High-speed Downstream Plasma Jet Generated due to Shock Reformation

Savvas Raptis

Co-authors : T. Karlsson (KTH), A. Vaivads (KTH), C. Pollock (Denali Scientific), F. Plaschke (Technische Universität Braunschweig), A. Johlander (IRF, Uppsala), H. Trollvik (KTH), P-A. Lindqvist (KTH)

8th MMS Community Workshop
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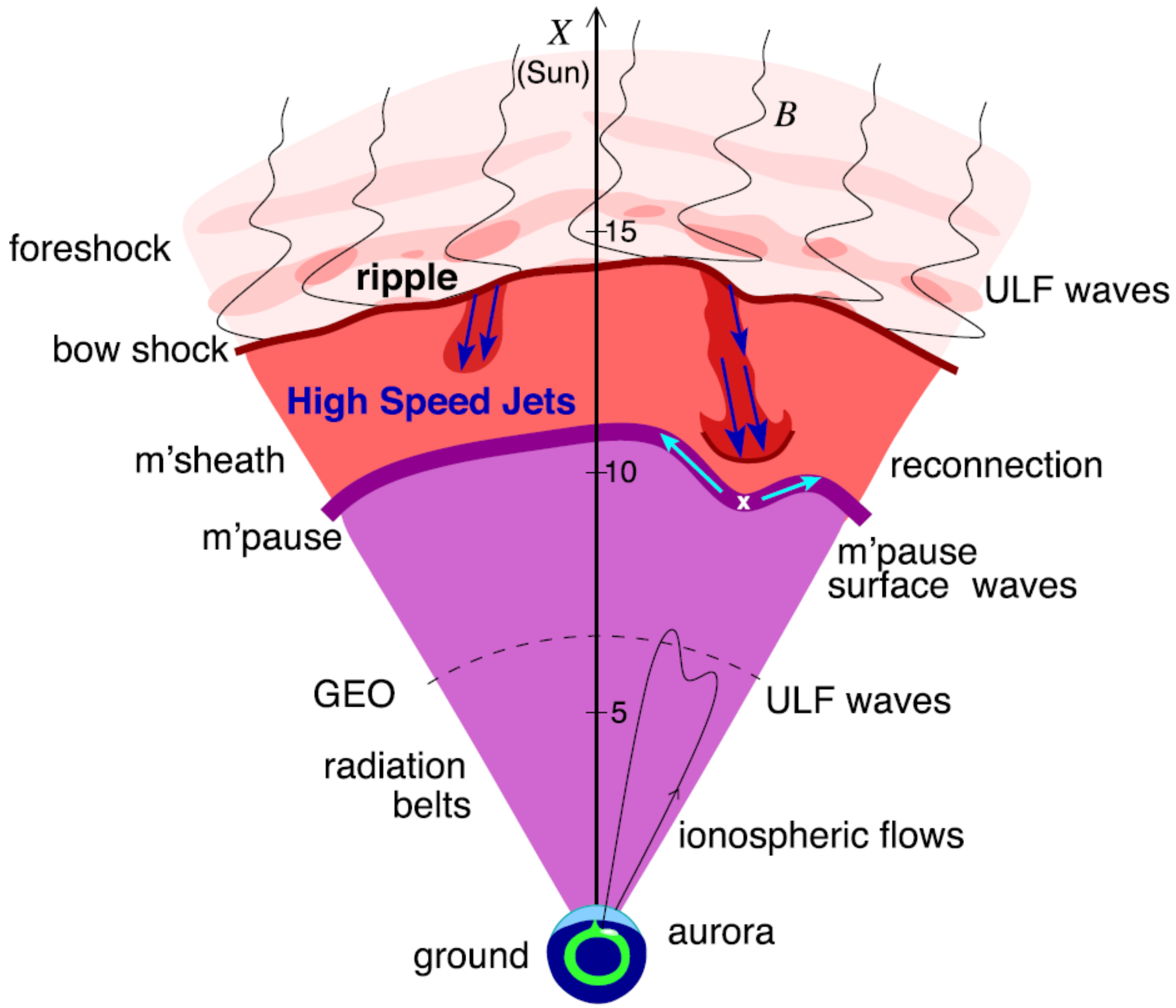
Introduction

Magnetosheath Jets – Definition



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

Definition

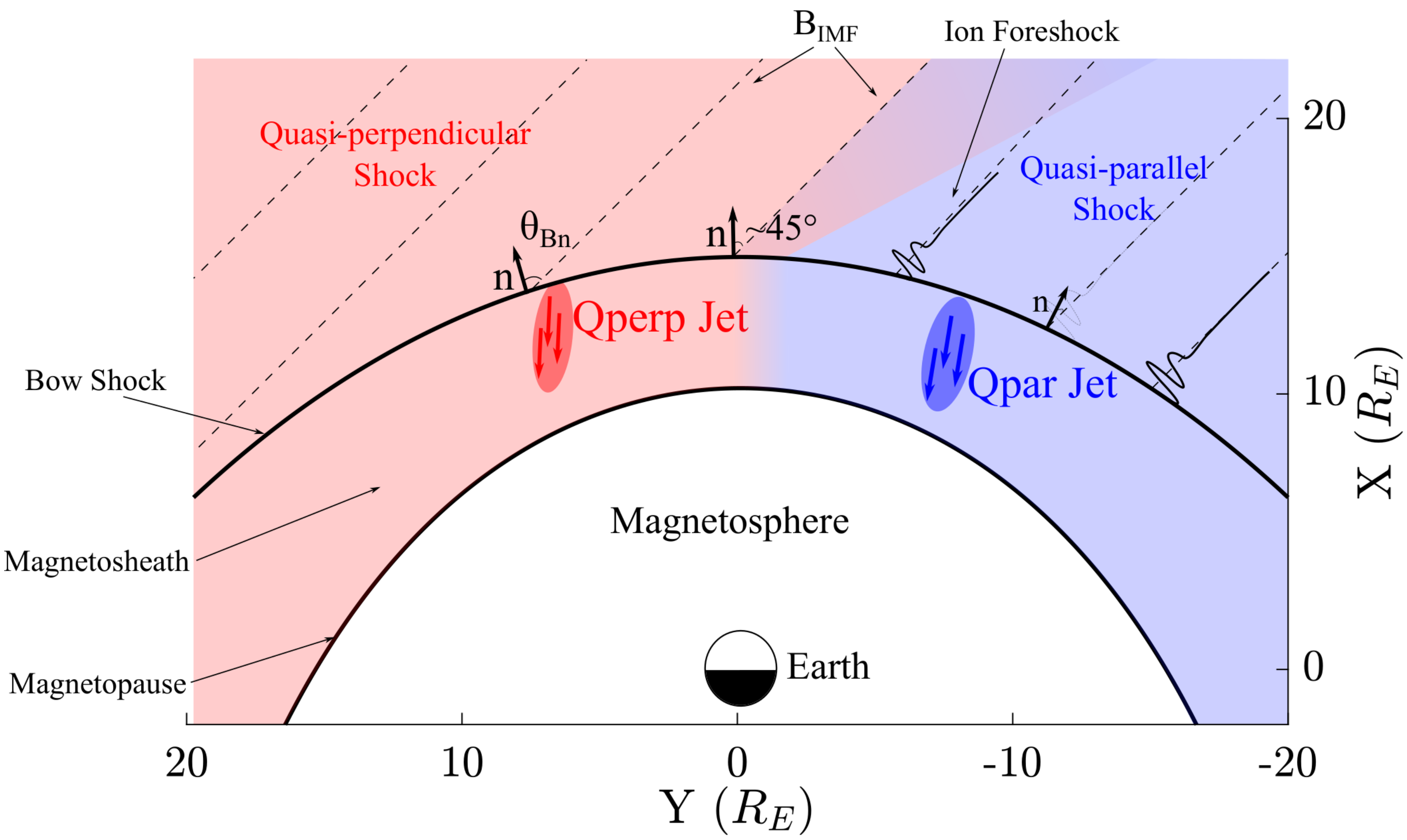
Magnetosheath jets are **transient localized enhancements** of **dynamic pressure** (density and/or velocity increase)

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

Shock, Magnetosheath & Jet classification



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

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

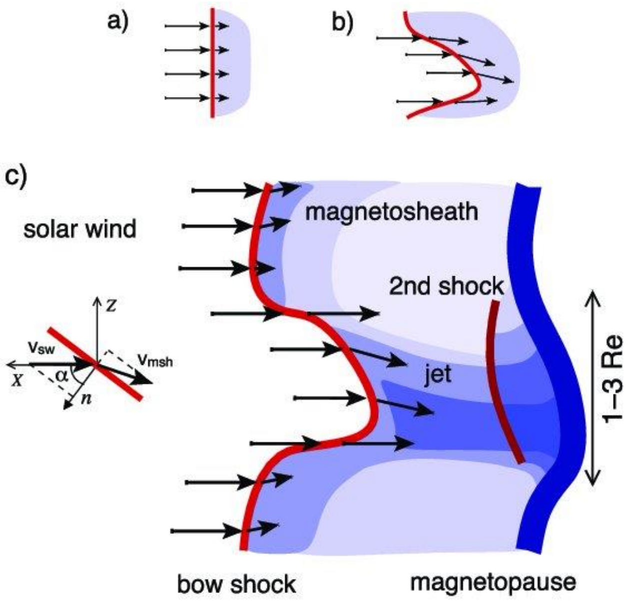
"Jets found ~9 times more often in the Qpar MSH"

Vuorinen et al. (2019)

Raptis, Karlsson, et al. (2020) | JGR
Raptis, Aminalragia-Giamini et al. (2020) | Front. Astron. Space Sci
Karlsson, **Raptis** et al. (2021) | JGR
Kajdič, **Raptis** et al. (2021) | GRL

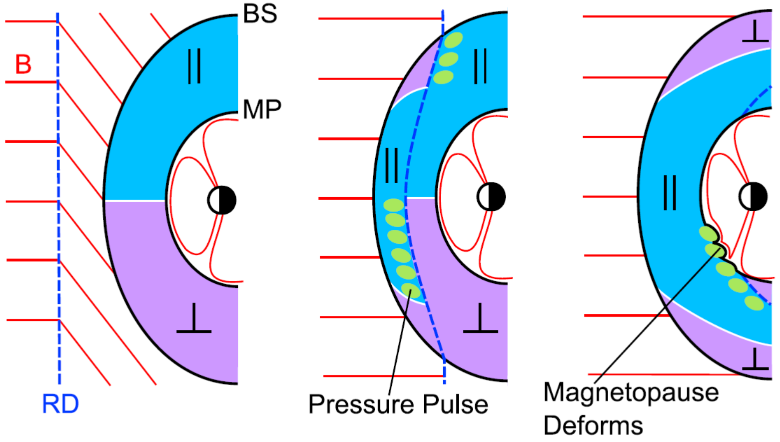
How are these jets created ?

