Solar wind turbulence

Olga Alexandrova
olga.alexandrova@obspm.fr

Astronome-adjointe, LESIA/Observatoire de Paris

I’m at distance ‘2’ in the ‘graph of co-authors’ from Annick ☺, i.e.,
I’m a person who worked with people who published with Annick:
Andre Mangeney, Luca Sorriso, Vincenzo Carbone and Joachim Saur

Message from Luca: Please send Annick my best wishes and say that I have been very lucky to have Annick as co-supervisor.

Message from Joachim: Please send Annick my best wishes and say that I am very glad and proud to have had a chance to work with her!
I love the combination of scientific openness and rigour.

In this lecture

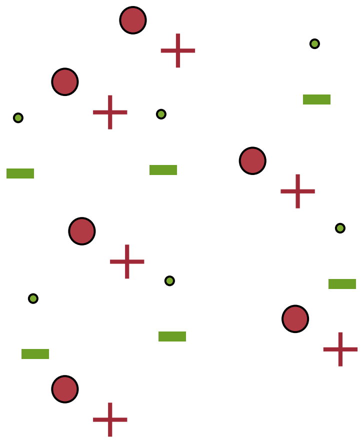
0. Solar wind & how do we measure turbulent spectra ?
1. Solar wind turbulence at MHD scales, f=[10^{-4},10^{-1}]Hz, l=[10^4,10^7]km
   - spectra of different physical quantities (B,V,n_e)
   - k-anisotropy
   - intermittency

2. Turbulence around ion scales, f=[0.1-1]Hz, l=[10^3,10^4]km
   - spectral shape and transition scale (Larmor radius? Inertial length? …?)
   - coherent structures
   - ion instabilities and waves

3. Turbulence at sub-ion scales up to electron scales f > 3Hz, l < 200 km (up to the observational limit of 400 Hz, 300 m)
   - general spectrum?
   - dissipation of e/m turbulence at electron scales ?
   - coherent structures
   - presence of polarized whistlers waves and electron instabilities

The solar wind

Closest stellar wind where we can do in-situ measurements with a number of space missions

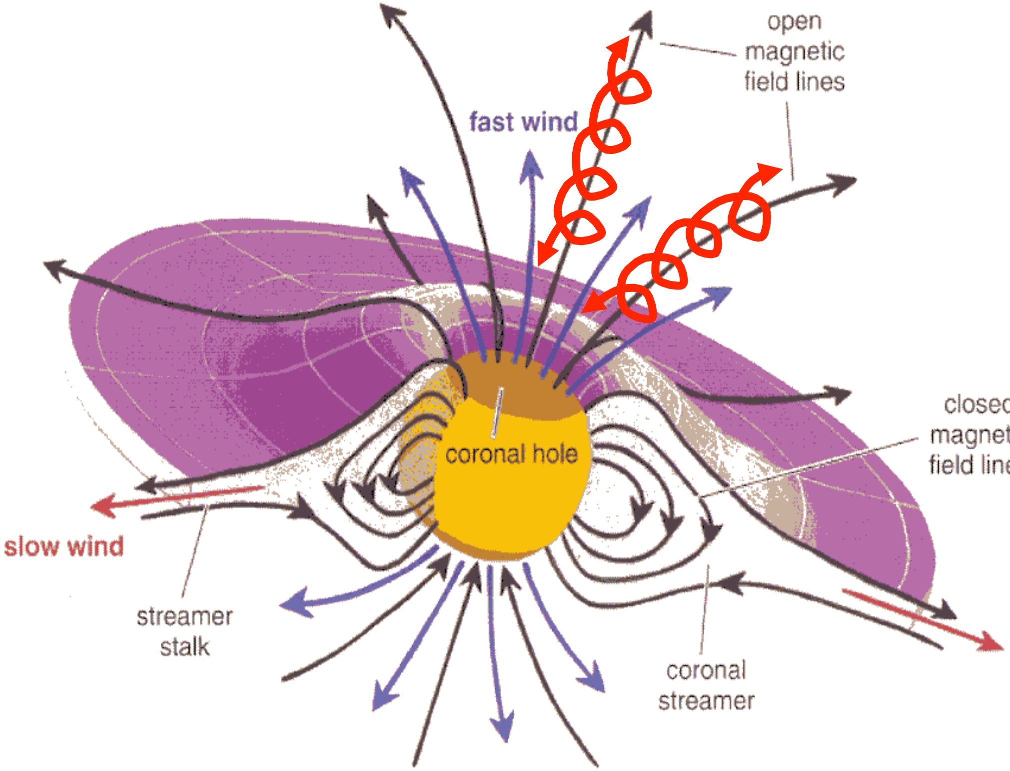


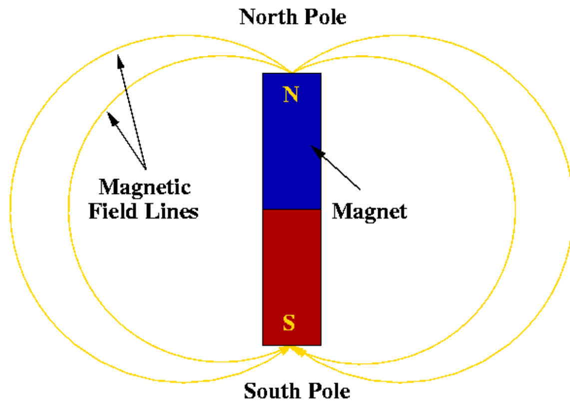
plasma : ionized gaz (e- , p+)

- Expansion of the solar corona in interplanetary space
- Plasma: ionized gas, essentially e- and p+ (+5% of heavier ions)
- Mean speed ~500 km/s; density ~5cm^{-3}, temperature (e-,p+) ~20 eV
- Few collisions (1 collisions/1AU) => conductivity ~ ∞ (viscosity η = 0) => magnetic field is frozen in plasma
- Solar wind transports coronal magnetic filed

$$\boxed{\partial_t B = \nabla \times (V \times B) + \eta \Delta B}$$

Magnetic field of the Sun: slow and fast streams and 11 years cycle





- Fast wind blows out from the coronal holes (open field lines). Slow wind – from the coronal streamers, above the closed field lines and along the heliospherical current sheet (c.f. purple zone).
- Every 11 years magnetic dipole of the Sun reverses.

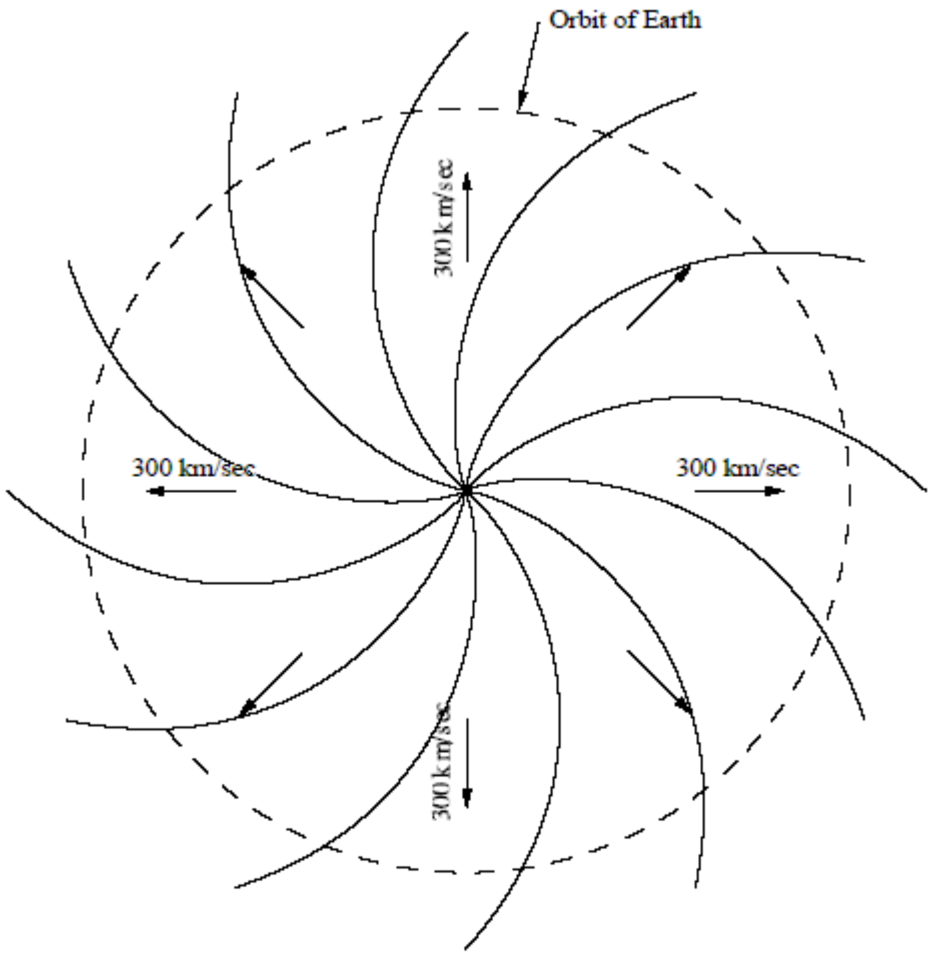
Magnetic field of the Sun: Parker’s spiral

Sun rotation =>

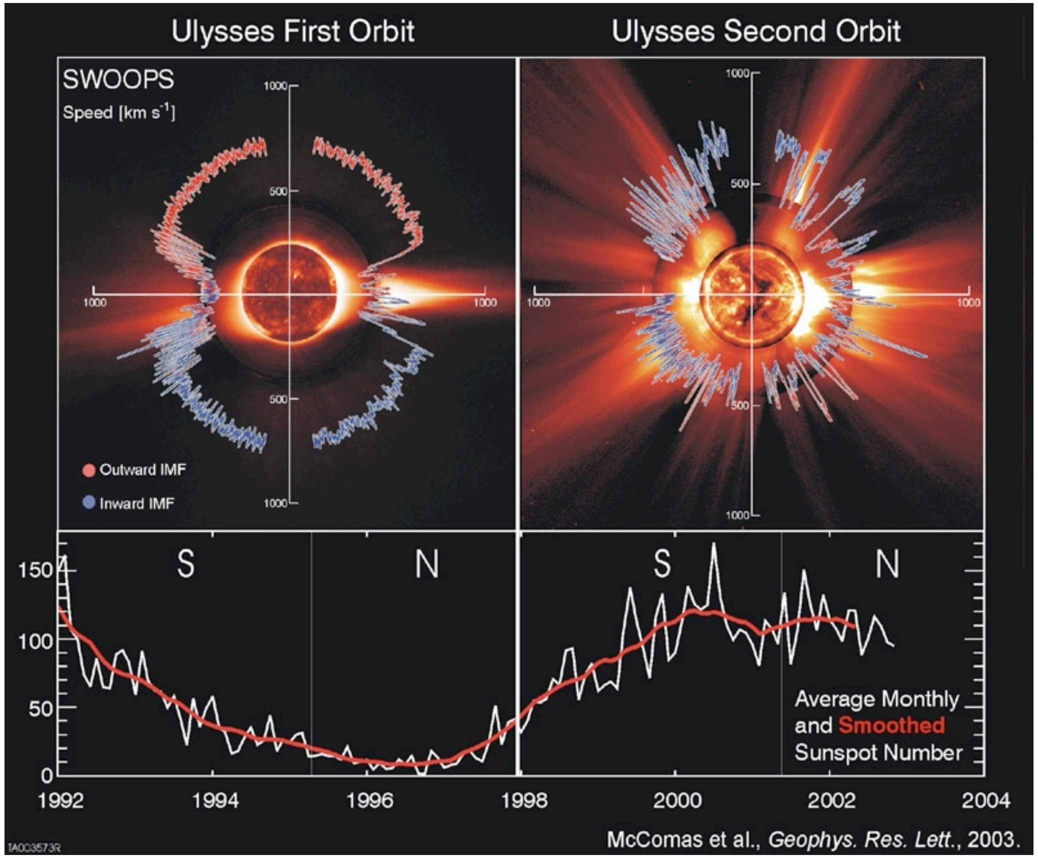
Interplanetary magnetic field form a spiral

(1 step = 6 AU = 25 days Vsw, Vsw=400km/s)

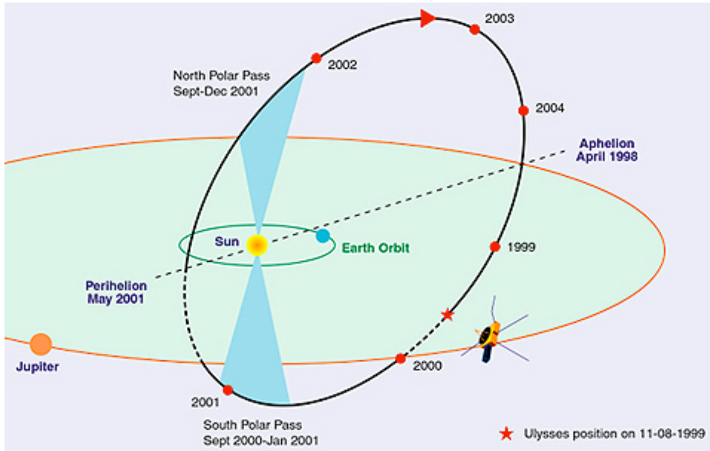
Predicted by Gene Parker



Solar wind (slow and fast) and the 11 years solar cycle



[McComas et al. 2003]



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

Two components, Slow and Fast streams :

Slow : V = 300-400km/s, n=5-25cm^{-3}, T_p= 5-20eV, T_e=5-20eV, B~5nT, β~1

Fast : V = 500-800km/s, n=1-10cm^{-3}, T_p=10-20eV, T_e=5-20eV, B~5nT, β~1

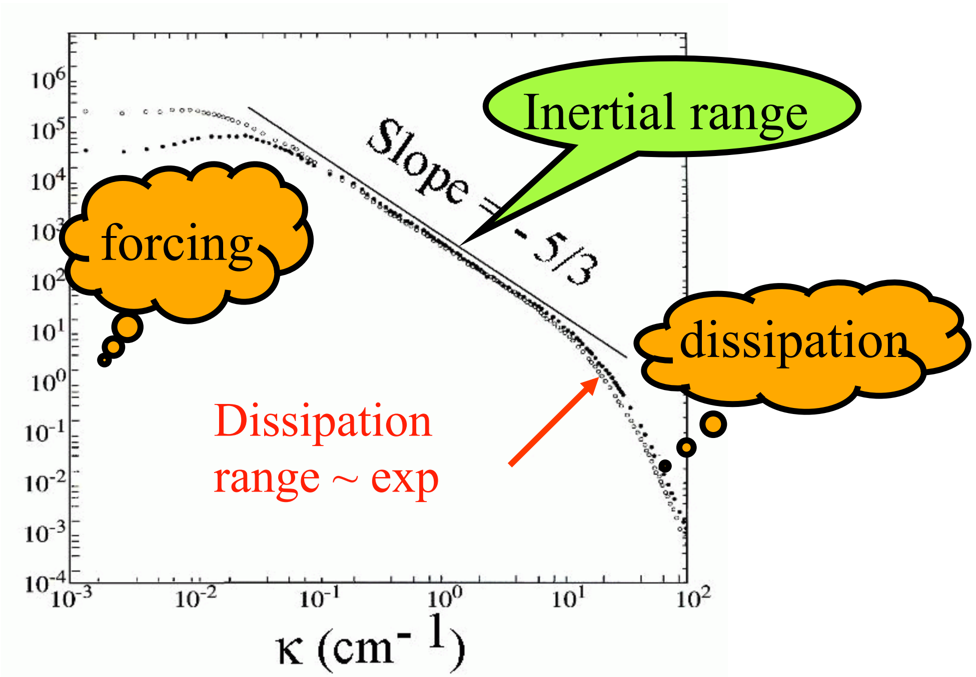
Mean free path ~ 1 AU (Sun-Earth distance) !

