Small scale solar wind turbulence: Recent observations and theoretical modeling

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Outline

- Motivations
- Solar wind turbulence : cascade *vs* dissipation below the ion scale ρ_i
- Different theoretical predictions on small scale plasma turbulence
- High resolution Cluster data to analyze small scale SW turbulence
  1. ***Clear evidence of a new inertial range below ρ_i***
  2. ***First evidence of a dissipation range @ ρ_e***
  3. ***Theoretical interpretation (KAW turbulence)***
- Conclusions

Turbulence in the Univers

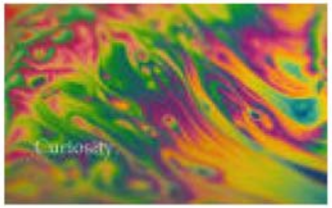
M100 galaxy 10^{23} m

Eagle nebula 10^{18} m

Sun-Earth ~*10^{11} m*

Earth's atmosphere 10^{7} m

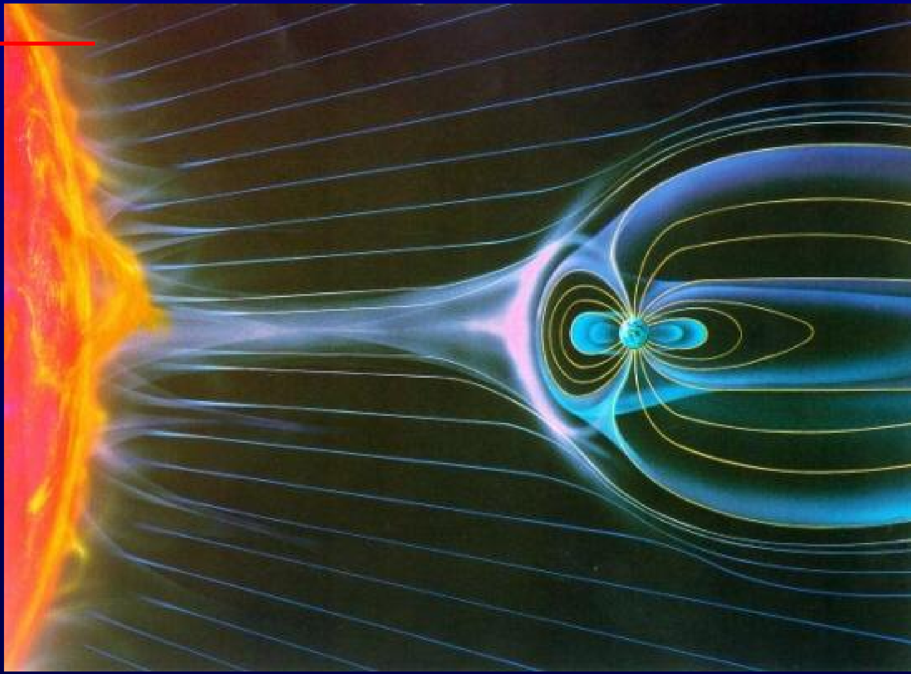
Clouds 10^{3} m



Soap film 10^{-1} m

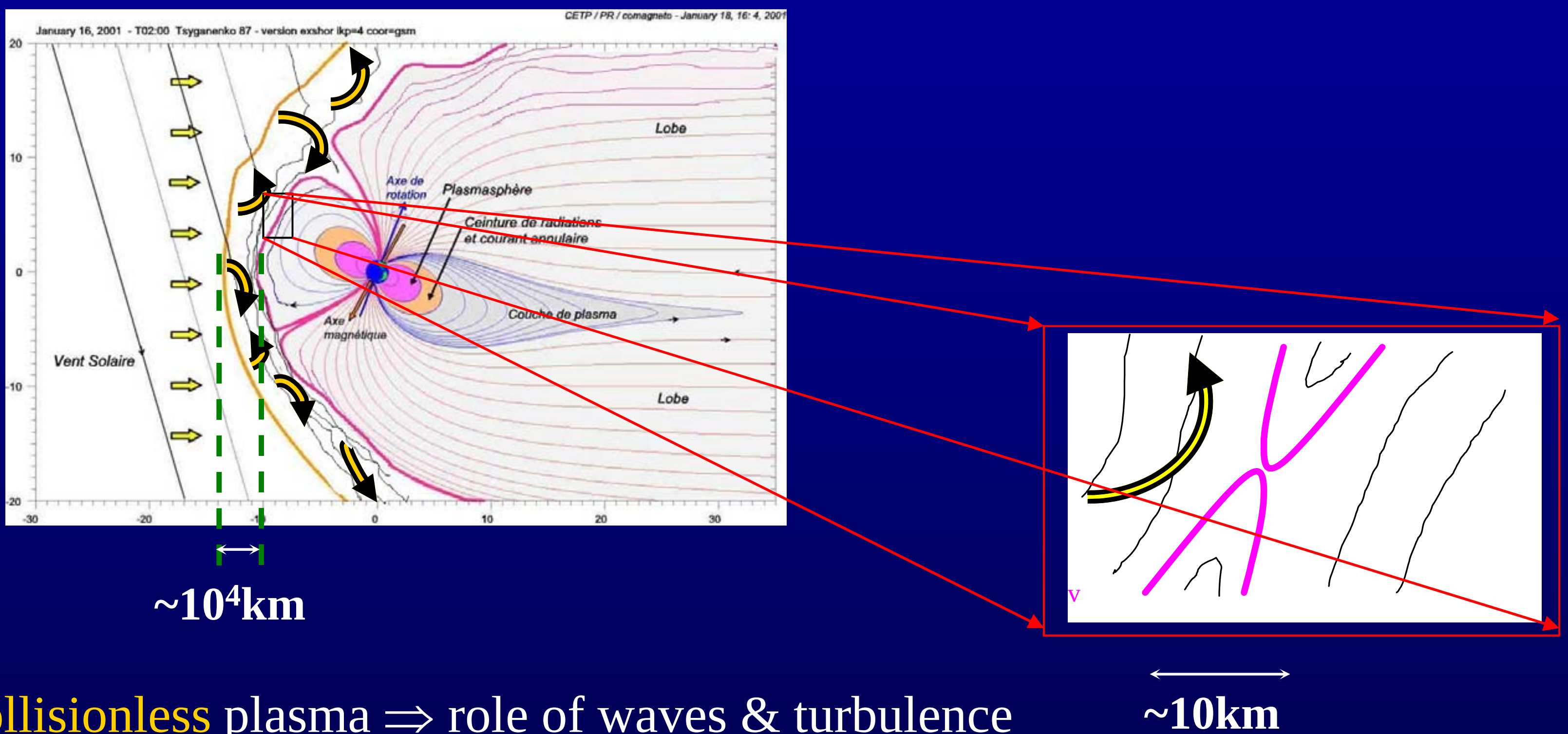
is observed from cosmological to quantum scales!

Controls mass transport, energy transfers & heating, ***magnetic reconnection in plasmas(?)***, …



Turbulent reconnection in the Magnetosphere

Can ULF turbulence drive transfers across the magnetopause?



Collisionless plasma ⇒ role of waves & turbulence

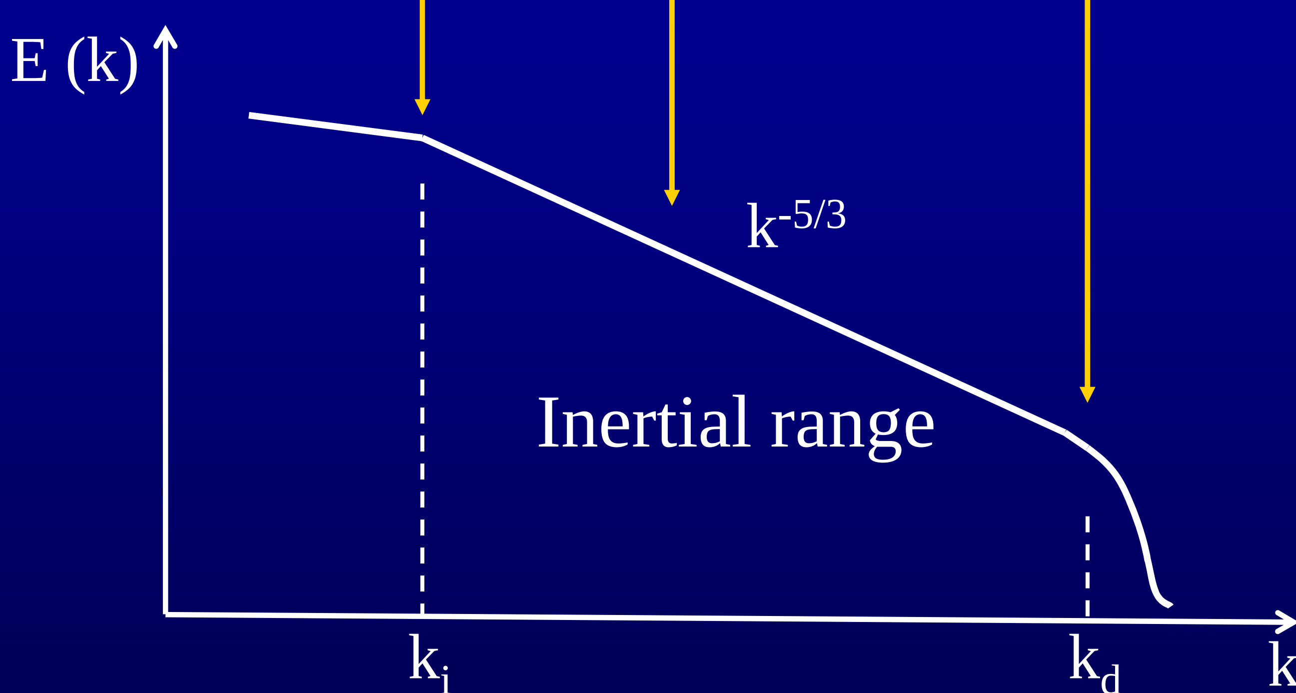
• Large scale ULF turbulence *(~10^4km)* in the magnetosheath may drive reconnection at small scales (*~km*) via a cascade process

