

# What Science Can We Do with The L1 Spacecraft Fleet?

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Acknowledgments\*:

- IMAP Mission

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# Questions & Outline

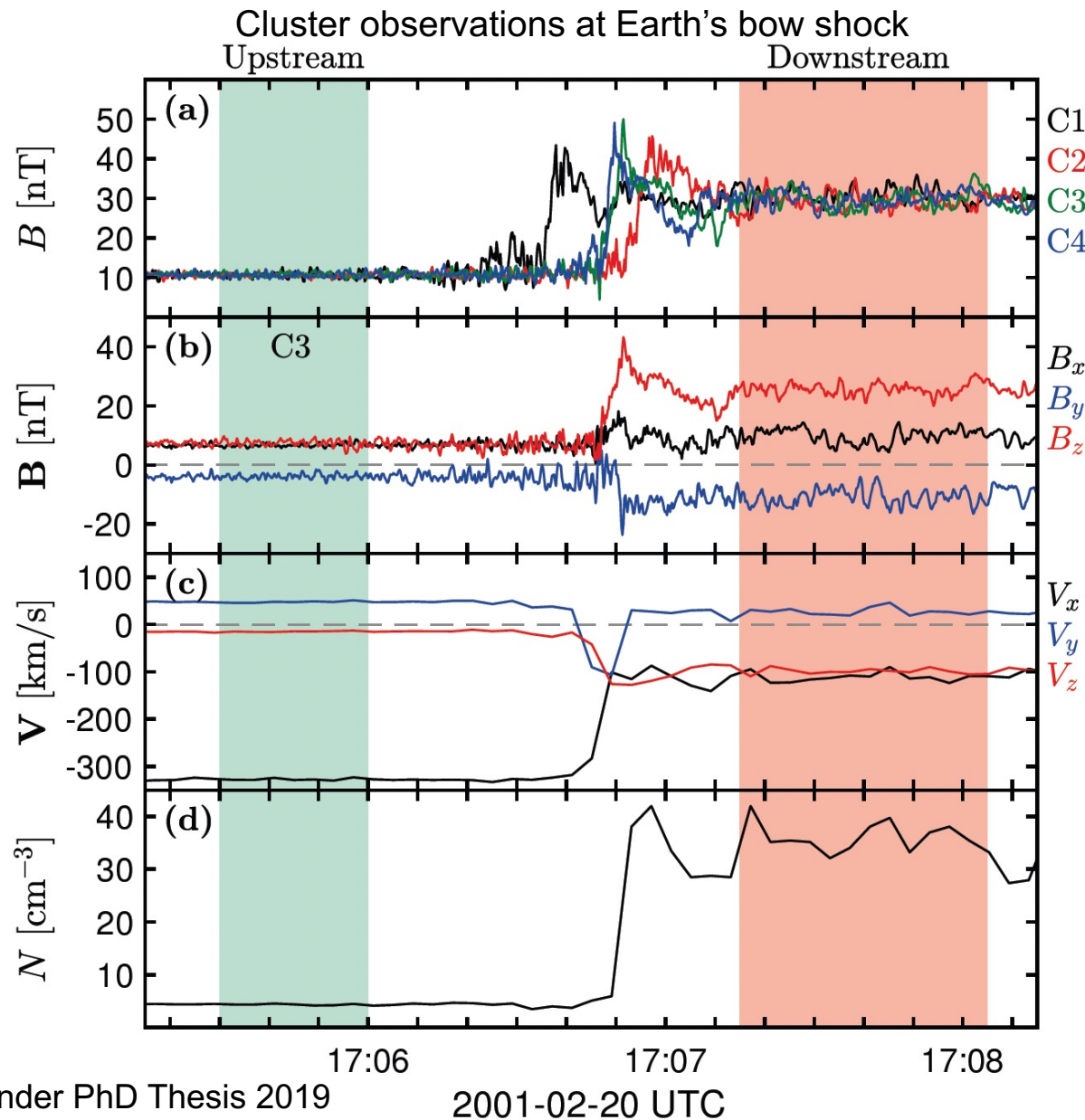
**We've gone from one solar wind L1 monitor to six.  
Which science questions changed because of that and how?\***

- (1) What is the SW magnetic field across multiple scales? Can we reconstruct it? and what can L1 fleet tell us about what eventually happens at Earth?
- (2) If we take one IP shock, can we find its orientation from one spacecraft? What about the whole fleet? What can this tell us about the shock?
- (3) How coherent is a CME across  $\sim 100$ -200 Re? When two signals correlate well, is it shared physics, a shared trend, or maybe even a coincidence?

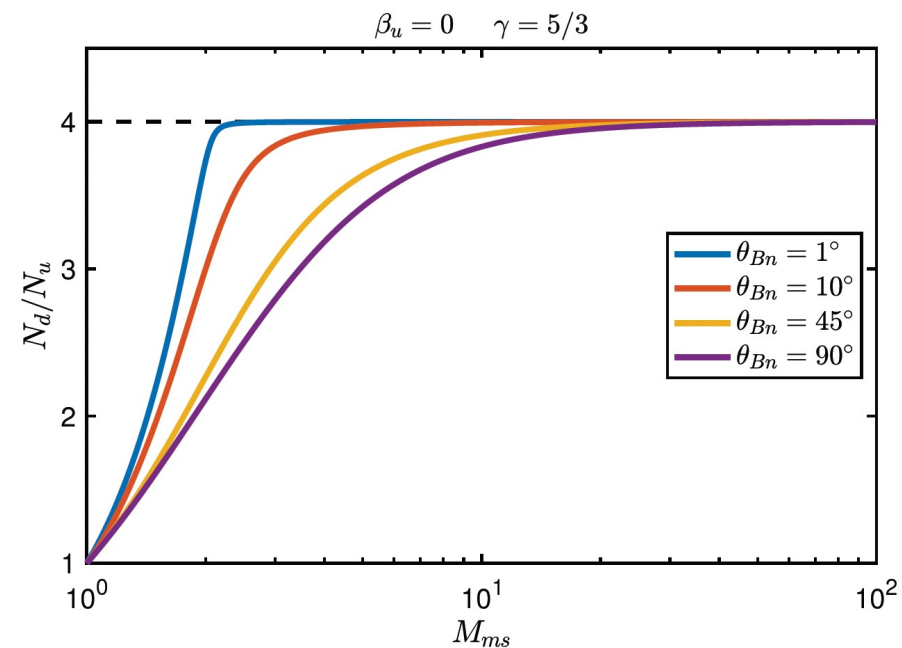
But first some intro about L1 fleet!

\*... a subjective and biased take from an in-situ data person studying mostly Earth

# Community Reminder: in-situ Data & Shocks



*“We can also see this in the compression factor that is 8, which we know from the Rankine-Hugoniot is not allowed”. This highlights one of the considerations regarding accuracy and reliability of methods when working with spacecraft data from shocks in space”*



# L1 Constellation/Fleet/Swarm/Monitors

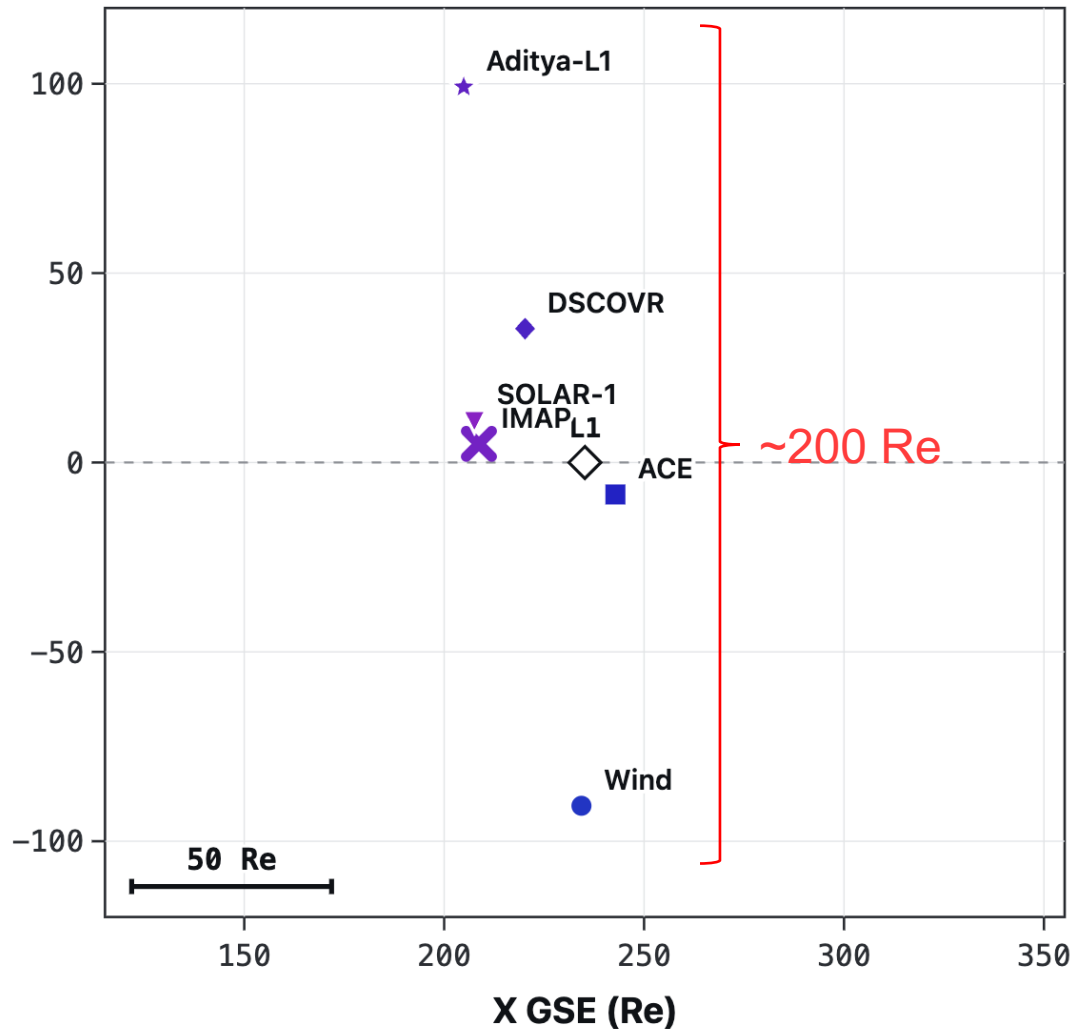
Six-spacecraft L1 era began practically a few months ago!

L1 Region

XY PLANE

$\pm 120 \text{ Re}$

2026-01-19 19:00 → 2026-01-19 20:00 UTC



S/C	Launched	At L1	B	Plasma	SEP	Comp.
Wind	Nov 1994	~2004	✓	✓	✓	✓
ACE	Aug 1997	1998	✓	✓	✓	✓
DSCOVR	Feb 2015	2015	✓	✓	–	–
Aditya-L1	Sep 2023	Jan 2024	✓	✓	✓	~
IMAP	Sep 2025	Jan 2026	✓	✓	✓	✓
SOLAR-1	Sep 2025	Jan 2026	✓	✓	✓	–

**IMAP:** No Later than August 1<sup>st</sup>, less than a month!

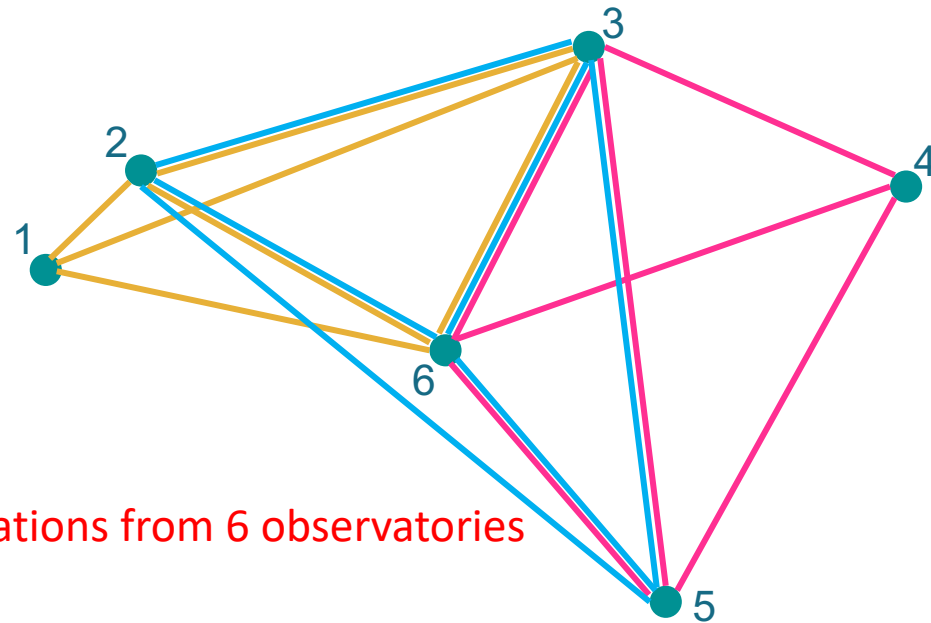
**SOLAR-1:** All data should be accessible already. Data of previous dates from releases (i.e., 1<sup>st</sup> of April for MAG, 27<sup>th</sup> of May for STIS (suprathermal/energetics), and 2<sup>nd</sup> of June for SWiPS (plasma), may take a while

