Turbulence in the Earth's magnetosheath and in the solar wind

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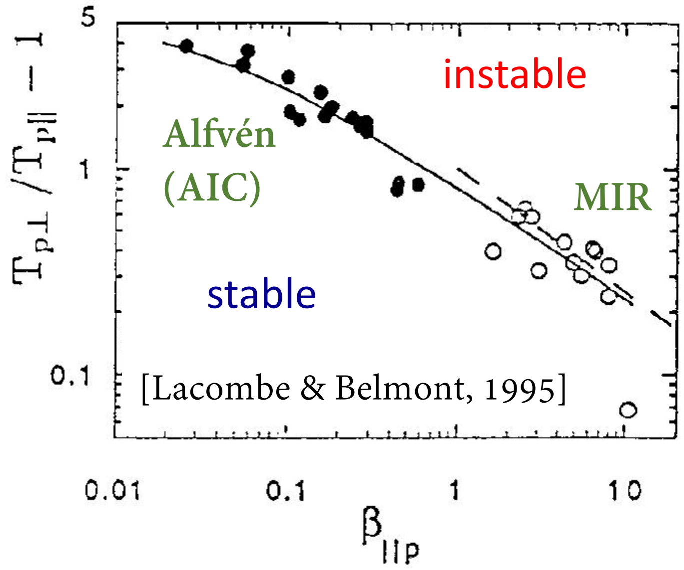
Magnetic fluctuations in the Earth's magnetosheath

1st observation of mirror waves [Hubert et al. 1989] and studies of Alfvén Ion Cyclotron (AIC) waves and mirror mode [Lacombe et al. 1990, 1992, 1995; Lacombe & Belmont 1995]



$$\beta_{\|p} = nkT_{p\|}/(B^2/8\pi)$$

The magnetosheath plasma is in a state of marginal stability

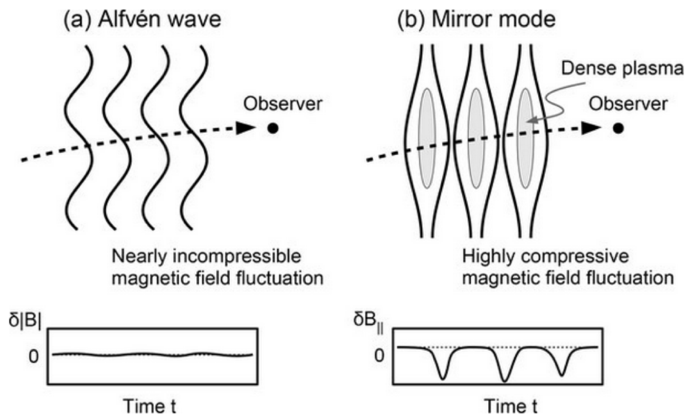
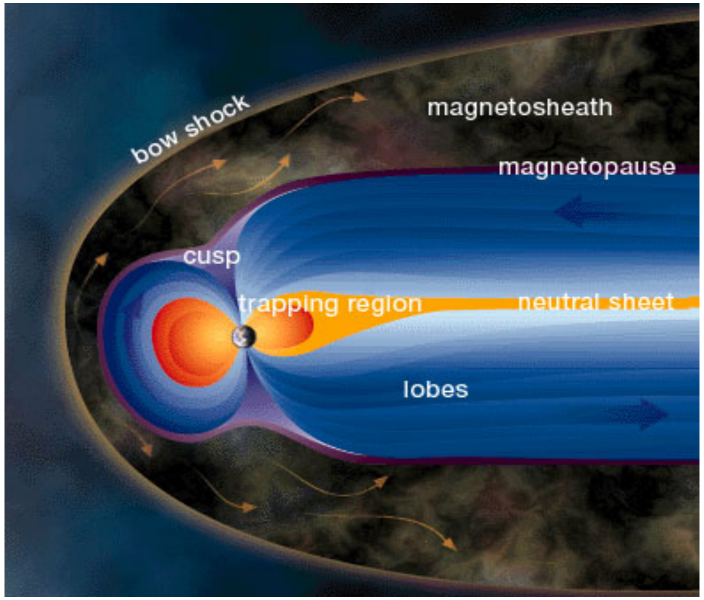


Schéma de [Schmid et al., 2020]



Magnetic fluctuations in magnetosheath with Cluster

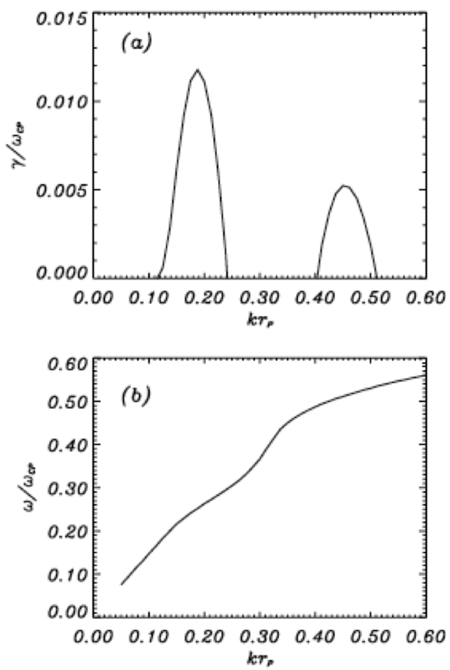
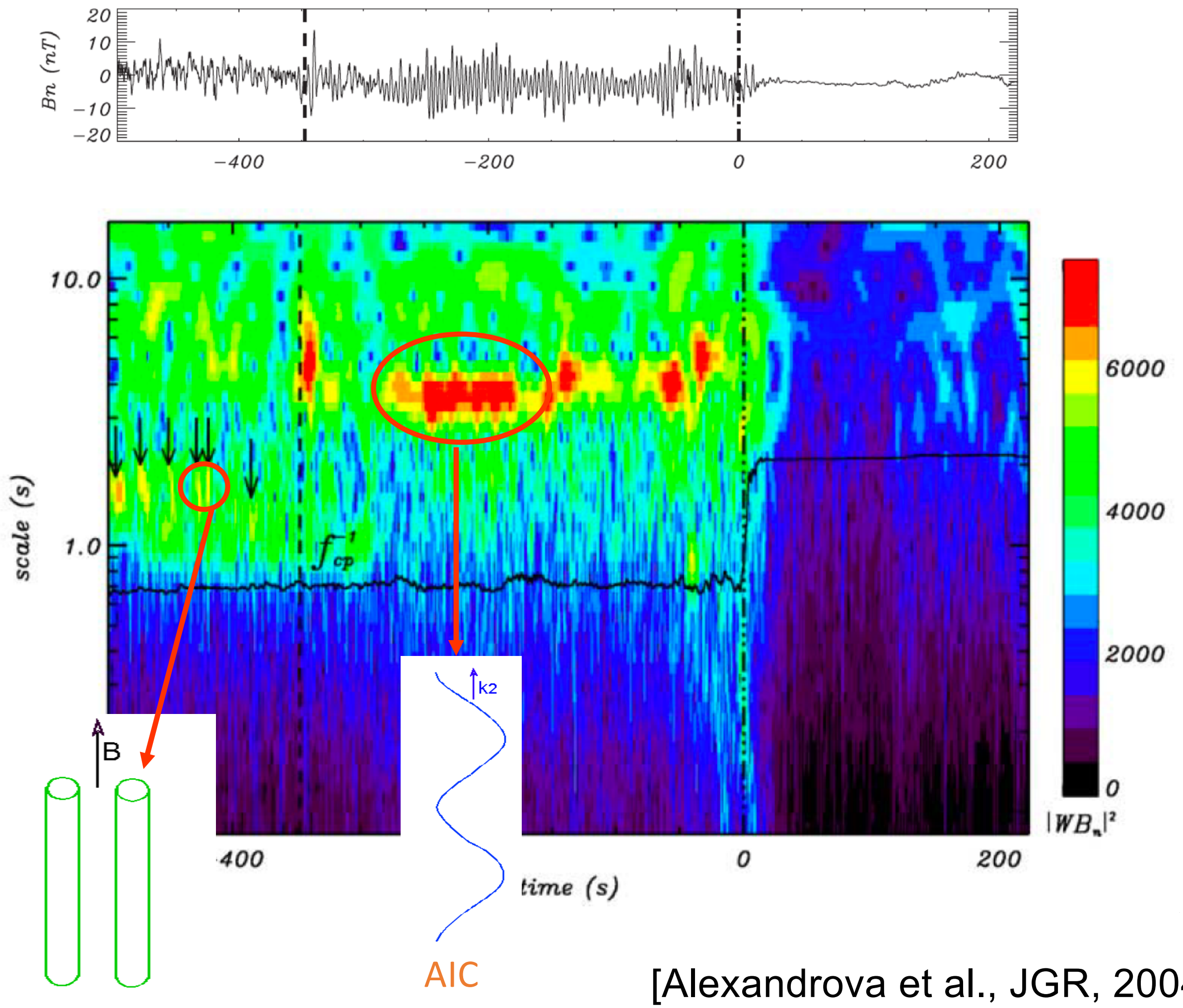
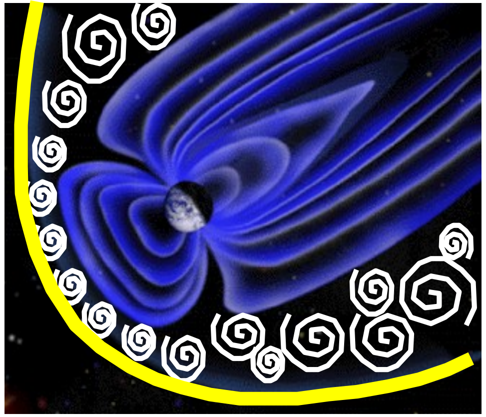


