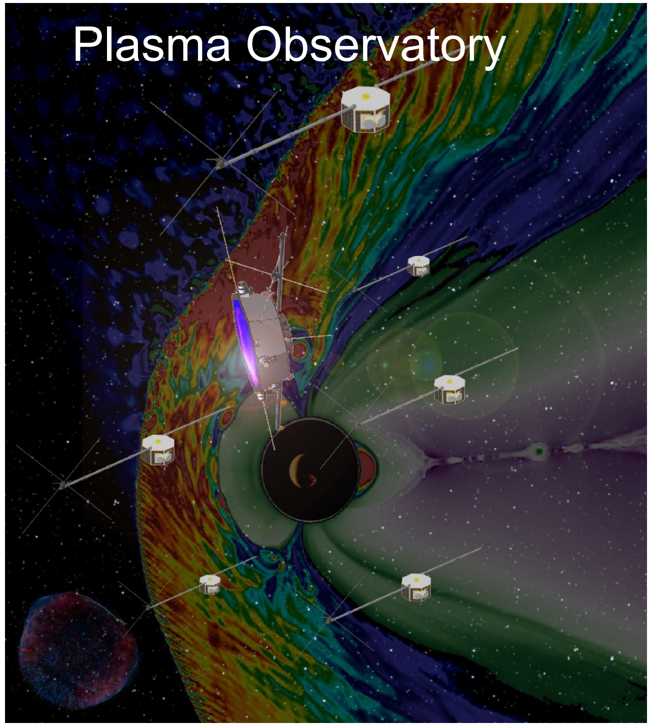

**Shocks, magnetosheath, fast plasma flows, foreshock transients etc. = kinetic structures**

# Future – MMS


MMS
Large Separation Campaign
Bow Shock and Magnetosheath
7. Magnetosheath (10B), pseudo-log spacing for turbuelnce.
6. Bow Shock (10A-B), slowly decrease MMS1, 2, and 3 separation.
Spacing at 15 $R_E$
~15,000 km
~150 km
~1500 km
4 (trails)
2
1
3 (leads)
Bow Shock
Magneto-sheath
20
10
-10
-20
NASA

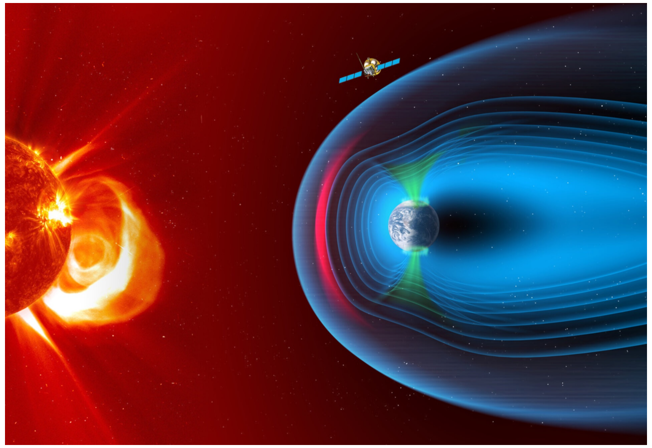
# Future – Data & Simulations




9 spacecraft
50 - 3,000 km

5-7 spacecraft
30 - 5,000 km



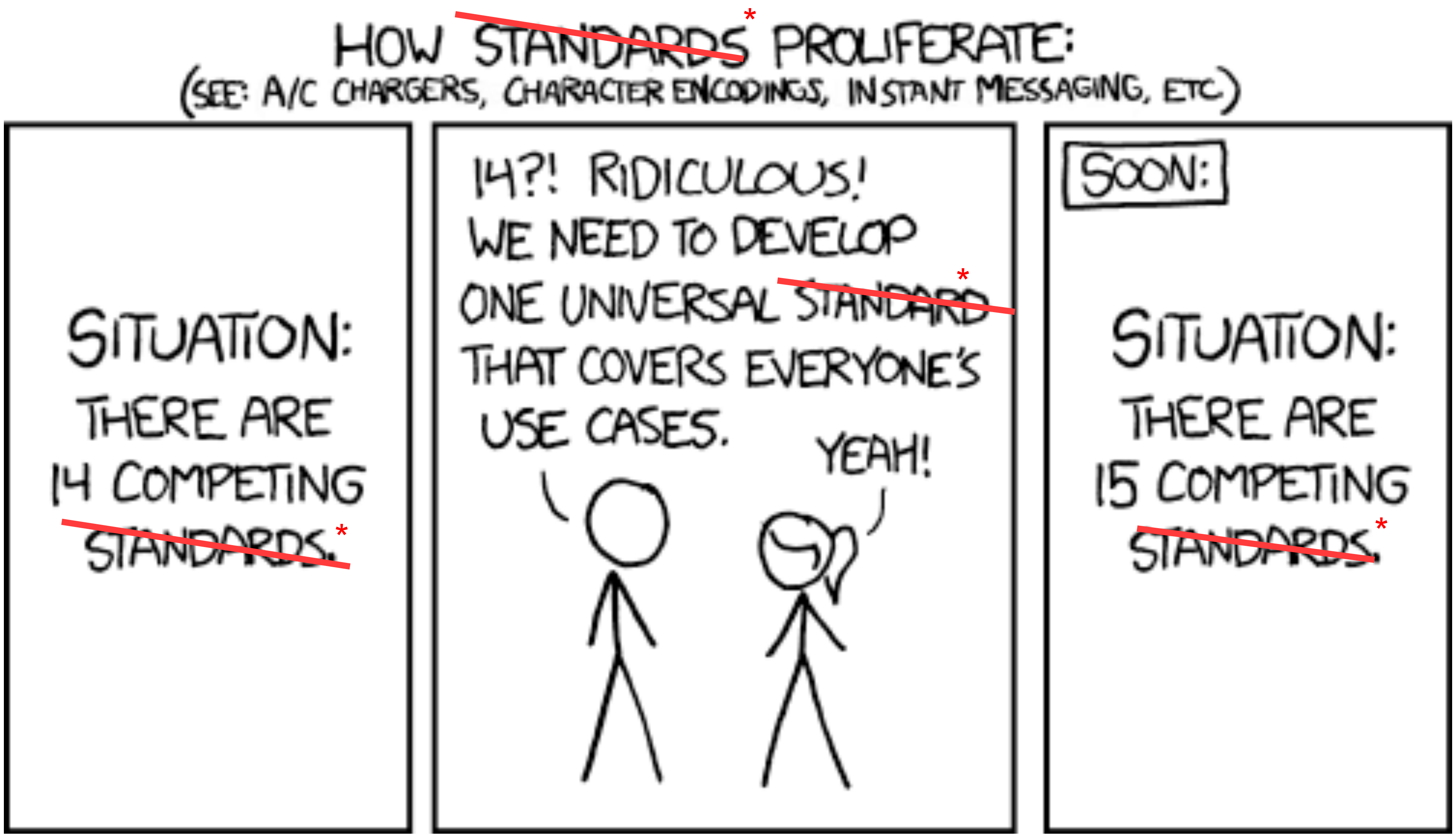
SMILE
Solar Wind Magnetosphere Ionosphere Link Explorer


