High-speed jets and related phenomena in Earth's bow shock and magnetosheath

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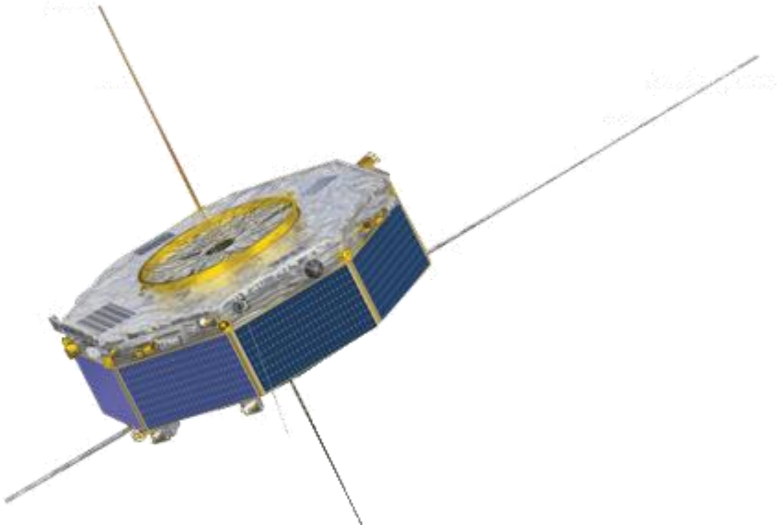
JHU APL presentation
19/08/2022

Space plasma observations & simulations

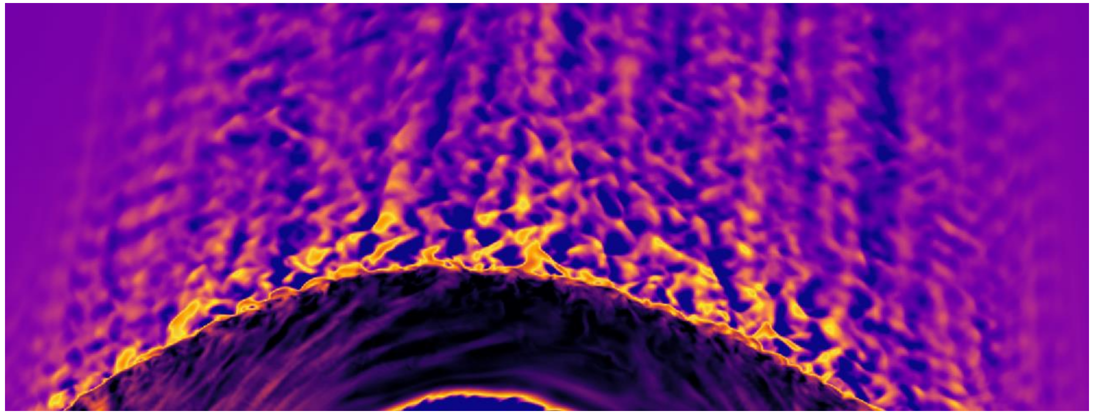
In-situ
(examples)

Cluster
MMS
THEMIS
Arase
ACE
WIND
PSP

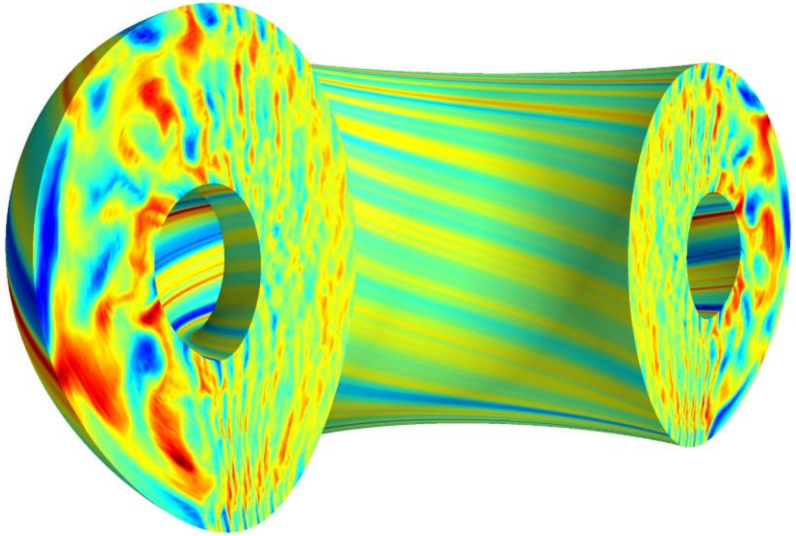


Remote Sensing
(examples)

SOHO
SDO
Solar Orbiter
SMILE



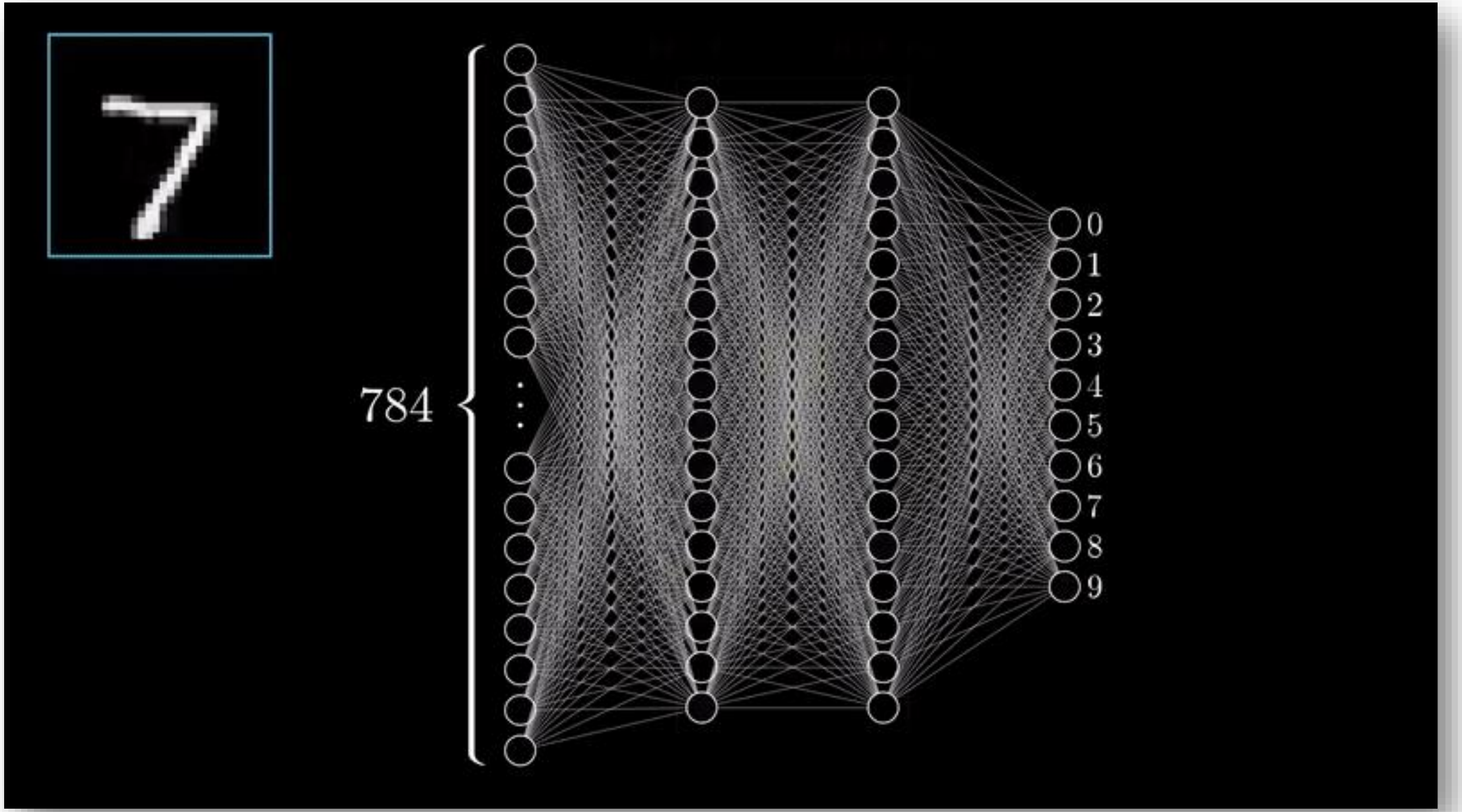
Fluid, Hybrid, PIC, Monte Carlo



[Top] MMS/NASA
[Bottom] : SDO/NASA

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

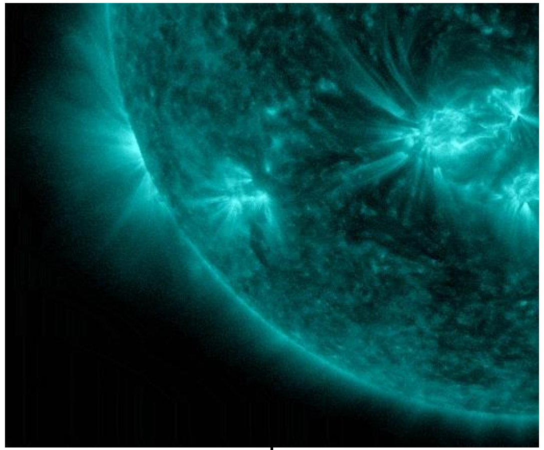
Neural Networks



*Video Courtesy**: 3Blue1Brown** (Check his YouTube page for more)

Application on forescasting SEPs

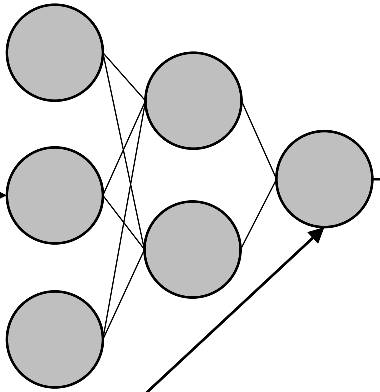
Problem description



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)

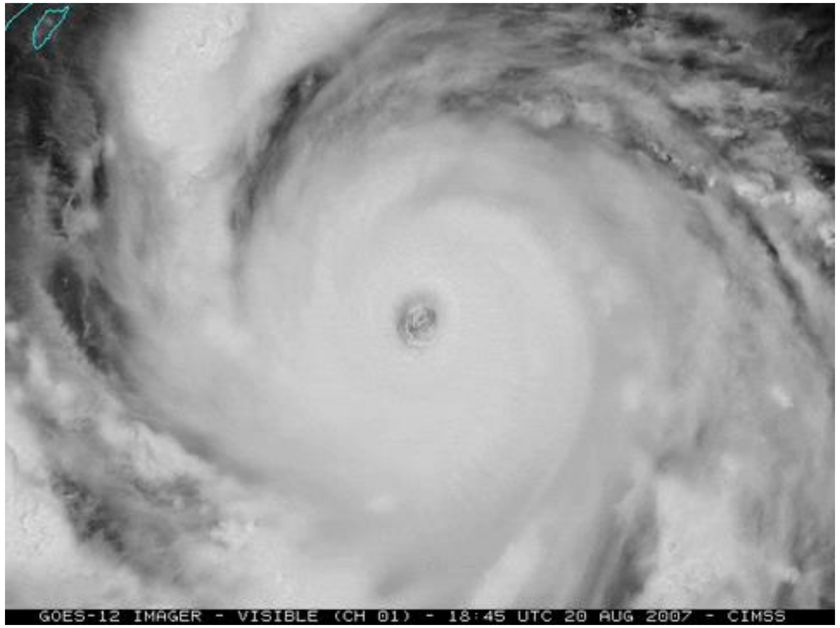
Aminalragia-Giamini, **Raptis** et al. (2021) | J. Space Weather Space Clim