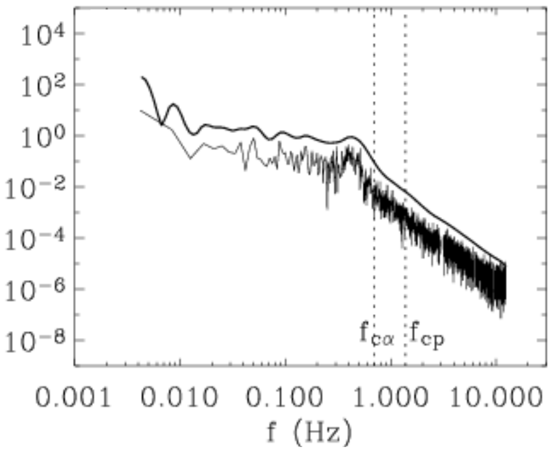
Figure 4. (a) Growth rate of the Alfvén ion cyclotron instability as a function of the nondimensional parallel wave vector kr_p. (b) Real part of the dispersion relation.

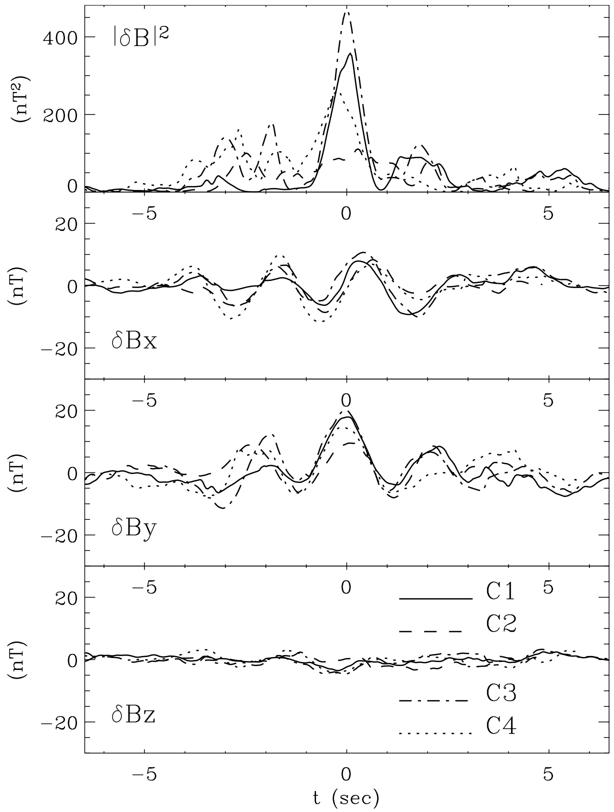


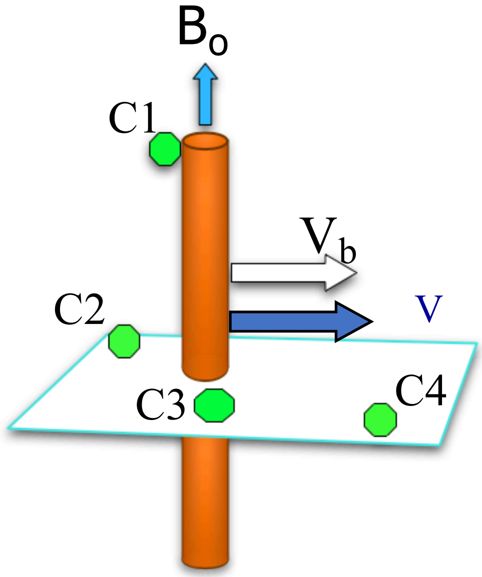
[Alexandrova et al., JGR, 2004]

Alfven vortex: downstream of the Earth's bow shock (first observation in space plasmas)









[Alexandrova et al. 2006, JGR]

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

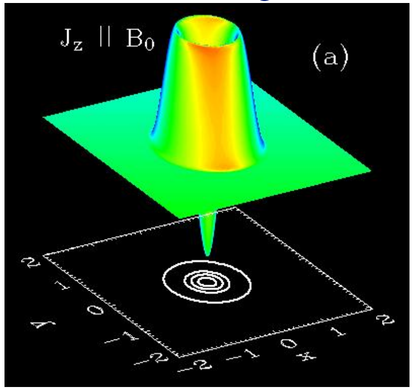
Alfven vortices

Vector potential, A, ~ to stream function ⇒ field lines || stream lines & current || vorticity [Petviashvilli & Pokhotelov, 1992]

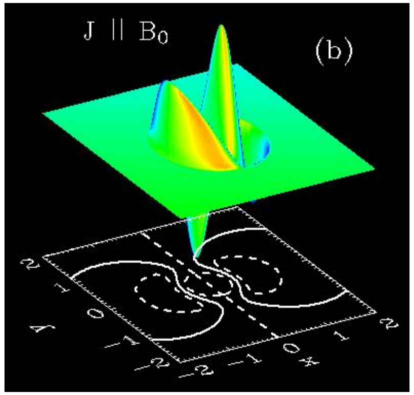
$$\frac{\partial_z}{\nabla_\perp} \sim \frac{\partial_t}{V_A \nabla_\perp} \sim \frac{\delta B_z}{\delta B_\perp} \sim \frac{\delta V_z}{\delta V_\perp} \sim \frac{\delta B_\perp}{B_0} \sim \frac{\delta V_\perp}{V_A} \sim \varepsilon.$$

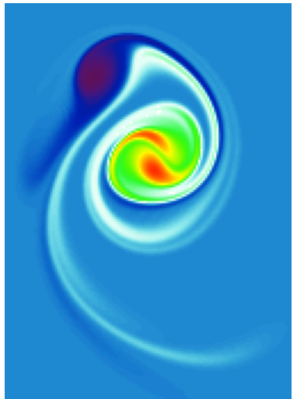
$$\delta V_\perp / V_A = \xi \delta B_\perp / B_0$$

