"Vlasov-Maxwell kinetics: theory, simulations and observations in space plasmas"
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Observations of solar wind turbulence at plasma kinetic scales

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Space plasmas :

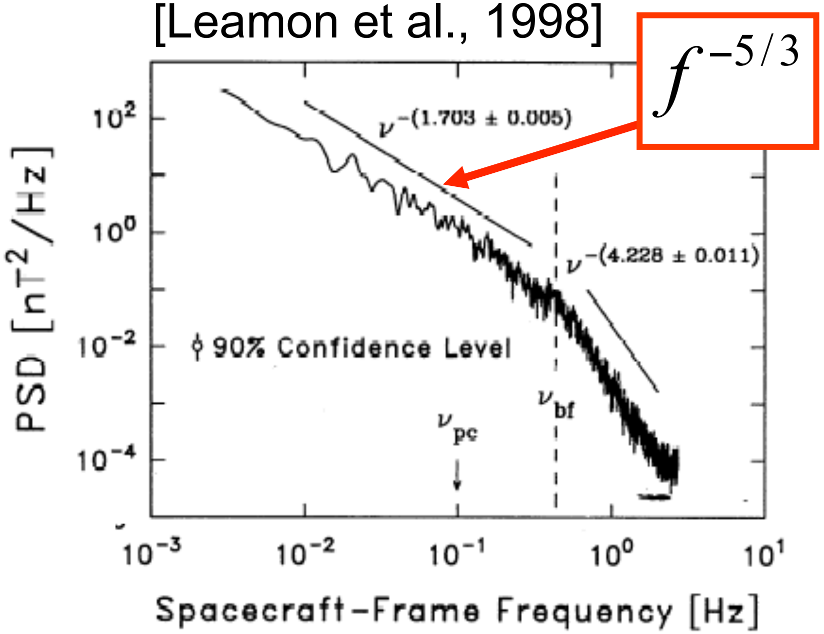
- no collisions $\Rightarrow$ dissipation ?
- Characteristic scales and frequencies
- $B_0 \Rightarrow$ anisotropy
- Turbulence ?

Turbulent spectrum in the solar wind

∃ a spectral break close to $f_{ci}, V_{sw}/\lambda_i, V_{sw}/R_{Li}$

[Leamon et al., 1998]

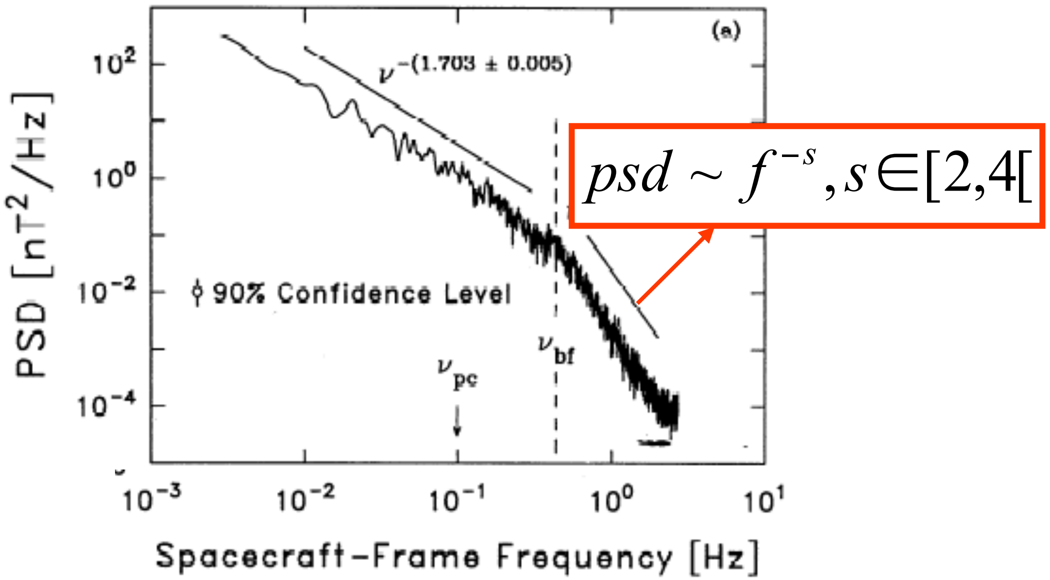
$\lambda_i = c/\omega_{pi}$

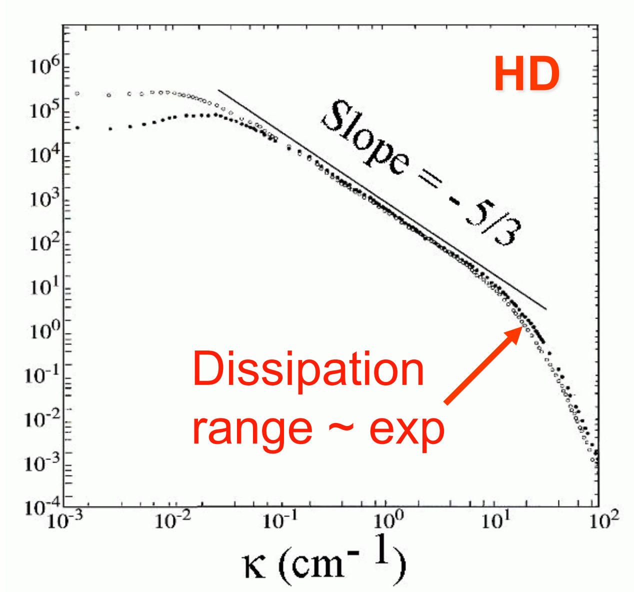


Below the spectral break :
Kolmogorov-like inertial range

On the spectral break ?

- onset of dissipation range
- starting point of another cascade



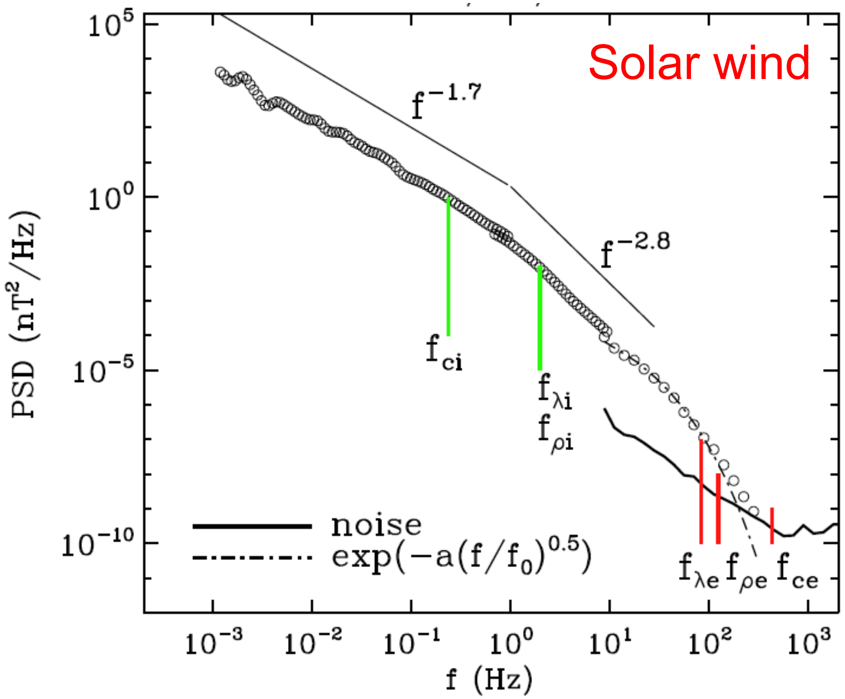


If it is a dissipation range ⇒

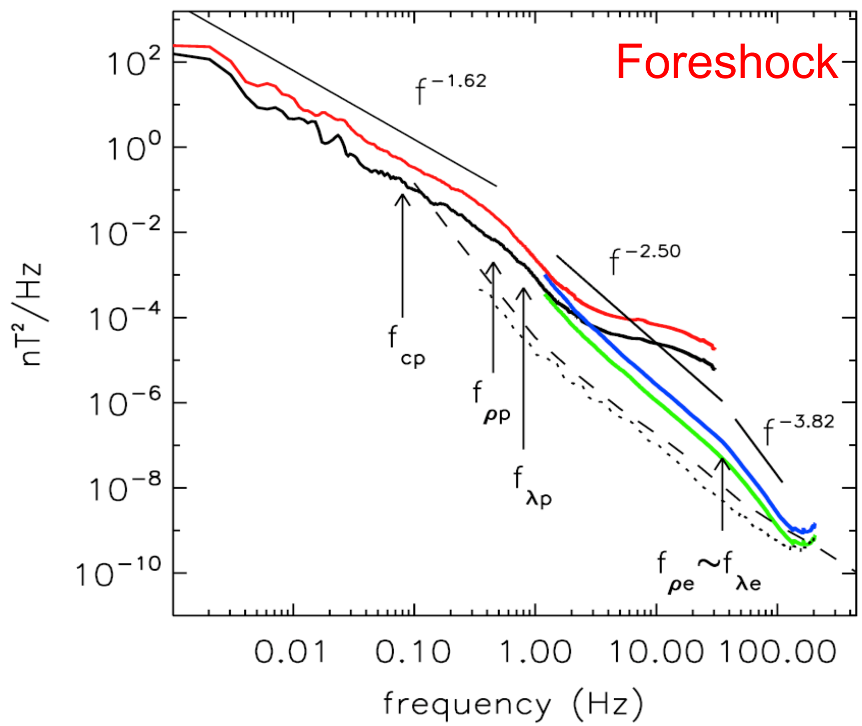
- Why a power law and not an exponential cut-off ?
- What happens at higher frequencies (where FGM instrument is not sensitive…)?