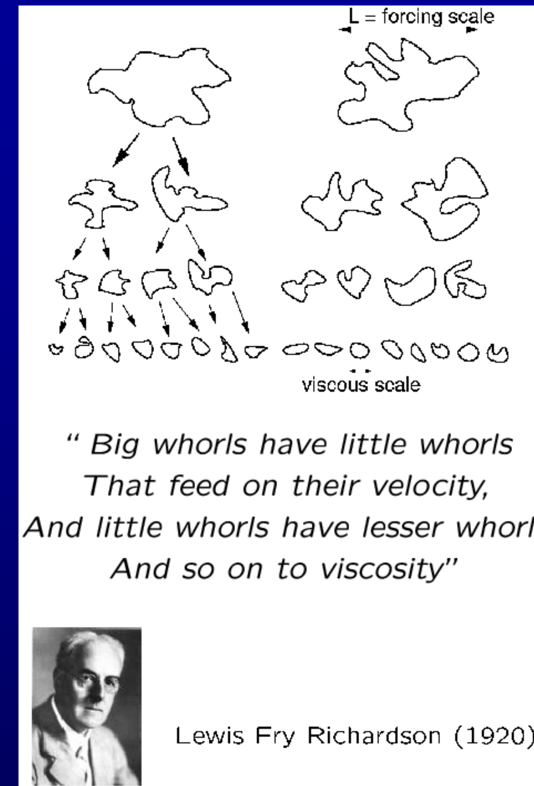
• Reconnection as a mechanism to dissipate small scale turbulence (Sundkvist et al., PRL, 07) dissipates

Phenomenology of turbulence

NS equation:

$$\partial_t \mathbf{V} + \mathbf{F}_i = \mathbf{V}.\nabla\mathbf{V} - \nabla P - \nu\nabla^2\mathbf{V}$$



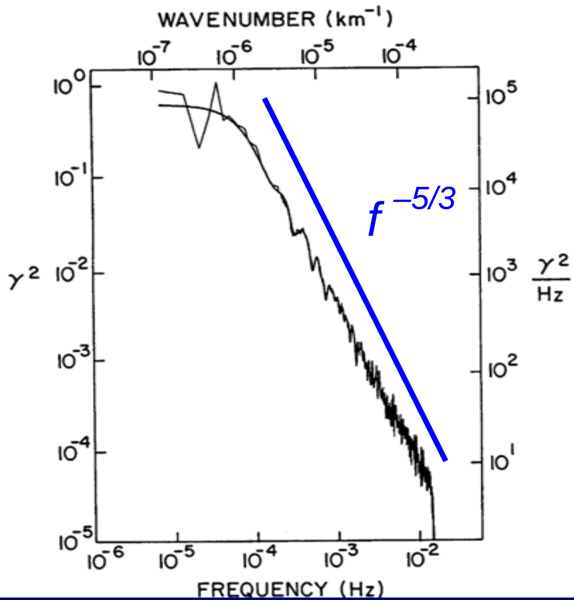


- Idealistic image (even in NS): e.g., doesn't account for intermittency
- More complex situation in plasmas: - several eigenmodes/observables **V**,**B**,**E**…

  - breaking of the scale invariance assumption at $\rho_{i,e}$ $d_{i,e}$

Solar wind turbulence

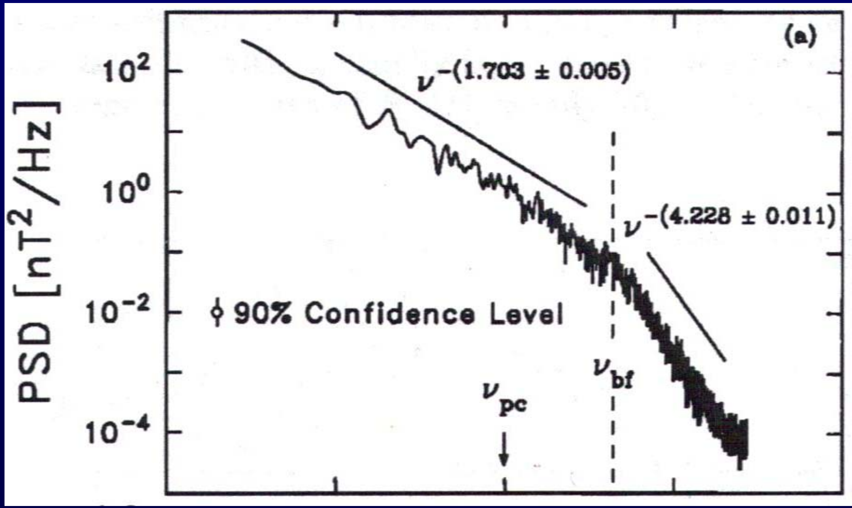
Matthaeus & Goldstein, 82



Typical power spectrum of magnetic energy at 1 AU

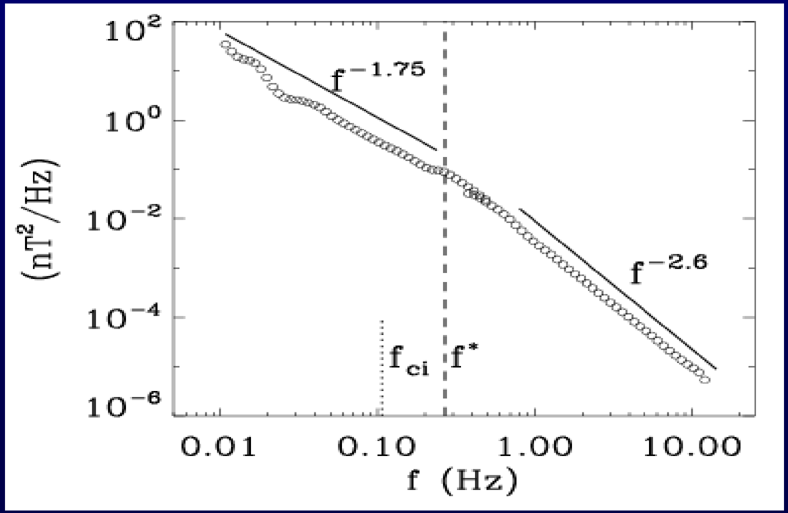
What happens to the energy at and below the ion scale ?

Dissipation at f_{ci} (or ρ_i)



Leamon *et al.* 98; Goldstein *et al.* JGR, 94

Cascade below f_{ci} (or ρ_i)

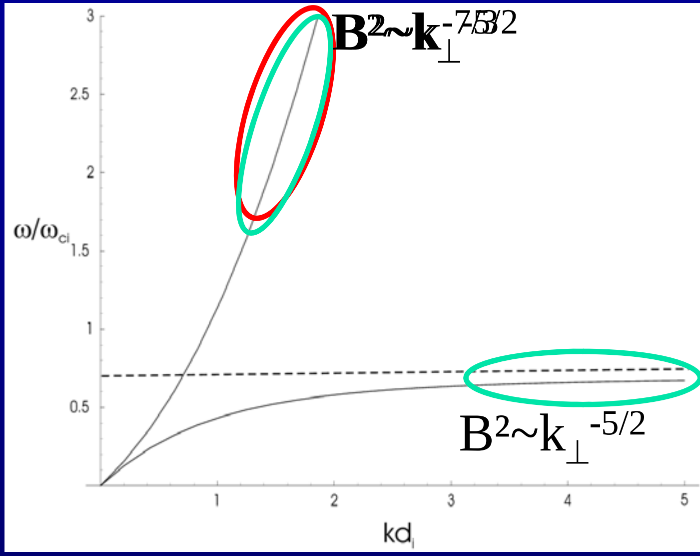


Alexandrova *et al.*, 08, Bale *et al.*, 05

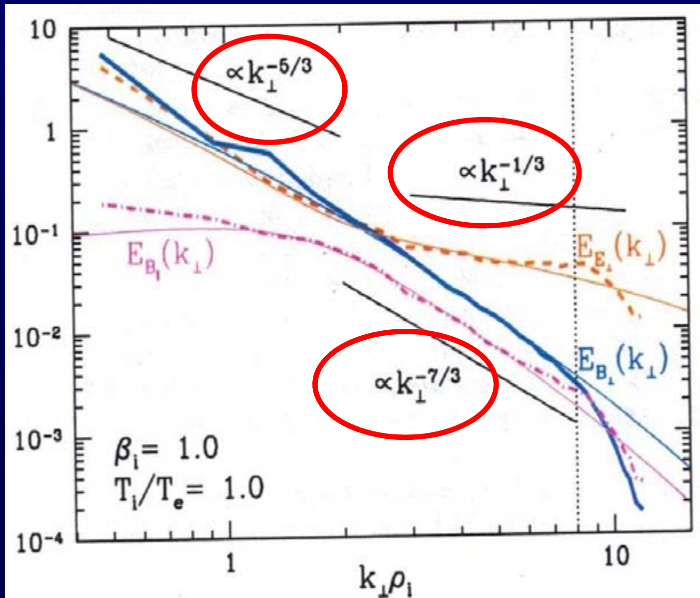
Theoretical predictions on small scale turbulence

$$\mathbf{E} + \mathbf{V} \times \mathbf{B} = \frac{1}{en} \mathbf{J} \times \mathbf{B} - \frac{\nabla P_e}{en} + \ldots$$