\* Important reminder: Intercalibration for plasma is difficult (impossible?), but magnetometers should be doable

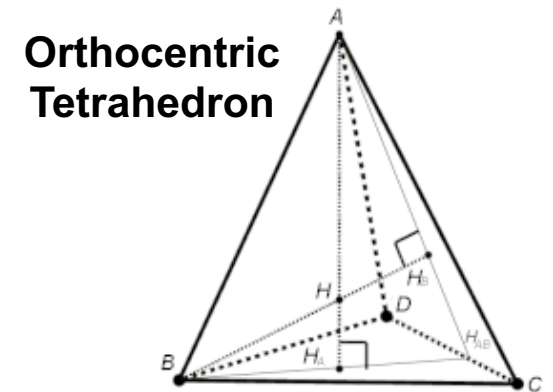
# Multipoint Data Analysis

- In 3D space, 4-points are needed to calculate vector gradients, divergence and curl, planar boundary orientations and speed, etc.
  - Ideal orientation of the 4-points is an orthocentric tetrahedron
- With 6 observatories around L1, there are 15 different tetrahedral sets
  - However, the *quality factor (Q)*, the *planarity (P)*, and the *elongation (E)* of the tetrahedra must be considered

	Permutations with 4 of 6 Spacecraft			
1	1	2	3	4
2	1	2	3	5
3	1	2	3	6
4	1	2	4	5
5	1	2	4	6
6	1	2	5	6
7	1	3	4	5
8	1	3	4	6
9	1	3	5	6
10	1	4	5	6
11	2	3	4	5
12	2	3	4	6
13	2	3	5	6
14	2	4	5	6
15	3	4	5	6



15 combinations from 6 observatories



# The Geometry of the L1 Constellation

- Tetrahedral quality factor for IMAP, SOLAR-1, ACE, Wind, DSCOVR, and Aditya-L1 between Sep-2025 and July-2026
- Due to orbital configuration around L1, **quality is typically not great**

Question: *Can we make up for some of this with sheer number of tetrahedra available?*

The overall quality factor is defined as:

$$Q = Q_v \cdot Q_s \quad (1)$$

where  $Q_v$  is the quality factor for the tetrahedron shape and  $Q_s$  is the quality factor for the spacecraft separation.  $Q_v$  is defined as:

$$Q_v = V_a / V_r \quad (2)$$

where  $V_a$  is the actual volume of the tetrahedron at a given point in the orbit and  $V_r$  is the volume of a regular tetrahedron of side  $L$ , the average of the sides of the actual tetrahedron.

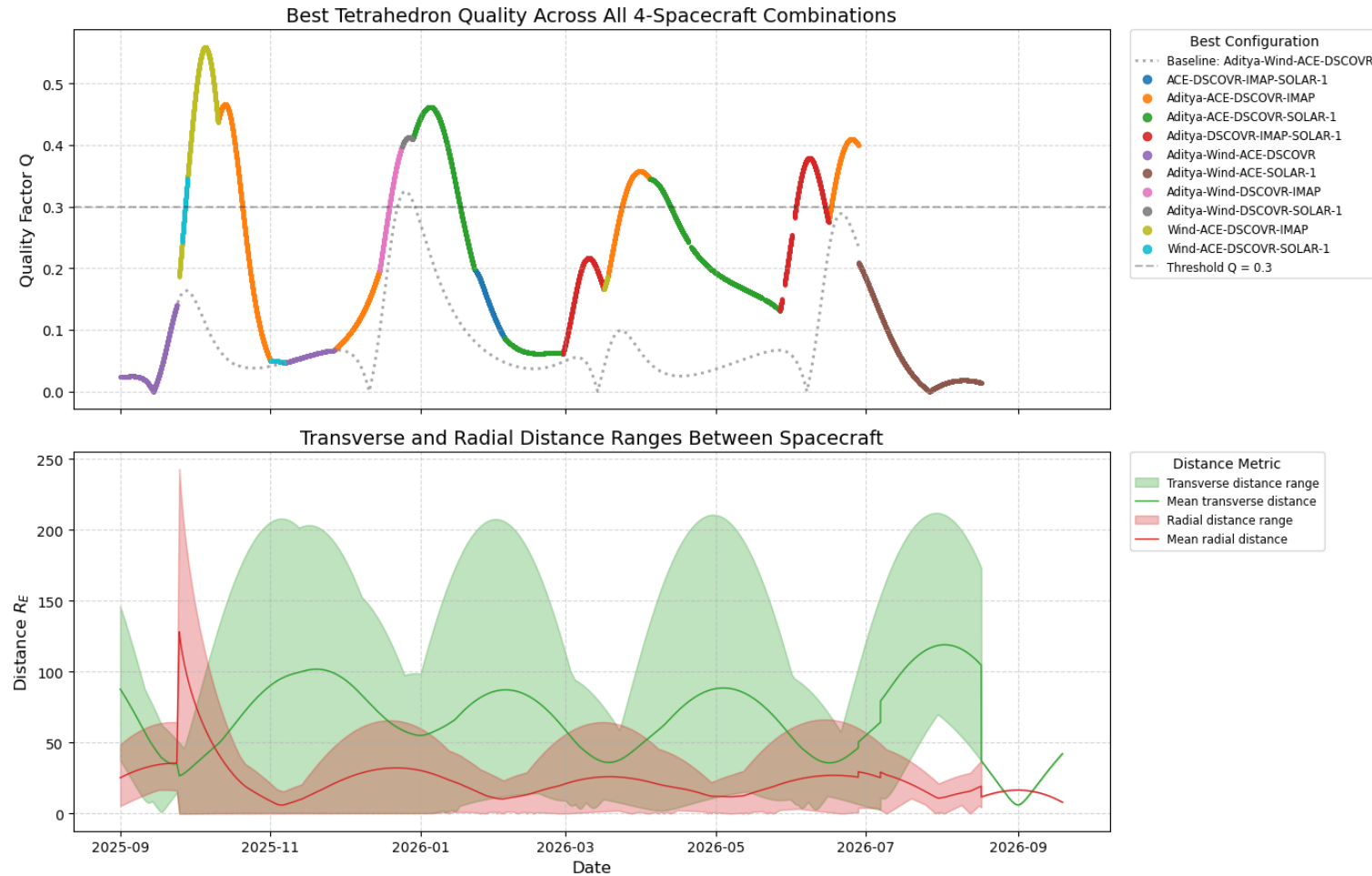
The quality factor for the spacecraft separation is defined through a set of conditions:

$$\text{If } L < L1, \text{ then } Q_s = 0, \text{ if } L2 < L < L3, \text{ then } Q_s = 1, \text{ and} \quad (3)$$

$$\text{if } L > L4, \text{ then } Q_s = 0$$

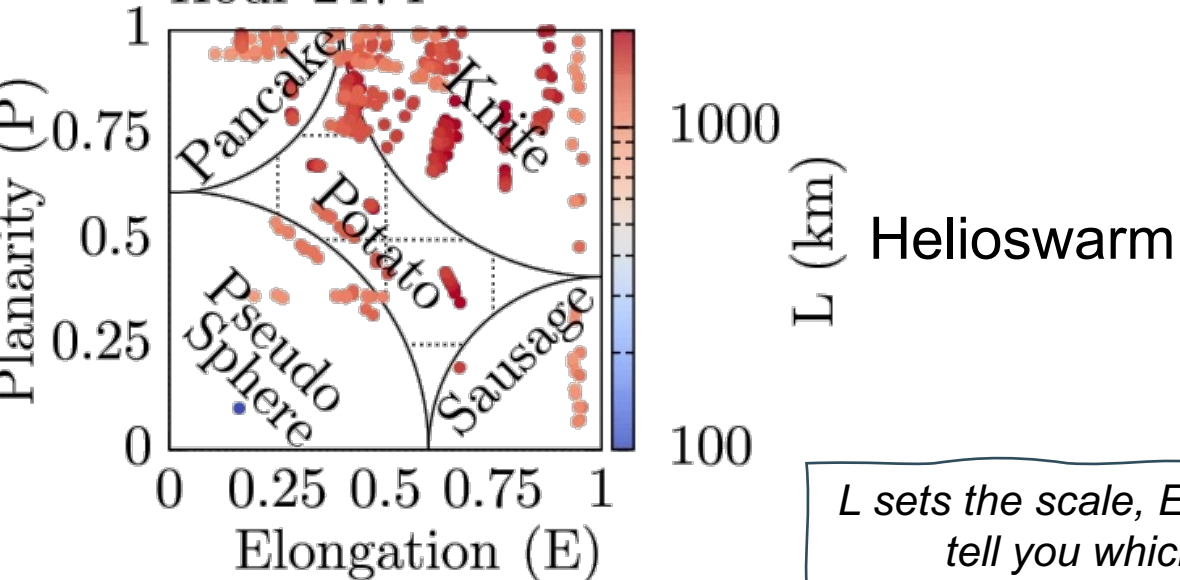
$$\text{If } L1 < L < L2, \text{ then } Q_s = (L - L1)^2(L + L1 - 2L2)^2 / (L2 - L1)^4 \quad (4)$$

$$\text{If } L3 < L < L4, \text{ then } Q_s = (L - L4)^2(L - 2L3 + L4)^2 / (L2 - L1)^4 \quad (5)$$



# The L1 fleet samples a huge range of shapes and scales, but it never chose any of them.

Klein+ [SSR, 2023]  
Hour 2474



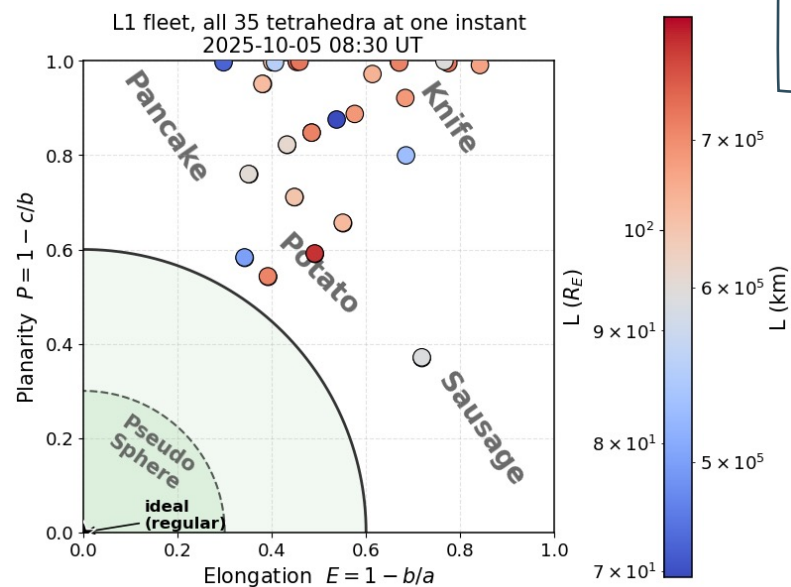
From the volumetric tensor:  $R = \frac{1}{N} \sum_{\alpha} (r_{\alpha} - \bar{r})(r_{\alpha} - \bar{r})^T$ ,

