Turbulence in the boundary regions and in the solar wind

Laurence Rezeau

http://www.lpp.fr/?Laurence-Rezeau

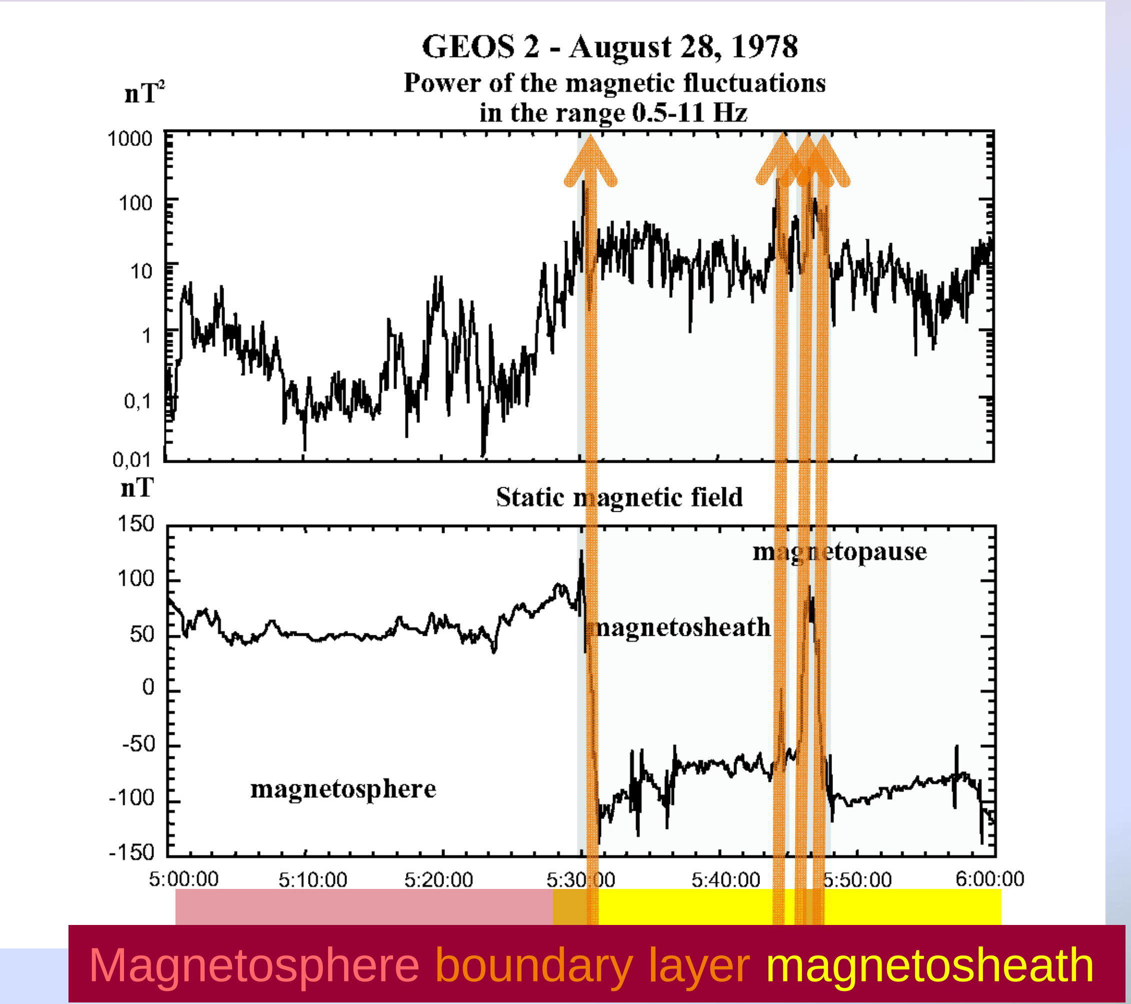
OUTLINE

- Evidence of turbulence in the boundary regions
- Cluster and multipoint measurements
- Our present knowledge and questions

Evidence of turbulence in the boundary regions

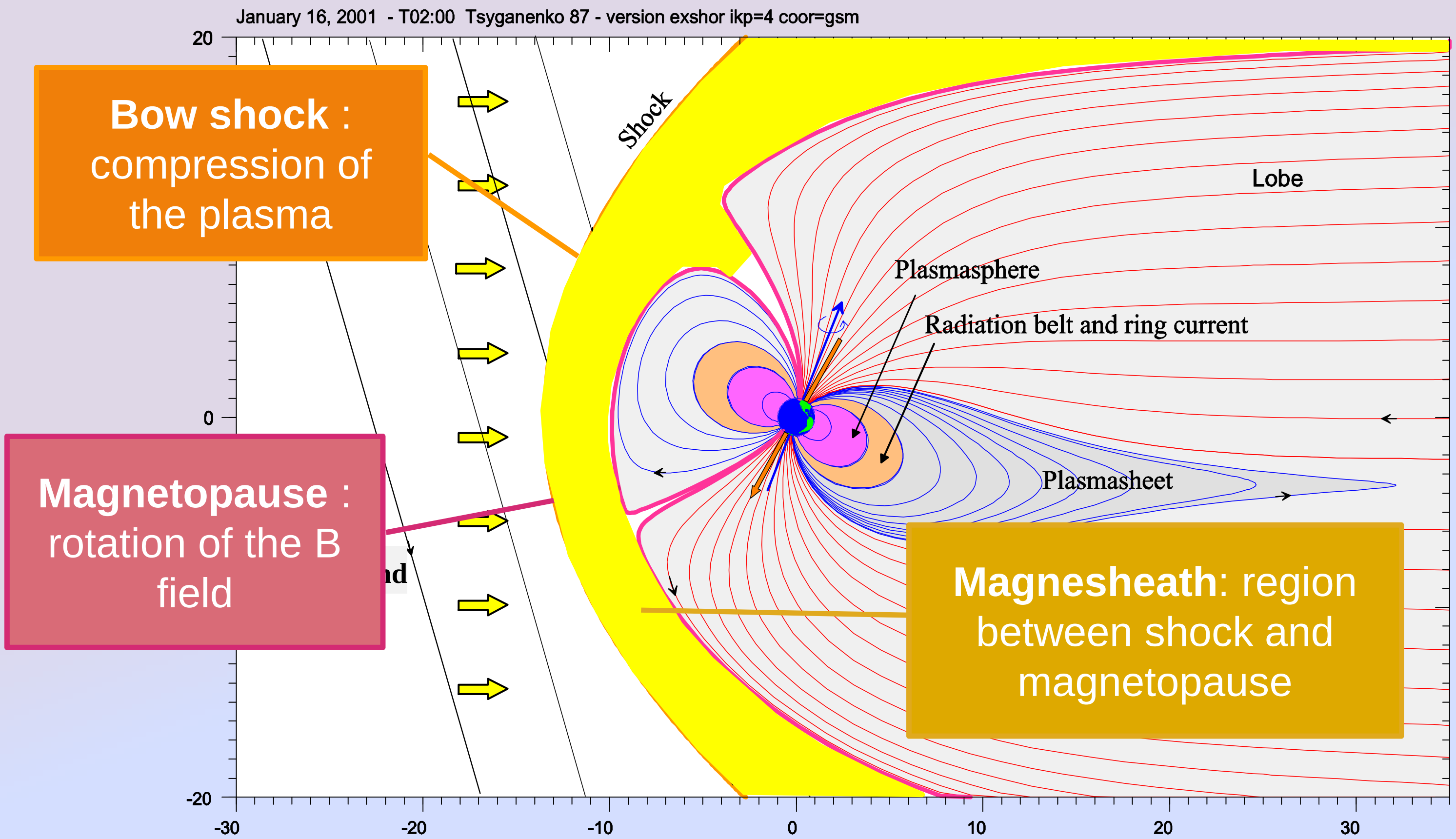
Magnetic turbulence

The AC measurements of the magnetic field have a good resolution that makes it possible to observe small scale turbulence in plasma. It is impossible with particle data (velocity fluctuations).



Rezeau et al, 1986

Magnetospheric boundaries



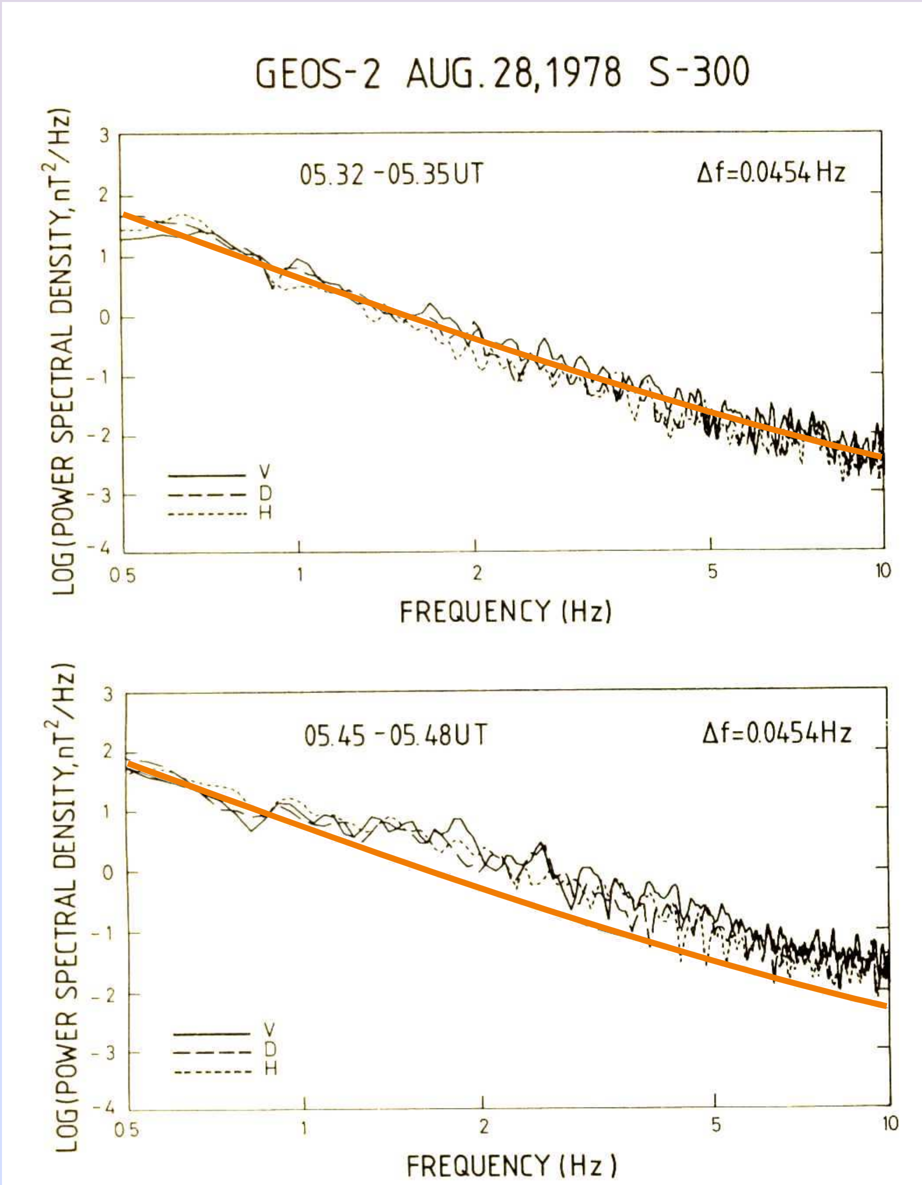
•Very high level of turbulence in the magnetosheath behind the shock