Turbulence at electron scales: Cluster observations

[Alexandrova et al., 2009, PRL]



[Sahraoui et al., 2009, PRL]

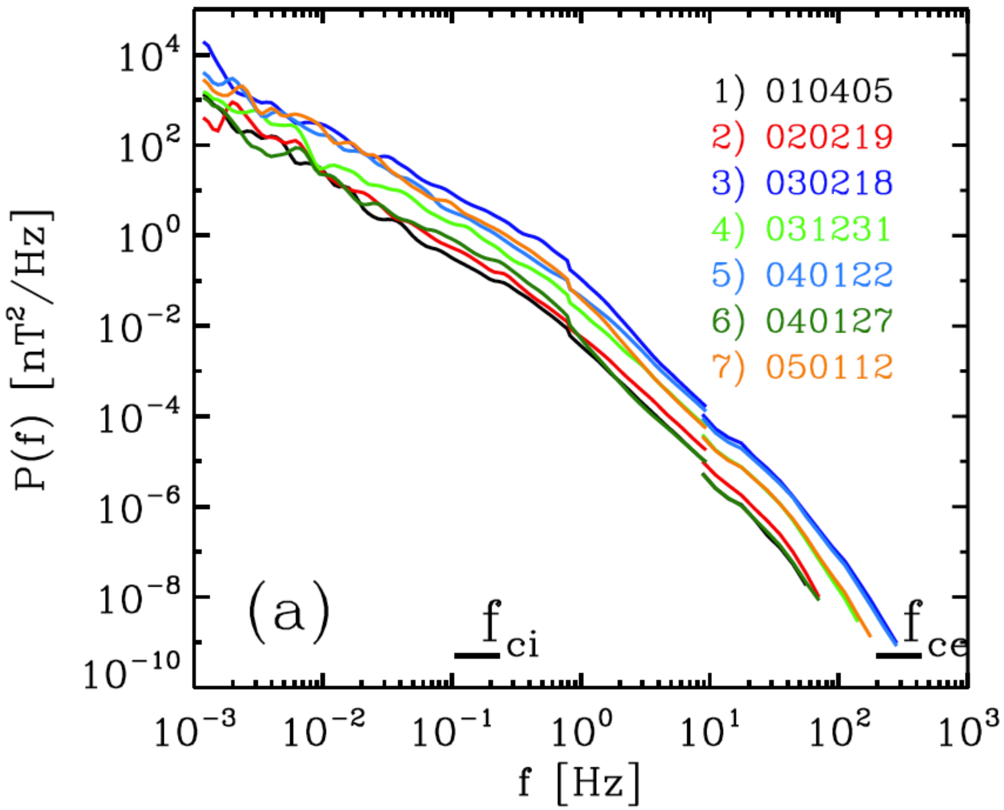


- Solar wind: ~exponential spectrum for $\Delta f \sim [10,100]$ Hz ($k\rho_e = [0.1,1]$)
- Foreshock region: spectral break at $k\rho_e = k\lambda_e = 1$
- Magnetosheath : ~exponential + whistlers [Alexandrova et al., 2008, AnGeo]

Universality of solar wind spectrum ?

7 solar wind spectra for different plasma parameters

$$V \in [360, 670] km/s,\ \beta_i \in [0.4, 2],\ \beta_e \in [0.2, 1.6],\ \Theta_{BV} \in [65, 85]^\circ$$



[Alexandrova et al., 2009, PRL]

Is there a universal spectrum ***g*** such as any observed spectrum ***P(f)*** is

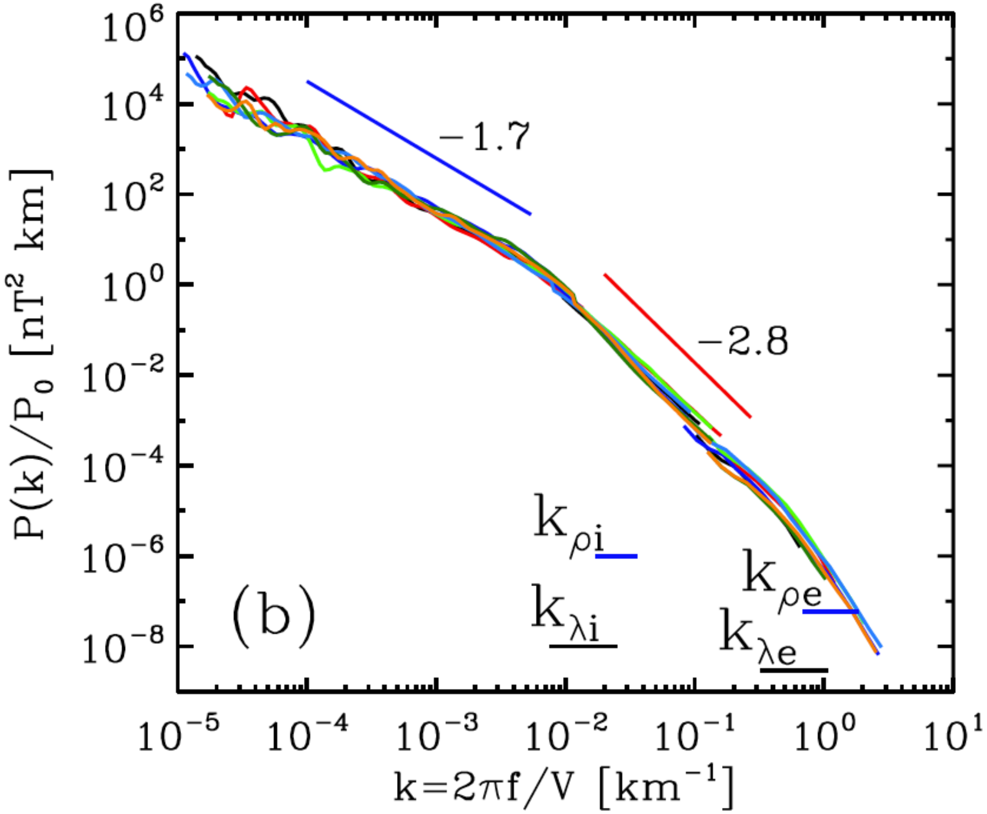
$$P(f) = P_0 g(\lambda f)$$

[Pedrosa, et al., 1999, PRL]

Quasi-universality of SW spectrum

Rescaled spectra :

$$P(f)/P_0 = g(\lambda f)$$



- Assuming the validity of the Taylor's hypothesis:

$$\lambda = 2\pi/V$$

- Factor P_0 (relative spectral level):

$$P_{0j} = \langle S_j/S_1 \rangle_{k\in[10^{-4},10^{-1}]km^{-1}}$$

$$j = 1, ..., 7$$

- We arrive to one clear spectrum g(k)
- 2 clear inertial ranges: (i) -5/3 ; (ii) -8/3
- There are 2 break points: (i) at ion scales; (ii) at electron ones