$$a = \sqrt{\lambda_1} \geq b = \sqrt{\lambda_2} \geq c = \sqrt{\lambda_3}$$

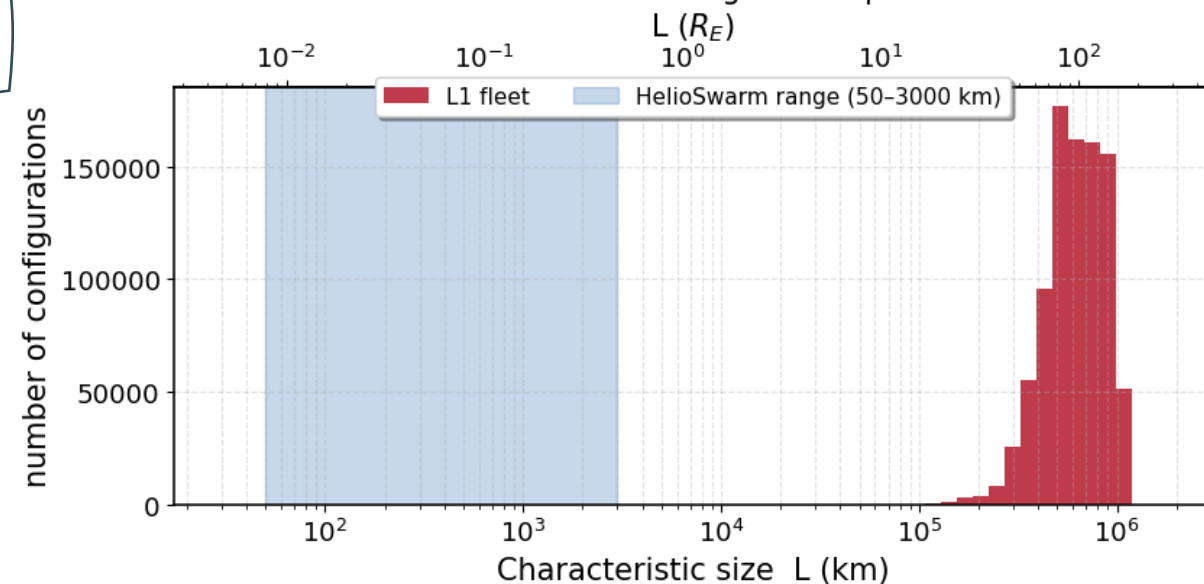
- Size:  $L = 2a$
- Elongation:  $E = 1 - \frac{b}{a}$  (stretched along one axis)
- Planarity:  $P = 1 - \frac{c}{b}$  (collapsed toward a plane)

Dunlop+ [Frontiers, 2024]

*L sets the scale, E and P tell you which components of the gradient you can believe*



Two to three orders of magnitude apart in scale



# Solar wind Structure & Modeling

(1)

What is the SW magnetic field across multiple scales? Can we reconstruct it? and what can L1 fleet tell us about what eventually happens at Earth?

# Probing the 3D Structure & Spatiotemporal Evolution of the Solar Wind

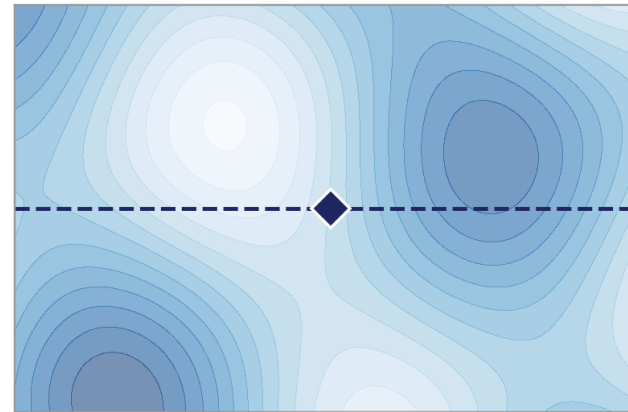
## Wind

- A single monitor gives only a 1-D cut, multiple points can help us map structure in 3-D rather than along one track.

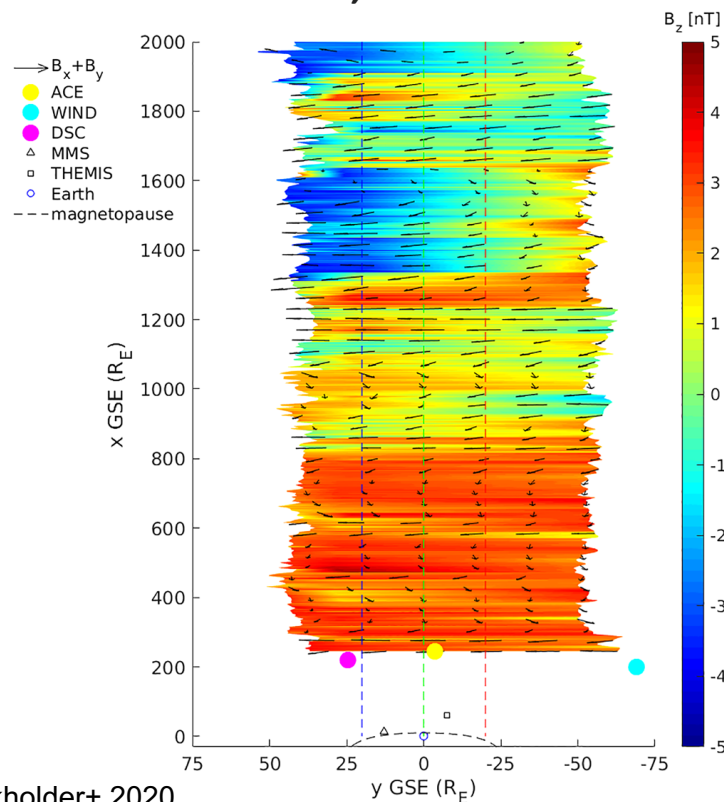
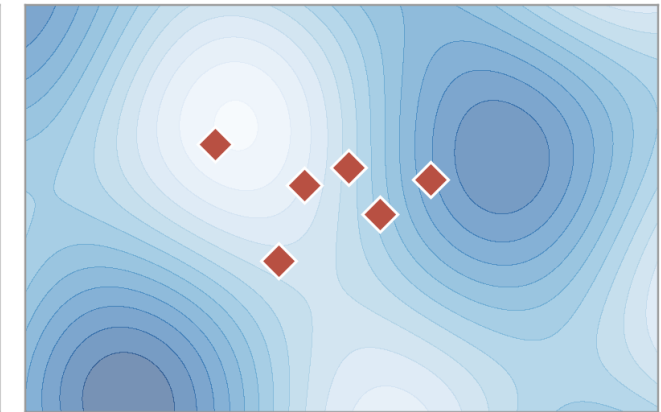
- Question with 2 monitors: *over what distance does the solar wind stay the same?* Now we can attempt:

“what is the structure, and how is it changing?”

