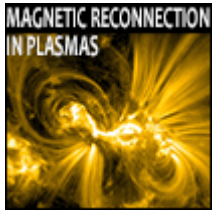
NORDITA, Stockholm



Magnetic Reconnection in Plasmas

Characterization of magnetic discontinuities from MHD to sub-proton scales

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Outline

- **Examples of magnetic discontinuities on different scales in the solar wind**

- **Statistical analysis of magnetic discontinuities at sub-proton scales from the dataset** *Cluster: FGM + STAFF, 20 January 2007 (12:00–14:00 UT)*

- **A simple model for micro-discontinuities**

- **Conclusions**

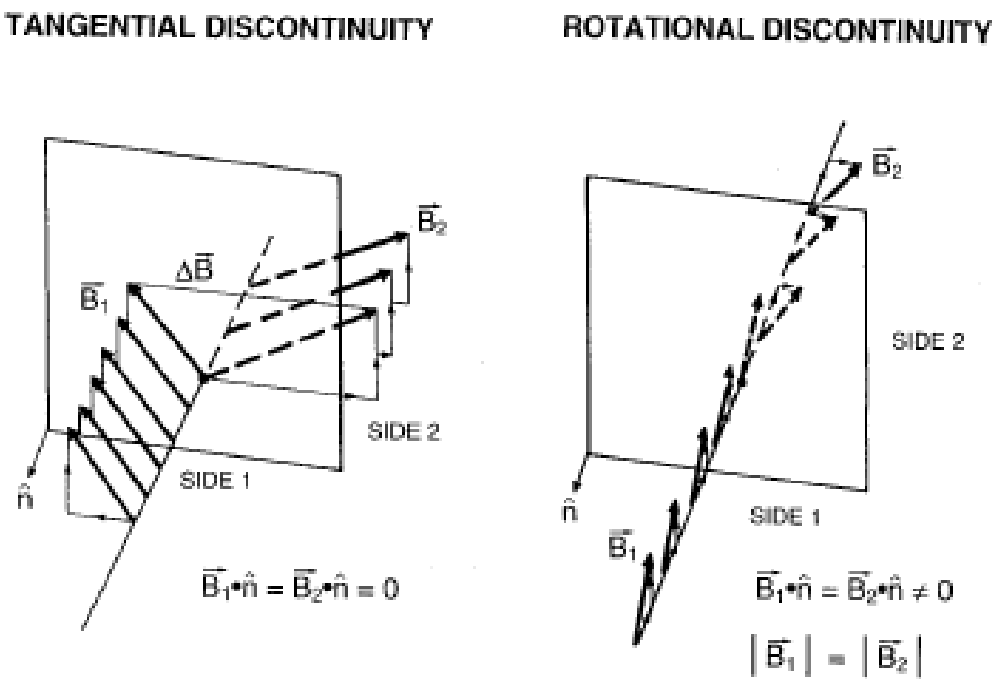
A brief overview on magnetic discontinuities

A discontinuity is an abrupt change in magnetic field vector that can be described by

$$\left|\Delta \mathbf{B}\right| = \left|\mathbf{B}(s+\Delta s) - \mathbf{B}(s)\right|$$

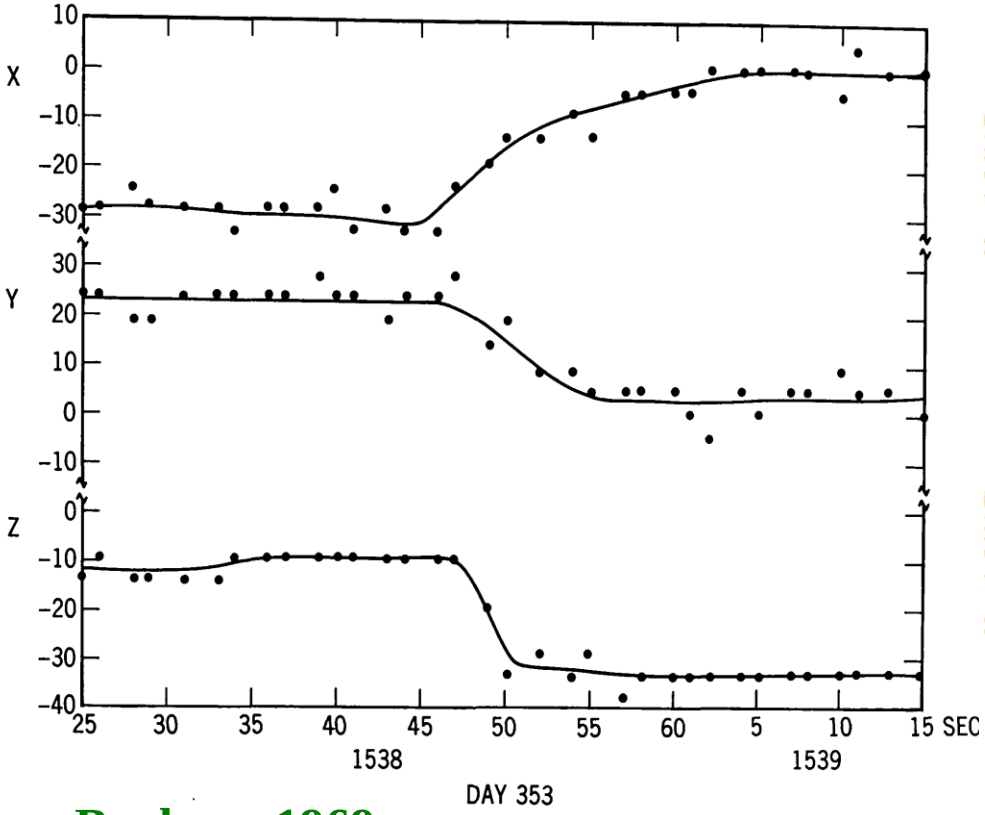
Pioneer works of ***Burlaga,* 1969** and ***Tsurutani and Smith* , 1979**

In ideal MHD, discontinuities are classified as tangential, contact, rotational, and shocks, depending on how mass, momentum and energy are transported across them



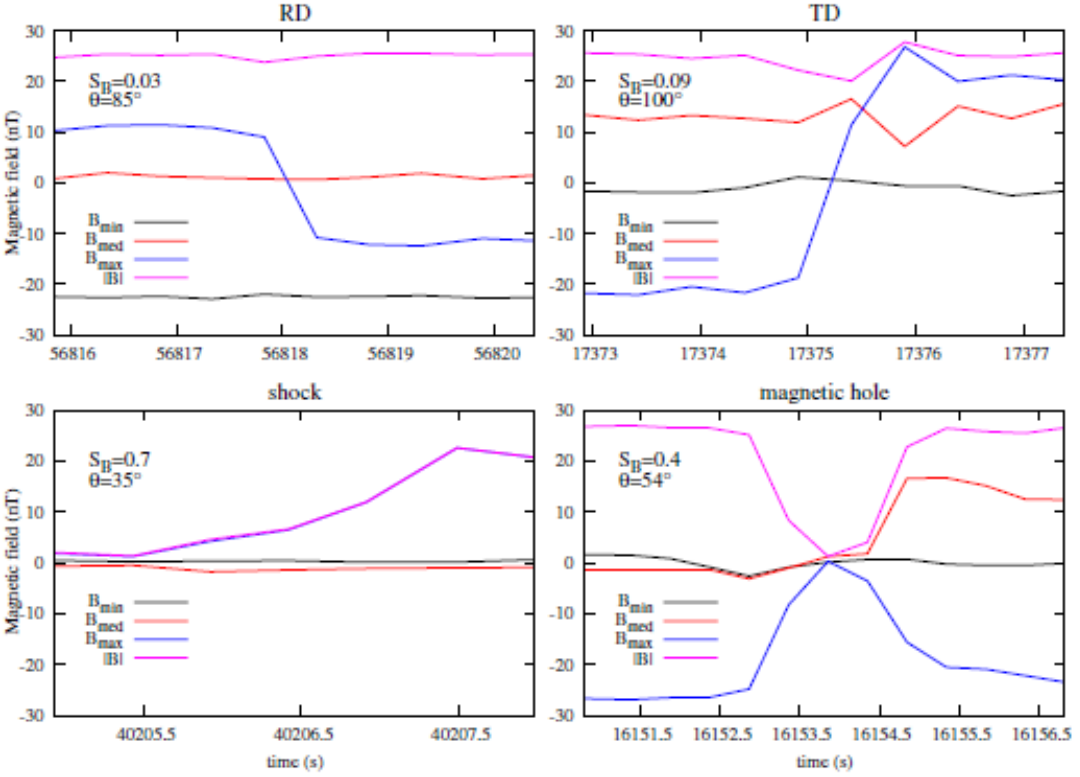
Magnetic discontinuities in the solar wind

