Laboratoire d'Études Spatiales et d'Instrumentation en Astrophysique

# STATISTICAL ANALYSIS OF SOLAR WIND COHERENT STRUCTURES AT ION SCALES USING MULTI-POINT MEASUREMENTS BY CLUSTER

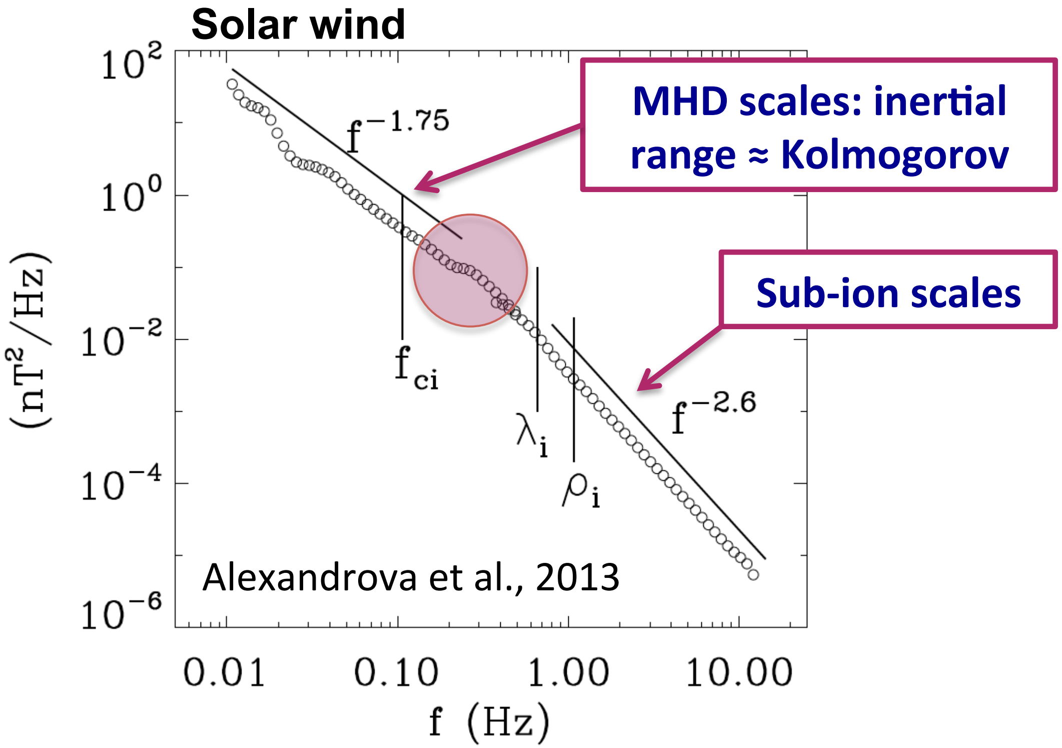
**Denise Perrone**

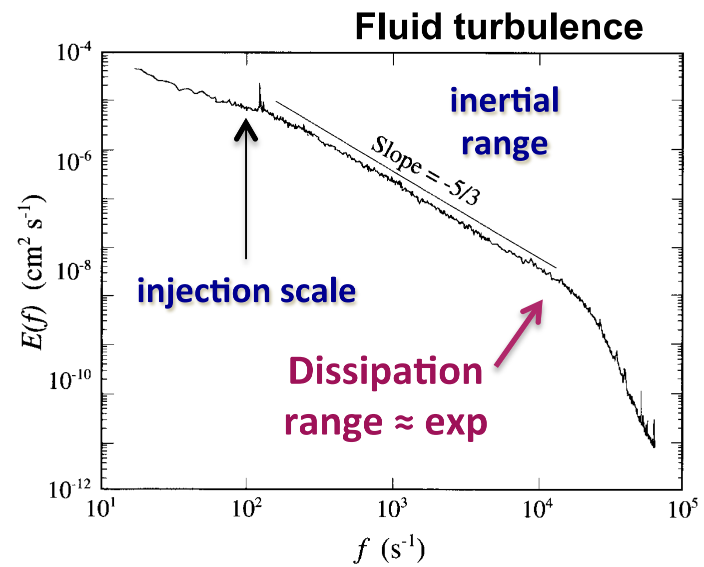
*denise.perrone@obspm.fr*

*O. Alexandrova, V. Racoto,*
*M. Maksimovic, A. Mangeney*

# SOLAR WIND TURBULENCE

*The solar wind as the best natural laboratory to study turbulence*




- Kolmogorov turbulence is observed at MHD scales
- There exists a 'break' close to ion scales ➡ onset of dissipation range (e.g. Leamon+'98,99,00; Smith'06) or starting point of another cascade (e.g Biskamp+'96; Galtier'06; Alexandrova+'08,13)?
- All characteristic time ($f_{ci}$) and spatial ($\rho_i$, $\lambda_i$) scales are observed close to the 'spectral break point'
- End of the turbulent cascade? Dissipation scales?

# SOLAR WIND TURBULENCE

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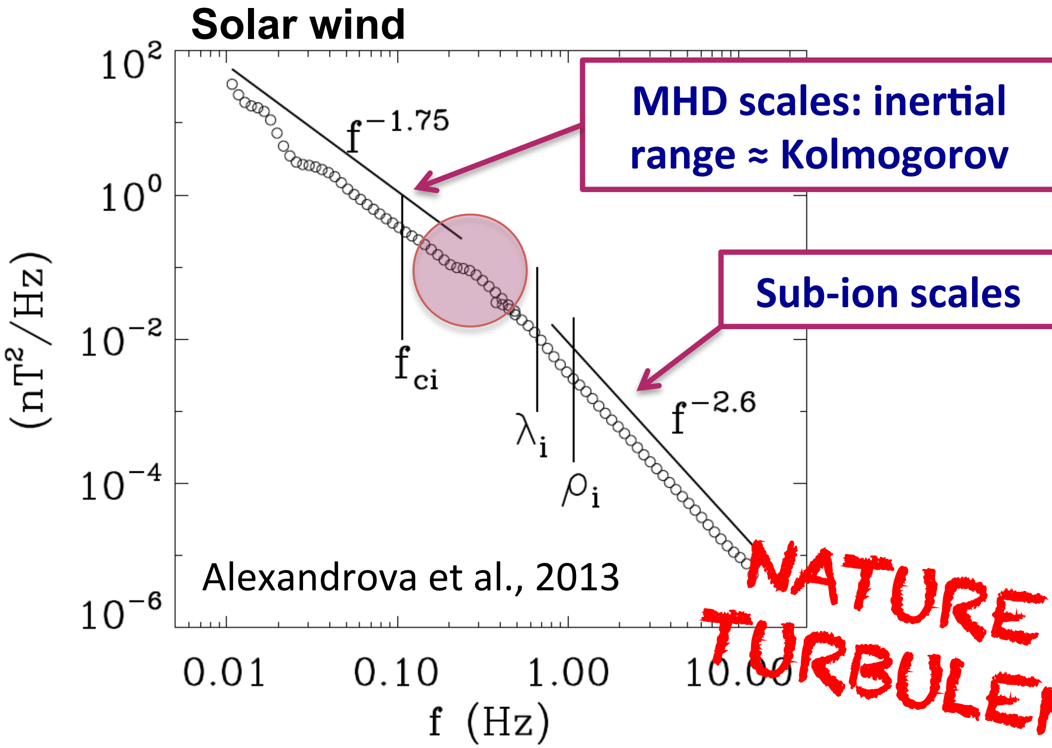


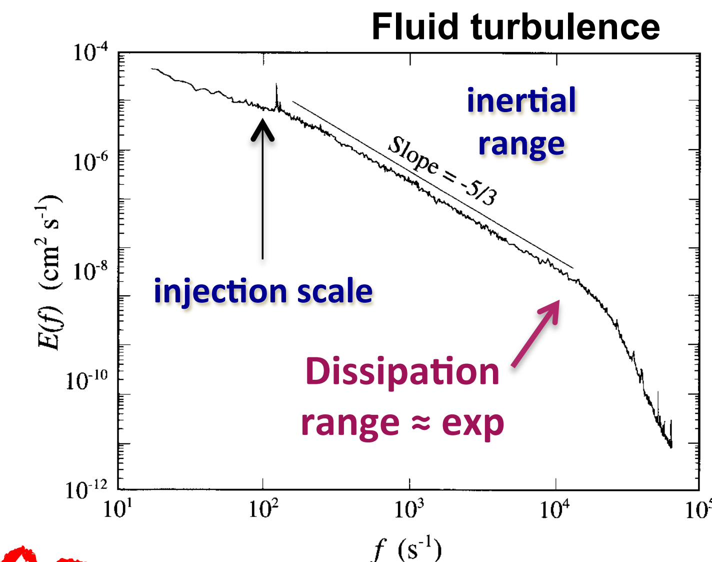



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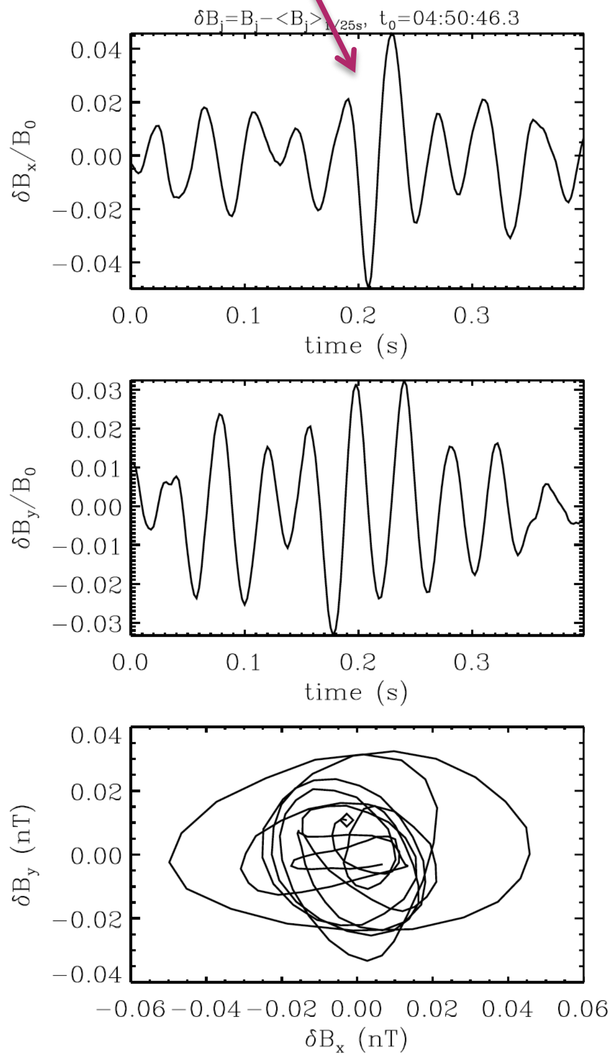
- All characteristic time ($f_{ci}$) and spatial ($\rho_i$, $\lambda_i$) scales are observed close to the 'spectral break point'
- End of the turbulent cascade? Dissipation scales?