•Still higher level at the magnetopause

Properties of the fluctuations

magnetosheath

magnetopause and boundary layer

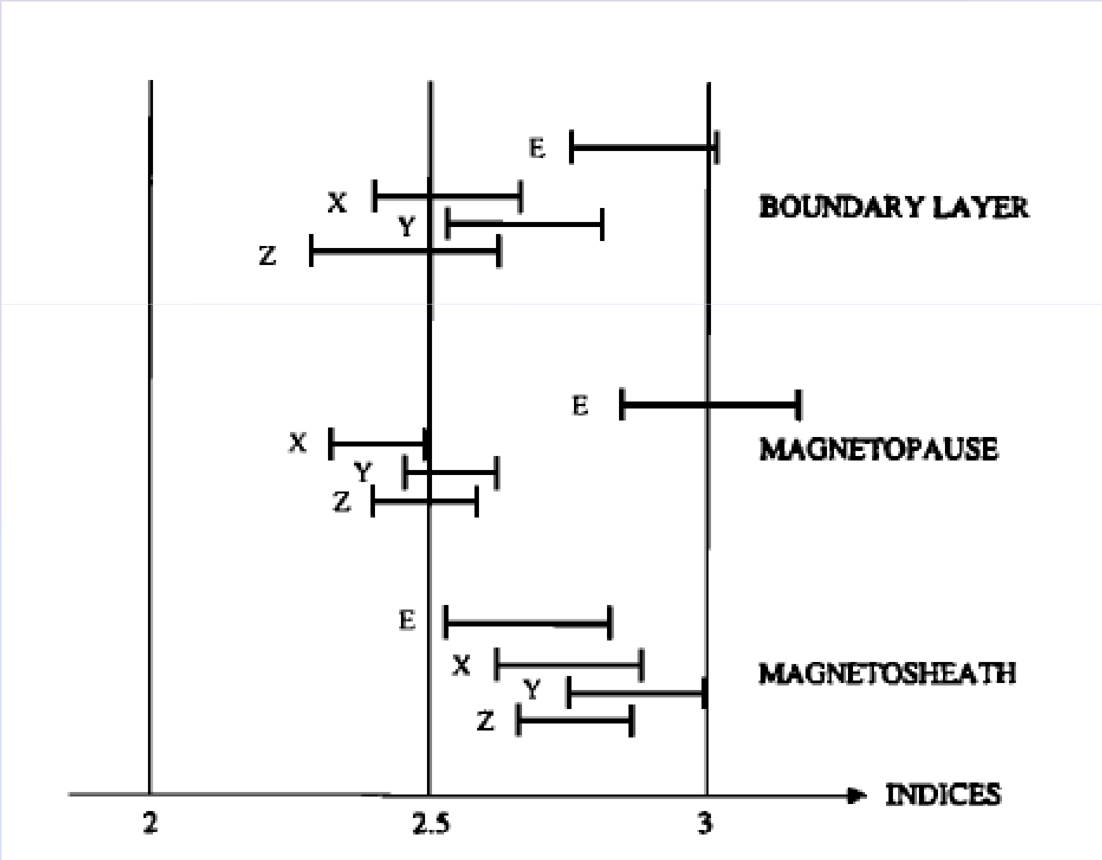


Turbulent like spectra

Steeper slope

Higher level

Statistical results on the spectral indices depending on the region



GEOS Data at the equatorial magnetopause

Rezeau et al, 1989

Why study turbulence in space?

- Turbulence may be a consequence of the shock (same as in hydrodynamics)

- Turbulence induces ***cross scale coupling***, leading to:

  * Increased diffusion (*anomalous*)

  * Increased transports of heat (*anomalous* thermal conductivity), momentum (*anomalous* viscosity, friction, resistivity)

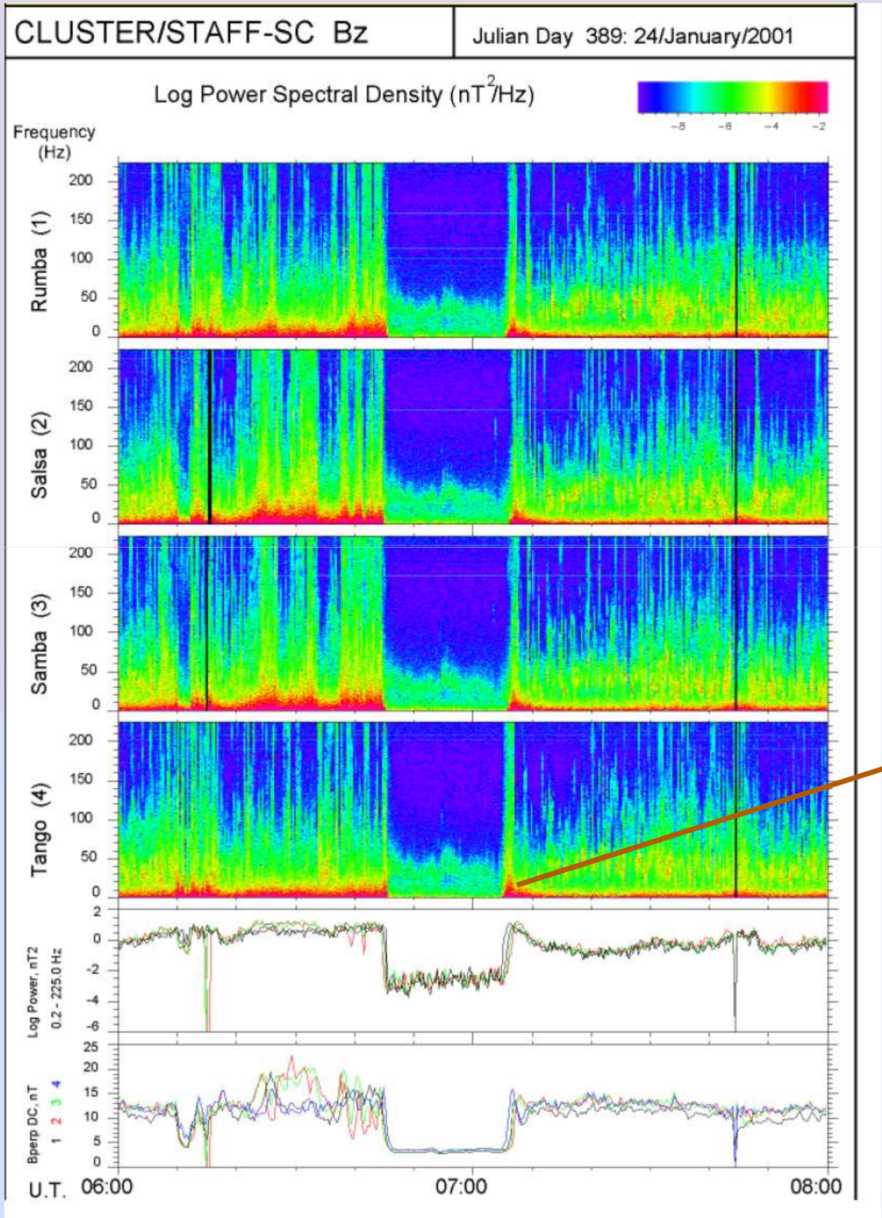
  * Accelerated mixing of different layers

  * Most generally modeled by effective "*non ideal*" terms to be added in large scale laminar equations

But still much **more crucial** in space than in hydrodynamics because no « normal » transport in collisionless plasmas