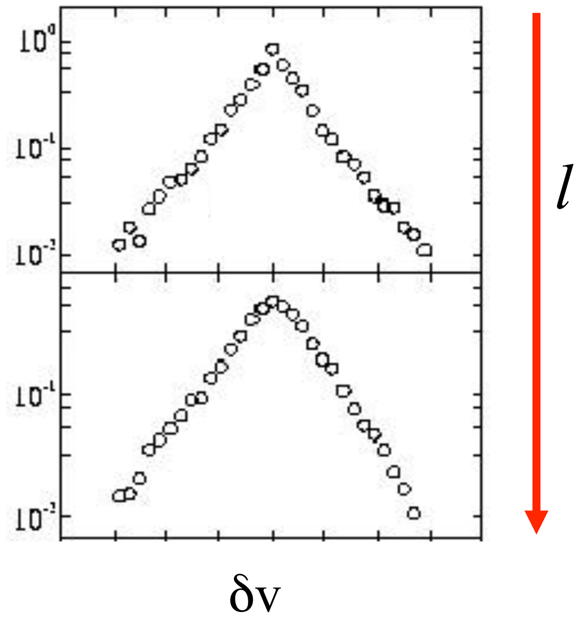
Turbulence

Locally unpredictable, but **statistical properties are predictable and universal**

1) velocity field energy~k$^{-5/3}$ (scale invariance, same physics at all scales l) [Kolmogorov'41]

2) intermittency : deviation from the Gaussianity at small l



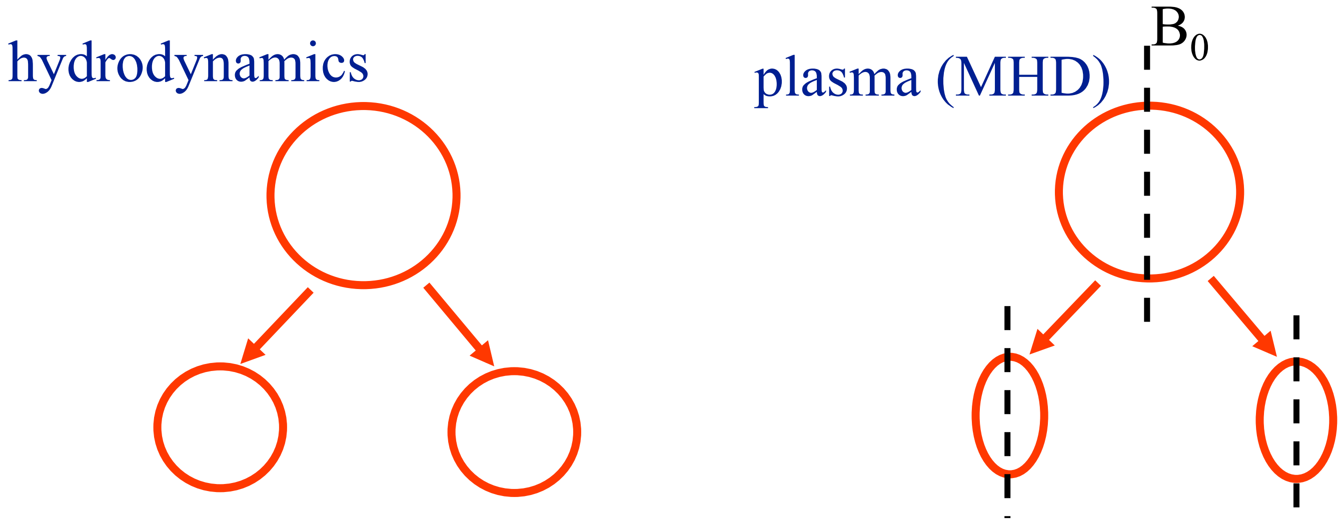


The Kolmogorov spectrum can be observed almost in all turbulent flows.

And what about space plasma turbulence?

- How is it different from HD turbulence?
- Does it share the above universal characteristics, as power-law spectra and intermittency ?
- How does the dissipation set in ? and is its spectrum universal ?

Turbulence in space plasmas

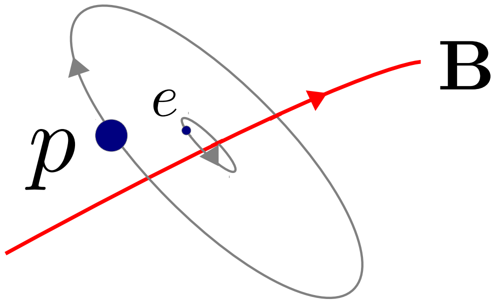


1. Presence of a mean magnetic field B_0 leads to an anisotropy of turbulent fluctuations.
2. Plasma waves: Alfven, magnetosonic, mirror, wistlers, kinetic Alfven waves (KAW), etc… (wave turbulence)
3. No collisions : m.f.p. ~ 1 AU
4. In plasmas there is a number of characteristic space and temporal scales

$$f_{ci}, c/\omega_{pi}, R_{Li} \qquad f_{ce}, c/\omega_{pe}, R_{Le} \qquad \lambda_D$$

Different plasma characteristic scales

- Larmor radius ($\rho_{i,e}$) and cyclotron frequency ($\Omega_{ci,e}$) of a charged particle (electron or ion=proton) in a magnetic field B:



$$\rho_{i,e} = \frac{V_{\perp i,e}}{\Omega_{ci,e}} \; ; \; \Omega_{ci,e} = \frac{eB}{mc}$$

- Inertial length $\lambda_{i,e}$ (scale of the demagnetization of the particles) and plasma frequency (ω_p) :

$$\lambda_{i,e} = \frac{c}{\omega_{pi,e}} \; ; \; \omega^2_{pi,e} = \frac{4\pi n e^2}{m_{i,e}}$$

- Debye length λ_D (sphere of influence of a given test charge in a plasma); at L>λ_D plasma is quasi-neutre :

$$\lambda_D^2 = \frac{k_B T}{8\pi n e^2}$$

Different plasma descriptions and typical plasma scales in the SW

- At very large scales ($L >> \rho_{i,e,}\ \lambda_{i,e}$) and at long times ($T>>1/\Omega_{ci,e}$): one magneto-fluid of ions and electrons (MHD description)

- Close to ion scales ($L \sim \rho_{i,}\ \lambda_i \sim 100$ km), ions should be considered as particles, electrons can be described as a fluid.

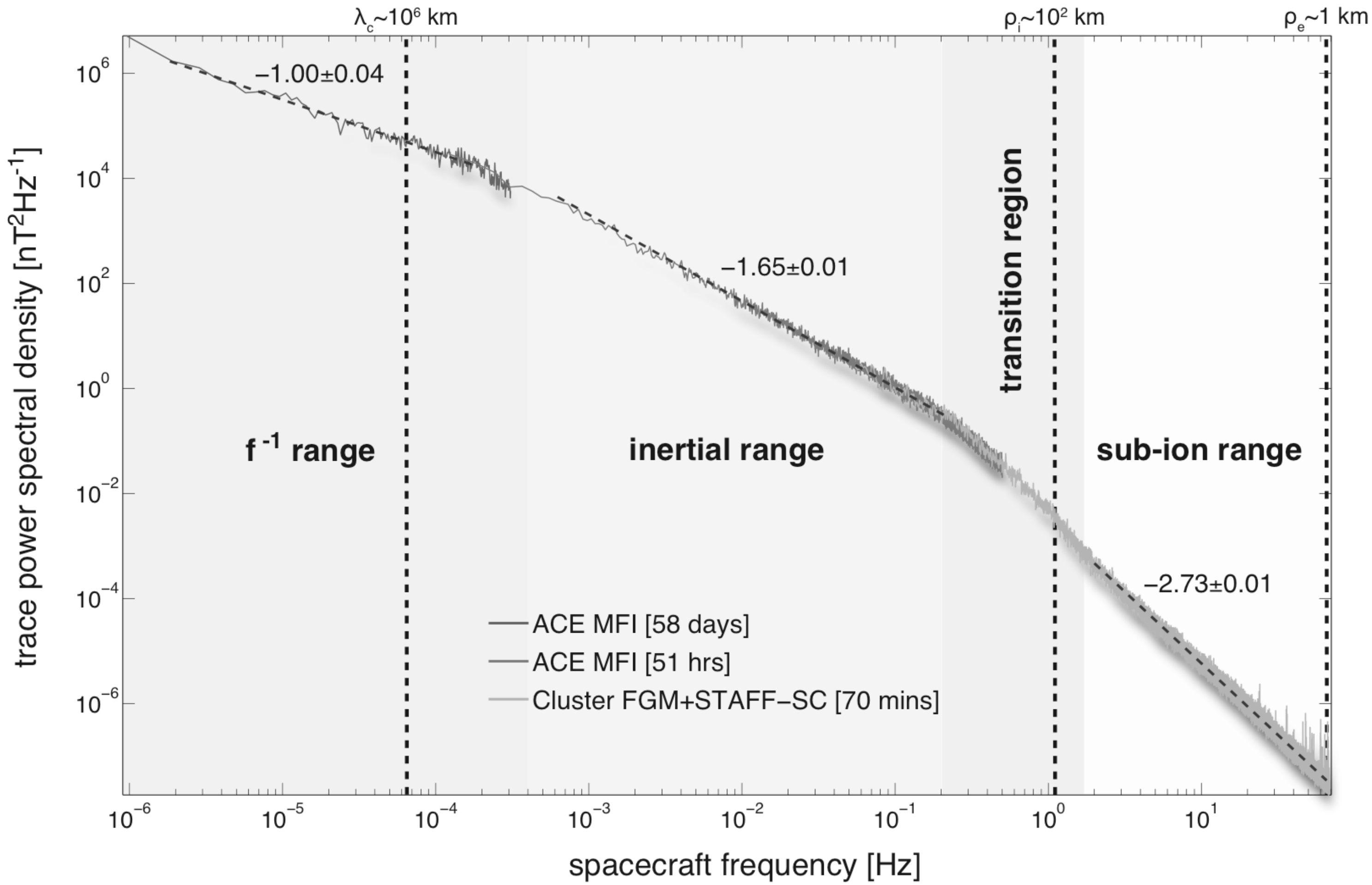
- At scales close to electron scales (~ 1 km): full kinetic description, ions and electrons are independent particles

- Debye length in the solar wind is ~10 m

- Satellite size ~ 1-2 m

[Kiyani et al. 2015]

Typical spectral density of solar wind turbulence



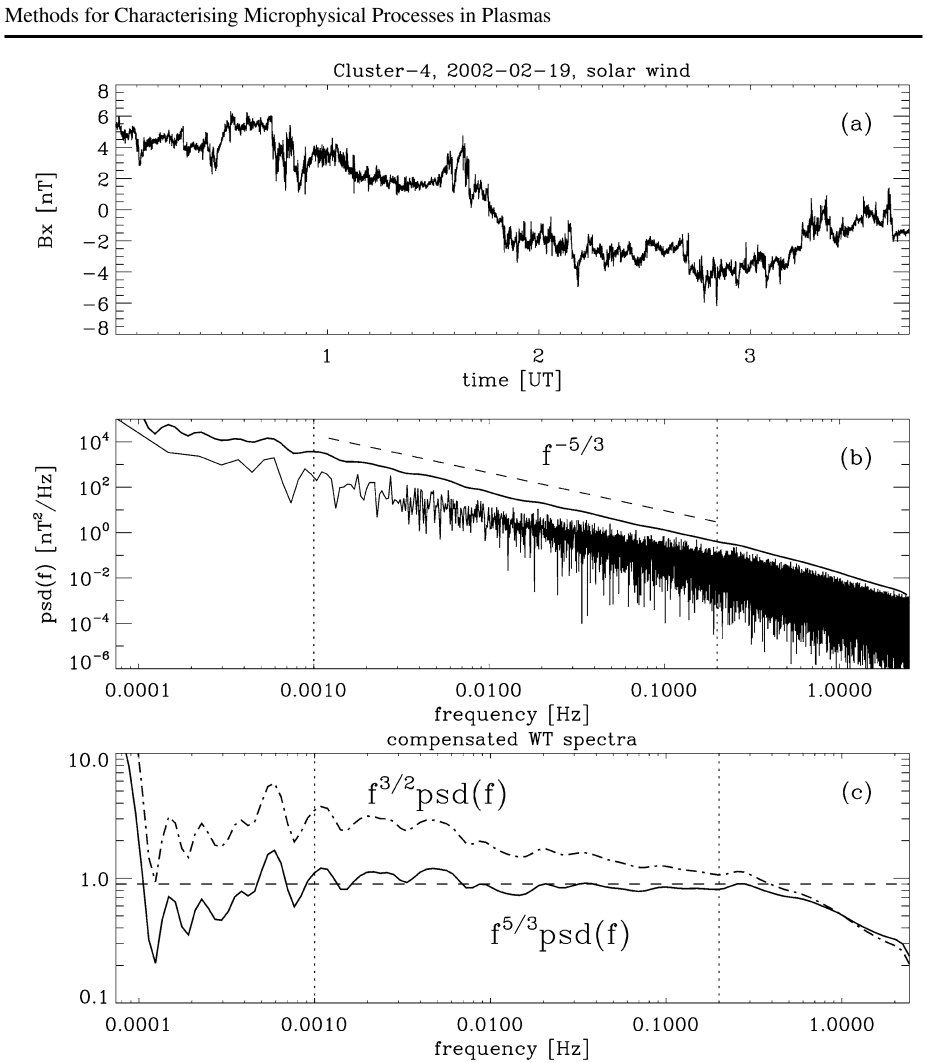
~ 8 (and more) decades in scales (frequencies)
~ 14 decades in energy density !

How do we measure turbulent spectra in space?

Frequency/k-spectra?

Satellites in-situ measurements are time series

=> Fourier Transform (signal) gives frequency spectra:



[Dudok de Wit et al. 2013, SSR]

- example of Cluster/FGM
(5 vectors/sec measuremets)

How do we get k-spectra?

Taylor hypothesis:

$$\boxed{\begin{aligned} \ell &= V_{sw}\tau = V_{sw}/f \\ k &= 2\pi/\ell = 2\pi f/V_{sw} \end{aligned}}$$

Taylor hypothesis

$$\omega_{obs} = \omega_0 + \mathbf{k} \cdot \mathbf{V}$$

Supposing that $\omega_0 << k.V$, ($V\varphi << V$) :

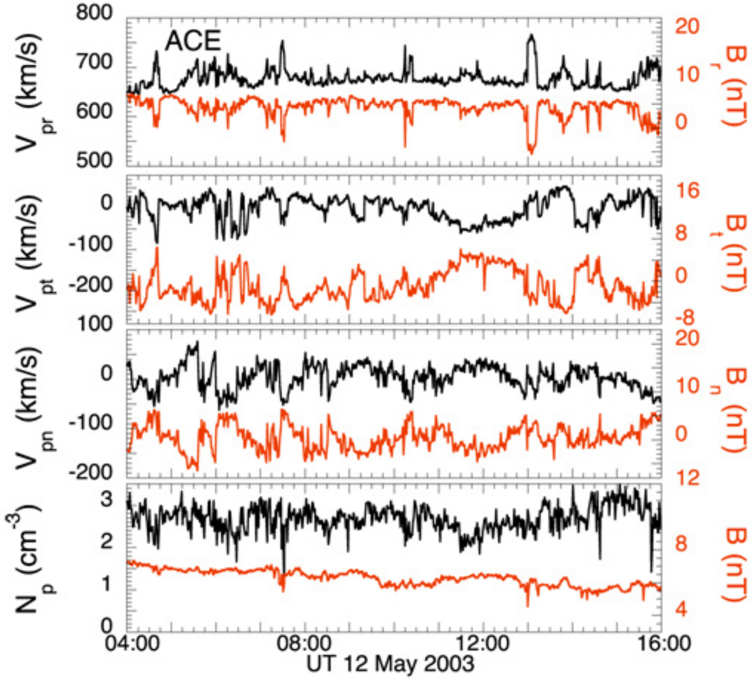
$$\omega_{obs} = \mathbf{k} \cdot \mathbf{V} = kV\cos(\Theta_{kV})$$

We don't know the angle between k and V
=> assumption of k || V:

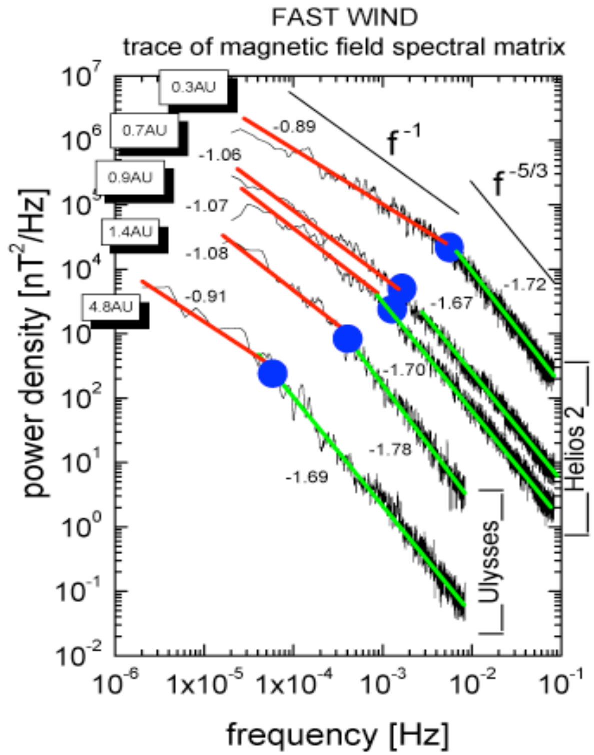
$$\boxed{\omega_{obs} = kV \rightarrow k = 2\pi f/V}$$

Solar wind Turbulence and Alfven waves

[Gosling et al., 2009; Belcher & Davis 1971]

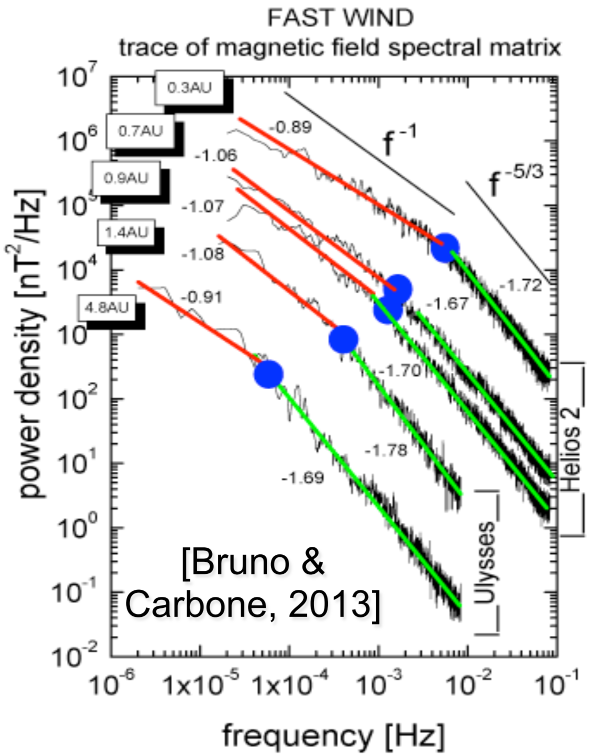


[Bruno & Carbone, 2013]



- Strong correlation between V and B fluctuations at 1 AU (Alfven waves)
- These waves belong to f^{-1} spectral range.
- Kolmogorov turbulence at smaller scales (MHD) is observed.

