Characterization of the Earth's Magnetosheath and its Fast Plasma Flows Using Upstream Measurements and Machine Learning

Savvas Raptis[1], Tomas Karlsson[1], Sigiava Aminalragia-Giamini[2], P-A. Lindqvist[1], Martin Lindberg[1] , Henriette Trollvik[1]

[1]Division of Space and Plasma Physics, KTH Royal Institute of Technology, Sweden
[2]Space Applications & Research Consultancy (SPARC), Greece

Asia Oceania Geosciences Society 2021 Meeting
03 August 2021

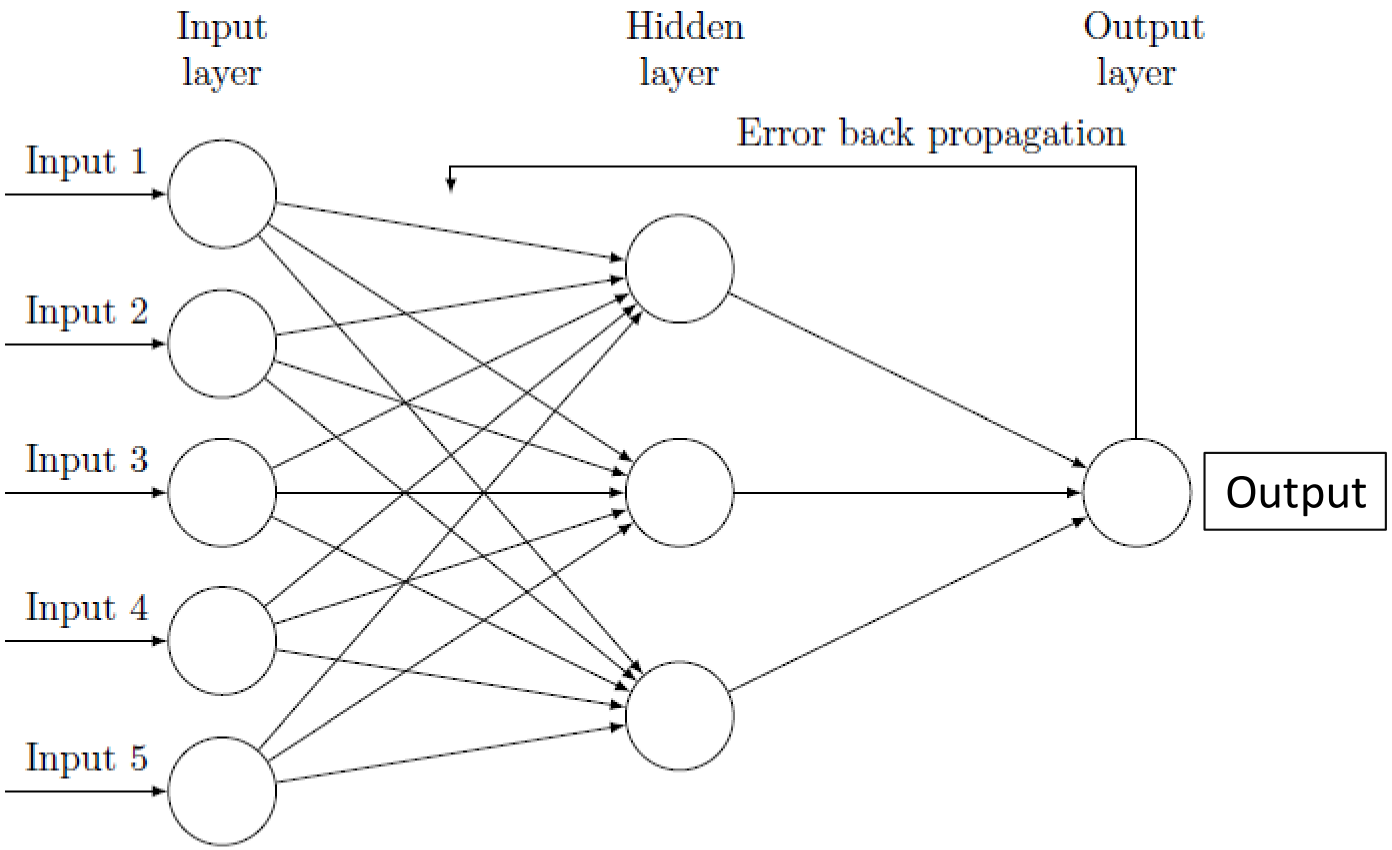
Introduction

(Neural Networks)

