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

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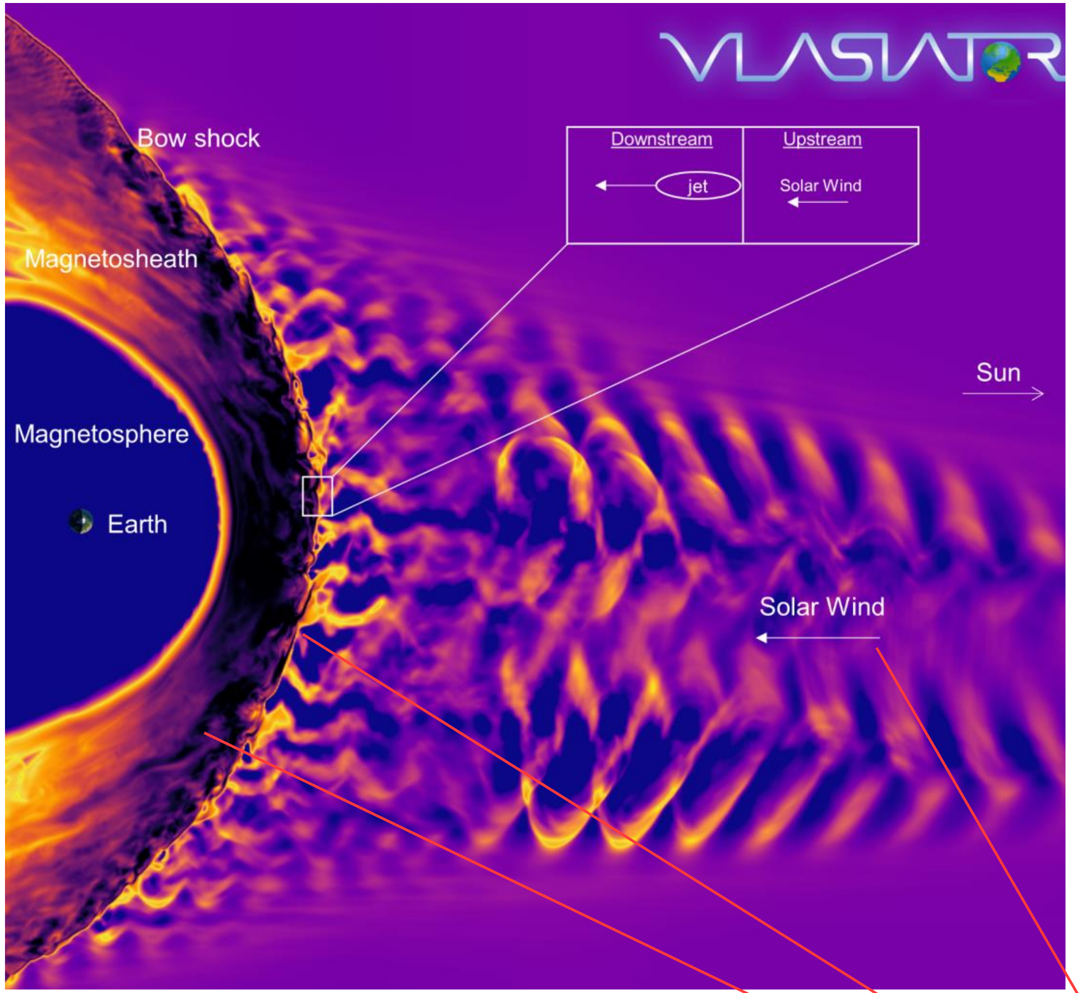
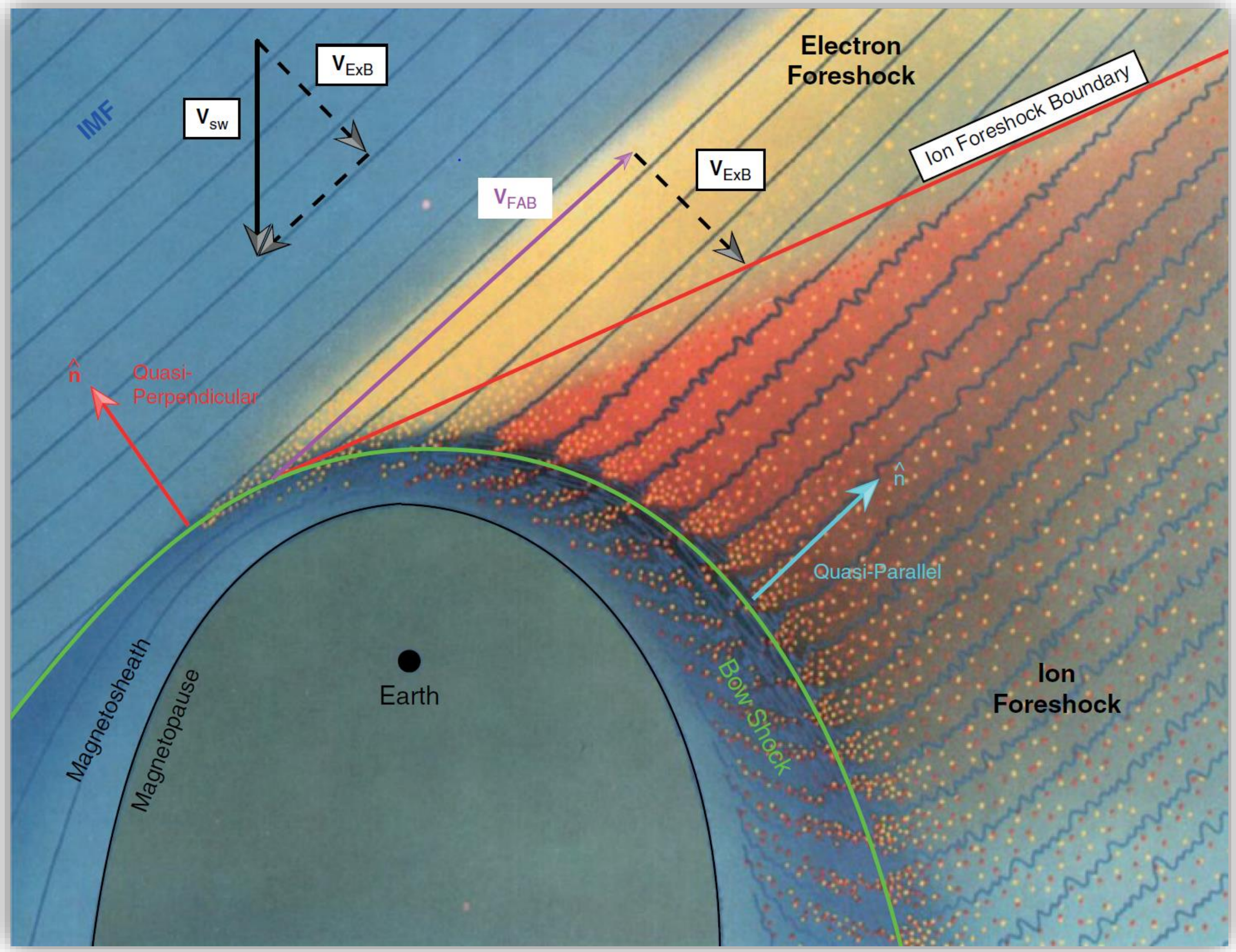
IRF Uppsala Seminars
16/03/2022

Earth's Magnetosphere & Shock environment





https://msolss.github.io/MagSeminars/

Lynn Wilson – Solar Wind
Heli Hietala – The Bowshock and Foreshock
Ferdinand Plaschke – The Magnetosheath

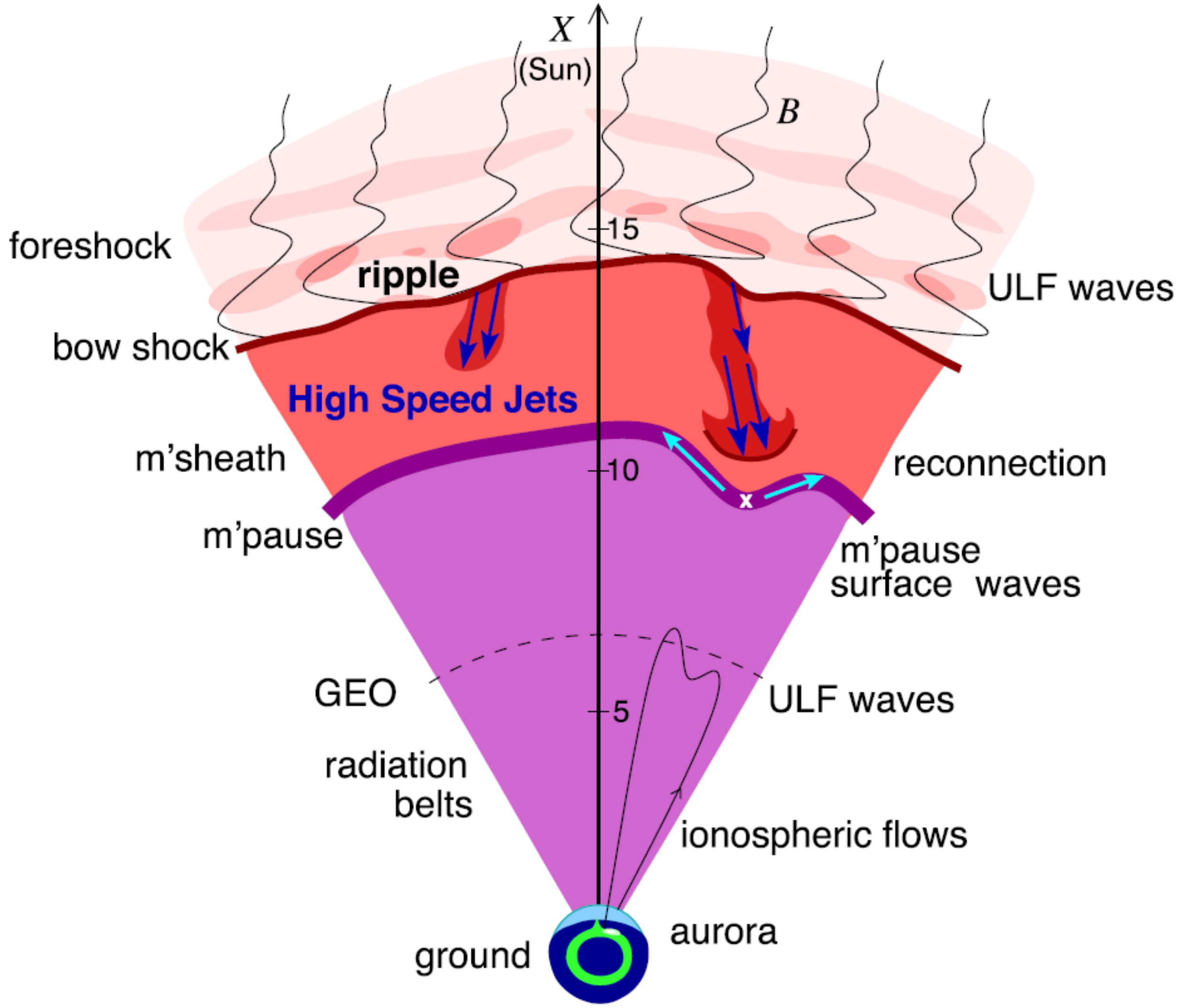
Courtesy of M. Palmroth, U Helsinki

L. B. Wilson (2016)

Introduction

Jets | Reformation | MMS

Magnetosheath Jets – Definition



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

<u>Definition</u>

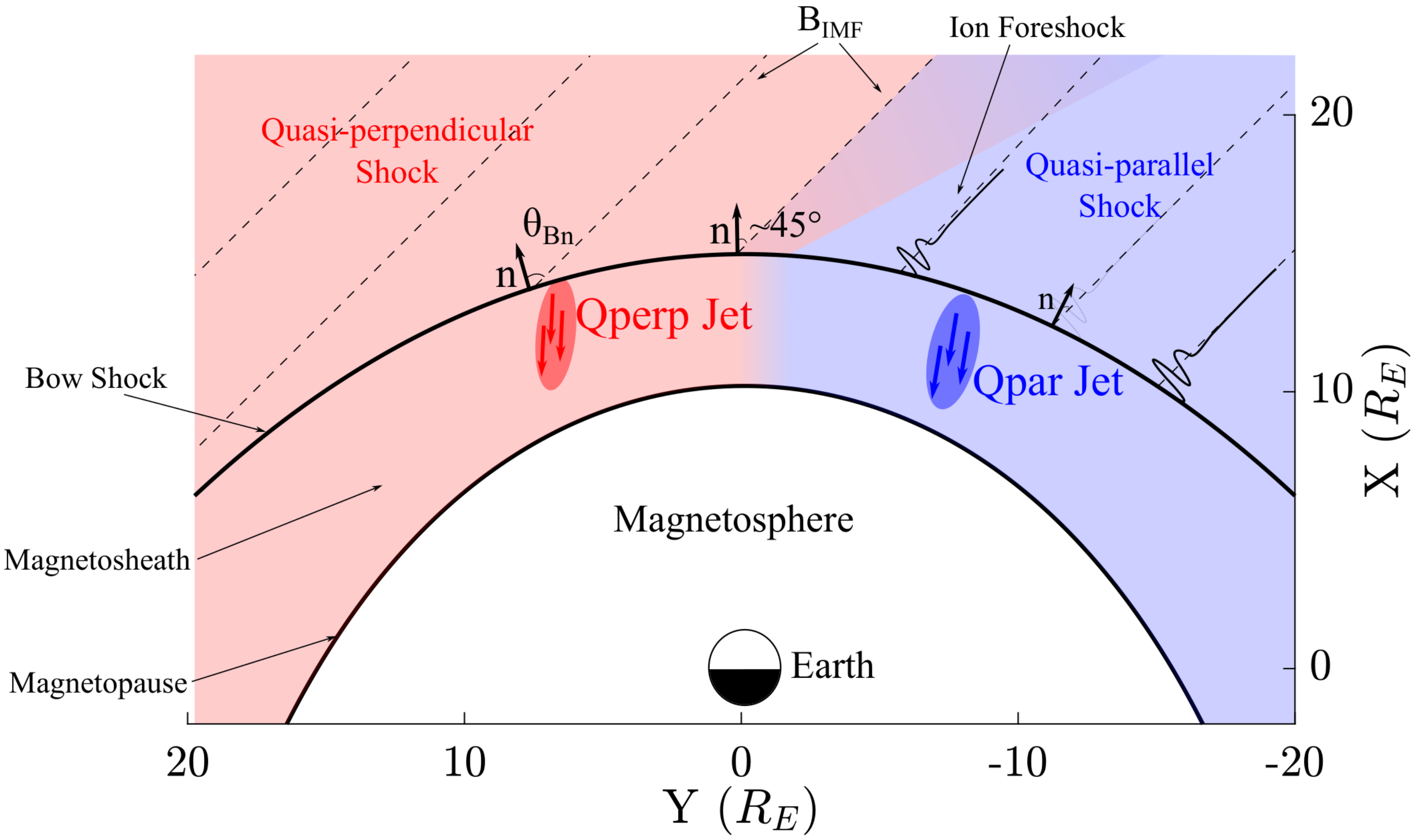
Magnetosheath jets are **transient localized enhancements** of **dynamic pressure** (density and/or velocity increase)

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

<u>Related phenomena</u>

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"

