Magnetosheath Jets: Simulations, Data Analysis & Machine Learning

Savvas Raptis

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Collaboration with: Tomas Karlsson, Minna Palmroth, Ferdinand Plaschke, Sigiava Aminalragia-Giamini, Anita Kullen, Per-arne Lindqvist et al.

Athens, 29/01/2020

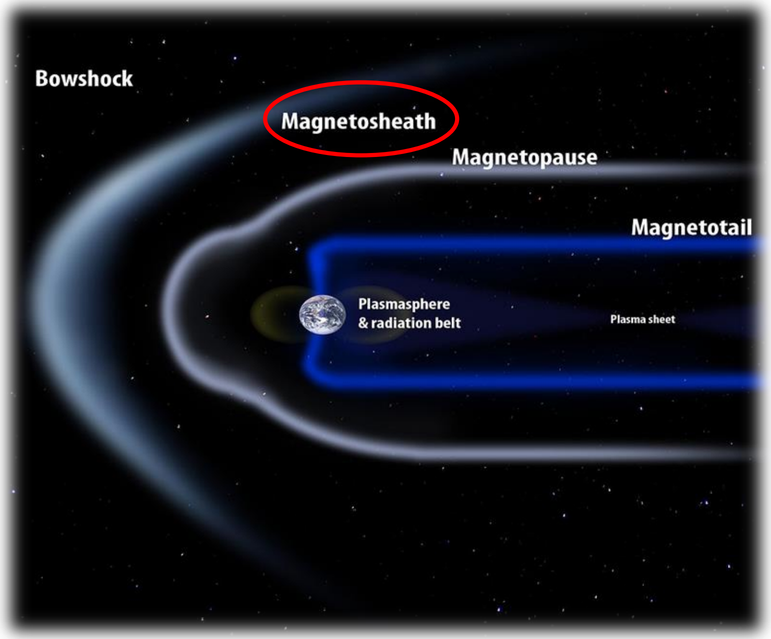
Introduction

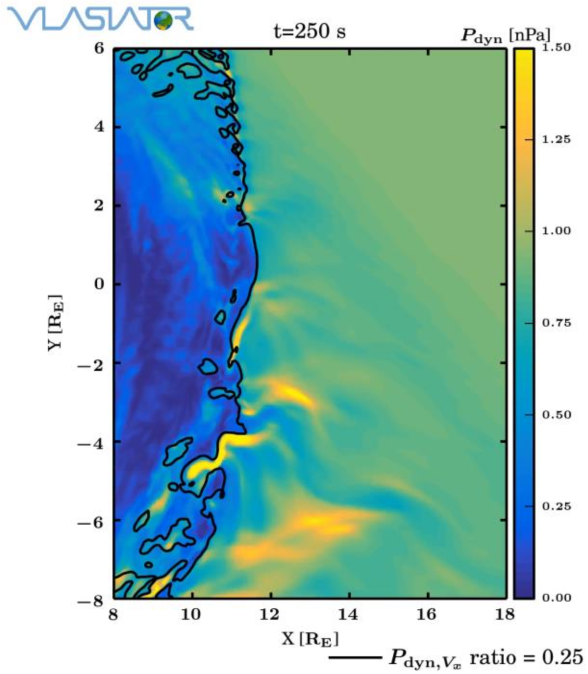
Magnetosheath Jets

Where: Magnetosheath

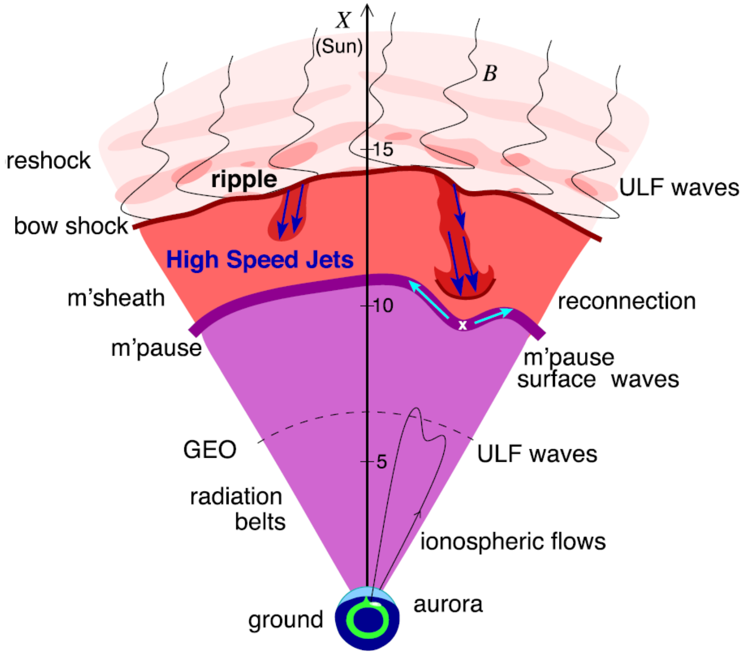
What: Enhancements of dynamic pressure above the general fluctuation level

Why: Interaction of SW & Magnetosphere, magnetopause reconnection, radiation belts, auroral features…



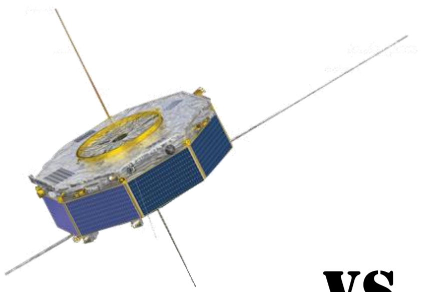
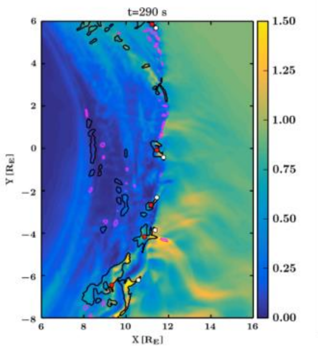


Palmroth Minna et al. (2018)



Plaschke F. et al. (2018)

Overview

Data vs Simulations	**Classification (Data Analysis)**	**Classification (Machine Learning)**
Question: How well can we model magnetosheath jets? Can we verify simulations and then generalize from their result?	Question: Can Jets happen in Quasi-perpendicular bow shocks? What are the different type of jets? Do they have different properties? Different generation mechanism?	Question: Can we verify somehow our previous classification? Can Machine learning outperform physical modeling? What is the solar wind doing when jets are happening?
 **VS** 		

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	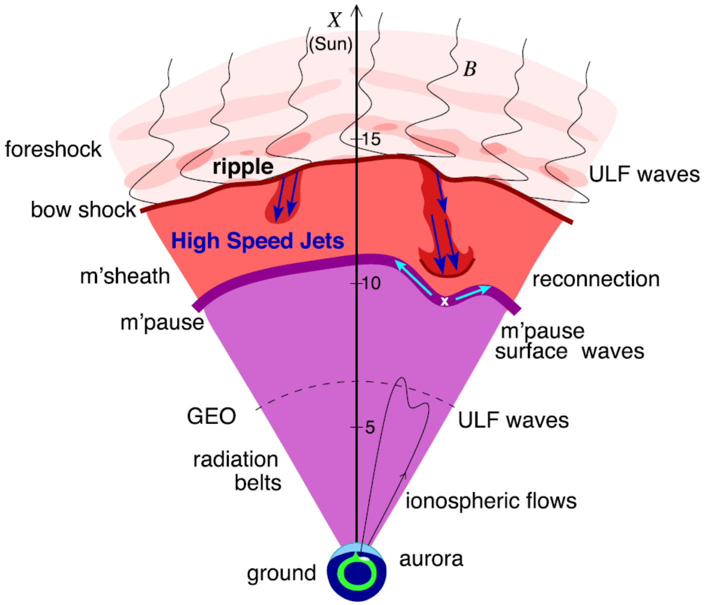	

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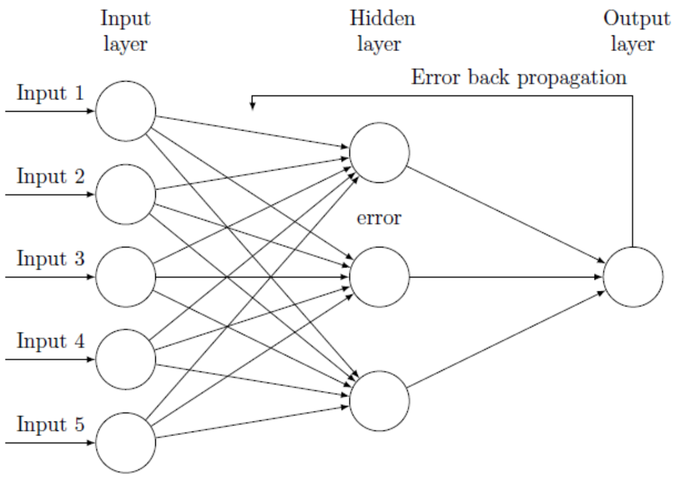
		

Part 1:

Simulations

vs

Measurements

Ongoing (Q1 2020)

Magnetosheath jet statistics: Global hybrid-Vlasov simulations compared to MMS observations

Minna Palmroth[1,2], Savvas Raptis[3], Jonas Suni[1], Tomas Karlsson[3], Lucile Turc[1], Andreas Johlander[1], Urs Ganse[1], Yann Pfau-Kempf[1], Xochitl Blanco-Cano[4], Mojtaba Akhavan-Tafti[5], Markus Battarbee[1], Thiago Brito[1], Maxime Dubart[1], Maxime Grandin[1], Vertti Tarvus[1], and Adnane Osmane[1]

[1]Department of Physics, University of Helsinki, Helsinki, Finland
[2]Space and Earth Observation Centre, Finnish Meteorological Institute, Helsinki, Finland
[3]KTH Royal Institute of Technology, Stockholm, Sweden
[4]Instituto de Geofisica, Universidad Nacional Autonoma de Mexico, Mexico City, Mexico
[5]Climate and Space Science and Engineering, University of Michigan, Ann Arbor, USA

Jets with Measurements – MMS

$$p_{dyn} = m_p n_i V_i^2$$

<u>MMS</u>

$$p_{dyn} > 2\langle p_{dyn}\rangle_{10}$$

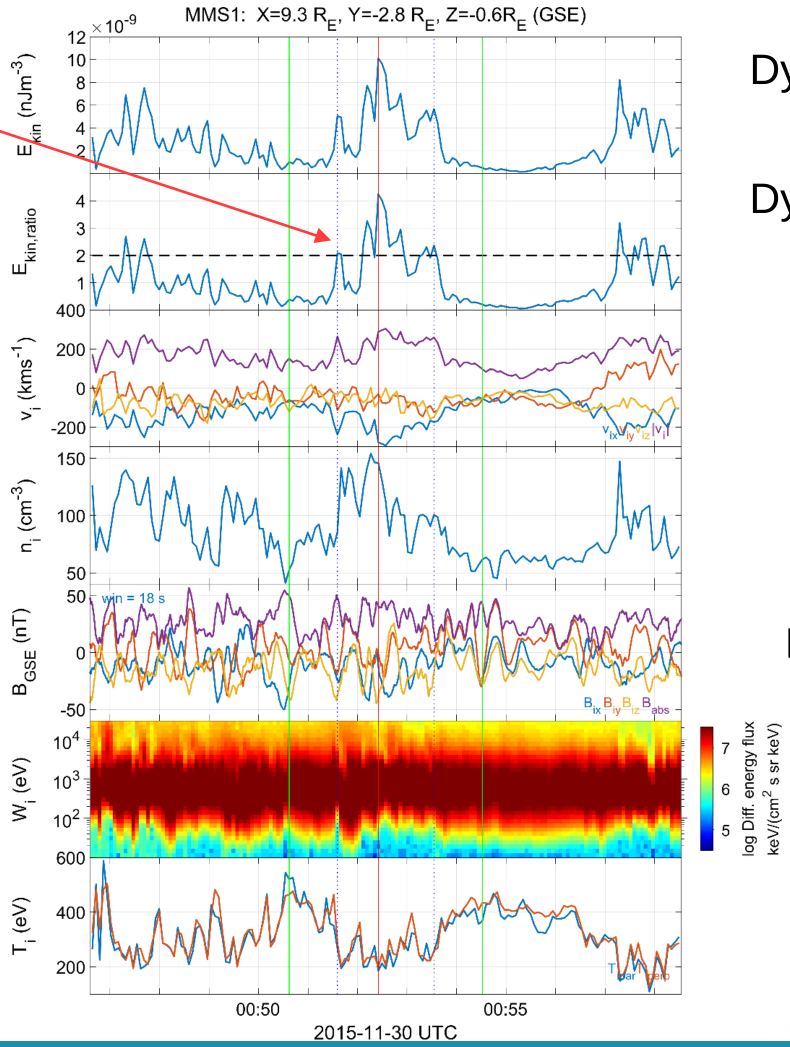
Database 2015 – 2018 (8499)

Data gaps (- 45)

Unstable SW conditions (- 2357)

Total:

6142



Dynamic Pressure

Dynamic Pressure Ratio

Velocity

Density

Magnetic Field

Ion Energy Spectrum

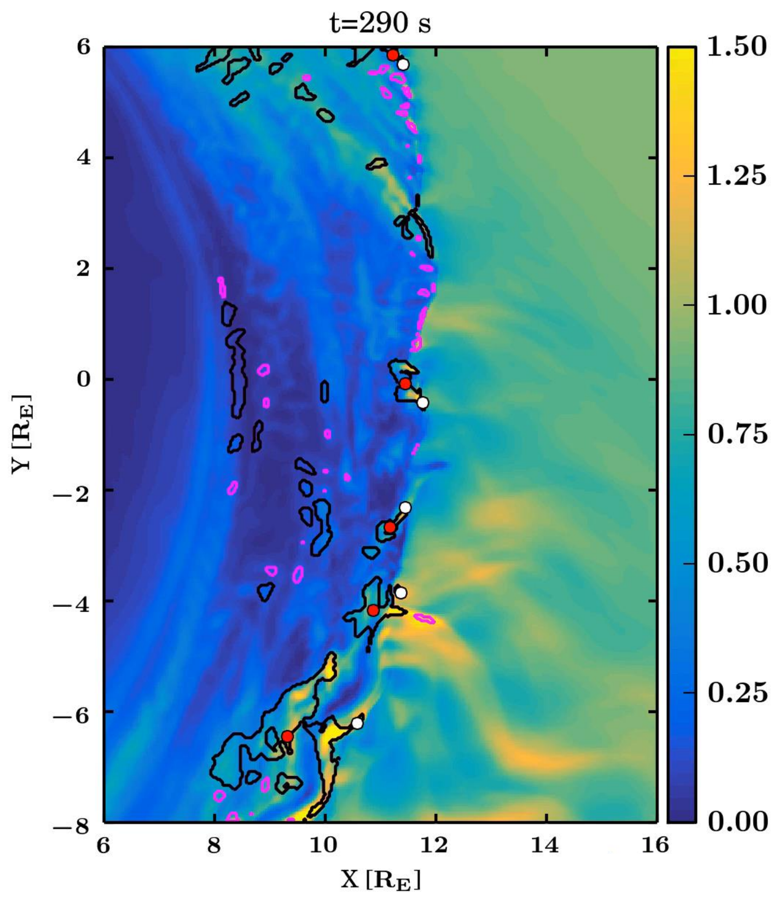
Temperature

Jets with Simulations – Vlasiator

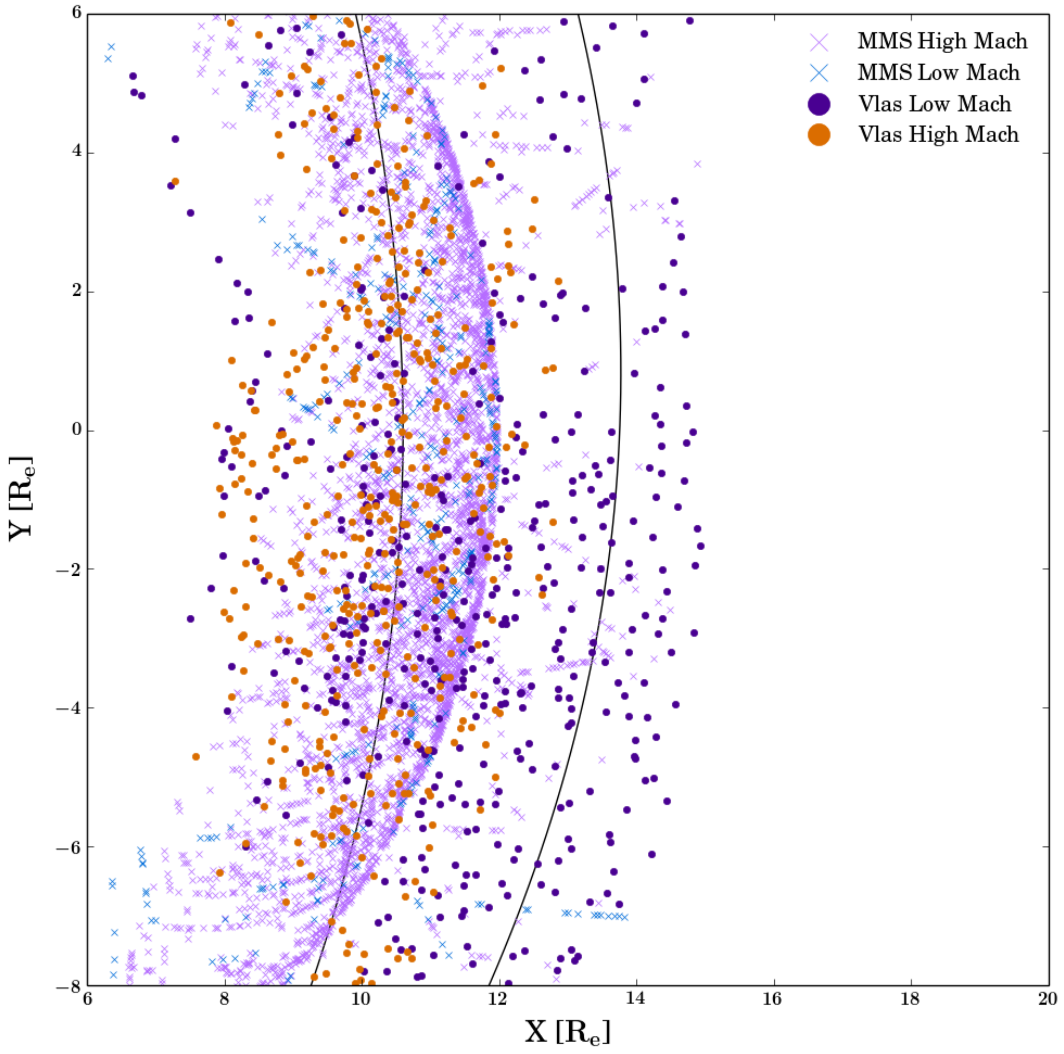
Vlasiator

- Global hybrid-Vlasov
- Protons = Distribution functions
- Electrons = Massless fluid
- 2D3V simulations (Although 3D possible)