1. Fluid models (Hall-MHD)
   - Whistler turbulence (E-MHD): (Biskamp *et al.*, 99, Galtier, 08)
   - Weak Turbulence of Hall-MHD (Galtier, 06; Sahraoui, 07)



2. Gyrokinetic theory: $k_{//} << k_\perp$ and $\omega << \omega_{ci}$ (Schekochihin *et al.* 06; Howes *et al.*, 08)

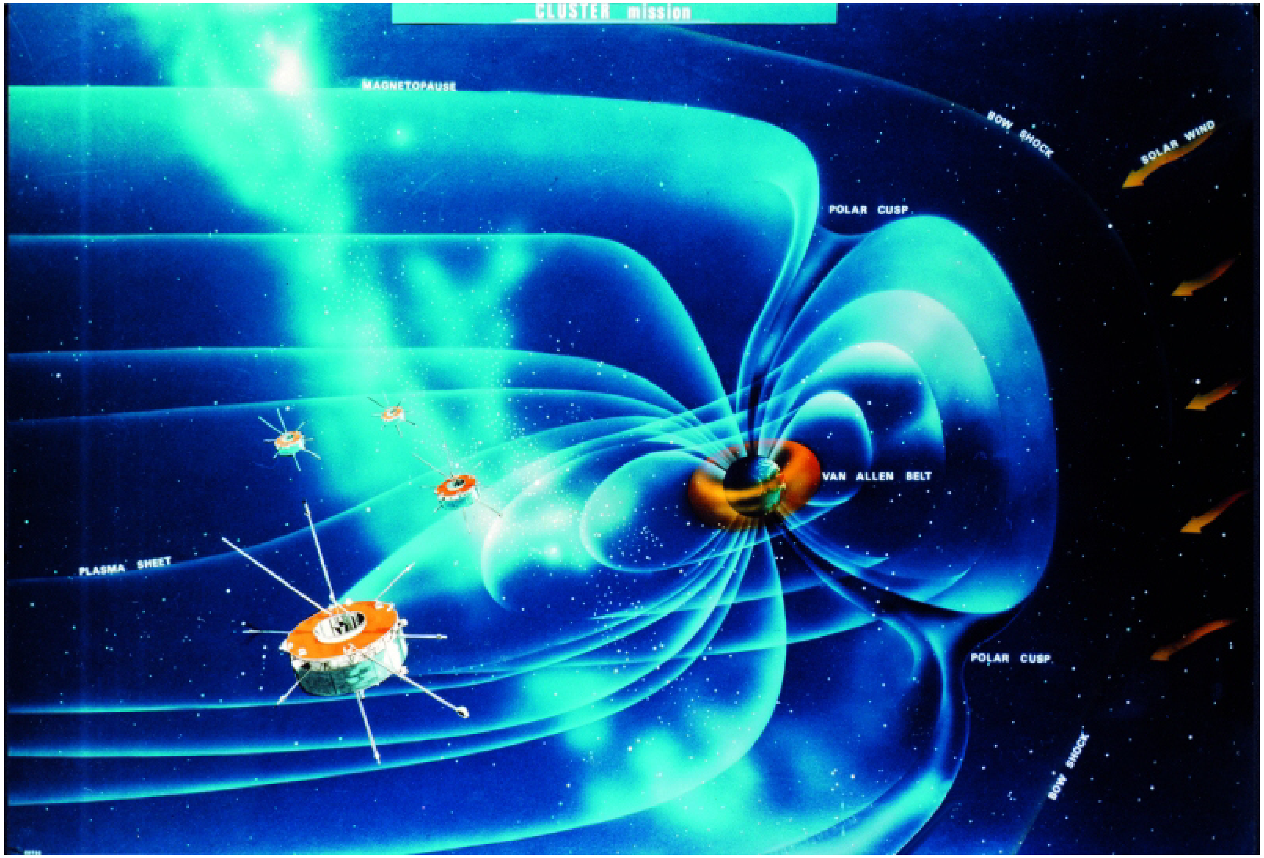


The Cluster mission

Four identical satellites of ESA

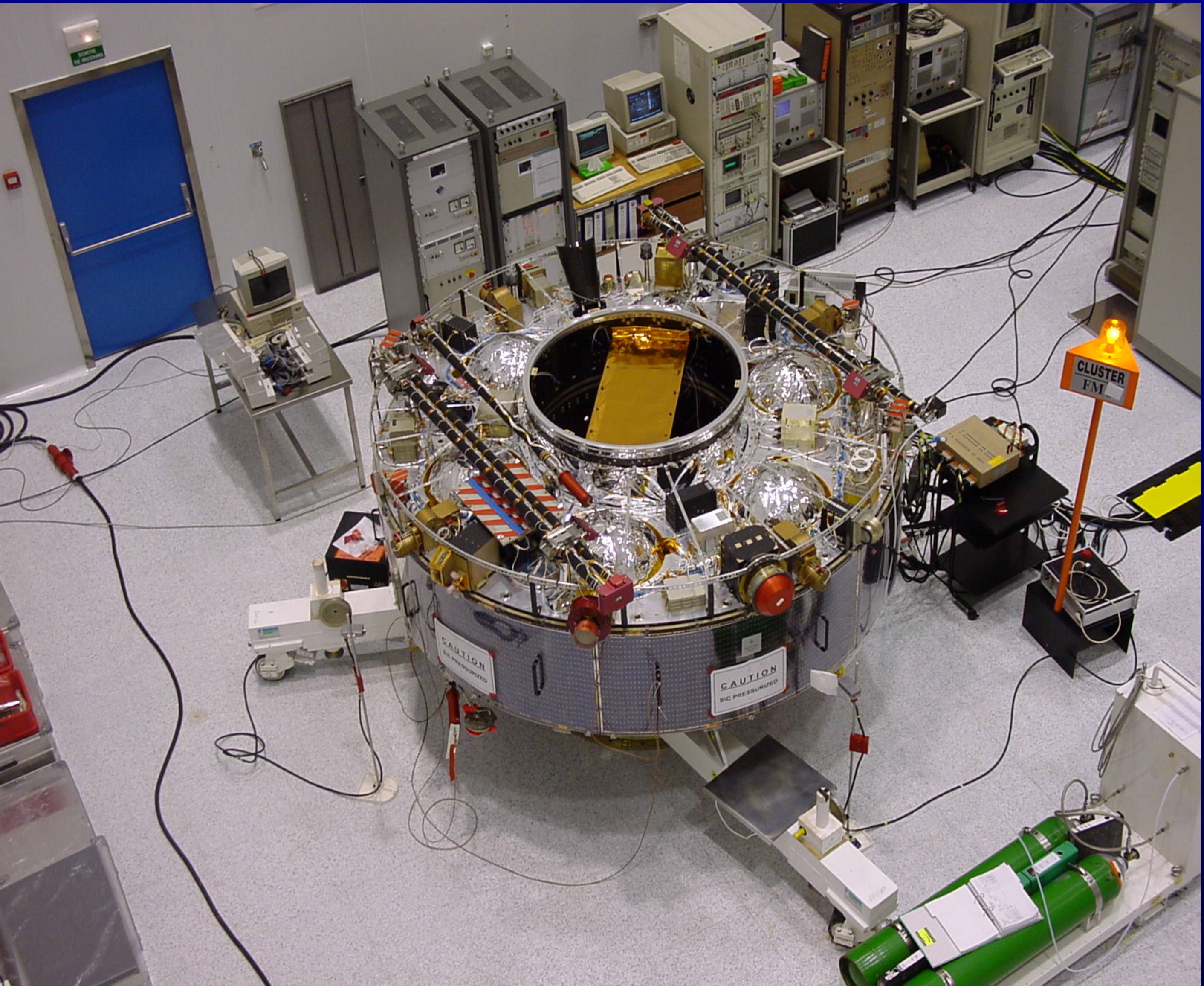
Objetives:

- **3D exploration** of the Earth magnetosphere boundaries (magnetopause, bow shock, magnetotail) & SW
- **Fundamental physics**: turbulence, reconnection, particle acceleration, …



