Turbulent cascade in the solar wind: anisotropy and dissipation
17-21 September 2012, Observatoire de Paris

Turbulent spectrum at plasma kinetic scales and coherent structures

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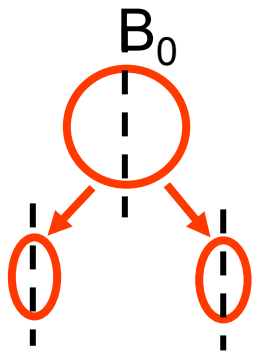
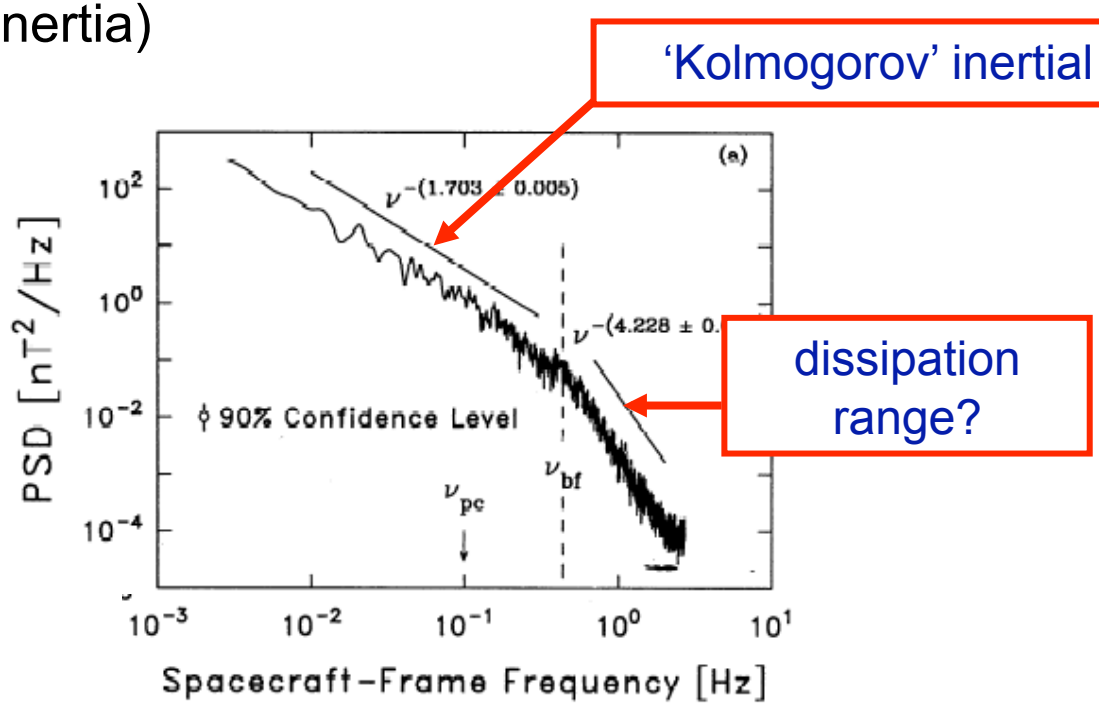
Turbulence in space plasma

- Magnetic field B_0 ⇒ anisotropy
- no collisions ⇒ dissipation?
- Characteristic scales and frequencies



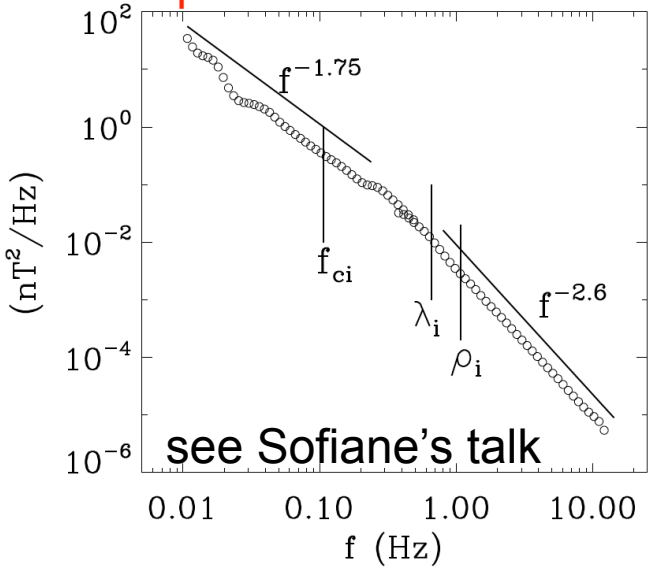
Solar wind turbulent spectrum

∃ spectral break around ion scales (gyration frequency, Larmor radius, ion inertia)



[Leamon et al,1998]

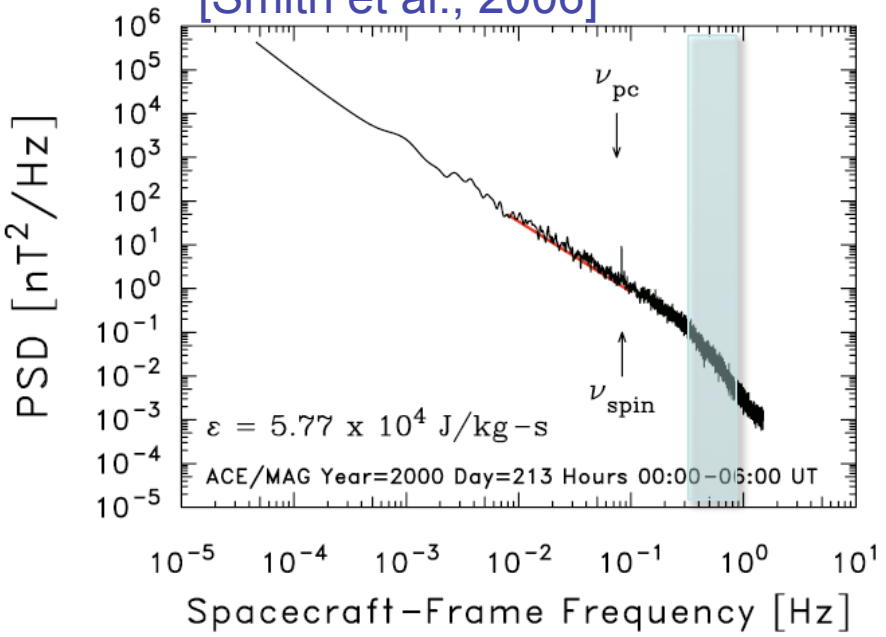
Which ion scale is responsible for the break?

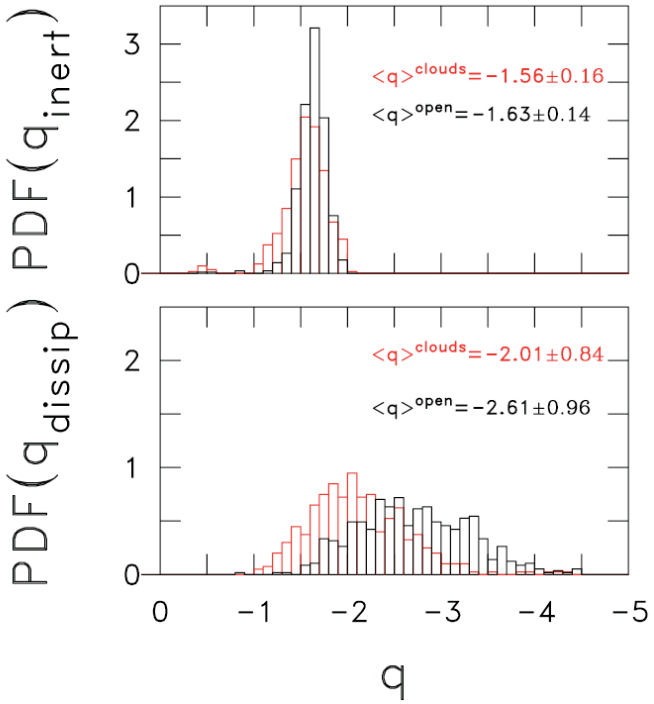


Spectral shape at kinetic scales (ion-electron scales)

Power-law variability in the “beginning of the dissipation range”

[Smith et al., 2006]

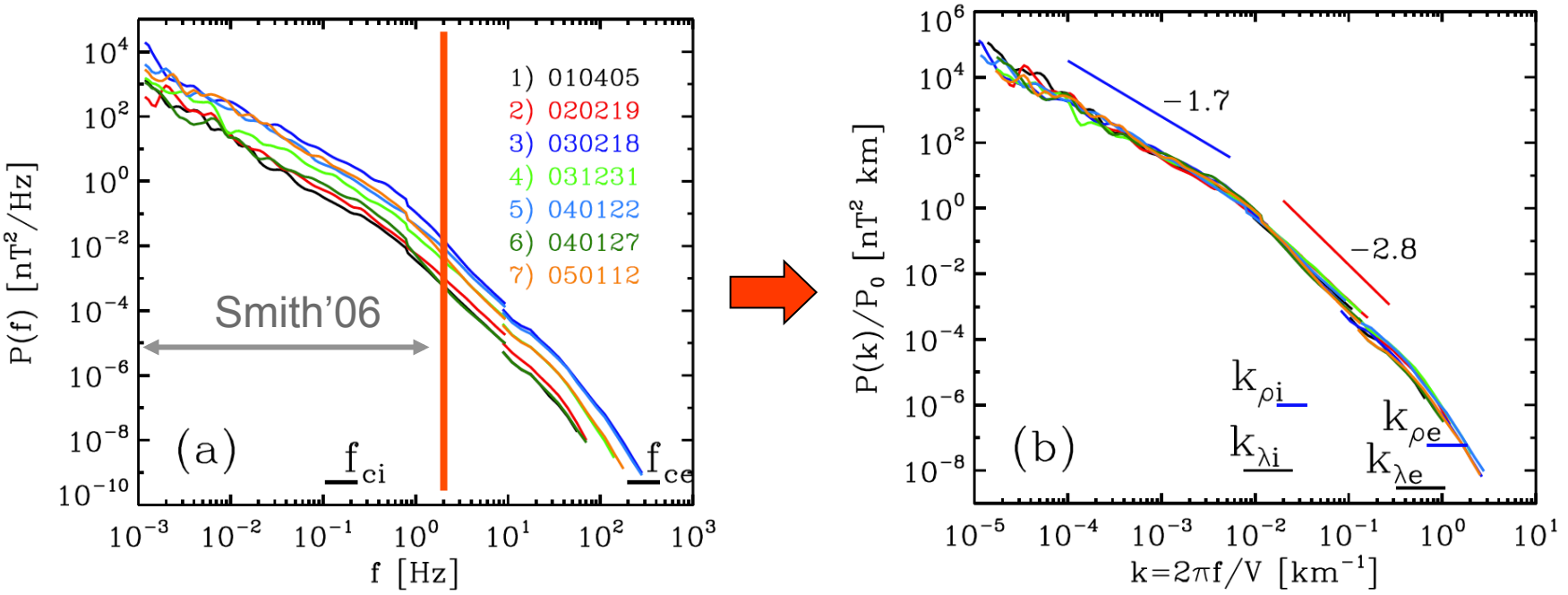




- Results for [0.5,1] Hz frequency range (FGM measurements)
- There is a broad range of spectral indices: [-4,-2].
- What is going on at smaller scales, not resolved by this instrument?