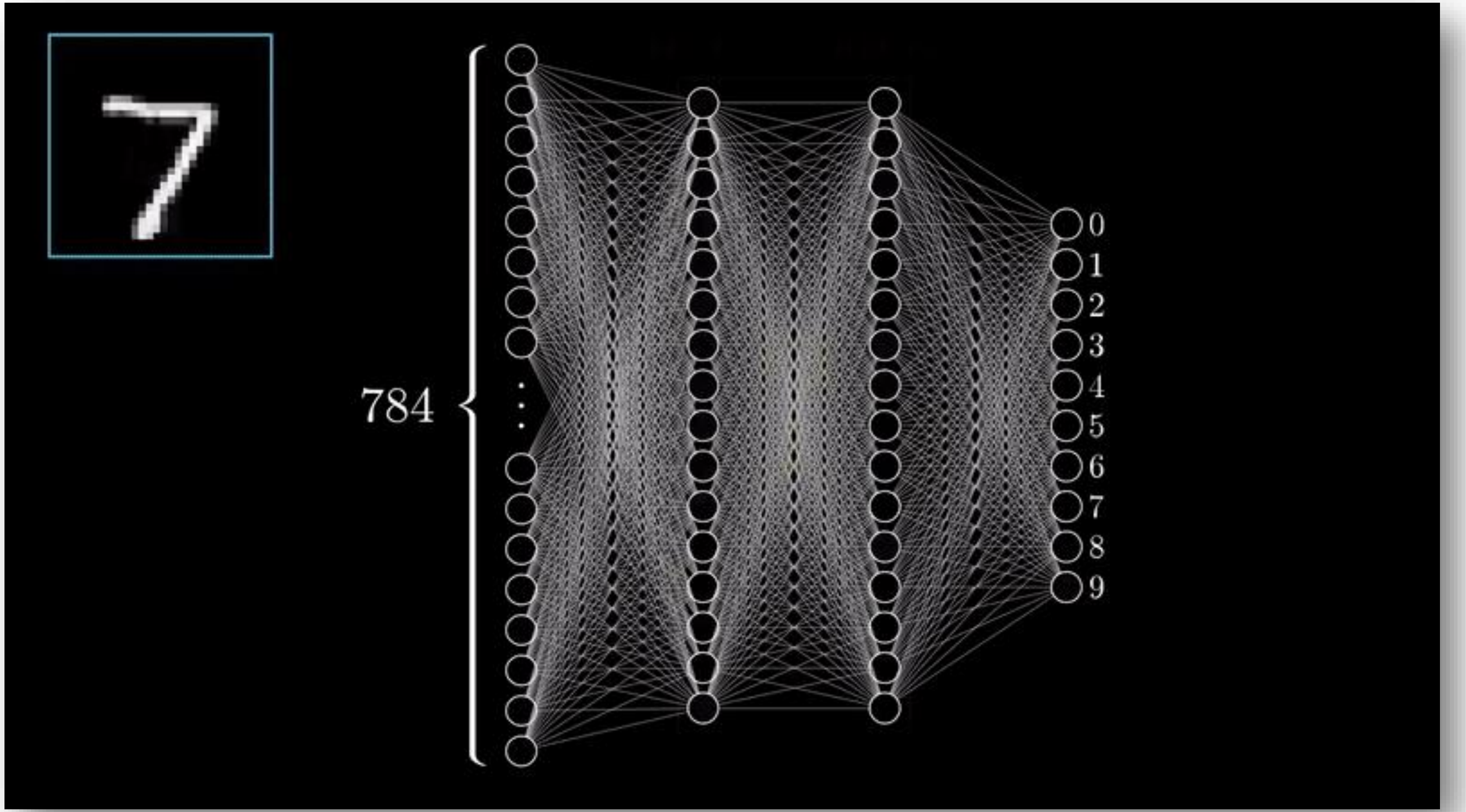
Neural Networks & Backpropagation

<u>Supervised Learning</u>

- Labeled Data
- Known input output
- Unknown map/relationship



A Trained Neural Network

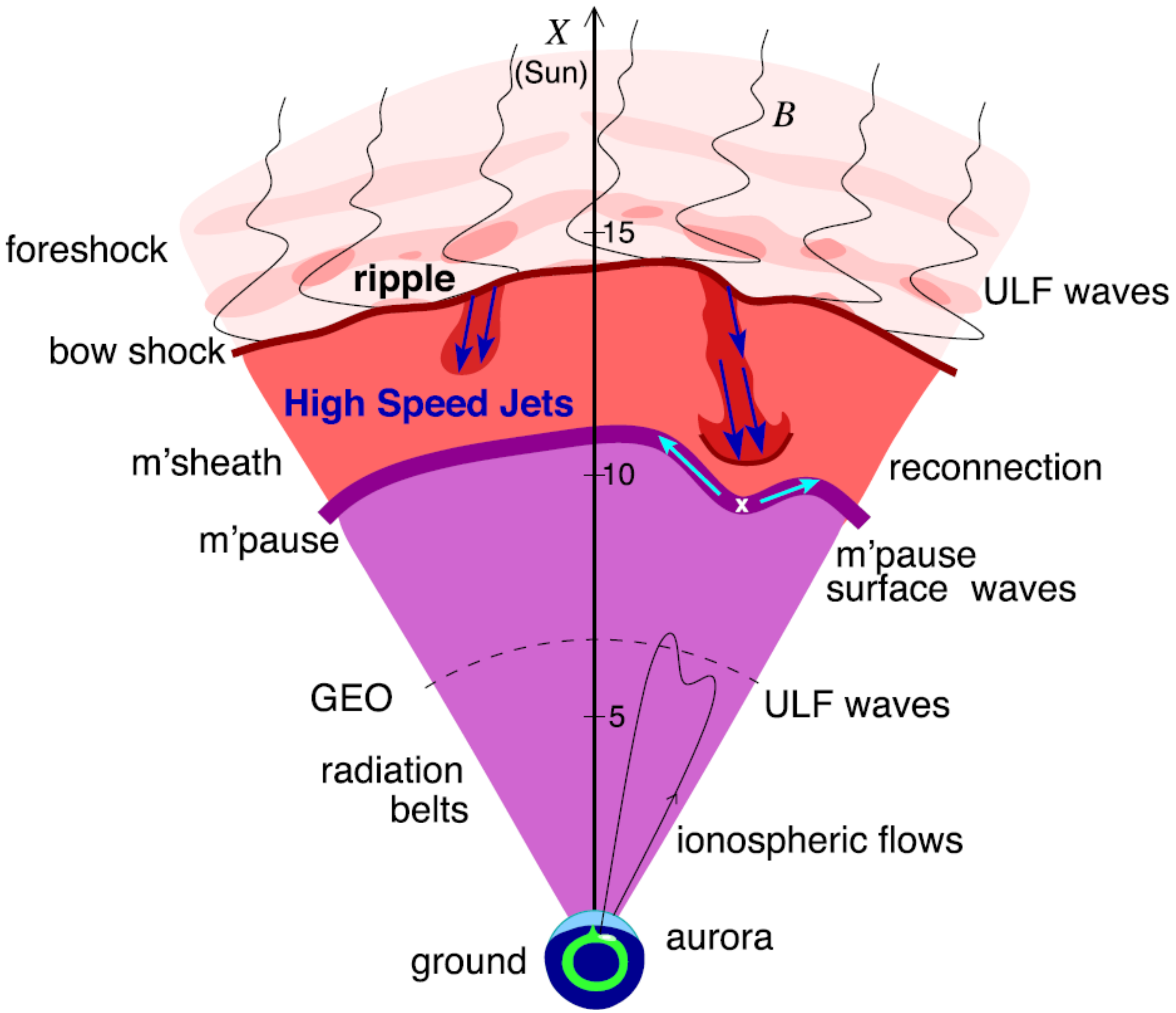


*Video Courtesy**: 3Blue1Brown** (Check his YouTube page for more)

Introduction

(Bow Shock, Magnetosheath and Jets)