Single spacecraft

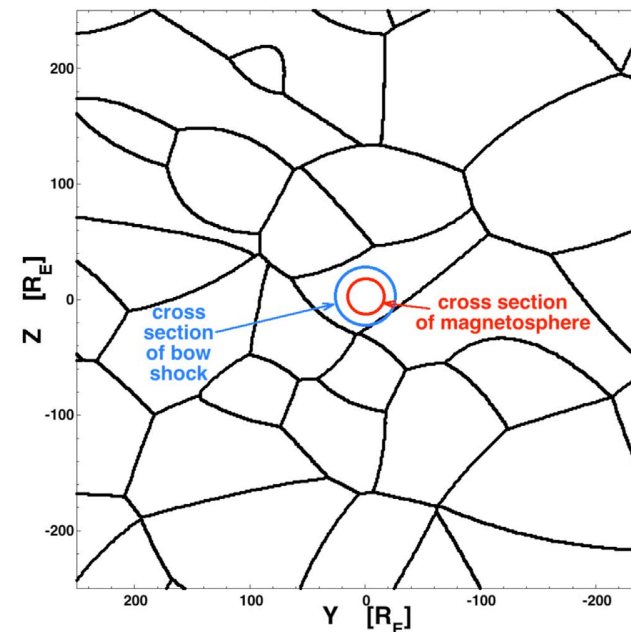


L1 fleet

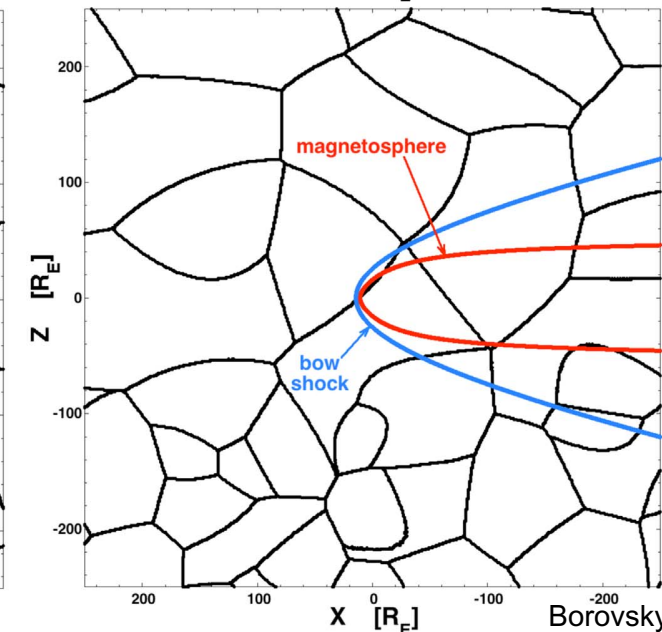


Burkholder+ 2020

1-D cut:  
space & time entangled

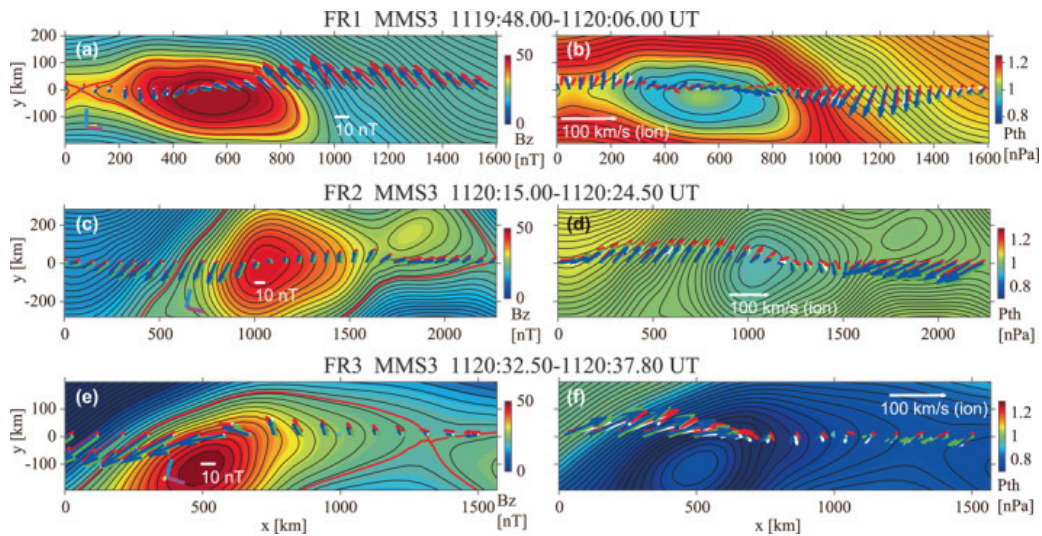


sample structure in space:  
separate space from time

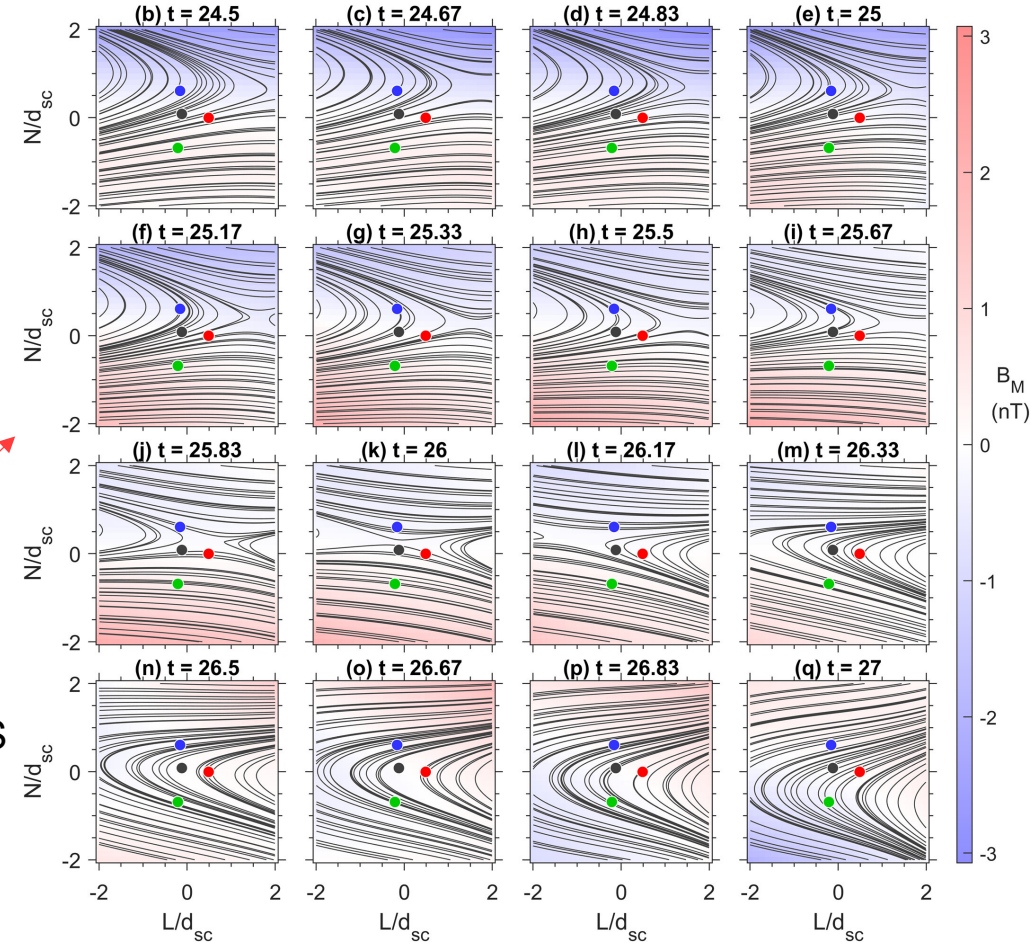
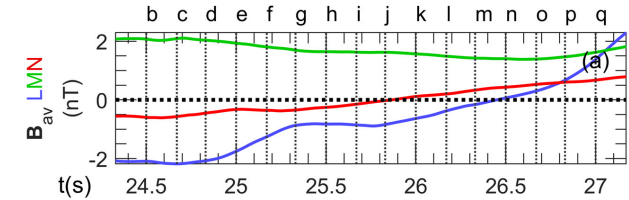


Borovsky 2017

# Magnetic Field Reconstruction

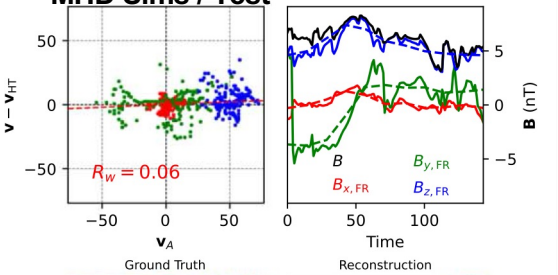


**Grad-Safranov**  
Using MHD to reconstruct  
B from time-series  
observations  
Assumes MHD &  
Equilibrium

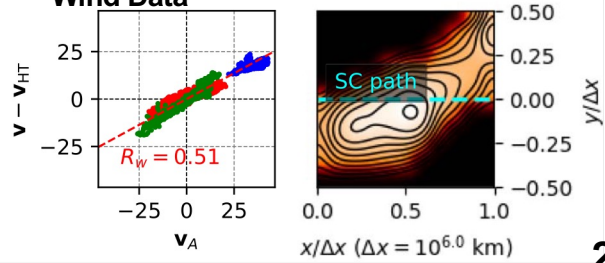


Hasegawa+ [JGR 2023]

MHD Sims / Test

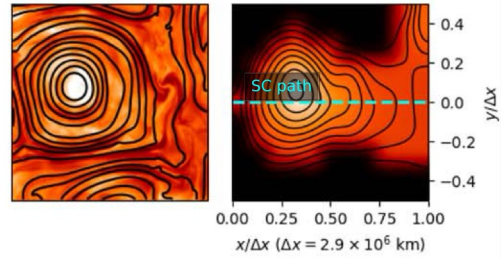


Wind Data

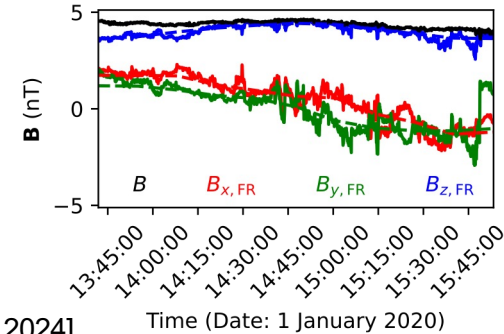


**2<sup>nd</sup> order Taylor**

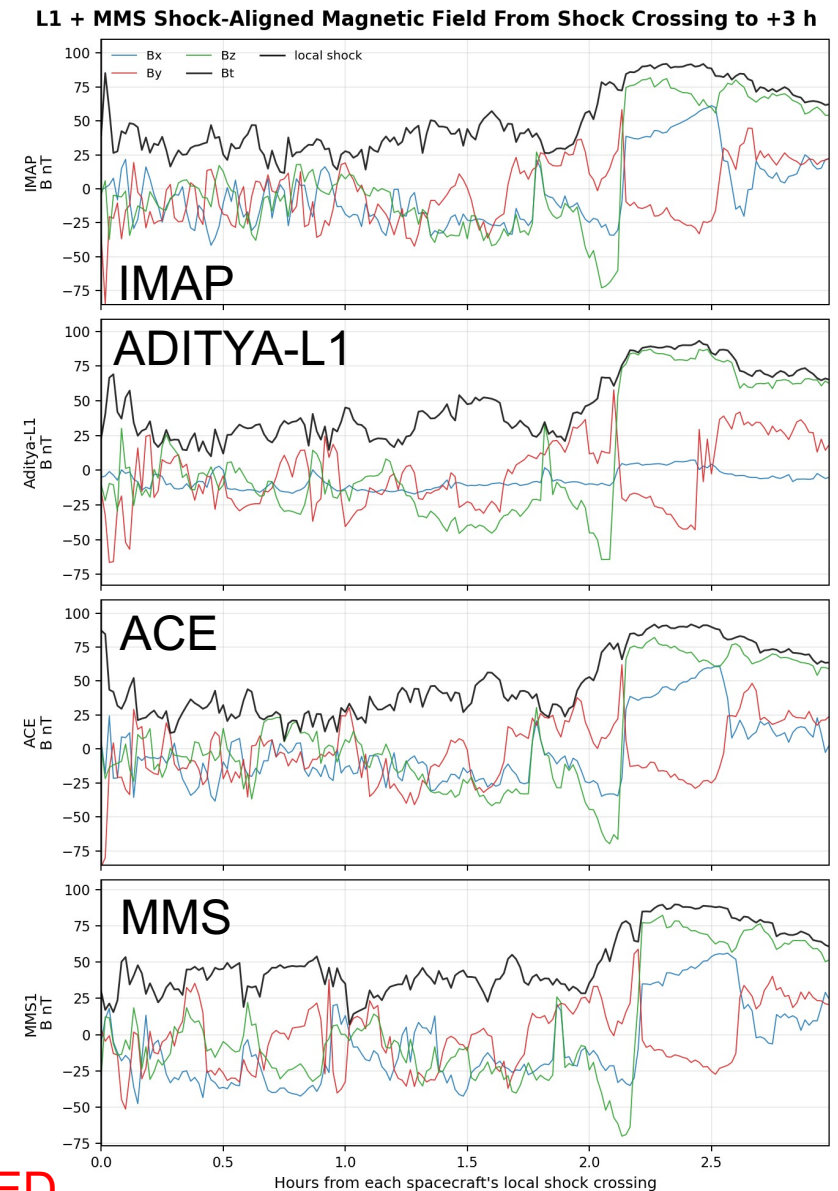
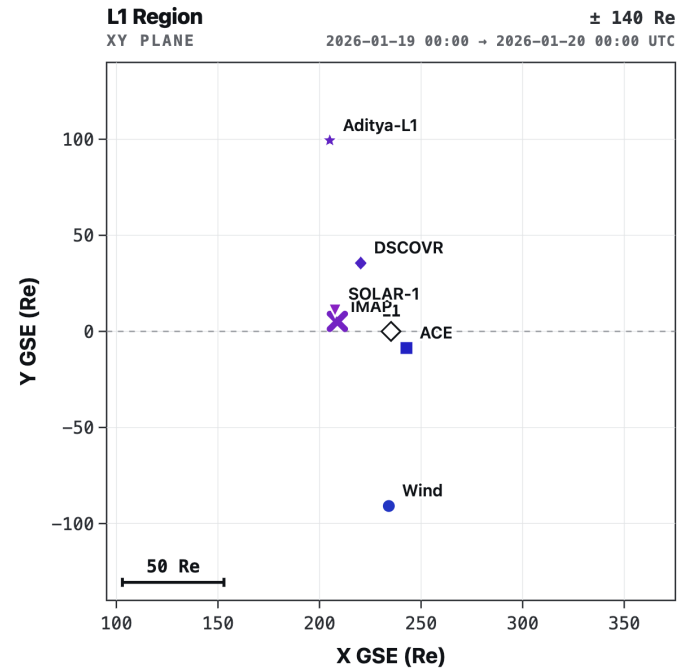
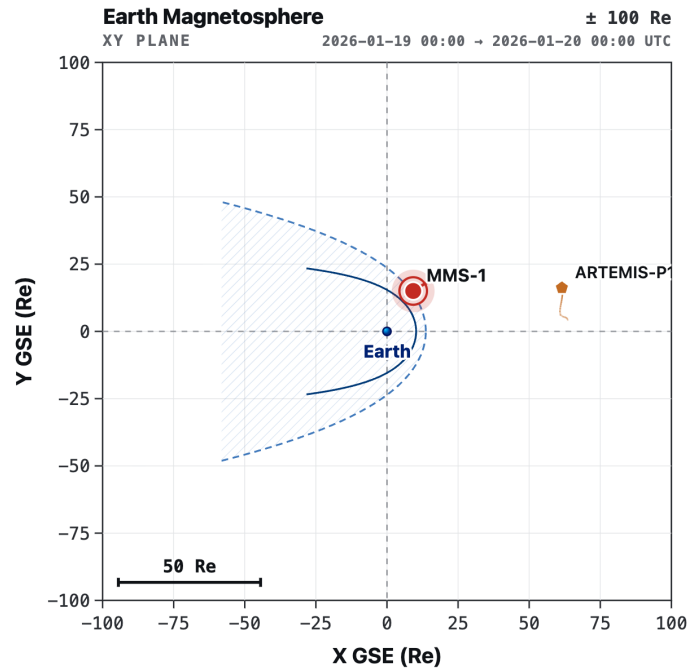
Essentially a polynomial  
reconstruction from MMS  
data



Farooki+ [ApJS 2024]



# Things evolve from L1 to Earth, sometimes significantly



➤ Propagation over ~100+ Re misses parts of the evolution, and the L1 fleet cannot sample that evolution.

➤ This is a limit of *position*. **No number of SC fleet can fully close this** without modeling or near-Earth observations to ground it.