SW spectra from MHD to electron scales

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

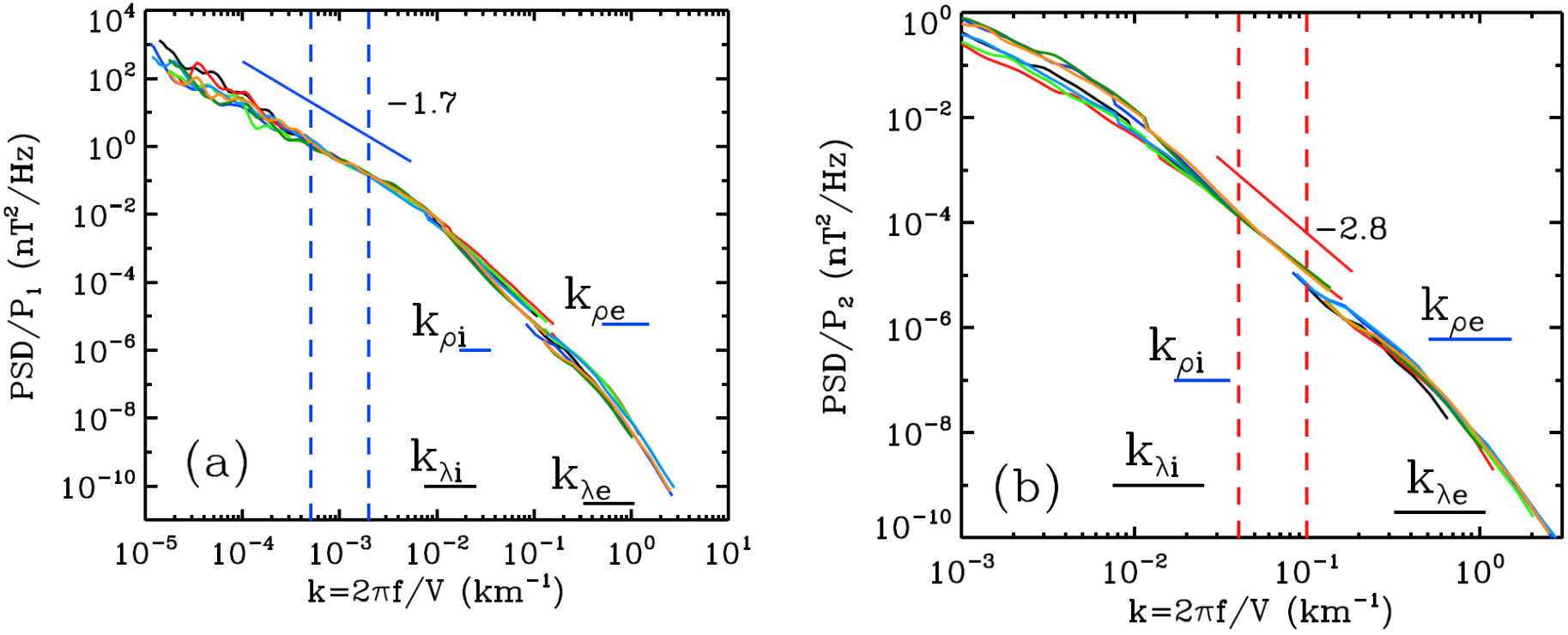


Superposition of different spectra gives one clear spectrum with 2 inertial ranges ~$k^{-5/3}$, $k^{-2.8}$ (and dissipation at electron scales?)

[Alexandrova et al. 2009, PRL]

Rescaled spectra at 2 inertial ranges independently

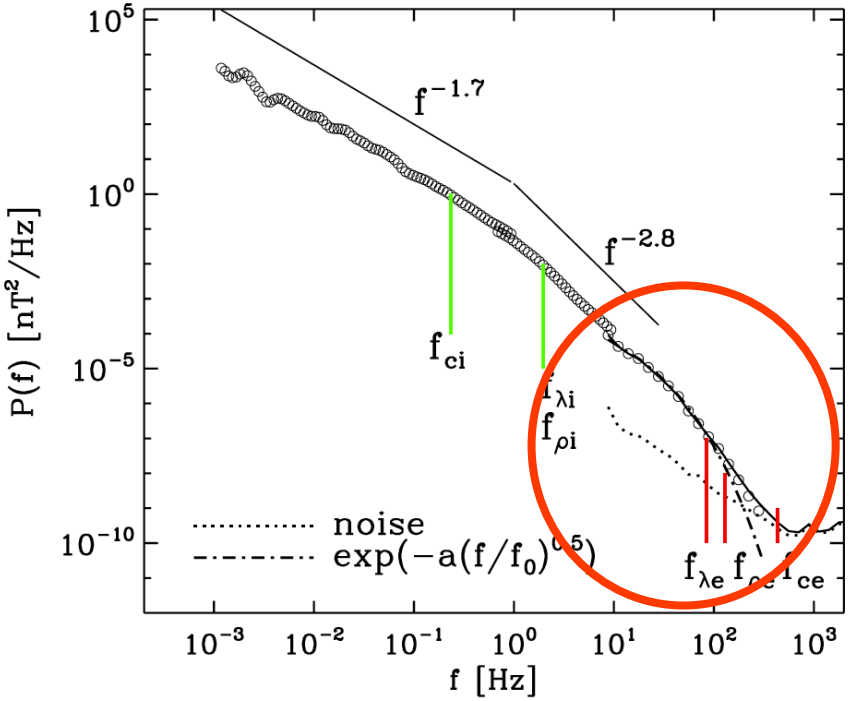
[Alexandrova et al, 2010, SW12]



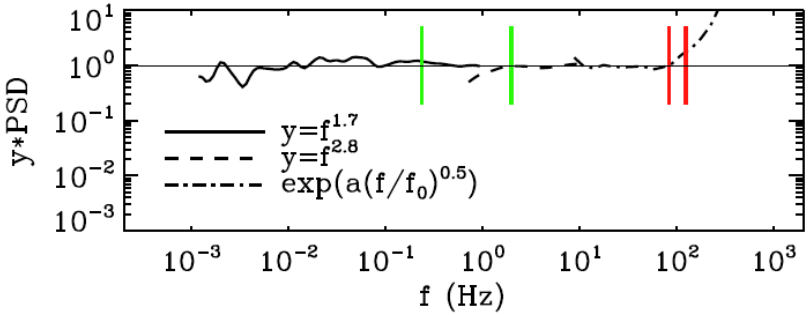
- Transition from $k^{-1.7}$ to $k^{-2.8}$ is not universal [~Smith et al. 2006]
- Depends on local ion instabilities? [see e.g. Bale et al. 2009]

Spectral shape at electron scales: spectral curvature /spectral break?

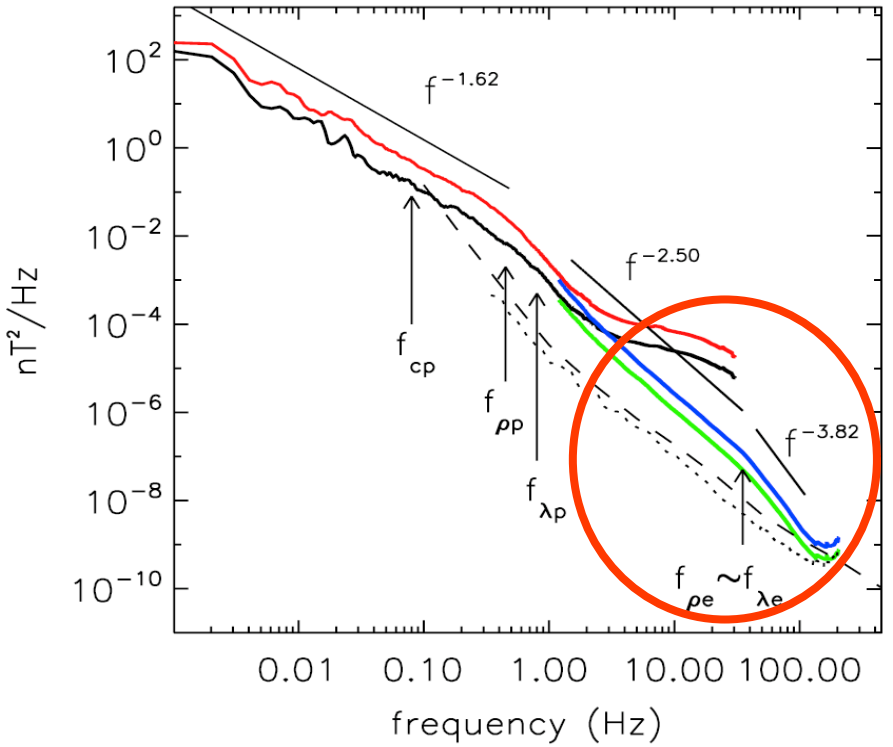
[Alexandrova et al. 2009, PRL]