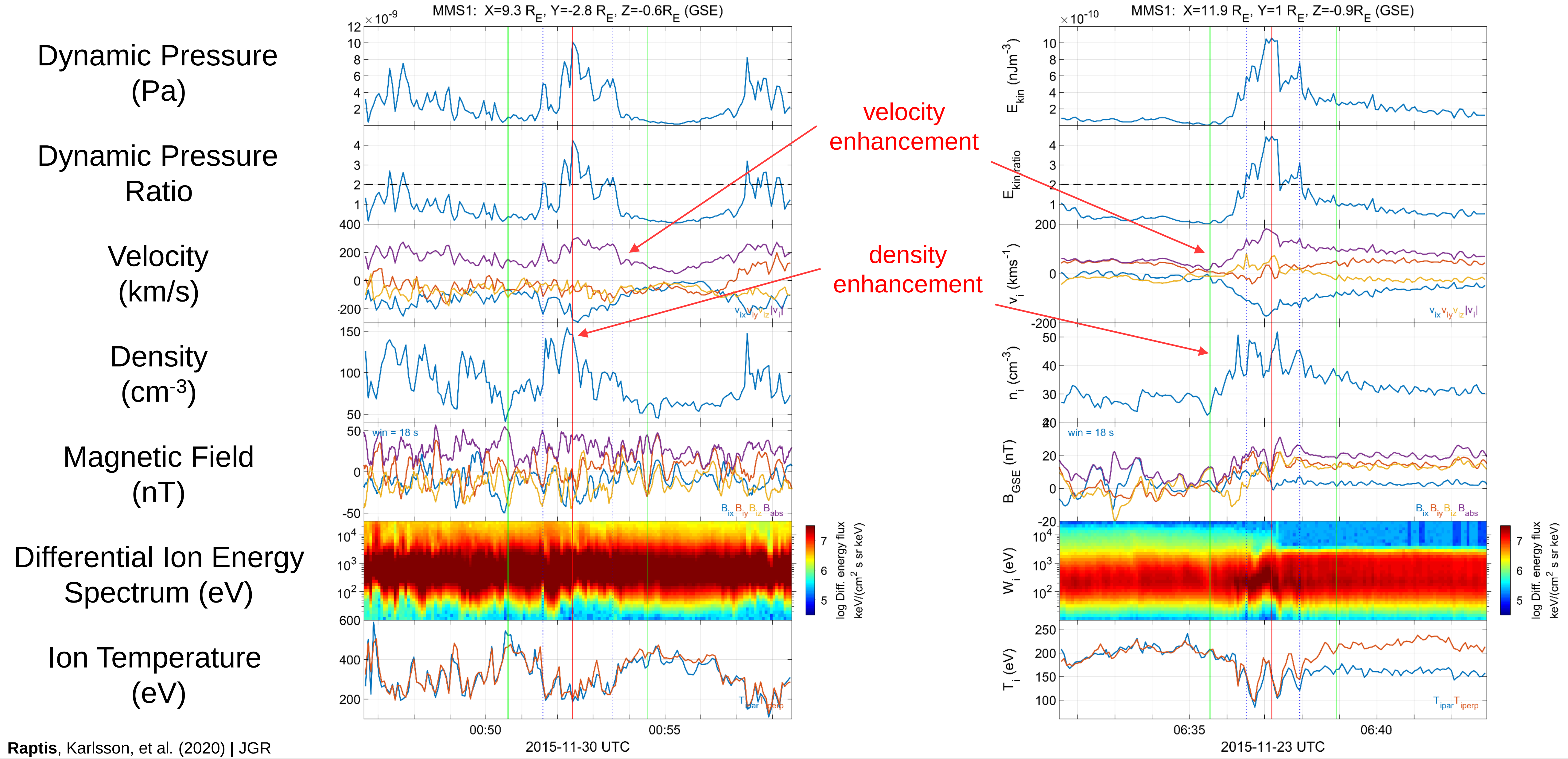
Qpar = $\Theta_{Bn} \lesssim 45°$
Qperp = $\Theta_{Bn} \gtrsim 45°$

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

Vuorinen et al. (2019)

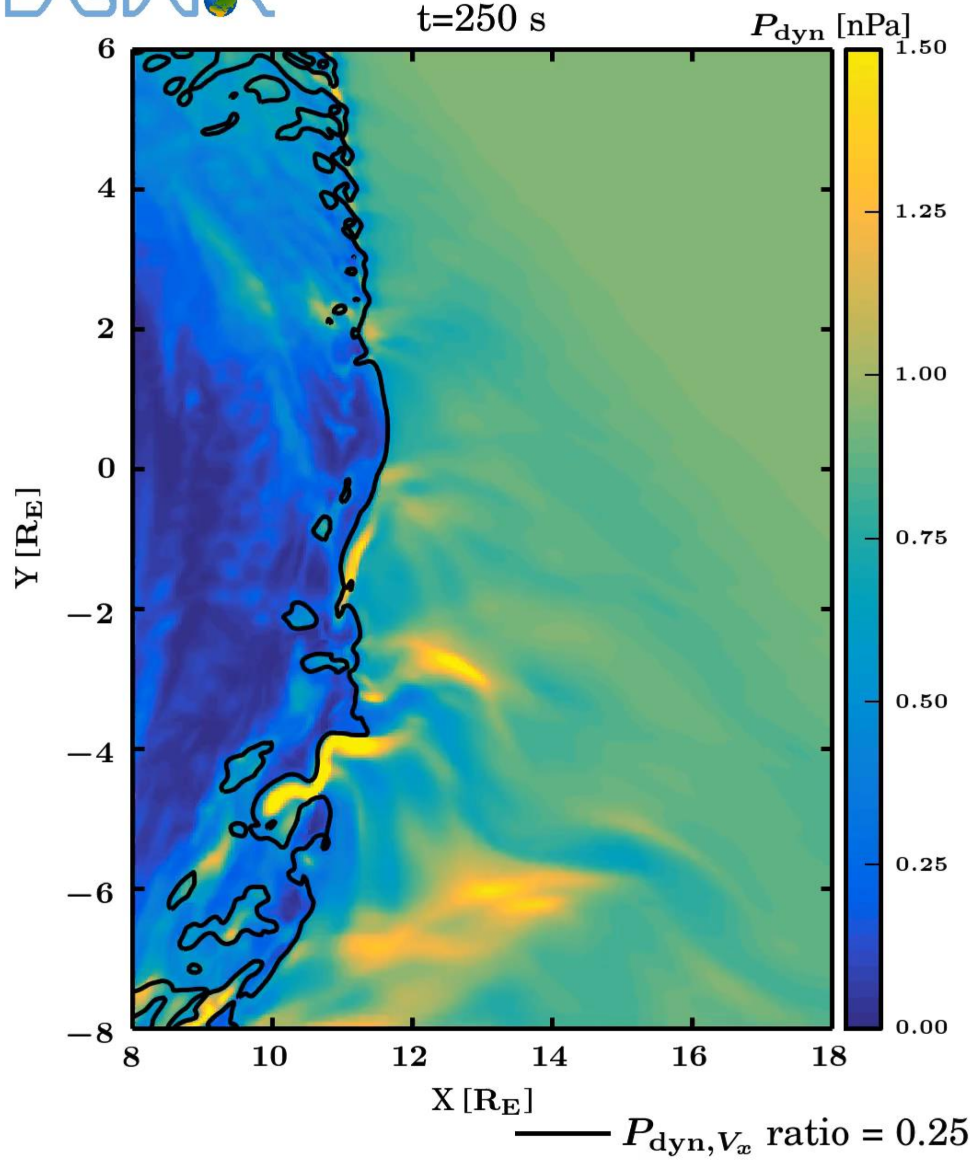
Raptis, Karlsson, et al. (2020) | JGR
Raptis, Aminalragia-Giamini et al. (2020) | Front. Astron. Space Sci
Karlsson, **Raptis** et al. (2021) | JGR
Kajdič, **Raptis** et al. (2021) | GRL

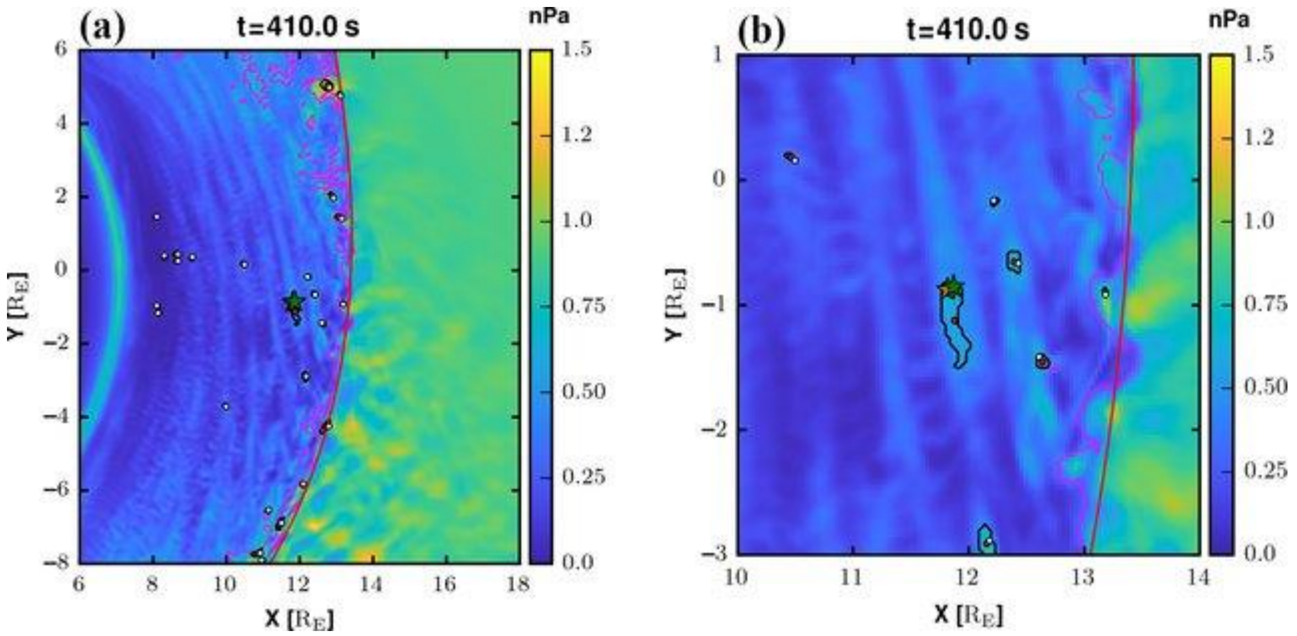
Jet – Typical Examples with MMS



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

Jets in simulations





Palmroth M., et al. (2018, 2021)

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

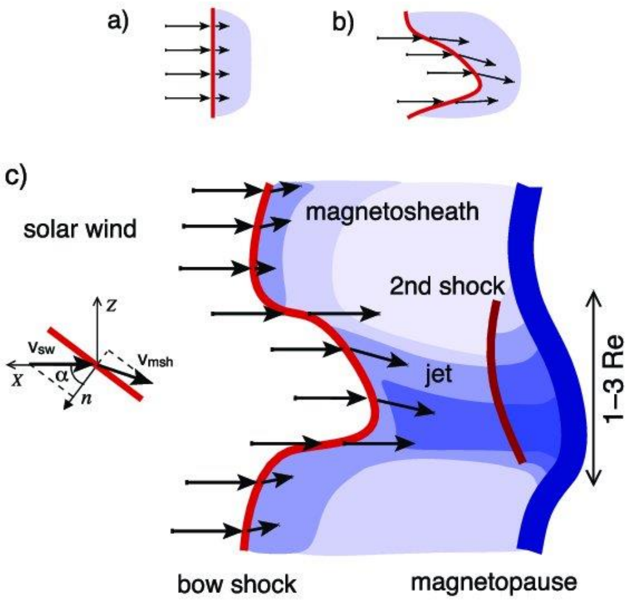
- **Velocity & magnetic field alignment** in jets **:** Plaschke et al. (2020)
- **Classification** of jets using MMS & Neural Networks : Raptis et al. (2020a,2020b)
- Comparison **MMS vs simulations** : Palmroth et al. (2021)
- **Solar wind effect** on jet formation : LaMoury et al. (2021)
- Magnetosheath 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.

But how are jets formed?

How are these jets created ?

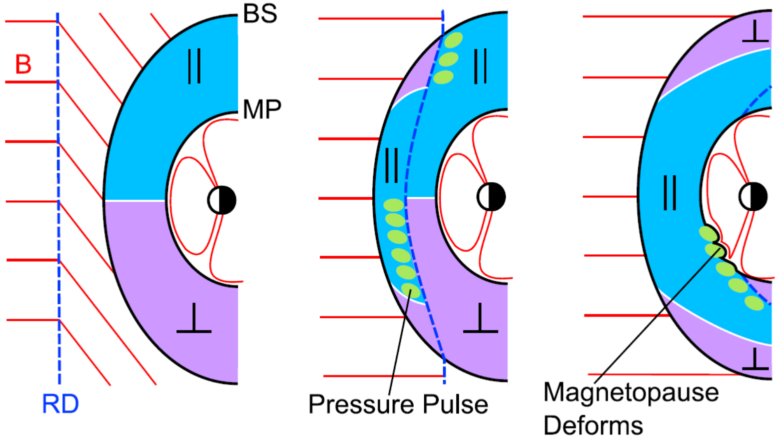
Shock ripples



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

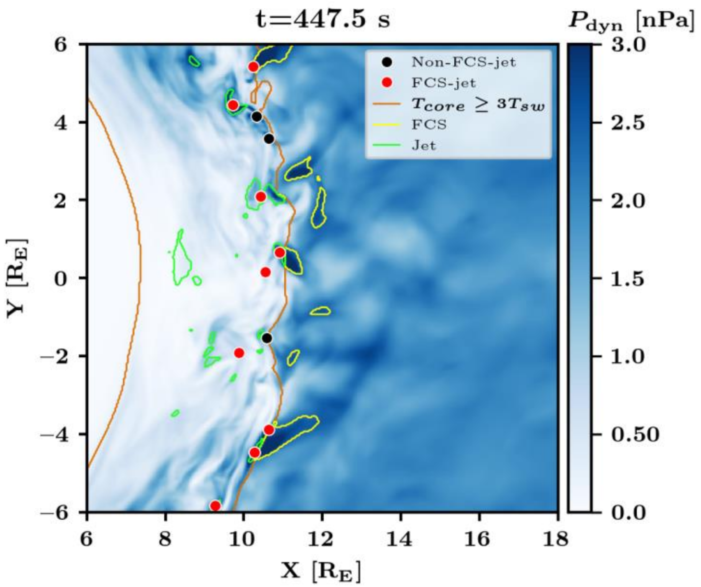
Hietala et al. (2009,2012)

SW discontinuities



Archer et al. (2012)

Foreshock Structures



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

Why foreshock & jets ?