Shock ripples



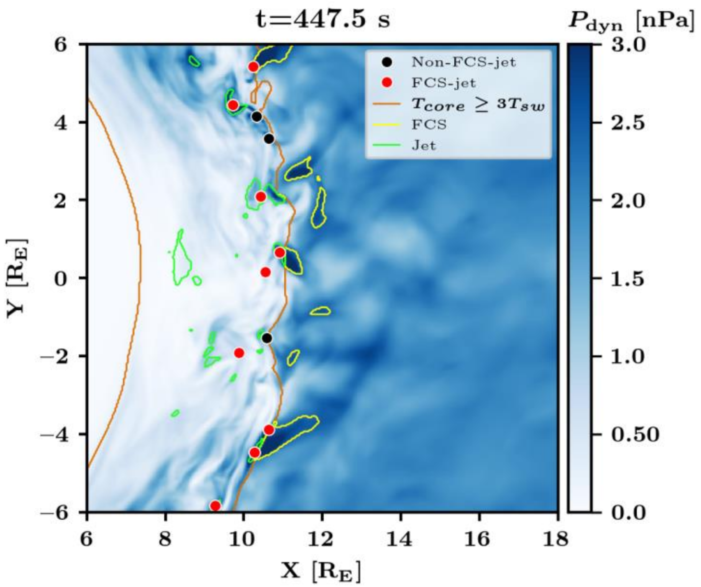
Hietala et al. (2009,2012)

SW discontinuities



Archer et al. (2012)

Foreshock Structures



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

Shock Reformation

<u>Shock Reformation</u>

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

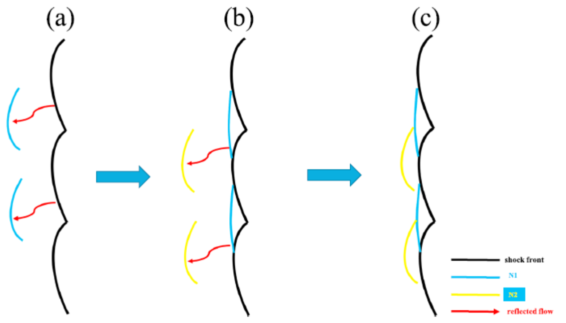
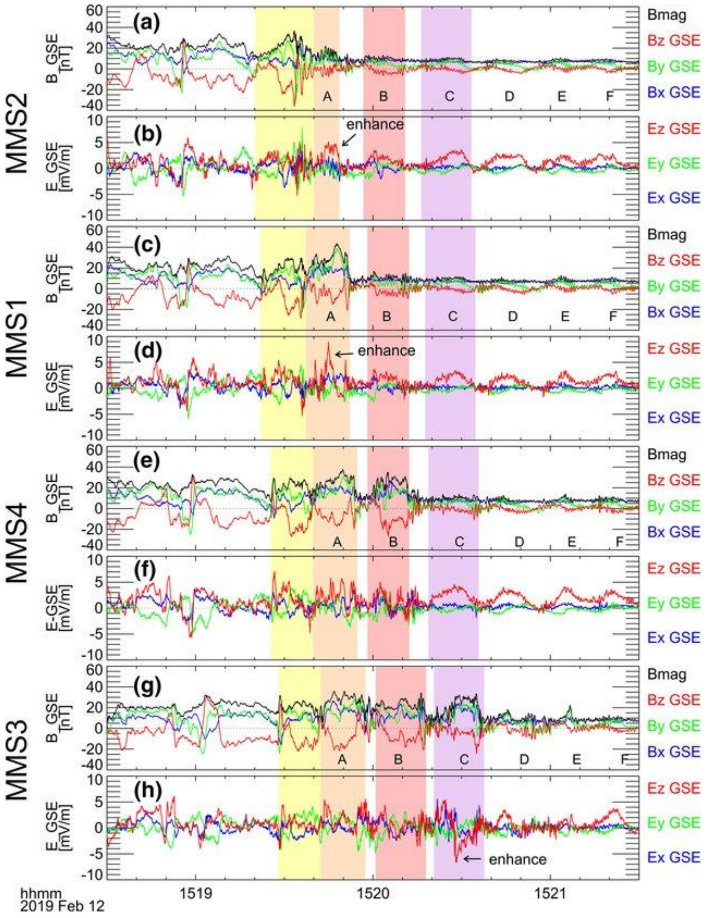
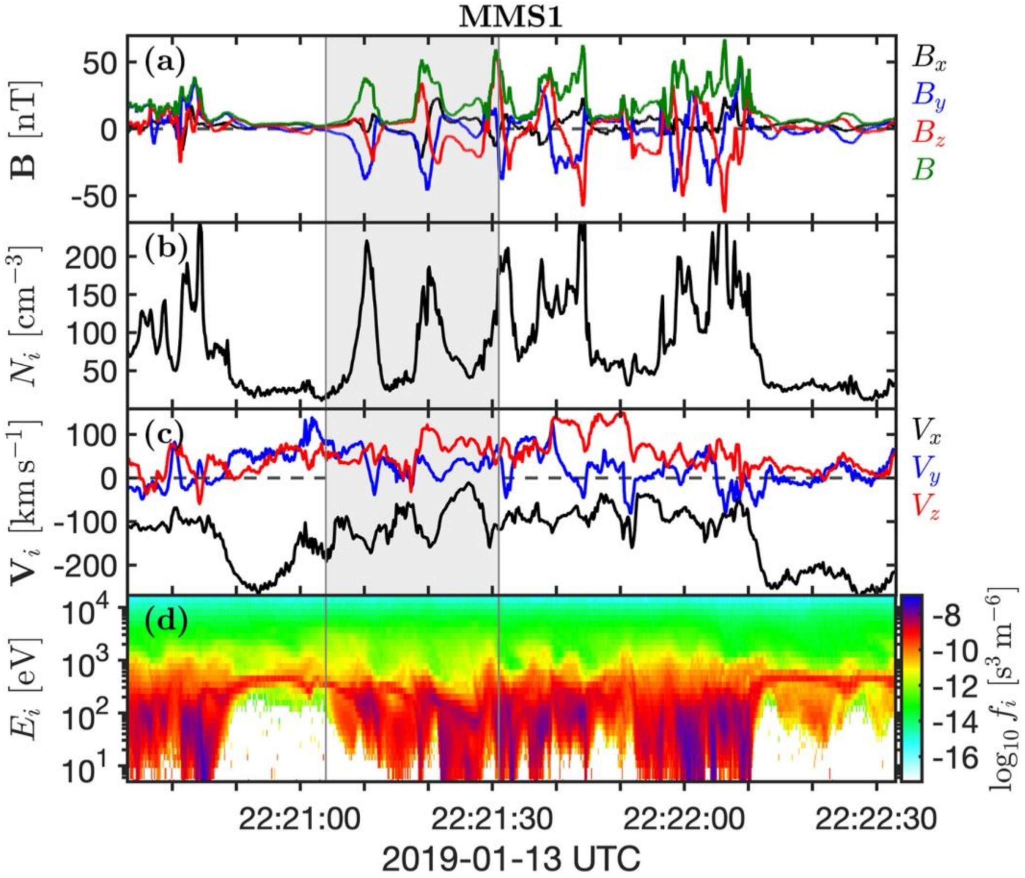


Figure 11. The sketch for evolution of shock front. (a) A rippled shock front, (b) a plane shock front, and (c) a rippled shock front. Solid lines and red arrows denote shock front and reflected beams, and N1 and N2 indicate new shock fronts.

Hao et al. (2017)



Liu et al. (2021)



Johlander et al. (2022)

ARTICLE

Check for updates

https://doi.org/10.1038/s41467-022-28110-4 OPEN

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

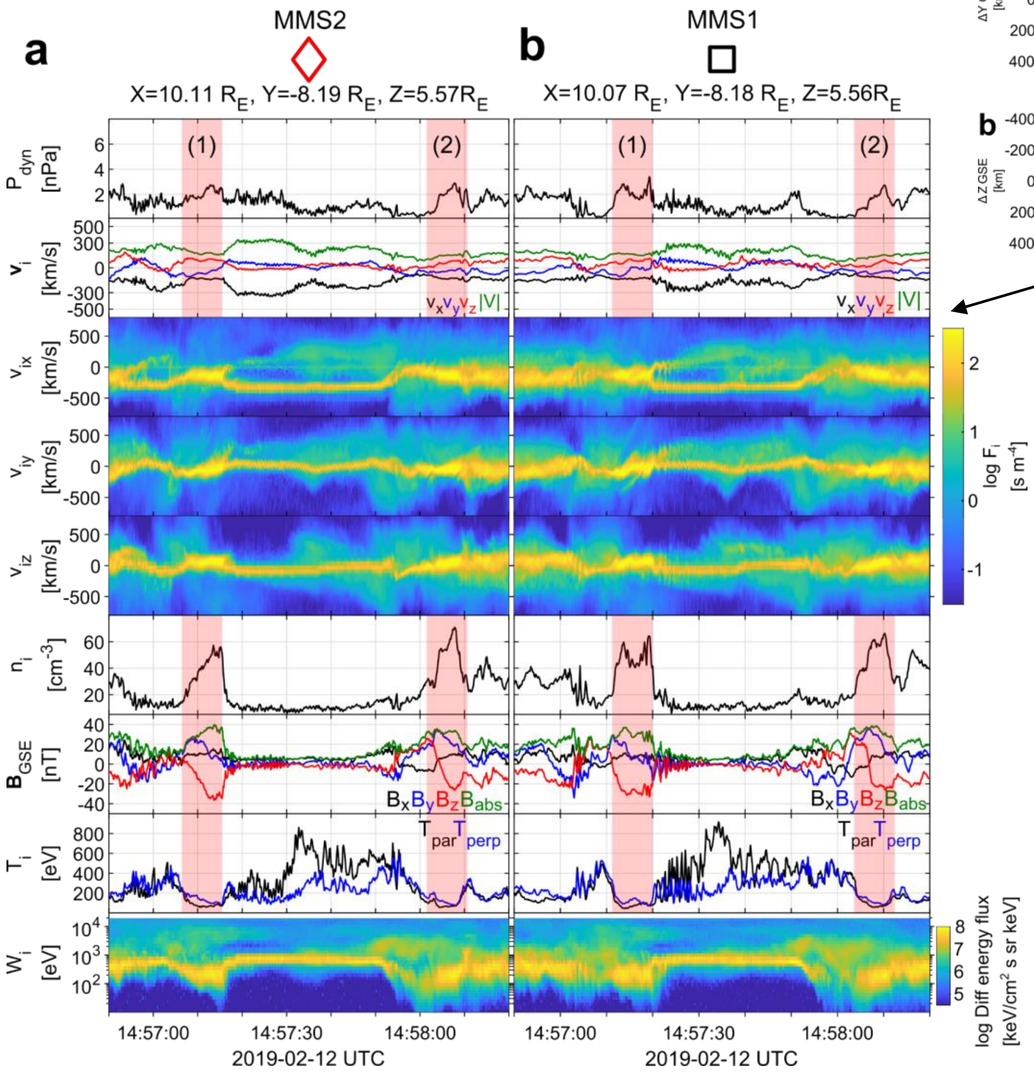
Savvas Raptis [1✉], Tomas Karlsson [1], Andris Vaivads [1], Craig Pollock [2], Ferdinand Plaschke [3,4], Andreas Johlander [5,6], Henriette Trollvik [1] & Per-Arne Lindqvist [1]

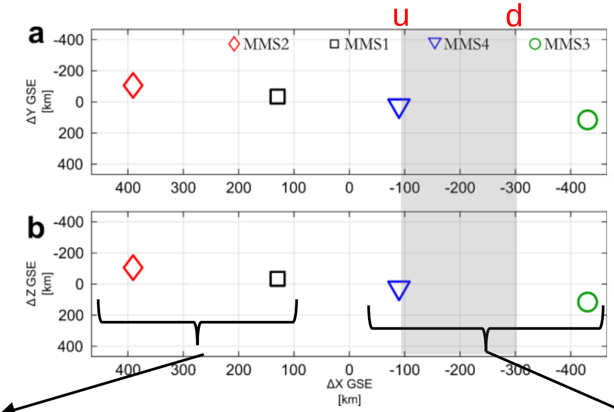
Raptis, S., Karlsson, T., Vaivads, A. et al. Downstream high-speed plasma jet generation as a direct consequence of shock reformation. Nat Commun 13, 598 (2022). https://doi.org/10.1038/s41467-022-28110-4