# TURBULENCE NATURE: OPEN QUESTION

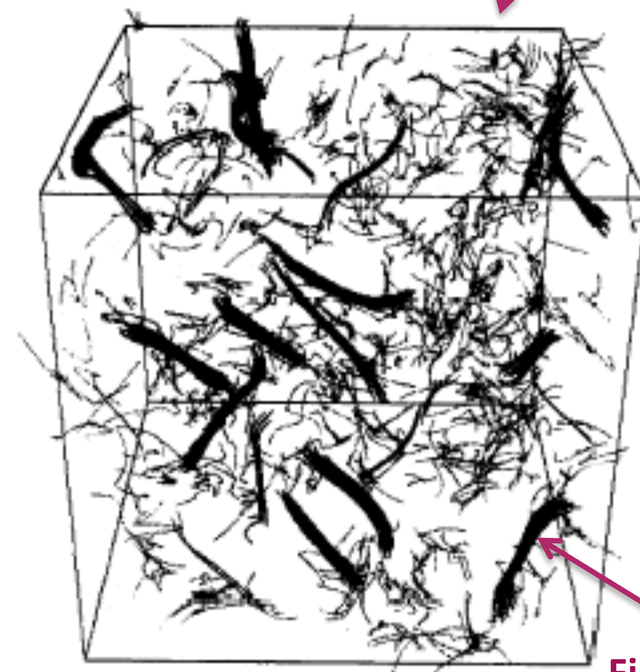
*Mixture of linear waves* *or* *strong turbulence with intermittent coherent structures?*

Lacombe et al., 2014




**In HD turbulence intermittency corresponds to the appearance of coherent structures**

**3D hydrodynamics simulation**



She al., 1991

**Filaments in vorticity field**

- **Intermittency: scale dependent non Gaussianity of turbulent fluctuations**
- **Coherent structures have coupled phases over all scales**
- **Role in dissipation?**

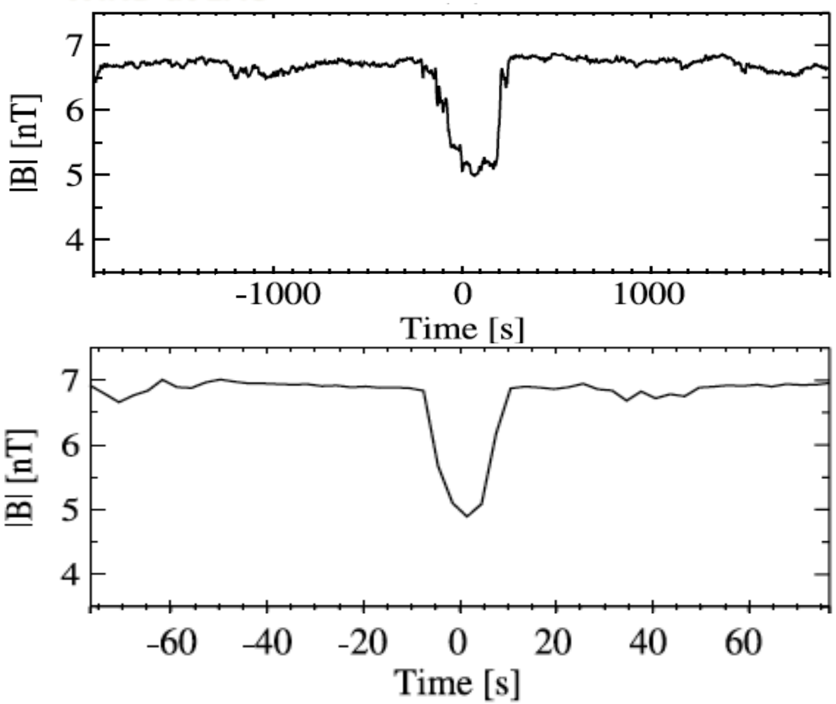
# SOLAR WIND COHERENT STRUCTURES

## Magnetic holes and Solitons

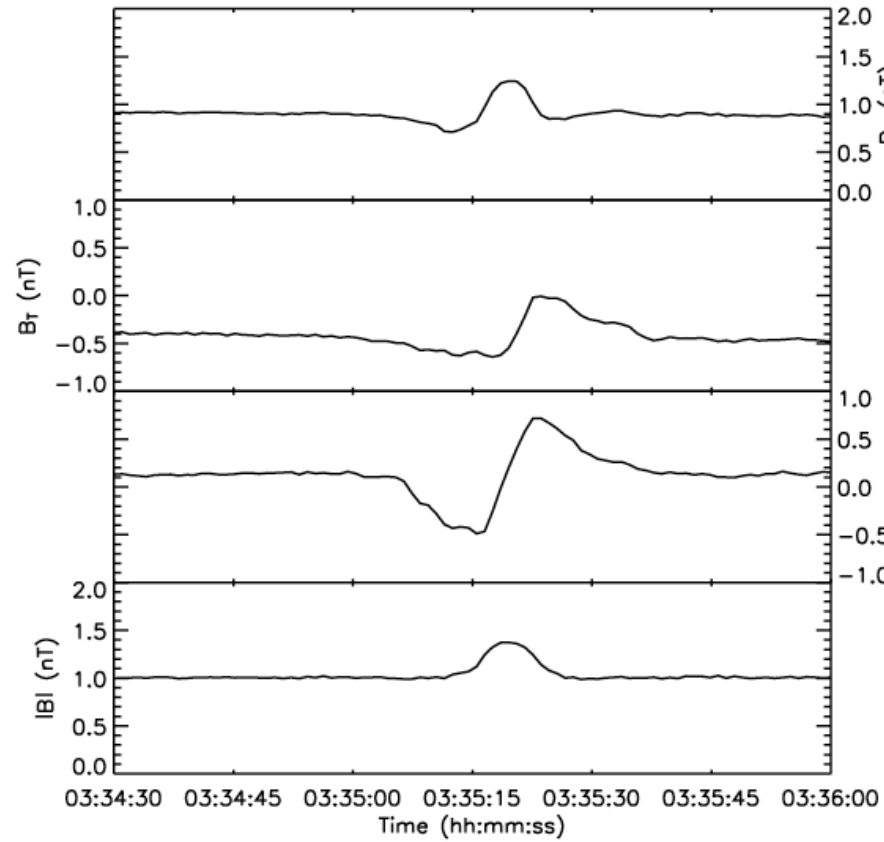
Turner et al (1977)
Baumgartel et al. (1999)

***WIND at 1AU***

Stevens & Kasper (2007)




***ULYSSES at 1.68AU***




Rees et al.(2006)

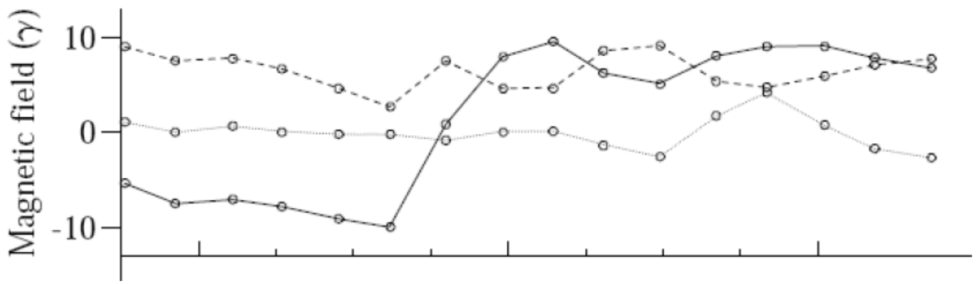
1. ***Localized single impulse in magnetic field magnitude and simultaneous changes in plasma density***
2. ***Propagation perpendicular to the ambient magnetic field, with small velocity***

# SOLAR WIND COHERENT STRUCTURES

## Current sheets

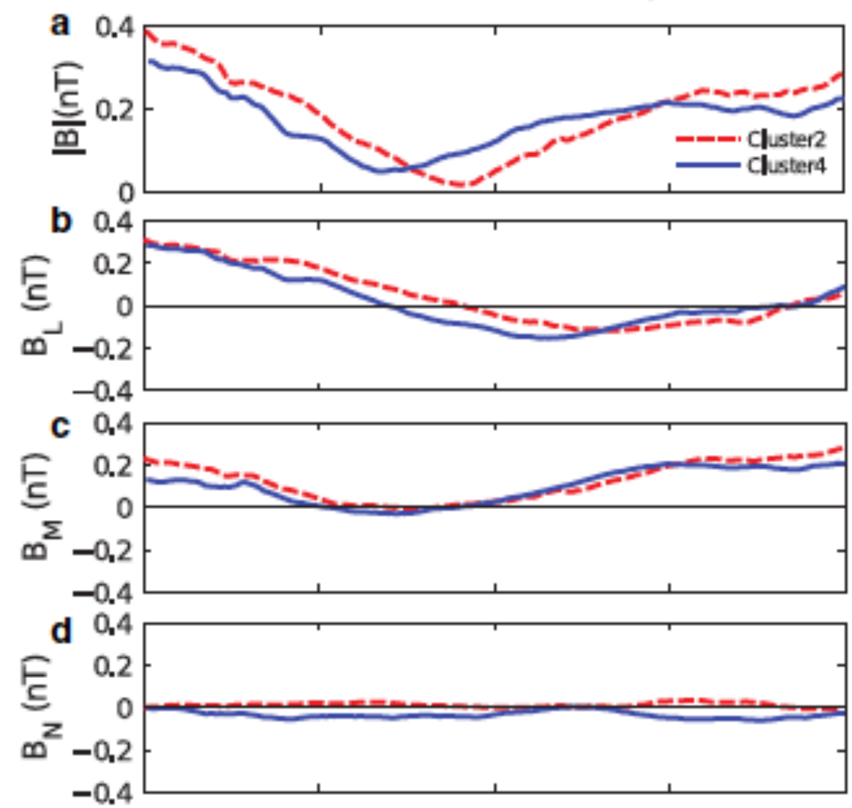
Veltri & Mangeney (1999)

***ISEE***




Veltri et al.(2005)

