JOHNS HOPKINS
APPLIED PHYSICS LABORATORY

Stormtime Plasma Sheet
Recent, Ongoing, & Future efforts

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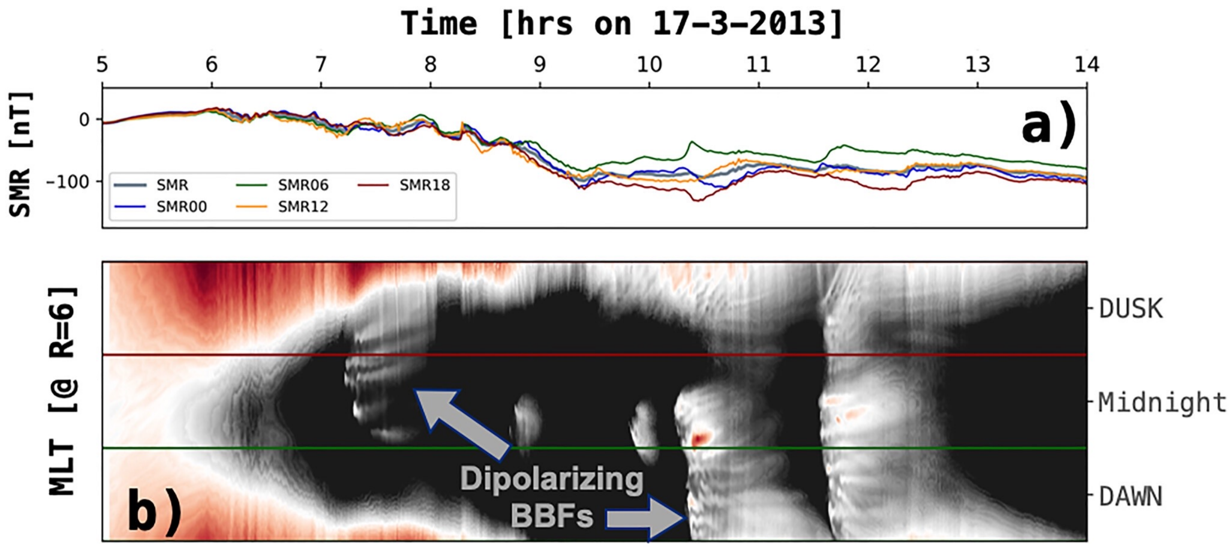
CGS | CENTER FOR GEOSPACE STORMS

Outline

- Global Convection Patterns of Magnetic Flux (1 published)
  - Question: How does convection in the magnetotail change during storms and how it affects magnetic flux transport
- Bursty Interval Contribution and Dawn/Dusk Asymmetries (1 “almost”* accepted + 1 ongoing)
  - Question: Is the occurrence distribution of BBFs different during storms? How much they contribute to flux transport and how do their properties change during storms?
- Machine Learning modeling of in-situ properties (1 “almost”* submitted)
  - Question: can we use SW information and ground magnetometers to model plasmasheet properties? How this changes during storms
- Future Work Ideas

*Very different definitions of “almost”

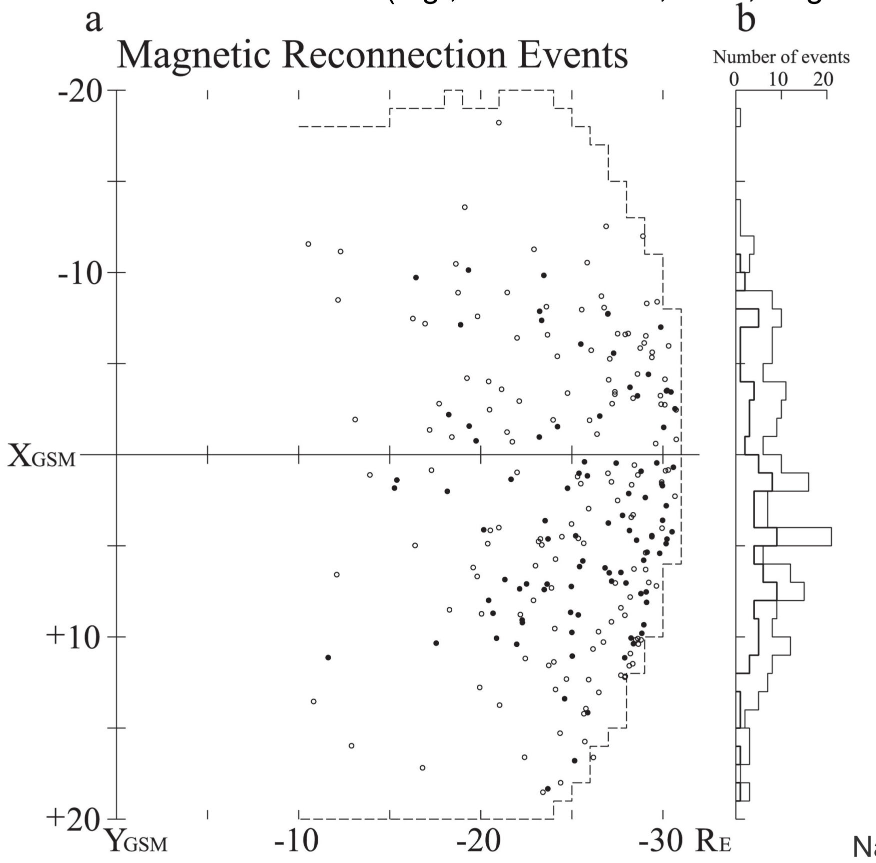
Dawnside Current Wedge & Asymmetries in Magnetopause Reconnection



Ohtani+ 2021,2024, Sorathia+ 2023

Dawnside Current Wedge is a distinct storm-time phenomenon associated **with increased westward auroral electrojet (AEJ) at the dawn sector**.

*Similar results with MMS (e.g., Hubbert et al., 2022; Rogers et al., 2023).

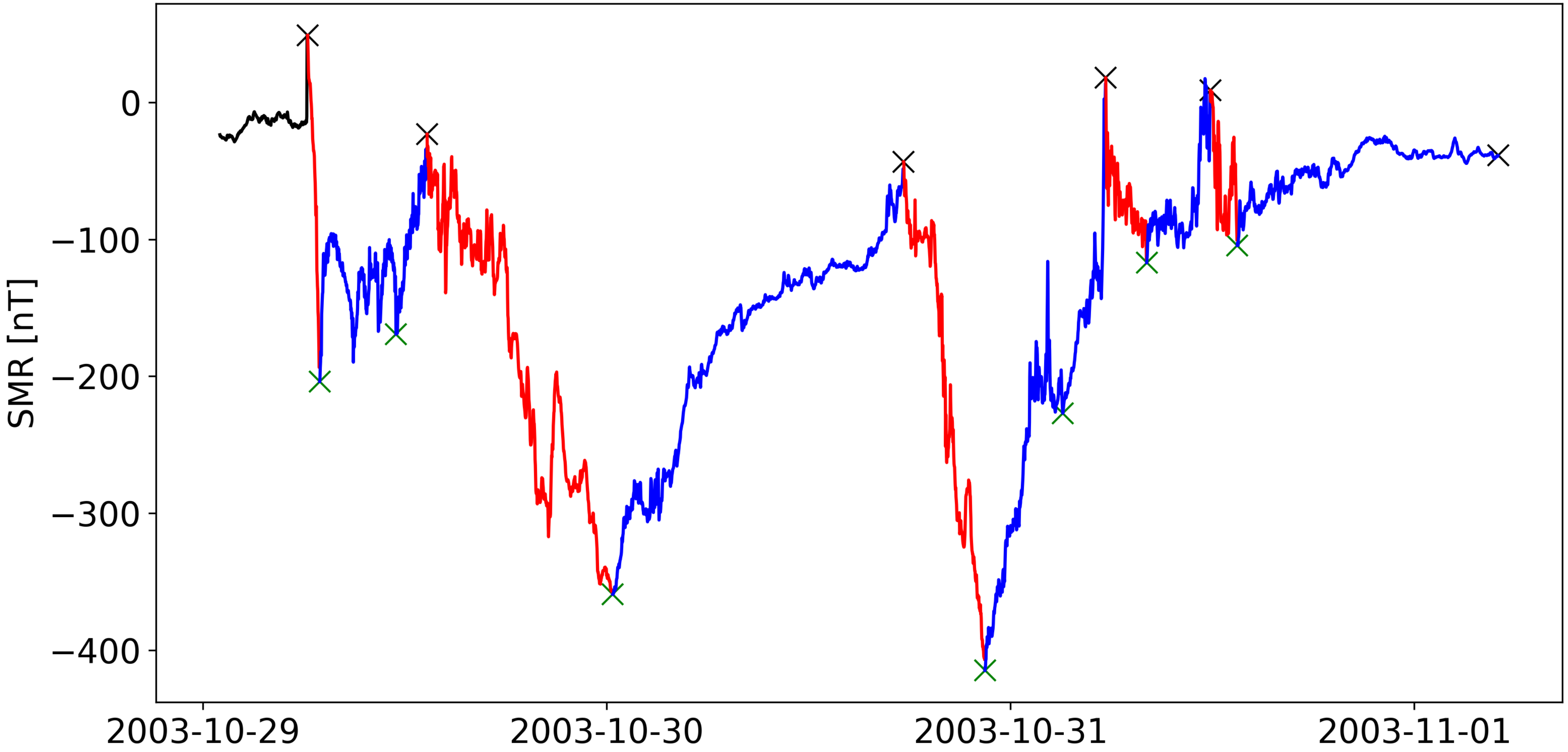


Nagai+ 2023

Magnetotail reconnection site is spatially skewed toward the dusk (pre-midnight) sector during typical activity, **<u>but</u>** this distribution shifts dawnward when the magnetosphere is being driven intensely (such as during major storms).

Needed Step: Storm phases classification

(semi)-automatic storm finder and classifier:



List is open, easy to use, easy to maintain

https://zenodo.org/records/15127938
(v3 updated to 2025, NOT manually verified)

Plasmasheet Coverage per mission

<u>Criteria to find CSP</u>

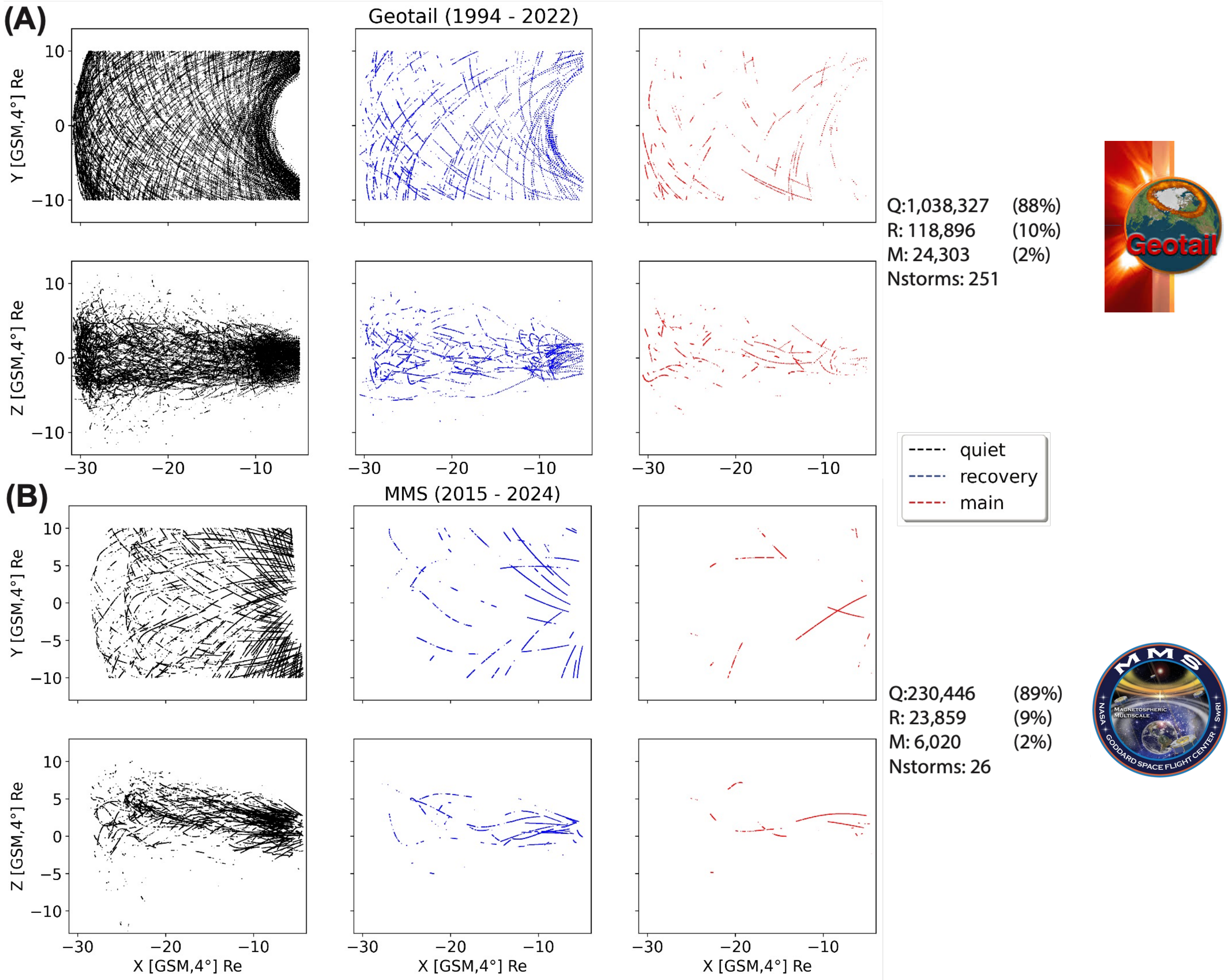
1. $|Y_{GSM,4°}| < 10$
2. $-5 < X_{GSM,4°} < -31$
3. $\beta = \frac{P_{the}}{P_{mag}} > 1$
4. $|Bz| > 2\sqrt{Bx^2 + By^2}$

See e.g., Ohtani+ 2008, Guild+ 2008, Roziers+ 2009, Vo+ 2023

Geotail > 1 million points ~250 storms
MMS ~ 250k points ~25 storms

<u>Findings:</u>

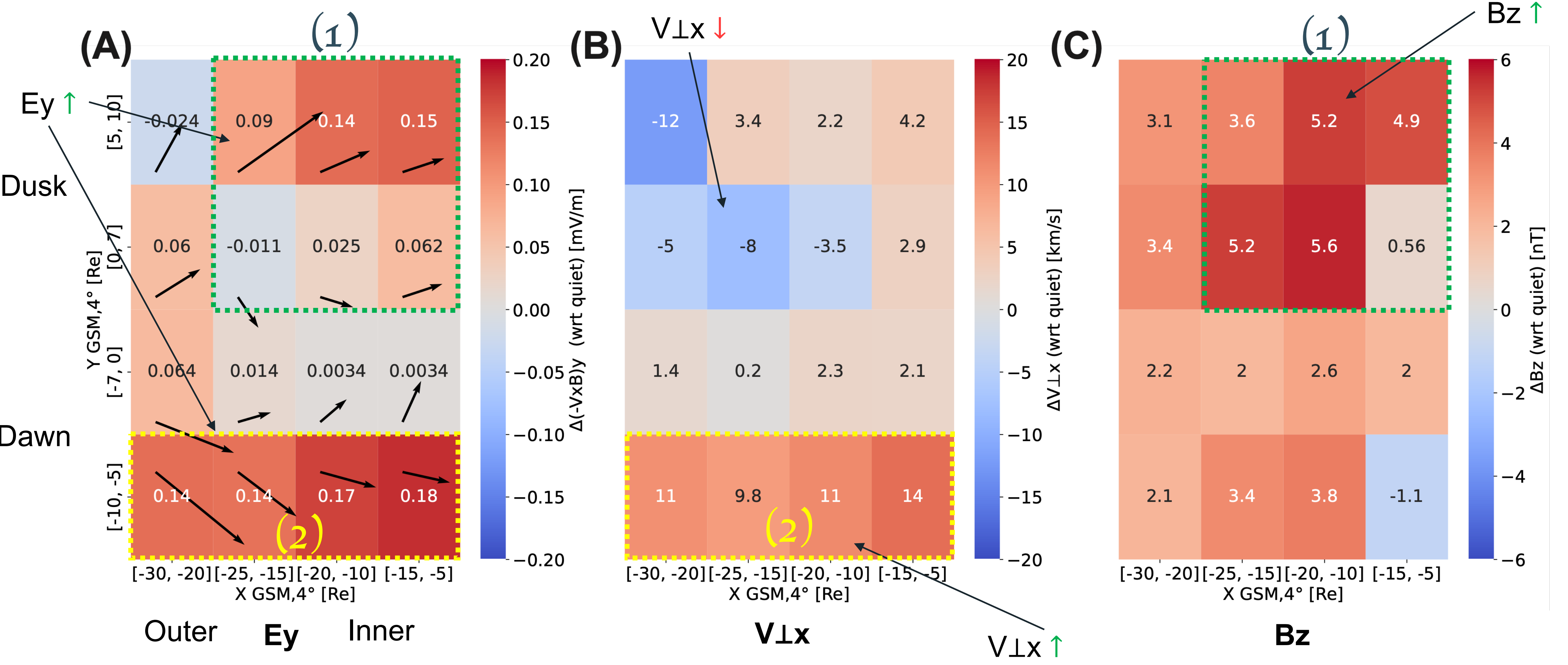
1. **MMS** have limited observations during storm times (especially main phase)
2. Main phase contains data from about 6 storms for **MMS**
3. Slightly more dawnside data during main phase for **Geotail**



Raptis+ 2024 | GRL

Storm - Main Phase Difference (Geotail | 1994 - 2022)

Dawn sector: storm-time magnetic flux transport linked to **faster plasma flows**
Dusk sector: storm-time magnetic flux transport linked to **stronger dipolar magnetic fields**



What do we know so far?

<u>**Plasma sheet storm time:**</u>

1. **Elevated Ey** associated with **increased Bz**, and **limited enhancement of** $V_{\perp x}$

2. **Dusk observations showing more dipolar magnetic field (Bz** ↑)

3. **Dawn** are associated to **relatively faster flow (**$V_{\perp x}$ ↑)

Let’s move to Bursty Intervals!

Bursty intervals (Jets, BBFs, BEIs, etc.) and constrains

Analyzing BBFs statistically is non-trivial:

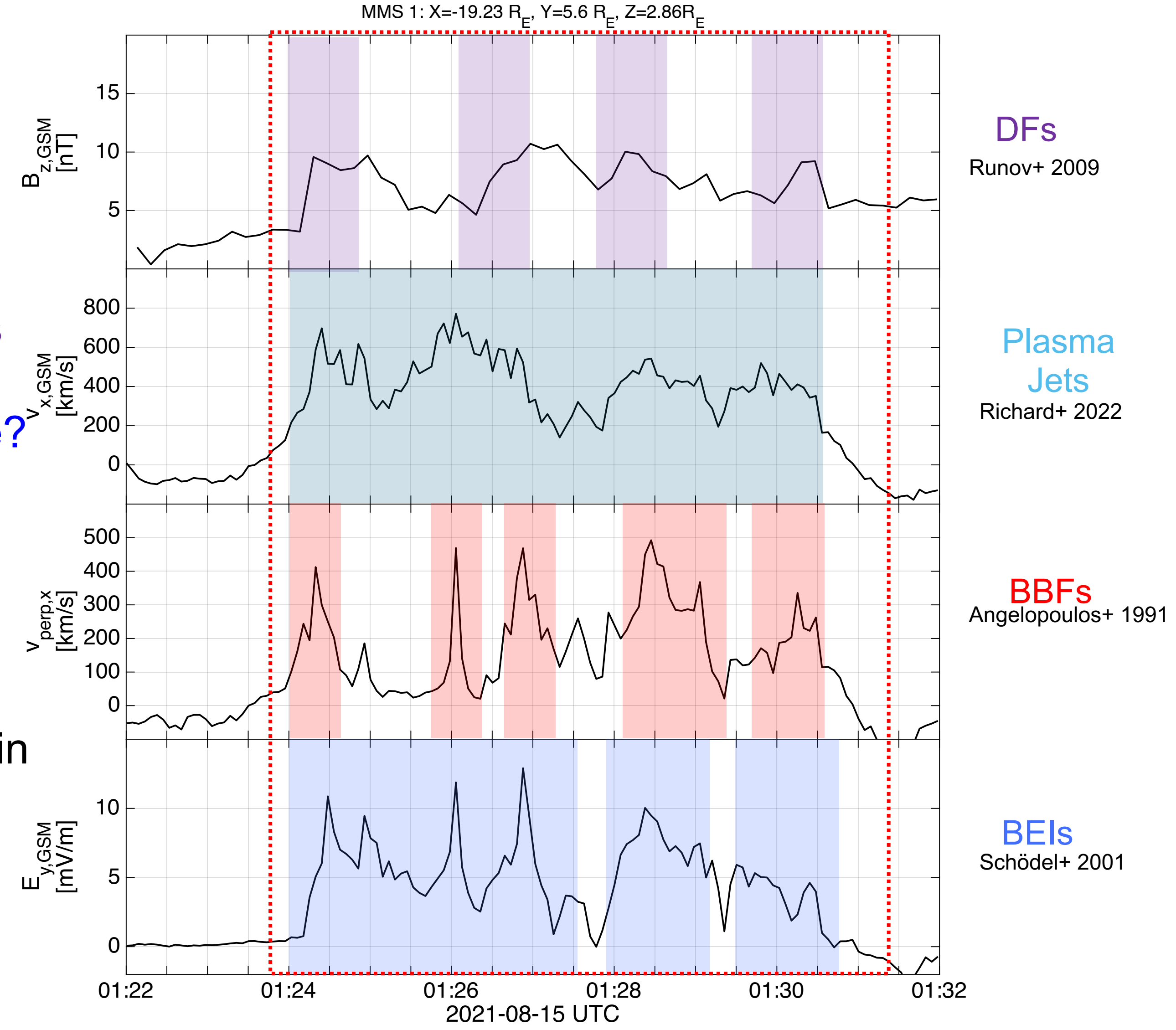
1. Arbitrary criteria and thresholds
2. BBFs are bursty, merge, and de-accelerate.
3. Orbital biases of missions
4. Are we even in the plasmasheet? (can discuss more)
5. Moment calculation, composition, energy and time res
6. No knowledge of spatial scales and relative location
7. Is it a direct hit or glazing? How probable is each case?
8. General sparsity of data and driving condition distribution.
9. Fast BBFs missed by instruments (e.g., v>1500 km/s)

….