Observations

Karlsson et al. (2012, 2015):

Embedded plasmoid = density
Fast plasmoid = density + velocity

*"…**plasmoids**, … **properties in common with SLAMS…**"*

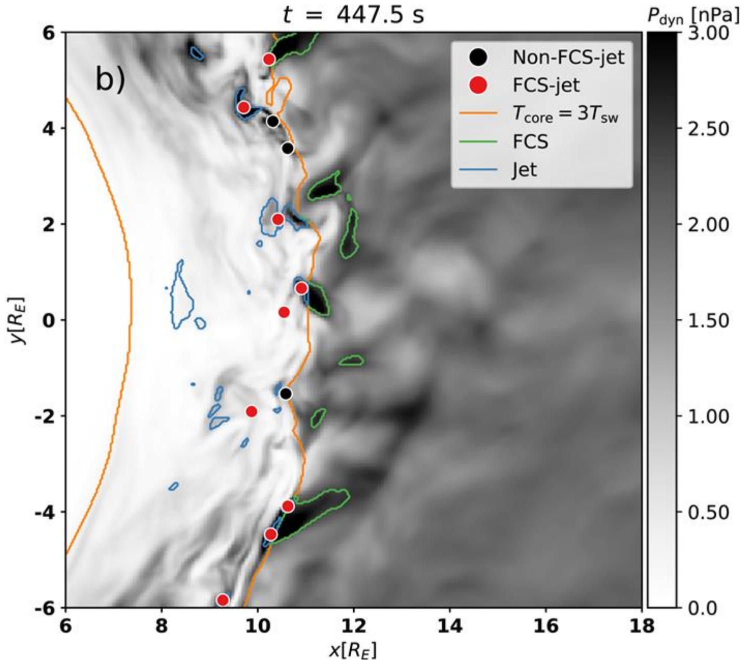
Raptis et al. (2020): *"… **SLAMS-associated mechanisms** are therefore supported and appear to be key elements of jet formation... "*

HFA : *Savin et al. (2012)*
SHFA : *Zhang et al. (2013)*
Foreshock Cavities : *Sibeck et al. (2021)*

Simulations

Palmroth et al. (2018): *"**high-dynamic-pressure structure** that **reproduces observational features associated with** a short, large-amplitude magnetic structure (**SLAMS**)"*

Suni et al. (2021): *"We find that **75% of jets are caused by Forceshock Compressive Structures**"*



HFA: *Omidi et al. (2013)*

Introduction

Jets | Reformation | MMS

Shock Reformation & SLAMS – Clarification

Shock Reformation

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

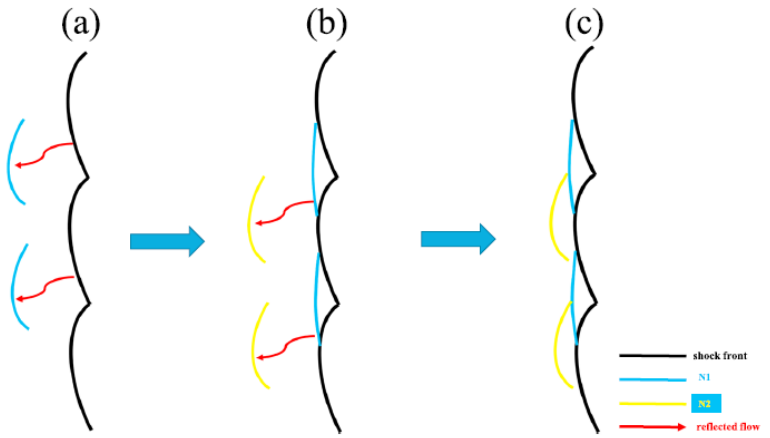
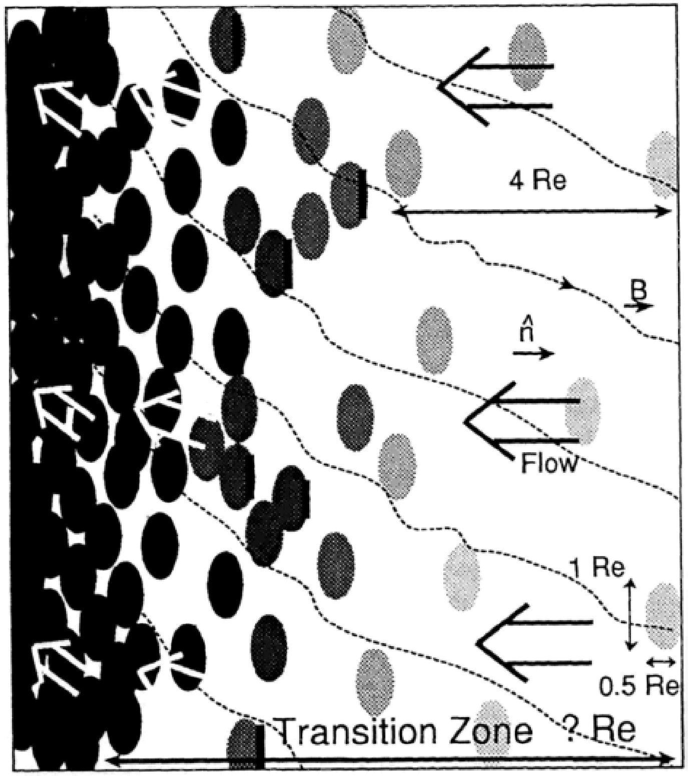


Figure 11. The sketch for evolution of shock front. (a) A rippled shock front, (b) a plane shock front, and (c) a rippled shock front. Solid lines and red arrows denote shock front and reflected beams, and N1 and N2 indicate new shock fronts.

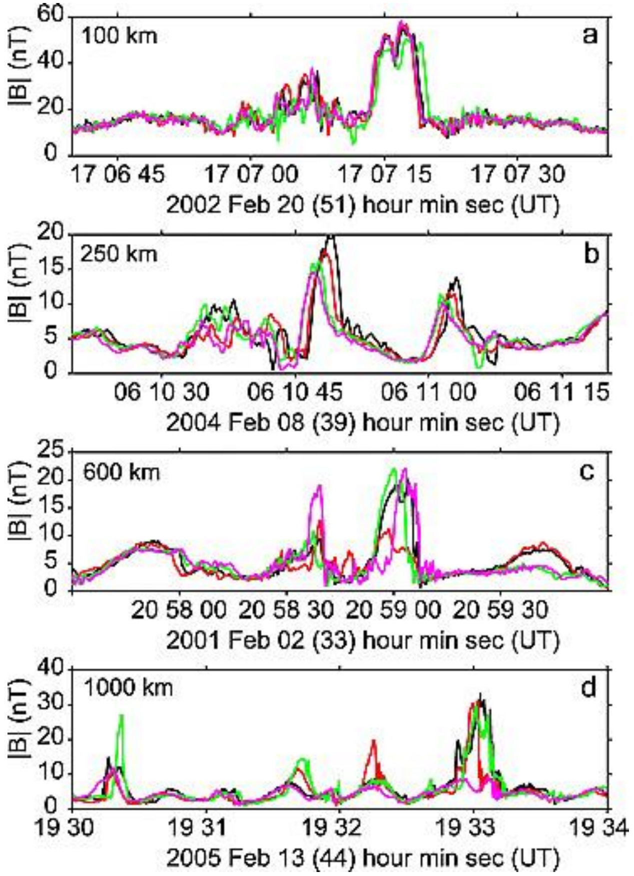
Hao et al. (2017)

ULF non-linear evolution = SLAMS

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



Schwartz, (1991)

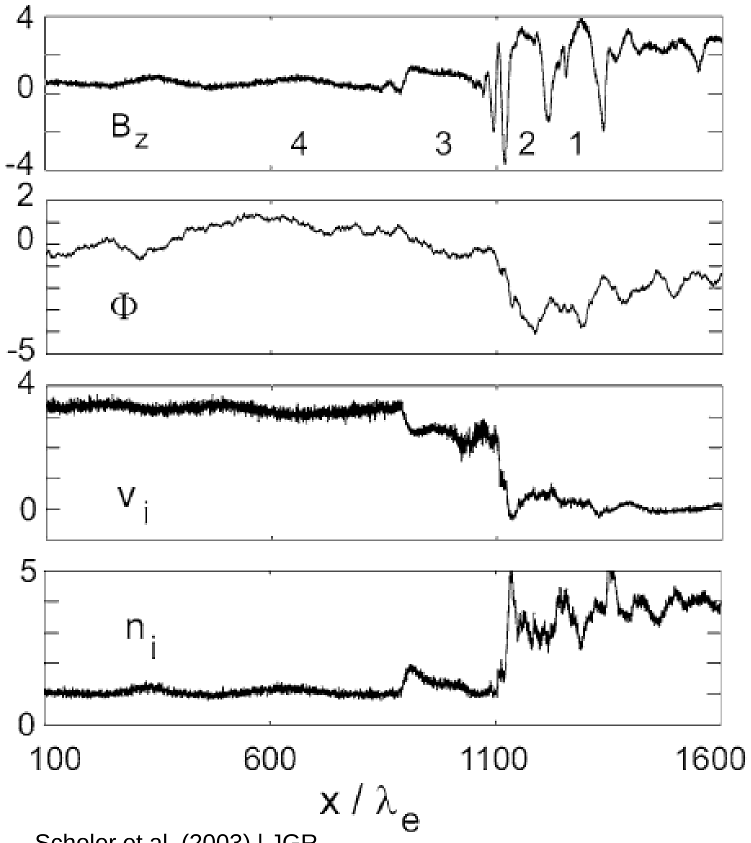


Lucek, (2008)

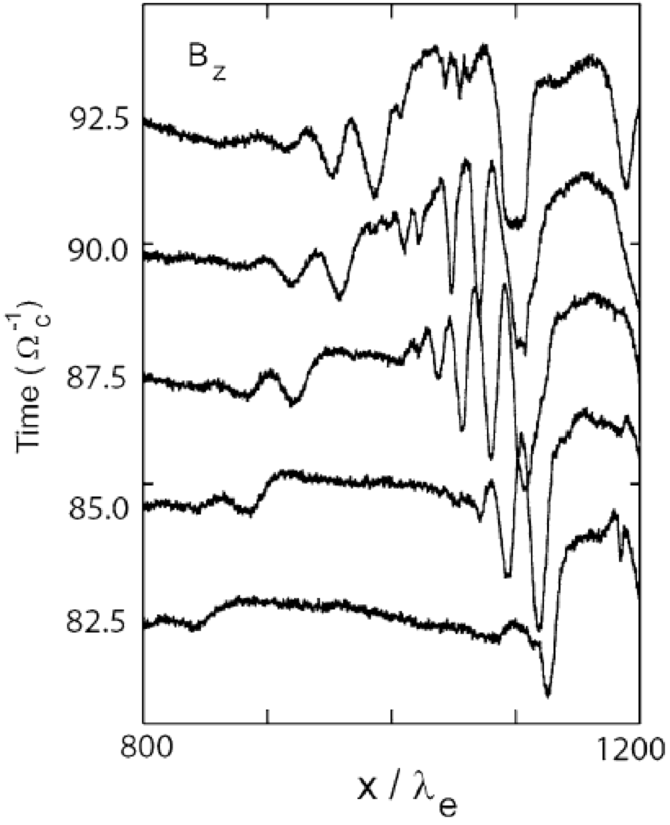
Similar definitions : Hao et al. (2016,2017), Liu et al. (2021), Johlander et al. (2022), Raptis et al. (2022)

Shock Reformation – Simulations

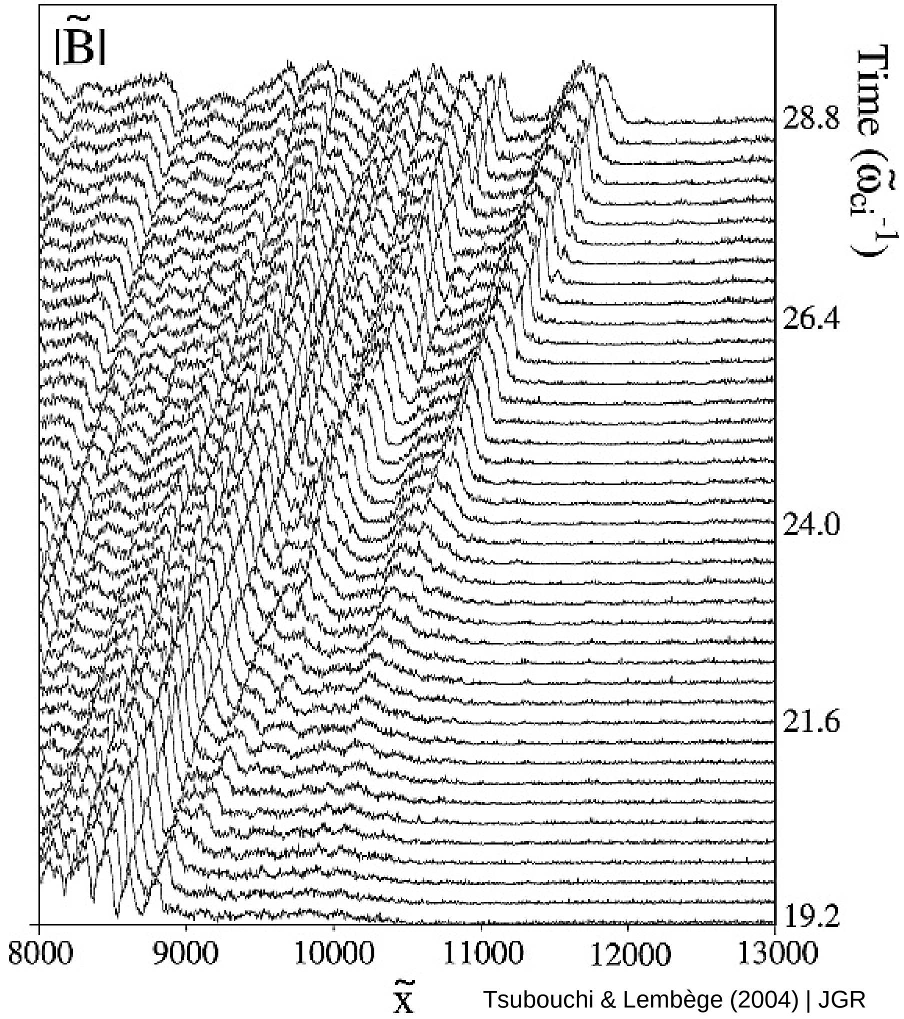
1D-PIC simulation (30°), $M_A = 4.7$
mi/me = 100 and ωpe/Ωce = $\sqrt{10}$.