Spectral level (factor P_0) and plasma parameters

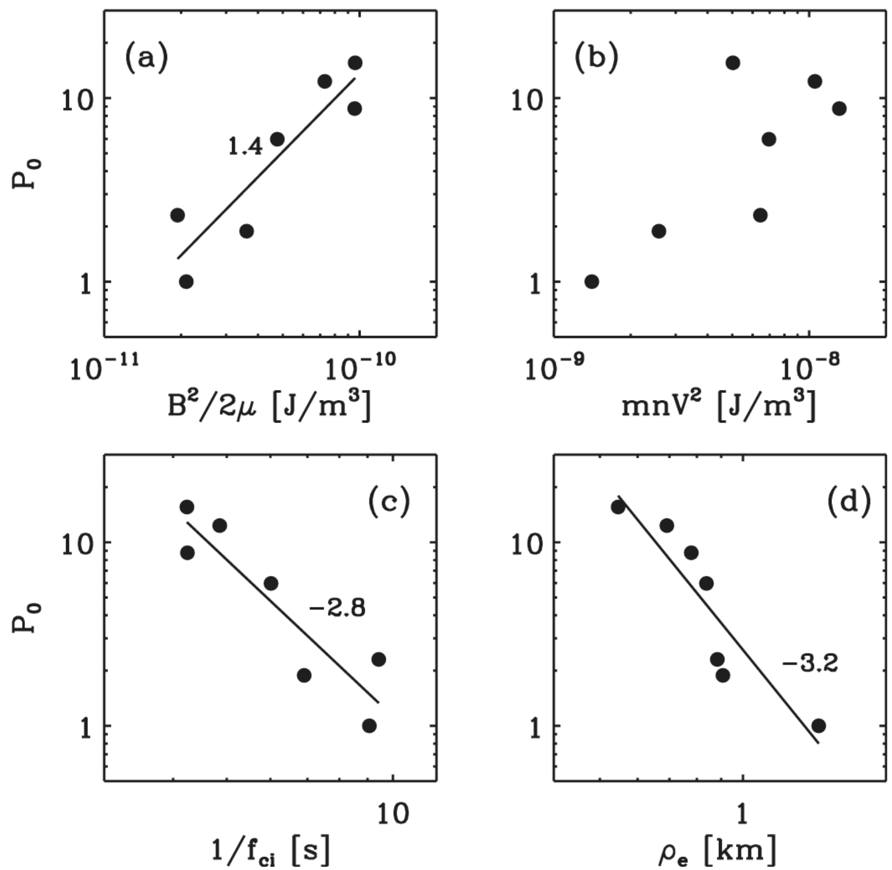
P_0-factor depends on

- Mean magnetic field (cyclotron periods)
- Dynamical and thermal (not shown) pressures
- Electron Larmor radius

$$\rho_e = \frac{V_{\perp e}}{\Omega_{ce}}$$

$$\Omega_{ce} \sim B_0$$

$$V_{\perp e} = V_{th,e} \sim \sqrt{T_{\perp e}}$$



What does it mean that turbulence level P_0 is related to a particular scale?

HD: in the vicinity of the dissipation scale L_d

$$v \cdot \nabla v \sim \eta \Delta v$$

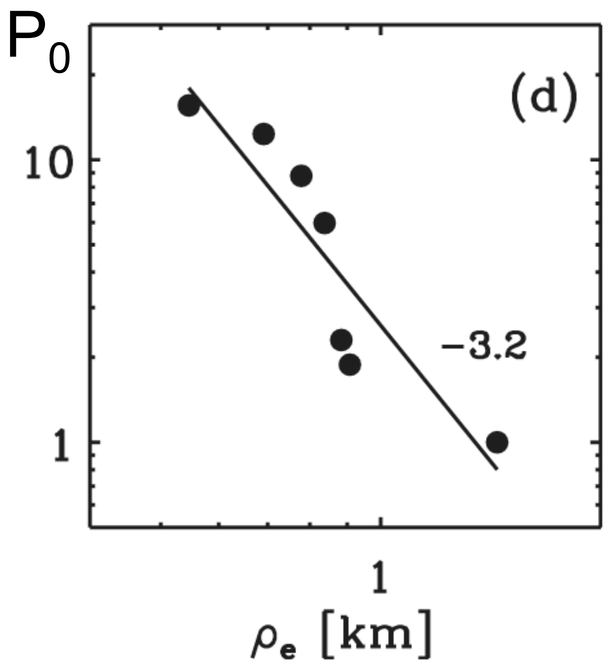
$$\frac{v^2}{L_d} \sim \eta \frac{v}{L_d^2}, \; \tau^{-1} \sim \frac{v}{L_d} \sim \frac{\eta}{L_d^2}, \; v \sim \frac{\eta}{L_d}$$

➡ Energy transfer rate $\varepsilon \sim L_d^{-4}$

Kolmogorov: $P_0 \sim \varepsilon^{2/3} k^{-5/3}$

➡ $P_0 \sim L_d^{-8/3}$

For a fixed k, at intermediate scales (inertial-dissipation rage)



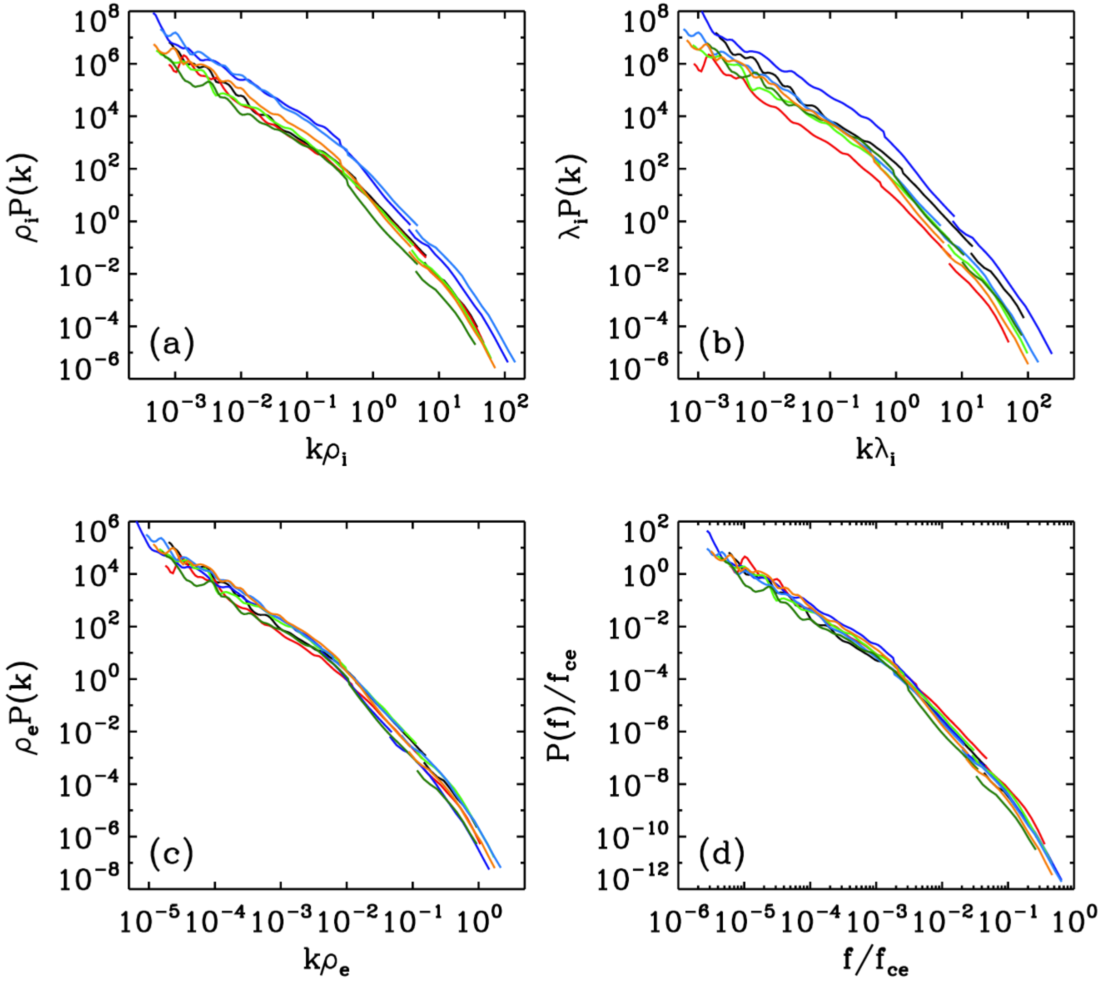
No HD-like viscosity in the solar wind, so the $P_0(L_d)$ should be different…

Dependence of P_0 on the electron gyroradius indicates that this scale is the dissipation scale of space plasma turbulence.