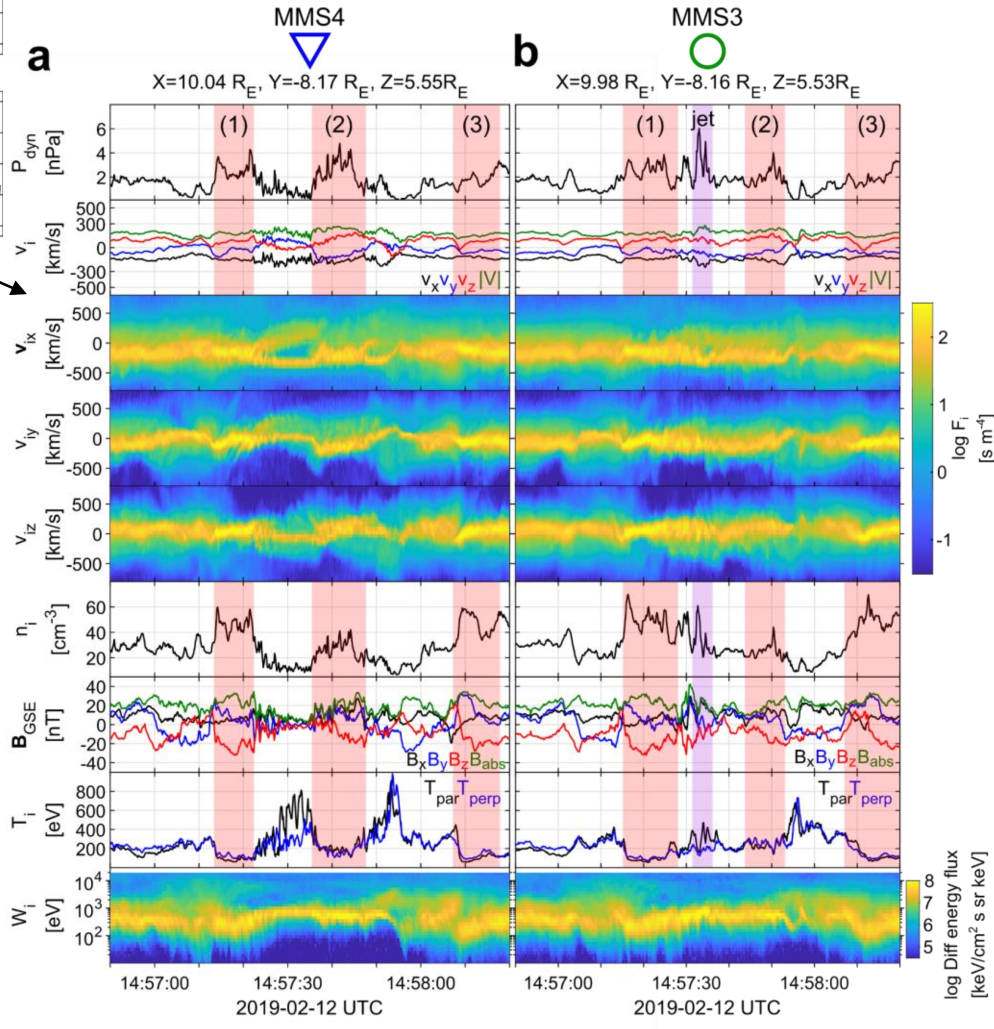
Results

MMS Data | Schematic

General Observations of MMS







<u>Solar Wind:</u>

$v_x \gg$

$v_{y,z} \sim 0$

$n_i \ll$

$\boldsymbol{B} \ll$

Beam like distribution

<u>Foreshock → Magnetosheath (compressed – thermalized plasma)</u>

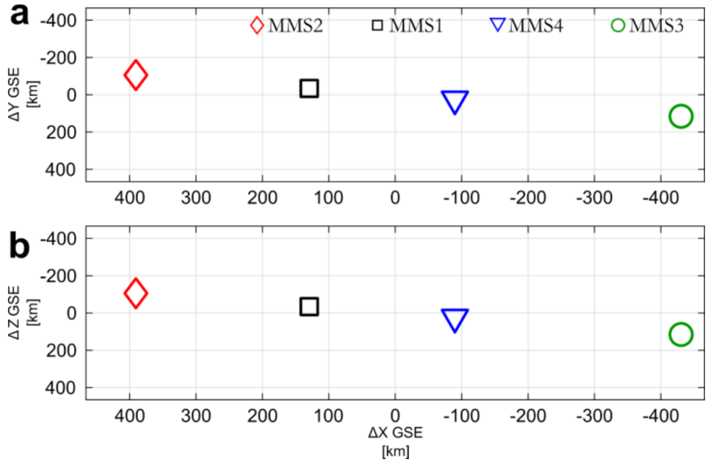
$v \ll v_{SW}$

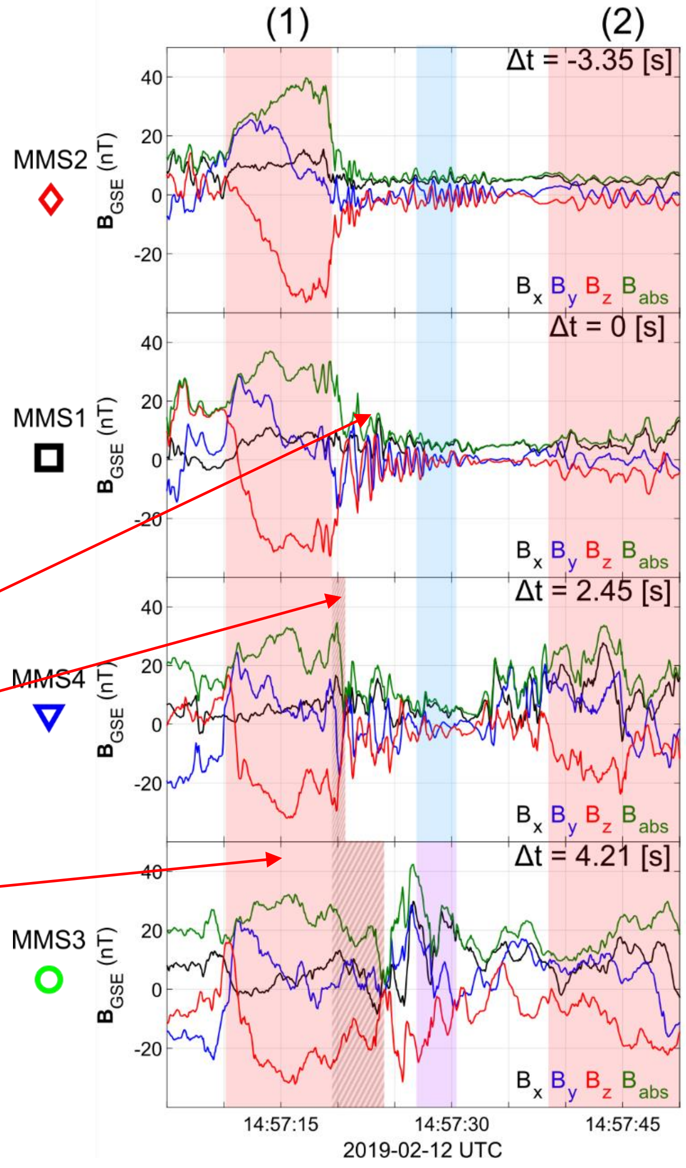
$n_i \gg n_{SW}$

$\boldsymbol{B} \gg$

Thermalized distribution

SLAMS & wave activity co-moving picture





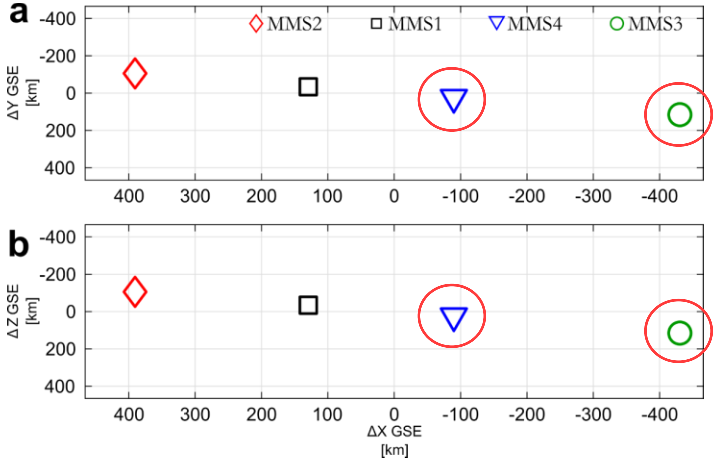
Evolution of SLAMS

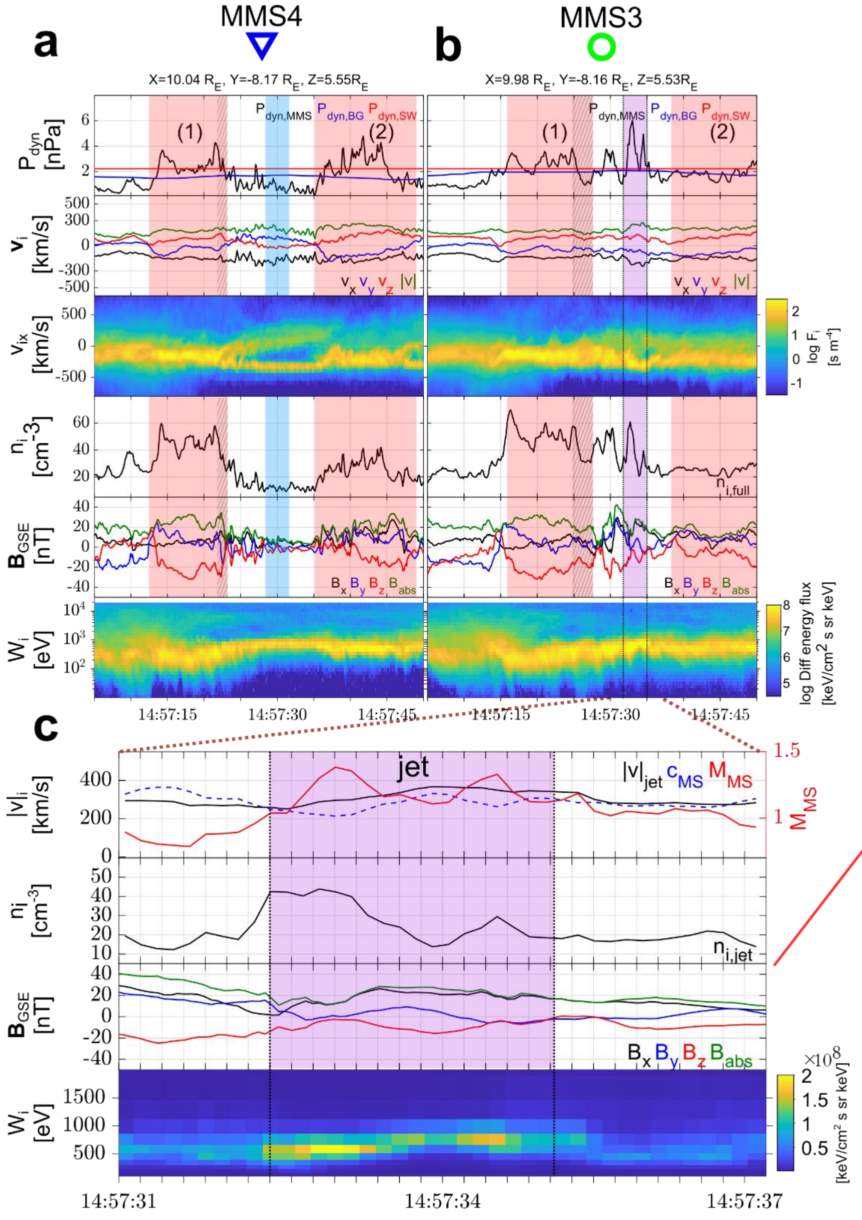
- Interaction with upstream whistler
- New peak /evolution*
- Formation of embedded plasmoid (*downstream density enhancement*)**

* See similar examples by Turner et al. (2021), Chen et al. (2021)