Scales larger than the proton skin depth (several minutes)



Burlaga, 1969

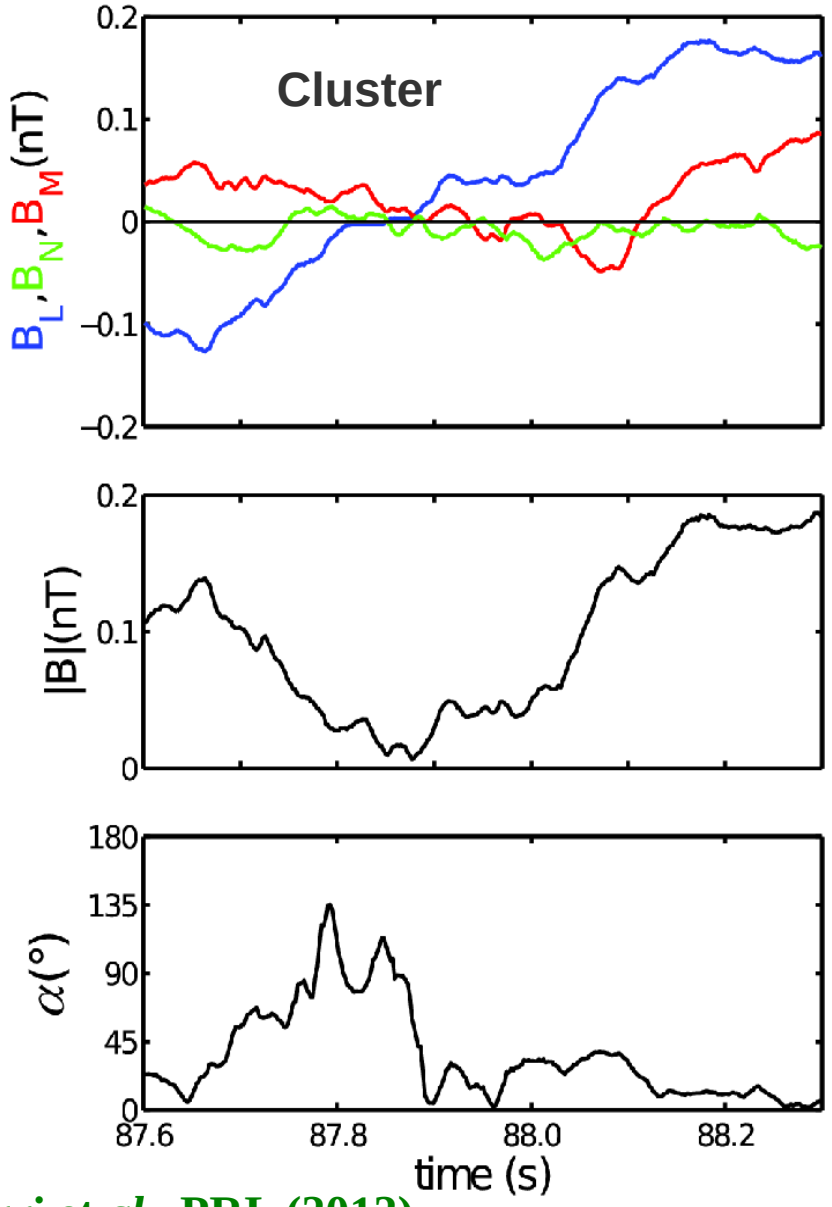
Scales of the order of the proton skin depth (few seconds)



Greco & Perri, 2014

Magnetic discontinuities in the solar wind

Spatial scales 200 km



Perri et *al.*, PRL (2012)

Spatial scales 100-200 km

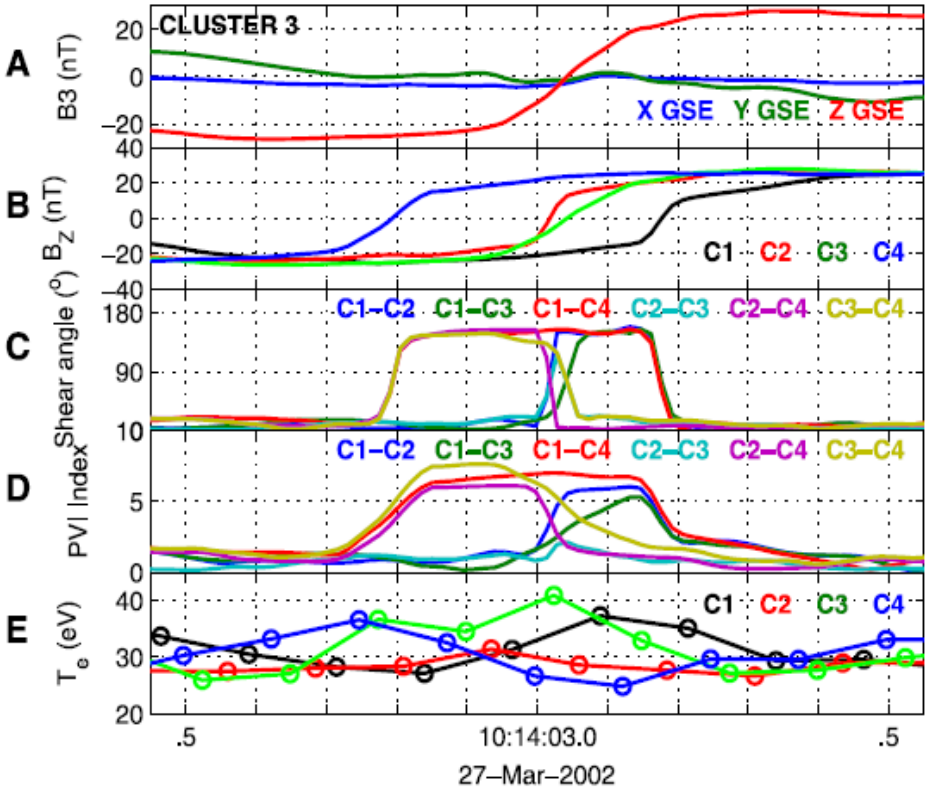
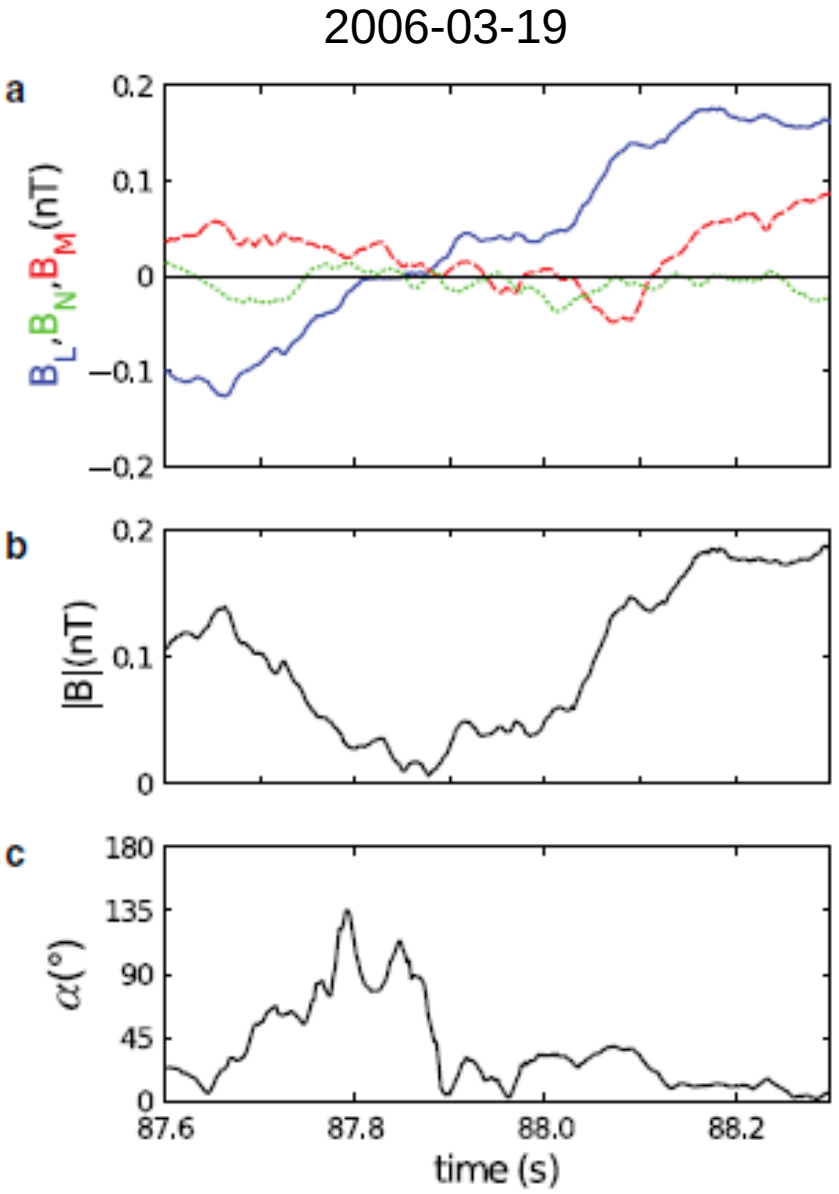