Starting point of the Kolmogorov spectrum

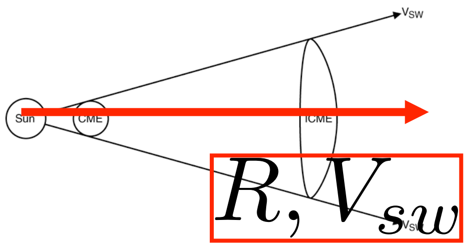


- The solar wind expansion time:

$$\tau_{exp} = R/V_{sw}$$

- The eddy-turnover time:

$$\tau_{NL} = \ell/\delta V_\ell$$

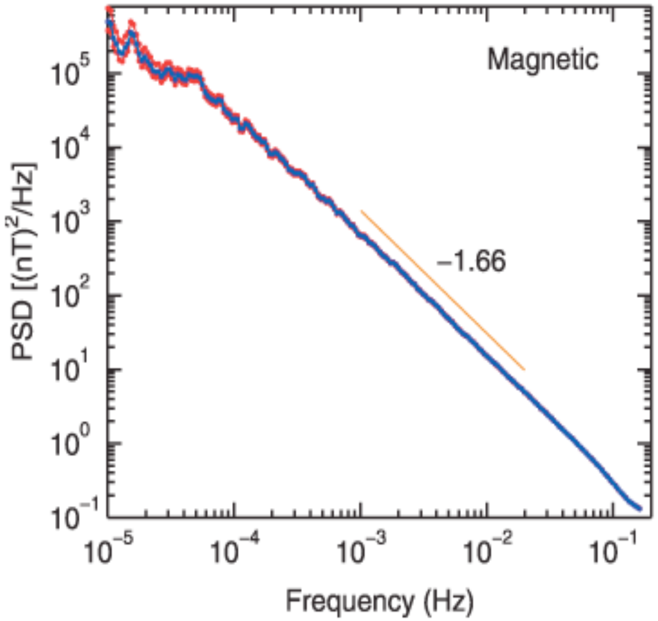


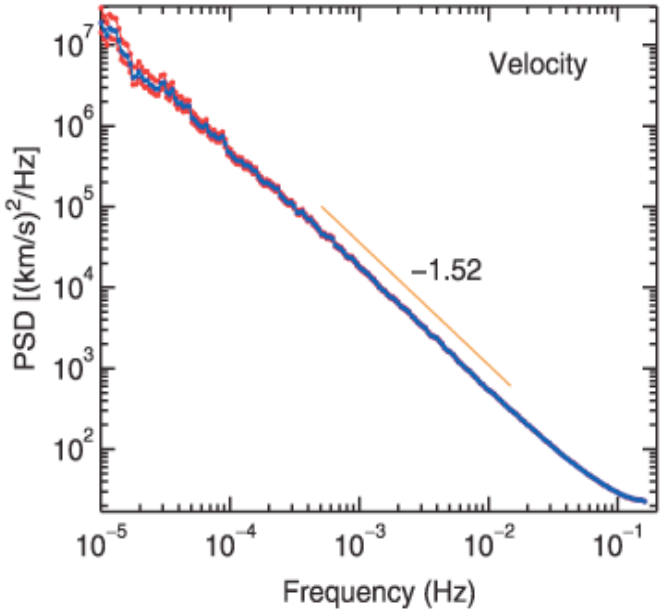
$\ell, \delta V_\ell$

- Transition between f^{-1} and $f^{-5/3}$ spectrum corresponds to a scale where these 2 characteristic times are of the same order [Mangeney et al. 1991; Meyer-Vernet 2007]: $\tau_{exp} \simeq \tau_{NL}$

Solar wind Turbulence and Alfven waves

[Podesta et al., 2007; Salem 2000]

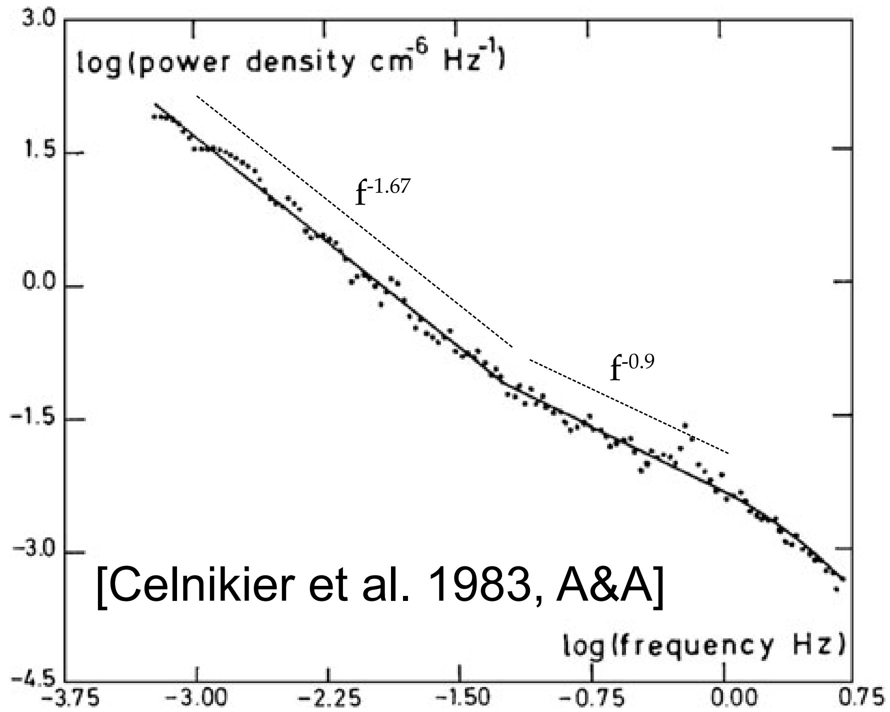




- Large scales fluctuations have Alfvénic nature dV ~ dB
- However, turbulent spectra for B and V are different…
- Why?
  - Local dynamo process (Grappin et al., 1983) ?
  - Compressibility ?

Solar wind turbulence is compressible

Spectrum of electron density fluctuations in the solar wind as measured by ISEE 1 & 2
See as well Chen et al. 13

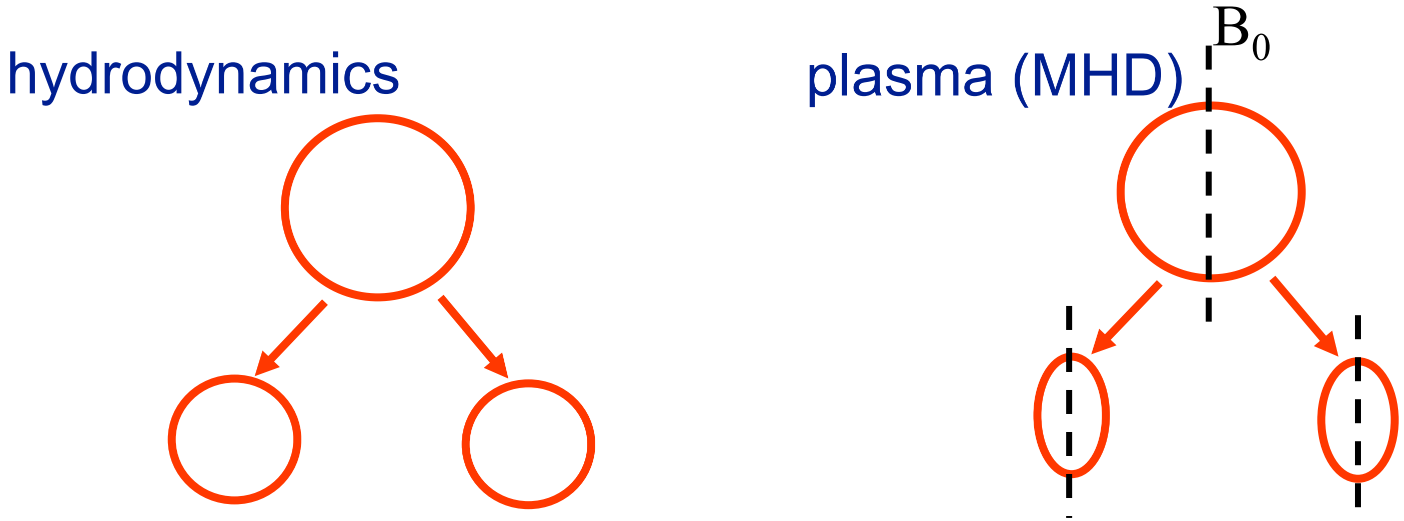


Can the compressibility be the source of the non-alfvenisity of the inertial range in the solar wind turbulence?

see S. Galtier, Les Houches 2015 cours, page 48:

$$\boxed{V = u\rho^{1/3} \rightarrow E_V \sim k^{-5/3}}$$

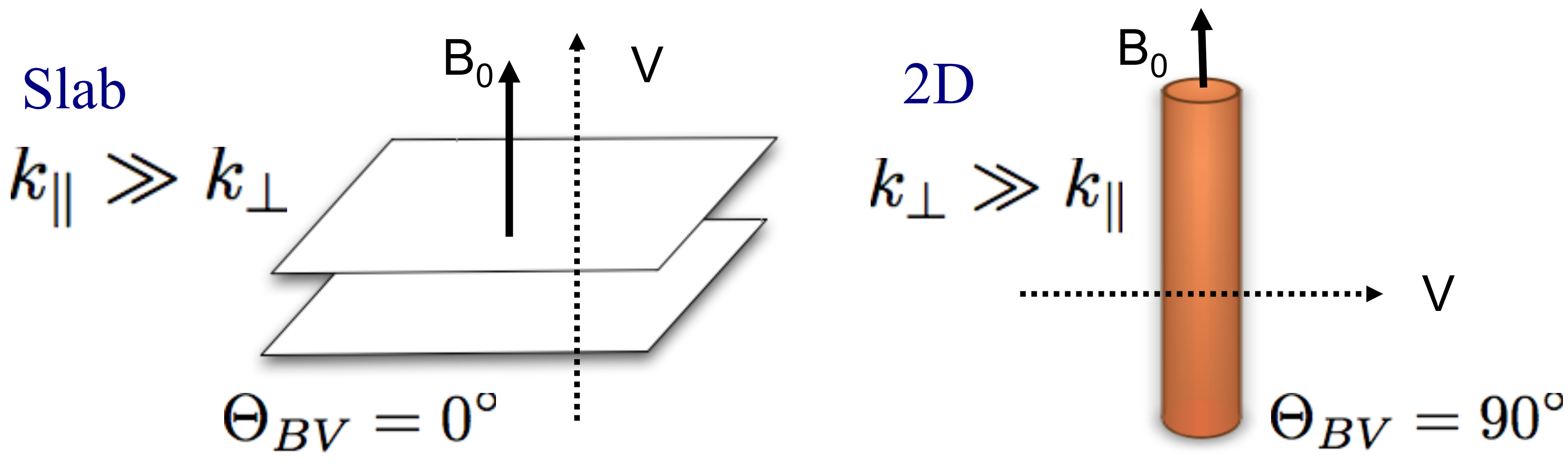
Anisotropy



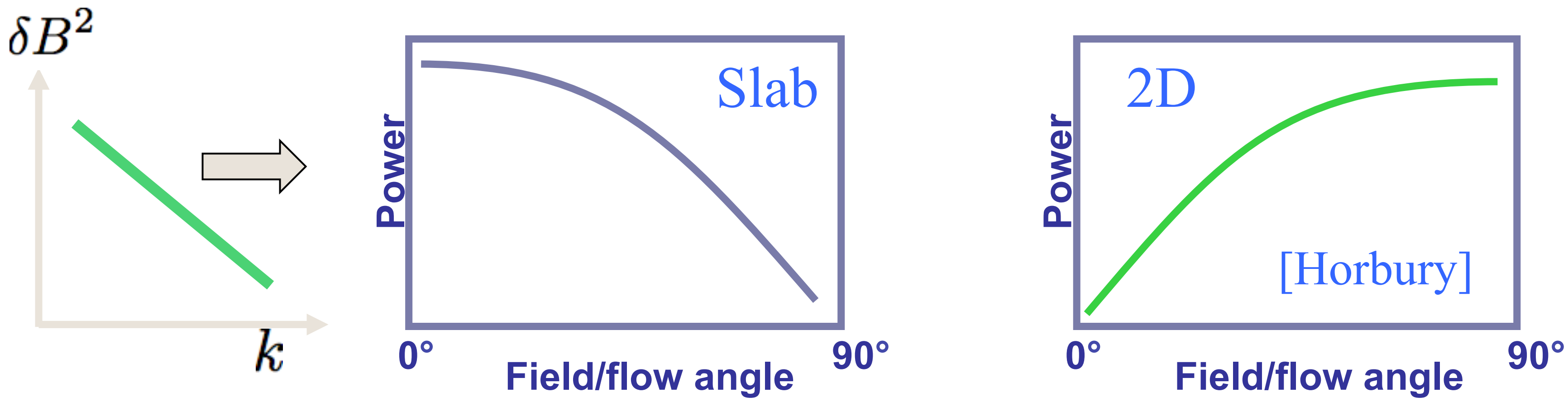
Presence of a mean magnetic field B_0 leads to an anisotropy of turbulent fluctuations:

- anisotropy in amplitudes of fluctuations;
- anisotropy in topology (wave vectors).

k-anisotropy of turbulent fluctuations



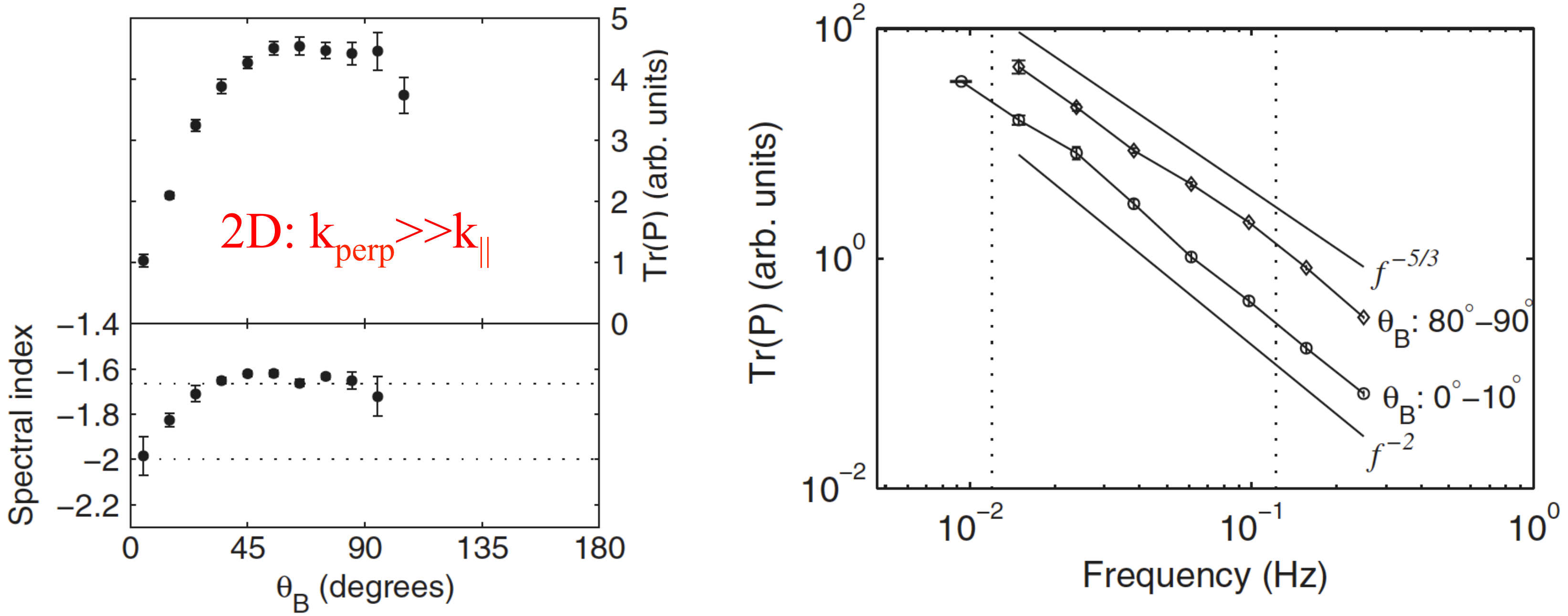
If Taylor hypothesis ($V_{\varphi} << V$) is verified ⇒ variation of field-flow angle allows to resolve slab fluctuations while V is || to B and 2D fluctuations while V is ⊥ to B. [Bieber et al., 1996; Horbury et al., 2008; Mangeney et al., 2006, Alexandrova et al. 2008, …]



Anisotropy of turbulent fluctuations at MHD scales

[Matthaeus et al. 1990, Bieber et al. 1996]: 2D + slab

[Horbury et al., 2008, PRL]: anisotropic cascade $k_{perp}^{-5/3}$, $k_{||}^{-2}$