Monopole ~ force free current, standing structure



Dipole ~ two inversed currents, propagates

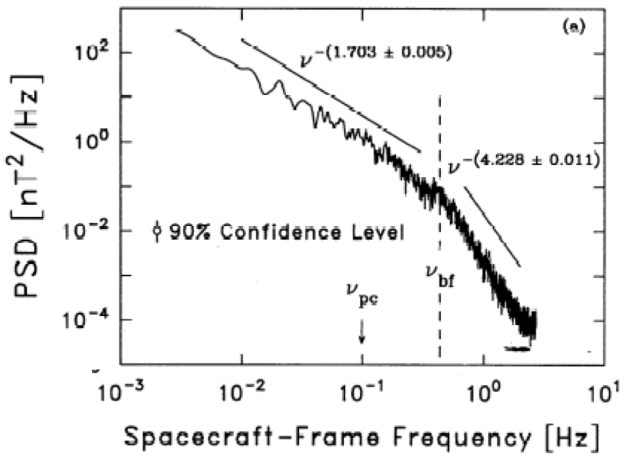




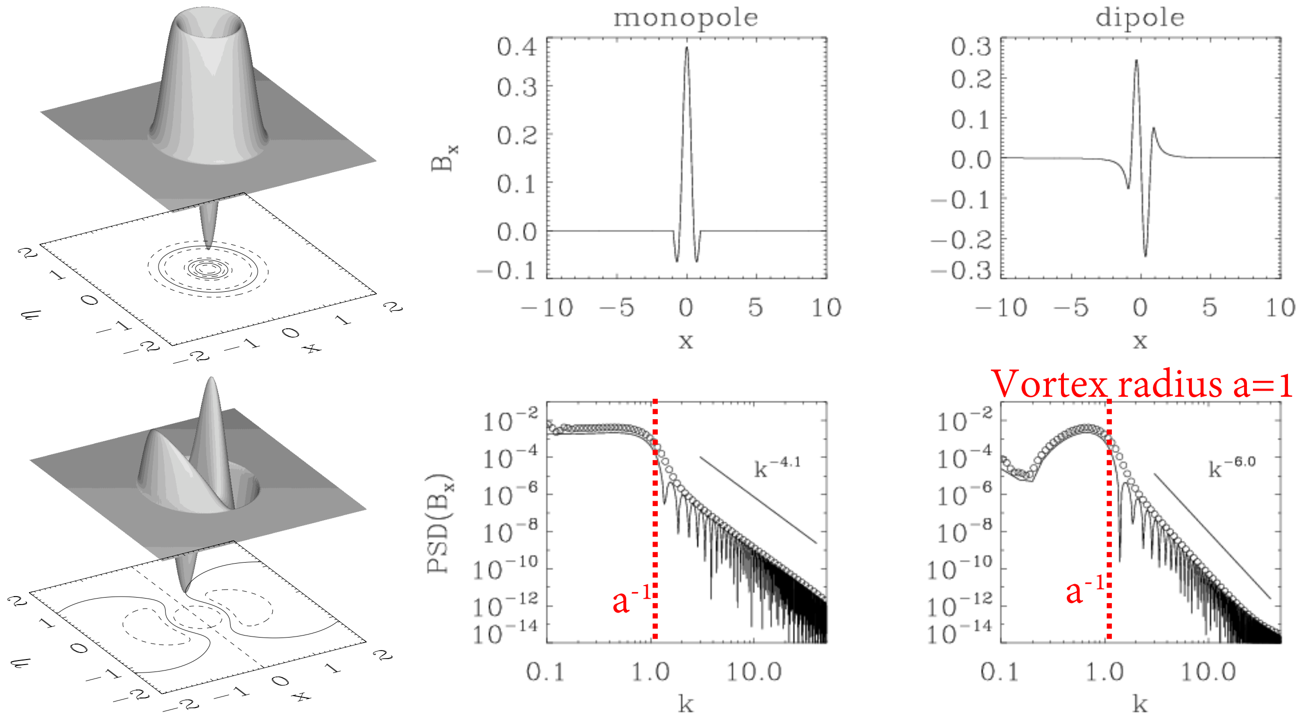
Alfven vortices ~ 2D incompressible HD vortices

Spectral properties of Alfvén vortices

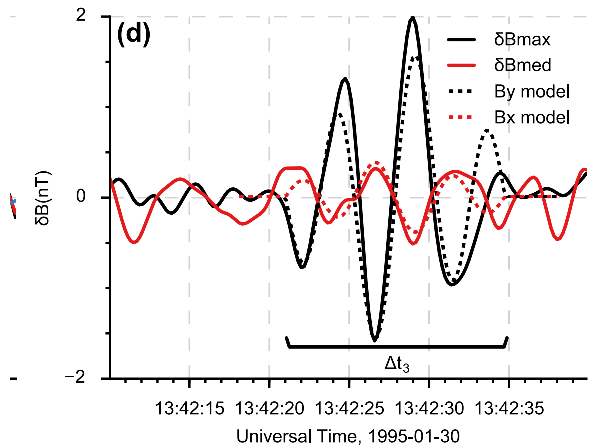
[Leamon+ 1998]



[Alexandrova 2008 NPG]

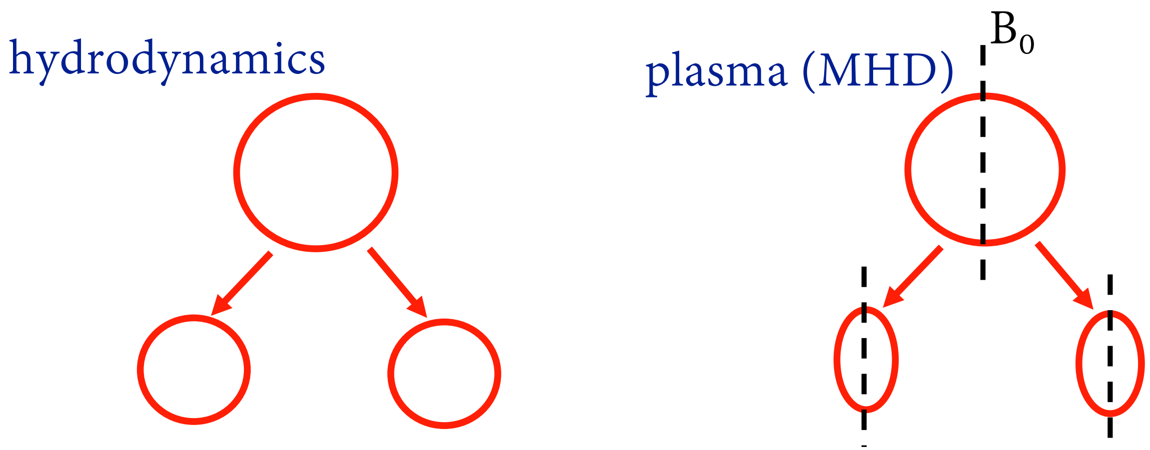


- Spectral knee at $k=a^{-1}$; power law spectra above it
- Monopole $\Rightarrow$ $\delta B^2 \sim k^{-4}$ (due to discontinuity of the current)
- Dipole $\Rightarrow$ $\delta B^2 \sim k^{-6}$ (due to discont. of the current derivative)



[Lion+ 2016]

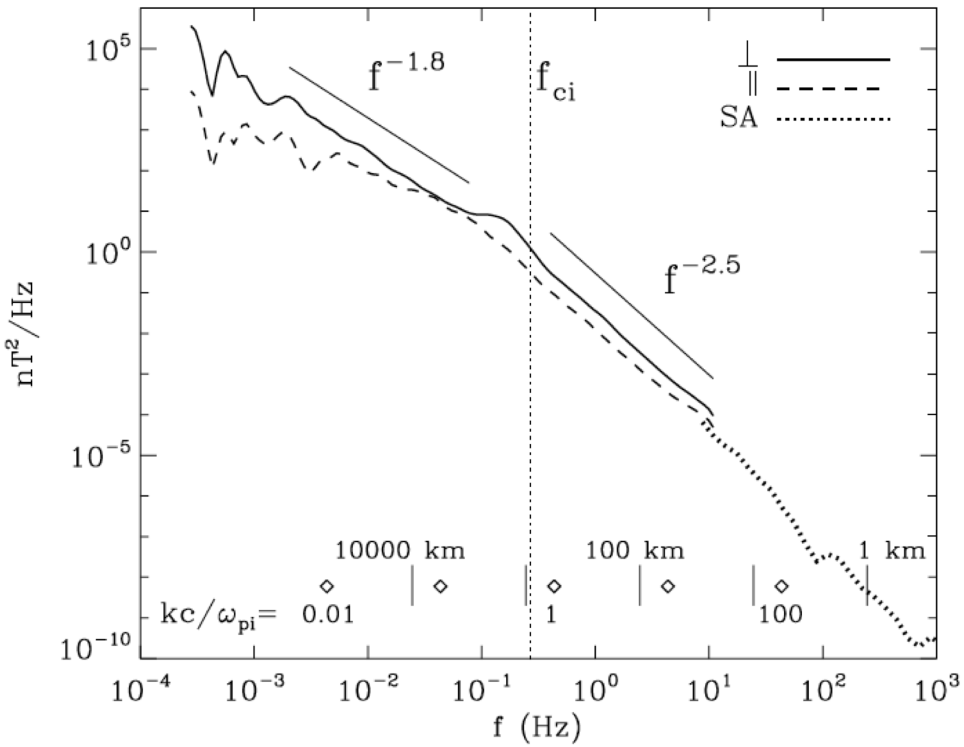
Turbulence in space plasmas

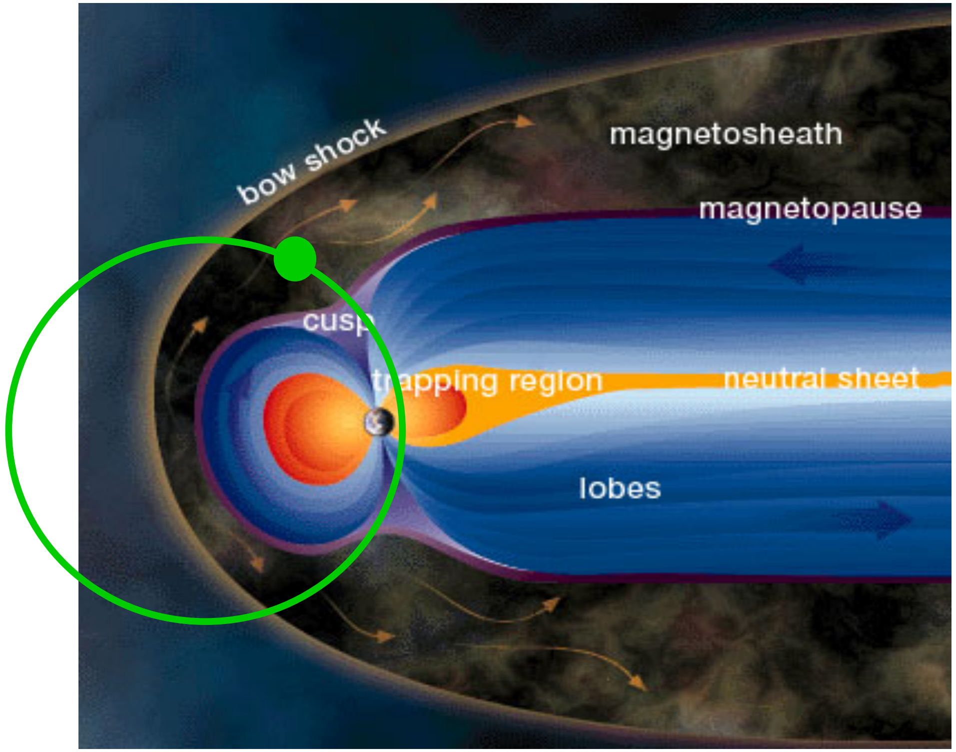


Presence of a mean magnetic field $B_0 \Rightarrow$ anisotropy of turbulent fluctuations