Figure 2. Example of a detected current sheet. Panel (A) shows the magnetic field measured by *Cluster*3. Panel (B) shows the *z*-component in GSE coordinates for the four spacecraft. Panels (C) and (D) show the measured angle of the magnetic field vectors and the PVI index for each pair of spacecraft. Panel (E) shows the estimated electron temperature for each spacecraft.

Chasapis et *al.*, ApJ (2015)
[few talks later]

At kinetic (sub-proton) scales in solar wind



From *Perri* et al., PRL 2012

STAFF-Cluster 2 (450 vec/s of sampling rate) observation of a thin current sheet that lasts 0.4 sec (even smaller structures have been observed up to 40 km).

The magnetic field components in the local current sheet reference frame computed via a minimum variance analysis: the B_L component is along the current sheet and shows a large rotation (blue solid line), B_N is parallel to the normal to the current sheet and is close to zero (green dotted line), and B_M is the out-of-plane component (red dashed line) whose bipolar signature suggests the presence of a Hall magnetic field generated by in-plane currents.

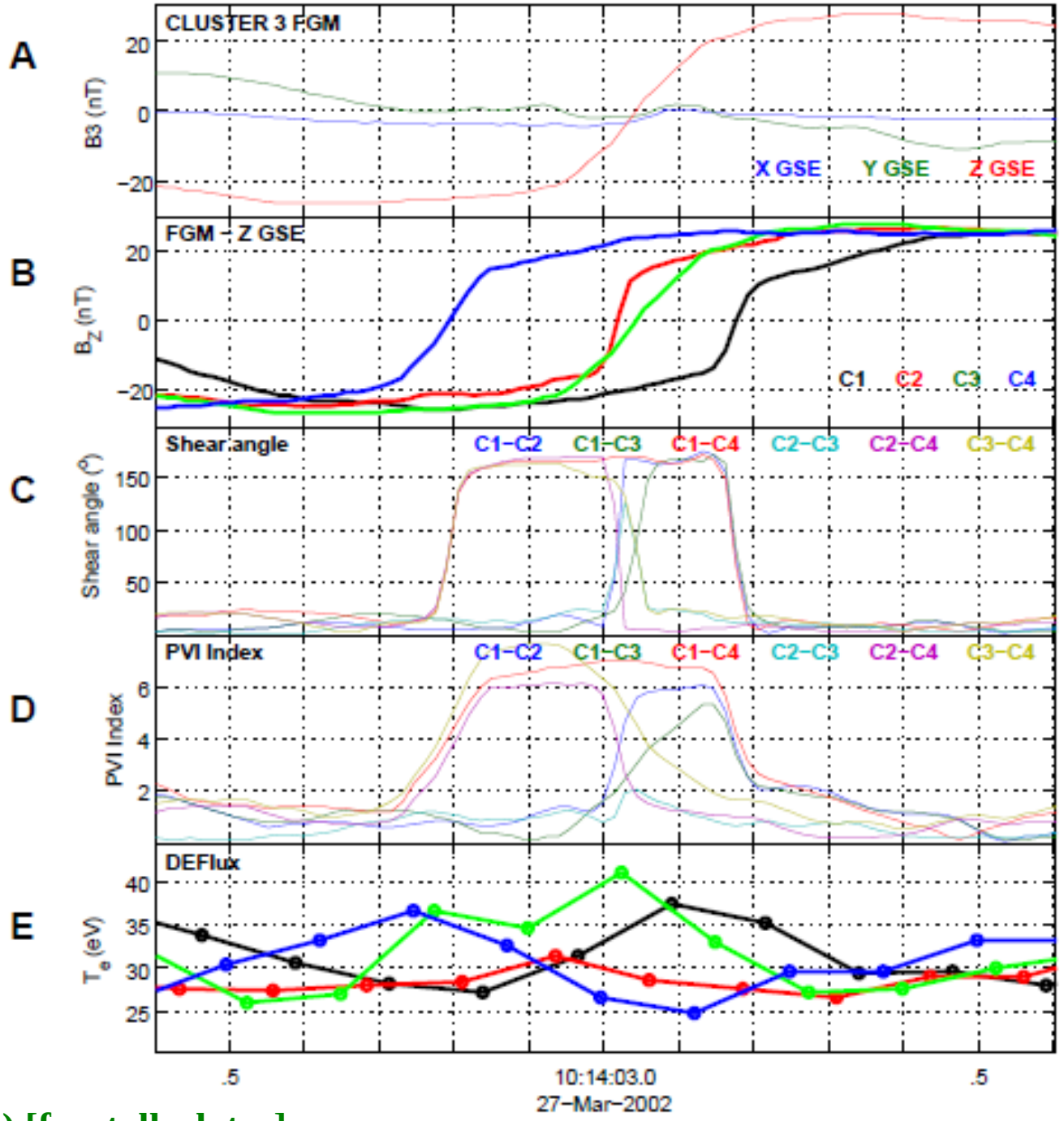
Reconnection may occur within the observed current sheets although such process cannot be identified in the data shown here.

Earth's magnetosheath downstream of the quasi-parallel shock.