Scholer et al. (2003) | JGR



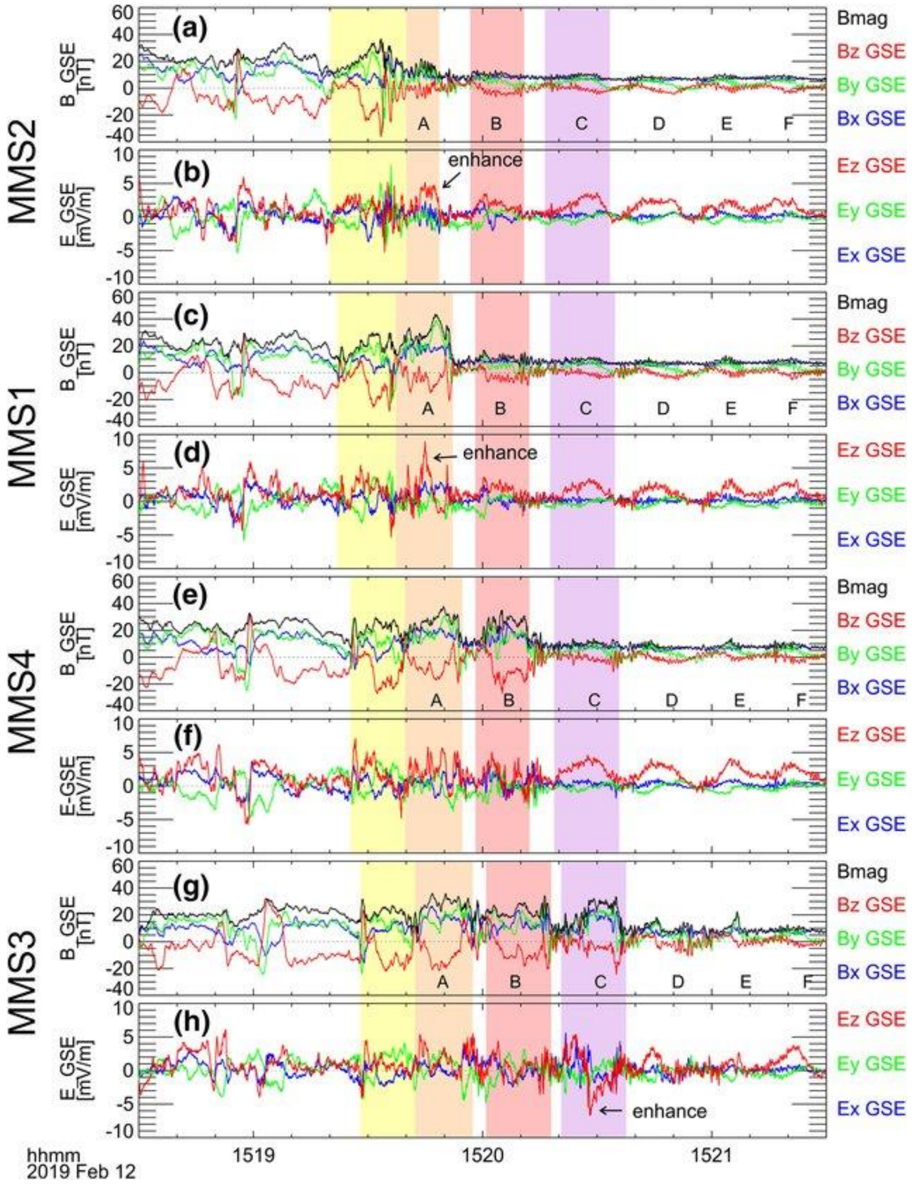
mi/me = 50 and ωpe/Ωce = 4.



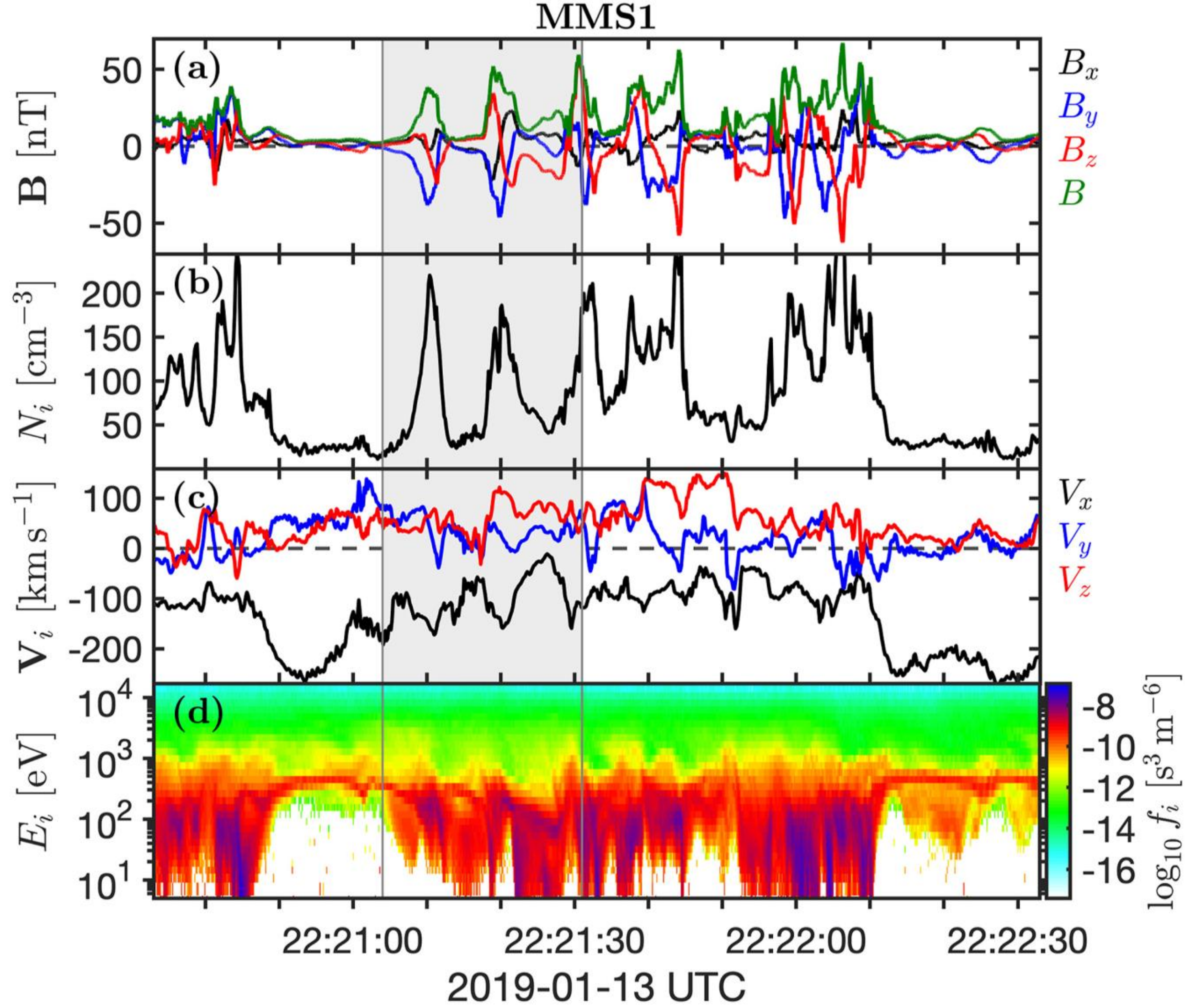
Tsubouchi & Lembège (2004) | JGR

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

Shock Reformation – Latest Results



Liu et al. (2021)



Johlander et al. (2022)

Introduction

Jets | Reformation | MMS

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

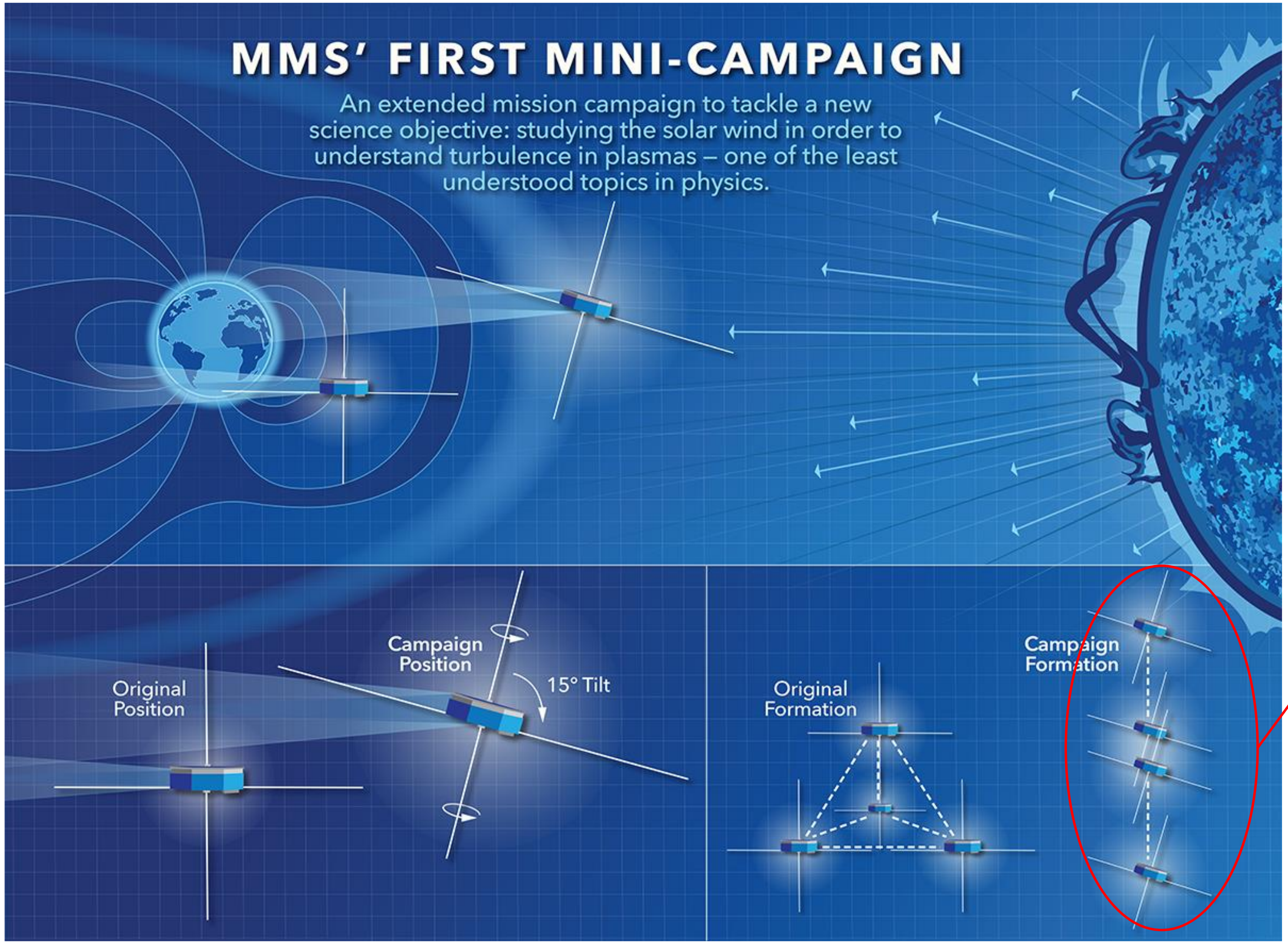
Jets with full burst data →

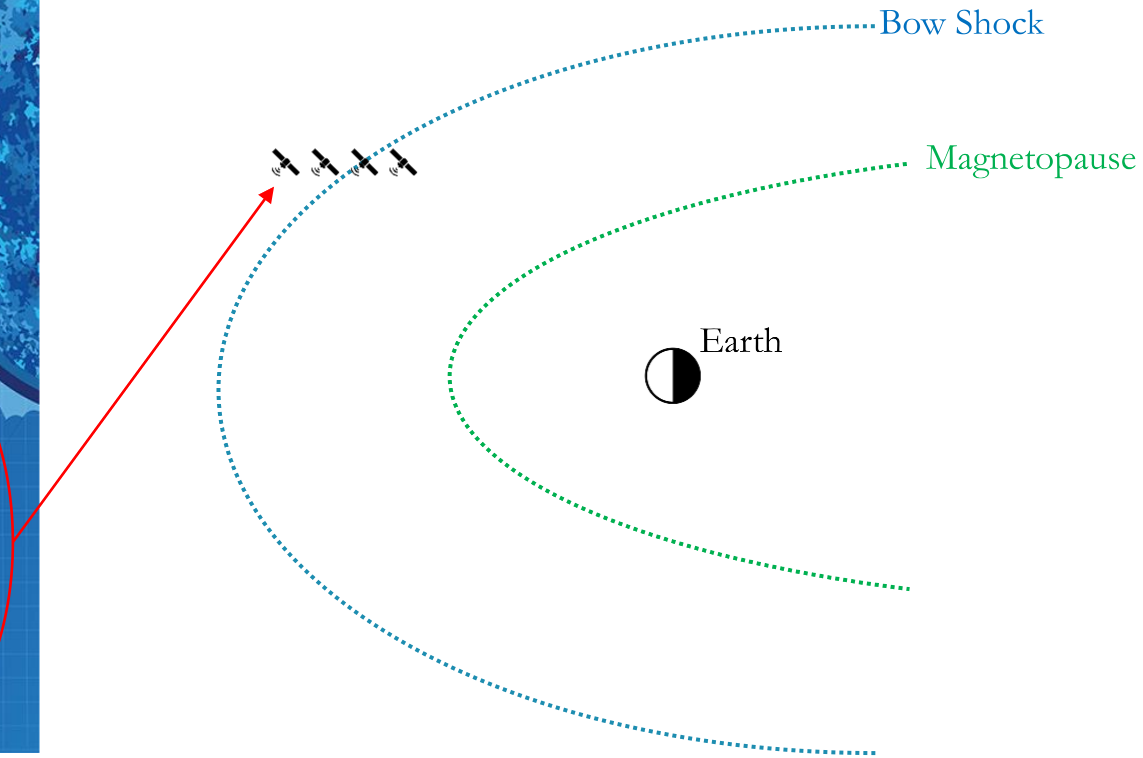
Qpar	423
Qperp	34
Boundary	35
Encapsulated	31
Close to BS / MP	495
Others	428

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

MMS spacecraft + String of Pearl Configuration





Credits: NASA's Goddard Space Flight Center/Mary Pat Hrybyk-Keith

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

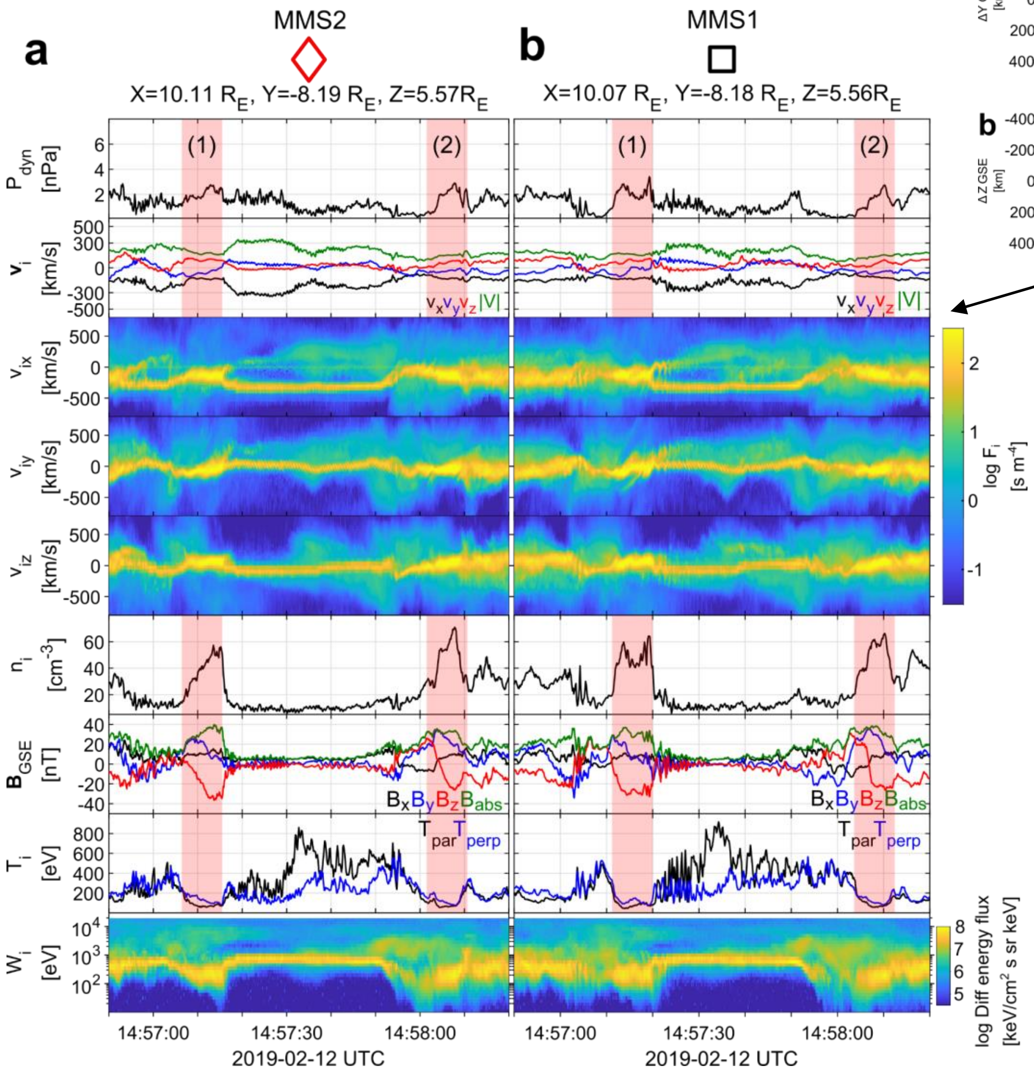
Savvas Raptis [1✉], Tomas Karlsson[1], Andris Vaivads [1], Craig Pollock[2], Ferdinand Plaschke [3,4], Andreas Johlander[5,6], Henriette Trollvik[1] & Per-Arne Lindqvist [1]