So at least, (3,6,7,9) and maybe (2, 4,5) are not that bad in simulations, however number (1, 8) get complicated…

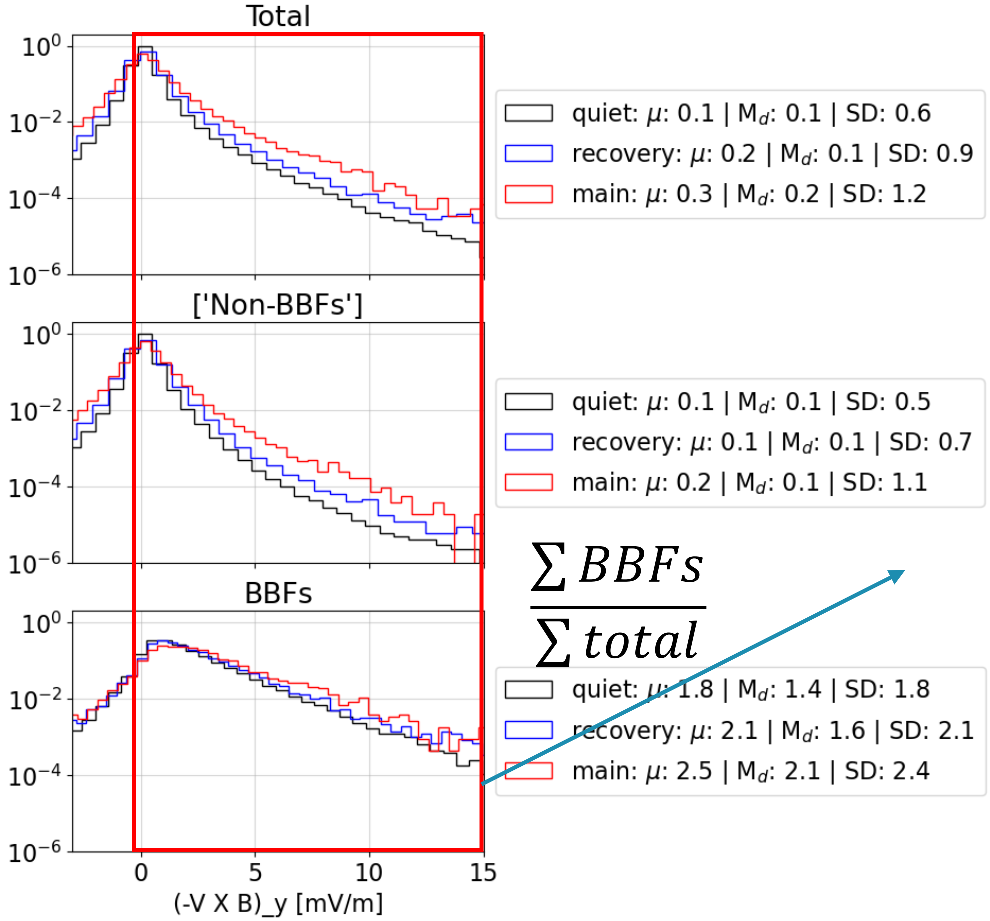
BBFs:

- Fast ion flows (v >400 km/s),
- 10-100s in duration
- ~ 4 Re size



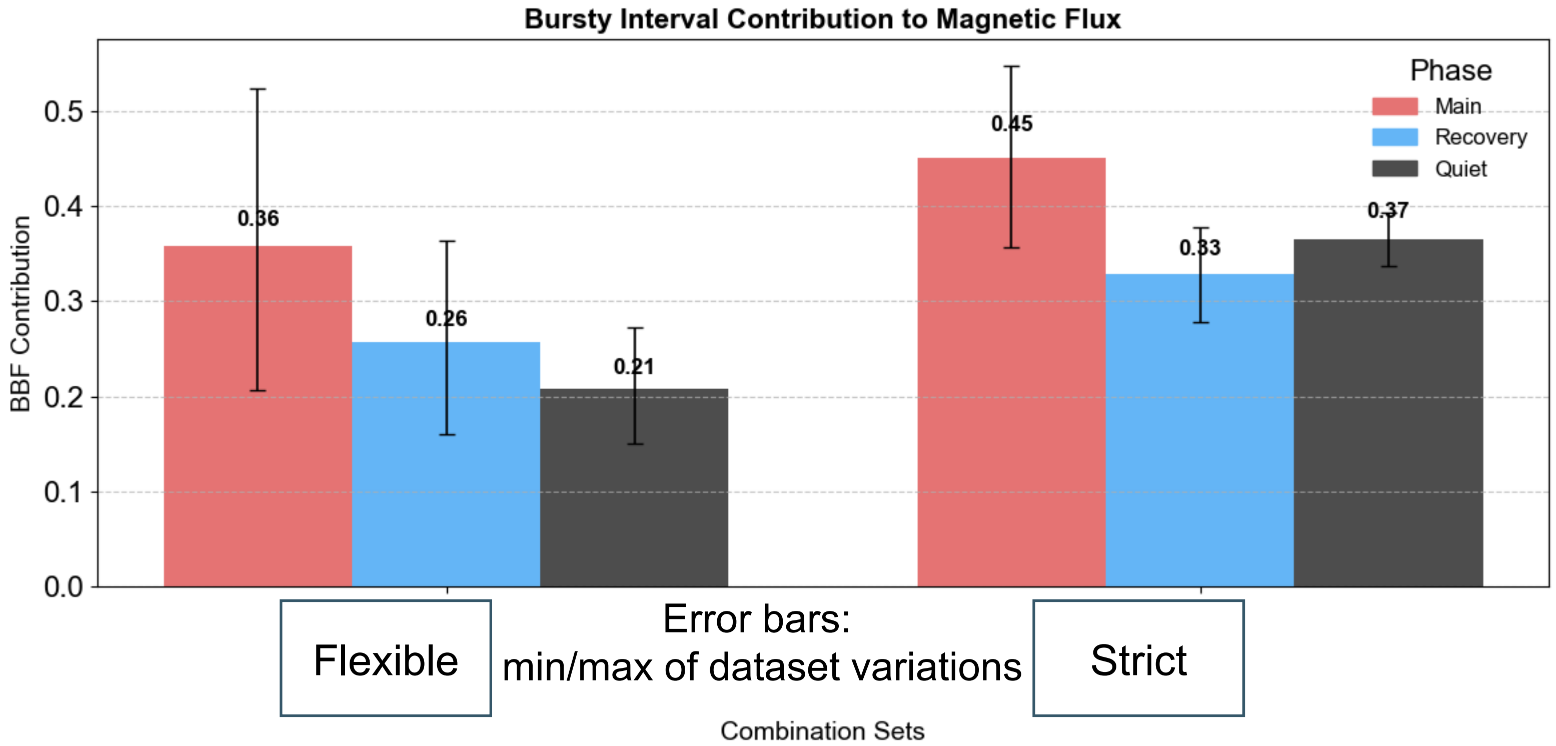
We can still do things: Earthward Bursty Magnetic Flux Transport

Histograms are normalized per phase



Strict: |Y| <10 [Re] | β >1 | $|Bz| > 2\sqrt{Bx^2 + By^2}$ | n<3 [1/cc])

Flexible: |Y|< 15 [Re] | β > 0.5 | n <5 [1/cc])



After Lunch **Anusree Devanandan: Statistics of Stormtime BBFs**

Part #1 Summary

1. Stormtime Global Convection (**published**):
    1. **Plasma sheet Ey** is elevated due to **increased Bz**, with **limited enhancement of** $V_{\perp x}$
    2. **Bz enhancement** is more **prominent** at **Dusk**
    3. $V_{\perp x}$ is more **elevated at Dawn**
2. Plasma sheet bursty Intervals (**accepted & ongoing**):
    1. **BBFs can** contribute **~25%** of **earthward magnetic flux** during **quiet and ~40% during main phase.**
    2. This enhancement linked to a **stronger background Bz**, while BBF velocity stays relatively constant (*See Anusree's presentation for more*).
    3. **There seems to be a Dawn/Dusk Asymmetry (will discuss at the end) on BBF occurrence and stormtime.**

Interesting take by ChatGPT on data & MAGE comparisons

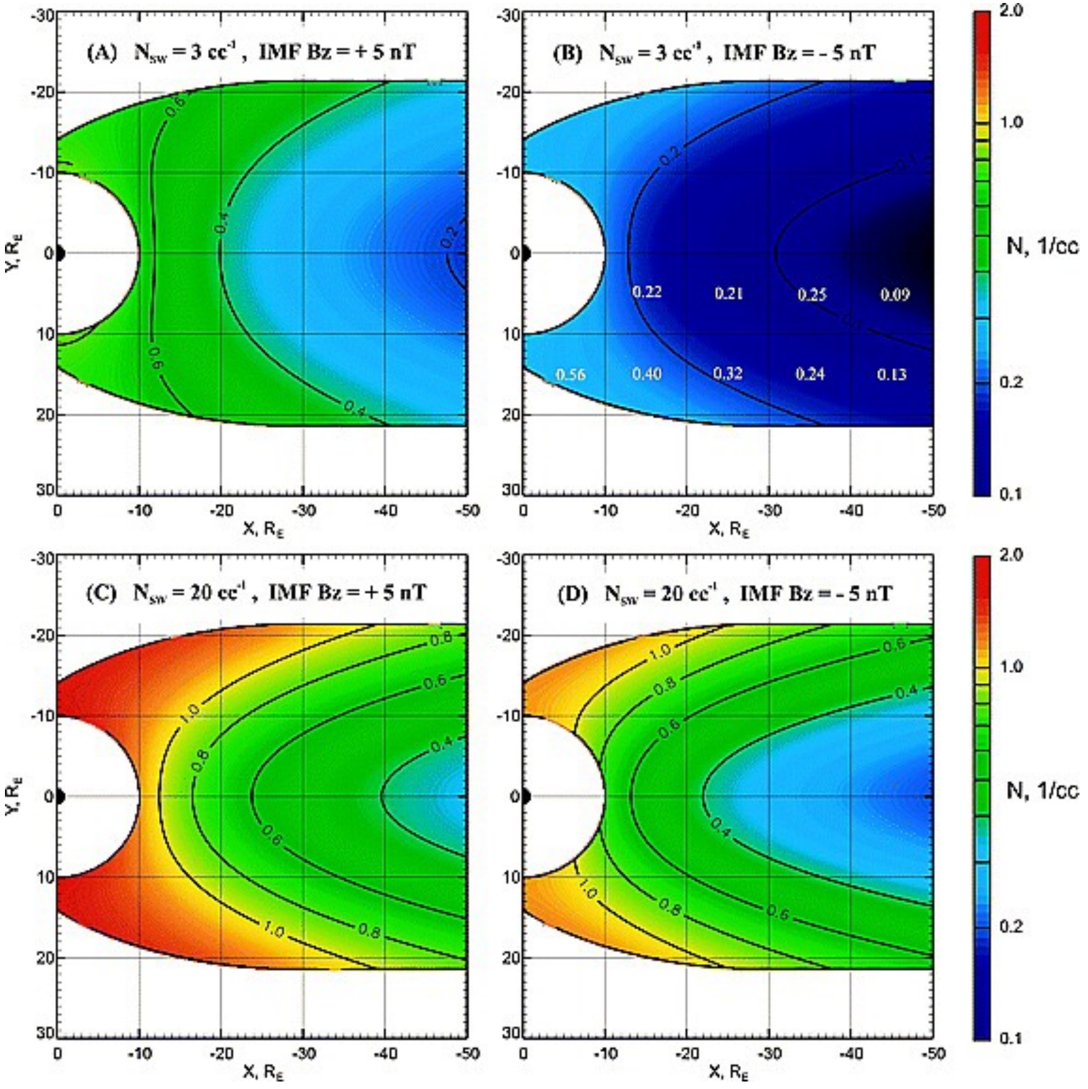
Detective MAGE looks at another simplified magnetosphere, MAGE also looks like a fox apparently

What can we do with all this data?

Machine Learning of course!

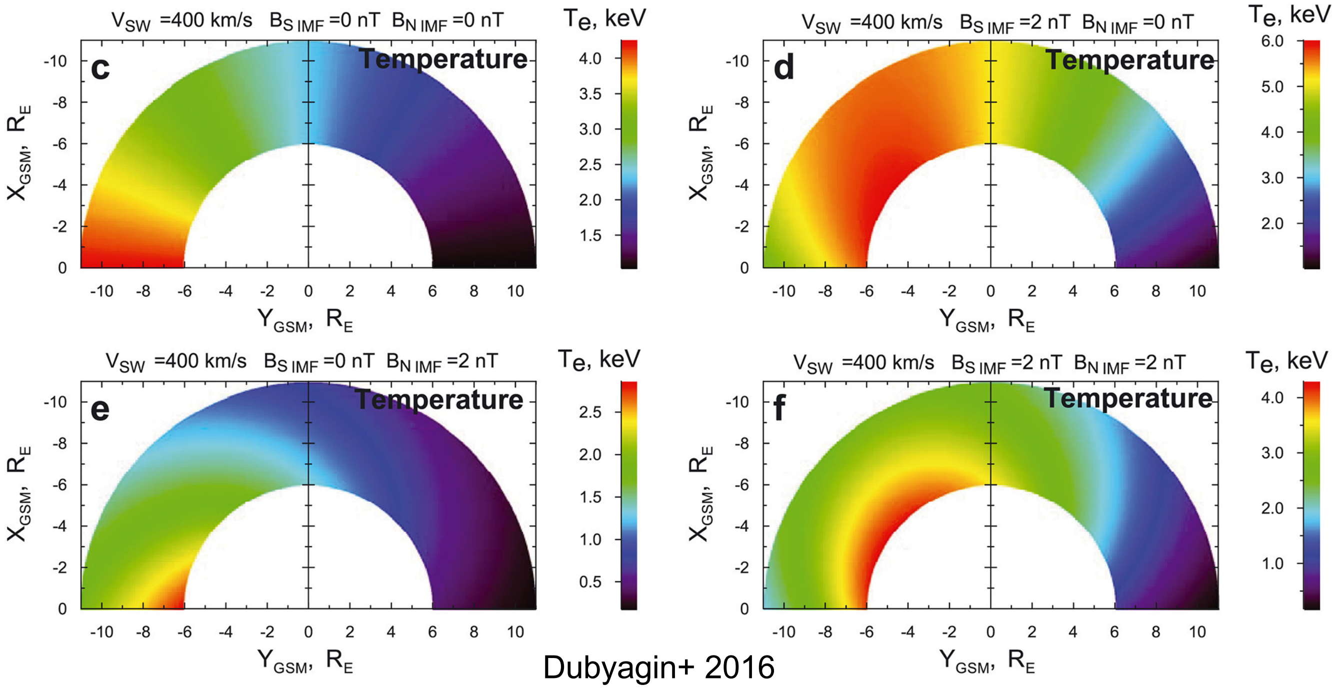
Baseline empirical models

Modelled with Geotail



Tsyganenko & Mukai 2003

Modelled with THEMIS

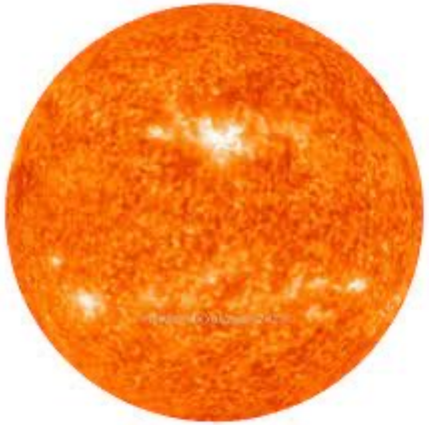


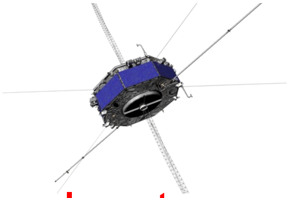
Dubyagin+ 2016

<u>Why then work on this?</u>

1. More data under different conditions
2. MMS was never used with its state of the art instrumentation
3. These models don’t include time history
4. ML methods can reveal non-linear relationships easily

Where are we & what are we doing?





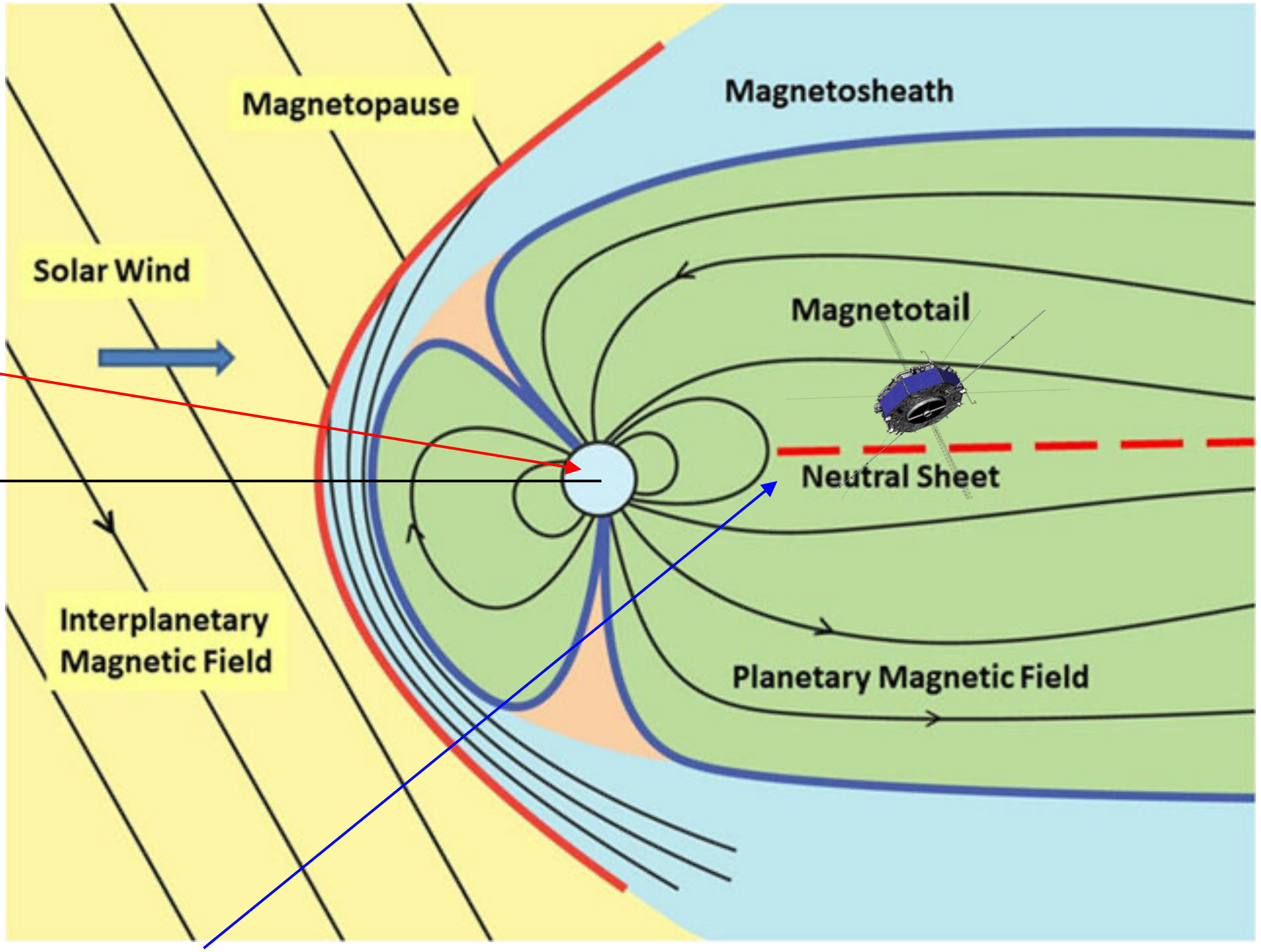
Input:

ACE/WIND/DSCVR

(L1)

+Geomagnetic

$200R_E$

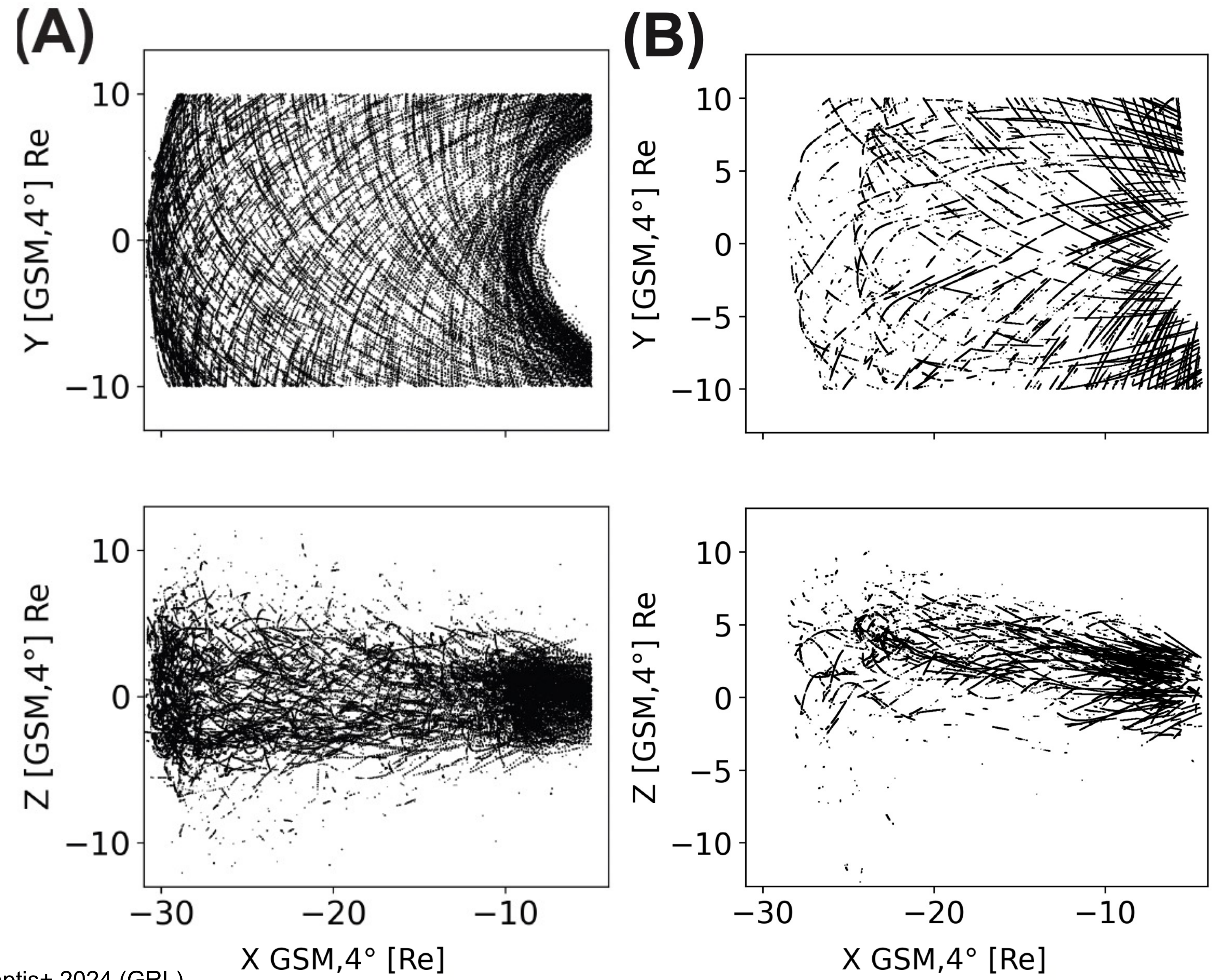


Output: *In-situ* properties from: MMS, Geotail, THEMIS

Goal: Model Plasmasheet properties based on driving (SW) and geomagnetic conditions

$R_E = 6371.2\ [km]$

The dataset (output – Central Plasma Sheet)



Raptis+ 2024 (GRL)

(A) Geotail (1994 - 2022)
>1 million points (~12s res)

(B) MMS (2015 – 2024)
~ 250k points (~12s res)

<u>Output</u>:
In principle, anything measured
(In this example plasma moments)