***STAFF/CLUSTER***

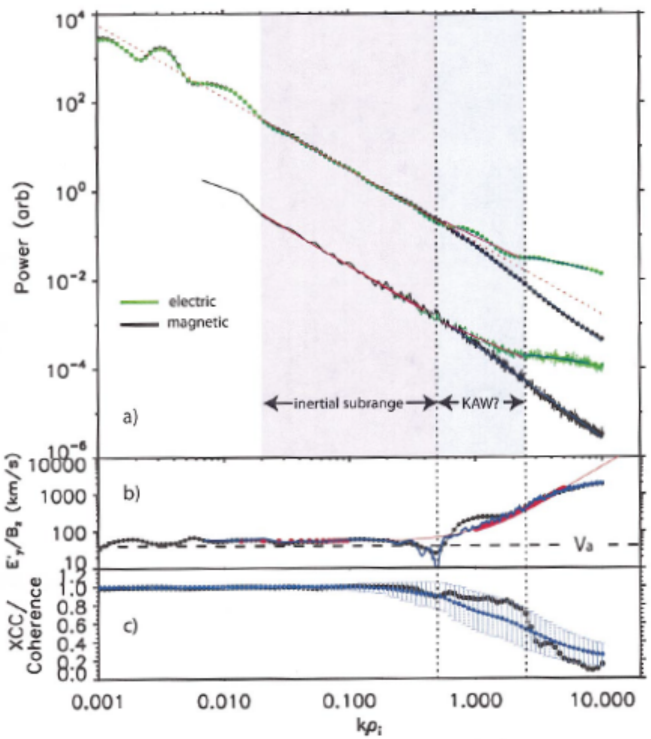



Perri et al.(2012)

1. ***Incompressible, pressure balanced, one-dimensional structures***
2. ***The component of maximum variation changes sign and it is perpendicular to the background magnetic field***

# CLUSTER DATA SET

Bale et al., 2005

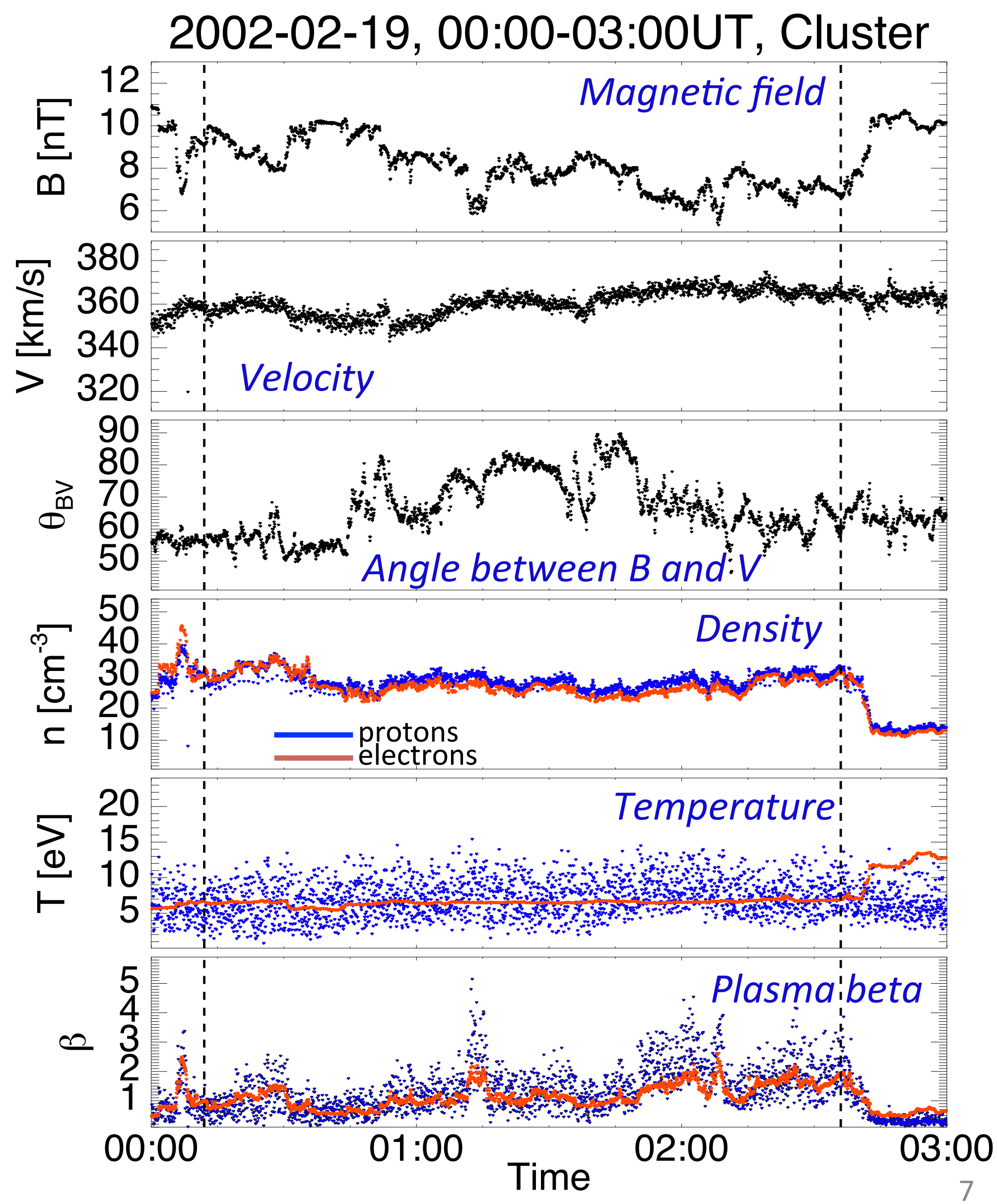



$$\langle B \rangle \approx 8nT$$

$$\langle V \rangle \approx 360km/s$$

$$\langle n_p \rangle \approx \langle n_e \rangle \approx 25cm^{-3}$$

$$\langle T_p \rangle \approx \langle T_e \rangle \approx 8eV$$



# WAVELET ANALYSIS

## INTERMITTENCY

**Morlet wavelet transform**

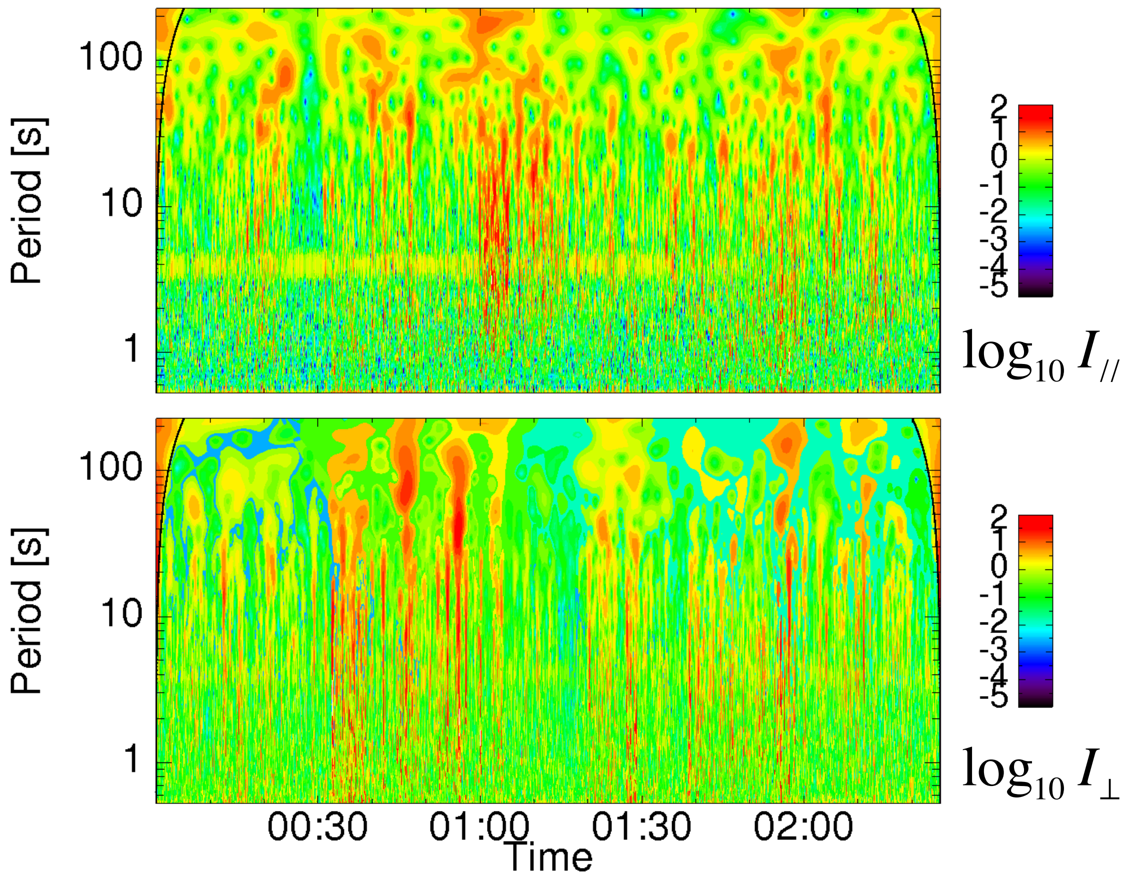
$$W_i(\tau,t)=\sum_{j=0}^{N-1} B_i(t_j)\,\psi^*\left[(t_j-t)/\tau\right]$$

$$\psi(u)=\pi^{-1/4}e^{-i\omega_0 u}e^{-u^2/2}$$

Farge, 1992

$$I(\tau,t)=\frac{\left|W(\tau,t)\right|^2}{\left\langle \left|W(\tau,t)\right|^2\right\rangle_t}$$

**2002-02-19, 00:12-02:36UT, CLUSTER/FGM**




- **Local Intermittency Measure I(t,τ)** → **localized events cover a scale range**