Introduction & previous results

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

Transient events – weather

Hurricanes

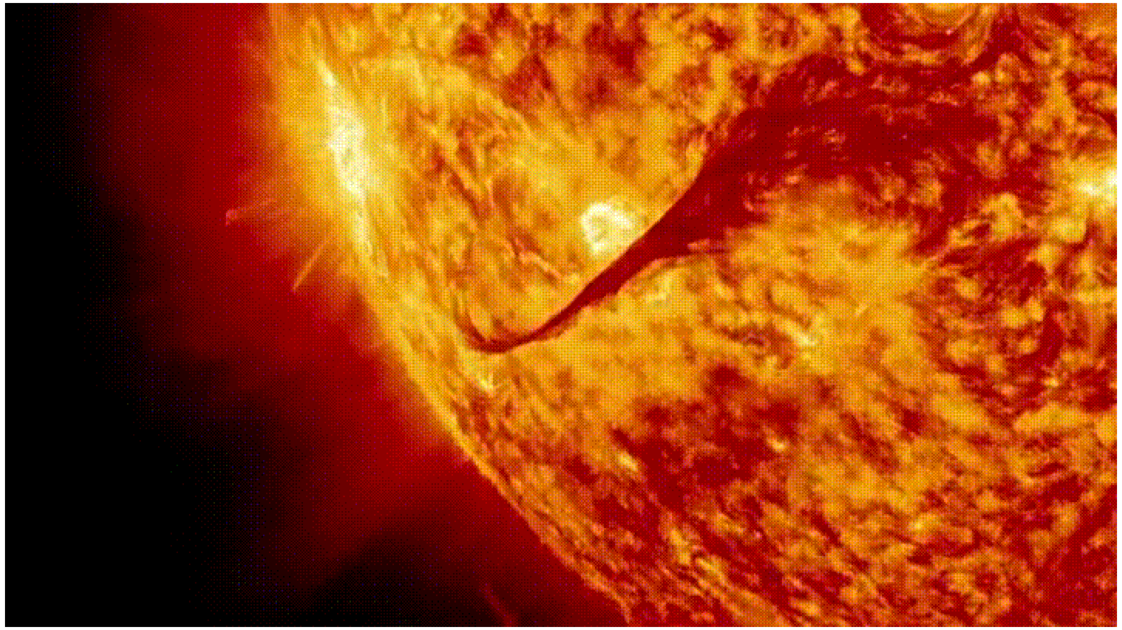


Rain

Snowstorms

Transient events – weather

CMEs/Solar Flares

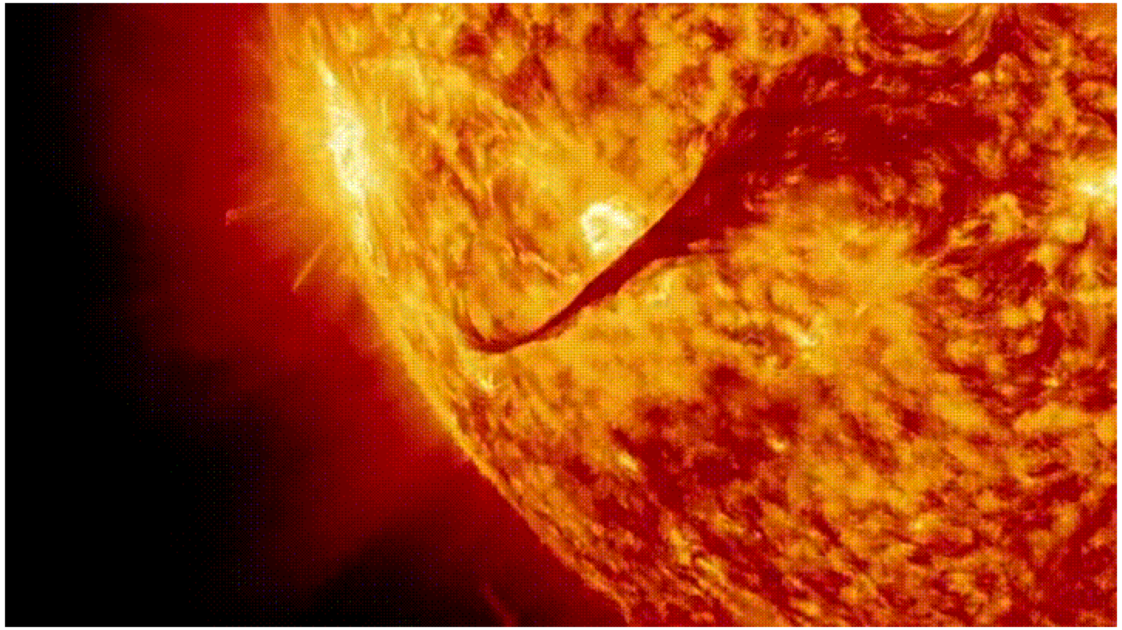


Rain

Snowstorms

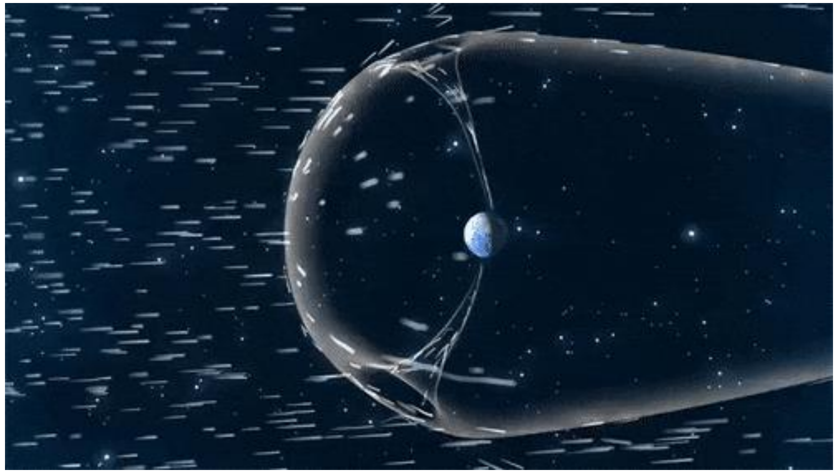
Transient events – weather

CMEs/Solar Flares



Rain

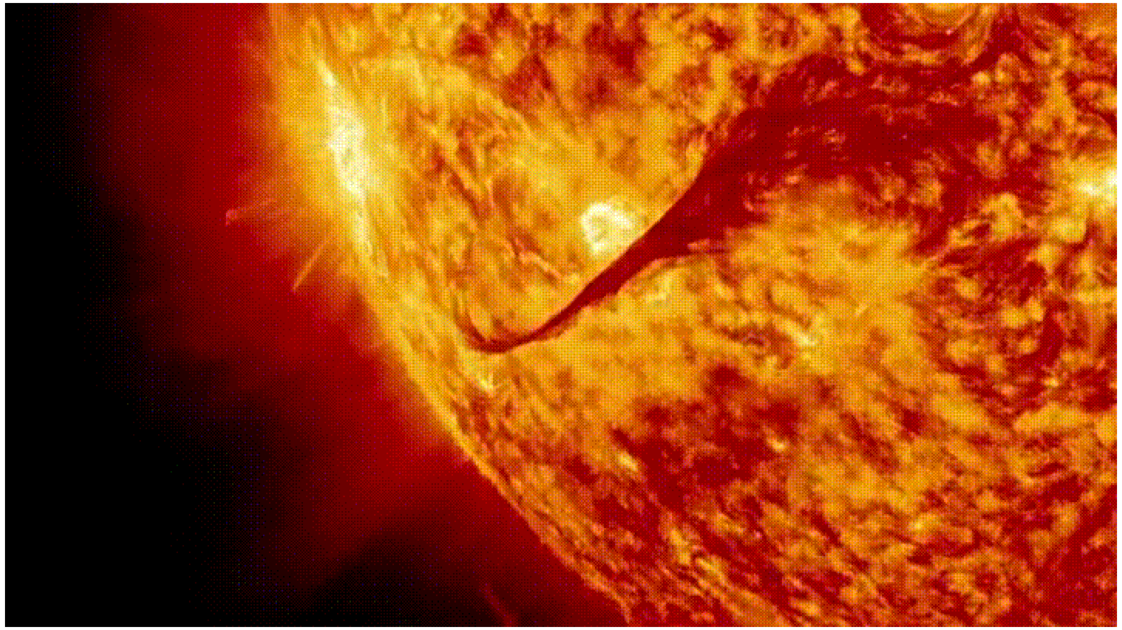
Solar cycle, streams, discontinuities



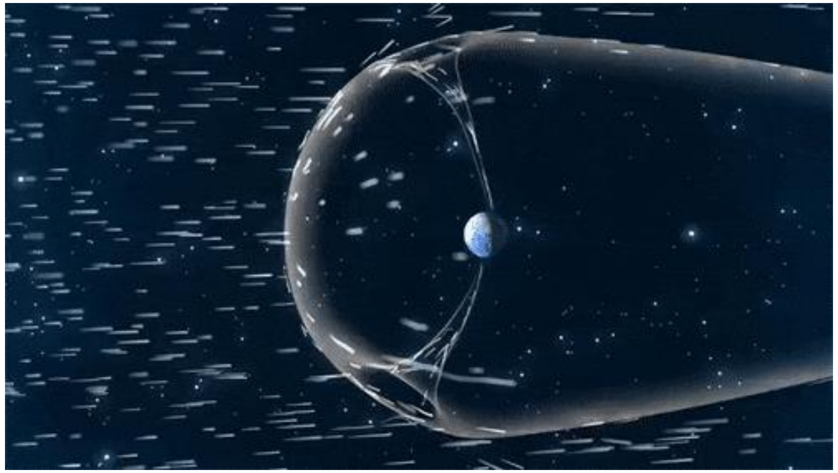
Credits : NASA

Transient events – *space* weather

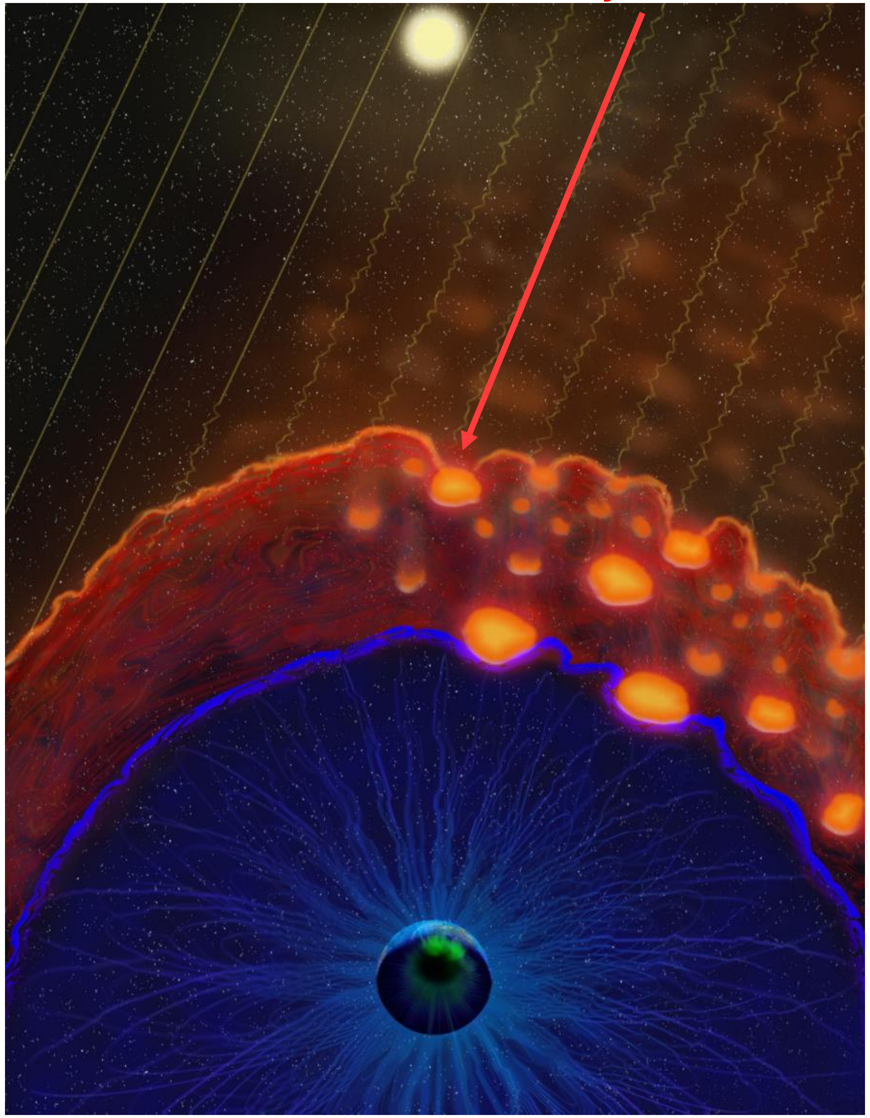
CMEs/Solar Flares



Solar cycle, streams, discontinuities



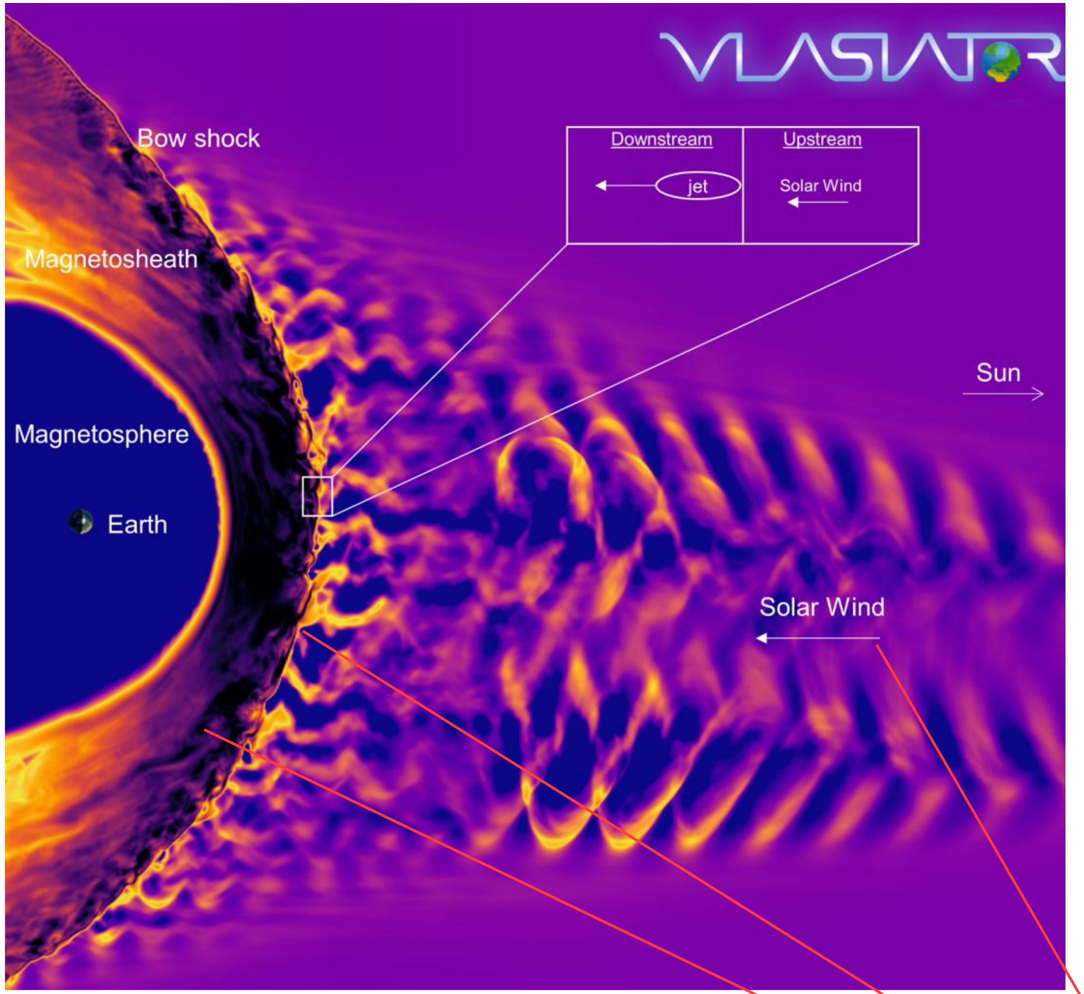
Foreshock structures & jets

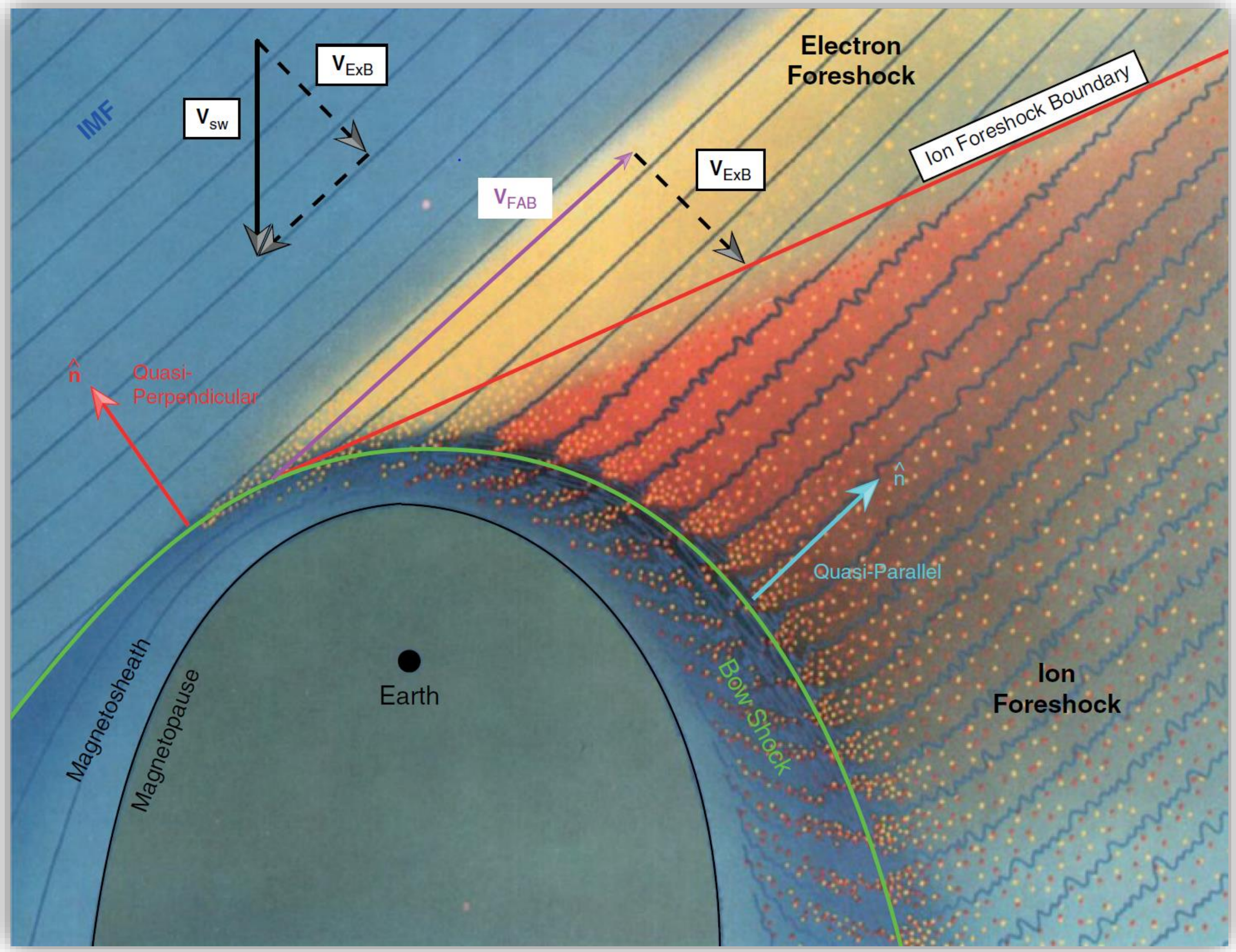


Credits : NASA

Illustration made by Emmanuel Masongsong

Earth's magnetosphere & shock environment





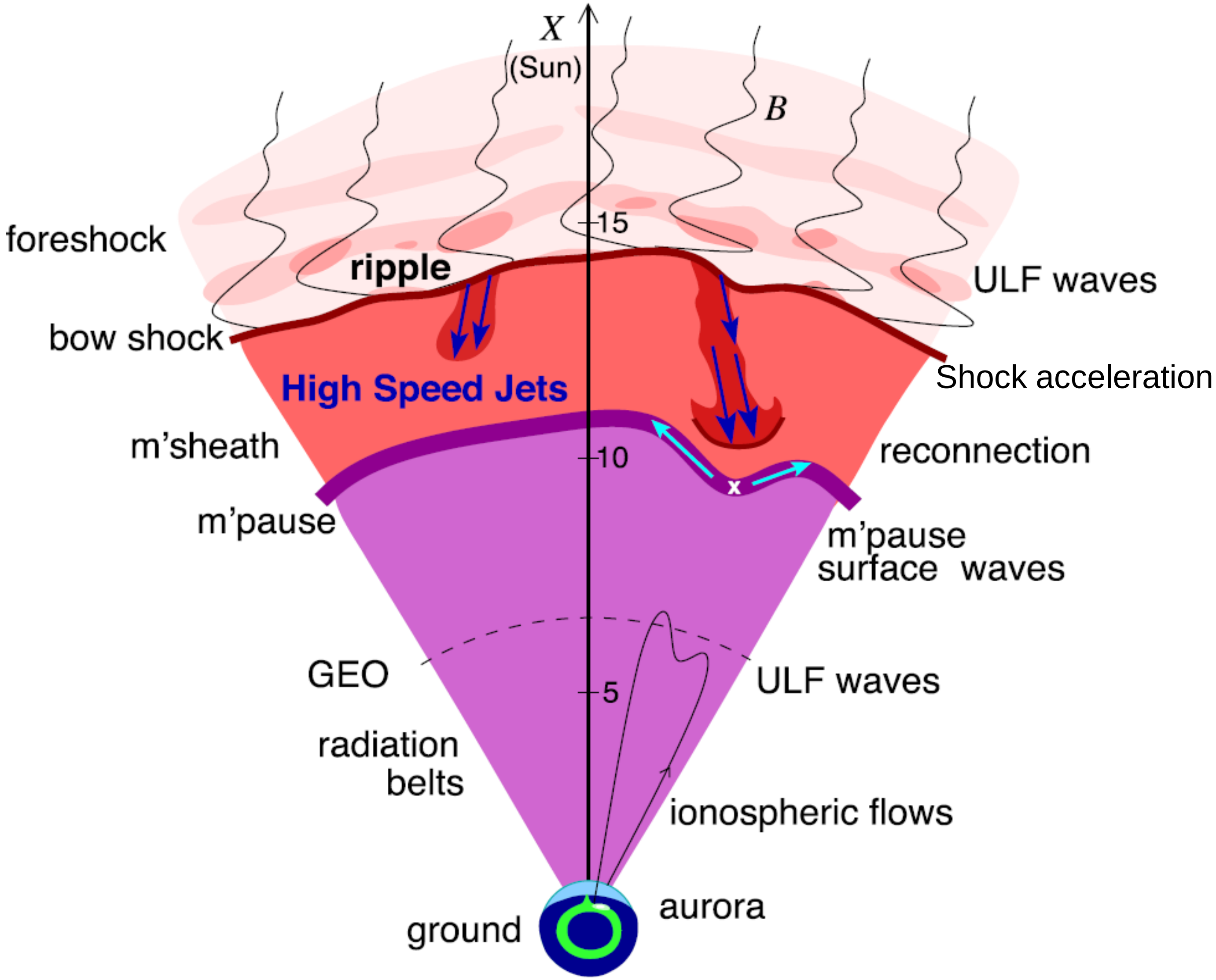
https://msolss.github.io/MagSeminars/

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

Courtesy of M. Palmroth, U Helsinki

L. B. Wilson (2016)

Magnetosheath jets effects



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
Substorms
Ground magnetometer detection

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

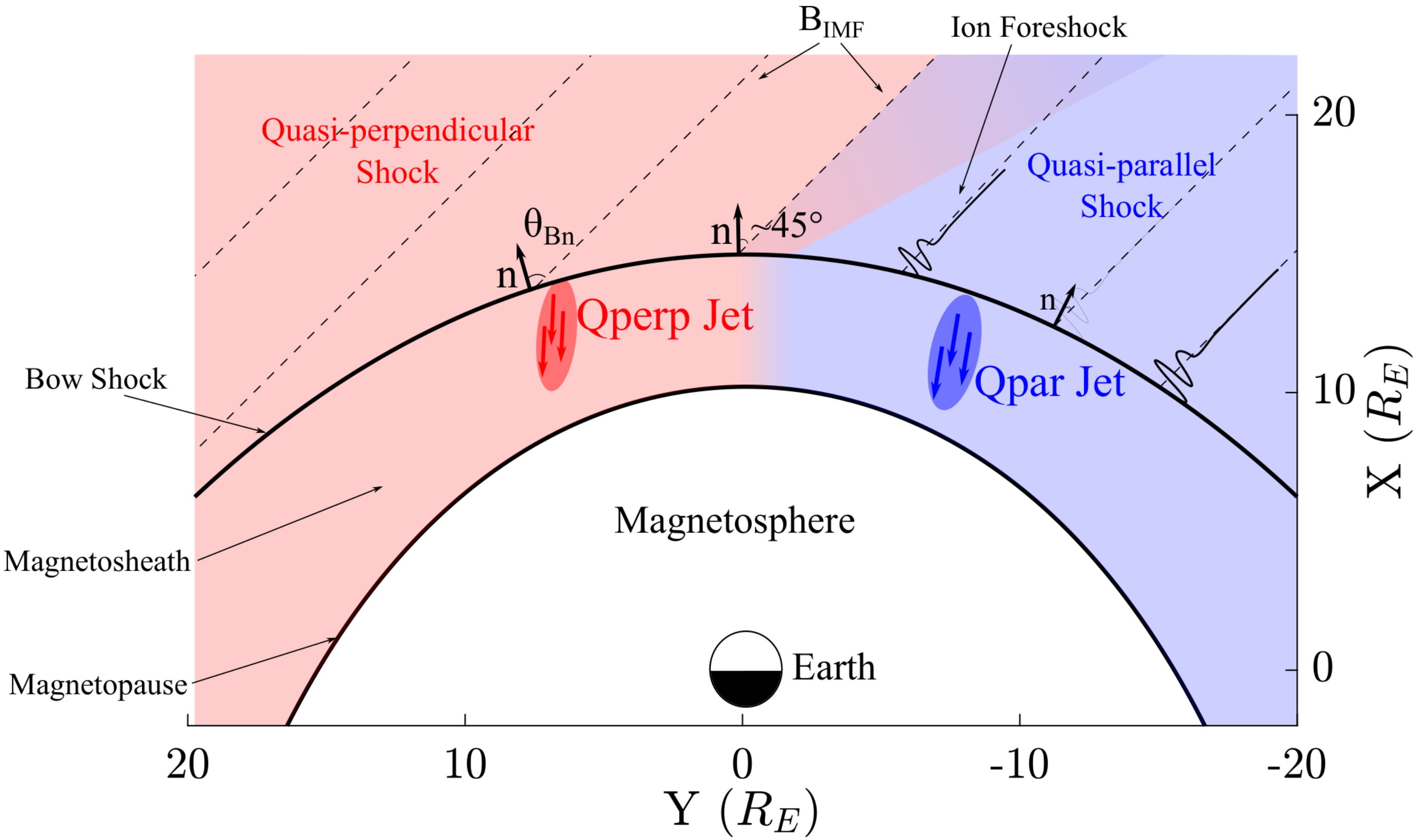
- **Excitation** of surface **eigenmodes** at magnetopause: Archer et al. (2019, 2021)
- **Mirror mode waves** and jets **:** Bianco-Cano et al. (2020)
- Bursty **magnetic reconnection** at the Earth's magnetopause : Ng et al. (2021)
- **Ground-based magnetometer** response : Norenius et al. (2021)
- 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)
- **Occurrence** in relation to **CMEs and SIRs** : Koller et al. (2022)

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.

Shock, Magnetosheath & Jet classification



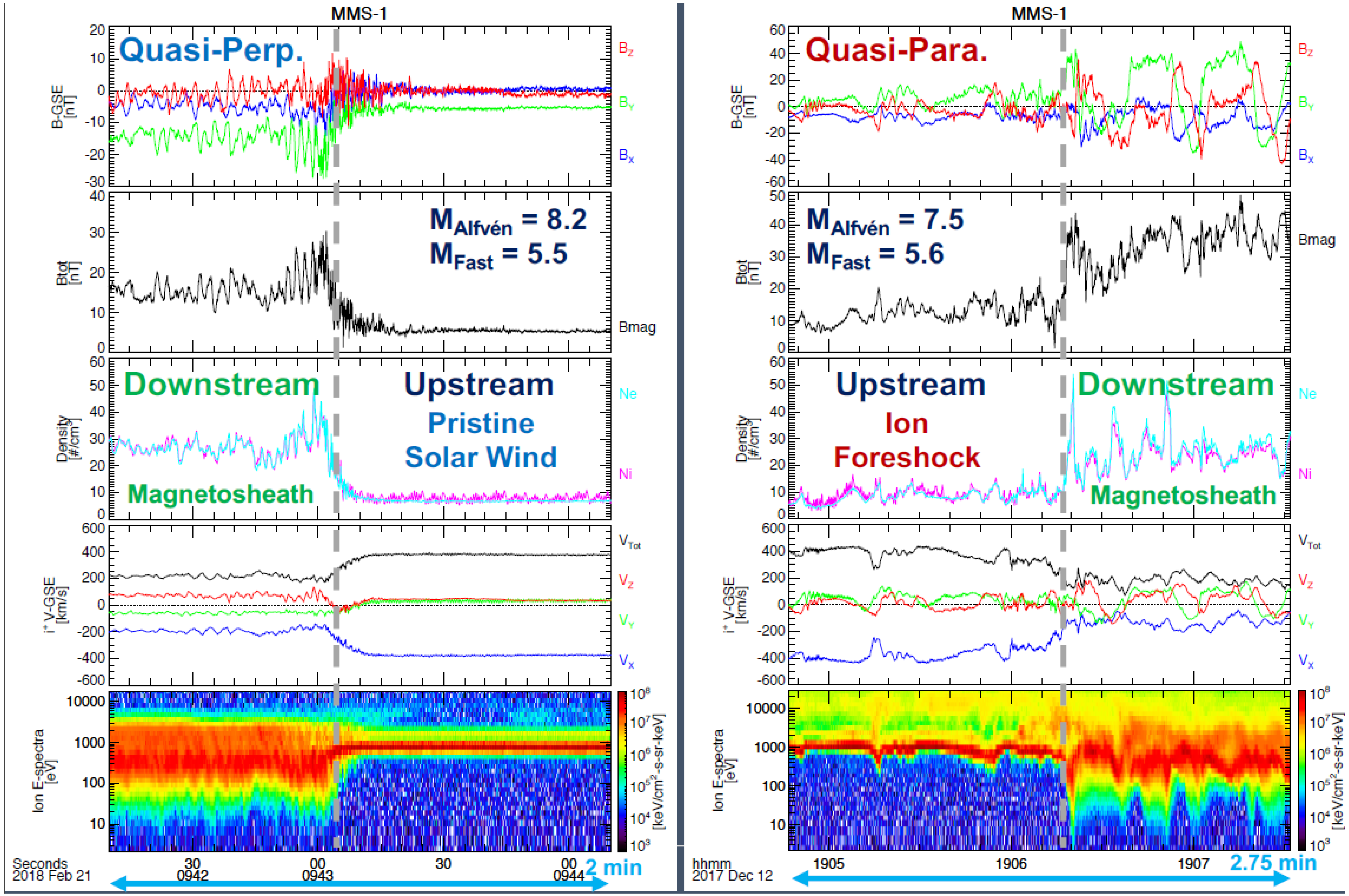
"Θ_{Bn} is the angle between the IMF and the shock's normal vector"

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

"~10 times more often in Qpar MSH"

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

Shock transitions with MMS



Notice difference in the downstream plasma ?

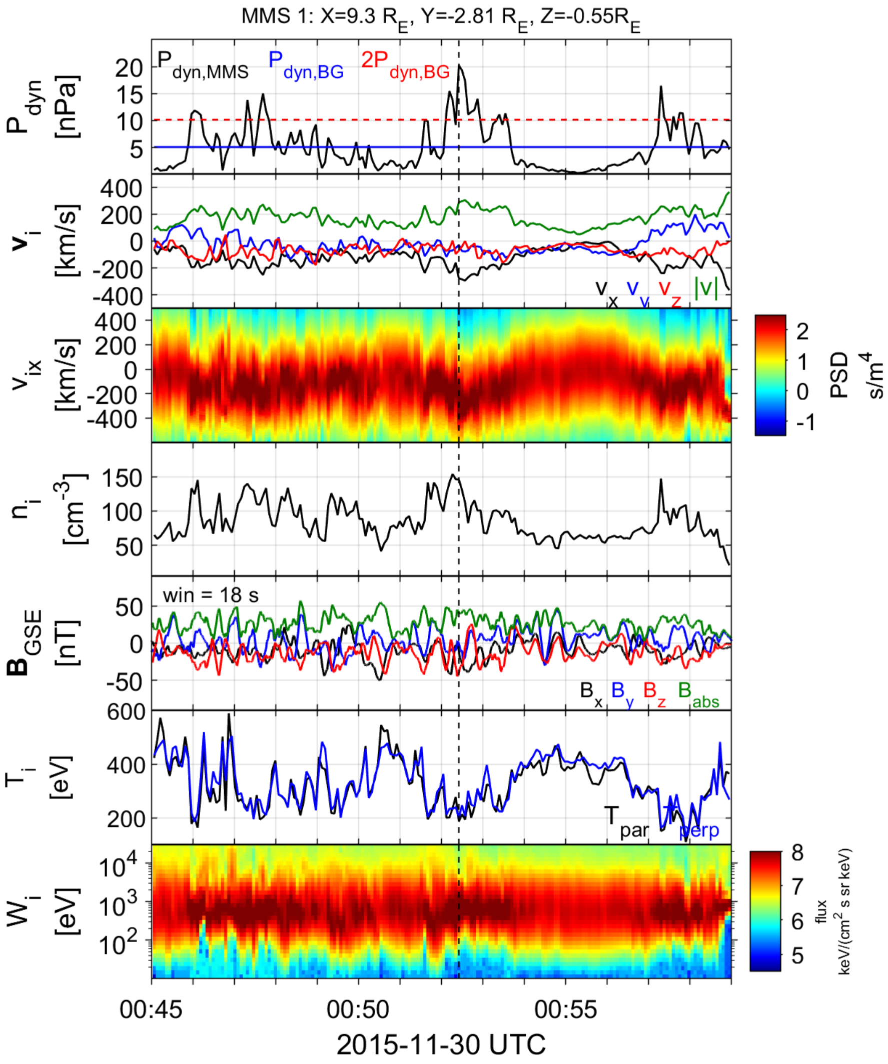
Figure taken from : Drew Turner's talk | SWSG2021

Summarized properties – Quasi Parallel

- Most common
- High dynamic pressure
- Primarily Earthward
- Associated with low temperature (ΔT)
- Associated with high |B| & ΔB
- High |B| variance
- Relevant to magnetospheric effects