Menura

MAGE
Multiscale Atmosphere-Geospace Environment

# Extras

# Proposing a new model

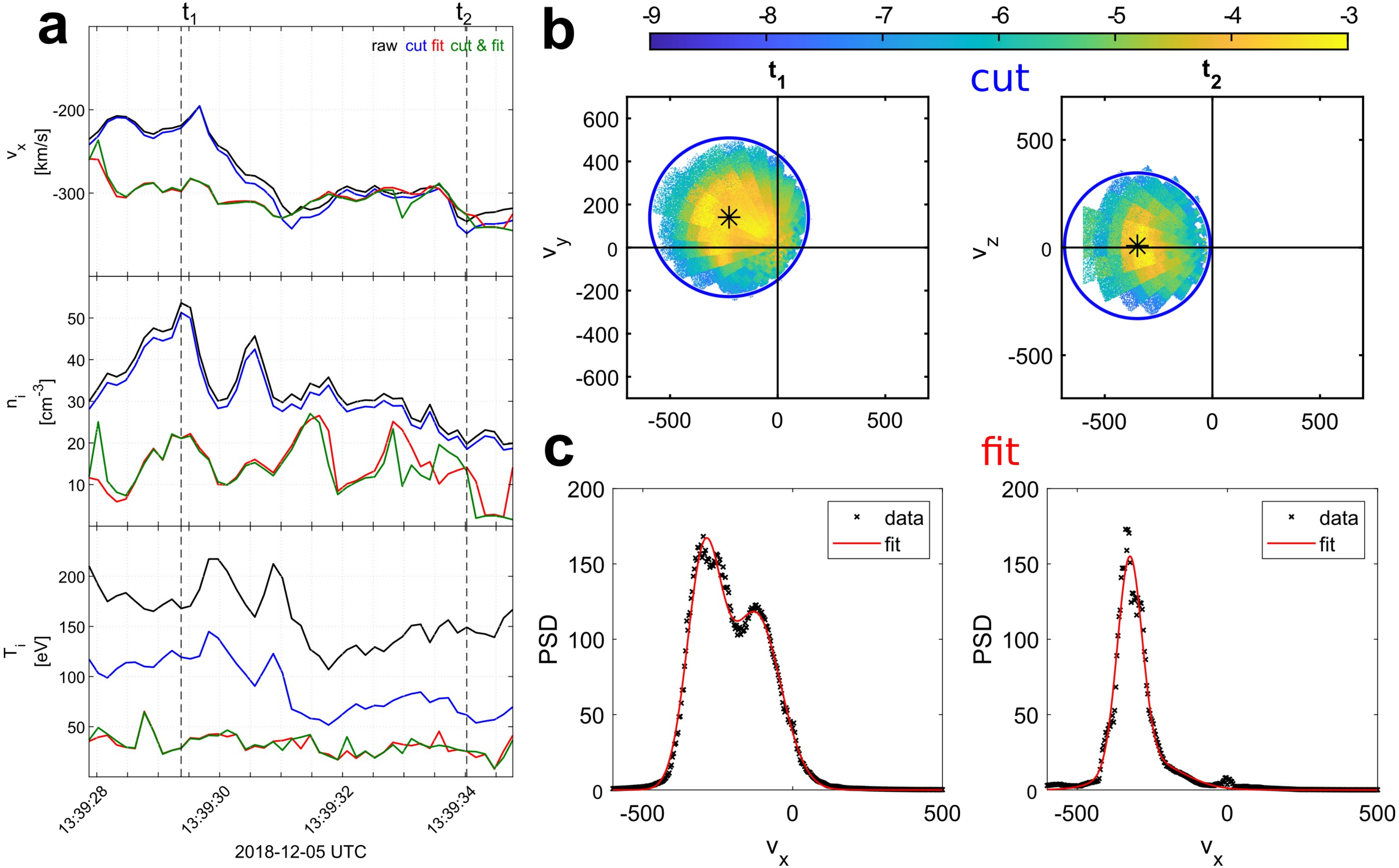



*Where, standards = models, mechanisms, explanations etc.

# Partial Moment Derivation

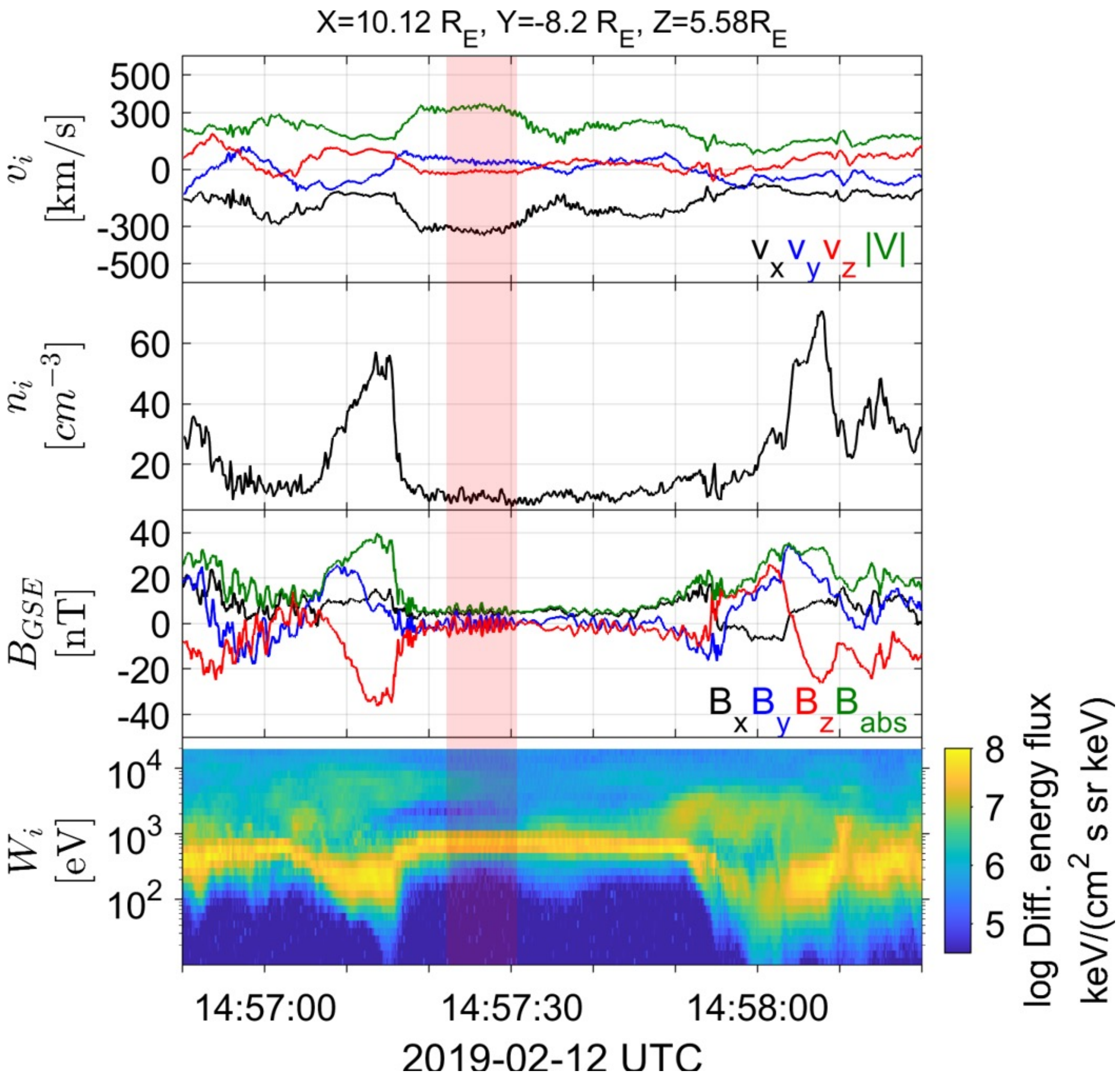
Methods:

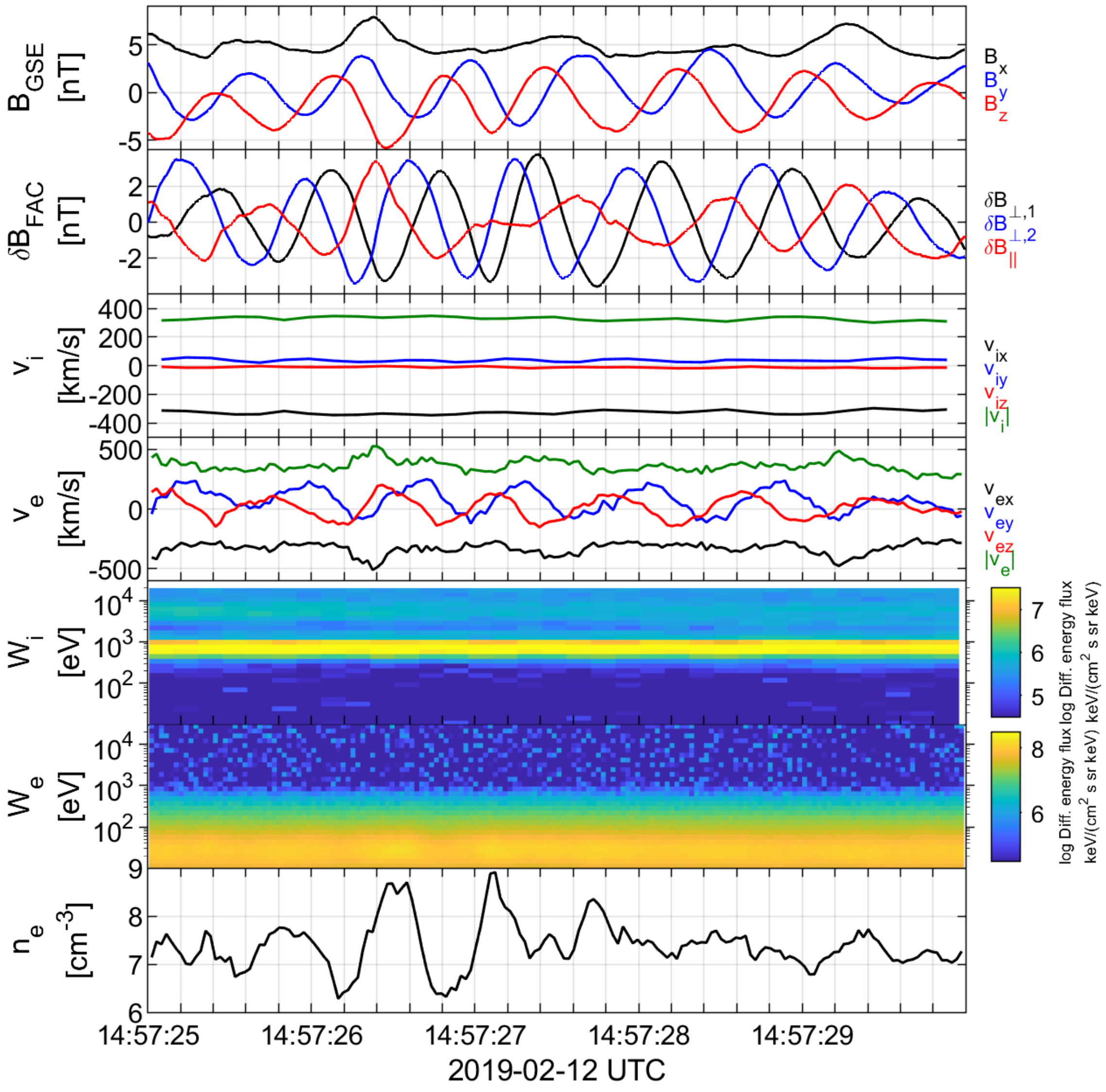
- Cut : $1v_{th}$ sphere in 3D VDF around bulk velocity
- Fit : Fit 2 Maxwellians in 1D reduced VDFs