# WAVELET ANALYSIS

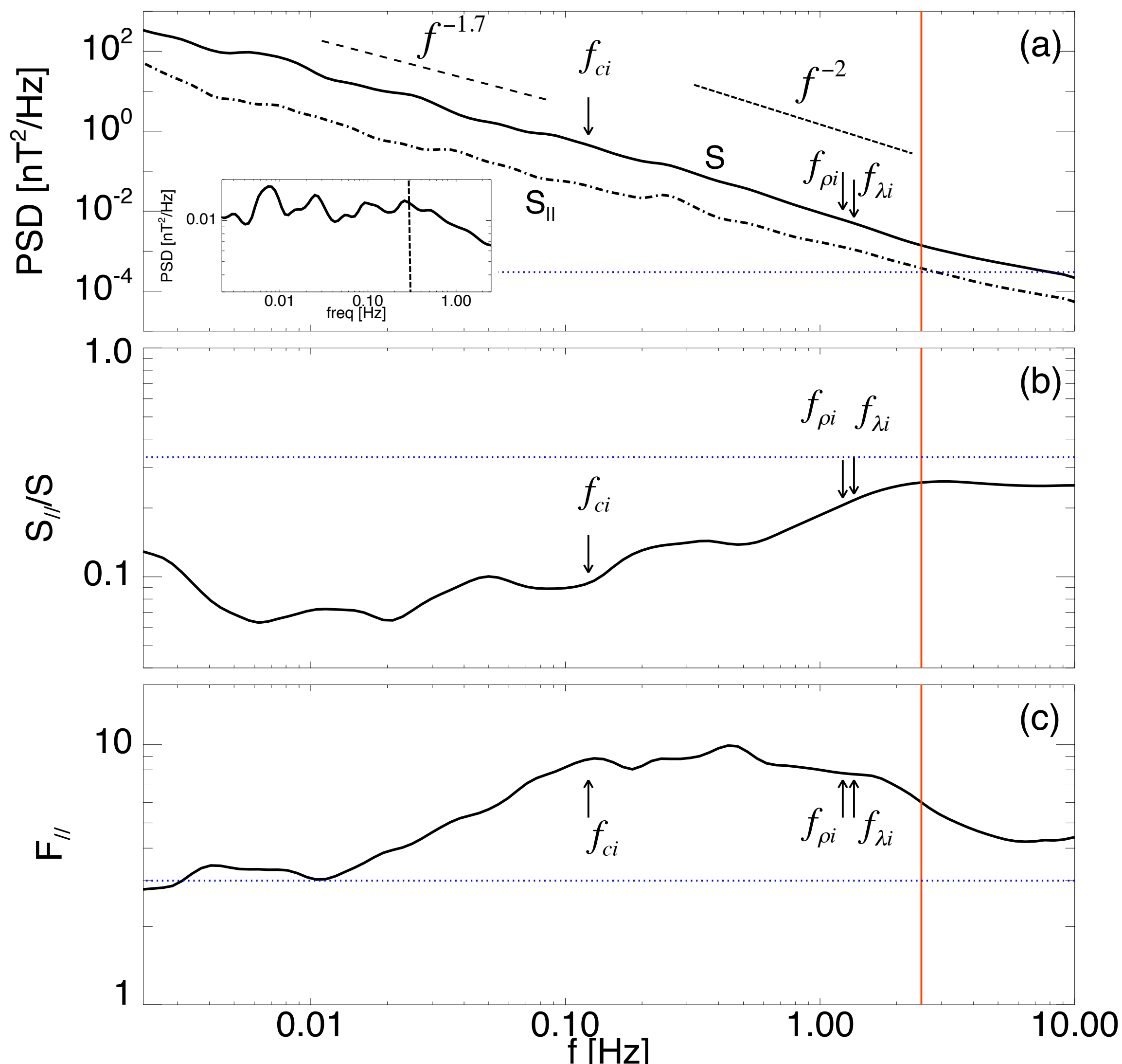
## TURBULENCE

- Kolmogorov-like spectrum
- Spectral break around 0.3 Hz

- Increasing of compressible fluctuations around ion characteristic scales

$$F_{//}(\tau) = \frac{\left\langle \left| \tilde{W}_{//}(\tau,t) \right|^4 \right\rangle}{\left\langle \left| \tilde{W}_{//}(\tau,t) \right|^2 \right\rangle^2}$$

- $F_{//}$ is more or less constant around ion characteristic scales



# WAVELET ANALYSIS

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- **Kolmogorov-like spectrum**
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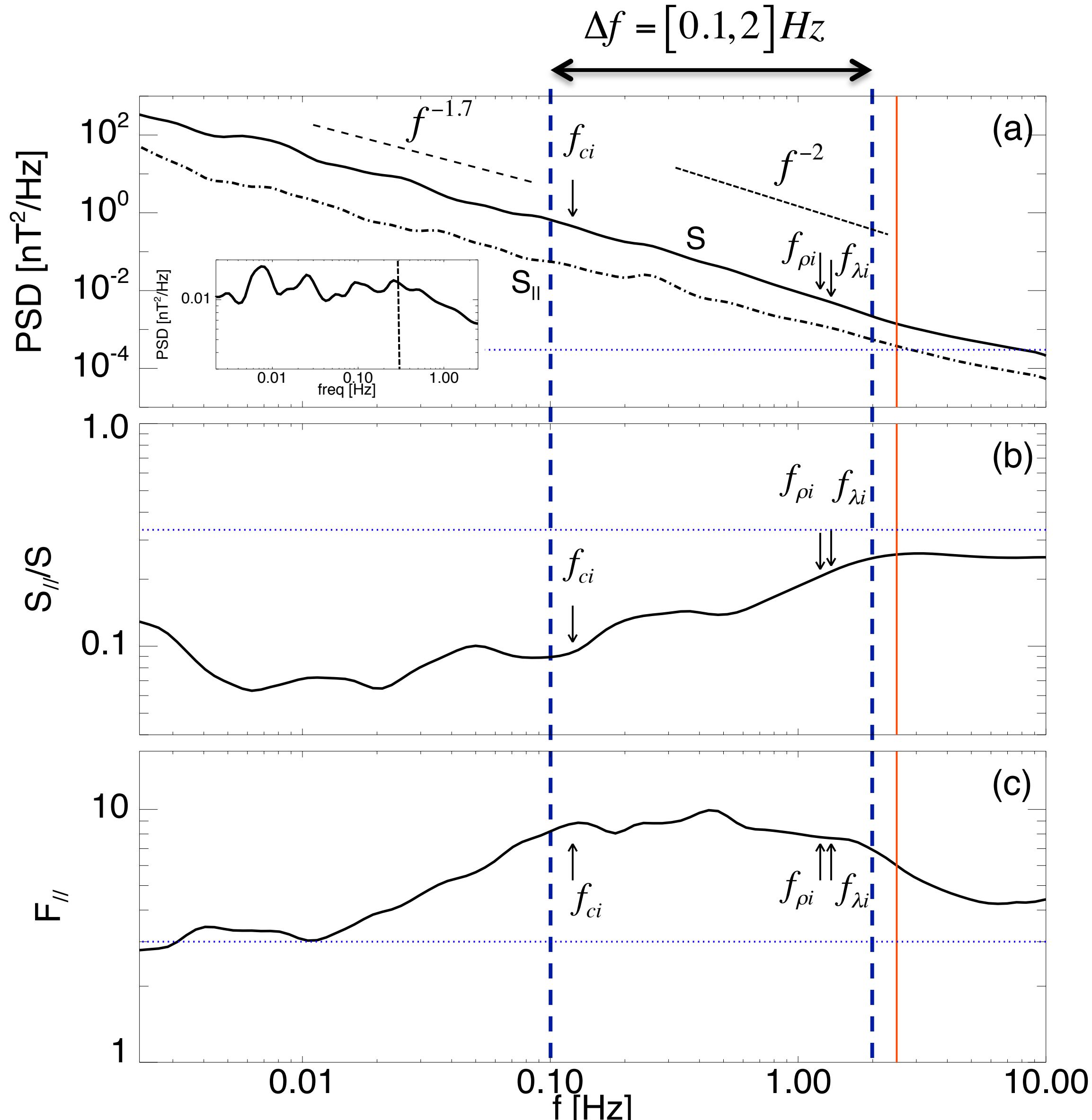
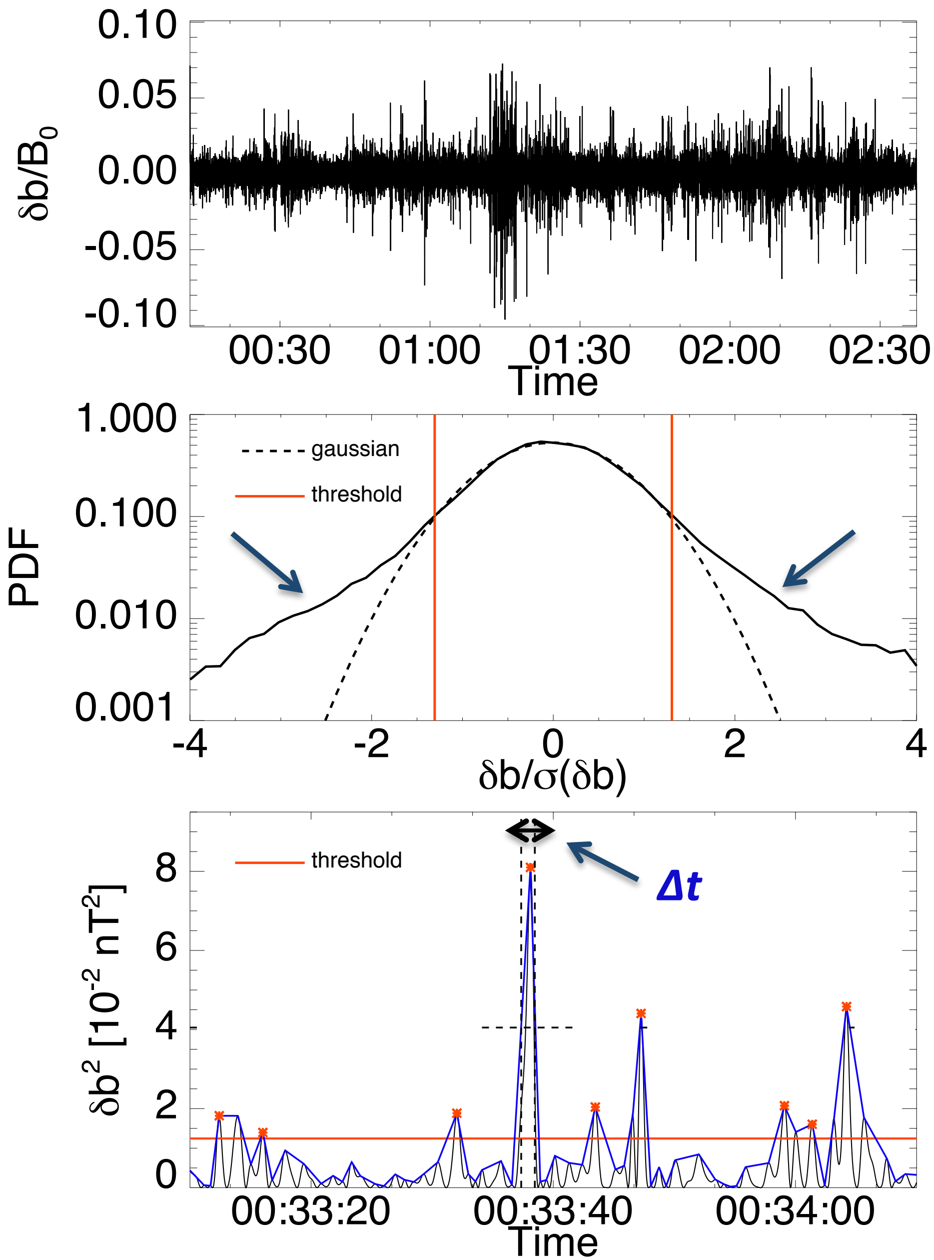