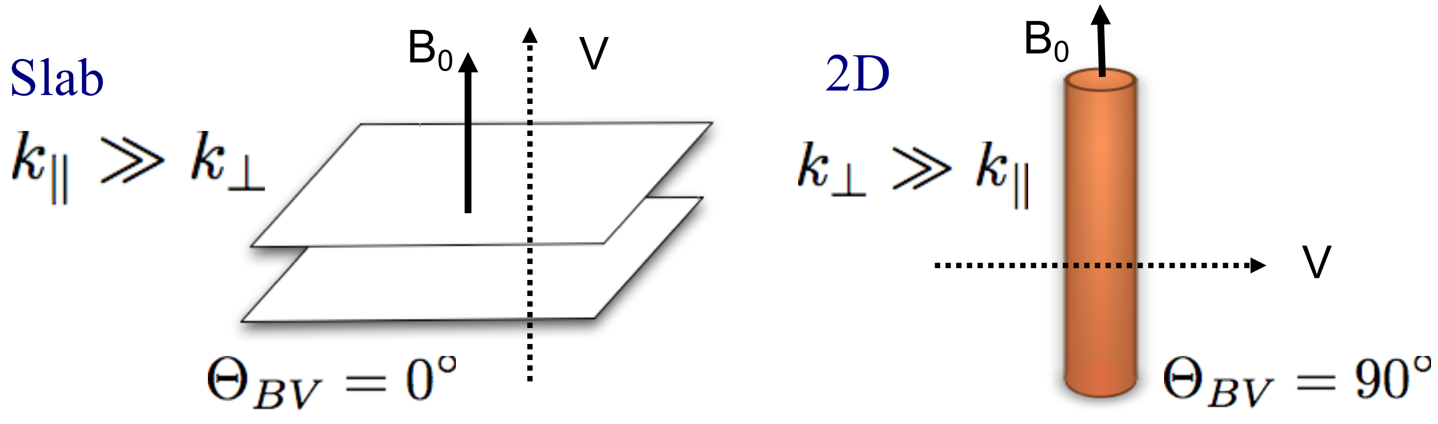
Anisotropy of turbulence in the magnetosheath

[Alexandrova, Lacombe, and Mangeney, 2008, AnGeo]

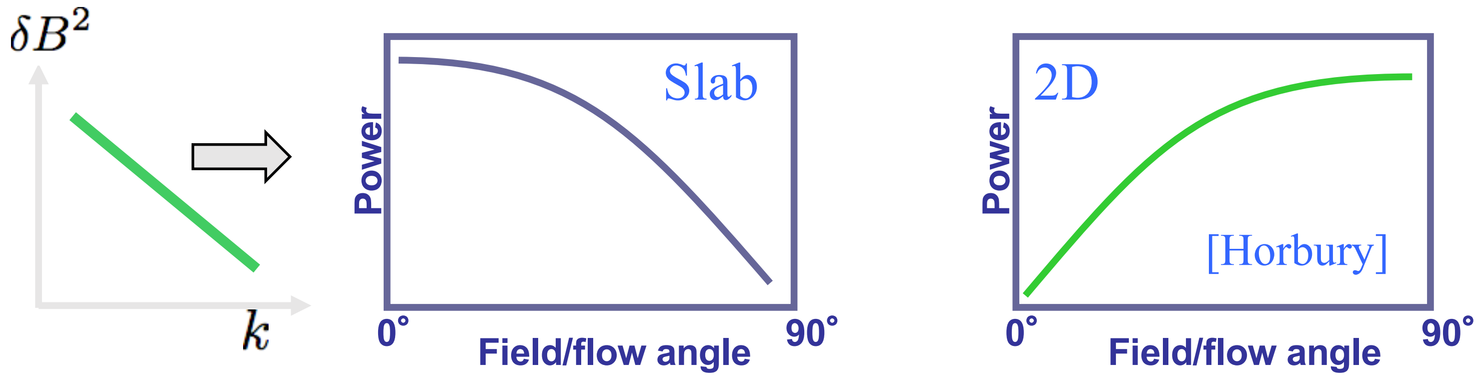




k-anisotropy of turbulent fluctuations

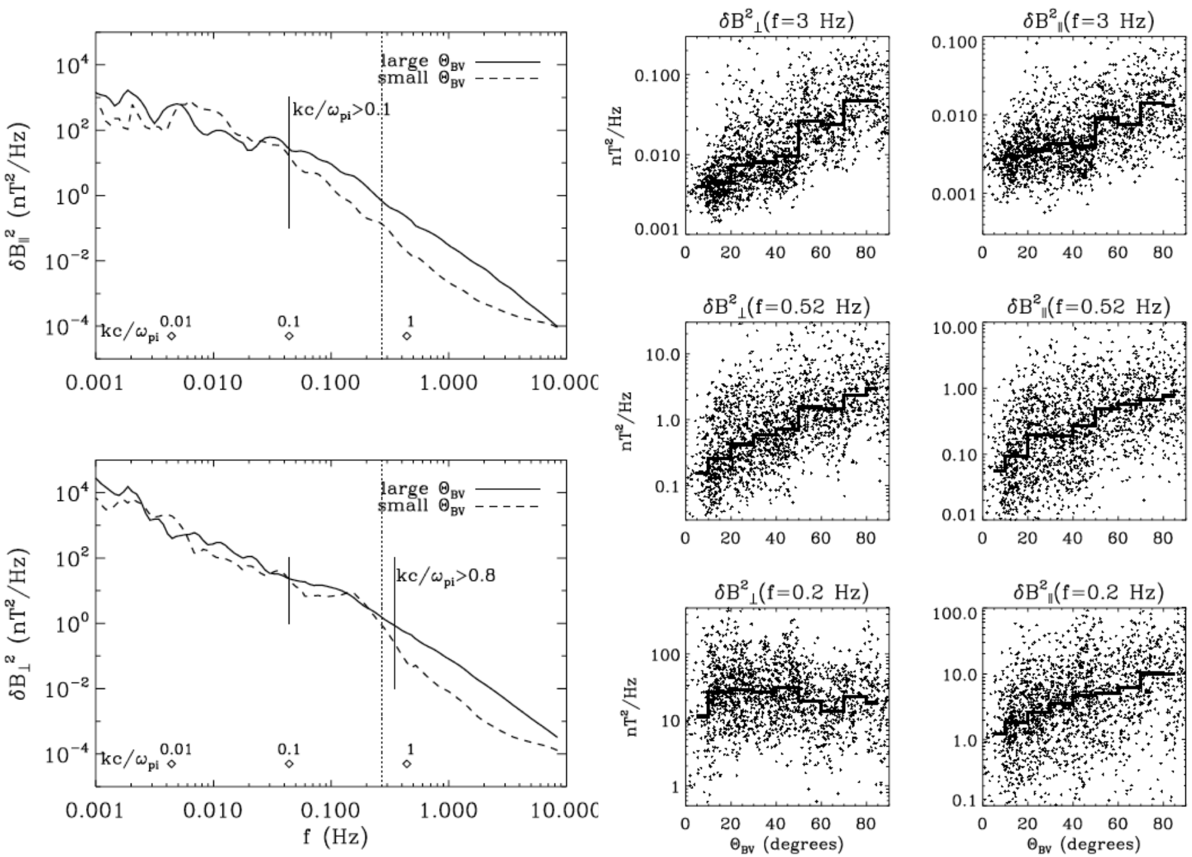


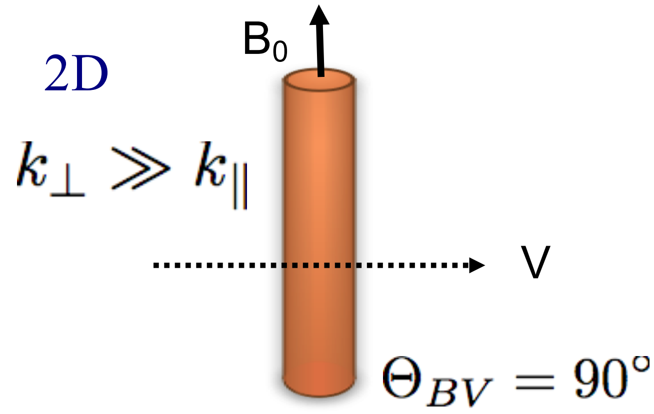
If Taylor hypothesis (V_{φ}<< V) is verified ⇒ variation of field-flow angle allows to resolve slab fluctuations while V is || to B and 2D fluctuations while V is ⊥ to B. [Bieber et al., 1996; Horbury et al., 2008; Mangeney et al., 2006, Alexandrova et al. 2008, …]