Universal Kolmogorov's function ~ $L_d E(k)/\eta^2$

From the balance between the energy input and the dissipation:

$$E(k)\ell_d/\eta^2 \sim (k\ell_d)^{-5/3}$$

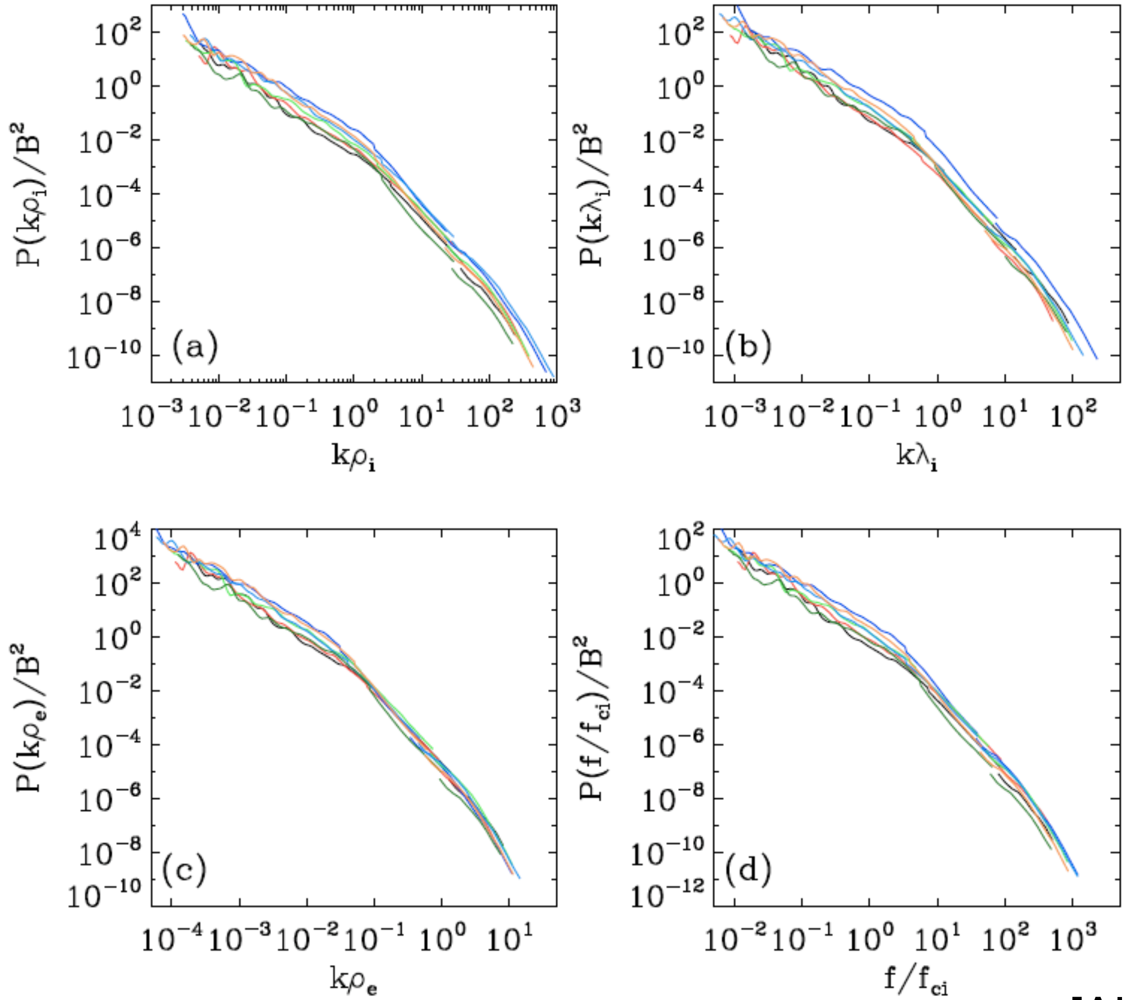


- Assumption: η=Const
- $k\rho_i$ & $k\lambda_i$ - normalizations are not efficient to collapse the spectra together
- $k\rho_e$ & f/f_{ce} (f/f_{ci}) - normalizations bring the spectra close to each other.
- There is a correlation between ρ_e & B_0 (& f_{ce})
- In terms of spatial scale, we could singled out for the 1st time with the observations the importance of ρ_e for the dissipation.

[Alexandrova et al., 2009, PRL]

Dimensionless spectra $P(kr)/B_0^2$

$$k \to kr, \;\; P(k) \to P(kr) = P(k)\frac{1}{r}.$$



- $k\rho_e$ - normalization => all the spectra collapse at scales smaller than the spectral break at ion scales
- This distinguishes ρ_e from the other spatial plasma kinetic scales as $\lambda_{i,e}$ & ρ_i

[Alexandrova et al. 2010, SW12]

Conclusions-I

- We have analyzed 7 spectra for 1h time intervals in the free solar wind, which cover MHD to electron scales.

- We have shown :

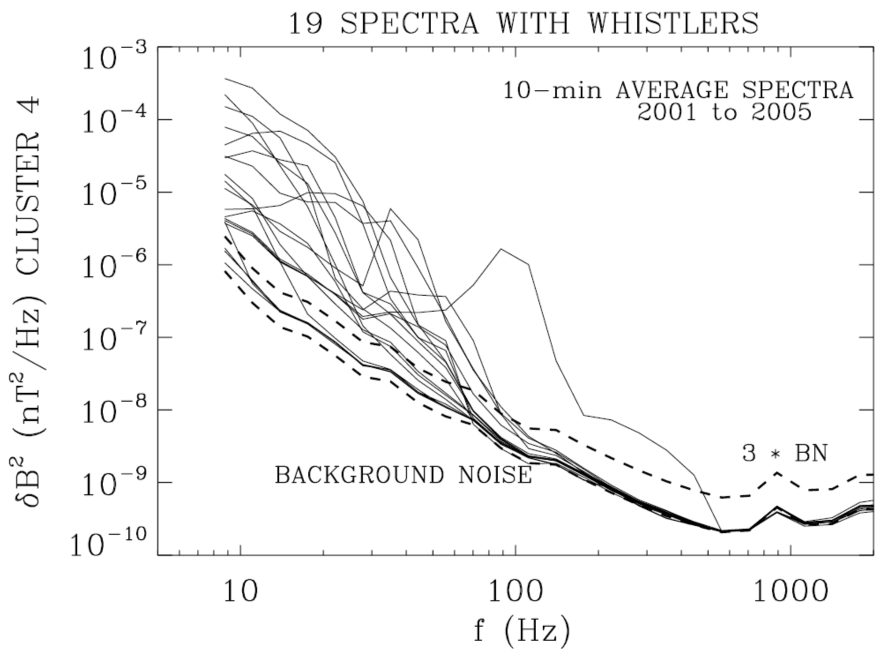
  - 1) Quasi-universal spectral shape : Kolmogorov -5/3 spectrum at MHD scales, -2.8 spectrum at ion scales (f=[0.2,10]Hz) and a curved (~exponential) spectrum at f=[10,100] Hz, indicating an onset of dissipation.

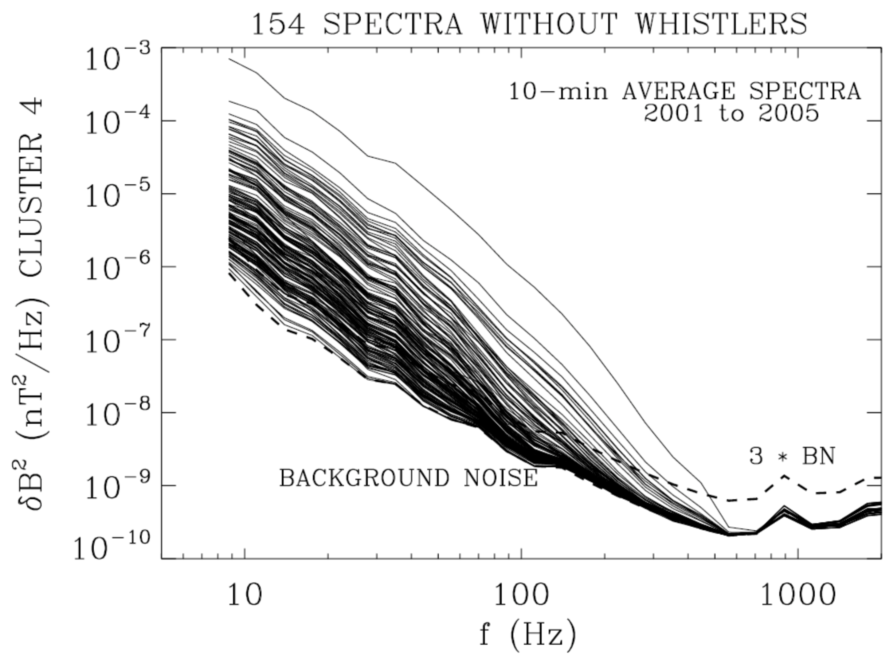
  - 2) Turbulence intensity depends on magnetic, kinetic and thermal energy of the solar wind (i.e. on energy input).

  - 3) Turbulence intensity depends on the electron Larmor radius ρ_e. This indicates that ρ_e plays a role in the dissipation of turbulent energy in the collisionless plasma.