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

MMS inner-spacecraft observations





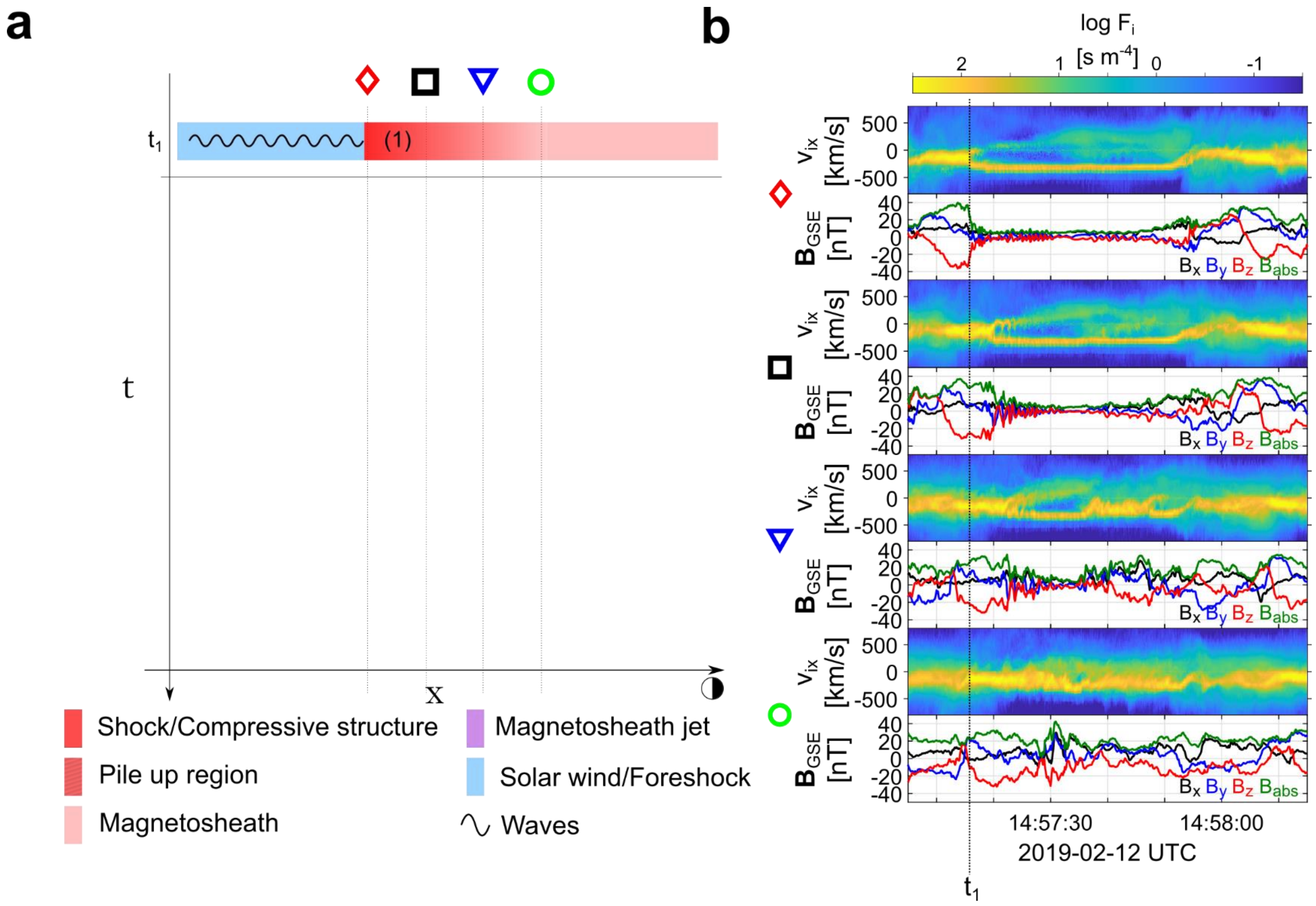
P_{dyn} increase

- *Velocity* : Reformation process, shock front generated upstream of the old, limited interaction with old shock front.
- *Density* : possible explanations
  - ➢ Turner et al. (2021)
  - ➢ Chen et al. (2021)
  - ➢ Stasiewicz et al. (2003)

