Multi-spacecraft analysis methods in space plasma: Towards a new era of multi-scale science

Alexandros Chasapis,
LASP, University of Colorado Boulder
LPC2E, CNRS
Contact: alexandros.chasapis@lasp.colorado.edu

Multi-Spacecraft Observations

- Remote Sensing:
  Stereo A &B, Solar Orbiter, Parker Solar Probe, …

- In situ Large Scale Observations:
  Earth L1 Point: WIND, ACE, SWFO
  Earth's Magnetosphere: THEMIS, ARTEMIS
  Mars: ESCAPADE, M-MATISSE

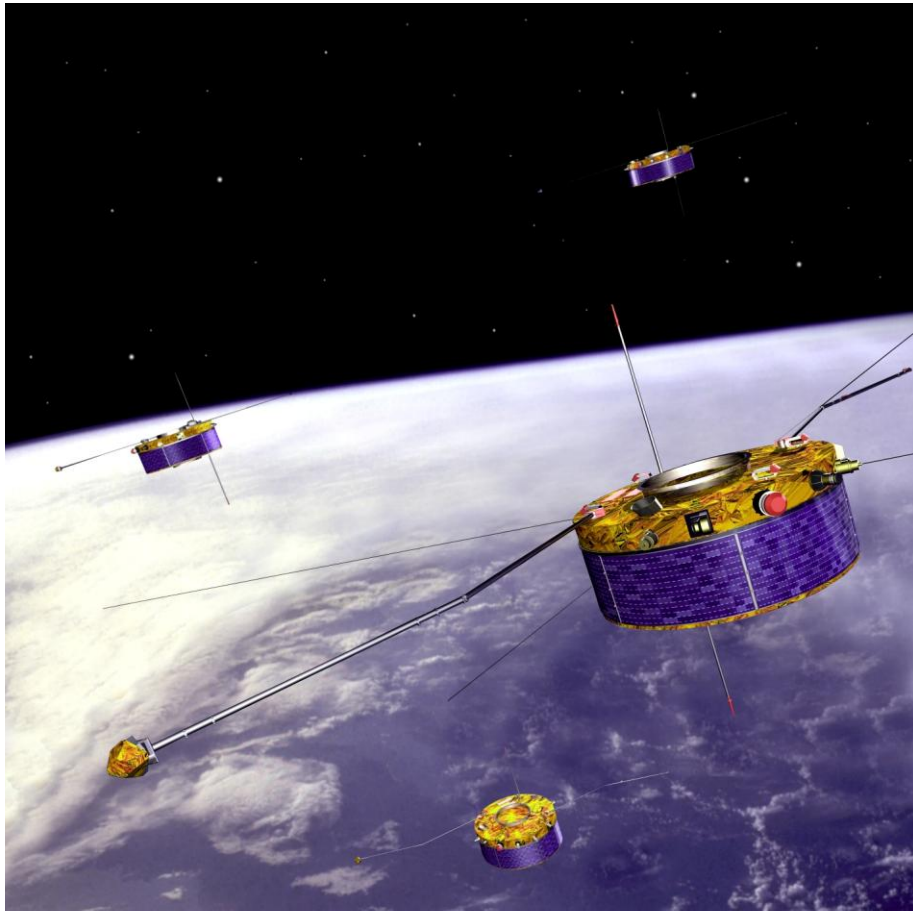
- **In Situ spacecraft formations:**
  CLUSTER
  MMS
  Multi-scale Spacecraft Observatories: HelioSwarm, Plasma Observatory

CLUSTER

- Launched in 2001 by ESA
- Deorbited in 2025
- 4 identical spacecraft flying in formation
- Inter-spacecraft separation:

  10000km – 100km
- Plasma measurements:

  Ions & Electrons at 4 second resolution

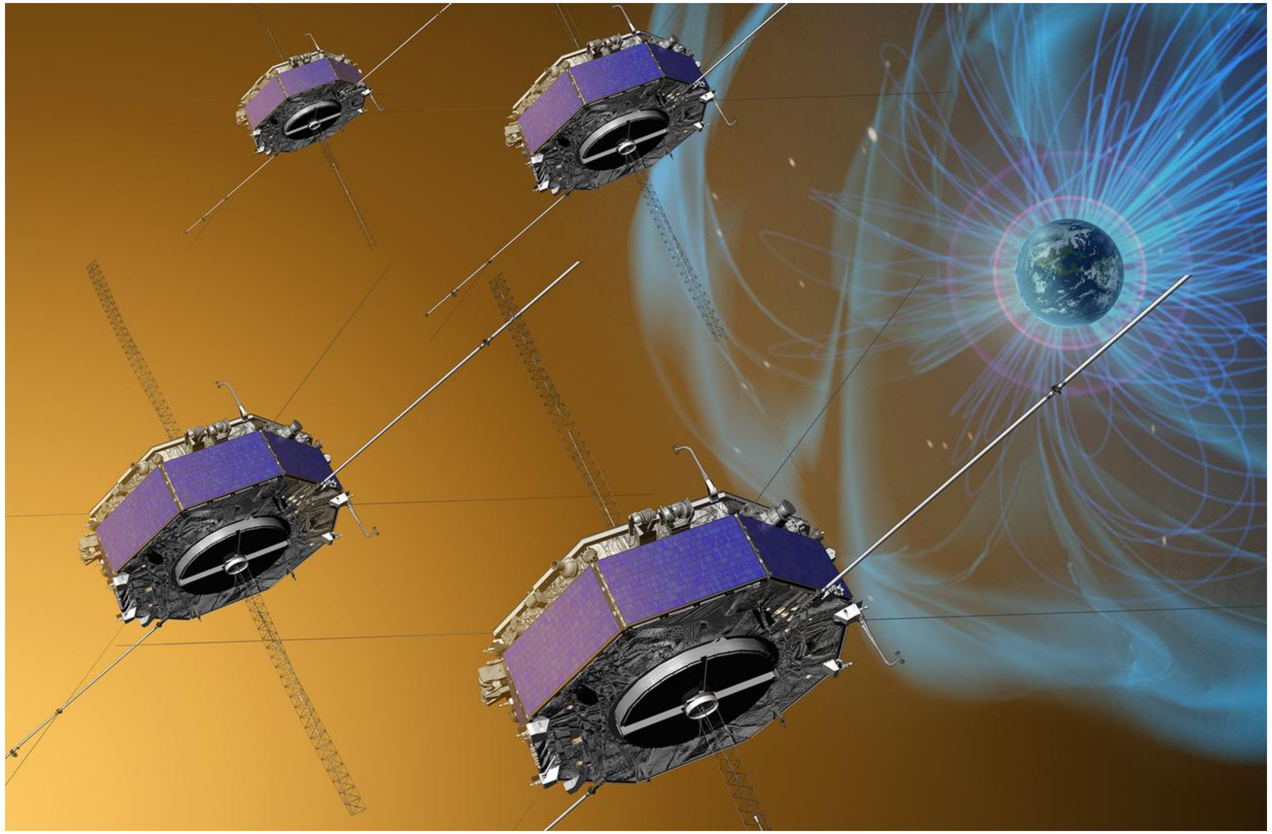


Magnetospheric MultiScale

- Launched in 2015 by NASA
- Operating through 2037
- 4 identical spacecraft flying in formation
- Inter-spacecraft separation:

  40km, down to 5km
- Plasma measurements:

  Ions at 120 ms & Electrons 30 ms resolution
- Axial Booms: 3-D electric field measurements

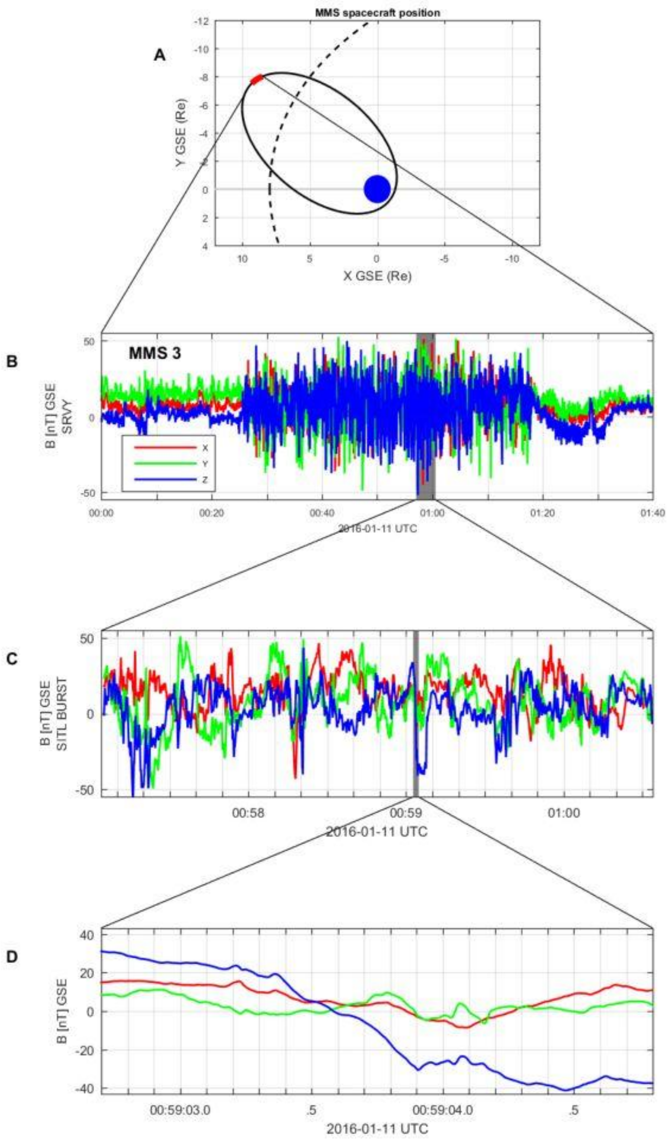


Magnetospheric MultiScale

- Launched in 2015 by NASA
- Operating through 2037
- 4 identical spacecraft flying in formation
- Inter-spacecraft separation:

  40km, down to 5km
- Plasma measurements:

  Ions at 120 ms & Electrons 30 ms resolution
- Axial Booms: 3-D electric field measurements



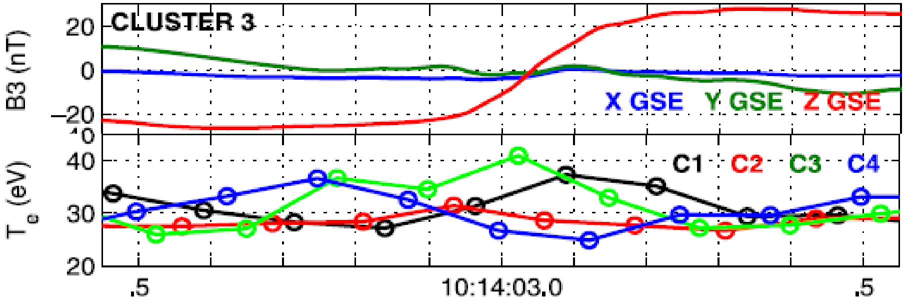
Magnetospheric MultiScale

- Launched in 2015 by NASA
- Operating through 2037
- 4 identical spacecraft flying in formation
- Inter-spacecraft separation:

  40km, down to 5km
- Plasma measurements:

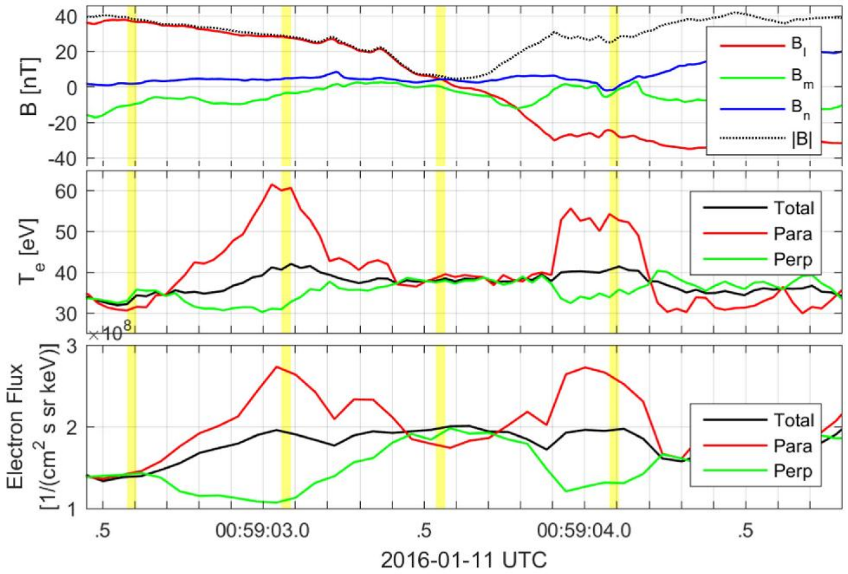
  Ions at 120 ms & Electrons 30 ms resolution
- Axial Booms: 3-D electric field measurements

Cluster



[Chasapis et al. ApJLett 2015]

MMS



[Chasapis et al. ApJ 2017]

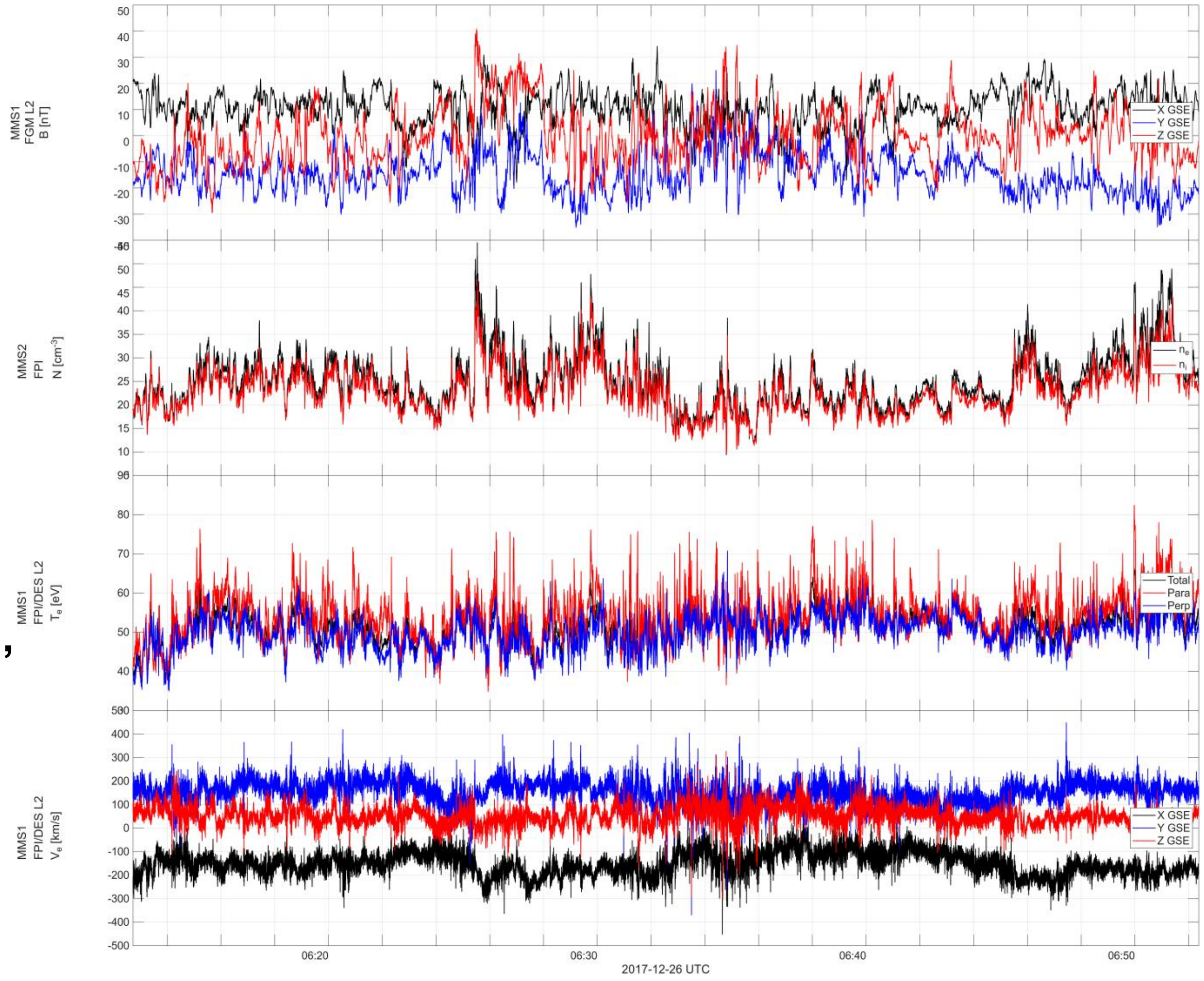
Smaller spacecraft separation requires higher time resolution

MMS Observations

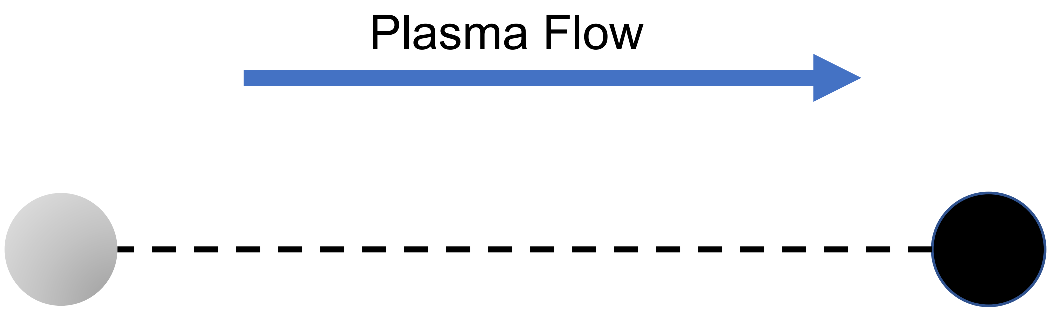
Plasma in the heliosphere is often characterized by strong turbulence:

- Collisionless energy transfer
- Formation of intermittent structures
- Energization of particles