Metrics & Results

$$MAE = \frac{1}{N}\sum_{i=1}^{N} |y_i - \hat{y}|$$

$$MSE = \frac{1}{N}\sum_{i=1}^{N} (y_i - \hat{y})^2$$

$$RMSE = \sqrt{MSE} = \sqrt{\frac{1}{N}\sum_{i=1}^{N} (y_i - \hat{y})^2}$$

$$R^2 = 1 - \frac{\sum (y_i - \hat{y})^2}{\sum (y_i - \bar{y})^2}$$

Where,

$\hat{y}$ – *predicted value of y*

$\bar{y}$ – *mean value of y*

Quick reminder on model evaluation

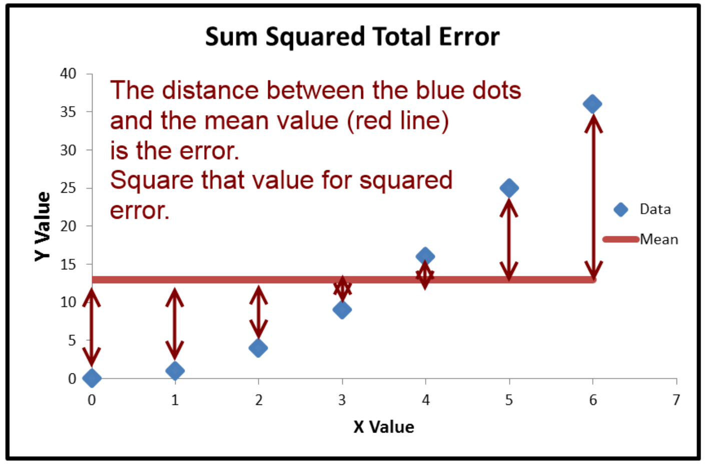
```
...   99/99 ━━━━━━━━━━━━━━━━━━━━ 0s 808us/step
      explained_variance:  0.019
      median absolute error:  0.11
      r2:  -0.01
      MAE:  0.157
      MSE:  0.055
      RMSE:  0.235
      Cor:  0.533
```

A complex and intriguing model

VS

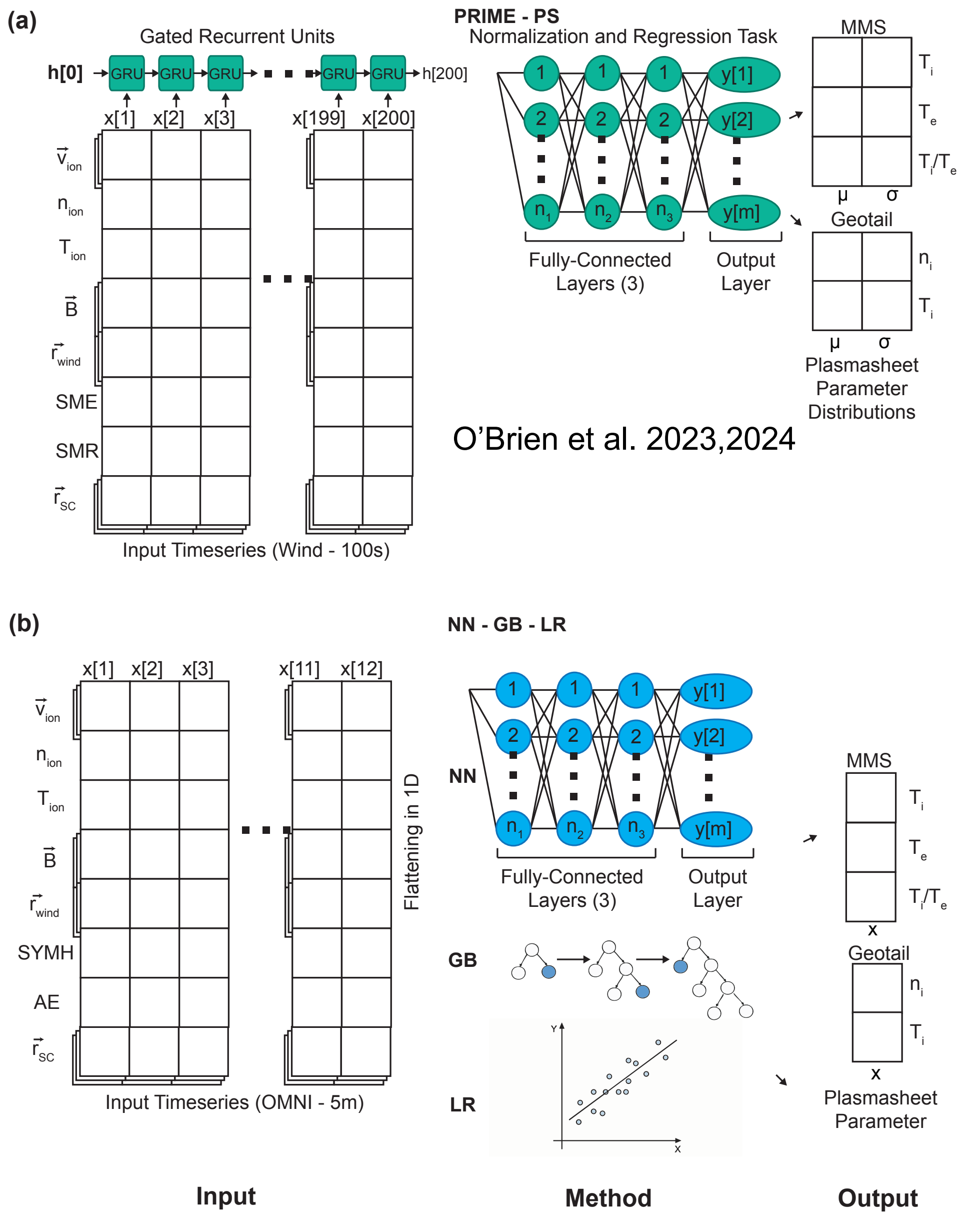
```
...   99/99 ━━━━━━━━━━━━━━━━━━━━ 0s 778us/step
      explained_variance:  0.0
      median absolute error:  0.14
      r2:  0.0
      MAE:  0.17
      MSE:  0.055
      RMSE:  0.234
      Cor:  0.0
```

np.mean()



When $R2$<0, the horizontal line explains the data better than your model (i.e., mean of observed).

Methodologies & input space



O'Brien et al. 2023,2024

Raptis, O'Brien et al., 2026 (under prep.)

- **PRIME Advantages:** Embedded uncertainty quantification and propagation from L1

Time History	Type of Input	Architectures
1-6h	Wind (L1)	Linear Reg
	OMNIweb	Gradient Boosting
		Neural Network
		RNN/LSTM/GRU (PRIME-PS)

Answering hypothetical questions:

✓ *Also tried different error functions, optimizers, hyperparameters etc.*

✓ *And different imbalanced learning techniques*

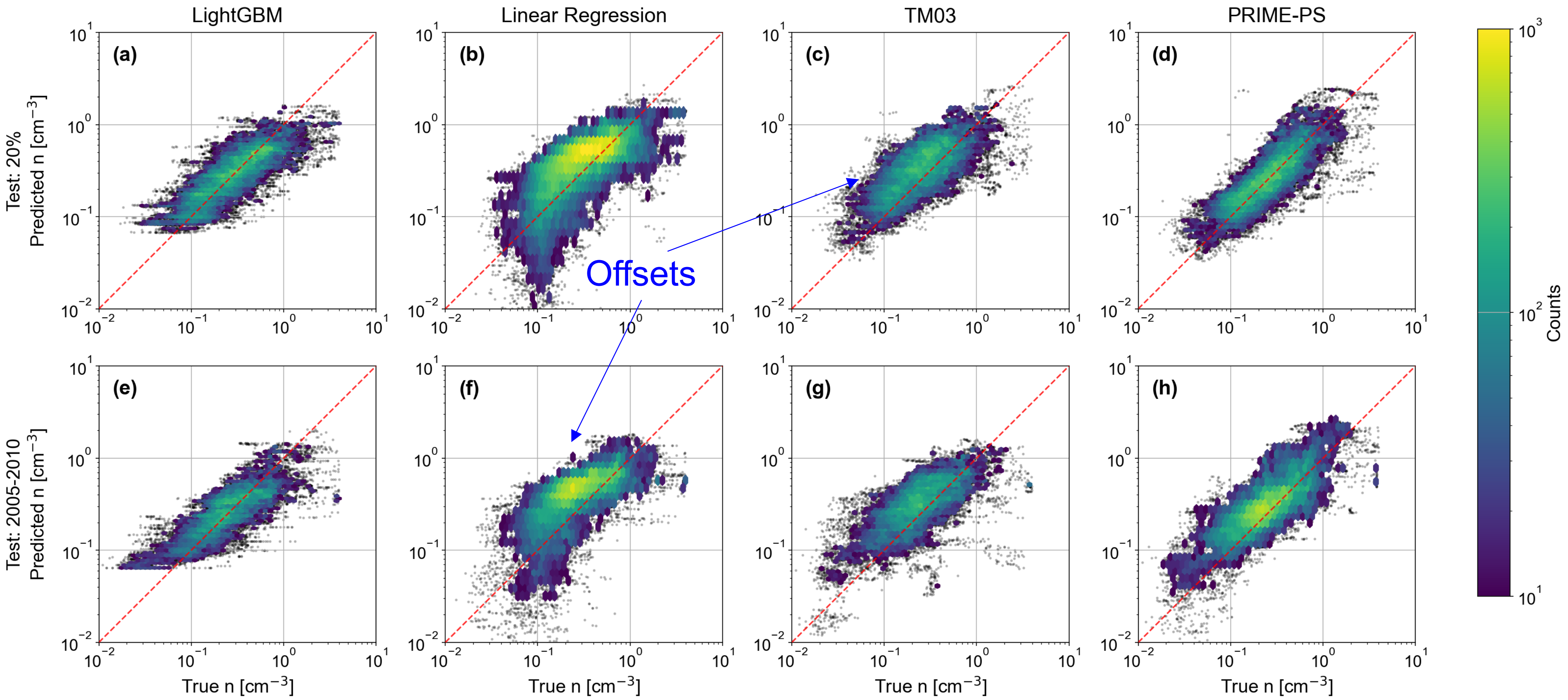
Key Takeaway:

To quantify our method's impact, we tested multiple variations of the problem.

Modeling Density | Predictions vs Observations

Key Message: PRIME/GB > Baseline ≈ TM03

Model Performance | Density (n)



Raptis, O'Brien et al., 2026 (under prep.)

Reminder: Close to x=y → good

Metrics using Test set (20% of data)

Method	MAE	R^2	r
LightGBM	0.129	0.373	0.631
Neural Net	0.152	0.325	0.603
Linear Reg	0.173	0.265	0.620
PRIME-PS	**0.113**	**0.453**	**0.707**
TM03	0.163	0.208	0.570

Key Results:

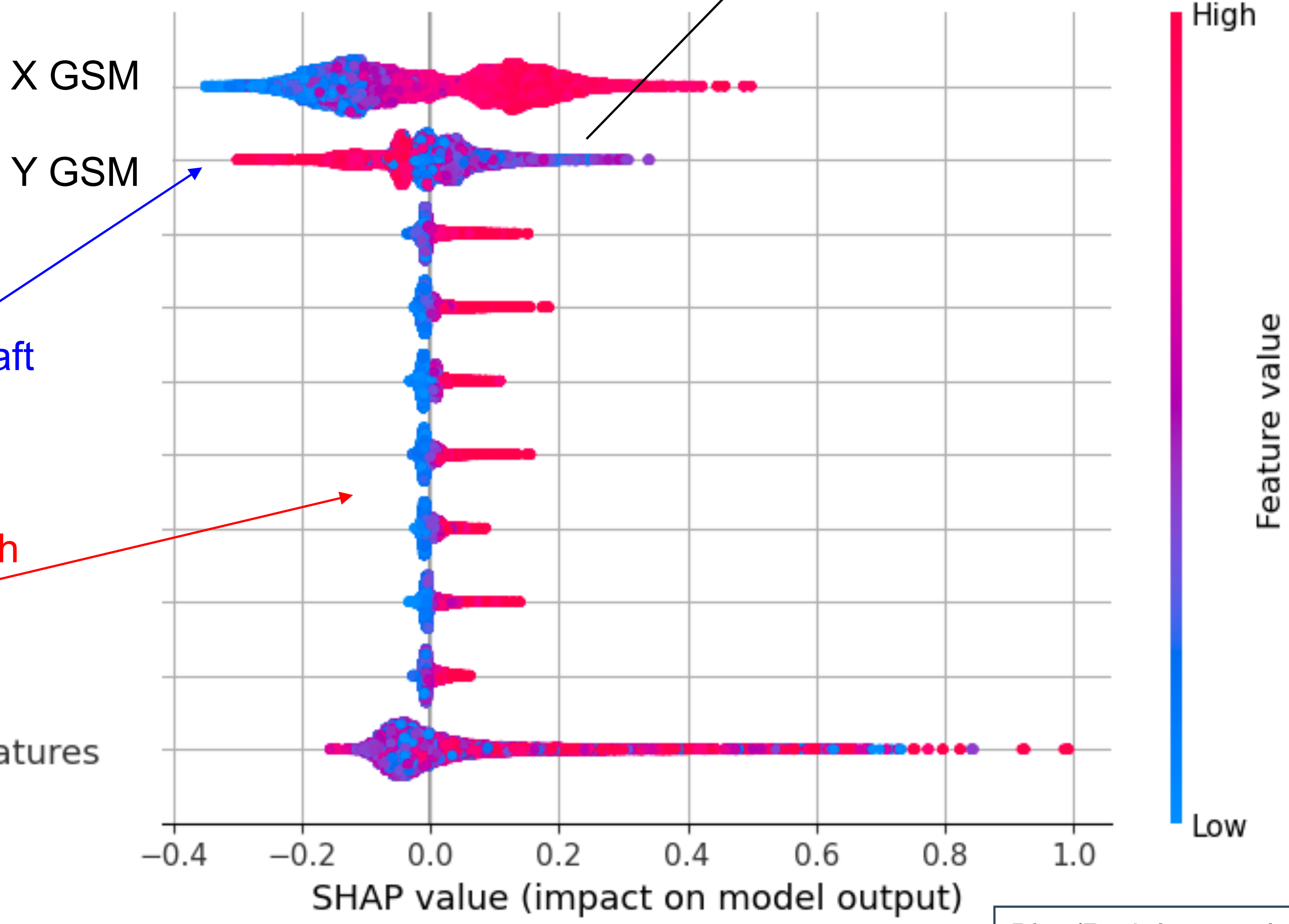
- PRIME-PS demonstrates a performance edge (~30% MAE from TM03 and ~15% from other ML approaches).
- This advantage can get relatively low (other train/test splits & crossvalidation).
- Different input, method, time-history, and hyperparameter tuning etc. had overall a statistically marginal effect. Why?

➢ Since PRIME-PS was statistically better, and Gradient boosting can't be used for modeling, we only keep this for next parts of analysis.

Raptis, O'Brien et al., 2026 (under prep.)

Feature Importance Analysis

*Higher density **close to earth and at dawn***



Answer: In most cases (statistically):

Model is predominantly driven by spacecraft location

Solar wind input has lower effect, although cumulative history is still important

Blue/Red: Input value
Left/Right: Output value

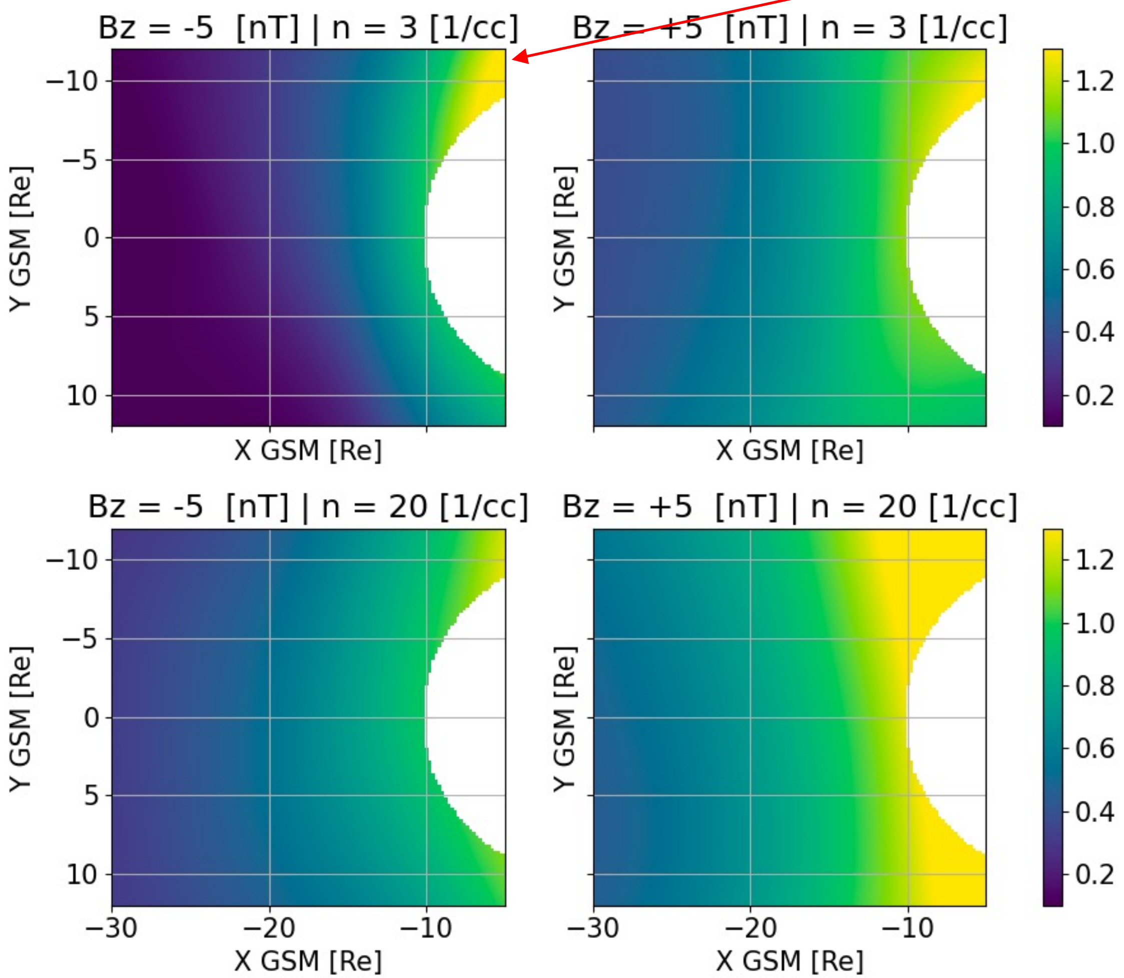
SHAP Values explain why a model made a specific prediction, by showing each feature's impact.

Actually pretty accurate

Modeling Efforts

Modeling Density | 2D Maps (Synthetic input)

<u>Assymetries Introduced</u>

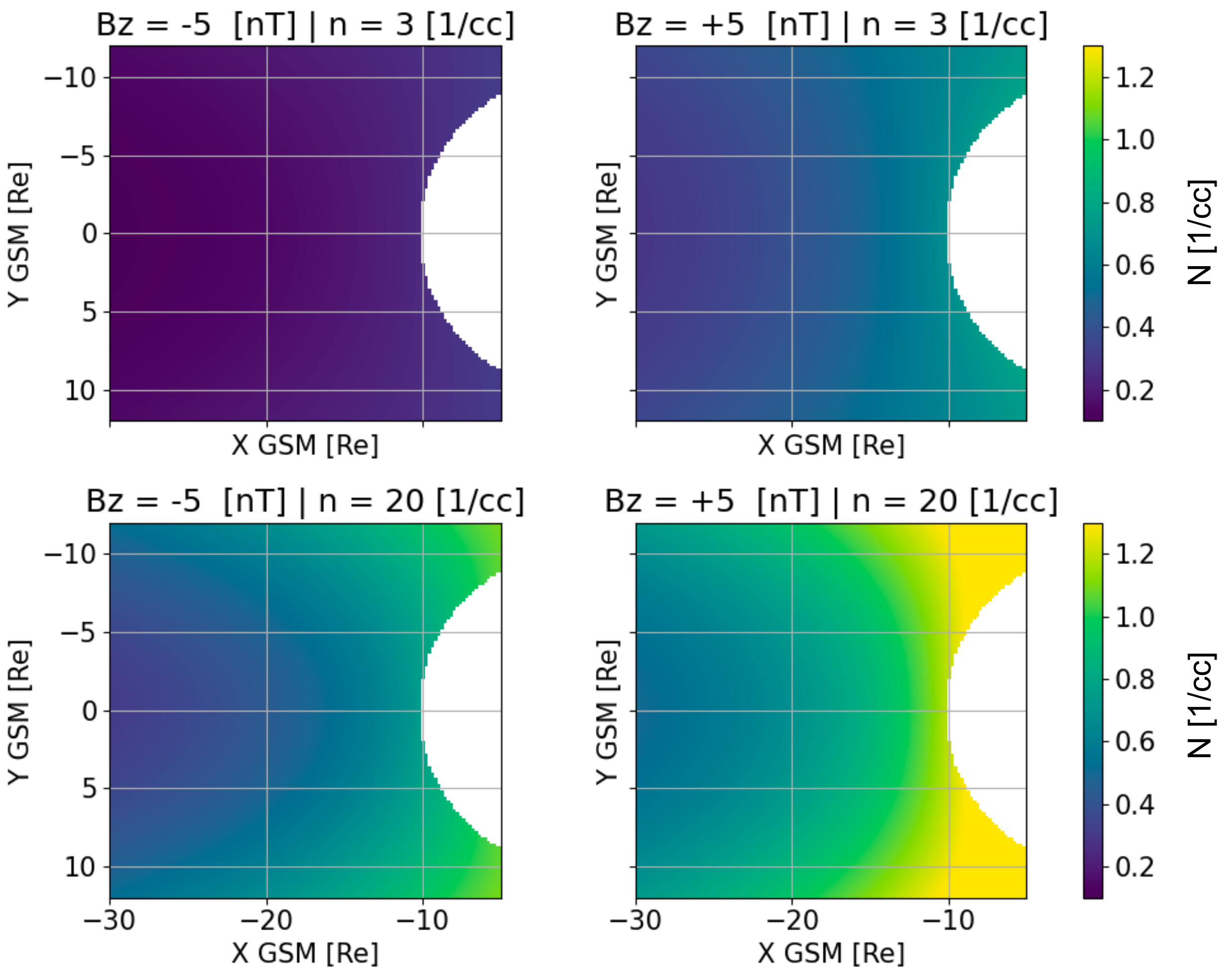


Neural Networks modeling

Raptis, O'Brien et al., 2026 (under prep.)