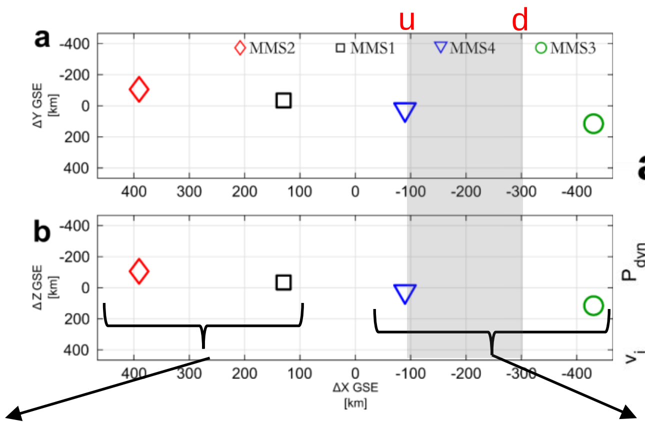
Link : https://www.nature.com/articles/s41467-022-28110-4
GitHub : https://github.com/SavvasRaptis/Jets-Reformation

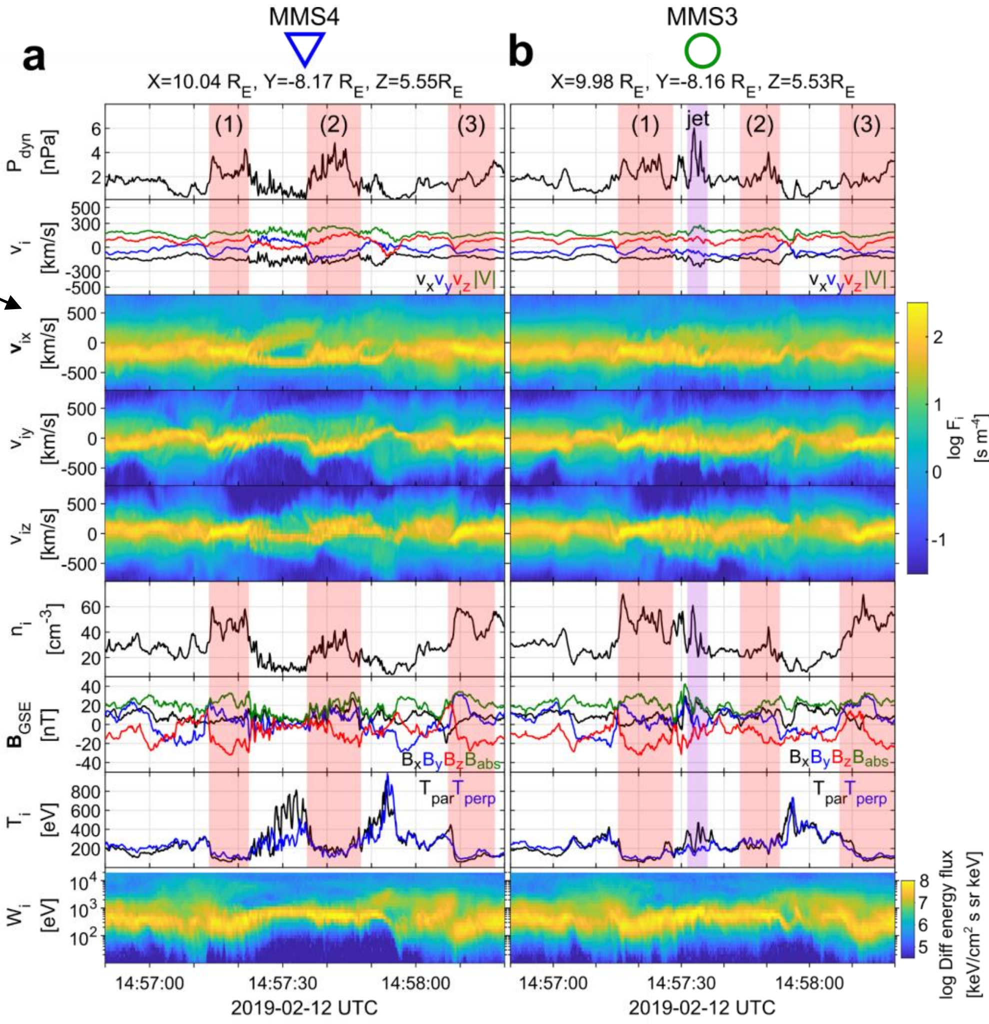
Results

MMS | 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>

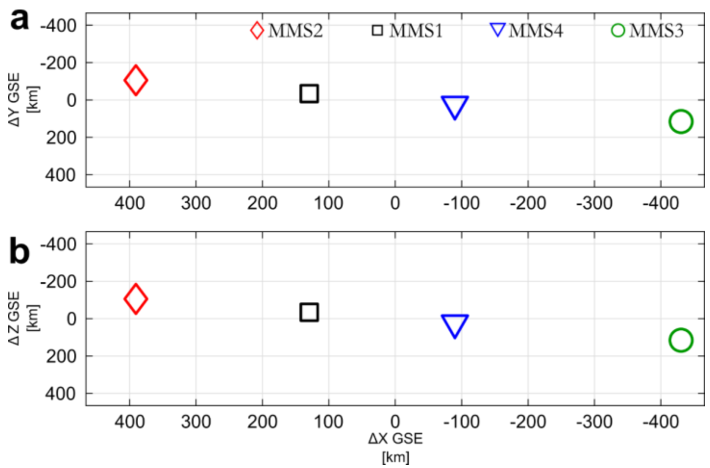
$v \ll v_{SW}$

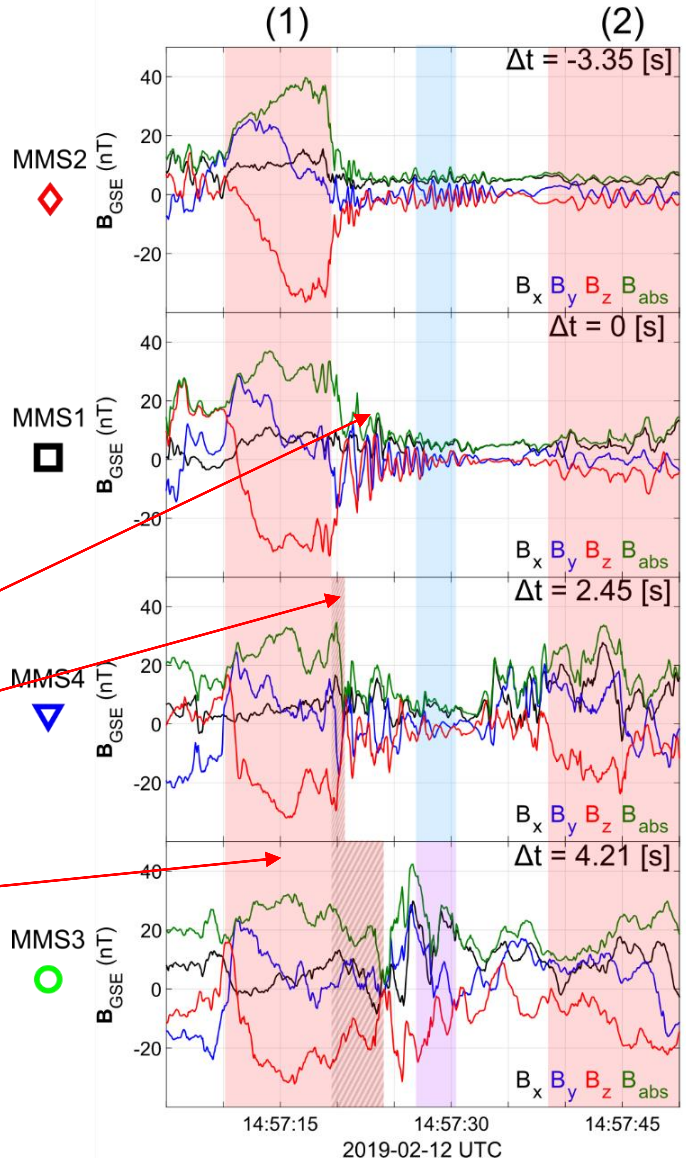
$n_i \gg n_{SW}$

$\boldsymbol{B} \gg$

Thermalized distribution

SLAMS & wave activity co-moving picture





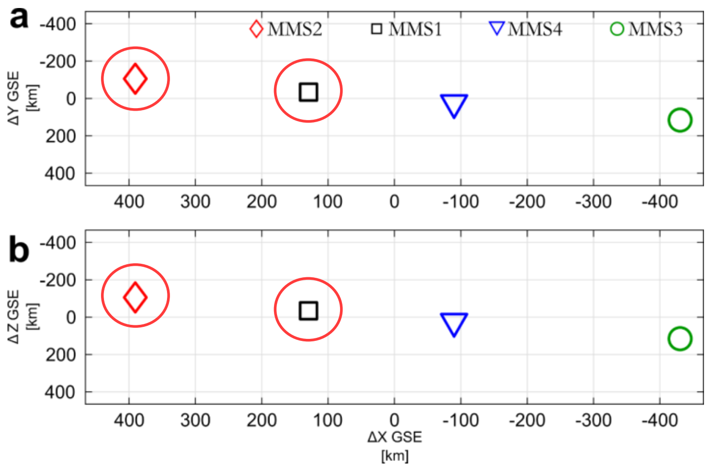
<u>Evolution of SLAMS</u>

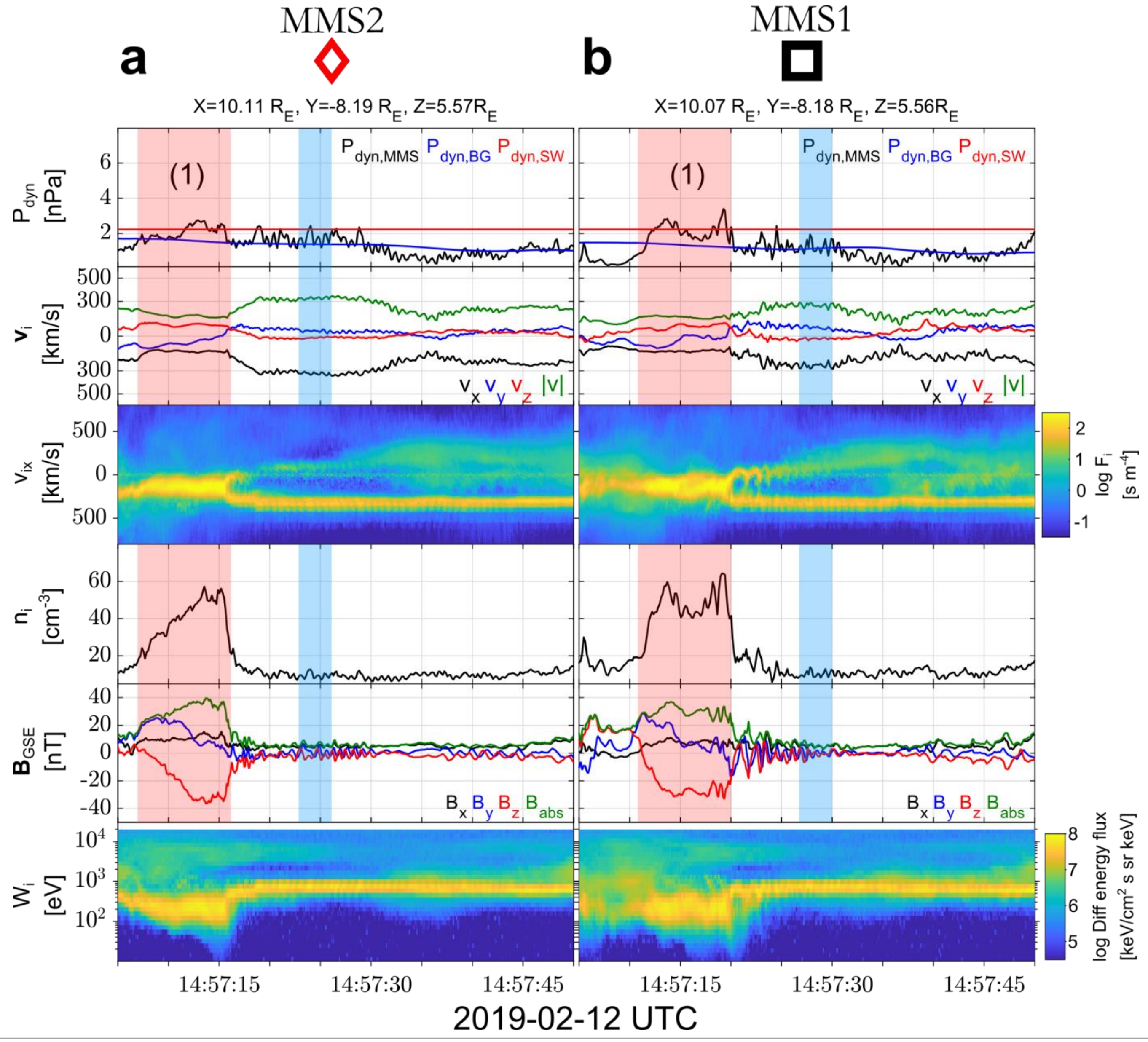
- Interaction with upstream whistler
- New peak /evolution*
- Formation of embedded plasmoid (*downstream density enhancement*)**

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

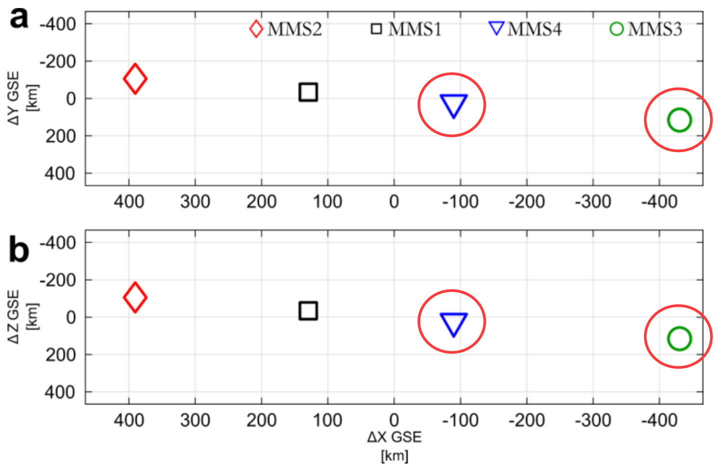
** See similar example by Liu et al. (2021)