**Raptis** S, et al,. 2022b | GRL

# Upstream whistlers associated to reformation

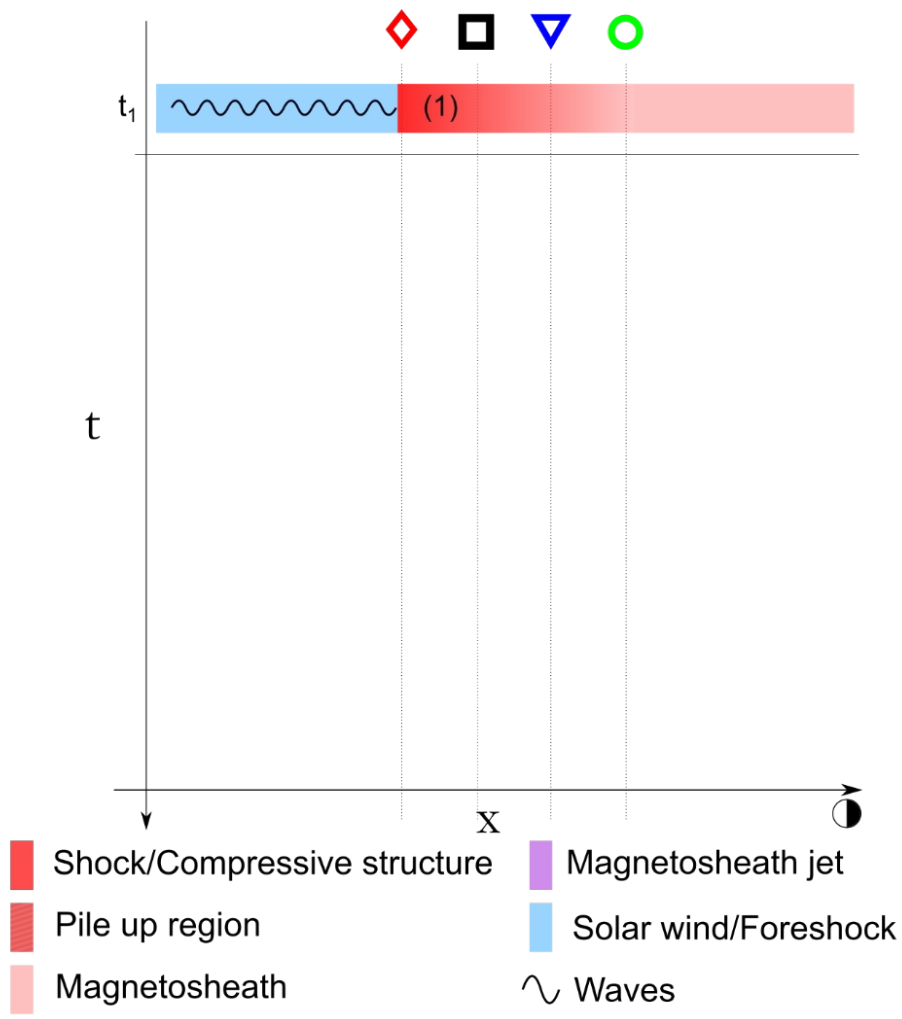


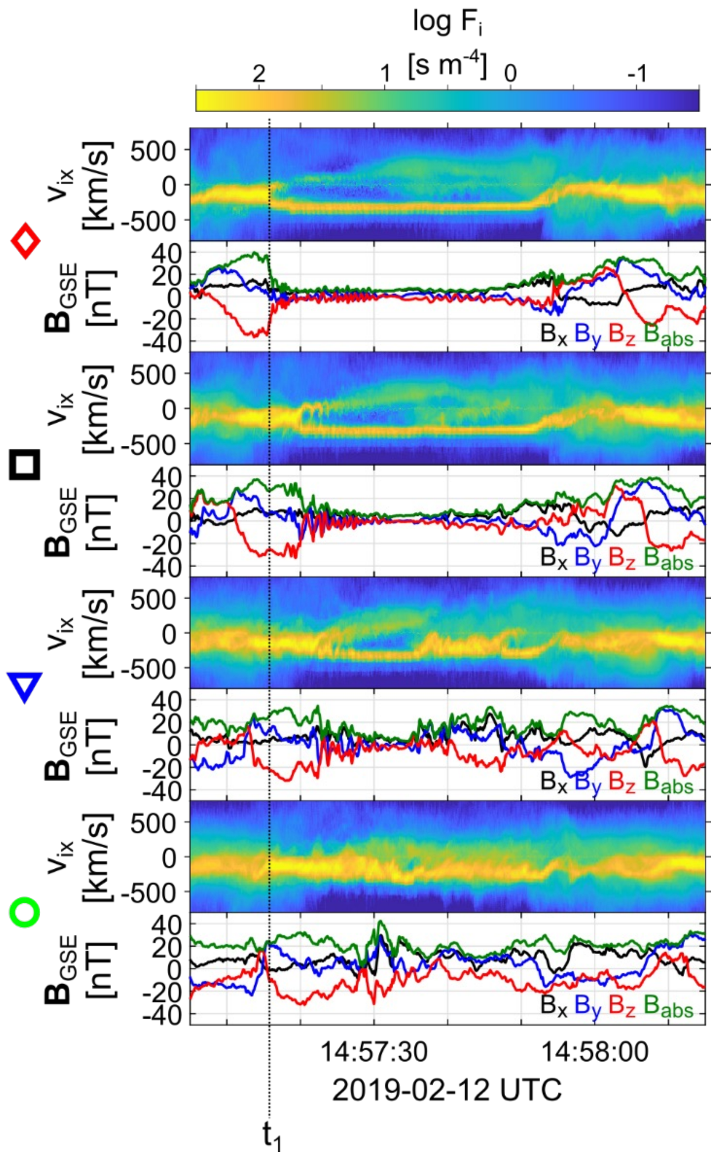

**Unpublished data - ongoing**

# Formation mechanism

a

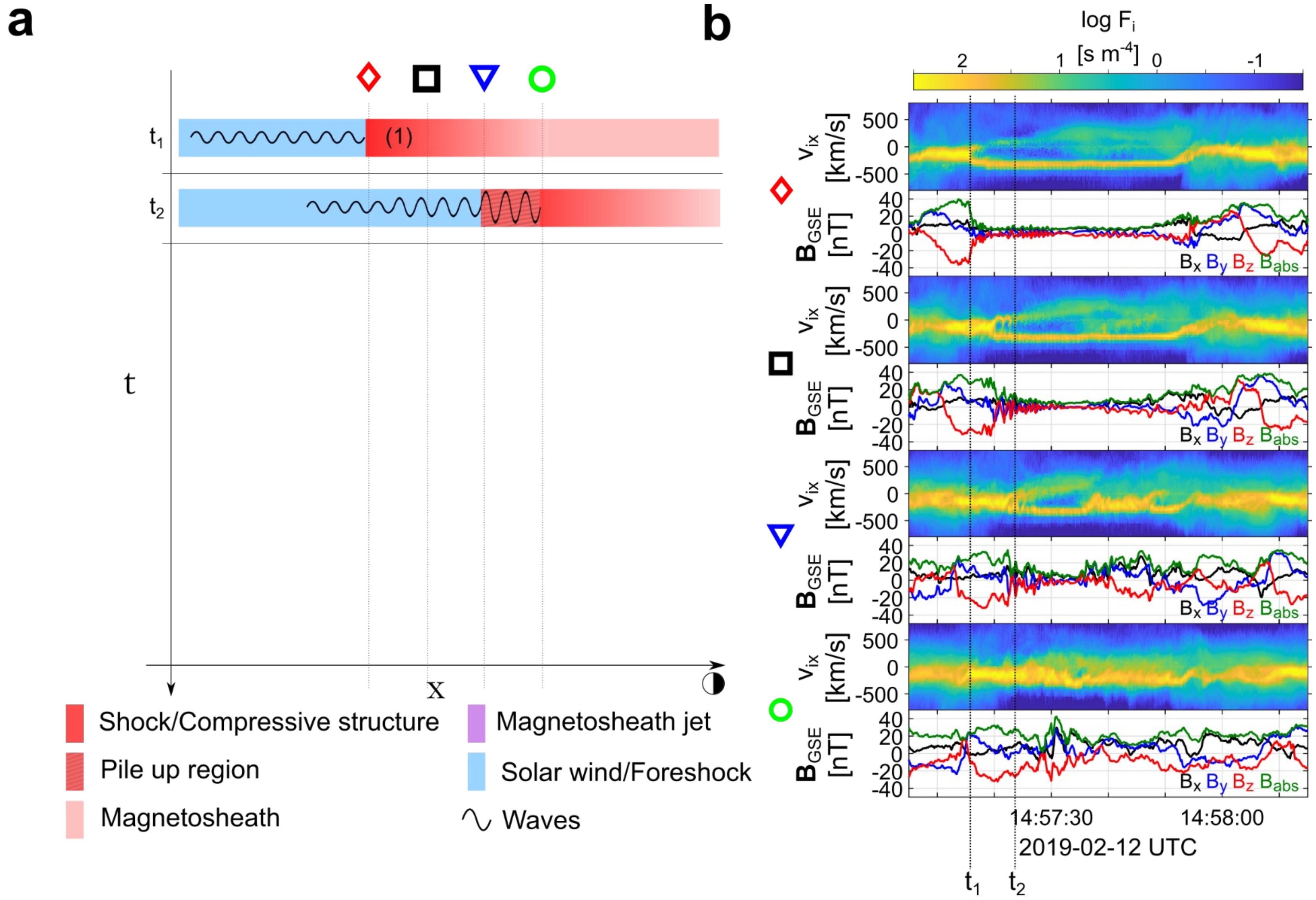



b



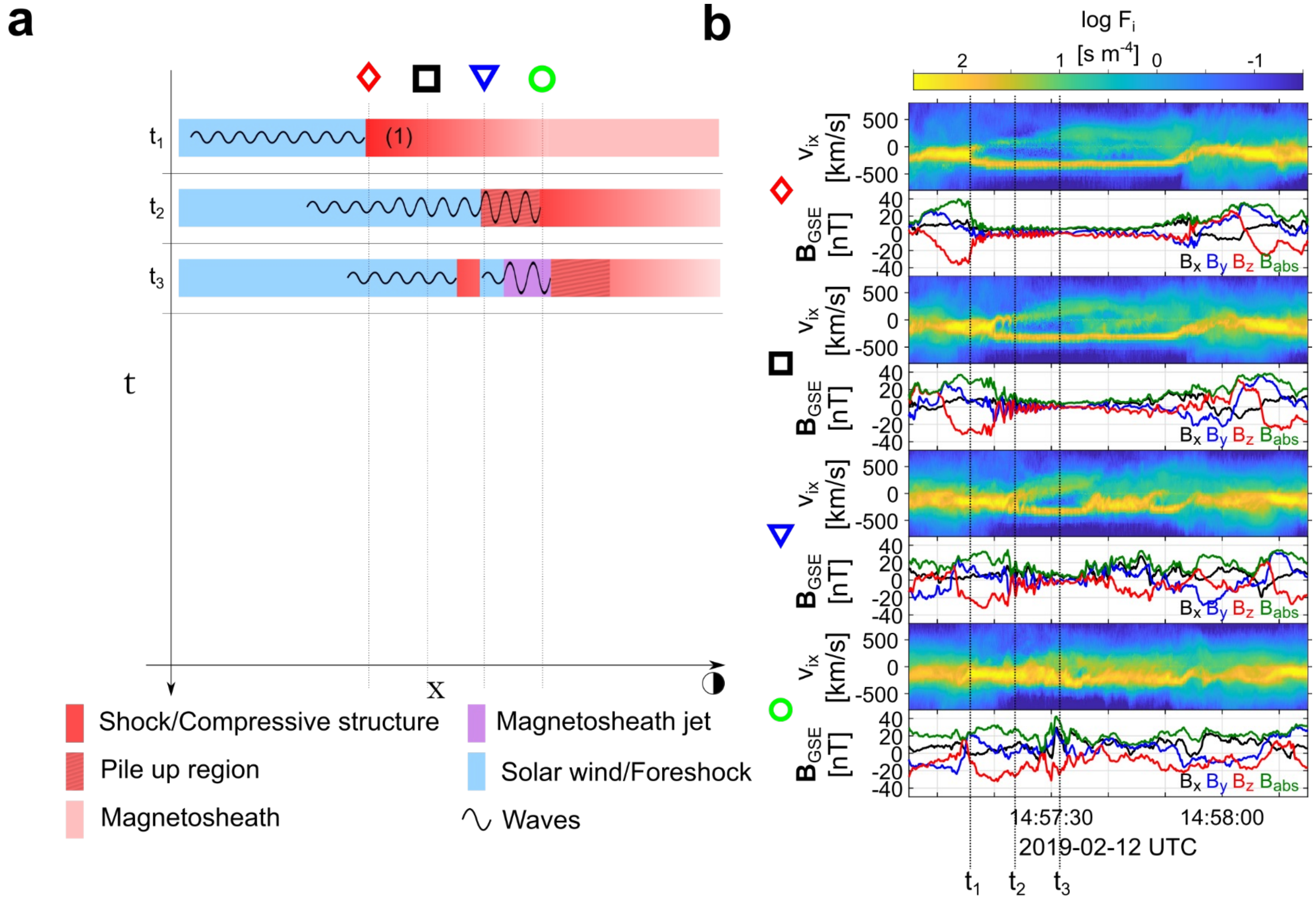