# 'DEFINITION' OF COHERENT STRUCTURES



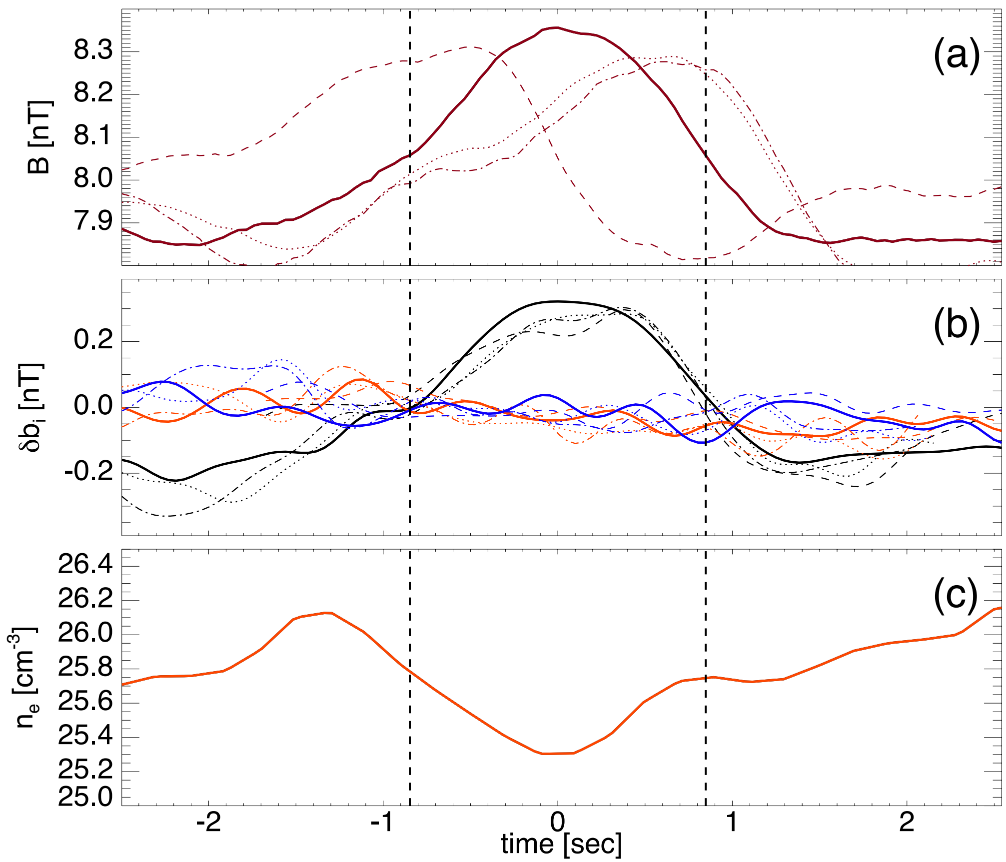

**Reconstruction of the signal in the range [0.1,2] Hz ≈ band pass filter**

Farge, 1992; He et al., 2012

$$\delta b_i\left(t_n\right) = \frac{\delta j \delta t^{1/2}}{C_\delta \psi_0(0)} \sum_{j=j_1}^{j_2} \frac{\tilde{W}_i\left(\tau, t\right)}{\tau^{1/2}}$$

**Around each selected peak over the threshold (energetic events) we perform a minimum variance analysis**

# EXAMPLE OF COHERENT STRUCTURE: SOLITON

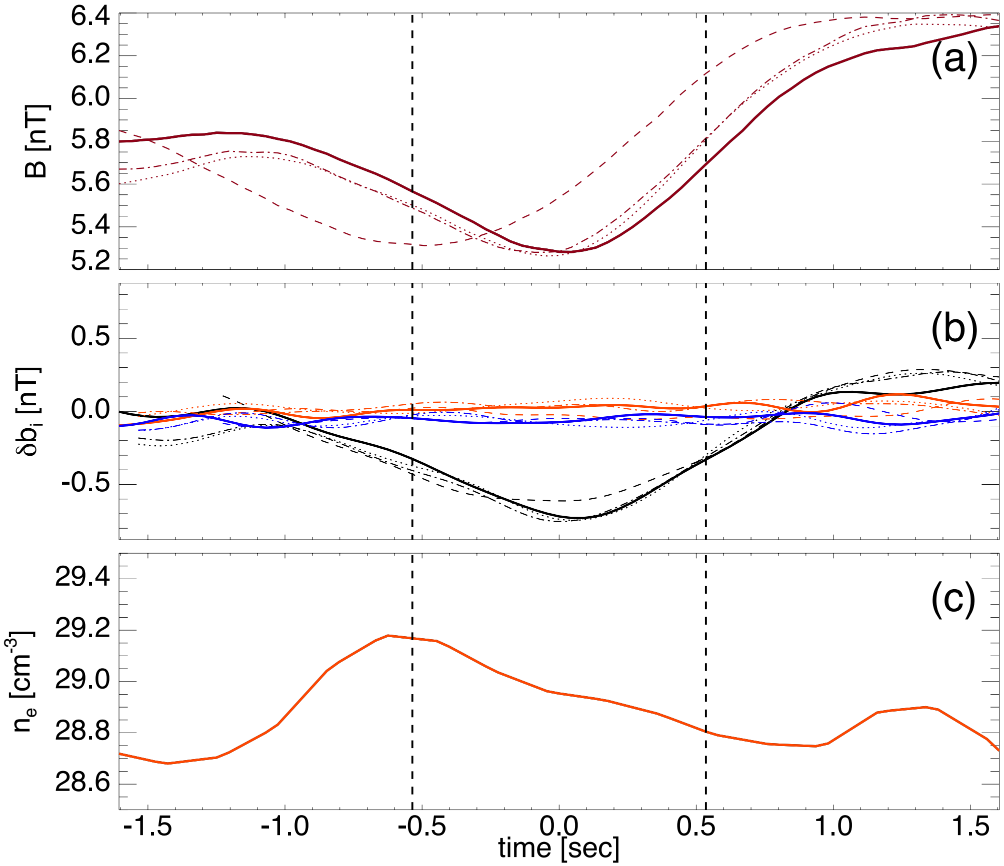



- One-dimensional structure
- Single impulse in magnetic field magnitude
- Direction of maximum variation along the local mean magnetic field
- Anti-correlation of magnetic field and electron density

| $\lambda_{int}/\lambda_{min}$ | $\theta_{max}$ | $\theta_{nB}$ | $\theta_{nV}$ | $V_0/V_A$ | $\Delta r/\lambda_p$ |
|---|---|---|---|---|---|
| 0.06 | 5.1° | 88.4° | 61.6° | -0.12±0.34 | 6.6 |

| $\beta_p$ | $A_p$ | $A_e$ | $V_A$ (km/s) | $\lambda_p$ (km) |
|---|---|---|---|---|
| 1.3 | 1.57 | 0.98 | 33 | 43.6 |

# EXAMPLE OF COHERENT STRUCTURE: HOLE

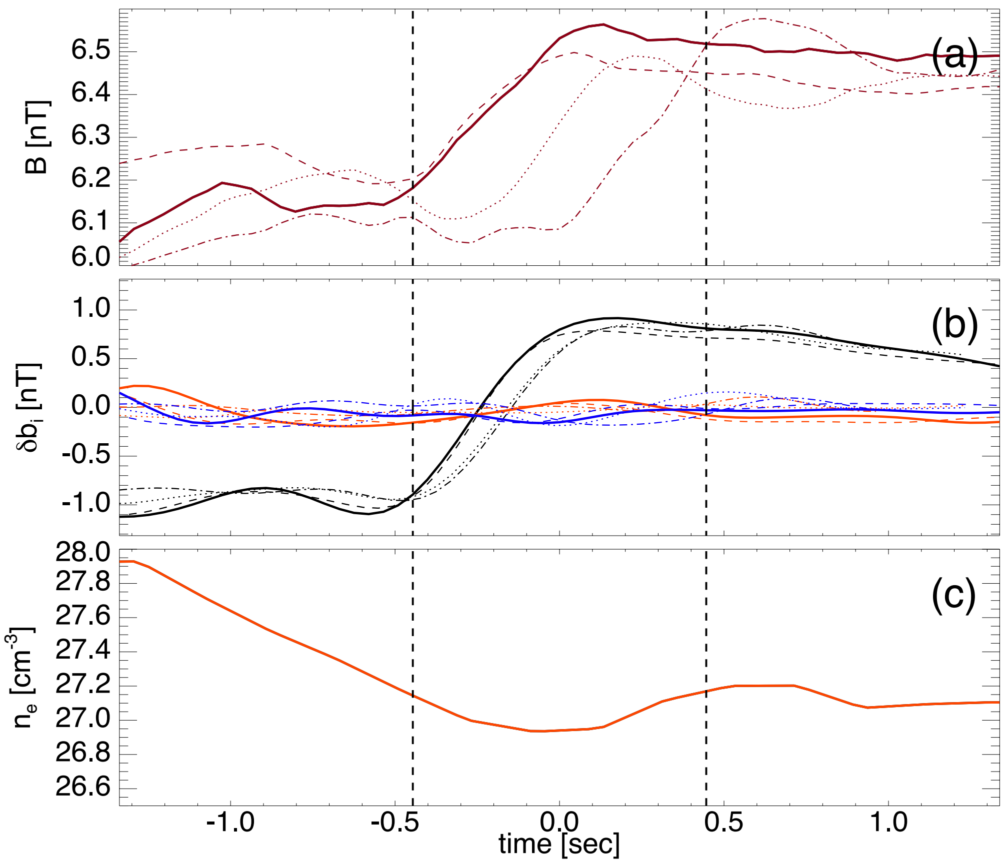



- One-dimensional structure
- Single depression in magnetic field magnitude
- Direction of maximum variation along the local mean magnetic field
- Anti-correlation of magnetic field and electron density

| $\lambda_{int}/\lambda_{min}$ | $\theta_{max}$ | $\theta_{nB}$ | $\theta_{nV}$ | $V_0/V_A$ | $\Delta r/\lambda_p$ |
|---|---|---|---|---|---|
| 0.02 | 1.9° | 89.3° | 20.4° | -0.32±1.52 | 8.5 |

| $\beta_p$ | $A_p$ | $A_e$ | $V_A$ (km/s) | $\lambda_p$ (km) |
|---|---|---|---|---|
| 3.2 | 1.8 | 0.98 | 23.6 | 41.5 |

# EXAMPLE OF COHERENT STRUCTURE: CURRENT SHEET




- One-dimensional structure
- Gradient in magnetic field magnitude
- Direction of maximum variation perpendicular to the local mean magnetic field
- Anti-correlation of magnetic field and electron density