The selected structures last between 0.25 and 4 seconds

A local increase in electron temperature was observed for high shear angles

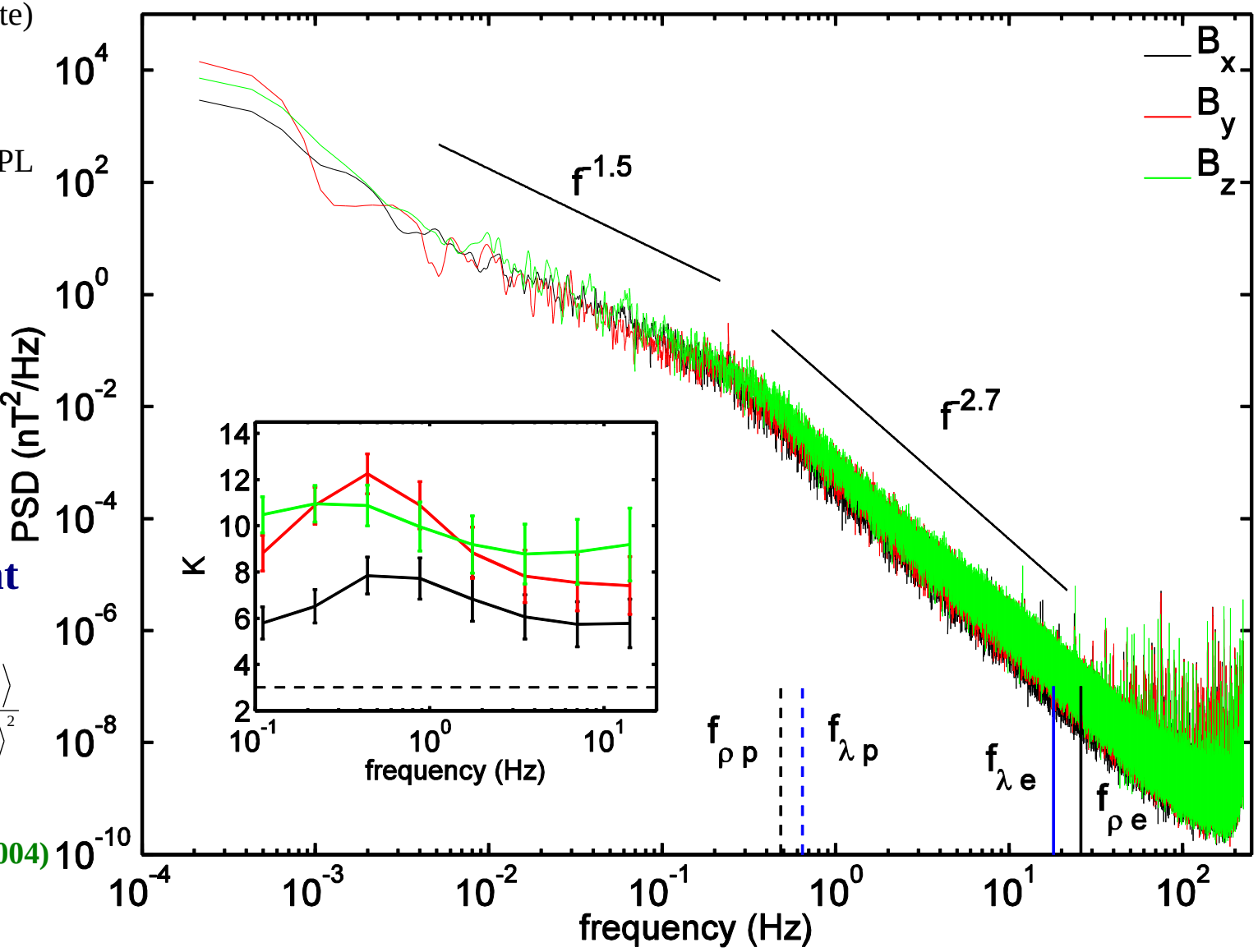
The high values of the shear angle and the bipolar signature in B_y make such as current sheets likely candidates for reconnection.
The local electron temperature increase could be considered evidence of local dissipation and in such a case would support such a suggestion.



From Chasapis et *al.*, ApJ (2015) [few talks later]

Small scale intermittent turbulence

- Cluster: FGM + STAFF (450 Hz sampling rate)
- 20 January 2007 (12:00–14:00 UT)
- GSE system (Yordanova et al., EPL 2015)



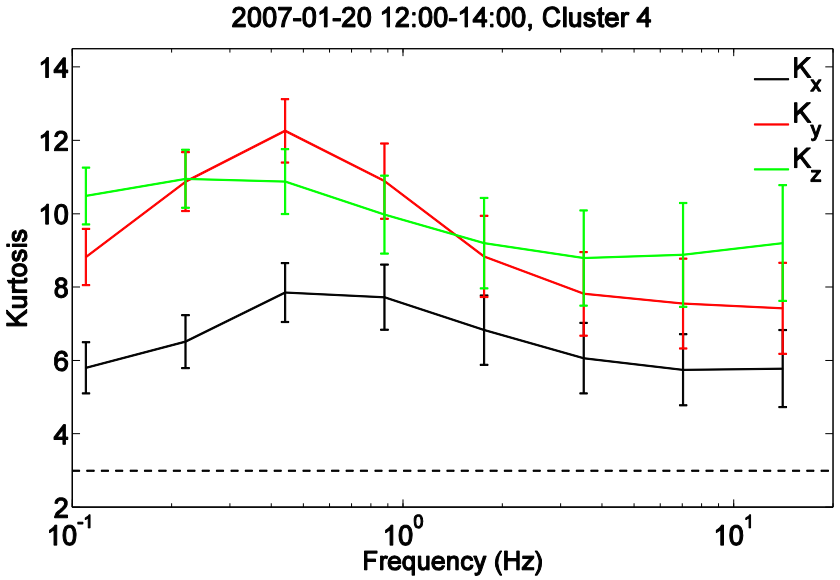
Scale dependent Kurtosis

$$K_i(\tau) = \frac{\left\langle \left(B_i(t+\tau) - B_i(t)\right)^4 \right\rangle}{\left\langle \left(B_i(t+\tau) - B_i(t)\right)^2 \right\rangle^2}$$

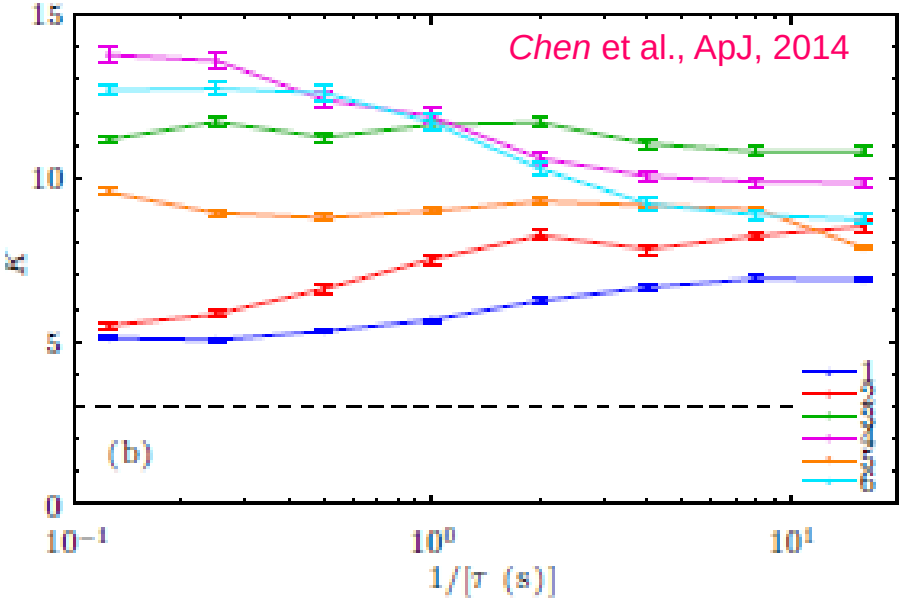
Convergence test

Dudok de Wit, PRE (2004)