Qpar Jet

Jets found in $Q_\parallel$ MSH

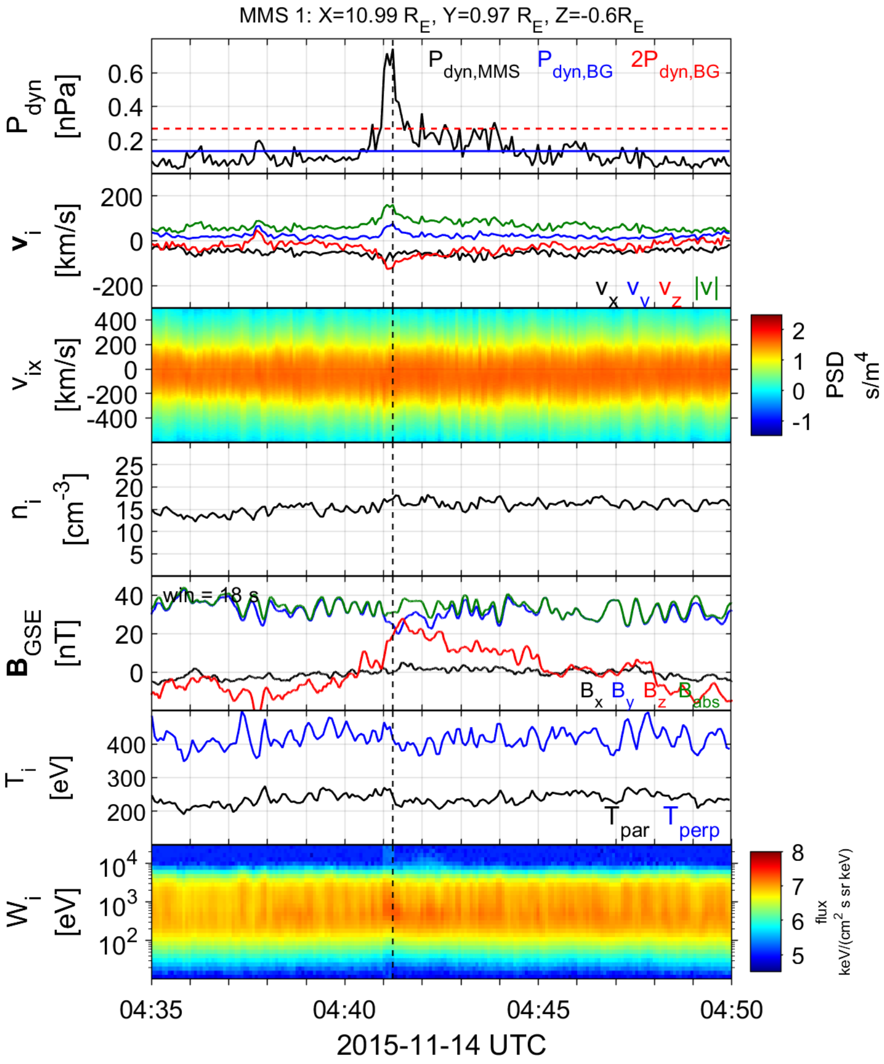


Subset	Number	Percentage (%)
Quasi-parallel	2458	26.7
Final cases	**901**	10.1
Quasi-perpendicular	542	5.9
Final cases	**214**	2.3
Boundary	781	8.5
Final cases	**191**	2.1
Encapsulated	80	0.9
Final cases	**60**	0.7
Other	5335	58.0
Unclassified/Uncertain	3789	41.2
Border	1500	16.3
Data Gap	46	0.5

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 or FTEs
- Connection mirror mode waves



Qperp Jet

Jets found in $Q_\perp$MSH

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Quasi-parallel	2458	26.7
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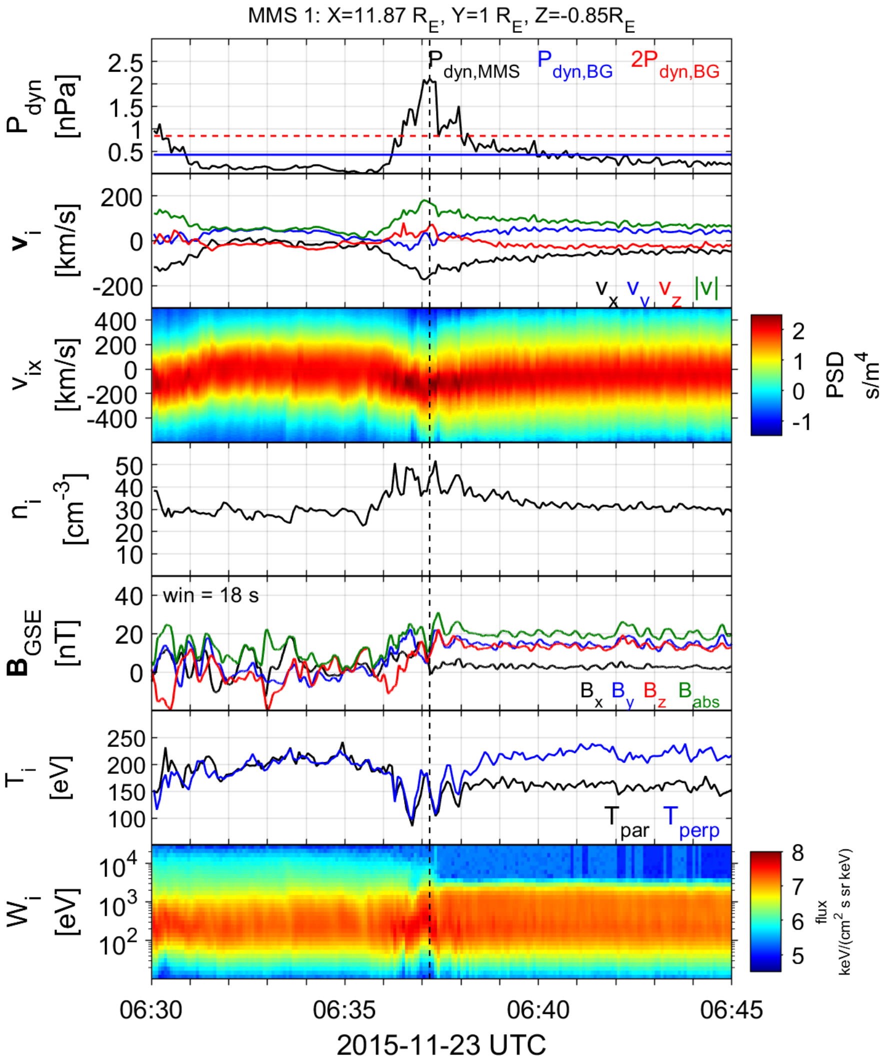
Raptis S., Karlsson T., et al. (2020) | JGR

Summarized properties – Boundary

- Hard to estimate their occurrence rate
- Quite energetic and long duration
- Similar properties to Qpar jets
- Could be geoeffective (GMAGs) [Norenius et al. 2021]
- Maybe associated to pressure pulses of SW [Archer et al. 2012]

Boundary Jet

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



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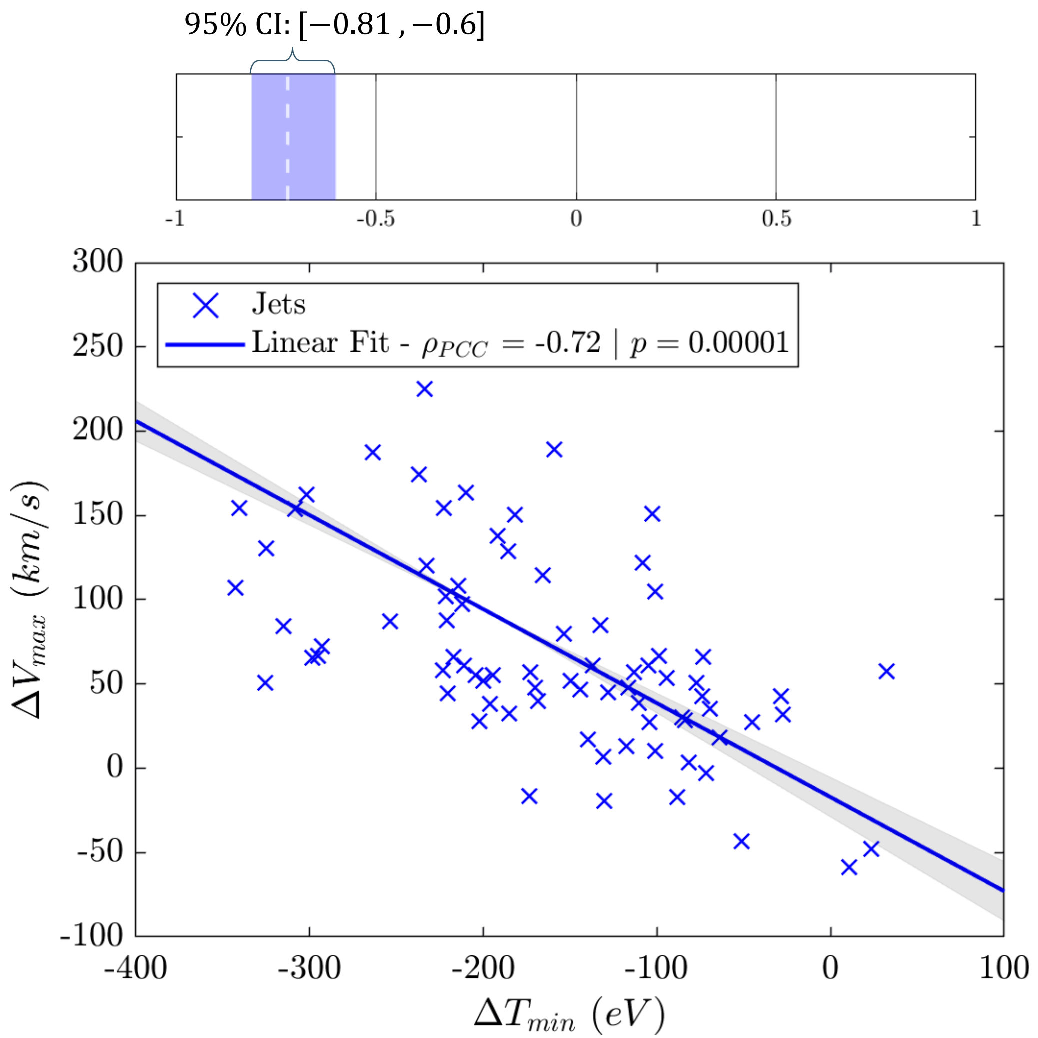
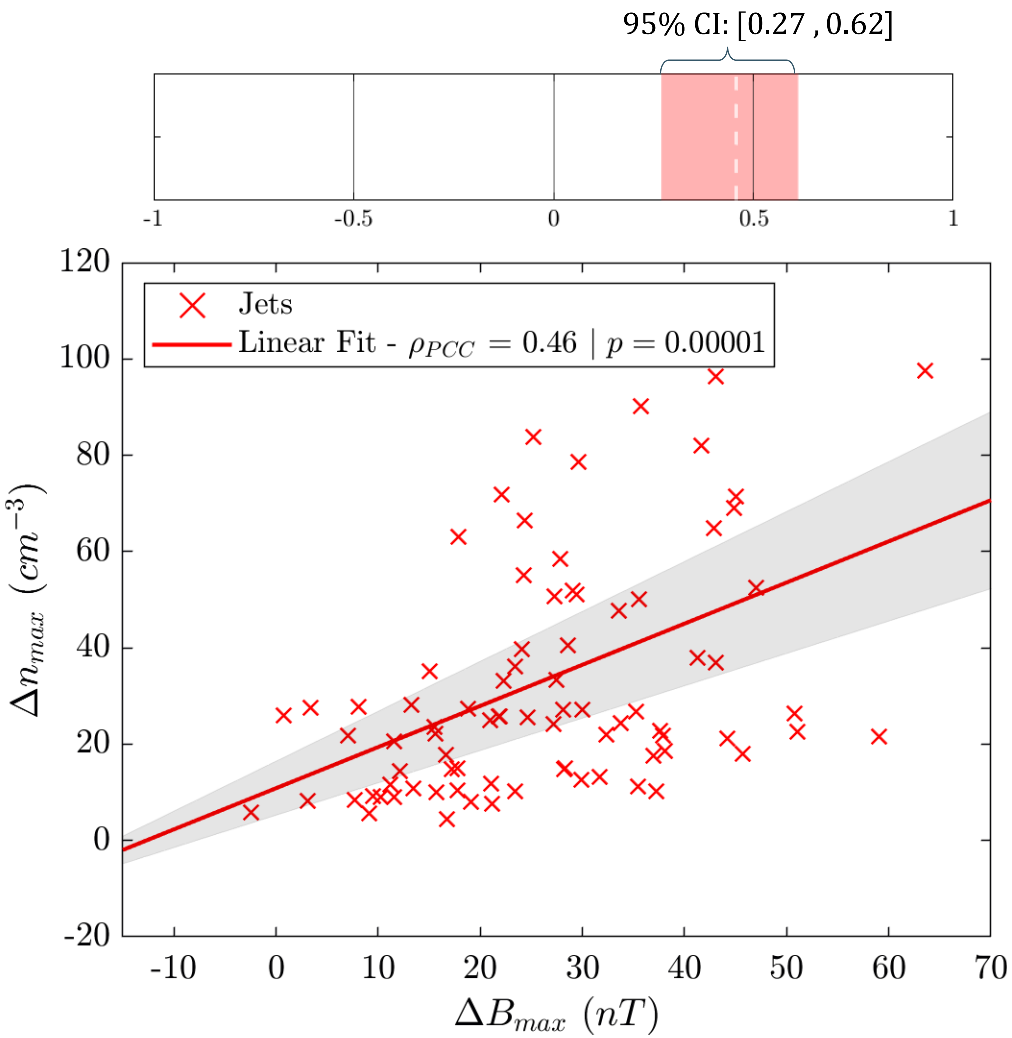
Raptis S., Karlsson T., et al. (2020) | JGR

Example : statistics of subset close to Bow shock

$n = 90$

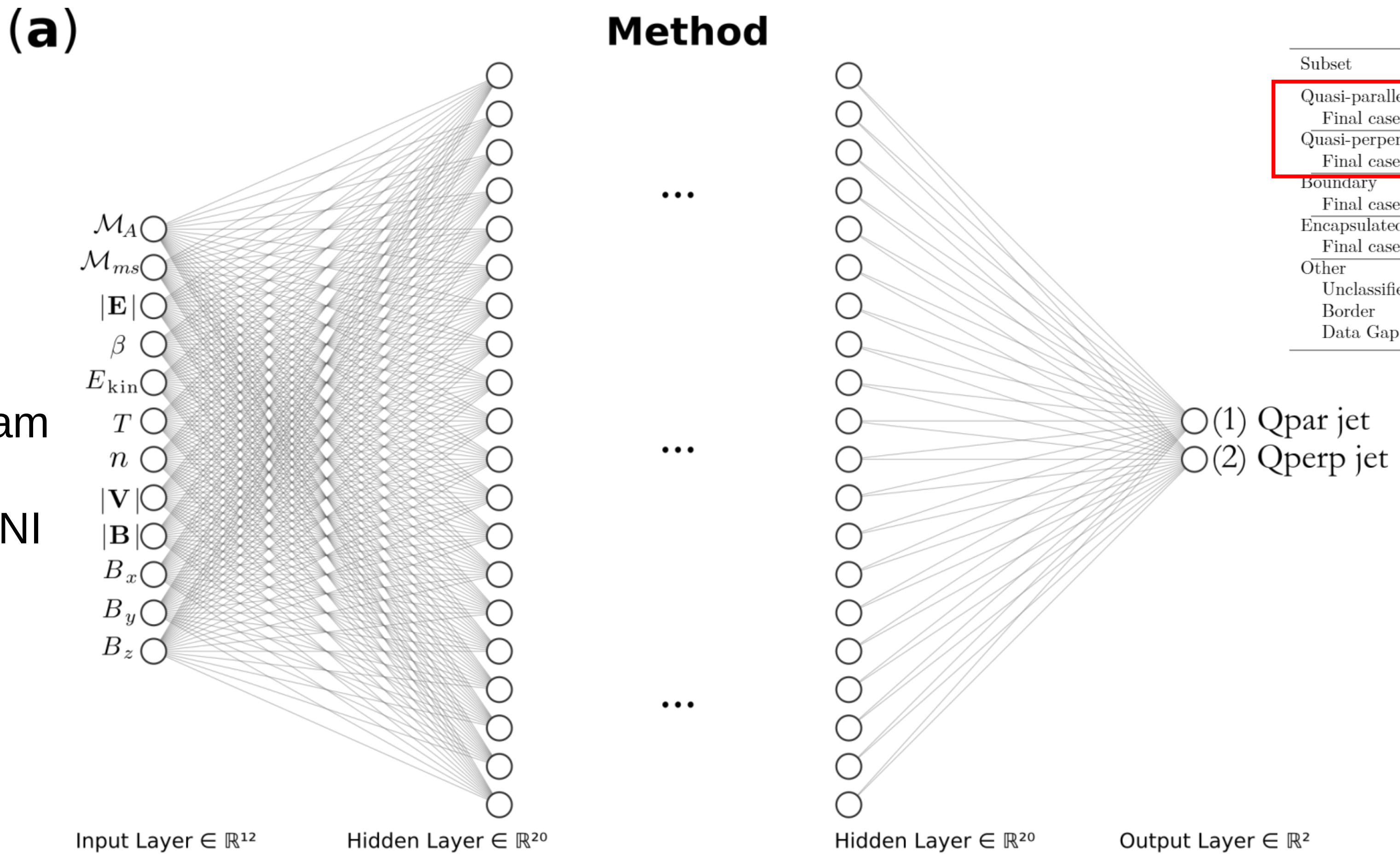




Raptis S., et al. | Ongoing

Classifying jets with Neural Networks

Upstream
SW
L1 OMNI



Downstream
MSH
MMS

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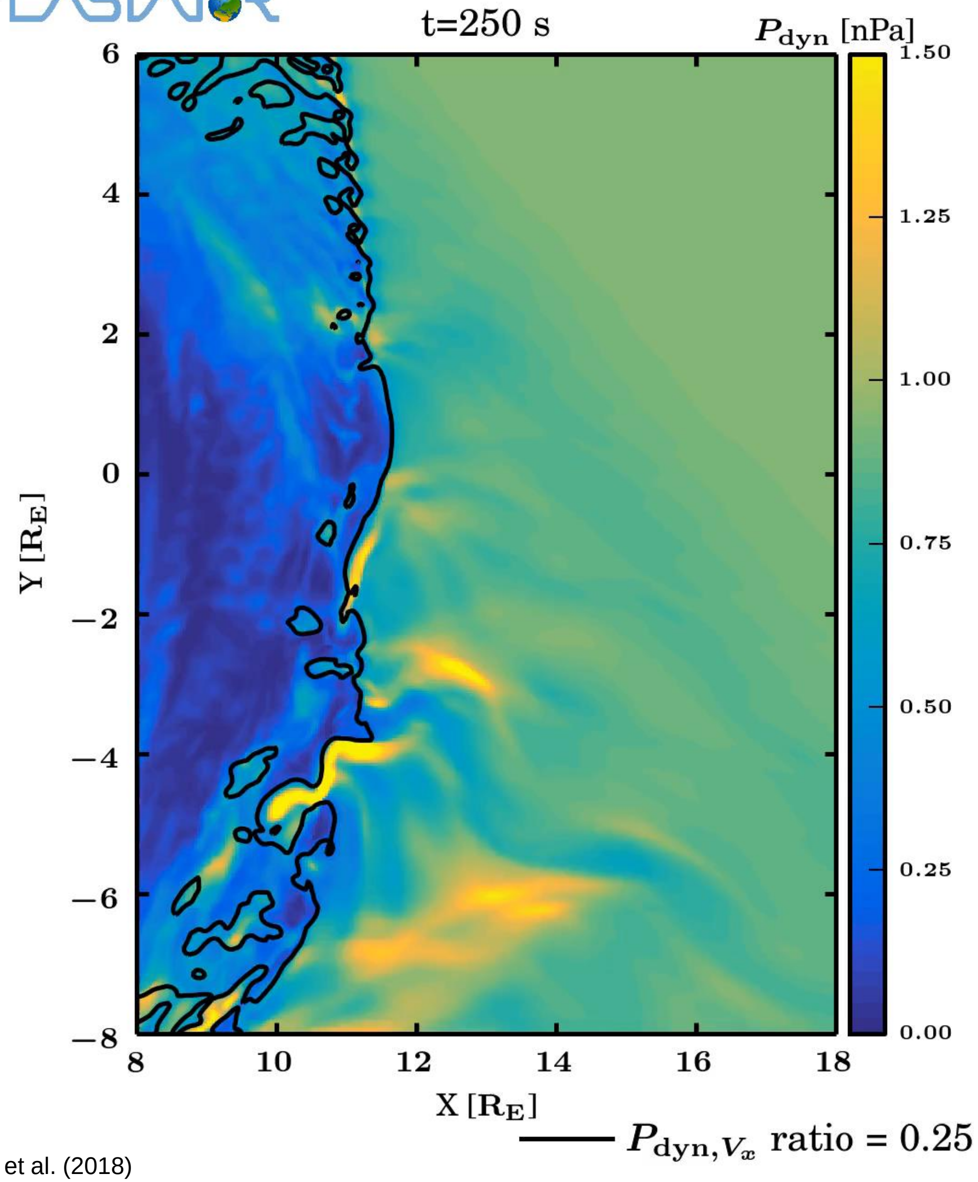
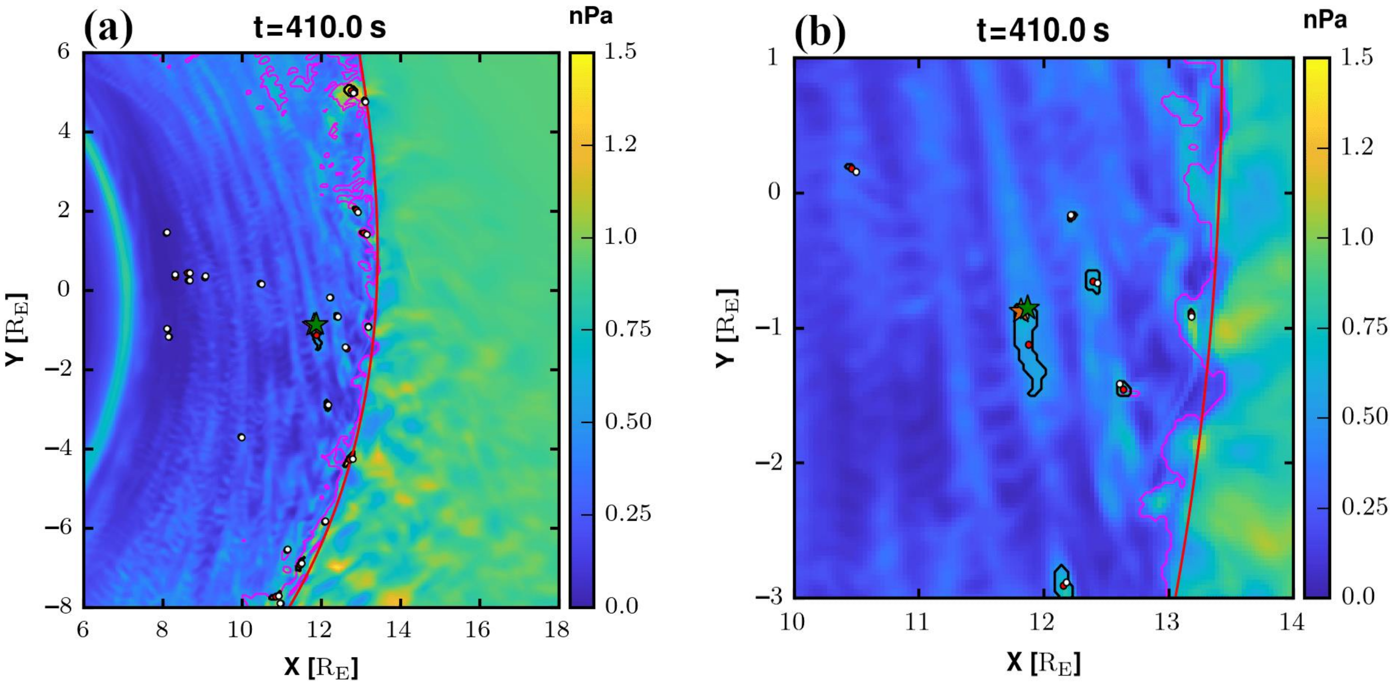
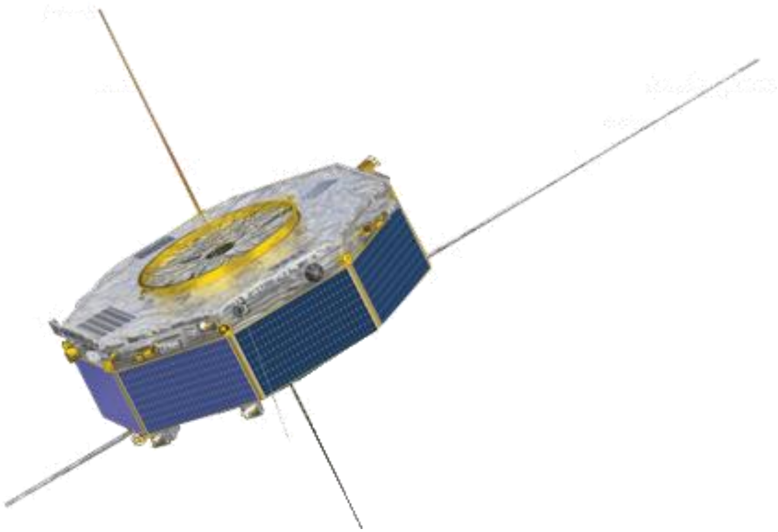
Raptis, Aminalragia-Giamini et al. (2020) | Front. Astron. Space Sci