**Raptis S.**, et al. 2022a | Nat. Commun.

# Formation mechanism



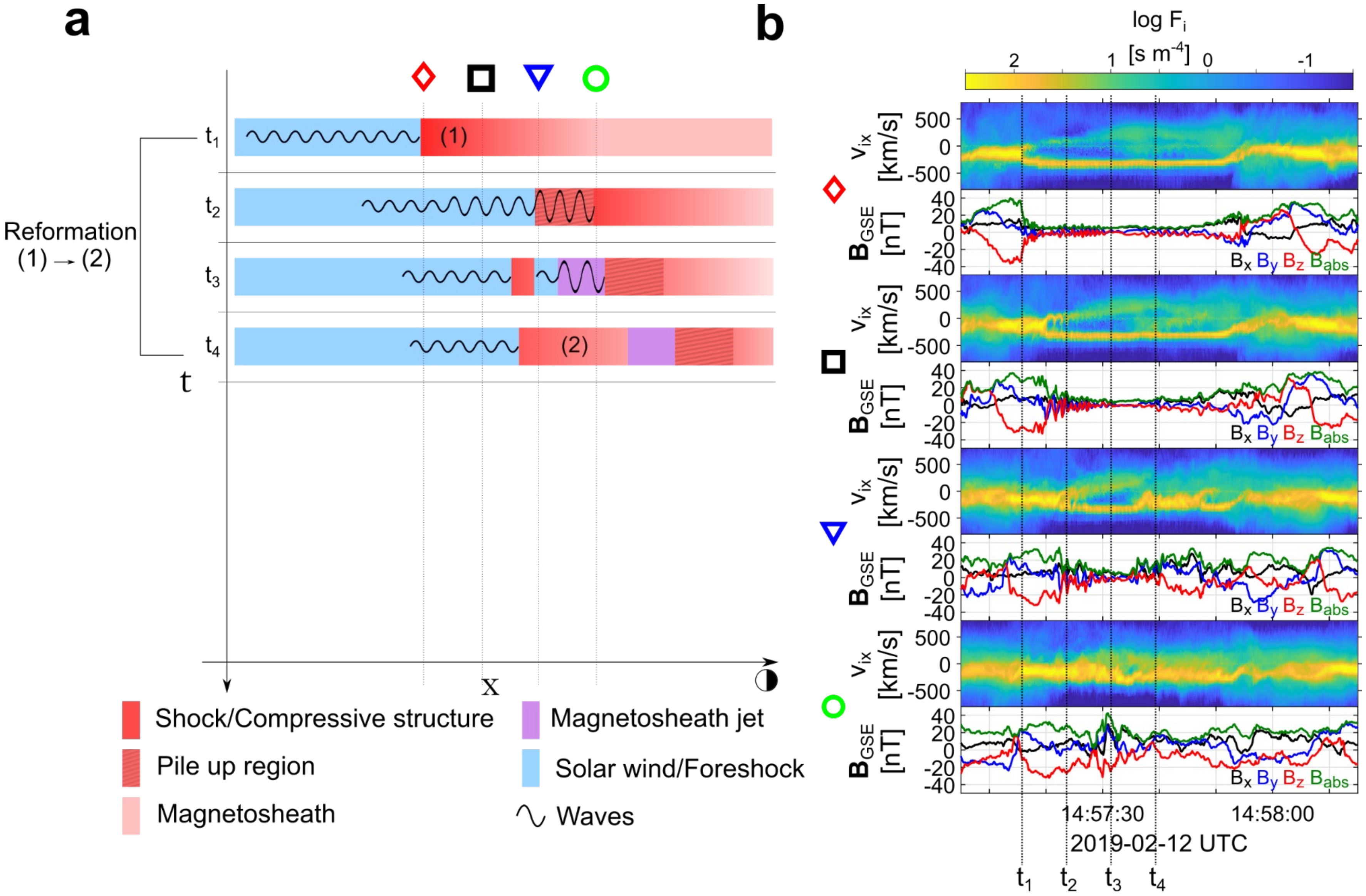

**Raptis S.**, et al. 2022a | Nat. Commun.

# Formation mechanism



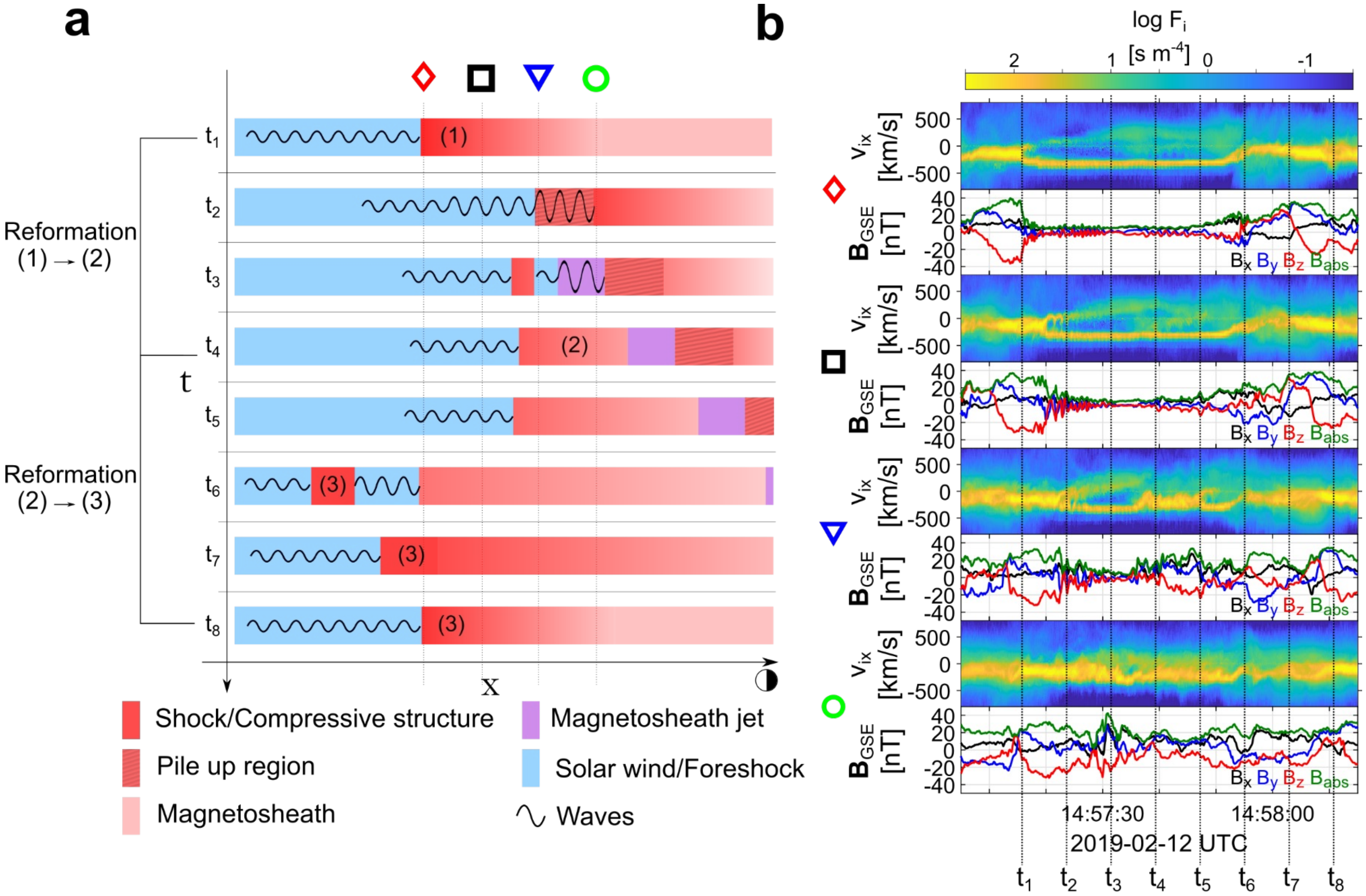

**Raptis S.**, et al. 2022a | Nat. Commun.

# Formation mechanism



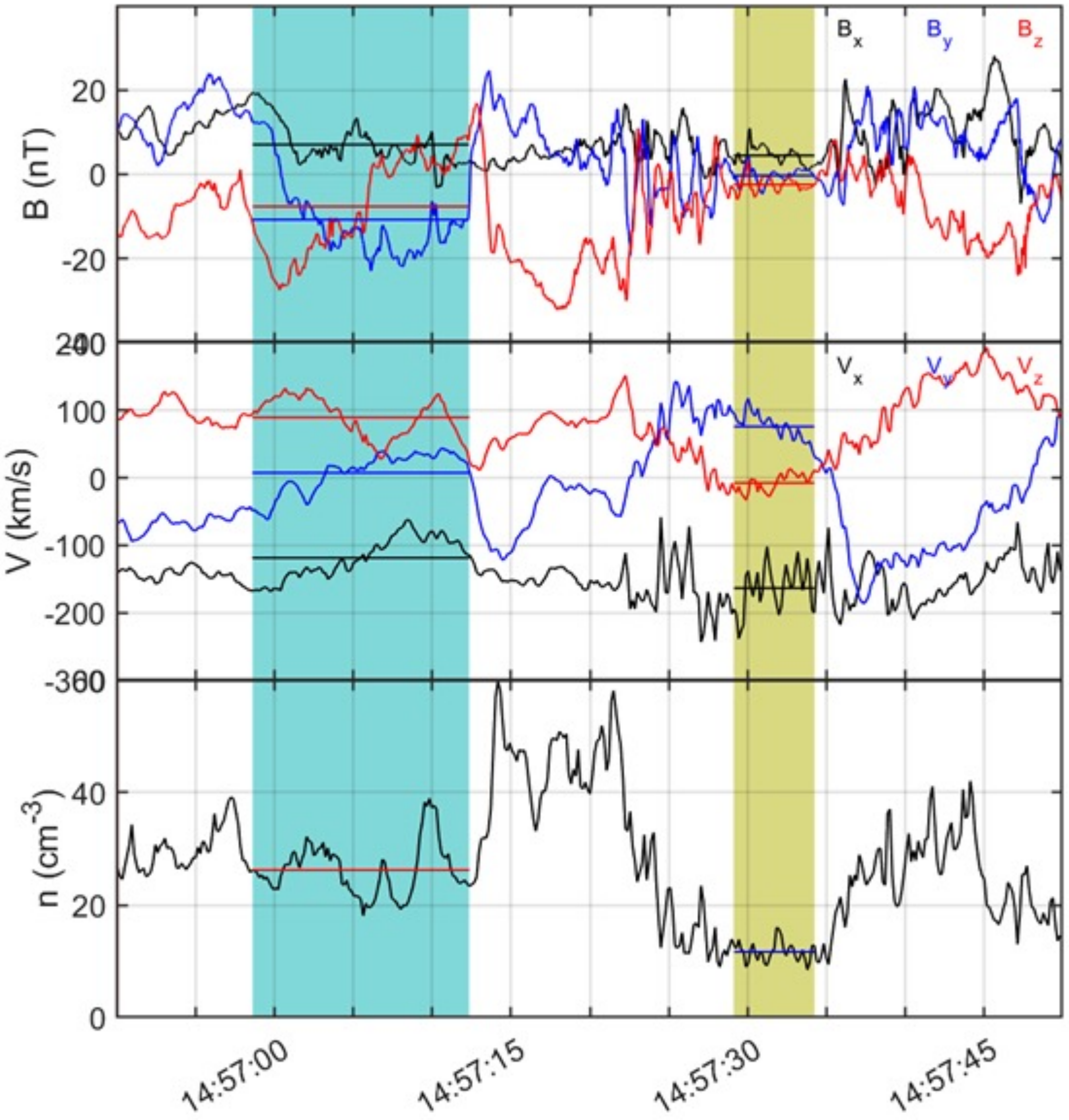

**Raptis S.**, et al. 2022a | Nat. Commun.

# Formation mechanism




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