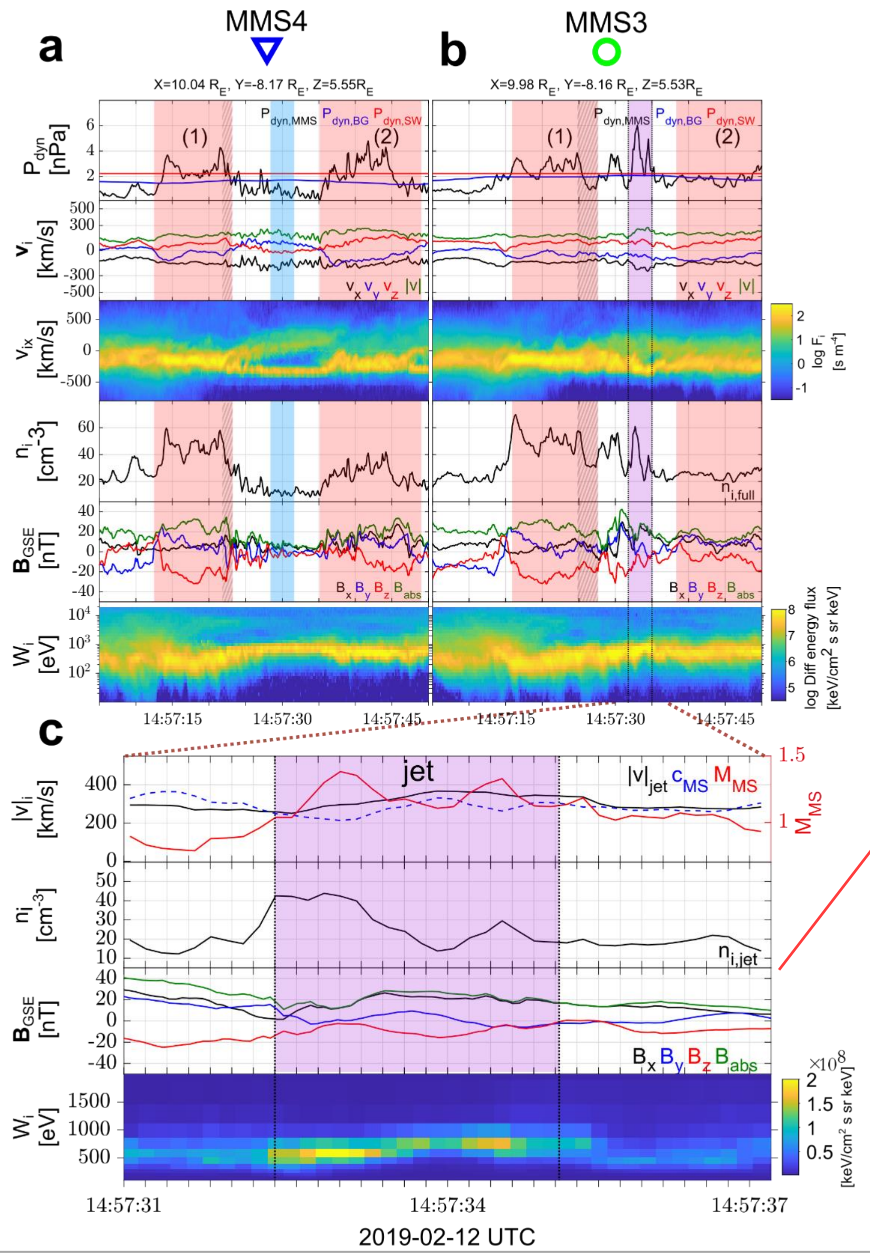
MMS outer-spacecraft observations





MMS inner-spacecraft observations





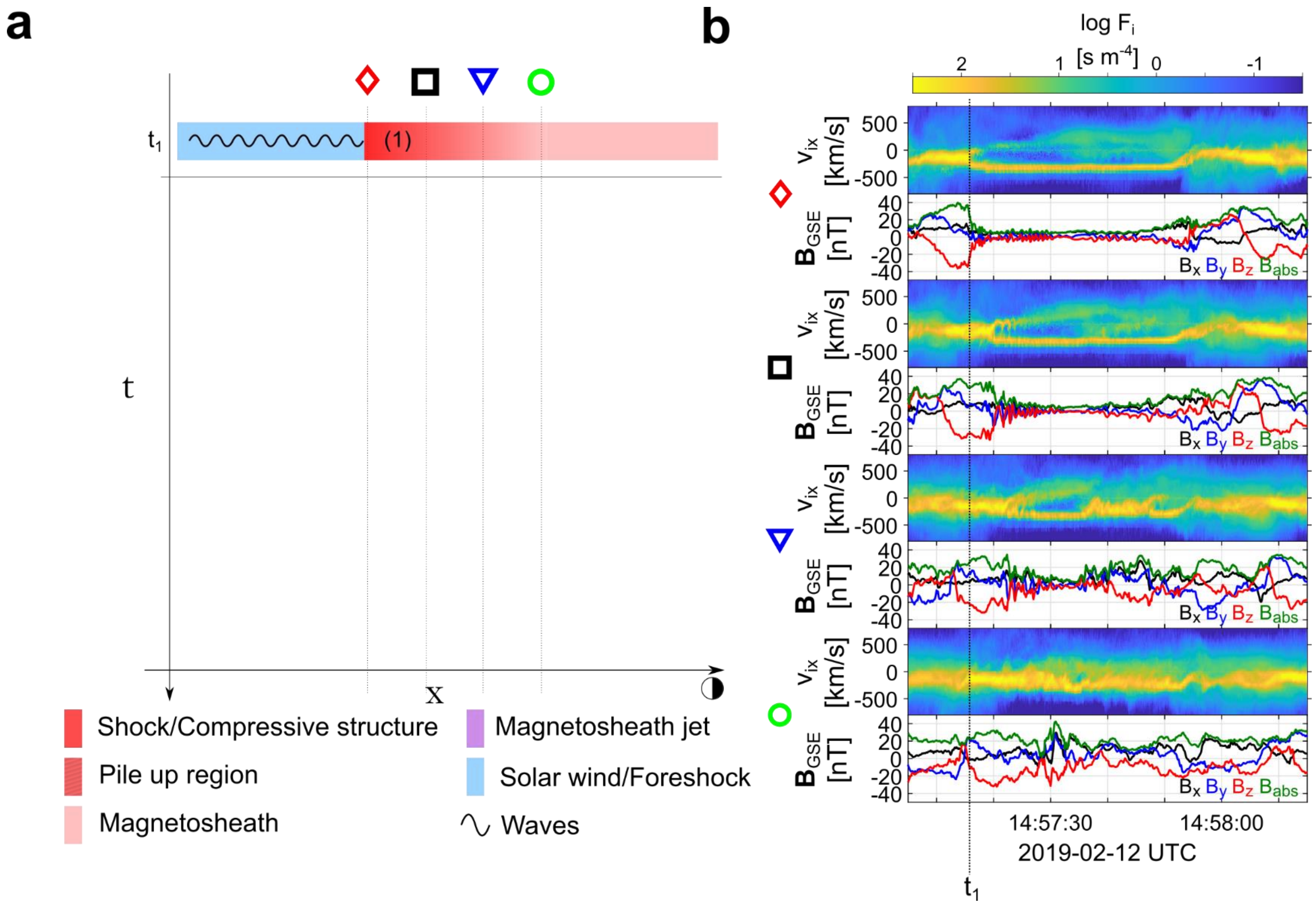
P_{dyn} increase

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

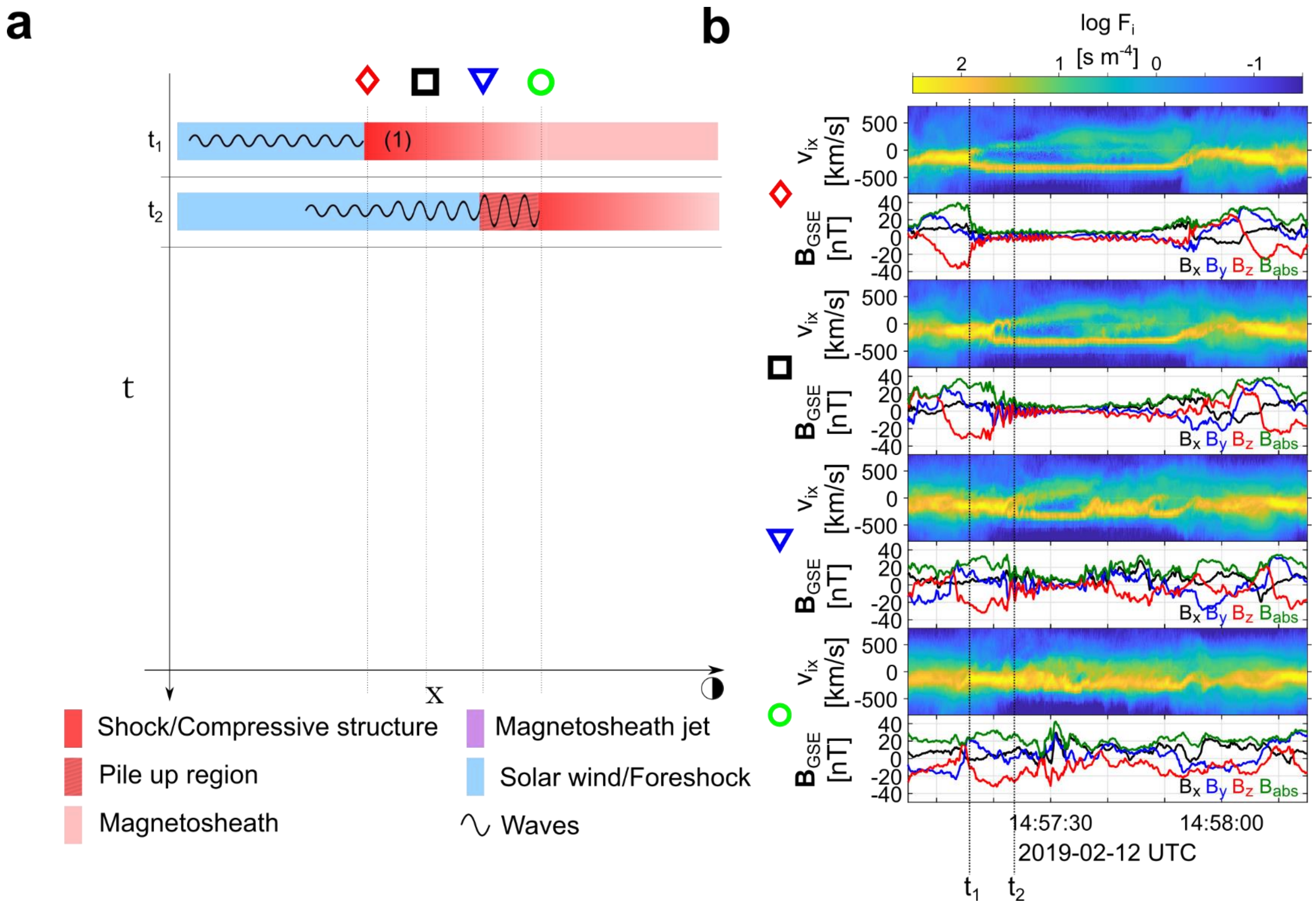
Results

MMS | Schematic

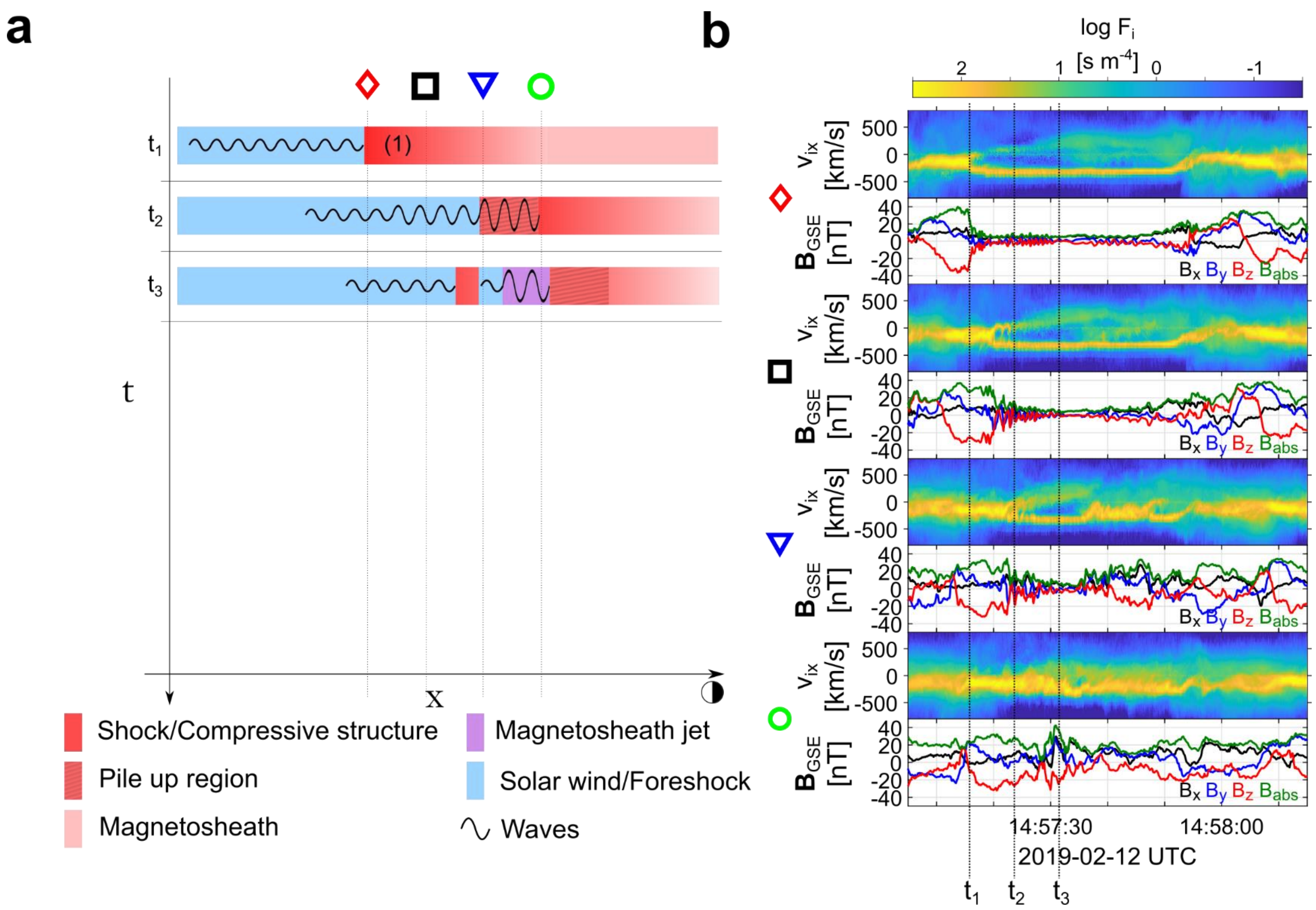
Formation mechanism



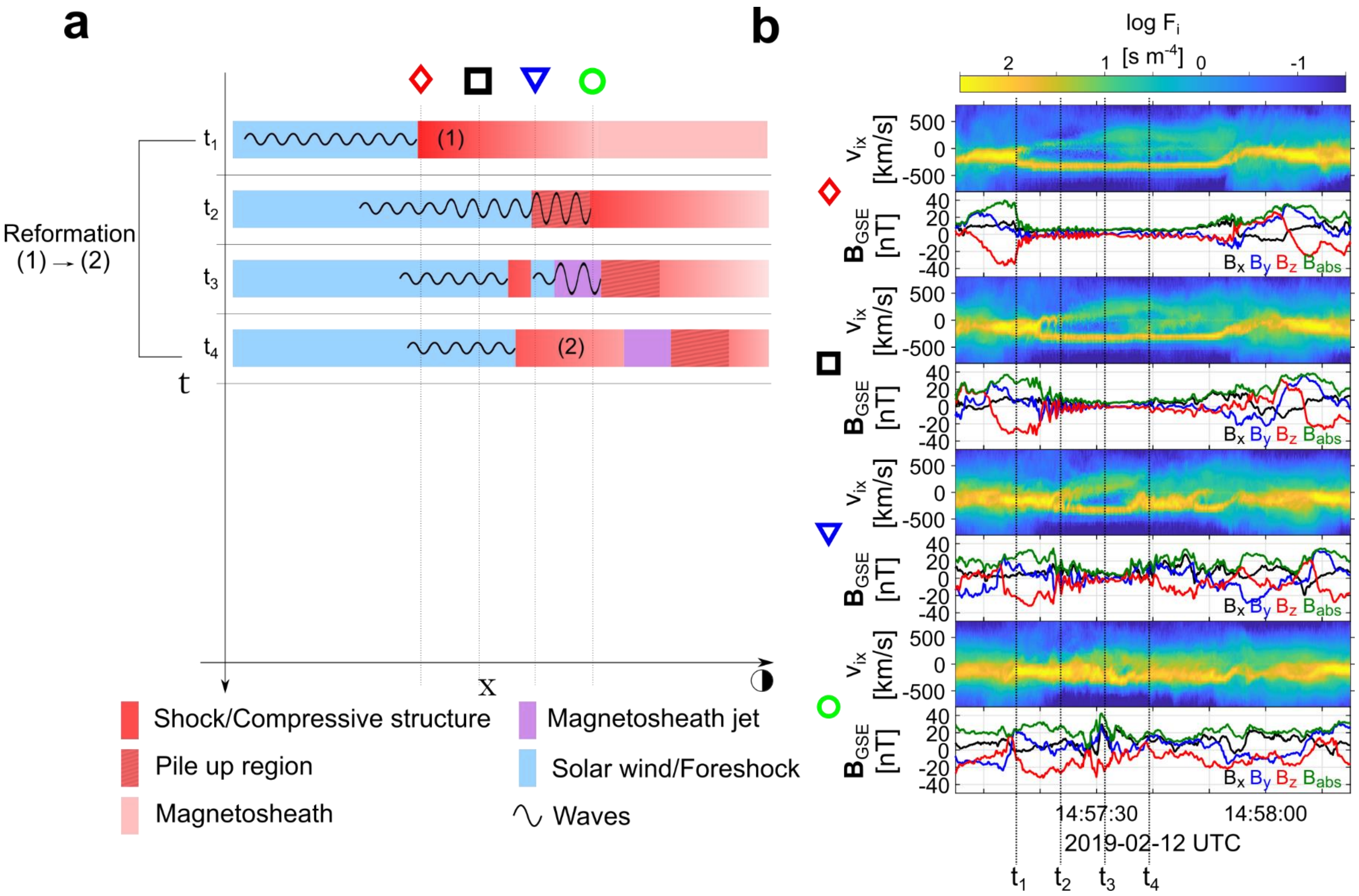
Formation mechanism



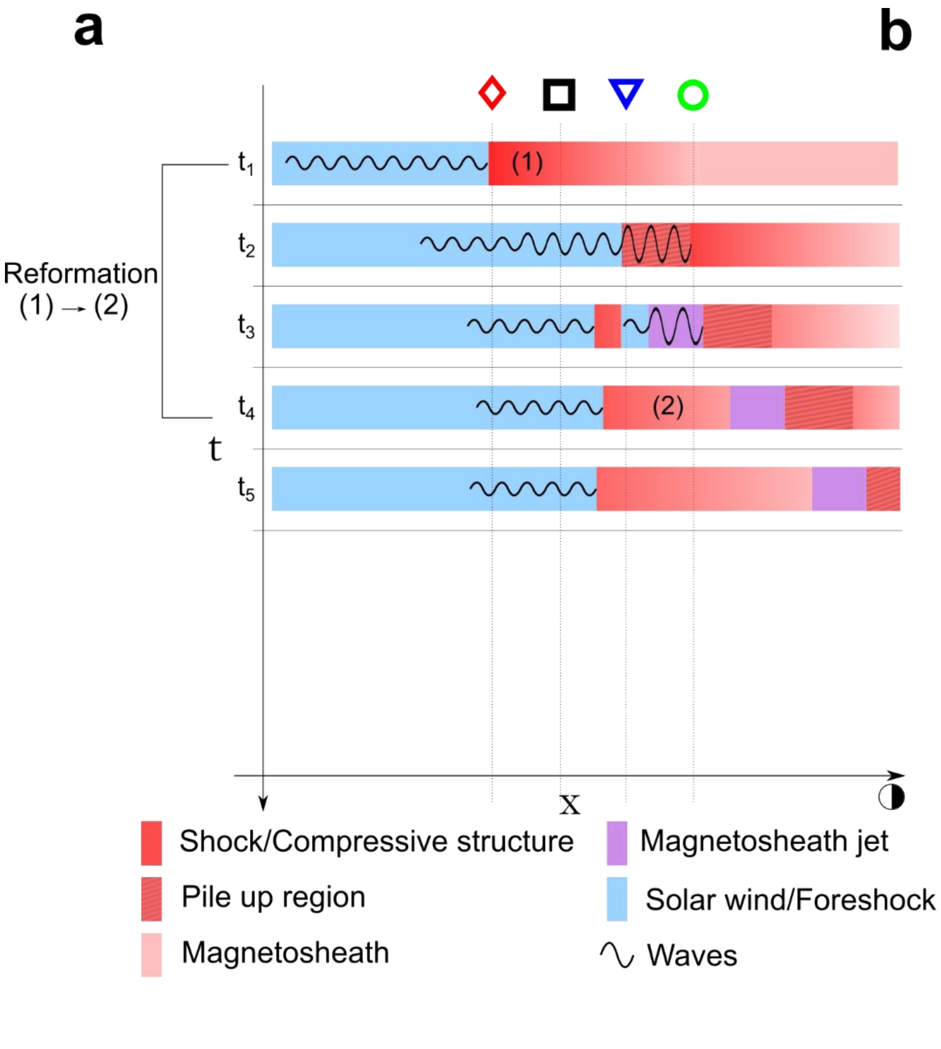
Formation mechanism



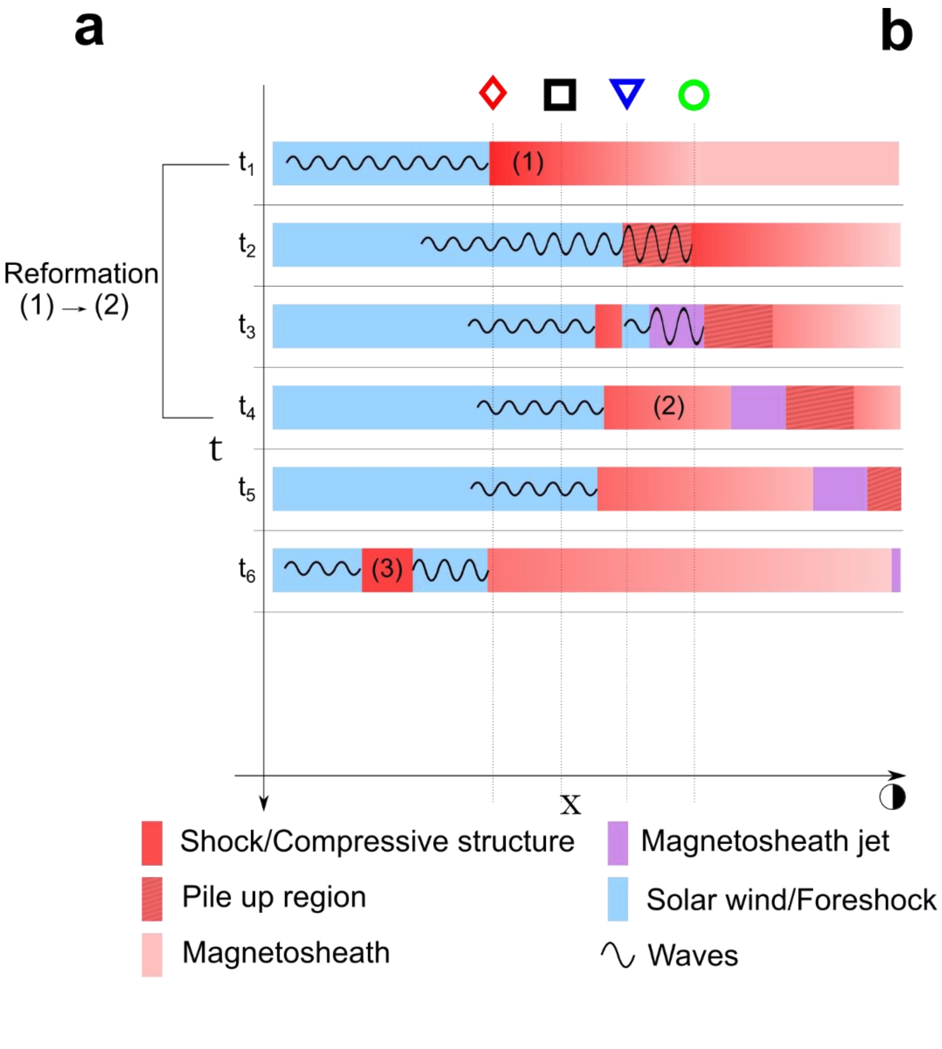
Formation mechanism