PRELIMINARY IMAP DATA  
PRE RELEASE - UNVALIDATED

# IP Shocks Geometry and Orientation

(2)

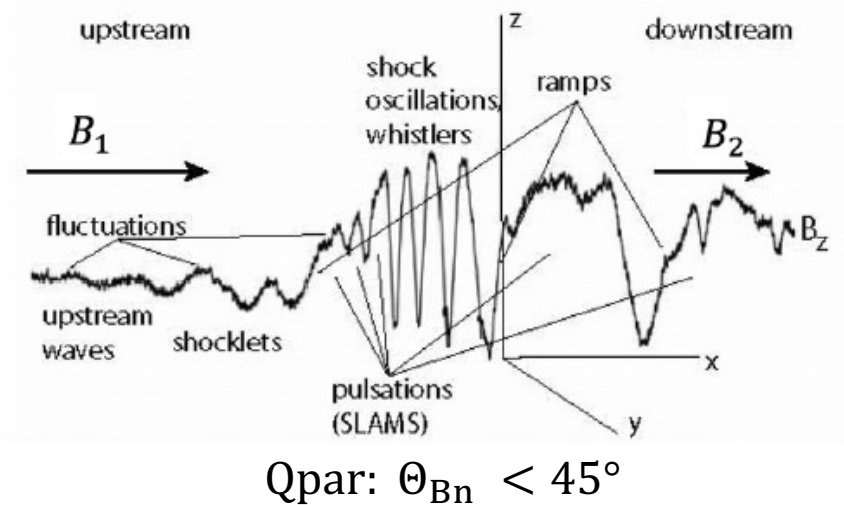
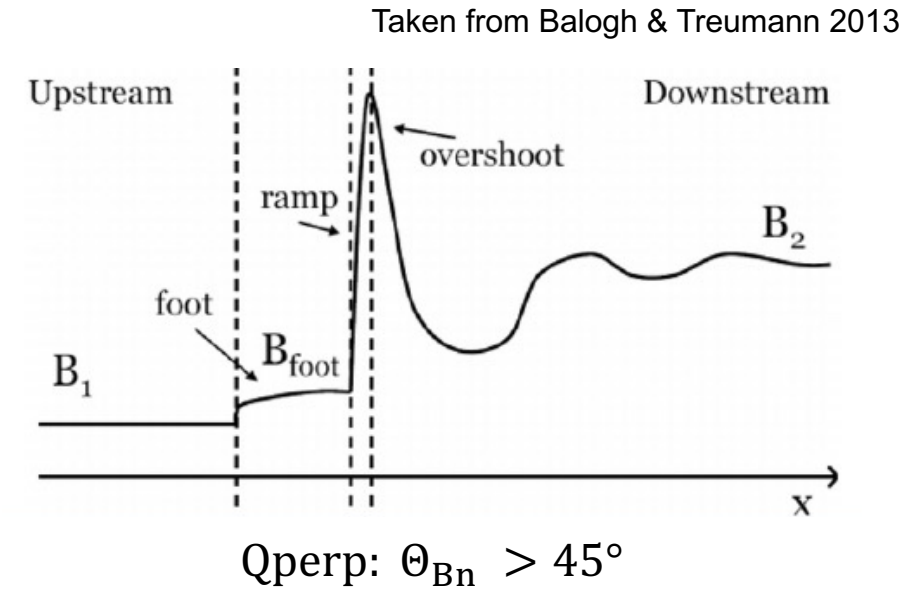
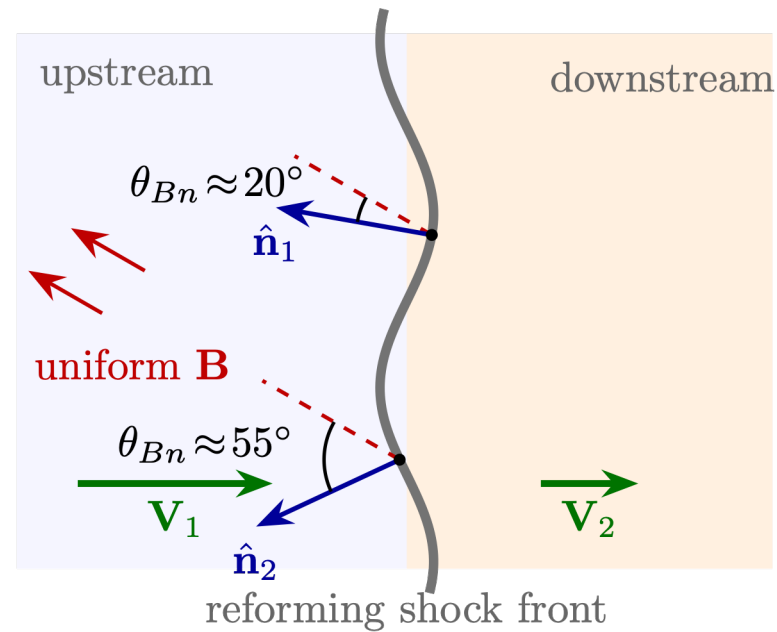
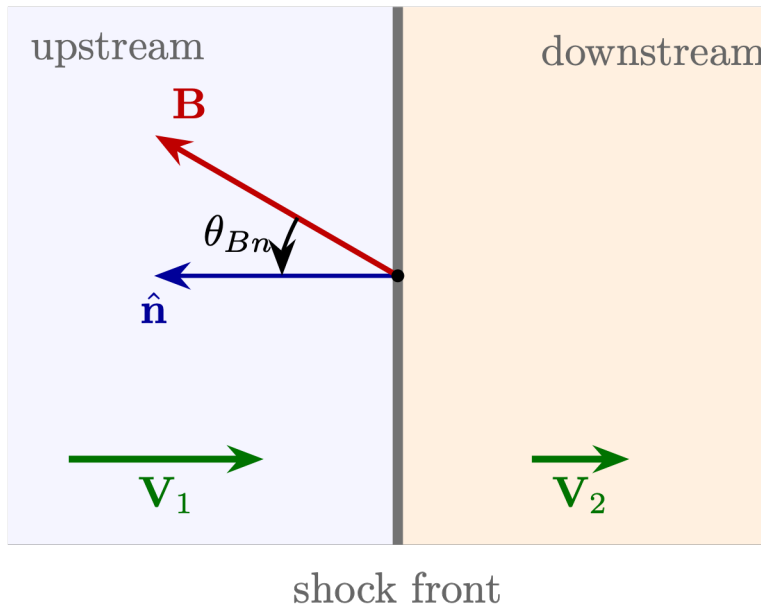
If we take one IP shock, can we find its orientation from one spacecraft? What about the whole fleet? What can this tell us about the shock?

# Collisionless Shocks Geometry

Typically, we care about many things:

**Ma**,  **$\theta_{Bn}$** , **Shock**, beta, etc. etc.

Let's focus just on,  $\theta_{Bn}$



Why we care? Totally different regimes, processes, and phenomena!

Shock properties change acceleration, rippling, transient processes, SEPs, Turbulence etc.:

Balogh & Treumann 2013, Burgess & Scholer 2015,

Trotta+2023, Jebaraj+2024, Kajdič+2024, Raptis+2026, Cuesta+2026 [L1;Ongoing],

Allen+2026 [L1;Ongoing] & many others

# How to Estimate the Orientation of the Shock

$$\hat{\mathbf{n}} = \pm \frac{(\mathbf{B}_d \times \mathbf{B}_u) \times \Delta \mathbf{B}}{|(\mathbf{B}_d \times \mathbf{B}_u) \times \Delta \mathbf{B}|}.$$

$$\hat{\mathbf{n}} = \pm \frac{\Delta \mathbf{V}}{|\Delta \mathbf{V}|}.$$

$$\hat{\mathbf{n}} = \pm \frac{(\Delta \mathbf{B} \times \Delta \mathbf{V}) \times \Delta \mathbf{B}}{|(\Delta \mathbf{B} \times \Delta \mathbf{V}) \times \Delta \mathbf{B}|}.$$

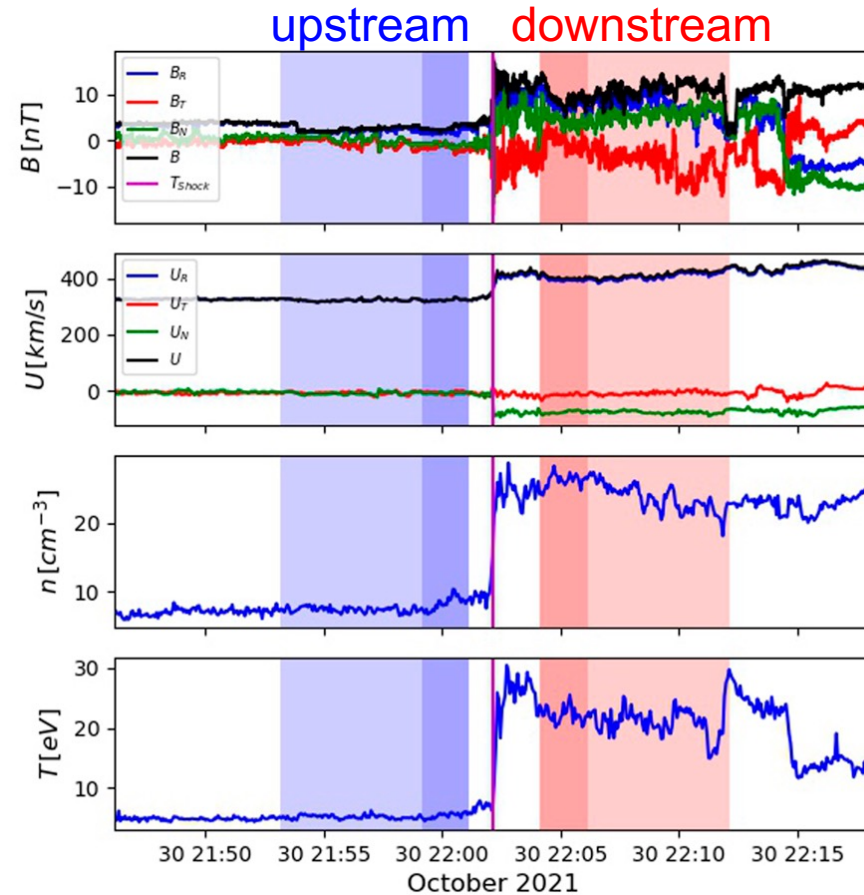
Abraham-Shrauner+1972, Schwartz, 1998

Now: with L1 Fleet we can do Multi-SC timing!

See: Paschmann & Daly, 1998, Vogt+2011, Toy-Edens+2025

$$\Delta t_{ij} = \mathbf{m} \cdot \Delta \mathbf{r}_{ij}, \quad \mathbf{m} = \frac{\hat{\mathbf{n}}}{V},$$

$$\hat{\mathbf{n}} = \frac{\mathbf{m}}{|\mathbf{m}|}, \quad V = \frac{1}{|\mathbf{m}|}$$



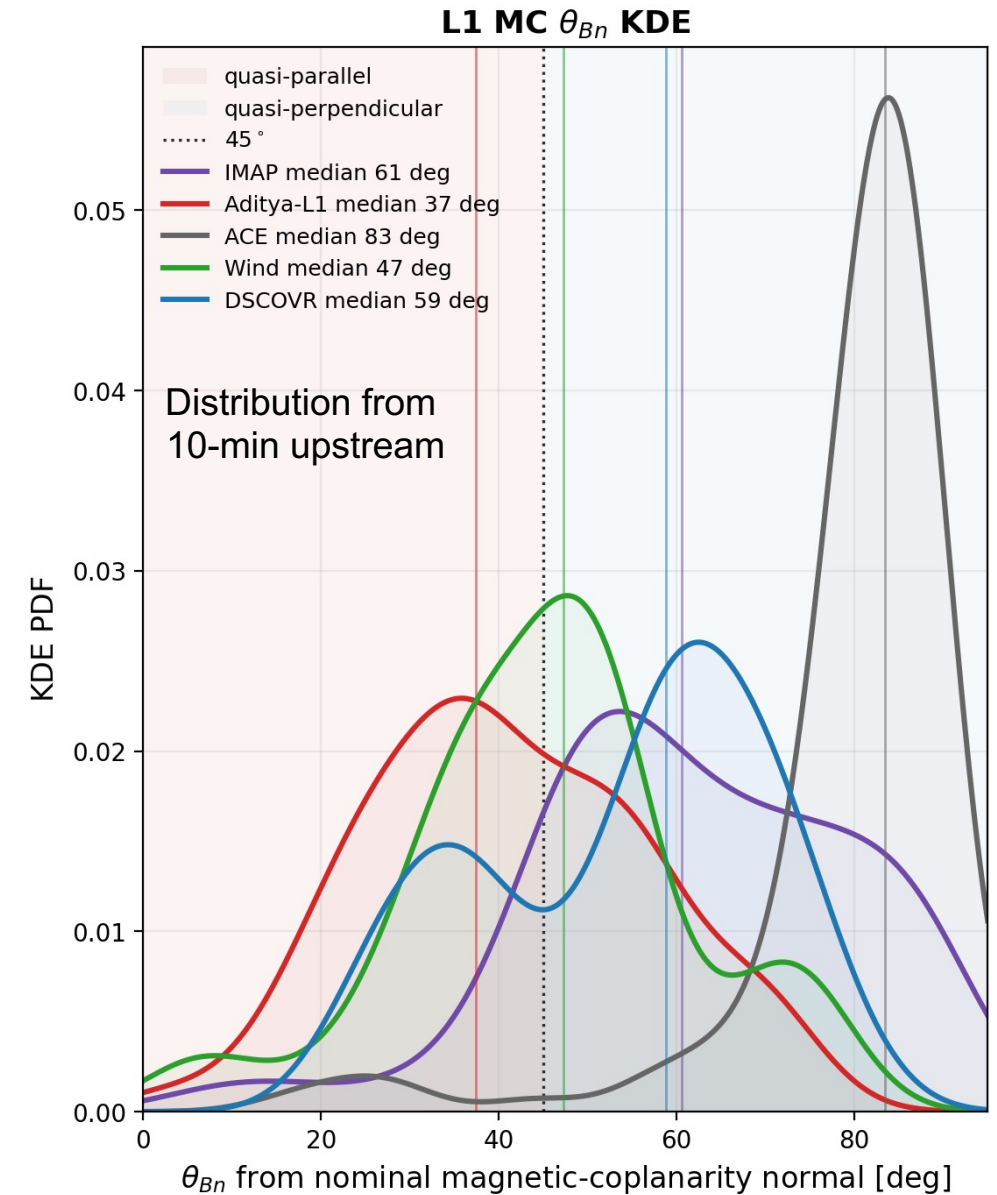
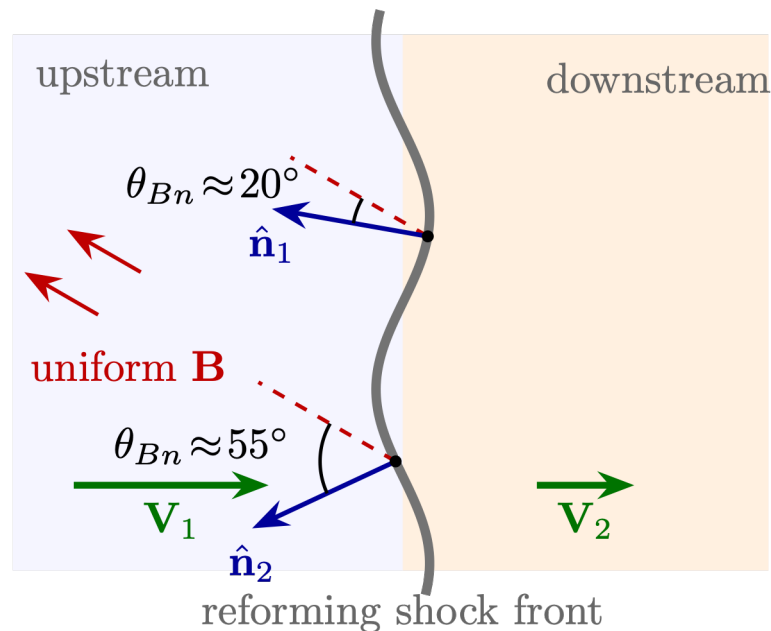
Question to the room: when two methods disagree on  $\theta_{Bn}$ , is that because of physics?  
 Ripples? Other things at the shock? or because of our method?