A big step ahead with 3D measurements : CLUSTER

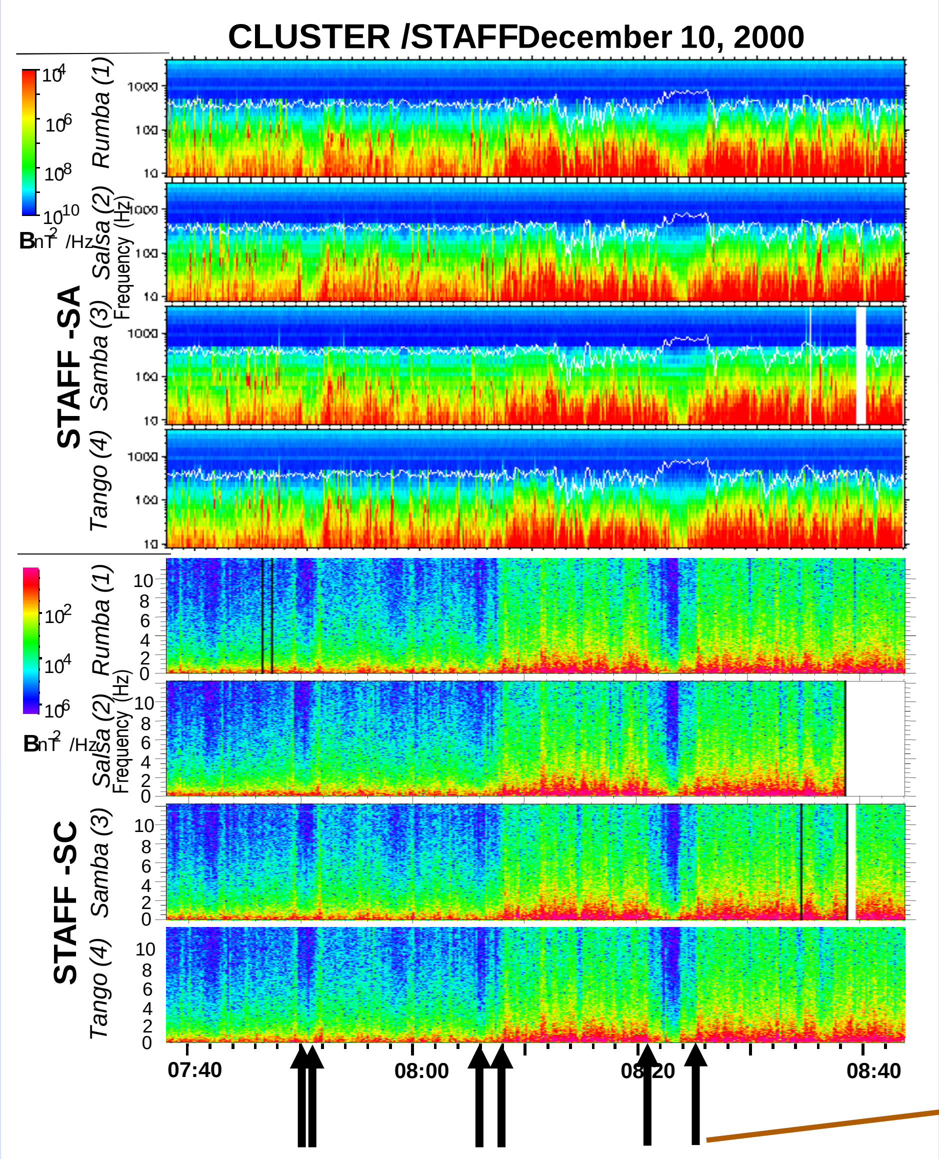
First CLUSTER results at the shock



Turbulence is observed behind the shock

Cornilleau et al, 2001

First CLUSTER results



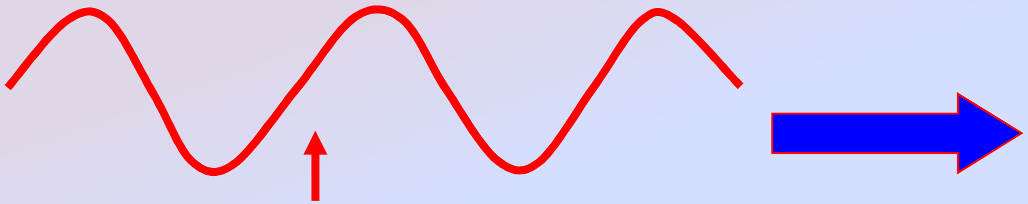
The magnetopause crossings can be diagnosed on the wave data

Rezeau et al, 2001

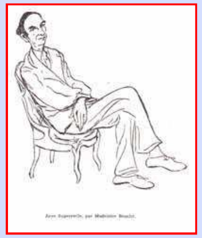
1 point vs 4 points measurements

From one single spacecraft, it is impossible to disentangle this spatio-temporal ambiguity

Even for one mono-k wave,
one observer cannot separate the role of the wavelength and the role of the propagation velocity in the temporal variation observed



Single observer



For several waves, or a complete spectrum, it is obviously worst. Except if the Taylor hypothesis can be made (Doppler effect dominant) : $\omega_s = \omega + \mathbf{k.v} \approx \mathbf{k.v} \approx k_f v$ only in the direction of the flow

But with multipoint measurements can we do better ?

- ω and **k** spectra ?
- Polarization at each ω, **k** ?

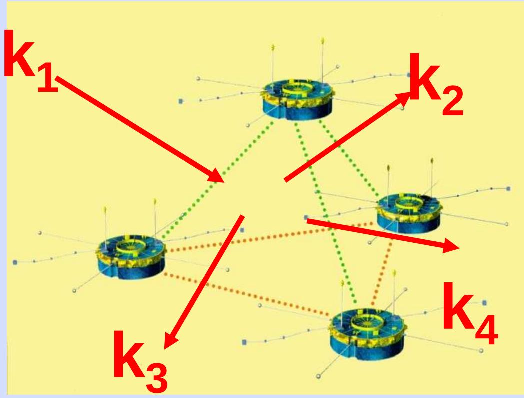
K-filtering

Idea: from two spacecraft, it is possible to separate ω and k_x by correlating two identical scalar quantities at the two points: ***if one single k*** $_{\boldsymbol{x}}$

$$\frac{B_{i1}B_{i2}^{*}}{|B_{i1}||B_{i2}|} = e^{i\phi_i} \quad \rightarrow \quad k_x = \frac{\phi_i}{x_2 - x_1}$$

K-filtering :

Optimization of the simultaneous use of all the possible correlations that can be calculated from the data:12x12 *correlation matrix for the 3* **B** *components and 4 spacecraft*



Non linear method of the «*maximum likelihood*» type, based on filters that are transparent for mono-*k* waves and depend on the data + external constraints such as

$$\nabla.\mathbf{B} = 0$$

Pinçon and Lefeuvre,1991 and Sahraoui et al, 2004

K -Spectra

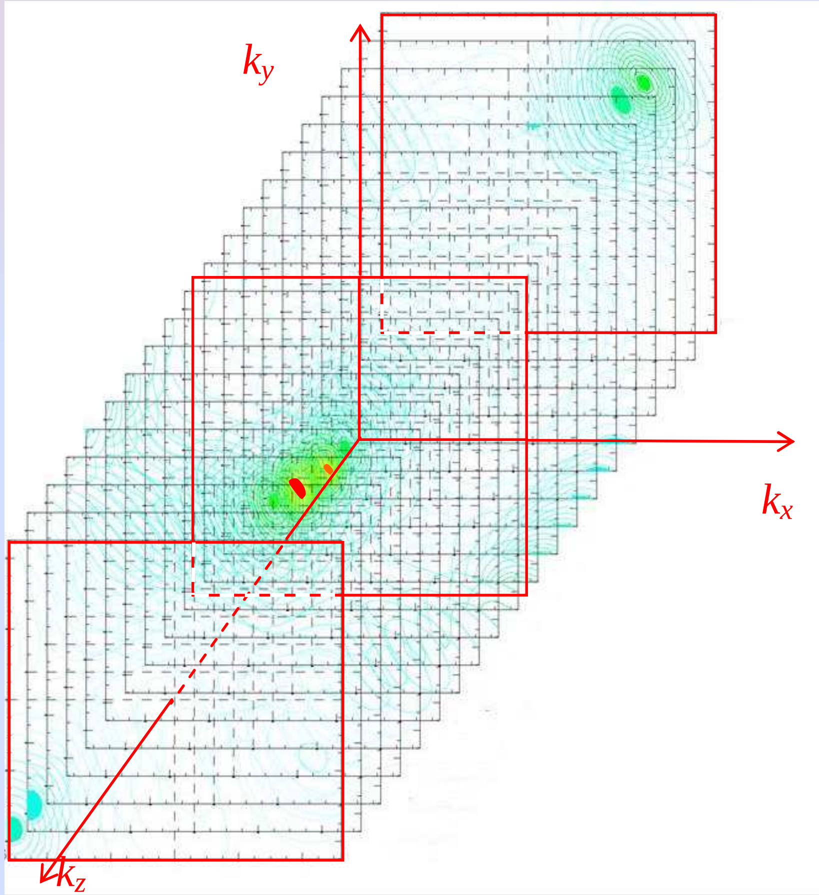
For each observed frequency f_s, the *k*-filtering analysis can provide a 3-D *k*-spectrum. An integration over f_s provides the full spatial spectrum.

Limits:

- Demands signals that are "sufficiently" stationary and homogeneous

- Aliasing effect if λ < spacecraft separation (*but the problem can be identified and generally corrected*)

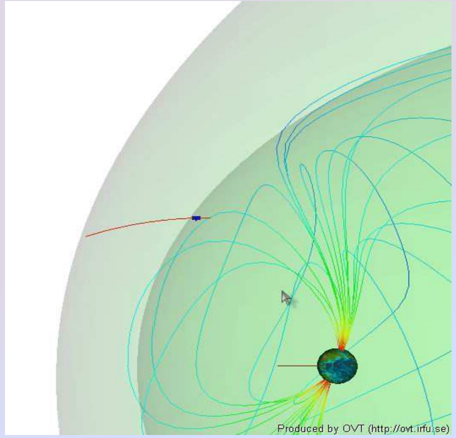
- the effective frequency range where k-filtering can apply is restricted a limited $[f_{min}, f_{max}] \approx 1.5$ decades

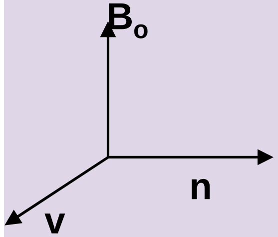


Sahraoui, 2003

Magnetosheath Turbulence:

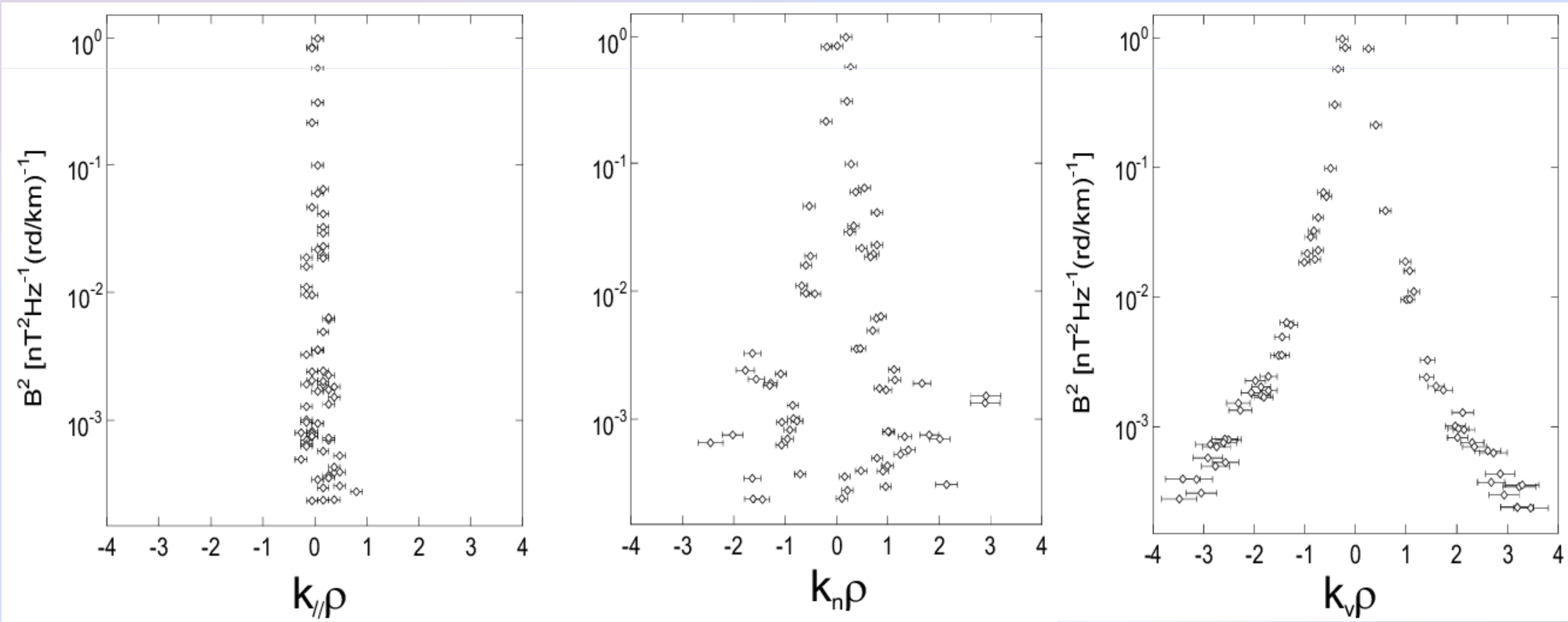
anisotropies





$(\mathbf{v},\mathbf{n}) \sim 104°$
$(\mathbf{v},\mathbf{B_o}) \sim 110°$
$(\mathbf{n},\mathbf{B_o}) \sim 81°$