Magnetosheath Jets



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

<u>Definition</u>

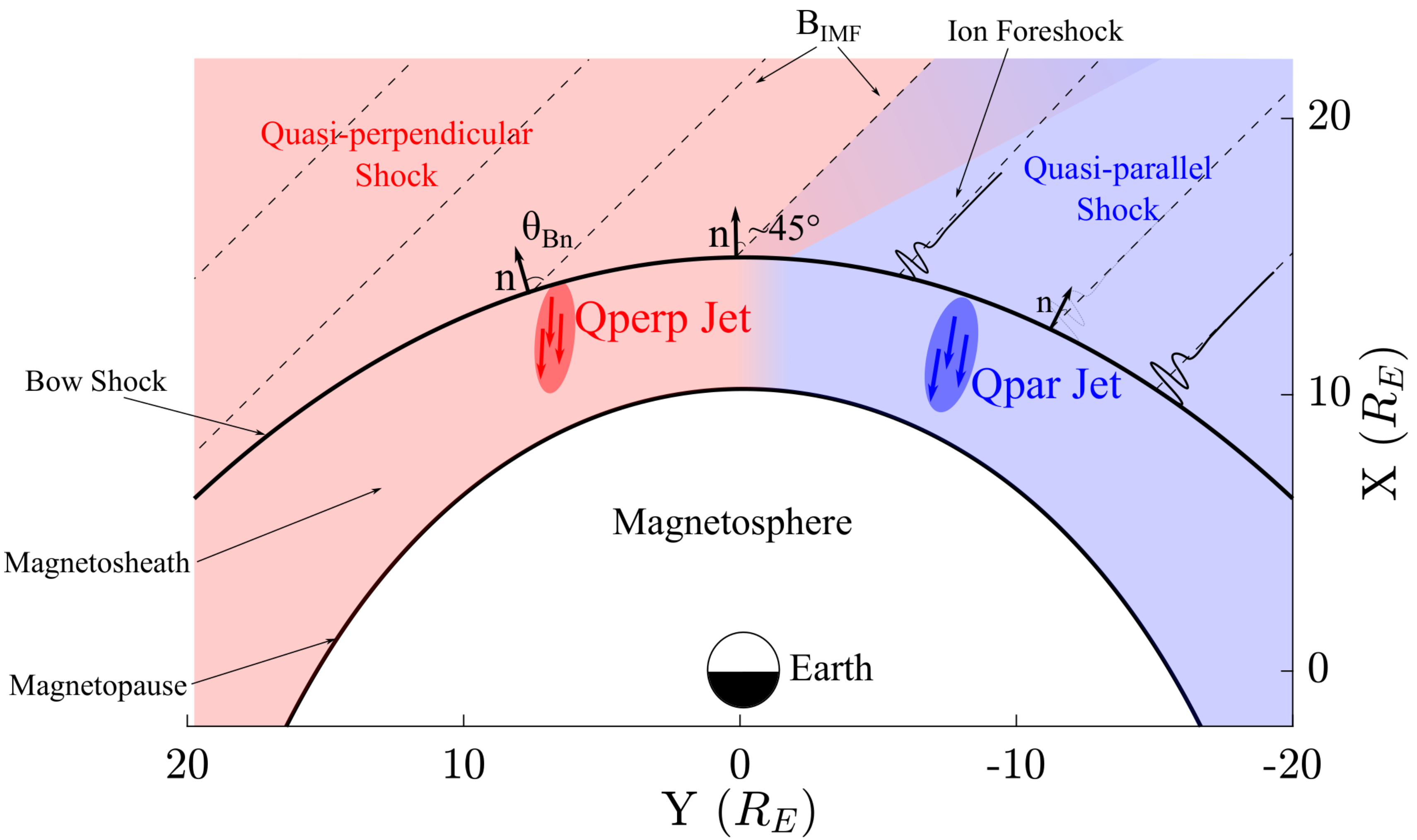
Magnetosheath jets are transient localized enhancements of dynamic pressure (density and/or velocity increase)

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

<u>Related phenomena</u>

Radiation belts
Aurora
Magnetopause reconnection
Magnetopause penetration
Shock acceleration
Magnetopause surface eigenmodes
ULF wave excitation

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 are found ~9 times more often behind the Qpar bow shock”

Vuorinen, et al. (2019)

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

Results

Review of current work

- (1) Statistical properties of jets (Raptis et al. (2020 | JGR)

"Showed us which quantities can be used for in-situ classification using MMS"

- (2) Classification of jets using Neural networks (Raptis et al. (2020) | Front. Astron. Space Sci)

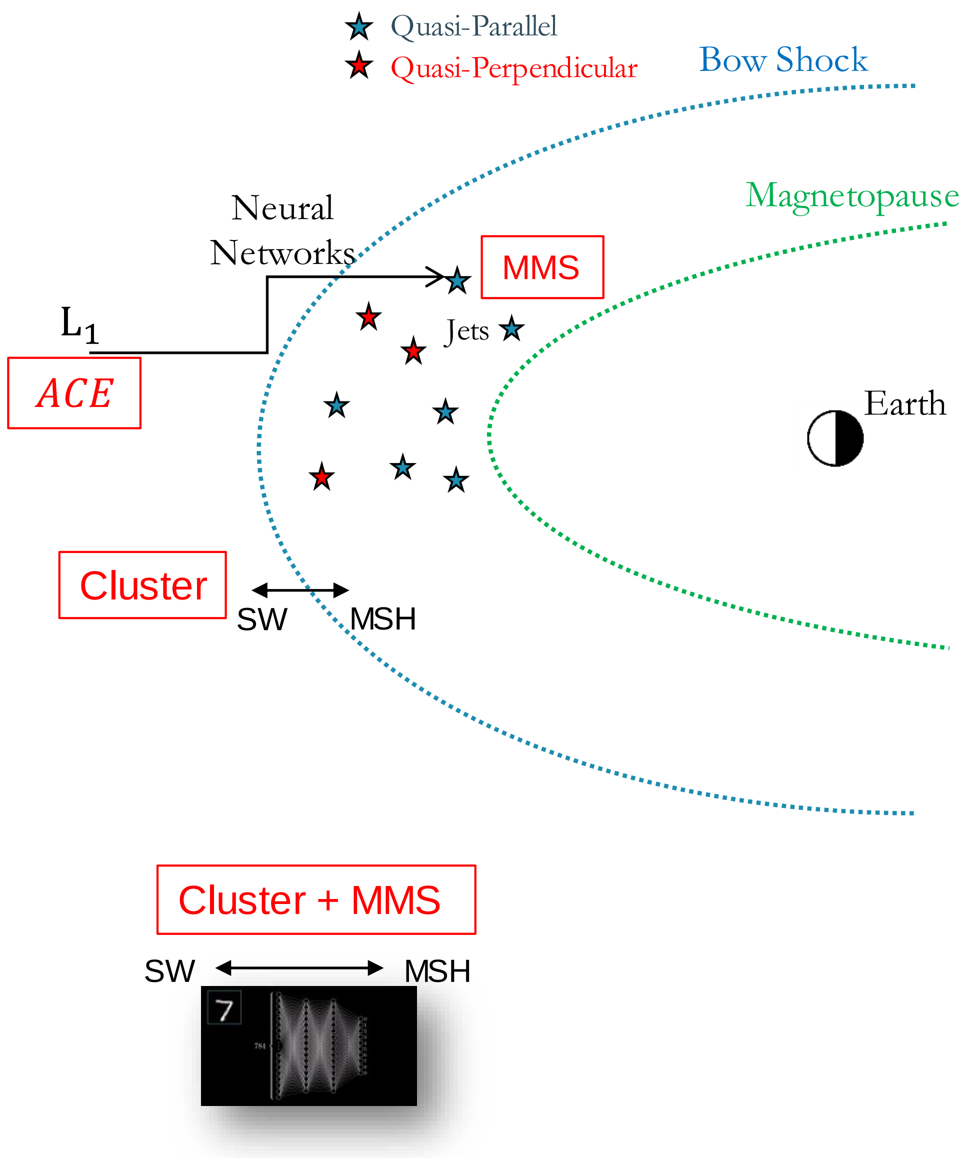
"Showed us that there is information in the Solar Wind that correspond to Qpar and Qperp jets and possibly to magnetosheath"

- (3) Classification of the magnetosheath (Karlsson et al. (2021) | JGR – Under review)

"Showed us that we can have strong statistical relationship between upstream and downstream measurements. Supporting the findings of (1) and (2)"