# Local & Global Shock properties




**Unpublished data - ongoing**

Local Measurements (e.g., MMS4)

$\theta_{Bn} \approx 65 - 80°$

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

$\theta_{Bn} \approx 25°$

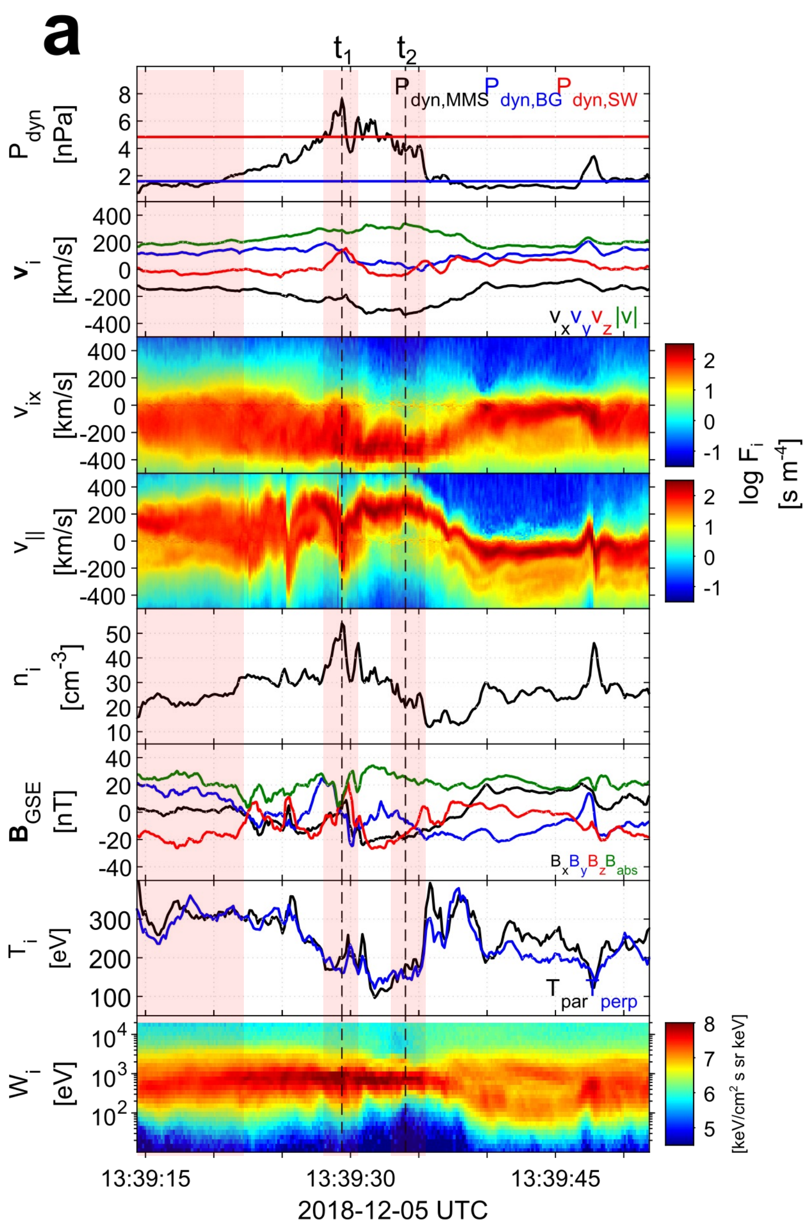
Consistent with FCS (i.e., SLAMS) acting locally as Qperp shocks.