II. Statistical study of magnetic turbulence spectra at electron scales in the solar wind

(Cluster-4/STAFF-SA)

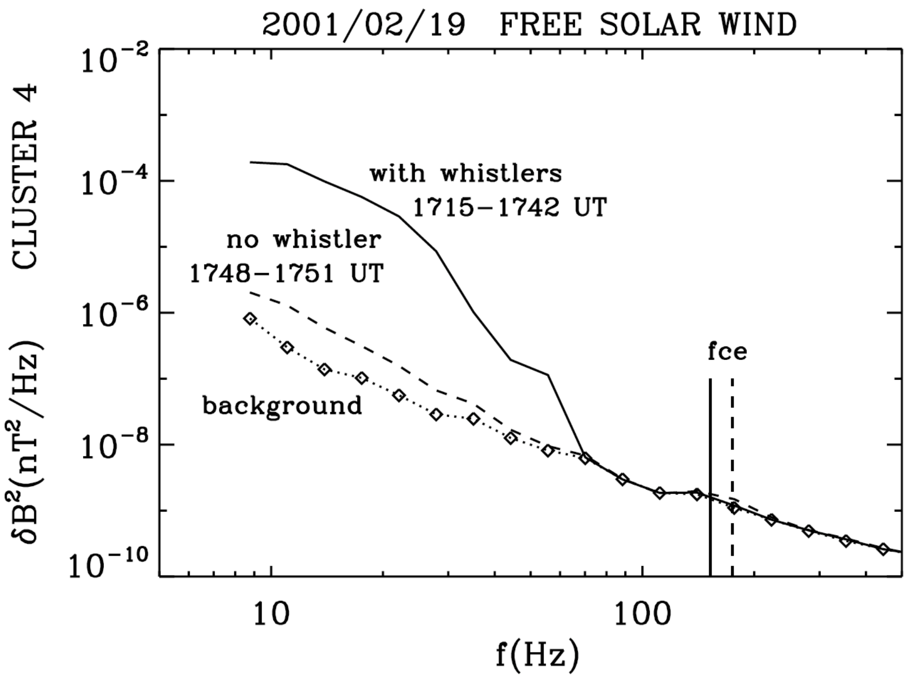


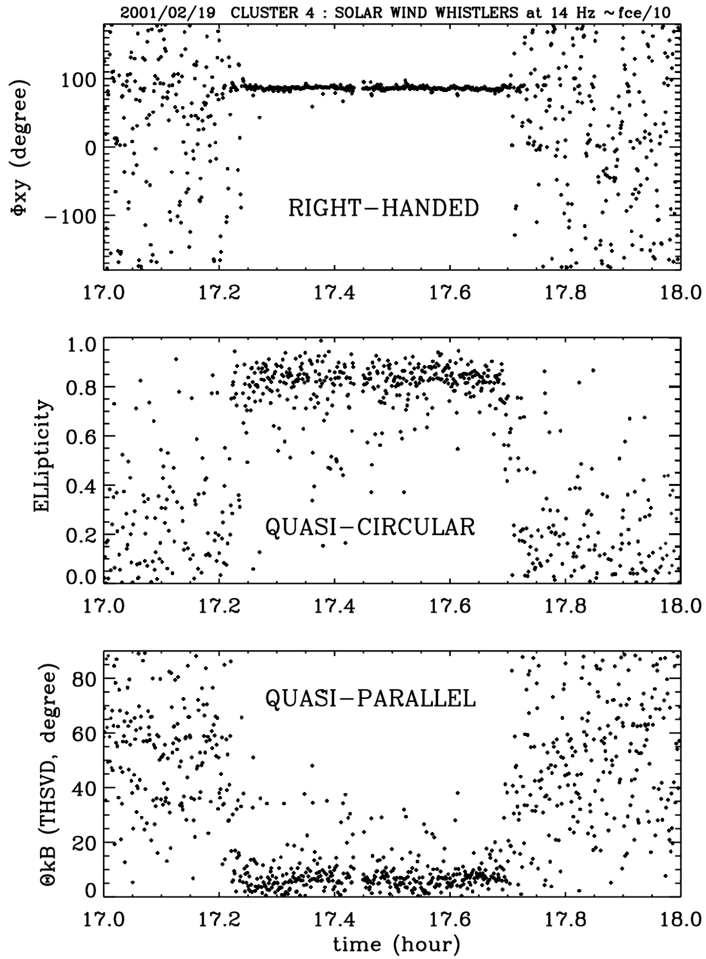


173 time periods of 10 minutes are considered

- 19 cases with parallel RH whistlers
- 154 time periods without whistlers (136 are 3 times more intense than the background noise)

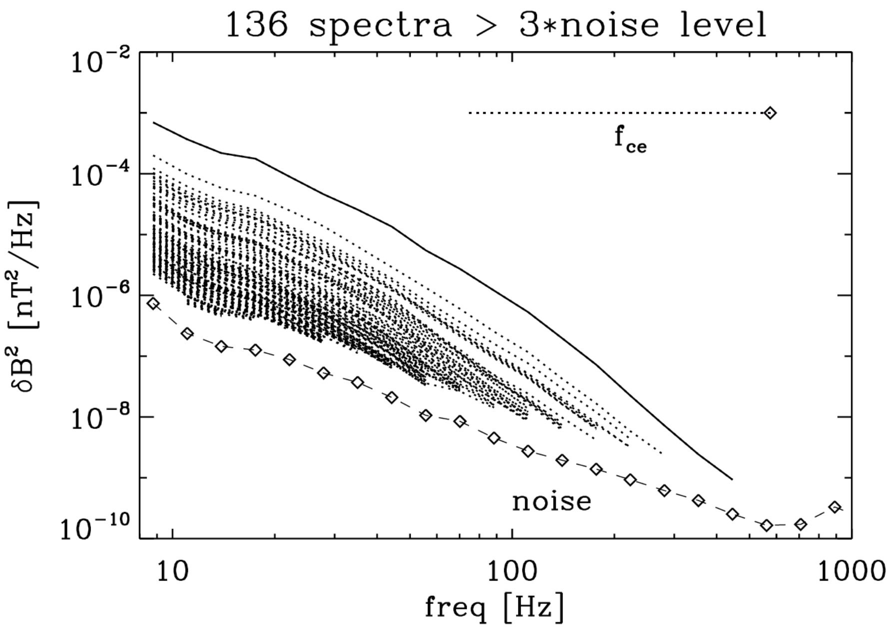
Detection of whistler waves in the solar wind by Cluster/STAFF-SA

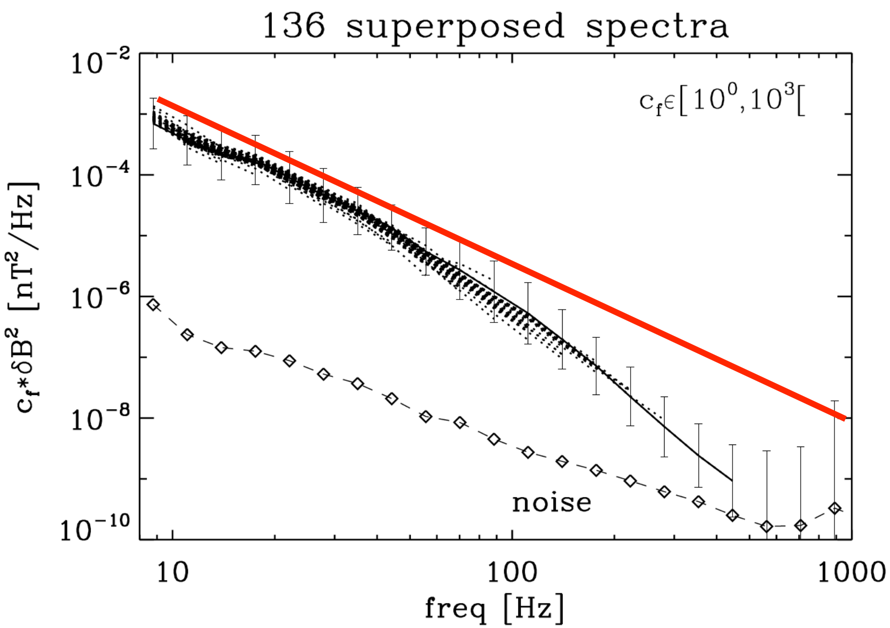




- The phase difference between B_x and B_y (in the plane perp to B_0) = 90^o. That indicates the Right Hand polarization of the waves.
- The wave vectors are determined to be quasi-|| to B_0

Spectra without whistlers
(as a function of satellite-frame frequency)