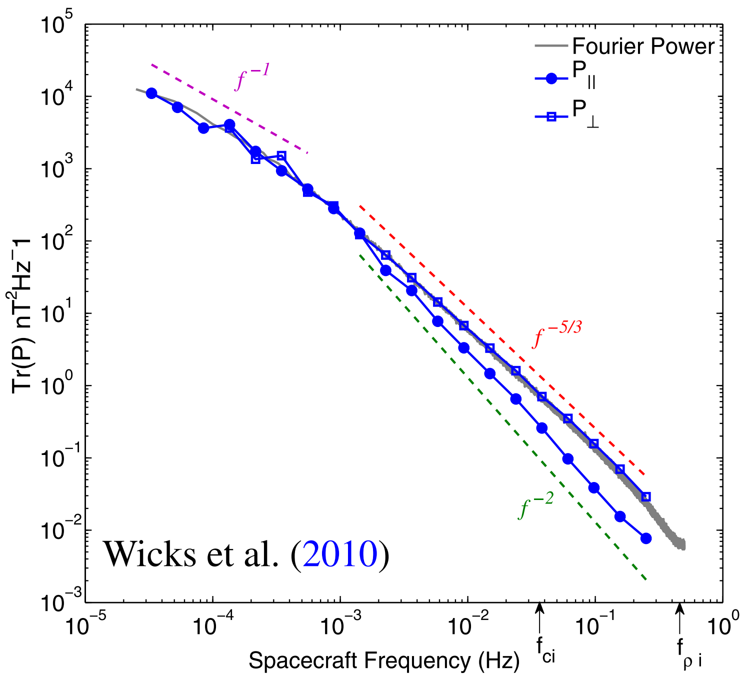


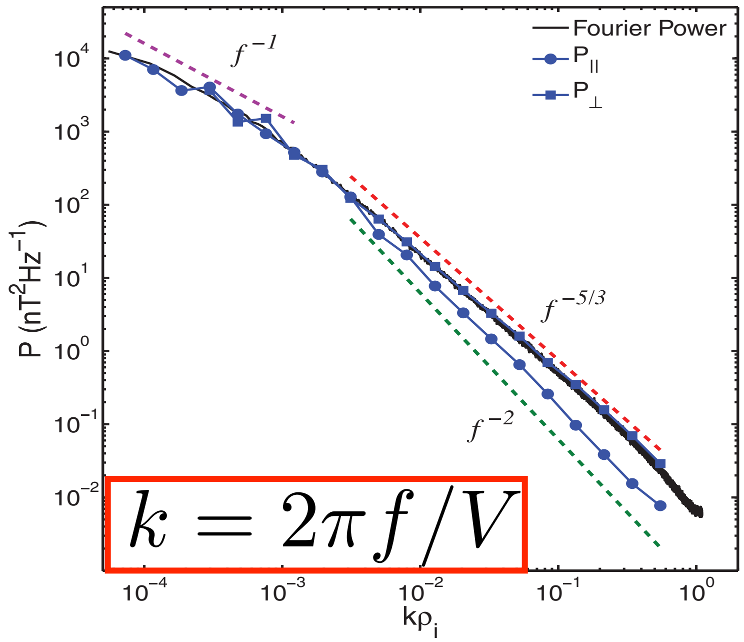
- In agreement with "Critical balance" model [Goldreich & Sridhar, 1995]
- Results obtained using a large statistical simple (30 days of data)

=> +/- general result

[see also Podesta et al., 2009]

Anisotropy of turbulent fluctuations at MHD scales



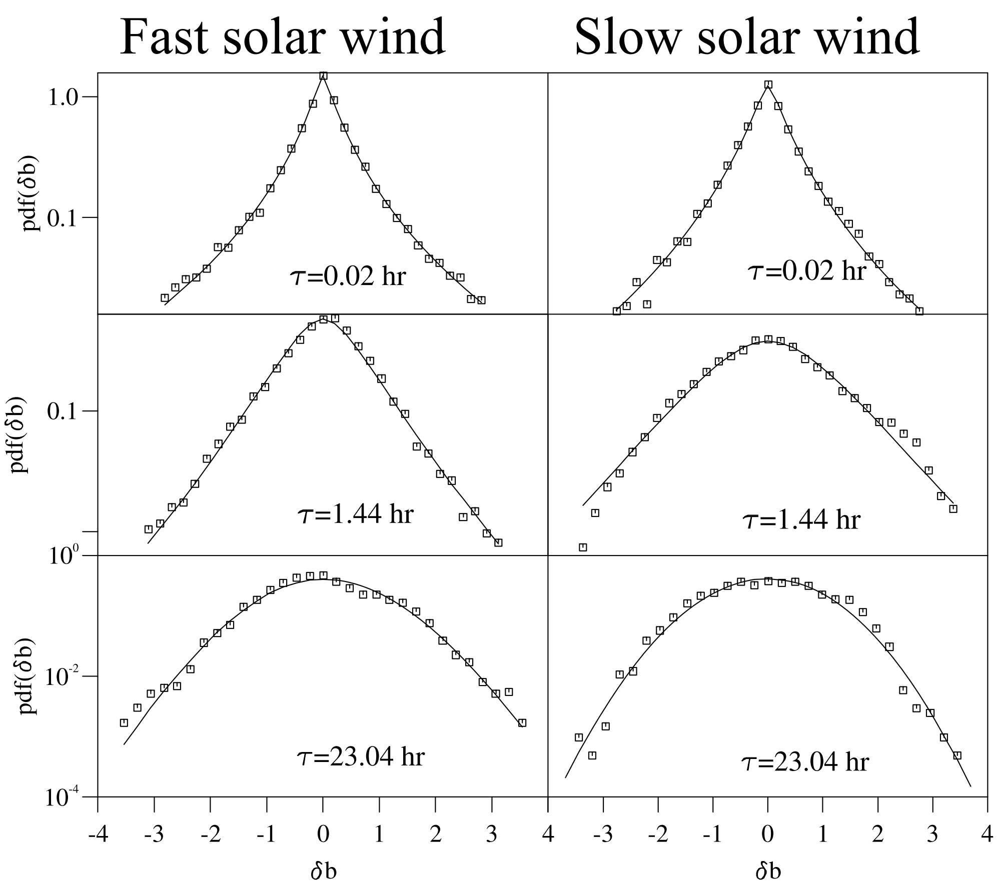


• Alfvénic turbulence of Goldreich and Sridha (1995) is based on the idea of a balance between linear Alfvén time (along B_0) and non-linear time (in plane perp. to B_0), see H. Politano lecture:

$$\boxed{\tau_A = \frac{\ell_\parallel}{V_A} \sim \tau_{NL} = \frac{\ell_\perp}{\delta V_\perp}}$$

$$\boxed{P(k_\perp) \sim k_\perp^{-5/3}\ ;\ P(k_\parallel) \sim k_\parallel^{-2}}$$

Intermittency of turbulent fluctuations (inertial range)



[Sorriso-Valvo et al. 1999; Greco, Servidio et al.]

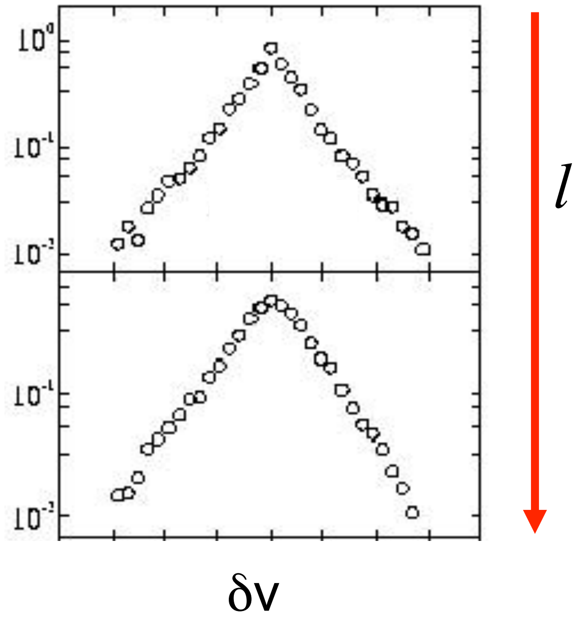
Non-Gaussianity of turbulent fluctuations

In the inertial range of HD turbulence (K4/5 law):

$$\left\langle \Delta u_\ell^3 \right\rangle = -\frac{4}{5}\langle \varepsilon \rangle \ell$$

< ε > averaged energy dissipation rate;
(see Politano & Pouquet, 98, for incompressible MHD)

- For Gaussian fluctuations the 3d moment is zero;
- Here, the third-order moment of fluctuations, which is related to the energy dissipation rate, is different from zero →
- Turbulence MUST shows some nongaussian features within the inertial range.



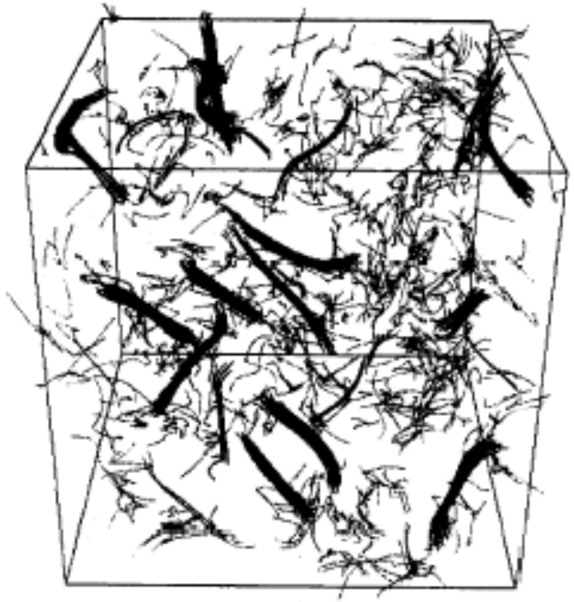
Intermittency: scale dependent non-Gaussianity of turbulent fluctuations

Intermittency = coherent structures

In HD turbulence intermittency corresponds to appearance of coherent structures:

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

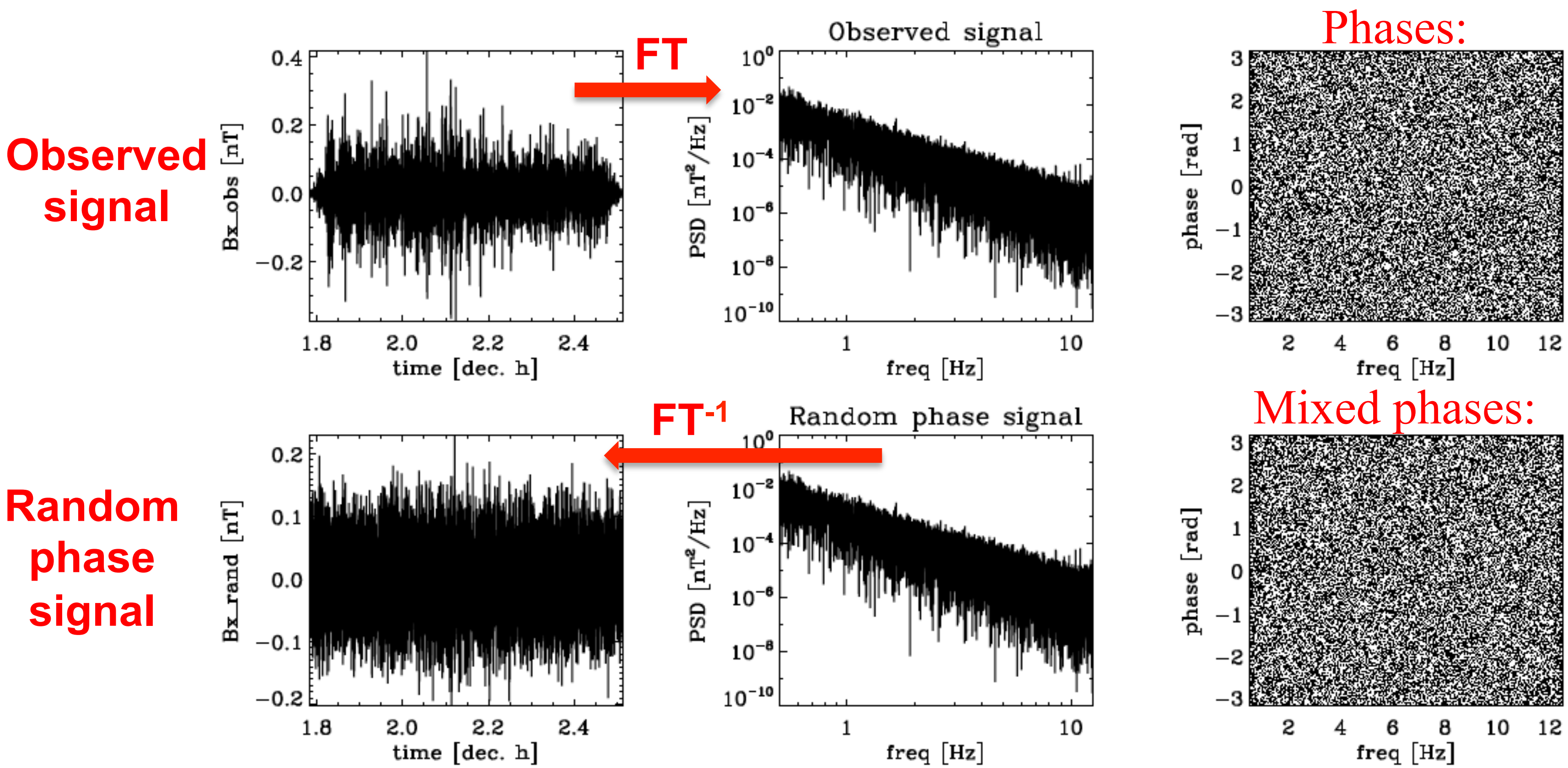
[She et al., 1991]



- Coherent structures have coupled phases over all scales
- Role in dissipation ?

Non-Gaussianity: what does it mean ?

Cluster-1/STAFF-SC measurements, 2002-02-19



From the observed signal we construct a signal with random phases but with the same spectrum.

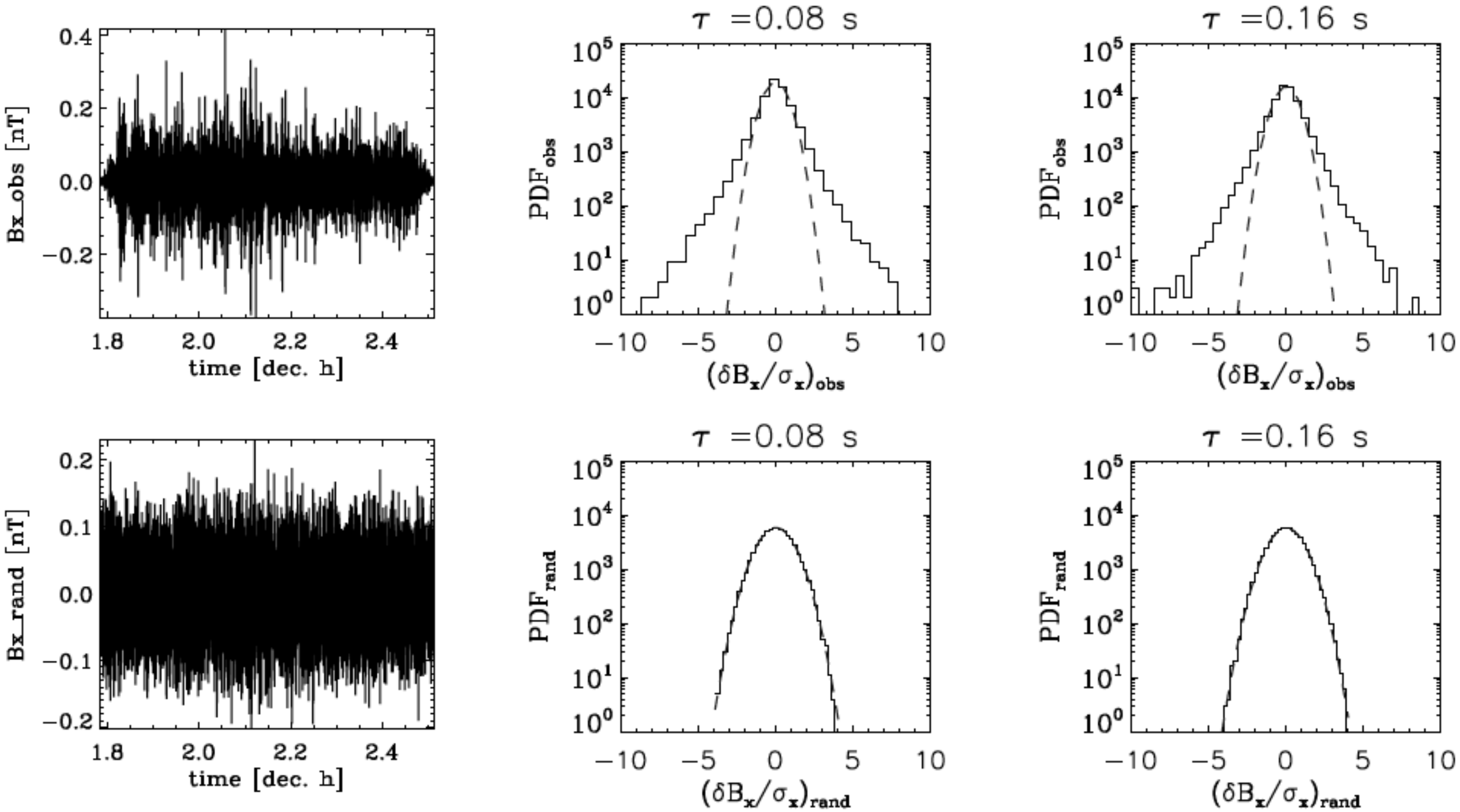
[Rossi, Tesi di Lauria, 2011; Hada et al. 2003; Koga & Hada, 2003; Sahraoui, 2008]

Non-Gaussianity: what does it mean ?