Jets in simulations

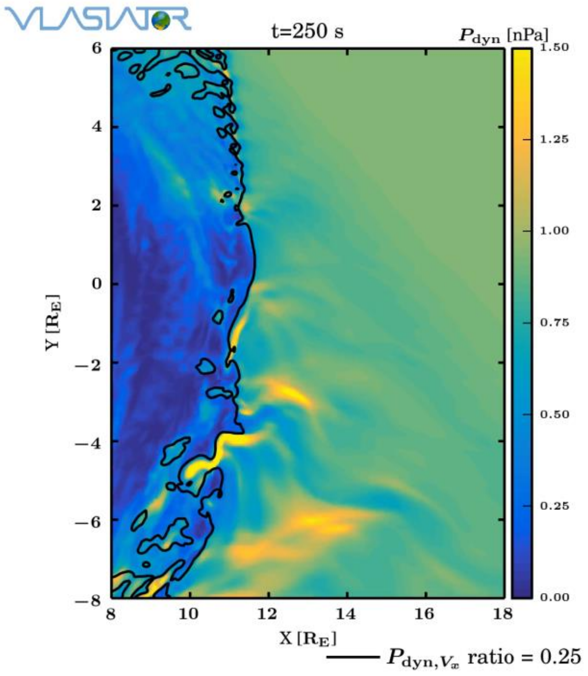




Palmroth, et al. (2018)
Palmroth, **Raptis** et al. (2021)

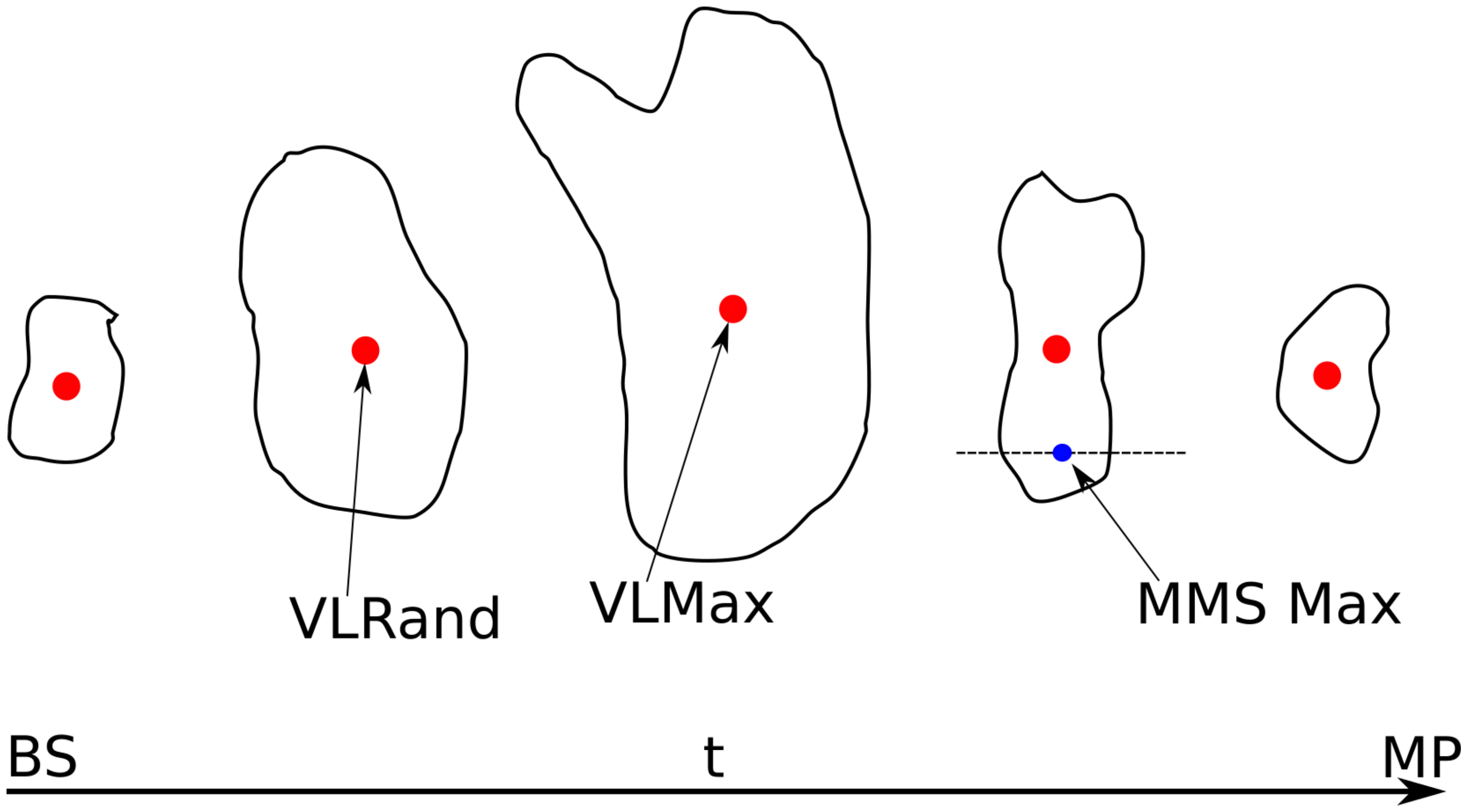


Comparison
MMS **VS** Vlasiator



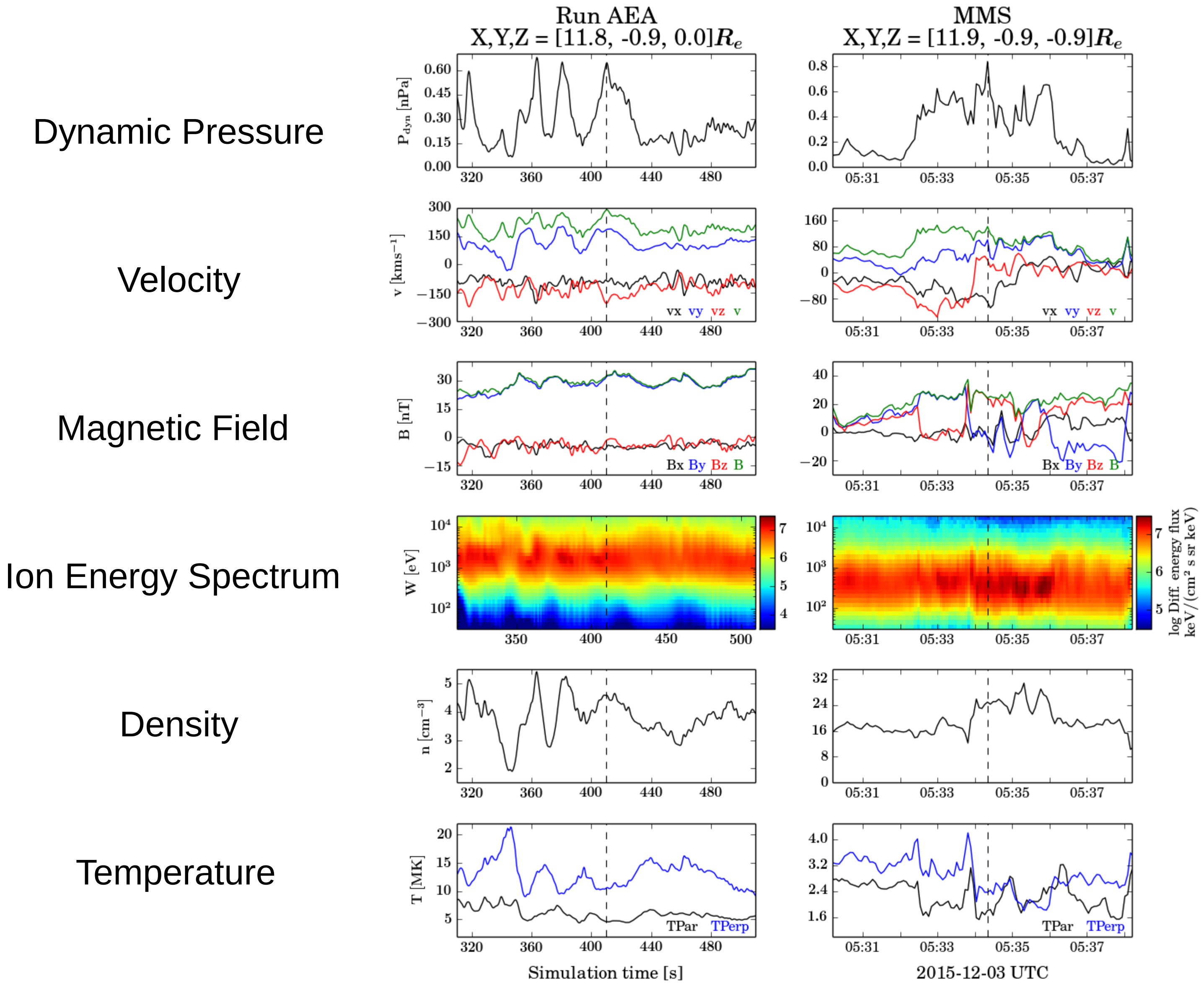
Palmroth M., **Raptis S.**, et al. (2021) | Annales

Main Difference between MMS & Vlasiator



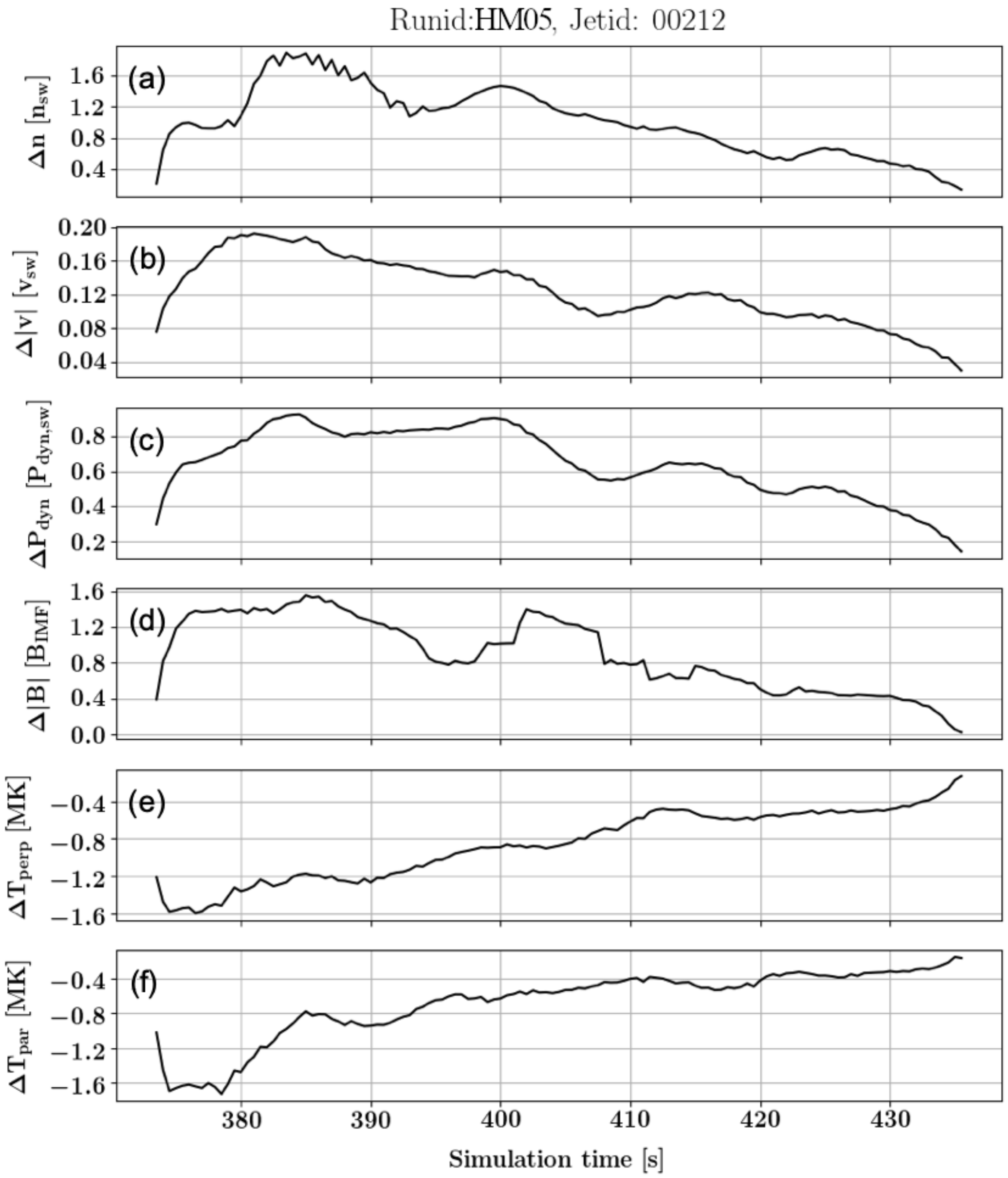
Palmroth M., **Raptis S.**, et al. (2021) | Annales

Case Comparison



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

An evolution of a jet using Vlasiator



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

What we learned so far

Jets & different techniques

Data & Statistics

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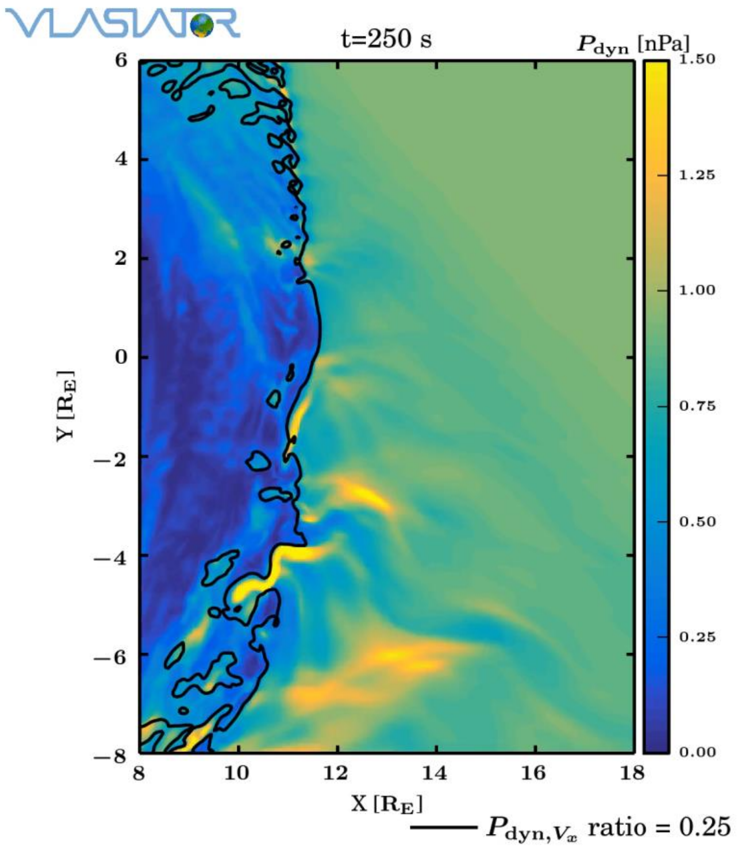
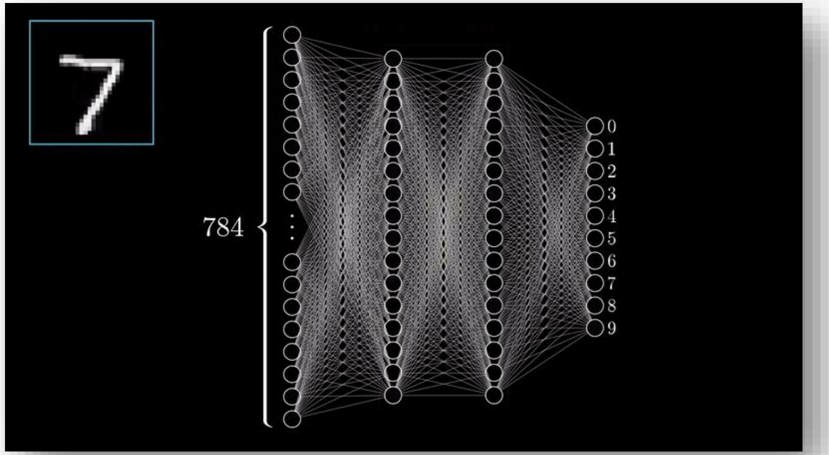
Simulations



Machine Learning



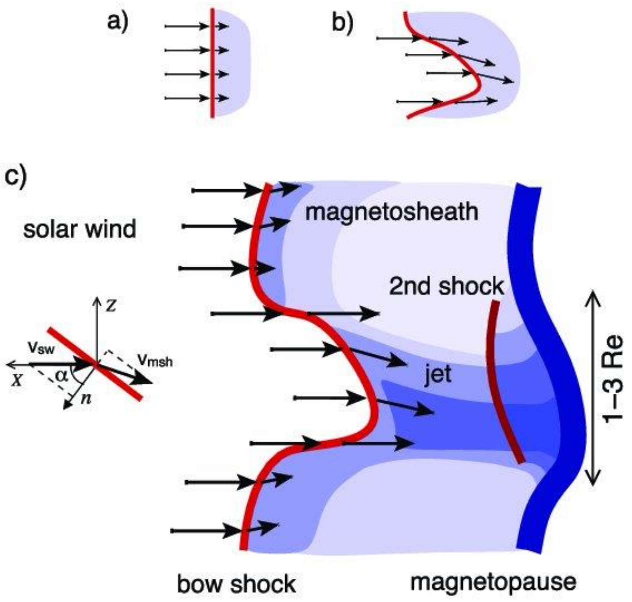
Fluid (Ideal) — Hybrid (in-between) — Kinetic (complex)

Big things — Medium things — Small things

How are jets formed ?

How are these jets created (Qpar) ?

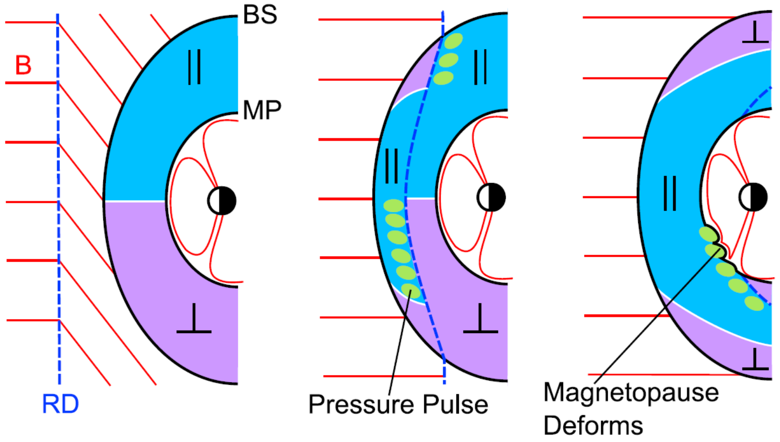
Shock ripples



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

Hietala et al. (2009,2012)

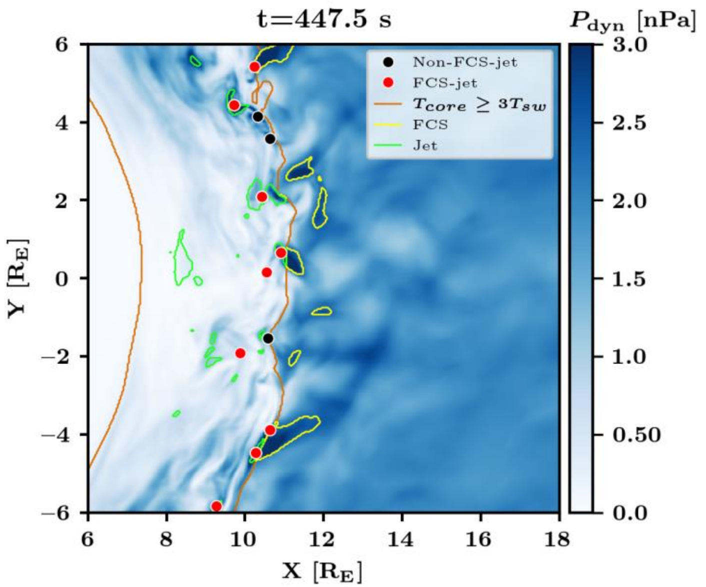
SW discontinuities



RD → Change in Foreshock position → Pressure pulses

Archer et al. (2012)

Foreshock Structures & Reformation



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

Why foreshock & jets ?

Observations

Karlsson et al. (2012, 2015):

Embedded plasmoid = density
Fast plasmoid = density + velocity

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

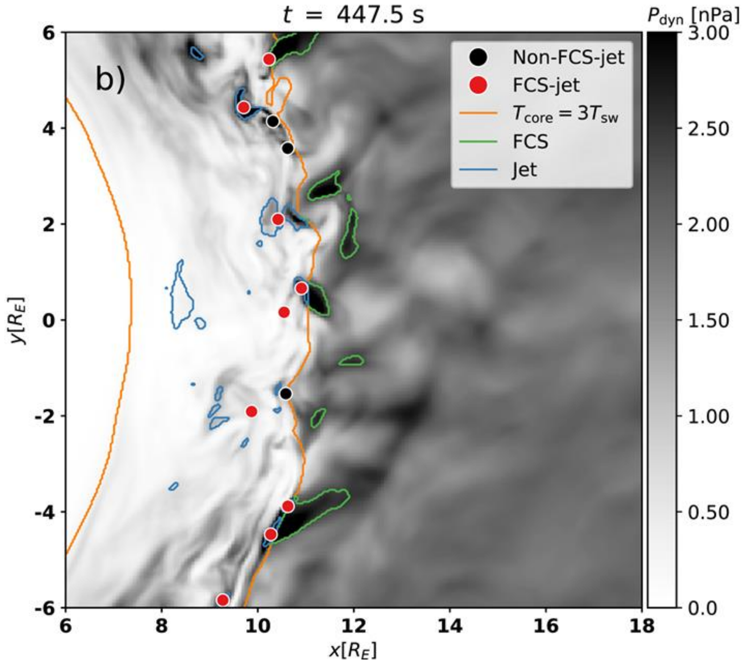
Raptis et al. (2020): *"… **SLAMS-associated mechanisms** are therefore supported and appear to be key elements of jet formation… "*