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

# Qpar magnetosheath jet – *Burst* data

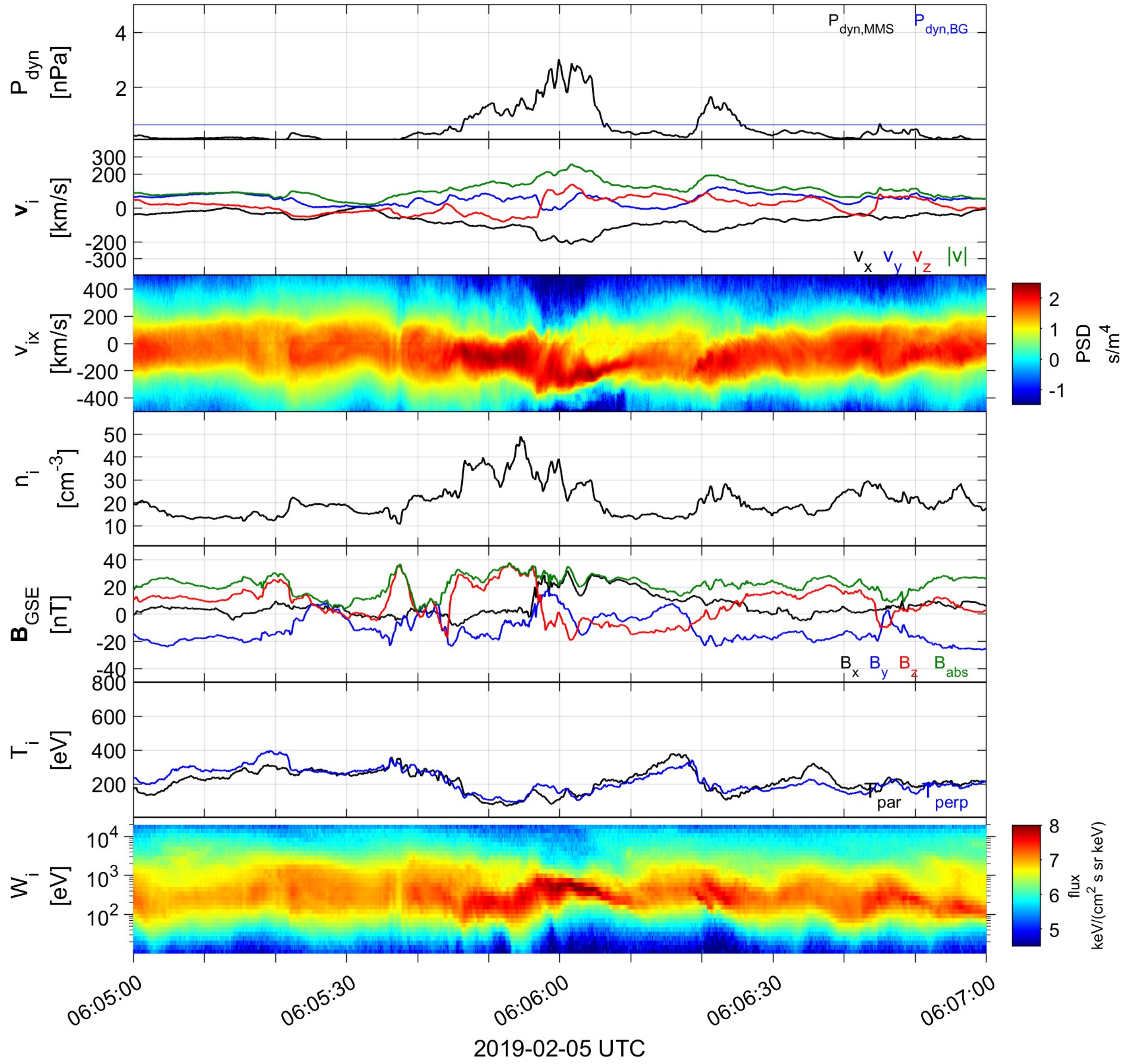
Areas of interest

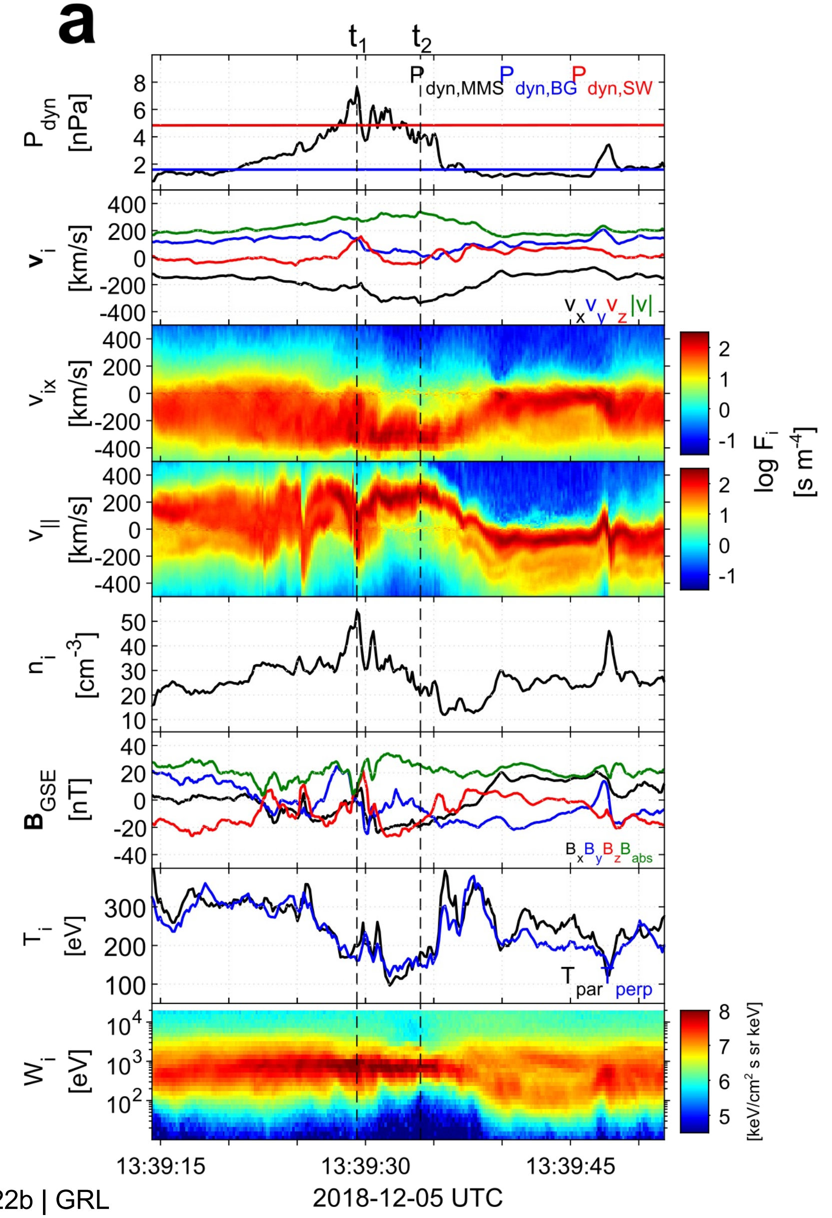
- Pre jet = Typical MSH
- $t_1 = P_{dyn}$ peak
- $t_2 = |V|$ peak