Compensated spectra



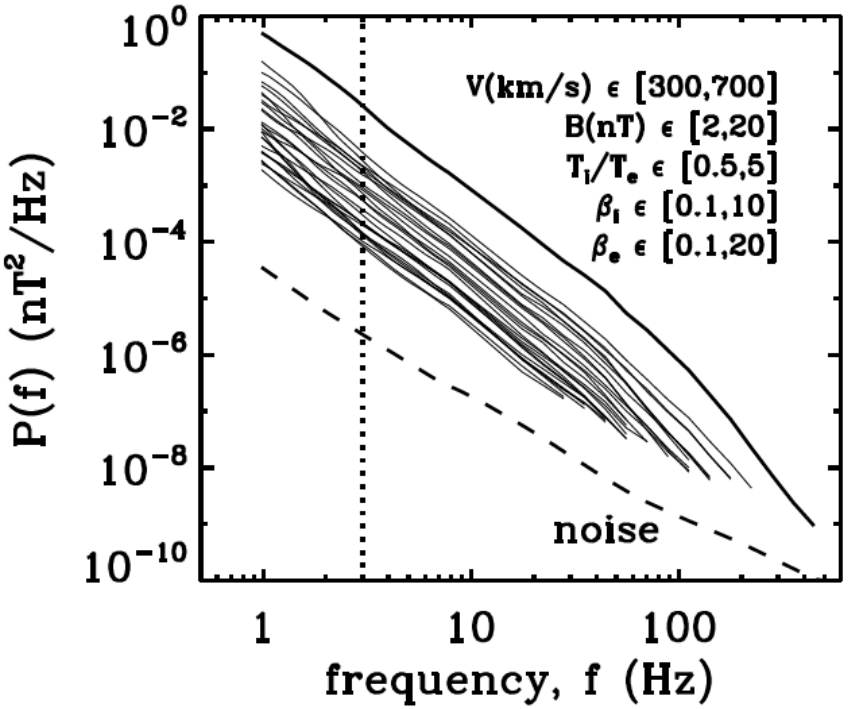
[Sahraoui et al. 2009, PRL]

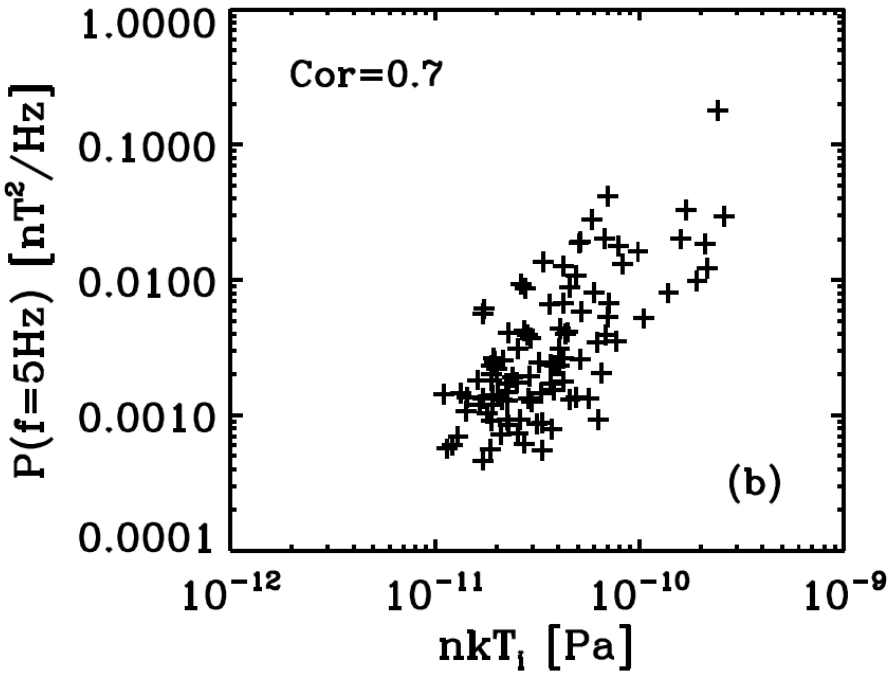


Contradictory solar wind observations?

SW spectra at kinetic scales: statistical study of 100 spectra

[Alexandrova et al. 2011, arxiv]

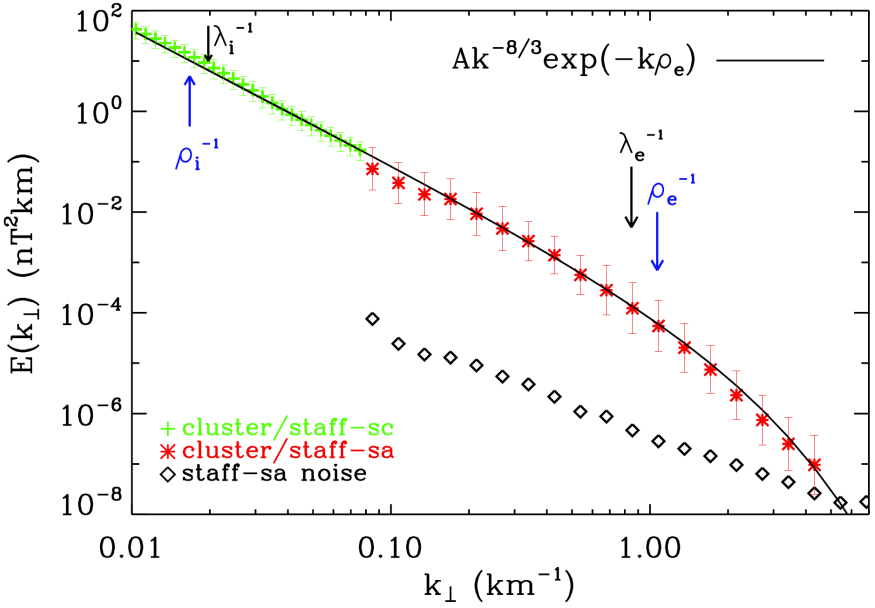


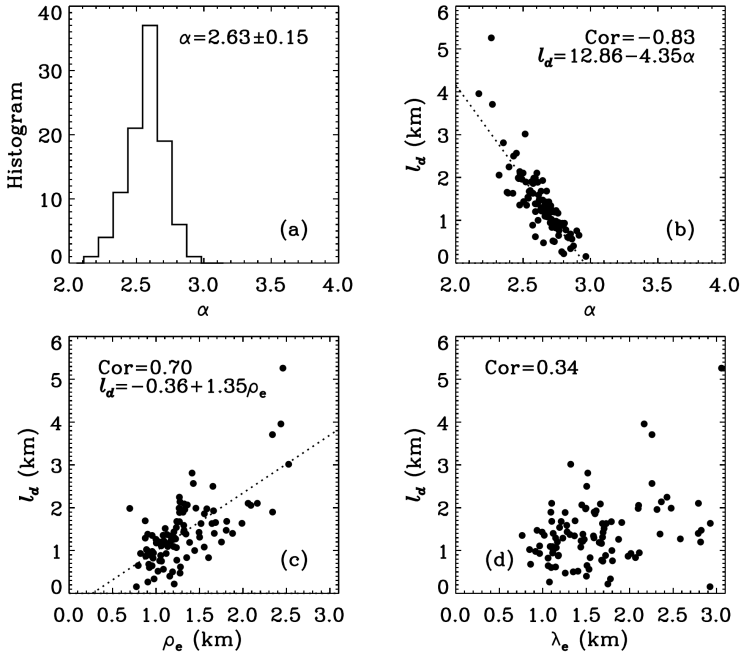


- Statistical study allows to select a range of scales where the spectra are all ~similar.
- Turbulence level at a fixed frequency correlates with ion thermal pressure nkT_i (~ as in the inertial range, see discussion of Y. Dong)

Description of sw spectrum at plasma kinetic scales : exp-model (3 free parameters)

$$E(k) = Ak^{-\alpha}\exp(-k/k_d)$$ [Chen, Doolen, et al., 1993, PRL]



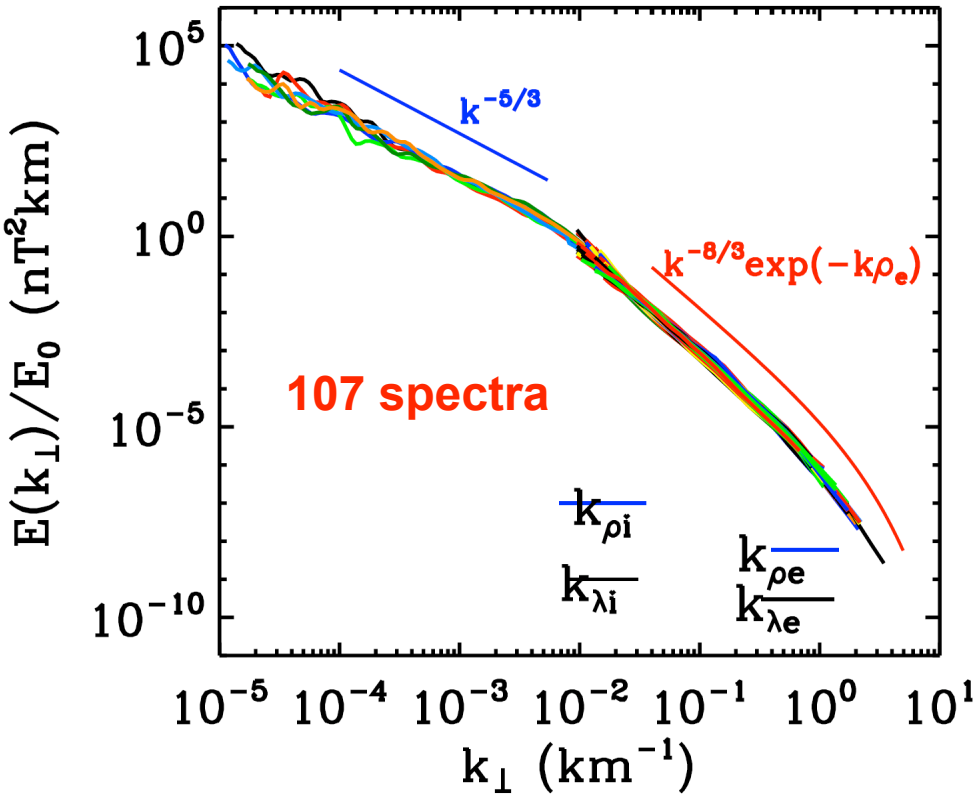


$$E(k) = Ak^{-8/3}\exp(-k\rho_e)$$

Actually, there is only 1 free parameter!