[Claudia Rossi, Tesi di Laurea, 2011]

Observed signal

Random phase signal

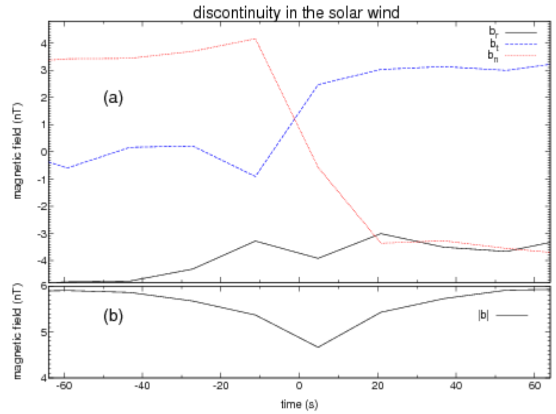


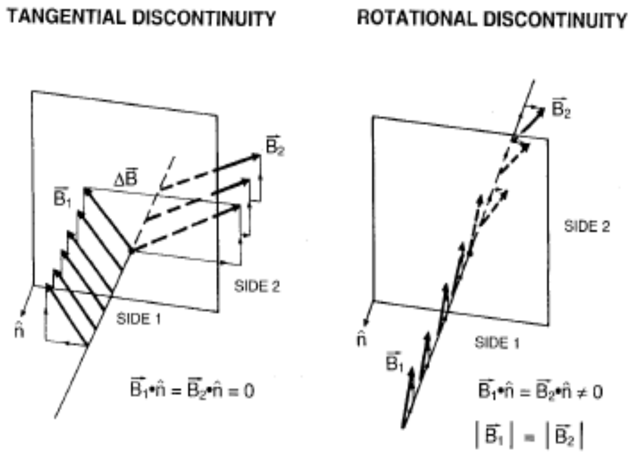
Non-Gaussian tails <=> coupled phases !

Intermittency = coherent structures

In HD turbulence intermittency corresponds to appearance of coherent structures:

[She et al., 1991]





Intermittency in the solar wind : current sheets ?
and what kind of structures around plasma kinetic scales ?

Turbulence at kinetic scales

1. Ion scales

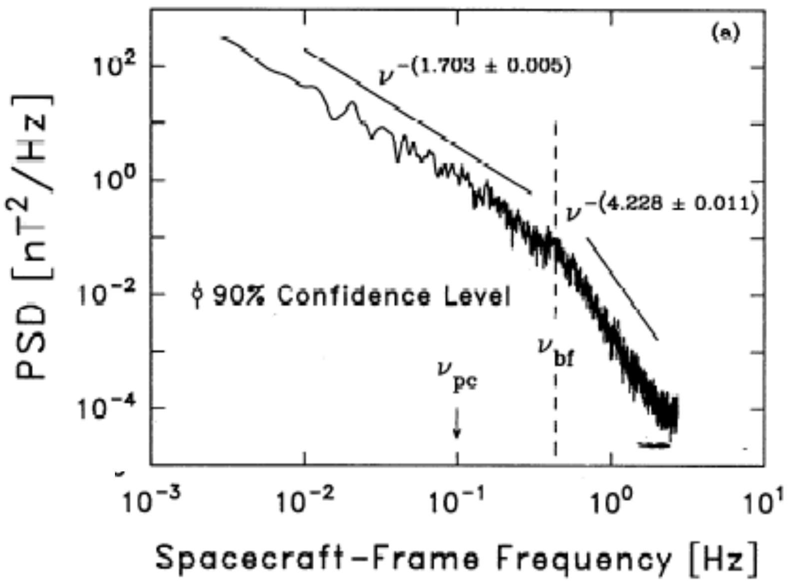
$$f_{ci} = \frac{eB_0}{2\pi m_i c}, \;\; k\rho_i \sim 1, \;\; kc/\omega_{pi} \sim 1$$

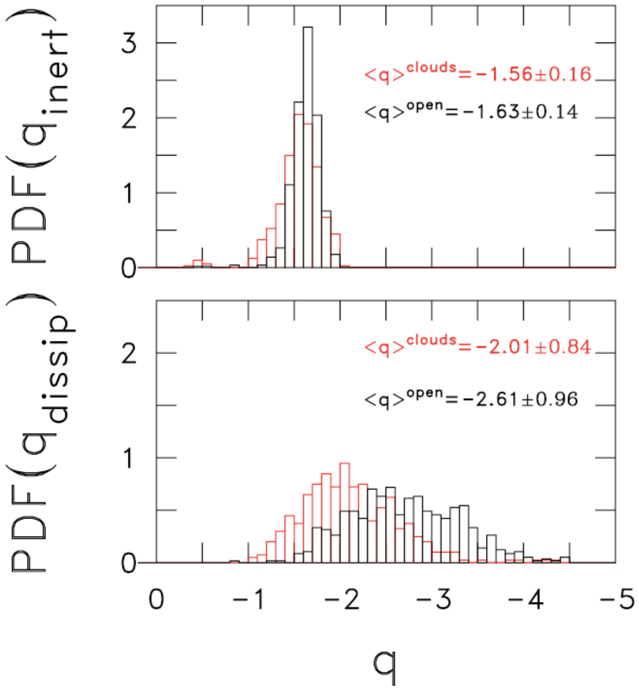
Turbulence around ion scales

Magnetic field spectrum

[Smith et al., 2006]

[Leamon et al,1998]





- There exist a spectral “break” close to ion scales
- Spectral variability within ion transition range (no universal behavior)
- Attention: less than 1 decade is measured…

Turbulence around ion scales

Ion moments spectra

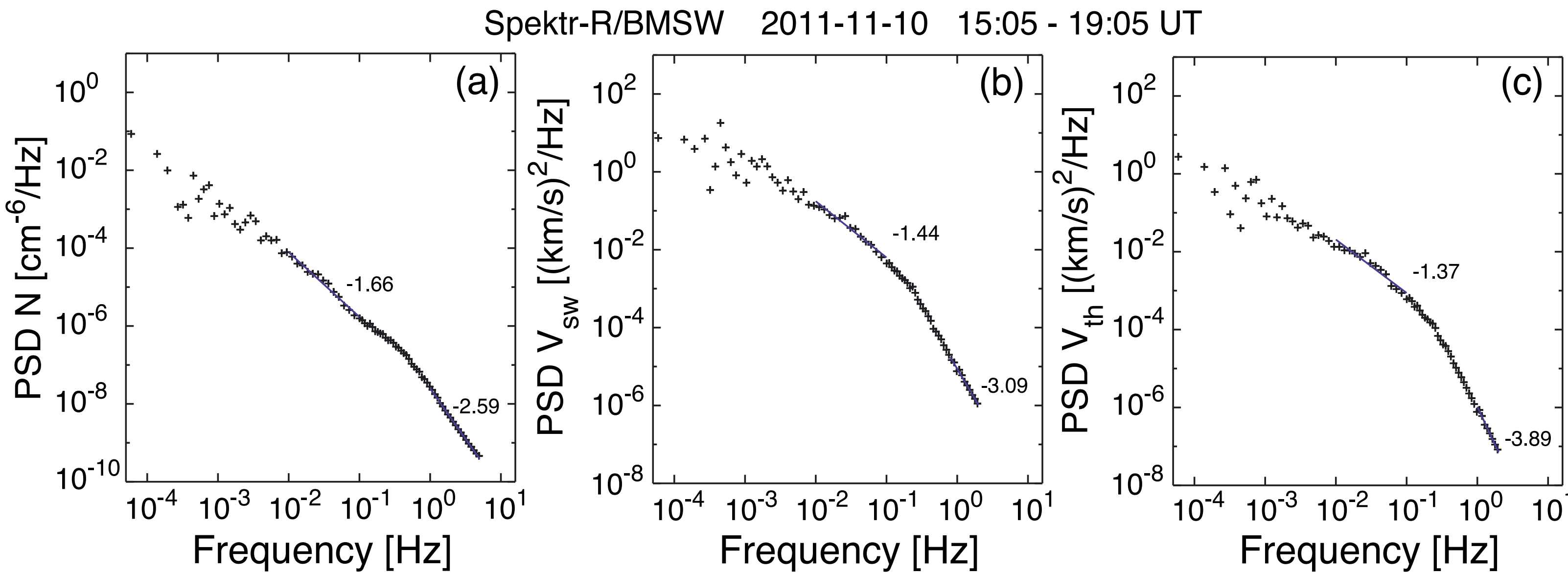
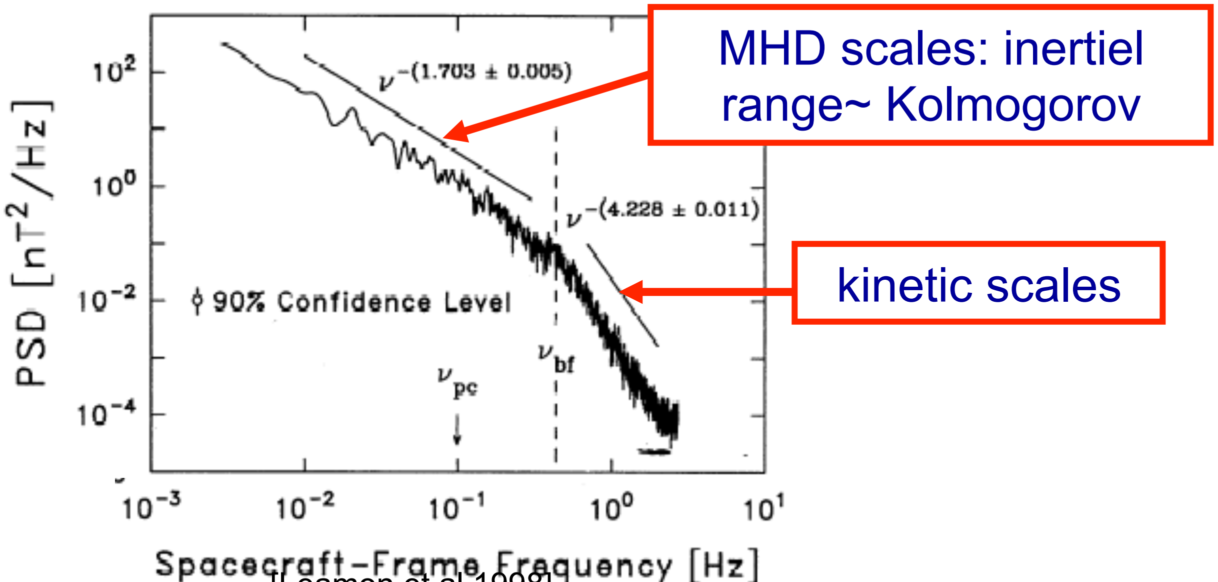


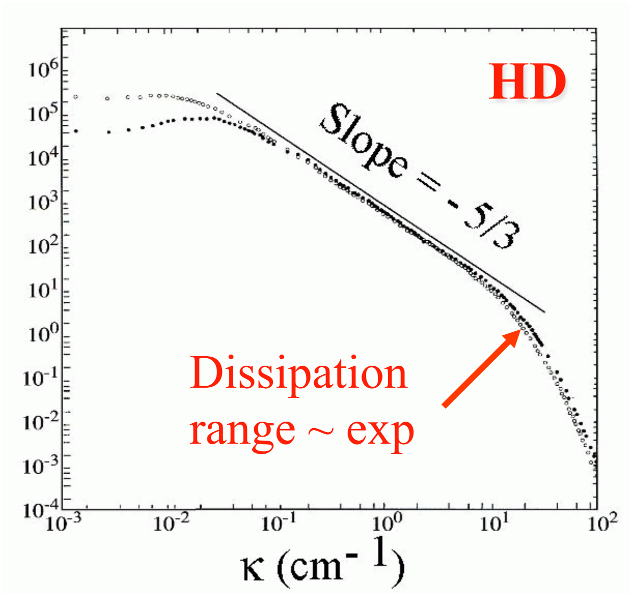
Fig. 10 Spectra of ion moments, (**a**) density, (**b**) velocity, (**c**) ion thermal speed, up to ~ 3 Hz as measured by *Spektr-R*/BMSW (Bright Monitor of Solar Wind) in the slow solar wind with $V_{sw} = 365$ km/s and $\beta_p \simeq 0.2$. Figure from Šafránková et al. (2013)

Turbulence around ion scales: open question?

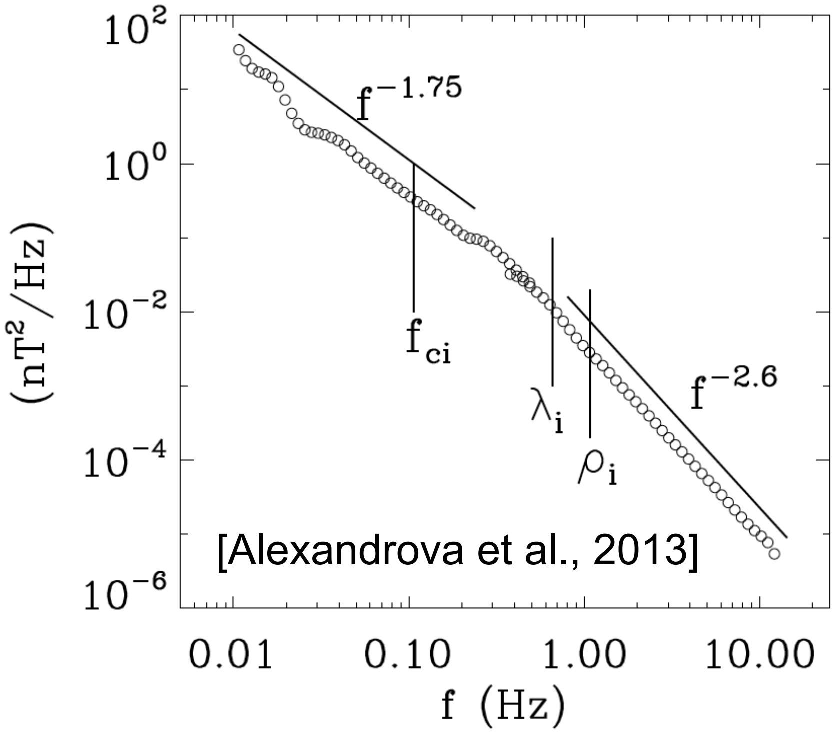
- onset of dissipation range [e.g Leamon+'98,99,00; Smith'06,…] ?
- starting point of another cascade [e.g. Biskamp+'96; Galtier'06; Alexandrova+'08,'13] ?
- or combination of both, c.f. Passot lecture
- which ion scale is responsible for the break ?
- Intermittency / presence of coherent structures ?



[Leamon et al,1998]



Which ion scale is responsible for the break?



Time scale (~0.1 Hz)

$$f_{ci} = \Omega_{ci}/2\pi \; ; \; \Omega_{ci} = eB/m_i c$$

Spatial scales (~100 km)

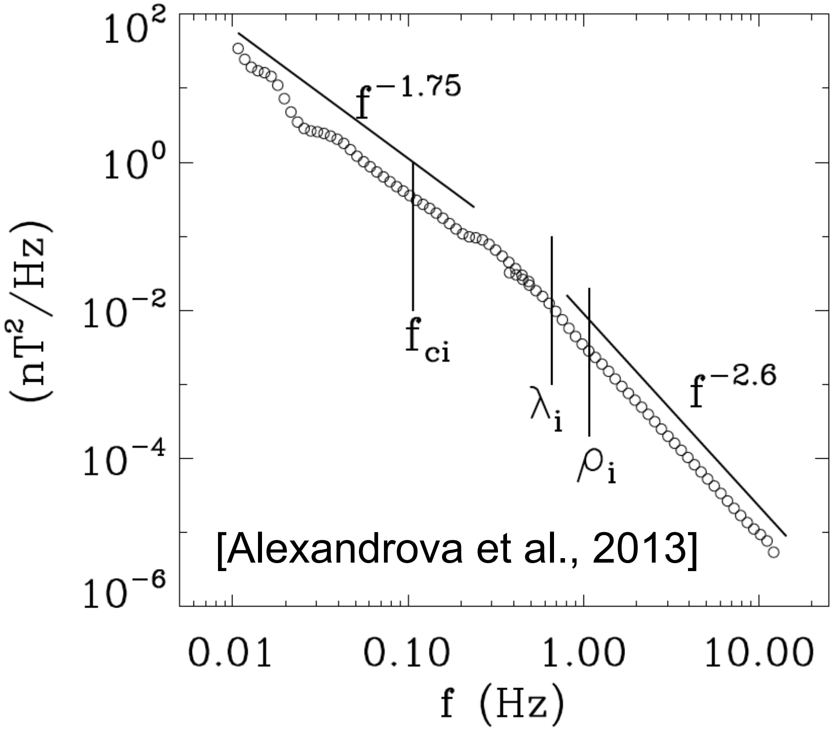
$$\rho_i = \frac{V_{\perp i}}{\Omega_{ci}} \; ; \; \lambda_i = \frac{c}{\omega_{pi}} = \frac{V_A}{\Omega_{ci}}$$

In frequency spectrum, these scales appear at Doppler shifted frequencies:

$$f_{\rho_i} \simeq \frac{V_{solar\ wind}}{\rho_i} \; ; \; f_{\lambda_i} \simeq \frac{V_{solar\ wind}}{\lambda_i}$$

- All characteristic time and spatial ion scales are observed close to the spectral break point…
- How can we distinguish between different scales?
- Important in order to understand which physical mechanisms “break the spectrum” (e.g., if it is f_{ci} => damping of Alfven waves).

Which ion scale is responsible for the break?



- Leamon et al. 2000 : λ_i
- Schekochihin et al. 2009: ρ_i
- Perri et al. 2010 : any of the scale/ combination of scales
- Bourouaine et al. 2012: λ_i
- Bruno et al. 2014: resonant k of parallel Alfven waves
- Chen et al. 2014: beta dependent.