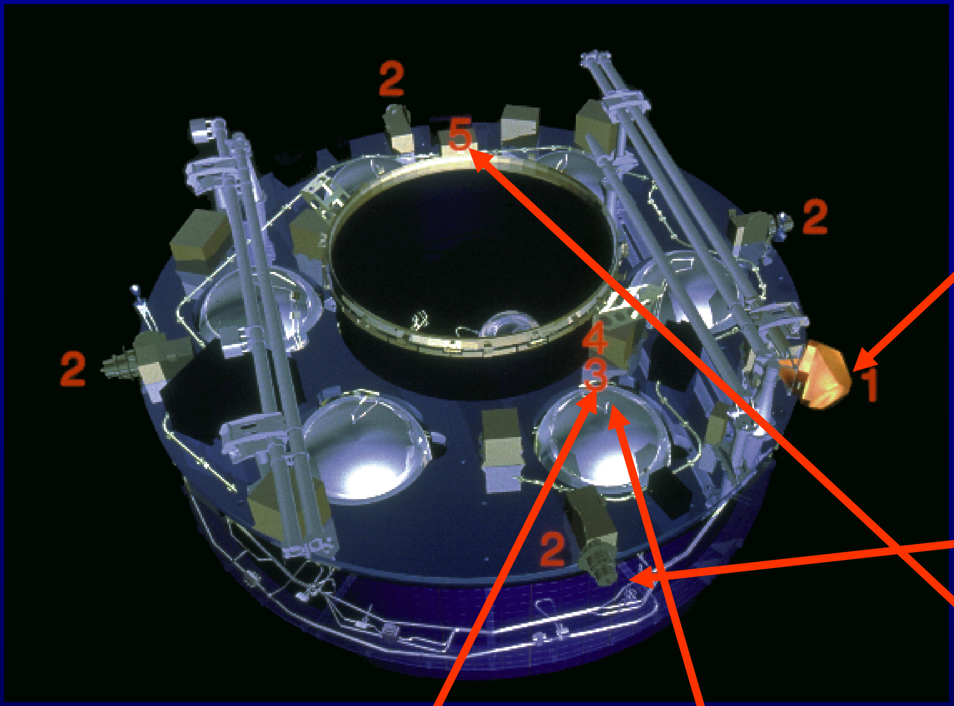
Different orbits and separations (100 to 20000km) depending on the scientific goal

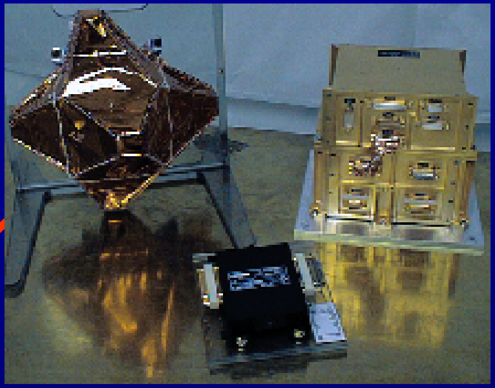
View of a single spacecraft



42 experiments provide wave & particle data since December 2000

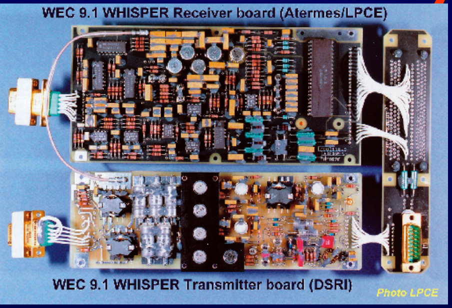
Wave consortium





STAFF (LPP/LESIA, France)

EFW (IRFU, Sweden)



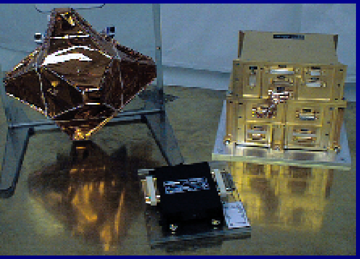
DWP (UK)

WBD

WHISPER, LPCE, France

The data used here

Flux Gate magnetometer ⇒ magnetic field data up to ~1Hz

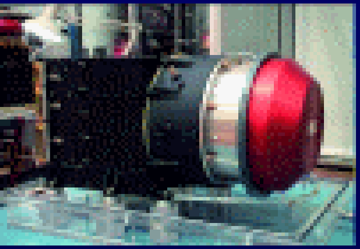


STAFF-Search Coil ⇒ magnetic field fluctuations

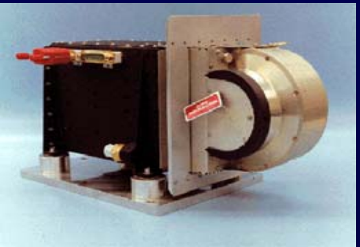
EFW ⇒ Electric field data

Two modes:

- 12Hz
- **225Hz**



Ion spectrometer ⇒ Ion moments: N_i, $\mathbf{V_i}$, T_i (4sec)



Electron Analyser ⇒ Electron moments: N_e, $\mathbf{V_e}$, T_e (4sec)

Small scale solar wind turbulence

Position of the Quartet on March 19, 2006

Position

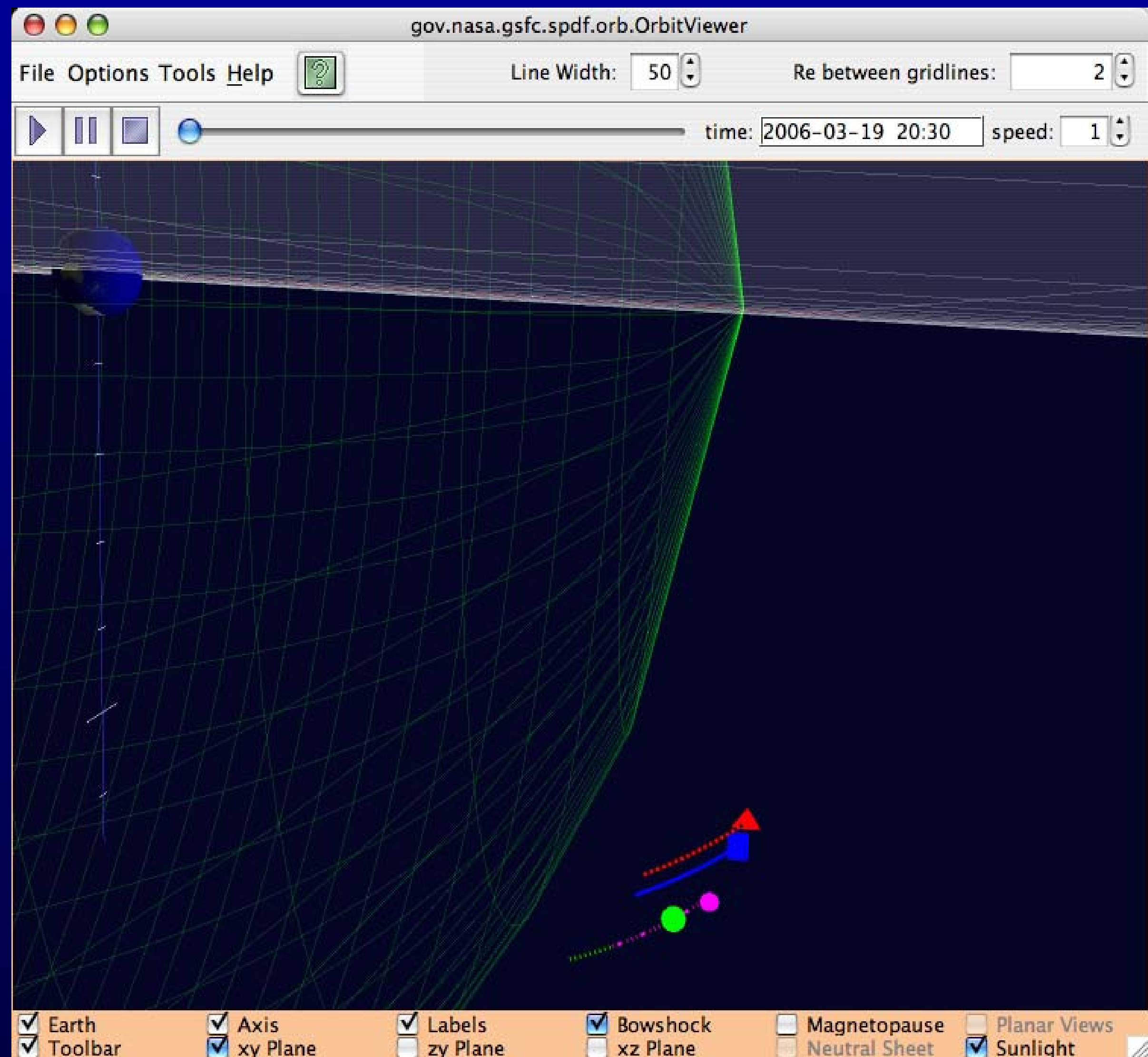
time:

2006-03-19 20:30

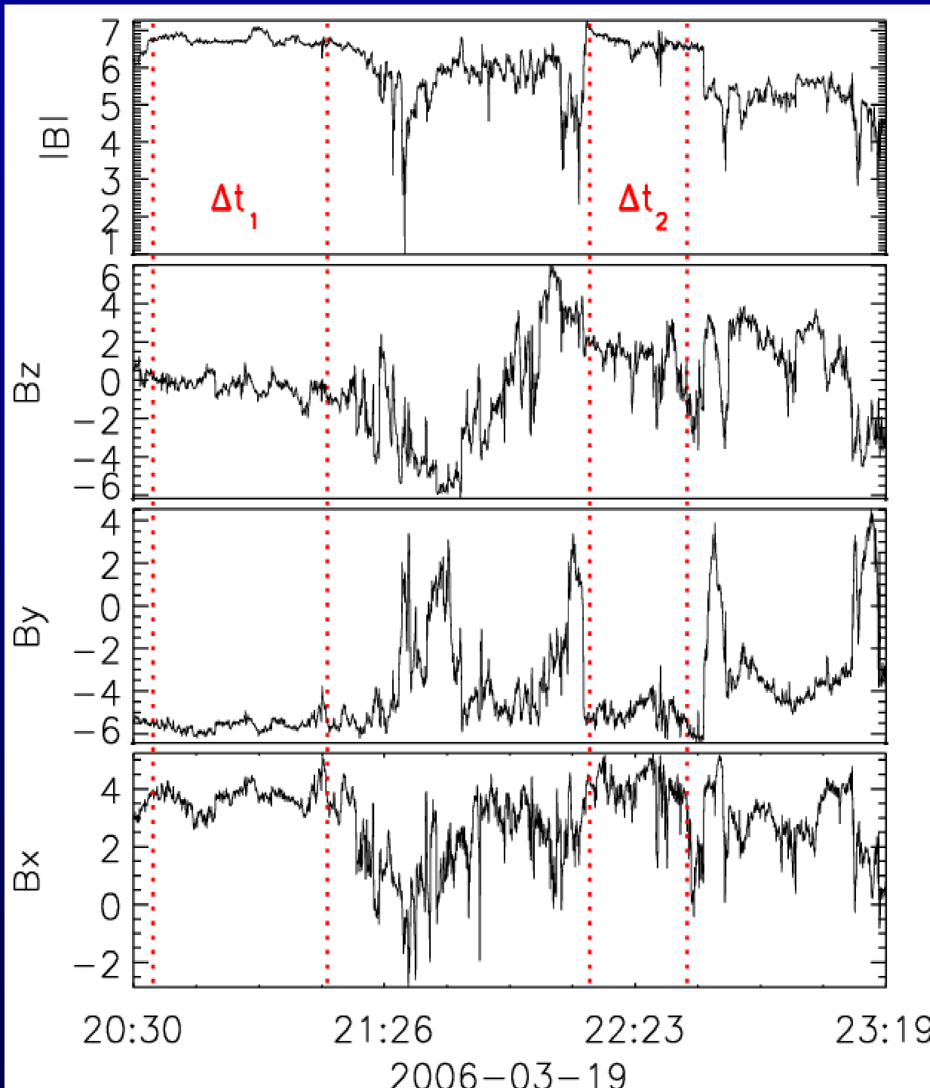
Coordinate System:

GSE

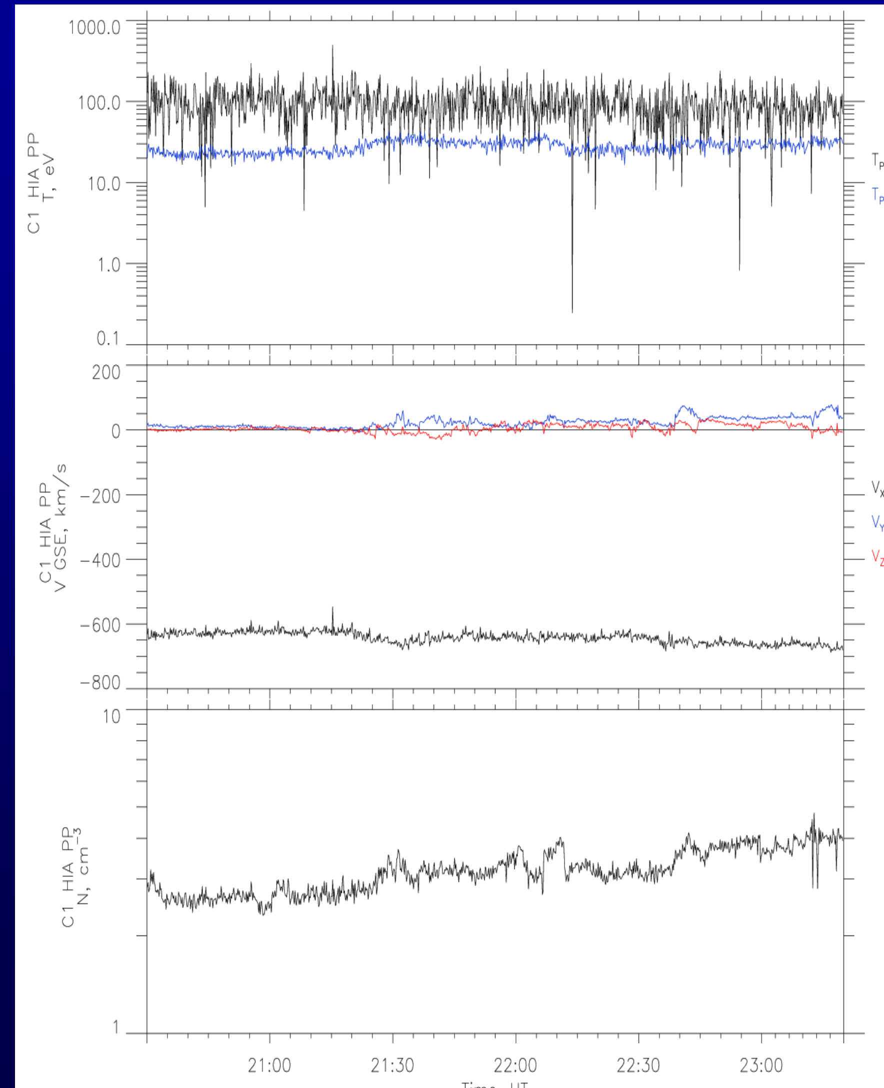
Satellite	Color	X	Y	Z
Cluster-1	blue	15.038	-6.569	-9.299
Cluster-2	red	15.139	-7.034	-8.672
Cluster-3	green	13.979	-7.397	-10.41
Cluster-4	magenta	14.587	-7.292	-9.987



FGM data (CAA, ESA)

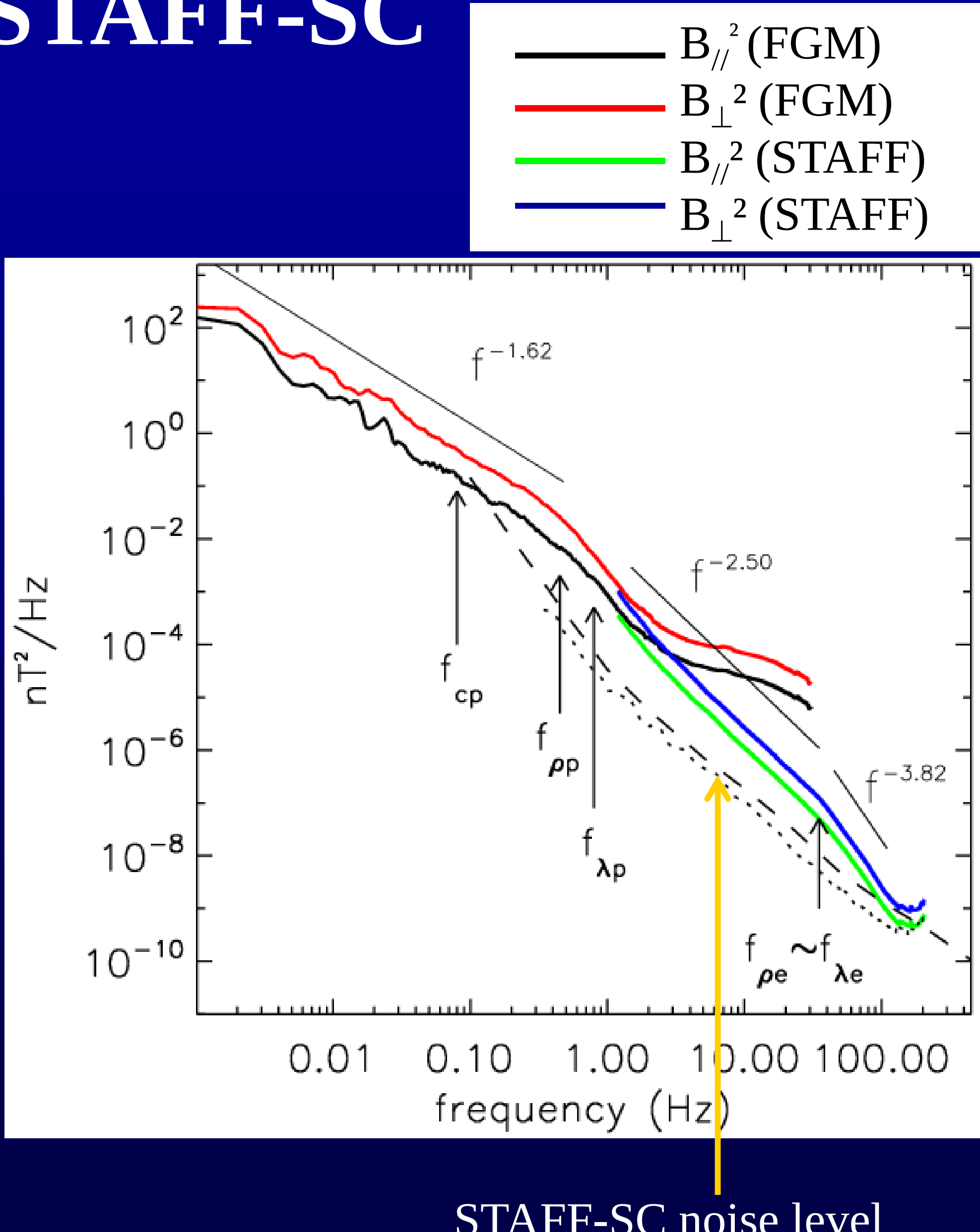


Proton plasma data from CIS (AMDA, CESR)