Understanding collisionless dissipation, plasma heating & particle acceleration



Magnetic Field Increments



$$|\overrightarrow{\Delta B}_{\tau}(t)| = |\vec{B}(t) - \vec{B}(t+\tau)|$$

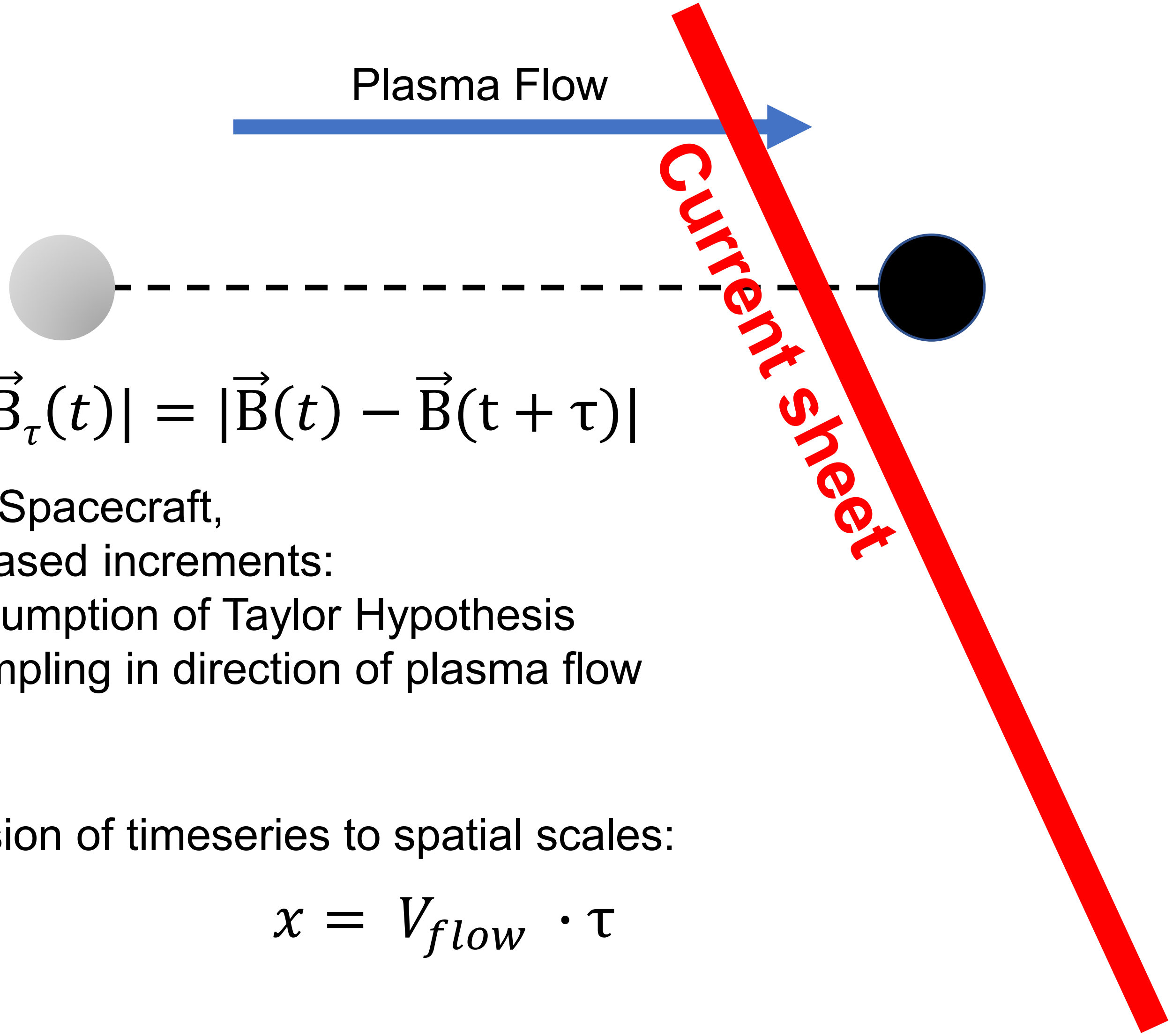
Single-Spacecraft,
Flow-based increments:

- Assumption of Taylor Hypothesis
- Sampling in direction of plasma flow

Conversion of timeseries to spatial scales:

$$x = V_{flow} \cdot \tau$$

Magnetic Field Increments



$$|\overrightarrow{\Delta B}_\tau(t)| = |\vec{B}(t) - \vec{B}(t+\tau)|$$

Single-Spacecraft,
Flow-based increments:

- Assumption of Taylor Hypothesis
- Sampling in direction of plasma flow

Conversion of timeseries to spatial scales:

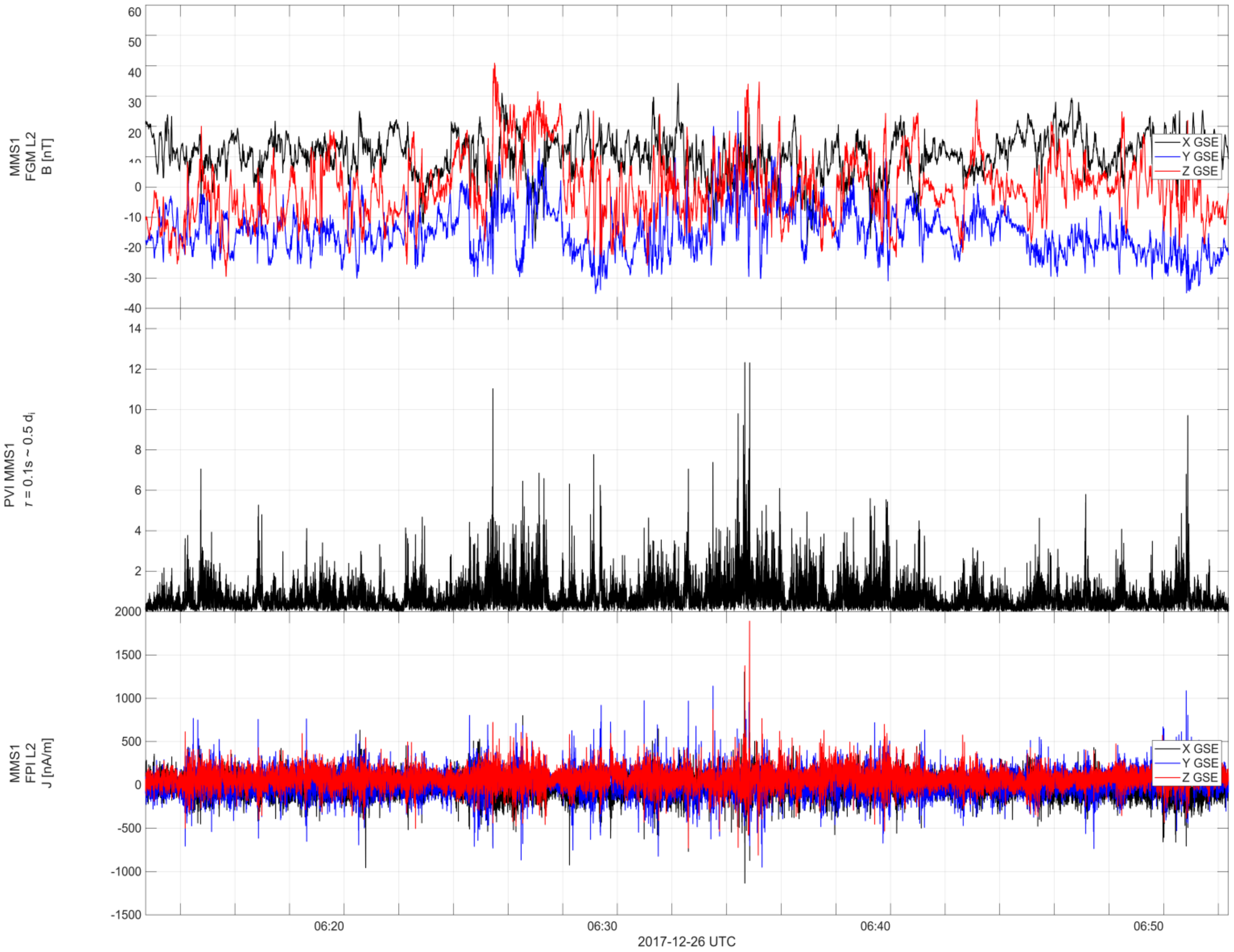
$$x = V_{flow} \cdot \tau$$

Magnetic Field Increments

Partial Variance of Increments:

$$PVI(t) = \frac{|\overrightarrow{\Delta \mathrm{B}}(t)|}{\sqrt{< |\overrightarrow{\Delta B}(t)|^2 >_T}}$$

(Greco et al. 2008,2009)



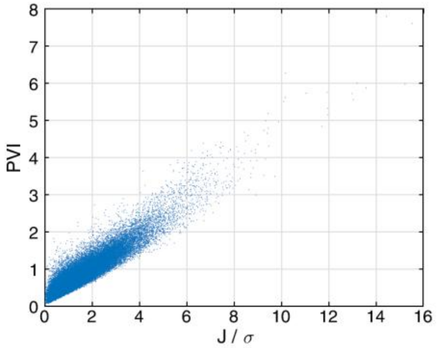
Magnetic Field Increments

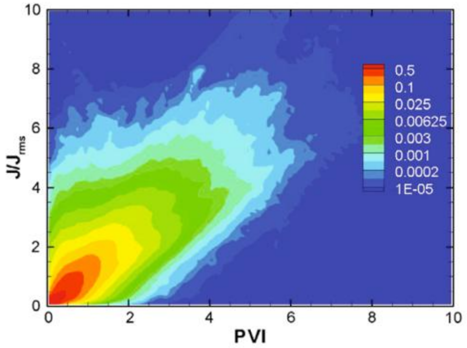
Partial Variance of Increments:

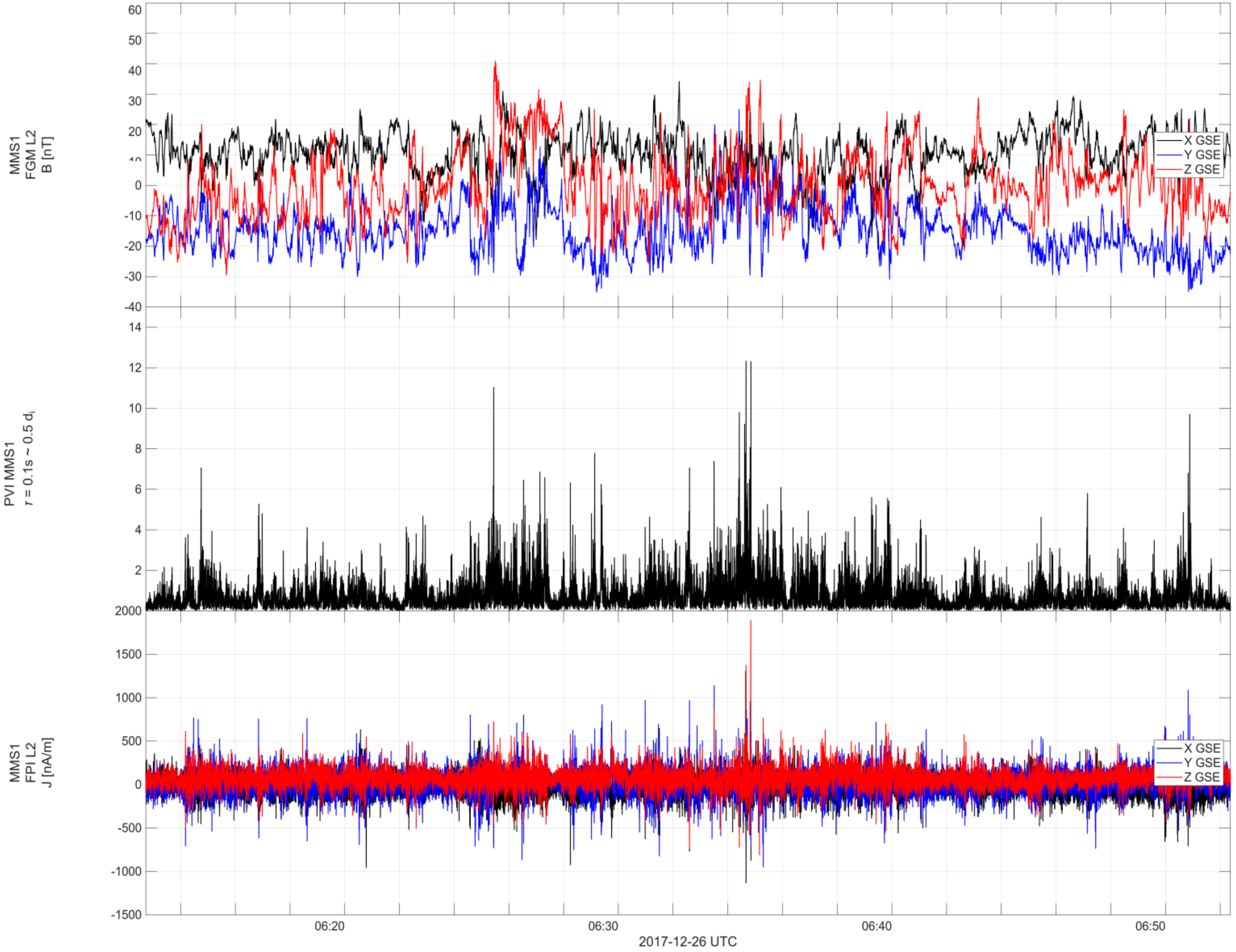
$$PVI(t) = \frac{|\overrightarrow{\Delta \mathrm{B}}(t)|}{\sqrt{< |\overrightarrow{\Delta B}(t)|^2 >_T}}$$

(Greco et al. 2008,2009)

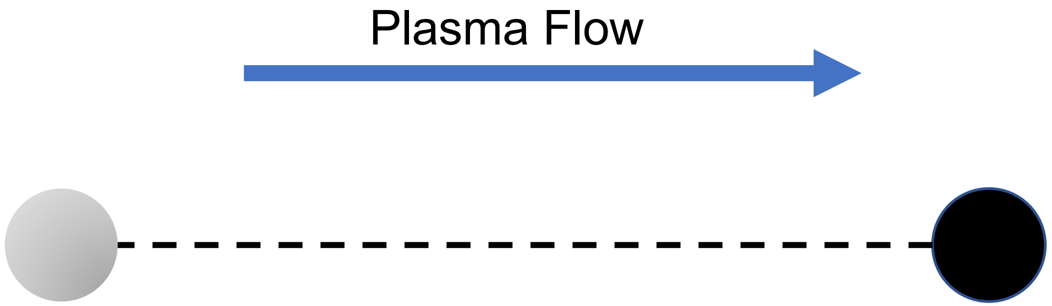
PVI follows the current density







Increments



$$|\overrightarrow{\Delta B}_{\tau}(t)| = |\vec{B}(t) - \vec{B}(t+\tau)|$$

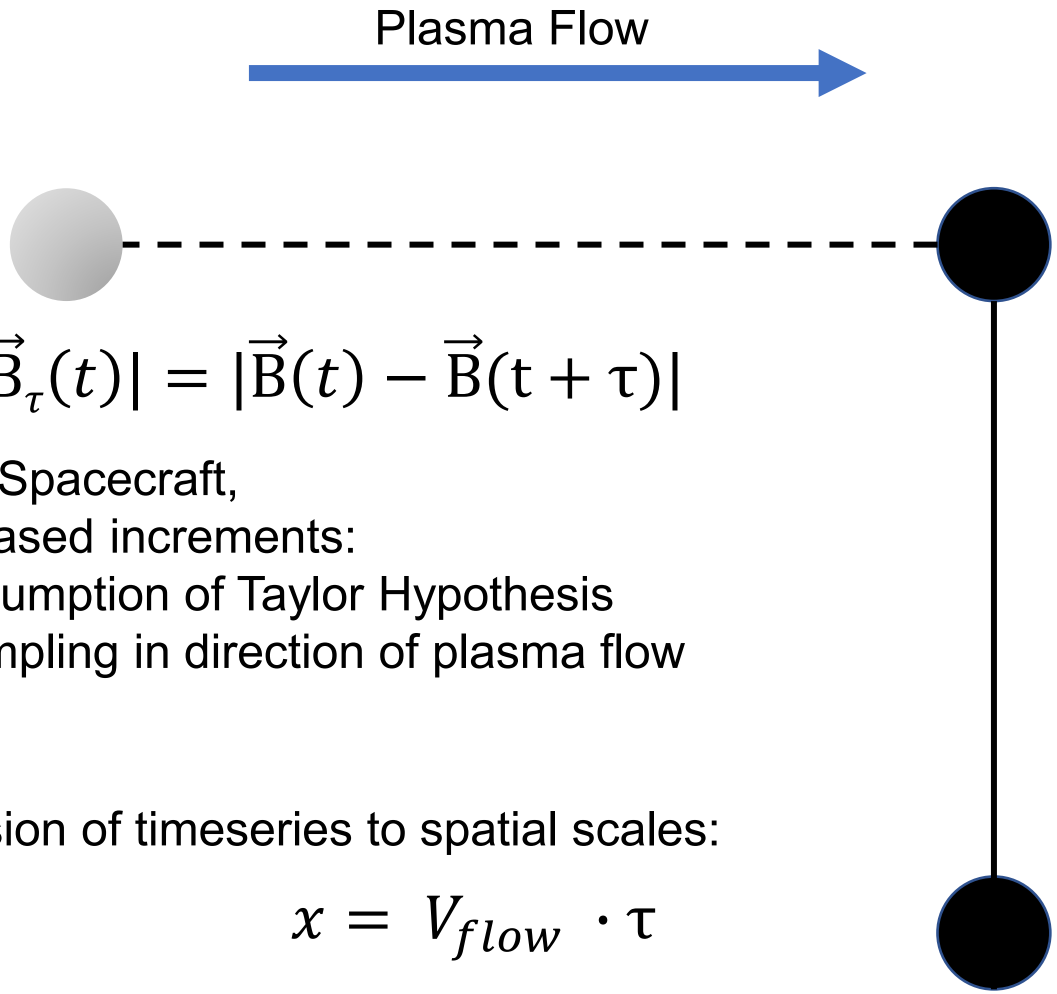
Single-Spacecraft,
Flow-based increments:

- Assumption of Taylor Hypothesis
- Sampling in direction of plasma flow

Conversion of timeseries to spatial scales:

$$x = V_{flow} \cdot \tau$$

Increments



$$|\overrightarrow{\Delta \mathrm{B}}_{\tau}(t)| = |\vec{\mathrm{B}}(t) - \vec{\mathrm{B}}(\mathrm{t}+\tau)|$$

Single-Spacecraft,
Flow-based increments:

- Assumption of Taylor Hypothesis
- Sampling in direction of plasma flow

Conversion of timeseries to spatial scales:

$$x = V_{flow} \cdot \tau$$

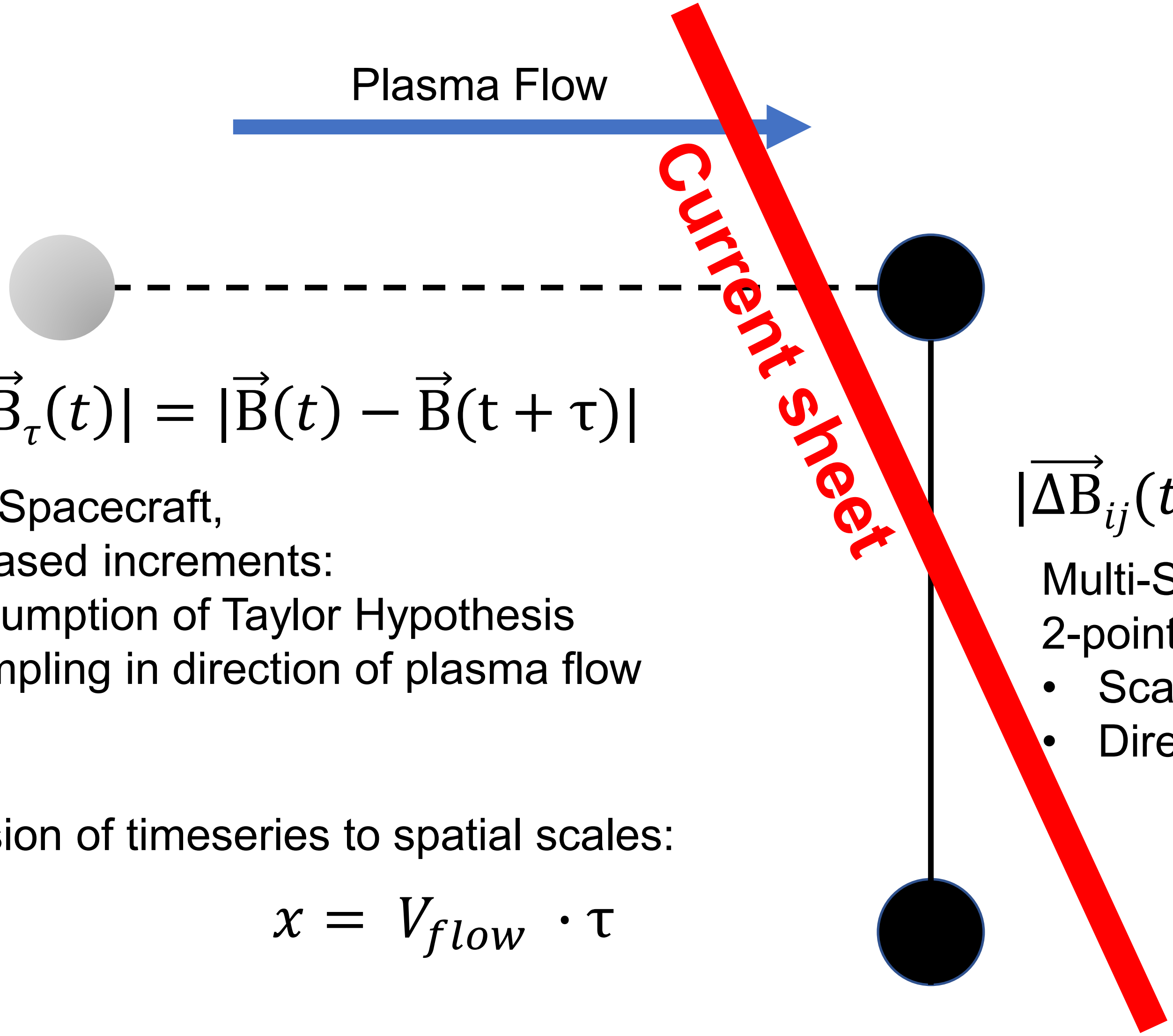
$$|\overrightarrow{\Delta \mathrm{B}}_{ij}(t)| = |\vec{\mathrm{B}}_{i}(t) - \vec{\mathrm{B}}_{\mathrm{j}}(\mathrm{t})|$$

Where I,j=1:4 for each spacecraft

Multi-Spacecraft,
2-point increments:

- Scale fixed by spacecraft separation
- Direction of each spacecraft pair
  (6 baselines for 4 spacecraft)

Increments



$$|\overrightarrow{\Delta B_\tau}(t)| = |\vec{B}(t) - \vec{B}(t+\tau)|$$

Single-Spacecraft,
Flow-based increments:

- Assumption of Taylor Hypothesis
- Sampling in direction of plasma flow

Conversion of timeseries to spatial scales:

$$x = V_{flow} \cdot \tau$$

$$|\overrightarrow{\Delta B_{ij}}(t)| = |\vec{B}_i(t) - \vec{B}_j(t)|$$

Where I,j=1:4 for each spacecraft

Multi-Spacecraft,
2-point increments:

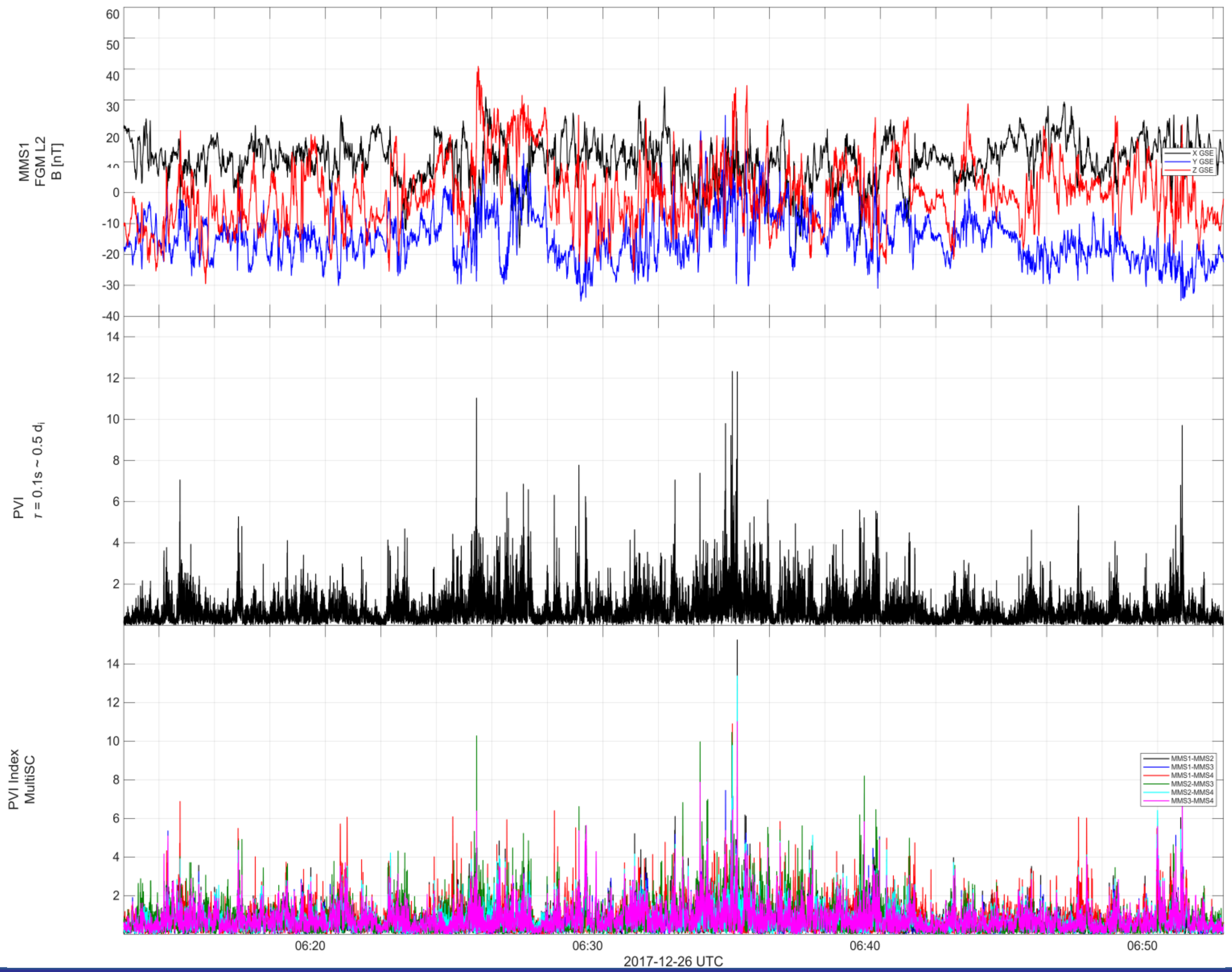
- Scale fixed by spacecraft separation
- Direction of each spacecraft pair
  (6 baselines for 4 spacecraft)

Partial Variance of Increments

Partial Variance of Increments:

$$PVI(t) = \frac{|\overrightarrow{\Delta \mathrm{B}}(t)|}{\sqrt{< |\overrightarrow{\Delta B}(t)|^2 >_T}}$$

(Greco et al. 2008,2009)



Partial Variance of Increments

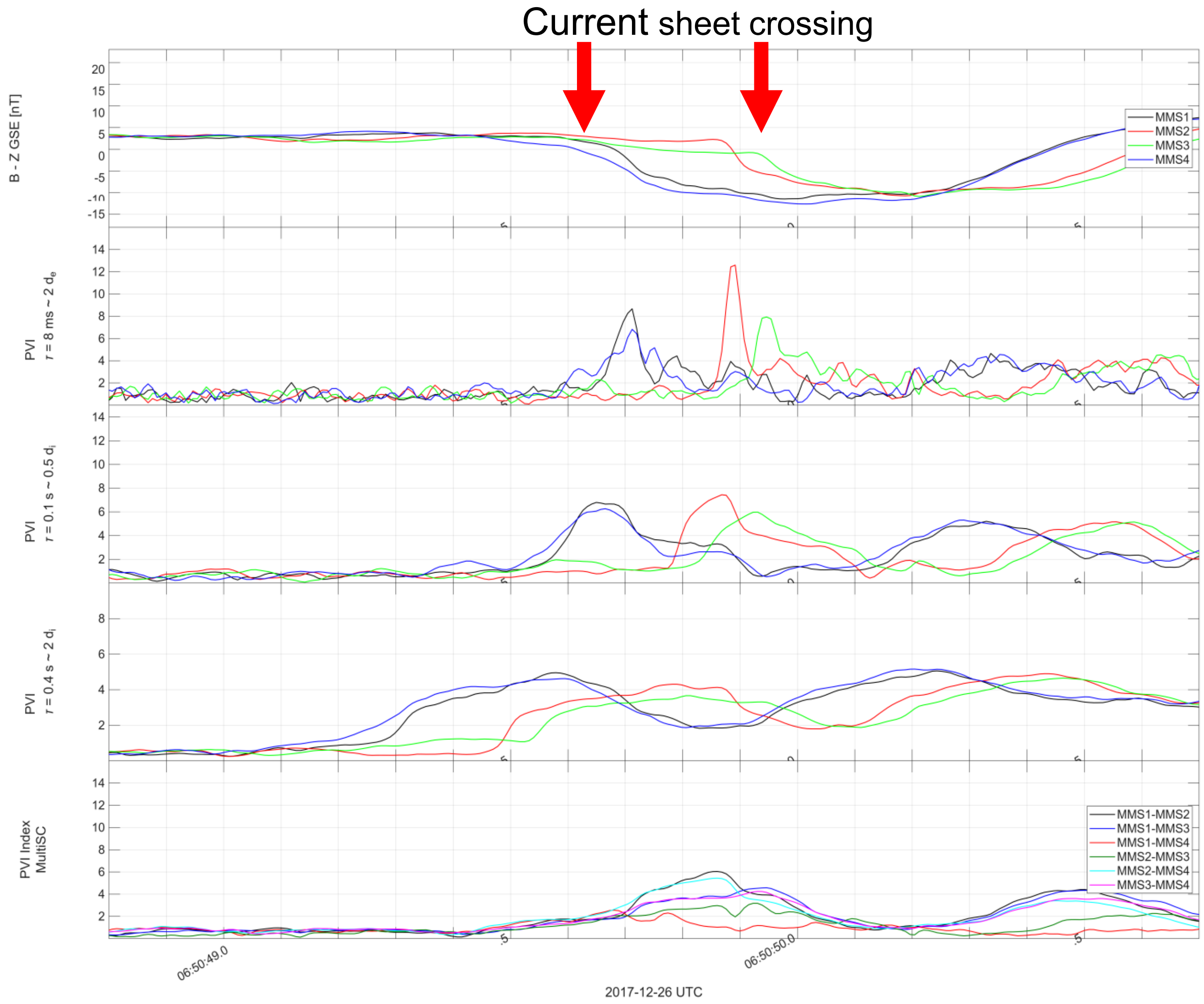
Partial Variance of Increments:

$$PVI(t) = \frac{|\overrightarrow{\Delta B}(t)|}{\sqrt{< |\overrightarrow{\Delta B}(t)|^2 >_T}}$$

(Greco et al. 2008,2009)

Multi-spacecraft measurements allow, multiple directions, no taylor hypothesis ~ average within the spacecraft formation

Limited at a scale fixed by the spacecraft separation

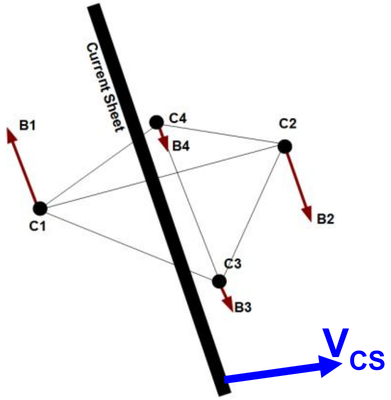


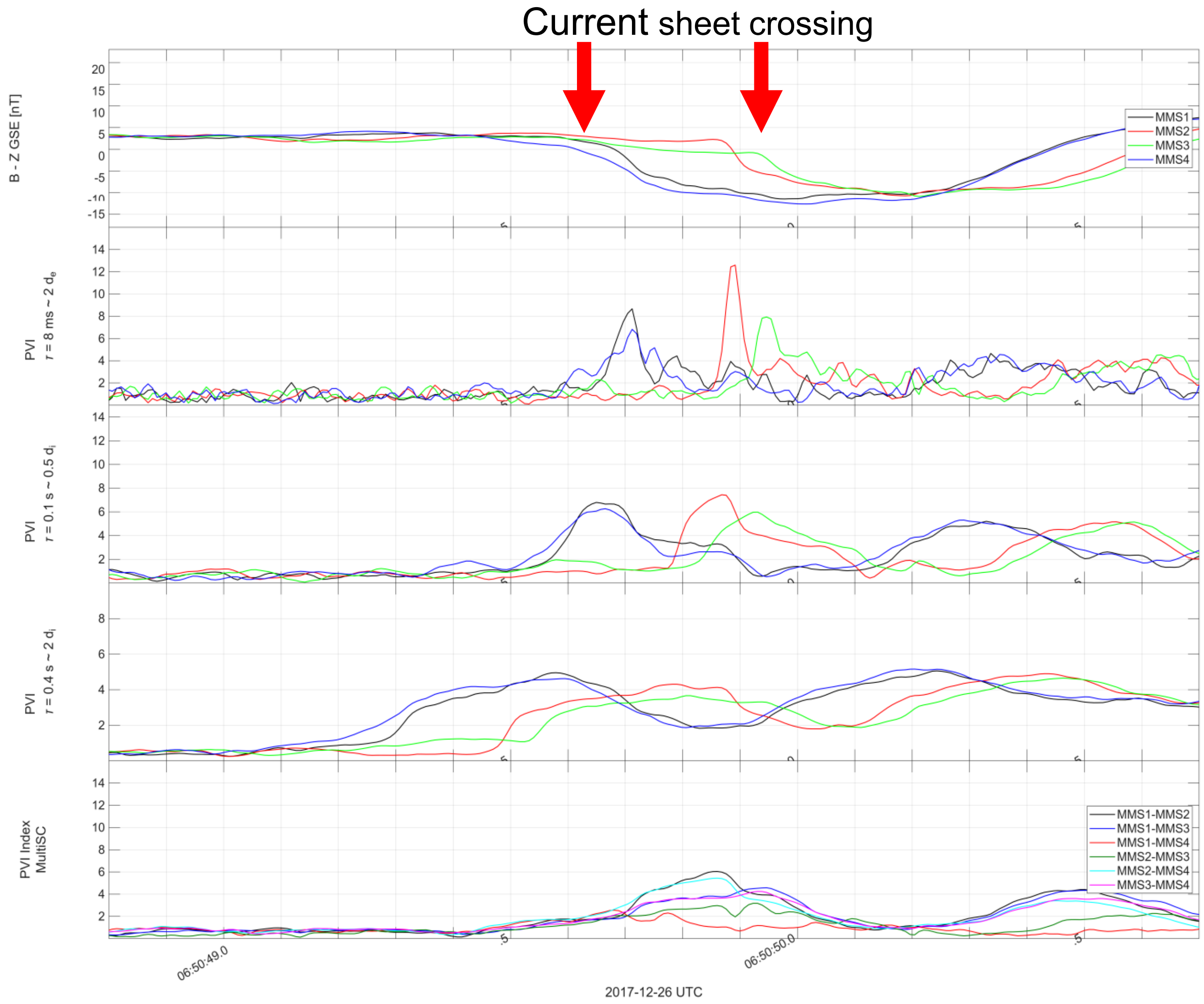
Orientation of current sheets

Timing method: Assume a plane crossing the 4 points at different times, solve a system of 4 linear equations for V_{cs}, n_x, n_y, n_z

$$\begin{pmatrix} \bar{r}_{12} \\ \bar{r}_{13} \\ \bar{r}_{14} \end{pmatrix} \frac{1}{V_{CS}} \begin{pmatrix} n_x \\ n_y \\ n_z \end{pmatrix} = \begin{pmatrix} t_{12} \\ t_{13} \\ t_{14} \end{pmatrix}$$