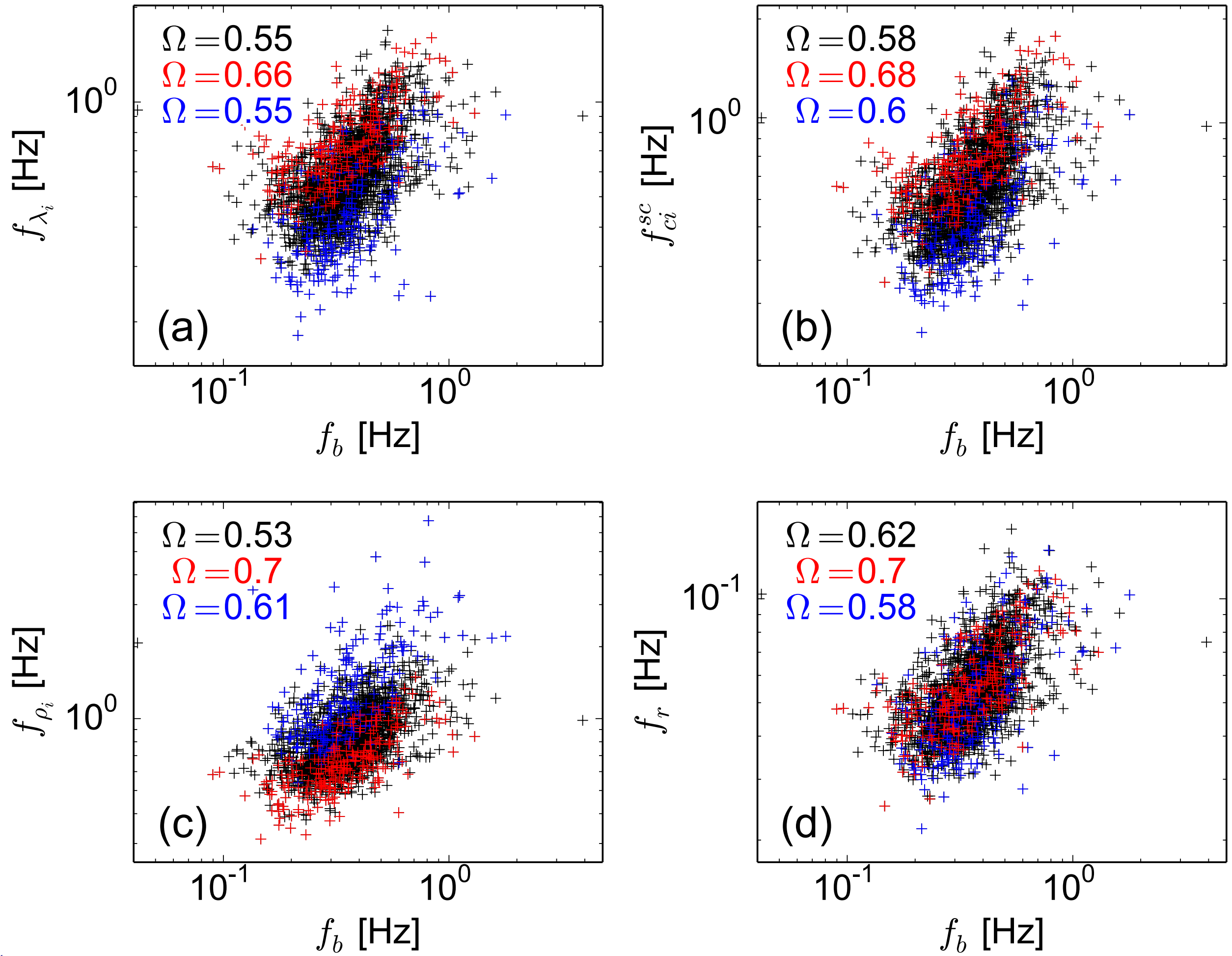
$$\boxed{\beta_i = 2\mu_0 n k_B T_i / B^2 = \rho_i^2/\lambda_i^2.}$$

$\Rightarrow$ The largest characteristic ion scale "breaks" turbulent spectrum [Chen et al. 2014].

Ion scales and spectral break (statistical study)

[Sonny Lion, PHD thesis, 6 years of STEREO/MAG data]

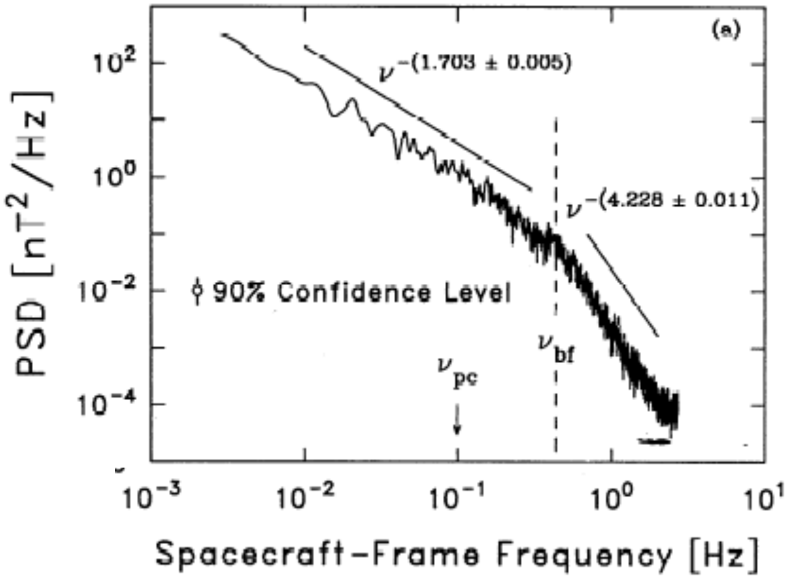
Red: high βp > 1
Blue: low βp < 0.2
Black: all data



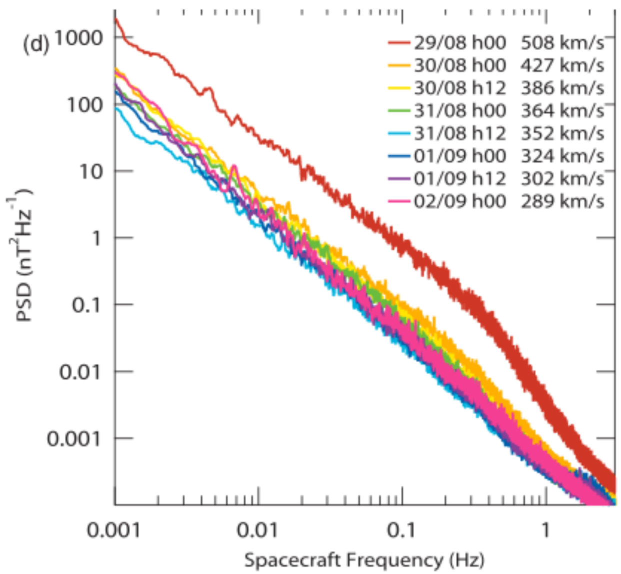
- Spectral break is not always well-defined => f_b= intersection of 2 power-laws
- All ion scales correlate well with f_b !!! => Not one scale (or physical mechanism) which is responsible for the spectral break?

Break at ion scales: permanent feature ?

- Sometimes: we observe a clear spectral "break" [Leamon et al. 1998].
- However, usually the break is not visible and we define it as an intersection of 2 power-laws.



[Leamon et al,1998]

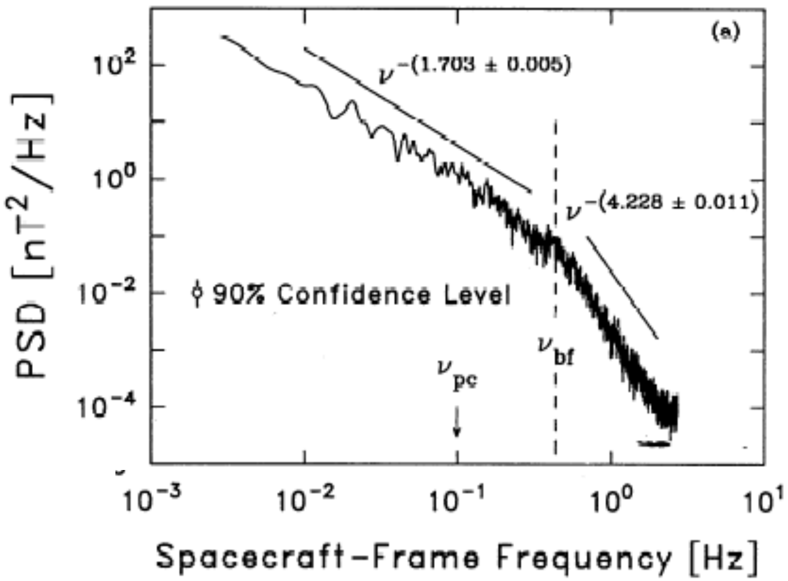


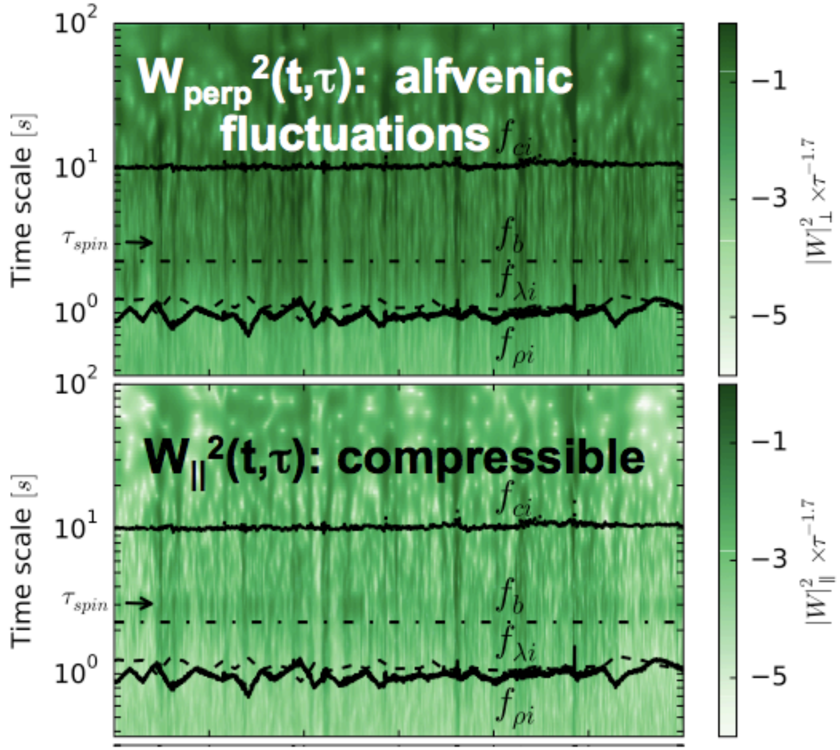
[Bruno et al. 2014]

- There exist spectra without a break [Bruno et al. 2014; Smith et al. 2006]…
- What is particular with the fast solar wind and Leamon's 1998 spectrum?

Let's re-visit Leamon's spectrum

The time interval studied in [Leamon et al,1998], with V=690km/s, $T_{perp}/T_{||}=1.8$, $\beta=0.5$





- Fourier (wavelet) spectra: mean characteristic of turbulence, no information on homogeneity of fluctuations.
- Time-frequency (time-scale) analysis with wavelets allows us to see the 'texture' of turbulence.

Fourier vs wavelet transforms

$$B_x[j] = B_x(t_j) = B_x(t_0 + j\Delta t)$$

$$\Delta t = T/N, \quad t_j = j\Delta t, \quad j = 0, 1, ..., N-1$$

Fourier Transform:

$$\hat{B_x}(f) = \frac{1}{N}\sum_{j=0}^{N-1} B_x(t_j)e^{-2\pi i f t}$$

$$f_n = n/T, \quad n = 0, ..., N-1$$

Fourier: Time dependence is lost, best frequency localization.
Wavelets: time-frequency dependence, frequency (or time scale τ=1/f) resolution verifies the uncertainty principle:

$$\Delta\tau^{-1}\Delta T \sim const$$

Wavelet Transform:

$$\mathcal{W}_x(\tau, t) = \sum_{j=0}^{N-1} B_x(t_j)\psi^*[(t_j - t)/\tau]$$

Morlet mother function:

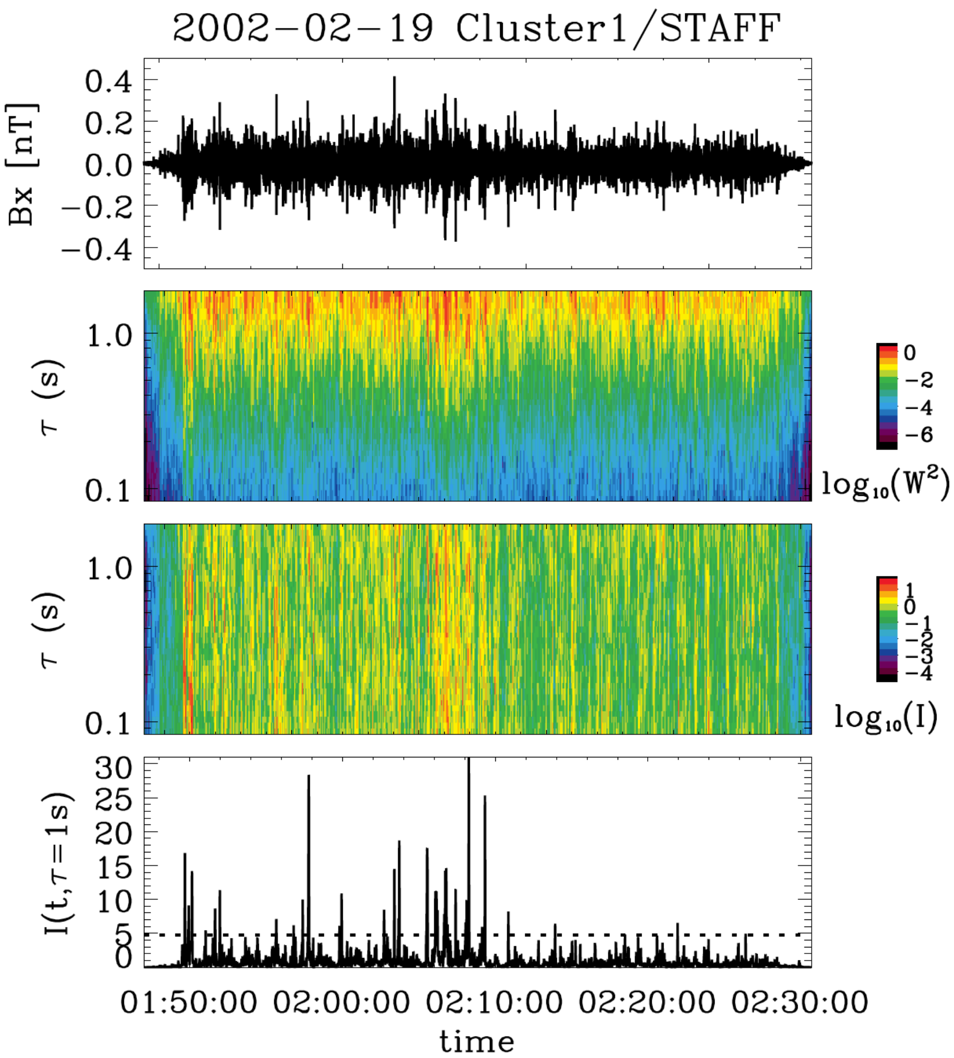
$$\psi_0(t) = \pi^{-1/4}e^{-i\omega_0 t}e^{-t^2/2}$$

$$\tau_m = \tau_0 2^m, \quad m = 0, 1, ..., M$$

$$M = \log_2(N\delta t/\tau_0)$$

[Farge, 1992; Torrence & Compo 1998]