- (4) Mapping magnetosheath & shock transitions using neural networks (Raptis et al. (2021) | Ongoing)

"Will proceed to map the relation between the different plasma population upstream and downstream by using machine learning techniques similarly to (2) and the datasets of (1-3)"



Review of current work

- (1) Statistical properties of jets (Raptis et al. (2020 | JGR)

“Showed us which quantities can be used for in-situ classification using MMS”

- (2) Classification of jets using Neural networks (Raptis et al. (2020) | Front. Astron. Space Sci)

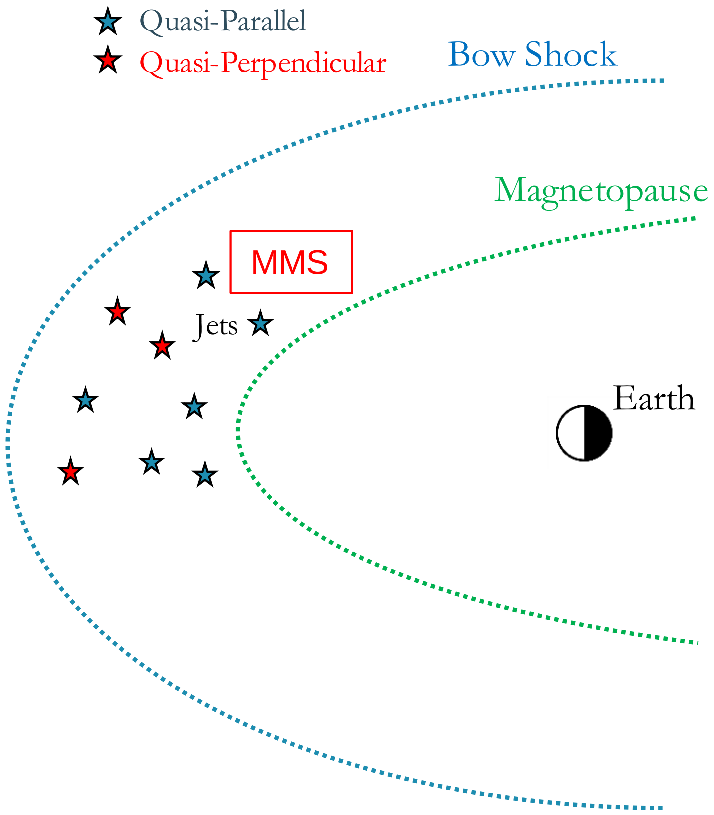
“Showed us that there is information in the Solar Wind that correspond to Qpar and Qperp jets and possibly to magnetosheath”

- (3) Classification of the magnetosheath (Karlsson et al. (2021) | JGR – Under review)

“Showed us that we can have strong statistical relationship between upstream and downstream measurements. Supporting the findings of (1) and (2)”

- (4) Mapping magnetosheath & shock transitions using neural networks (Raptis et al. (2021) | To be submitted)

“Will proceed to map the relation between the different plasma population upstream and downstream by using machine learning techniques similarly to (2) and the datasets of (1-3)”