[Alexandrova et al., accepted, 2012; arxiv, 2011]

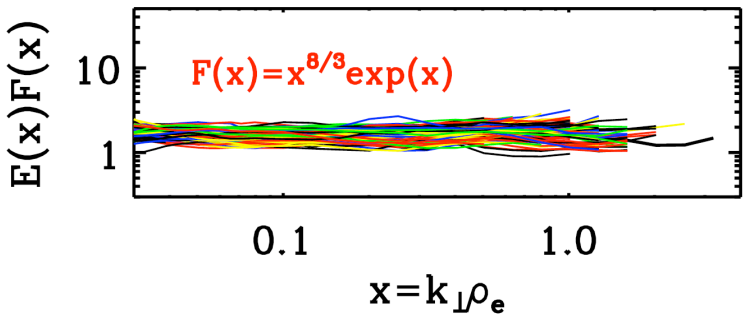
General shape of $k_\perp$-spectra



MHD scales: ~$k^{5/3}$

Kinetic scales:

$$E(k) = Ak^{-8/3}\exp(-k\rho_e)$$

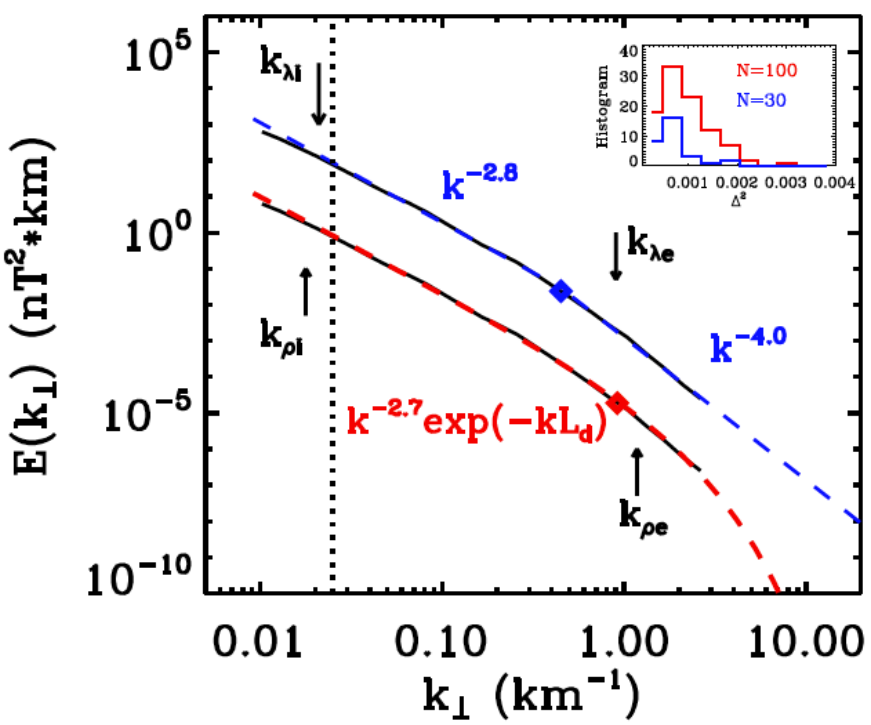


Compensated spectra are flat at $k\rho_e$>0.03 and for ~2 decades in scales => the model describes well all observed spectra.

Another description of the spectrum at small scales ?
Break-model (5 free parameters)

$$E(k) = A_1 k^{-\alpha_1}(1 - H(k - k_b)) + A_2 k^{-\alpha_2} H(k - k_b)$$

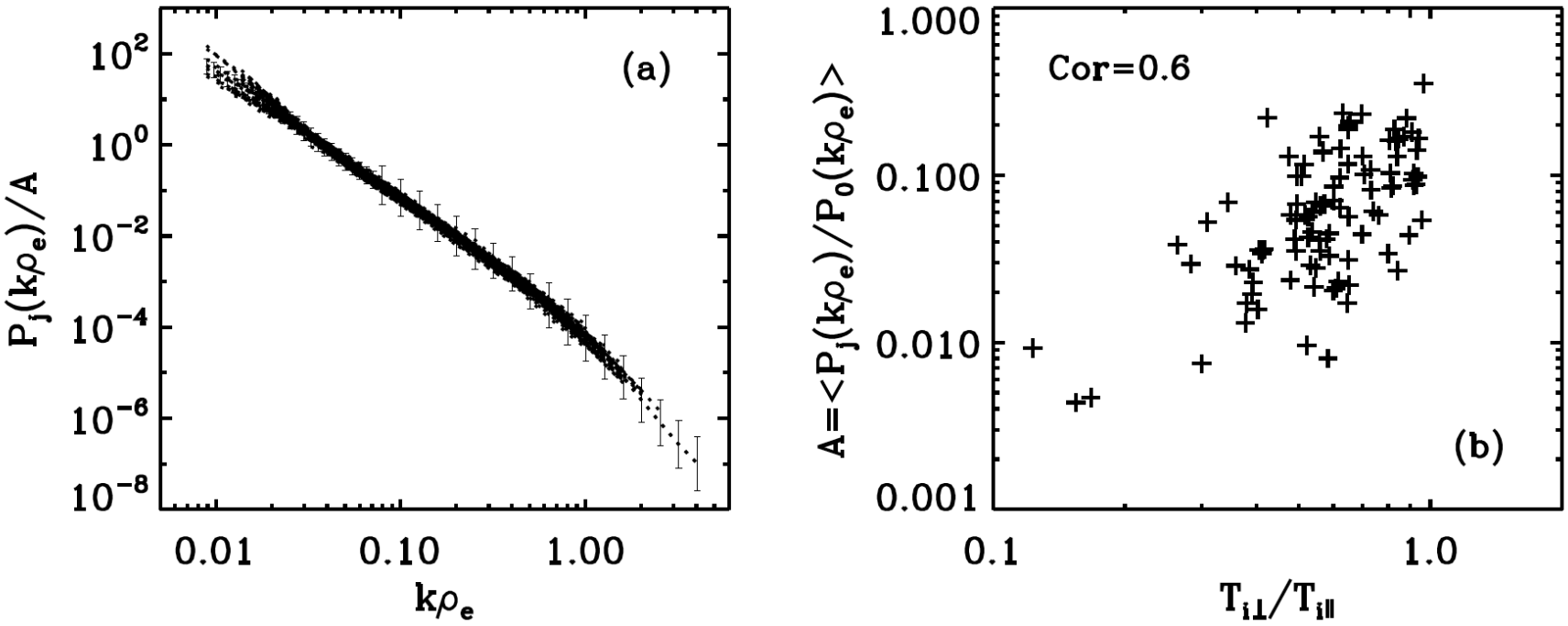
where H is the function of Heaviside, $k_b = L_b^{-1}$ break wavenumber, $A_{1,2}$=amplitues, $\alpha_{1,2}$=spectral indices.



- "Break"-model can describe only 30 (of 100) spectra
- For these 30 spectra, both models fit well to the data with equivalent $\Delta^2 = \sum(y_{obs} - y_{th})^2/N$
- This leave us free to chose the model, based on other criteria than goodness of the fit:
  - ✓ number of degree of freedom
  - ✓ number of described cases

Simple algebraic description of kinetic spectrum ~ $k^{-8/3}\exp(-k\rho_e)$

[Alexandrova et al. 2011, arxiv]