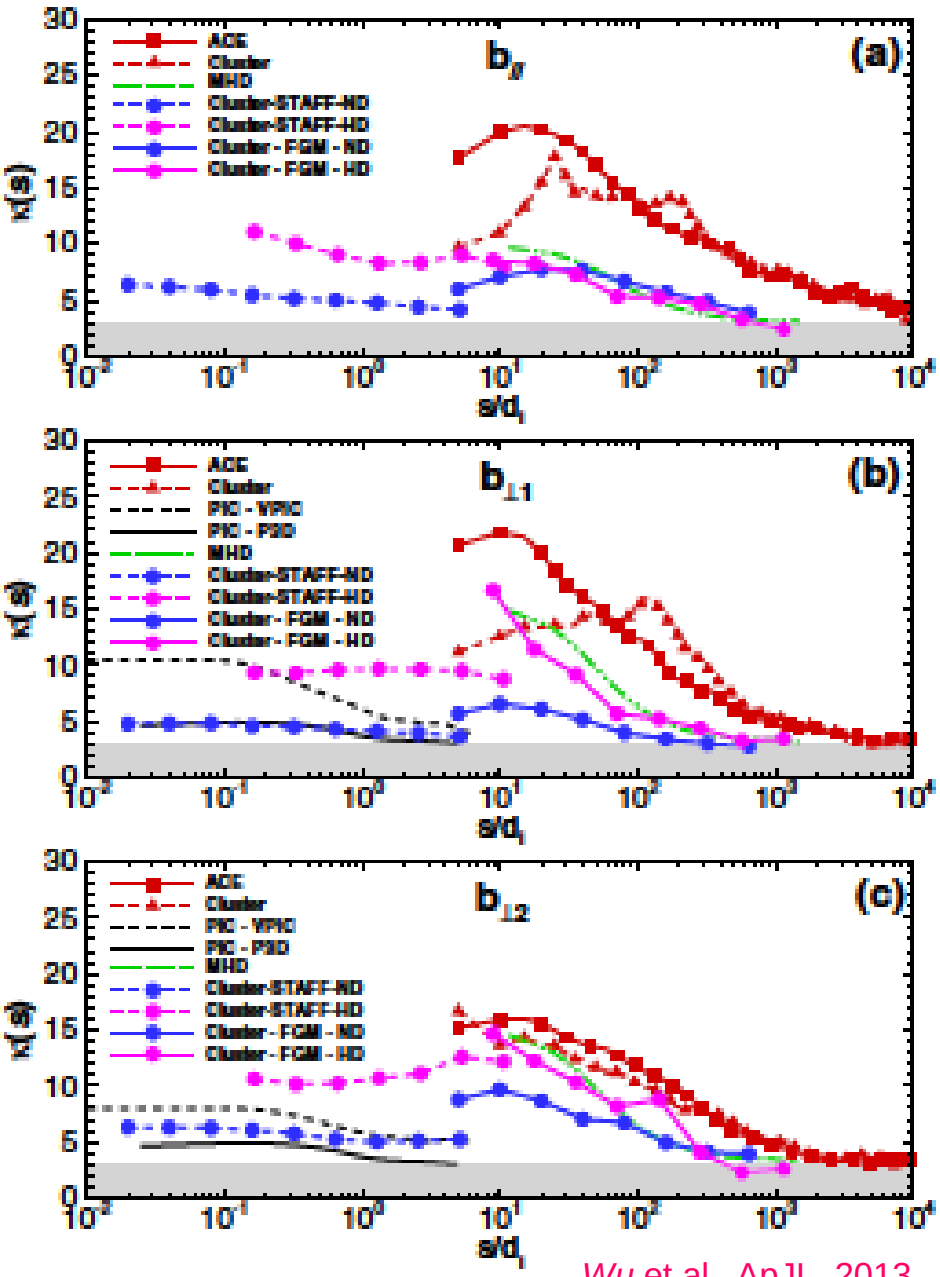
Scale dependent kurtosis (not fully understand yet): MHD, PIC sim, SW comparison



small scales



small scales



Wu et al., ApJL, 2013

Data from the BMSW instrument of the Plasma-F experiment on the *Spektr-R* spacecraft were used at 32 Hz of sampling

Coherent structure detection

Partial Variance of Increments (PVI)

$$\mathrm{PVI}(t,\tau) = \frac{|\Delta \mathbf{B}|^2}{\langle |\Delta \mathbf{B}|^2 \rangle}$$

Greco *et al.*, GRL (2008)

where $\Delta \mathbf{B}(t,\tau) = \mathbf{B}(t+\tau) - \mathbf{B}(t)$ along 1D path

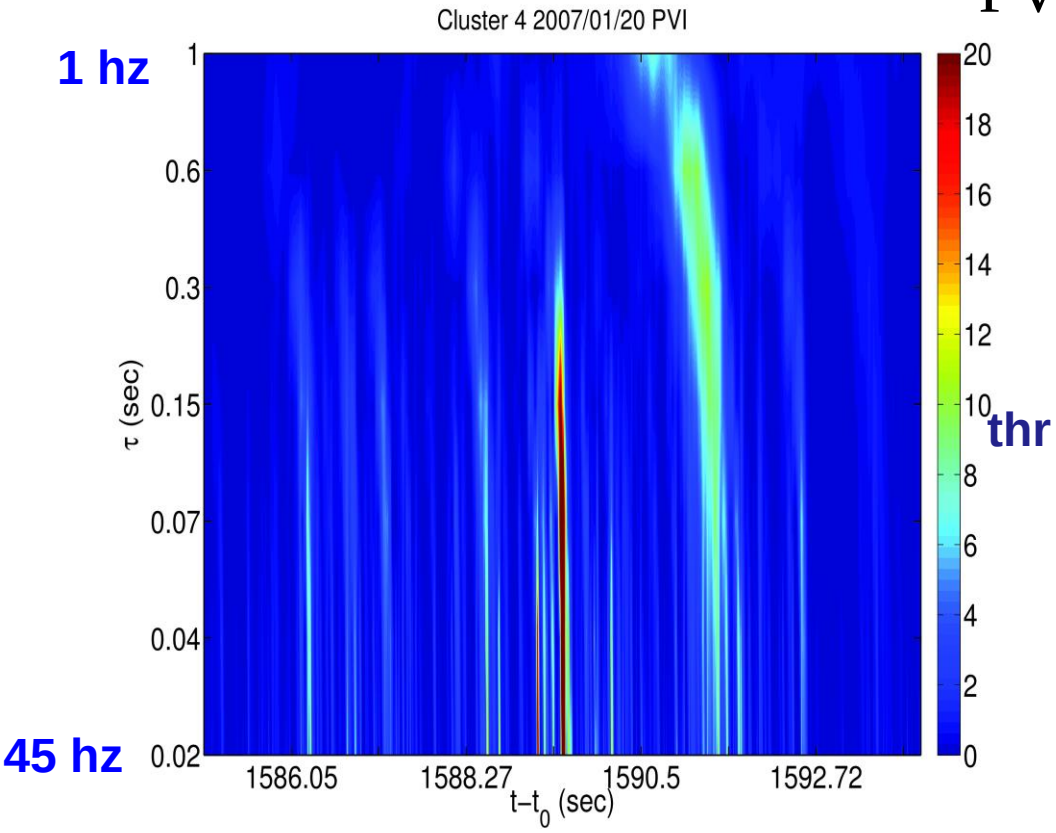
PVI selects regions containing discontinuities/current sheets (Event above threshold=magnetic structure. For each threshold, a number of discontinuities can be localized and "counted"**)**
[Servidio *et al.*, JGR (2011), Greco *et al.*, ApJ (2012), X. Wang *et al.*, APJL (2013), L. Zhang *et al.*, APJ (2015), ...]