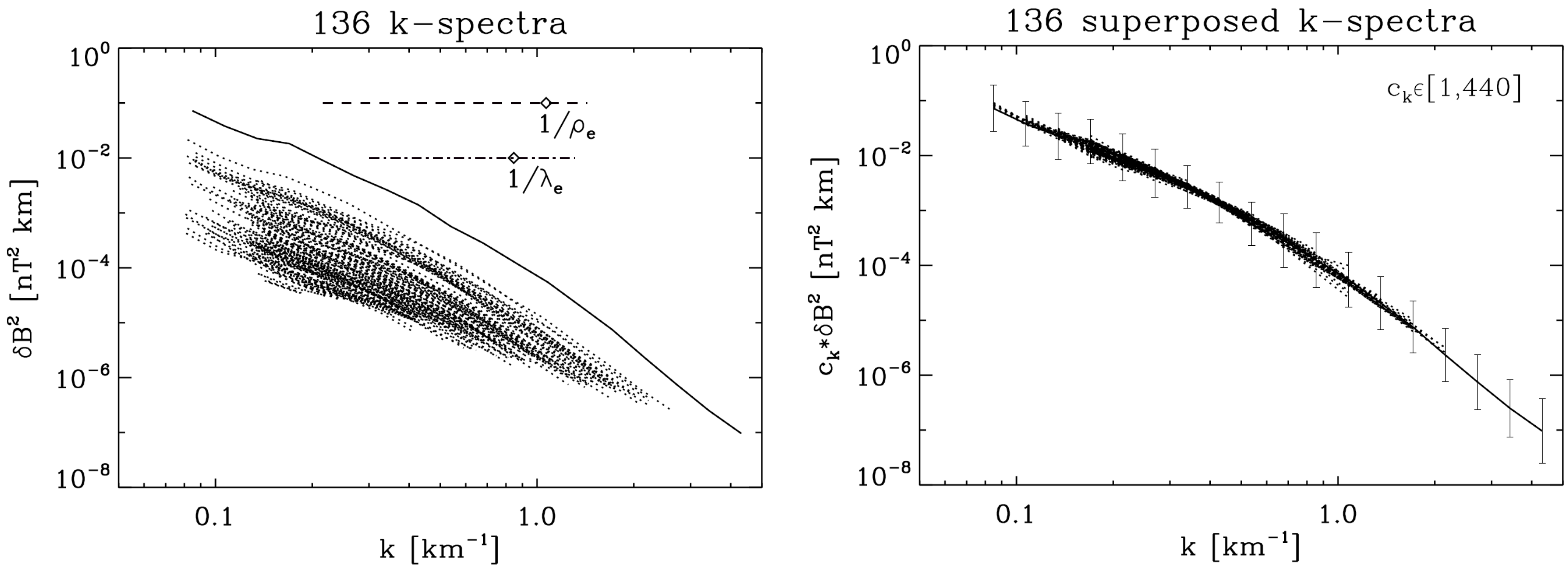


- All magnetic spectra at these scales are very similar (left plot).
- Simple translation along y-axes gives a nice superposition (right plot).

k-spectra ($k || V_{sw}$)

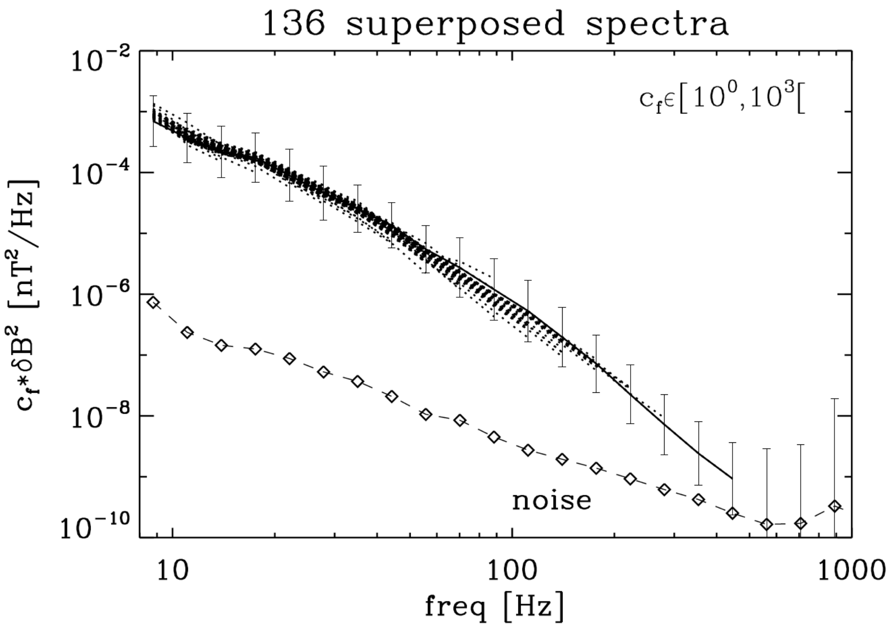
The Taylor hypothesis is used for the time intervals where whistler waves are not observed.

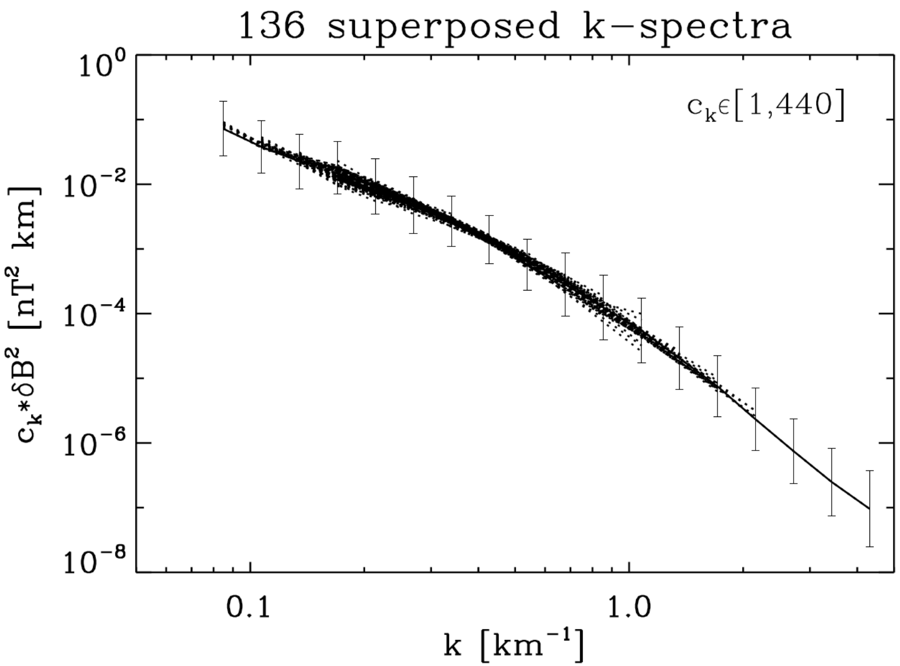
- Doppler shift : $k=2\pi f/V$ and $S(k)=S(f)V/2\pi$



Confirmation of universality of the spectral shape at electron scales.

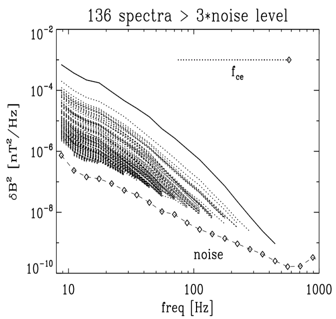
Comparison of superposed frequency and k-spectra



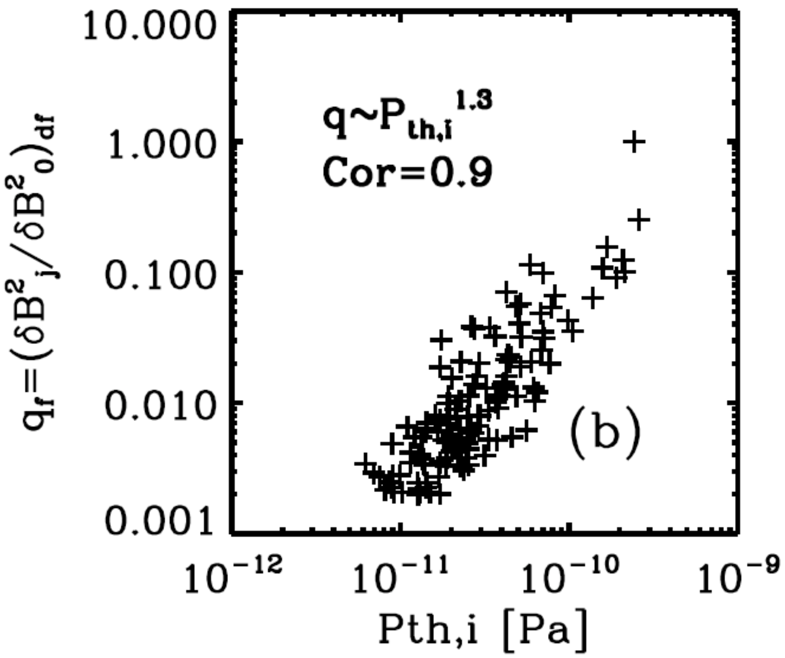


- The superposition of k-spectra is better than the one of f-spectra.
- This indicates that we really measure the Doppler shifted k-spectra (frequencies of the fluctuations in the plasma frame are very small, ~zero).

Turbulence intensity and ion thermal pressure in the solar wind



Large scale turbulence level depends on the ion thermal speed in the solar wind (Cor=0.8) [Grappin, Mangeney, Marsch, 1990, JGR].