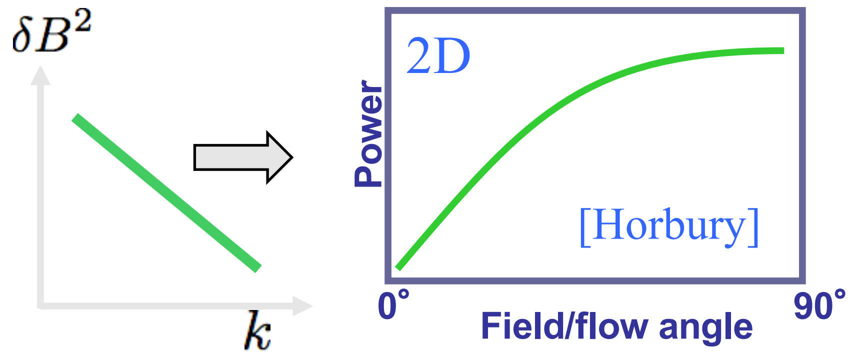
k-anisotropy of turbulent fluctuations

[Alexandrova, Lacombe, Mangeney, 2008]



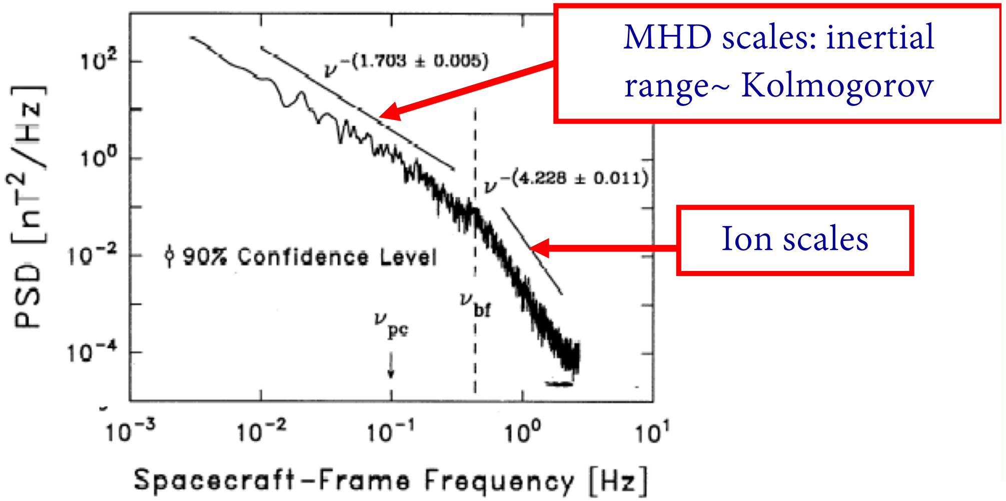


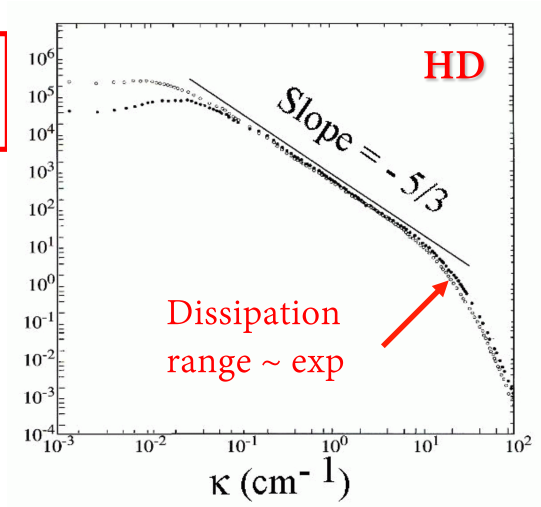
2D fluctuations while V is $\perp$ to B
[Mangeney et al., 2006, Alexandrova et al. 2008]

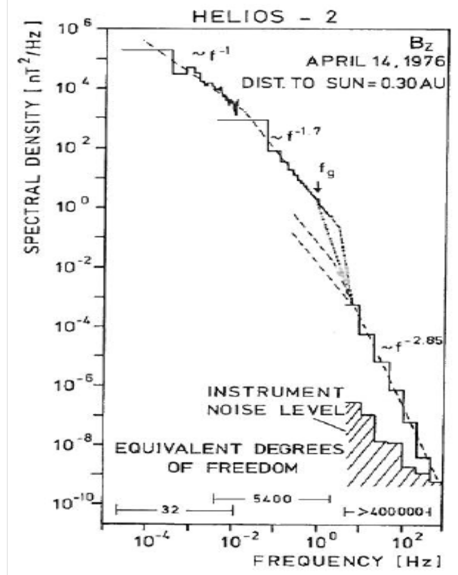


Solar wind turbulence

[Leamon et al,1998] Wind/MAG





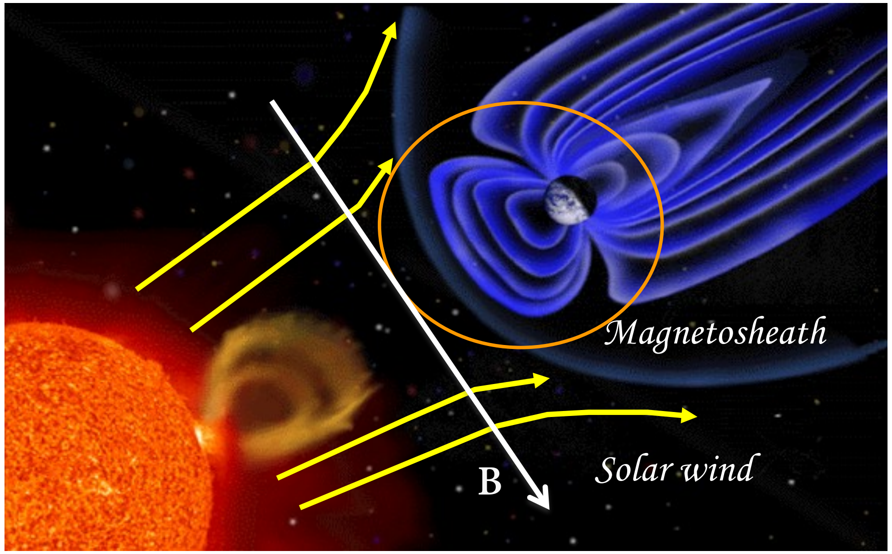


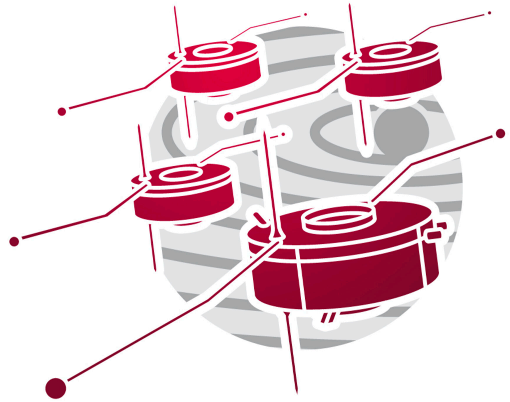
[Denskat et al., 1983]

1. Large (MHD) scales: $f^{-5/3}$ spectrum
2. There exists a spectral "break" close to ion scales ⇒

- starting point of a small scale cascade or onset of dissipation.
- If dissipation range ⇒ Why a power law and not an exponential cut-off ?
- Helios shows $f^{-2.8}$ spectrum between ion and electron scales [1983].