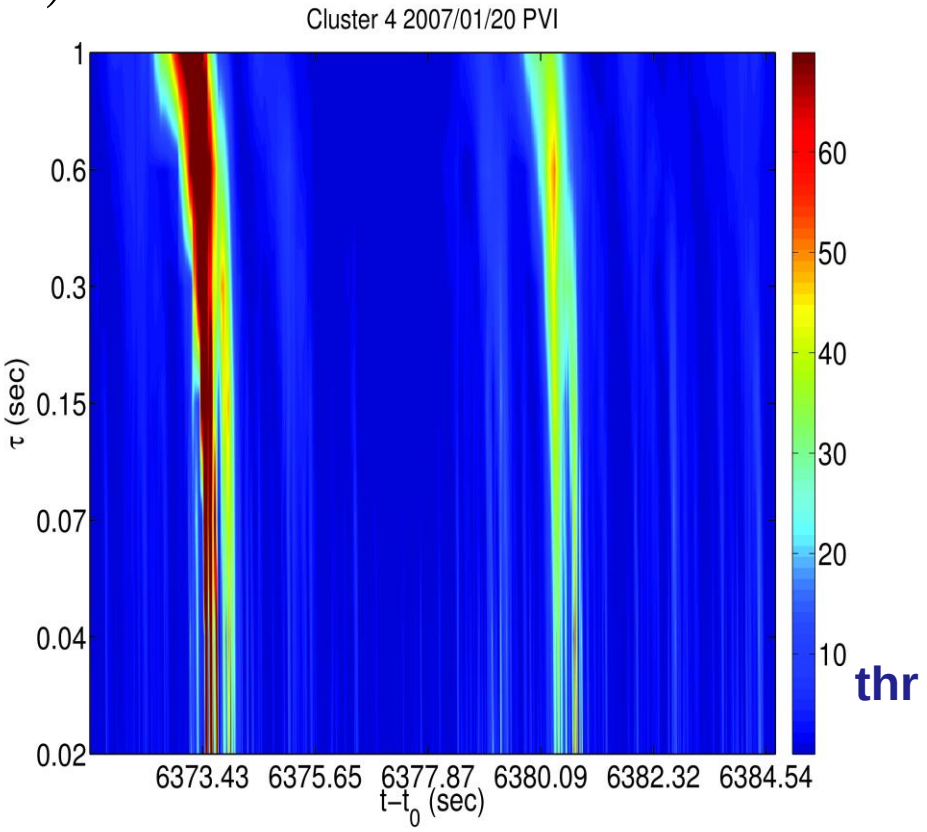
Similar to Local Intermittency Method, Phase Coherence Method (selected parts of a data set are contributing to non-Gaussian statistics; kurtosis provides complementary global information about non-Gaussianity at different scales.
[Greco & Perri, ApJ (2014)]

High PVI values might correspond to local reconnection events, sites of enhanced heating, and non-homogeneous kinetic effects (see Servidio talk)**[Osman et al., ApJ (2011), Osman *et al.*, PRL (2014), Chasapis *et al.*, ApJ (2015)]**

PVI scalogram

$$\mathrm{PVI}(t,\tau)$$





Examples of structures persistent down to sub-proton scales

intermittency

Current sheets on the order of the proton skin depth (or bigger) possibly break up into smaller subproton current sheets

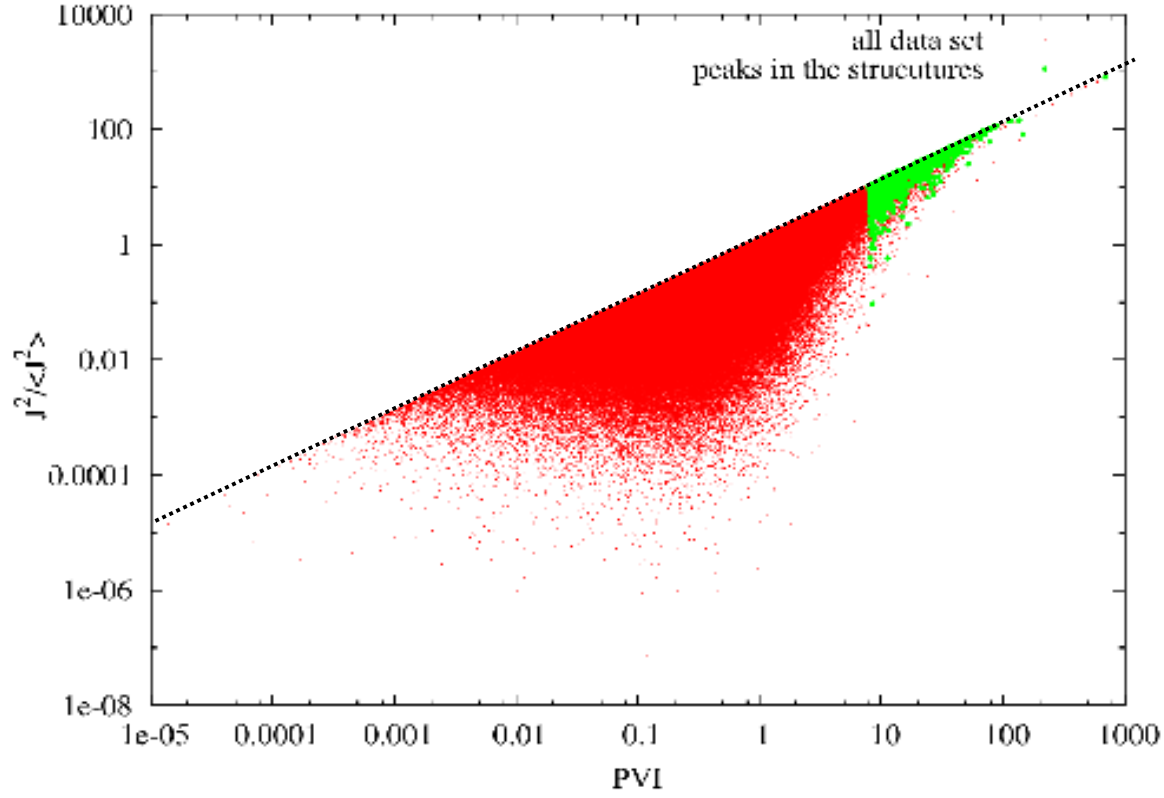
Current Density

"Reduced current density"

$$\mu_0 \mathbf{j} = \nabla \times \mathbf{B} \longrightarrow J_y(t) \sim -\frac{B_z(t+\tau) - B_z(t)}{(-V_{SW}\tau\mu_0)}$$

$$J_z(t) \sim \frac{B_y(t+\tau) - B_y(t)}{(-V_{SW}\tau\mu_0)} \qquad \tau \to 0$$

$$\frac{J^2}{\langle J^2 \rangle} \propto \Delta B_z^2 + \Delta B_y^2, \text{ while } PVI \propto \Delta B_x^2 + \Delta B_y^2 + \Delta B_z^2$$

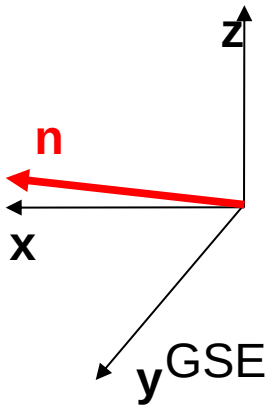


The better correlation is between the two quantities, the better evaluation is in computing the reduced current from a single satellite