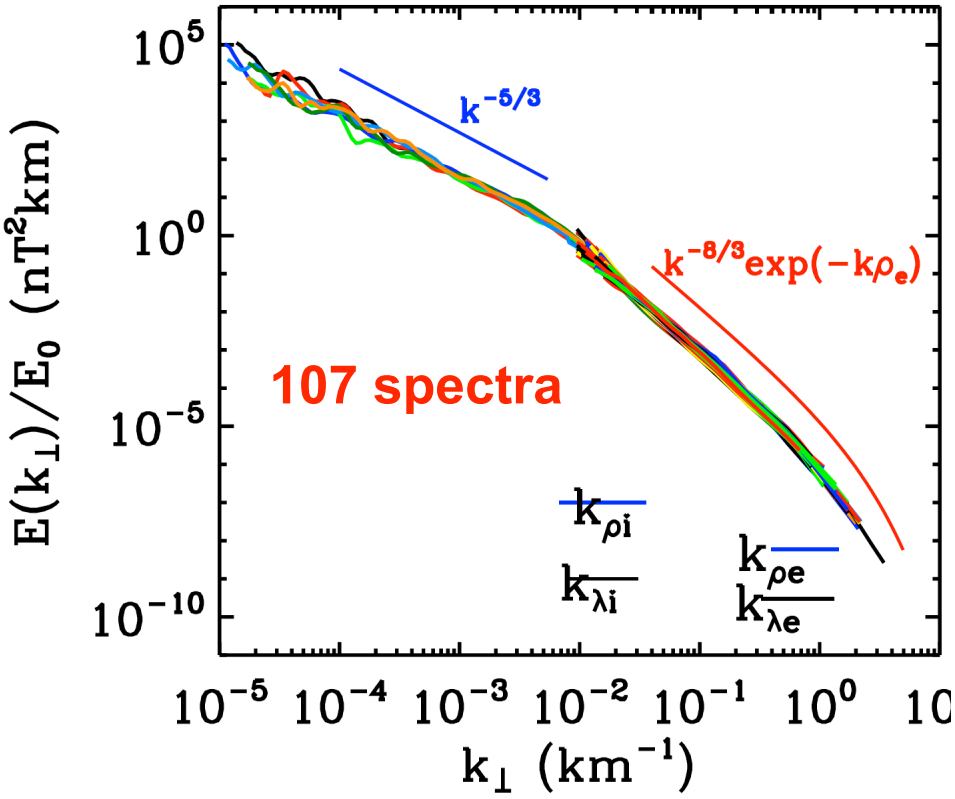


$$E(k) = A(T_i, T_{i\perp}/T_{i\parallel})k^{-8/3}\exp(-k\rho_e)$$

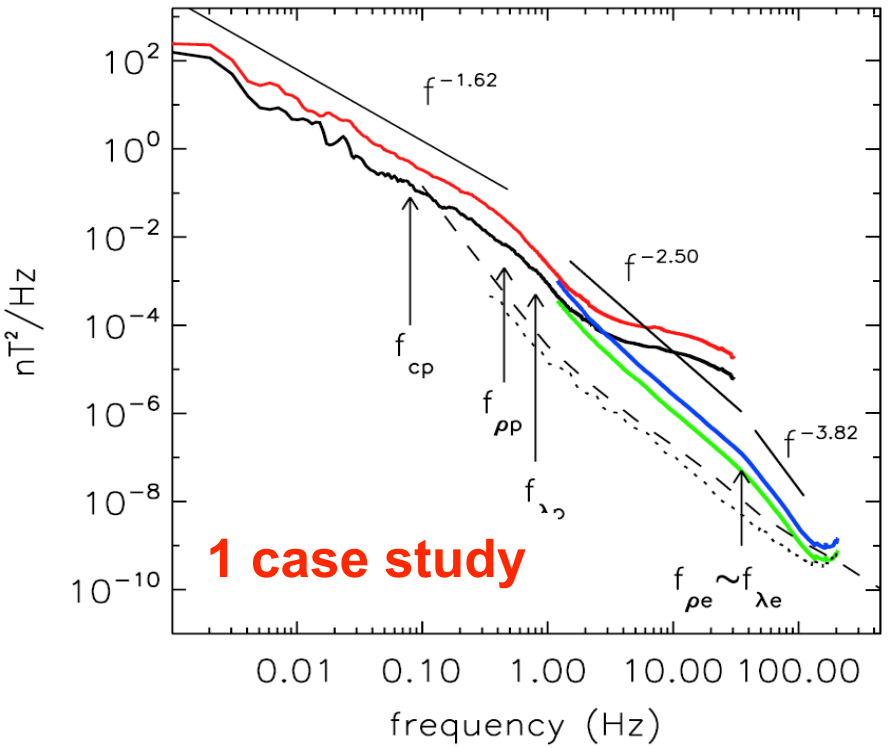
Constant A depends on the ion temperature anisotropy.
=> Role of ion instabilities?

On contradiction of sw observations

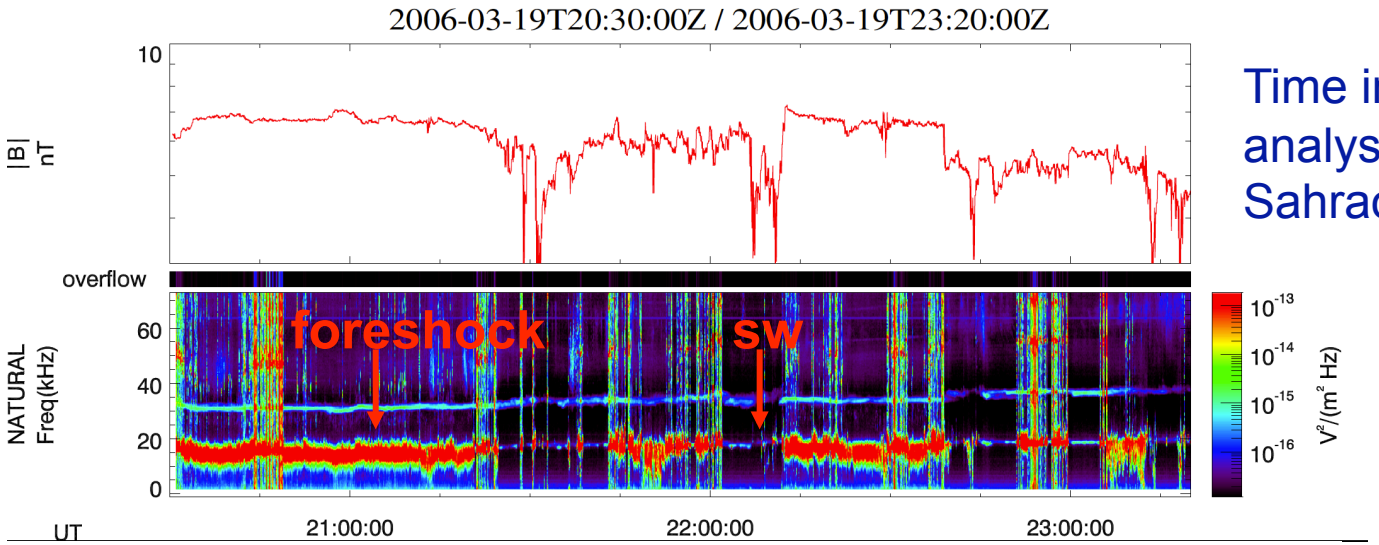
[Alexandrova et al. 2009, PRL, 2012]



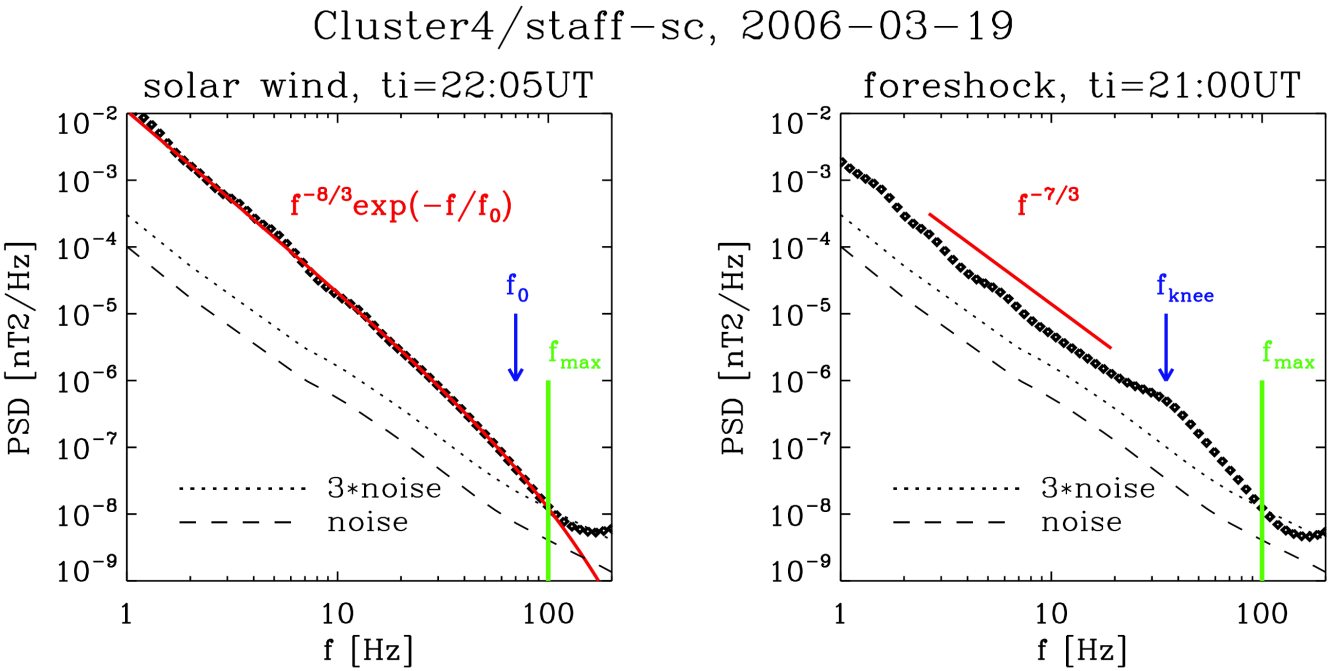
[Sahraoui et al. 2009, PRL]



No contradiction in the free solar wind :



Time interval analysed by Sahraoui et al. [2009]

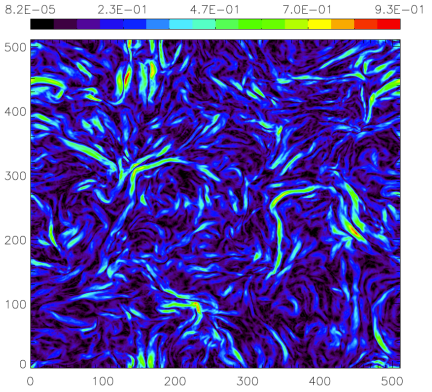


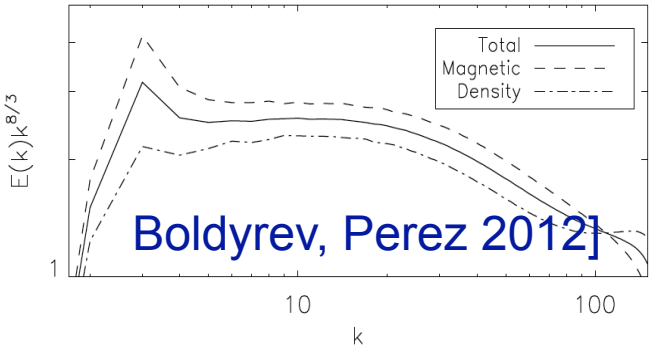
Spectral knee <=> foreshock physics !

Interpratation of the solar wind kinetic spectrum?

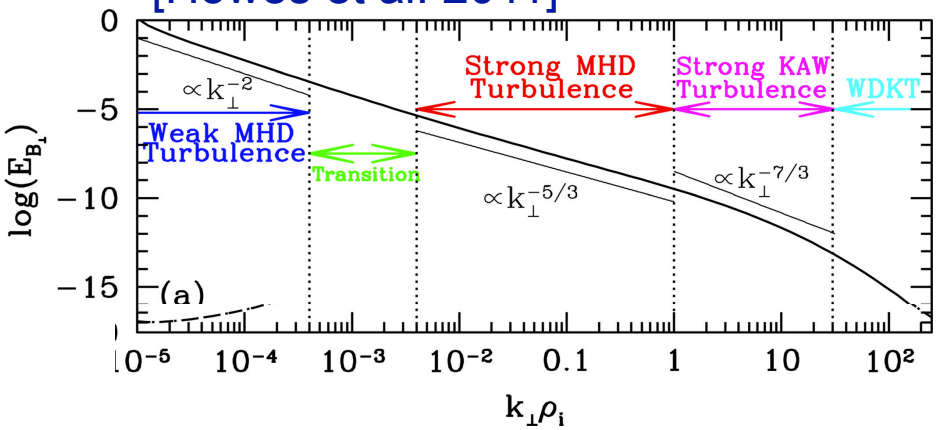
$$E(k) = Ak^{-8/3}\exp(-k\rho_e)$$

Compressible NL KAW fluctuations have -8/3 spectrum between ion and electron scales [Boldyrev and Perez 2012]:





[Howes et al. 2011]



Cascade model with ~k^2 damping term (dissipation via linear Landau damping of KAW's) [Howes et al. 2006, 2011]