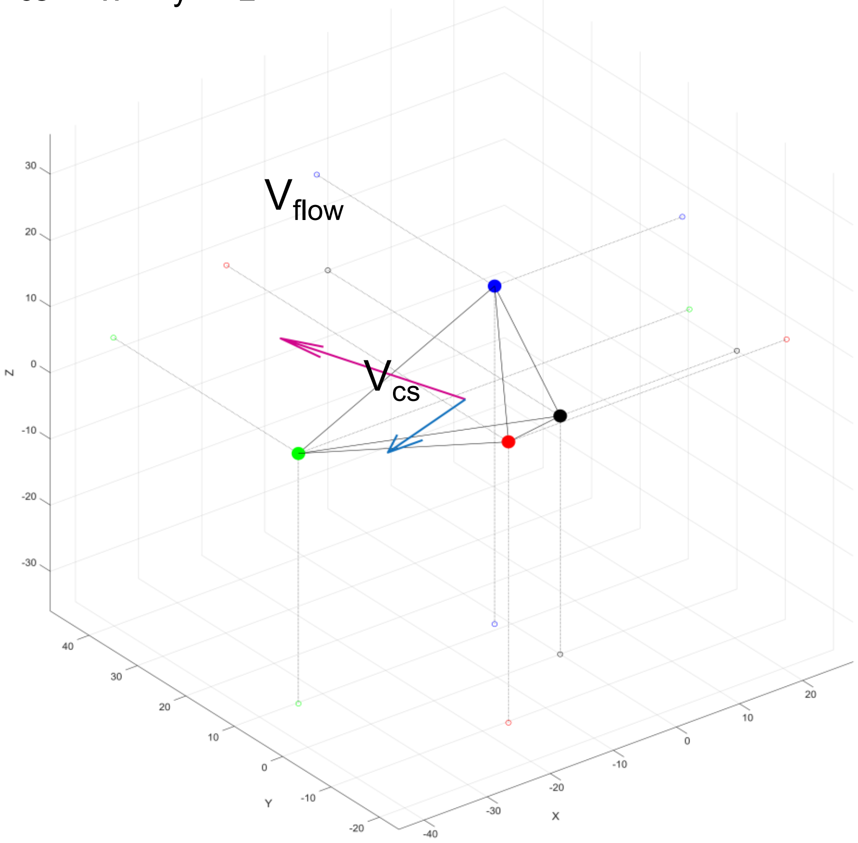
center of current sheet

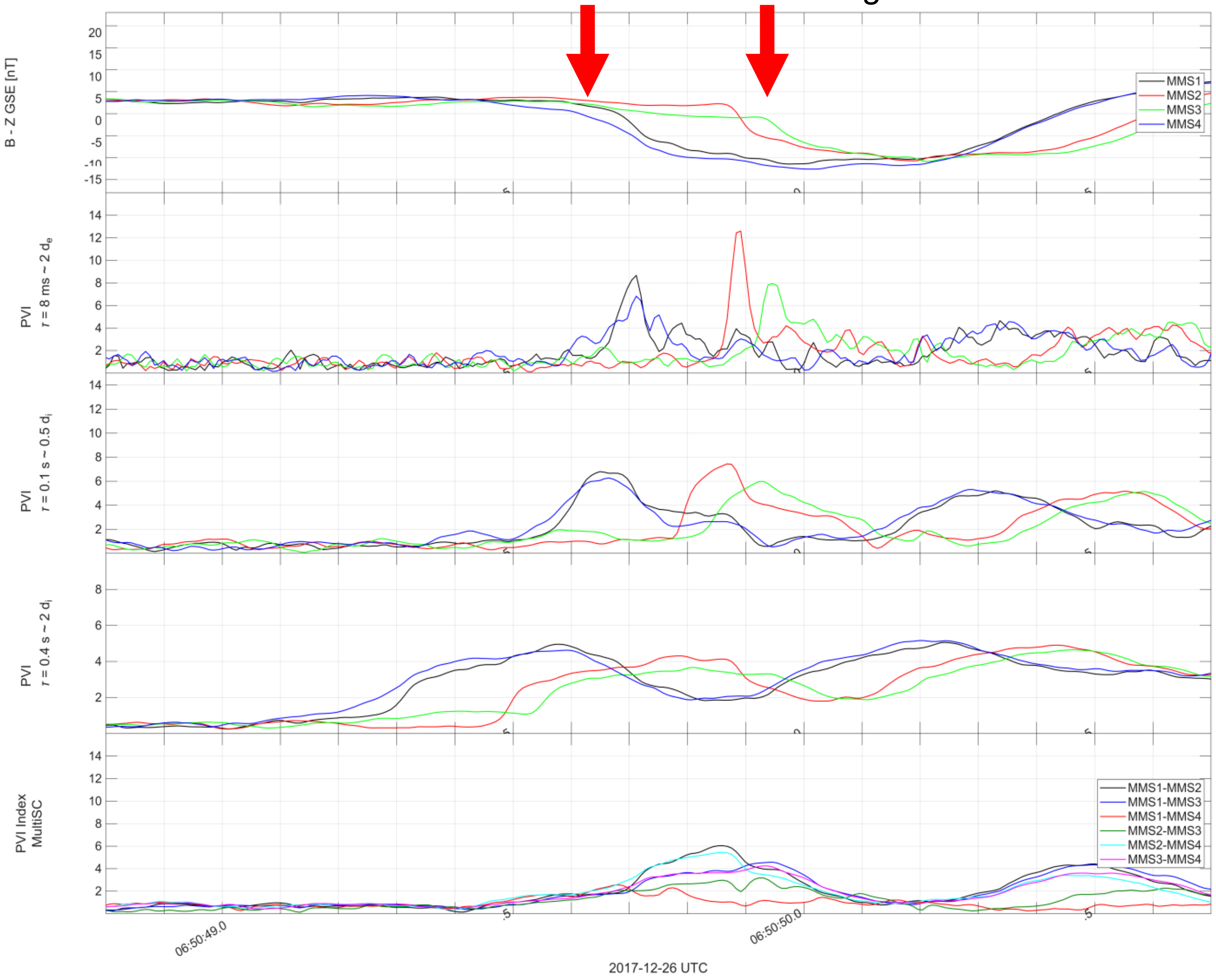




Orientation of current sheets

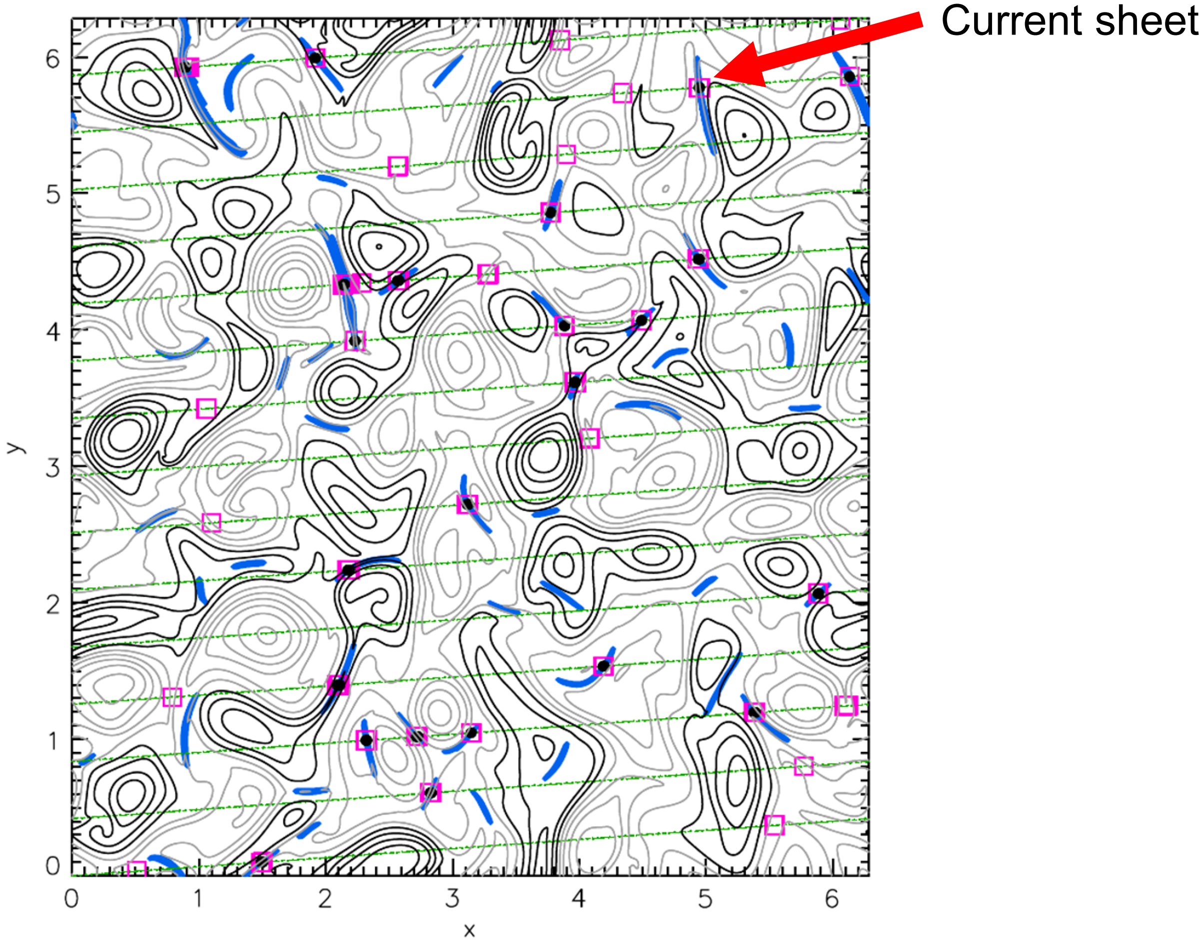
Timing method: Assume a plane crossing the 4 points at different times, solve a system of 4 linear equations for V_{cs}, n_x, n_y, n_z

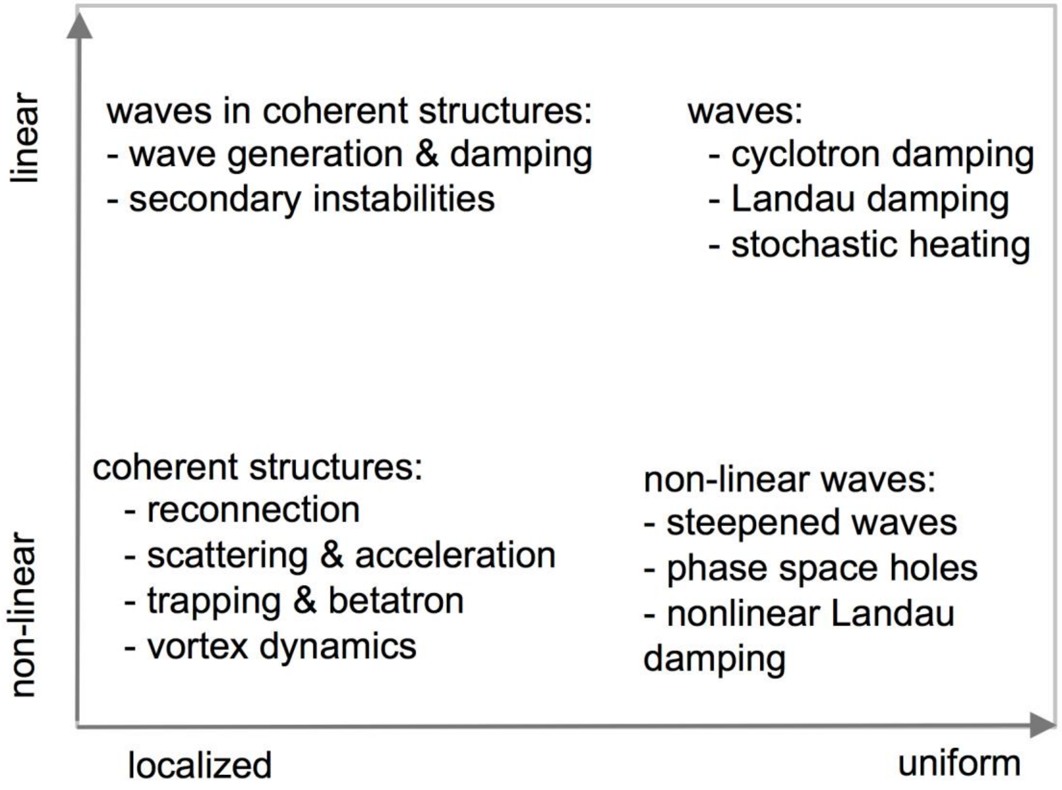




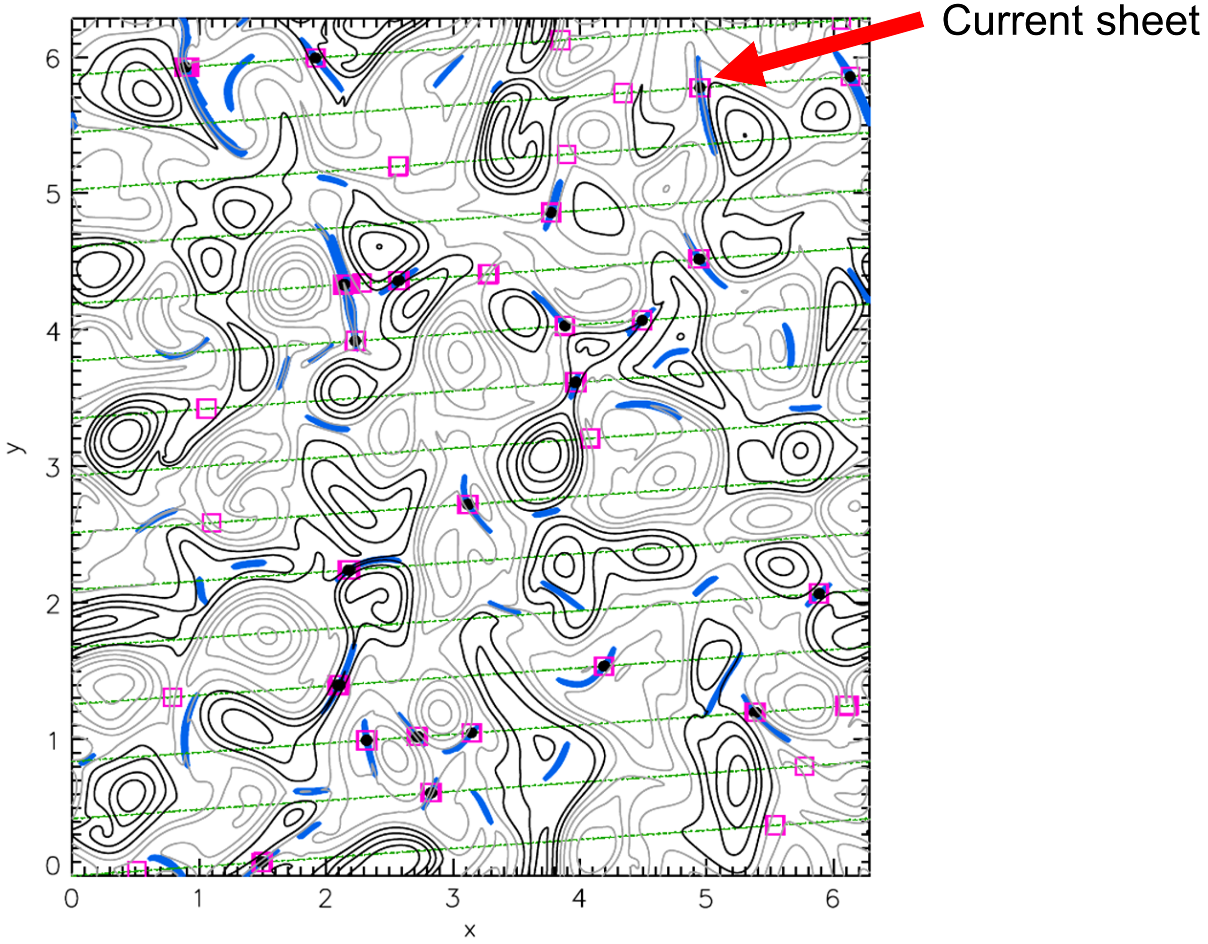
Turbulent Dissipation

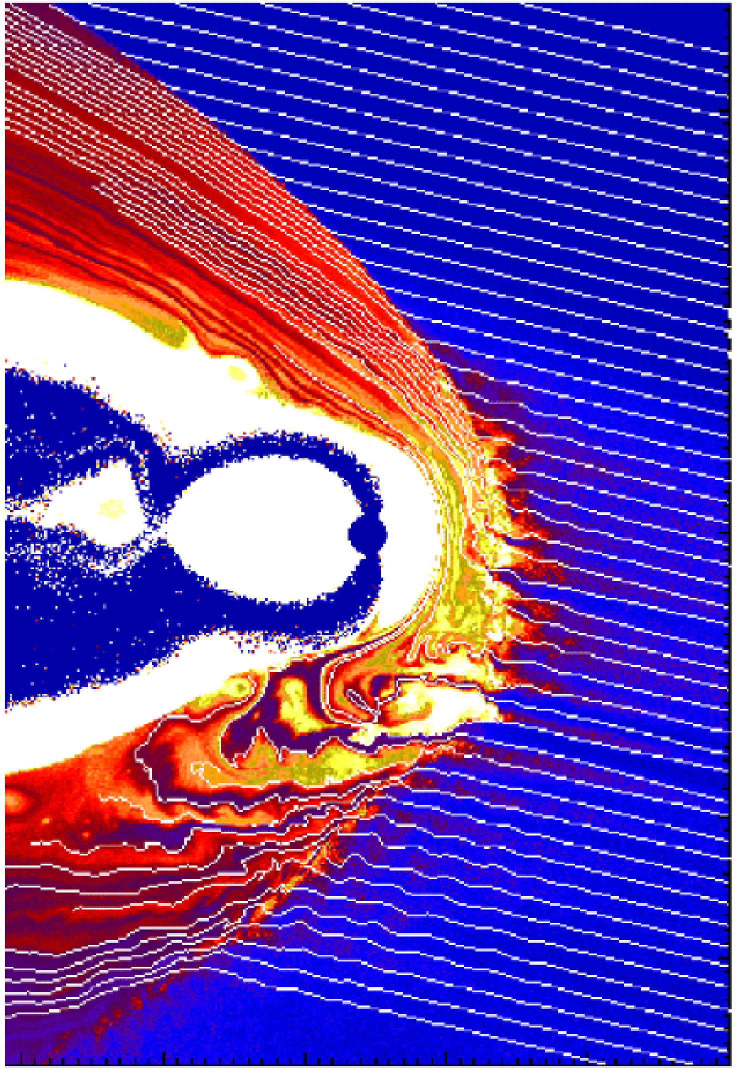
How is energy dissipated in collisonless turbulence?