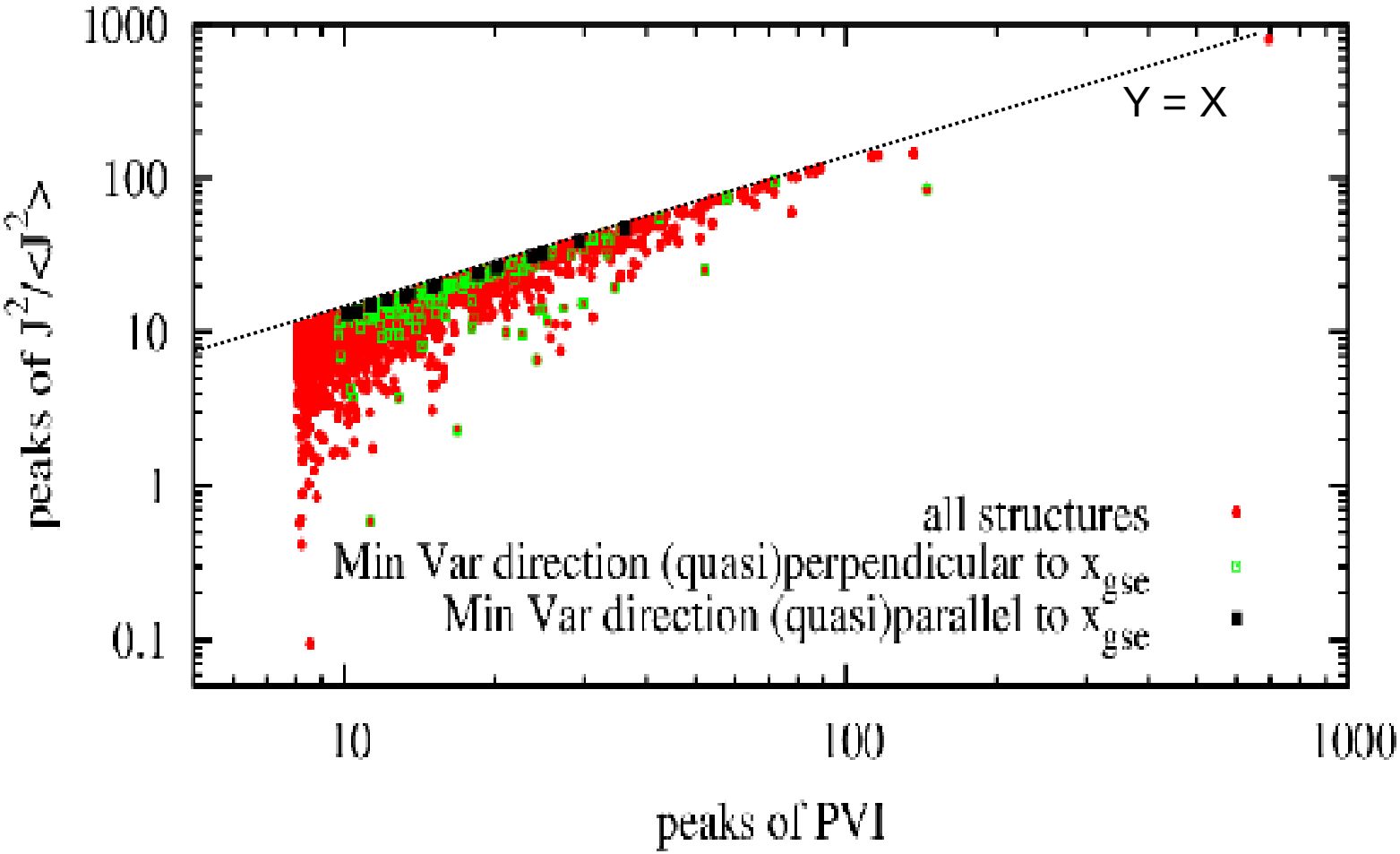
Estimating the current density ...

Sonnerup and Cahill (1967)

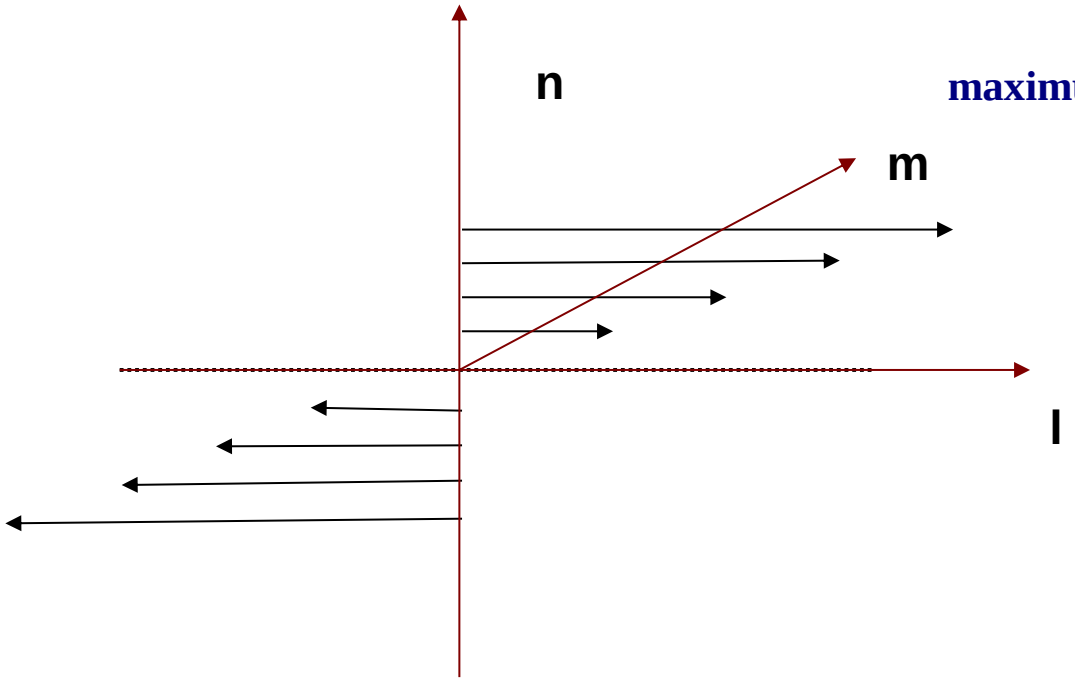
Minimum Variance direction *n*



If we look inside the structures,
there is a further better correlation for those structures that have the minimum variance direction *n* parallel to X_{GSE}



A simple 1D current sheet



(*l*, *m*, *n*)

maximum, medium and minimum variance directions

Harris sheet

$$B_m = B_n = 0$$
$$B_l = B_{max}(n)$$

$$B_{max}(n) = B_0 \tanh(n/\lambda)$$

J in the GSE

$$J_x(x) = 0$$

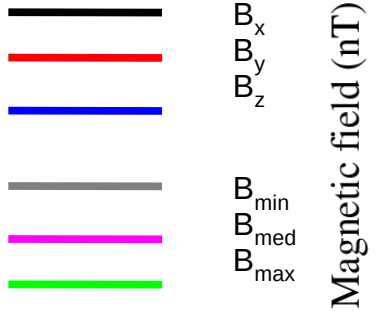
$$J_y(x) \propto \cos\alpha\cos\gamma \frac{B_0}{\lambda} \frac{1}{\cosh(x/\lambda)^2}$$

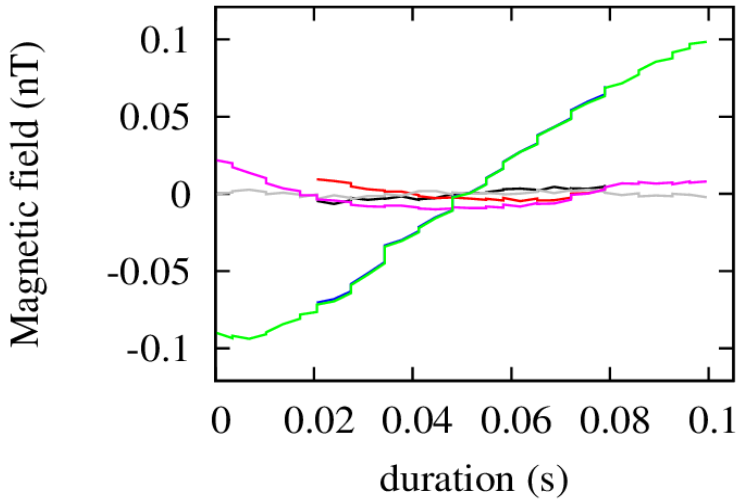
$$J_z(x) \propto \cos\alpha\cos\beta \frac{B_0}{\lambda} \frac{1}{\cosh(x/\lambda)^2}$$