**Raptis** S, et al,. 2022b | GRL

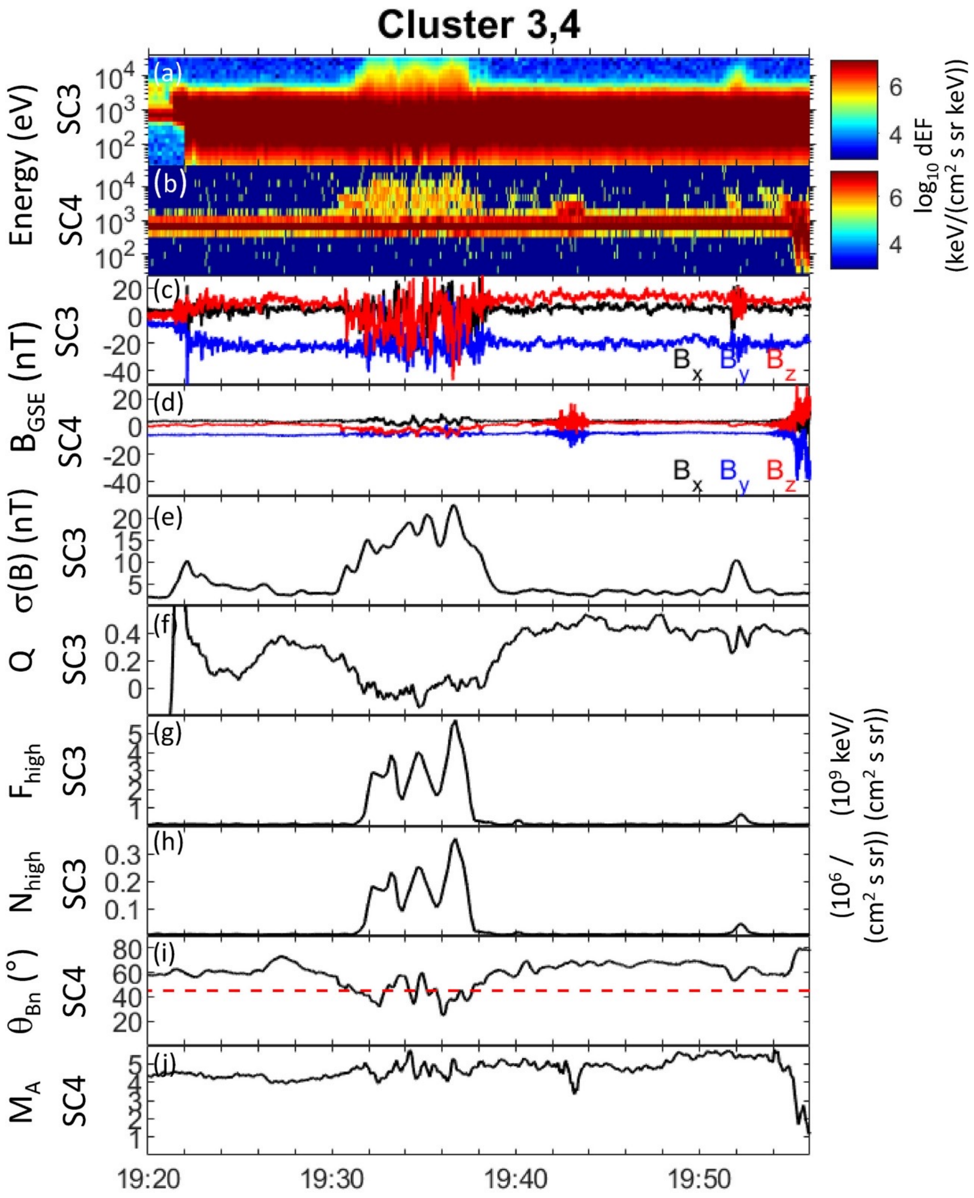
# Burst data show jets = SW




**Raptis** S, et al,. 2022b | GRL

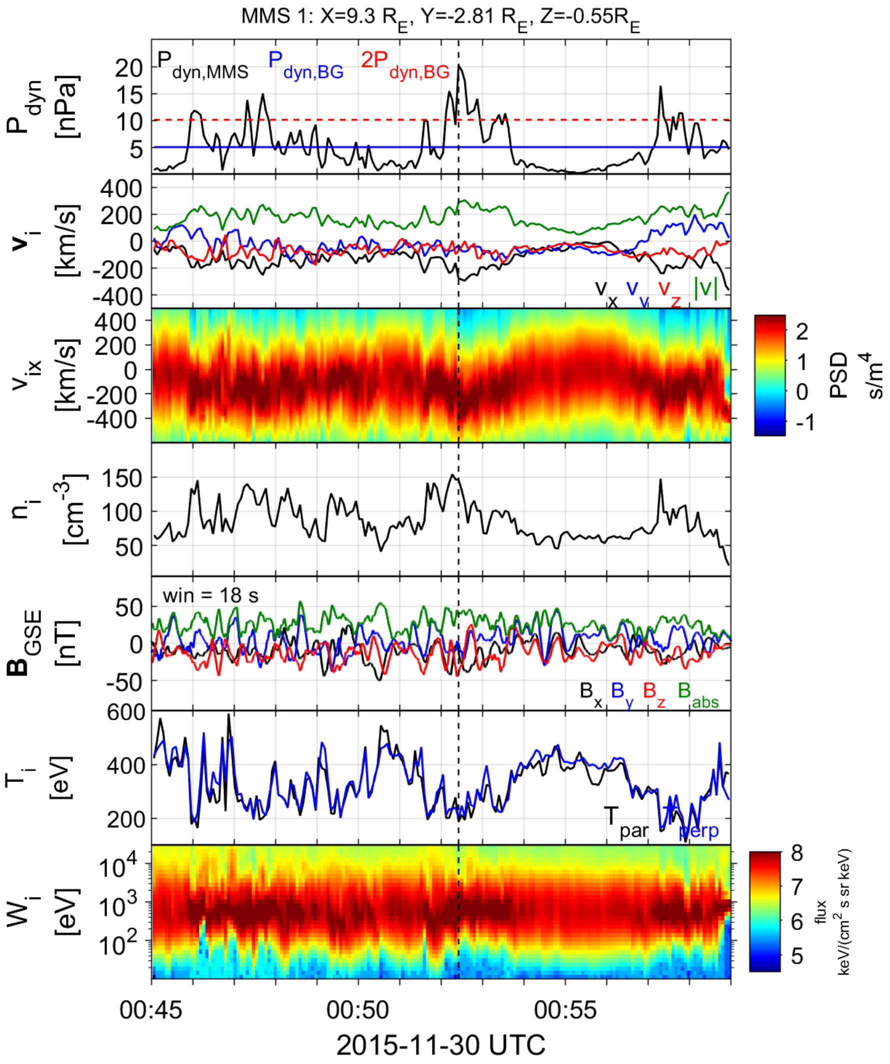
# Classification Cluster




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

# Summarized properties – Quasi parallel

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




| 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 |

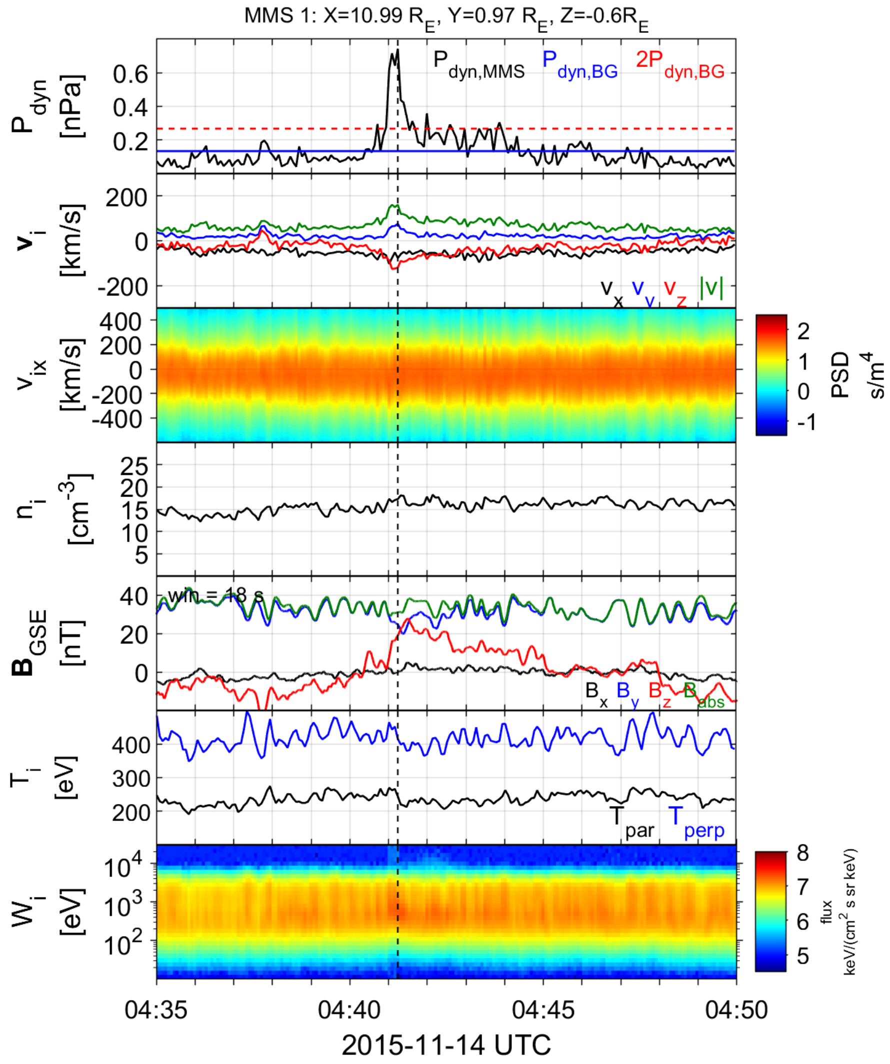
Qpar Jet

Jets found in $Q_{\parallel}$ MSH

**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




| Subset | Number | Percentage (%) |
|---|---|---|
| Quasi-parallel | 2458 | 26.7 |
| Final cases | **901** | 10.1 |
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| Final cases | **60** | 0.7 |
| Other | 5335 | 58.0 |
| Unclassified/Uncertain | 3789 | 41.2 |
| Border | 1500 | 16.3 |
| Data Gap | 46 | 0.5 |