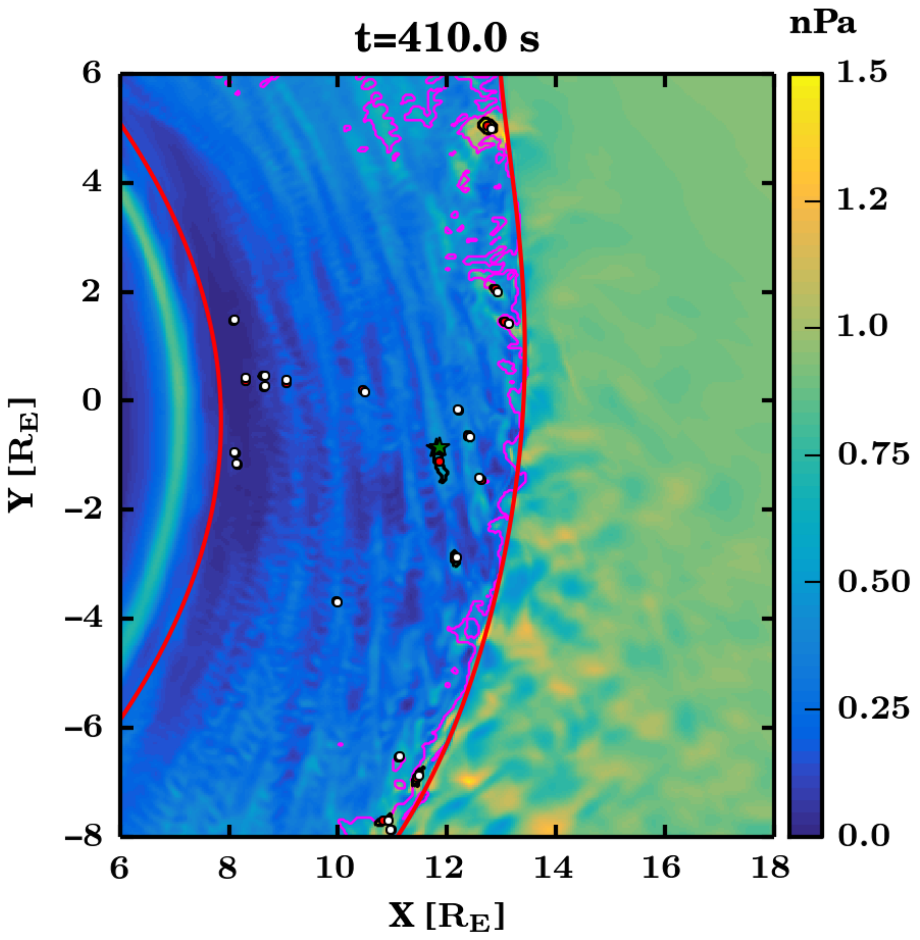
Number of Jets: 273

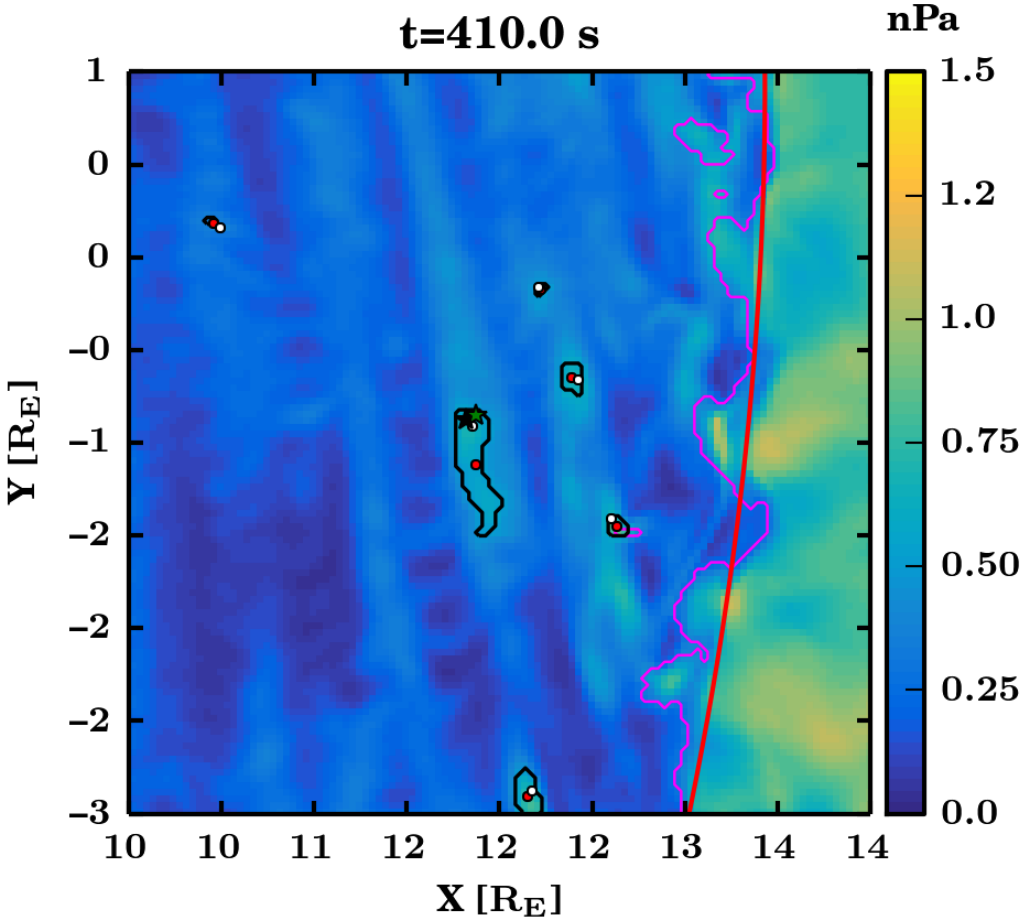


Magnetosheath Jets – Full Dataset



Main Results – Case Comparison





Main Results – Case Comparison

Dynamic Pressure

Velocity

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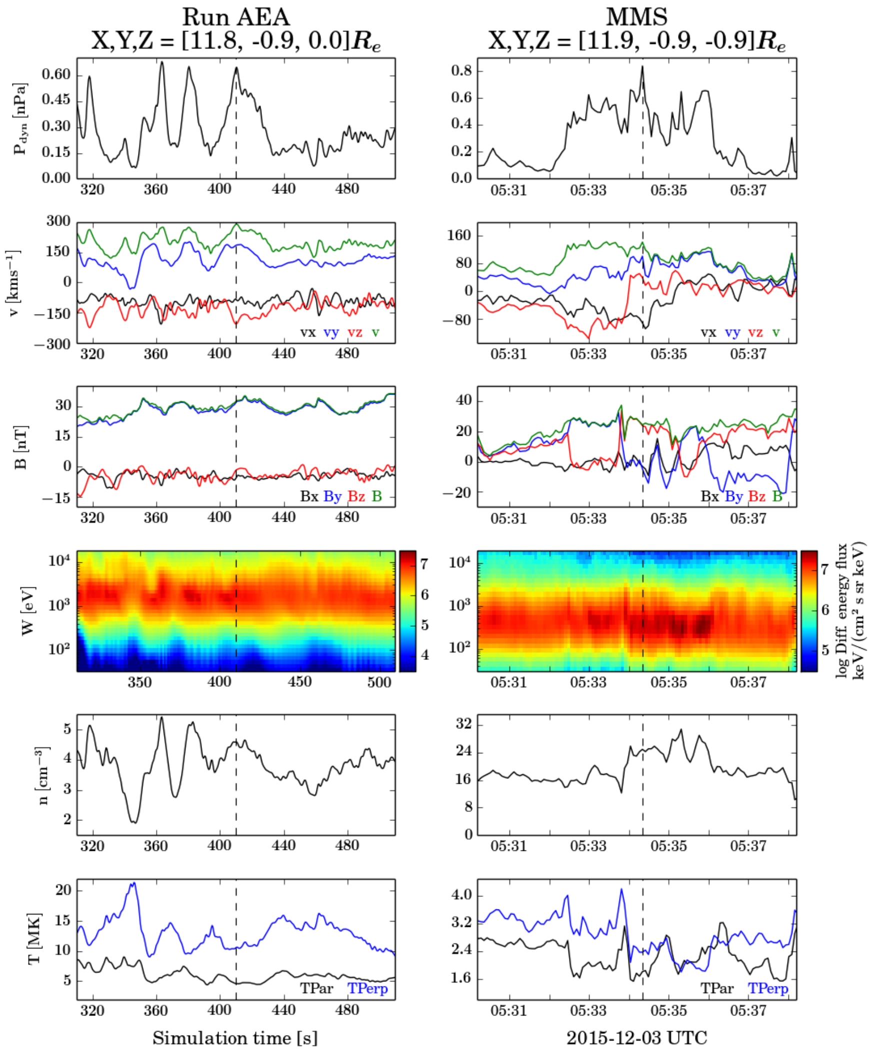
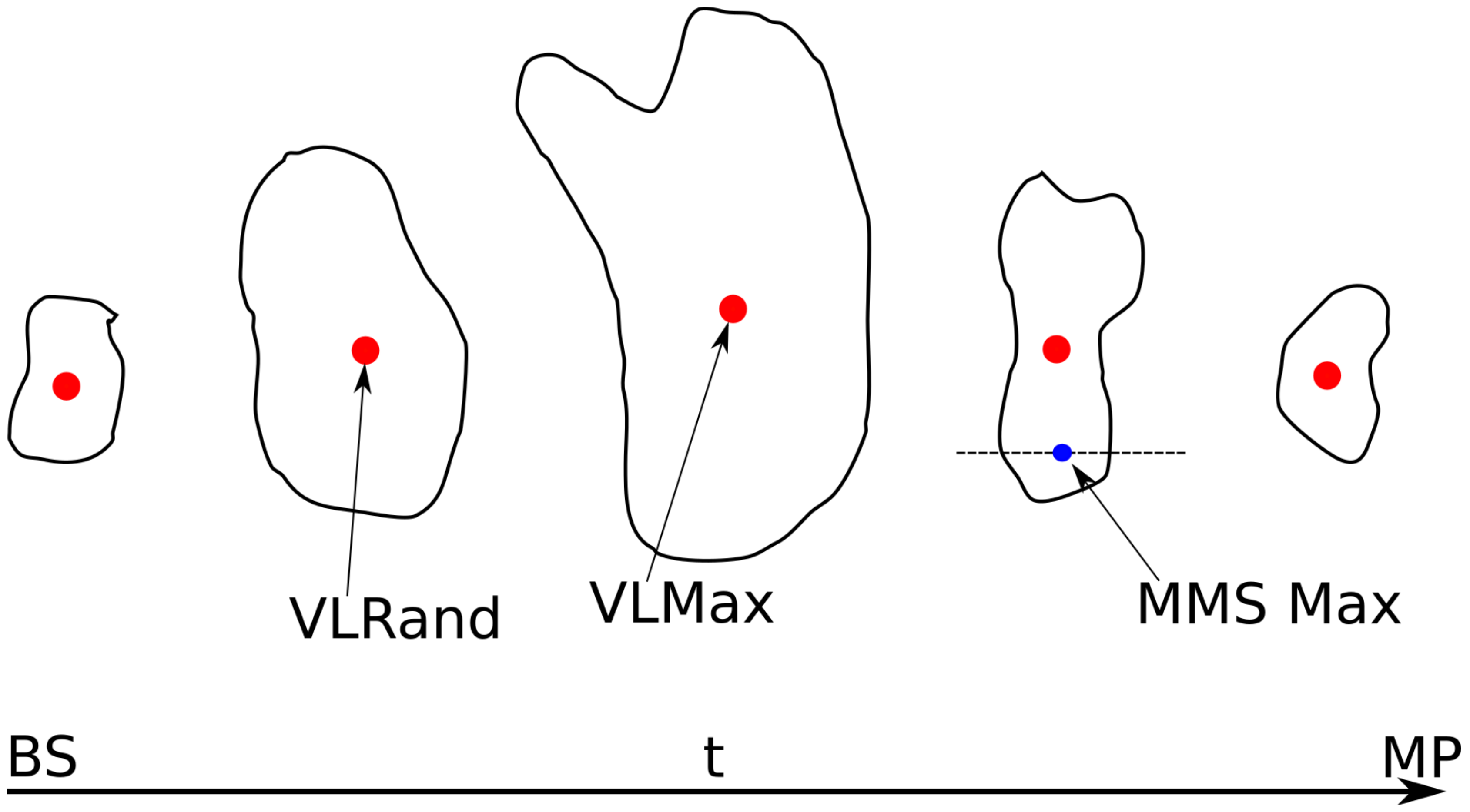
Density

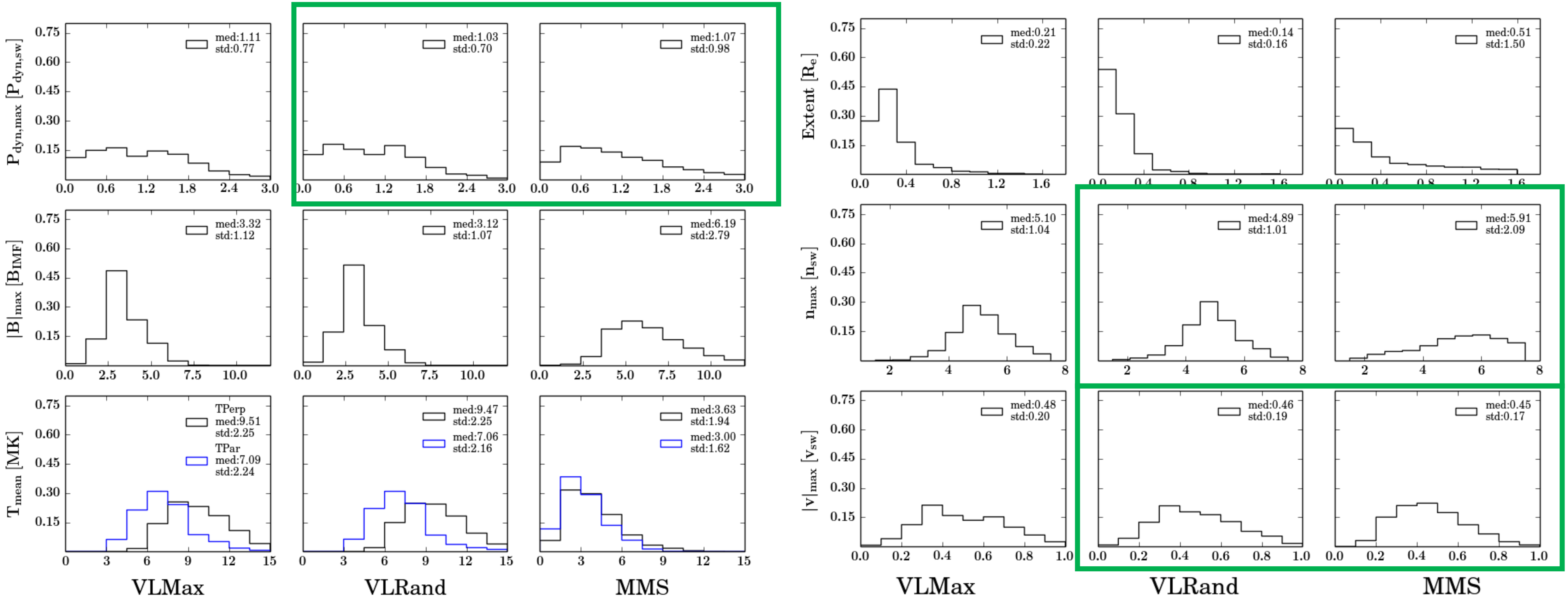
Temperature



Main Difference between MMS & Vlasiator



Main Results – Some Statistical Properties



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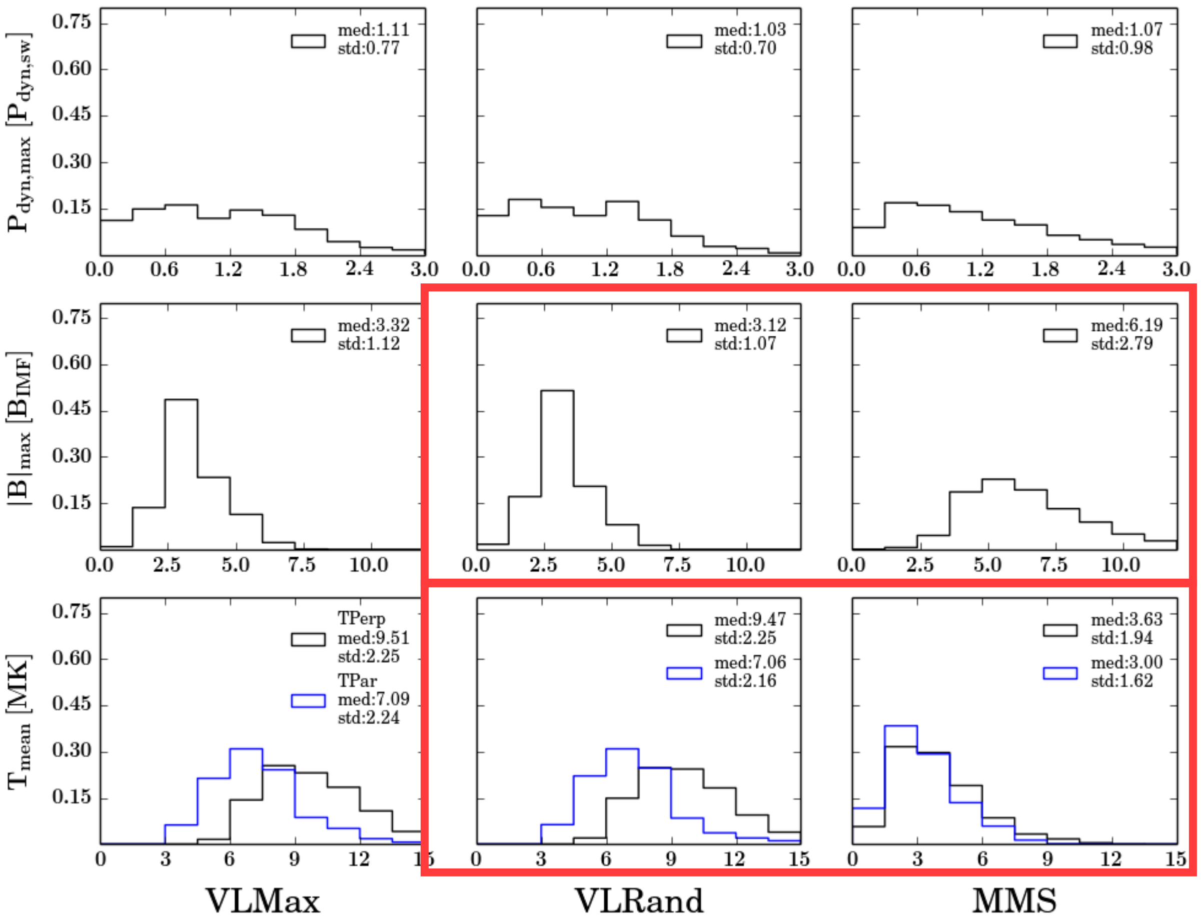
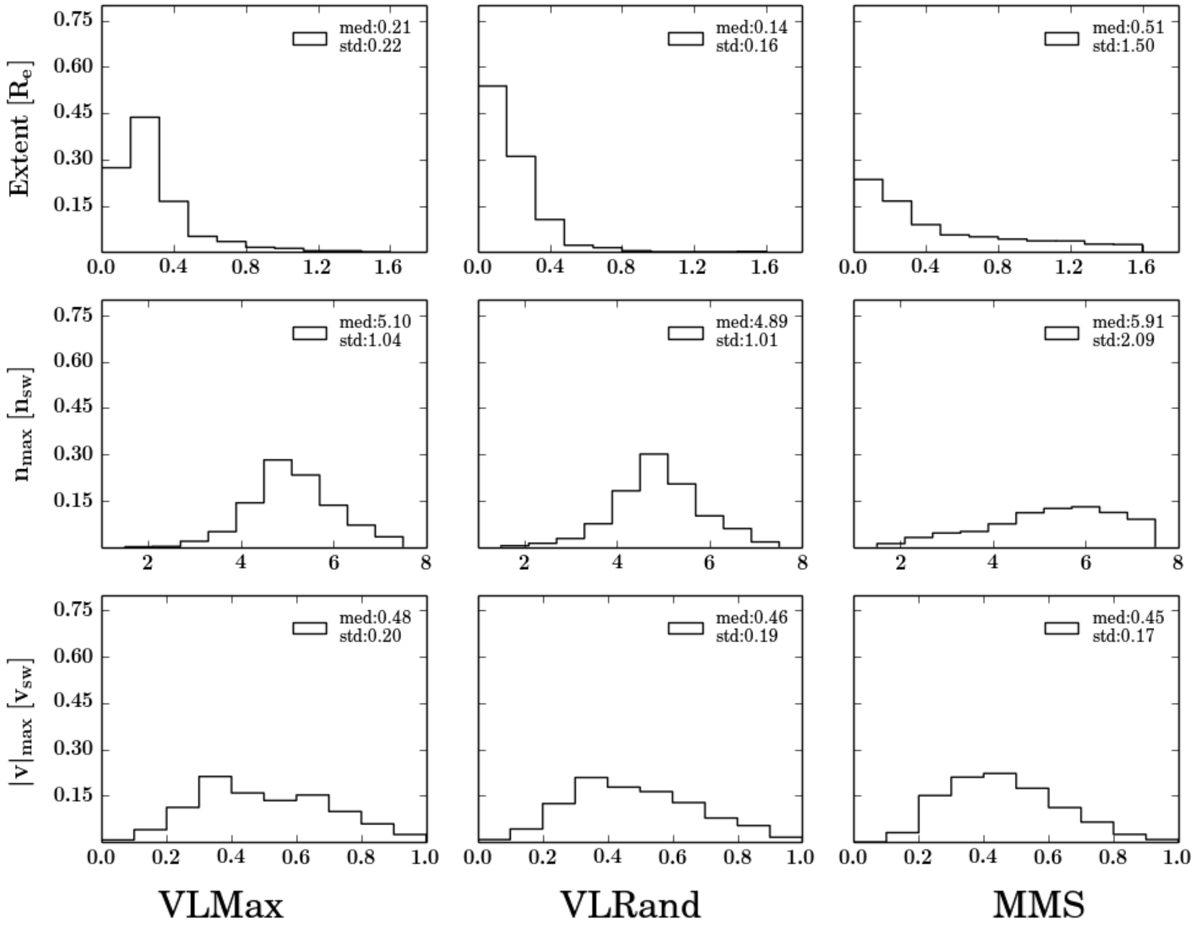


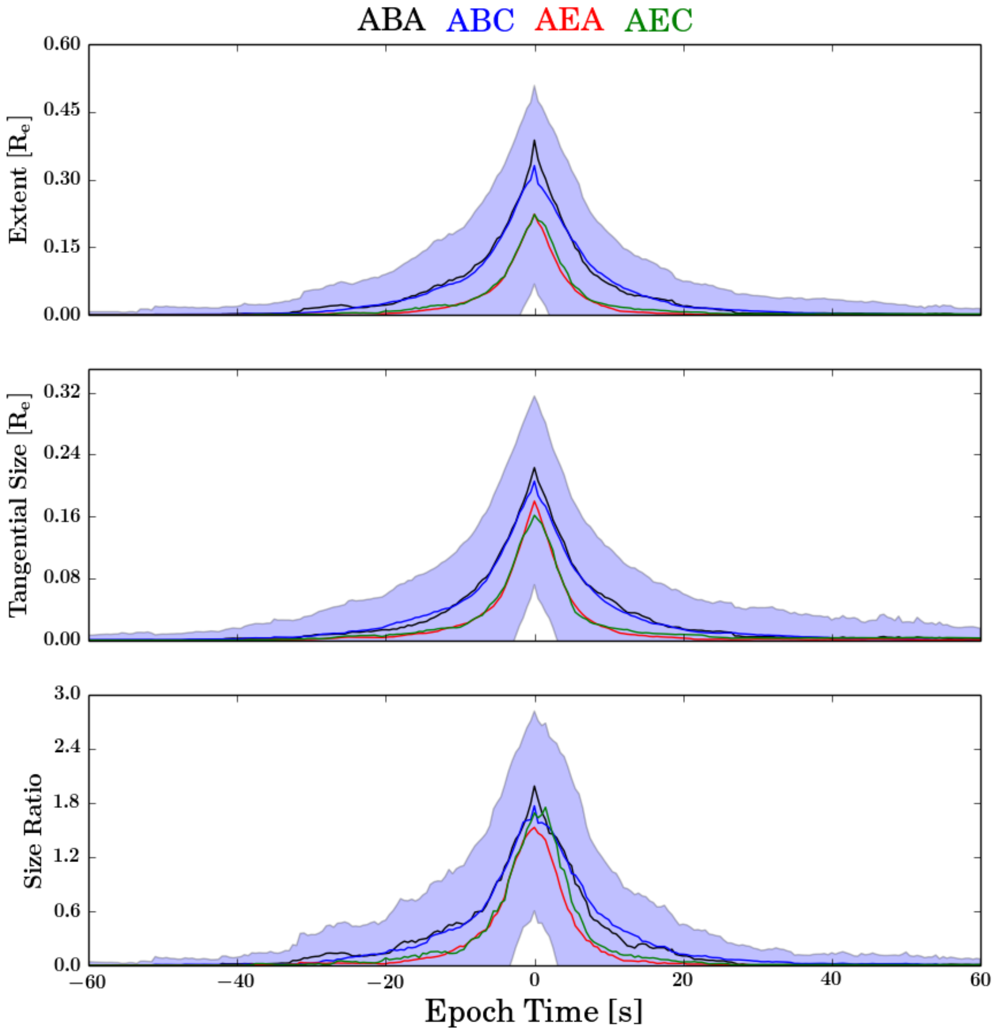


Only Vlasiator Statistics – Superposed Epoch Analysis

Extend (# Cells)

Tangential Size (# Cells)

Radial/Tangential



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• Vlasiator can model jets ✓
• MMS data support Vlasiator results ✓
• New results:
  • Sizes
  • Lifetime ✓
Future work:
Follow the simulations! how jets are created? Can we follow the creation of the jet upstream ?		