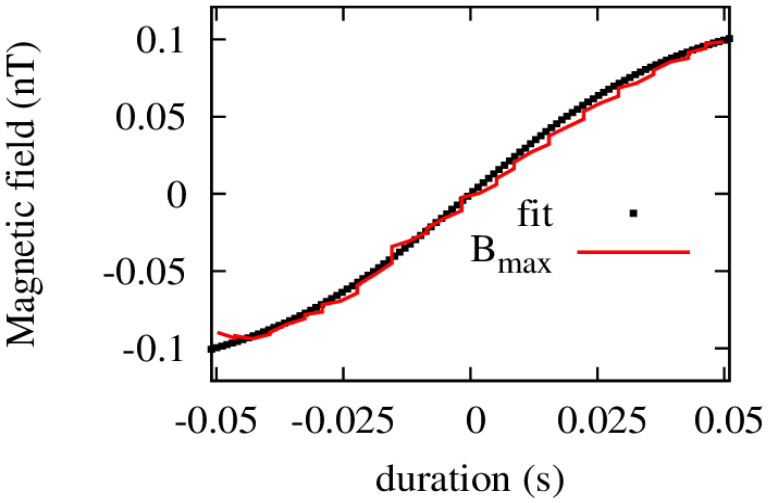
Where α is the angle between **n** and $\mathbf{x}_{GSE}$
γ and β are the angles between
B_{max} and z_{GSE} and B_{max} and y_{GSE}, respectively

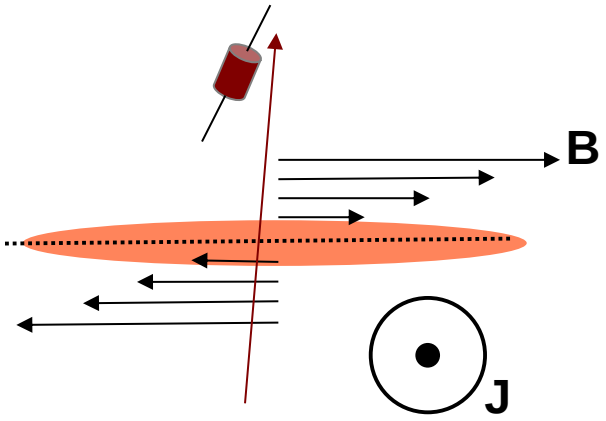
Harris current sheets

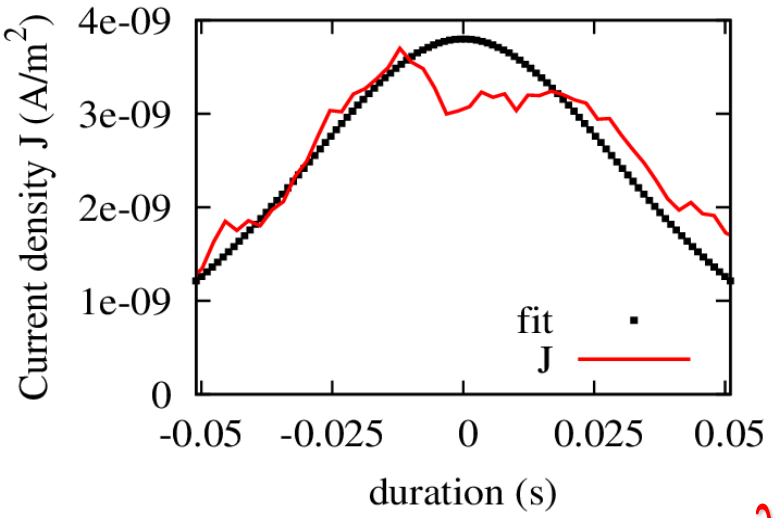
An example where the two reference systems (GSE and MIN VAR) coincide and the sheet is almost 1D











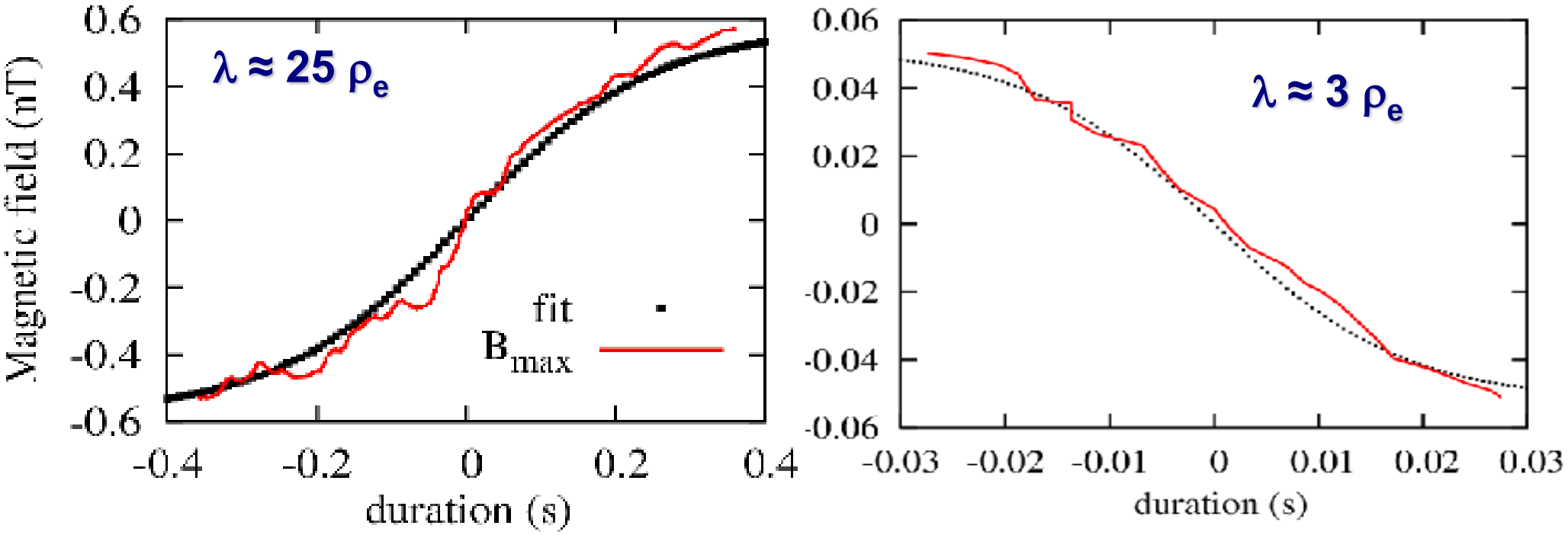
$\alpha \sim 4°$

$$B_{max} \sim 0.12 \tanh(t/0.042)$$

$$J \sim 3.8e\text{-}9/\cosh(t/0.042)^2$$

$\lambda \approx$ 4-5 $\rho_e \approx$ 25 km

Micro current-sheets



The Harris profile persists down to electron scales, in a self similar way

Large & small scale discontinuities
They resemble the result of a secondary tearing instability (in a turbulent medium)
A sheet that generates smaller ones

At this stage, we cannot distinguish between time and spatial evolution.
We have not plasma data at this resolution, but comparison with simulations are possible and could help the understanding

Conclusions

- **Solar wind turbulence is strongly intermittent, characterized by magnetic discontinuities that might be also sites of magnetic reconnection;**

- **Spacecraft observations reveal the presence of discontinuities at scales on the order of the electron Larmor radius. These discontinuities are connected to large scale PVI values, and tend to cluster at small scales;**

- **The strongest discontinuities are related to peaks in the current density, which might be well-estimated, in some circumstances, by single spacecraft techniques;**

- **Some of the smallest scale discontinuities still obey to a kinetic Harris (quasi)equilibrium, motivating further theoretical and numerical studies.**