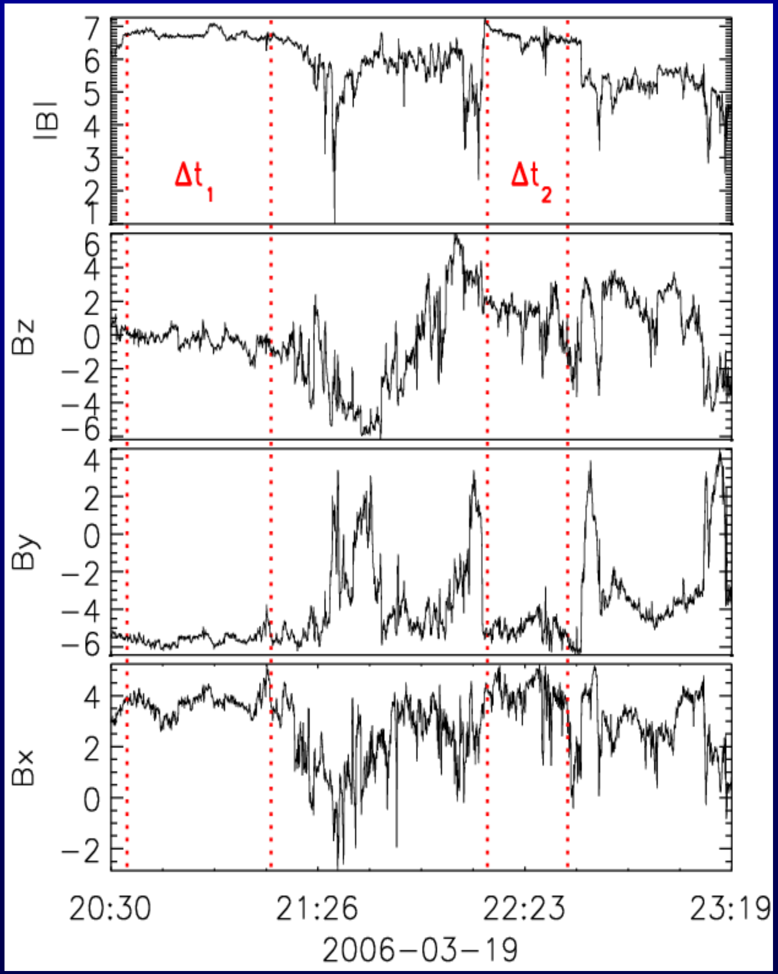


High resolution magnetic field data from FGM and STAFF-SC

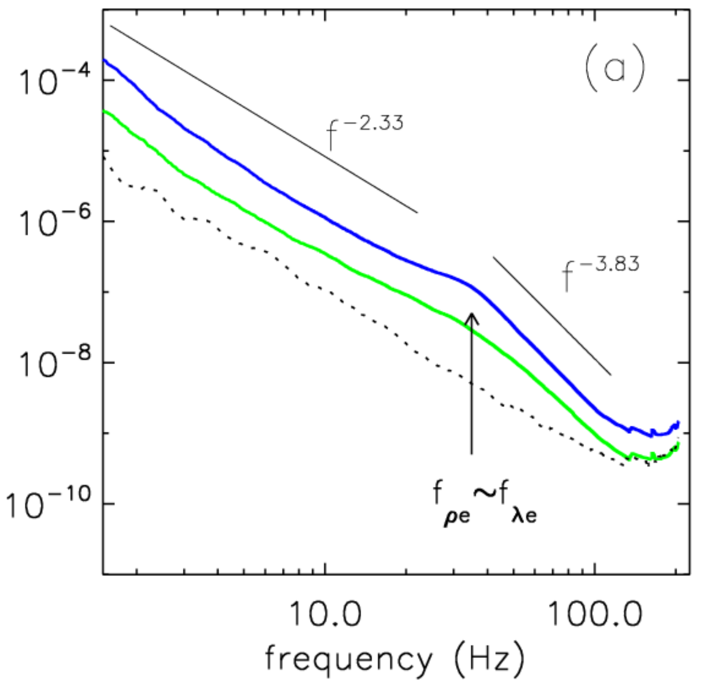
1. Two breakpoints, corresponding to ρ_i and ρ_e, are observed.
2. A clear evidence of a new inertial range ~ $f^{-7/3}$ below ρ_i
3. ***First evidence of a dissipation range ~ f^{-4} at electron scale ρ_e***



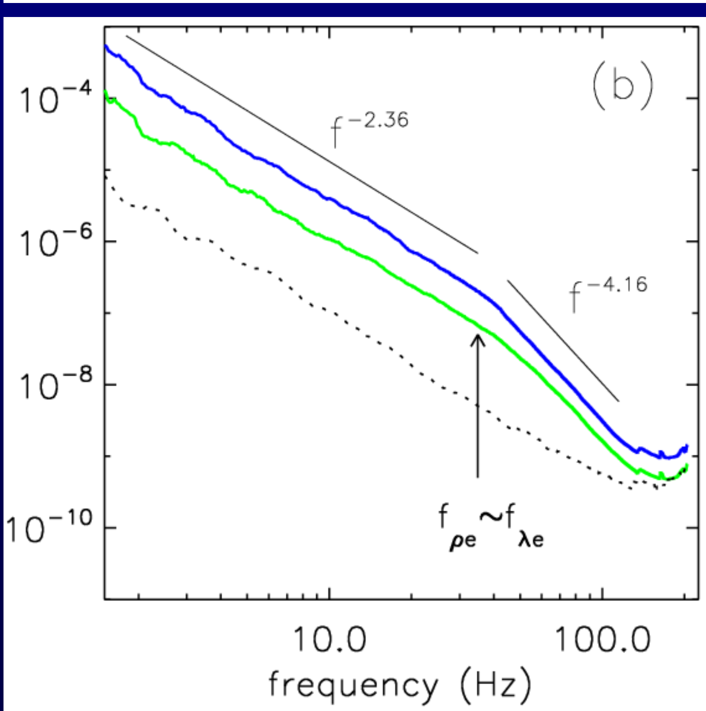
Zoom on small scales



From ΔT_1



From ΔT_2



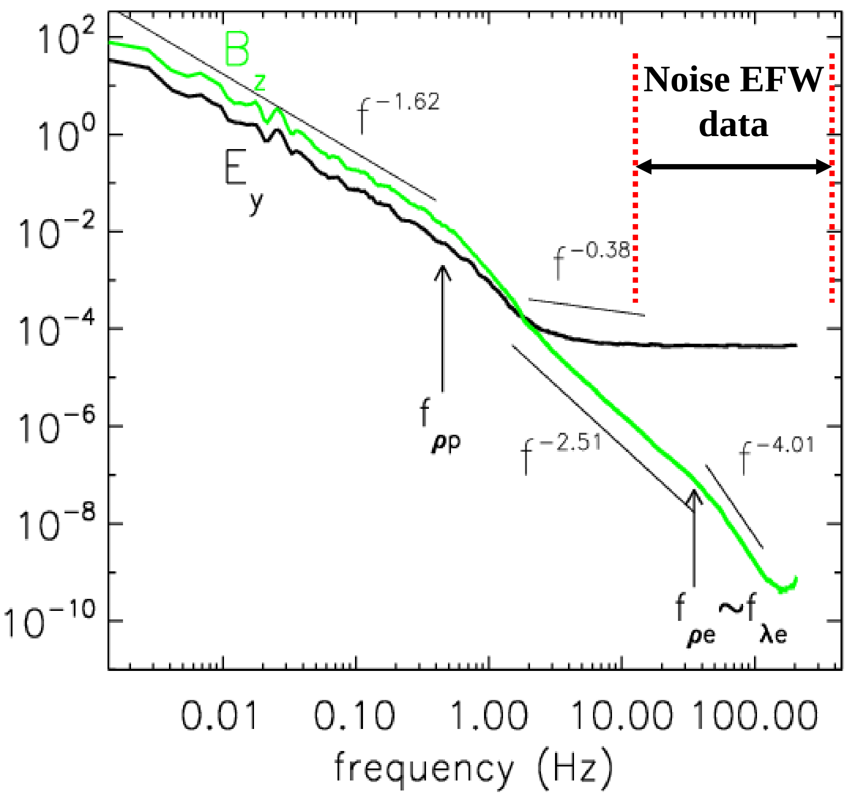
Further investigation: (B+E) field data

1. Large scales ($L>\rho_i$): strong correlation of E_y and B_z in agreement with **E=-VxB**

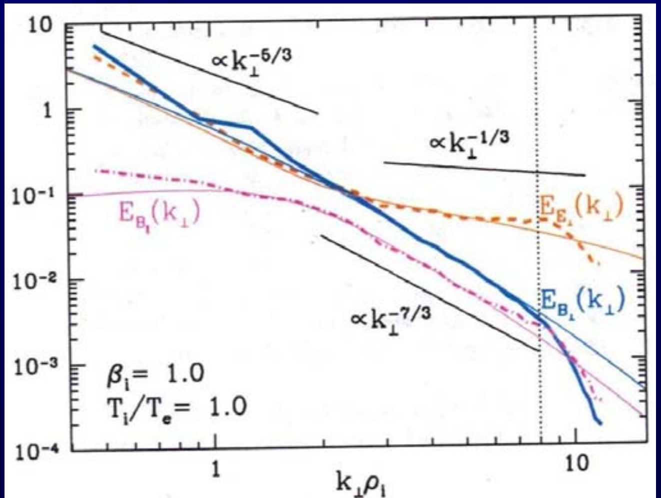
2. Small scales ($L<\rho_i$): steepening of B² and enhancement of E² (however, strong noise in E_y for f>5Hz)