$Bz > 0$ ↑ n_{ps}

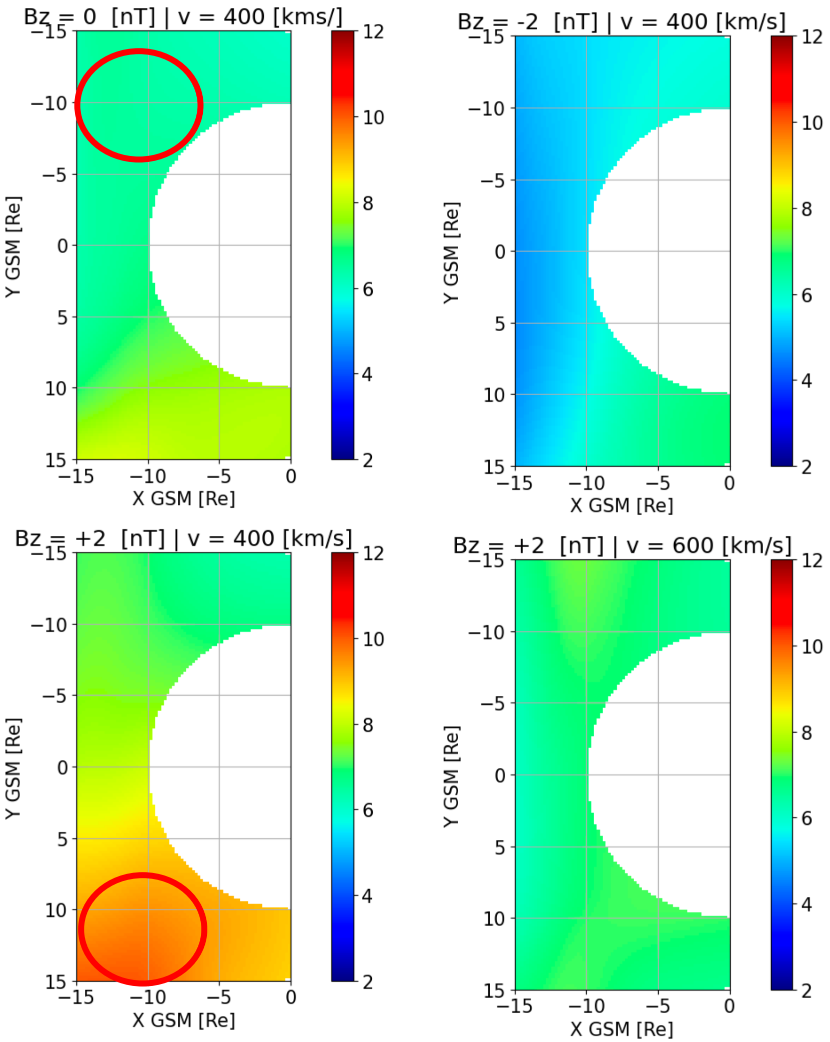
$n_{sw} \rightarrow$ ↑ n_{ps}



Empirical modeling (TM03)

Modeling Temperature Ratios with MMS | 2D Maps

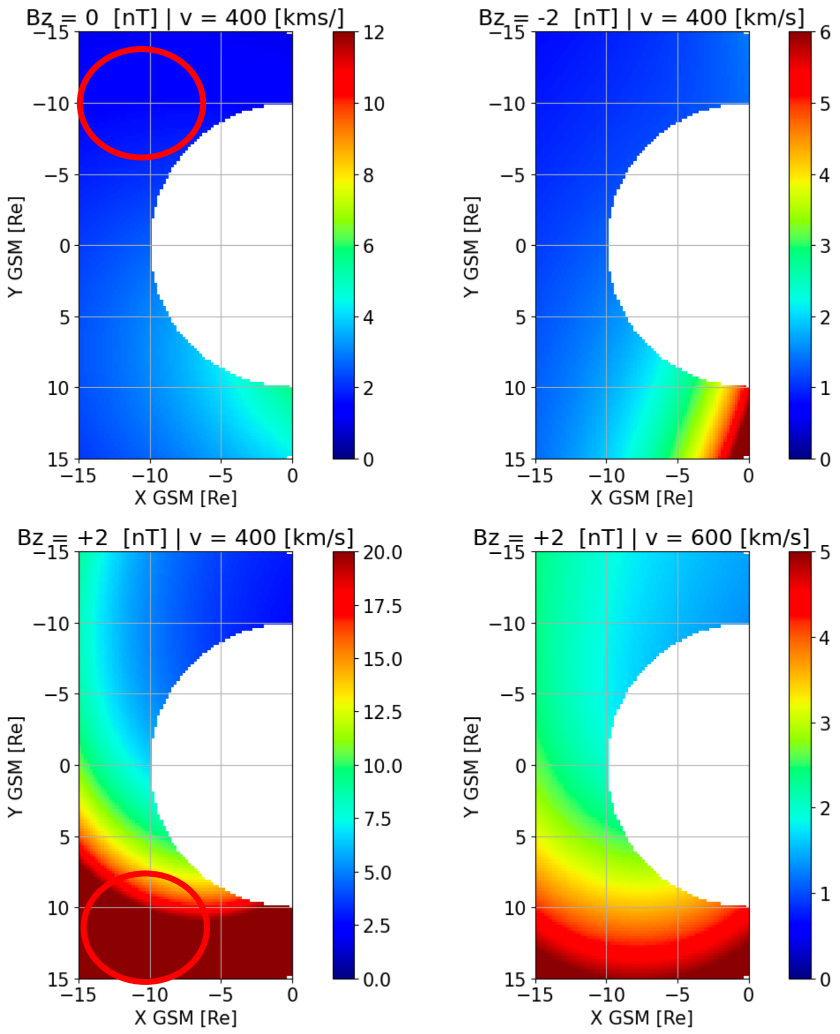
Note: Agreement Wang et al., 2010 with dusk Ti/Te higher than dawn (Using THEMIS)



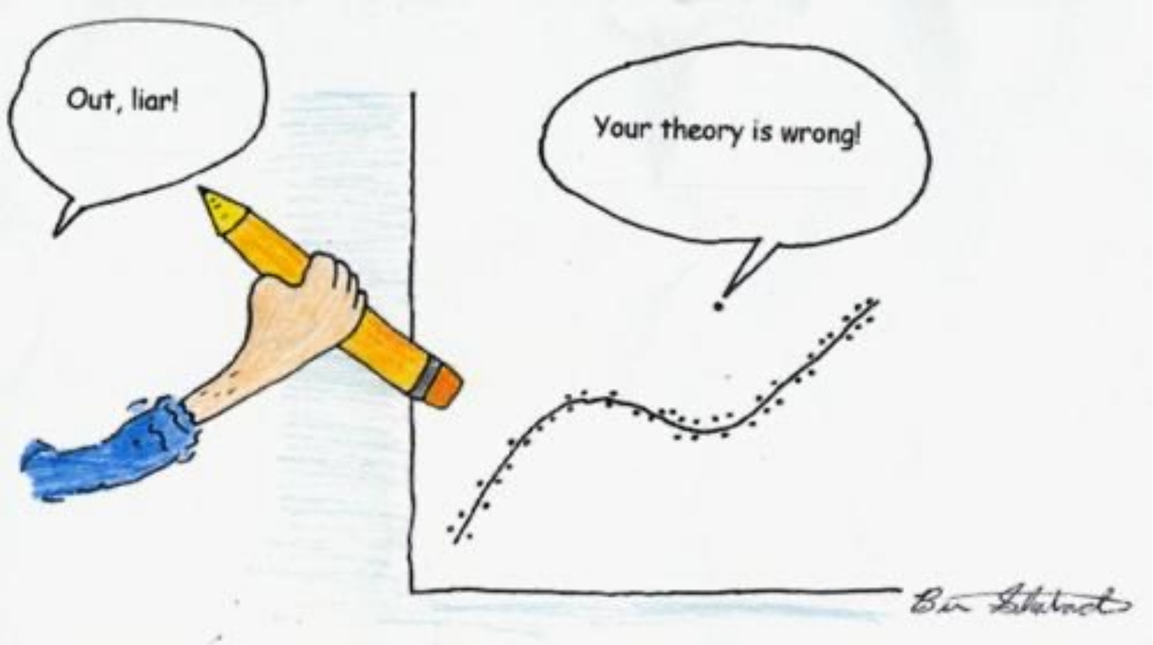
Neural Networks modeling

Pros:
+No extreme values
+Asymmetries shown
+ Coherent physical picture

Cons:
- Not easily available analytical form



Empirical modeling (TM03/DSGR16)



Storm Time Behavior and Importance of Outliers

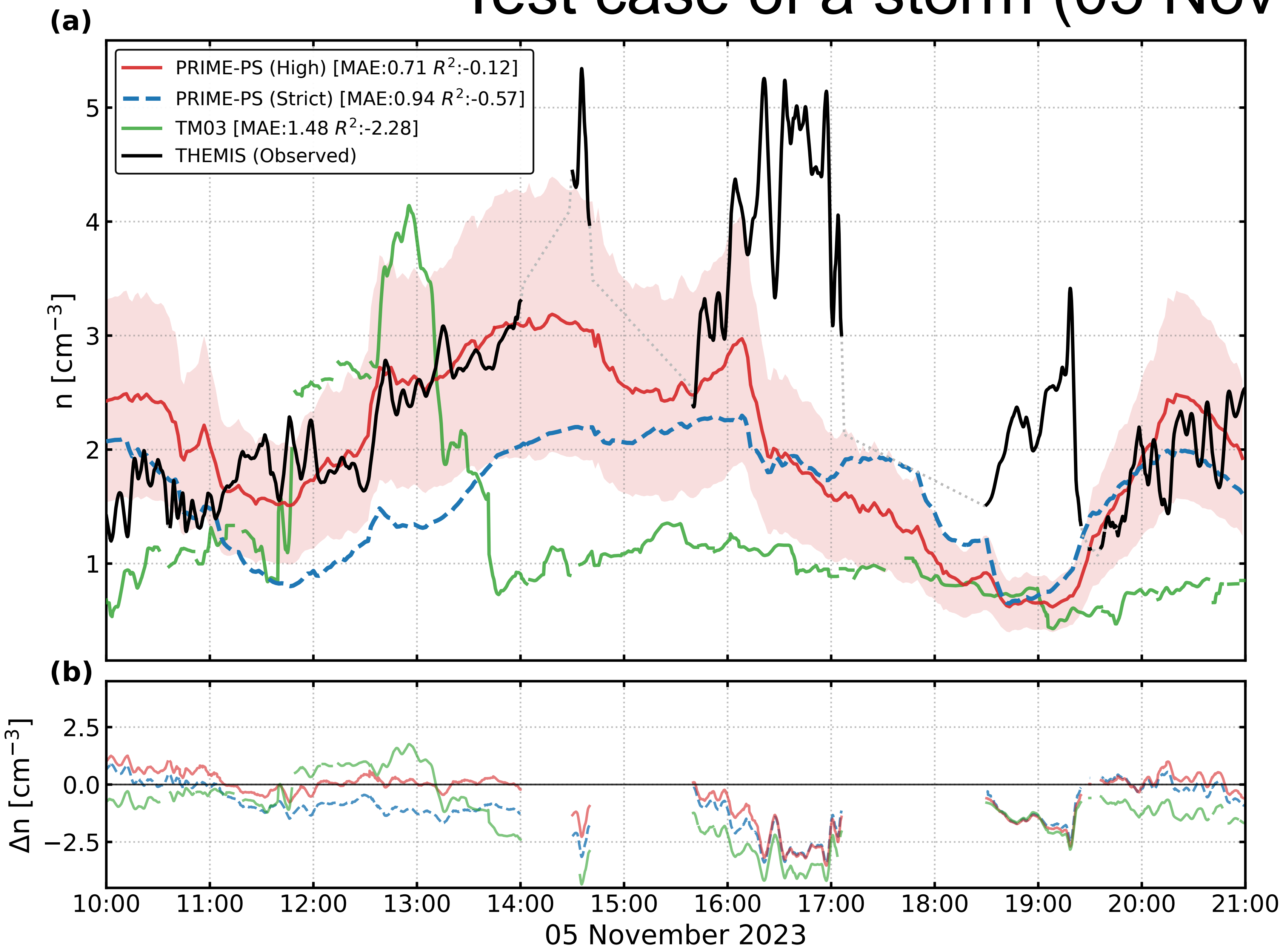
The Problem: We use static thresholds for dynamic environents.

The Risk: Therefore we can mistakenly remove the crucial "stormtime plasmasheet.”

The ”Horible yet Practical Solution": Manually find the missing data and add it to the dataset.

Strict CPS (e.g., Ohtani et al., 2008 Raptis et al., 2024) & Flexible CPS (e.g., Richard et al., 2022)

Test case of a storm (05 Nov 2023)



Note: values <1 cm⁻³, are boundary layer transitions, gray shaded linear interpolation

<u>Process:</u>

High: Includes manually picked high-density intervals from Geotail

Strict: Normal threshold-based classification of plasma sheet

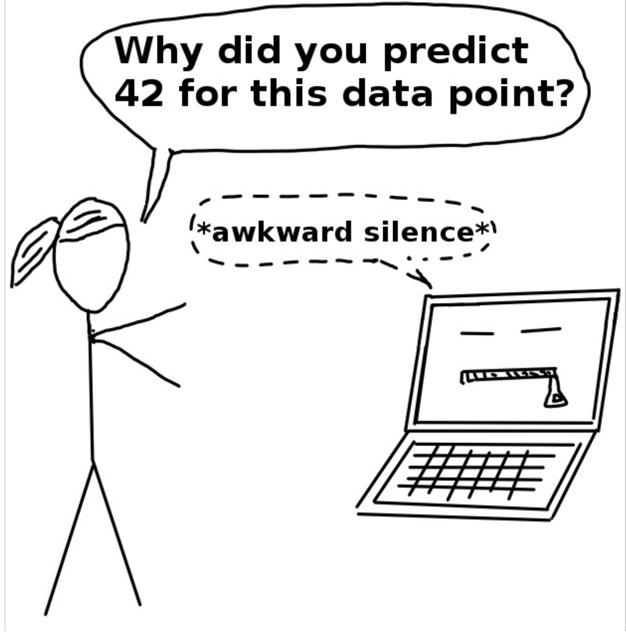
<u>Test:</u>

THEMIS observations

<u>Results</u>

ML model (high dens): 0.7 [1/cc]
- ML model (normal): 0.94 [1/cc]
- TM03: 1.48 [1/cc]

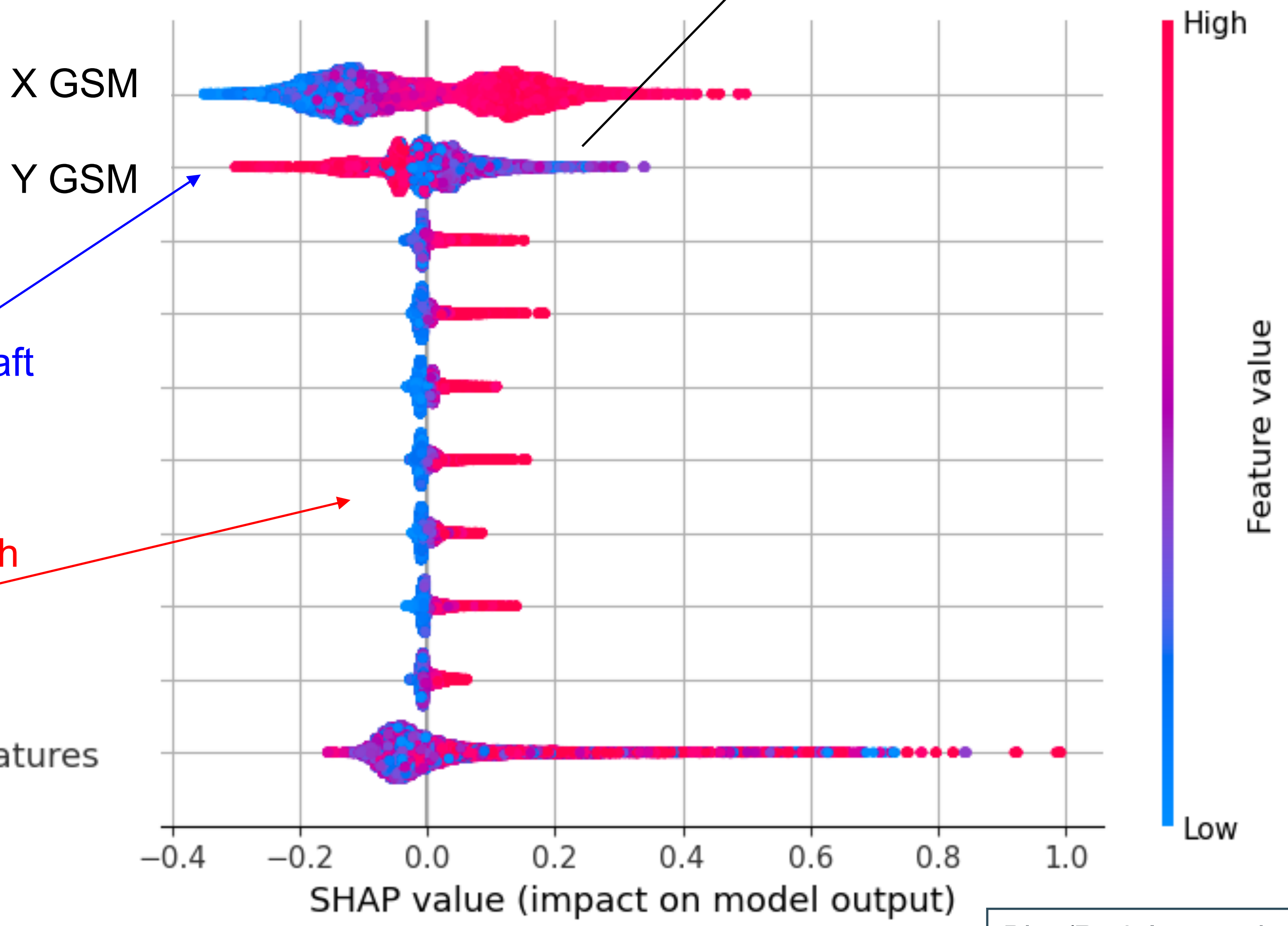
Key Message: >50% improvement



Preliminary & Simplistic Feature analysis

Feature Importance Analysis

Higher density ***close to earth and at dawn***



Answer: In most cases (statistically):

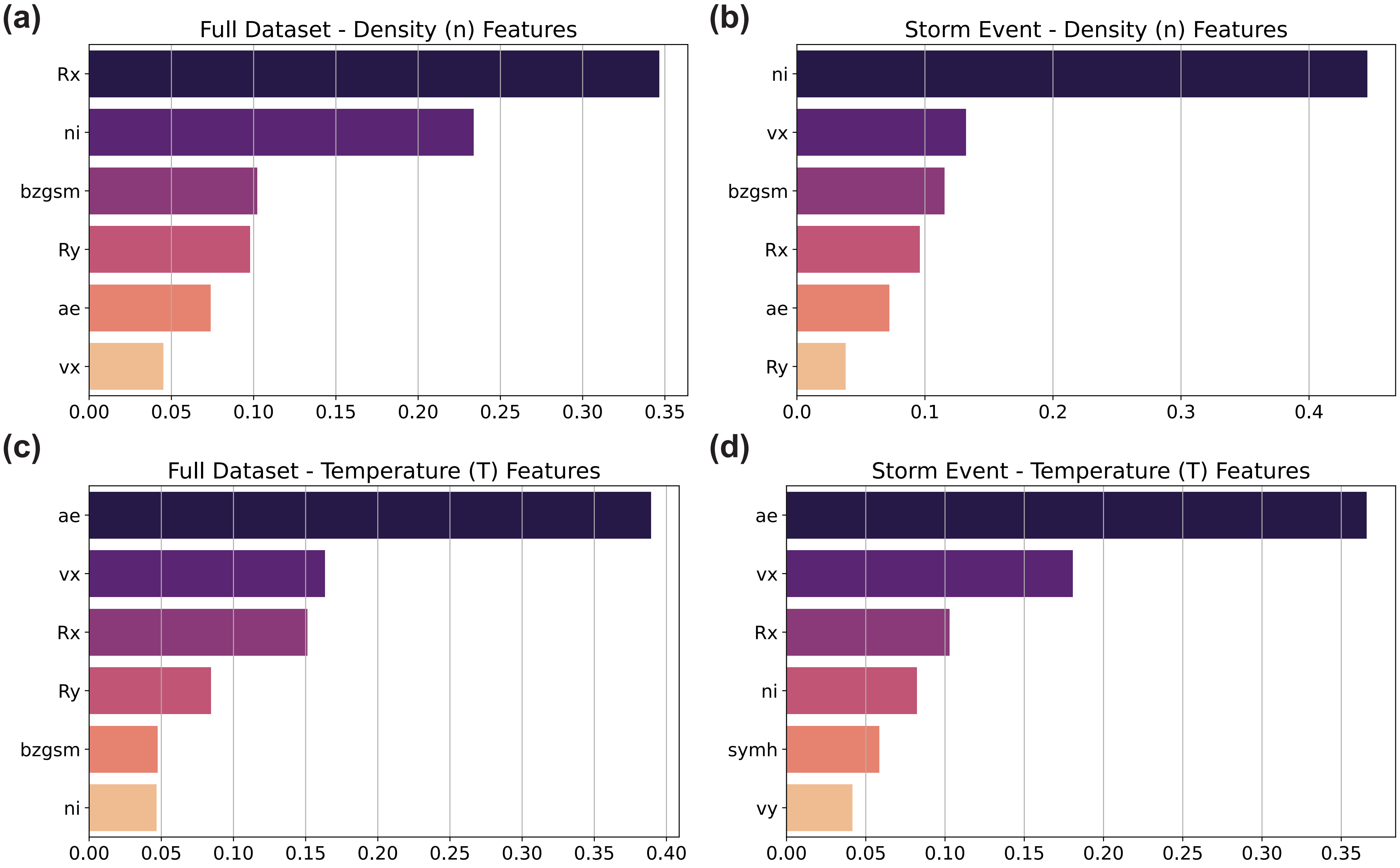
Model is predominantly driven by spacecraft location

Solar wind input has lower effect, although cumulative history is still important

Blue/Red: Input value
Left/Right: Output value

SHAP Values explain why a model made a specific prediction, by showing each feature's impact.

Feature Importance Analysis – Merged Time history



<u>Quiet times</u>

- More internally driven
- T is more external, maybe
- Density is largely dictated by location

<u>Storms</u>:

- More externally driven
- Location matters less

<u>Issues with this analysis:</u>

- Intercorrelation between variables is large (ae well correlated to vx)
- Same with SW types (dense solar wind is typically slower)
- Combines all time history (1h in this particular example)

Part #2 (i.e., ML model) Summary

Results

✅ **Significant Gains:** PRIME-PS and ML models outperform analytical methods & show asymmetries.

❌ **Mediocre Storm Predictability:** We mainly capture "boring" conditions, not the rare events.

🧠 **A Core Problem:** Our training data is biased. Extreme events, are not always captured by simple threshold, and including them is methodologically challenging

Future Work

- **Understand the output:** Focus on feature importance under different conditions.
- **Hybrid Modeling:** Use simulations to generate extreme events we lack in data? (Need to be careful here).