Cluster mission ESA/NASA, 4 s/c, since 2000

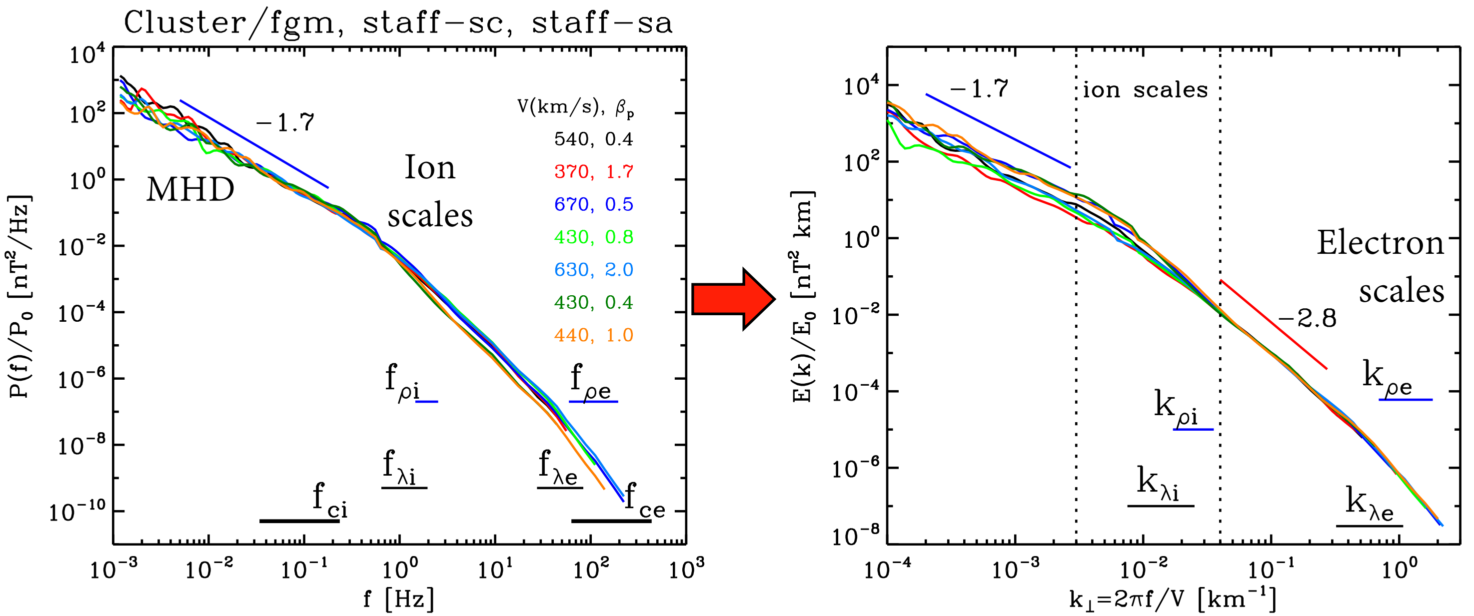




- Cluster is in the free solar wind when the field/flow angle is quasi-perpendicular ($Q_{BV} > 65^o$)
- Otherwise, Cluster is connected to the bow-shock => shock physics and not solar wind turbulence.
- Thus, with Cluster we can resolve k_{perp} fluctuations
- **STAFF (LPP/LESIA) is the most sensitive instrument by today to measure kinetic plasma scales**

Turbulent spectrum from MHD to electron scales

[Alexandrova et al. 2009, PRL; 2013, SSR]



$$\beta_p = \frac{nkT_p}{B^2/8\pi}$$

$$f_{\rho_e} = V/2\pi\rho_e$$

$$\rho_e = \frac{V_{th,e}}{2\pi f_{ce}}$$

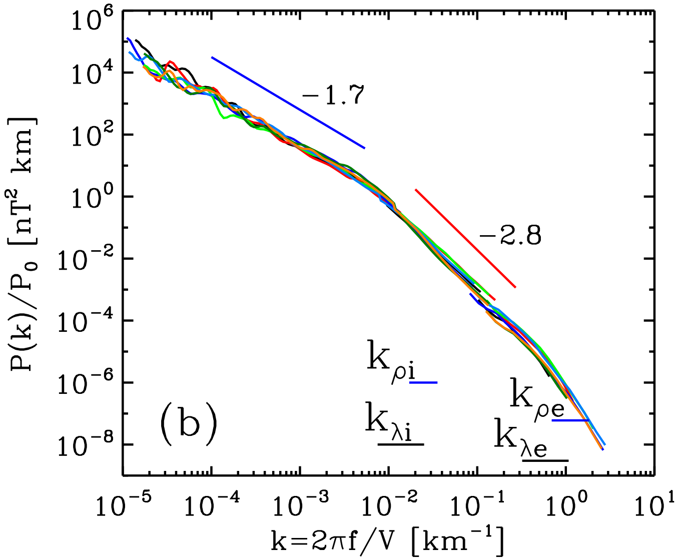
$$k_{\rho_e} = 1/\rho_e$$

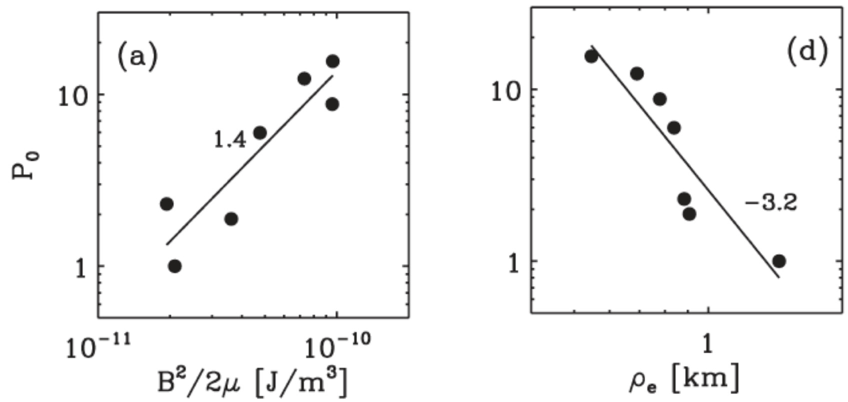
$$\omega_{obs} = \mathbf{k}_\perp \cdot \mathbf{V} = k_\perp V \cos(\Theta_{kV}) = k_\perp V \sin(\Theta_{VB})$$

- Superposition of different spectra at sub-ion scales seems to indicate general behaviour: spectrum ~$k_{perp}^{-2.8}$
- End of the cascade? Dissipation scales?

Dissipation scale?

[Alexandrova et al. 2009, PRL] Cluster/FGM+STAFF data





?

$$\ell_d \sim \rho_e$$

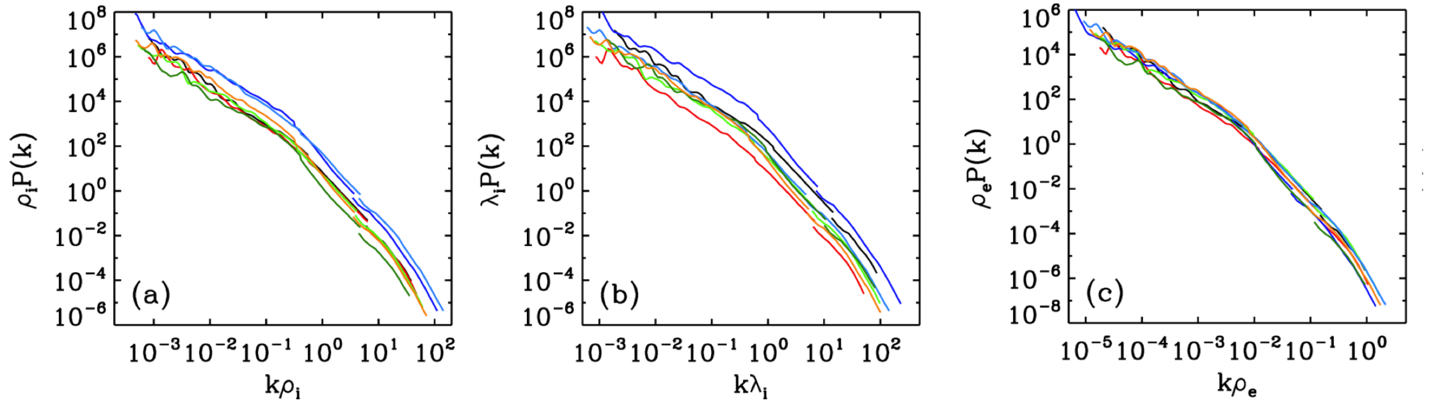
Quasi-stationary turbulence

- energy transfer rate ε = energy dissipation rate ε_d
- $\varepsilon = \eta^3 \, l_d^{-4}$, where l_d is dissipation scale, η is viscosity
- amplitude of the spectrum $P_0 \sim \varepsilon^{2/3} \sim l_d^{-8/3}$

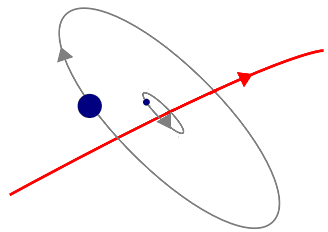
Dissipation scale in the solar wind?

Universal Kolmogorov's function: $$E(k)\ell_d/\eta^2 = F(k\ell_d)$$

Let us try to apply this kind of normalization for solar wind spectra and for different candidates for the dissipation scale: $\ell_d = \rho_{i,e}, \lambda_{i,e}$



- Assumption: η=Const
- $\kappa\rho_i$ & $\kappa\lambda_i$ - normalizations are not efficient for collapse
- $\kappa\rho_e$ normalization bring the spectra close to each other