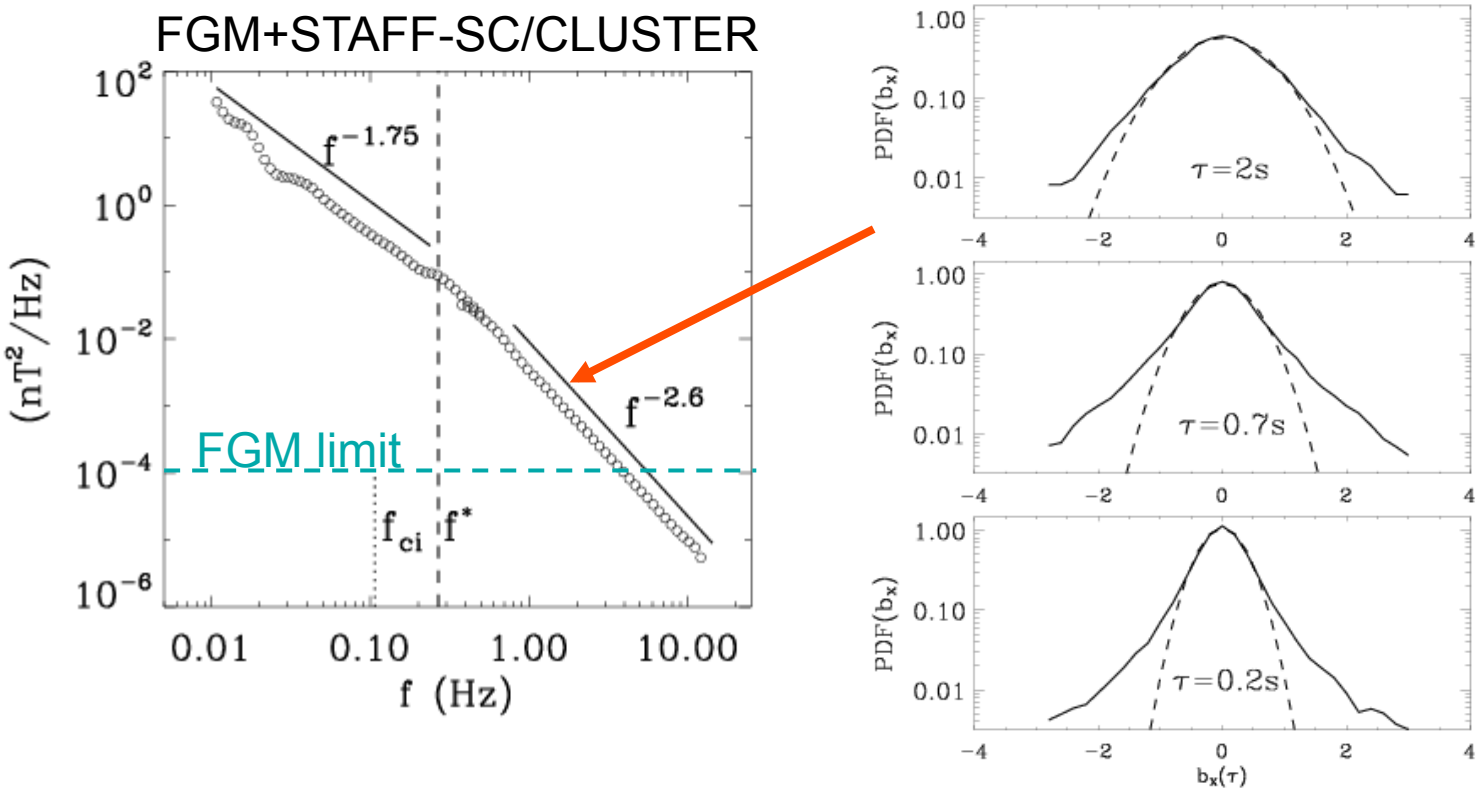
Applicability of these models to the solar wind?

Nature of turbulent fluctuations: weak/strong turbulence

There are two schools of thought :

1) wave turbulence (KAW, whistlers);
2) strong turbulence (non-linear fluctuations and coherent structures)

Observation of intermittency in the dissipation range



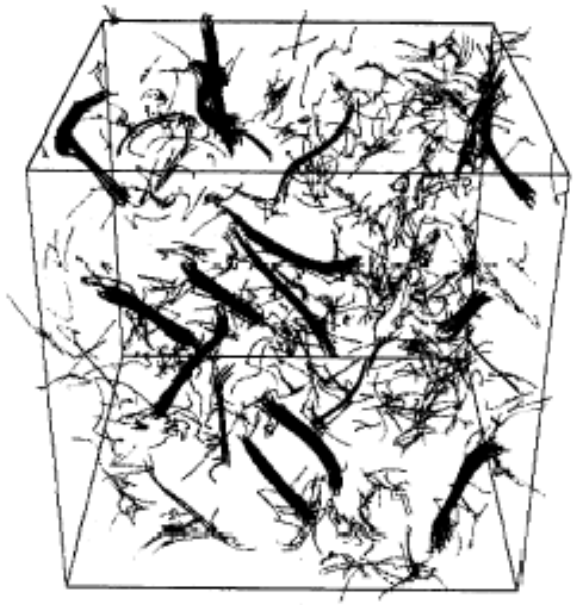
- Intermittency increases toward smaller scales as in the MHD inertial range.
- (This need to be verified for more sw intervals.)

[Alexandrova et al., 2008, ApJ]

Intermittency = coherent structures

In HD turbulence intermittency corresponds to appearance of coherent structures:

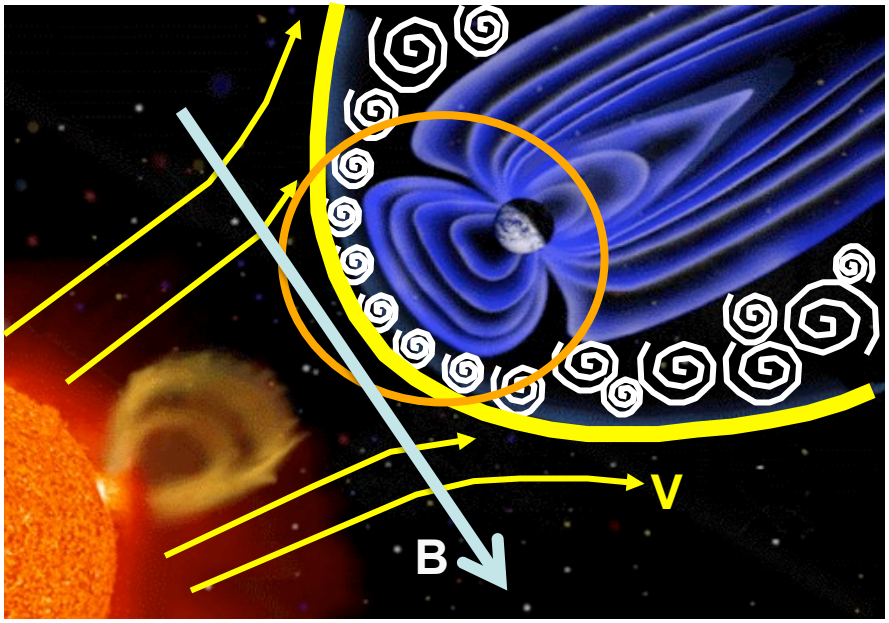
[She et al., 1991]

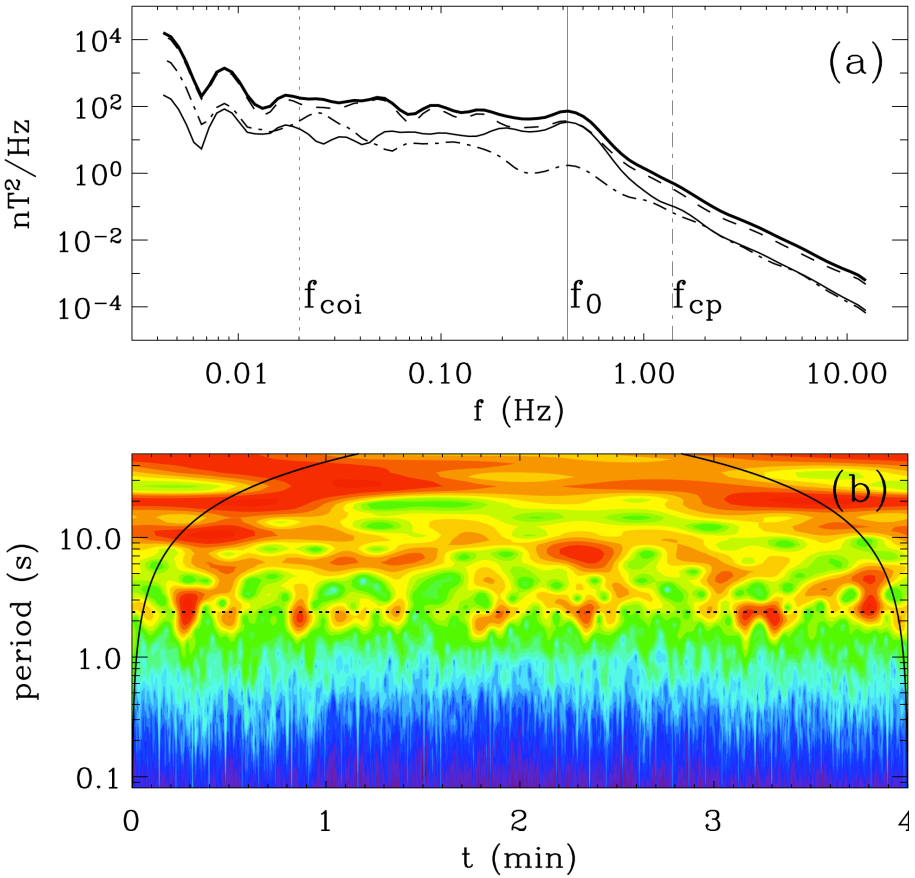


3D Simulations HD : filaments of vorticity with cross-section ~ $L_{dissipation}$, and length ~ $L_{injection}$