Main Categories of magnetosheath & jets

Dynamic Pressure

Dynamic Pressure Ratio

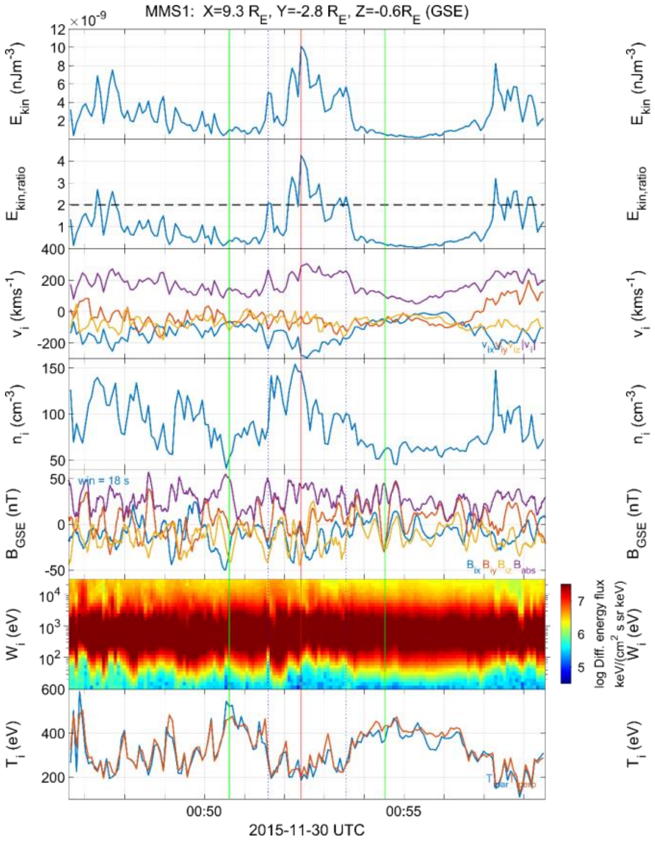
Velocity

Number Density

Magnetic Field

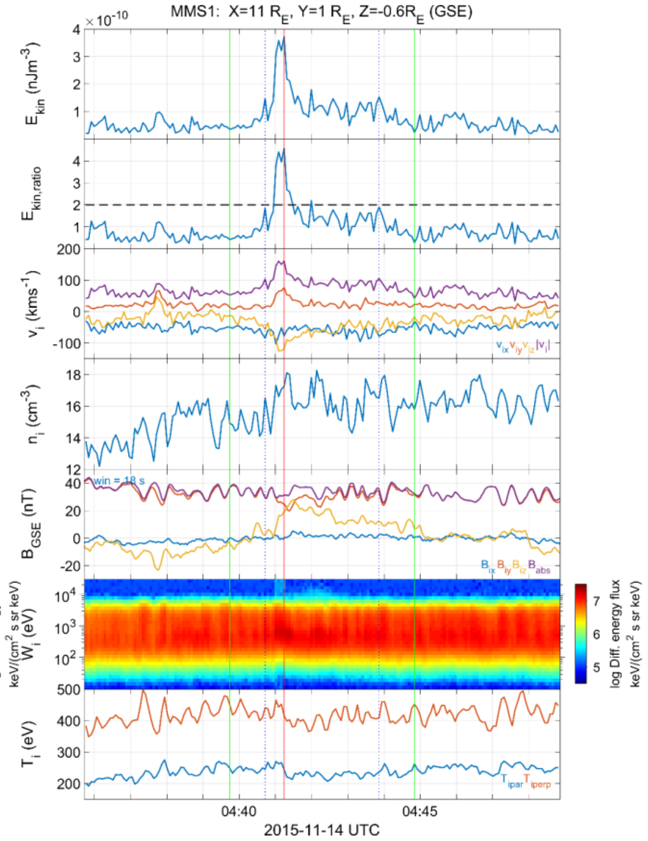
Ion Energy Spectrum

Ion Temperature



Qpar Jet

Jets found in $Q_{\parallel}$ MSH

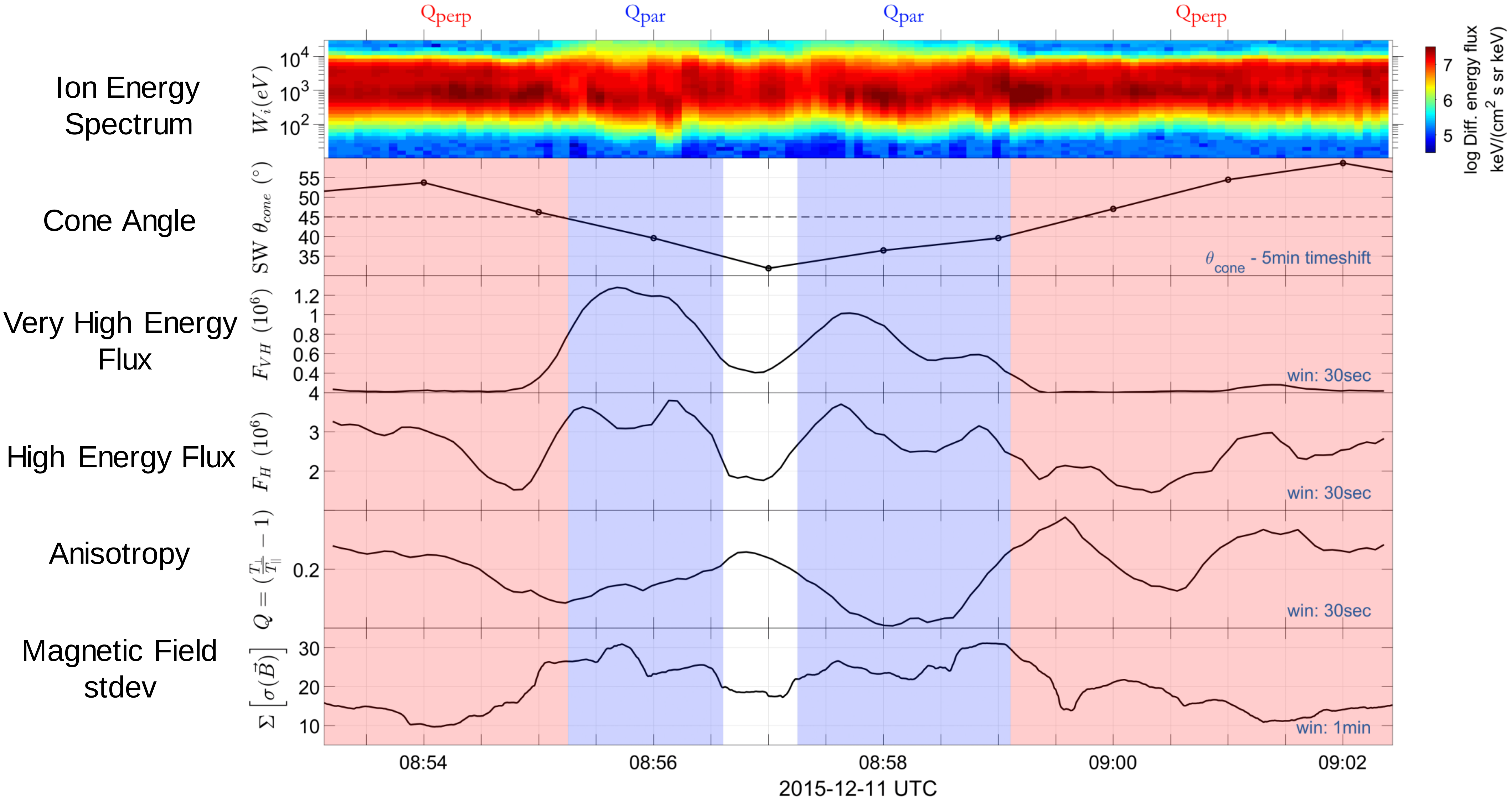


Qperp Jet

Jets found in $Q_{\parallel}$ MSH

Raptis, Karlsson et al (2020) | JGR

Classification Procedure in progress



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

Classifying Magnetosheath Jets Using Neural networks

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

Review of current work

- (1) Statistical properties of jets (Raptis et al. (2020 | JGR)

"Showed us which quantities can be used for in-situ classification using MMS"

- (2) Classification of jets using Neural networks (Raptis et al. (2020) | Front. Astron. Space Sci)

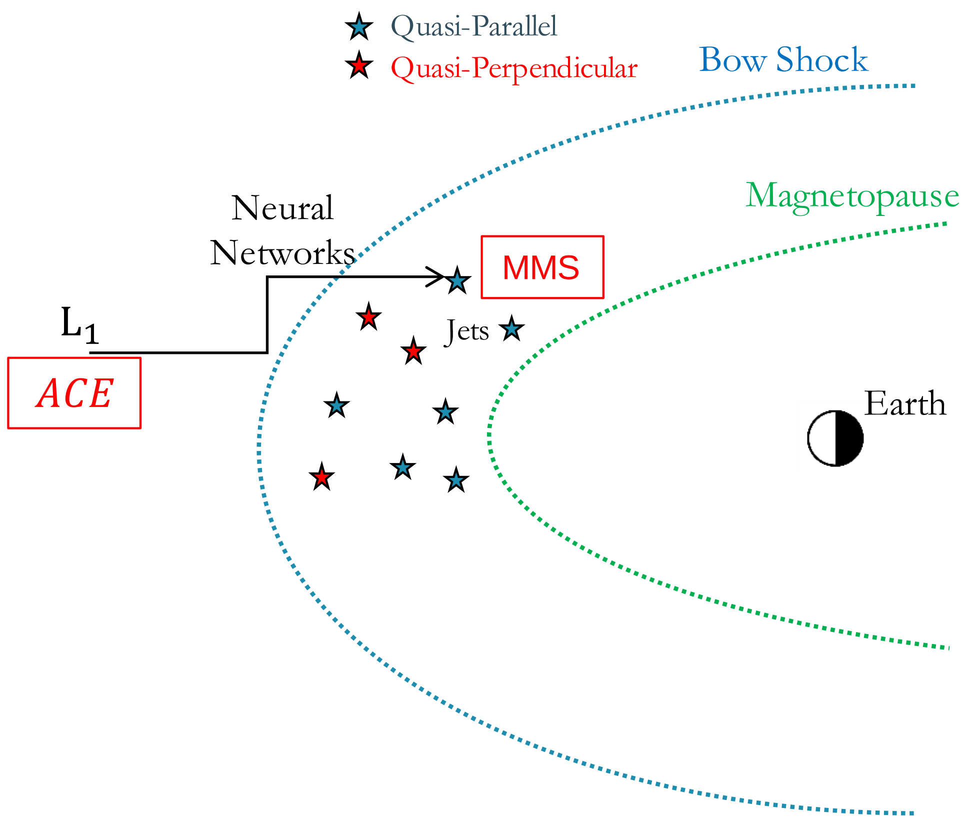
"Showed us that there is information in the Solar Wind that correspond to Qpar and Qperp jets and possibly to magnetosheath"