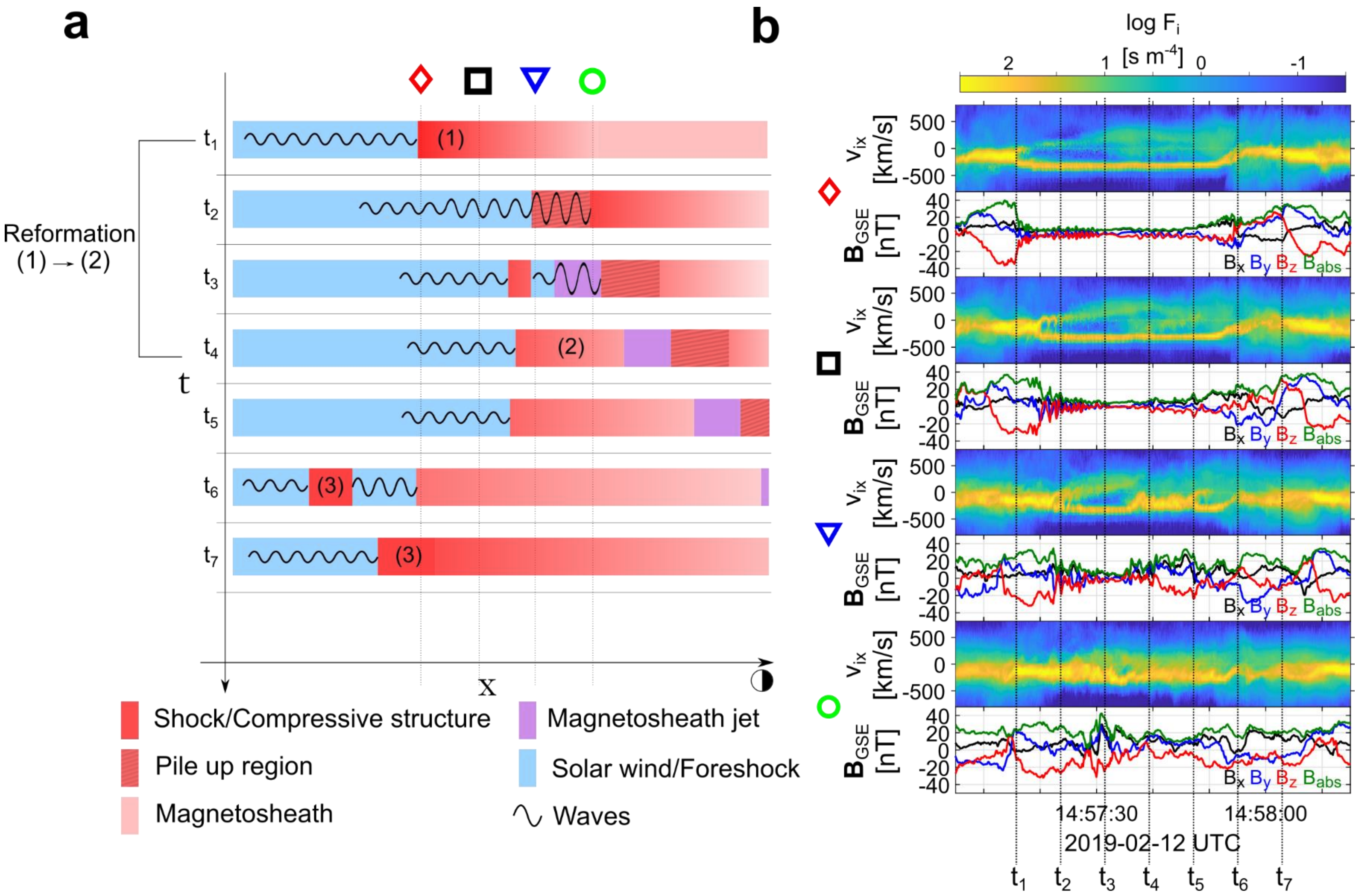
Formation mechanism



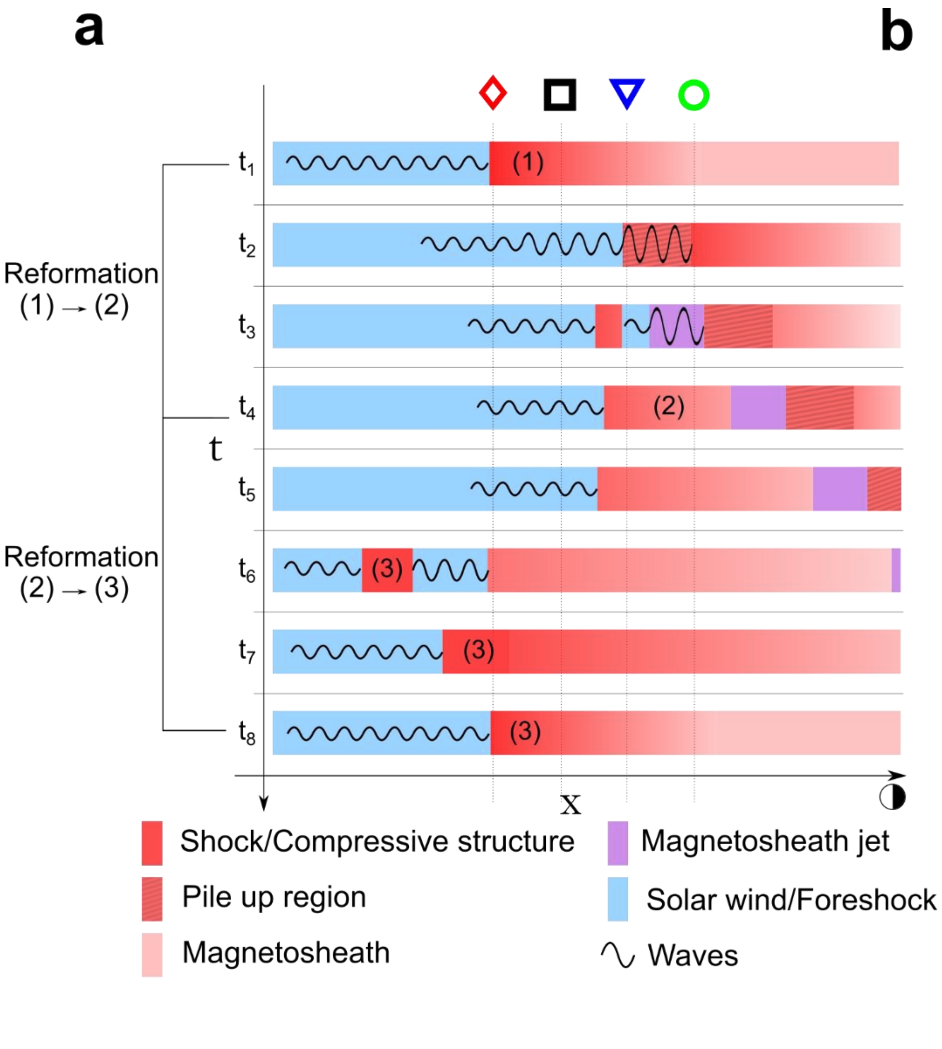
Formation mechanism



Formation mechanism



Formation mechanism



Summary & Conclusion

Main points

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

Implications

- Possibly a general process of collisionless shocks that could be found in planetary, astrophysical and laboratory shocks.
- Are ripples or SW phenomena "needed" to explain a subset of jets ? Or could a part of them be a foreshock phenomena extending downstream of the shock ?