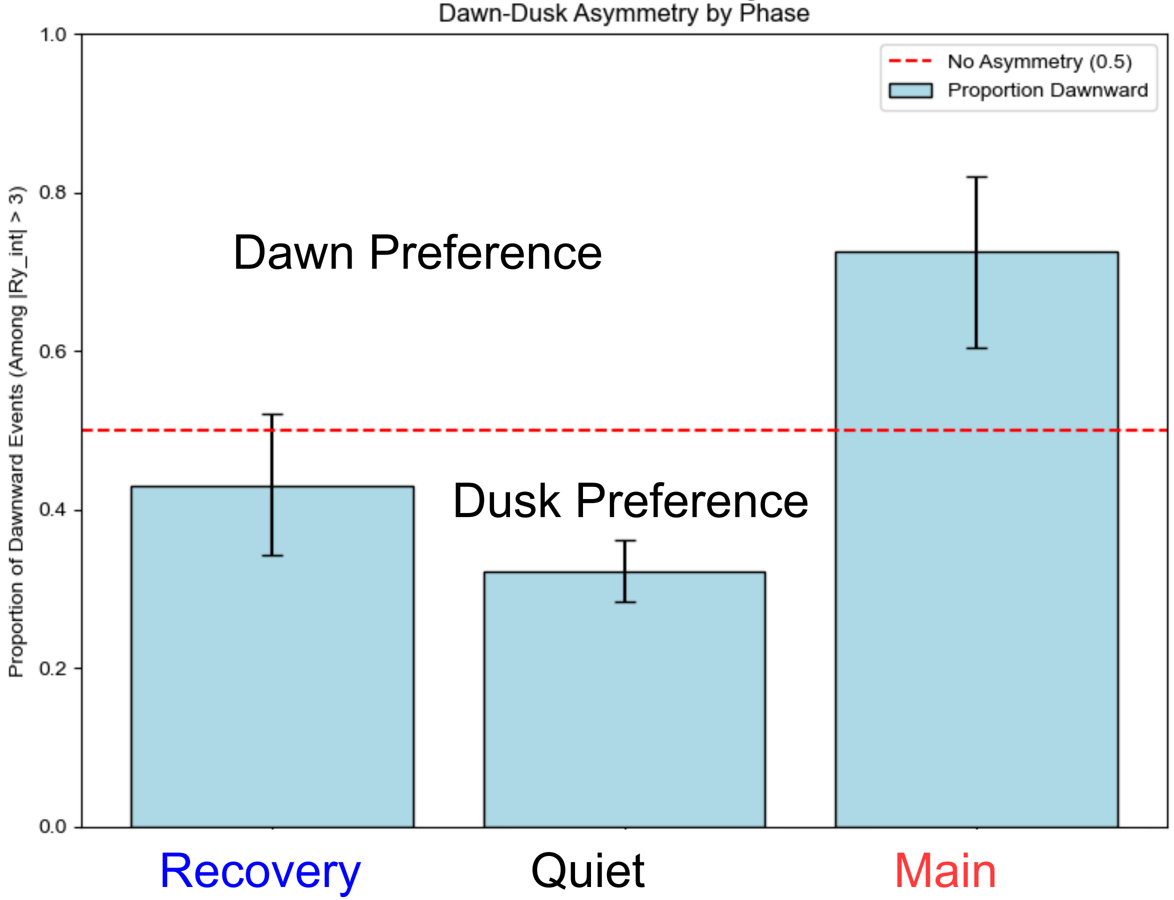
Discussion Points/Opinions

- ➢ A model with R^2 ~0 can have a correlation of 0.7 and very low MAE depending on the problem.
- ➢ “Unique and extreme” events with parameter distribution can be more important than typical metrics.
- ➢ “Better” data can yield ~30% difference, while a better model improved metrics by ~40% (better measurements are needed for ground truth)
- ➢ Reminder GIGO applies to ML as much as physics models https://en.wikipedia.org/wiki/Garbage_in,_garbage_out

Future work Ideas
Working with Modelers

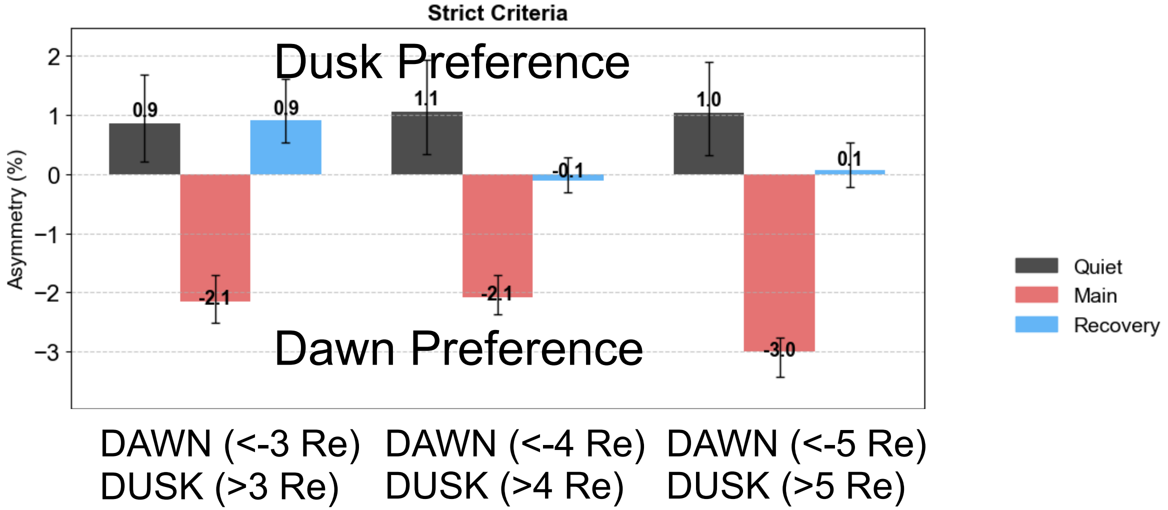
Dawn/Dusk Asymmetries - Reconnection and BBFs

Geotail dataset from Nagai+2023



Geotail dataset BBF list (Devandan+2026)

$$\text{Asymmetry} = \frac{\text{Occurrence Dusk}}{\text{Occurrence Dawn}}$$



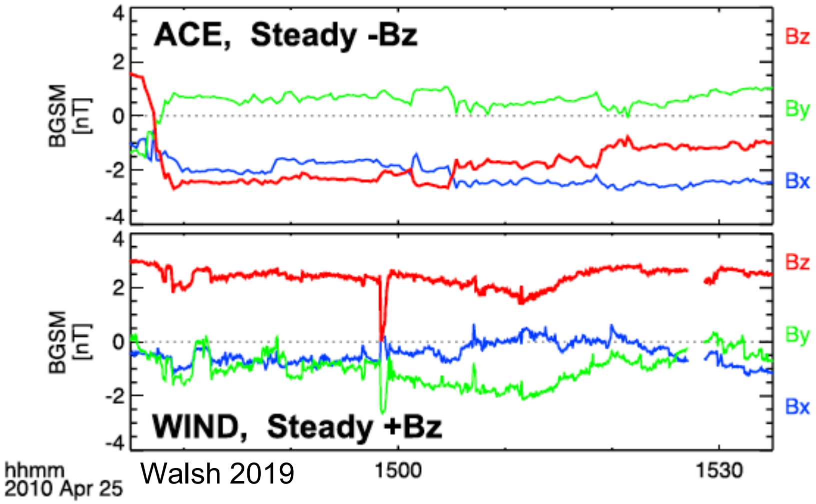
Key Point:

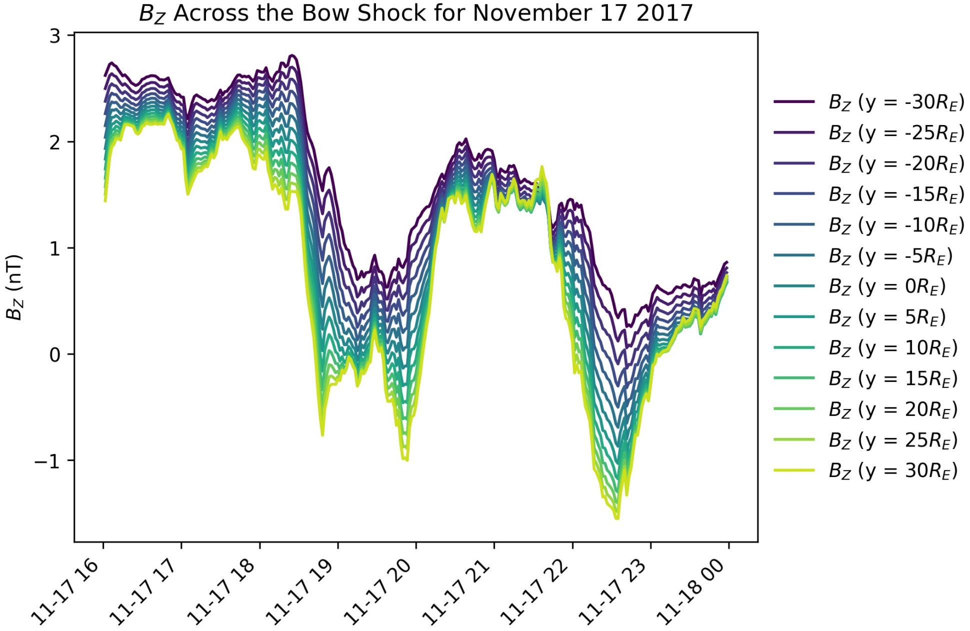
Asymmetries in occurrence during Main phase are shown in both BBF and Reconnection list datasets

TODO:

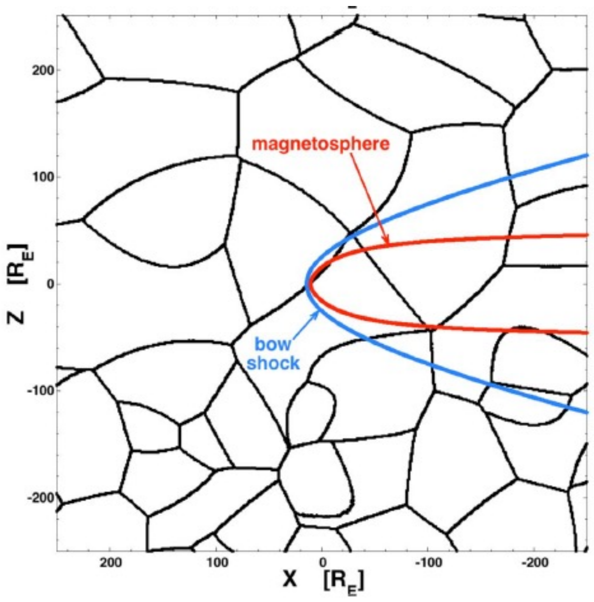
- **Observational** analysis including **MMS and THEMIS** statistics
- **Compare to simulation intervals** of storm and non-storm time

Spatial and Temporal Solar Wind Variability

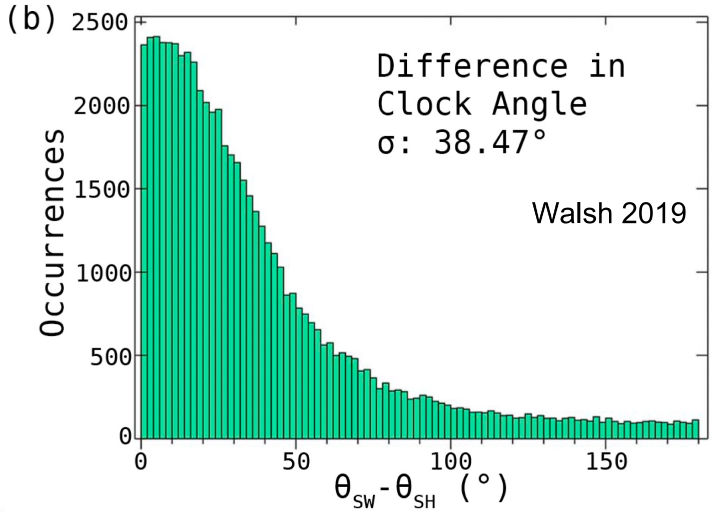


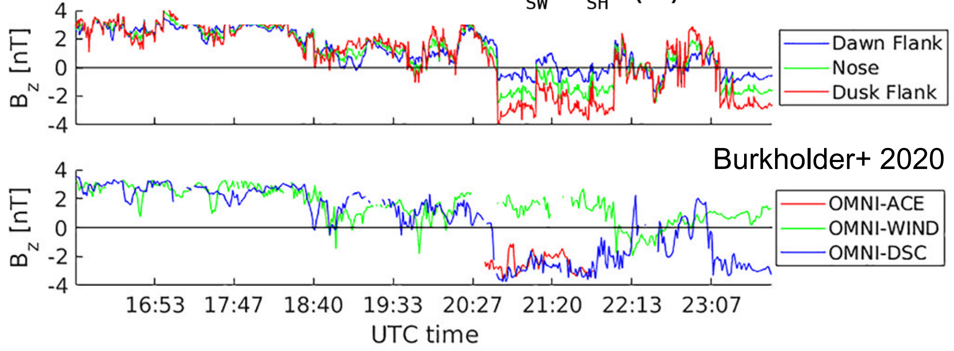


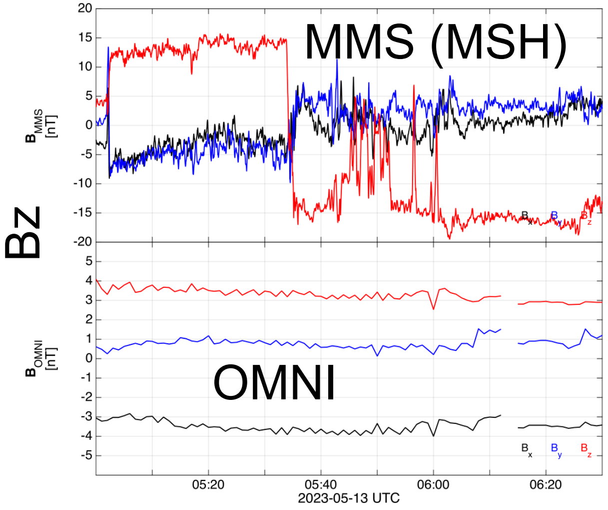
O' Brien+ 2023

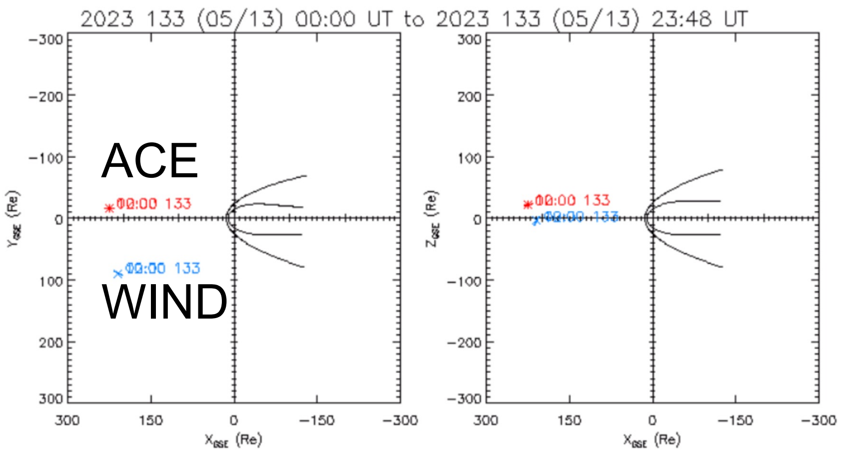


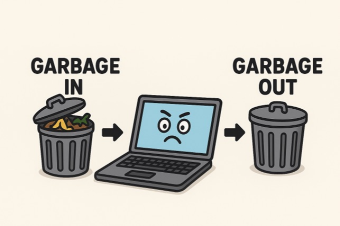
Borovsky 2017



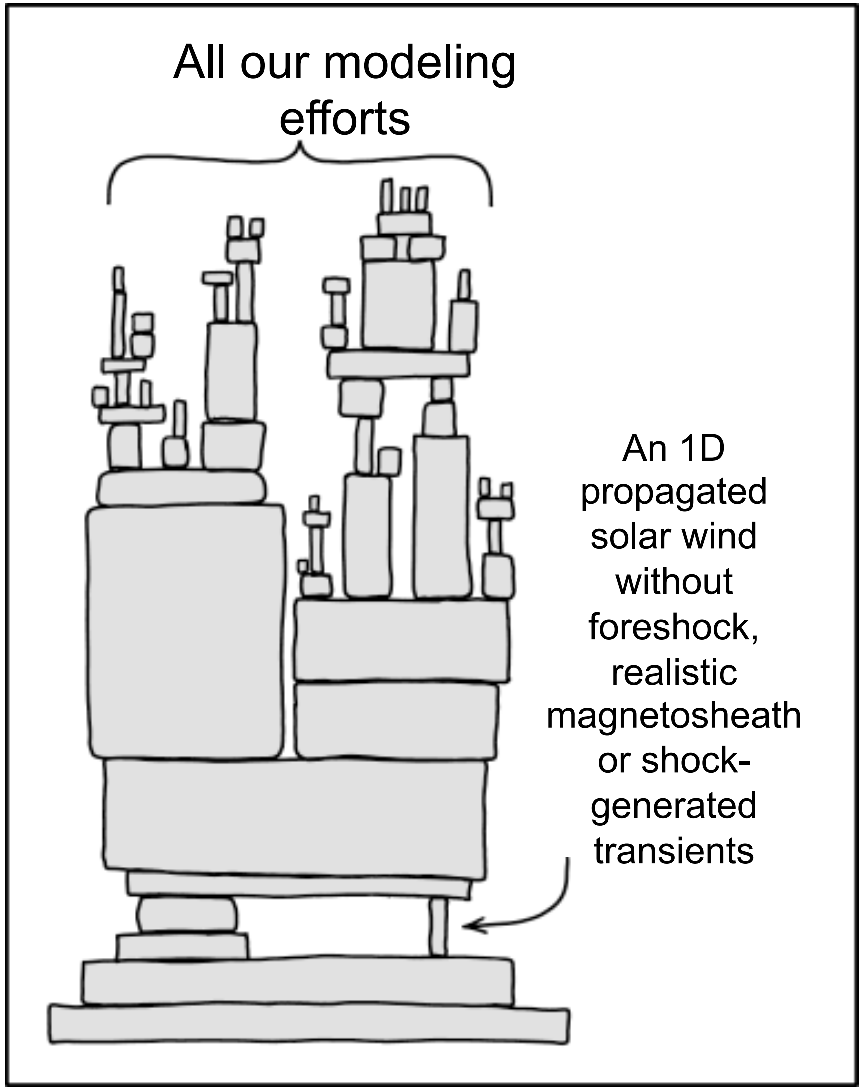








What are we dealing with?



Two challenges:

Solar wind information limitations:

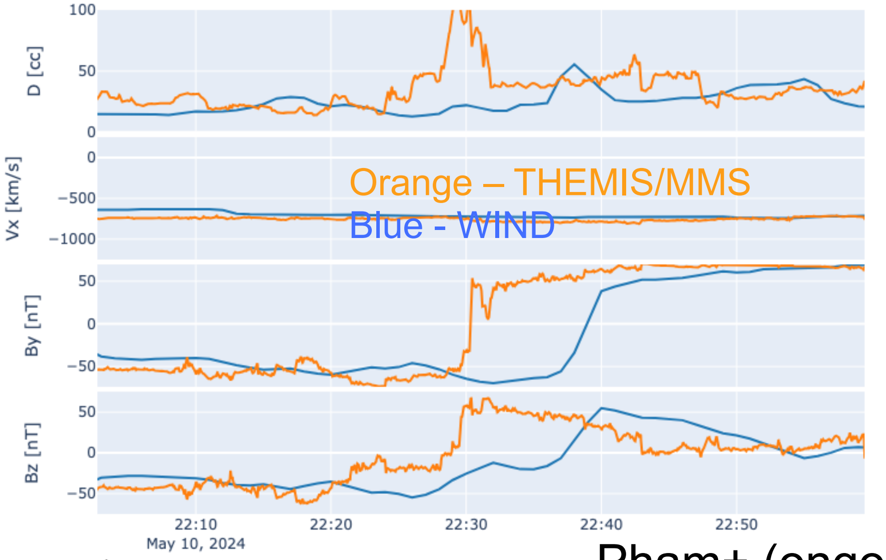
- Reality has complex 3D structure and spatial variability.
- It is easier to rely on simple 1D picture that is available than do the extra effort.

Neglected foreshock and magnetosheath transients:

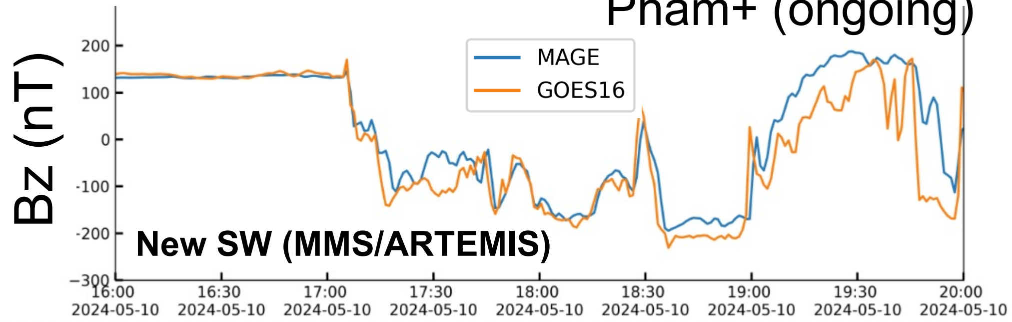
- These transients can affect magnetopause reconnection, and more.
- They are often omitted because they are difficult to include.