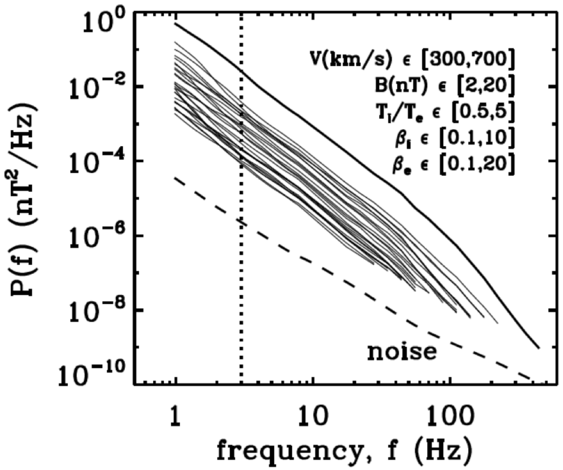


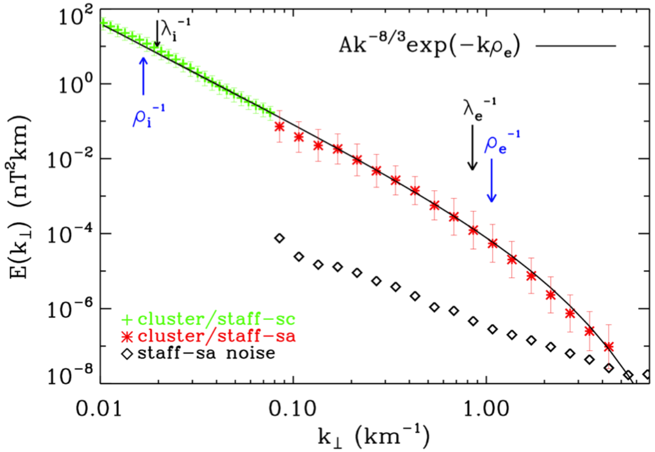
➡ $$\ell_d \sim \rho_e$$

[Alexandrova et al., 2009, PRL]

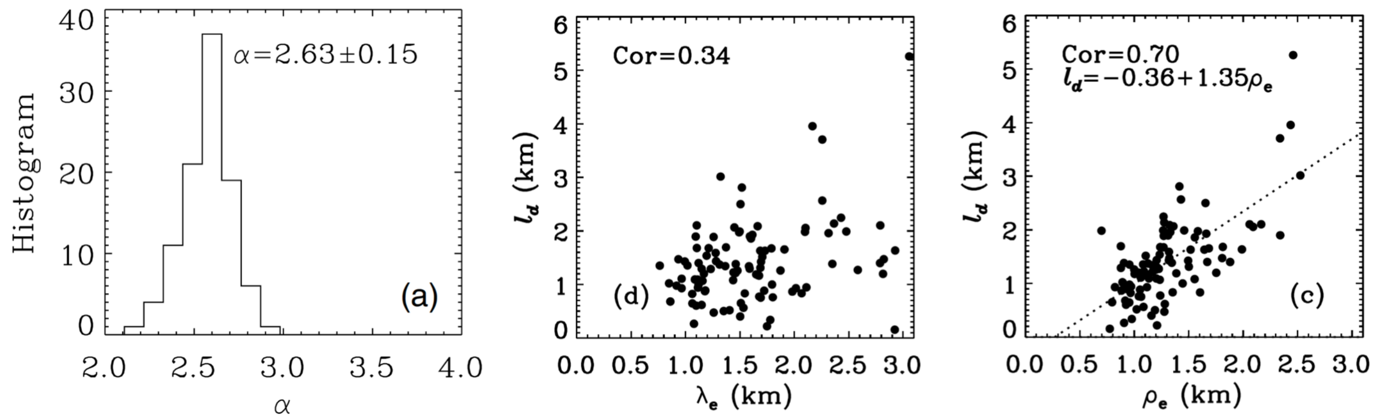
Larger statistical study with Cluster/STAFF

[Alexandrova et al., 2012, APJ]



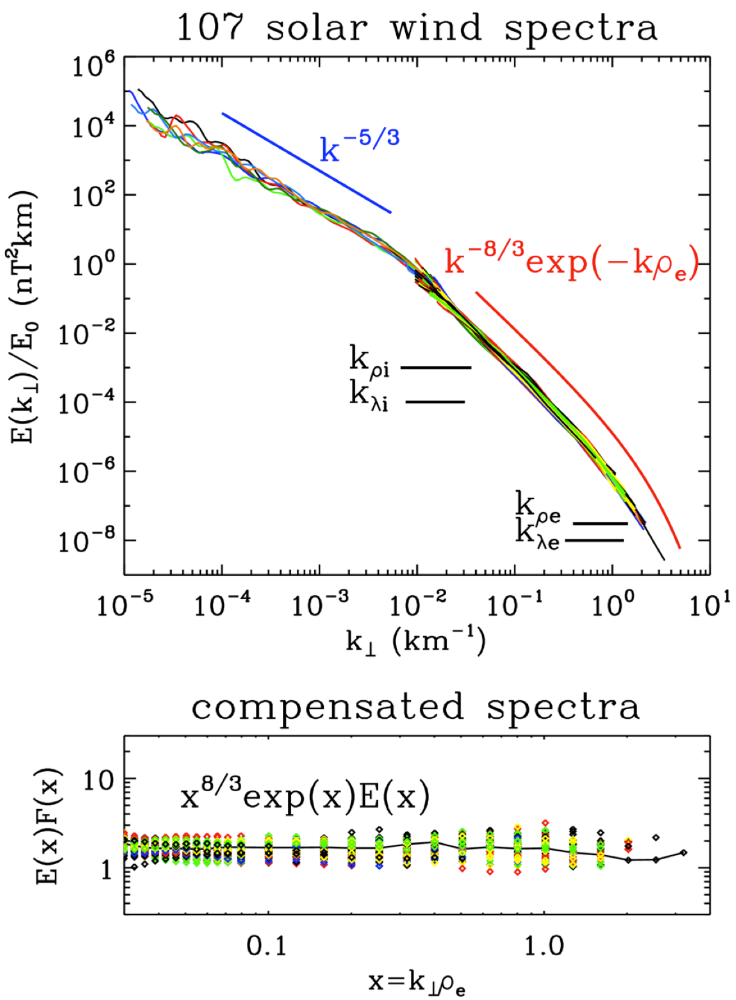


[Chen, et al., 1993, PRL] dissipation range spectrum in fluids: $E(k) = Ak^{-\alpha} \exp\left(-k\ell_d\right)$



$\ell_d \sim \rho_e$

General spectrum at kinetic scales



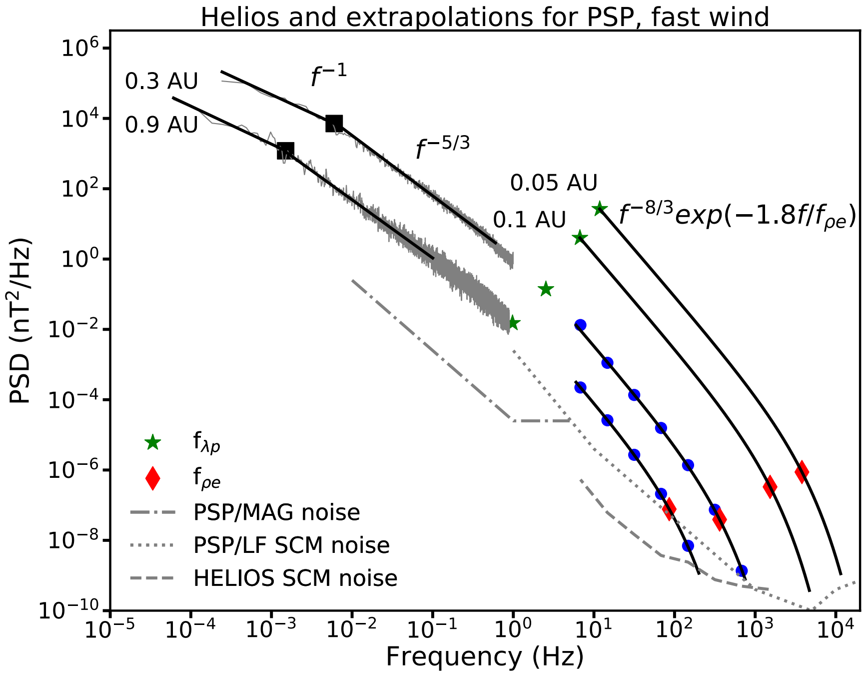
- For **different solar wind conditions** we find a **general spectrum** with "fluid-like" roll-off spectrum at electron scales (dissipation)

- **Electron Larmor radius** seems to play a role of the **dissipation scale** in collisionless solar wind [Alexandrova et al., 2009 PRL, 2012 APJ]

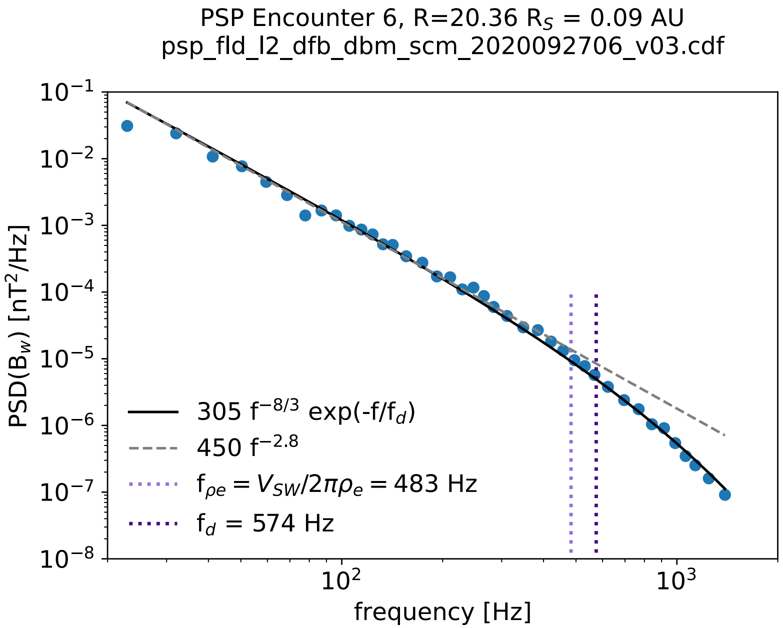
$$E(k) = Ak^{-8/3}\exp(-k\rho_e)$$

- k-anisotropy at kinetic scales : k_perp >> k_|| [Lacombe et al., 2017, Matteini et al. 2020]