Turbulence intensity depends as well on

- kinetic pressure $\sim \rho V^2$ (Cor=0.8)
- magnetic pressure $\sim B^2$ (Cor=0.7)
- electron thermal pressure $\sim nT_e$ (Cor=0.5)

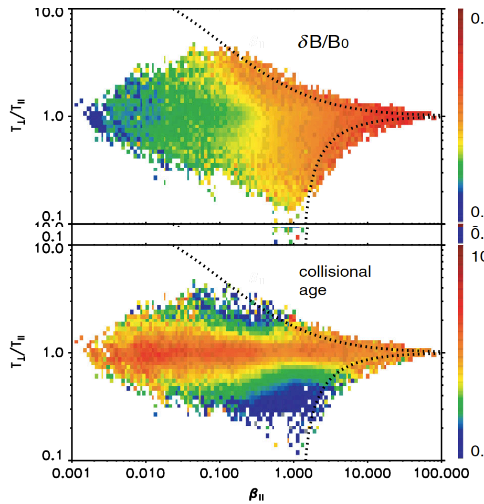
But all the pressures are cross-dependent in the solar wind :

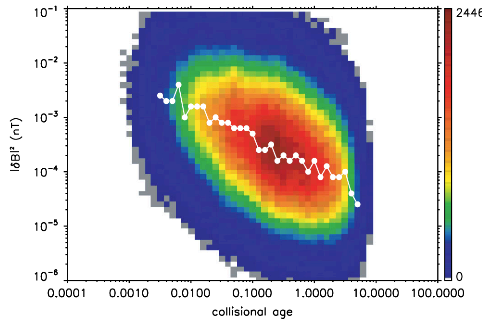
- Cor(Pthi,Pmag)=0.7
- Cor(Pthi,Pthe)=0.6
- Cor(Pthi,Pkin)=0.5

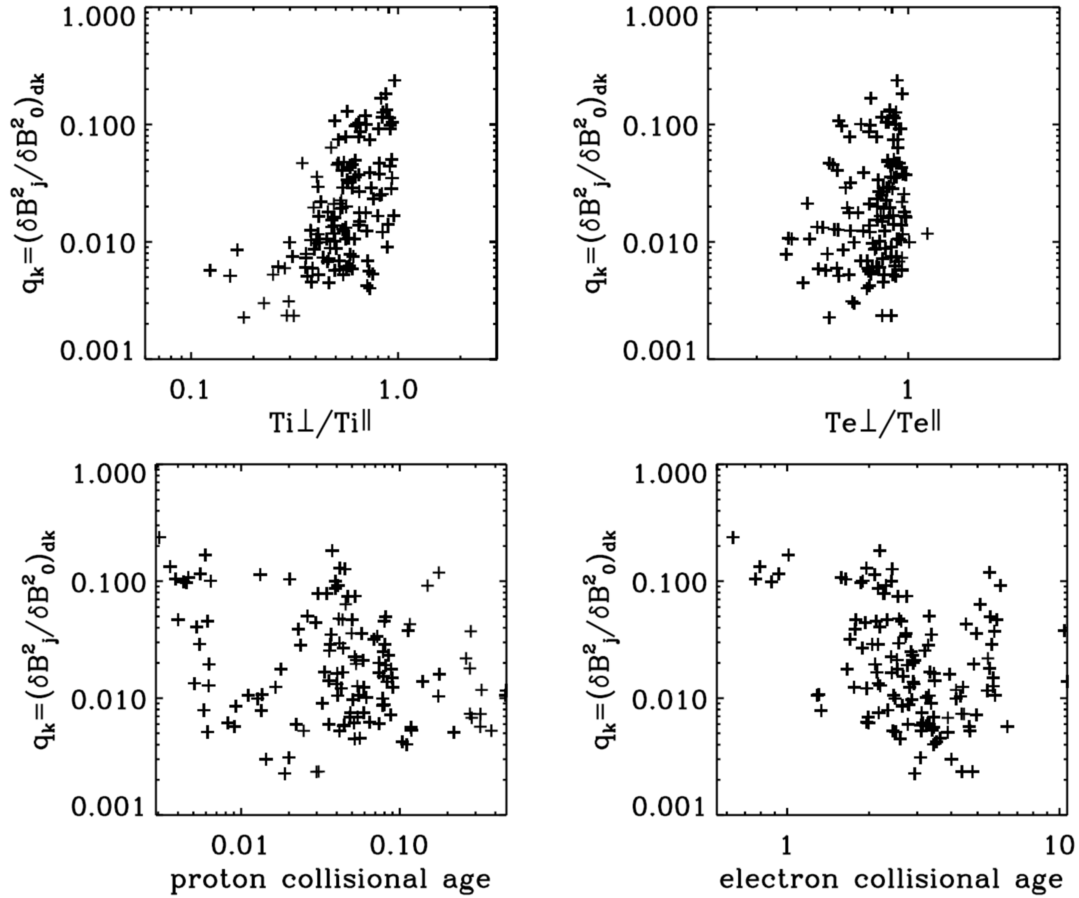
The same dependences are present for the k-spectra (however, all the correlations are lower), but not for normalized $k\rho_e$-spectra.

Turbulence intensity vs temperature anisotropy & collisional age

Turbulence intensity at 0.3 Hz ~ ion temperature anisitropy (and collisional age) [Bale et al. 2009, PRL]:



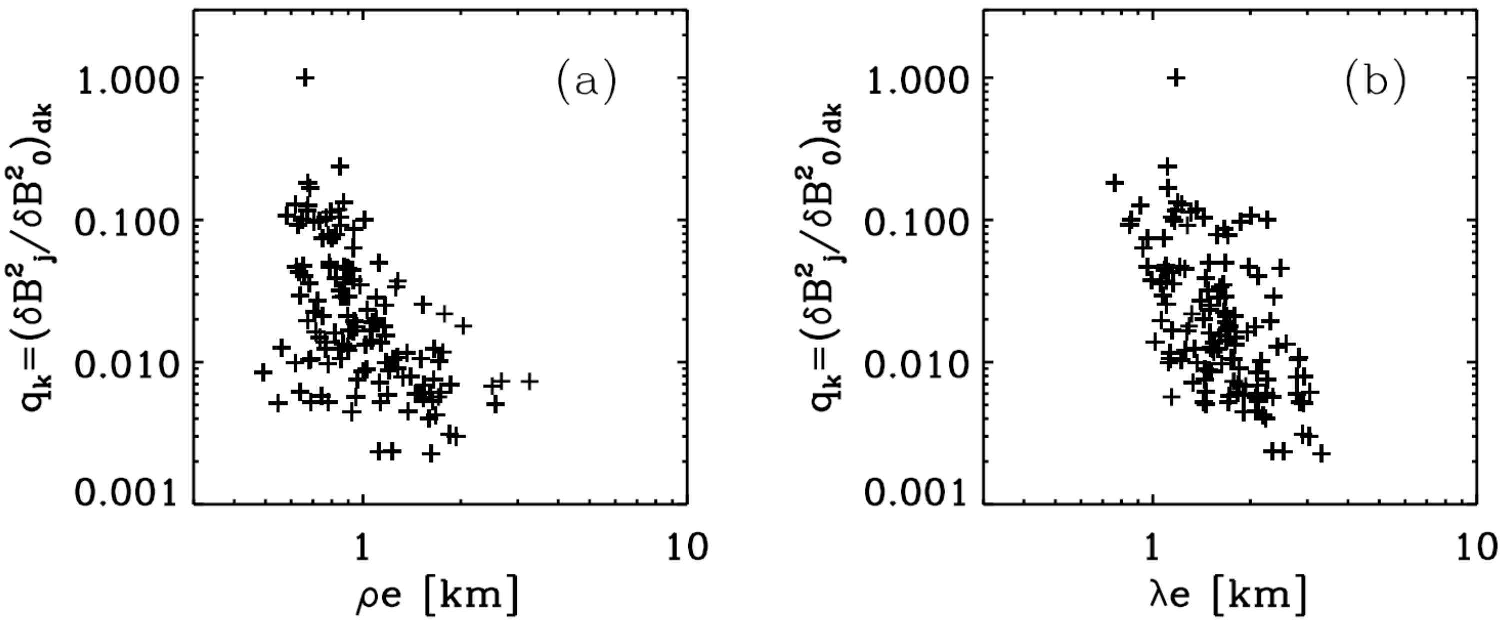




- There is a +/- dependence on ion temp. anis. (Cor=0.6)
- No dependence on the collisional age

Turbulence intensity and electron scales

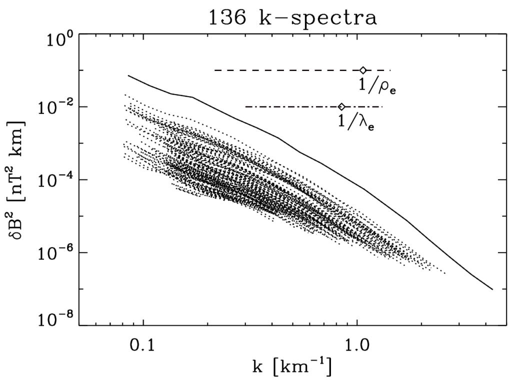
In fluids, turbulence intensity (in the vicinity of k_d) depends on k_d