B_o **N** **V**

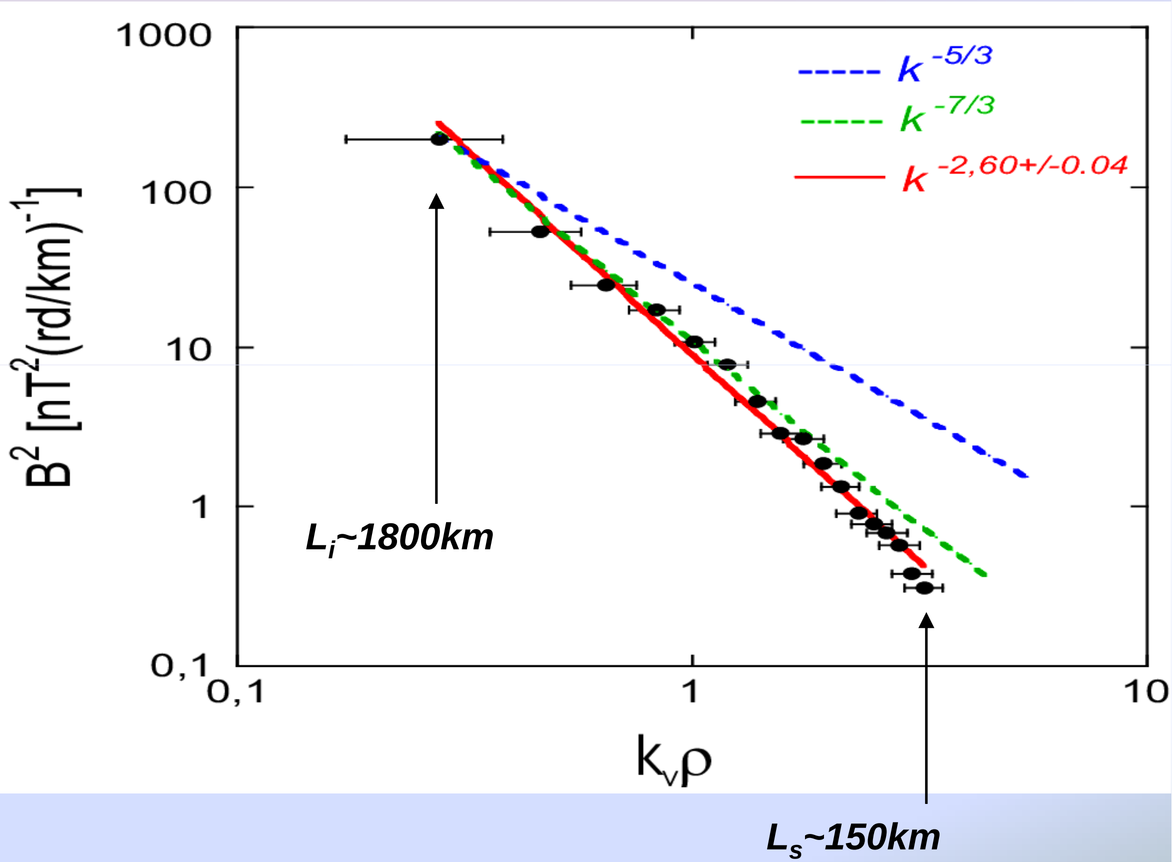


Strong anisotropies along $\mathbf{B}_o$ and the magnetopause normal **N**

Power law spectrum

along **v**:

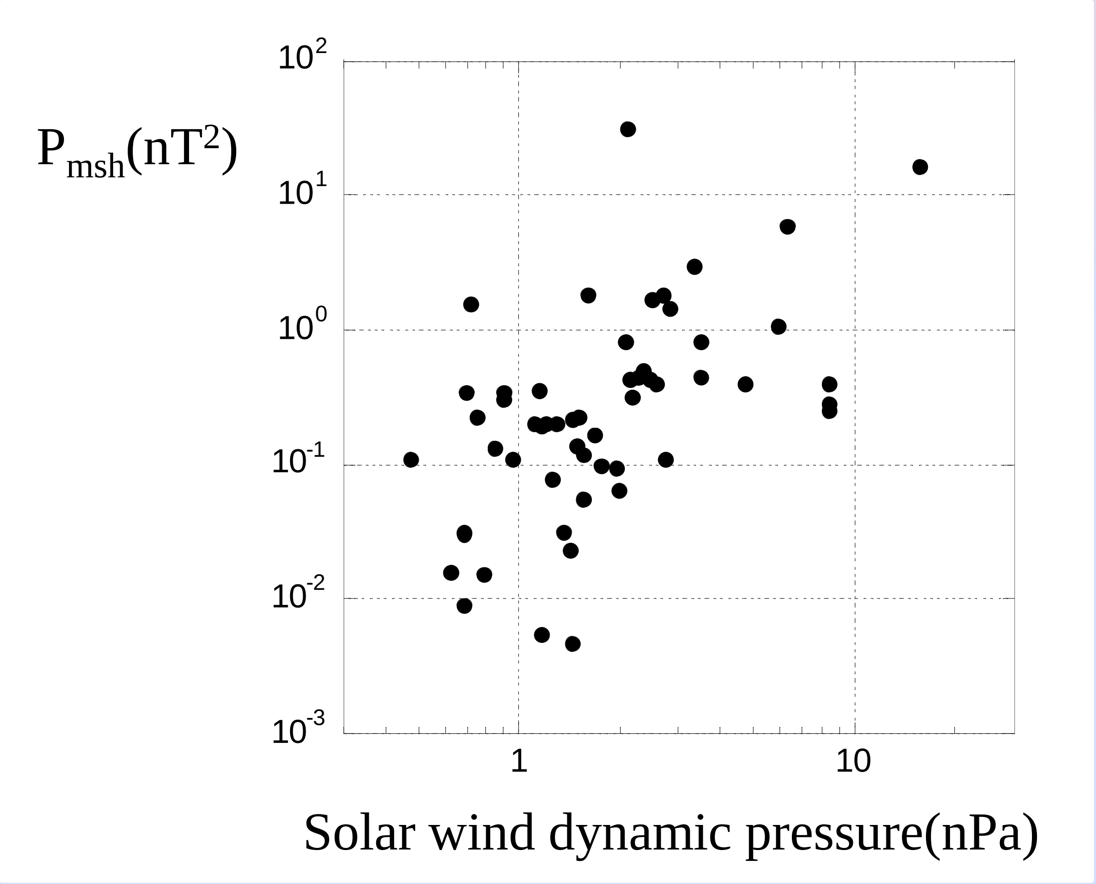
$$B^2 \sim k_v^{-8/3}$$



[Sahraoui et al., PRL., 2006]

Correlation with upstream activity

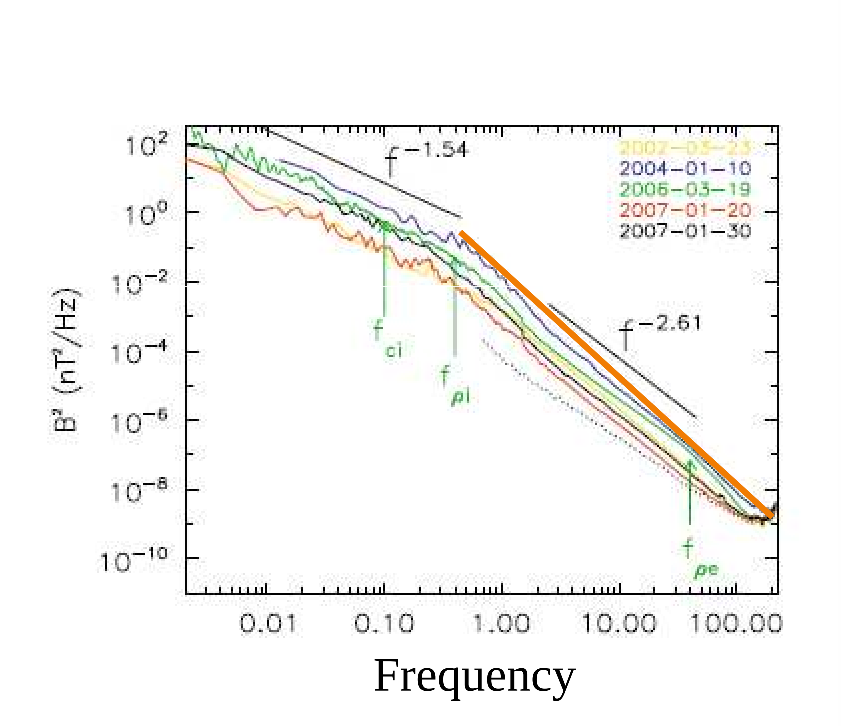
(CLUSTER)

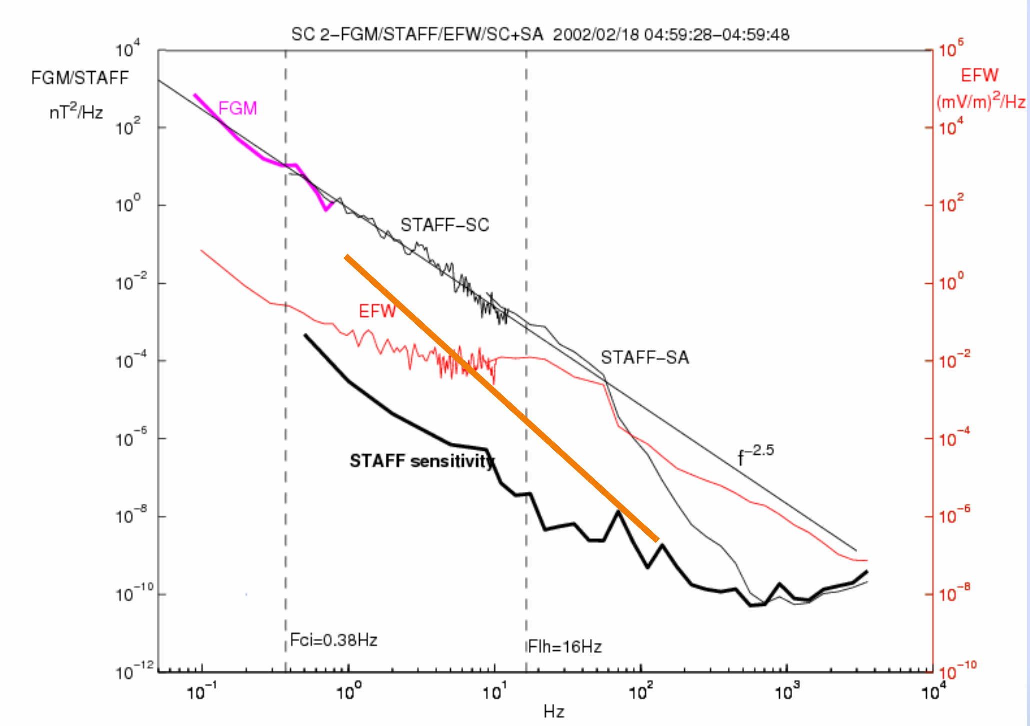


The magnetosheath low frequency fluctuations power is correlated to solar wind dynamic pressure