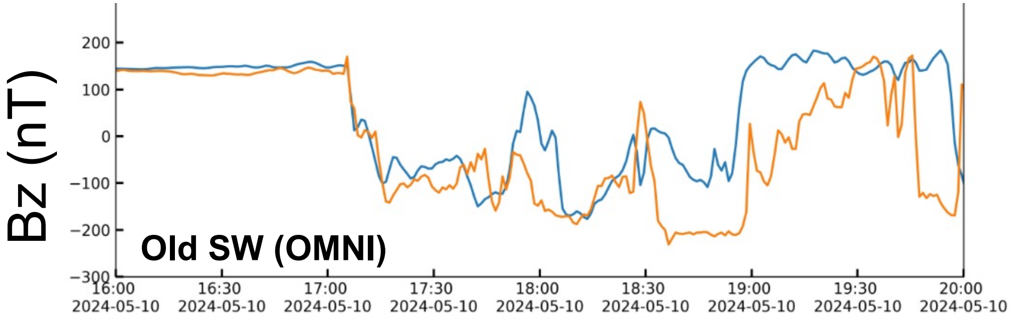
Examples from Gannon Storm

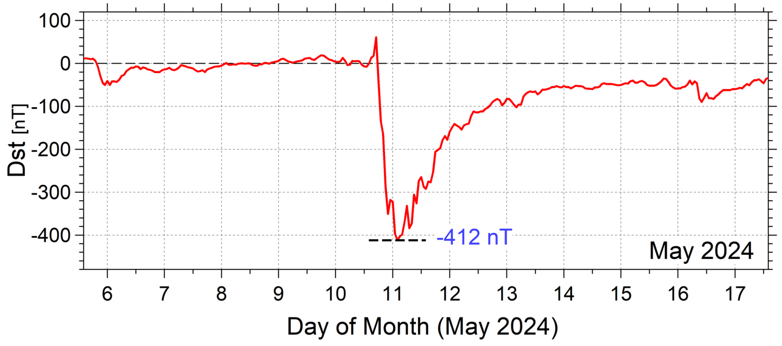
This density enhancement may play a crucial role



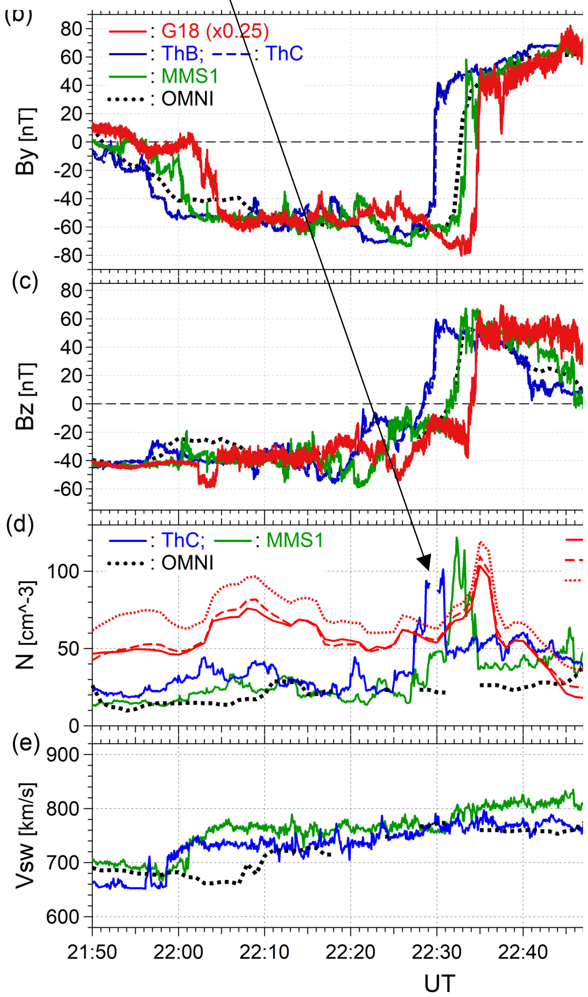
Pham+ (ongoing)







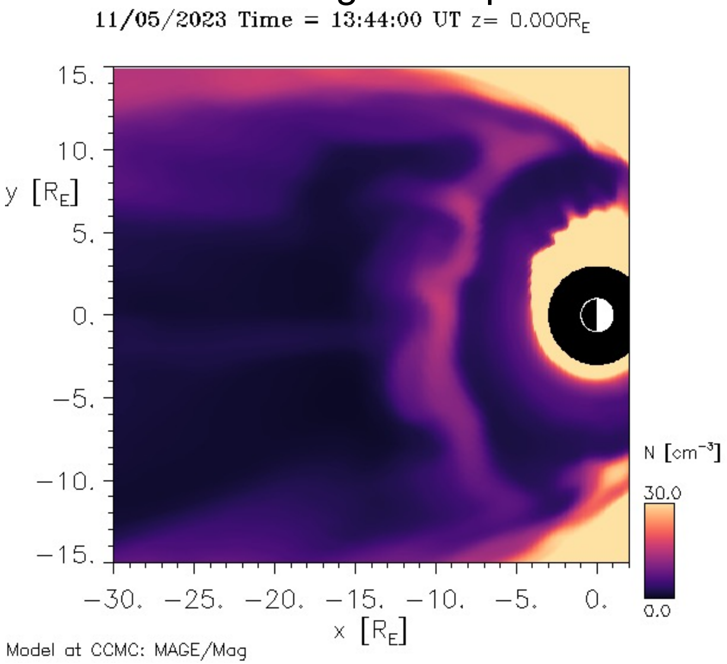
- Introduced local upstream (~10 min) transient variability from local in-situ observations
- Data–model agreement increased drastically
- Physical interpretation of ground data changed significantly

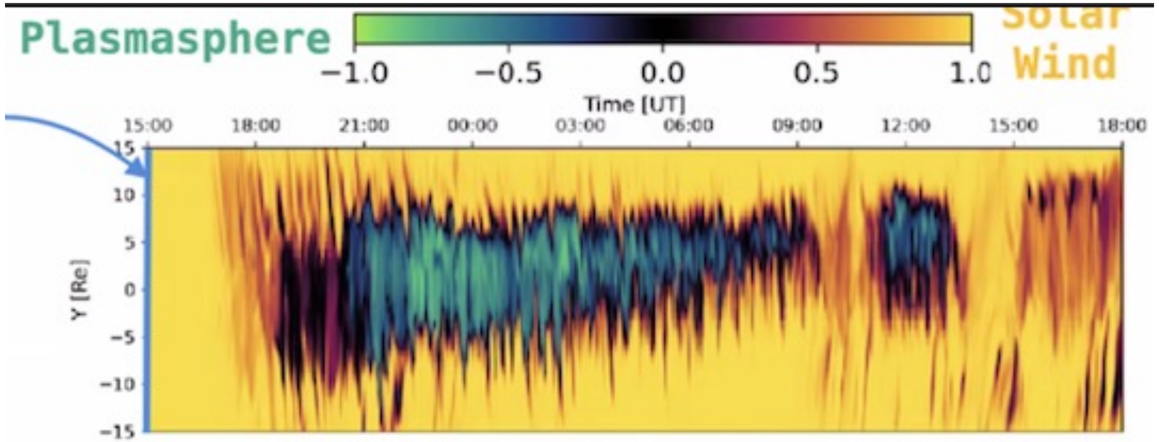


Ohtani+ (2025)

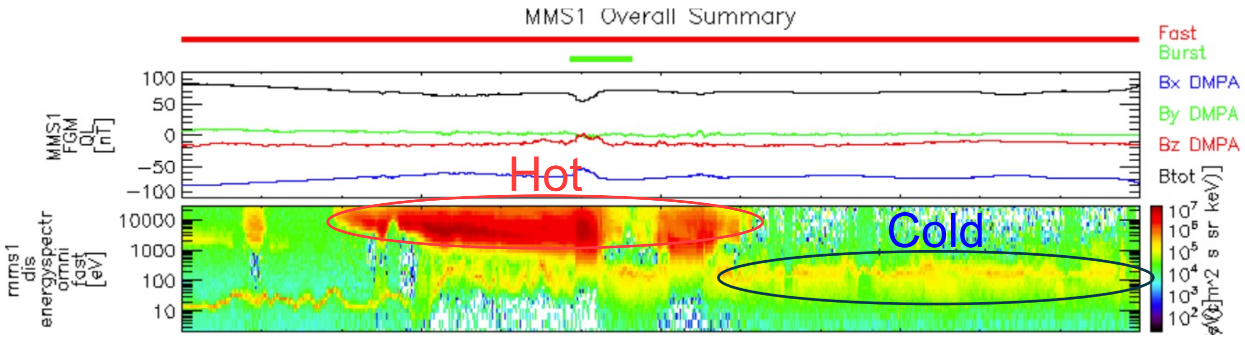
Origin of high-Density plasmasheet intervals

CCMC run showing whole plasmasheet with high density

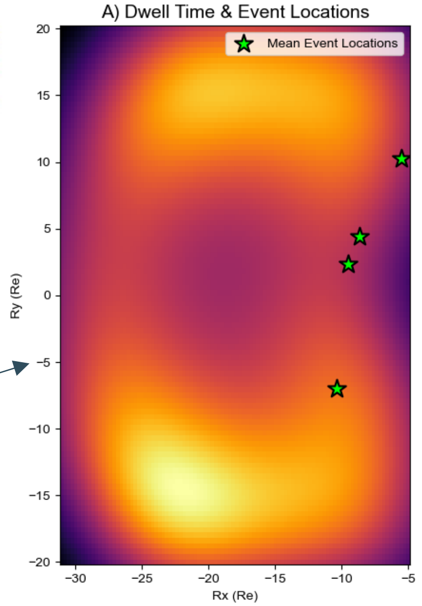




Screenshot from Kareem's presentation



MMS data during a storm, localize density peaks (n>4 [1/cc]) at x<11Re



Geotail events of high density events during storm main phases

<u>Todo</u>: Calculate partial moments from MMS,THEMIS,Geotail during these events to evaluate presence of secondary population and compare with MAGE

Kang et al., 2025 Using BATS-R-US: "During the early main phase, these ions can contribute up to 60% of the total plasma sheet pressure"

Machine learning & *Data-Model "Fusion"*

1. **Proper train/testing**, we need to make sure models generalize (magnetosphere community is not doing great here)

2. Avoid data modeling based on other in-situ quantities (*non-unique solutions*)

3. Providing incomplete physics (e.g., ideal MHD) can bias data-model fusion models towards wrong solutions rather the other way around

4. **Residual modeling**: Train ML to predict the simulation error against data (residuals) rather than the full state (i.e., the correction, can be great for storm specific modules)

5. Investigate more PINNS and data assimilation (i.e., what people mean with data-model fusion)

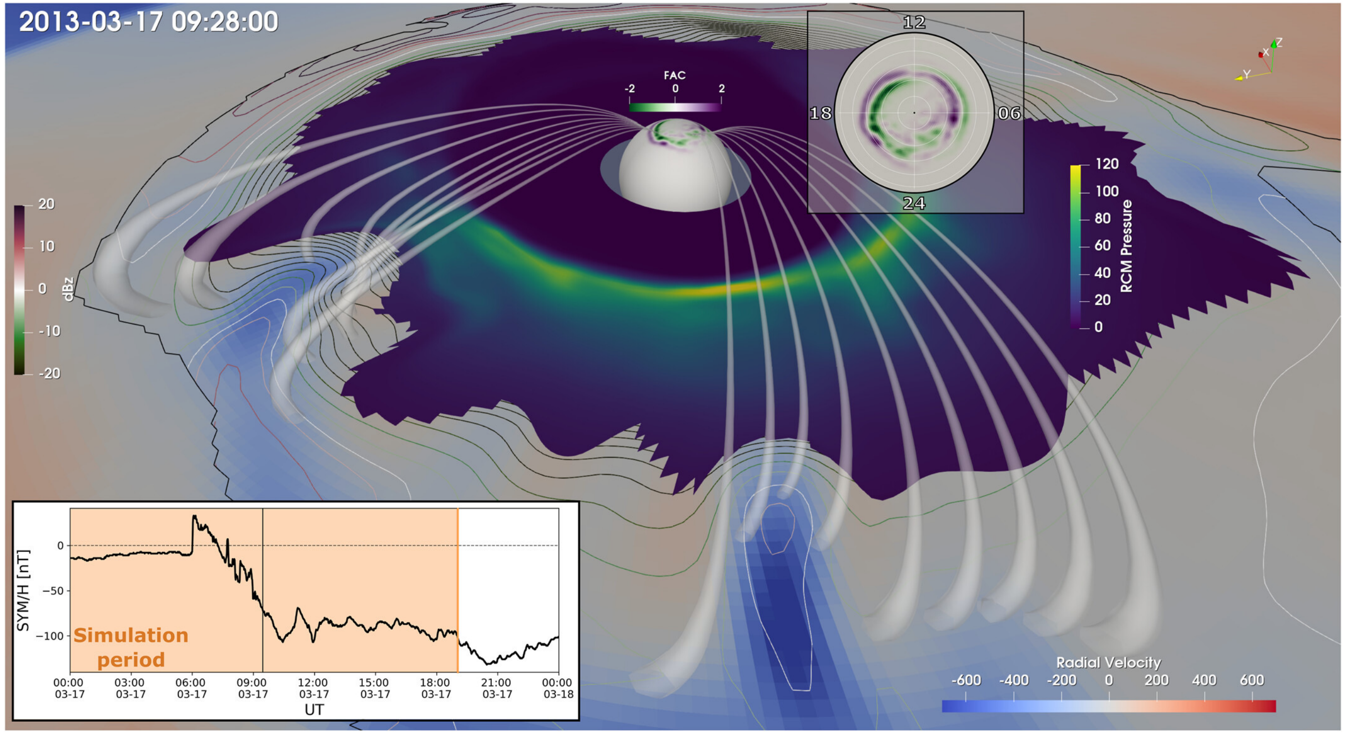
6. Use techniques that are easy to implement algorithmically and to interpret (e.g., Symbolic Regression)

7. Reduce in-situ observations to only these that are useful for their task

```
...   Original dataset size: 241311
      Reduced dataset size: 6978
```

Extras

General Context & Motivation



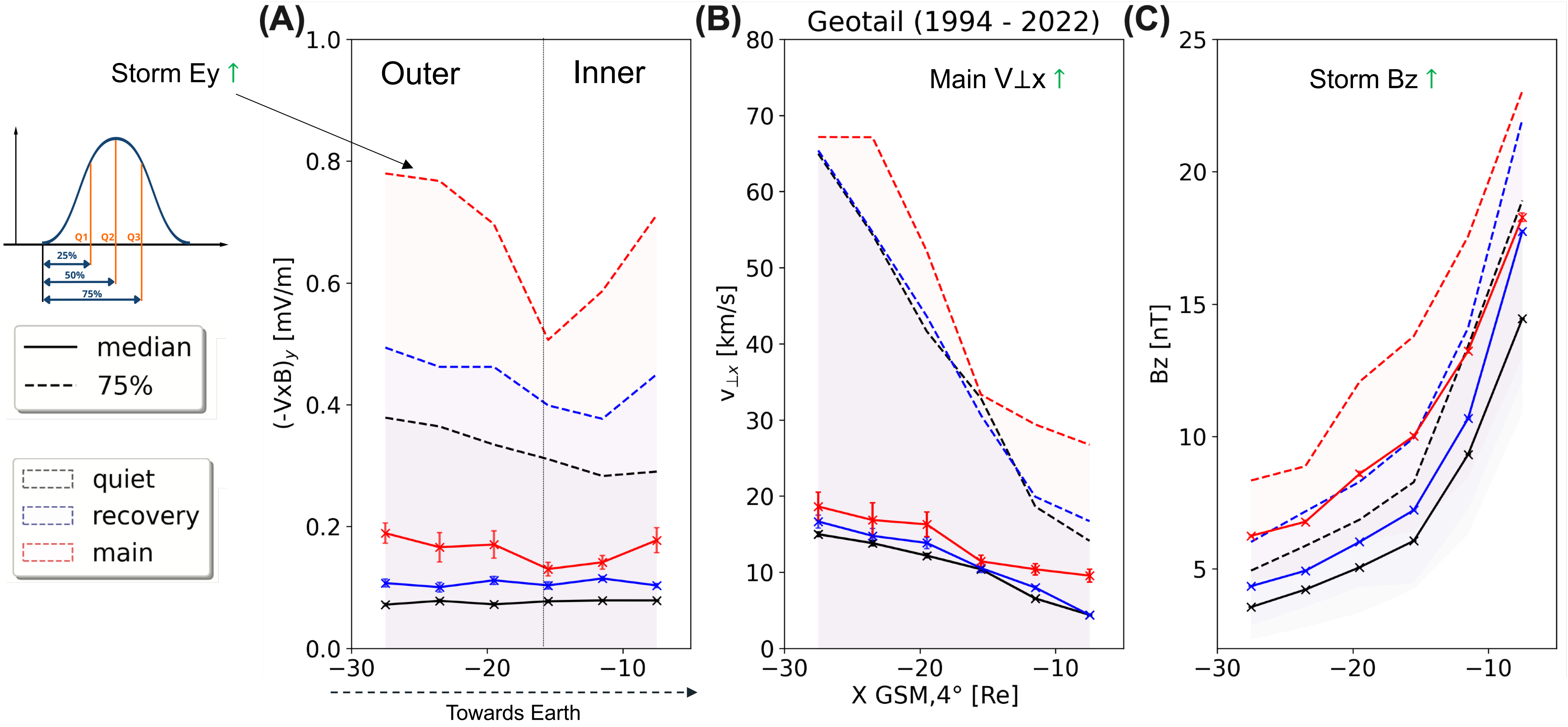
Sciola+ 2023

<u>One of CGS objectives:</u>
The role of **mesoscale plasma sheet** transport in the **ring current** build-up

➢ To tackle this **we need** to establish a **clear understanding** of the overall **plasmasheet transport during quiet and storm times**.

50% of total energy flux transported into the inner magnetosphere by mesoscale structures

Plasma Sheet Convection – Geotail

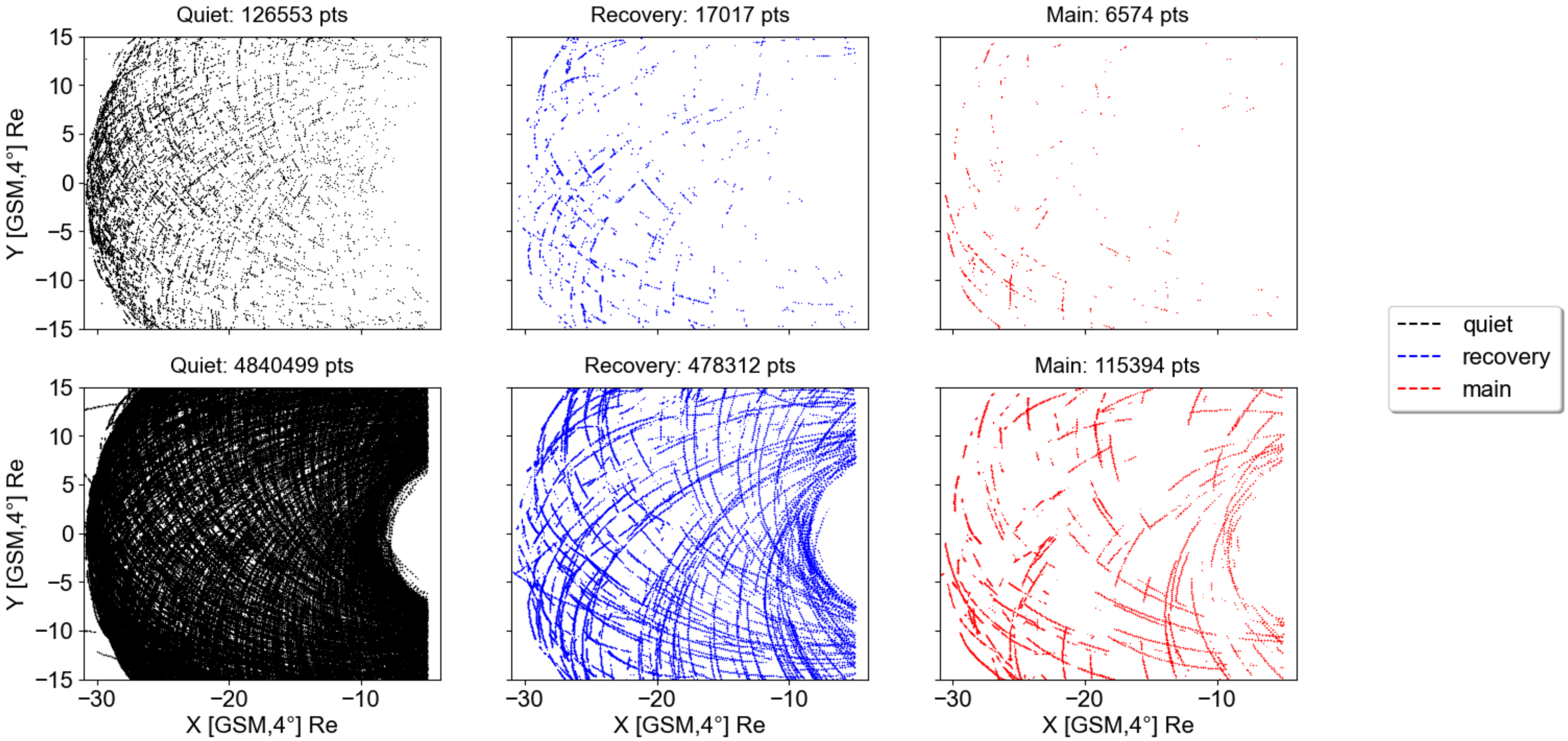


Similar for MMS, just more noisy…

Statistics Caveat for bursty flows – Geotail (1994 – 2022)

BBFs

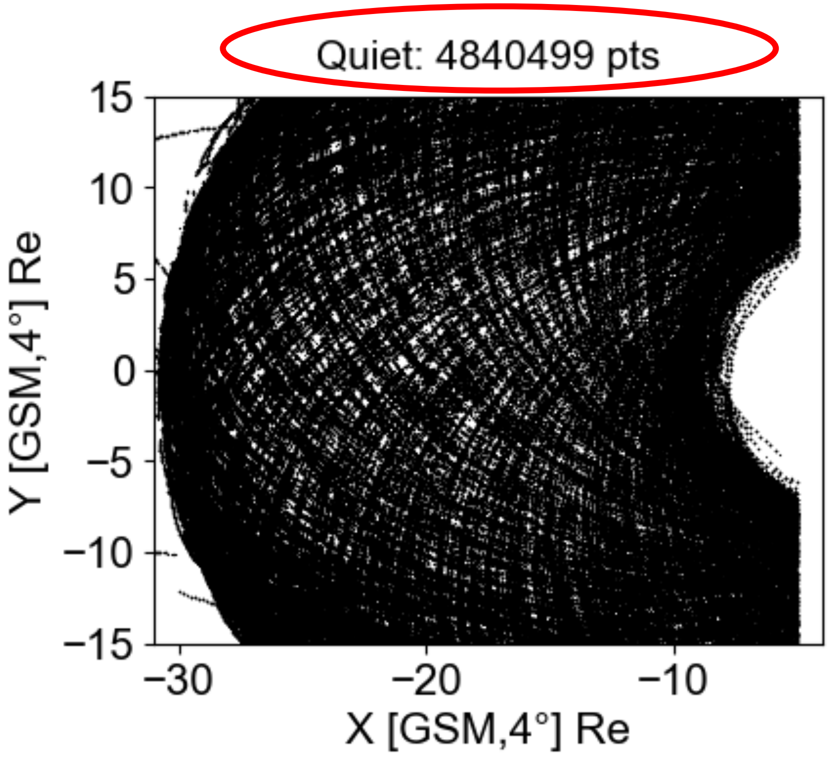
No BFFs

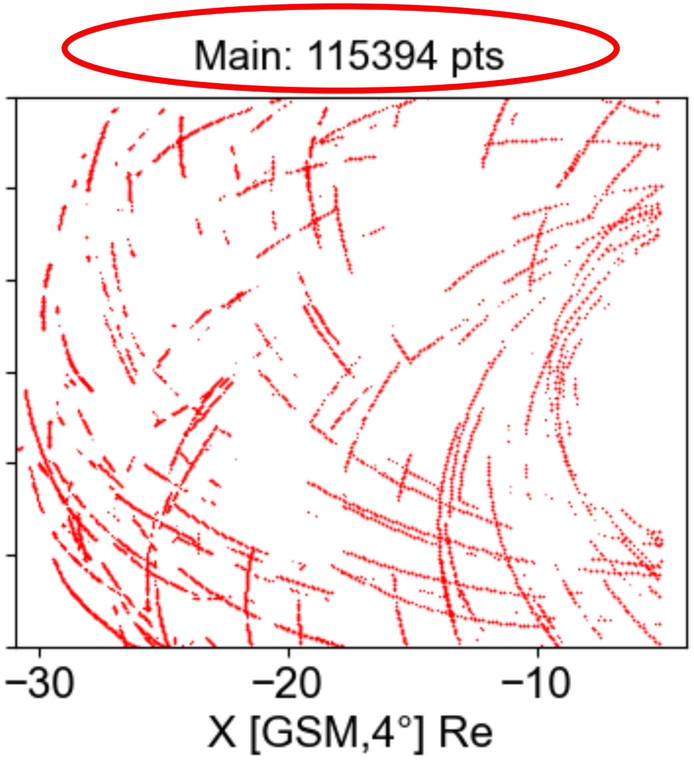


Keypoint: Number of data points can be misleading

Community Reminder: Data Sparsity During Extreme Events

Geotail data (1994 – 2022), time resolution: 12 seconds





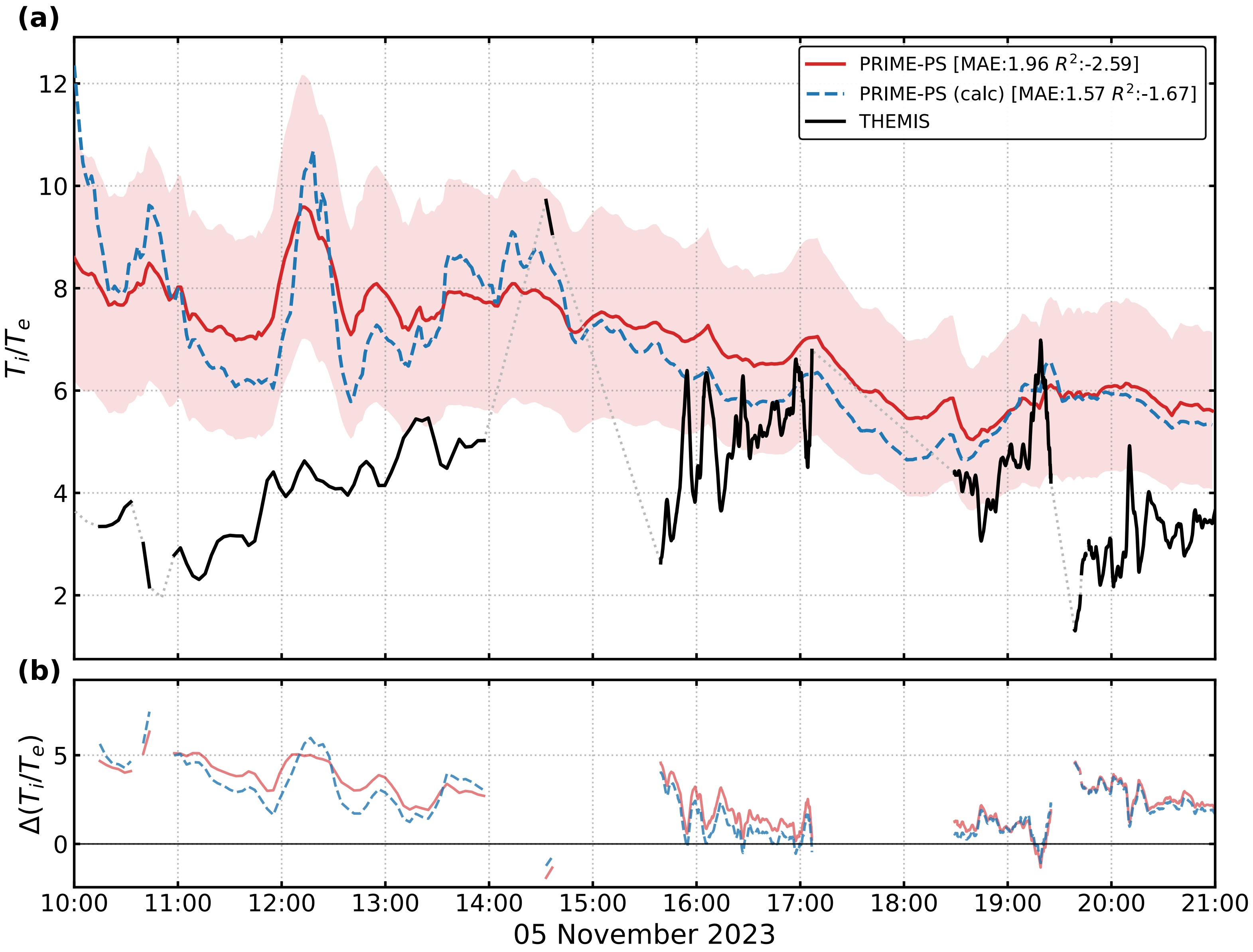
(#of unique days, # unique storms)

Geotail						
Main	7377 (36|32)	3006 (22|19)	2715 (17|17)	6240 (22|19)	6009 (21|19)	2450 (24|23)

Keypoint: Number of data points can be misleading

Note: This doesn't even include the incomplete driver (SW) distribution.