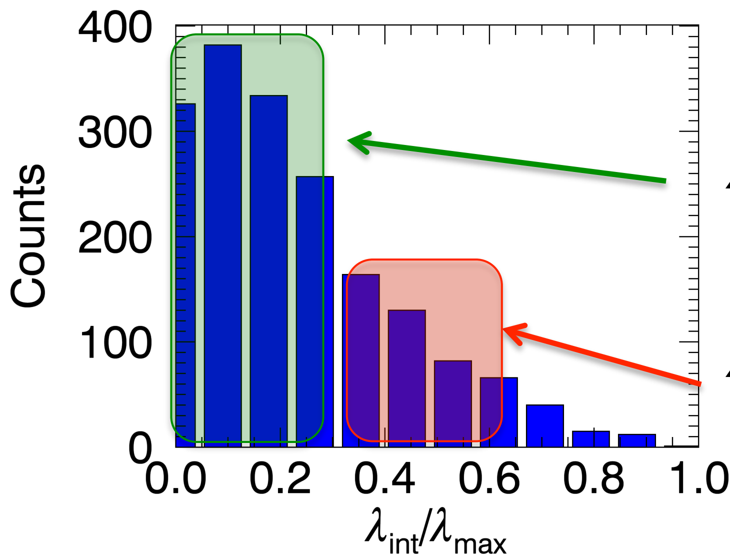
| $\lambda_{int}/\lambda_{min}$ | $\theta_{max}$ | $\theta_{nB}$ | $\theta_{nV}$ | $V_0/V_A$ | $\Delta r/\lambda_p$ |
|---|---|---|---|---|---|
| 0.02 | 77.8° | 88.4° | 38.6° | -0.15±1.13 | 6.2 |

| $\beta_p$ | $A_p$ | $A_e$ | $V_A$ (km/s) | $\lambda_p$ (km) |
|---|---|---|---|---|
| 2.48 | 1.02 | 0.98 | 25.6 | 42.2 |

# STATISTICAL ANALYSIS: MINIMUM VARIANCE ANALYSIS

***For ≈1500 coherent structures in the selected interval***

*ectors of maximal ($\lambda_{max}$), intermediate ($\lambda_{int}$) and ($\lambda_{min}$) variations, respectively.*

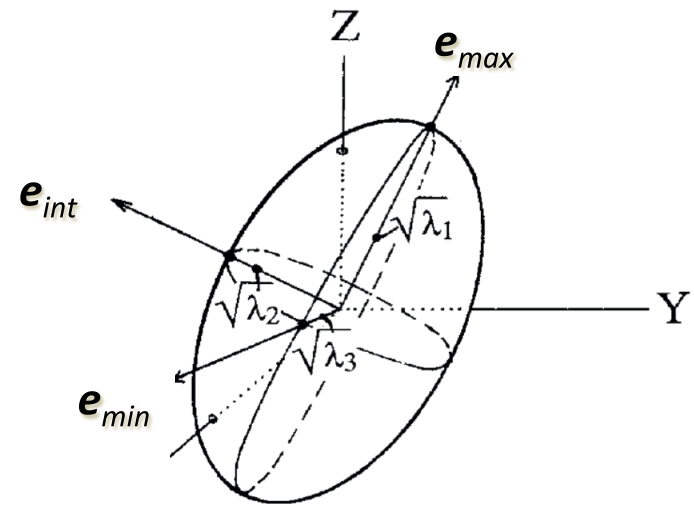



$\lambda_{int} / \lambda_{max} \leq 0.3$

***1D structures***

$\lambda_{int} / \lambda_{max} > 0.3$

***2D structures***

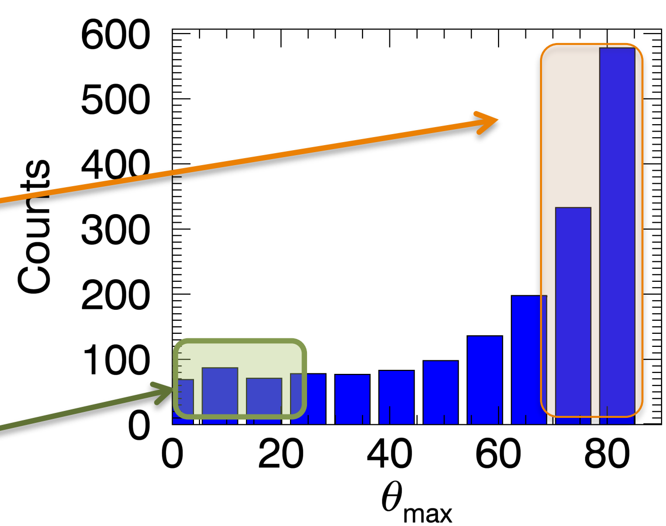



$\theta_{max} \geq 65 \Leftrightarrow e_{max} \perp \mathbf{B_0}$

***Alfvénic structures***

$\theta_{max} \leq 25 \Leftrightarrow e_{max} \, // \, \mathbf{B_0}$

***Compressible structures***



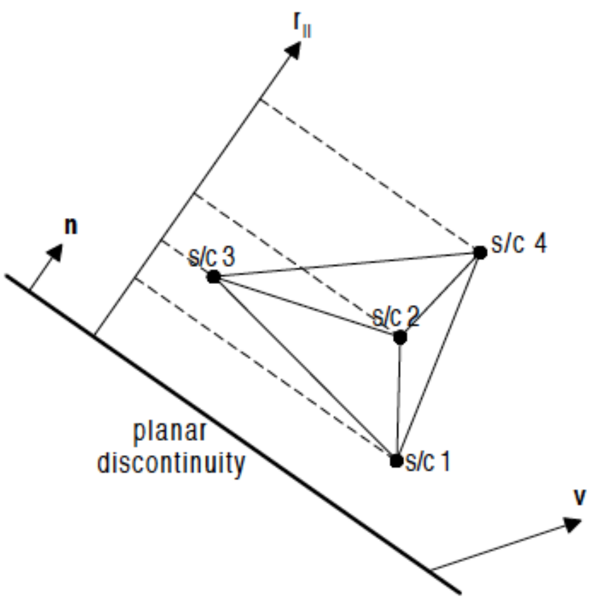

$$\theta_{max} = ar\cos\left(\left|\frac{\mathbf{B}_0^{struc} \cdot \hat{e}_{max}}{B_0^{struc}}\right|\right)$$

$$\theta_{min} = ar\cos\left(\left|\frac{\mathbf{B}_0^{struc} \cdot \hat{e}_{min}}{B_0^{struc}}\right|\right)$$

# TIMING METHOD

## LOCAL MULTI-SATELLITE ANALYSIS

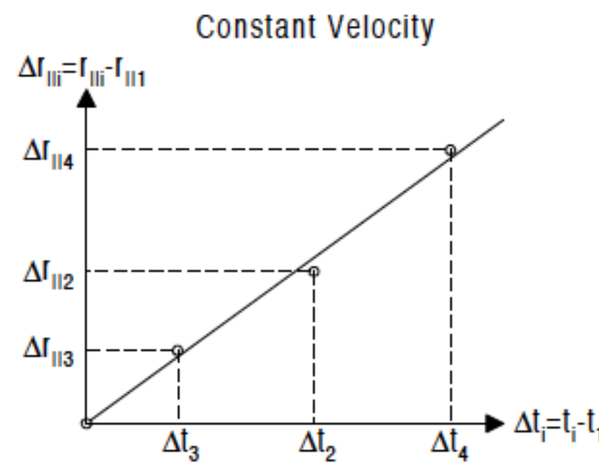
*Using Custer, it is possible to determine the velocity and the direction of propagation of a locally planar structure moving with a constant speed in the satellite frame:*




$$\mathbf{D}_{1i}\cdot\frac{\mathbf{n}}{v}=\Delta t_{1i}$$

$$i=2,3,4$$

$$\mathbf{D}_{1i}=\mathbf{D}_i-\mathbf{D}_1$$




*The time delay is given by the maximum of*

$$R_{ij}(\tau)=\frac{\left\langle \delta\mathbf{B}_i(t)\cdot\delta\mathbf{B}_j(t+\tau)\right\rangle}{\sqrt{\left\langle \delta B_i^2\right\rangle\left\langle \delta B_j^2\right\rangle}}$$

*The same event is observed by the satellites $C_i$, $C_j$ and $C_k$ if the time delays $\Delta t_{ij}=t_j-t_i$ satisfy the compatibility relation*

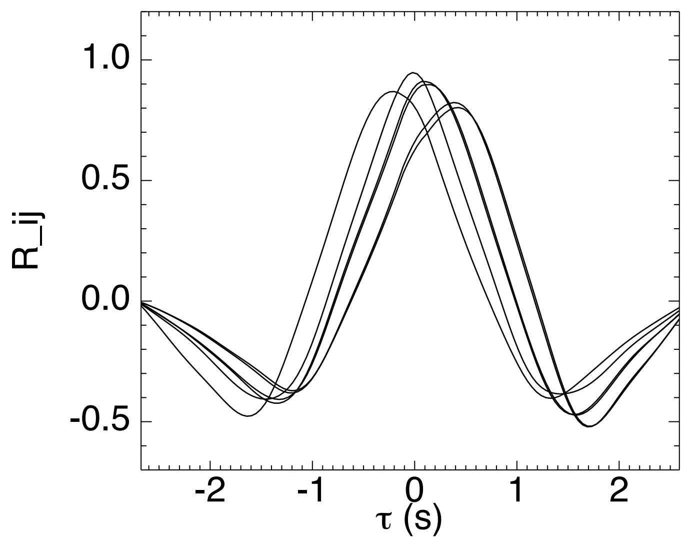
$$\Delta t_{ij}=\Delta t_{ik}-\Delta t_{kj}\longrightarrow\Delta t_{ij}=-\Delta t_{ji}$$