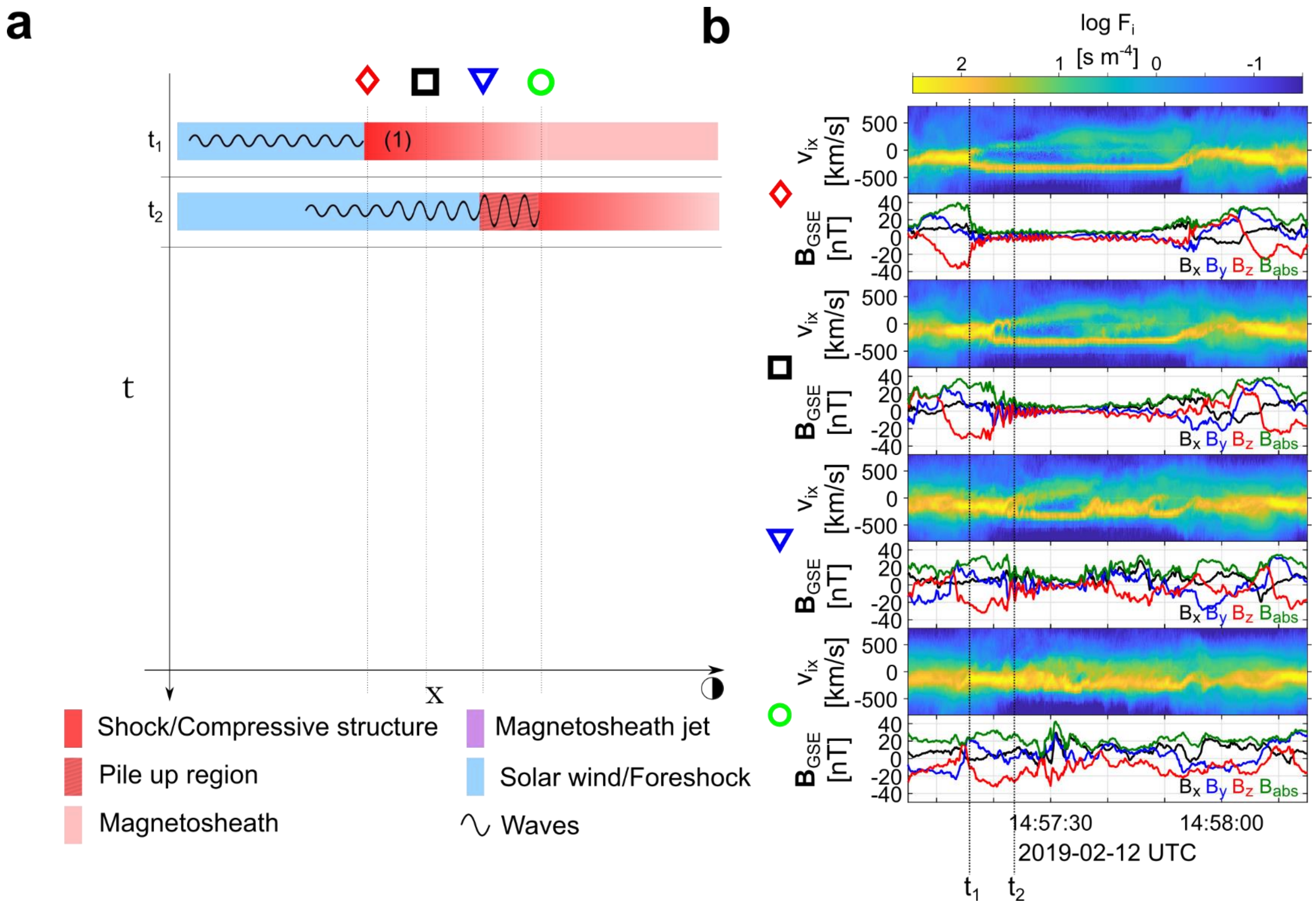
Results

MMS Data | Schematic

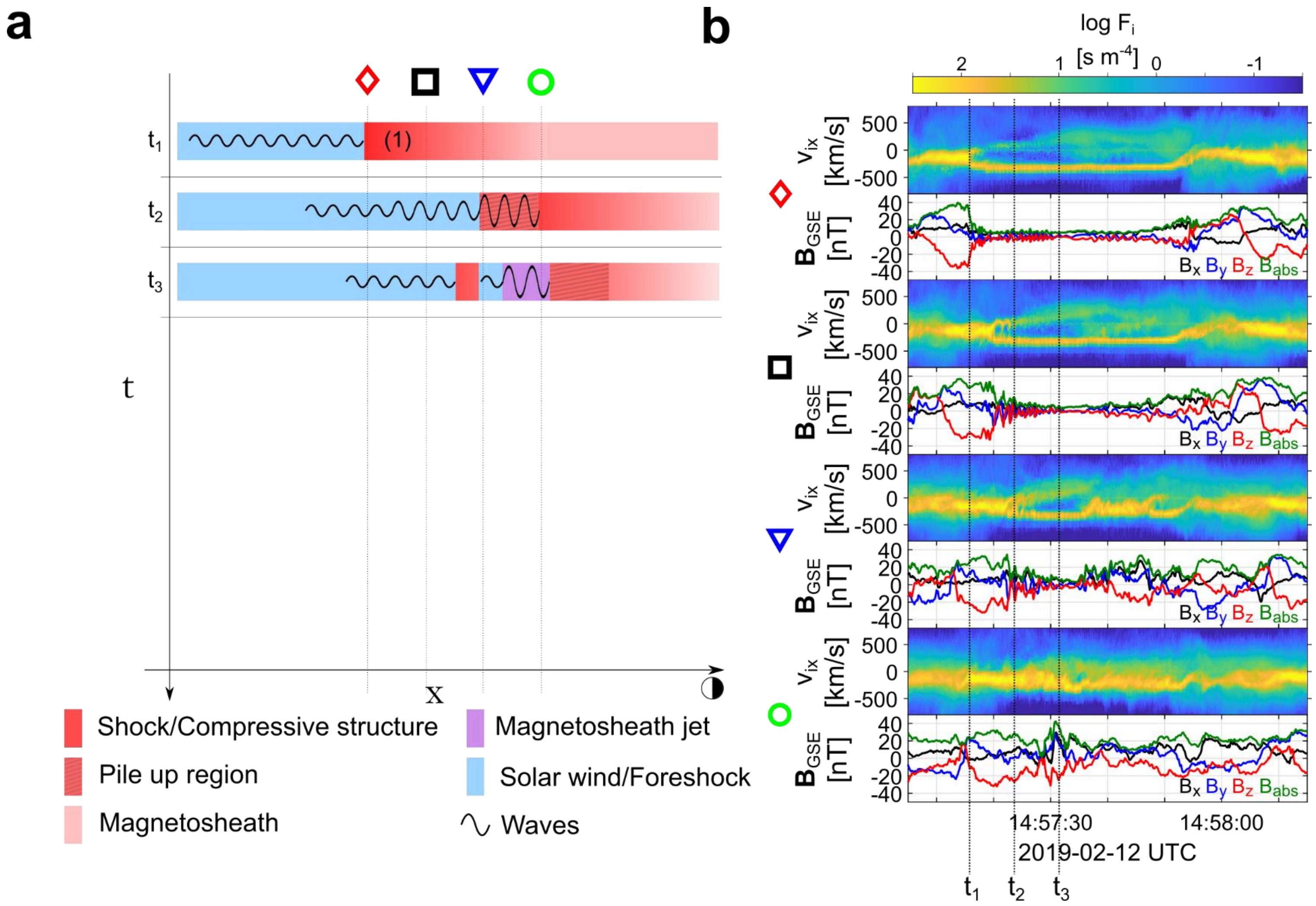
Formation mechanism



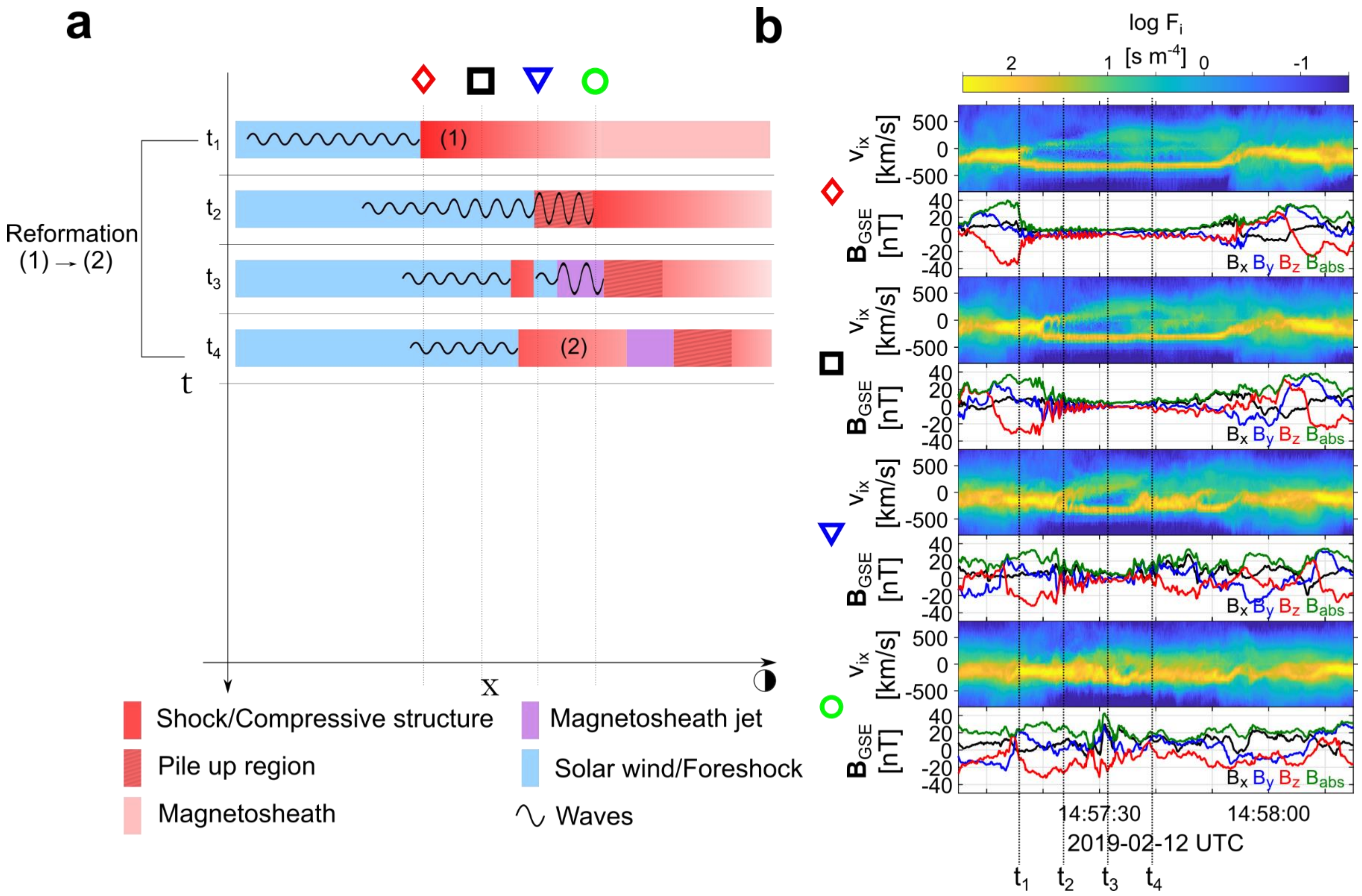
Formation mechanism



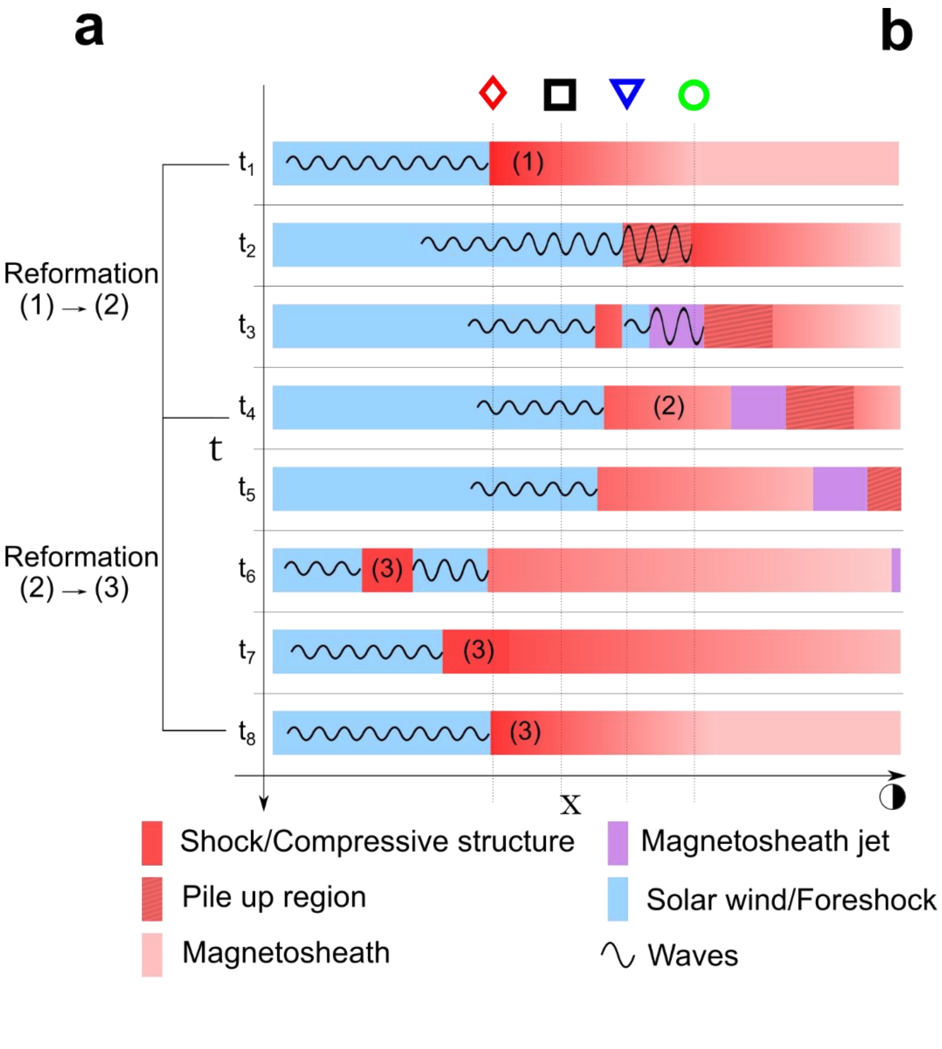
Formation mechanism



Formation mechanism

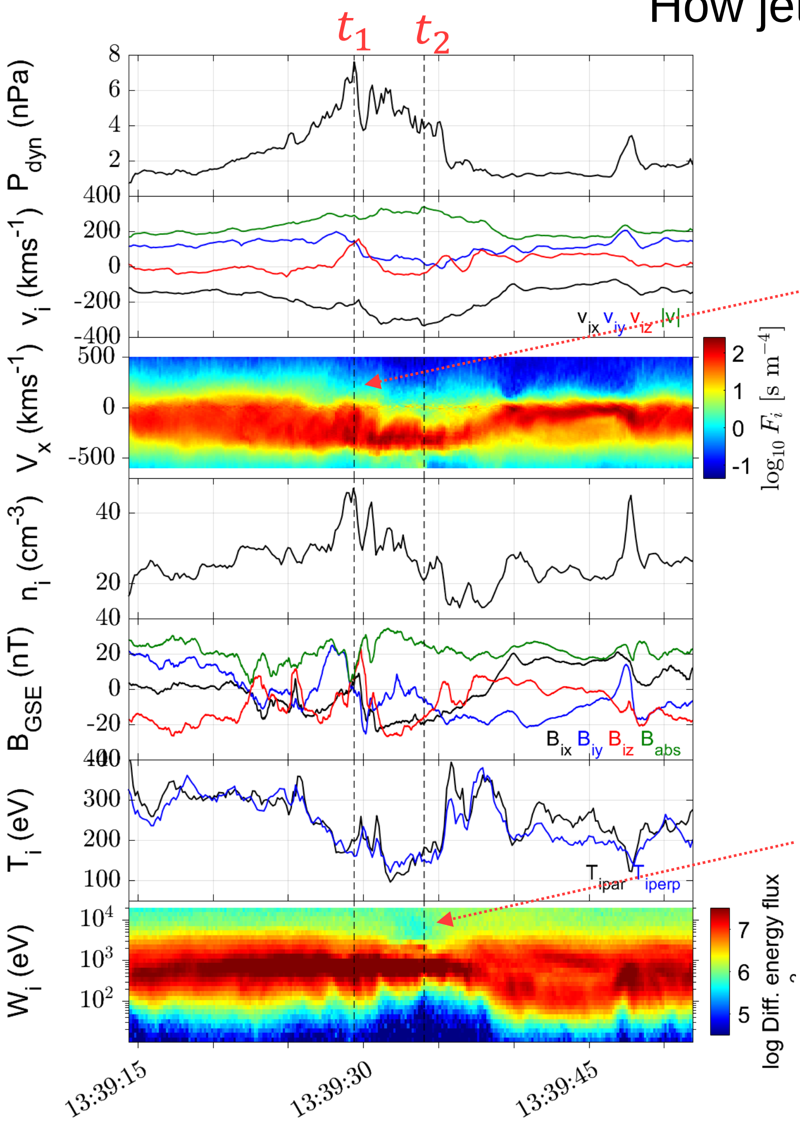


Formation mechanism

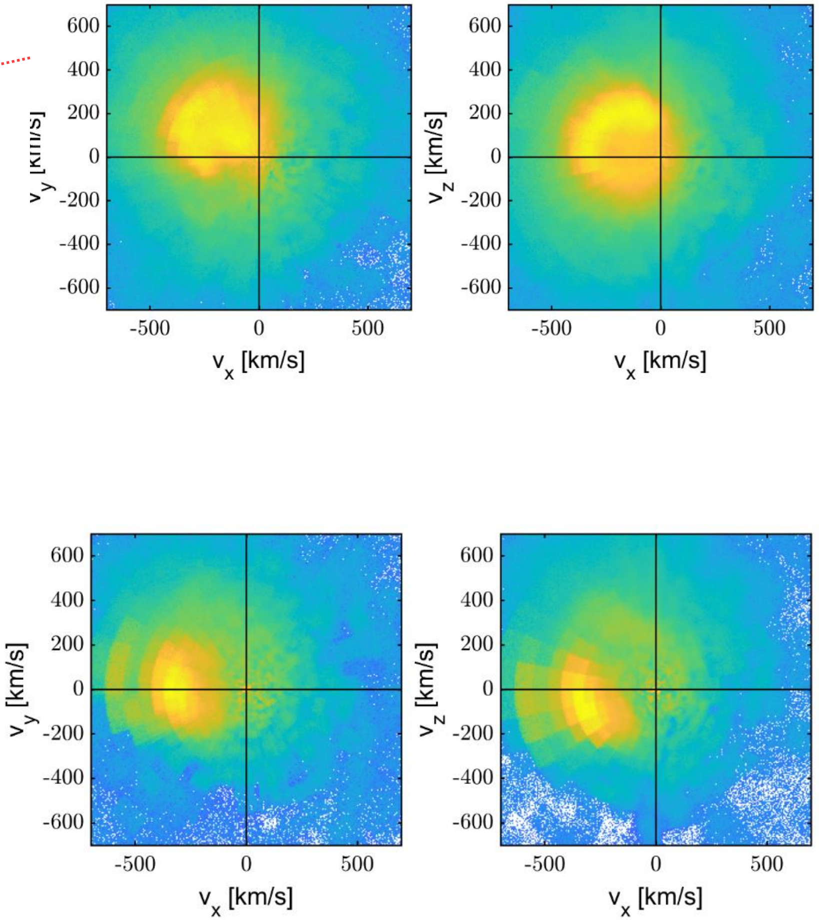


Ongoing results

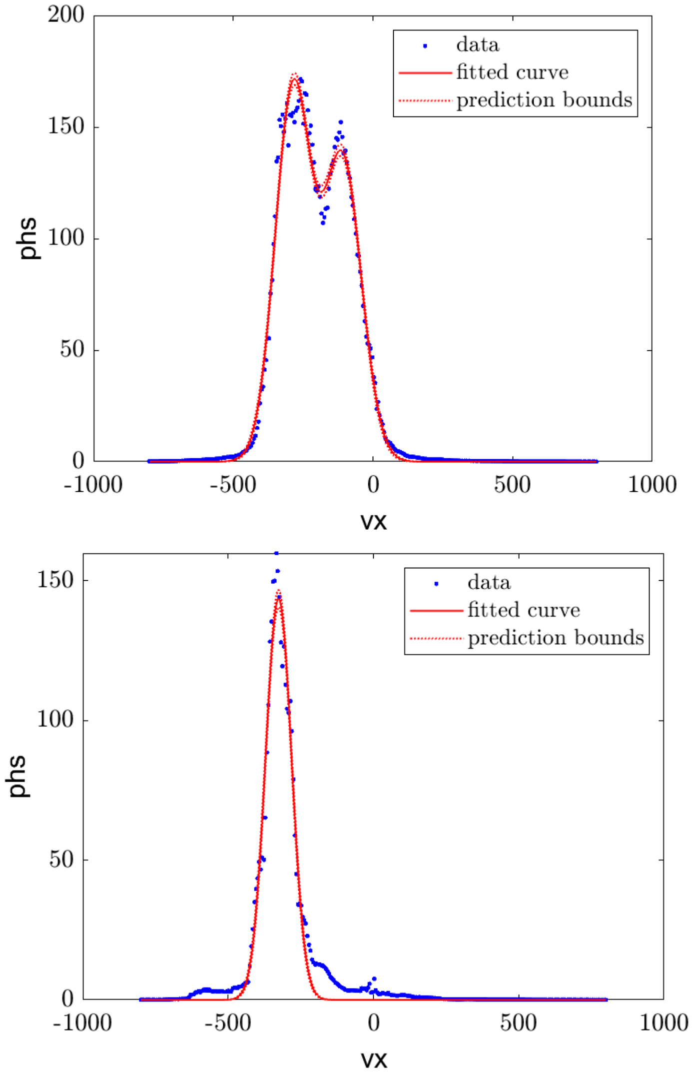
How jets develop after the shock ? How do they interact with the Background ?



Integrated 2D VDFs



Integrated 1D Vx



Raptis, Karlsson et al. (2022 - Ongoing)

Summary & Conclusion

Main points

- ***In-situ* observations** of **SLAMS** becoming "***embedded plasmoids***" (density enhanced downstream regions).
- ***in-situ* observations** of **jets** forming through the dynamical evolution of collisionless shock (**reformation**)

Open Questions

- *Details on SLAMS/waves* – Exact properties & evolution study of FCs numbered 1-3 (TBD)
- *Simulation* comparison – Can we find cases like these in simulations (*ongoing*) ?
- *Statistics* – We need more events, currently found ~3 with similar signatures (TBD).
- *Modeling* – Can we explain jets close to MP ? How long do these jets "survive" in the MSh ? (*ongoing*)
- Morphology & Evolution – What's their interaction with the background ? How their properties vary ? (*ongoing*)