Test case of a storm (05 Nov 2023)



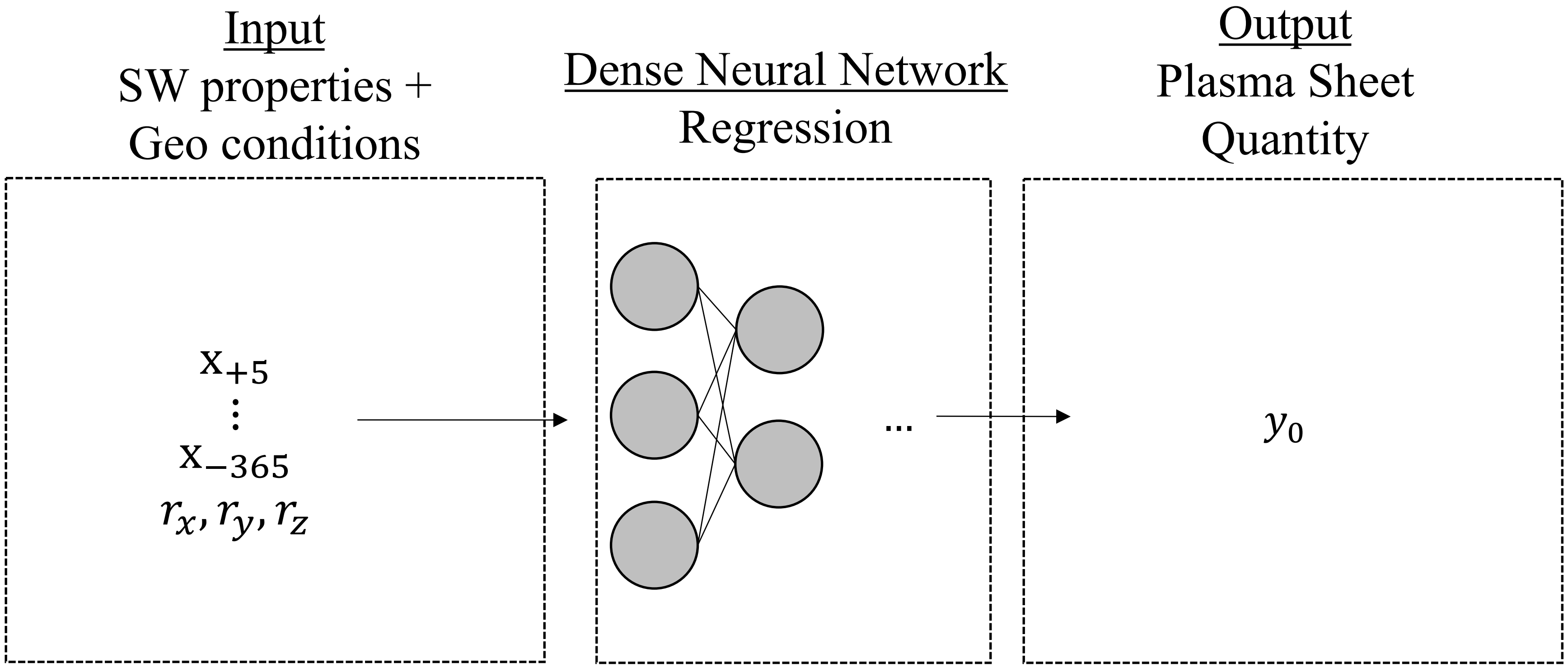
Process:

PRIME: Directly predicted
Calc: Calculated

Test:

THEMIS observations 2 years after the Geotail data stopped operating

Data Scientist POV
(i.e., Input, output & regression)



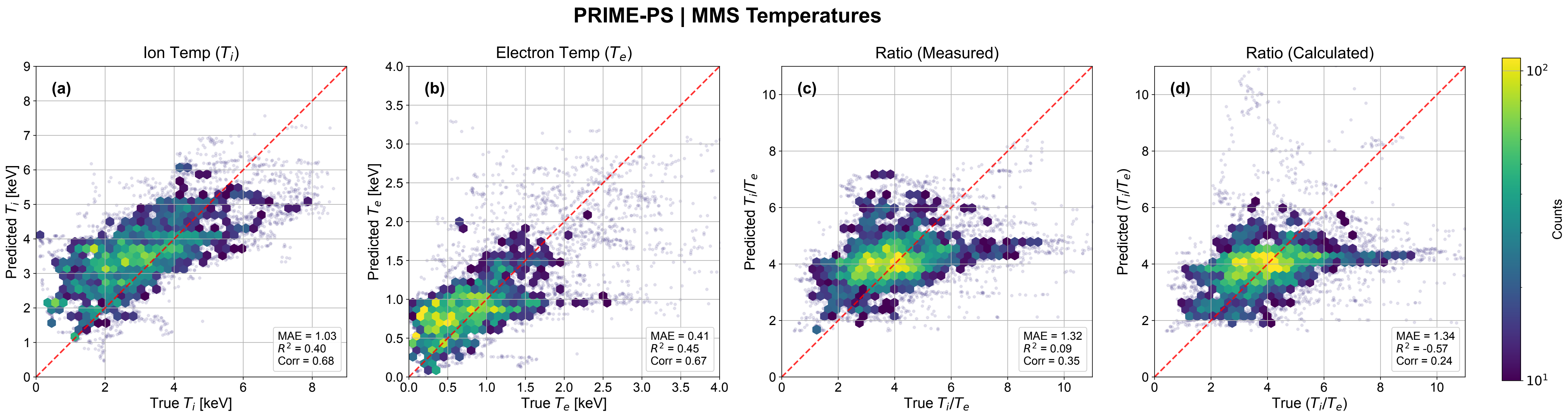
Input:
x: Different solar wind features (e.g., n, B, etc.) + geomagnetic indices including time history up to 6h
r: Location of SC measuring output

Output:
y: Different quantities at plasma sheet (e.g., n, B, T etc.)

SW Input tried: Wind (1min res) – OMNIweb (1/5 min res)

Results here shown for 1min averaged quantities for output

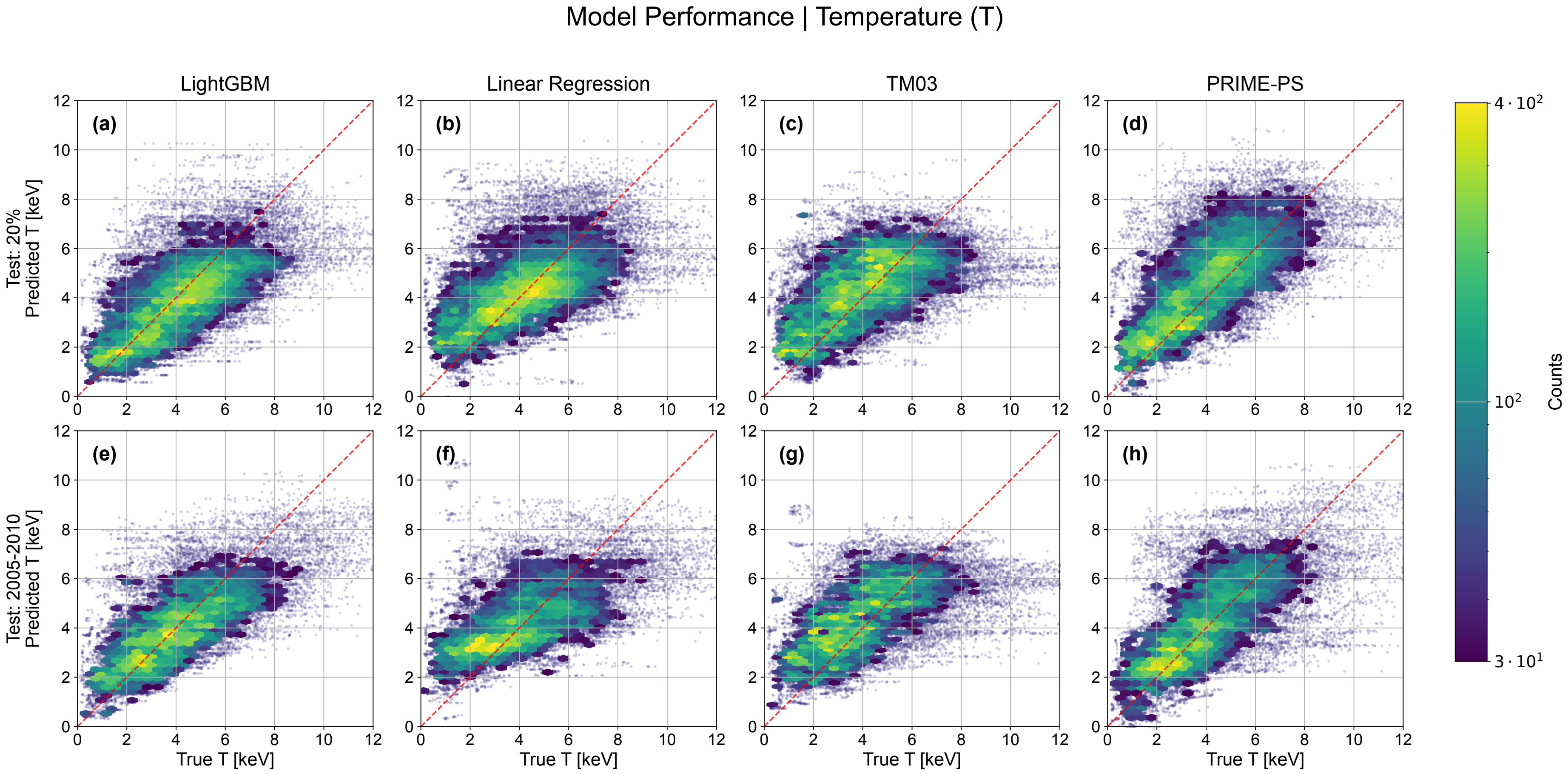
Temperature and Ti/Te MMS output



Note: Not showing analytical model, but essentially it does not agree with observations since DGSR16 and TM03 are trained on different domains, spatial distances, and from different missions

Modeling Temperature | Predictions vs Observations

Key Message: PRIME – PS/GB > Baseline ≥ TM03



Raptis, O'Brien et al., 2026 (under prep.)

Is all this data needed? (Discussion point – Imbalanced learning)

1. **Identify Outliers:**
   - **Find Outliers:** Detected using *Isolation Forest* (unusual feature patterns)

2. **Build a Diverse Core (Farthest Point Sampling):**
   - Selects a *core subset* where points are maximally distant
   - Ensures broad coverage and *high diversity* of the original data

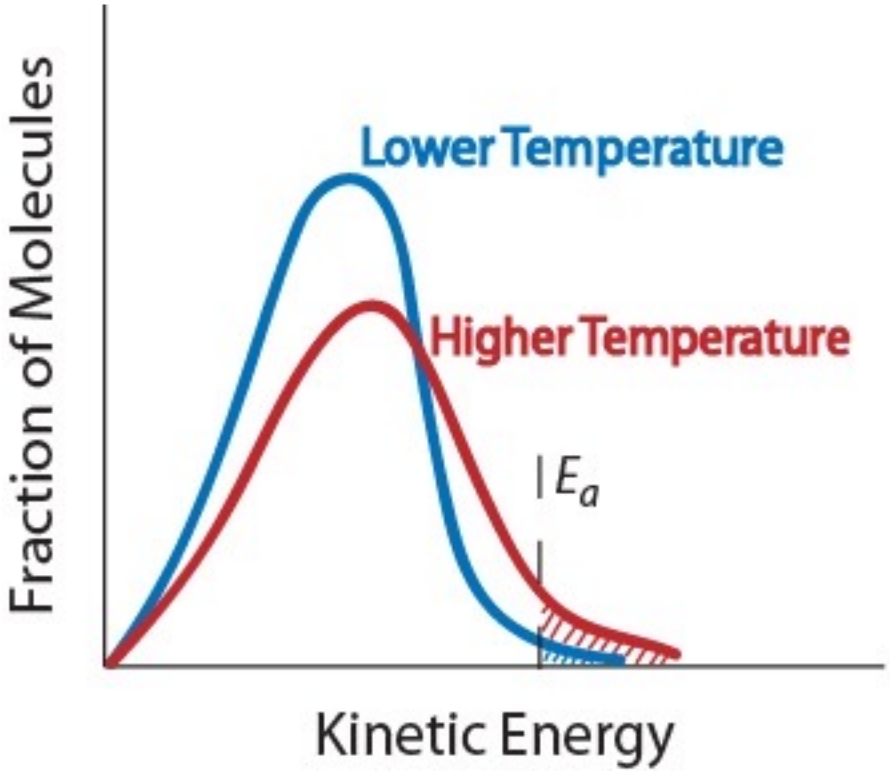
3. **Balance with Rare Samples (Kernel Density Estimation):**
   - Adds points from *under-represented regions*

Reduced by 1-2 order of magnitudes.

Almost Identical performance on test set.

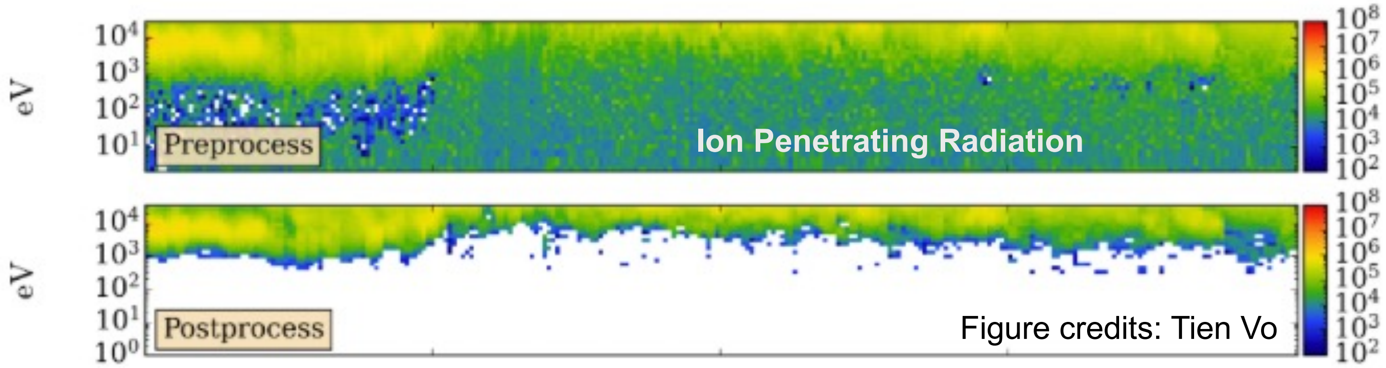
```
...   Original dataset size: 241311
      Reduced dataset size: 6978
```

Community Reminder on Temperature



$$T = \frac{m}{3k_B n} \int (\mathbf{v} - \mathbf{v}_b) \cdot (\mathbf{v} - \mathbf{v}_b) f(\mathbf{v}) d^3 v$$

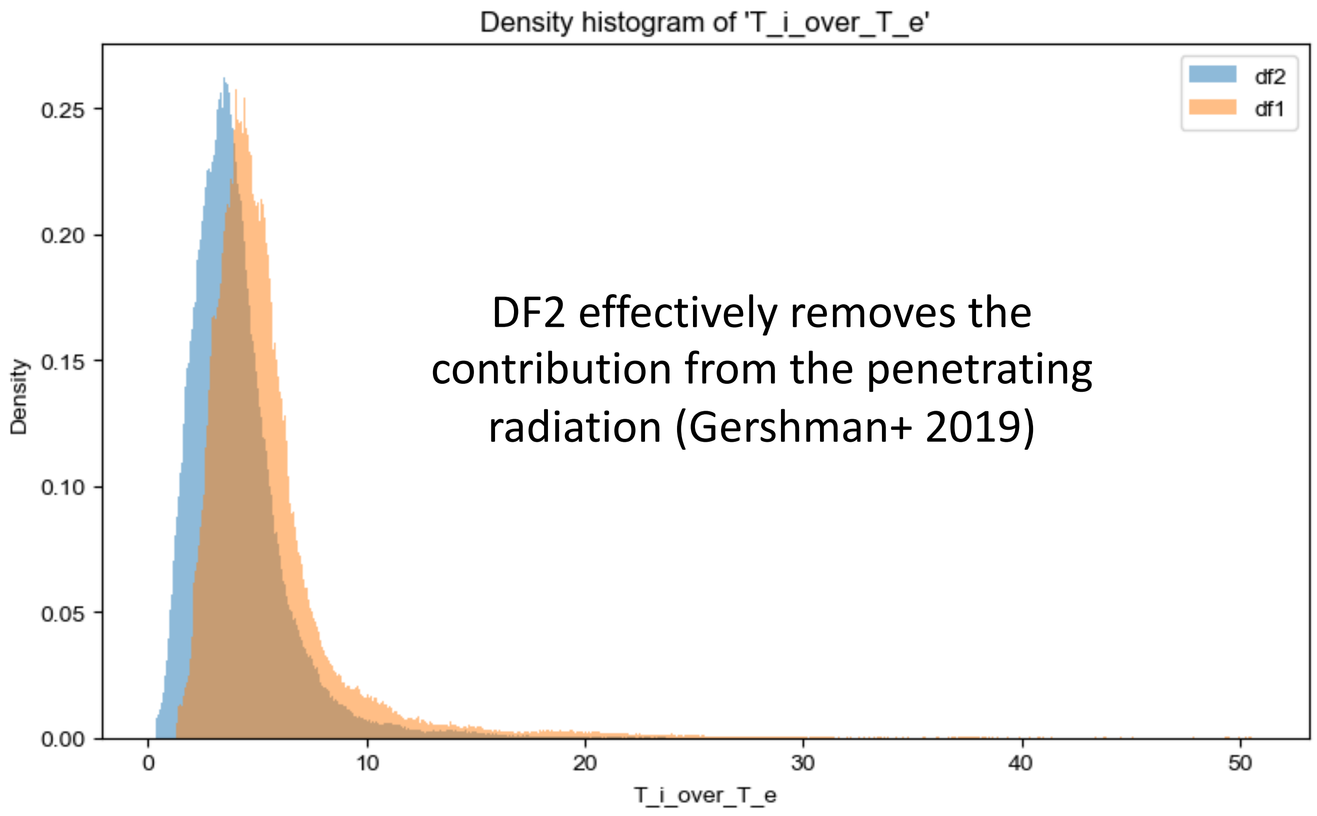
- Temperature is the 2nd plasma moment
- The higher the moment, the more uncertain because you rely more on the poorly sampled tails of the distribution.
- So, 0 and 1st moment (**Density and Velocity**) are usually ok, but Temperature, we got to be careful



The temperature here was completely incorrect, and the velocity increased from about 200 km/s to over 1500 km/s.