Part 2:

Classification of Magnetosheath Jets

Submitted

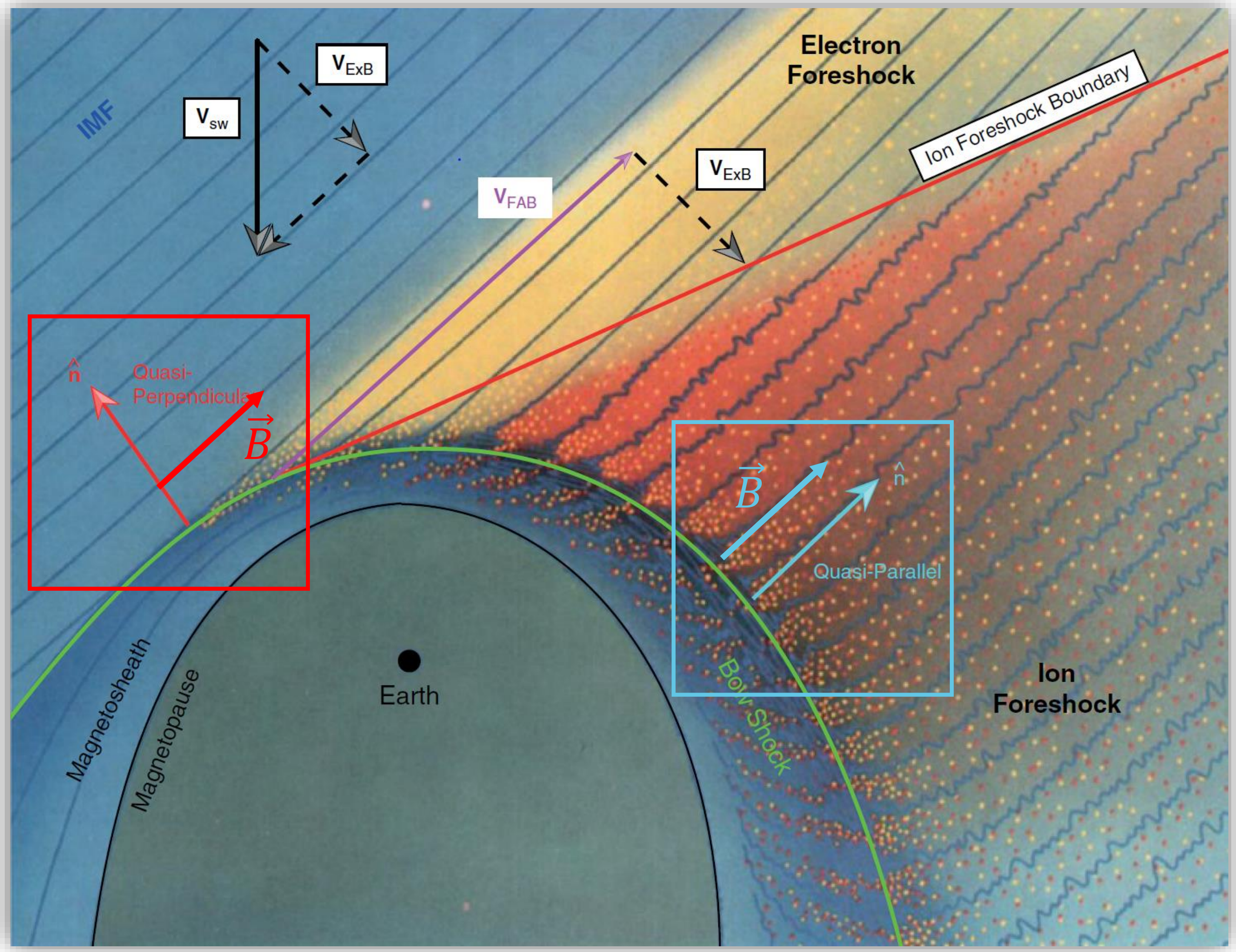
Classifying Magnetosheath Jets using MMS - Statistical Properties

Savvas Raptis[1], Tomas Karlsson[1], Ferdinand Plaschke[2], Anita Kullen[1], Per-Arne L. Lindqvist[1]

[1]Space and Plasma Physics, School of Electrical Engineering and Computer Science, KTH Royal Institute of Technology, Stockholm, Sweden
[2]Space Research Institute, Austrian Academy of Sciences, Graz, Austria

* https://www.essoar.org/doi/10.1002/essoar.10501493.1

Motivation – Main Subcategories

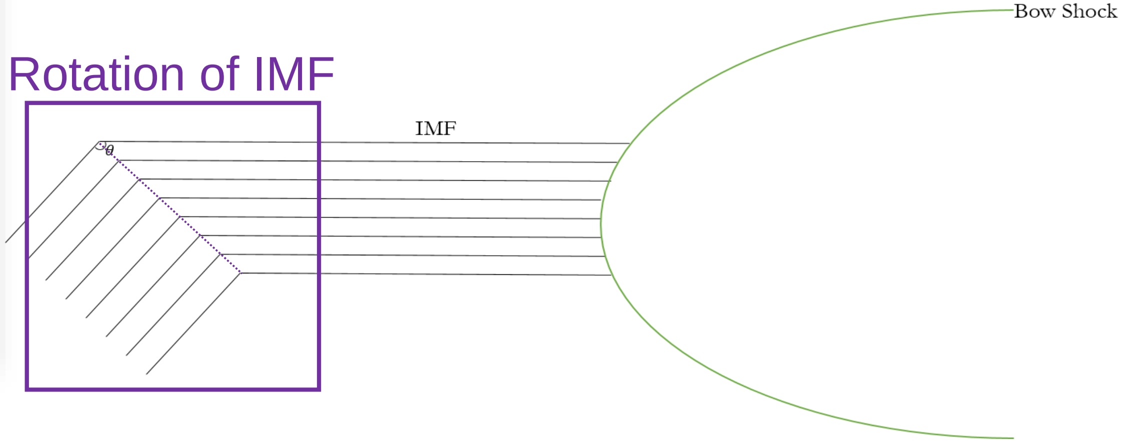


L. B. Wilson (2016)

Jets are found mainly in Quasi-parallel shock ($\theta_{Bn} < 45°$). However, fluctuations also found in Quasi Perpendicular regions.

Q_{par}	Q_{per}	$Boundary$

Rotation of IMF

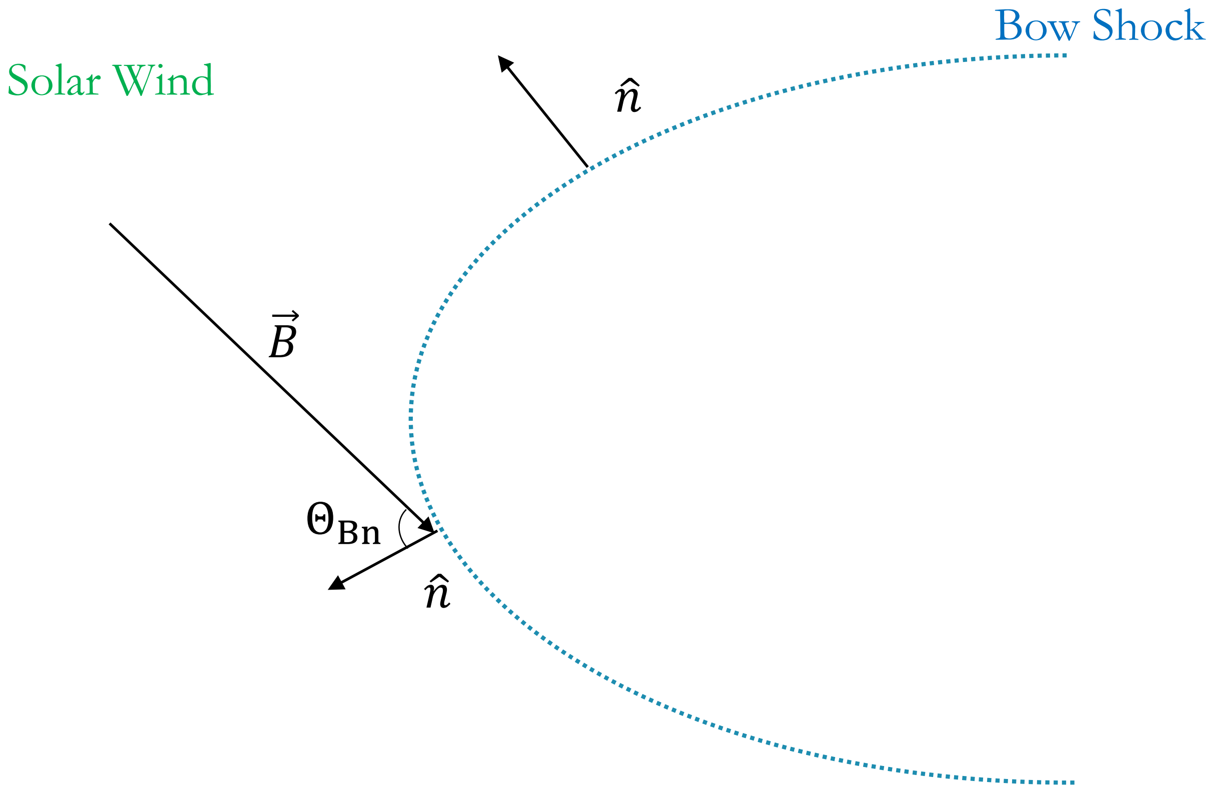


Task – Find Θ_{Bn}

- Angle between $\hat{n}$ and $\vec{B}$…

Steps:

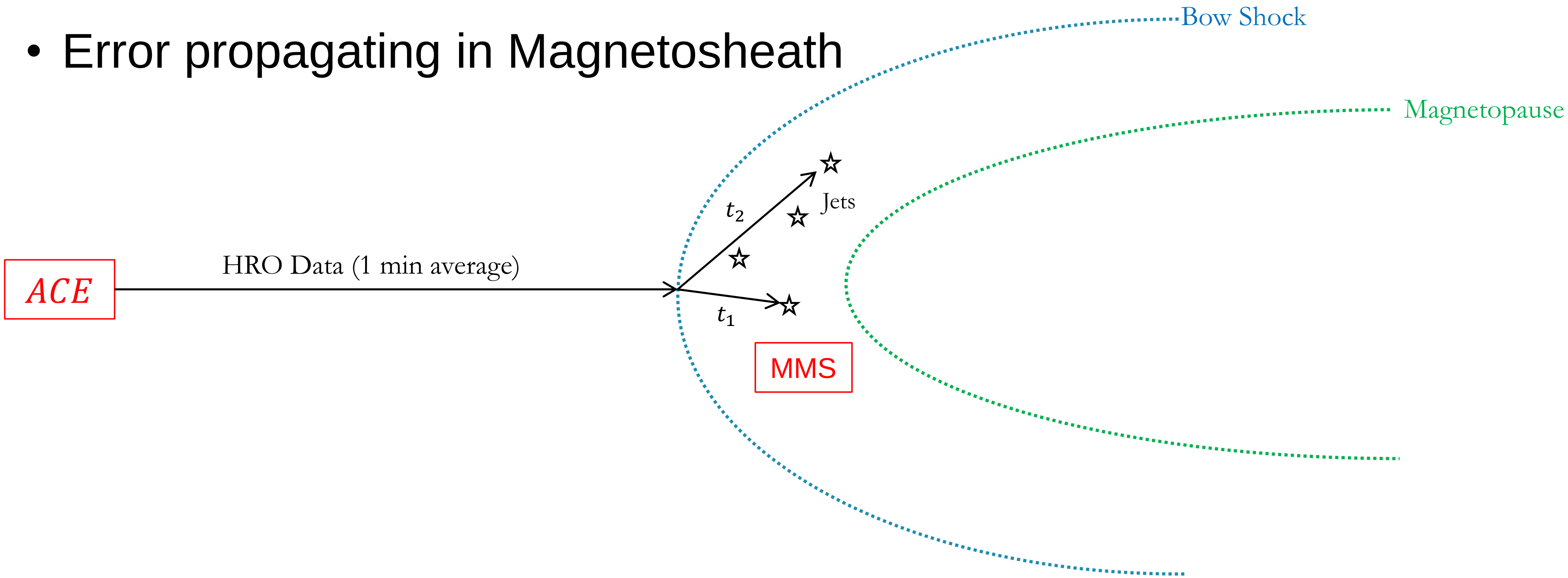
1. Bow shock model for $\hat{n}$
2. IMF vector
3. Profit



Task – Find Θ_{Bn}

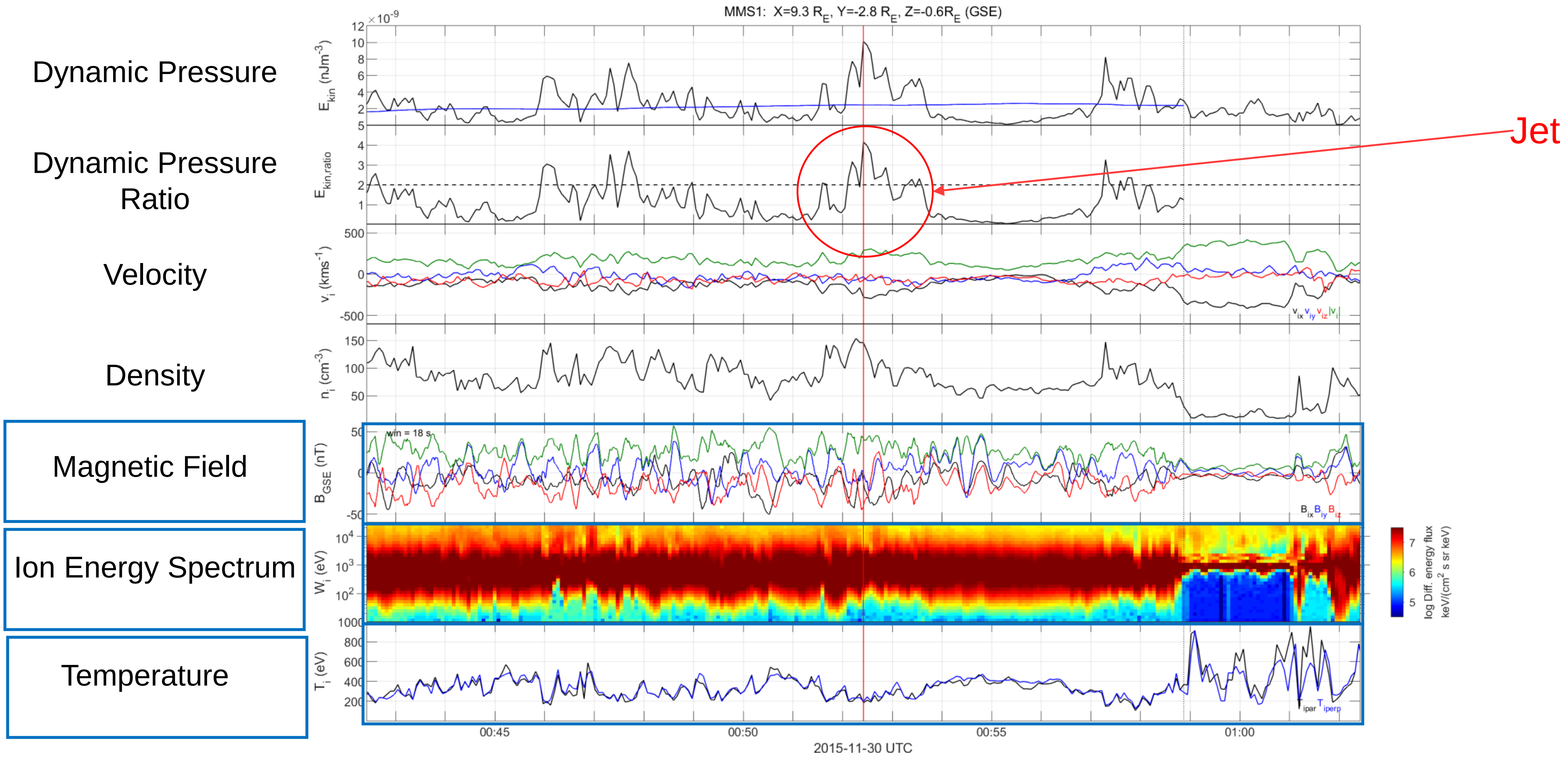
Why not directly $\theta_{B\mathrm{n}}$ from Solar wind data ?

- Worse availability
- Error in propagating to Bow shock
- Error propagating in Magnetosheath