# What if one method gives different answers per spacecraft?

Question: Is this real?

Methodological? What orientation the actual shock has locally there?

**Can multi-spacecraft timing from the L1 fleet help us answer this?**



NOTE: Here I used a fix window for upstream and downstream for MC, if I bootstrap this, the result varies even more! Can timing constrain this?

# IP Shock & CME Coherency

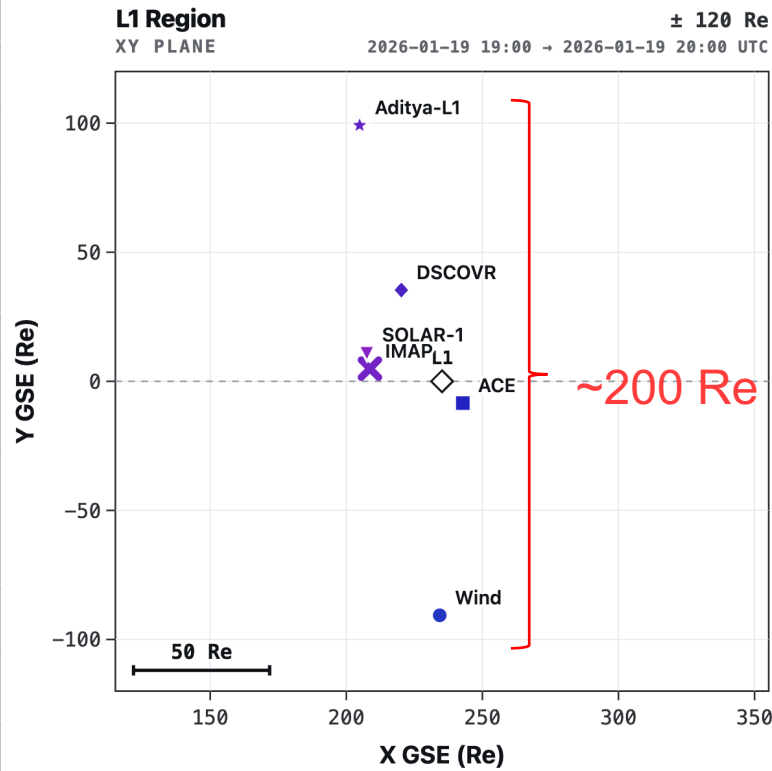
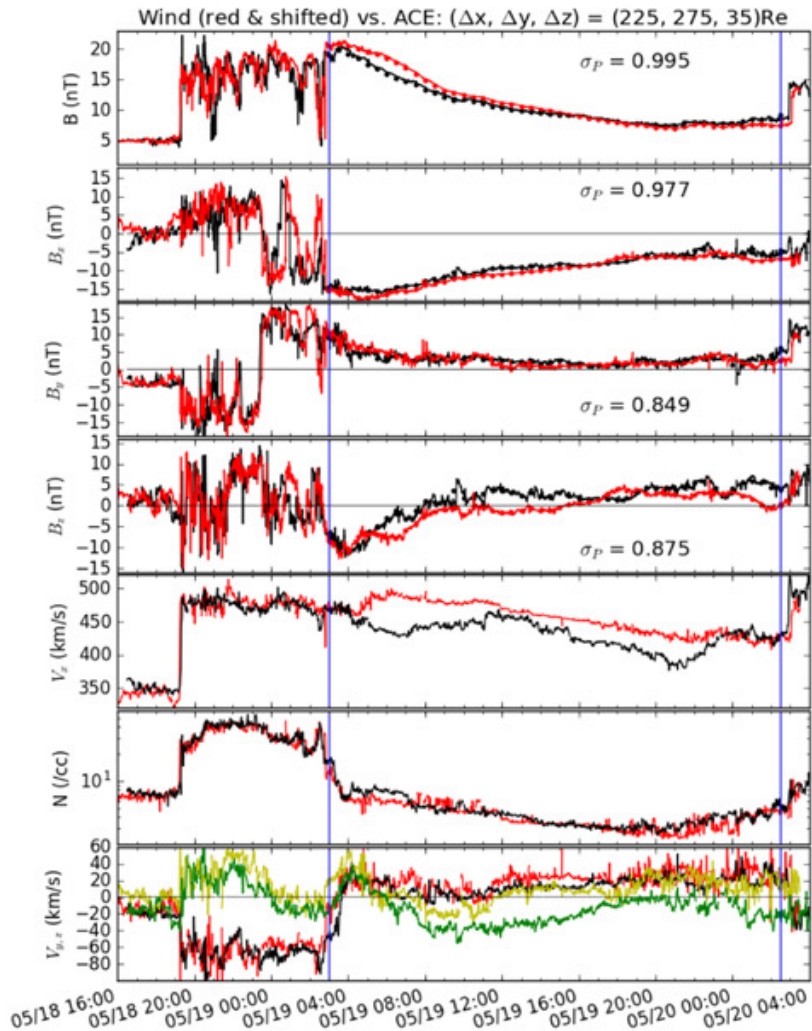
(3)

How coherent is a CME across ~100-200 Re? When two signals correlate well, is it shared physics, a shared trend, or can it even be a coincidence?

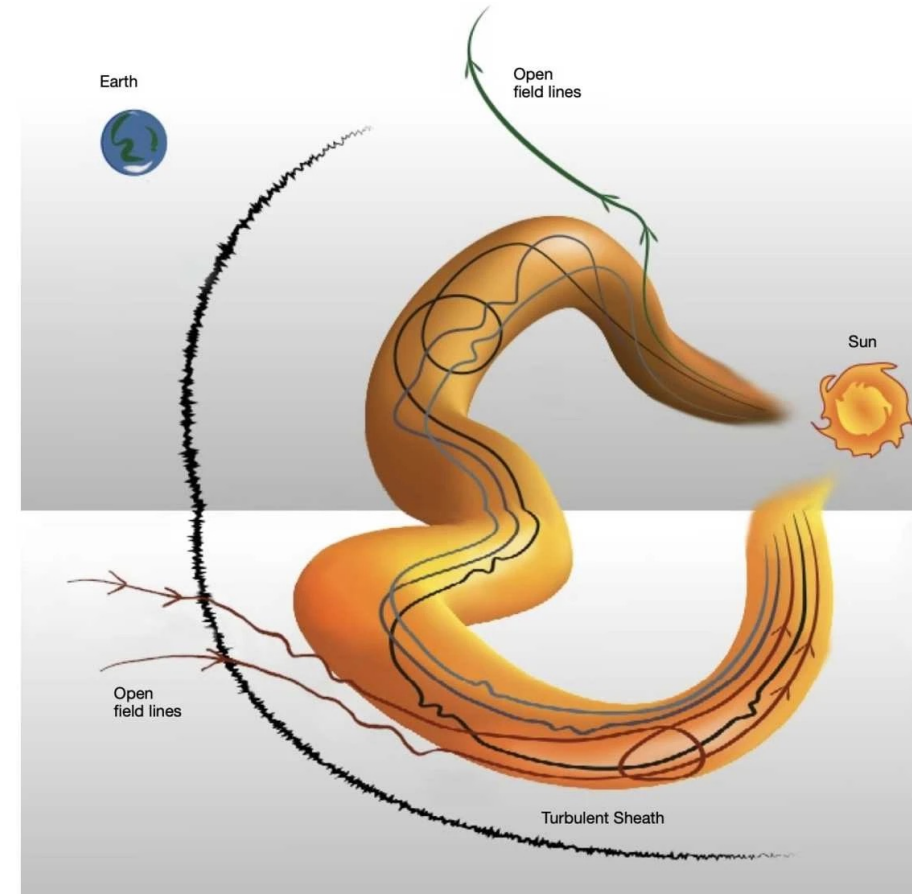
# Are CMEs Coherent Structures?

*Magnetic coherence inside MEs of 0.25–0.35 au for the magnitude of the magnetic field, but 0.06–0.12 for B components”*

Lugaz+ [ApJL 2018]



Al-Haddad & Lugaz [SSR 2025]



Now, we can ask: How coherent is a CME across ~100-200 Re?

# The Random Walk Trap (#1 issue)

Let's do an exercise! Can unrelated timeseries be correlated?