Important for dissipation

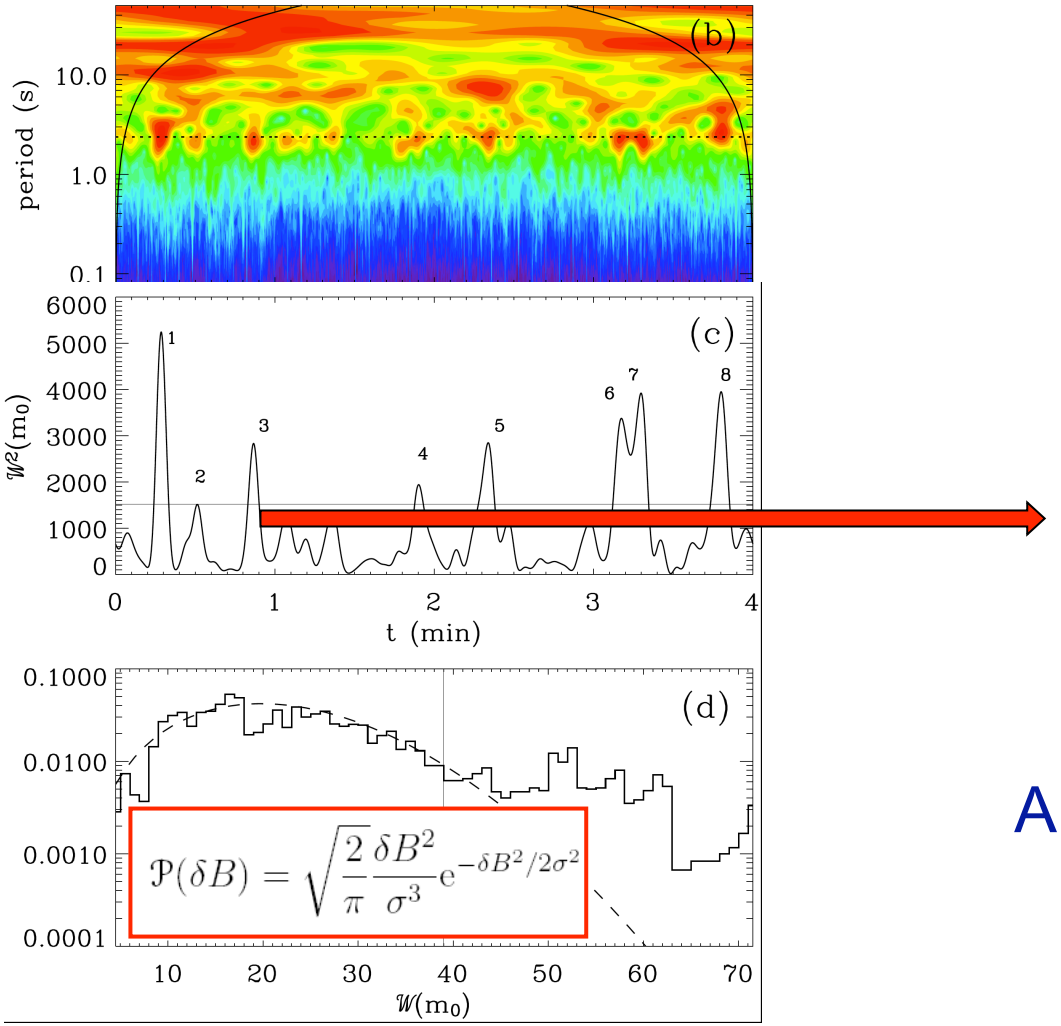
Planetary magnetosheath



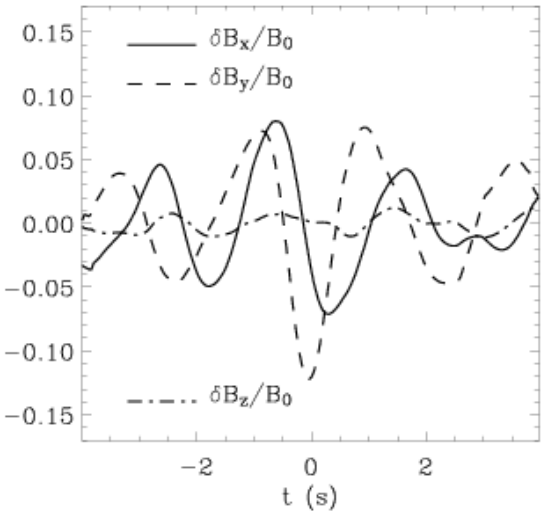


- turbulent transition between SW and Magentosphere

Detection of Alfven vortices in the Earth's magnetosheath

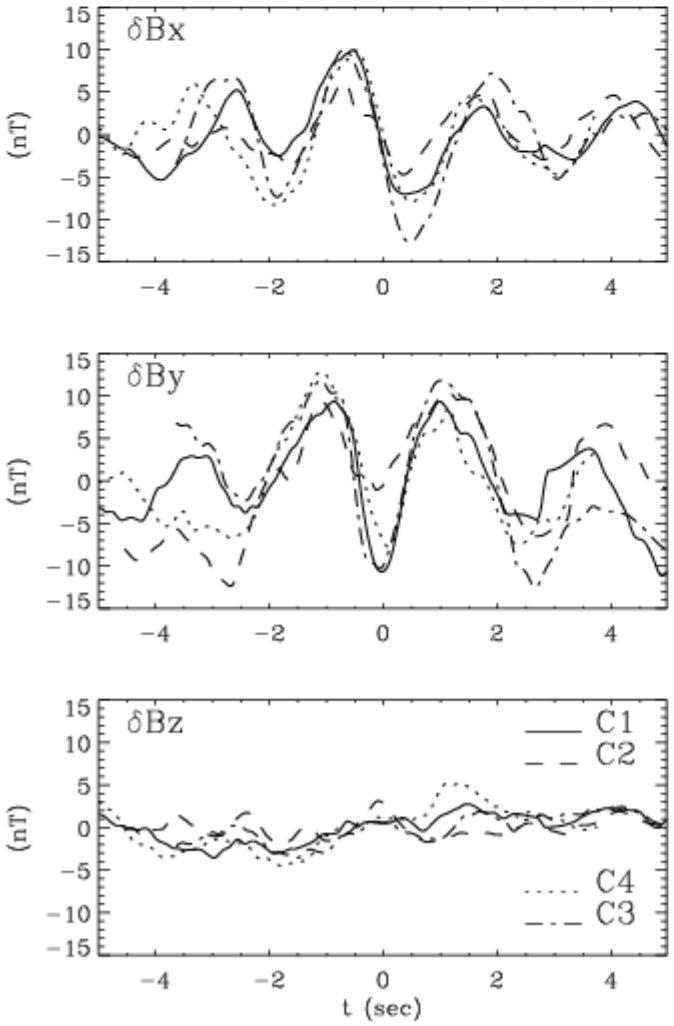


Histogram of the amplitudes of wavelet coefficients on the scale $1/f_0$



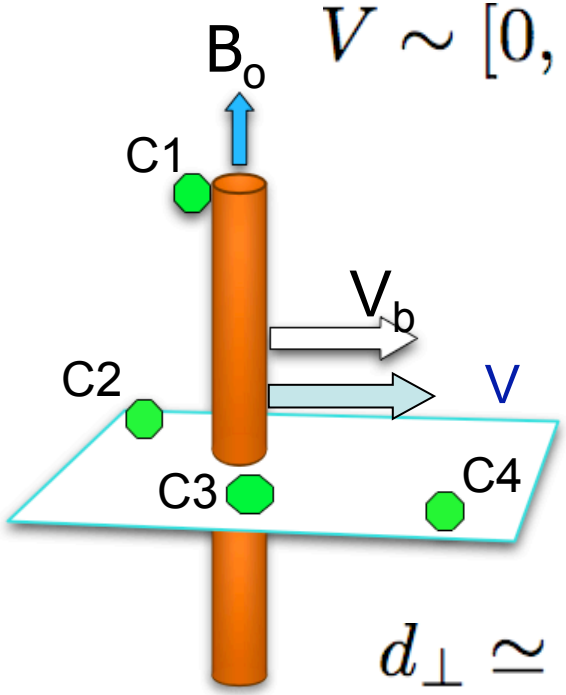
A wave packet or a structure?

Detection of Alfven vortices



In plasma frame:

$$V \sim [0, 0.3]V_A$$



$$d_\perp \simeq 500km$$

$$d_\perp \sim 10c/\omega_{pi}$$

[Alexandrova et al., 2006, JGR]

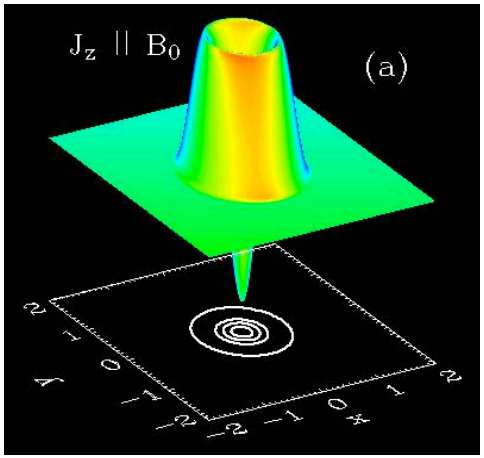
Quasi-2D Alfven Vortex

Properties of the observed coherent fluctuations :

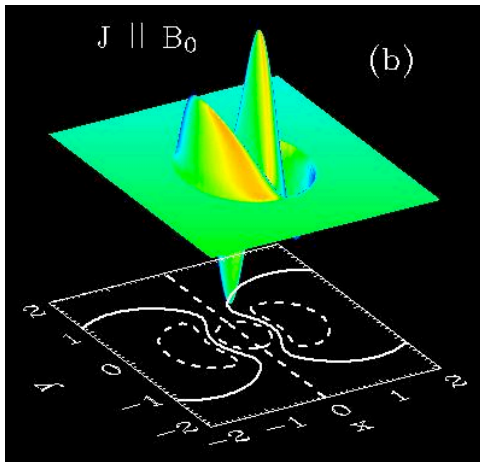
- 2D ($\nabla_{||} < \nabla_{\perp}$)
- incompressible ($\delta B_{||} < \delta B_{\perp}$)
- Alfvénic ($\delta V_{\perp} \,||\, \delta B_{\perp}$)