Quasi-parallel jet using MMS

High B Variance, High Energetic Particles, Low Anisotropy



Quasi-perpendicular jet using MMS

Low B Variance, Low Energetic Particles, High Anisotropy

Dynamic Pressure

Dynamic Pressure Ratio

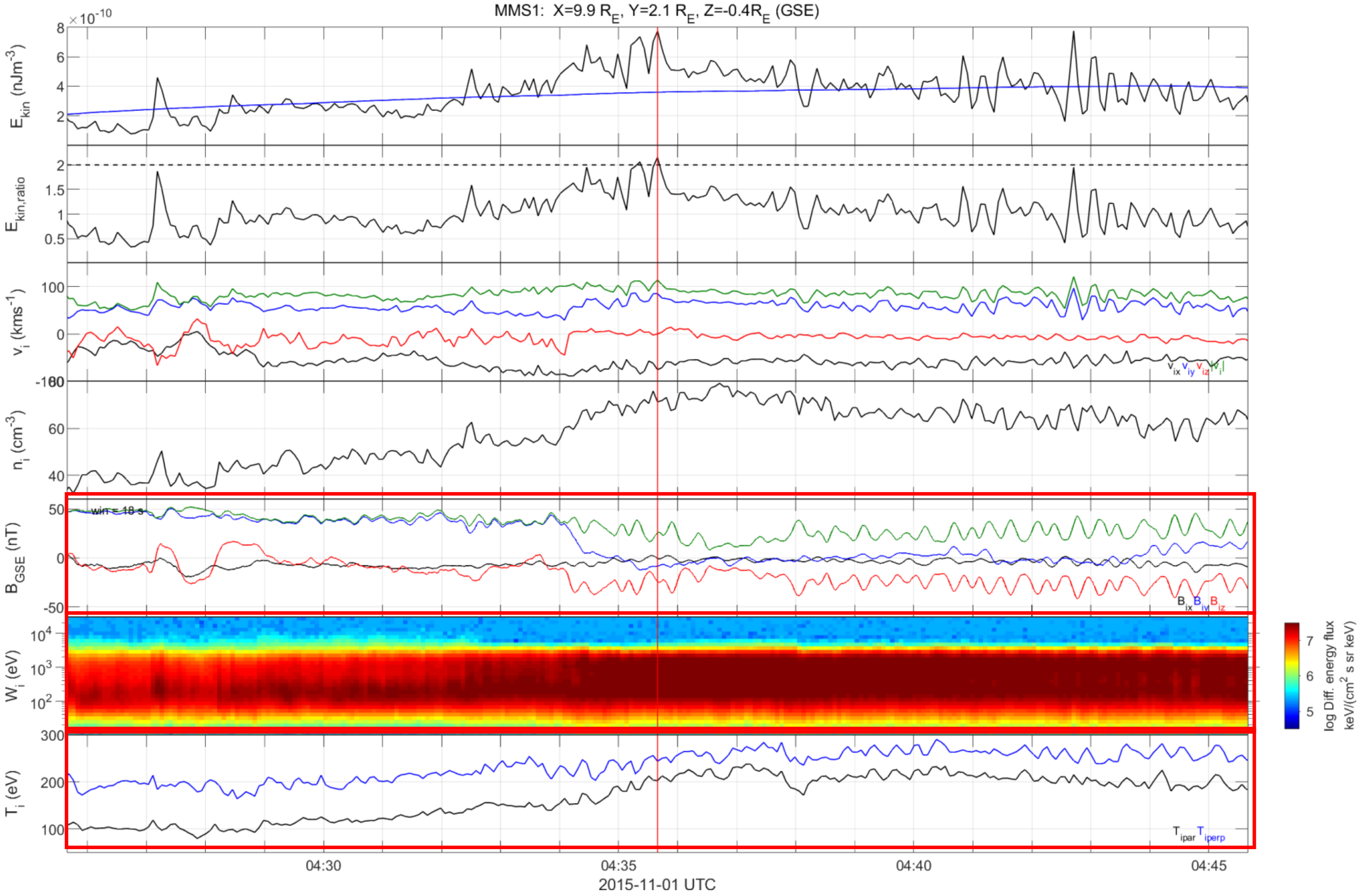
Velocity

Density

Magnetic Field

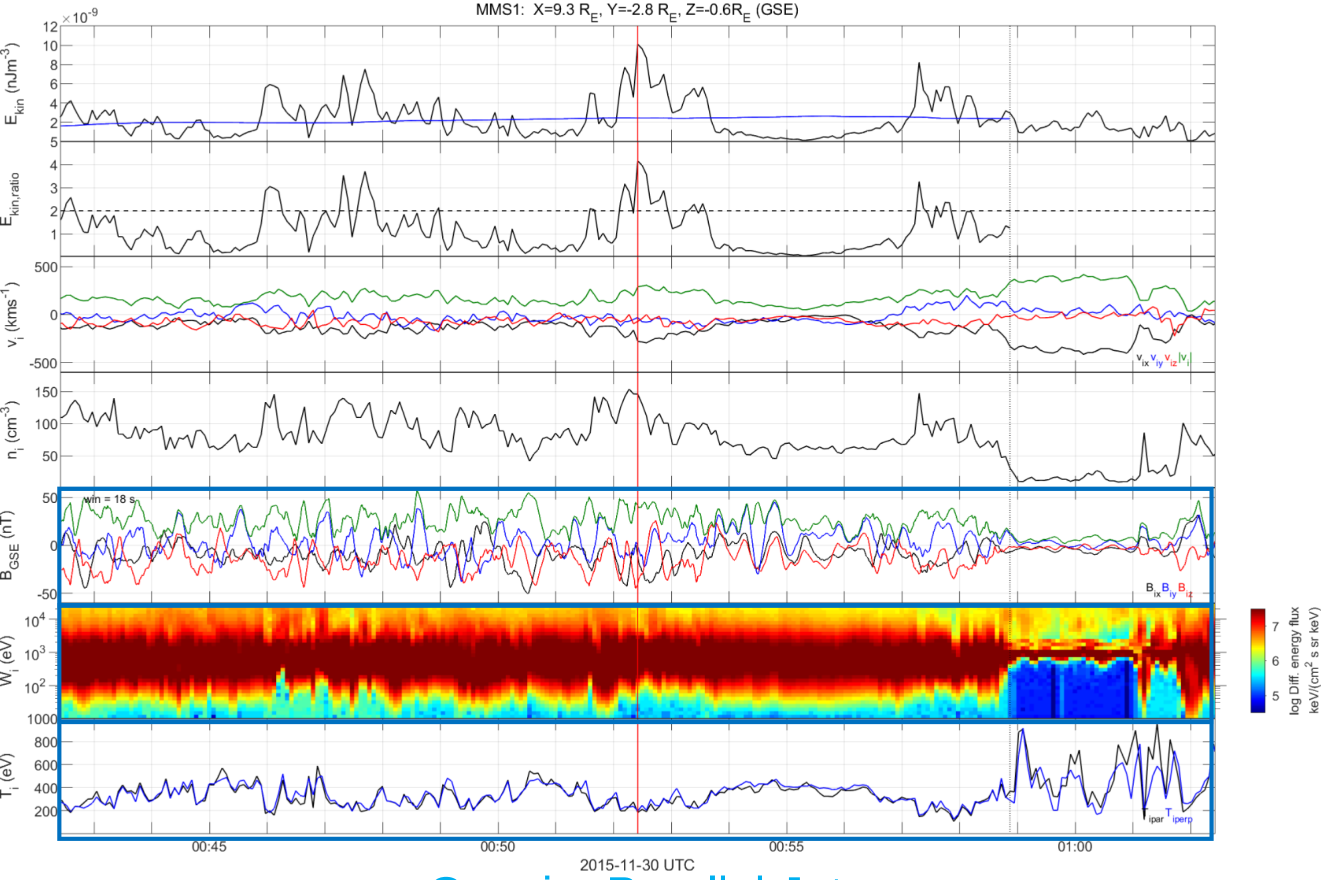
Ion Energy Spectrum

Temperature



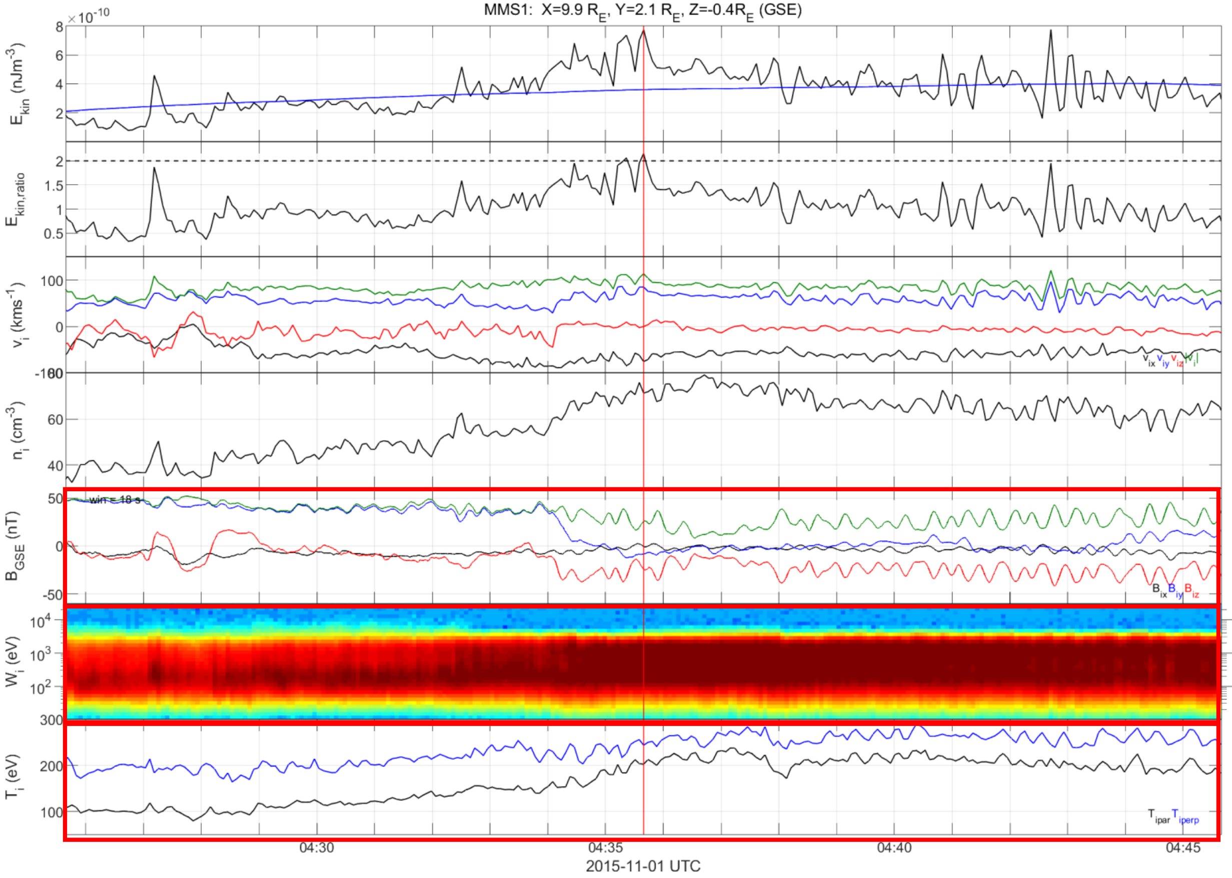
Differences of each class

High Variance, High Energetic Particles, Low Anisotropy



Quasi – Parallel Jet

Low Variance, No Energetic Particles, High Anisotropy



Quasi – Perpendicular

Classification Procedure in progress

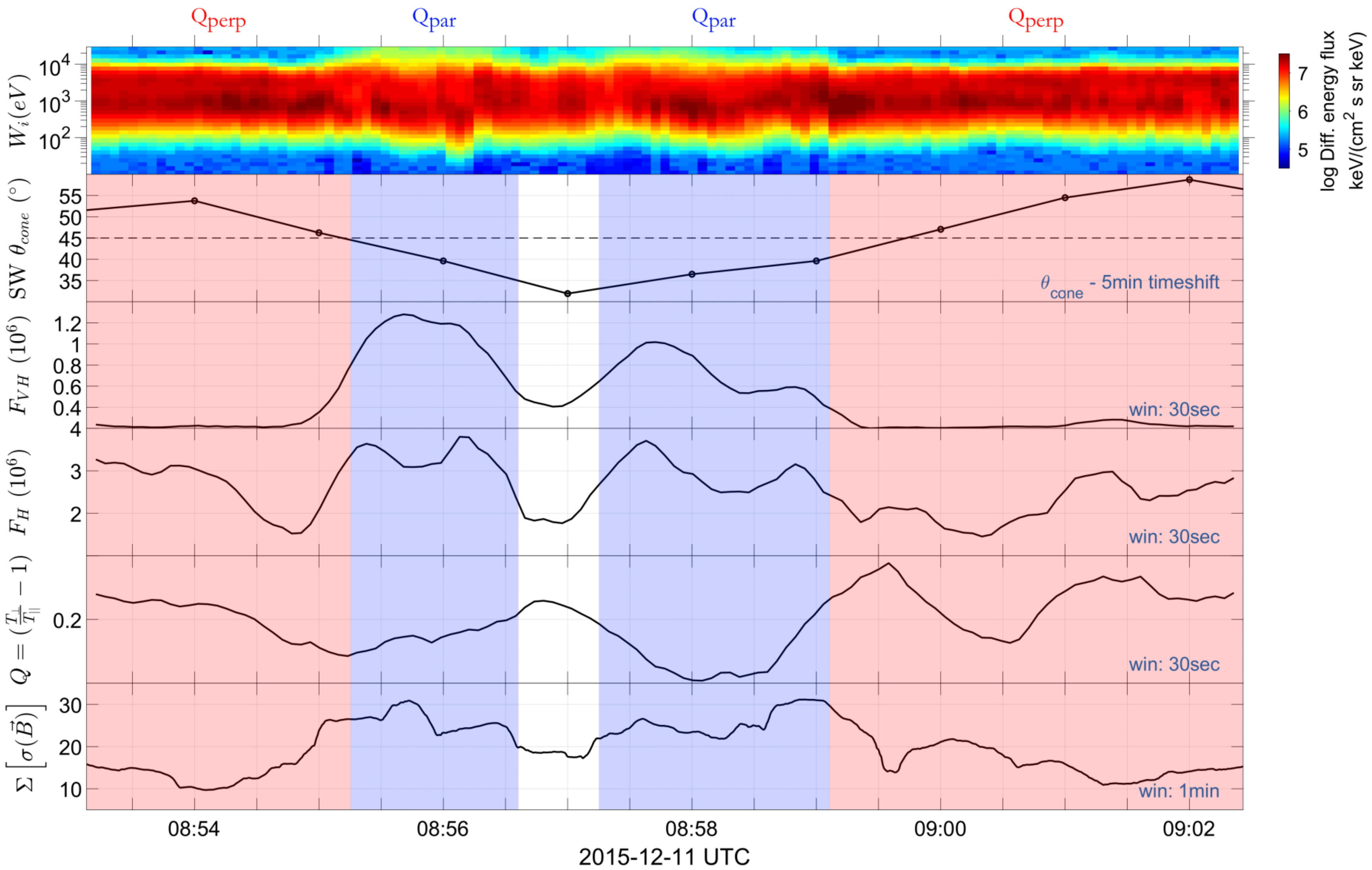
Cone Angle

Very High Energy Flux

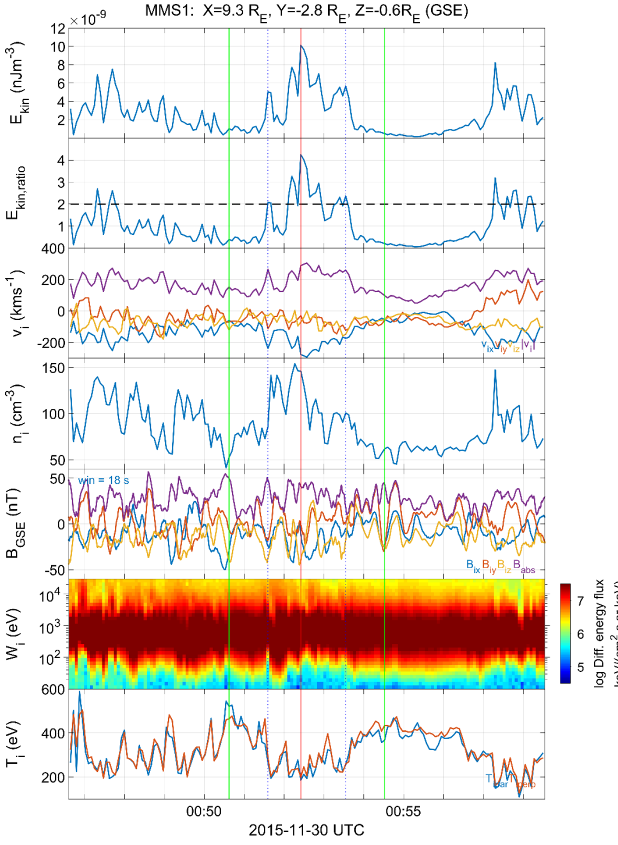
High Energy Flux

Anisotropy

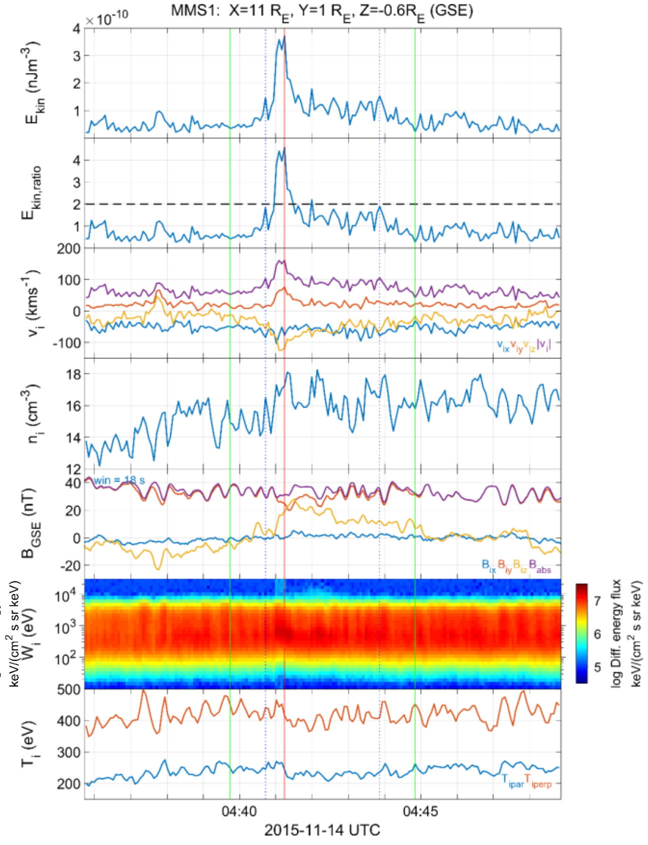
Magnetic Field Variance



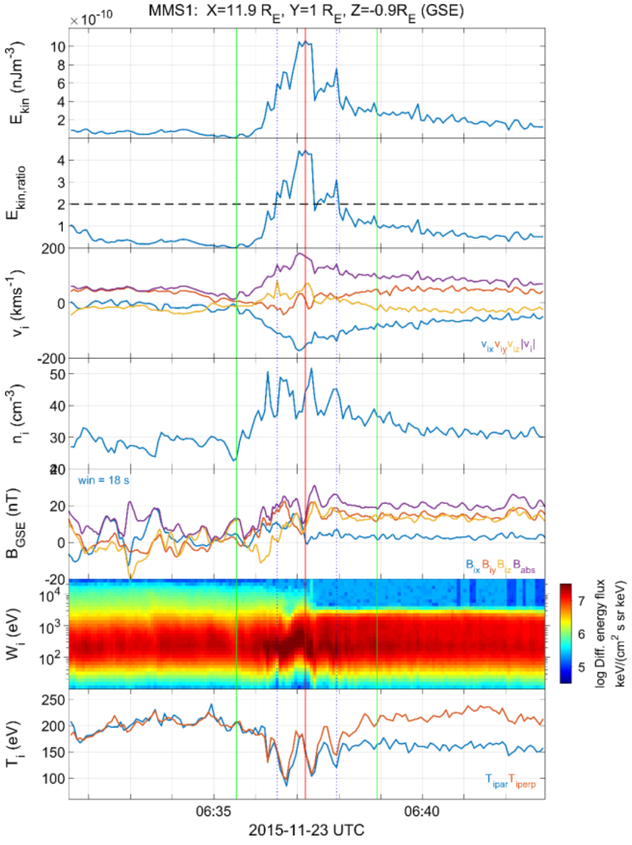
Main Categories



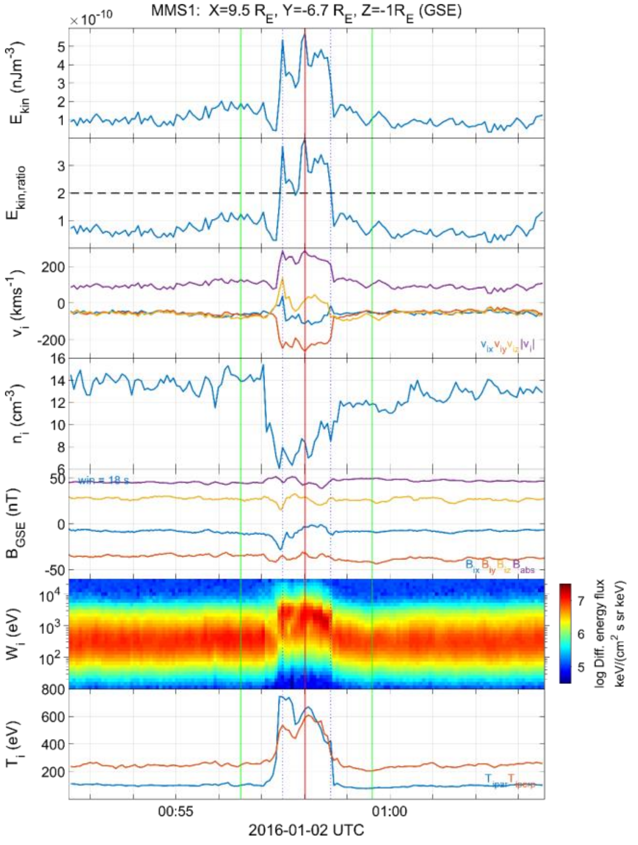
Qpar Jet



Qperp Jet

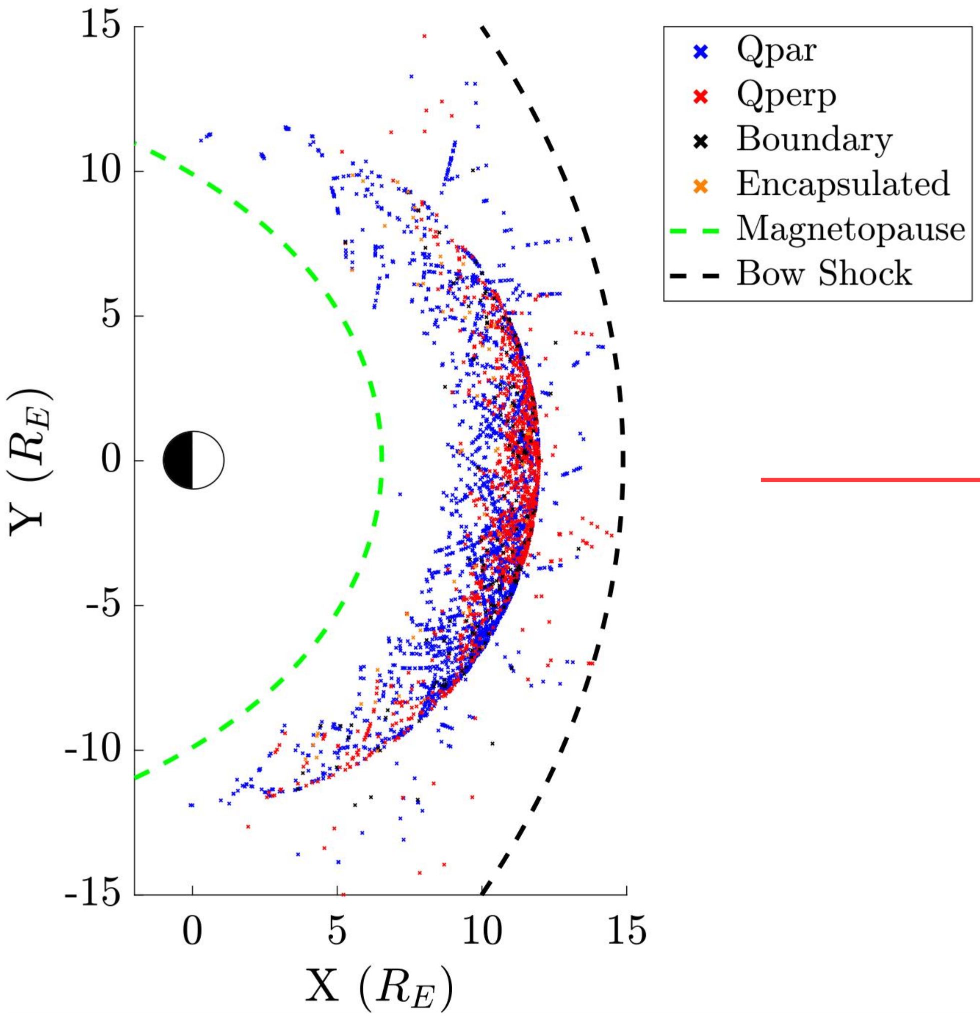


Boundary Jet



Encapsulated Jet

Database of Jets



$n = 8499$

Subset	Number	Percentage (%)
Quasi-parallel	2284	26.9
Best cases	**860**	10.1
Quasi-perpendicular	504	5.9
Best cases	**211**	2.5
Boundary	744	8.8
Best cases	**154**	1.8
Encapsulated	77	0.9
Best cases	**57**	0.7
Other	4890	57.5
Unclassified/Uncertain	3499	41.2
Border	1346	15.8
Data Gap	45	0.5

What are we looking for (?)

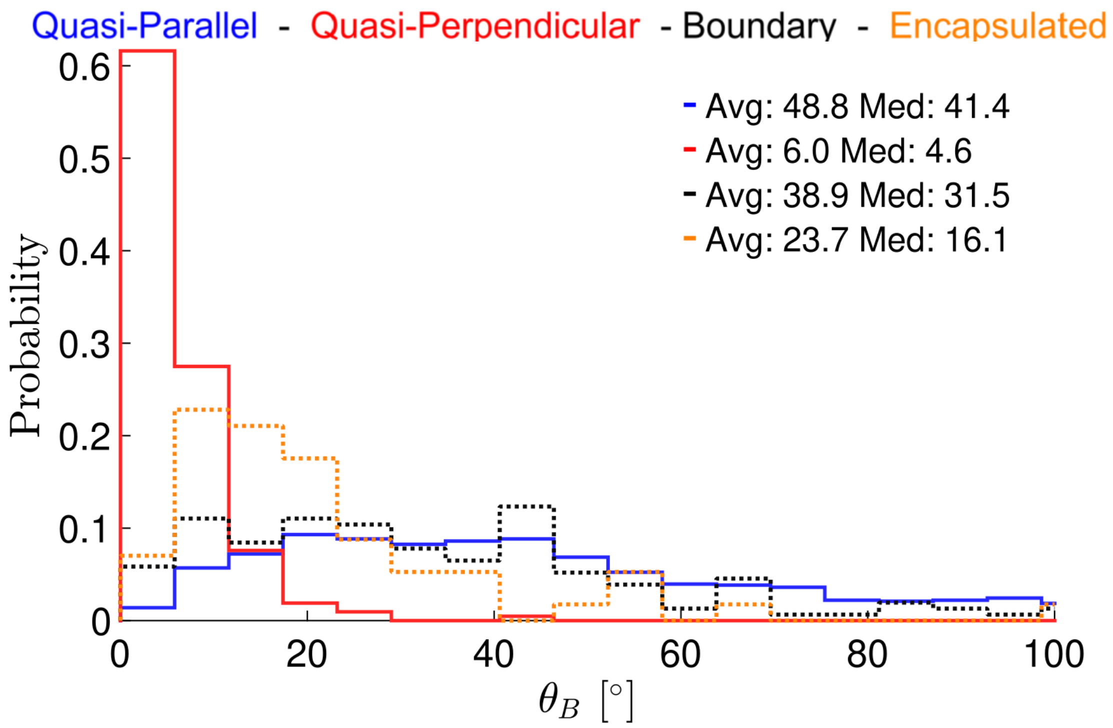
Problem: No idea where Jet come from?