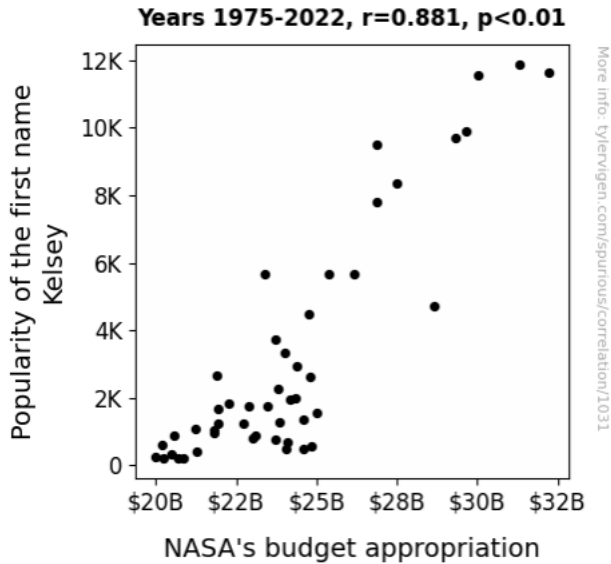
A question from 100 years ago  
**JOURNAL** Yule+1926

**OF THE ROYAL STATISTICAL SOCIETY.**

**JANUARY, 1926.**

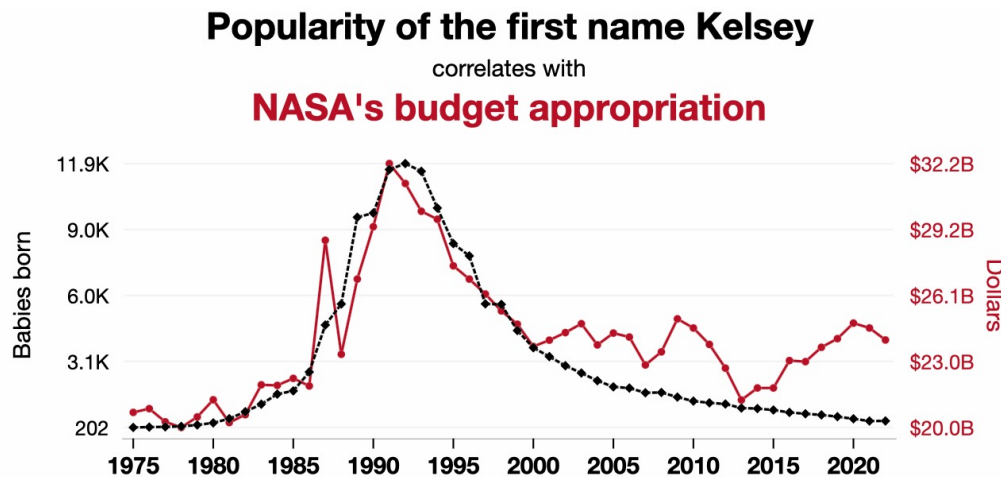
**WHY DO WE SOMETIMES GET NONSENSE-CORRELATIONS BETWEEN TIME-SERIES?—A STUDY IN SAMPLING AND THE NATURE OF TIME-SERIES.**

**THE PRESIDENTIAL ADDRESS OF MR. G. UDNY YULE, C.B.E., M.A., F.R.S., FOR THE SESSION 1925-26. DELIVERED TO THE ROYAL STATISTICAL SOCIETY, NOVEMBER 17, 1925.**

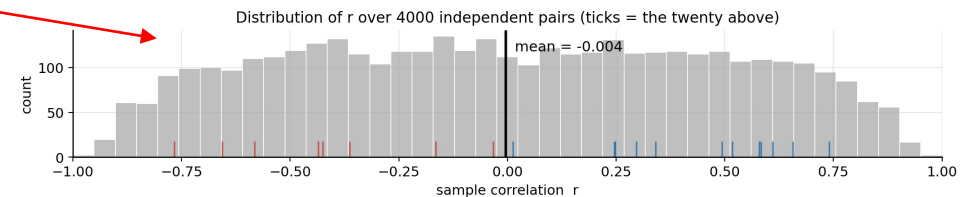
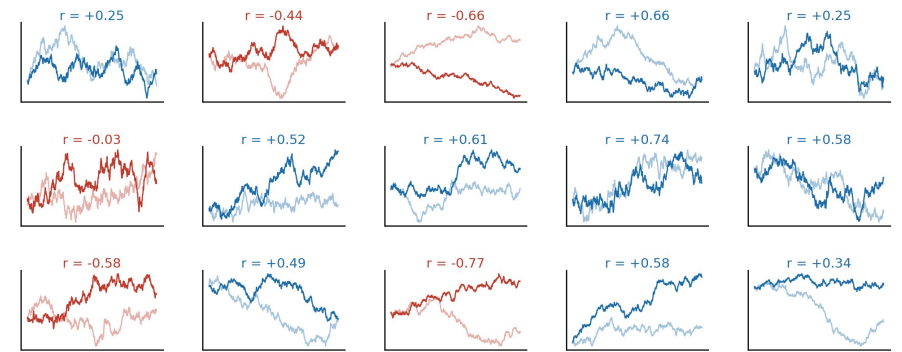


The solution to our funding issue:

Have kids and name them Kelsey!



- (1)  $r$  assumes that your  $n$  points are  $n$  independent observations.
- (2) Random walks are uniformly distributed in  $r$



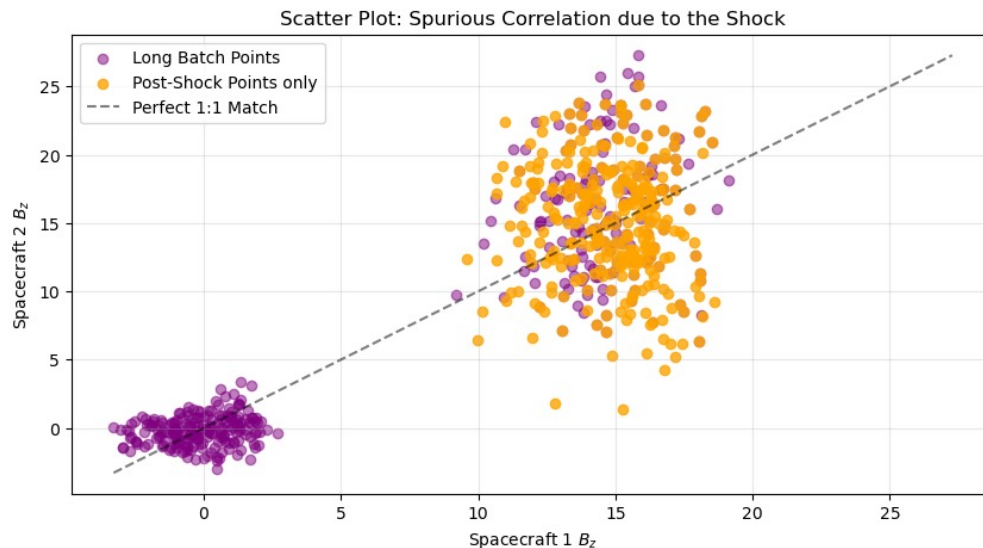
# The Spurious Correlation Plasma Mixing Trap (#2 issue)

Mixing two distinct regimes **breaks "stationarity."** *Macro-scale* variations wash out *micro-scale* differences in metrics such as correlations

Pre-Shock Only:  $r = 0.267$

Post-Shock Only:  $r = -0.076$

Spanning the Shock:  $r = 0.914$



## Broader Discussion

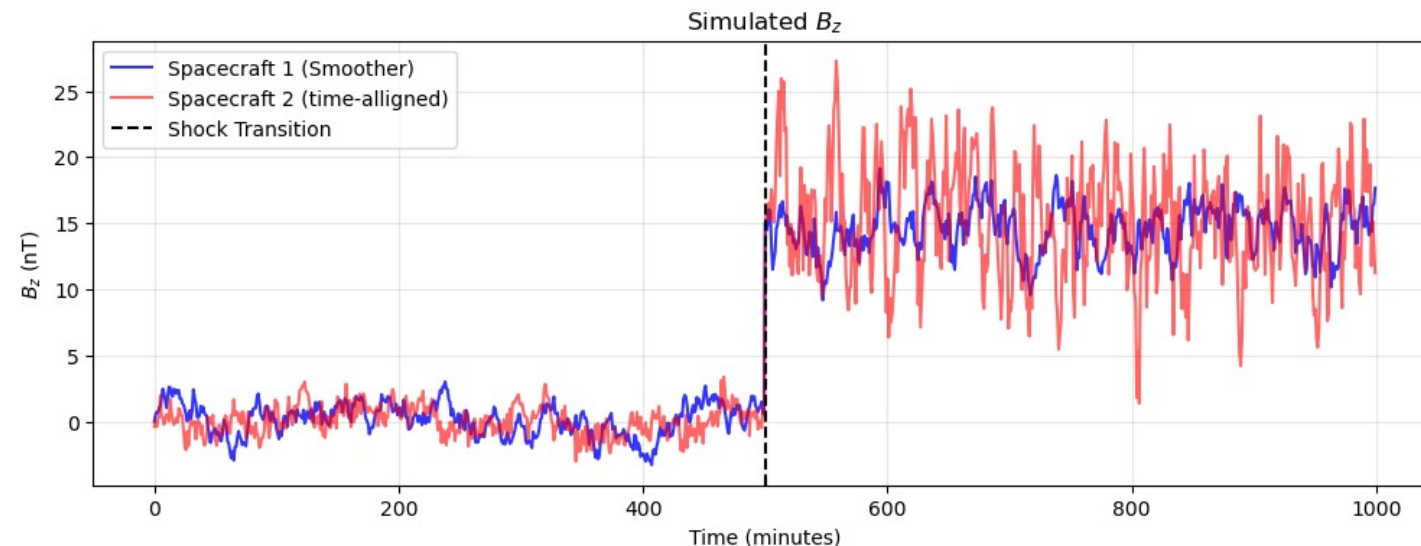
Granger & Newbold 1974 (Economics); Matthaeus & Goldstein 1982

Jagaramudi+2019: "Most studies of turbulence in the solar wind invoke stationarity as a working hypothesis. Unfortunately, this concept is difficult to verify in practice"

See novel method of calculating ACF: Perez+2026 (also #175 poster)

## Let's do another exercise and ask a question:

*What happens when we observe an IP shock/discontinuity between two spacecraft and we ask whether these signals are correlated?*



# L1 Dataset & How to make it useful?

# Current efforts for combining L1 data, what else does the community needs?

## Ongoing effort lead by IMAP team (1 Dataset – 6 SCs):

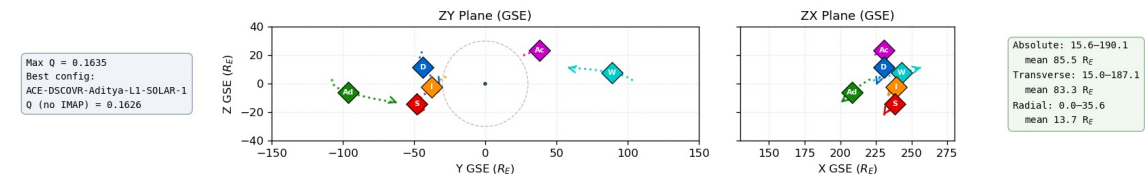
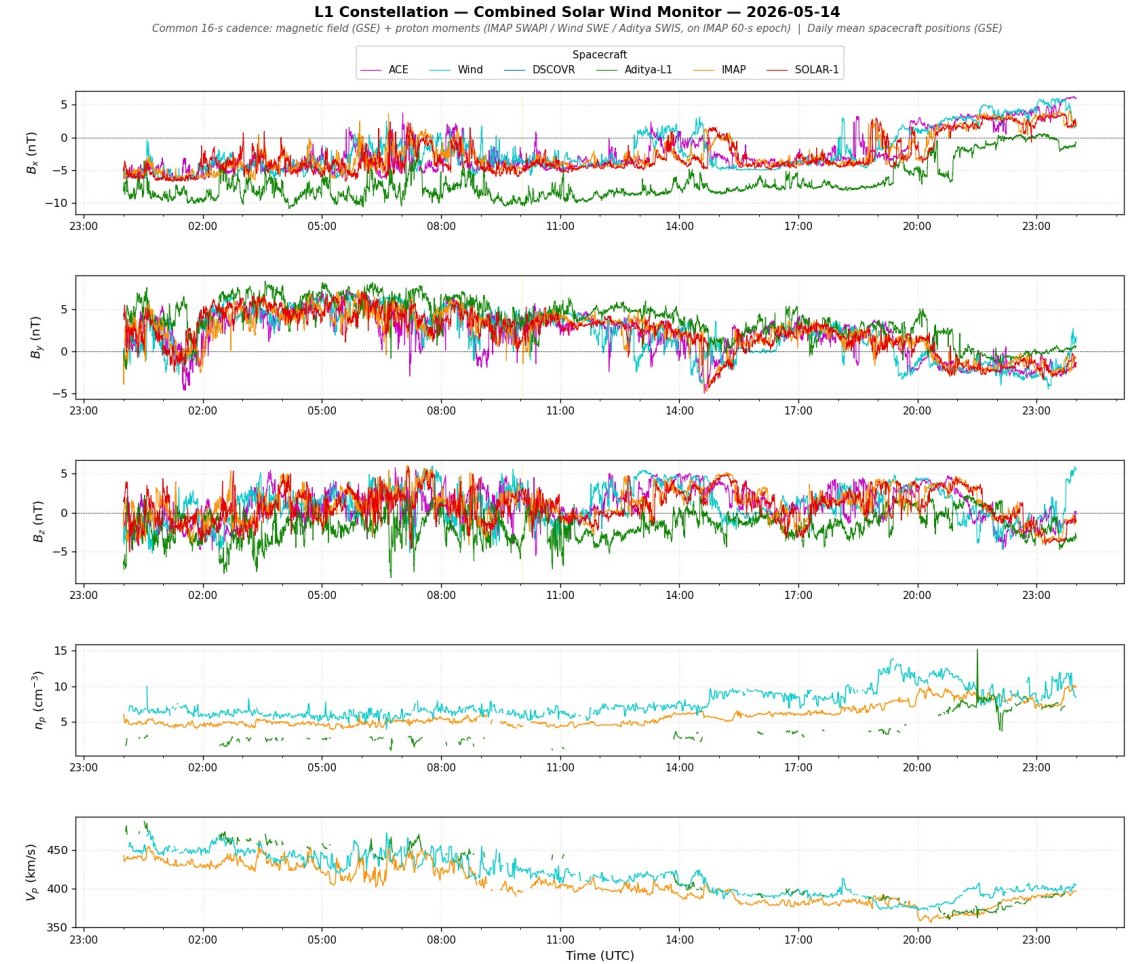
- One merged product (R, B, V, n, T)
- Common/Native cadence
- Common frame (GSE)
- Documented gaps.
- Formation Characteristics (Q, P, E, L)

Preview  
Quickplot

## Few open questions:

- How do you make this useful to the community?
- What else do you wish to see?
- Who maintains it after the mission teams move on?