Looking for coherent structures with Morlet wavelets



Morlet Wavelet Transform

$$\mathcal{W}_x(\tau, t) = \sum_{j=0}^{N-1} B_x(t_j)\psi^*[(t_j - t)/\tau]$$

$$\psi_0(t) = \pi^{-1/4} e^{-i\omega_0 t} e^{-t^2/2}$$

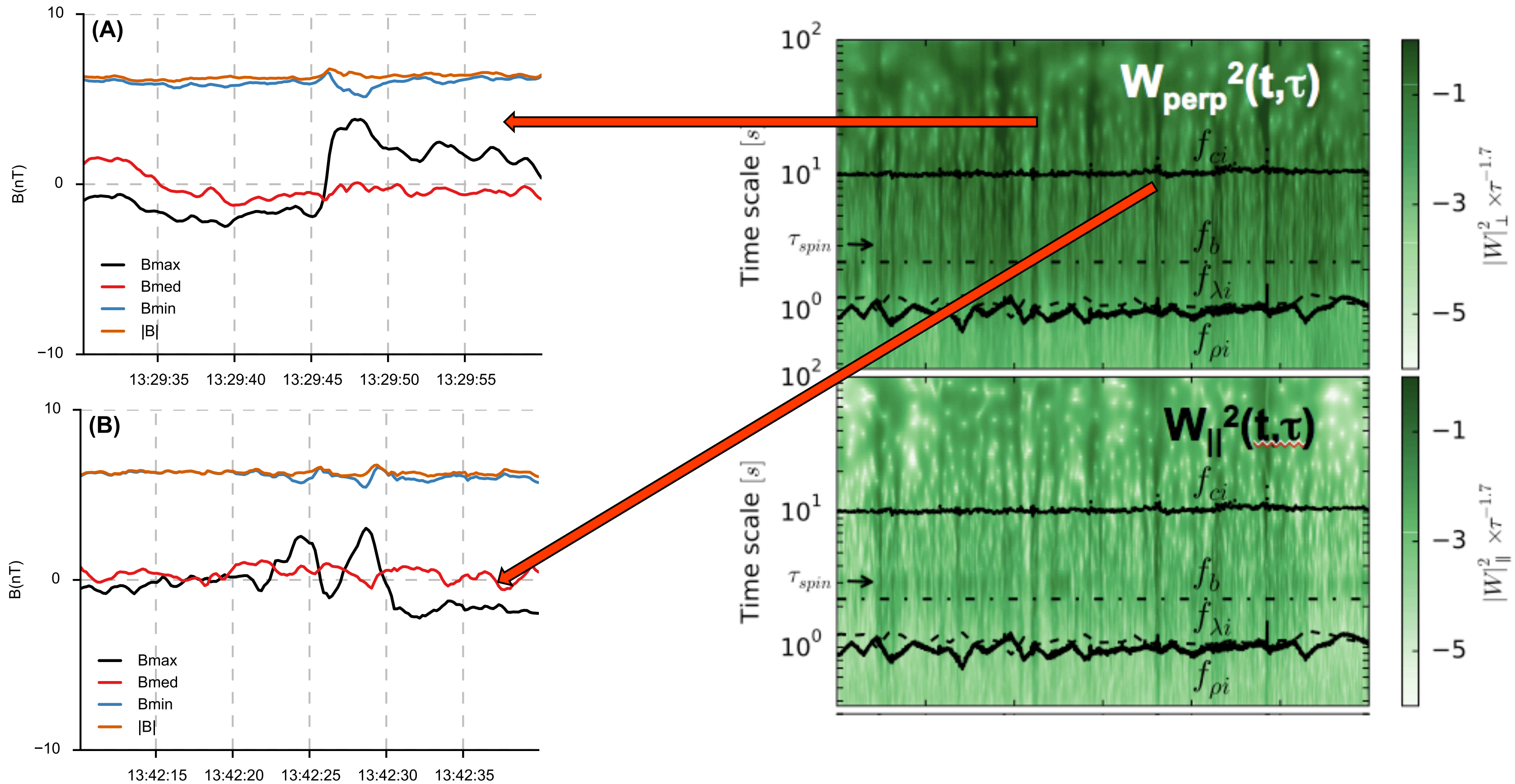
Intermittency measure [Farge 1992] :

$$I(t,\tau) = \frac{|W(t,\tau)|^2}{< |W(t,\tau)|^2 >_\tau}$$

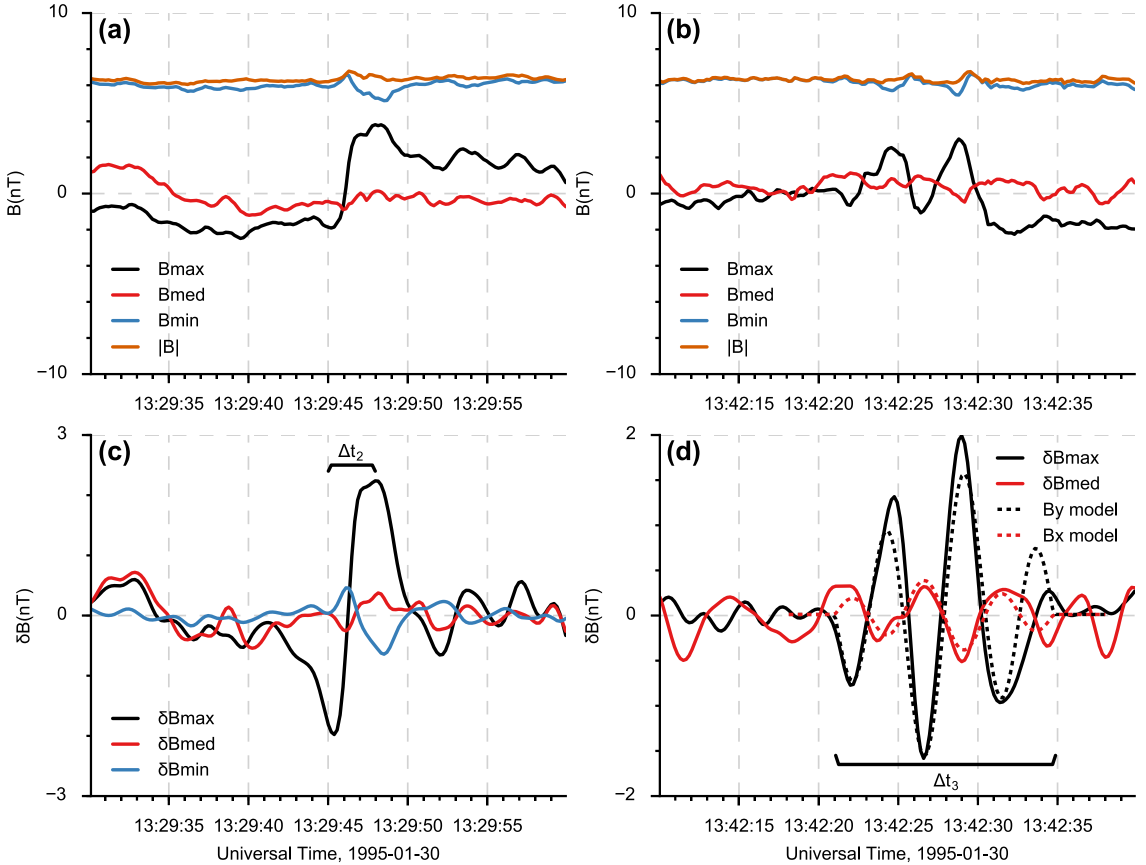
=> we see localised events covering all scales > mean

Coherent current sheets and vortices

- Distributions of energy in time and scales for Alfvenic and compressible fluctuations (wavelet scalogrammes W_{perp}^2 and $W_{||}^2$) => presence of coherent events simultaneously in W_{perp}^2 and $W_{||}^2$.



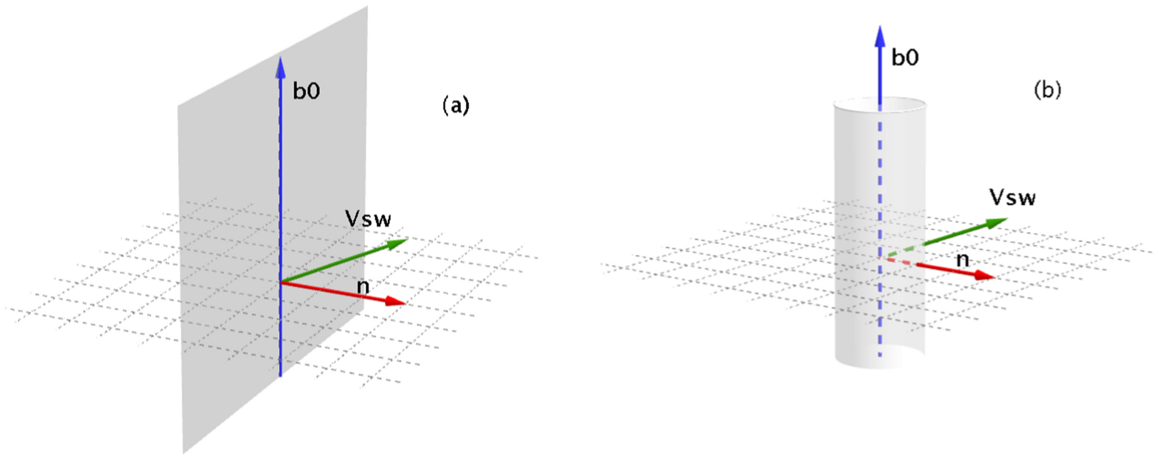
- Large amplitude current sheets and Alfven vortices ($\delta B/B_0$=0.7)



Raw magnetic data

Magnetic fluctuations
$\delta B_i = B_i - \langle B_i \rangle_{10s}$

$L_{current\ sheet} \sim 5$ ion scales
$L_{vortex} \sim (5\text{-}30)$ ion scales

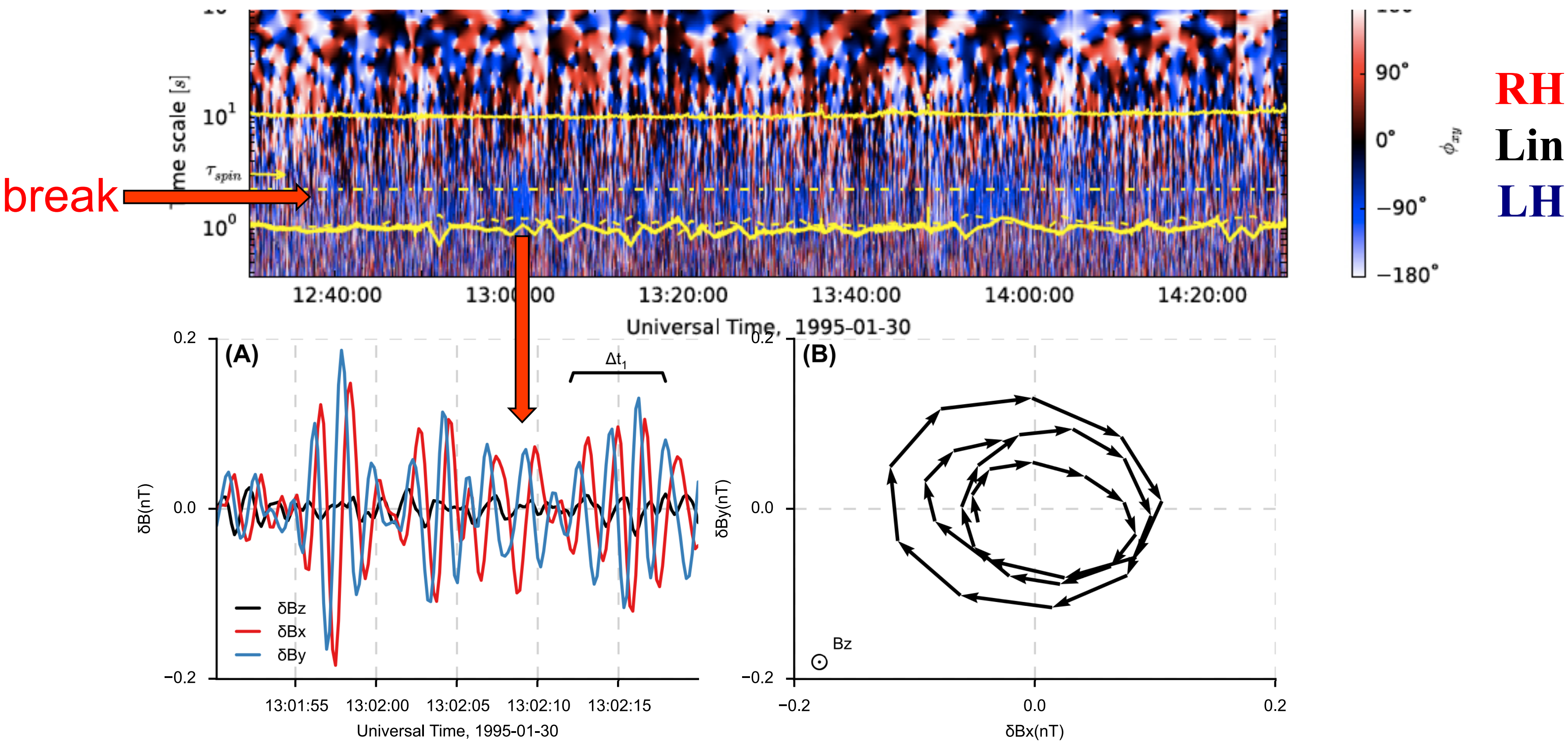


[Lion et al, 2016, APJ]

Polarization in the plane perpendicular to B

Phase difference between Bx and By:

$$\Delta\phi_{xy}(t,\tau) = \phi_x(t,\tau) - \phi_y(t,\tau)$$



Alfven-Ion-Cyclotron waves at ion break frequency

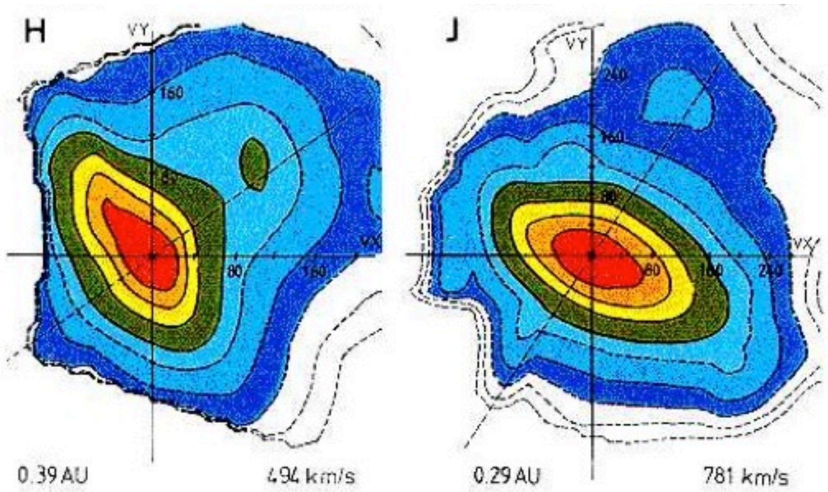
$$\delta B/B_0 = 0.03,\ \Theta_{BV} = 160^\circ$$

$$T_\perp/T_\| = 3.5,\ \beta_\| = 0.2$$

Ion scale instabilities in the solar wind

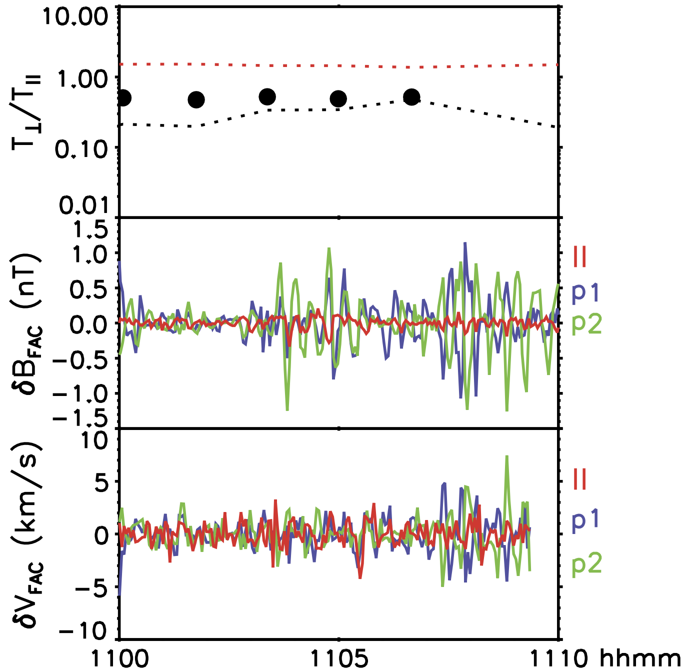
- In the solar wind ion distribution functions $f(V_i)$ are anisotropic =>
- ion temperature anisotropy instabilities develop to isotropy $f(V_i)$
- => quasi-monochromatic waves at a frequency/scale close to ion scales

[Marsch et al. 1983]

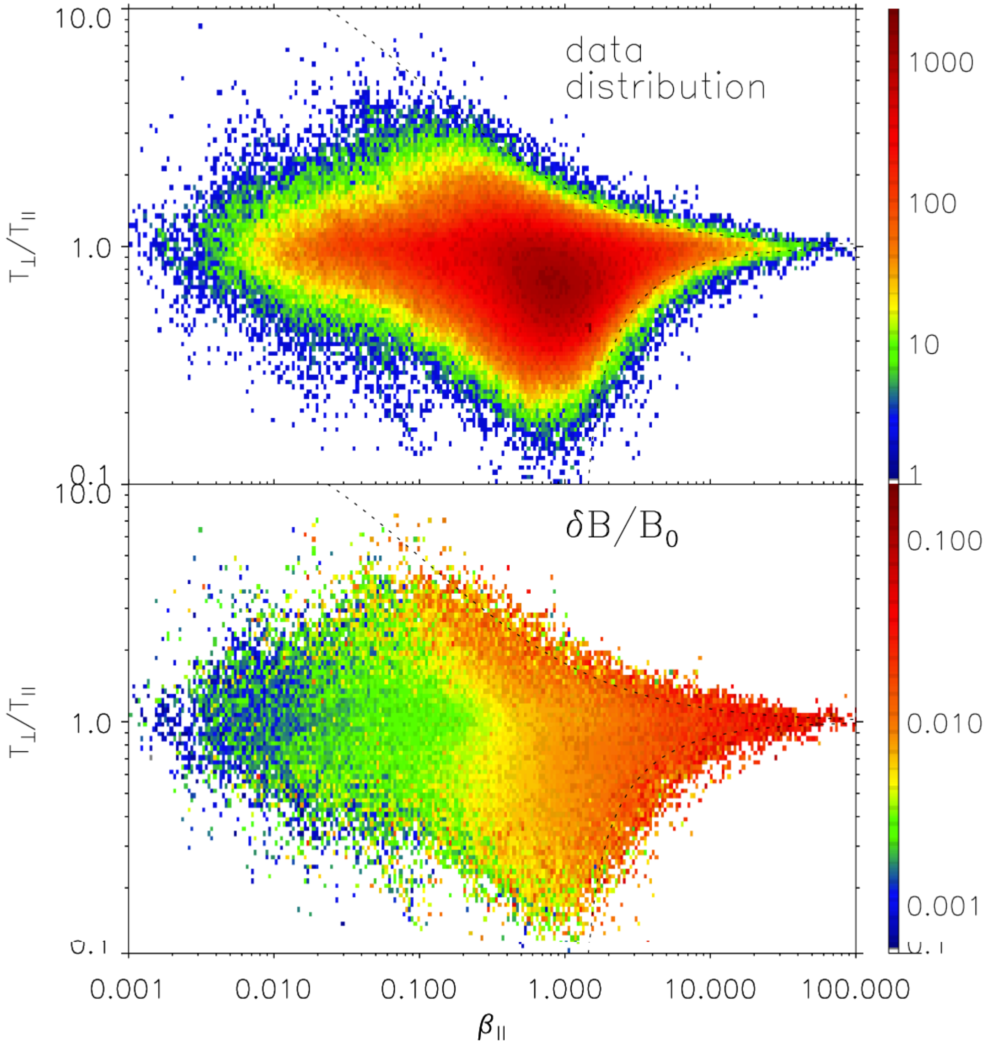


$$\boxed{T_{i\perp} \neq T_{i\parallel}}$$

[Alexandrova et al. 2013]