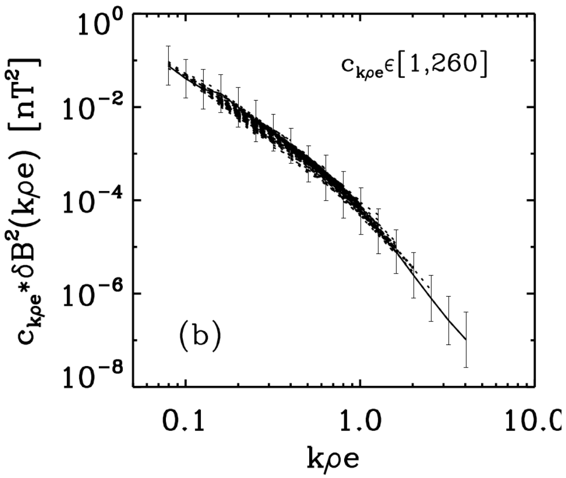


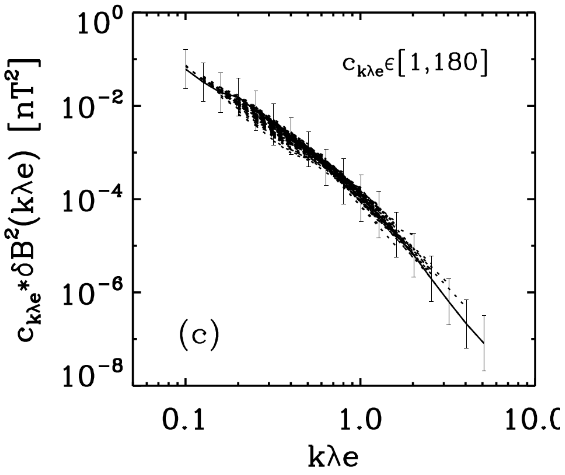
Both scales control turbulent spectrum independentelly?

Rescaled spectra (dimensionless x-axis)

$$k \rightarrow kr, \;\; P(k) \rightarrow P(kr) = P(k)\frac{1}{r}.$$

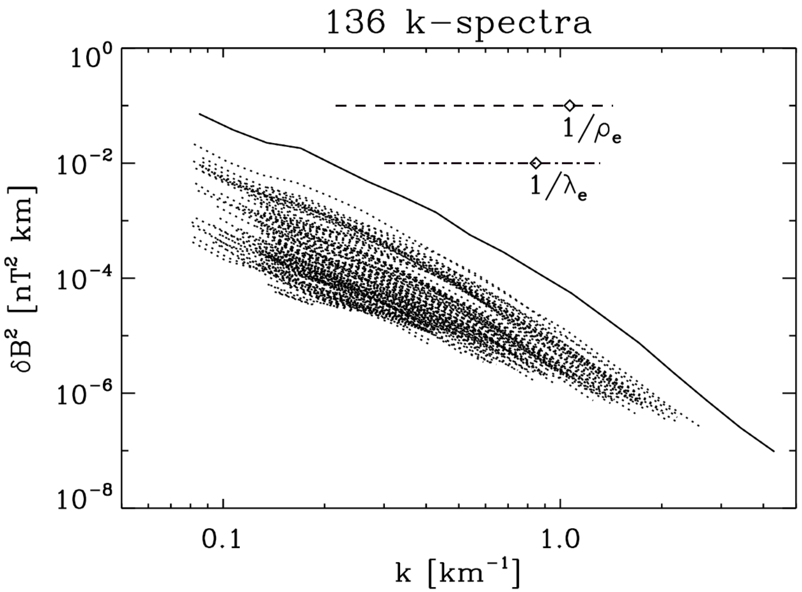


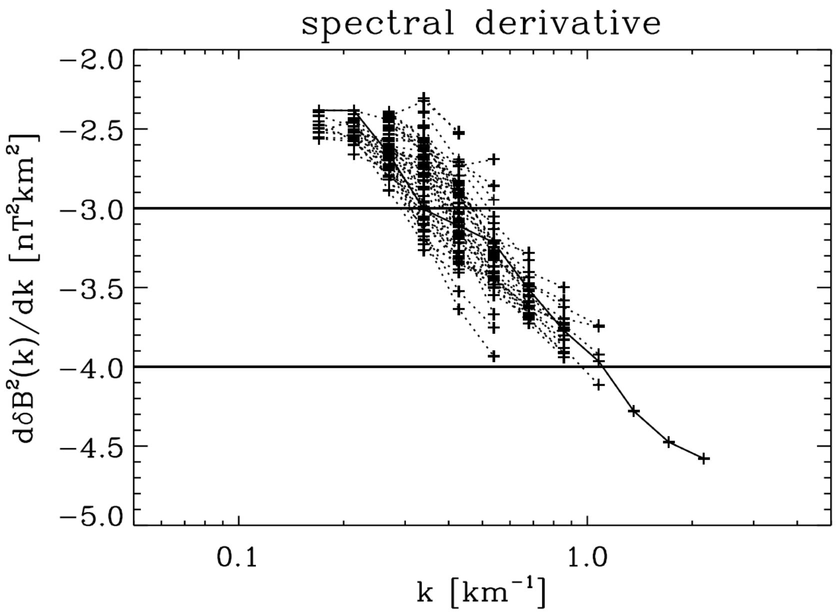




- Dispersion is less for $k\lambda_e$-superposition
- Shape is better for $k\rho_e$-superposition
- … difficult to choose one scale
- May be both scales are important for dissipation in the solar wind?
- (To do the same analysis but for the complete spectrum (MHD-ion-electron scales), before a final conclusion…)

Spectral shape : curvature or succession of 2 power-laws?





- We calculate the 1st derivative of the 136 PSD.
- For each PSD, it is not constant.

→ Spectra are curved!

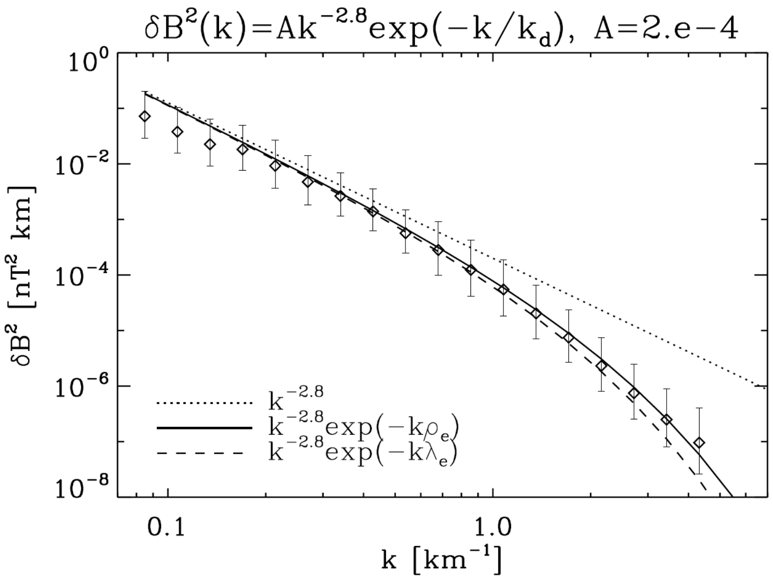
Spectral shape: exponential/polynomial

Dissipation range spectrum in fluid turbulence
[Chen, Doolen, Herring, Kraichnan, Orszag, She, 1993, PRL] :

$$E(k) \sim k^{\alpha} \exp(-ck/k_d)$$

In our previous study [Alexandrova et al. 2009] we have shown that α=-2.8 and $k_d=1/\rho_e$. In the present study we show that inertial length can be important as well.

$$E(k) = Ak^{\alpha} \exp(-k/k_d),\ k_d = 1/\rho_e,\ k_d = 1/\lambda_e$$



- Fluids dissipation range spectrum coincide with solar wind data without any particular fitting for $k_d=1/\rho_e$ & $k_d=1/\lambda_e$

- Fitting with 136 spectra => the same result!
- Advantage in comparison with polynomial fitting : only 1 parameter to fit (A) and we describe the whole spectrum from ion to electron scales.

Conclusions II

- 173, 10min avared spectra at f > 8Hz in the free solar wind are analysed.
- During 19 (/173) intervals we observe whistler emissions (around fce/10).
- The other 154 intervals have very similar spectra

- The analysis of the spectra >3*noise (136/154) =>
  - Confirmation of a universal spectral shape
  - Turbulence level ~ Pthi and ~ρ_e and λ_e ; but no dependence on ρ_i
  - Dissipation range is fluid like, with the law ~$k^{-2.8}\exp(-k/k_d)$!

  (With $1/k_d$=electron plasma scales.)

- Why? How it works? The exact mechanism of dissipation seems to be not so important as far as we arrive to the same spectrum as in fluids…?

- $k_d=\rho_e$ or λ_e ? Small scale dissipation structures at ρ_e and λ_e ?