Turbulence is observed also in the solar wind

Spectra from STAFF and FGM merged at 1.5 Hz





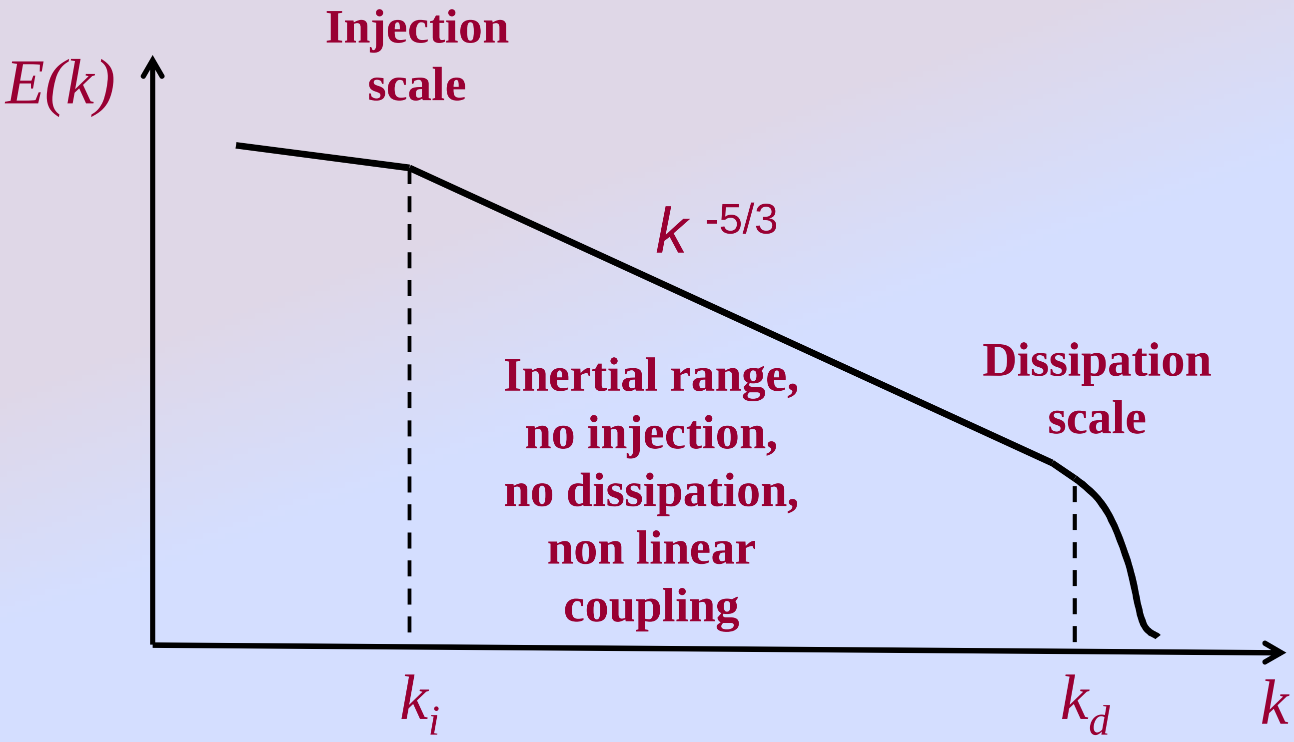
Solar wind

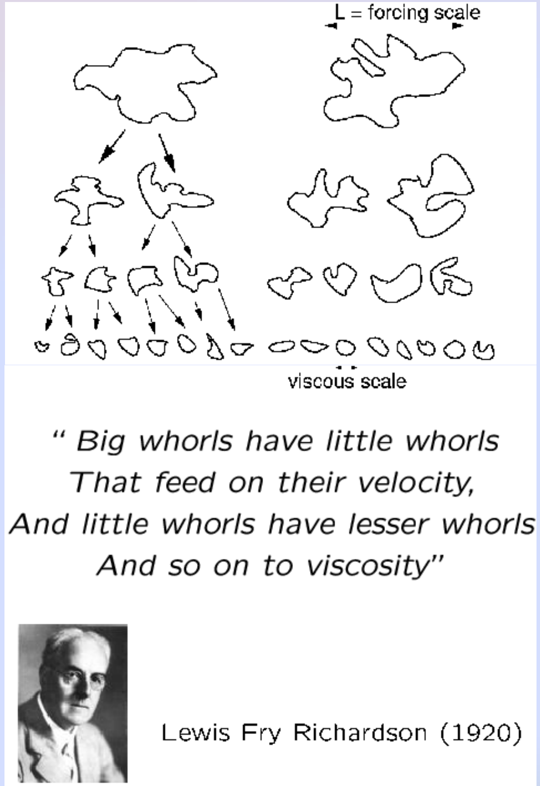
Magnetosheath

- The level is lower in the solar wind but higher than the sensitivity of the magnetometer
- Power laws are also observed

Our present knowledge and questions

Classical view of turbulence (hydrodynamics)



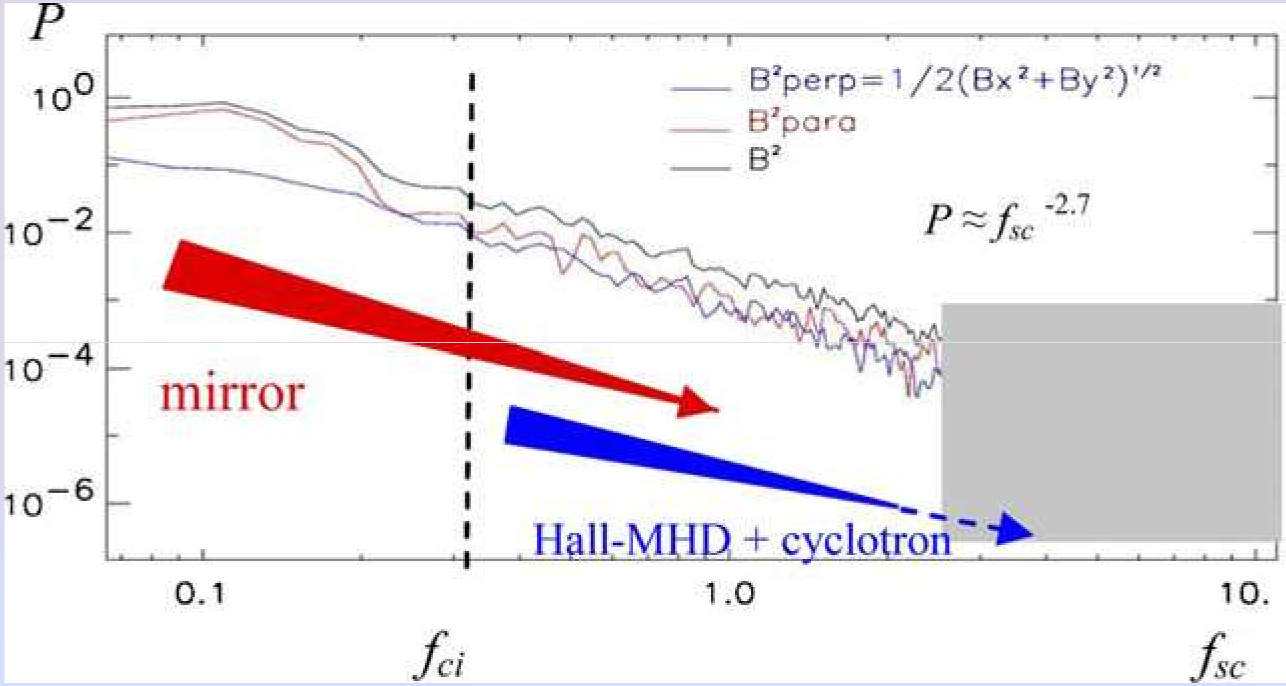


Is what we observe in space plasmas similar ?

Scales in the collisionless plasmas

- Very large scales in the solar wind
- Scale of the system (size of the magnetosheath) 50 000km
- Breaking of the scale invariance at ρ_i or d_i 100 km
- Breaking of the scale invariance at ρ_e or d_e 1 km
- No viscous dissipation scale $1/k_d$

Interpretation of the turbulence in the magnetosheath



Nature of the main modes determined in the magnetosheath by k-filtering, as a function of the frequencies observed in the spacecraft frame (superimposed on a magnetic energy spectrum).