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**"*

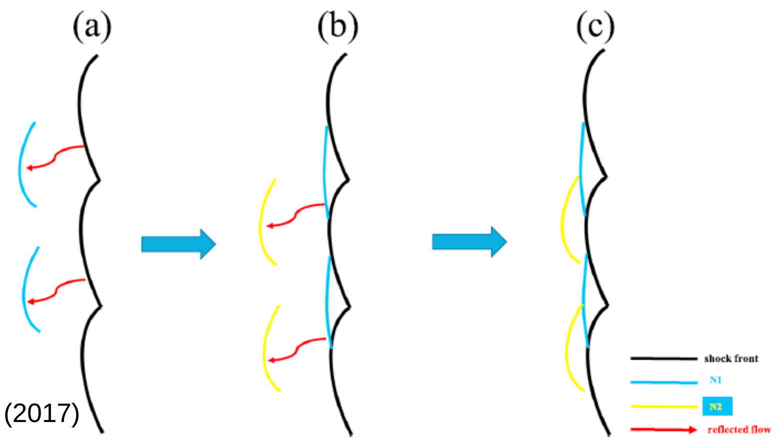


HFA: *Omidi et al. (2013)*

Shock Reformation

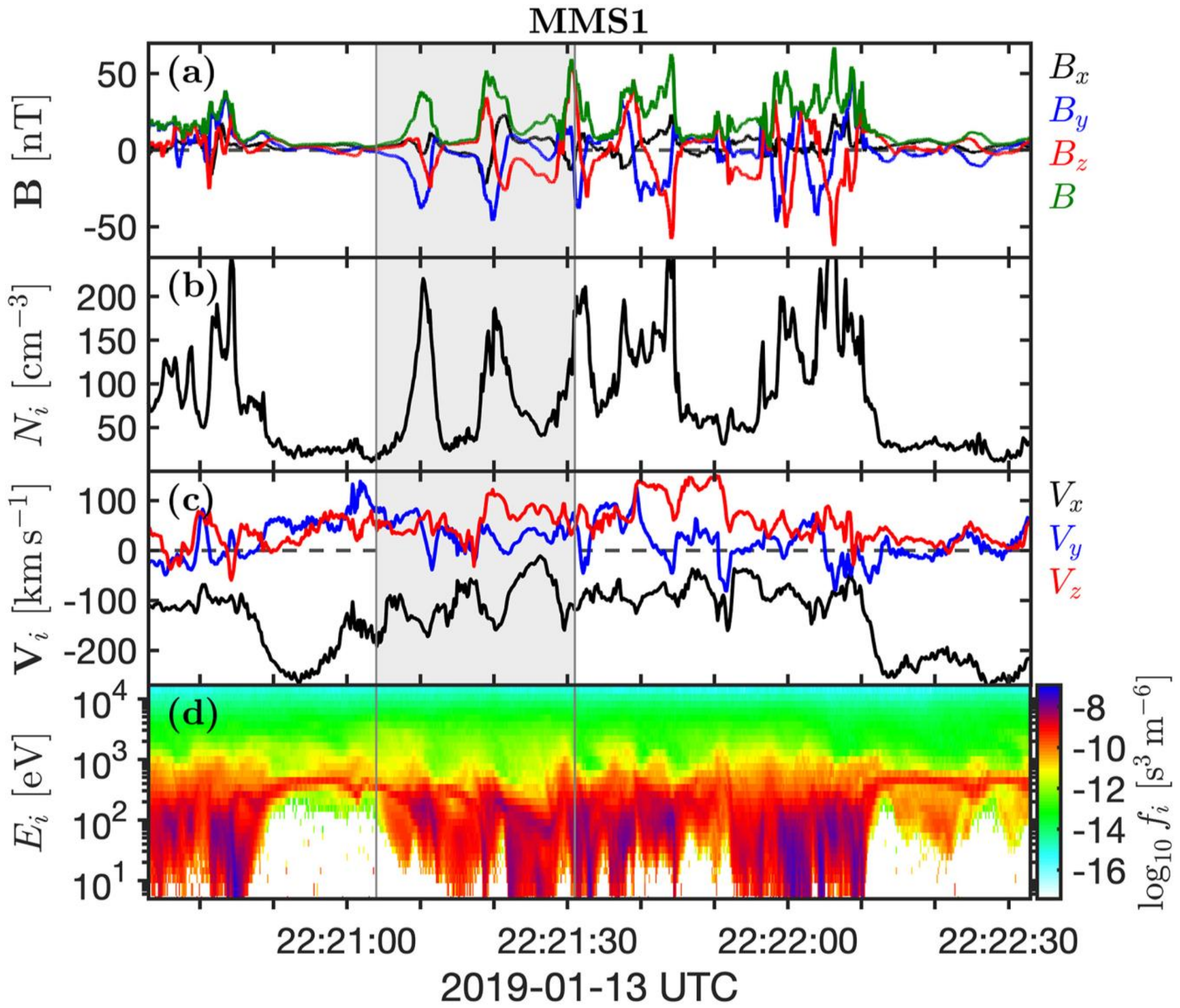
<u>Shock Reformation</u>

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. (2022)

Johlander et al. (2022)

Fluid (Ideal) — Hybrid (in-between) — Kinetic (complex)

Big things — Medium things — Small things

New Results

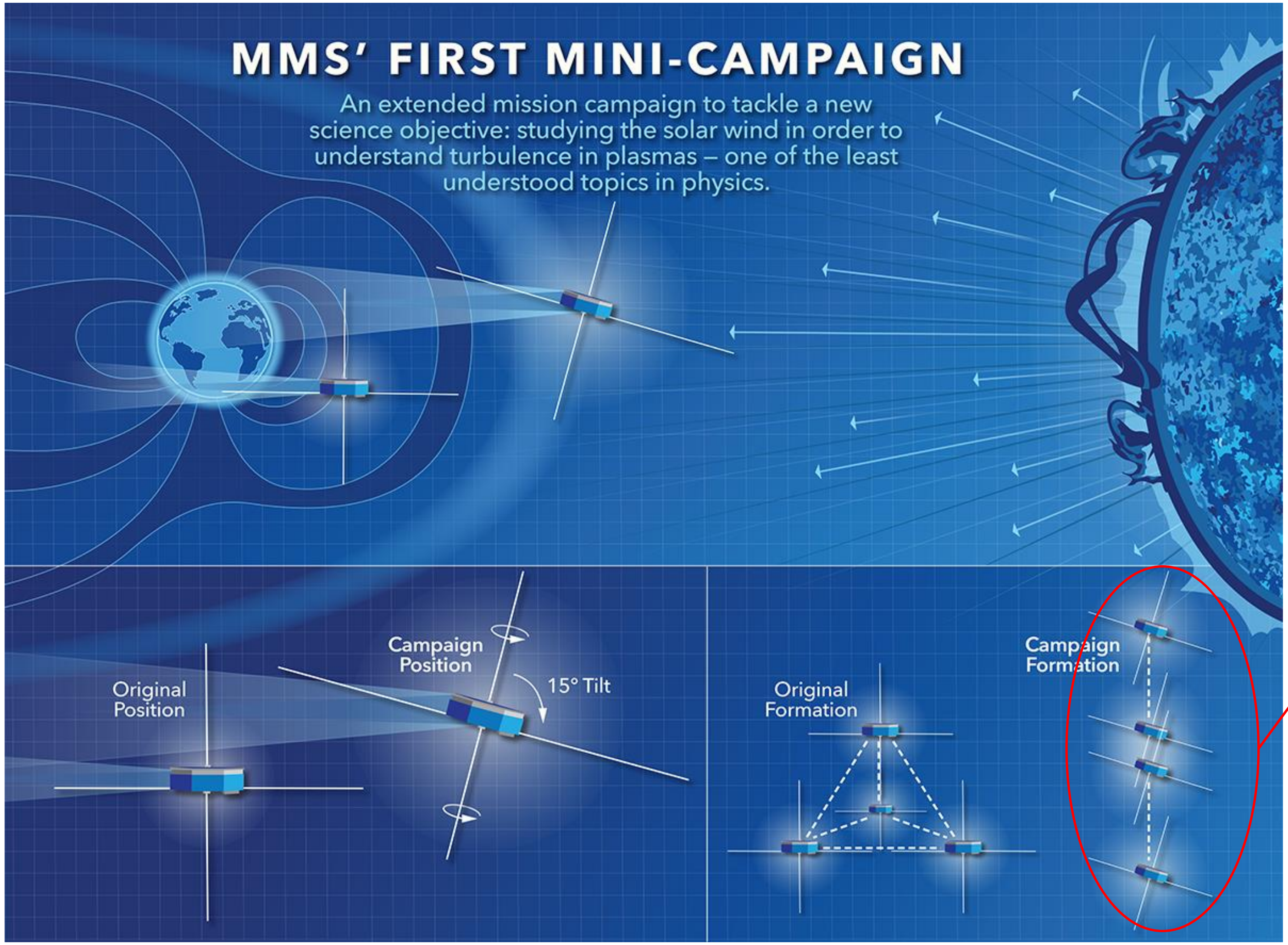
2022

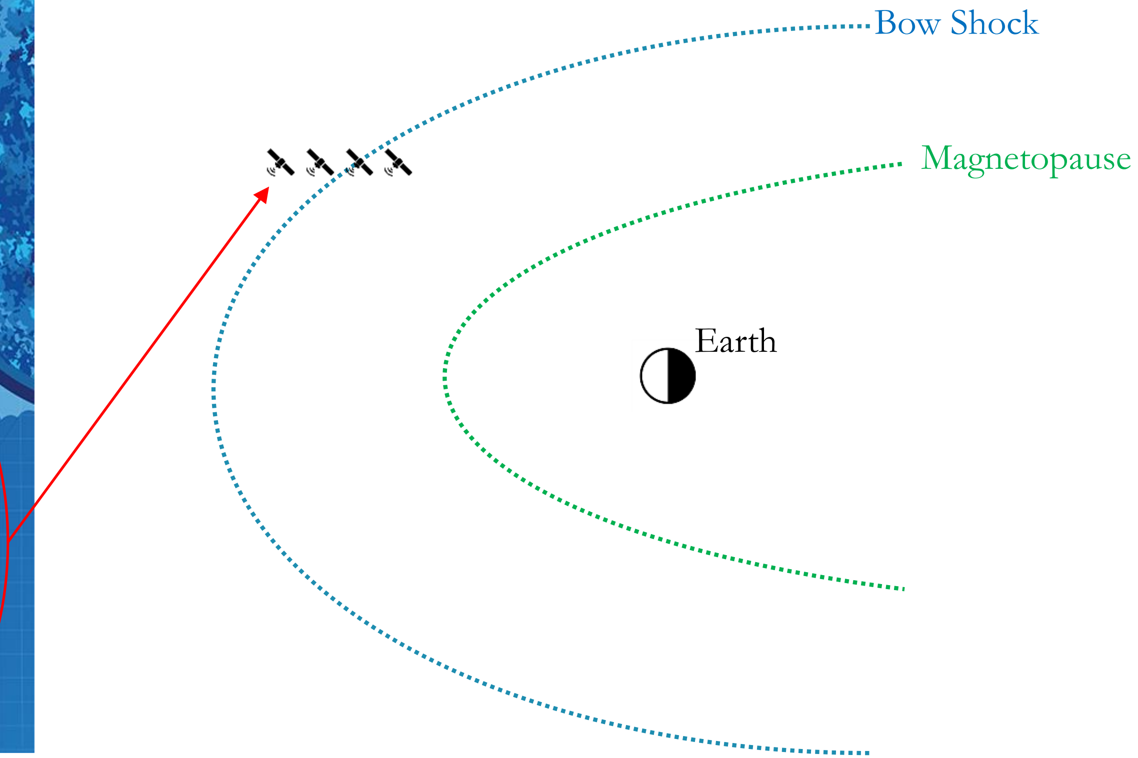
Raptis, S. et al. Downstream high-speed plasma jet generation as a direct consequence of shock reformation. *Nature Communications* 13, 598 (2022). https://doi.org/10.1038/s41467-022-28110-4

Raptis, S. et al. On Magnetosheath Jet Kinetic Structure and Plasma Properties. Geophysical Research Letters (GRL) (2022 - Under Review)

GitHub : https://github.com/SavvasRaptis/Jets-Reformation

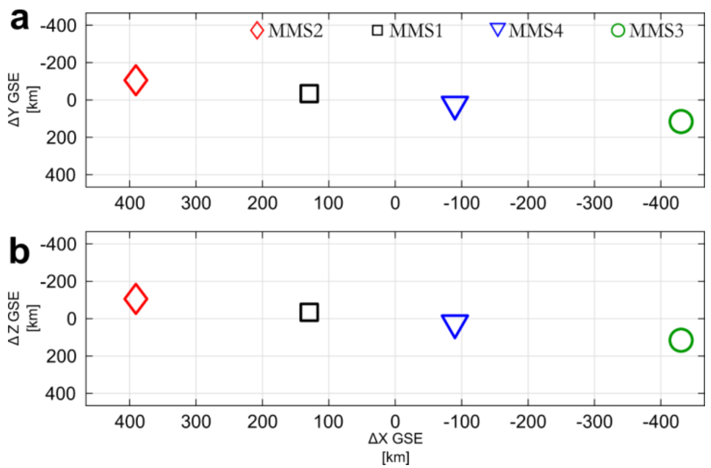
MMS spacecraft + String of Pearl Configuration

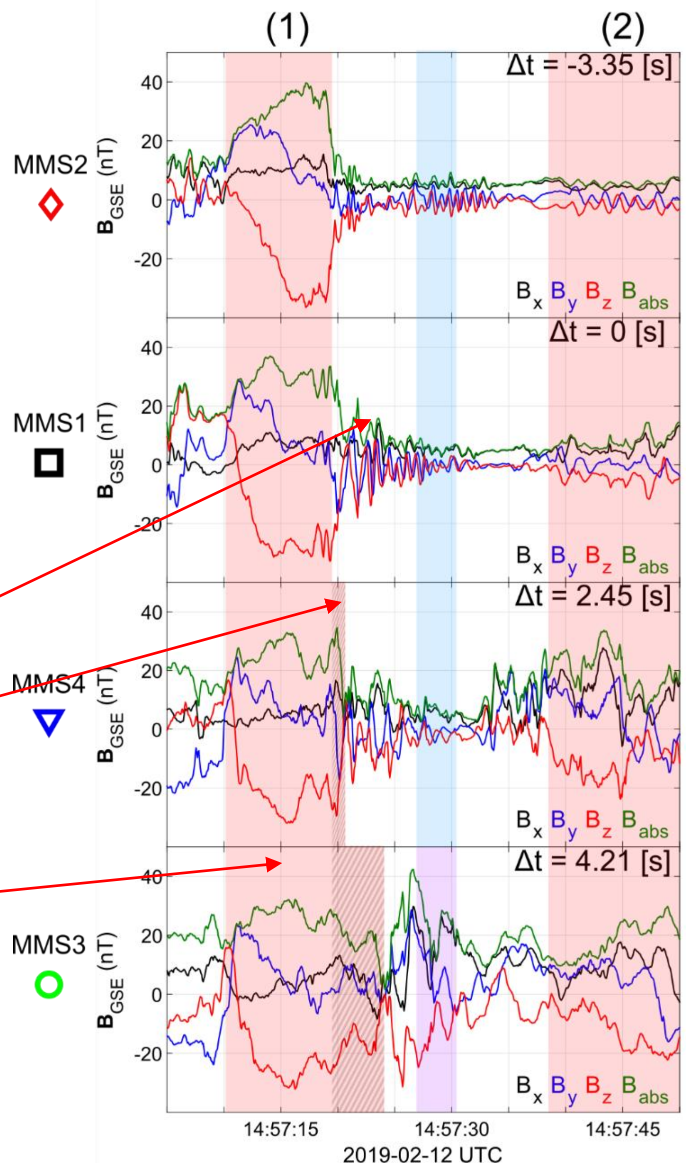




Credits: NASA's Goddard Space Flight Center/Mary Pat Hrybyk-Keith

SLAMS & wave activity co-moving picture





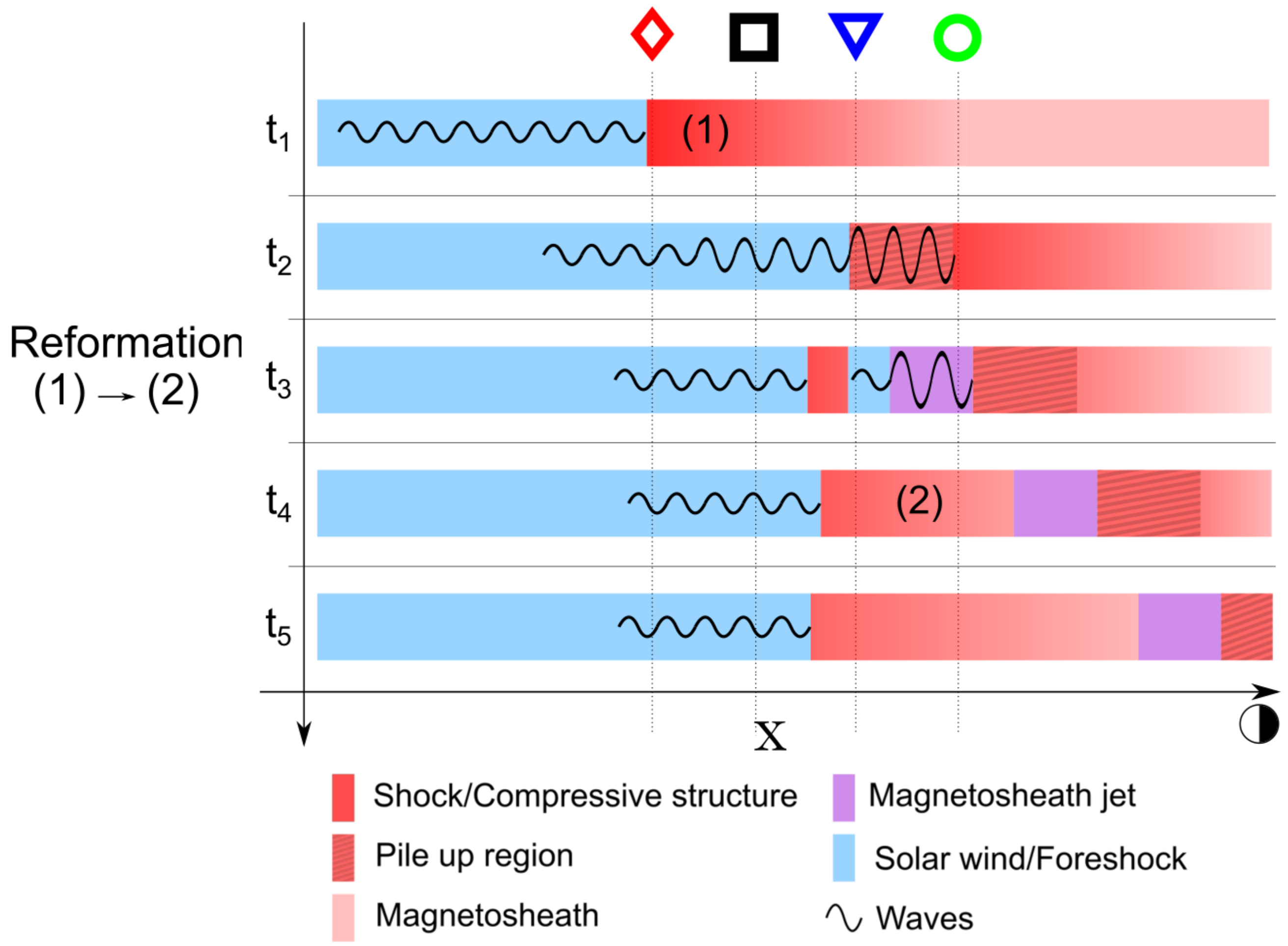
<u>Evolution of SLAMS</u>

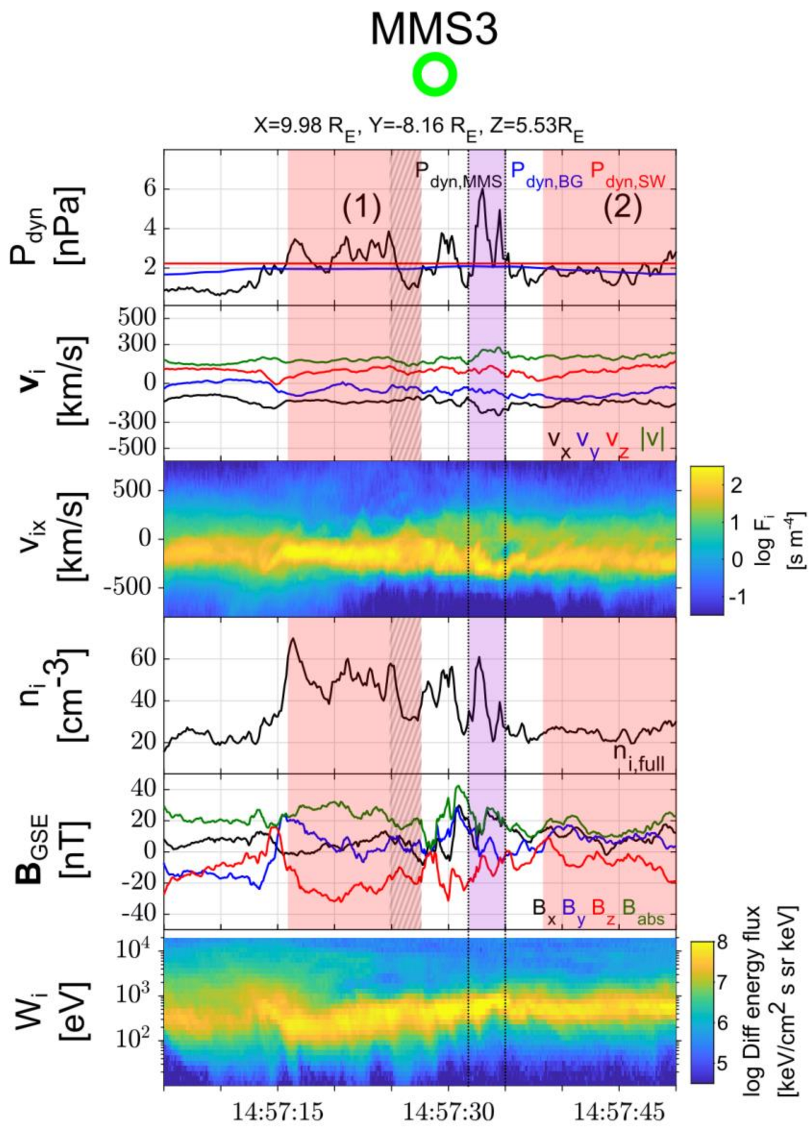
- Interaction with upstream whistler
- New peak /evolution*
- Formation of *downstream density enhancement***

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

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

Shock Reformation & Magnetosheath Jets





Raptis S., et al. (2022a) | Nature Communications

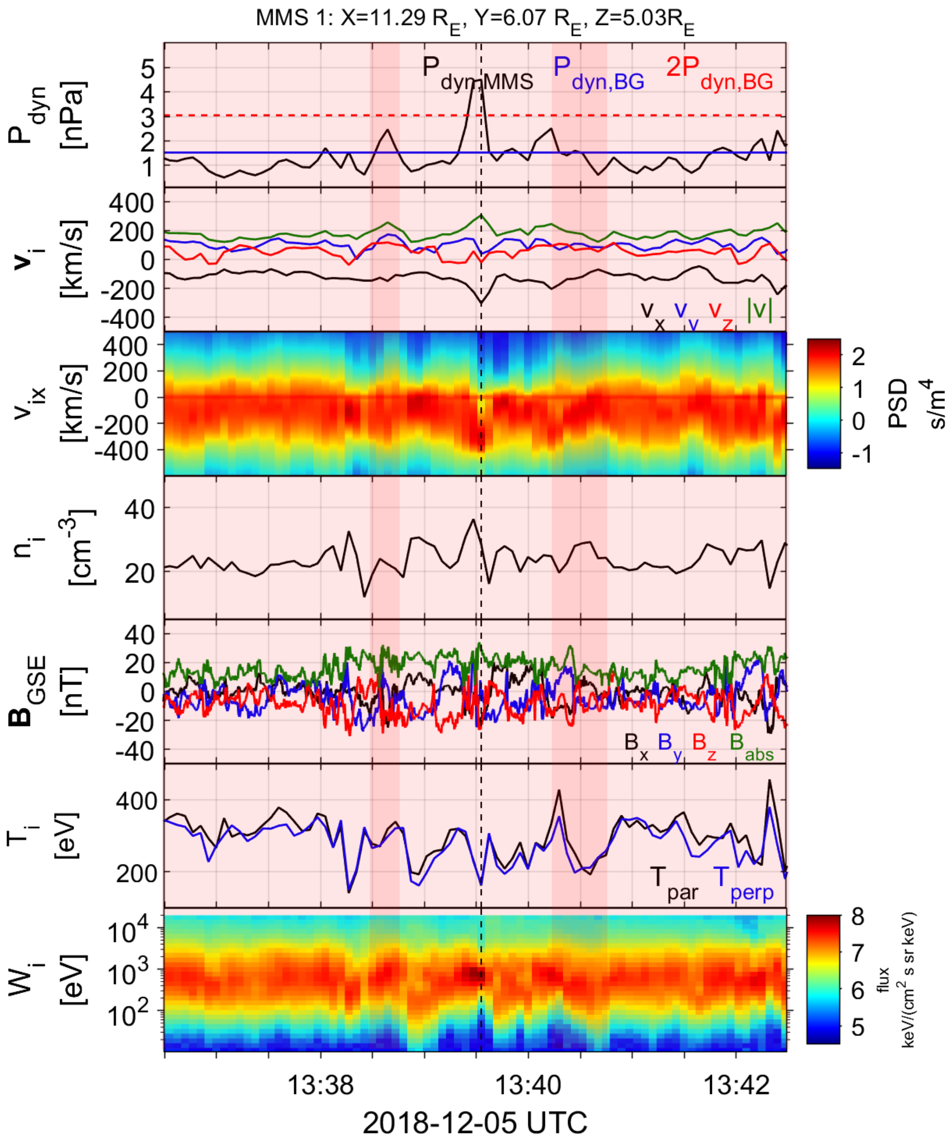
What happens after jets are formed ?