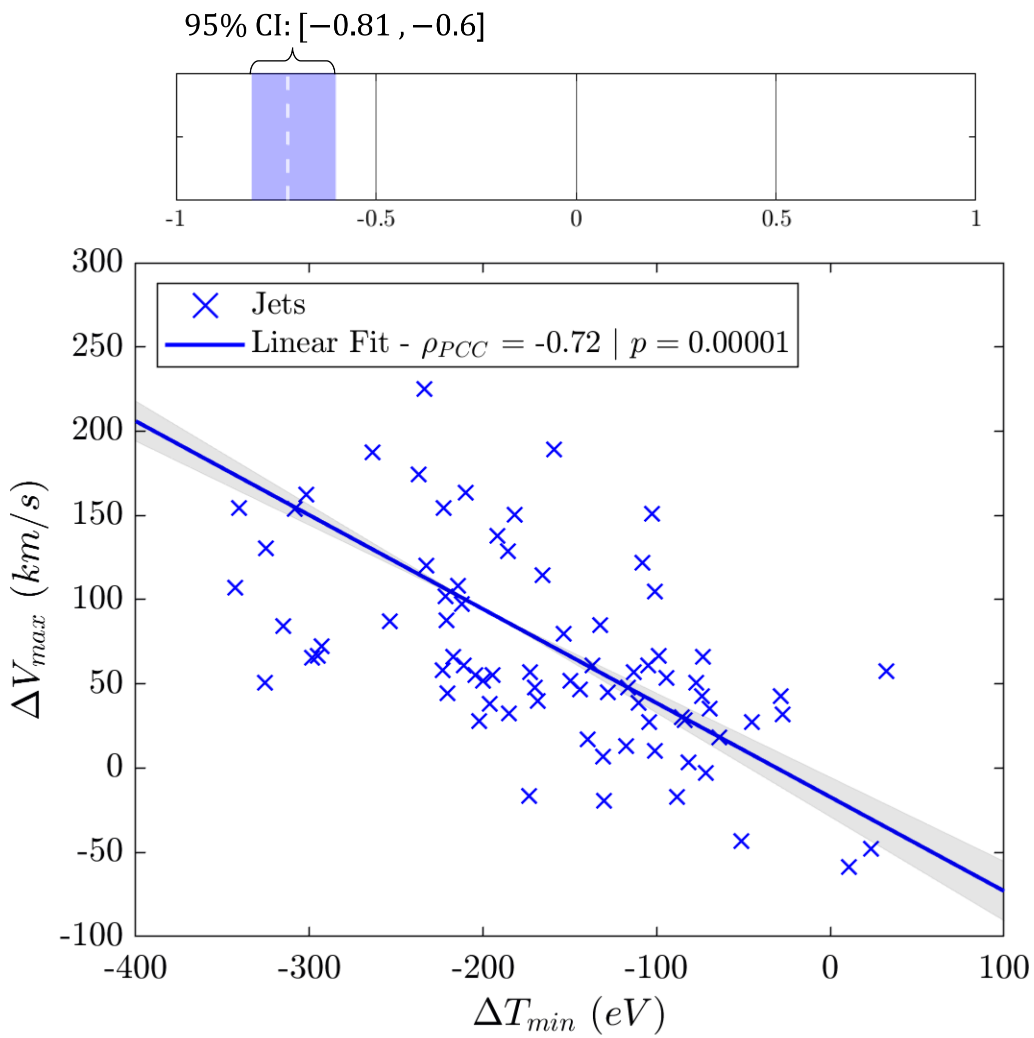
Qperp Jet

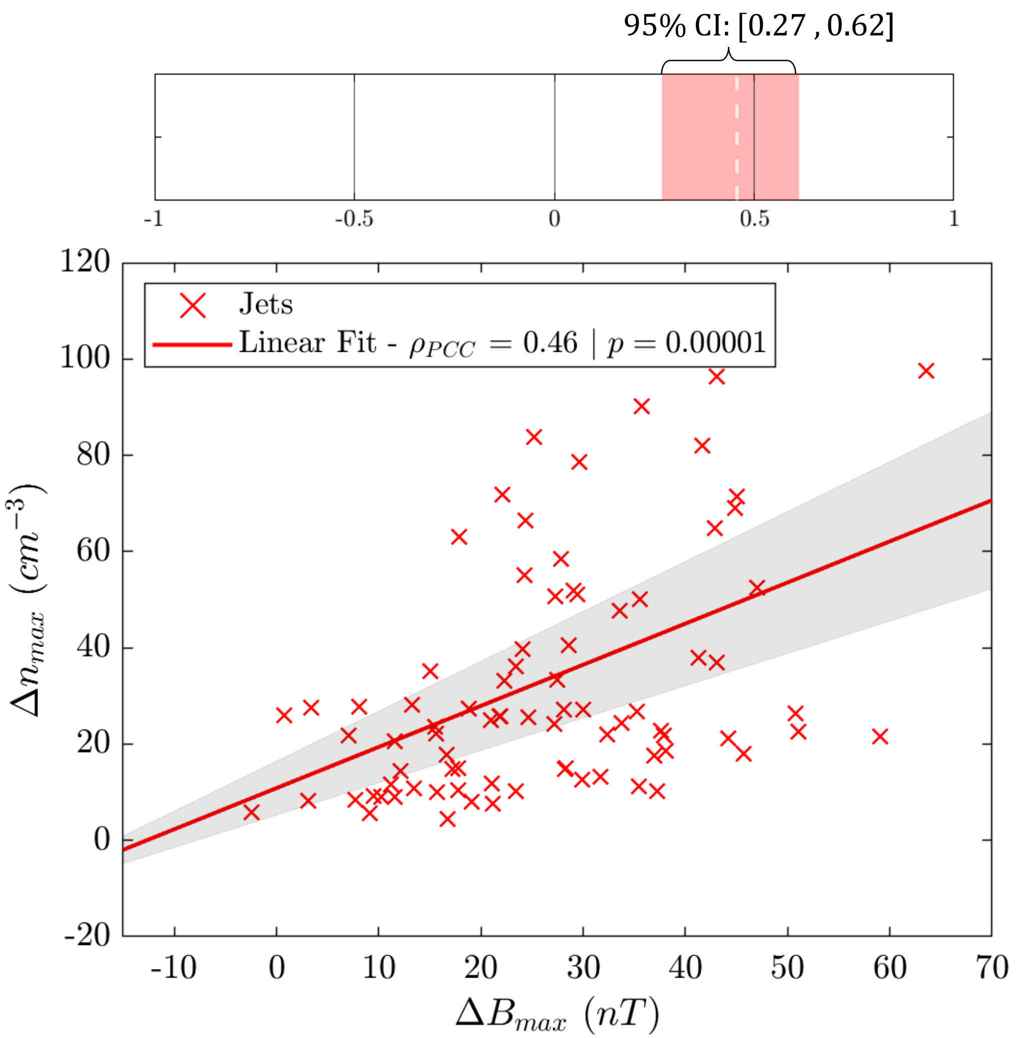
Jets found in $Q_\perp$MSH

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

# Example: statistics of subset close to bow shock

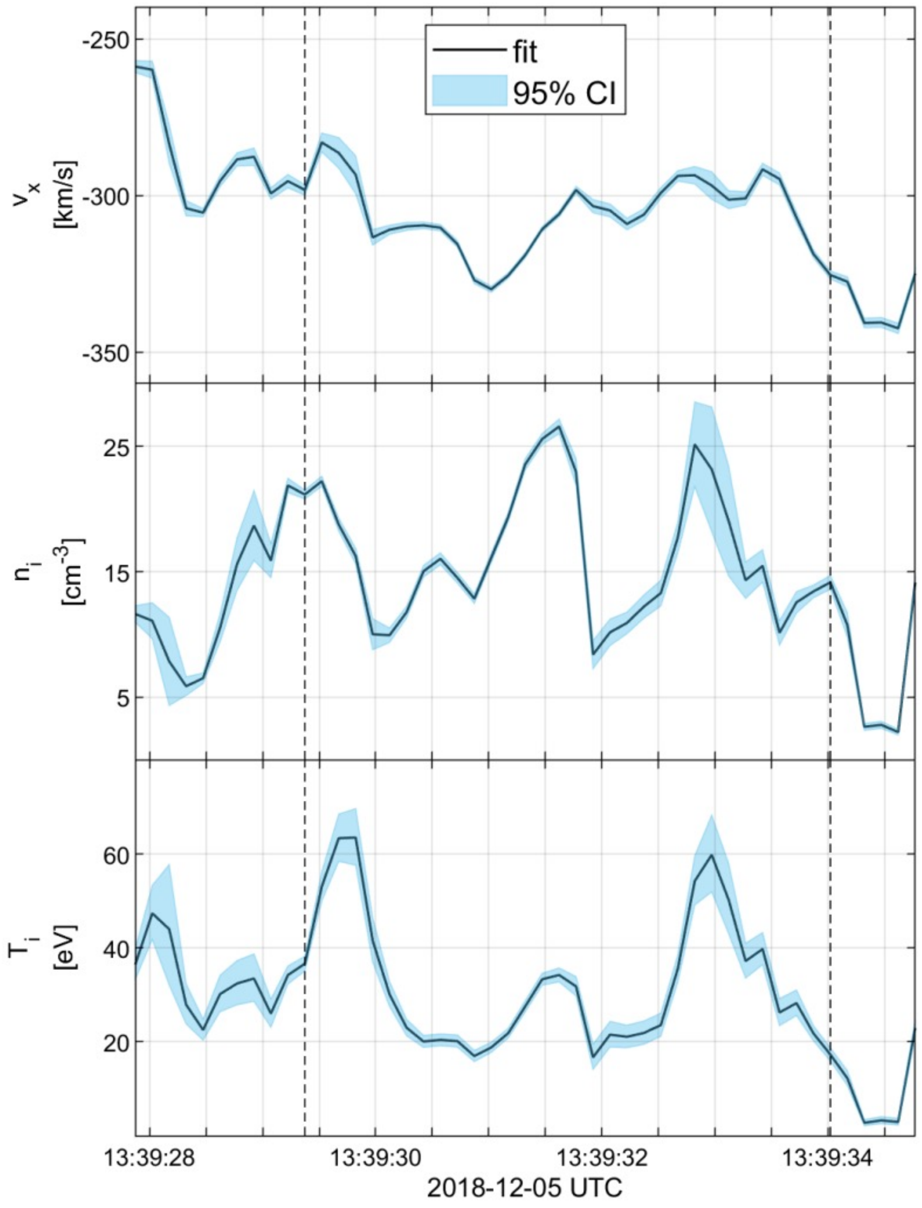
$n = 90$




(unpublished data – Ongoing work)

# Errors on fitted quantities




**Raptis** S, et al,. 2022b | GRL

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

Hot Flow Anomaly (HFA) self-reformation

n = [- 0.540, 0.379, 0.737]

$$v_{SH} = -62.1\frac{km}{s}$$

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]

$$v_{SH} = \sim 60\frac{km}{s}$$

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*