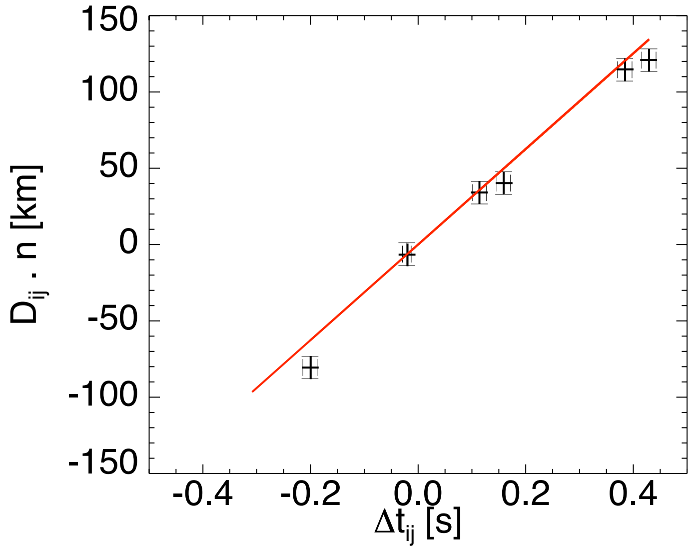
# TIMING METHOD: AN EXAMPLE

## LOCAL MULTI-SATELLITE ANALYSIS

$$R_{ij}(\tau) = \frac{\langle \delta \mathbf{B}_i(t) \cdot \delta \mathbf{B}_j(t+\tau) \rangle}{\sqrt{\langle \delta B_i^2 \rangle \langle \delta B_j^2 \rangle}}$$

$$\mathbf{D}_{ij} \cdot \frac{\mathbf{n}}{v} = \Delta t_{ij}$$



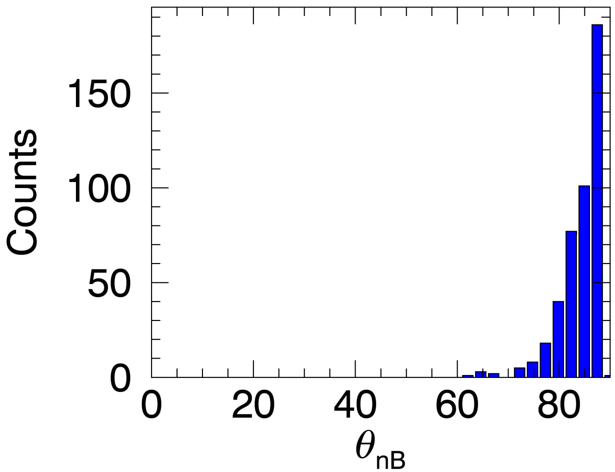



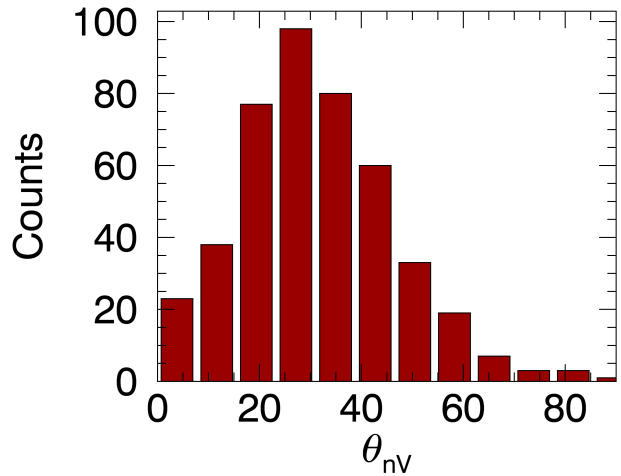

- For the six satellite pairs: the maxima are well defined and the time lags, corresponding to the maxima, give the time delays
- The time delays verify the compatibility relation
- The assumption of planarity is satisfied

# STATISTICAL ANALYSIS: MULTI-SATELLITE ANALYSIS

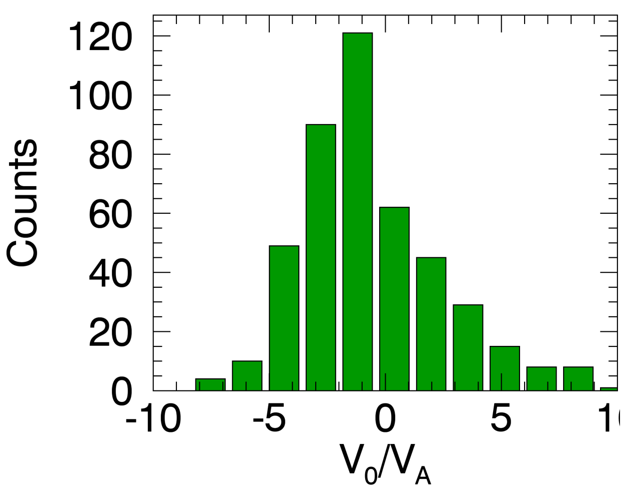
*For ≈400 coherent structures in the selected interval*

## DIRECTION OF PROPAGATION

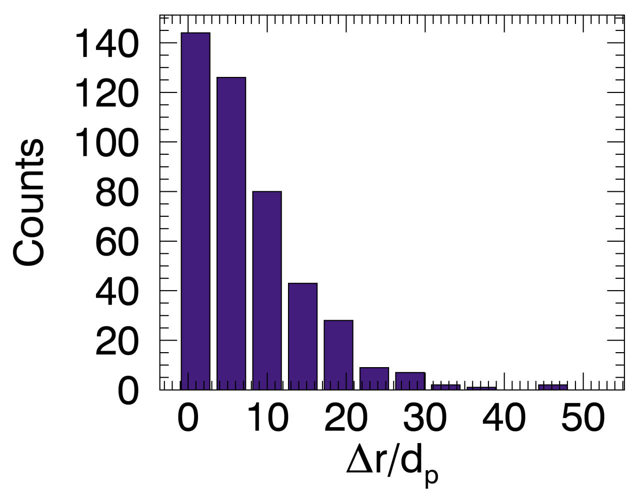



## VELOCITY IN PLASMA FRAME




## SPATIAL SCALES

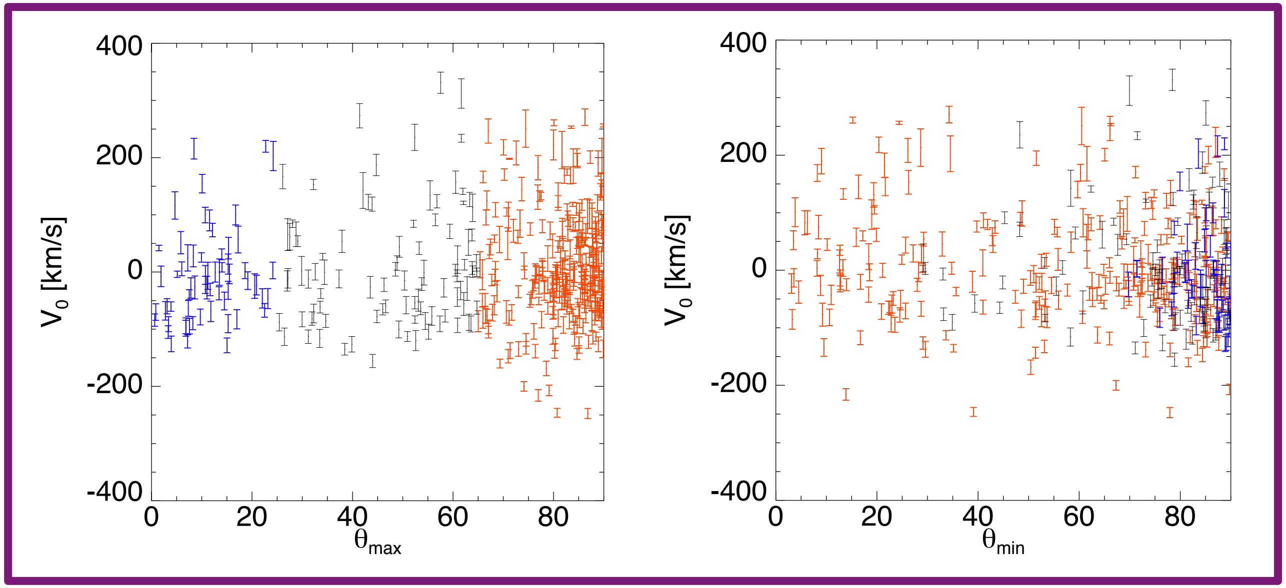



1. ***The direction of propagation is almost perpendicular with respect to the local mean magnetic field***
2. ***The structures are not simply carried by the wind***
3. ***The mean value of the width is about 3 ion inertial length ($d_p$)***

$$d_p = \frac{V_A}{\Omega_{cp}}$$

Perrone, Alexandrova, Maksimovic et al., in preparation (2015)