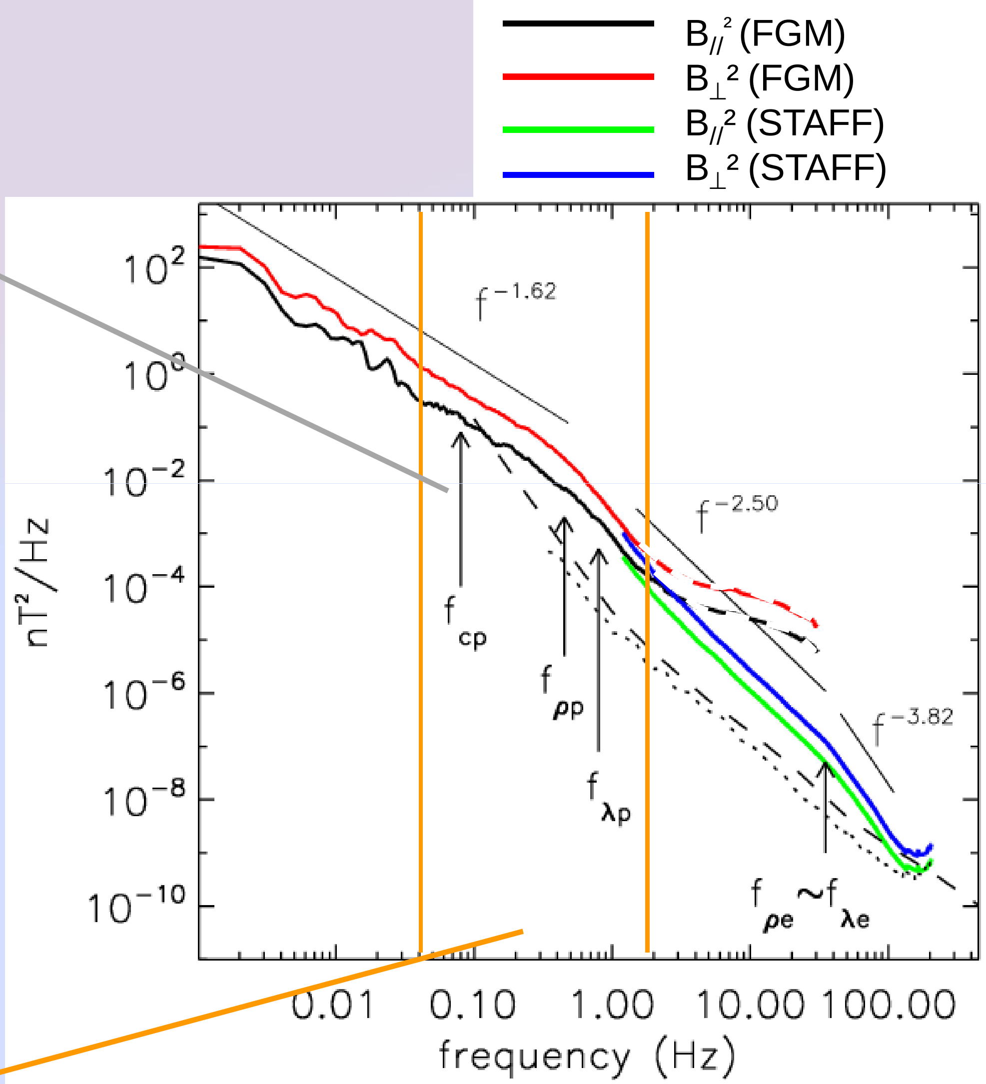
[Belmont et al., 2004]

Interpretation of the turbulence in the solar wind

Caracteristic frequencies obtained by Doppler-shifting the corresponding scales

1. Two breakpoints corresponding to ρ_i and ρ_e are observed.
2. A clear evidence of a new inertial range ~ $f^{-2.5}$ below ρ_i
3. First evidence of a dissipation range ~ f^{-4} near the electron scale ρ_e

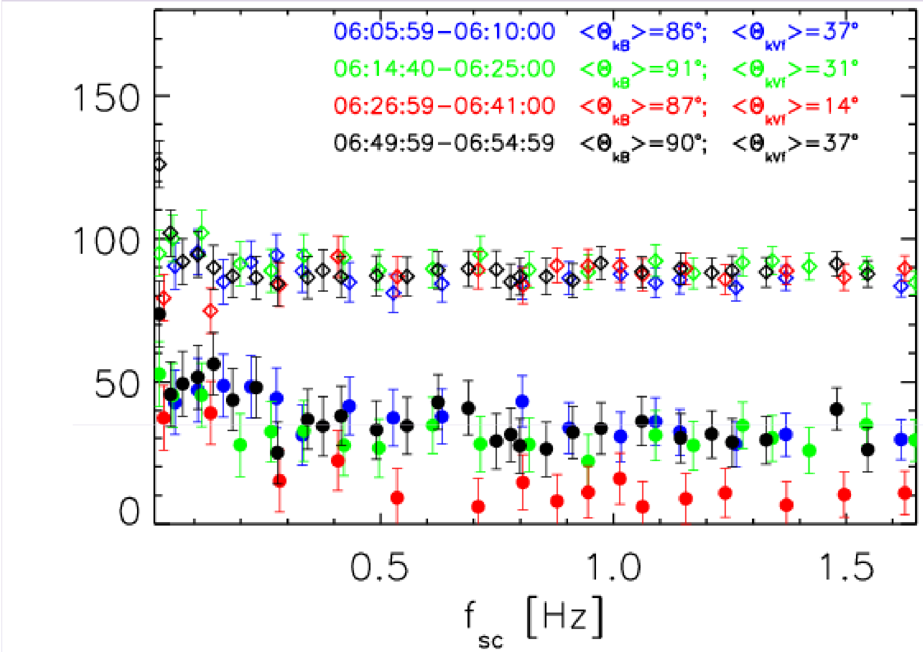
Range where k-filtering applies

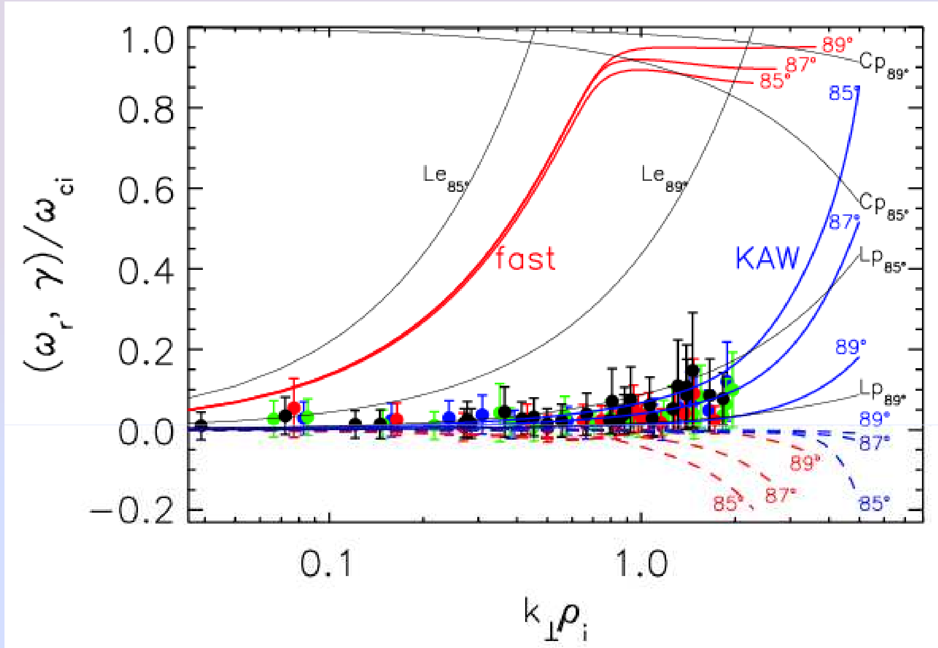


[Sahraoui et al., PRL, 2009]

K-filtering analysis

◇ $\Theta_{k,B}$ ● $\Theta_{k,V}$

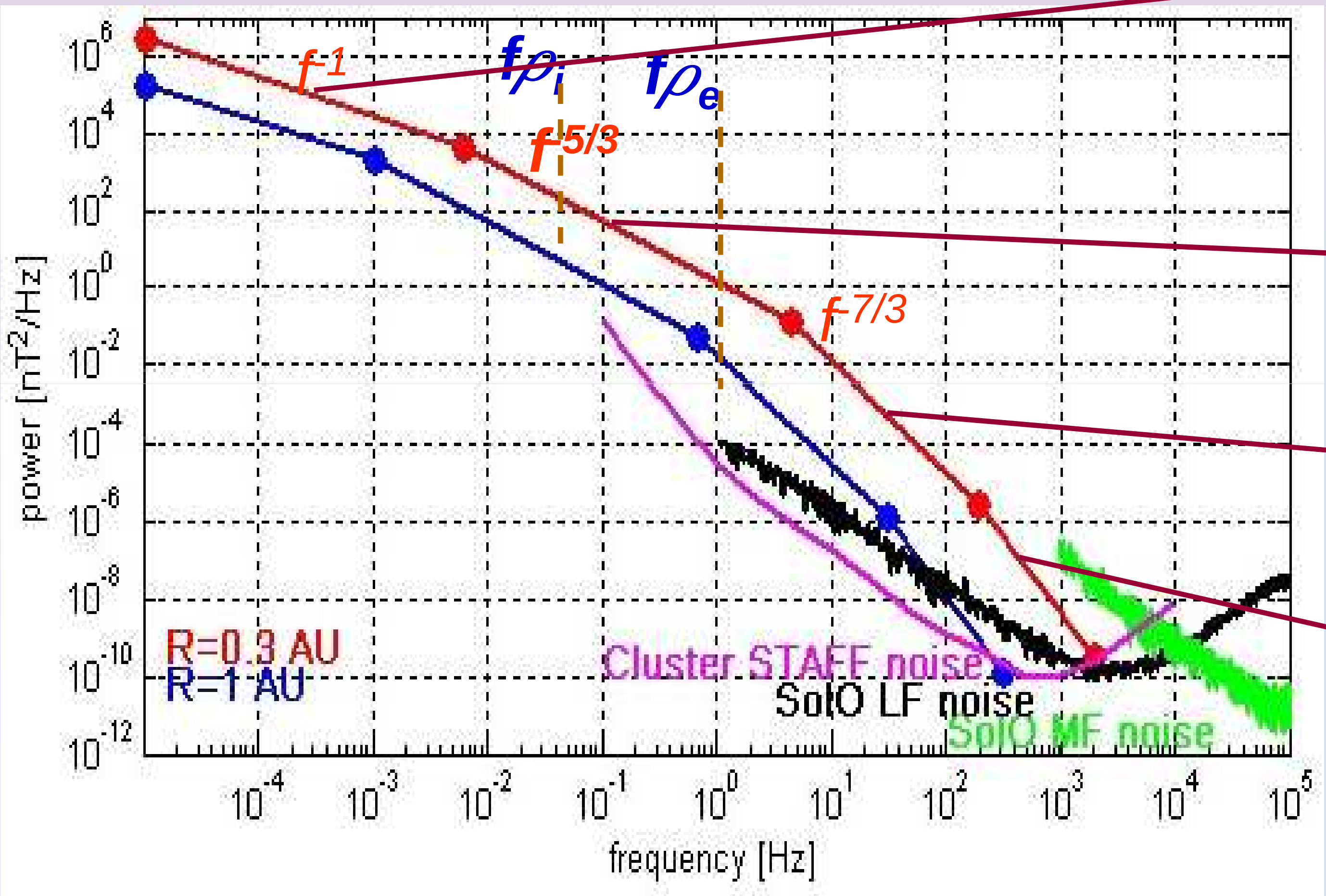




Turbulence is $\perp$ B_0 *but non axisymmetric* and quasi-stationnary ($\omega_{plas} \sim 0$)

Turbulence develops following the Kinetic Alfvén mode (KAW)