MHD has solutions in the form of magnetic vortex (~ HD incompressible vortex)

$$\delta V_{\perp}/V_A = \xi \delta B_{\perp}/B_0$$



Monopole ~ force free current, standing structure

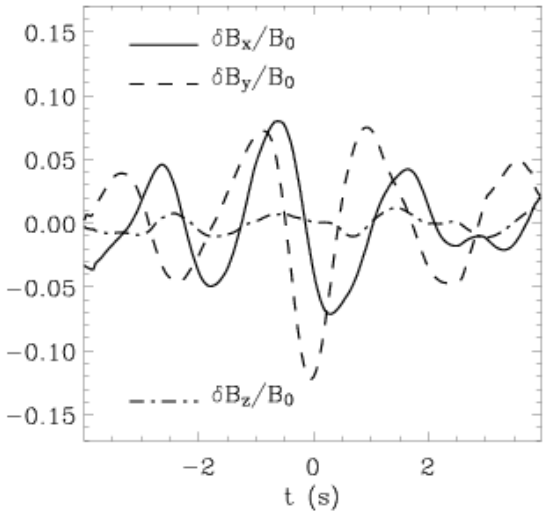


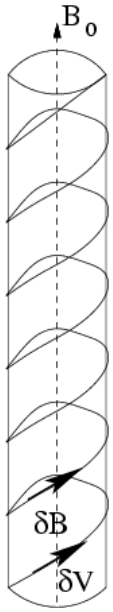
Dipole ~ two inversed currents, propagates

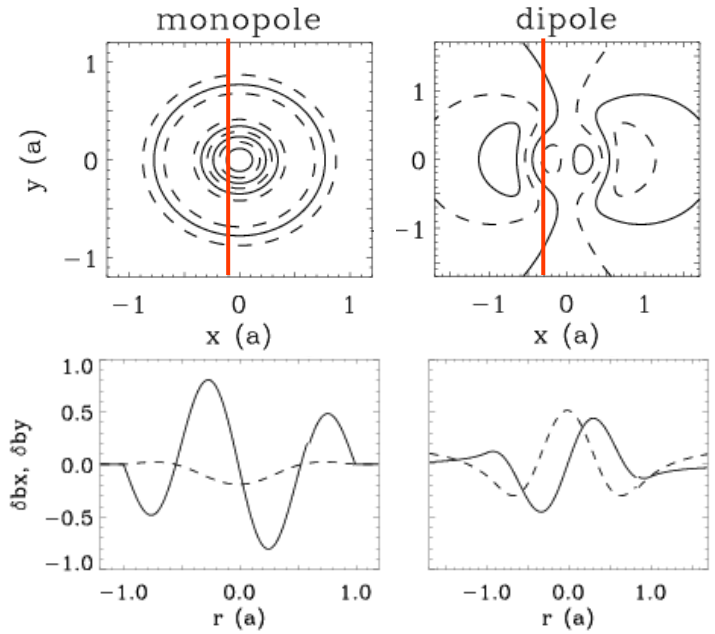
[Petviashvilli & Pokhotelov, 1992]

Alfven Vortices (2D structures)

in the Earth's and Saturn's Q⊥-magnetosheath (~10-20 ion scales), and in the Earth's cusps (~1 ion scale)



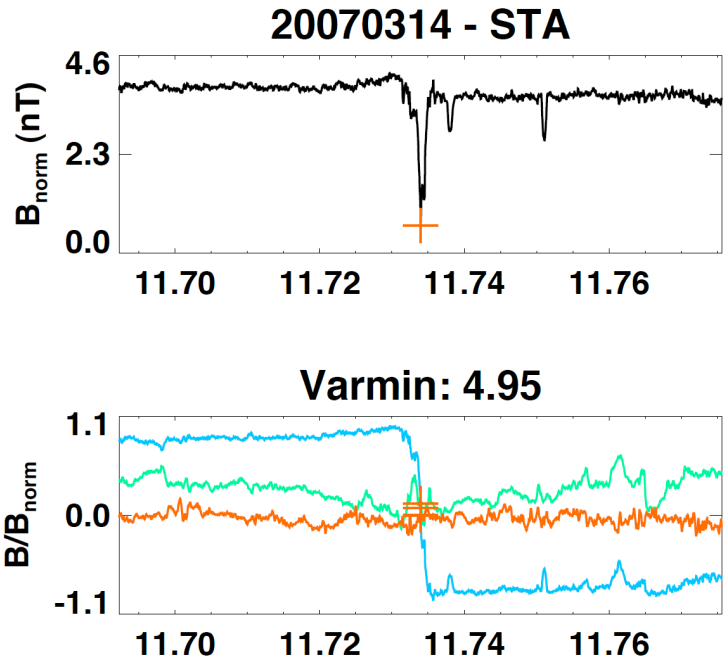




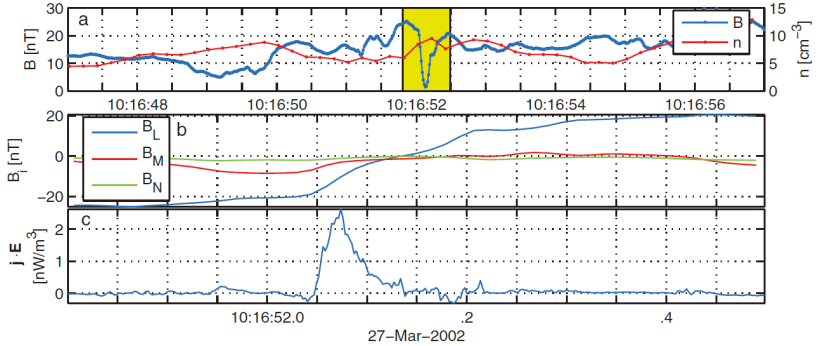
[Alexandrova et al. 2004, 2006, Alexandrova & Saur, 2008, Sundkvist, et al., 2005, 2008]

Other examples of coherent structures in space plasmas

- Magnetic holes and current sheets in SW and Q||-magnetosheath (1D structures)



Cluster & STEREO observations
[Briand, Soucek, et al., 2010, JGR]

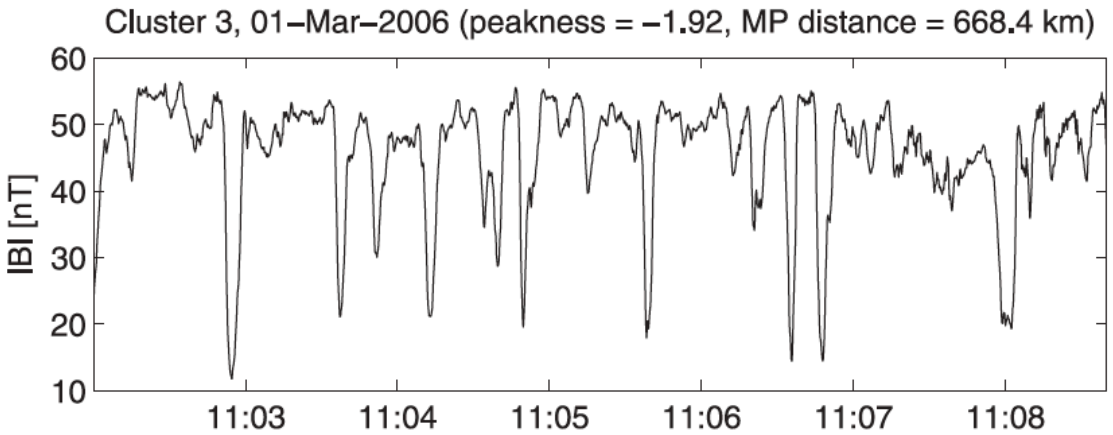


Scales ~ ion scales.
[Retino et al., 2007, Nature,
Sundkvist et al., 2007, PRL]

See also Mangeney, Veltri, Salem observations;
Hall MHD simulations of Greco et al., Servido et al.

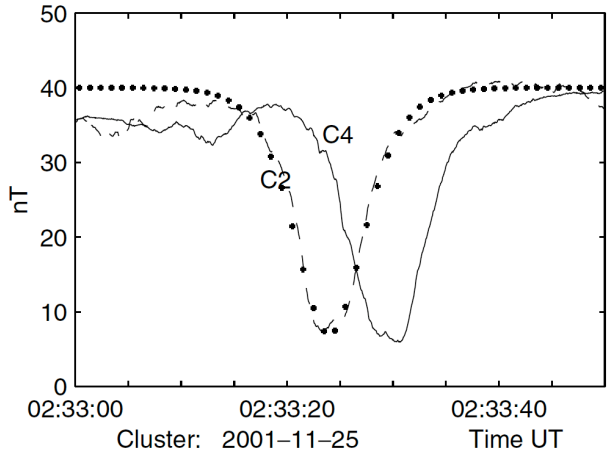
- Magnetic dips and peaks (mirror modes)

[Soucek et al., 2008; Genot et al., 2008]



Scales are [5,80] ion Larmor radius.

- Slow m/sonic solitons at magnetopause [Stasiewicz et al, 2003]



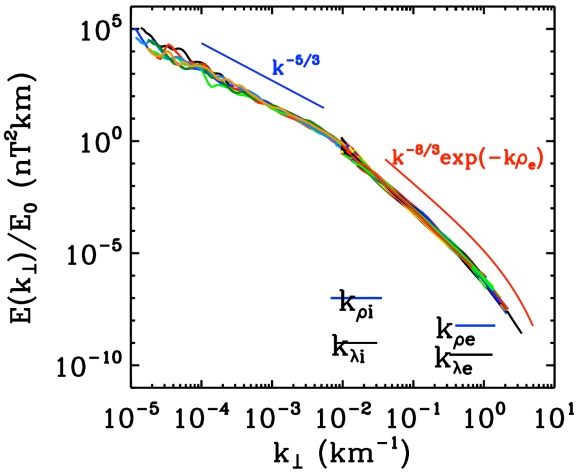
~ Ion scales

SW structures?

Conclusion/discussion

Turbulent spectrum in the solar wind :

- MHD inertial range with k_perp spectrum ~ $k^{-5/3}$
- 1st spectral change at ion inertial length (in fast sw for $\beta<1$), Bourouaine et al. 2012, ApJ
- 2nd characteristic scale (for any plasma β and sw streams) is the electron Larmor radius, Alexandrova et al. 2009, 2011, 2012 accepted.
- single algebraic description for $k>k_i$



Open questions

- Theoretical understanding ?
- What is behind the turbulent spectrum?
- Dissipation of turbulent energy in collisionless plasmas
  - ✓ role of coherent structures?
  - ✓ temperature anisotropy and q-lin. Instabilities?
  - ✓ Landau damping?
  - ✓ …