- (3) Classification of the magnetosheath (Karlsson et al. (2021) | JGR – Under review)

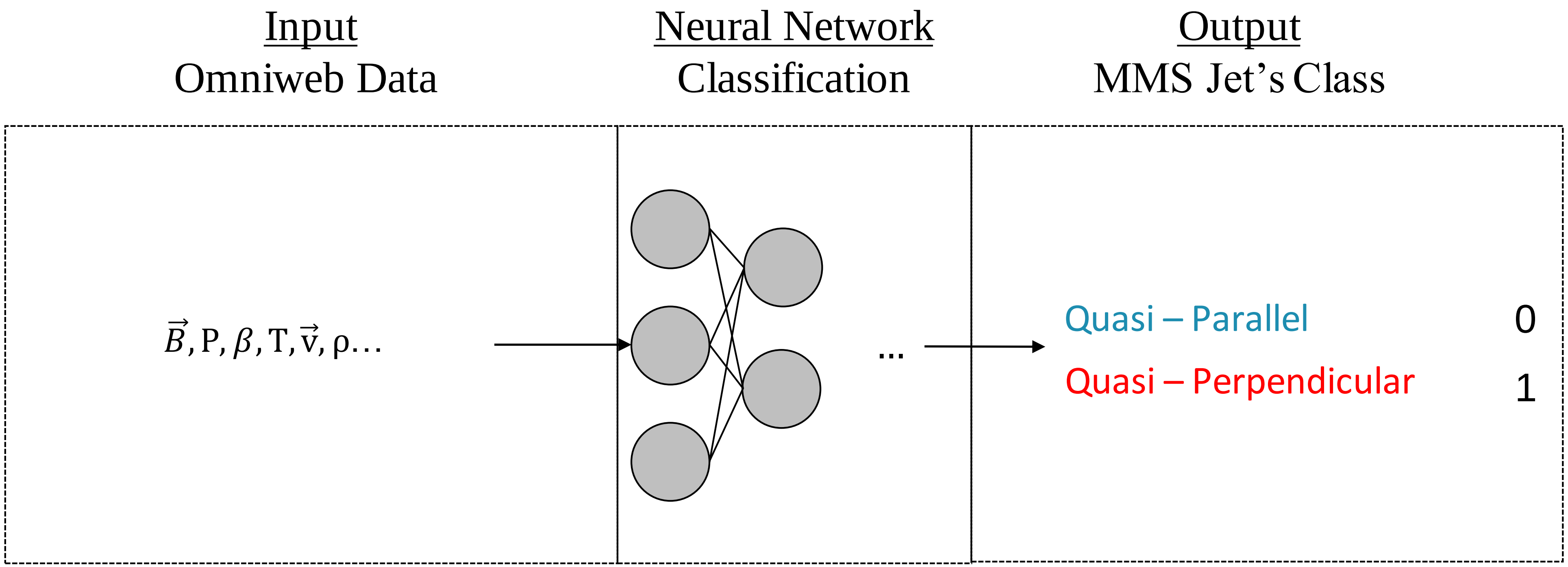
"Showed us that we can have strong statistical relationship between upstream and downstream measurements. Supporting the findings of (1) and (2)"

- (4) Mapping magnetosheath & shock transitions using neural networks (Raptis et al. (2021) | To be submitted)

"Will proceed to map the relation between the different plasma population upstream and downstream by using machine learning techniques similarly to (2) and the datasets of (1-3)"



Schematic of Procedure



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

Neural Networks vs Physical Models

Table 4. Accuracy of each method used per class. The neural network accuracy is taken as the average performance of the 100 random iterations as shown in Figures 5 and 6.

Class	NN - avg (%)	NN - leave-1-out (%)	θ_{cone} (%)	Coplanarity (%)	Bow Shock Model(%)
Qpar	98	97	61	81	74
Qperp	88	88	94	79	86
Mean	93	93	77.5	80	80

Neural Networks — Physical Modeling Approach

Neural networks outperformed "all" the physical methods quite drastically

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

Classification of the Magnetosheath
(Under Review)

Karlsson, **Raptis** et al (2021) | JGR (Under review)

Review of current work

- (1) Statistical properties of jets (Raptis et al. (2020 | JGR)

"Showed us which quantities can be used for in-situ classification using MMS"

- (2) Classification of jets using Neural networks (Raptis et al. (2020) | Front. Astron. Space Sci)

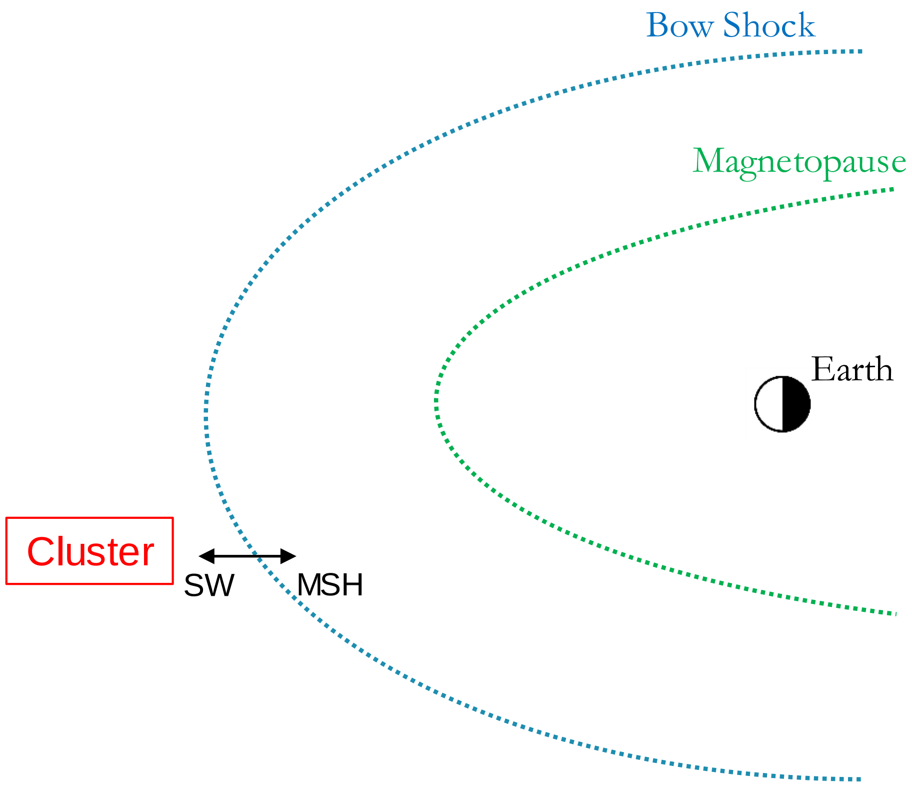
"Showed us that there is information in the Solar Wind that correspond to Qpar and Qperp jets and possibly to magnetosheath"