# STATISTICAL ANALYSIS: VELOCITY AND DIRECTION

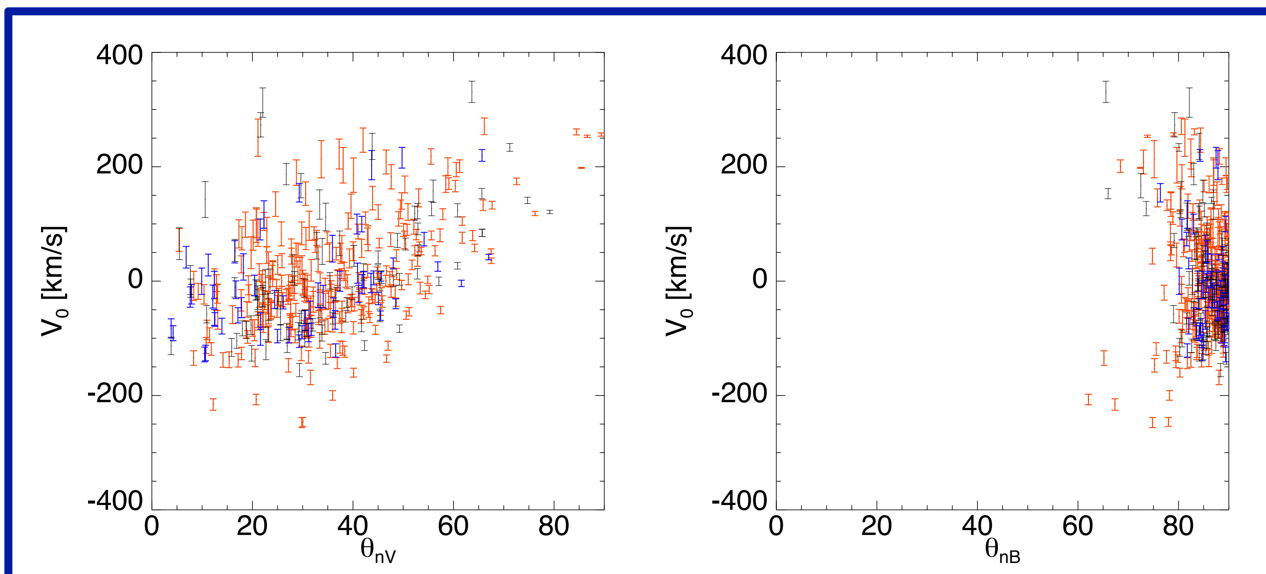



compressible

alfvénic

*Almost linear dependence between velocity and $\theta_{nV}$*

*Propagation almost perpendicular to the local mean magnetic field*

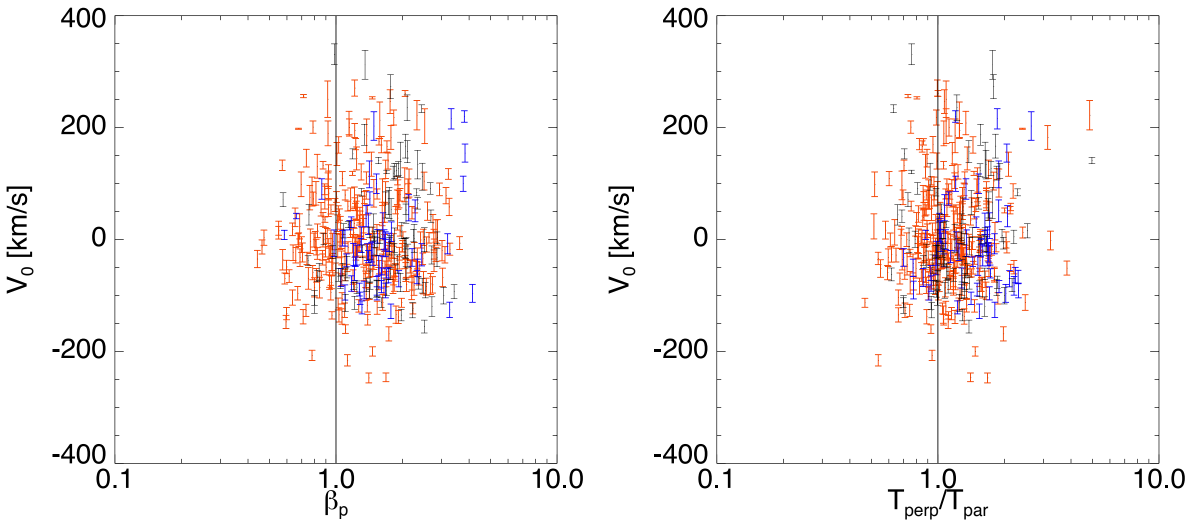


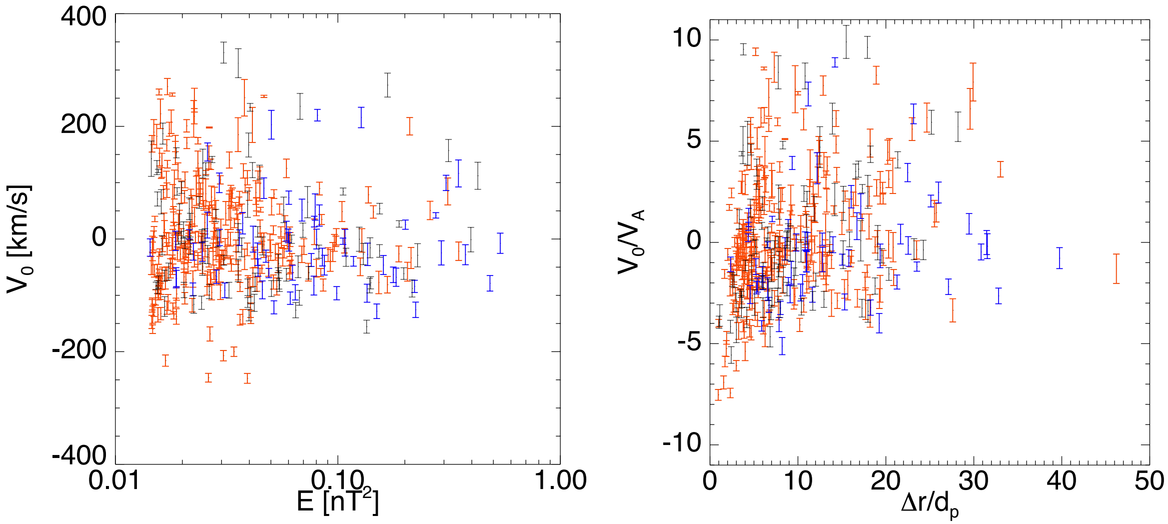
# STATISTICAL ANALYSIS: PHYSICAL CHARACTERISTICS

compressible

*β>1 and temperature anisotropy >1*

The most energetic events are compressible




alfvénic

More uniform distribution for β and for temperature anisotropy

# SUMMARY AND CONCLUSIONS

*A multi-satellite analysis has been employed to study coherent structures close to the ion spectral break in the solar wind turbulent cascade using CLUSTER data*

*The method is based on Morlet wavelet decomposition of magnetic signal and a successive reconstruction of magnetic fluctuations in the frequency range [0.1, 2] Hz*

- *Different kind of coherent structures have been detected, from soliton- or magnetic hole-like compressible structures to current sheet-like alfvénic structures*
- *We observe that these structures propagate quasi-perpendicularly with respect to the local mean magnetic field, with finite velocity in plasma reference frame*

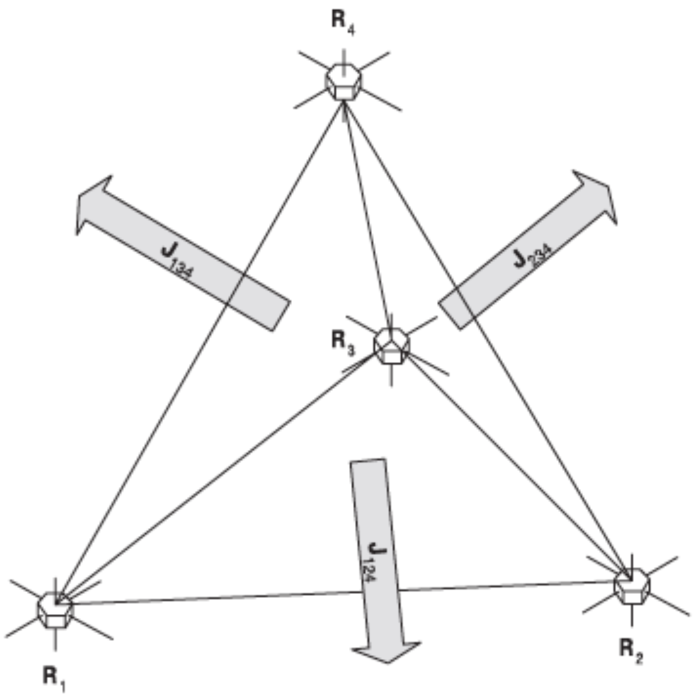
○ **What is the role of coherent structures in the dissipation?**
**Reconnection within current sheets?**
**Particle trapping/acceleration within vortices?**
**…**

➡ Importance to detect and study coherent structures

# CURLOMETER TECHNIQUE

## LOCAL MULTI-SATELLITE ANALYSIS

*Using Custer, it is possible to determine the current density:*




$$\mu_0 \mathbf{J} = \nabla \times \mathbf{B}$$ *Ampere's law*

$$\mu_0 \frac{1}{2} J_{ijk} \left| \Delta\mathbf{R}_{ji} \times \Delta\mathbf{R}_{jk} \right| =$$

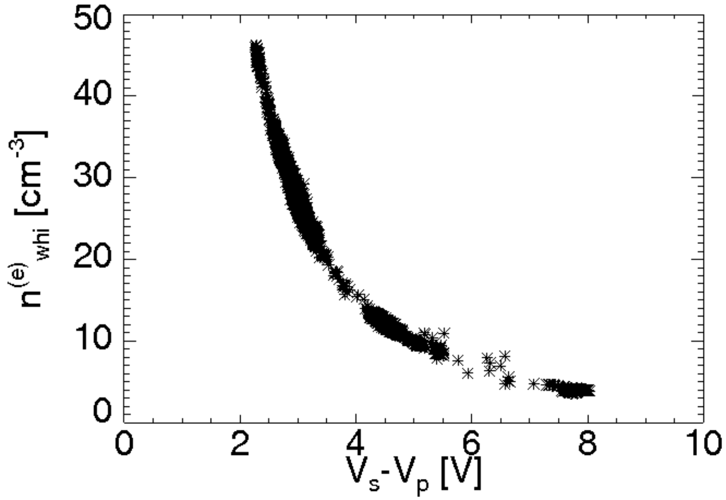
$$= \langle \mathbf{B} \rangle_{ij} \cdot \Delta\mathbf{R}_{ij} + \langle \mathbf{B} \rangle_{ik} \cdot \Delta\mathbf{R}_{ik} + \langle \mathbf{B} \rangle_{jk} \cdot \Delta\mathbf{R}_{jk}$$

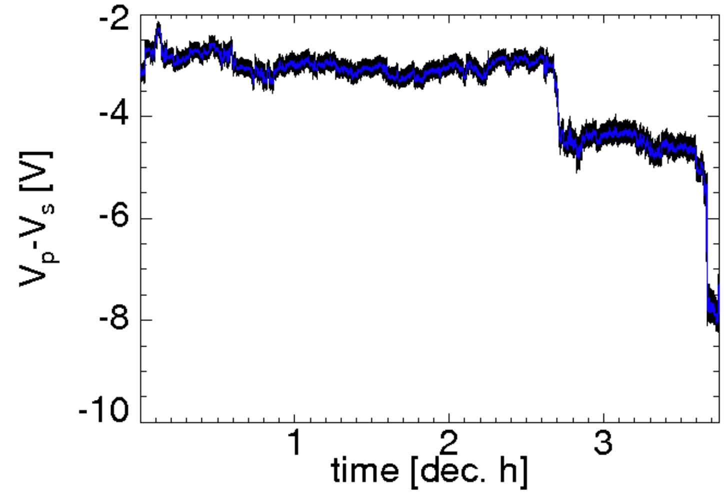
*Assuming the current density is a constant in the whole surface and the magnetic field changes very slowly*

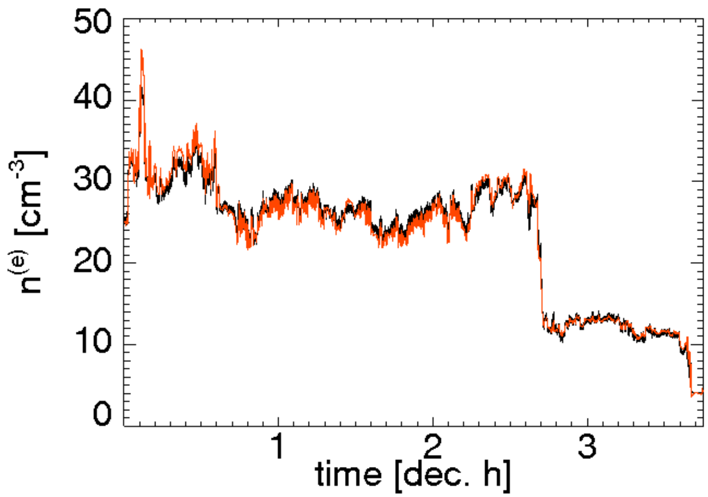
*Factor quality:* $\nabla \cdot \mathbf{B} / \nabla \times \mathbf{B}$

# ELECTRON DENSITY ESTIMATION

***Electron density is estimated from the equilibrium floating potential of the satellite***




$$n_e\left[\phi(t)\right] = \sum_{i=1}^{3} a_i 10^{b_i \phi(t)} =$$

$$= 155.3 \cdot 10^{-0.24\phi(t)} - 6.8 \cdot 10^{-0.083\phi(t)}$$

$$+ 0.87 \cdot 10^{0.078\phi(t)}$$

Bale et al., 2003

# THANK YOU FOR THE ATTENTION