Raptis, S. et al. On Magnetosheath Jet Kinetic Structure and Plasma Properties. Geophysical Research Letters (GRL) (2022 - Under Review)

Qpar Magnetosheath jet – Fast data

<u>Qpar Magnetosheath:</u>

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



<u>Magnetosheath Jet</u>

$|V| \uparrow$

$V_x \uparrow$

$n \uparrow$

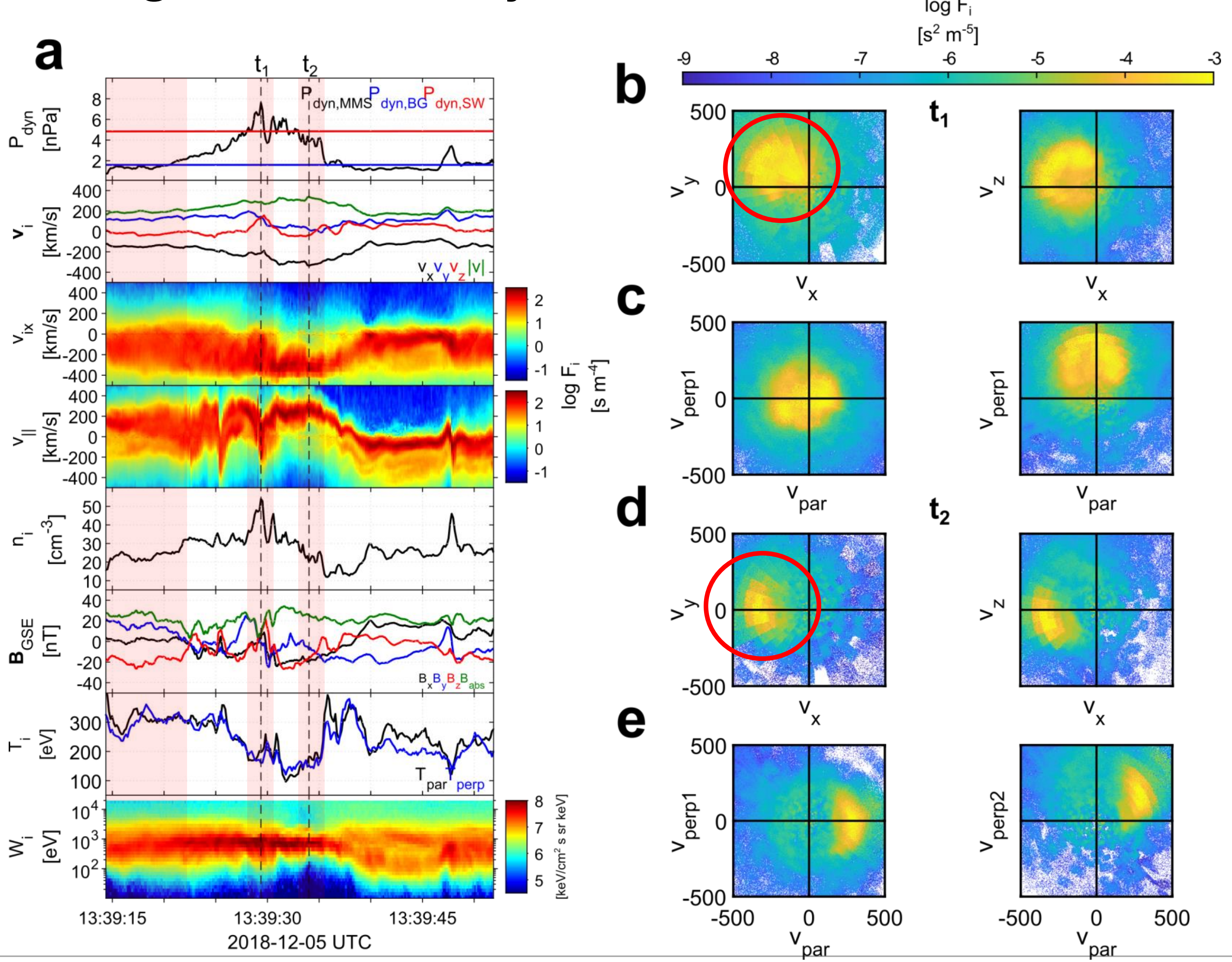
$$P_{dyn} > 2\ P_{dyn,BG}$$

Raptis S, et al,. 2022b | GRL (Under Review)

Qpar Magnetosheath jet – MMS Burst data

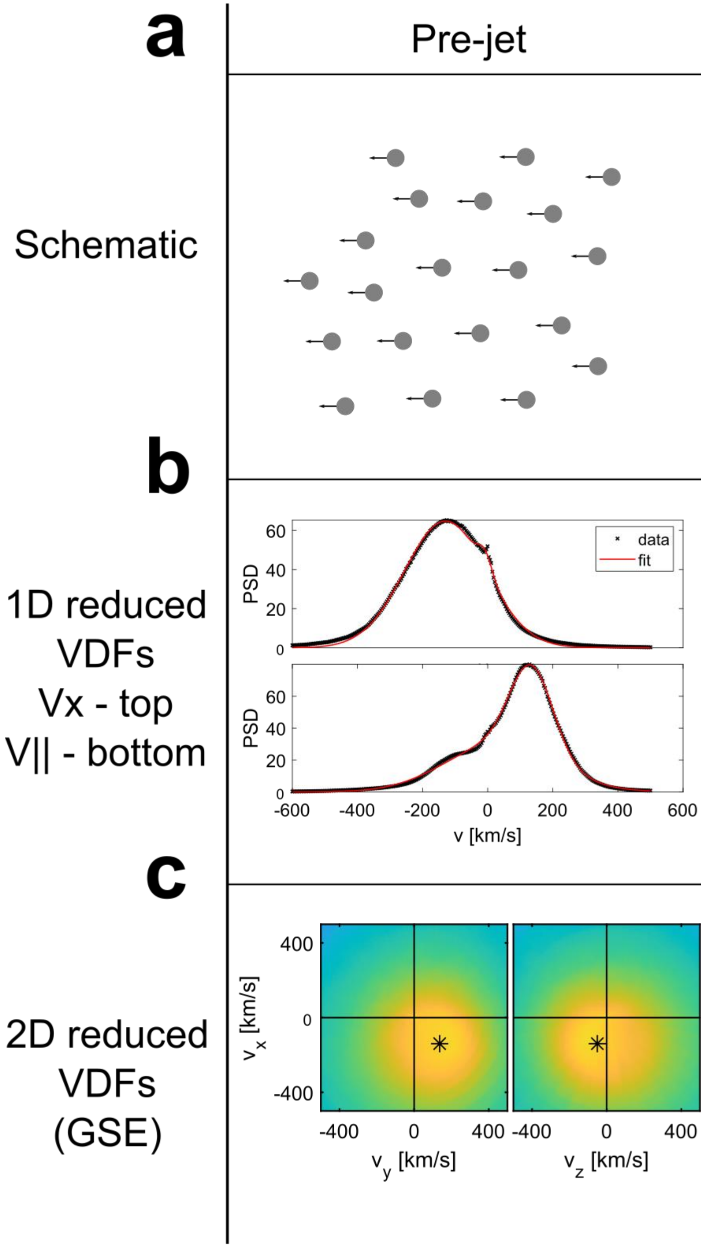
Areas of Interest

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



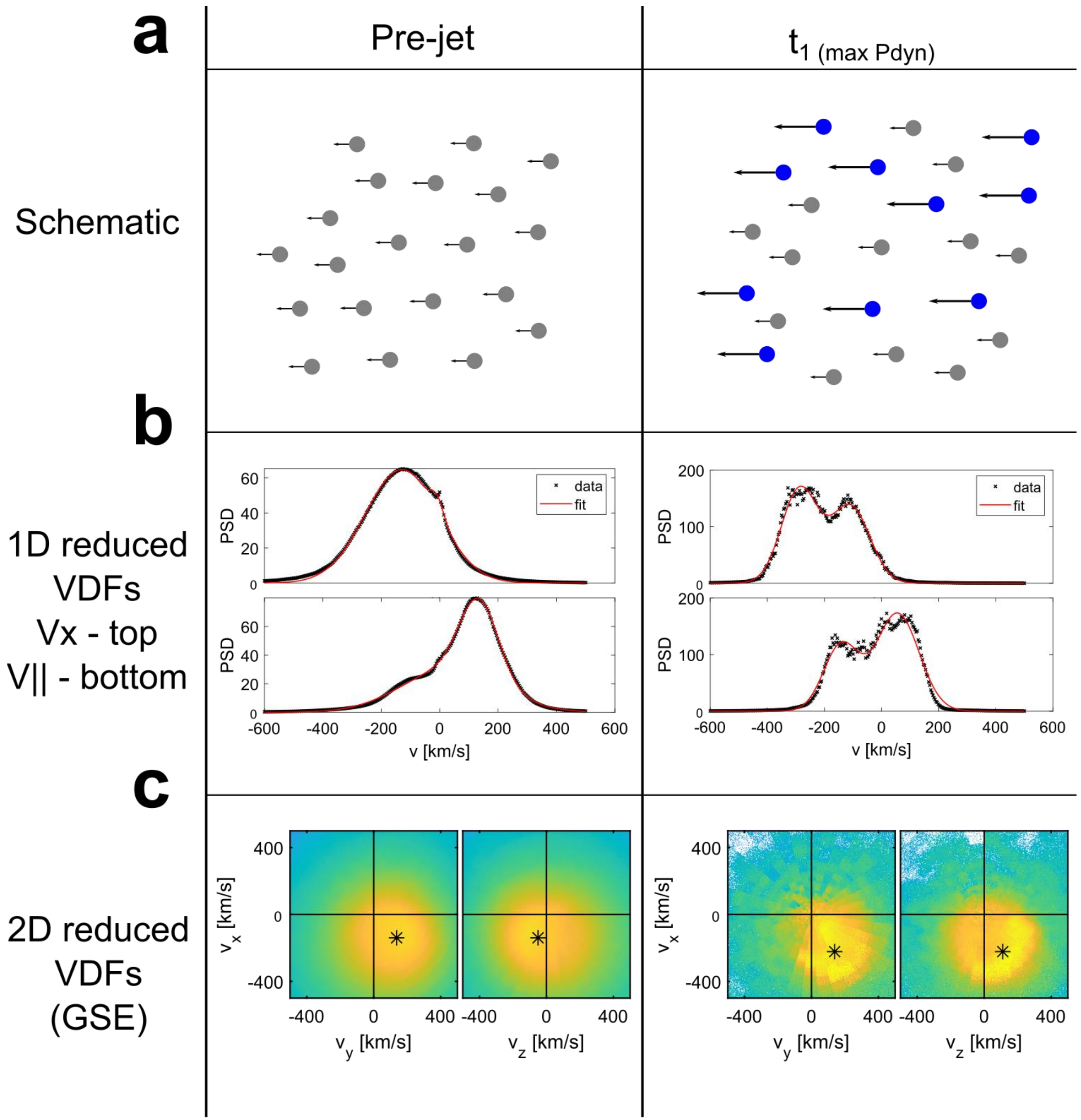
Raptis S, et al,. 2022b | GRL (Under Review)

Jet evolution in Qpar Magnetosheath



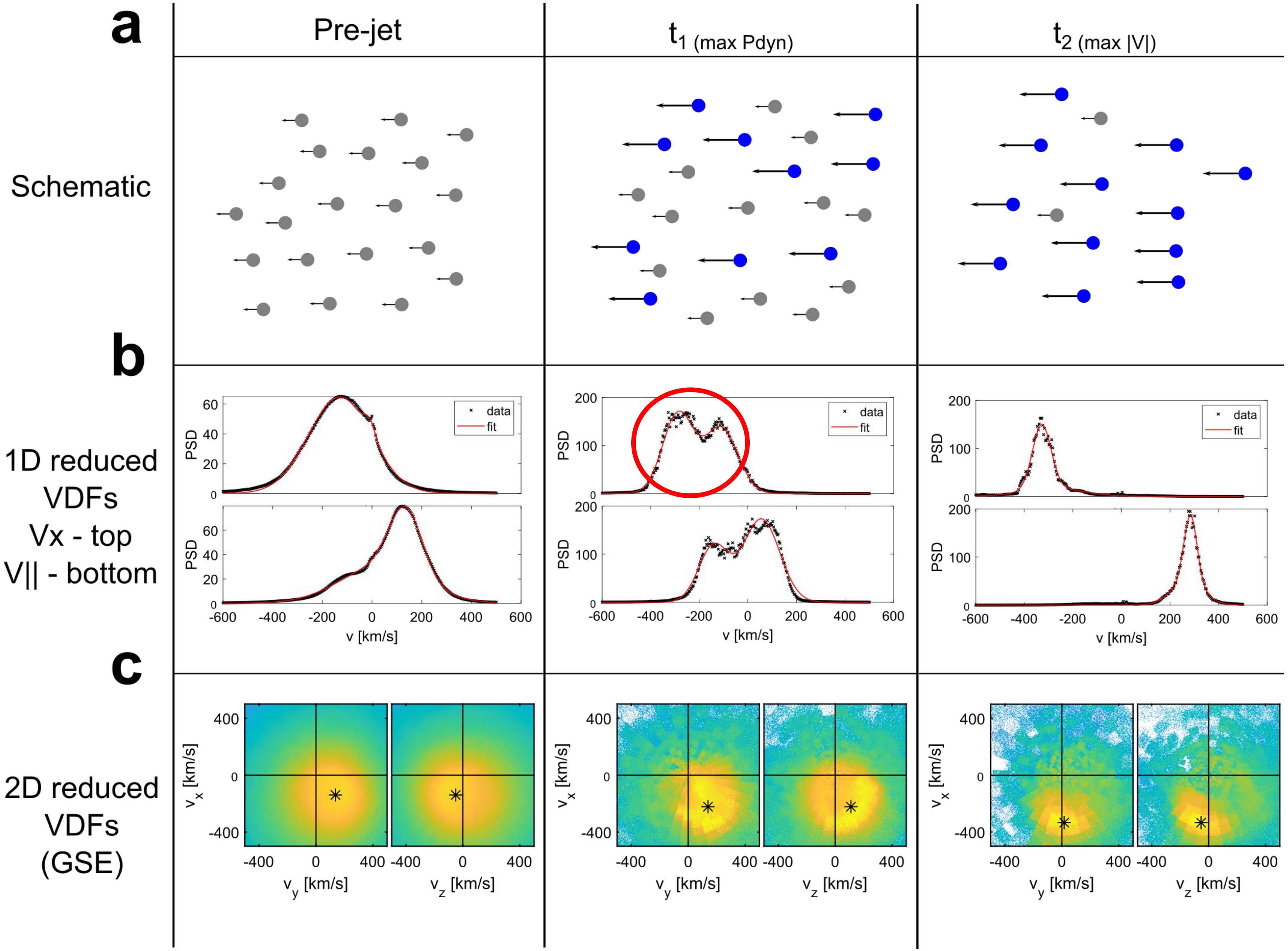
Raptis S, et al,. 2022b | GRL (Under Review)

Jet evolution in Qpar Magnetosheath



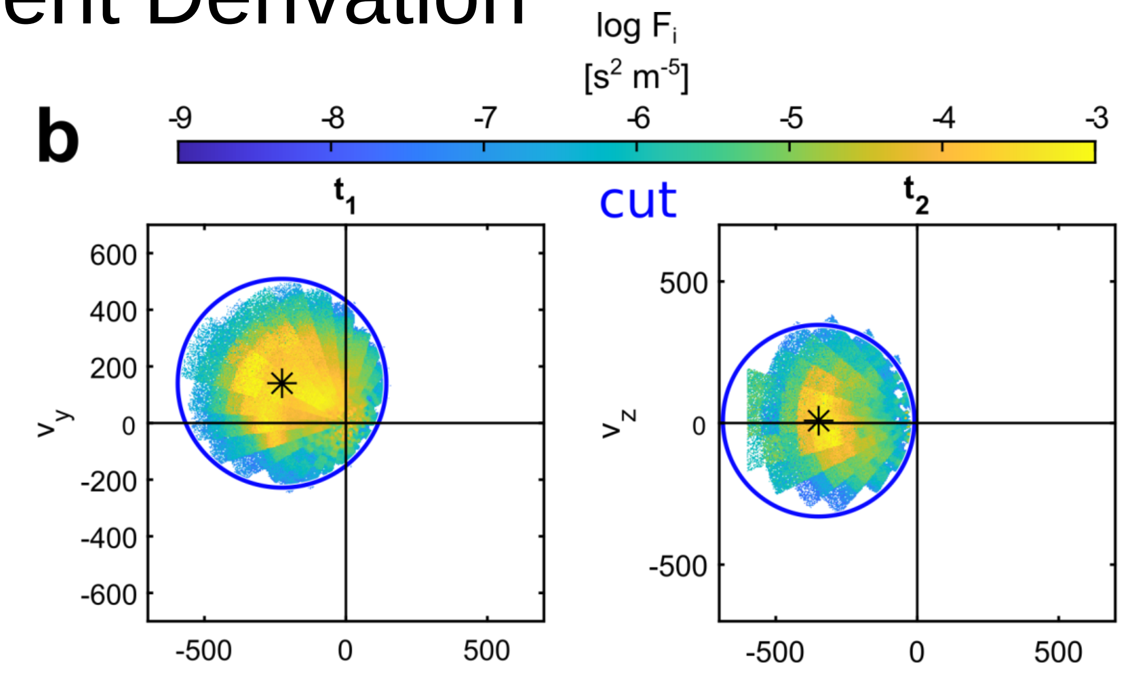
Raptis S, et al,. 2022b | GRL (Under Review)

Jet evolution in Qpar Magnetosheath



Raptis S, et al,. 2022b | GRL (Under Review)

Partial Moment Derivation



Methods:

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

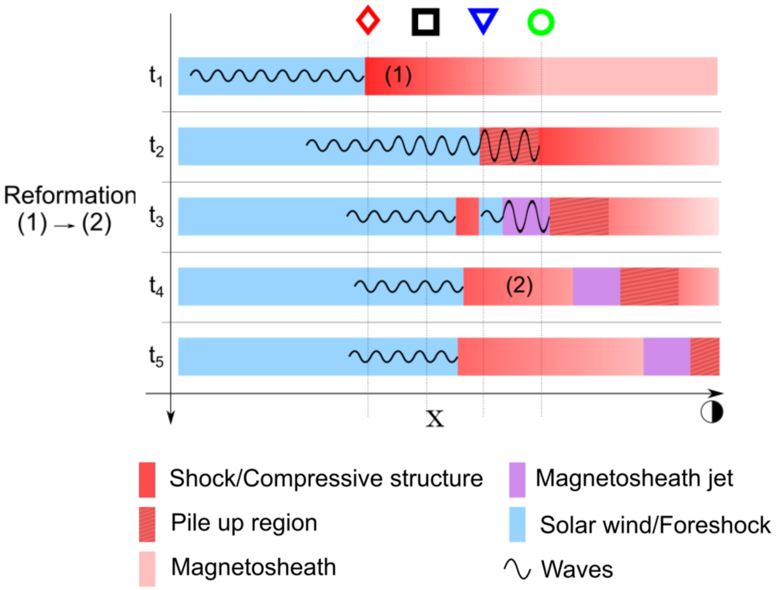
Raptis S, et al,. 2022b | GRL (Under Review)

Outlook & discussion

Discussion

Question 1

How do they form ?



Foreshock & shock reformation

Raptis S., et al. (2020) | JGR
Raptis S., et al. (2022a) | Nature Communications

Question 2

What are their typical properties & relation to shock?

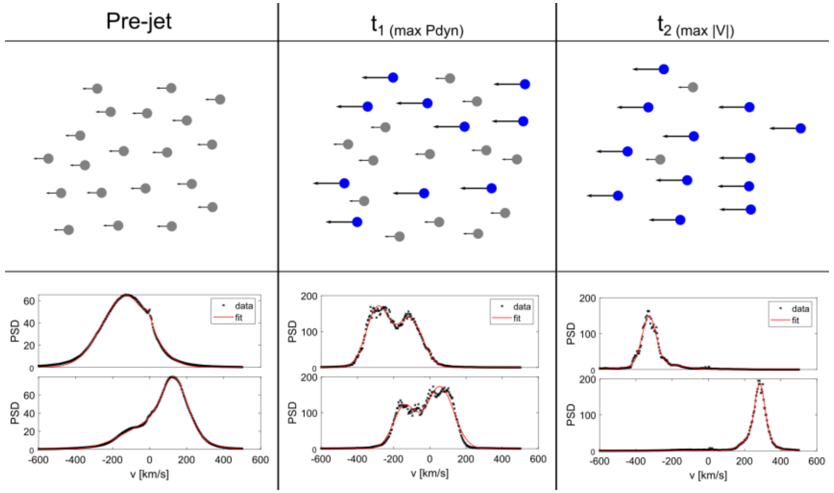
Subset	Number	Percentage (%)
Quasi-parallel	2458	26.7
Final cases	**901**	10.1
Quasi-perpendicular	542	5.9
Final cases	**214**	2.3
Boundary	781	8.5
Final cases	**191**	2.1
Encapsulated	80	0.9
Final cases	**60**	0.7
Other	5335	58.0
Unclassified/Uncertain	3789	41.2
Border	1500	16.3
Data Gap	46	0.5

Importance of classes in statistics & big picture

Raptis S., et al. (2020) | JGR
Raptis S., et al. (2020) | Frontiers
Palmroth M., **Raptis S.**, et al. (2021) | Annales
Karlsson, Raptis et al. (2021) | JGR
Kajdic P., **Raptis S.**, et al. (2021) | GRL
Raptis S., et al. (2022b) | GRL (Under review)

Question 3

How they evolve & interact with MSH plasma?