- (3) Classification of the magnetosheath (Karlsson et al. (2021) | JGR – Under review)

"Showed us that we can have strong statistical relationship between upstream and downstream measurements. Supporting the findings of (1) and (2)"

- (4) Mapping magnetosheath & shock transitions using neural networks (Raptis et al. (2021) | To be submitted)

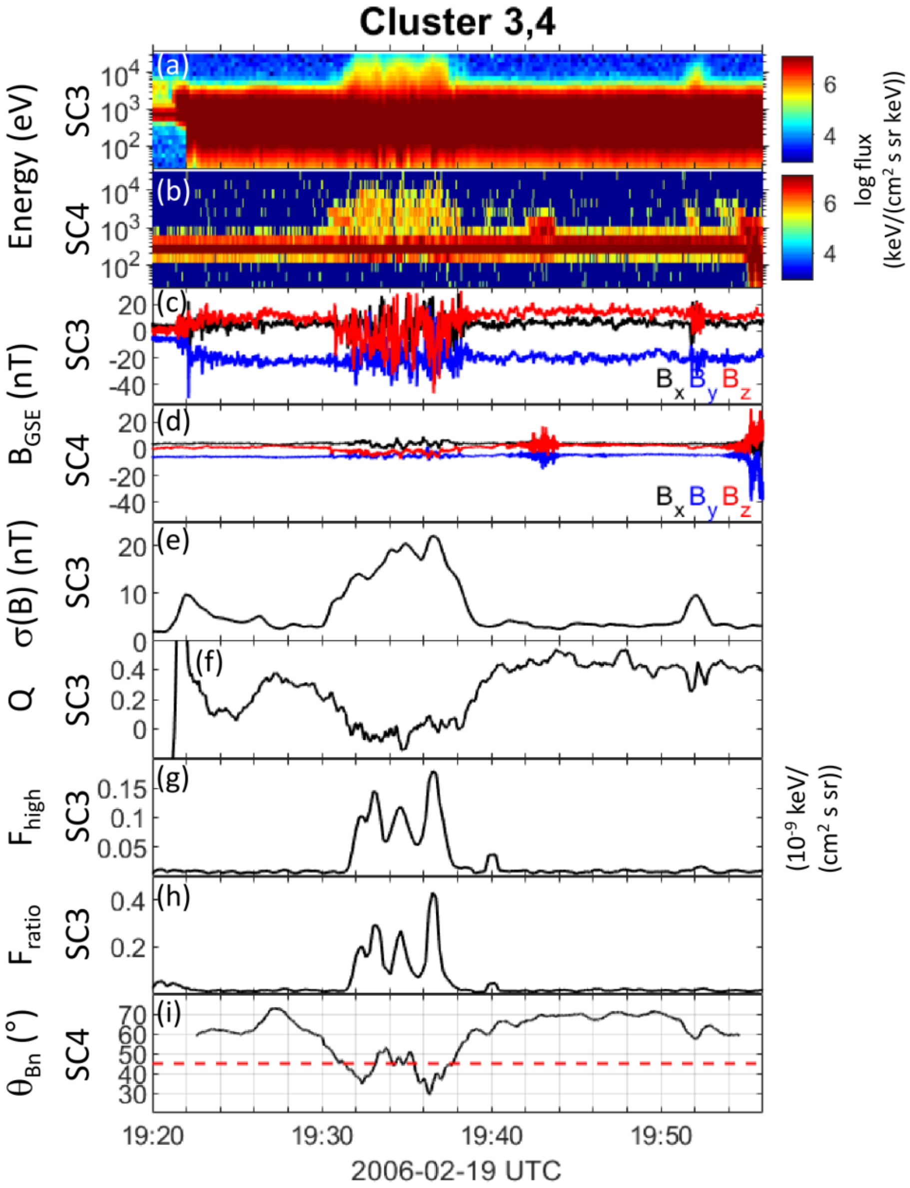
"Will proceed to map the relation between the different plasma population upstream and downstream by using machine learning techniques similarly to (2) and the datasets of (1-3)"

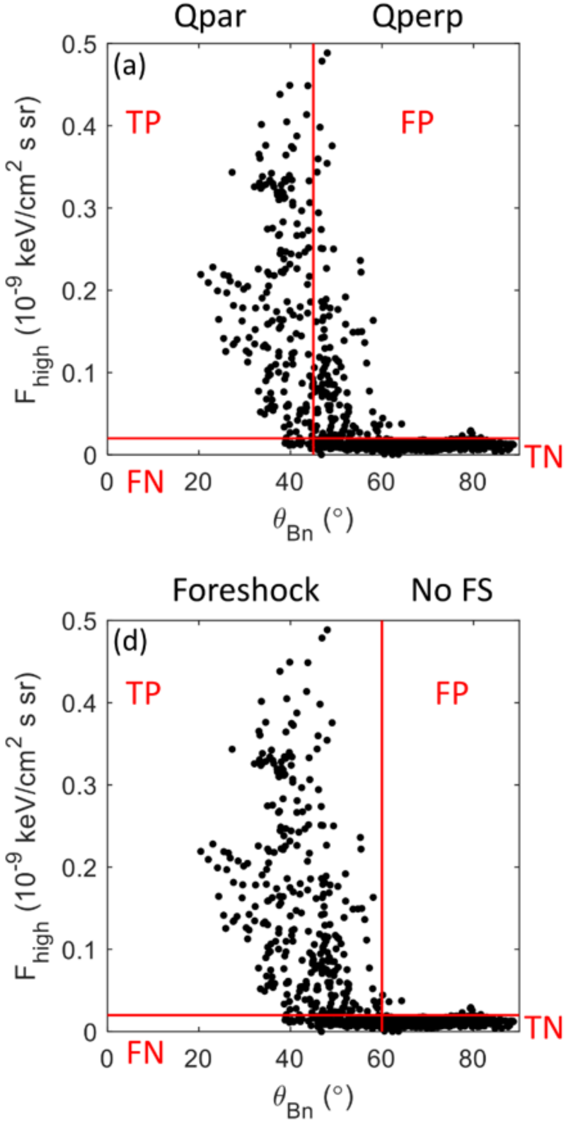


Magnetosheath vs Solar Wind/Foreshock

Downstream satellite

Upstream satellite





Classification results using

F_H

Similar results were found with:

$\sigma(\mathbf{B})$

And

Q

Karlsson, **Raptis** et al (2021) | JGR (Under review)

Characterization of the Magnetosheath Using Neural Networks (ongoing)

Raptis et al. (2021) | (Ongoing)

Review of current work

- (1) Statistical properties of jets (Raptis et al. (2020 | JGR)

"Showed us which quantities can be used for in-situ classification using MMS"

- (2) Classification of jets using Neural networks (Raptis et al. (2020) | Front. Astron. Space Sci)