Lets think, any clues from previous works?

1) Boundary Jets = Pressure pulses associated to IMF (Archer et al. 2013)
2) Quasi – Parallel jets = Ripples in the bow shock + SLAMS (Hietalla et al. 2009, Karlsson et al. 2018)
3) Quasi – Perpendicular jets = Ripples in the shock (Jolander et al. 2016)
4) Encapsulated jets = ????

Boundary Jets

- All Statistical properties ≅ Quasi-parallel jets
- No significant changes in magnetic field rotation angles

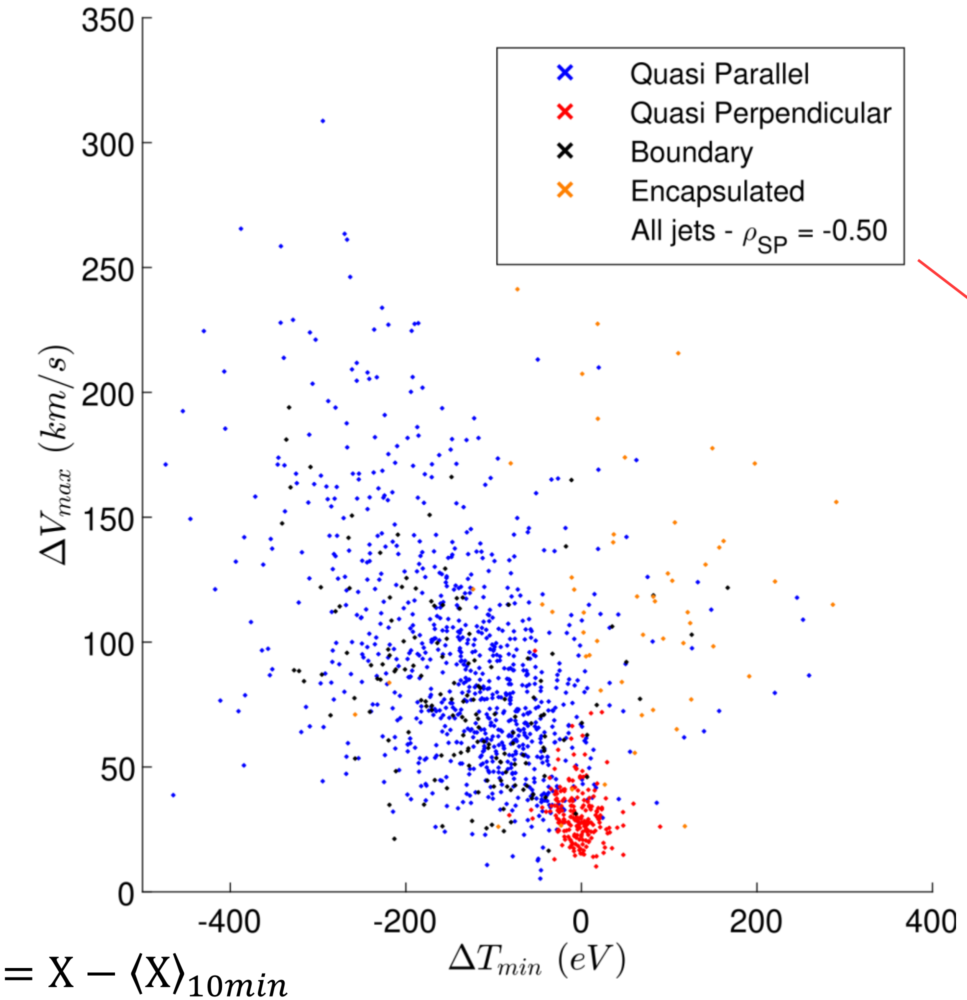


Verdict: Subset of Quasi-parallel jets, more careful analysis could:

1. Show difference in frequency.
2. Show smaller scale variations in magnetic field.

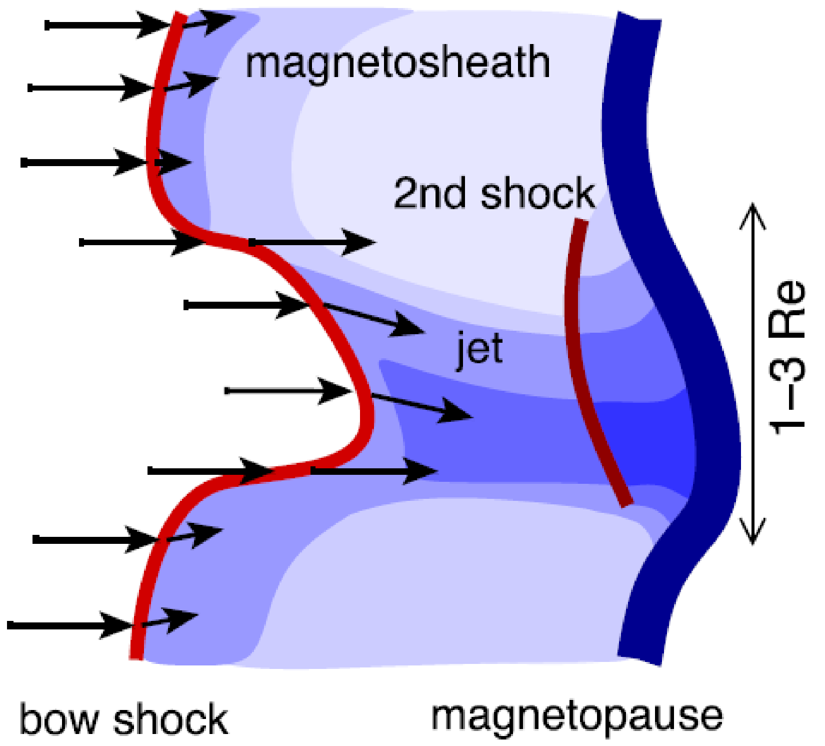
Quasi Parallel Jets – Shock ripples

- Bow shock ripple mechanism = Anti-correlation $\Delta \mathrm{T}$ and $\Delta \mathrm{V}$



$\Delta \mathrm{X} = \mathrm{X} - \langle \mathrm{X} \rangle_{10min}$

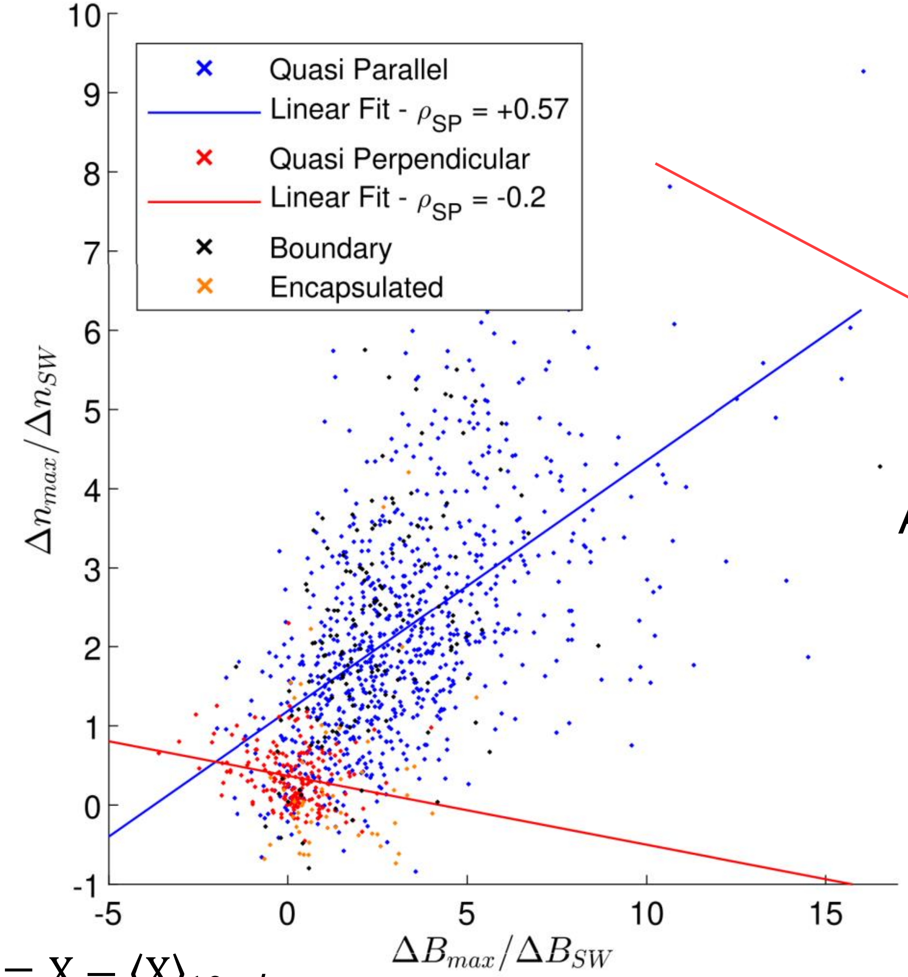
Close to BS, $\rho_{SP} \approx -0.8$



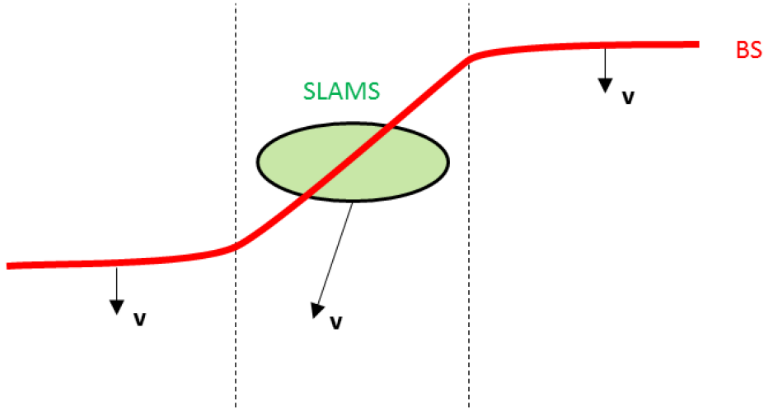
Verdict: Seems to be “supported” requires more careful analysis… (future)

Quasi Parallel Jets – SLAMS

- SLAMS mechanism = Correlation ΔB and Δn



$\Delta X = X - \langle X \rangle_{10min}$

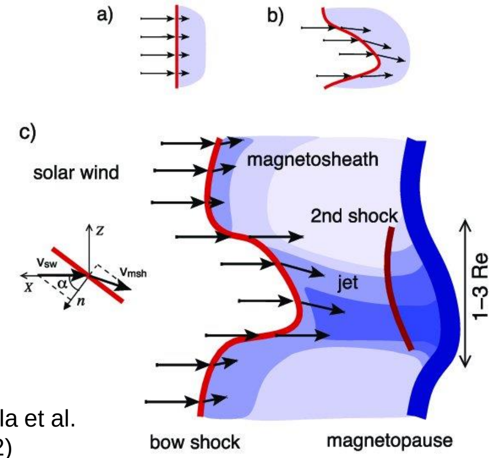


All variations of $\Delta B \backslash \Delta n \sim 0.6$

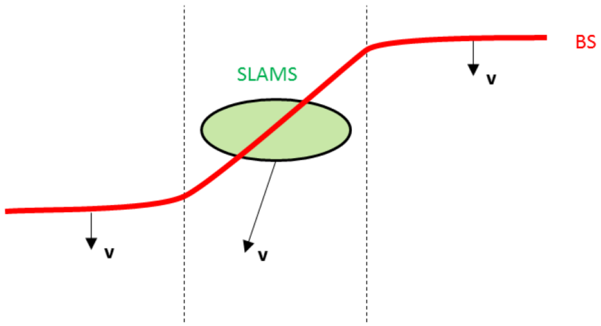
Verdict: Seems to be "supported". Only Qpar and Boundary jets give correlations (cases that we expect SLAMS)… still more work to be done (future)

Mechanisms ideas for each jets

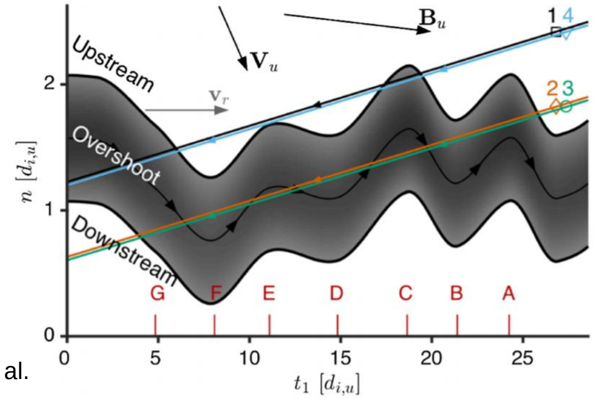
Quasi – Parallel



Hietala et al. (2012)

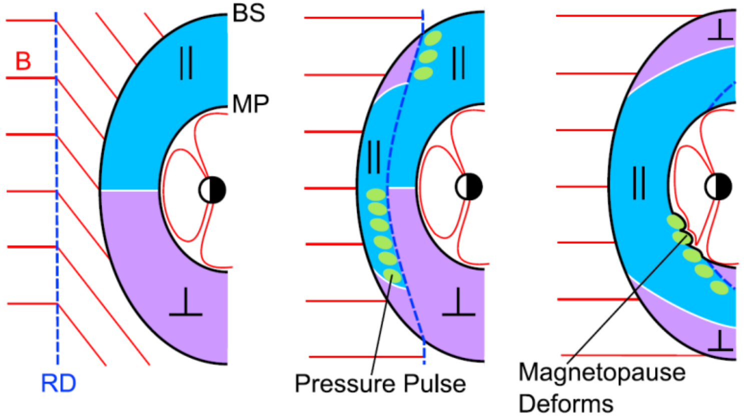


Quasi – Perpendicular



Johlander et al. (2016)

Boundary



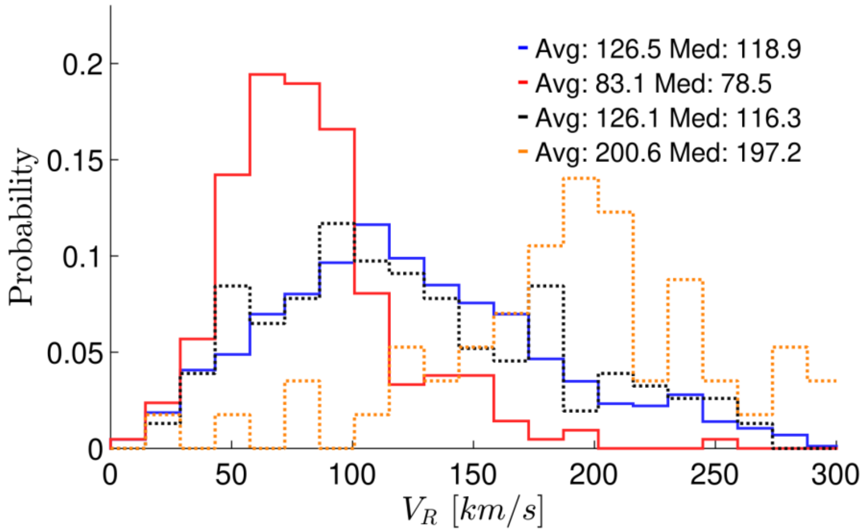
Archer et al. (2012)

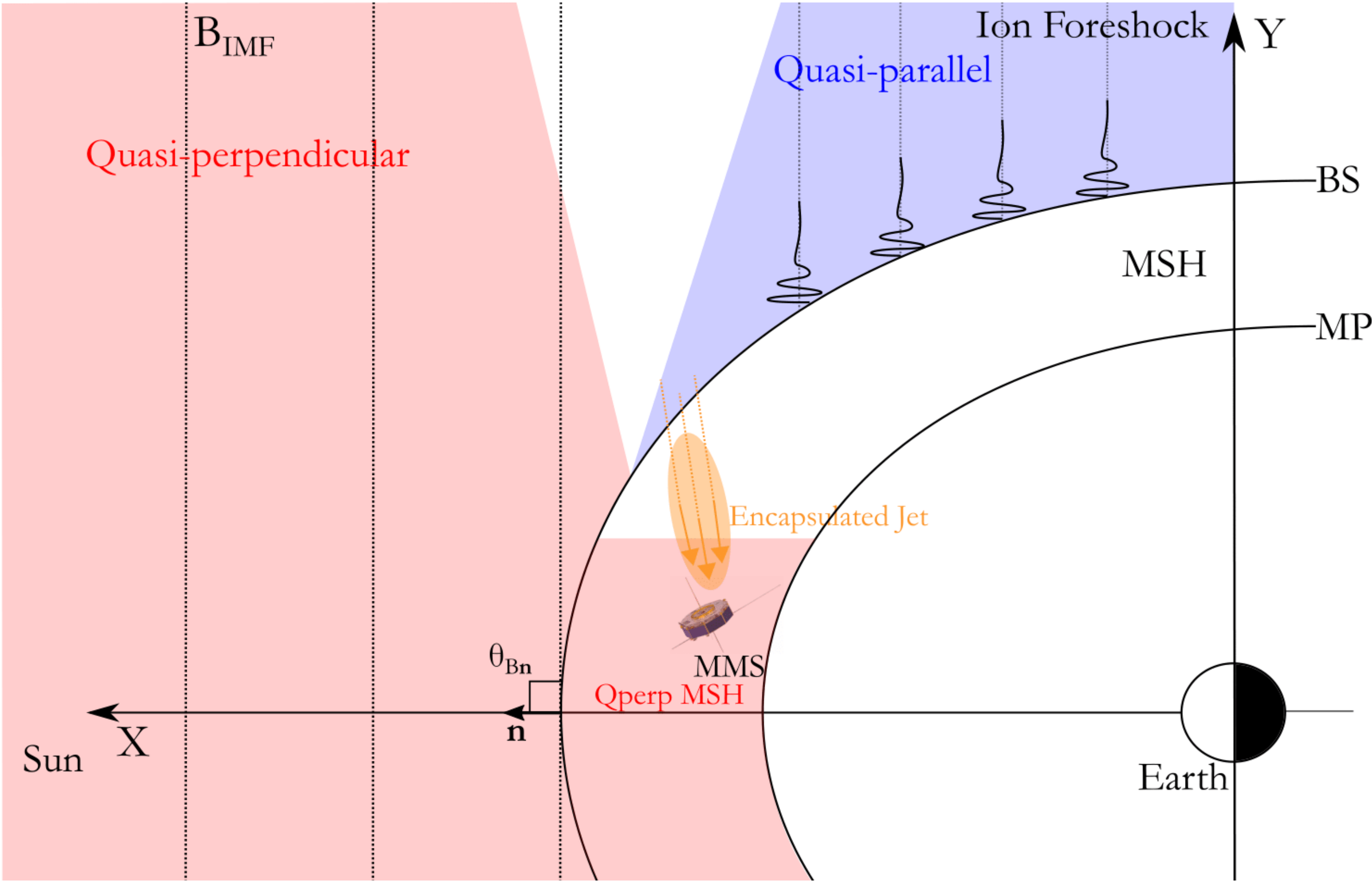
Encapsulated

???