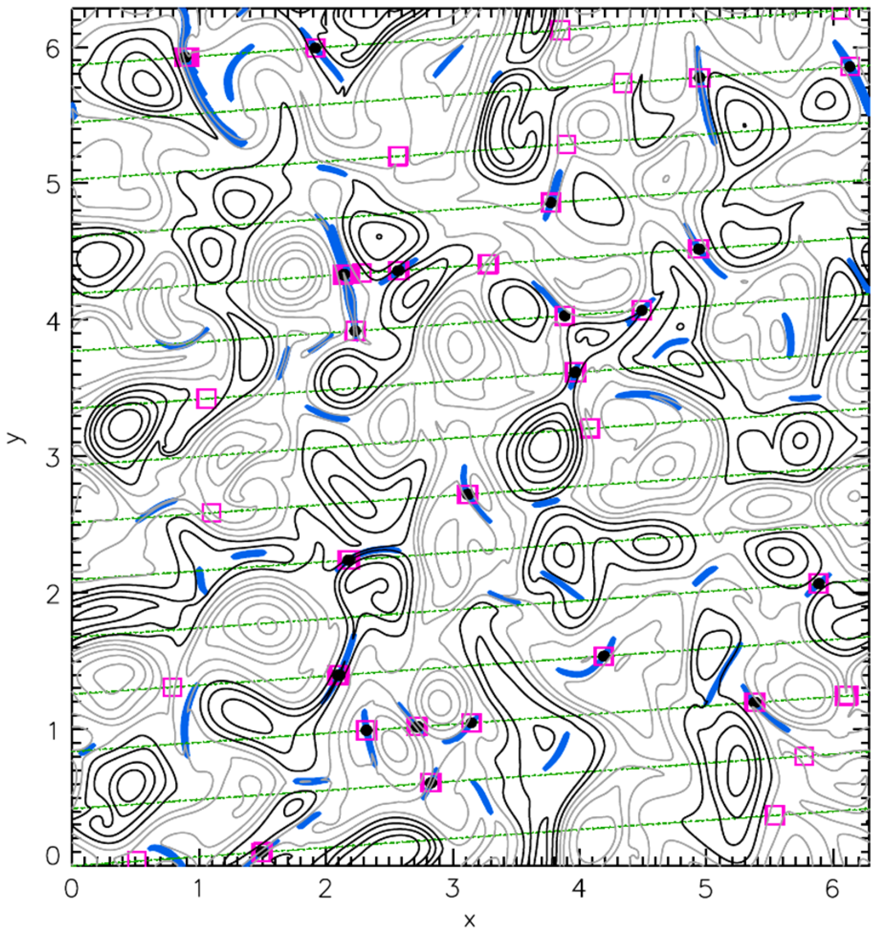


Turbulent Dissipation





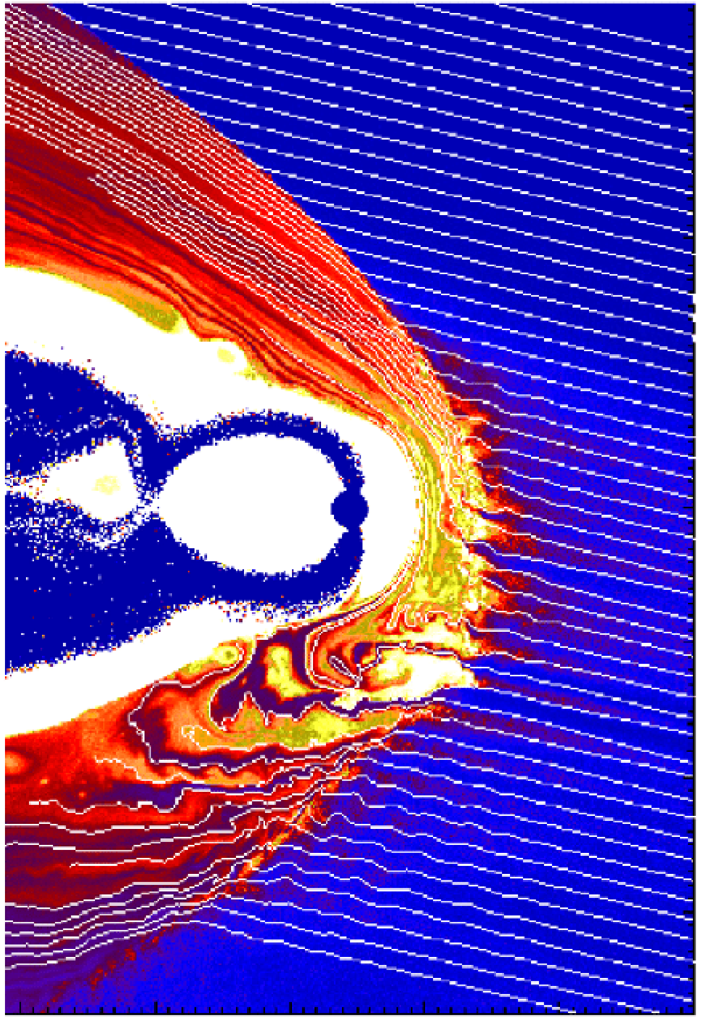
Turbulent Dissipation



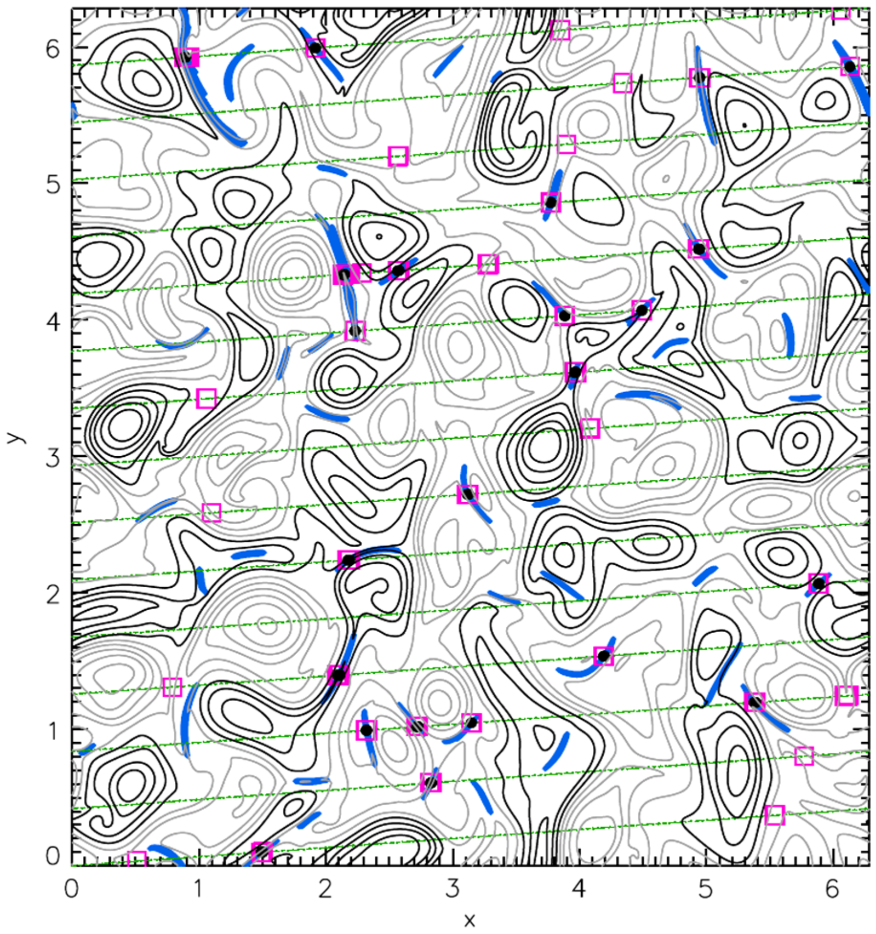
Earth's Magnetosheath:
Interface between the solar wind and Earth's magnetic environment:

Highly dynamic region of strong turbulence

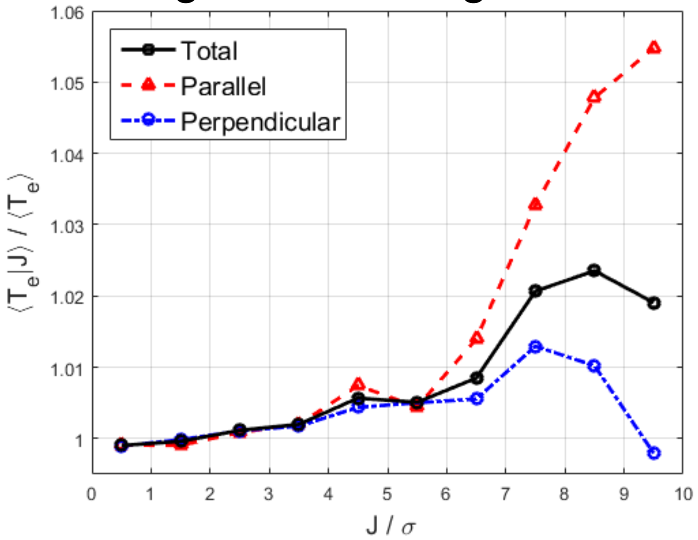
MMS operates at optimal conditions, large quantities of high-quality data available for statistical analysis



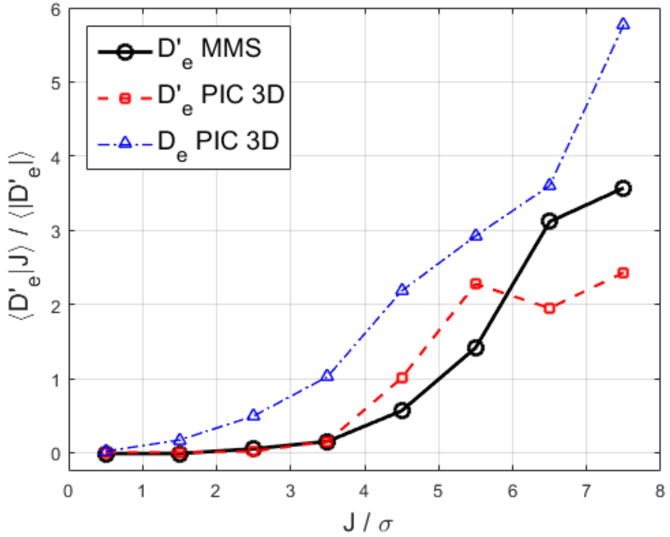
Turbulent Dissipation



Electron temperature in regions of strong current



E.J in regions of strong current



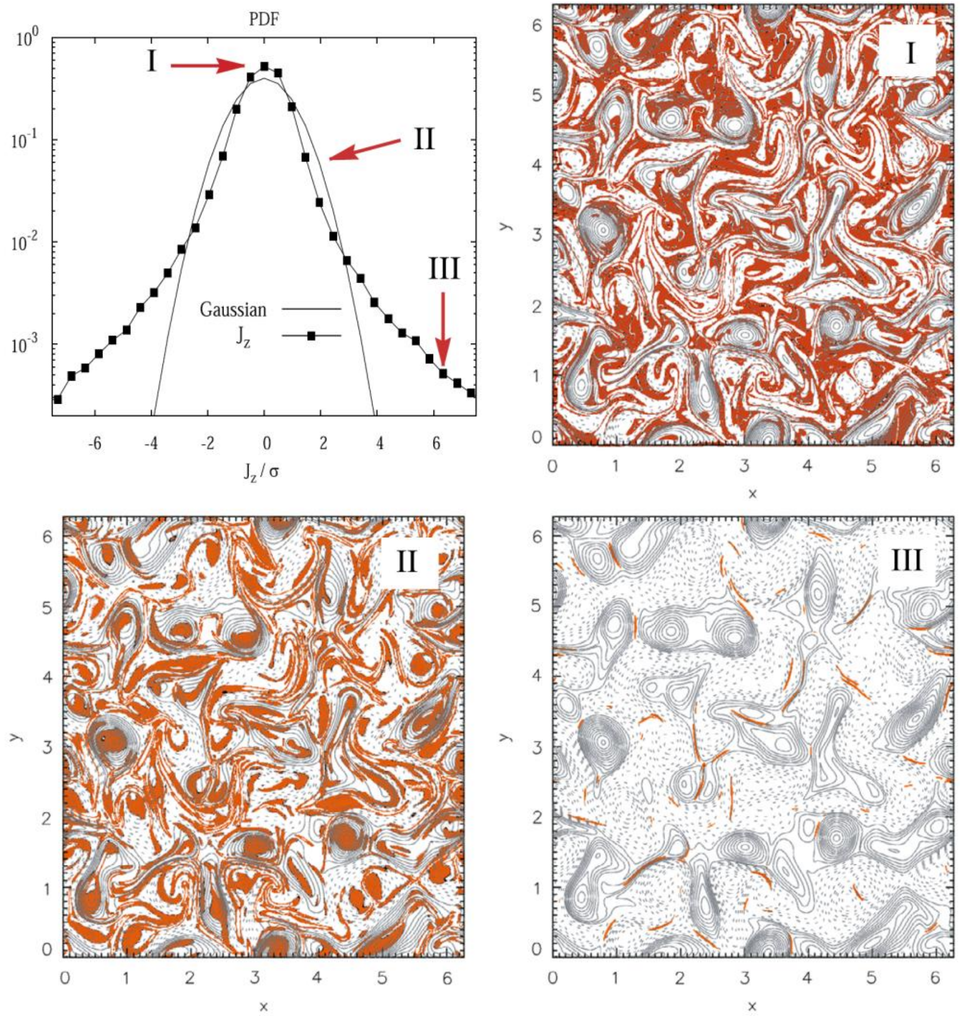
Chasapis et al. ApJLett, 2018

Strong dissipation localized in regions of strong current

Statistics of Increments

The statistical distribution of increments can provide information about the structure forming in turbulence

Intermittent structures (current sheets) are associated with heavy tails of in the distribution of increments of B



Statistics of Increments

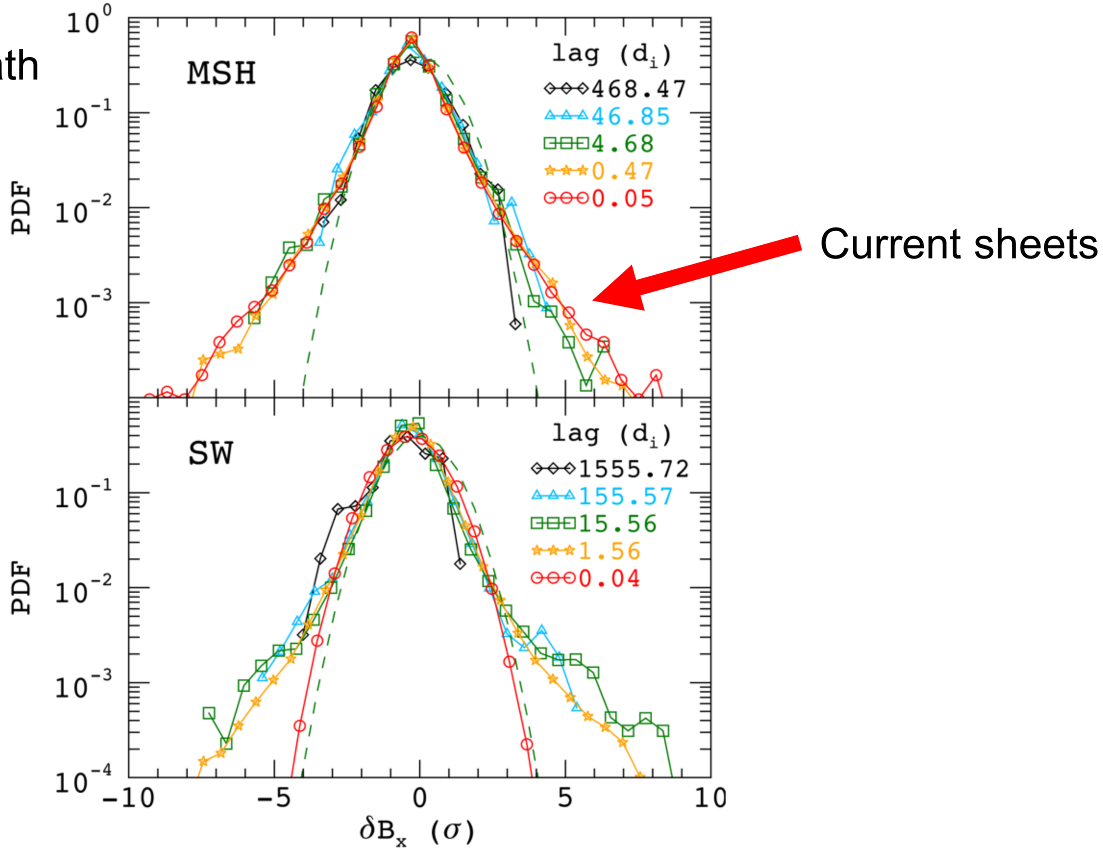
The statistical distribution of increments can provide information about the structure forming in turbulence

Intermittent structures (current sheets) are associated with heavy tails of in the distribution of increments of B

Observations show structures forming at small scales

Magnetosheath
$\delta B/B \sim 1$

Solar wind
$\delta B/B \sim 0.1$



See Chhiber et al. JGR 2018 and Bandyopadhyay et al. ApJ 2018

Scale Dependent Kurtosis

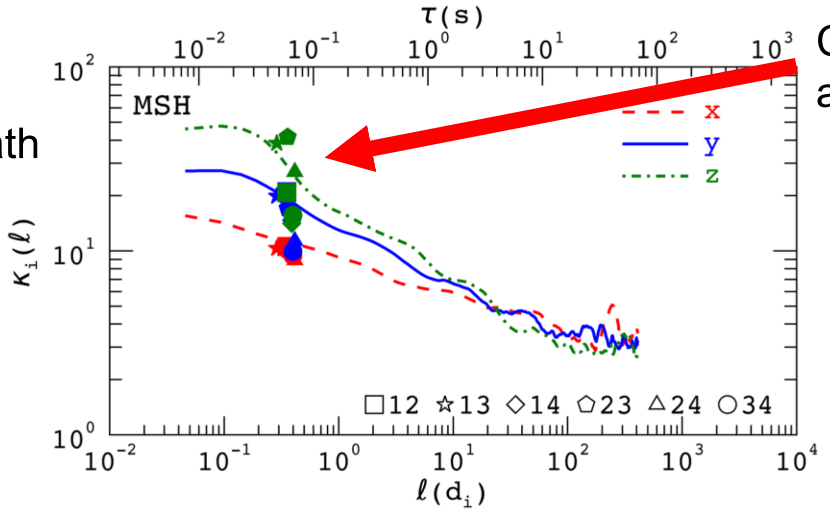
Kurtosis (or flatness) is a qualitative measure of how heavy-tailed is a statistical distribution