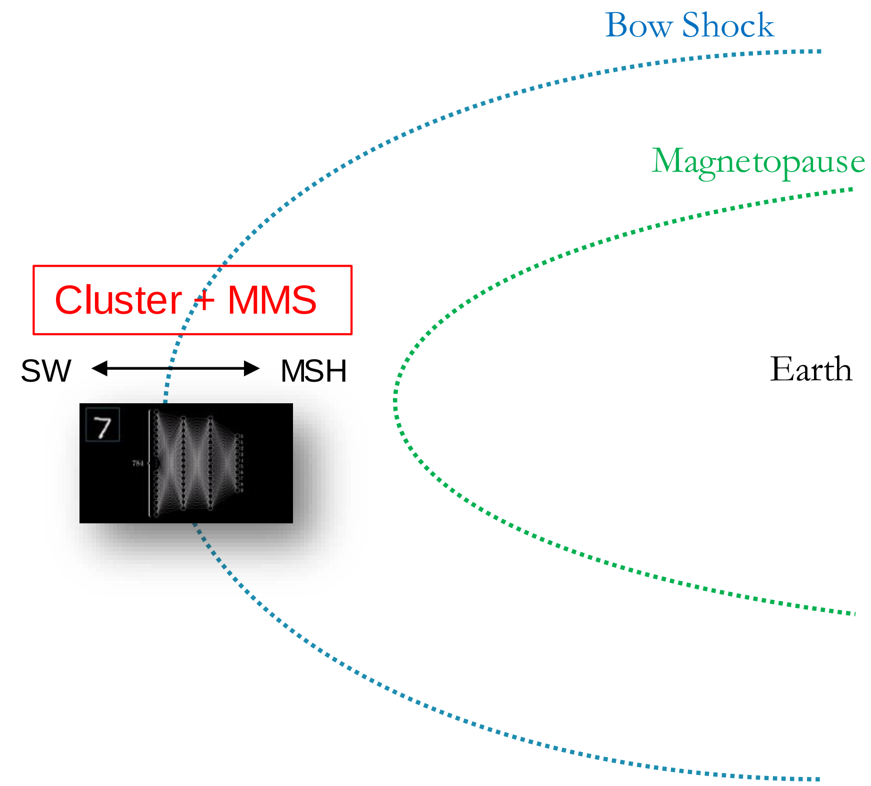
"Showed us that there is information in the Solar Wind that correspond to Qpar and Qperp jets and possibly to magnetosheath"

- (3) Classification of the magnetosheath (Karlsson et al. (2021) | JGR – Under review)

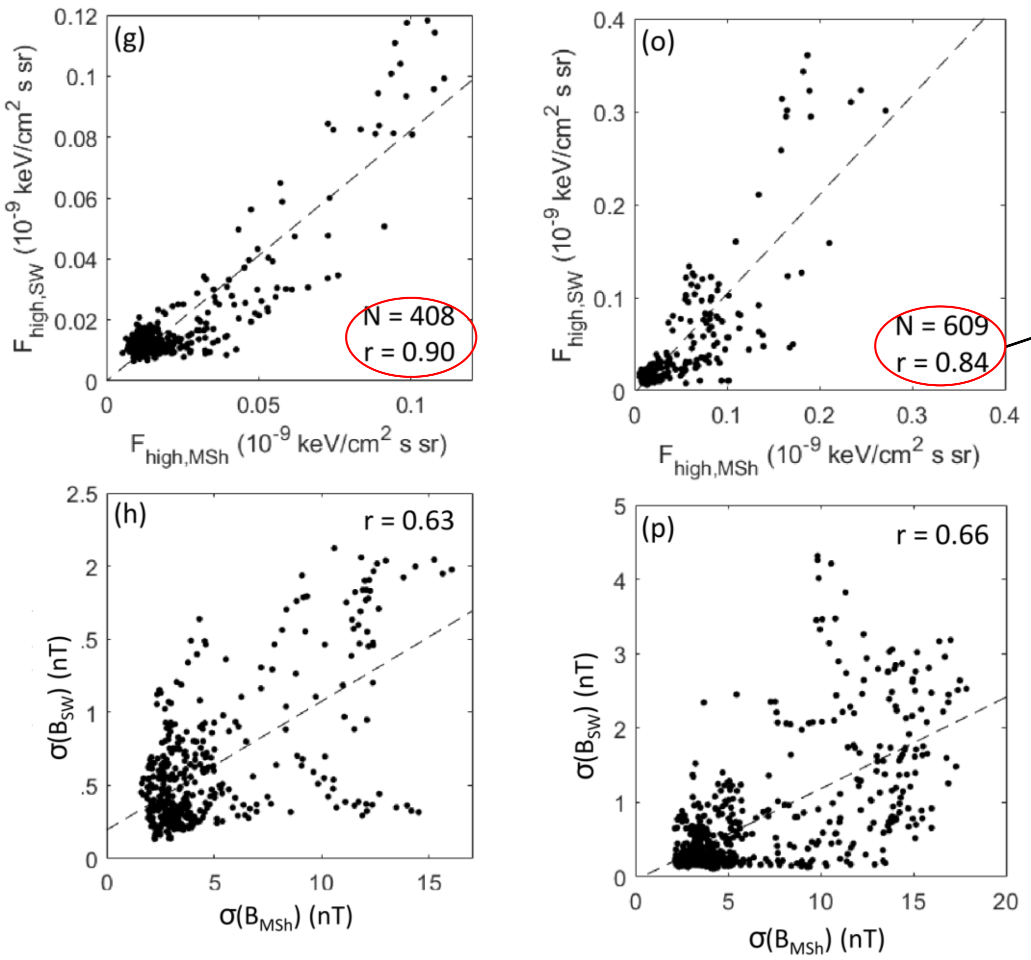
"Showed us that we can have strong statistical relationship between upstream and downstream measurements. Supporting the findings of (1) and (2)"

- (4) Mapping magnetosheath & shock transitions using neural networks (Raptis et al. (2021) | To be submitted)

"Will proceed to map the relation between the different plasma population upstream and downstream by using machine learning techniques similarly to (2) and the datasets of (1-3)"



Motivation & Current approach



Full dataset of cross correlated Upstream & downstream measurements

High linear correlation → Good news

Input: Upstream data
Output: Downstream Flux & classification to Qpar/Qperp/FS/No-FS

Or vice versa!

Finally: Can we use Cluster for MMS and MMS for cluster ? (generalizing dataset for magnetospheric physics)

Raptis et al. (2021) | (Ongoing)

Summary & Ongoing work

- **Successfully used Neural networks to classify jets** in the magnetosheath in different categories **using MMS**
- **Found correlations and relationships between upstream and downstream measurements using Cluster** that sufficiently separate the regions of a shock even in the absence of upstream or downstream data

Ongoing work:

- Use the extended **dataset (MMS & Cluster**) generated from previous works to **train a neural network** to **map upstream to downstream and vice versa of Earth's bow shock** and test resulting using both MMS and Cluster missions
  - Generalize multiple spacecraft measurements (Cluster & MMS)
  - Provide indirect classification of foreshock environment when magnetosheath measurements are available and vice versa.