Shock relevance, complex structure & fluid picture limitations

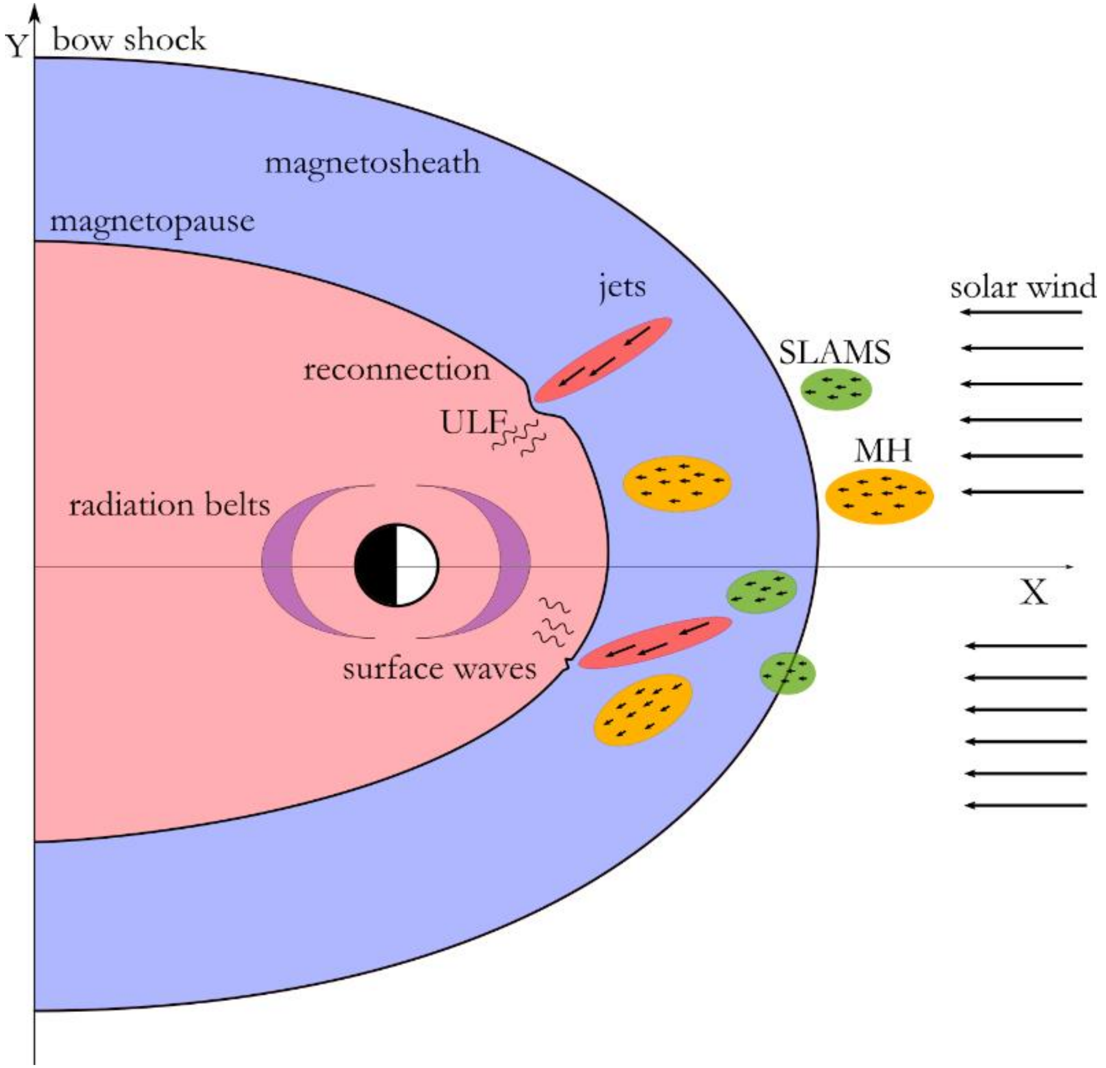
Raptis S., et al. (2022a) | Nature Communications
Raptis S., et al. (2022b) | GRL (Under review)

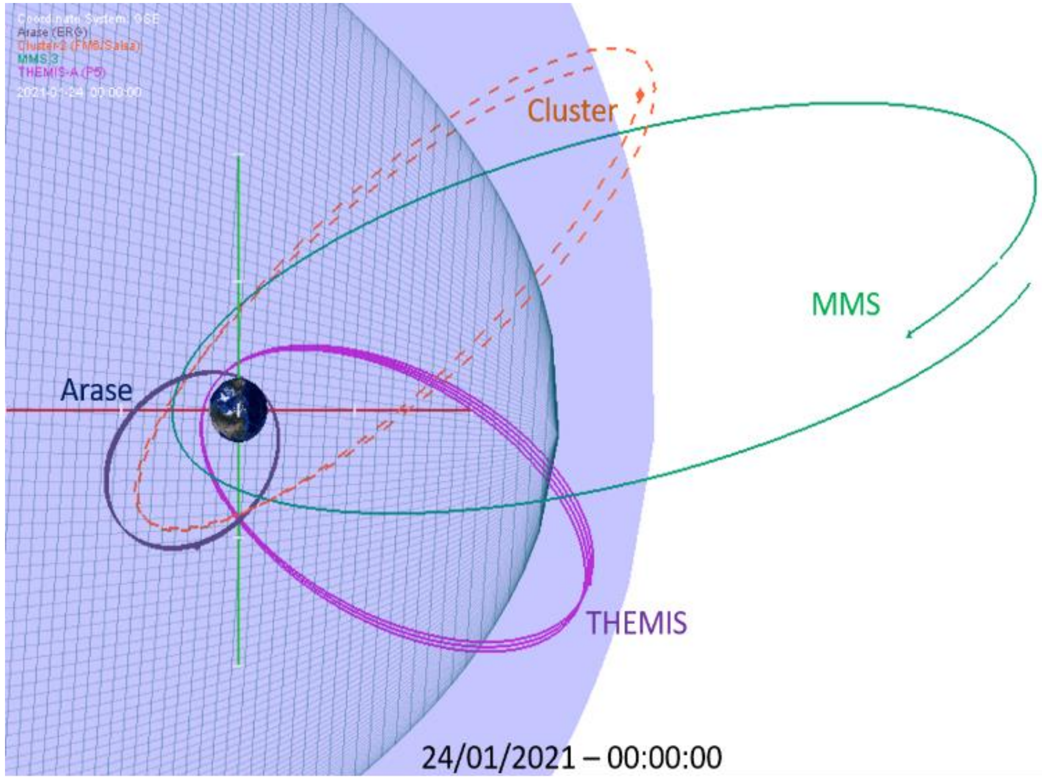
Open questions

- Are jets a global phenomenon ?
- How do VDFs change as jets approach the magnetopause?
- Which are the different waves excited by the interaction of jets with MSH?
- Do jets contribute to the turbulence of the magnetosheath ?
- Should we re-evaluate the definition based on the VDFs rather than plasma moments?
- How are the statistics affected by the time resolution and plasma moment derivation ?

And many more…

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





Without even discussing missions away from Earth's environment

Thank you, a lot, for listening ☺

Credits : Savvas Raptis

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 especially these related to electron moments
- ✗ Could be misleading close to boundary surfaces (Magnetopause, Bow shock etc.) due to very similar observational signatures

Burst MMS data

Pros

- ✓ Very high resolution
- ✓ Able to resolve smaller scale 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 – 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
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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

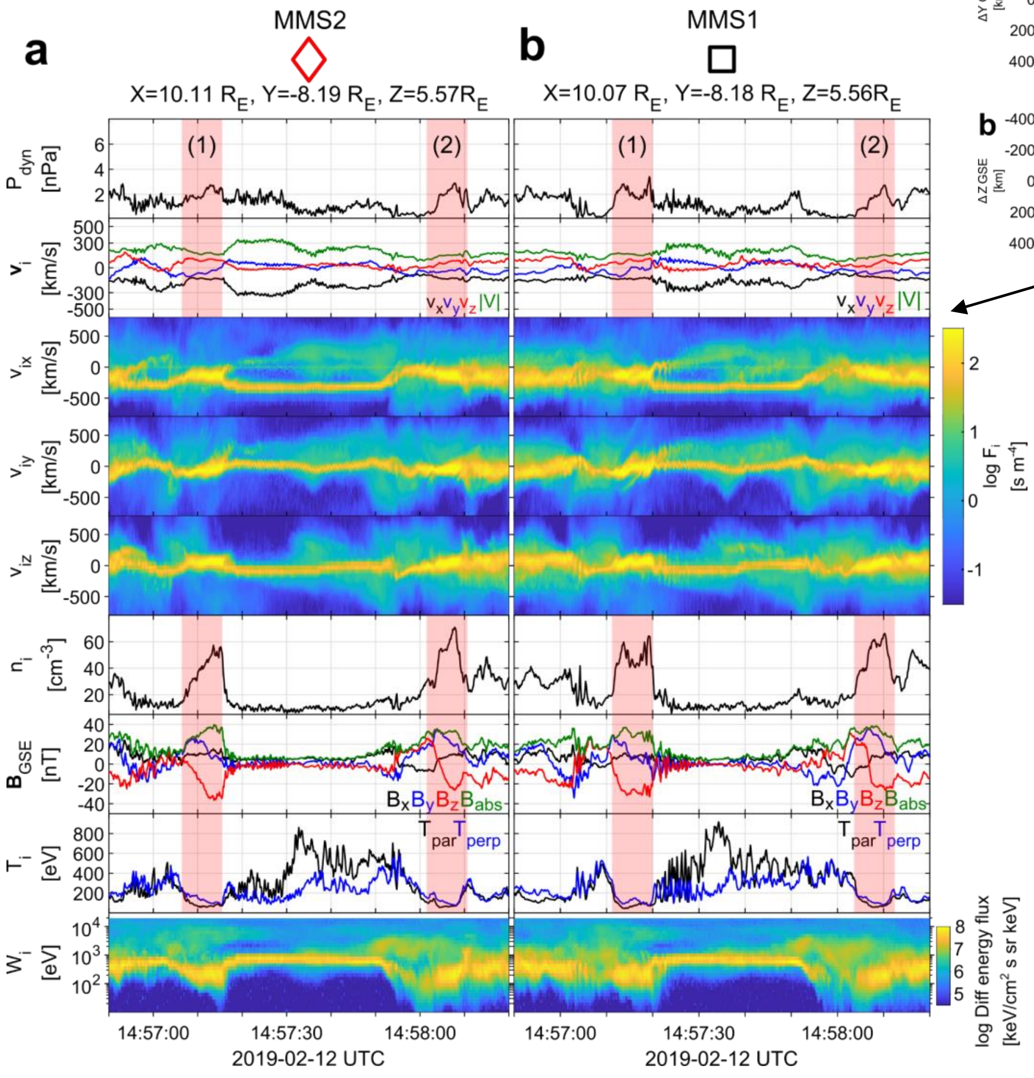
Burst

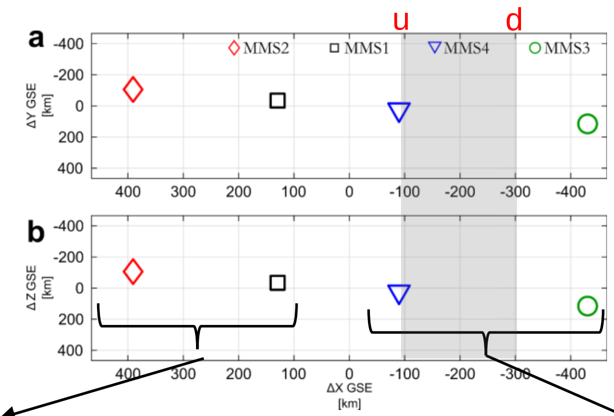
Jets with full burst data →

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. (2022a) | Nat. Commun
Raptis S., Karlsson T., et al. (2022b) | GRL

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

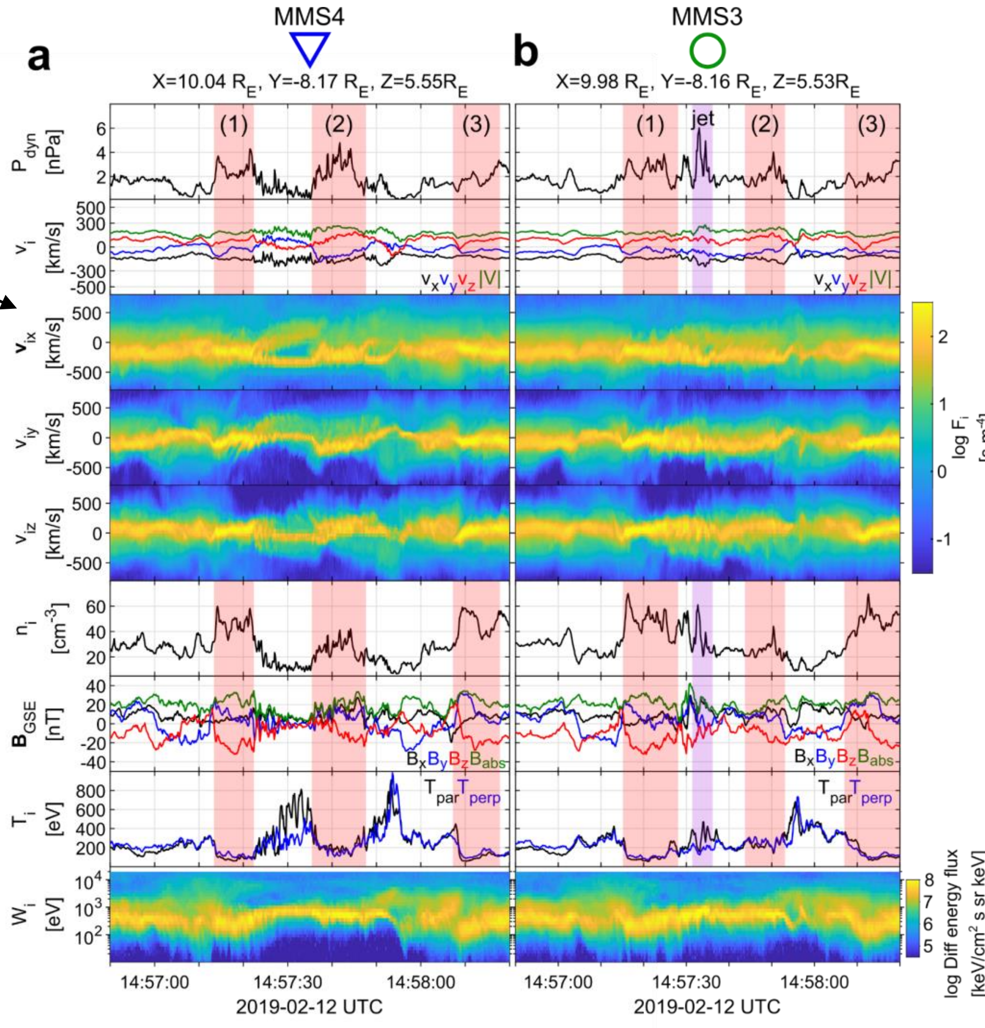
<u>Foreshock → Magnetosheath (compressed – thermalized plasma)</u>

$v \ll v_{SW}$

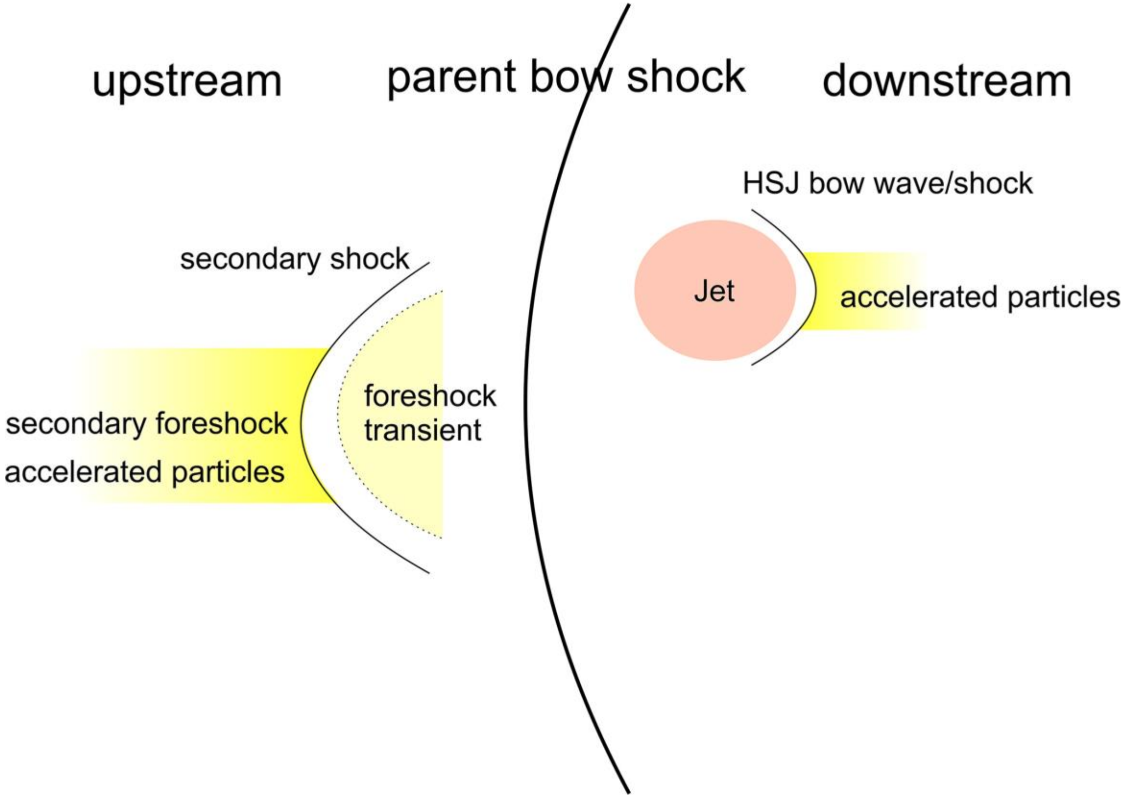
$n_i \gg n_{SW}$

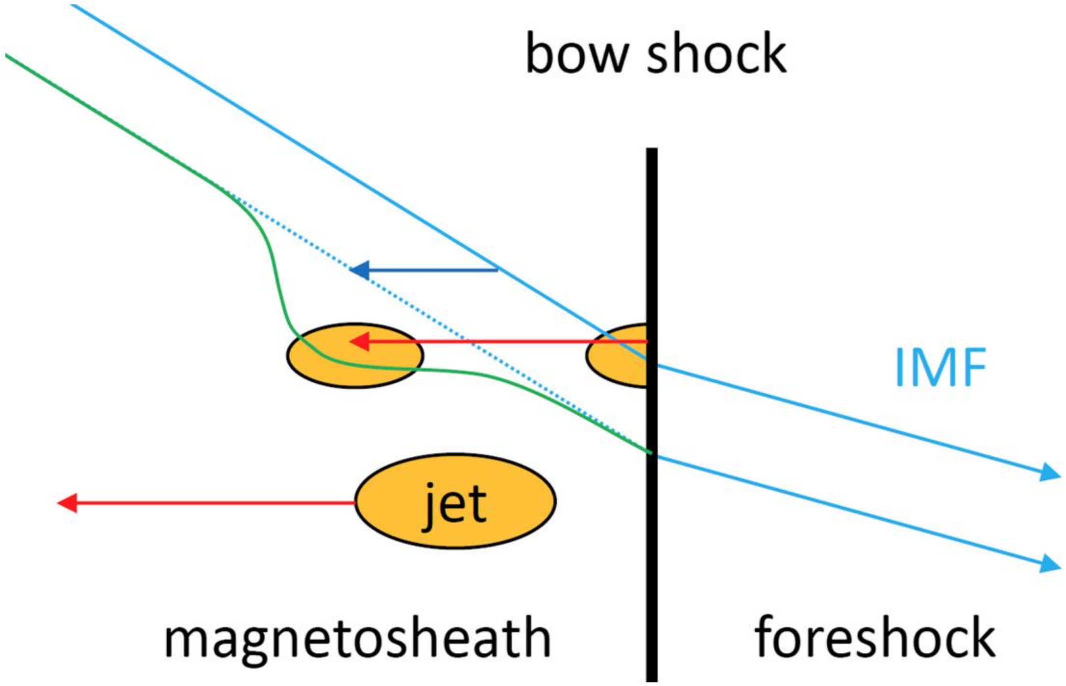
$\boldsymbol{B} \gg$

Thermalized distribution



Jets interaction with ambient plasma



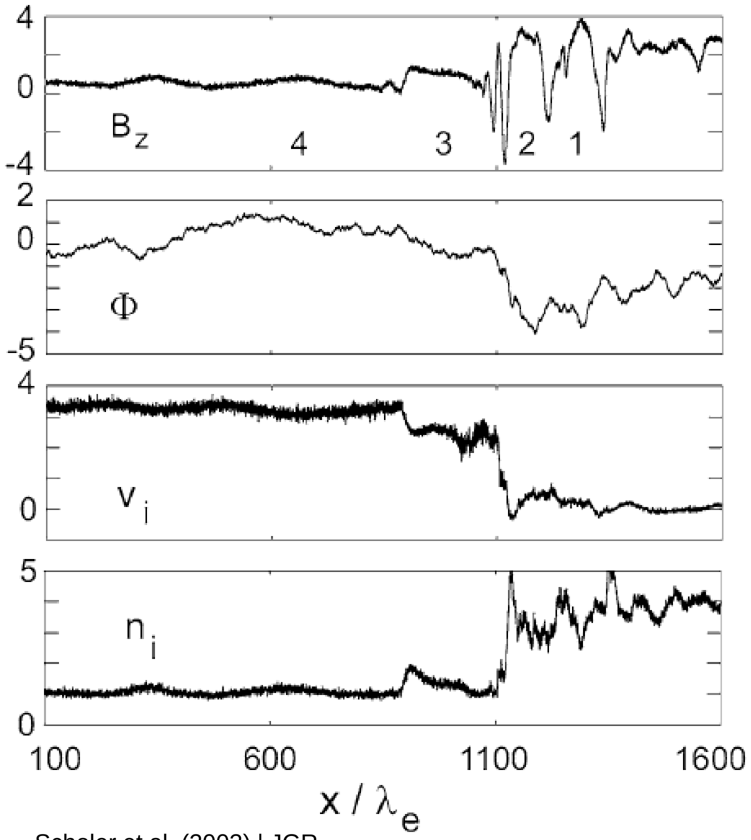


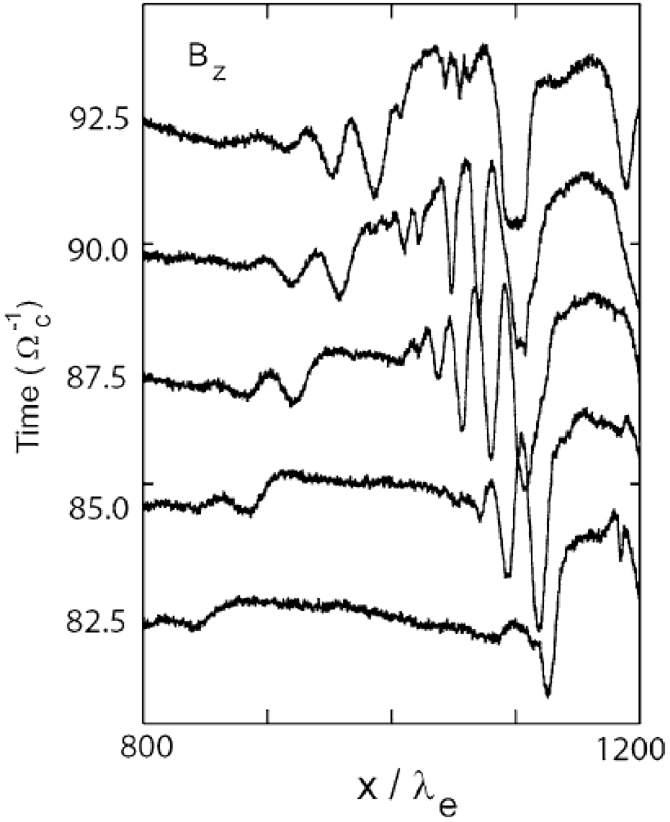
Liu et al. (2020)

Plaschke et al. (2018,2020)

Shock Reformation – Simulations

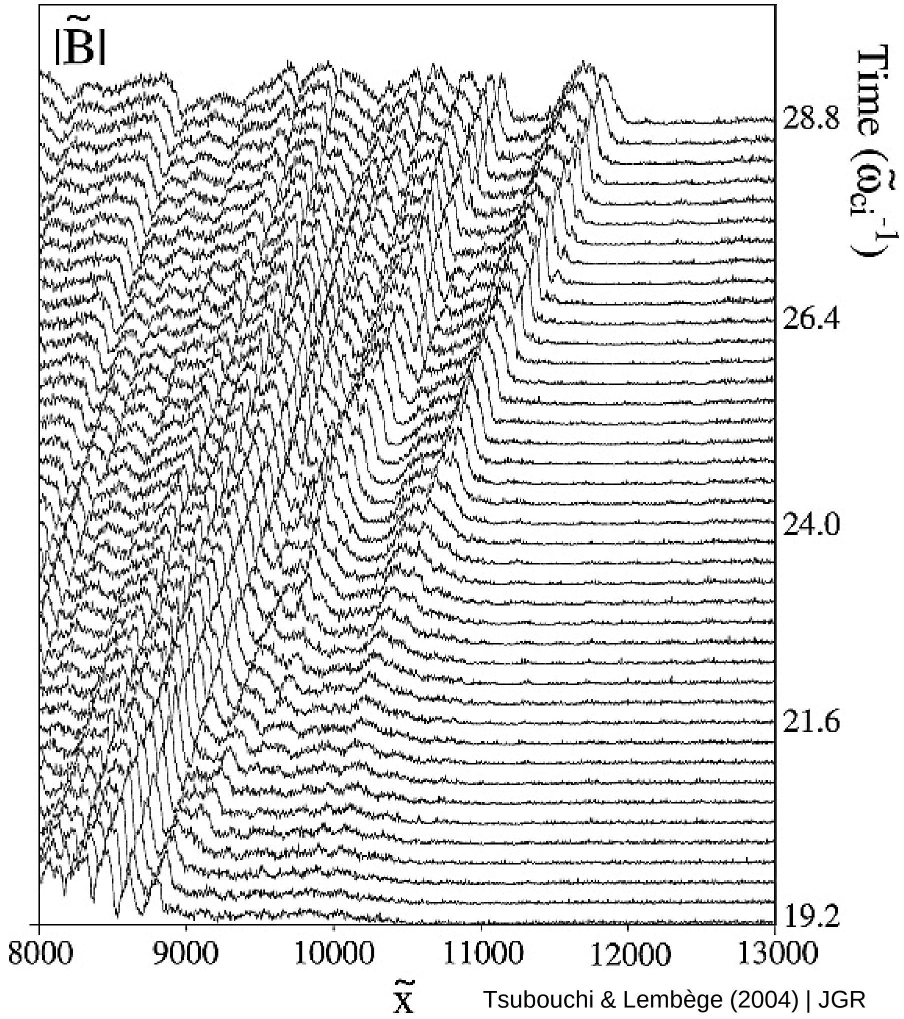
1D-PIC simulation (30°), $M_A = 4.7$
mi/me = 100 and ωpe/Ωce = $\sqrt{10}$.