Scale Dependent Kurtosis is derived from increments computed at different scales

Multi-spacecraft increments are fixed at the separation of the spacecraft

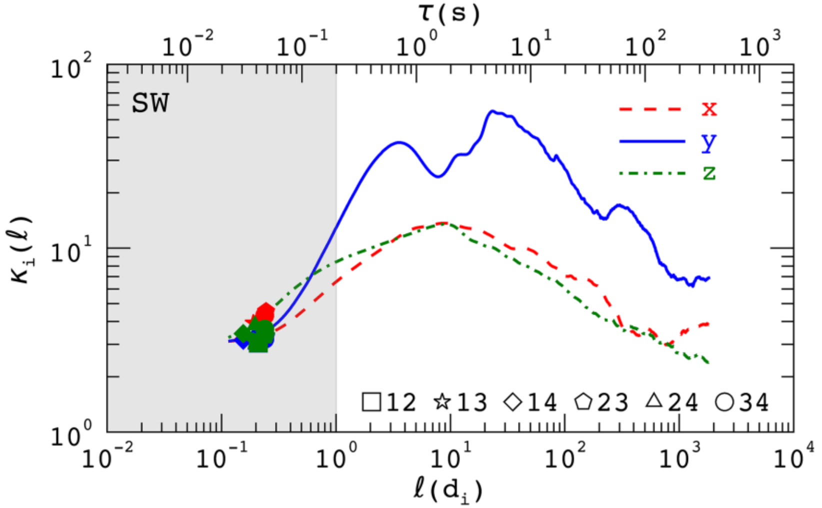
$$k(\tau) = \frac{< (\delta B_\tau)^4 >_t}{< (\delta B_\tau)^2 >_t^2}$$

Magnetosheath
δB/B ~1



Current sheets at sub-ion scales

Solar wind
δB/B ~0.1



See Chhiber et al. JGR 2018 and Bandyopadhyay et al. ApJ 2018

Multi-Scale Observatories

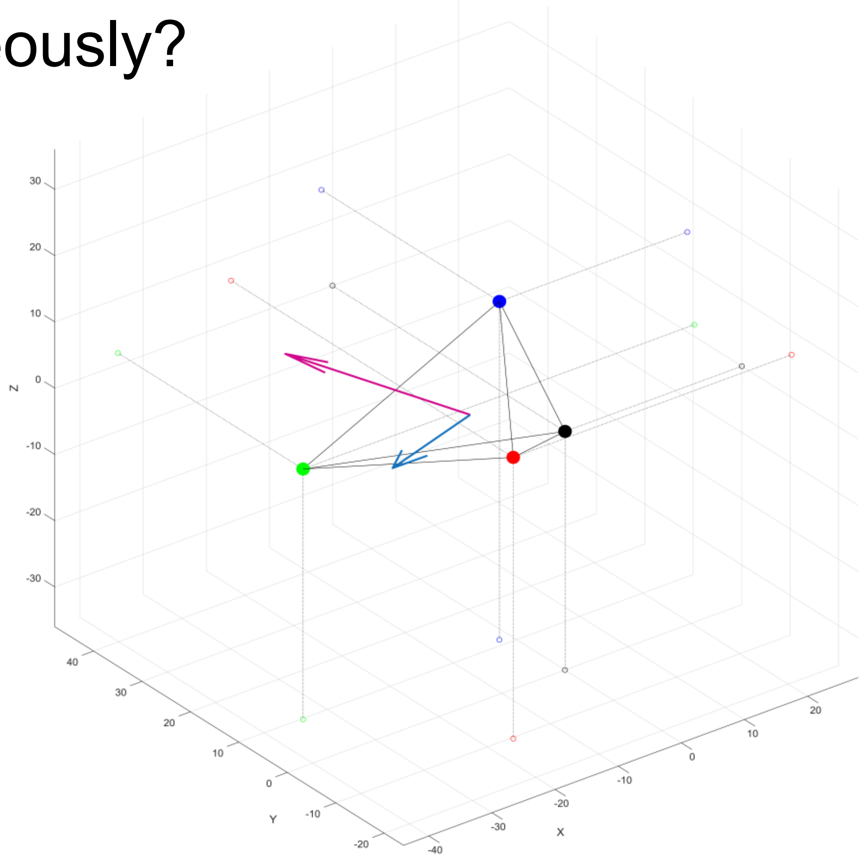
4-spacecraft formations enable study of energy transfer at a fixed scale

How do we observe multiple scales simultaneously?

Multiscale Spacecraft Observatories

HelioSwarm, Plasma Observatory, etc

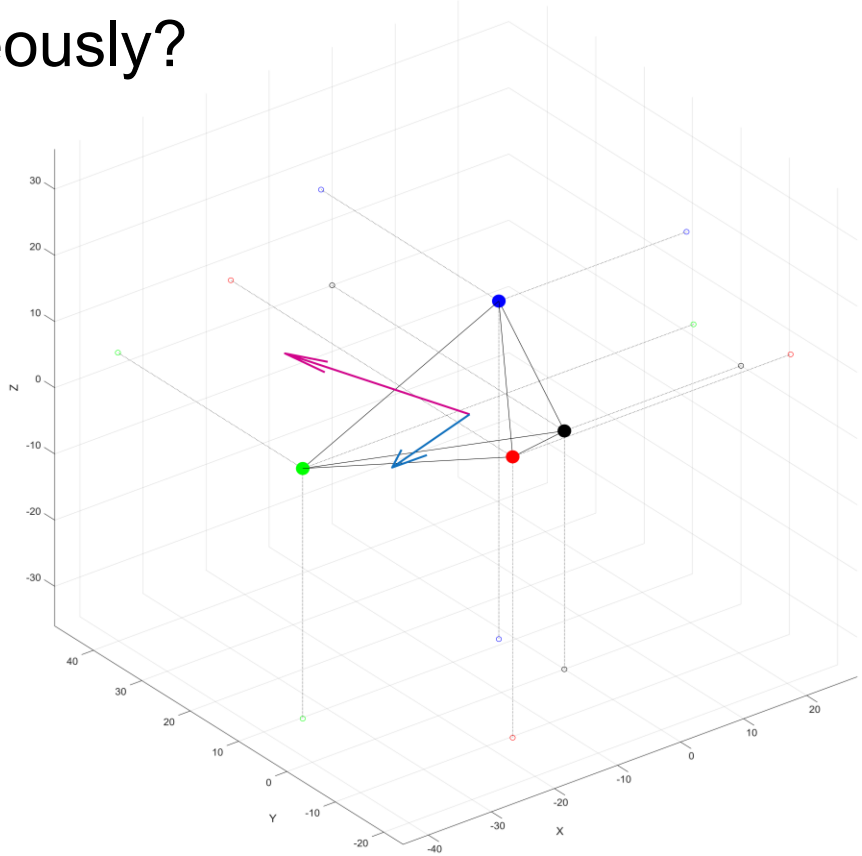
In the meantime…



Multi-Scale Observatories

4-spacecraft formations enable study of energy transfer at a fixed scale

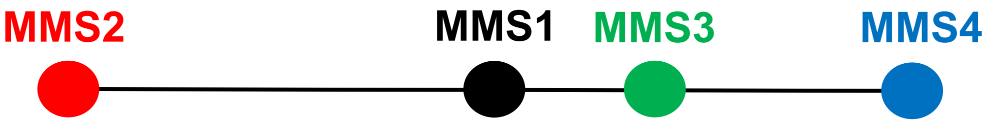
How do we observe multiple scales simultaneously?



Multiscale Spacecraft Observatories

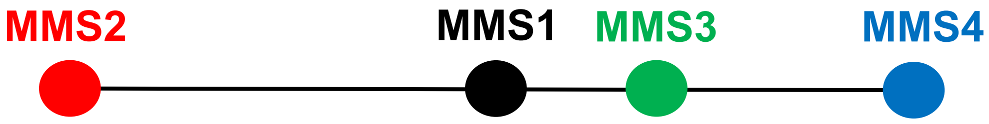
HelioSwarm, Plasma Observatory, etc

In the meantime…



MMS Colinear configuration

The MMS spacecraft can be arranged in a colinear configuration



V_{plasma} →

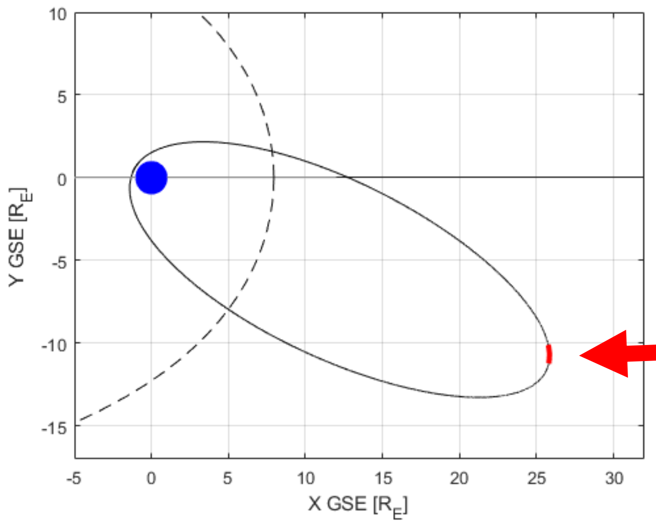
We can observe temporal evolution along the spacecraft separation

↓ V_{plasma}

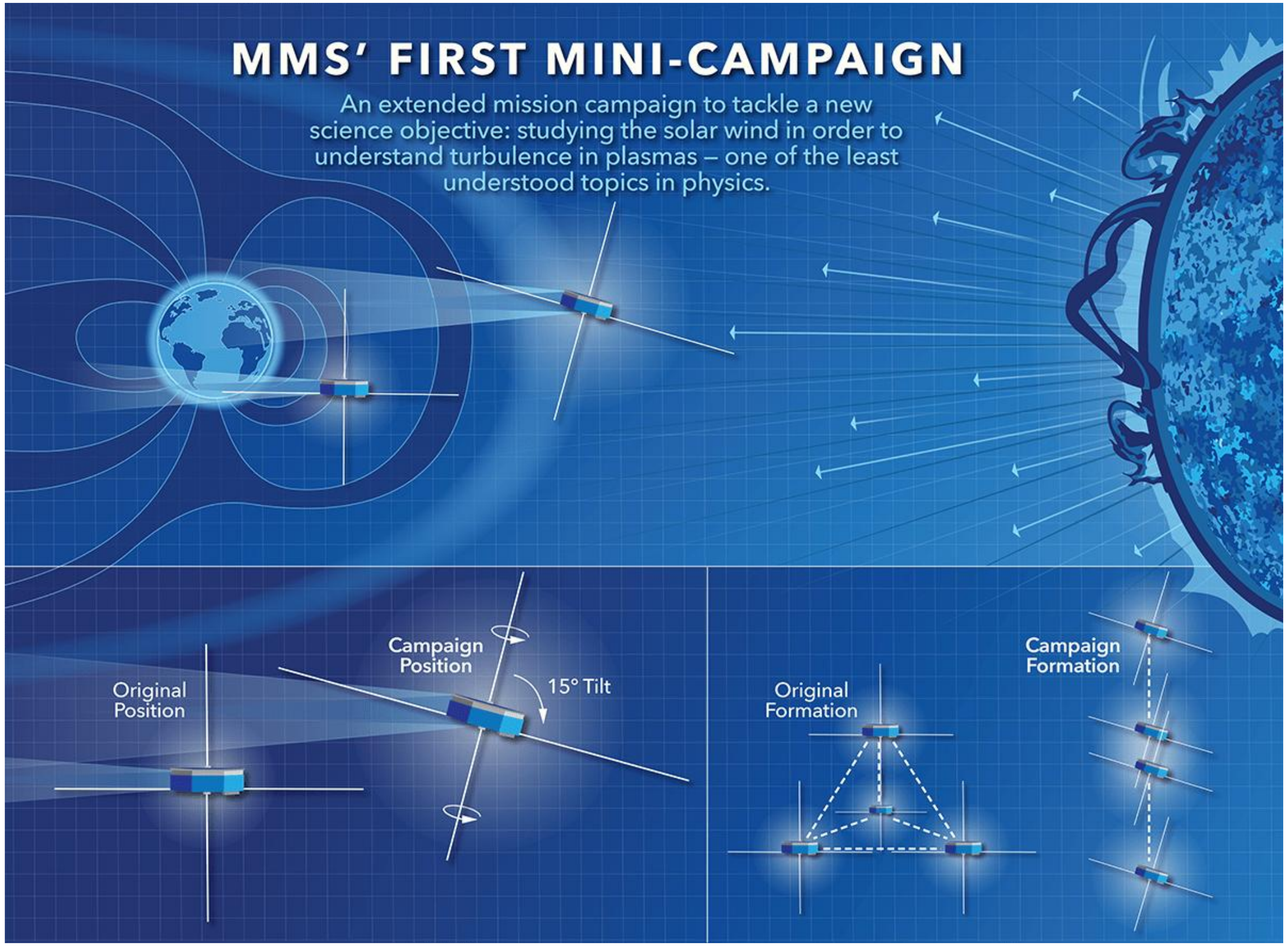
Cross-scale spatial structure in the transverse direction

MMS Colinear configuration

- 1 to 5 hours of continuous burst data in the solar wind
- Separation ranged from 30km to 200km
- Spacecraft orientation perpendicular to solar wind flow



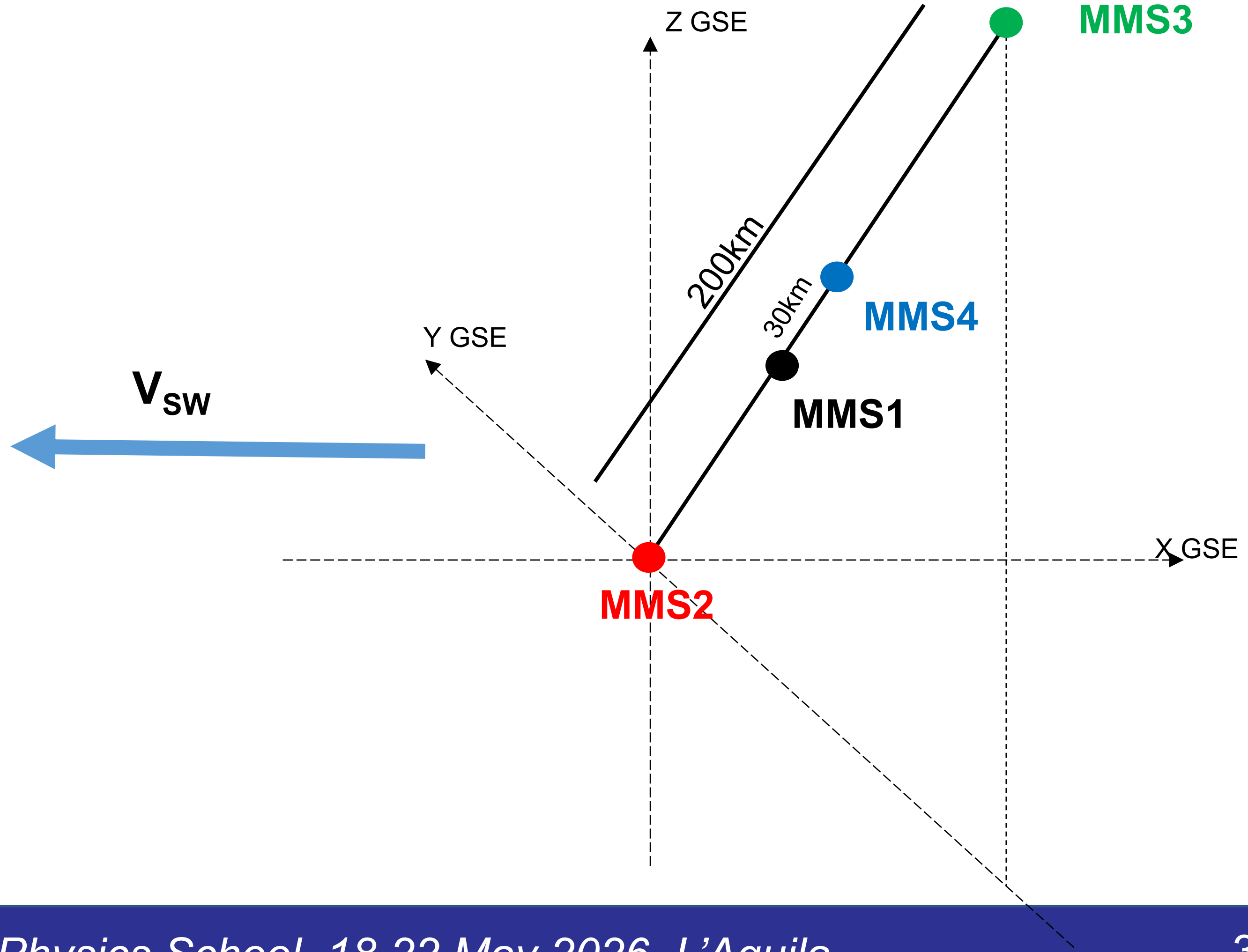
5 hours of Solar wind burst data



MMS colinear configuration

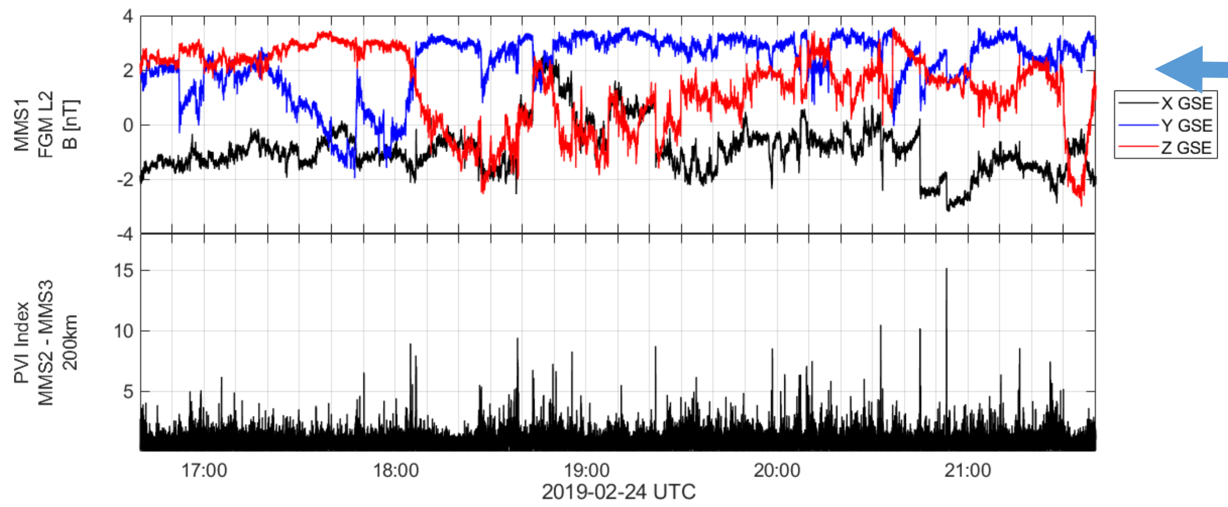
- 1 to 5 hours of continuous burst data in the solar wind
- Separation ranged from 30km to 200km
- Spacecraft orientation perpendicular to solar wind flow