**PRELIMINARY IMAP DATA  
PRE RELEASE - UNVALIDATED**



# Summary

**Six monitors at L1 are available, but only since practically this year 2026!**

## **What we can do now**

- Multi-spacecraft techniques at L1 for the first time: timing, gradients, reconstruction
- Probe coherence and structure across 100s of Re
- Reconstruct a more realistic magnetic field than any single point allows

## **What we can't fully do (?)**

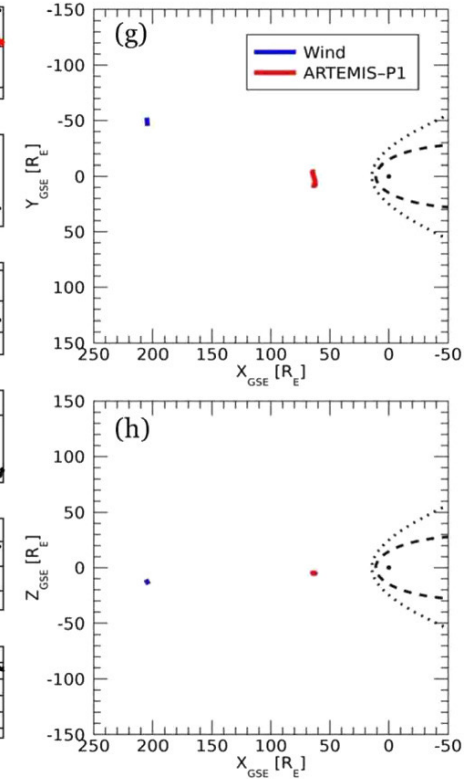
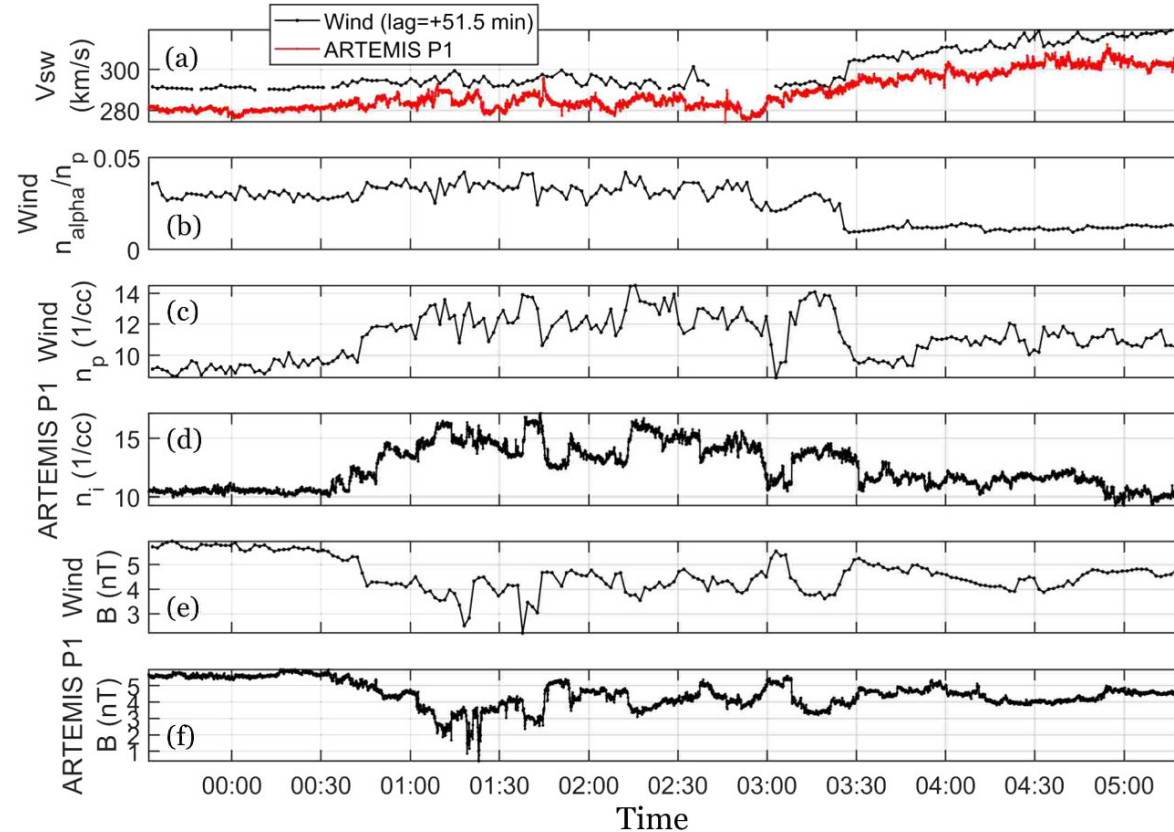
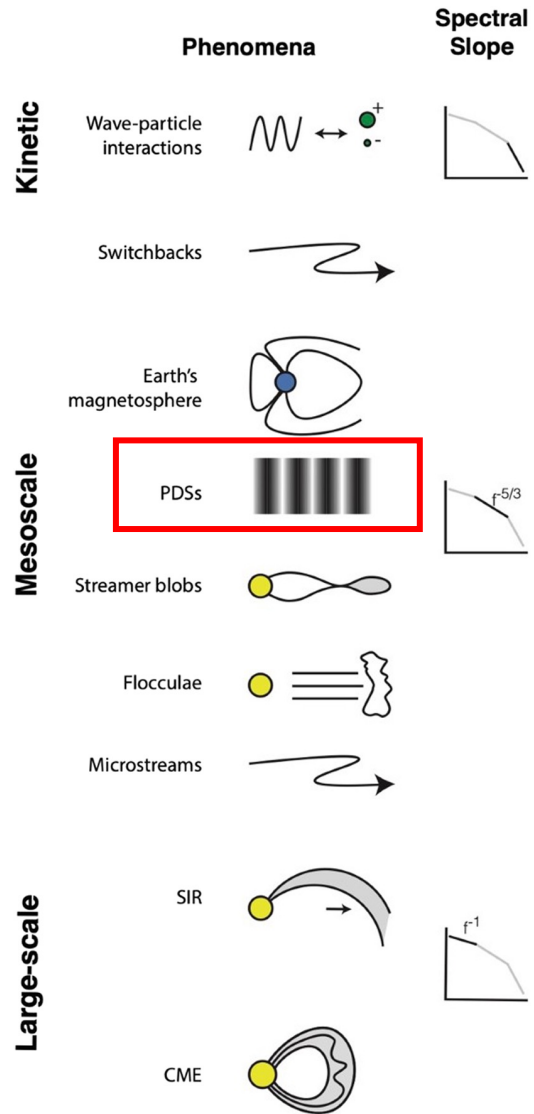
- Follow the L1-to-Earth evolution from L1 data alone (needs modeling or near-Earth data to assess evolution)

In about 20 years we went from one monitor to six. The real question is not whether we have enough data, but which questions change because of this and whether we have build the expertise & capabilities to answer them

Things I didn't talk: (1) connection from PSP, SoLO to L1, (2) Evolution of Turbulence, (3) Heliospheric Current Sheet modeling, (4) Machine Learning capabilities, (5) Space Weather modeling, and many many more...

# Appendix

# Mesoscale Structures in the Solar Wind – Example PDSs



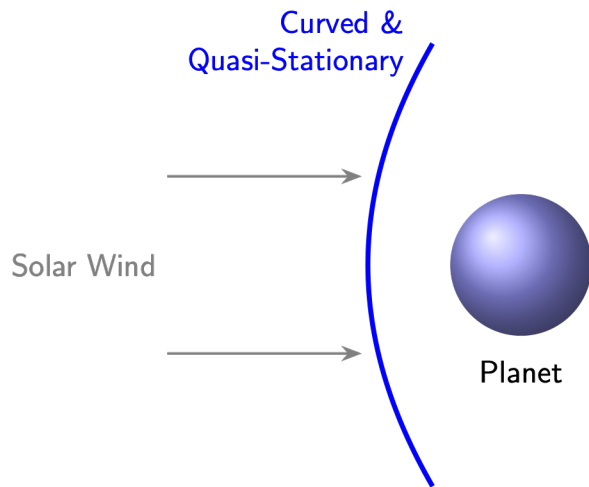
**Mesoscales:** bridge kinetic physics and global solar-wind structure, shaped by both solar sources and propagation.

**PDSs:** An example of mesoscales structure, a quasi-periodic density trains carried by the solar wind

Di Matteo et al., 2024

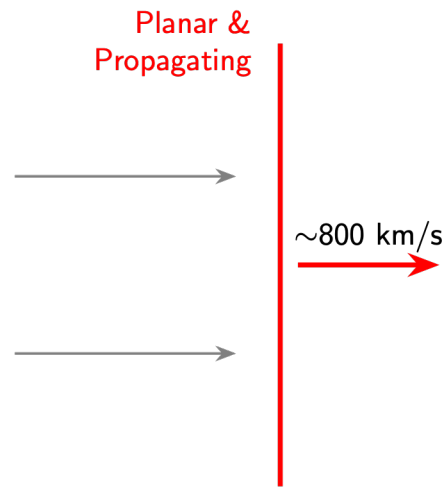
# Bow shocks vs IP shocks

## Planetary Bow Shock



- "Cross-talk" from  $Q_{\perp}$
- Hours of observations

## Interplanetary (IP) Shock



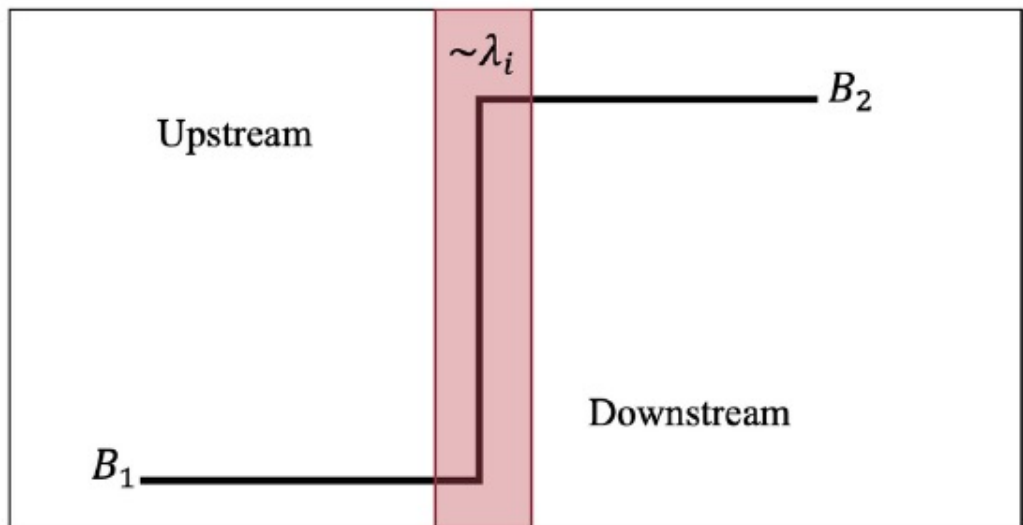
- Restricted foreshock
- Limited observation time

**Planetary Bow Shocks:** A **curved**, quasi-stationary obstacle. Reflected ions are **magnetically connected for long durations**, allowing observations to be **taken** showing waves to grow and steepen into complex structures.

**IP Shocks:** A "planar" and **propagating** structure **moving rapidly** ( $\sim 800$  km/s) through the solar wind, potentially **restricting the foreshock development and limiting our observation capabilities**.

# Quasi-parallel and Quasi-perpendicular shocks

**Qperp**  
transition



**Qpar**  
transition