Future work

- *Details on SLAMS/waves* – Exact properties & evolution study of FCs numbered 1-3
- *Simulation comparison* – Can we find cases like these in simulations ?
- *Statistics* – We need more events, currently found ~3 of similar signatures.
- *Modeling* – Can this process explain jets close to MP ? Or are just a subset of "small" jets ?
- *Electron Acceleration* – Liu et al. (2020a, 2020b) : jets → bow wave → electron acceleration

Extras

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

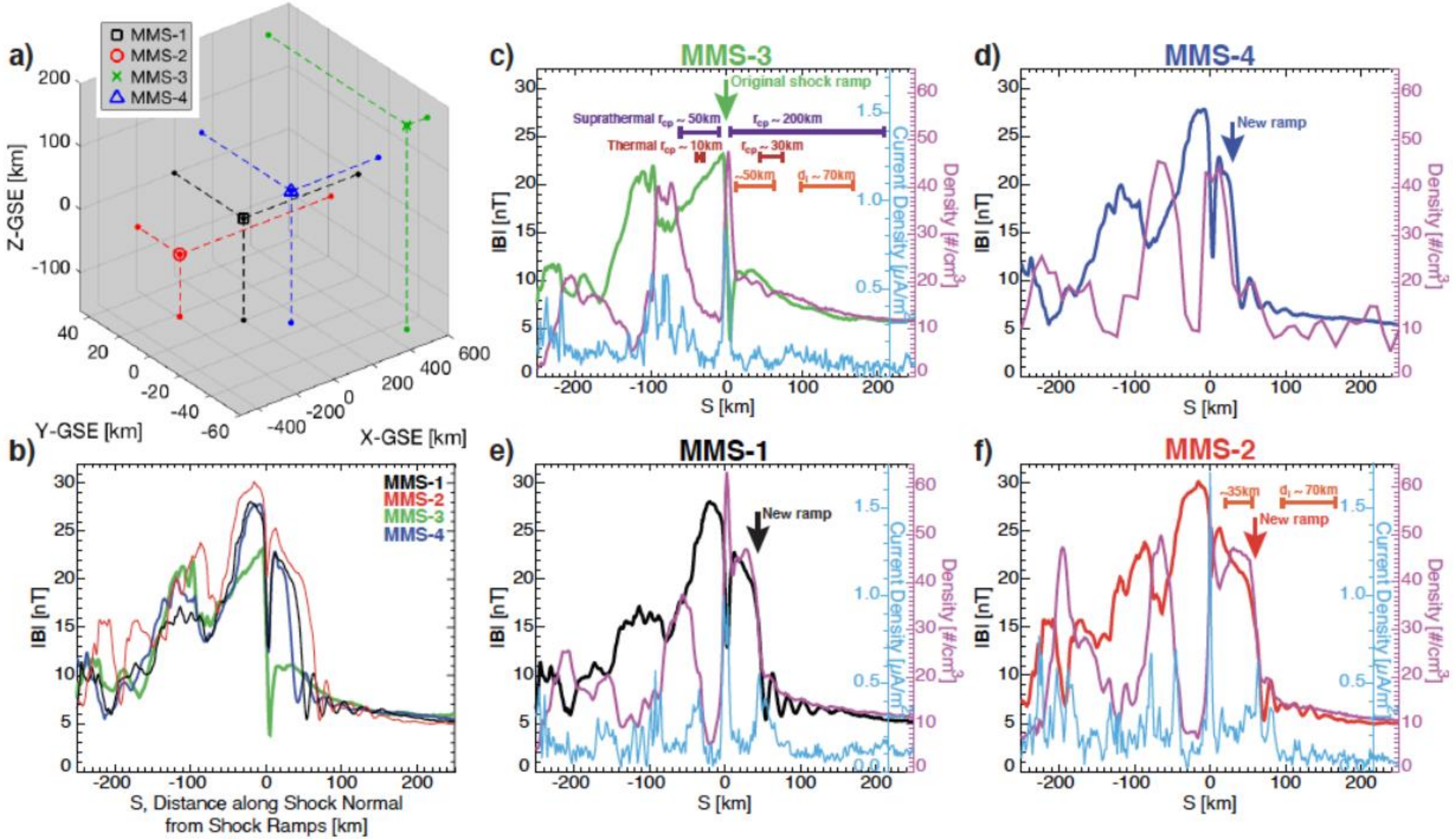
- ✓ Very high resolution
- ✓ Able to resolve structures close to boundary surfaces (e.g. mix of plasma close to magnetopause, bow shock, foreshock etc.)

Cons

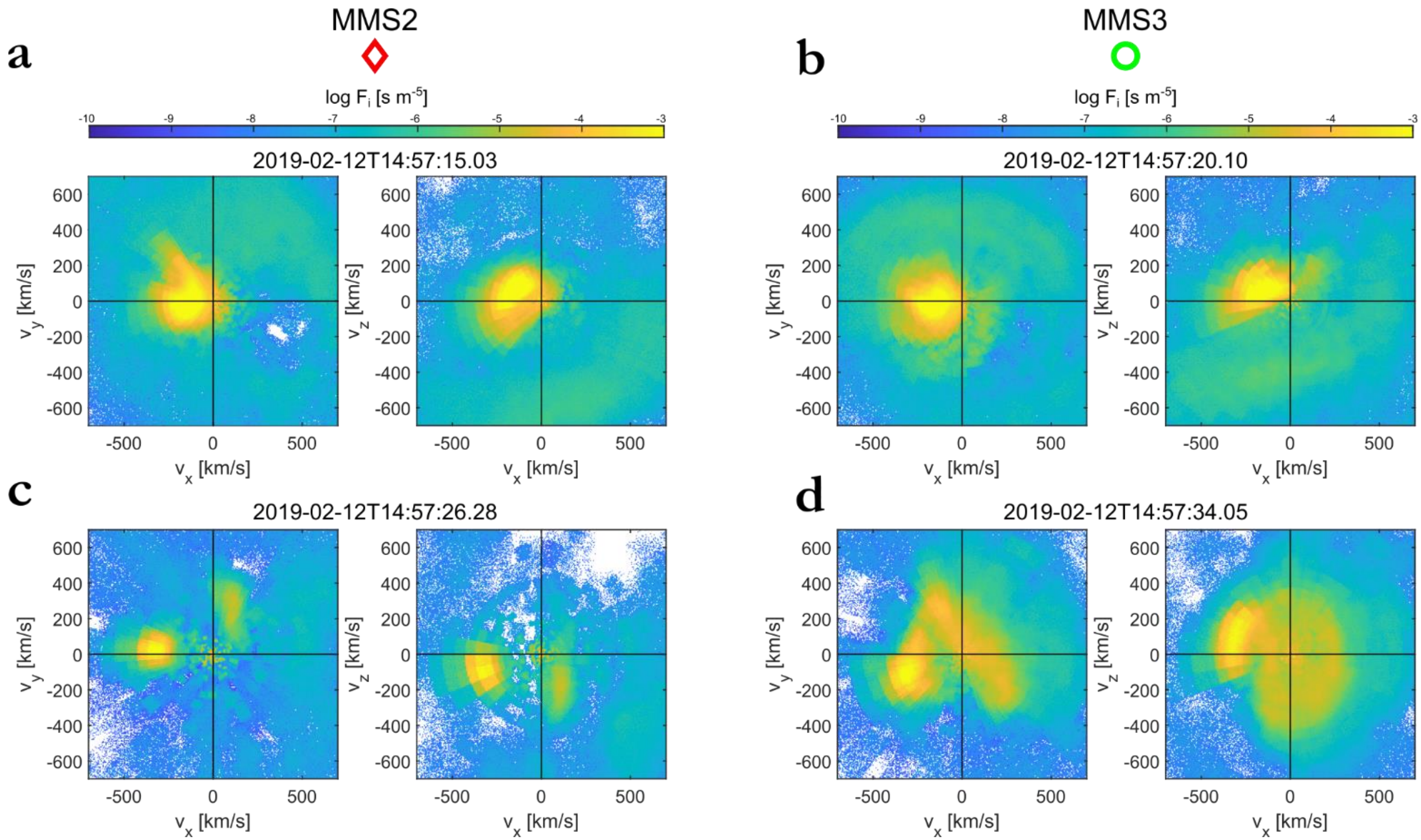
- ✗ Not available all the time, mostly available close to vital mission objectives (magnetopause, diffusion regions, shock transitions etc.)
- ✗ Hard to do proper large scale statistics due to biases generated from specific availability and manual choice of intervals

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

Turner et al. 2021 (local reformation/evolution)

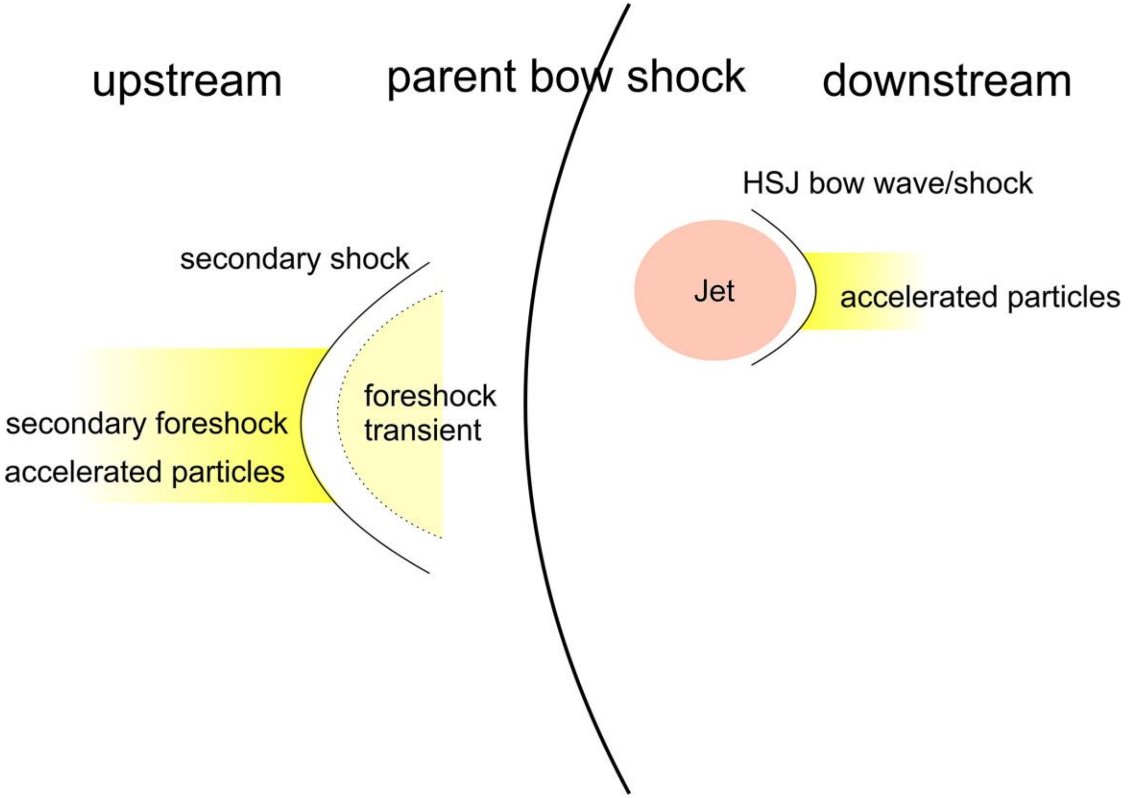


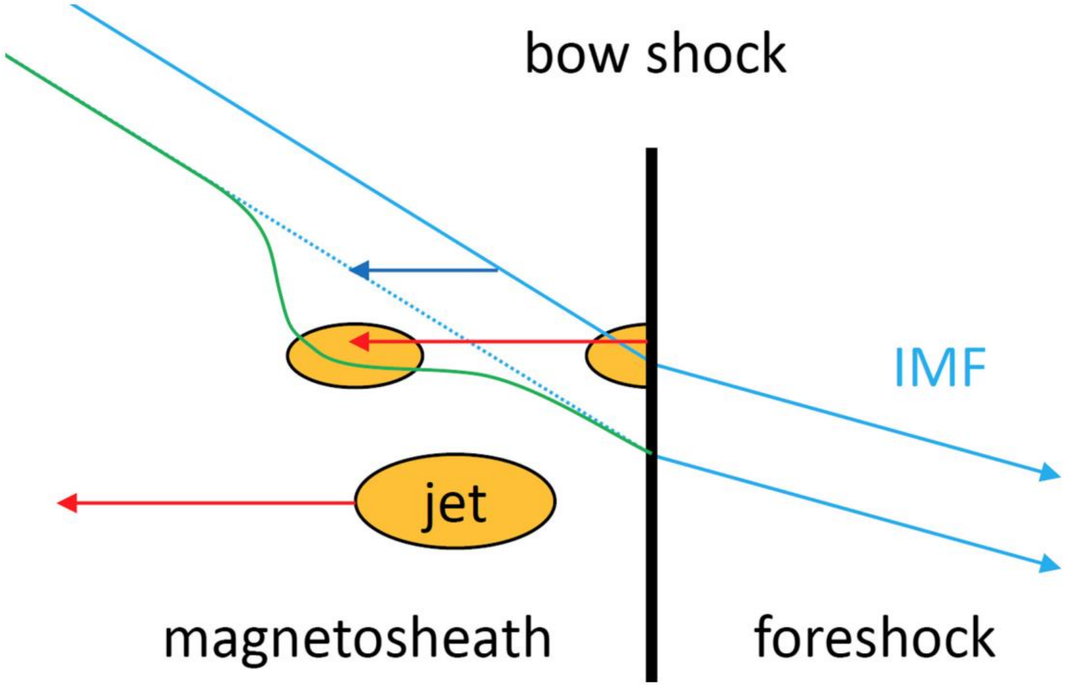
VDFs



MMS2
MMS3
a
b
c
d
log F_i [s m^{-5}]
-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)