Spacecraft configuration

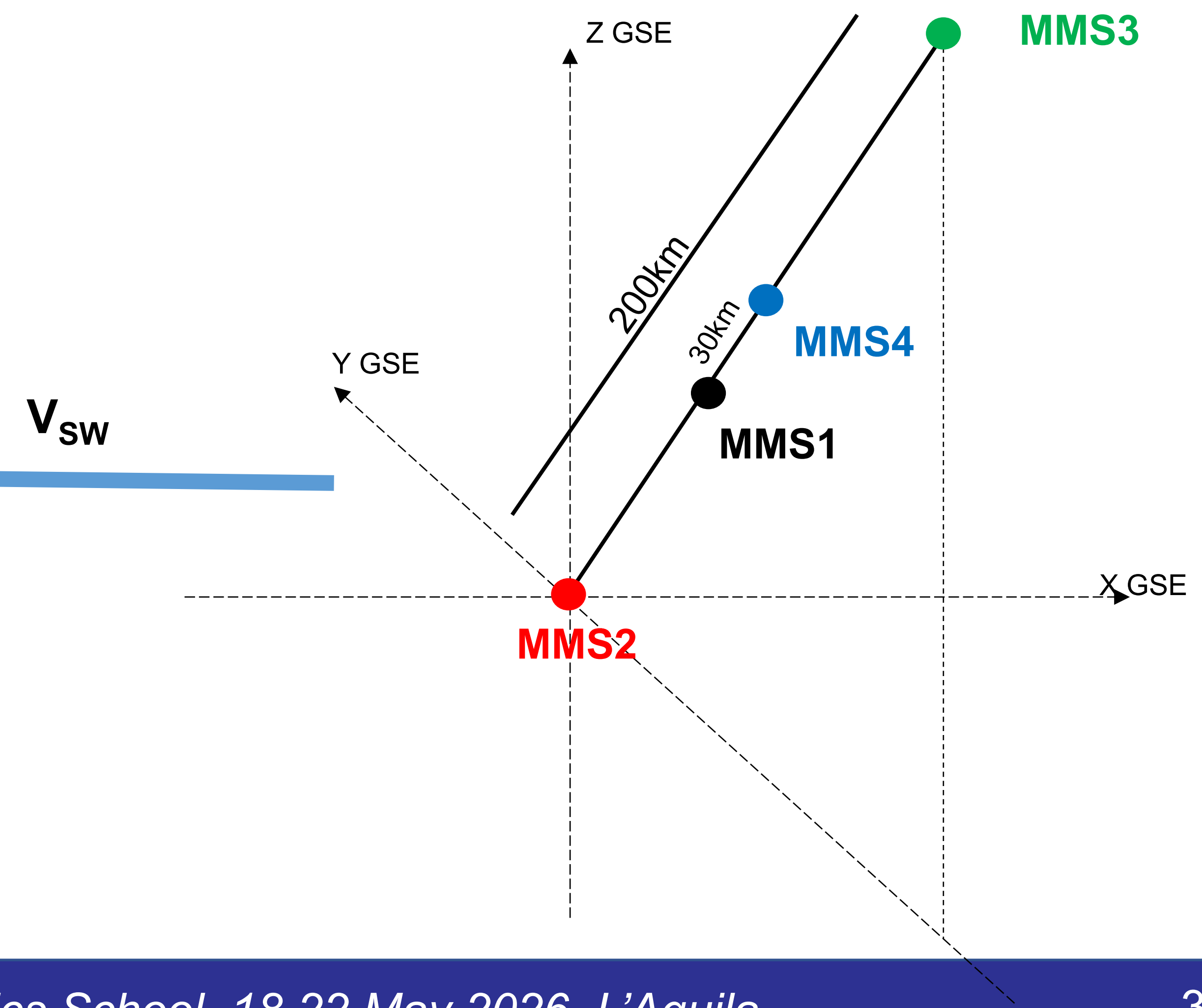


MMS colinear configuration

- 1 to 5 hours of continuous burst data in the solar wind
- Separation ranged from 30km to 200km
- Spacecraft orientation perpendicular to solar wind flow

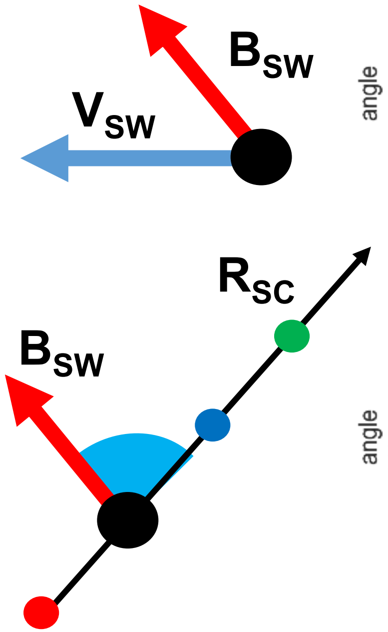


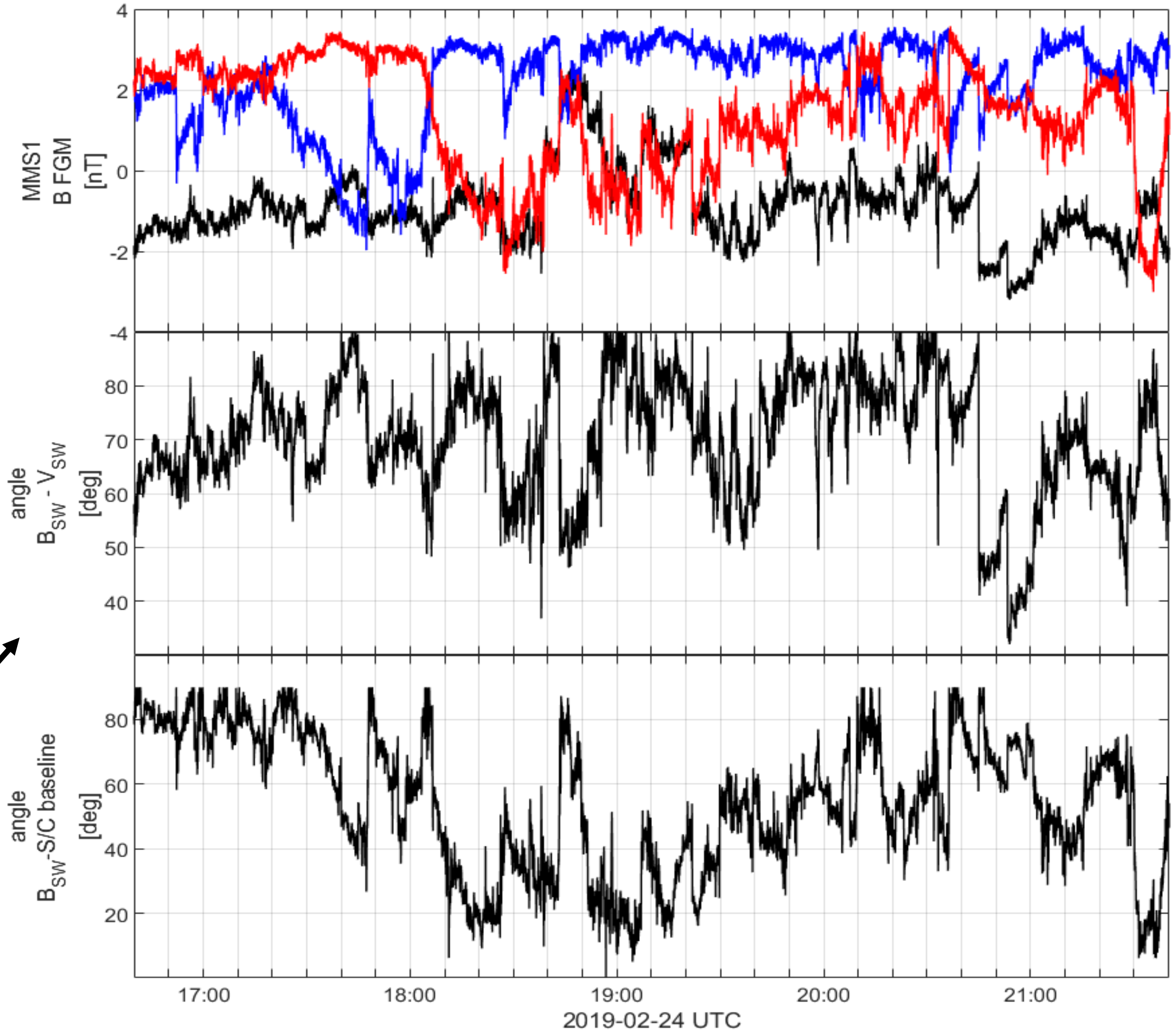
Spacecraft configuration



MMS colinear configuration

- Angle between S/C Baseline and V_{SW} ~90°
- Angle between B_{SW} and V_{SW} approx. Parker spiral
- Angle between S/C baseline and B_{SW} varies a lot

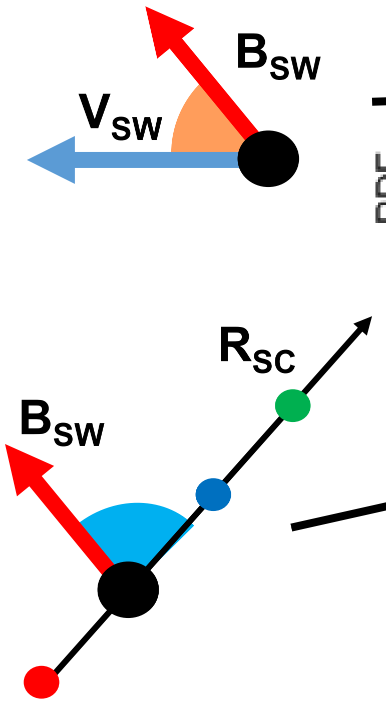


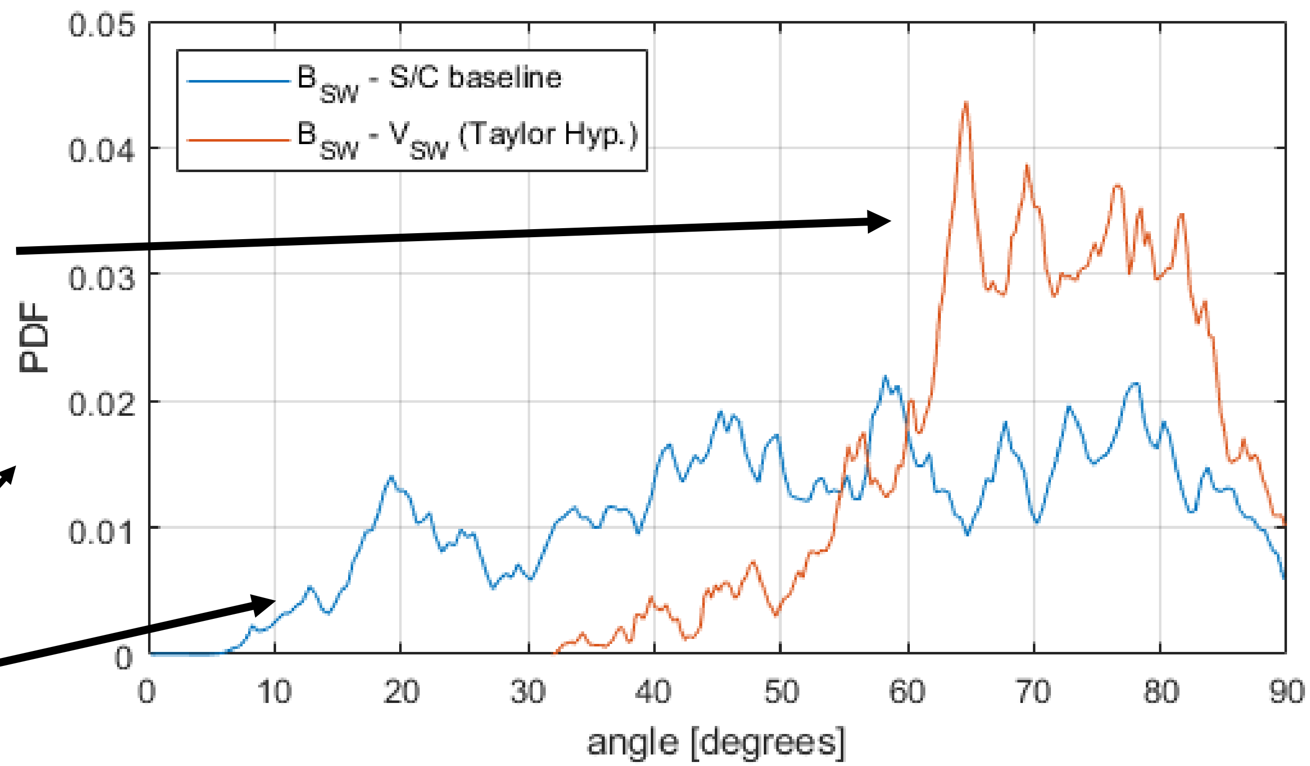


MMS Colinear configuration

- Angle between S/C Baseline and V_{SW} ~90^o
- Angle between B_{SW} and V_{SW} approx. Parker spiral
- Angle between S/C baseline and B_{SW} varies a lot

Multi-spacecraft analysis allows for a direct investigation of the 3-D structure of the solar wind





S/C baseline samples wide range of directions over 5 hours

MMS Colinear configuration

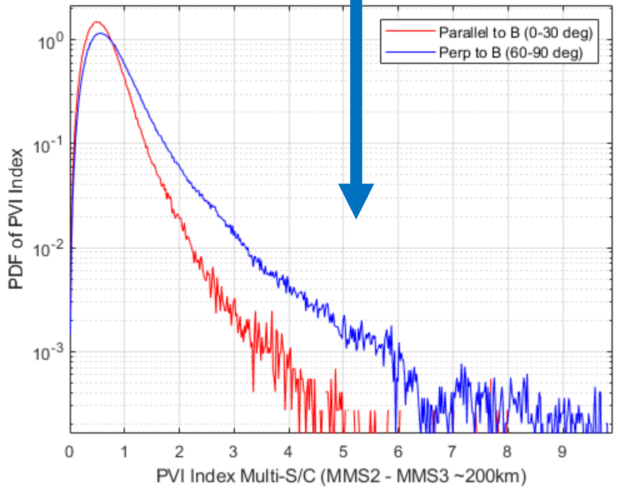
- Direct measurement of intermittency parallel and perpendicular to B
- Increase observed perpendicular to magnetic field
- Non-Gaussian fluctuations peak at 65^o

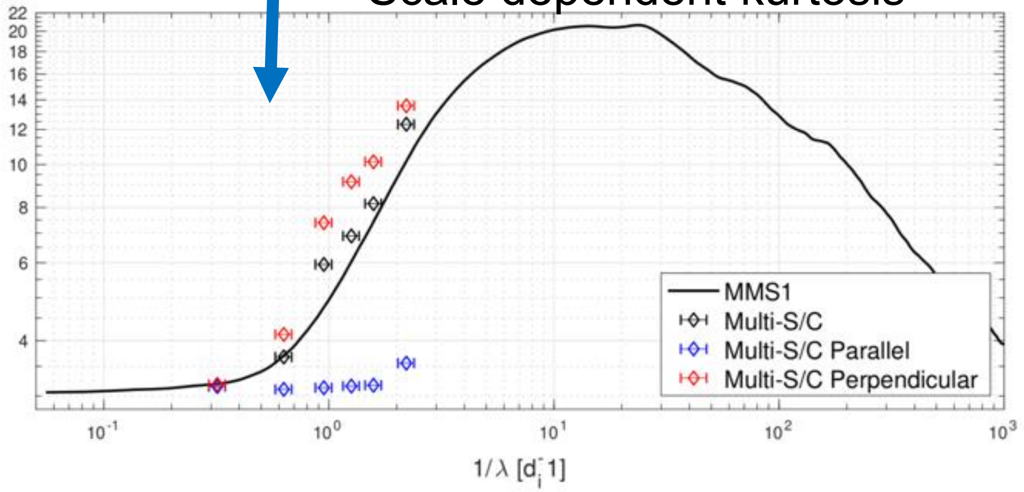
Maximum observed at ~ 65^o

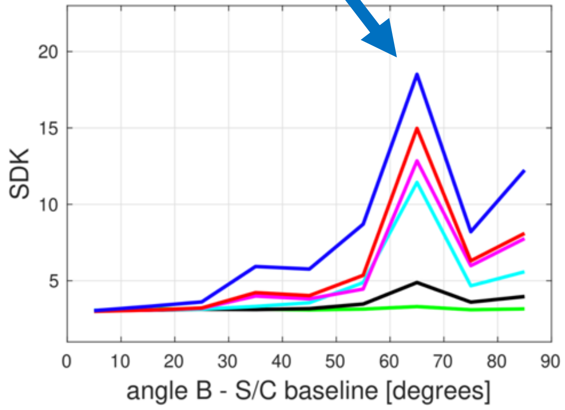
Current sheets predominantly perpendicular to B