⇒ Good agreement with GK theory of Kinetic Alfvén Wave turbulence

FGM, STAFF-SC and EFW data

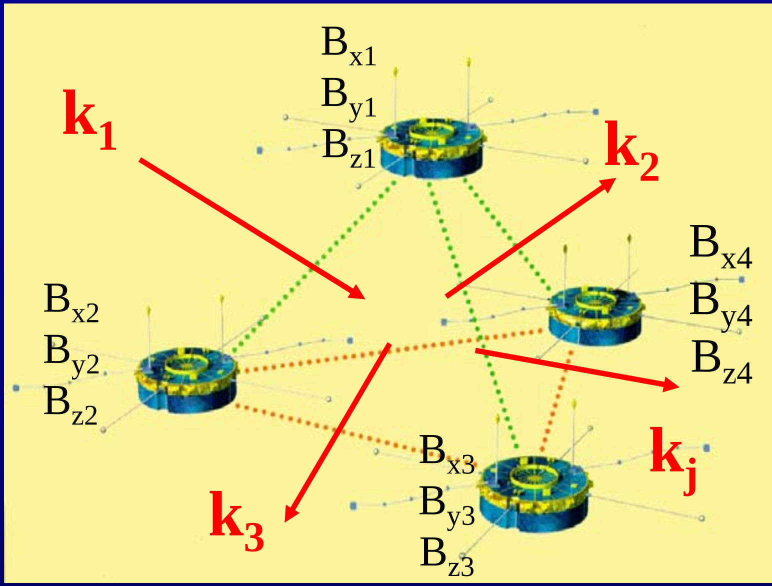


Howes *et al.* PRL, 08



k-spectra determination using the k-filtering technique

Pinçon & Lefeuvre, 91;
Neubauer & Glassmeier, 90



Interferometric method: it provides, by using a NL filter bank approach, an optimum estimation of the **4D spectral energy density P(ω,k)** from simultaneous multipoints measurements

P(ω,k) can be used to

1. **Calculate experimental dispersion relations ⇒plasma mode identification** *(Sahraoui et al., 03a, 04, Tjulin et al., 05)*

2. **Determine 3D k-spectra (anisotropies, power laws, …)**

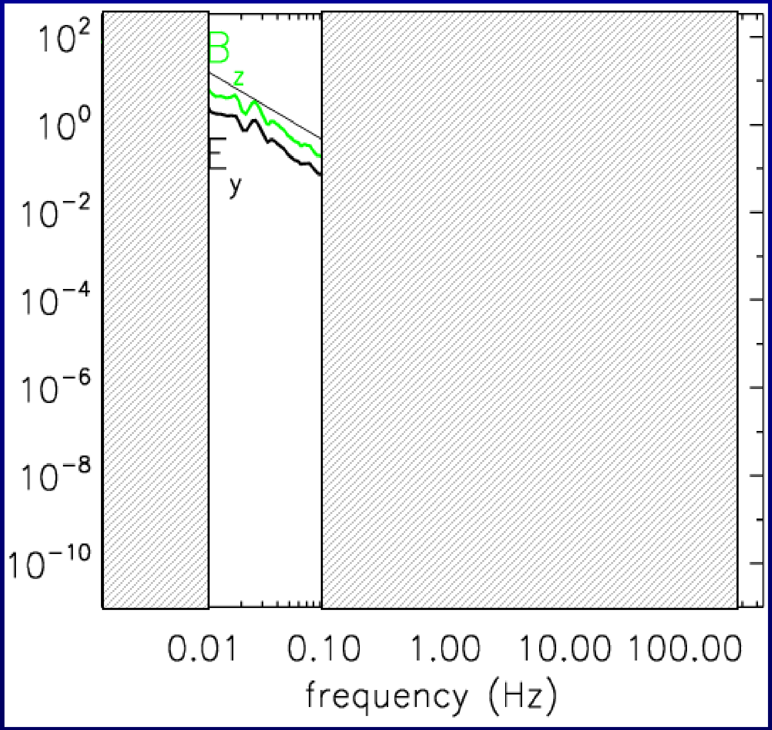
Sahraoui et al., PRL, 06; Narita et al. 06

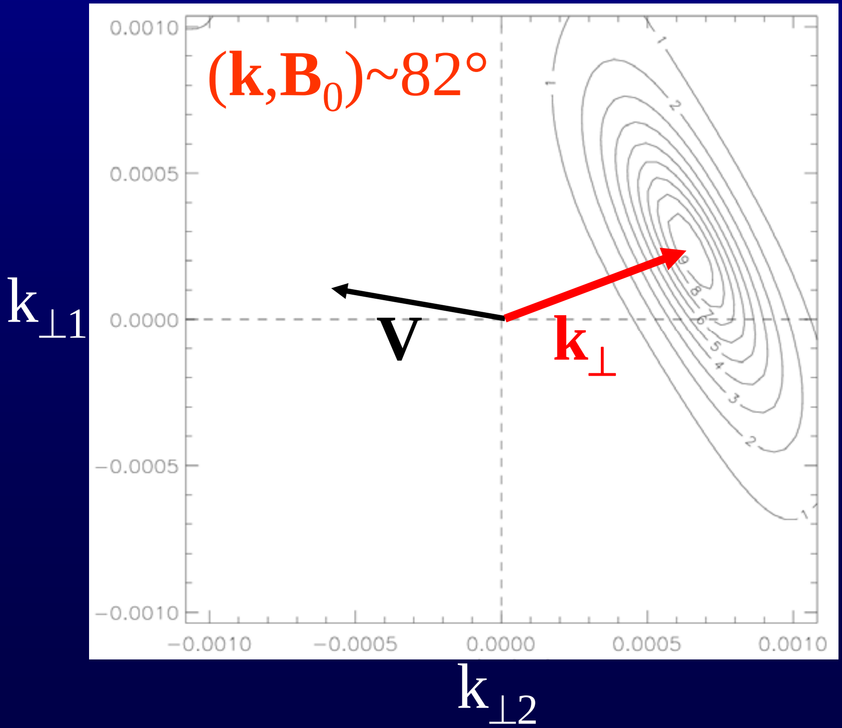
k-spectra at large scale

Sahraoui & Goldstein, in prep.

Cluster separations *d* limit the interval of study to $[f_{min}, f_{max}]$

$f_{max} \sim k_{max} V/2p \sim V/d$ (otherwise aliasing occurs)





⇒ turbulence at large scale is quasi-2D

Assumption used below: turbulence at small scales remains 2D

Theoretical interpretation of the small scales

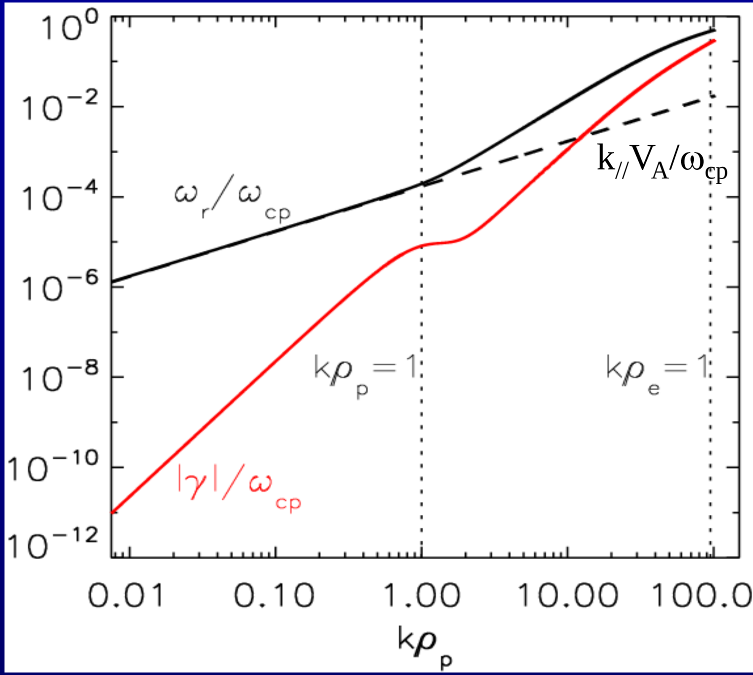
Solutions of the Maxwell-Vlasov equations using the observed plasma parameters:

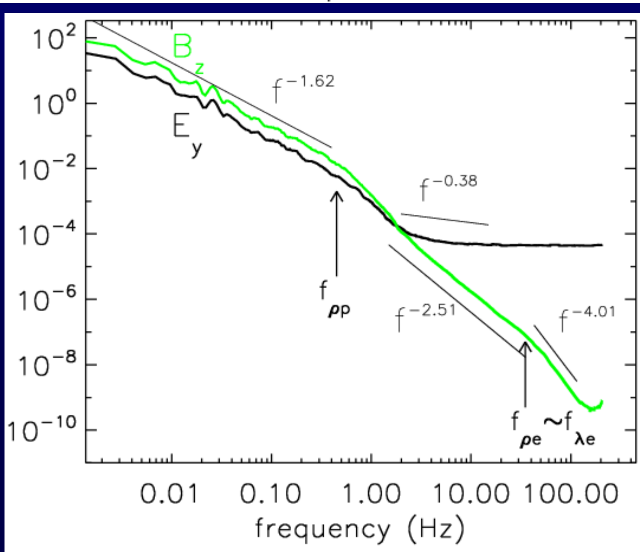
1. The Kinetic Alfvén Wave extends **down to $k\rho_e \sim 1$** with $\omega_r < \omega_{cp}$

2. Only a slight damping @ $k\rho_i \sim 1$ ($|\gamma| \sim 0.1\omega_r$) $\Rightarrow$ may explain the slight stepening to $f^{-7/3}$

3. Strong damping @ $k\rho_e \sim 1$ ($|\gamma| \sim \omega_r$) $\Rightarrow$ may explain the strong steepening to f^{-4}

$\beta_i \sim 2.5$, $\beta_e \sim 1$, $T_e/T_i \sim 0.2$, $\theta = (\mathbf{k},\mathbf{B}) = 89°$

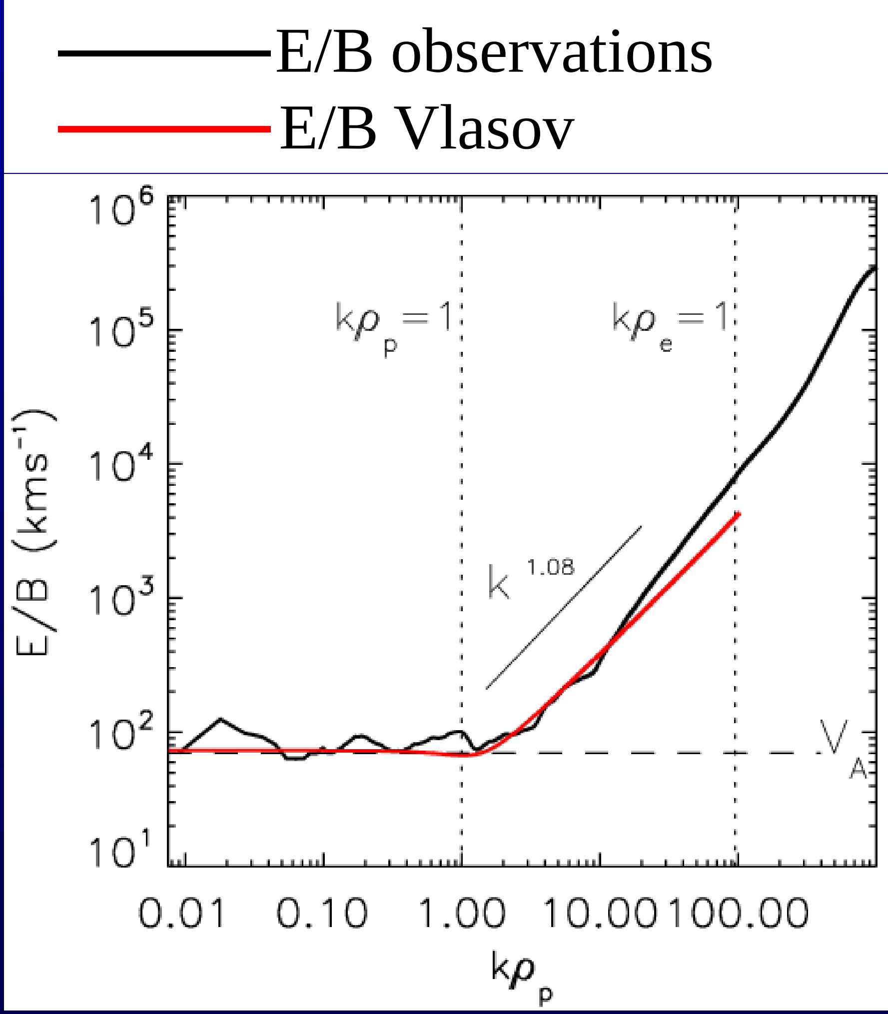




E/B estimation from KAW theory and from Cluster observations

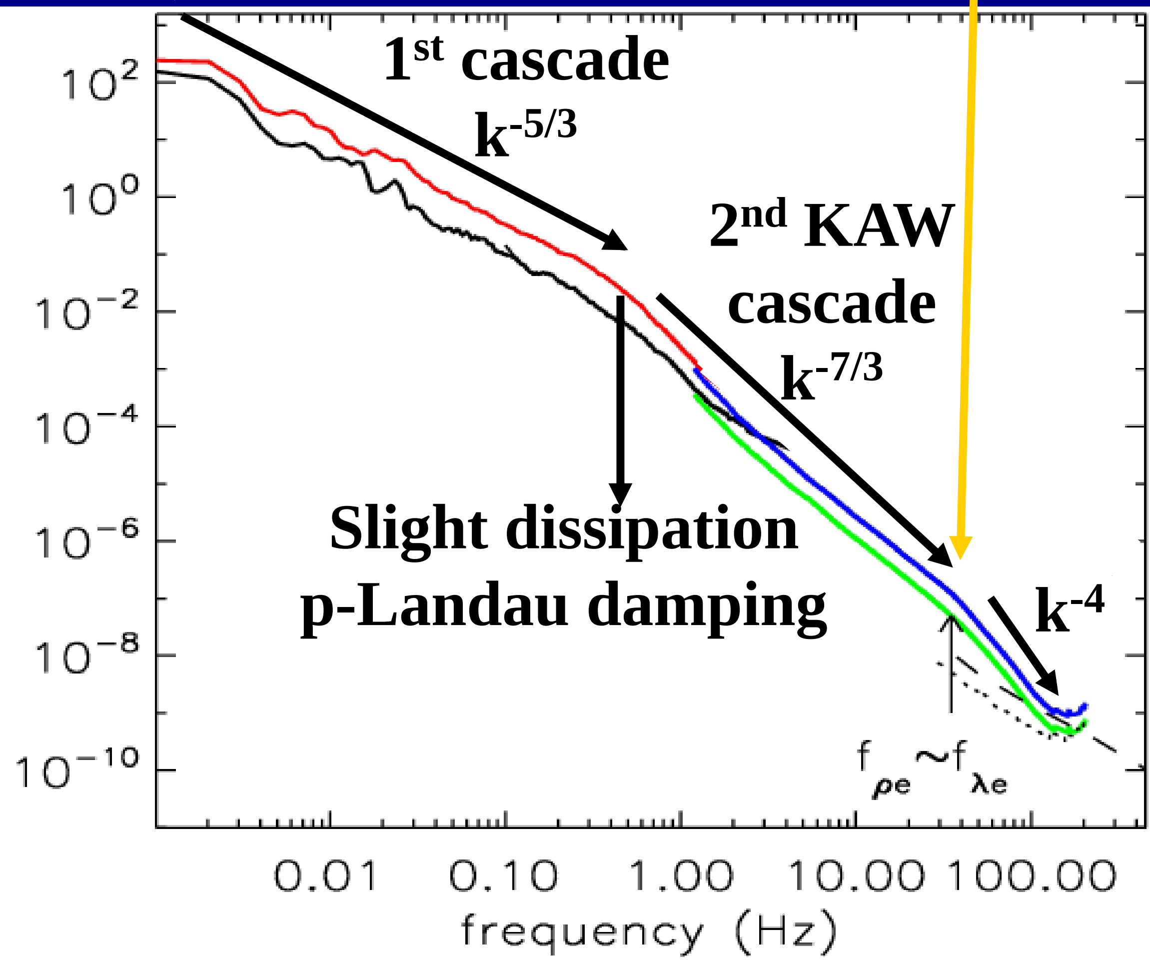
- ➢ Lorentz transform: $\mathbf{E}_{sat}=\mathbf{E}_{plas}+\mathbf{V}\mathrm{x}\mathbf{B}$
- ➢ Taylor hypothesis to transform the spectra from f (Hz) to kρ

1. Large scale ($k\rho_i<1$): $E/B\sim V_A$
2. Small scale ($k\rho_i>1$): $E/B\sim k^{1.1} \Rightarrow$ in agreement with GK theory of KAW turbulence $E^2\sim k_\perp^{-1/3}$ & $B^2\sim k_\perp^{-7/3} \Rightarrow E/B\sim k$
3. The departure from linear scaling ($k\rho_i>20$) is due to noise in Ey data



Sahraoui et al., PRL 102, 231102 (2009)

Journey of the energy through scales: 2D cascade



1. Turbulence
2. e-Acceleration
3. Heating
4. Reconnection

Conclusions

- Evidence of a second inertial range of SW turbulence below the ion gyroscale ρ_i with the scaling ~ $f^{-7/3}$.
- First evidence of dissipation below the electron gyrosclae $\rho_e \Rightarrow$ *electron heating by turbulence cascade*
- Remarkable agreement with the prediction of the Gyro-kinetic theory of the Kinetic Alfvén Wave turbulence.
- Consequences on solar wind heating and on modeling of magnetic reconnection