Helios turbulent spectrum & preliminary results of PSP



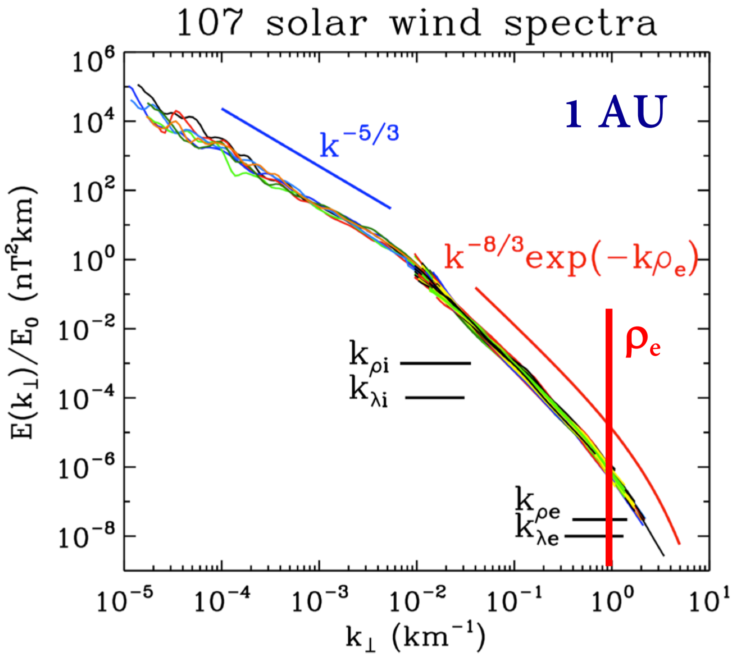
[Alexandrova, et al. 2021 PRE]

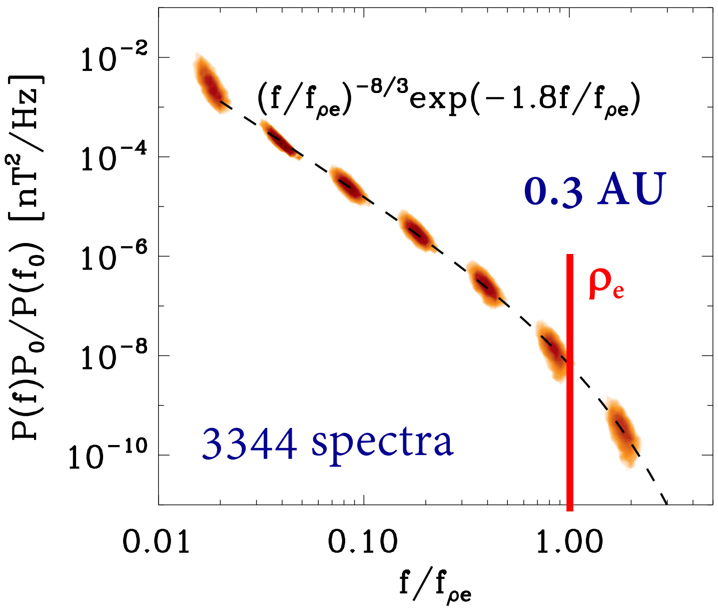


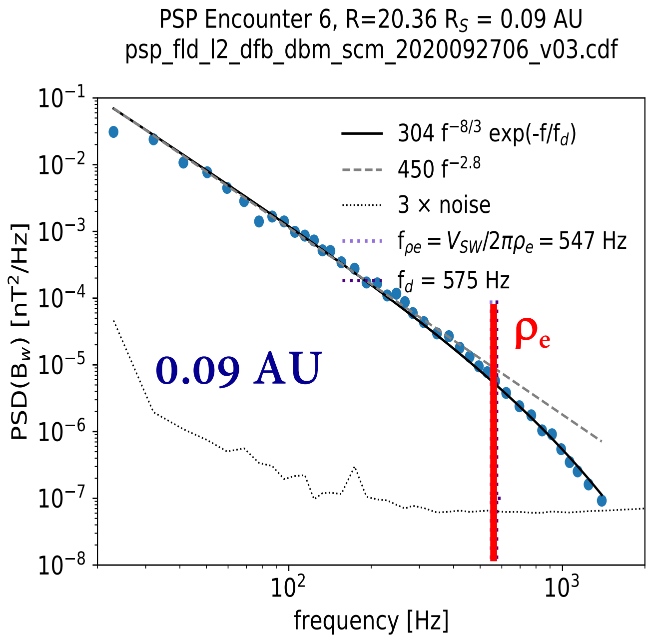
[Master thesis of Jessica Martin, June 2021]

The same spectral shape is observed at 0.09 AU (PSP) as at 0.3 AU (Helios) and at 1 AU (Cluster).

Dissipation range and ℓ_d in the solar wind





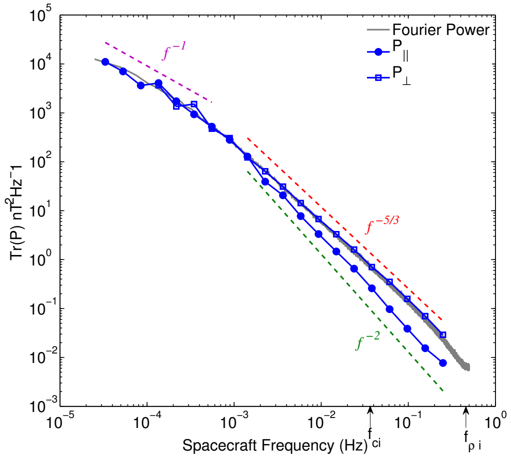


- The same form of spectrum at 1 au (Cluster), 0.3 (Helios) and at 0.09 au (PSP) in the Heliosphere => general for space plasmas?
- The e/m cascade ends onto the electrons with ρ_e ~ dissipation scale ℓ_d.

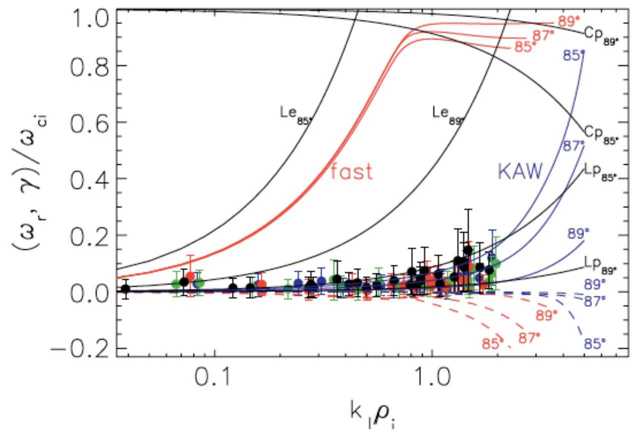
Solar wind turbulence : widely accepted picture

- Inertial range: Alfven waves propagating from the Sun, Critically Balanced turbulence ($\tau_A = \tau_{NL}$)
- Ion transition: Alfven waves become Kinetic Alfven Waves (KAWs), e.g., Schekochihin et al., 09
- Sub-ion scales: Critically Balanced KAW turbulence ($\tau_{KAW} \sim \tau_{NL}$), e.g., Boldyrev and Perez 12
- Dissipation: Landau damping of KAWs, e.g., Howes et al. 11, Passot & Salem 15, Schreiner & Saur, 17

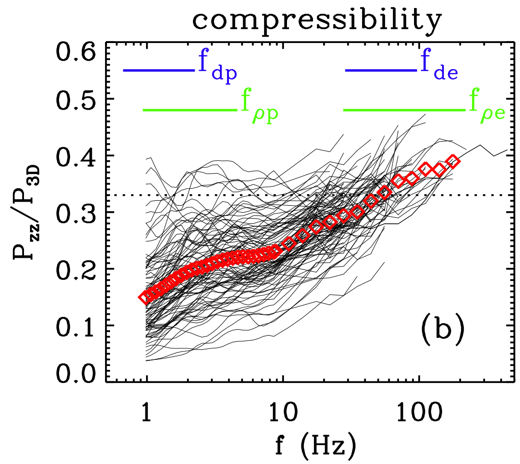
This picture is based on mean properties of turbulent flows, e.g.,:



Spectra are in agreement with Critical Balance



Linear dispersion of KAWs describes the data [Sahraoui et al. 10, Roberts et al., 13]



Compressibility in agreement with KAWs [Lacombe et al. 17, Groselji et al. 19, Matteini et al. 20]

Intermittency in all this ?