Encapsulated Hypothesis

Quasi-Parallel - Quasi-Perpendicular - Boundary - Encapsulated





1. Qpar like characteristics
2. Different velocity distribution
3. Closer to flanks of bow shock

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	• Quasi-Perp jets exist although weak ✓ • Bow shock ripple mechanism is supported ✓ • SLAMS associated mechanism is supported ✓ Future: See closer to the bow shock. More robust association of ripples and SLAMS to jets	

Part 3:

Machine Learning

Ongoing (Q1 2020)

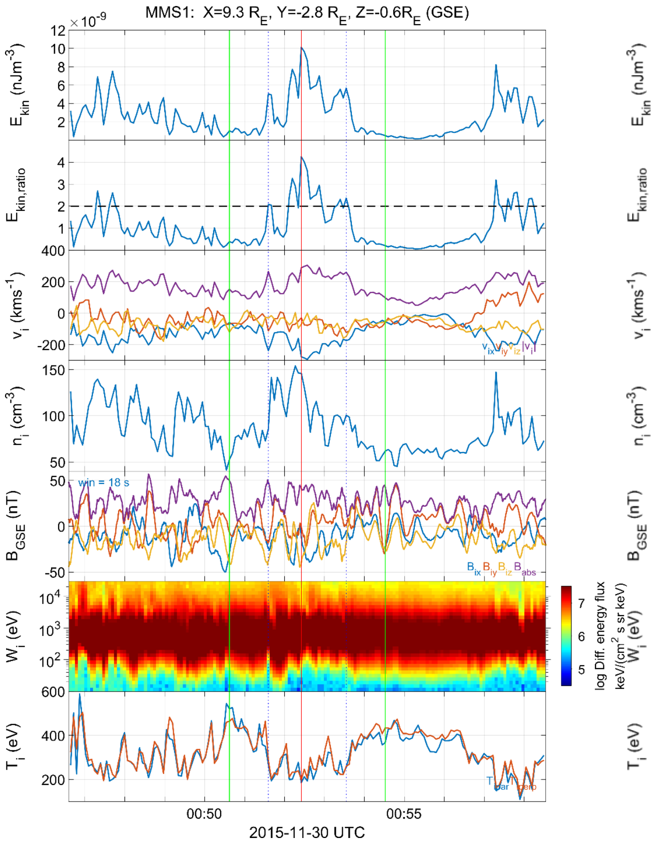
Classification of Magnetosheath Jets using Neural Networks and High Resolution OMNI (HRO) data

Savvas Raptis [1,*], **Sigiava Aminalragia-Giamini** [2] **and Tomas Karlsson** [1]

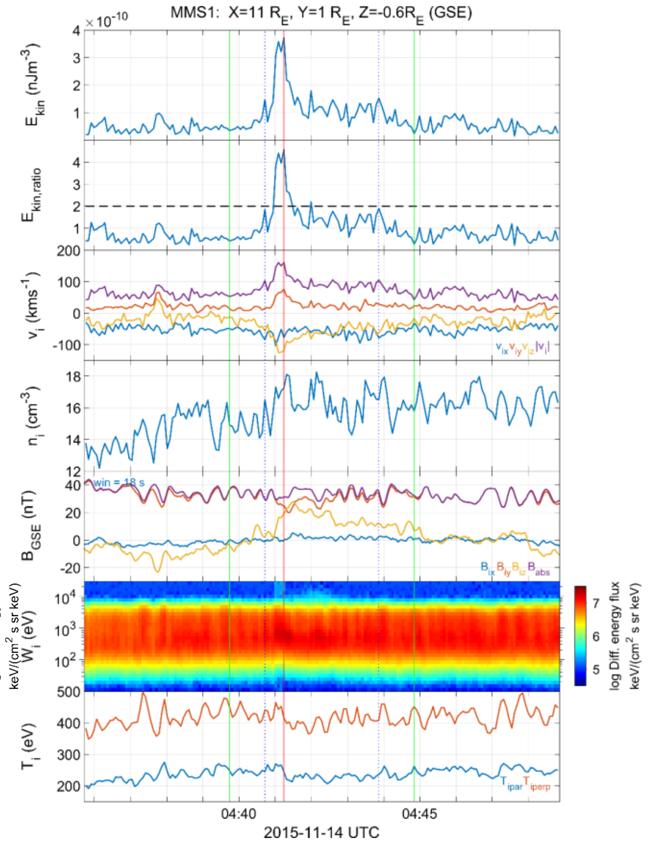
[1] *Division of Space and Plasma Physics, School of Electrical Engineering and Computer Science, KTH Royal Institute of Technology, Stockholm, Sweden*
[2] *Space Applications & Research Consultancy (SPARC), Athens, Greece*

Part 3:
Machine Learning

Main Categories

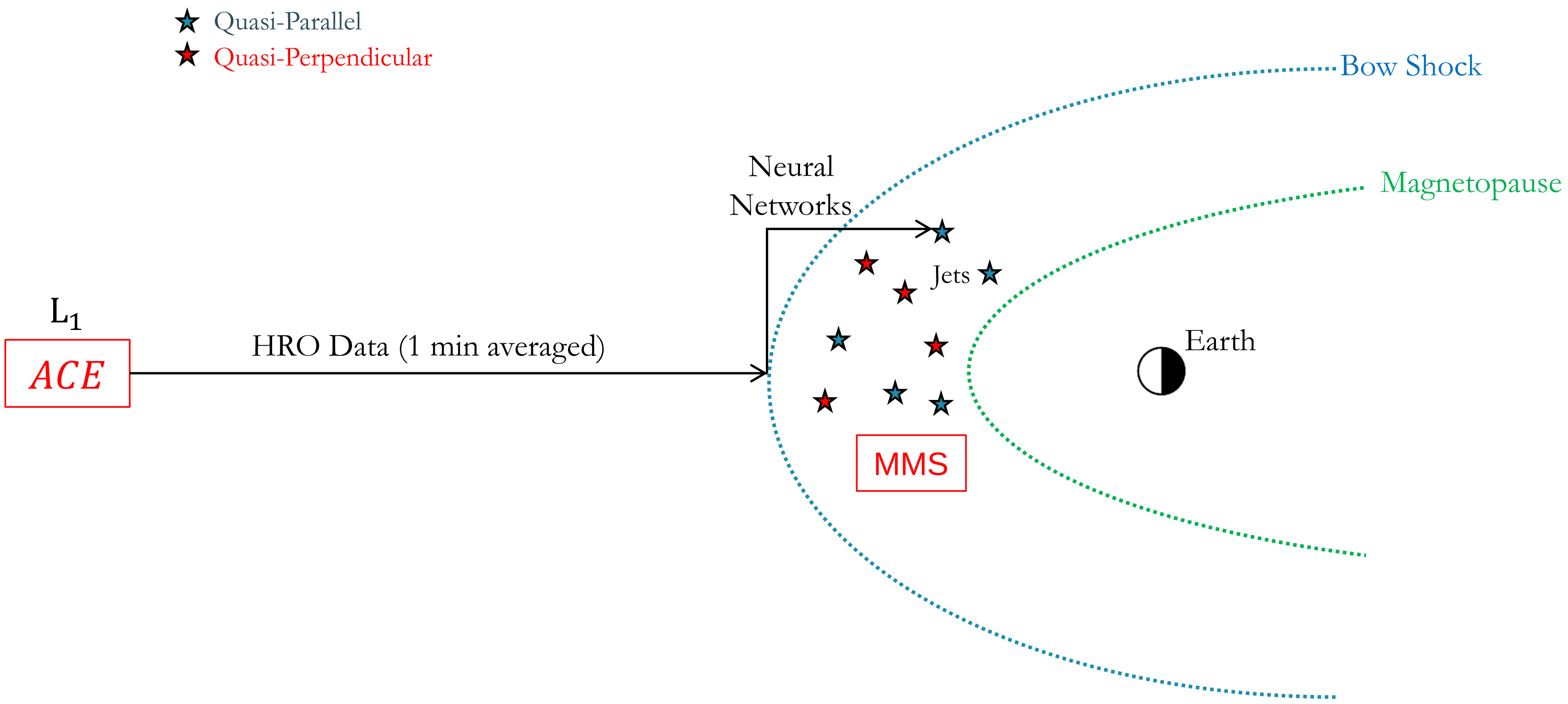


Qpar Jet



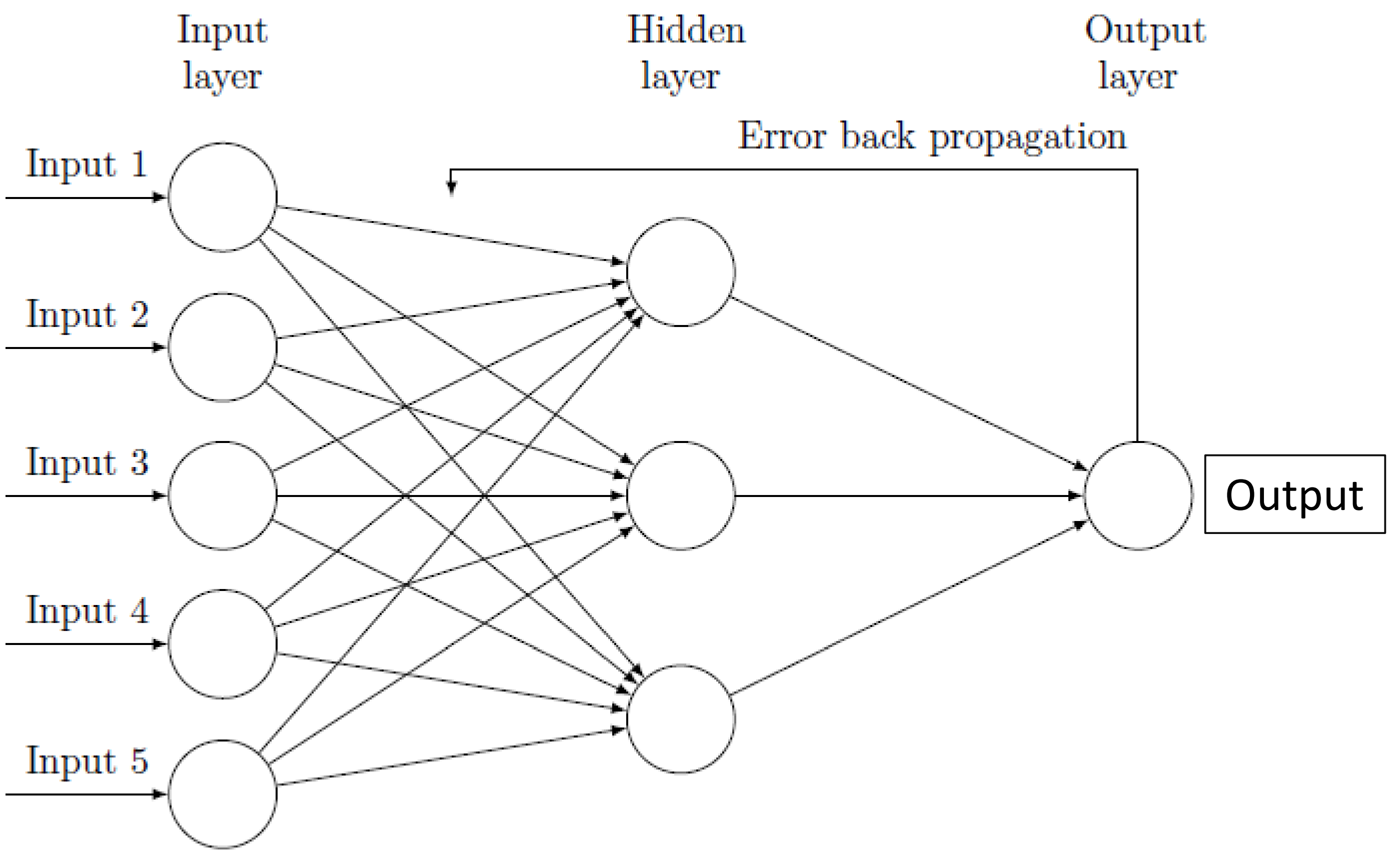
Qperp Jet

Motivation

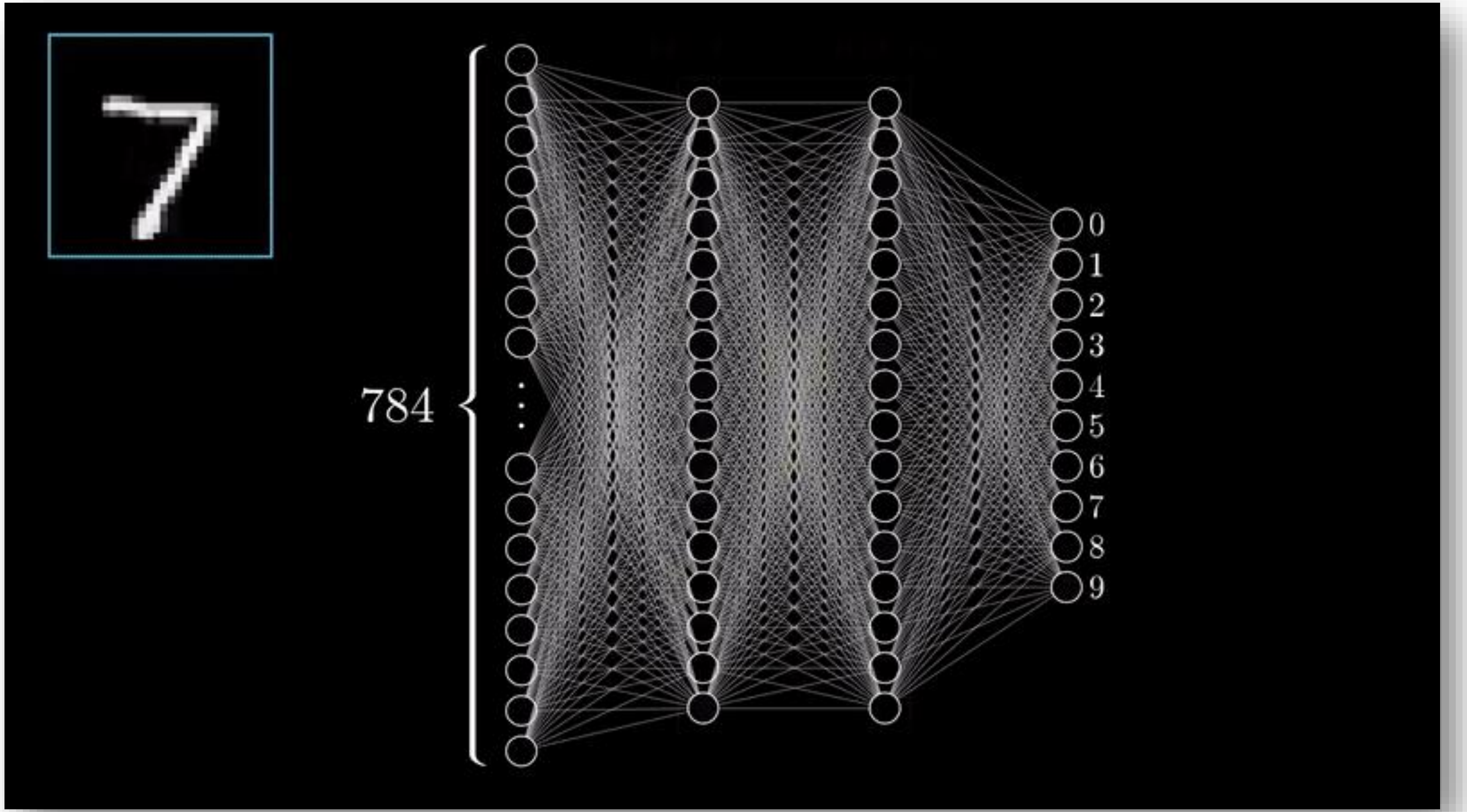


Quasi-Parallel
Quasi-Perpendicular
Bow Shock
Magnetopause
Neural Networks
Jets
L_1
ACE
HRO Data (1 min averaged)
Earth
MMS

Neural Networks & Backpropagation

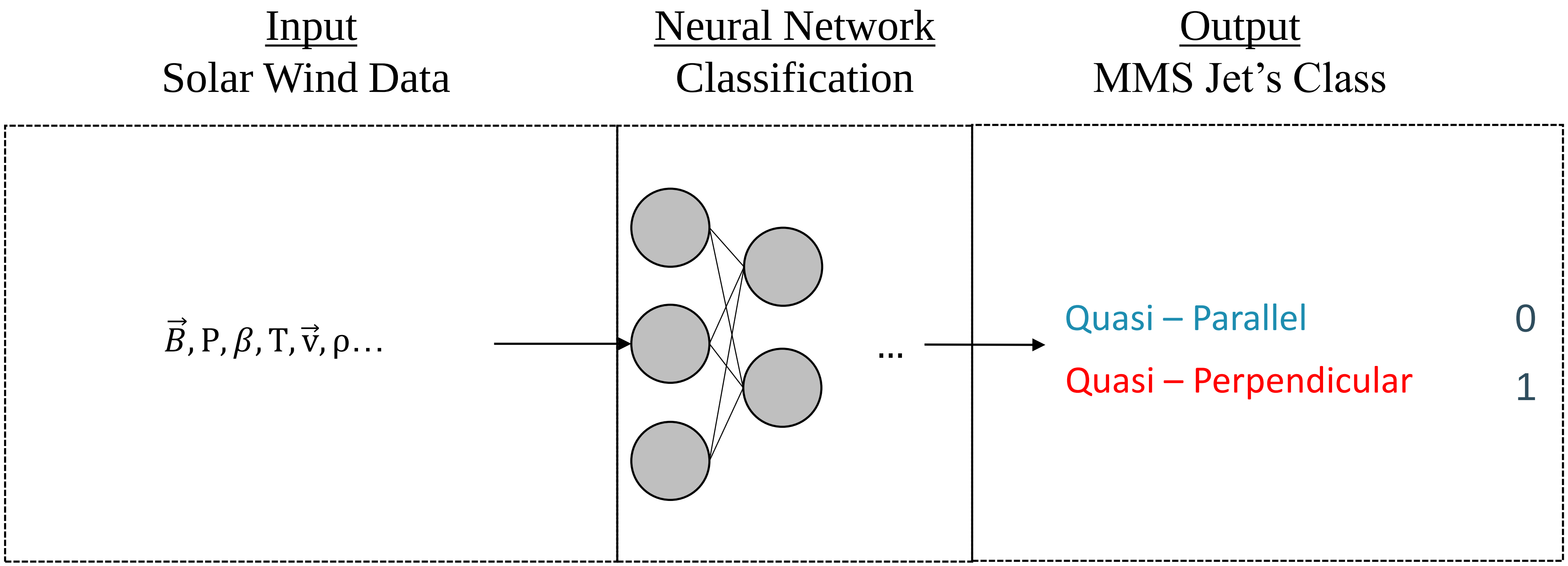


A Trained Neural Network



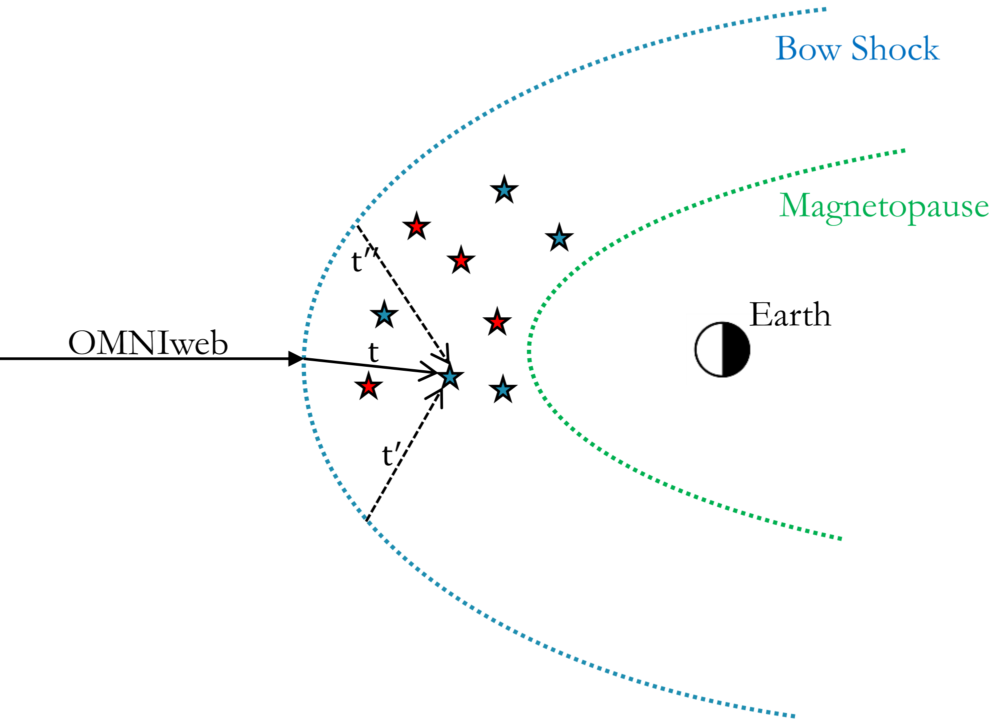
*Video Courtesy: **3Blue1Brown** (Check him on YouTube!)

Schematic of Procedure



Solar Wind --> Magnetosheath

Input (Solar Wind)



- Solar Wind at $t_0 = t_{MMS}$ ✗
- Mean Solar Wind $(t_0 - 10, t_0 + 5)$ ✗
- Mean Solar Wind $(t_0 - 5, t_0)$ ✓
- Max Solar Wind $(t_0 - 5, t_0)$ ✓

Results – Example

$[train, test]$
$[C1, C2]$

	All Jets [2651, 662] [458, 213]		
Mean$(t_0 - 5, t_0)$	360	89	80%
	32	181	86%

Results – Example

Input

	All Jets [2651, 662] [458, 213]		
Mean$(t_0 - 5, t_0)$	360	89	80%
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Results – Example

	<u>All Jets</u> [2651, 662] [458, 213]
Mean$(t_0 - 5, t_0)$	360 | 89 — 32 | 181 — $\frac{80\%}{86\%}$

360	89	80%
32	181	86%

True	False	Acc_1
False	True	Acc_2

Results – Classification Accuracies

		Certain Jets [728, 181] [139, 42]		
✓	Mean$(t_0 - 5, t_0)$	135	4	97%
		2	40	95%
✗	Max$(t_0 - 5, t_0)$	131	8	94%
		4	38	90%

Results – Comparison to Traditional Methods

	Machine Learning		Physical Methods		
	NN – With $\vec{B}$	NN – Without $\vec{B}$	Coplanary Method	Cone angle approx.	Θ_{Bn} modeling
$Q_{\parallel}$			81%	61%	71%
$Q_{\perp}$			93%	94%	88%

$Q_{\parallel}$ Jets : 860
$Q_{\perp}$ Jets : 211

And the winner is………..

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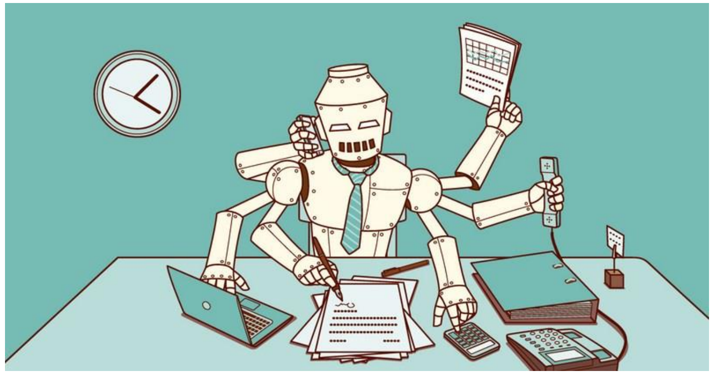

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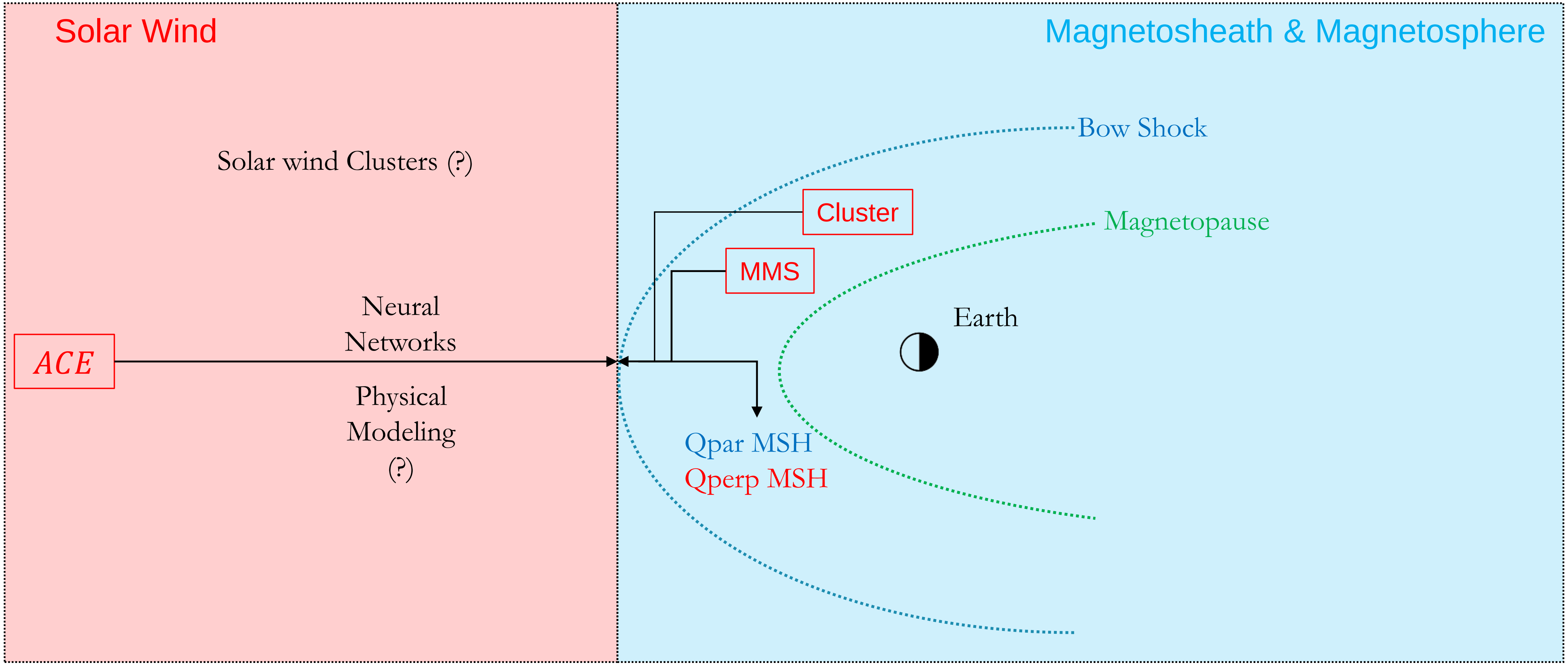
Interesting result!