Extras

Extras

MMS – Jet Database

Fast/Survey

9/2015 - 9/2020

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

Burst

Jets with full burst data →

Qpar	423
Qperp	34
Boundary	35
Encapsulated	31
Close to BS / MP	495
Others	428

Raptis S., Karlsson T., et al. (2020) | JGR
Raptis S., Aminalragia-Giamini S., et al. (2020) | Frontiers
Palmroth M., **Raptis S.**, et al. (2021) | Annales
Kajdic P., **Raptis S.**, et al. (2021) | GRL

Raptis S., Karlsson T., et al. (2022) | Nat. Commun
Raptis S., Karlsson T,, et al. (2022) | Ongoing

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)

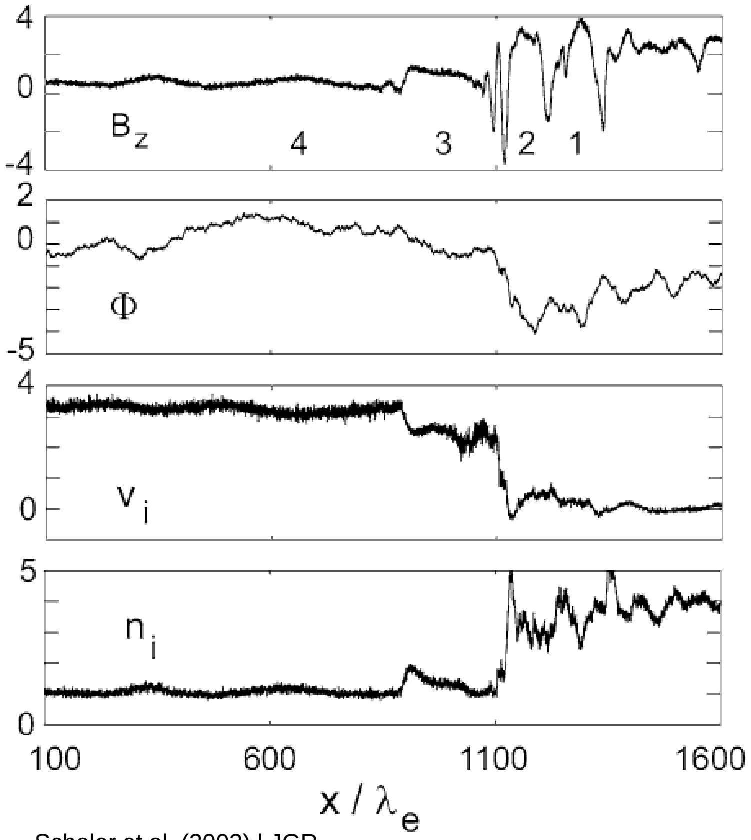
Modeling & formation

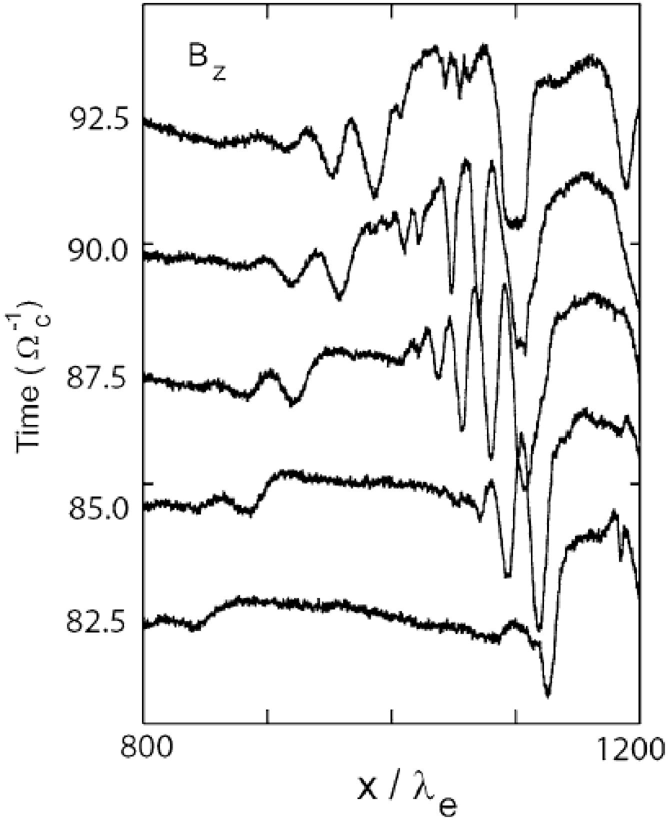
- **Velocity & magnetic field alignment** in jets **:** Plaschke et al. (2020)
- **Classification** of jets using MMS & Neural Networks : Raptis et al. (2020a,2020b)
- Comparison **MMS vs simulations** : Palmroth et al. (2021)
- **Solar wind effect** on jet formation : LaMoury et al. (2021)
- Magnetosheath Jets and **Plasmoids** - Hybrid Simulations : Preisser et al. (2020)
- **Formation** of jets in **Quasi-perpendicular magnetosheath** : Primoz et al. (2021)

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. etc.

Shock Reformation – Simulations

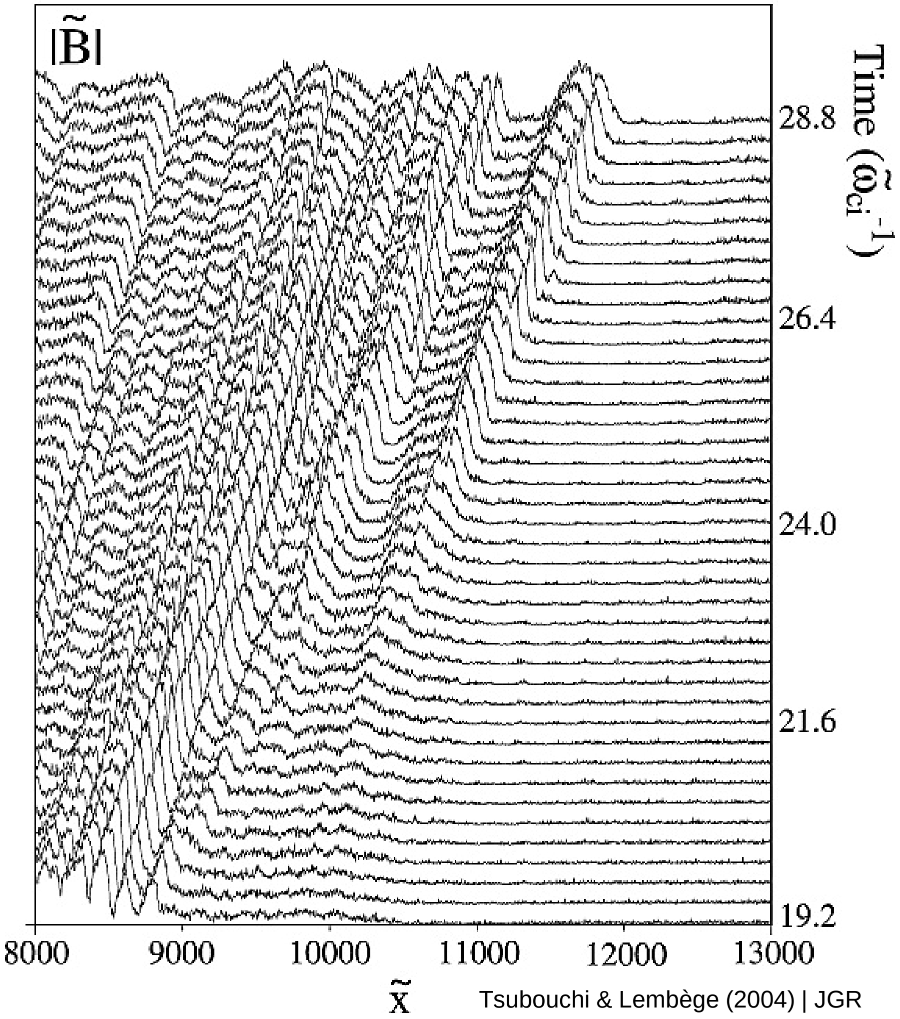
1D-PIC simulation (30°), $M_A = 4.7$
mi/me = 100 and ωpe/Ωce = $\sqrt{10}$.