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 & SLAMS – Clarification

Shock Reformation

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

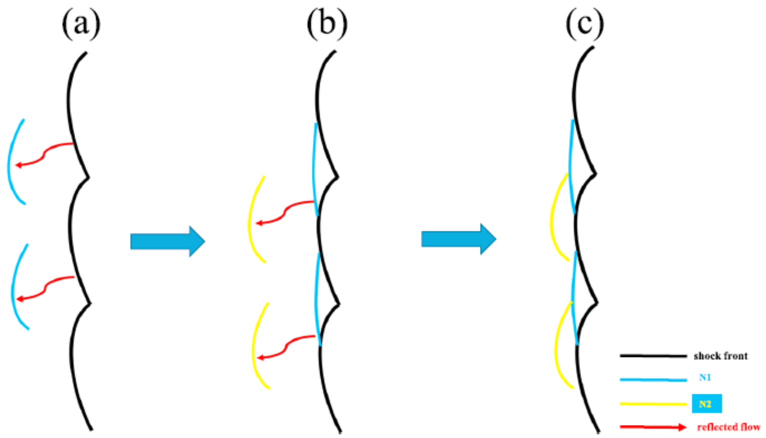
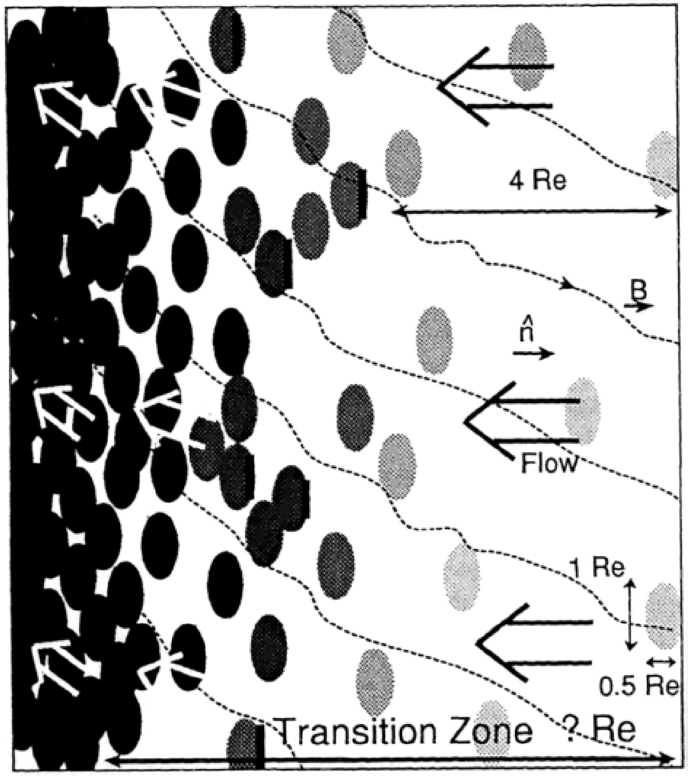


Figure 11. The sketch for evolution of shock front. (a) A rippled shock front, (b) a plane shock front, and (c) a rippled shock front. Solid lines and red arrows denote shock front and reflected beams, and N1 and N2 indicate new shock fronts.

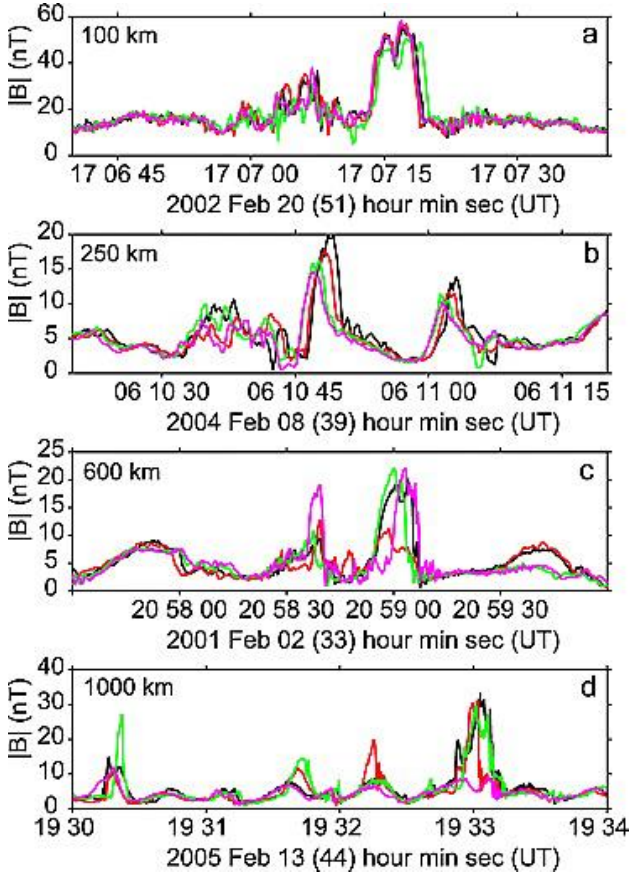
Hao et al. (2017)

ULF non-linear evolution = SLAMS

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



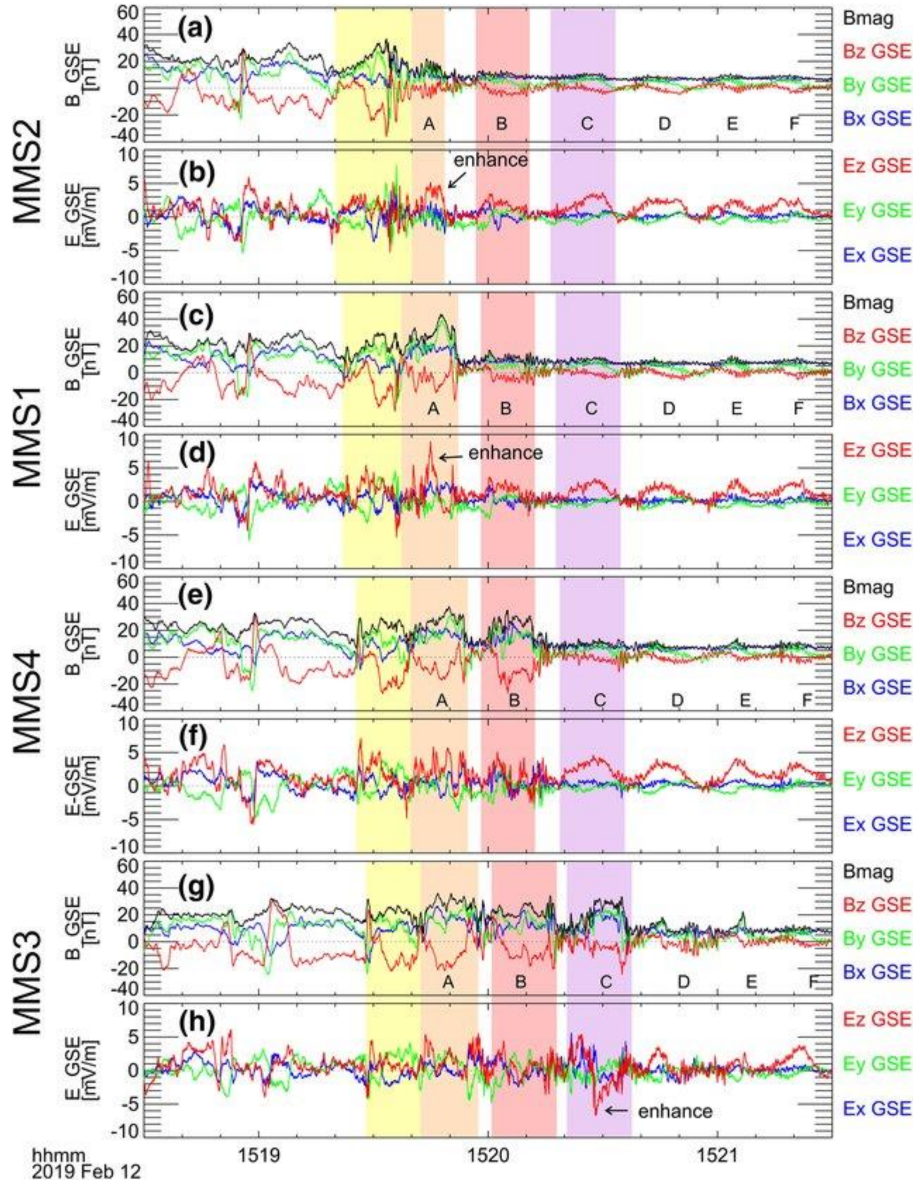
Schwartz, (1991)



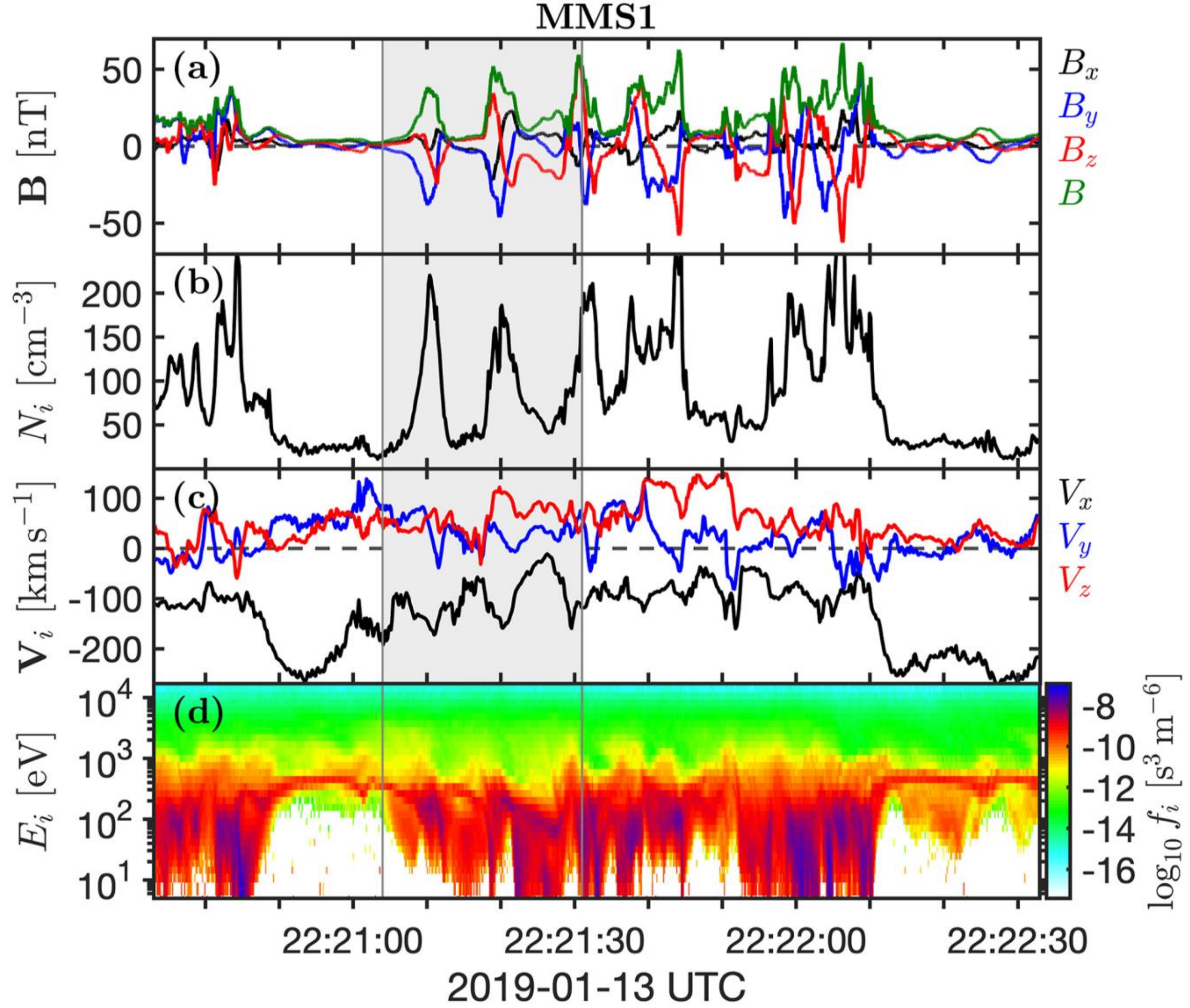
Lucek, (2008)

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

Shock Reformation – Latest Results

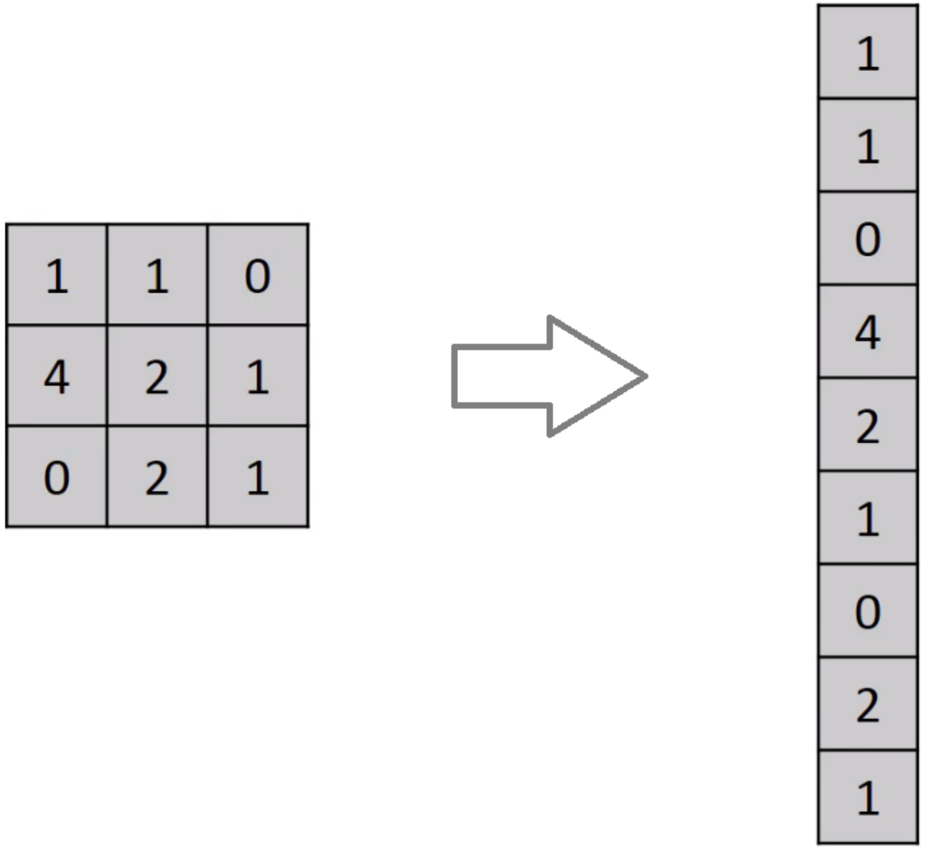


Liu et al. (2021)

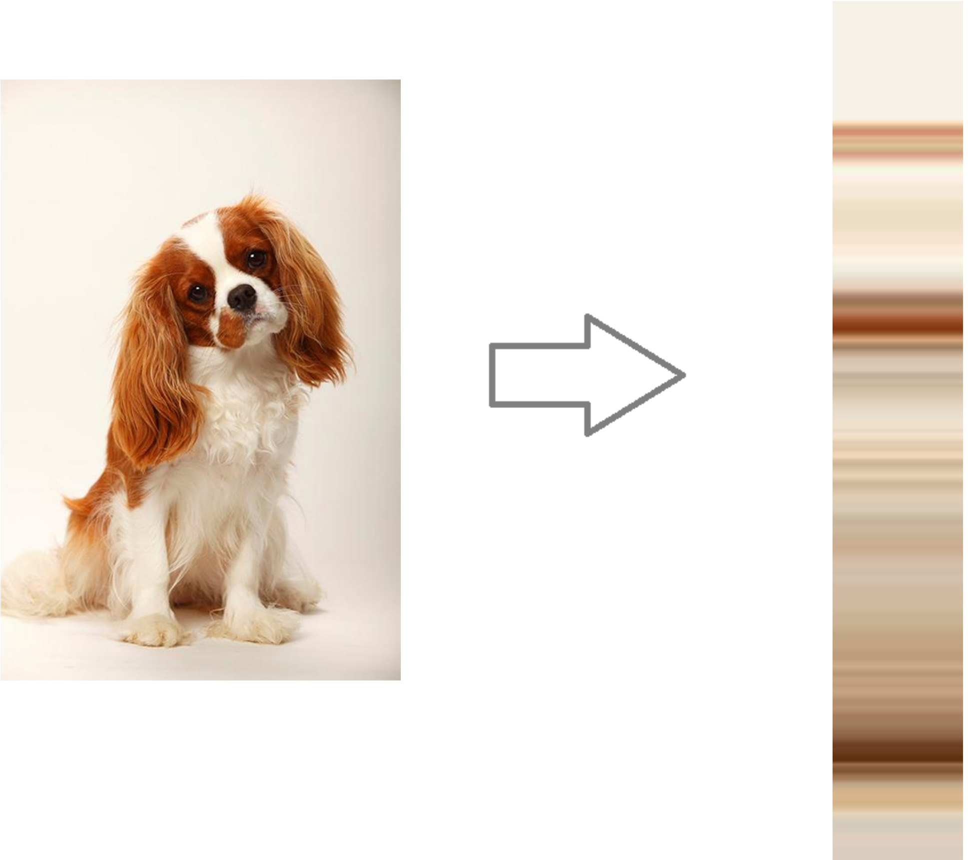


Johlander et al. (2022)

Neural Networks with Images



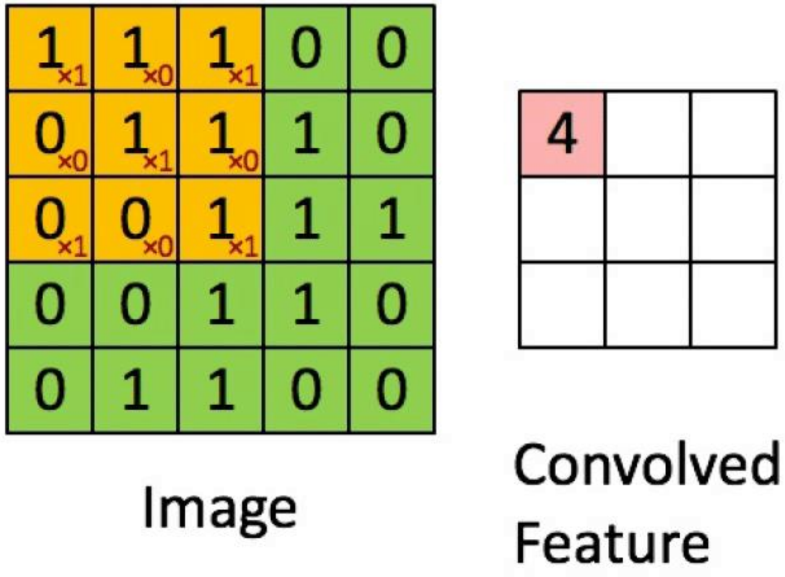
Neural Networks with Images – Dog example



Convolution Neural Networks

Convolution Neural Network (CNN) Layers

Convolution
Extract features & Keep spatial relationship



Pooling/Subsampling
Reduce dimensionality & retain information

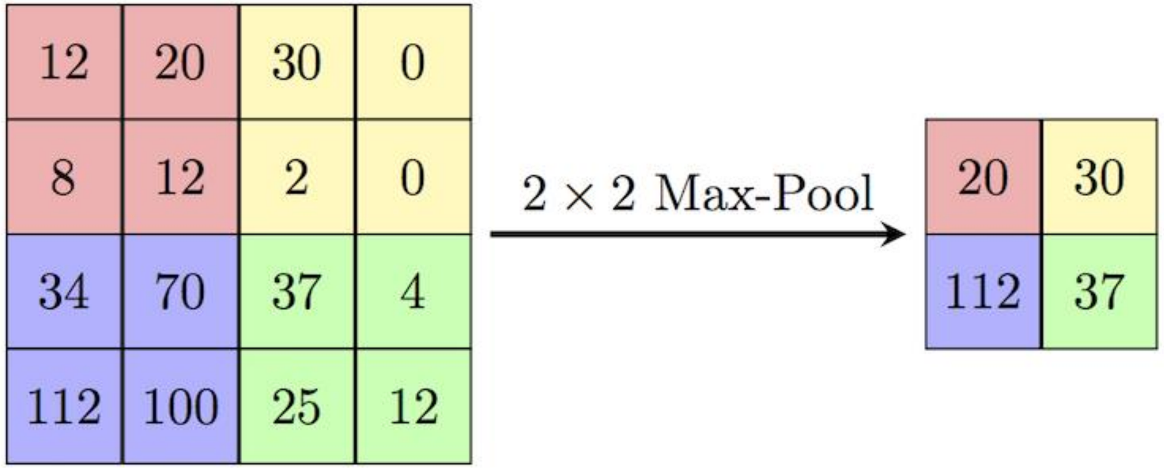


*Figure Courtesy: Erik Reppel

*Figure Courtesy: Cambridge Spark Ltd

Example of CNN

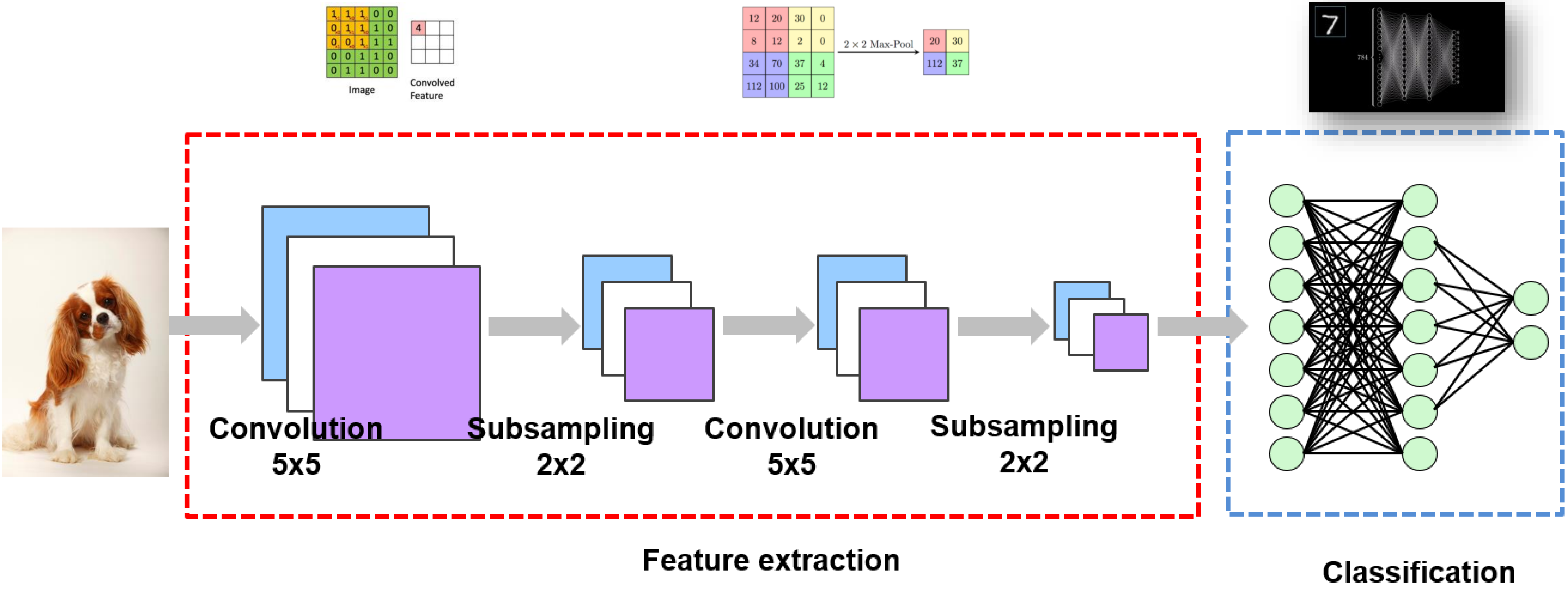


*Figure Courtesy: Suhyun Kim iSystems Design Labs