$Q_{\parallel}$ Jets : 860
$Q_{\perp}$ Jets : 211

Back to Overview

Data vs Simulations	Classification (Data Analysis)	Classification (Machine Learning)
Question: How well can we model magnetosheath jets? Can we verify simulations and then generalize from their result?	Question: Can Jets happen in Quasi-perpendicular bow shocks ? What are the different type of jets ? Do they have different properties? Different generation mechanism?	Question: Can we verify somehow our previous classification? Can Machine learning outperform physical modeling? What is the solar wind doing when jets are happening?
		• Validated database ✓ • Neural Networks outperformed all methods for Θ_{Bn} ✓ • Qperp and Qpar jets happen under different SW ✓ Future: Why different solar wind ? Physical reasons ? Unsupervised learning …

Work in progress …



Take home Message

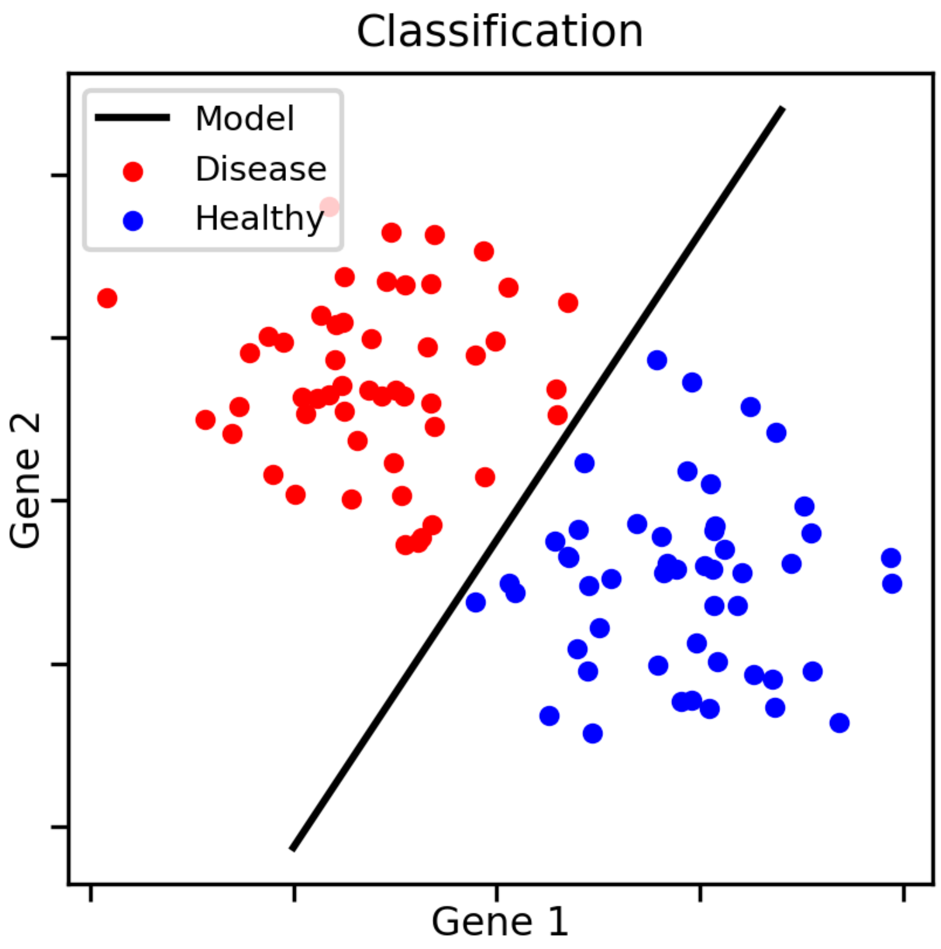
1. Magnetosheath **Jets** are very important and an interesting topic to do research.

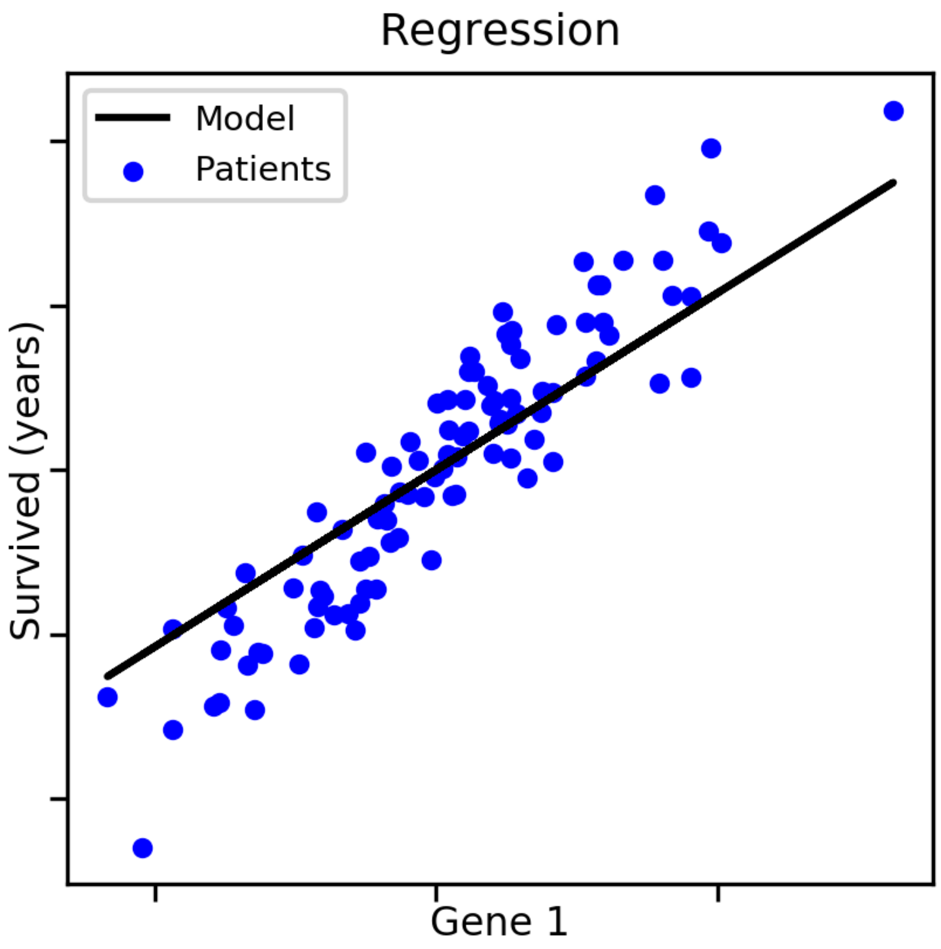
2. For every space phenomenon there are **many different ways to conduct research**, Theory, Data, Simulations, Machine learning etc.

Extras

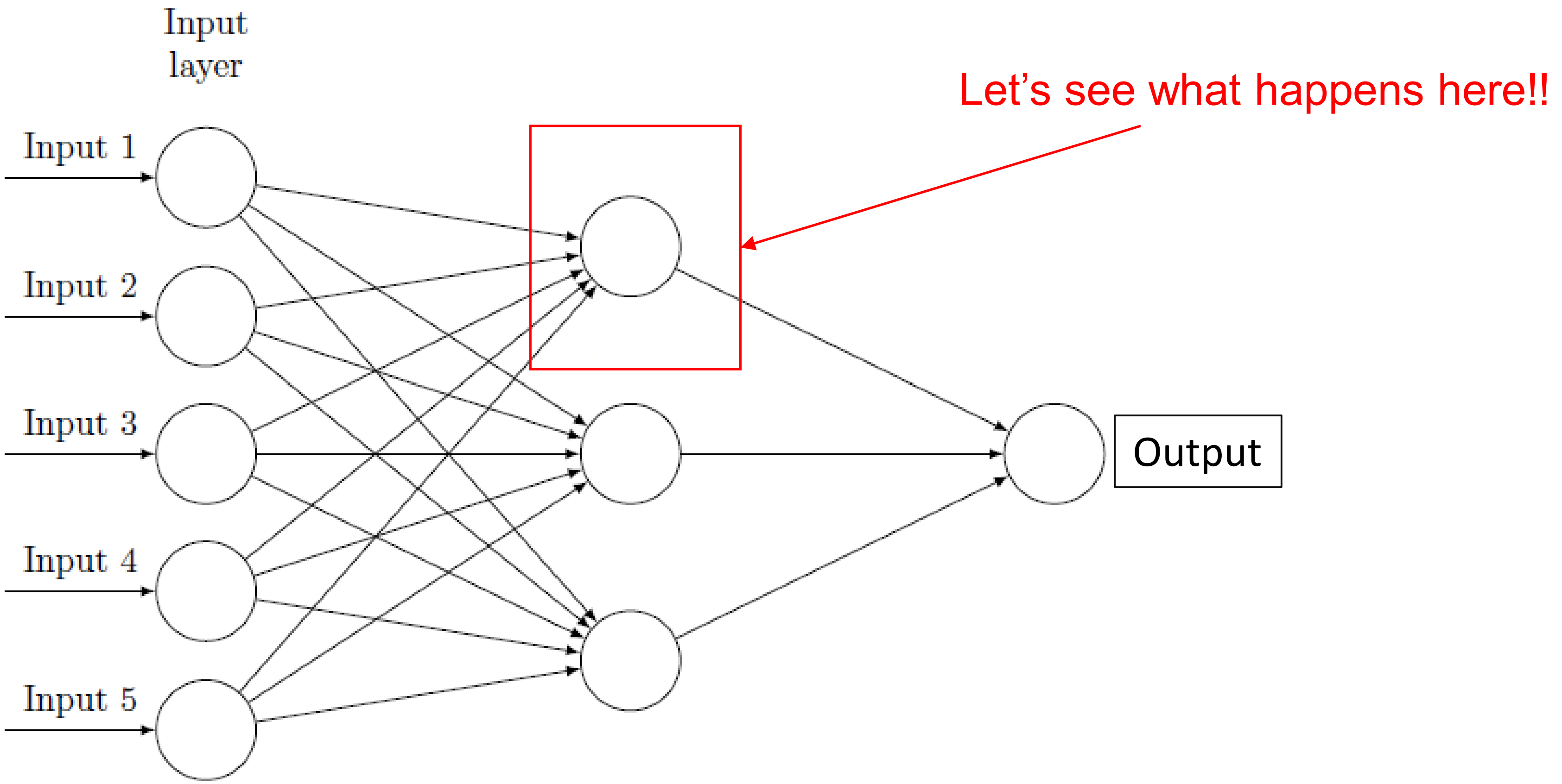
Neural Networks

(Main) Types of Machine Learning Problems





Neural Networks



A Neural Network Input and Output

$$y = f(x_1 w_1 + x_2 w_2 + \cdots + x_n w_n + b)$$

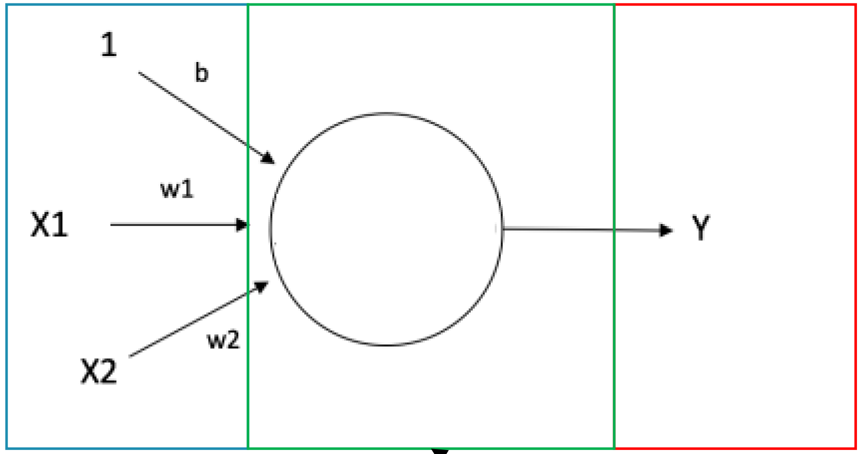
y : Output of Neuron

x_i: Inputs of Neuron

w_i: Weights of each Input

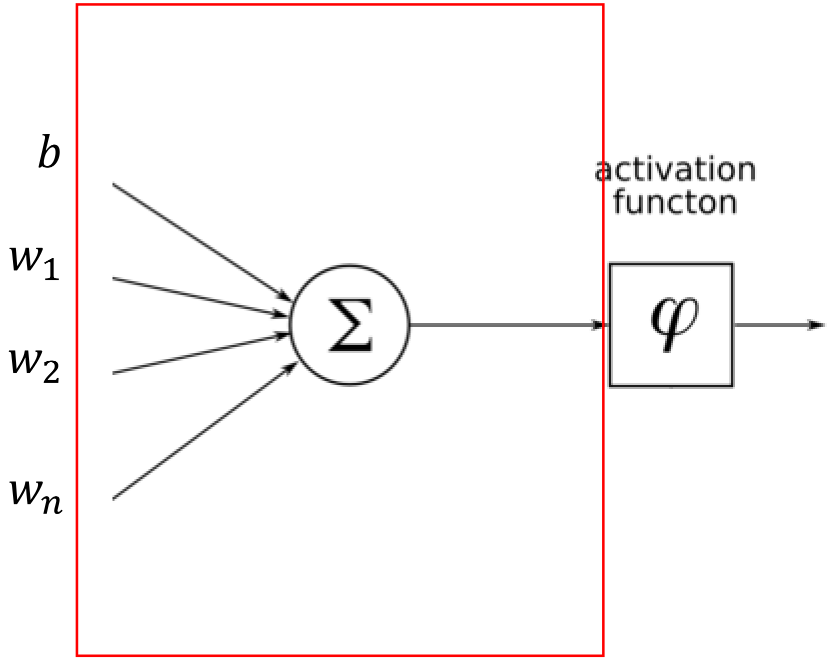
b : bias for each neuron

Random Numbers



Magic happens here

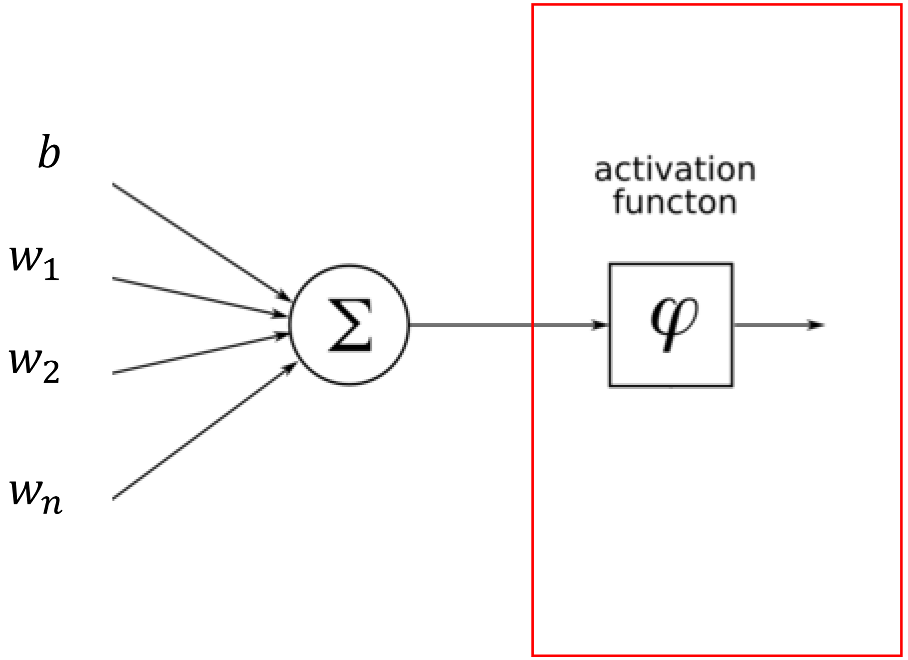
Activation Function



Sum of all Data(x_i), Weights (w_i) and Biases (b)