Scholer et al. (2003) | JGR

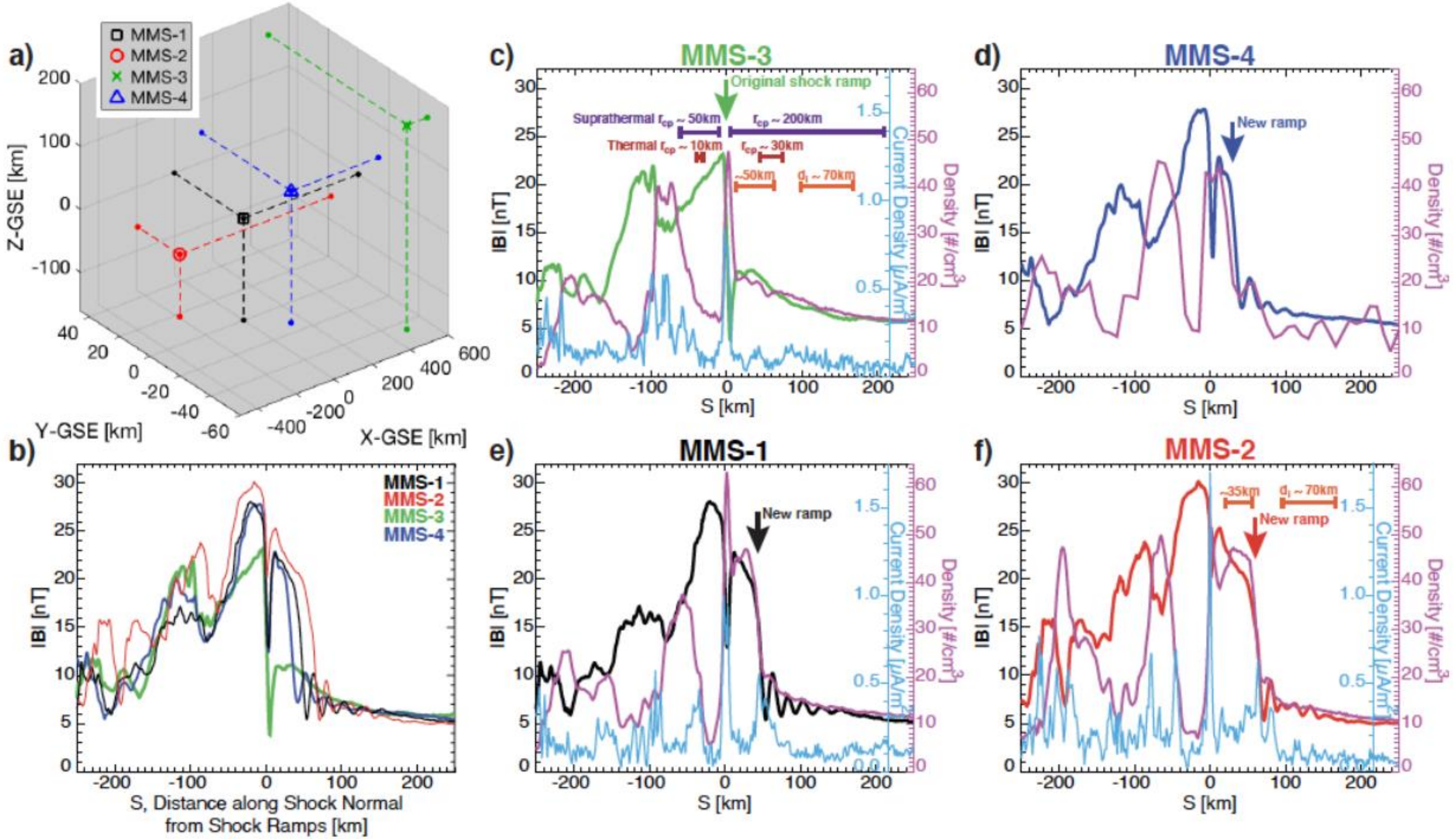
mi/me = 50 and ωpe/Ωce = 4.



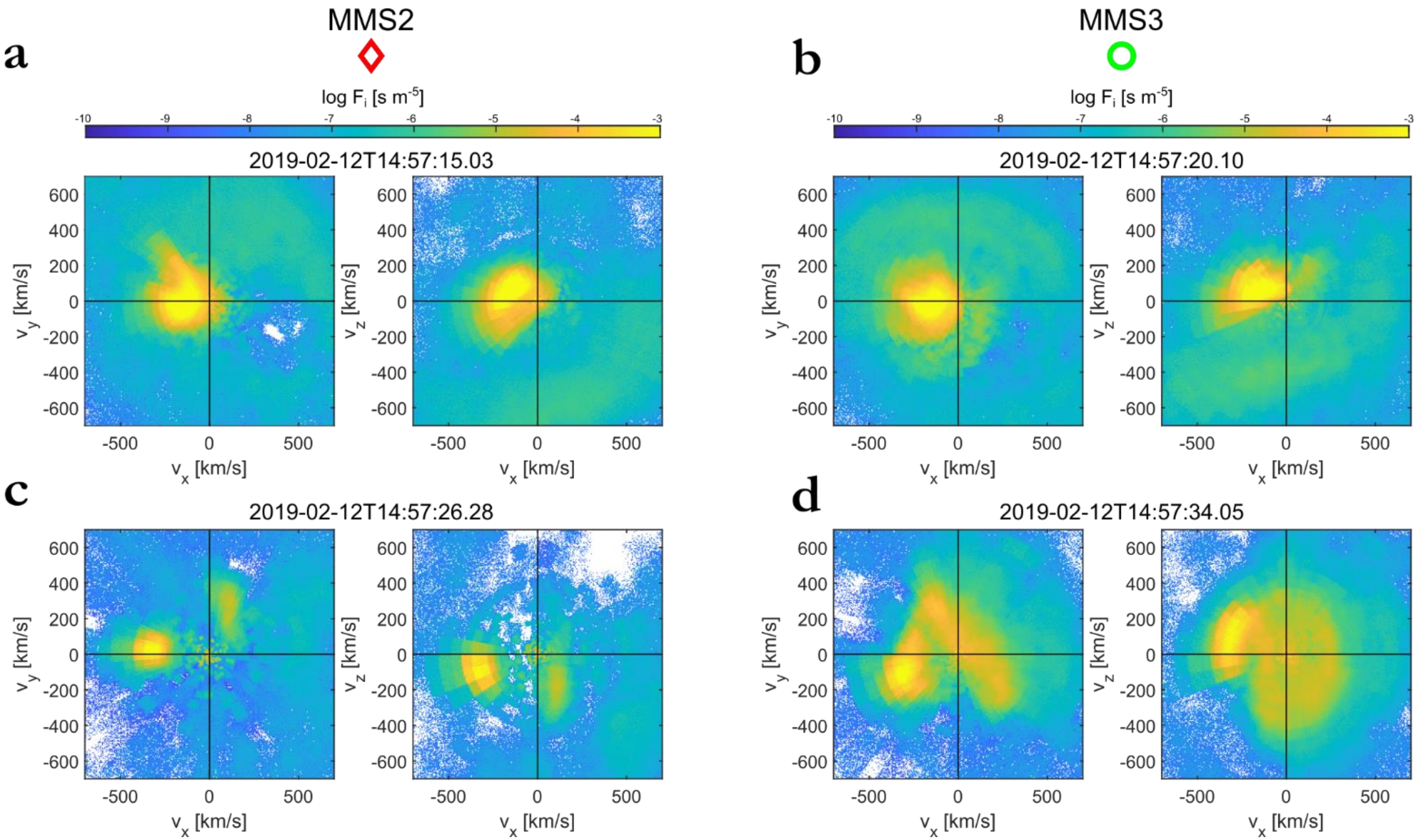
Tsubouchi & Lembège (2004) | JGR

More nice sources for review : Burgess & Scholer (2015), Willson (2016)

Turner et al. 2021 (local reformation/evolution)