Interpretation of the turbulence in the solar wind



Very large scale coming from the Sun

Kinetic Alfven waves

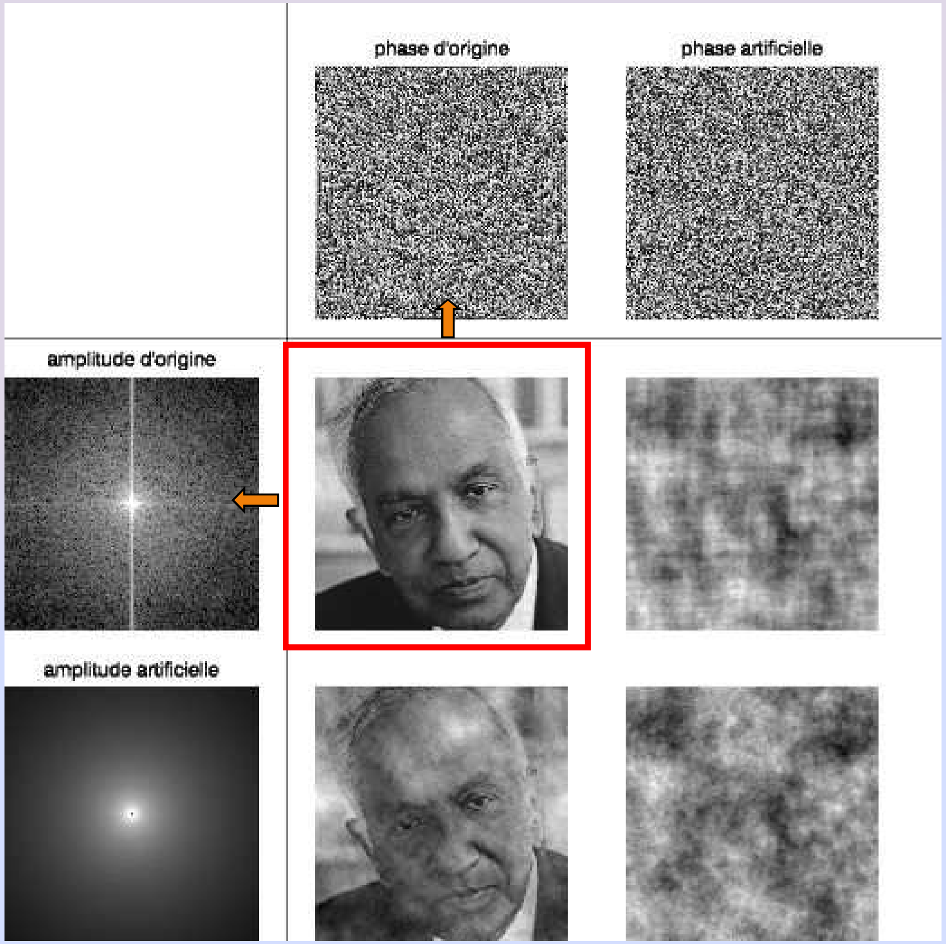
Hall MHD including ions

Electron dynamics Dissipation ?

[Sahraoui et al., PRL, 2009]

Phase analysis is important

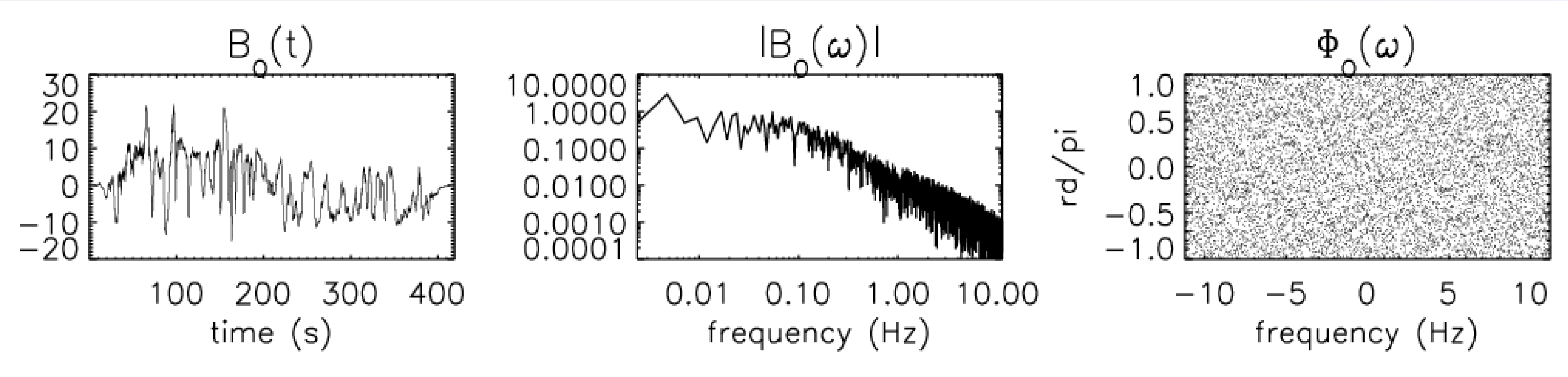
Respective role of waves and coherent structures: vortices have been observed in some cases
Possibility of intermittency



Phases contain critical information for understanding the structure of the signal

And we shouldn’t drop half of the information

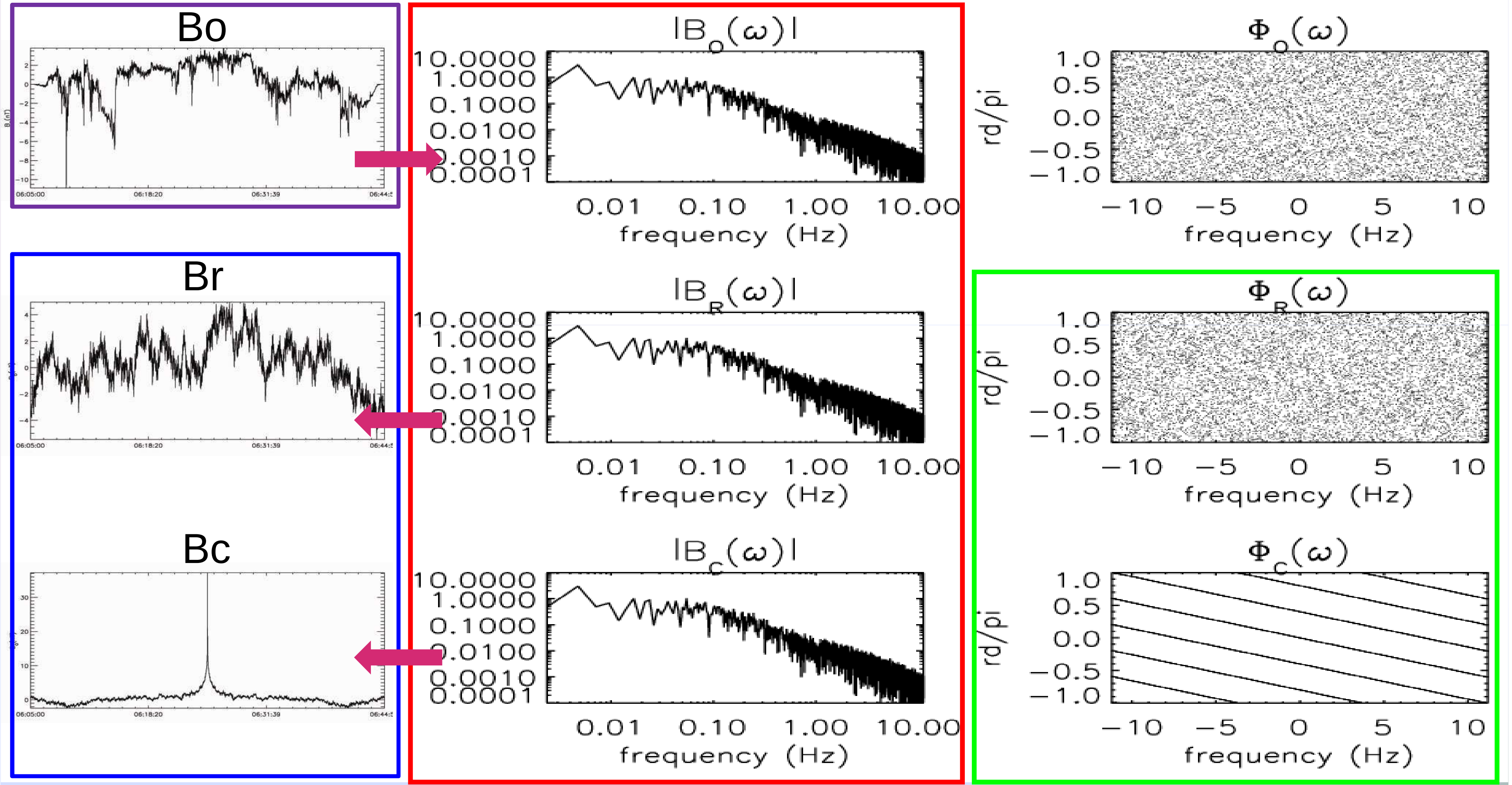
Direct use of phases impossible



Because of the folding between 0 and 2π, the phases always look random

Surrogate signals

Original signal



Reconstructed signals **The spectrum is not modified** **The phases are changed**

Structure functions and coherence index

Structure functions

$$S_q(\tau) = \frac{1}{n_\tau} \sum_{t=0}^{n_\tau} \left| x(t+\tau) - x(t) \right|^q$$

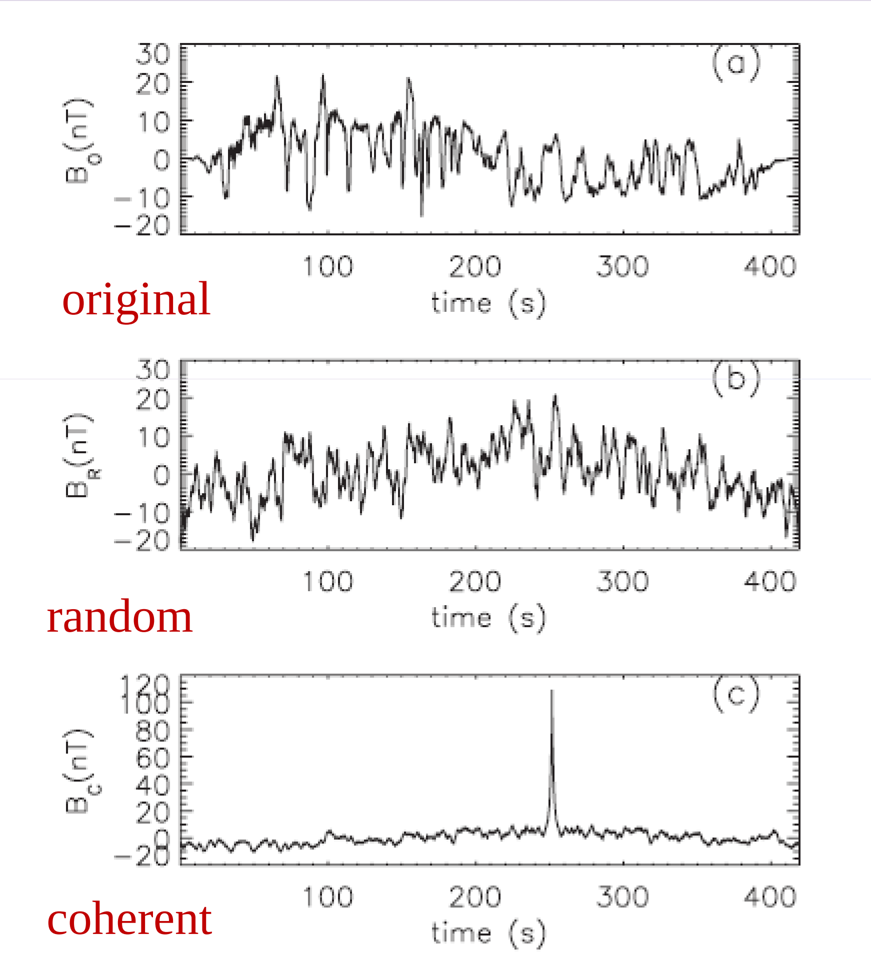
calculated for original signal, random signal and coherent signal