$$z = \sum x_i w_i + b$$

Activation Function

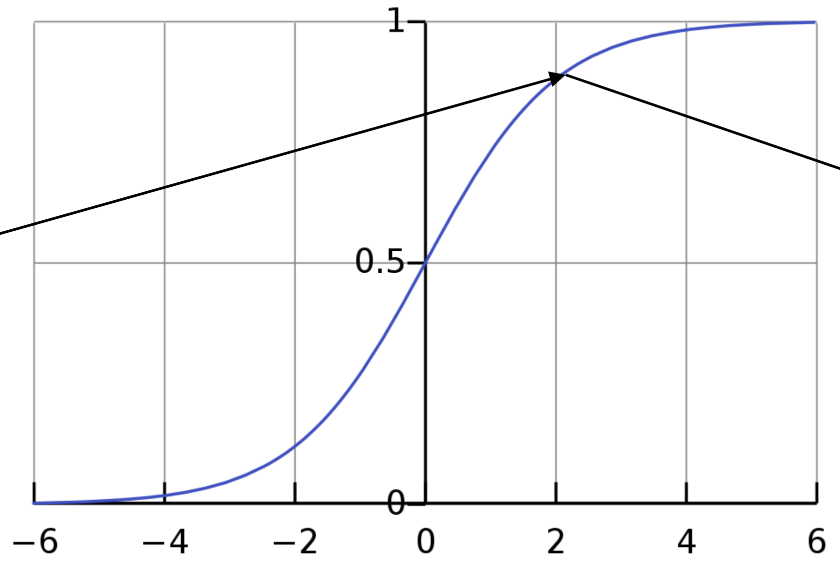


Apply $f(z)$ depending on **goal**

Activation function Examples

Goal: Classification

$\sum x_i w_i + b = 2$

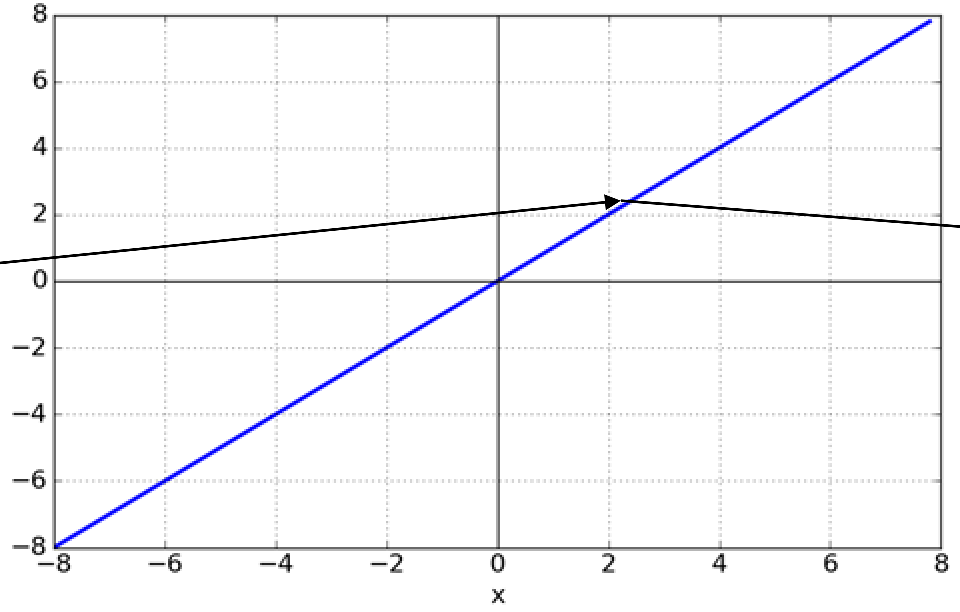


$y = 0.8 \rightarrow Class\ 1$

Activation function Examples

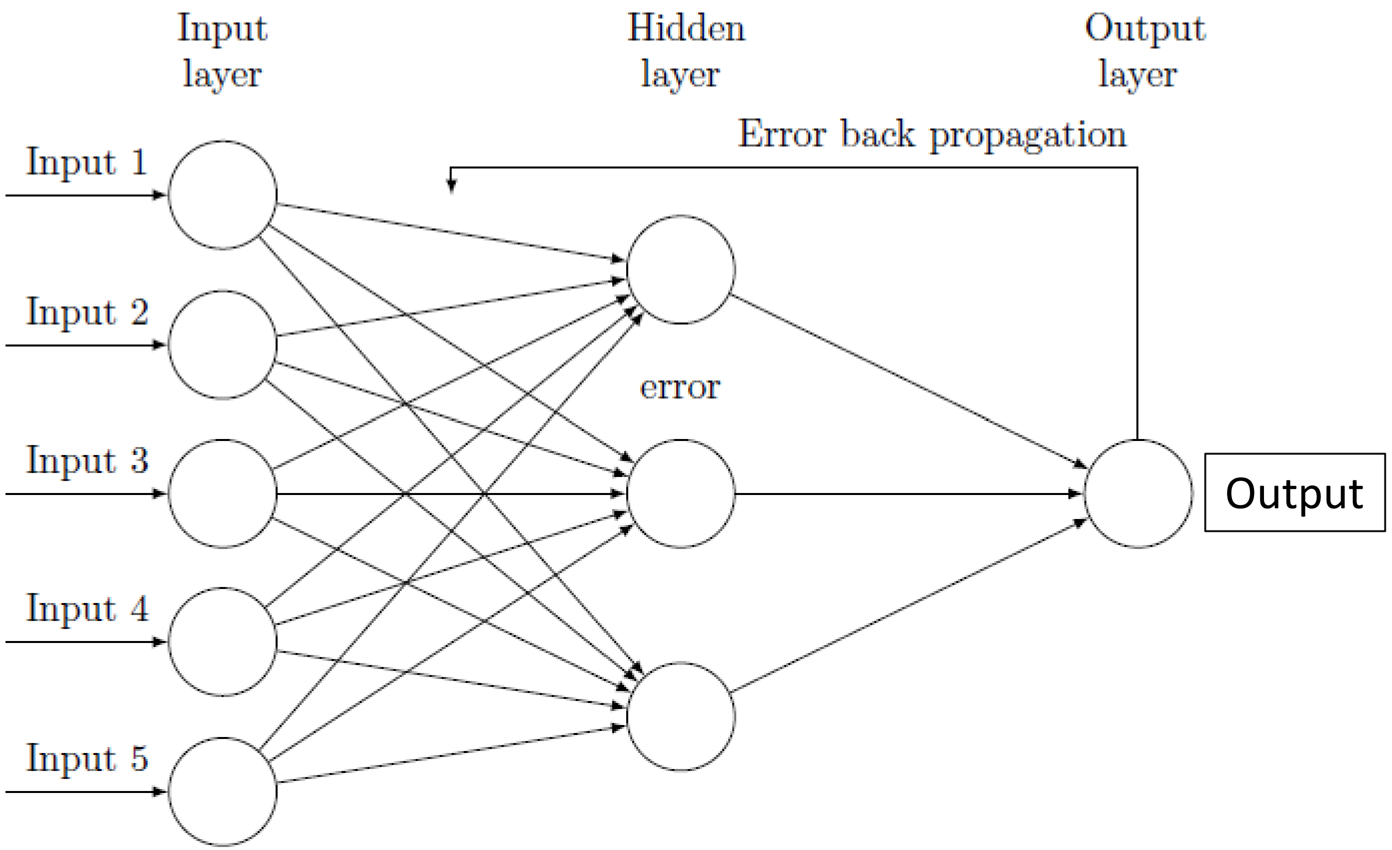
<u>Goal</u>: Regression

$$\sum x_i w_i + b = 2$$

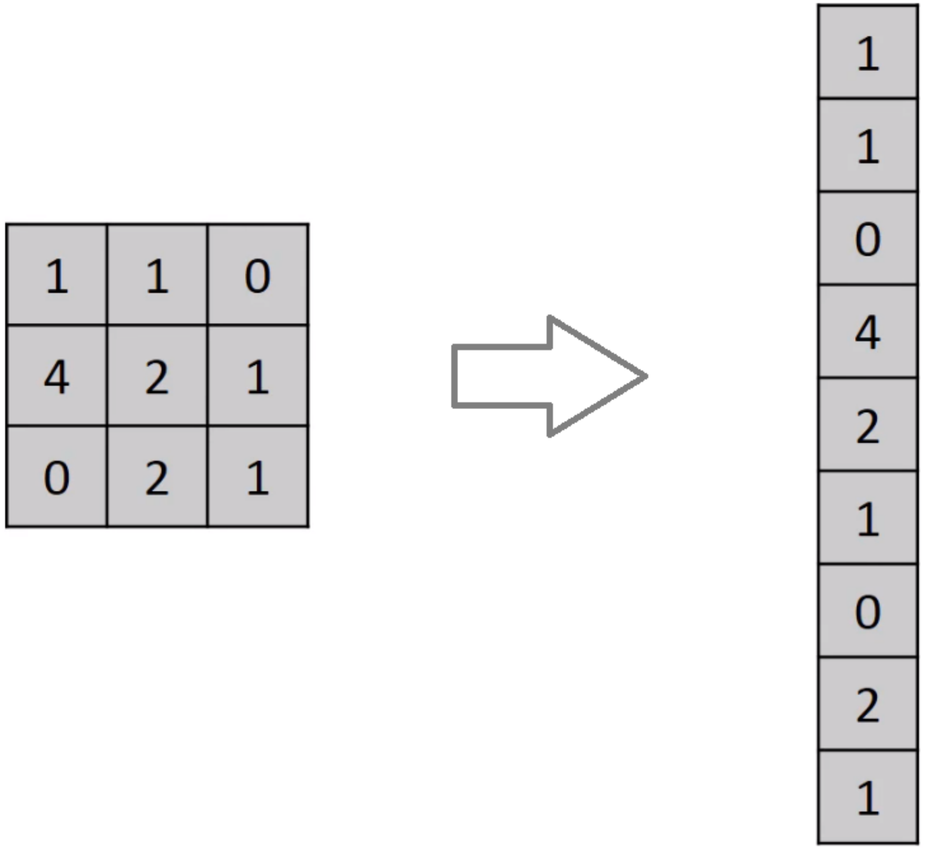


$$y = 2$$

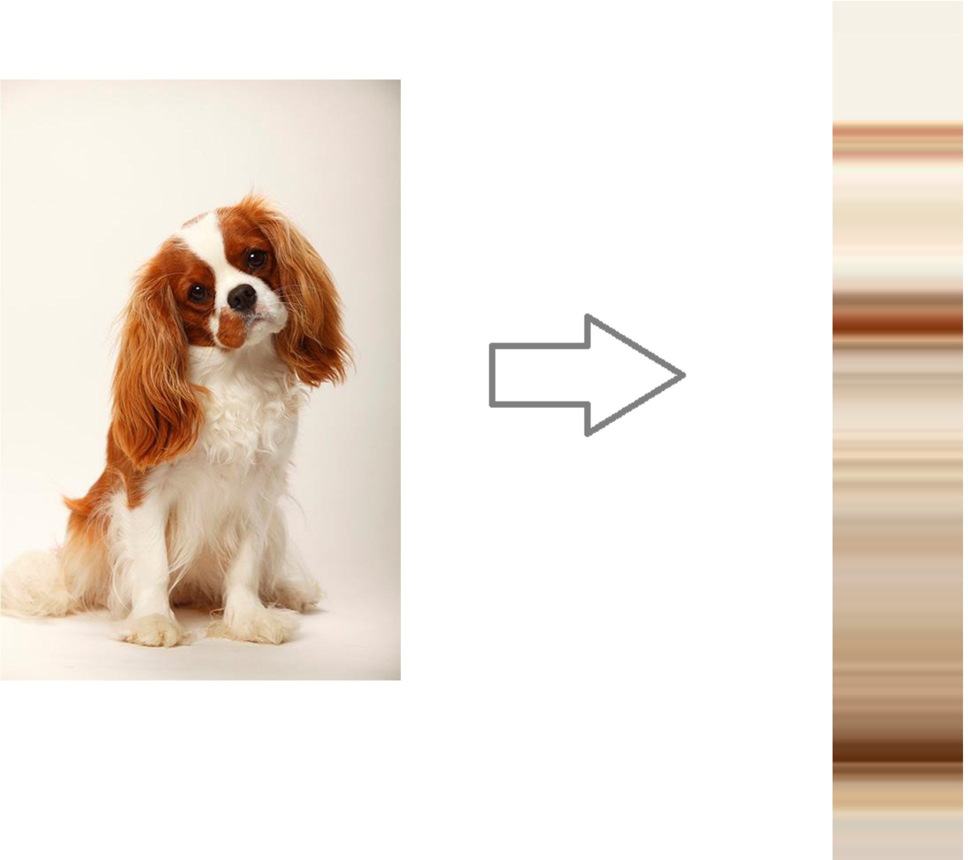
Neural Networks & Backpropagation



Neural Networks with Images



Neural Networks with Images – Dog example



Convolution Neural Networks

Convolution Neural Network (CNN) Layers

<u>Convolution</u>
Extract features & Keep spatial relationship

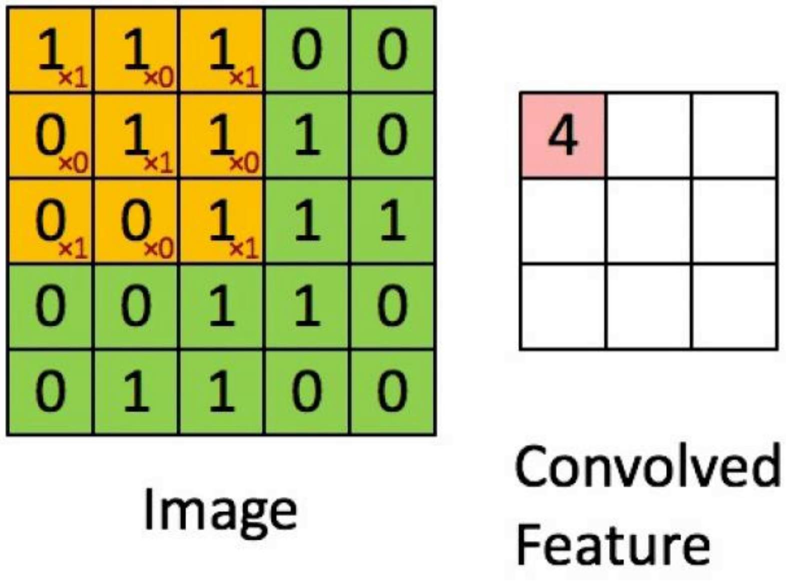


*Figure Courtesy: Erik Reppel

<u>Pooling/Subsampling</u>
Reduce dimensionality & retain information

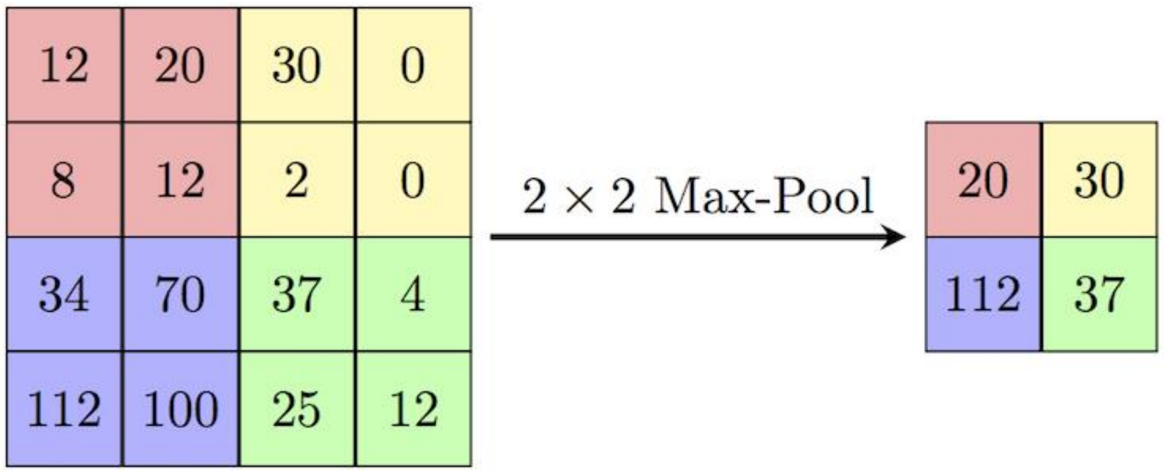


*Figure Courtesy: Cambridge Spark Ltd

Example of CNN

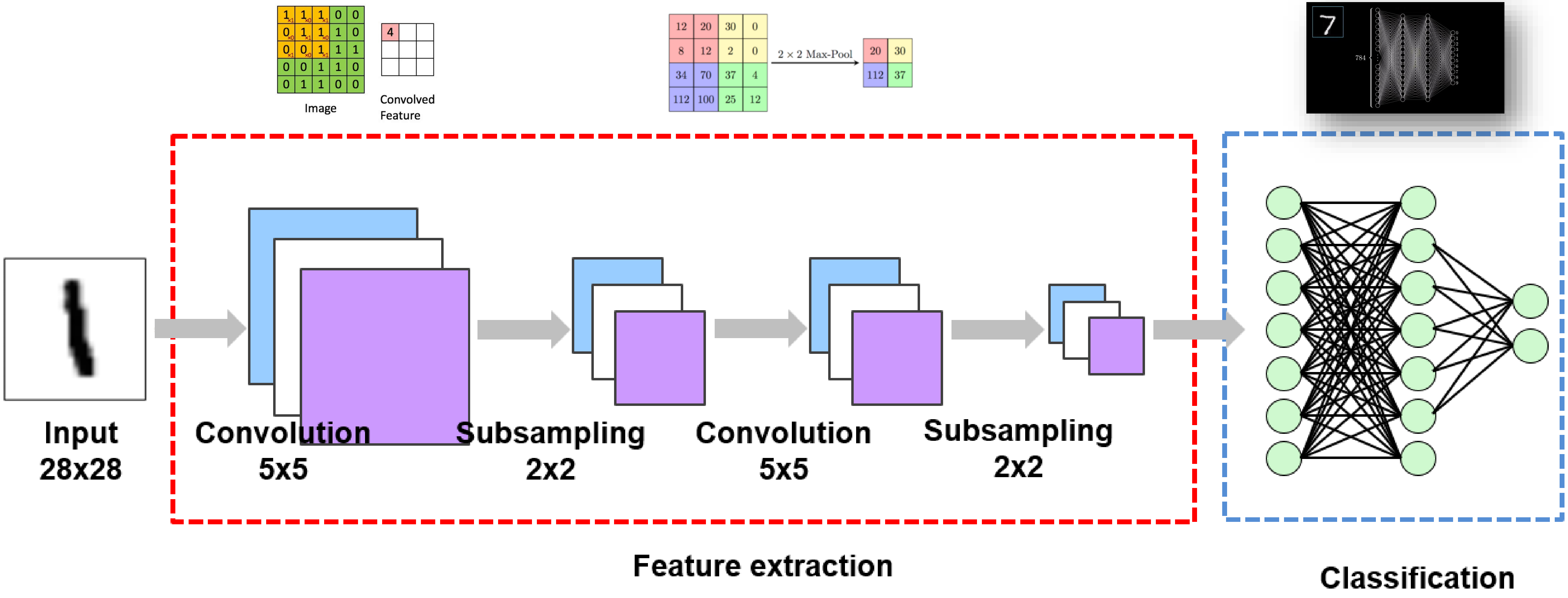
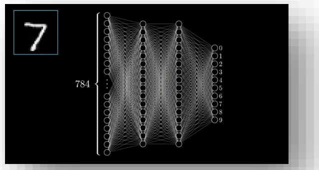


*Figure Courtesy: Suhyun Kim iSystems Design Labs

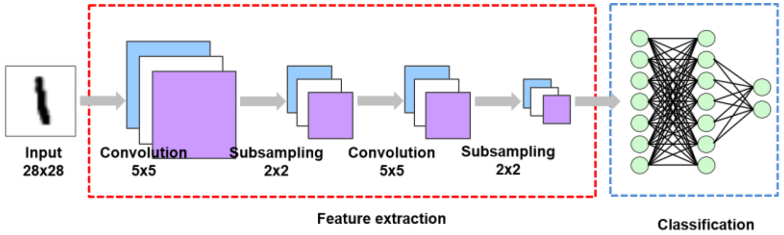
NN vs CNN

Input: MNIST database



Neural Network Result:

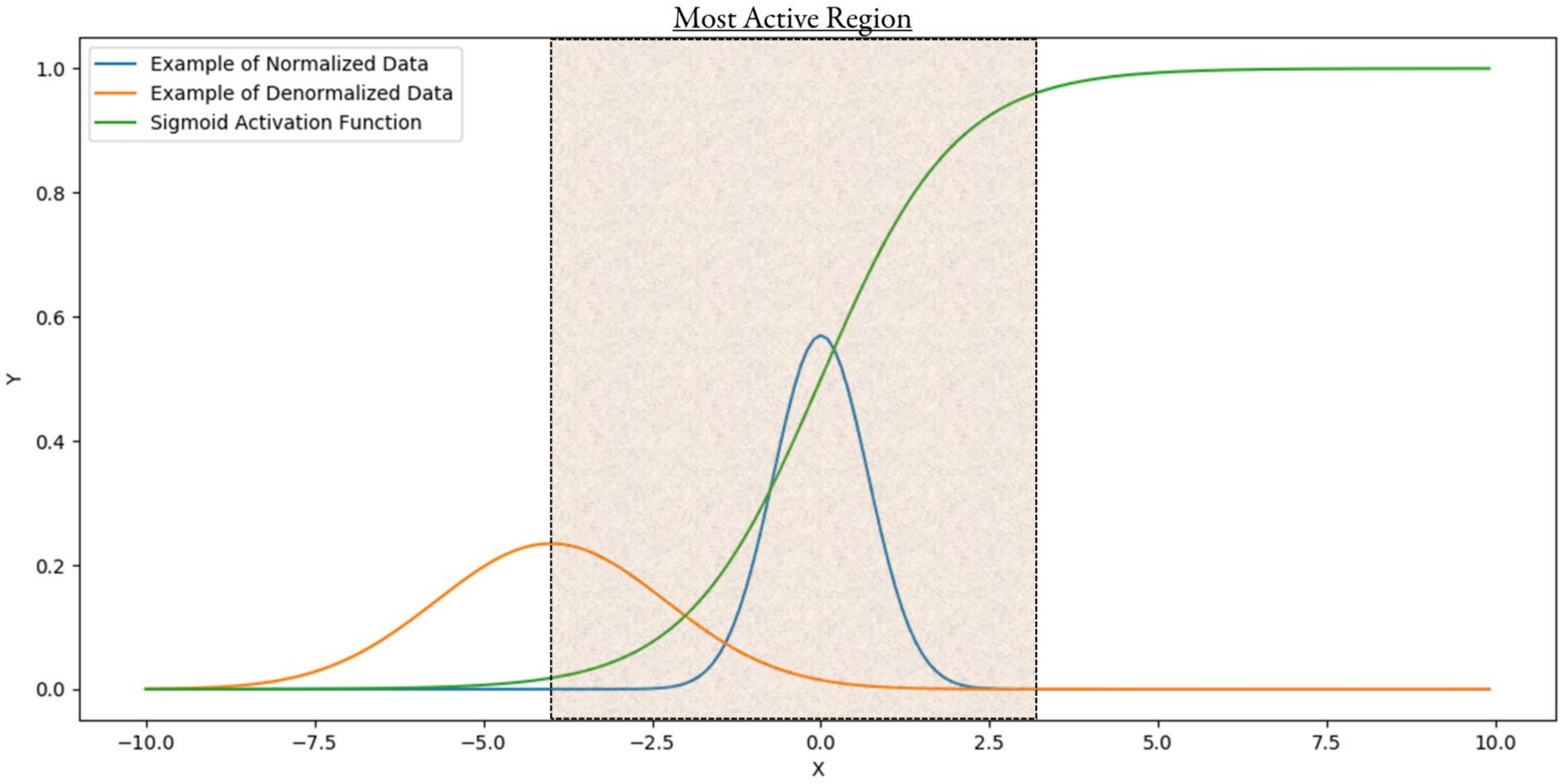
97.3%



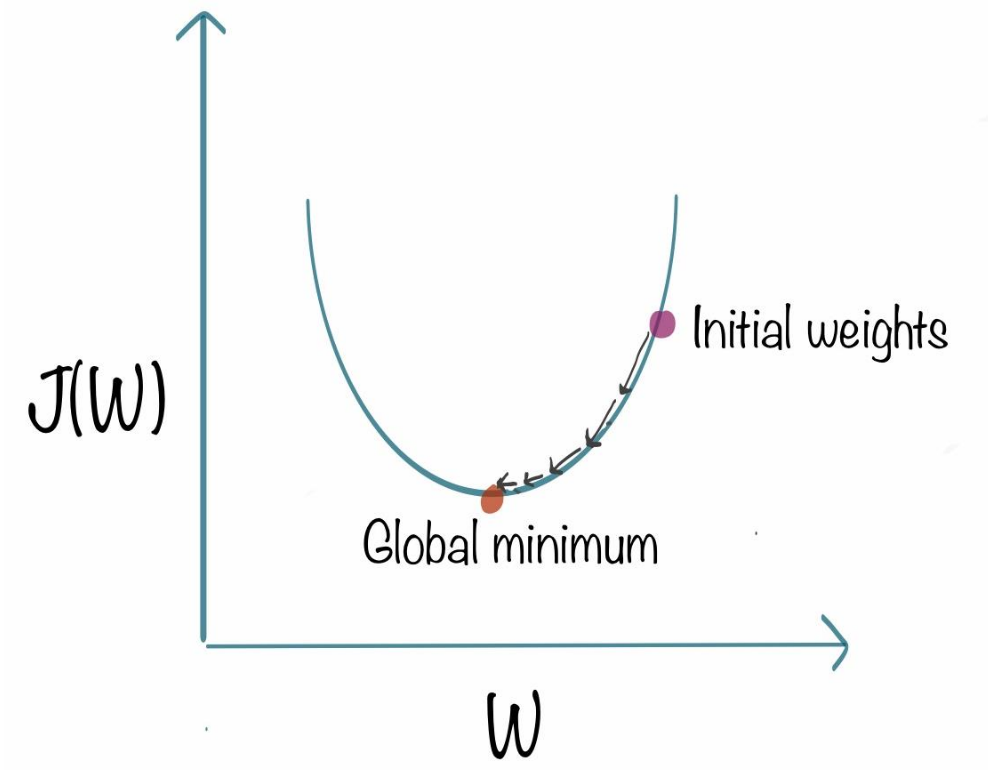
Convolution Neural Network Result:

99.07%

Why normalization is vital?



Gradient Descent - Training



Loss Function/Error:

$$E = \frac{1}{2}\sum_i (a_i - t_i)^2$$

Advanced Activation functions

Goal → Complexity

Non-linear activations (Hidden Layers)