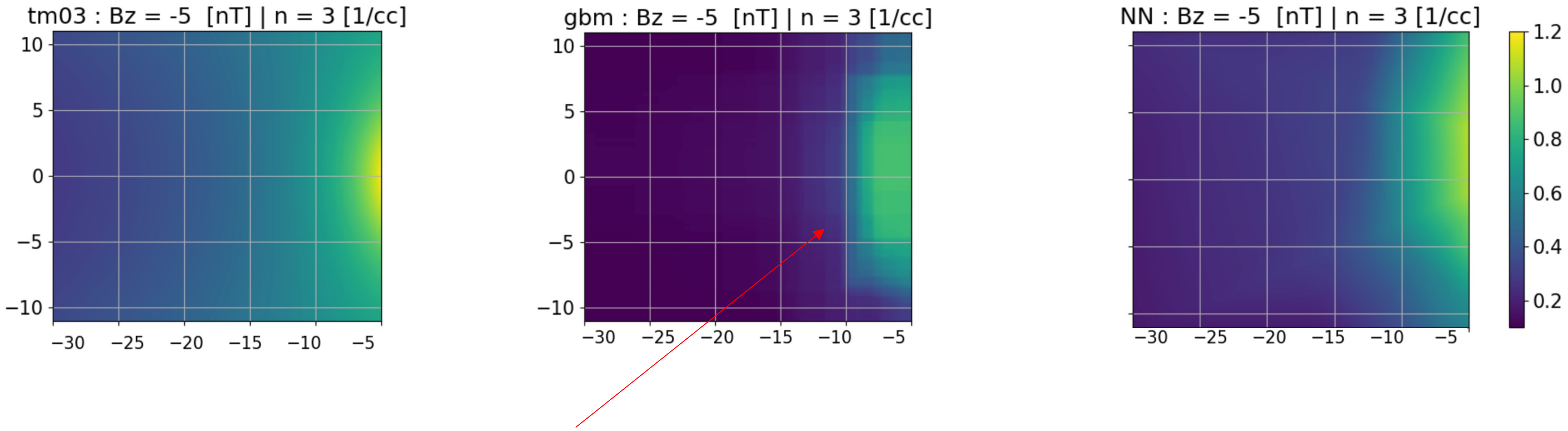
MMS Ti/Te plasmasheet ratio example (Full vs Partial moments)

mean df1 (full distribution moments): 5.5513
mean df2 (partial distribution moments): 4.0797



Key Message1: The mean differenced changed by 1.5 (>30%) simply by recalculating moments
Key Message2: A model with +30% is exciting, but we need to know if "*ground truth*" vary by the same magnitude

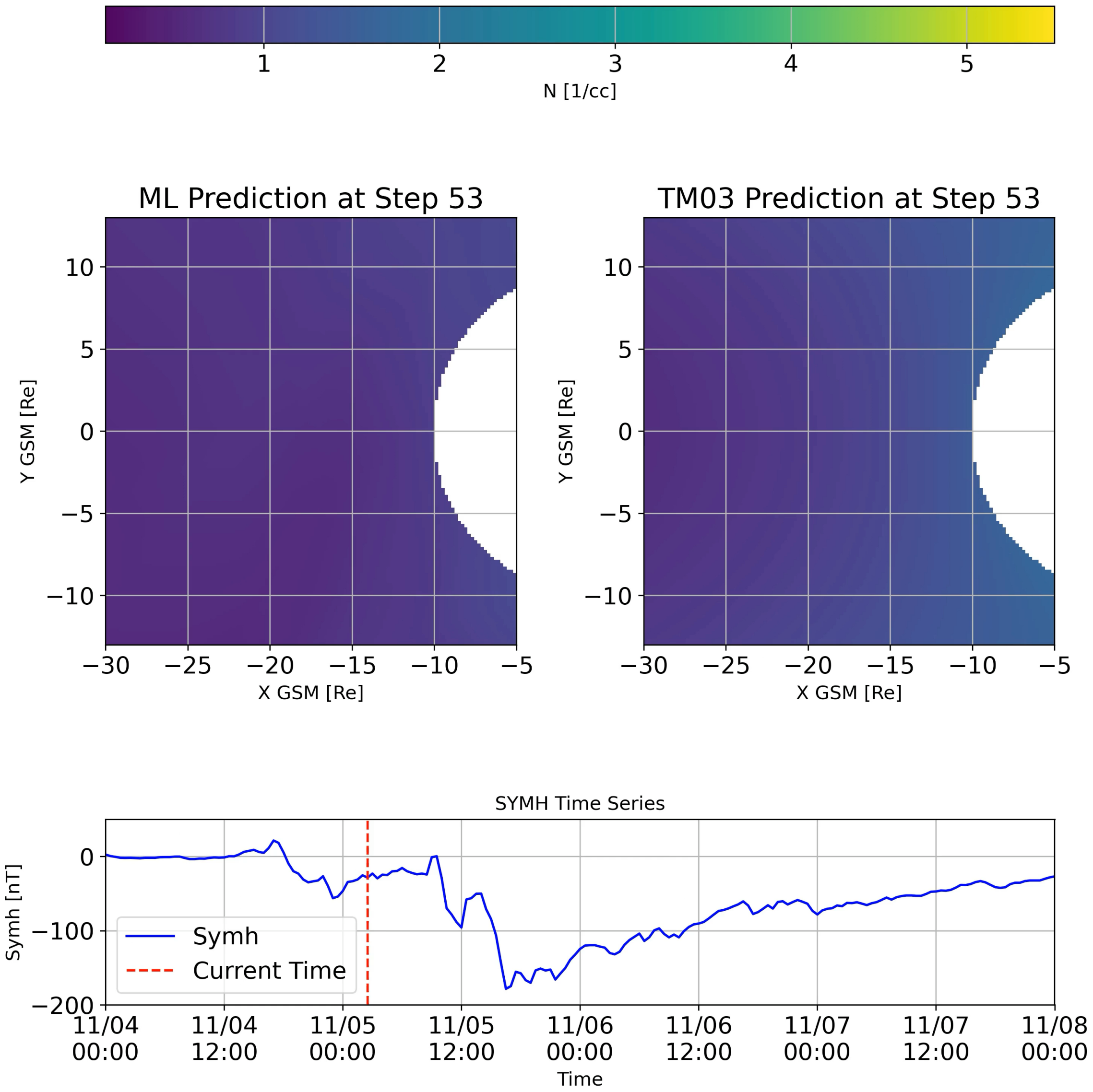
Community Reminder via Modeling Bz



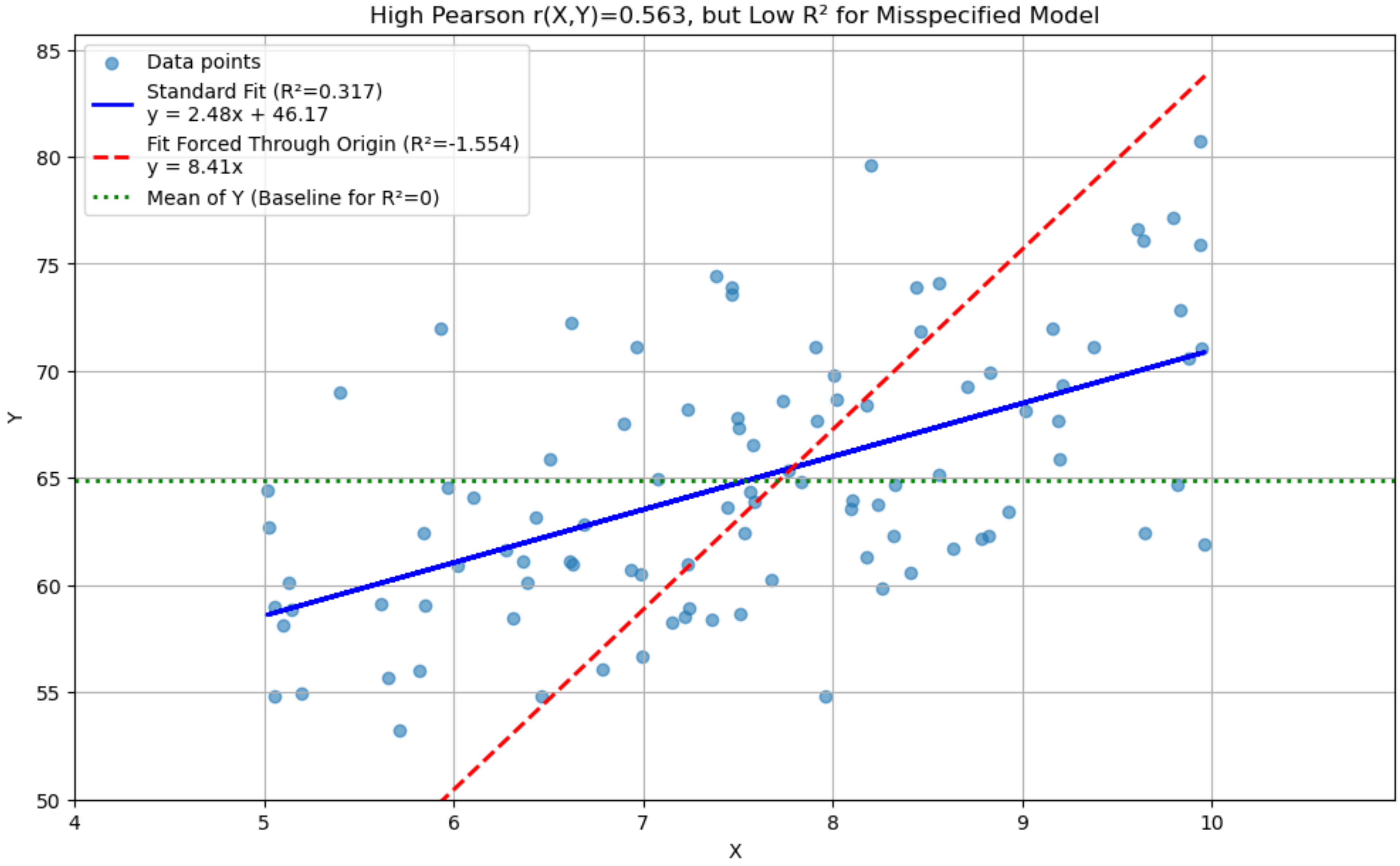
Gradient boosting is powerful, but it’s a poor extrapolator.

Since it’s built on decision trees, it predicts from nearby data rather than extending patterns like a neural network.

ML storm time density modeling

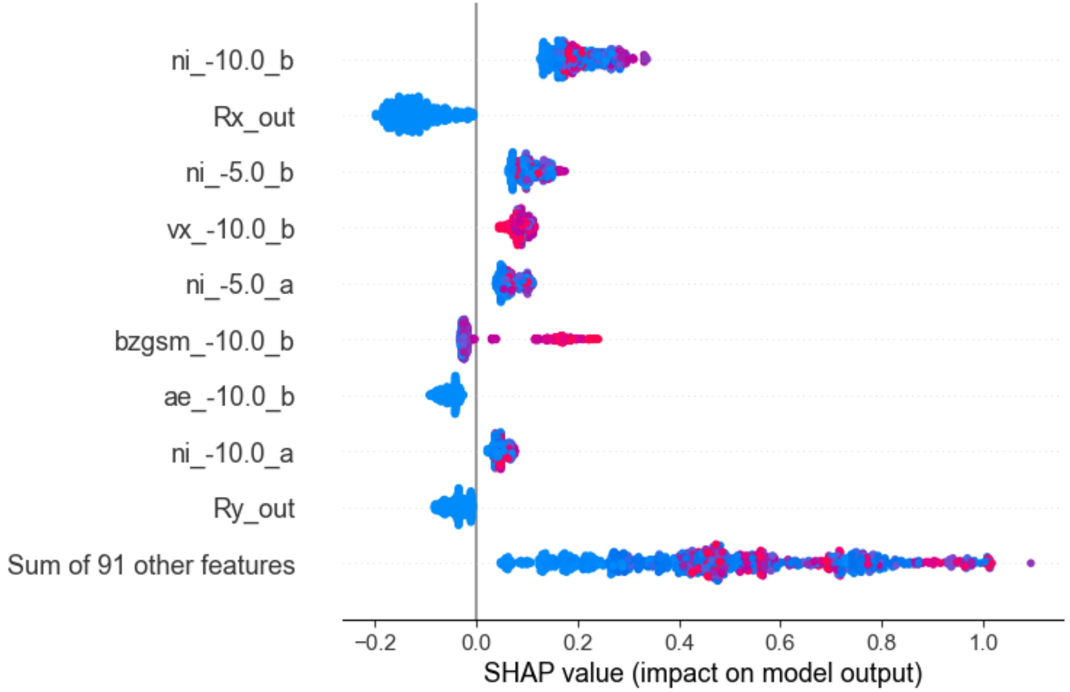


Correlation and Rsquared difference

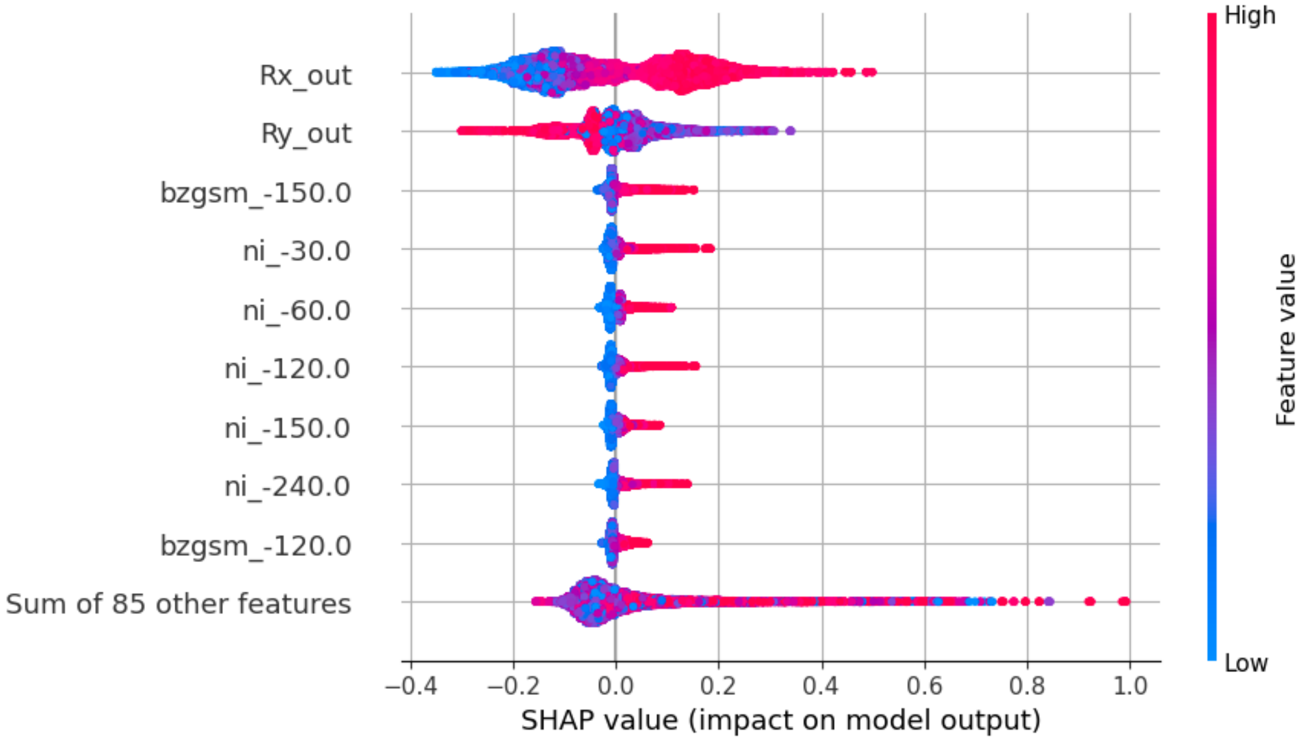


Model Feature importance storm vs quiet

In other words, the increased upstream density (-1h) had a greater impact during the storm than the SC location.

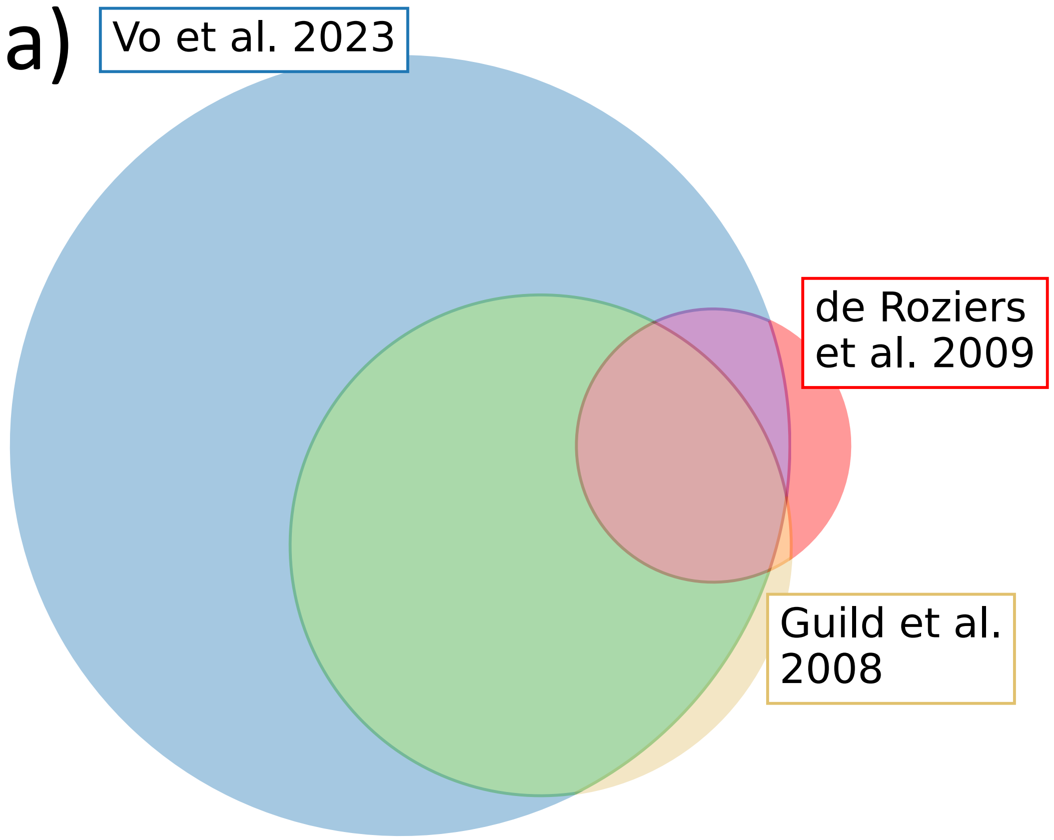


X_test_storm



X_test_total

Classifying plasma sheet is not trivial



Plasma Sheet Criteria			
Vo et al. 2023	de Roziers et al. 2009	Guild et al. 2008	**Number**
Yes	No	No	1,259,896
No	Yes	No	39,451
No	No	Yes	28,828
Yes	Yes	No	46,399
Yes	No	Yes	686,527
No	Yes	Yes	10,483
Yes	Yes	Yes	170,467

Note Vo+2023, had a multi-step process based on interval, this is just using the point-by-point classification

Criterion	Strict CPS	Flexible CPS	High density
$\beta > 1$	yes	—	—
$\beta > 0.5$	—	yes	—
$\sqrt{B_x^2 + B_y^2} < 2\|B_z\|$	yes	—	—
$N < 6$	yes	—	—
$N > 6$	—	—	yes
EA1SW0 = EA	yes	yes	yes
$-31 < R_x < -5$	yes	yes	yes
$\|R_y\| < 15$	yes	yes	yes
$\|R_z\| < 10$	yes	yes	—
$V_x > -20$	—	—	yes

Table 1. Plasma sheet classification thresholds for the strict CPS, flexible CPS, and high-density subsets. *beta* is the ion plasma beta parameter, density (N) is in 1/cc units, V_x is in km/s, and all the locations ($R_{x,y,z}$) are in Earth radius. The coordinate system for all vectors is the aberrated Geocentric Solar Magnetospheric (GSM) coordinates

Storm Time Behavior and Importance of Outliers

The Problem: We use static thresholds for dynamic environents.

The Risk: Therefore we can mistakenly remove the crucial "stormtime plasmasheet."

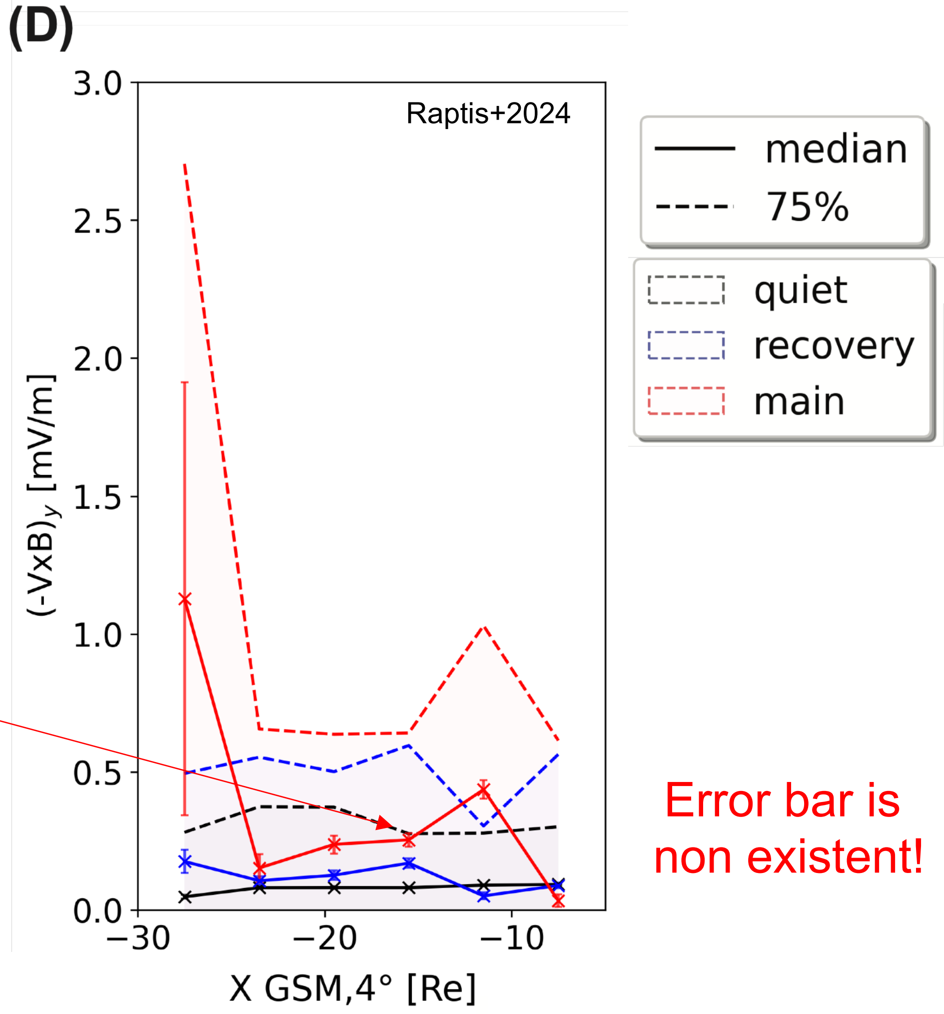
The "Solution": Manually find the missing data and add it to the dataset.

Strict CPS (e.g., Ohtani et al., 2008 Raptis et al., 2024) & Flexible CPS (e.g., Richard et al., 2022)

Data number & storms

Table S1. Distribution of points for Geotail and MMS, used to generate Figure 2 of the main text. Each cell indicates the number of points along with the number of unique days and unique storms (#days | #storms). The bins used for the X axis are shown in the last row.

Geotail						
Main	7377 (36|32)	3006 (22|19)	2715 (17|17)	6240 (22|19)	6009 (21|19)	2450 (24|23)
Recovery	27254 (77|66)	19855 (68|58)	17770 (60|53)	14892 (58|52)	26234 (79|68)	35488 (102|93)
Quiet	220027 (553)	122734 (425)	104663 (401)	128919 (438)	234532 (666)	382446 (833)
MMS						
Main	8 (1|1)	573 (3|3)	1476 (3|3)	1512 (3|3)	1299 (3|3)	1987 (7|5)
Recovery	781 (3|2)	4412 (8|6)	3889 (10|8)	4284 (12|10)	7907 (13|13)	7451 (18|16)
Quiet	21036 (52)	53739 (135)	40825 (126)	37538 (132)	46777 (166)	72190 (195)
Bins x	**[-30, -25]**	**[-26, -21]**	**[-22, -17]**	**[-18, -13]**	**[-14, -9]**	**[-10, -5]**



Error bar is non existent!

What does it mean to have 1500 data points if they originate from 3 storms/3days?

Key Message: #of unique days, # unique storms, and distribution of upstream conditions is more important than SE