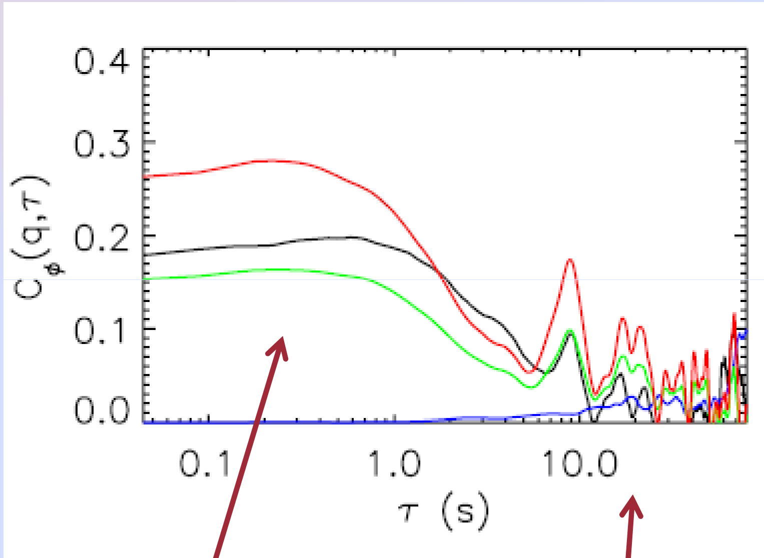
Coherence indices for $q \neq 2$

$$C_\Phi(q,\tau) = \frac{|S_O(q,\tau) - S_R(q,\tau)|^{1/q}}{[|S_O(q,\tau) - S_R(q,\tau)| + |S_O(q,\tau) - S_C(q,\tau)|]^{1/q}}$$

$C_\Phi(q,\tau) = 1 \rightarrow B_O$ is coherent
$C_\Phi(q,\tau) = 0 \rightarrow B_O$ is random

Example on magnetosheath Cluster data





Significant coherence at small scales

No coherence at large scales

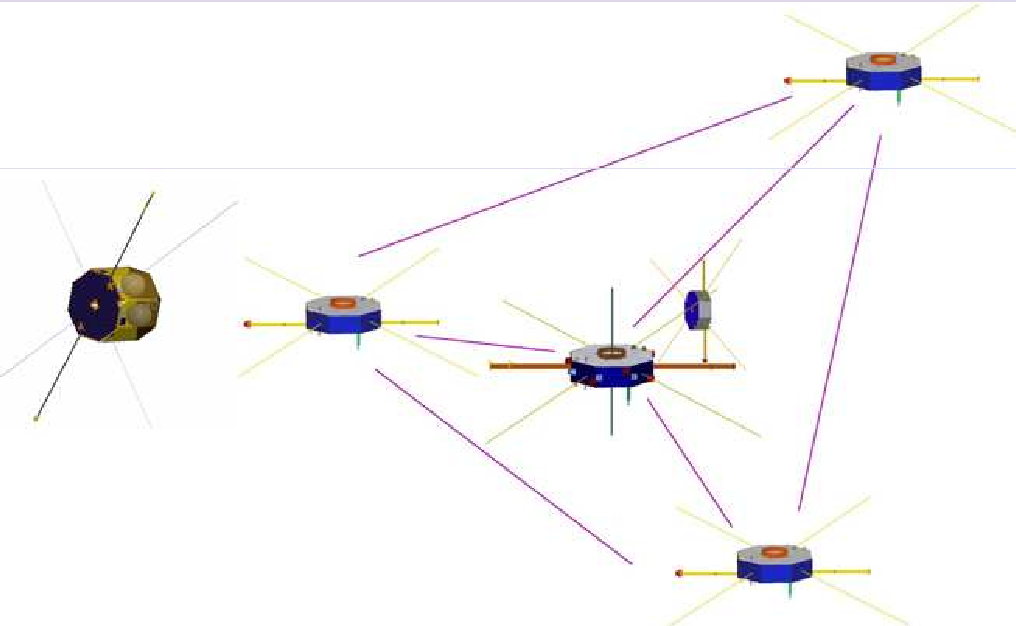
[Sahraoui, 2008]

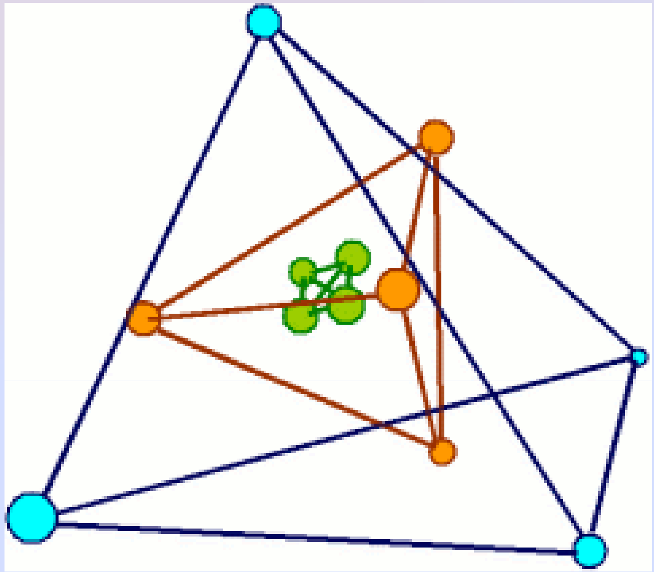
Conclusion

The 4 point CLUSTER measurements together with sophisticated signal processing methods allow to understand the physics of the small-scale fluctuations in the different regions of the magnetophere and solar wind….

But we are limited in the scales we can explore
→ new concepts of missions

Future possible missions



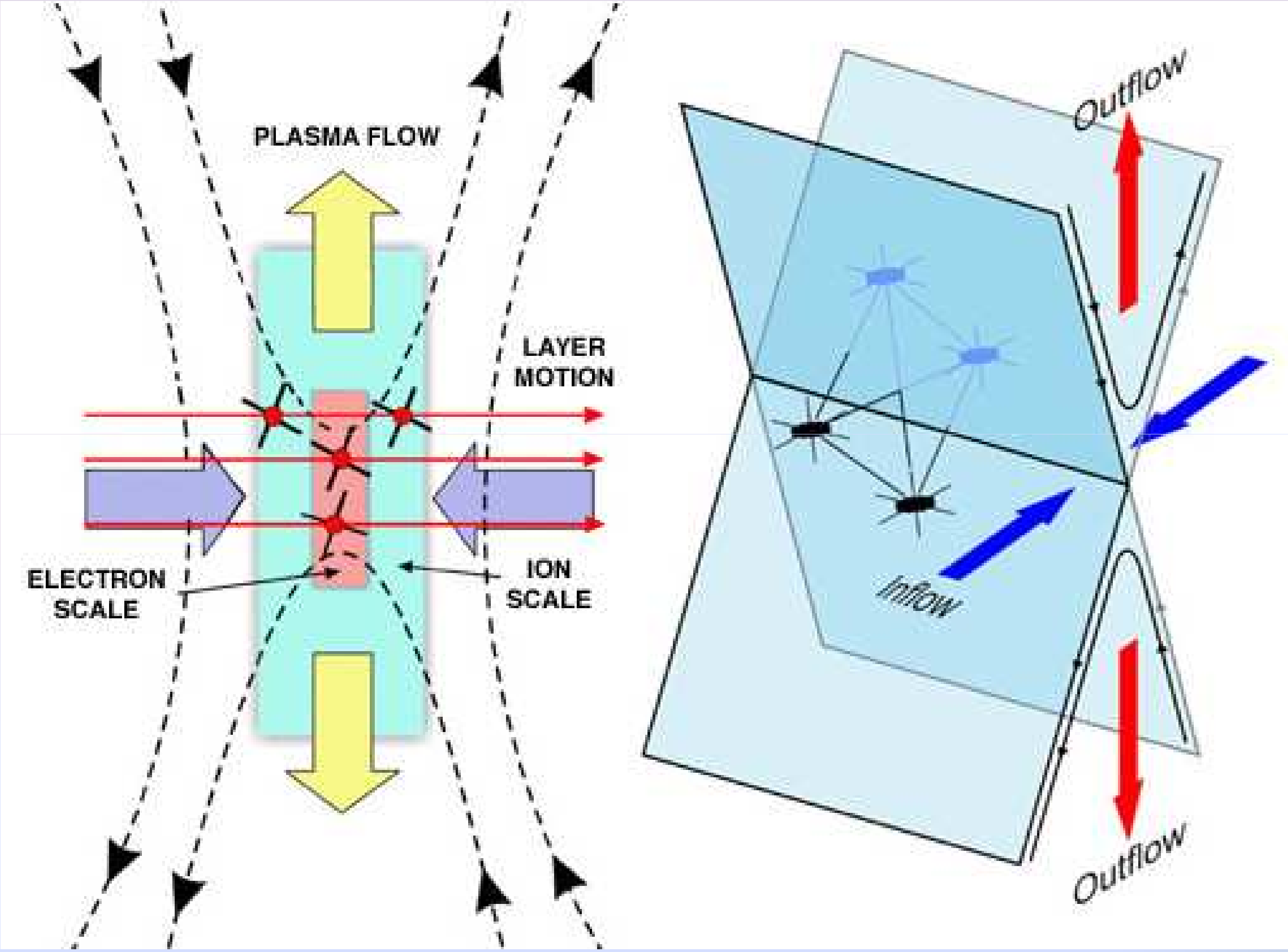


CROSS-SCALE

EIDOSCOPE

multiscale

MMS: launch August 2014



Magnetospheric Multiscale Mission (NASA)

small scale

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