Increased intermittency perpendicular to B

Scale dependent kurtosis





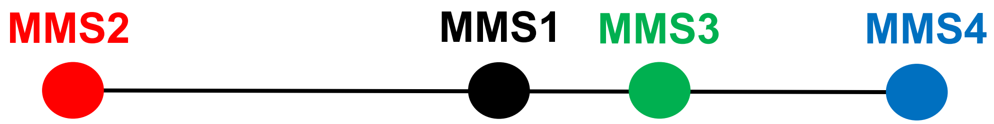


Chasapis et al. ApJ 2020

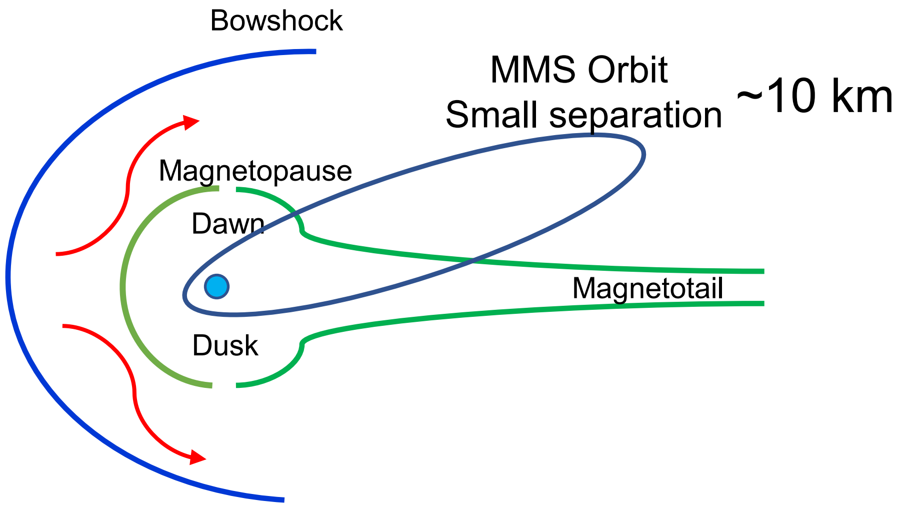
Variable separation - Tail

The MMS spacecraft can be arranged in a colinear configuration

The spacecraft slowly drift apart, increasing the separation on each orbit

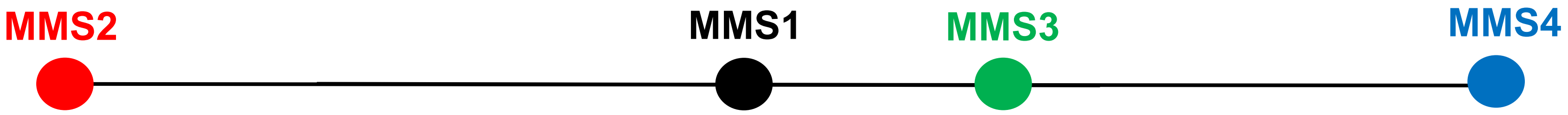


- Small to large separation during the tail season

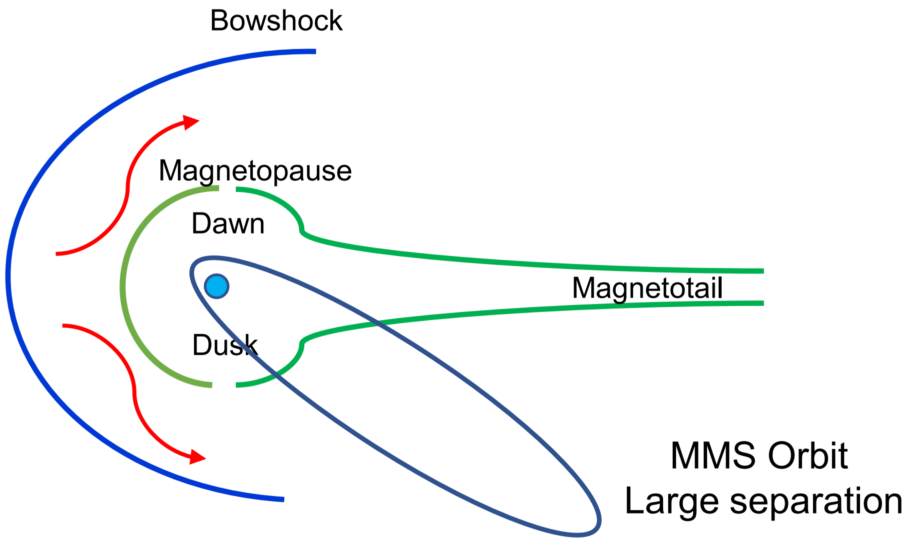


The MMS spacecraft can be arranged in a colinear configuration

The spacecraft slowly drift apart, increasing the separation on each orbit



- Small to large separation during the tail season

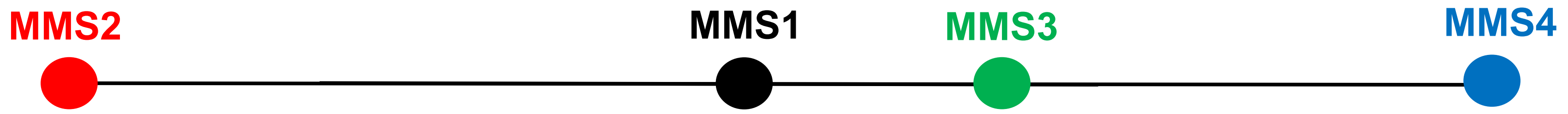


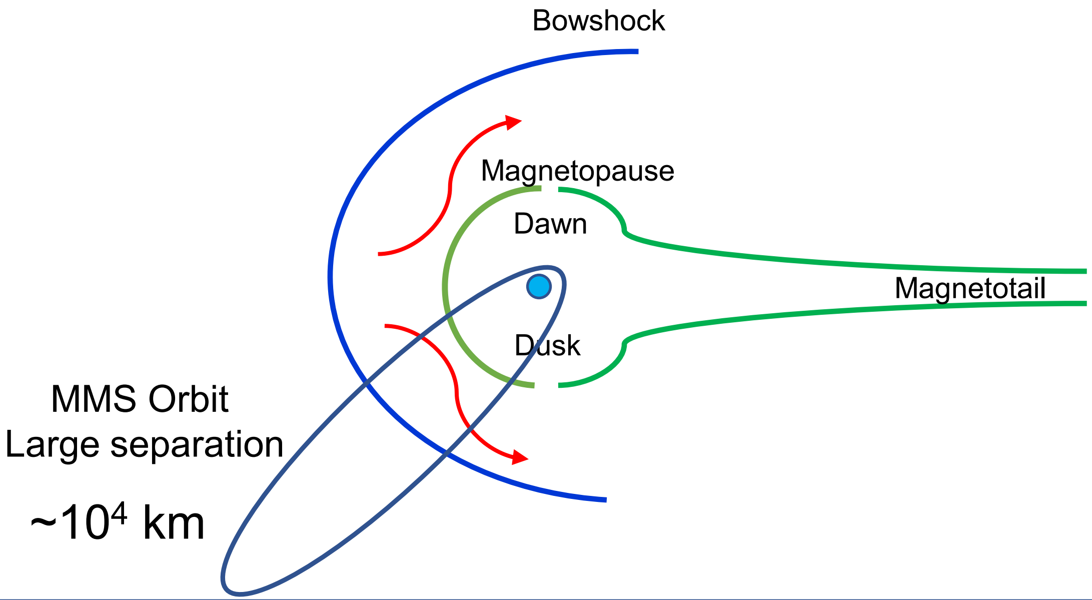
~10^4 km

Variable separation - Dayside

The MMS spacecraft can be arranged in a colinear configuration

The spacecraft slowly drift apart, increasing the separation on each orbit



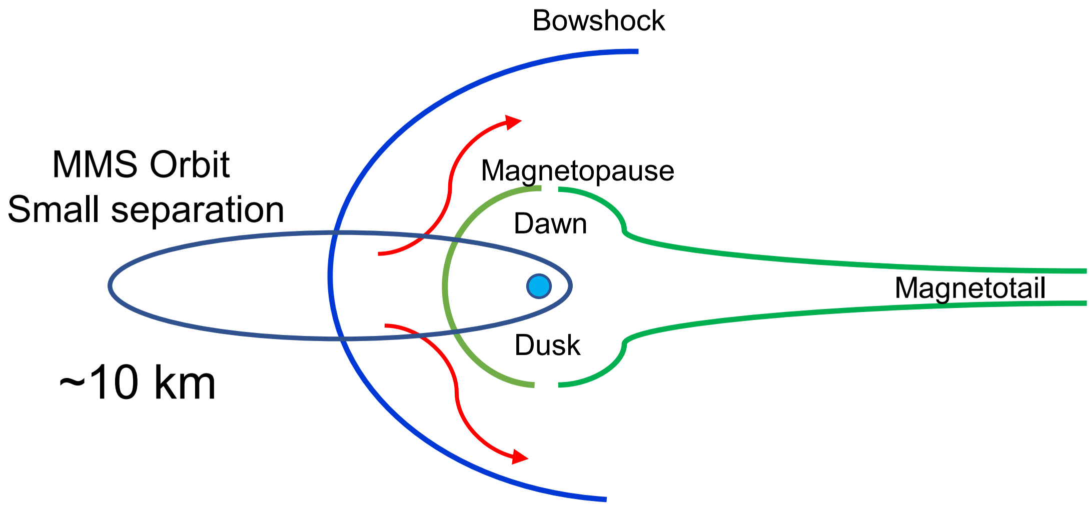


- Small to large separation during the tail season
- Large to small separation during the following dayside season

Variable separation - Dayside

The MMS spacecraft can be arranged in a colinear configuration

The spacecraft slowly drift apart, increasing the separation on each orbit

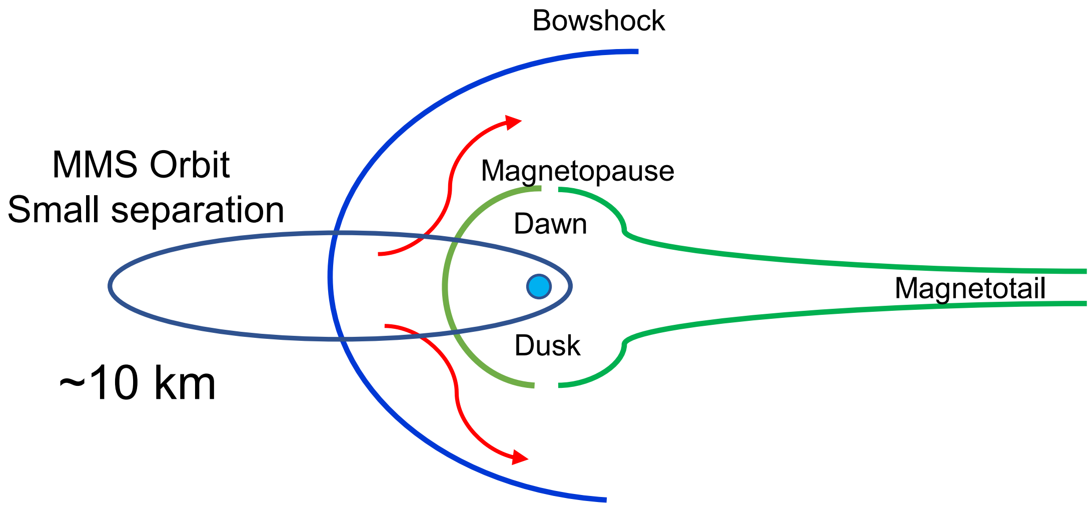


- Small to large separation during the tail season
- Large to small separation during the following dayside season

Variable separation - Dayside

The MMS spacecraft can be arranged in a colinear configuration

The spacecraft slowly drift apart, increasing the separation on each orbit

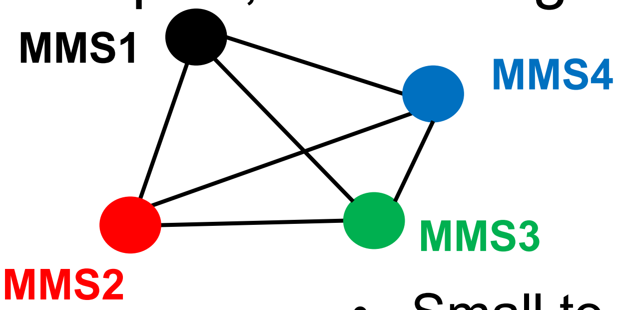


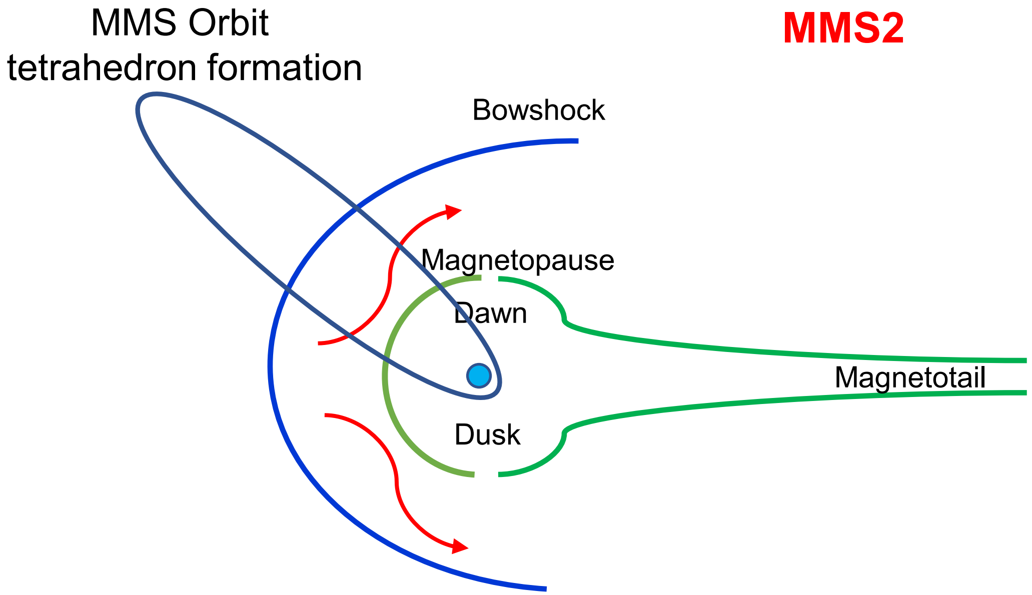
- Small to large separation during the tail season
- Large to small separation during the following dayside season *with one trailing spacecraft

Variable separation - Dayside

The MMS spacecraft can be arranged in a colinear configuration

The spacecraft slowly drift apart, increasing the separation on each orbit

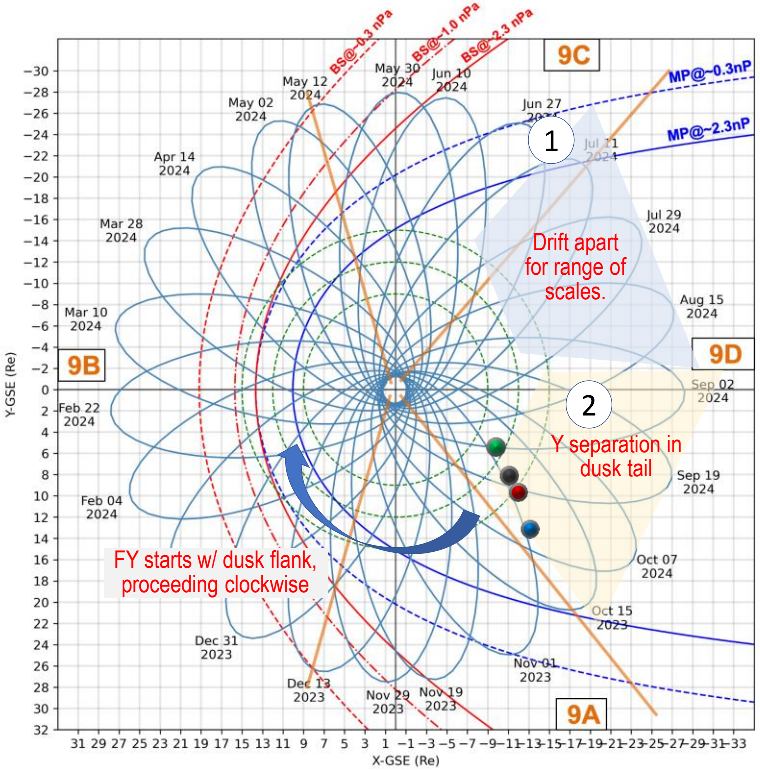




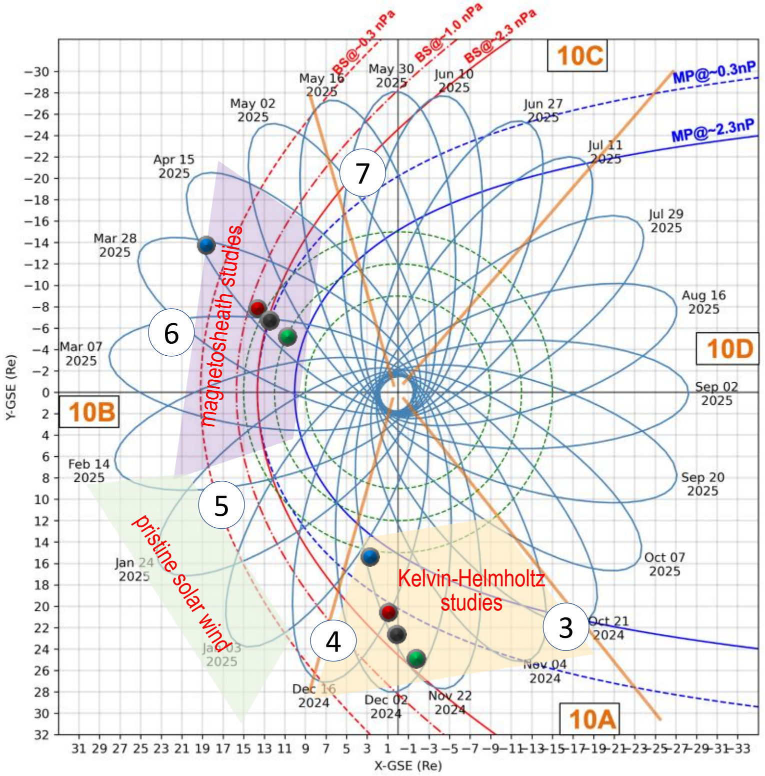
- Small to large separation during the tail season
- Large to small separation during the following dayside season *with one trailing spacecraft
- Back to tetrahedron for the next phase

Future Plans

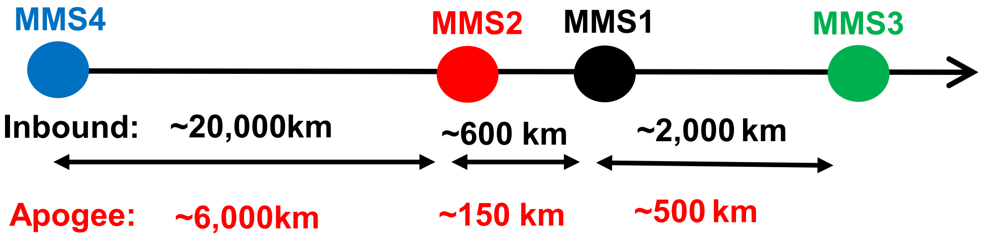
FY24 – Year 9



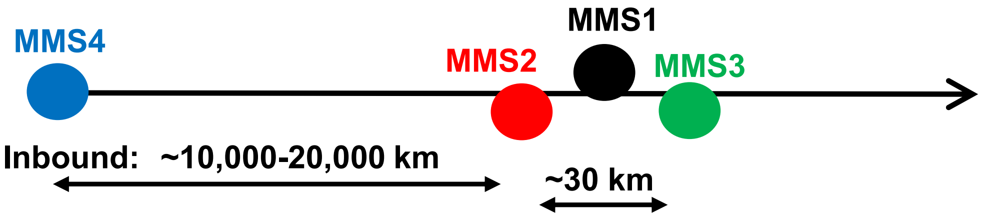
FY25 – Year 10



Stages 2-5: logarithmic spacing with varying scale along track up to ~10^4km



Stage 6: MMS1-3 close triangle at ~80km, while MMS4 trails by ~10^4km



- **Colinear Configuration:** separation varying up to several thousand km
- Science opportunities: Tail, Flanks, Solar wind, Magnetosheath & Magnetopause:
- Multi-Scale observations of near-Earth space