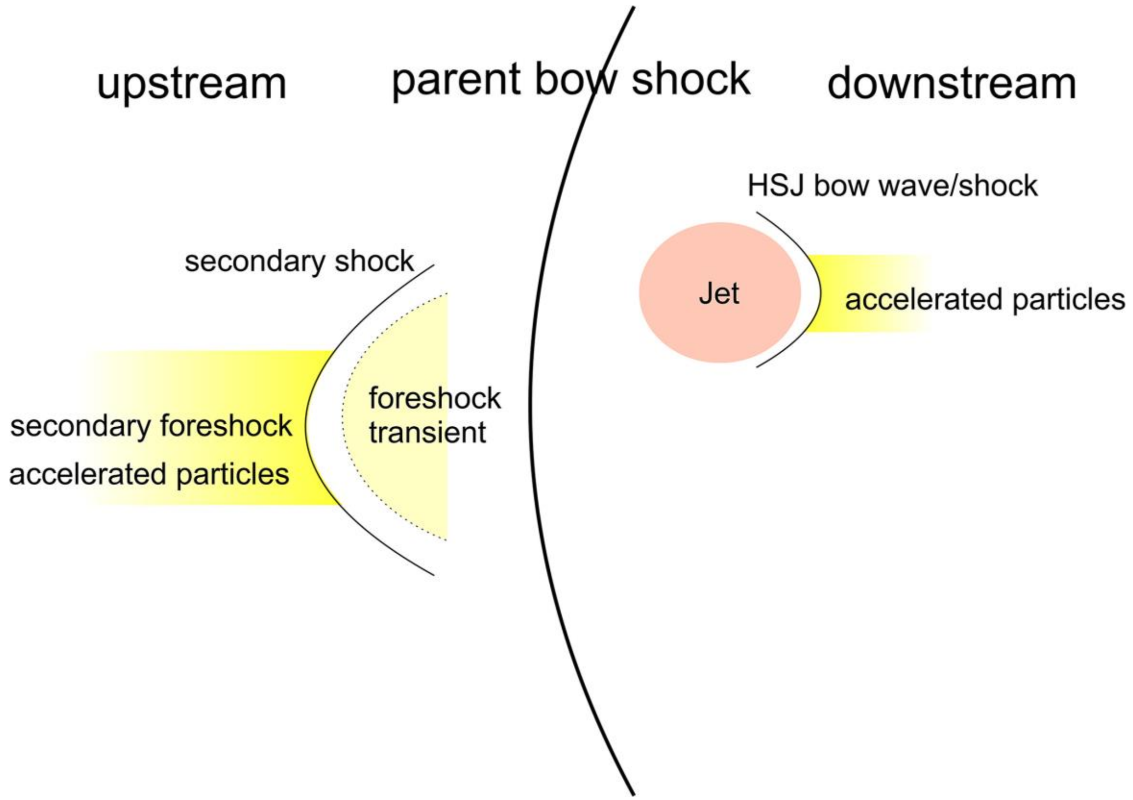


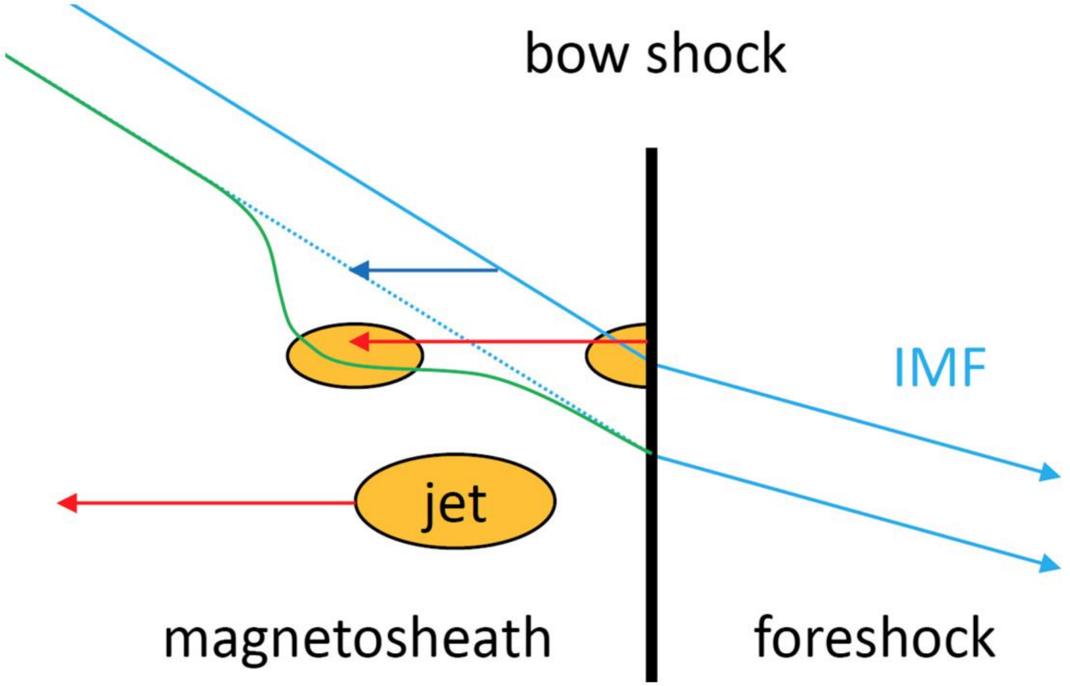
VDFs



MMS2
MMS3
a
b
c
d
log F$_i$ [s m^{-5}]
log F$_i$ [s m^{-5}]
-10 -9 -8 -7 -6 -5 -4 -3
-10 -9 -8 -7 -6 -5 -4 -3
2019-02-12T14:57:15.03
2019-02-12T14:57:20.10
2019-02-12T14:57:26.28
2019-02-12T14:57:34.05
v$_y$ [km/s]
v$_z$ [km/s]
v$_x$ [km/s]
600 400 200 0 -200 -400 -600
-500 0 500

Jets interaction with ambient plasma





Liu et al. (2020)

Plaschke et al. (2018,2020)

Fast/Survey MMS data	**Burst** MMS data
Resolution (samples/s)	Resolution (samples/s)
FGM (magnetic field): 0.0625	0.0078
FPI (plasma moments | ions): 4.5	0.15
EDP (electric field): 0.0313	0.00012218

Fast/Survey MMS data

Pros

- ✓ Always available
- ✓ Decent resolution
- ✓ Can be good for statistics due to availability

Cons

- ✗ Not suitable for small scale studies
- ✗ Could be misleading close to boundary surfaces (Magnetopause, Bow shock etc.)

Burst MMS data

Pros

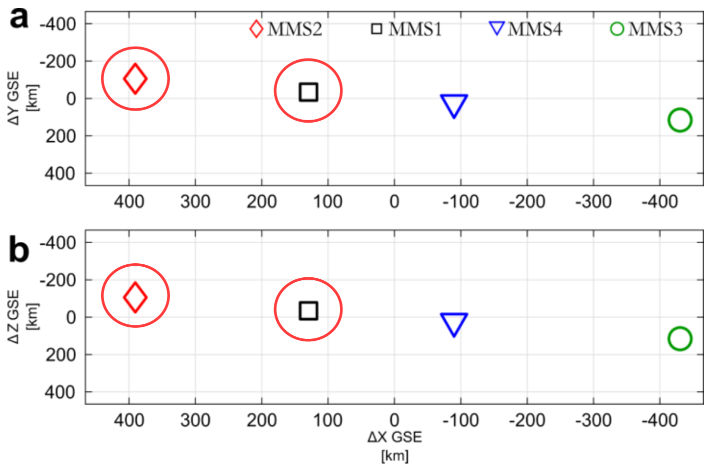
- ✓ Very high resolution
- ✓ Able to resolve structures close to boundary surfaces (e.g. mix of plasma close to magnetopause, bow shock, foreshock etc.)

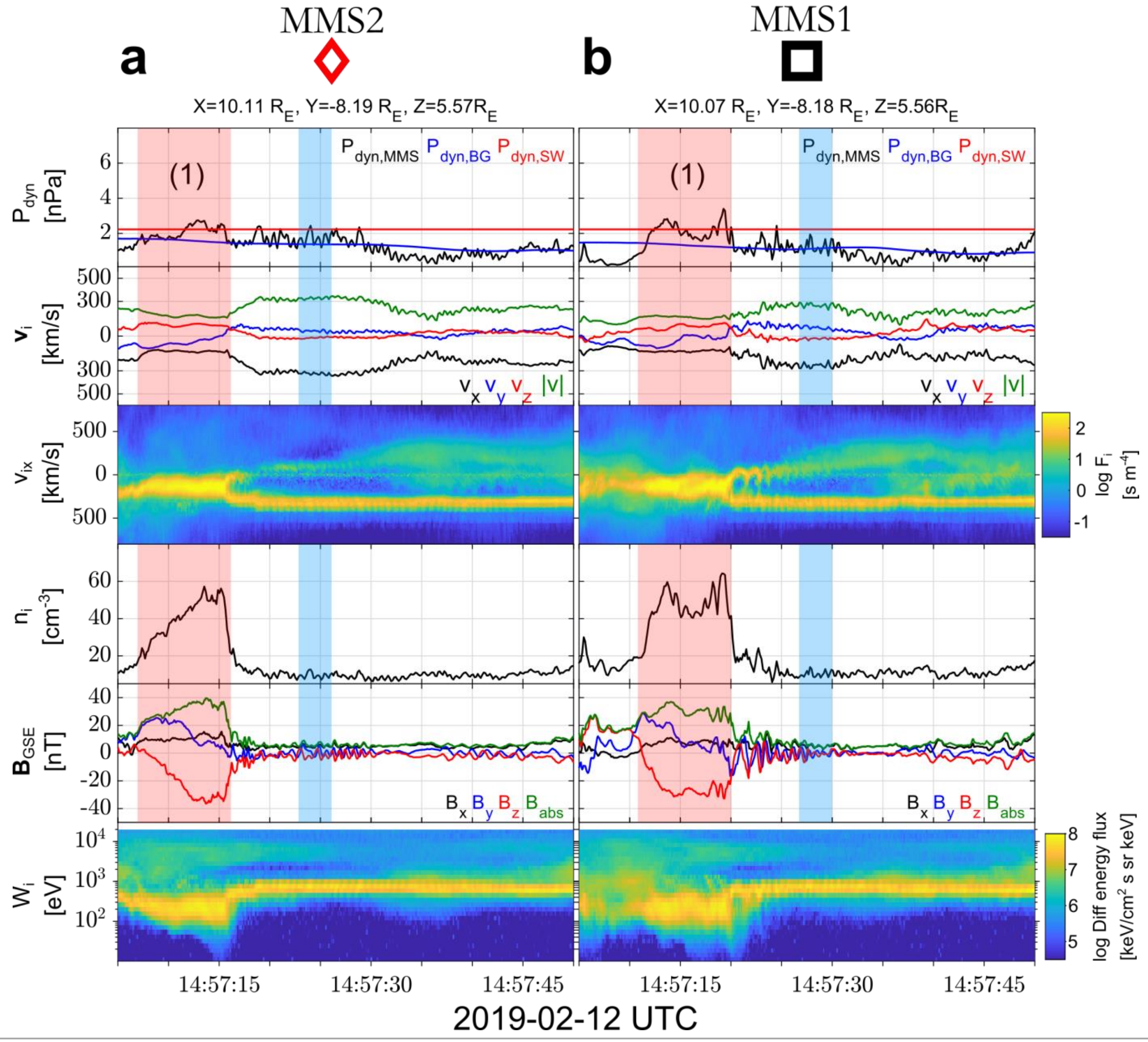
Cons

- ✗ Not available all the time, mostly available close to vital mission objectives (magnetopause, diffusion regions, shock transitions etc.)
- ✗ Hard to do proper large scale statistics due to biases generated from specific availability and manual choice of intervals

More information: Baker, et al. (2016) | Space Sci Rev 19

MMS outer-spacecraft observations





Boundary Jet – Typical Examples with MMS

Dynamic Pressure (nPa)

Dynamic Pressure Ratio

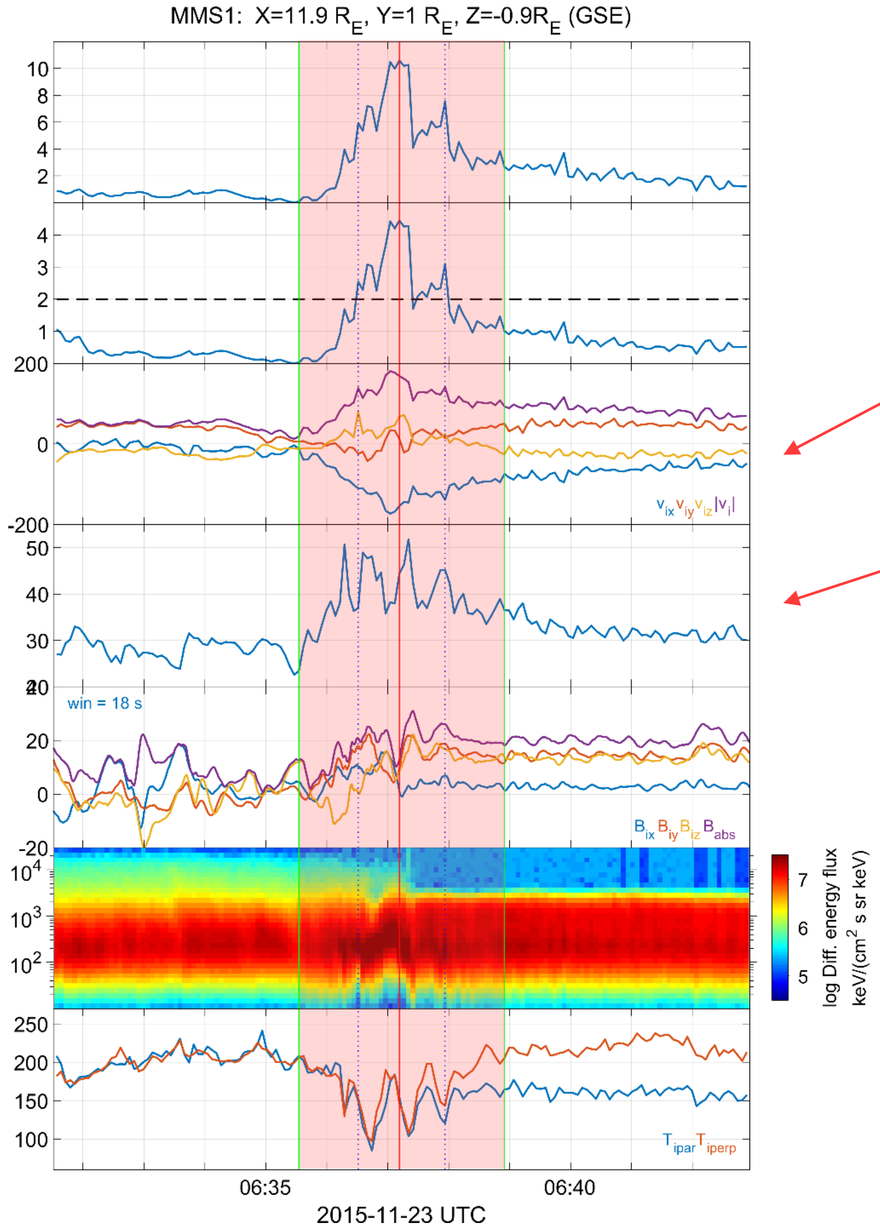
Velocity (km/s)

Density (cm^{-3})

Magnetic Field (nT)

Differential Ion Energy Spectrum (eV)

Ion Temperature (eV)



velocity enhancement

density enhancement

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