Ion temperature anisotropy as a function of plasma beta and 10 years of *Wind* data



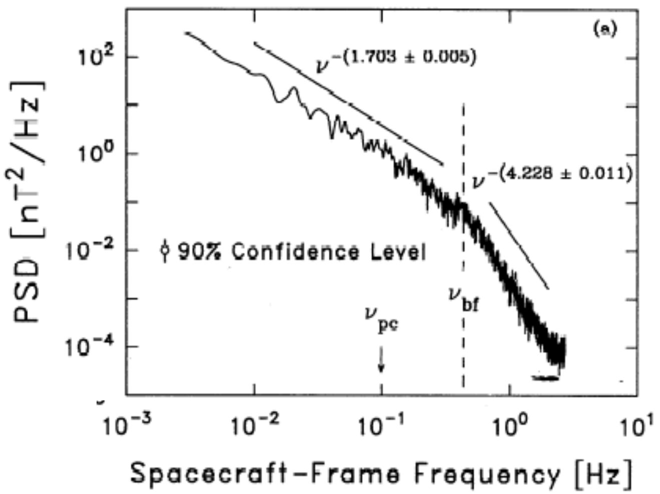
$$\beta_{p\parallel} = \frac{nkT_{p\parallel}}{B^2/8\pi}$$

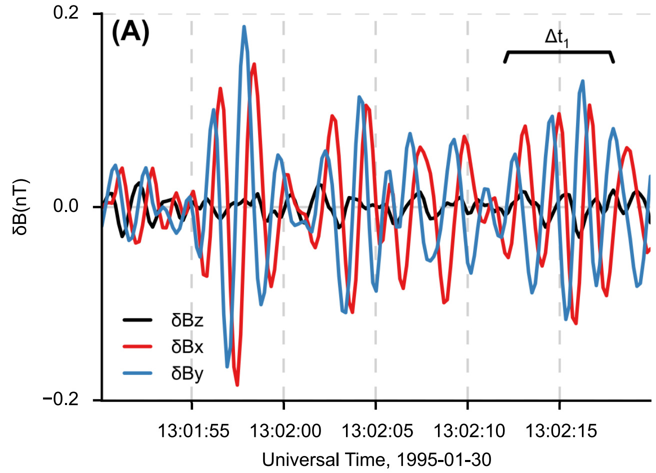
[Bale et al. 2009, PRL]

=> At ion scales one expects to have a superposition of background turbulence + waves/instabilities.

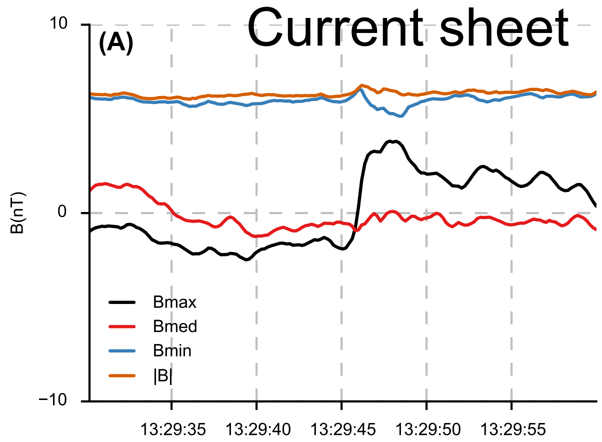
Ion scales: superposition of different phenomena

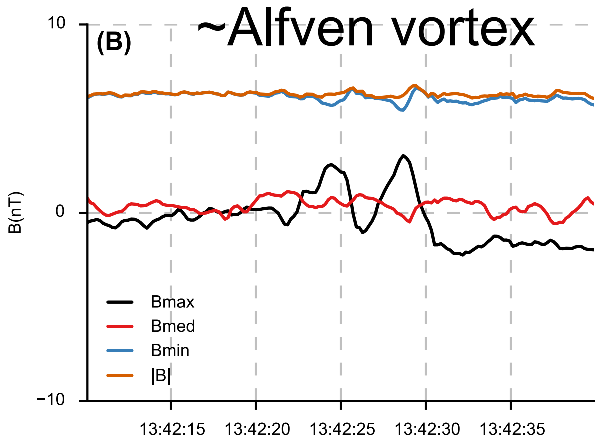
[Leamon et al. 1998]



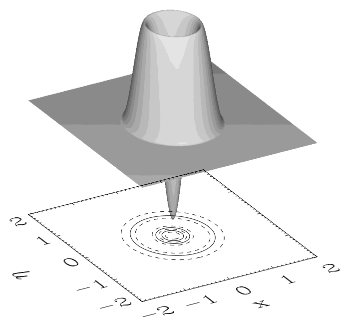


Monochromatic Alfven waves at freq~f_{ci} with $k_{||}$ (generated by AIC instability).



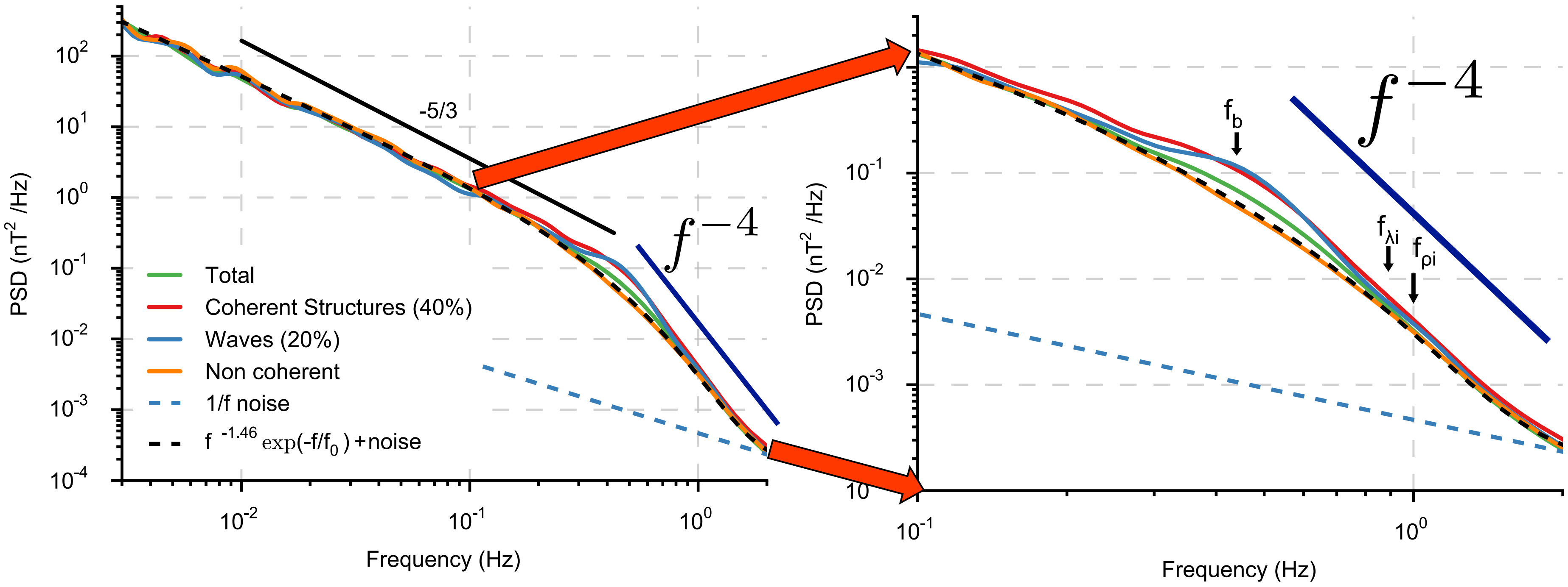


Localized spatial structures with k_{perp} at scale ~ ion Larmor Radius



[Lion et al, 2016, ApJ]

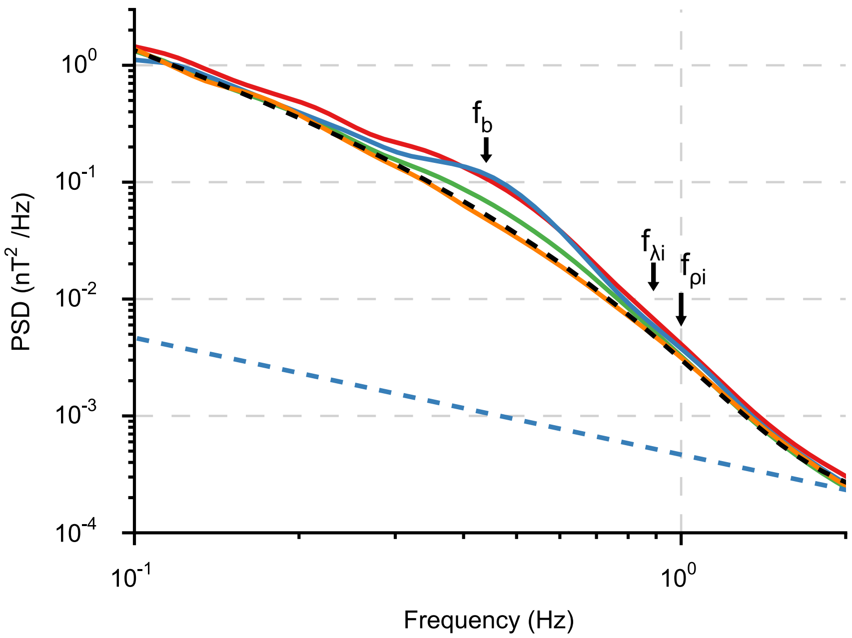
Total and individual spectra of 3 families: waves, structures, background



- AIC waves (20%) spectrum has a bump around the break f_b
- Structures (40%) spectrum has a knee around f_b and $\sim f^{-4}$ power-law at $f>f_b$
- Spectrum of non-coherent fluctuations (40%) has NO break, but a smooth transition which can be described by :

$$\boxed{E_B \sim f^{-3/2}\exp(-f/f_0), \quad f_0 = 0.3\mathrm{Hz}}$$

Nature of turbulence around ion scales: fast solar wind



- Alfven Ion Cyclotron waves (with $k_{||}$)
- Coherent structures (with k_{perp})
- Non coherent signal, which can be described by

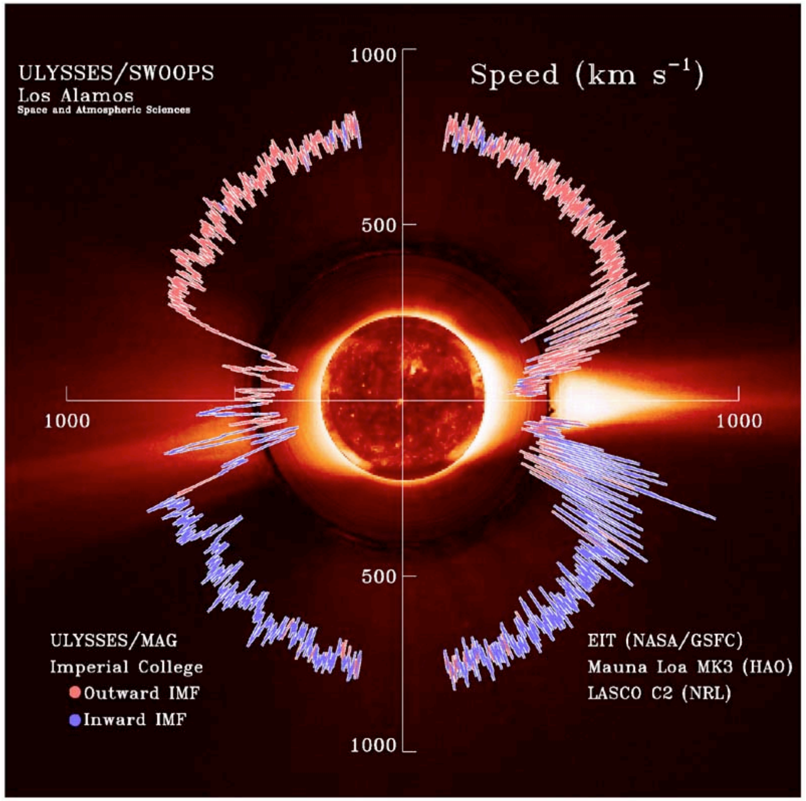
$$E_B \sim f^{-3/2} \exp(-f/f_0), \quad f_0 = 0.3\mathrm{H}z$$

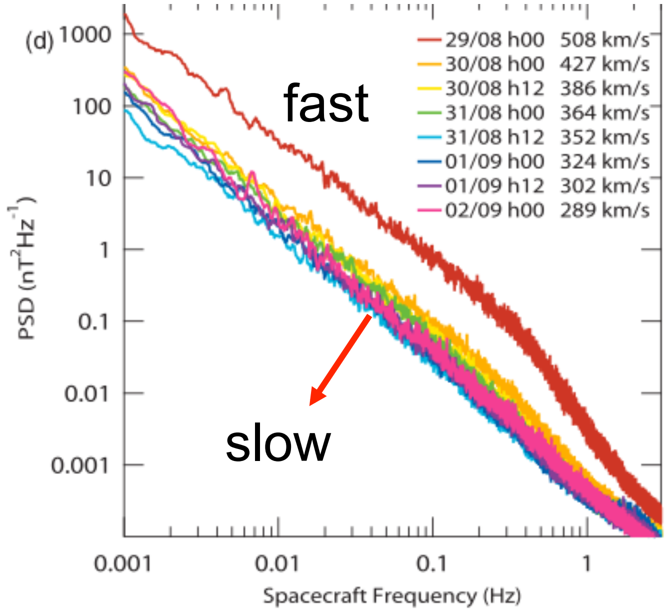
⇒The total observed spectrum depends on the contribution (percentage) of each event (which depends on the local plasma parameters and field-to-flow orientation)

⇒These results may explain spectral variability around ion scales.

[S. Lion, O. Alexandrova, A. Zaslavsky, 2016, APJ]

Nature of turbulence around ion scales in the slow solar wind ?

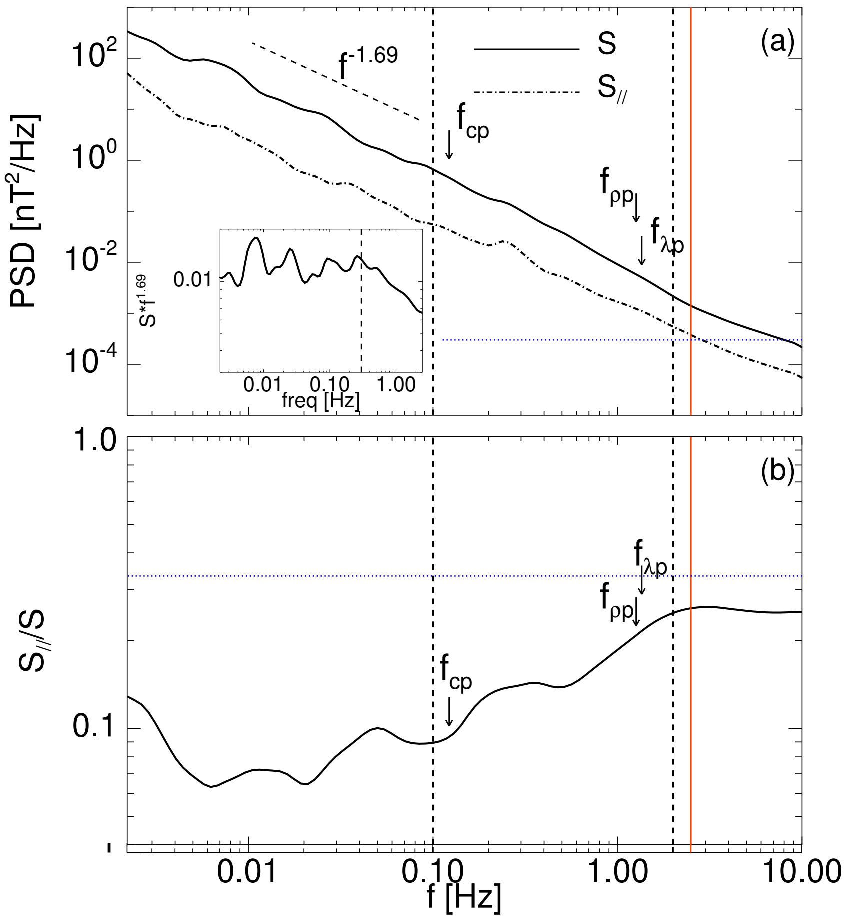




[Bruno et al., 2014, APJ]

Nature of turbulence around ion scales in the slow solar wind ?

[Perrone et al., 2016, APJ]



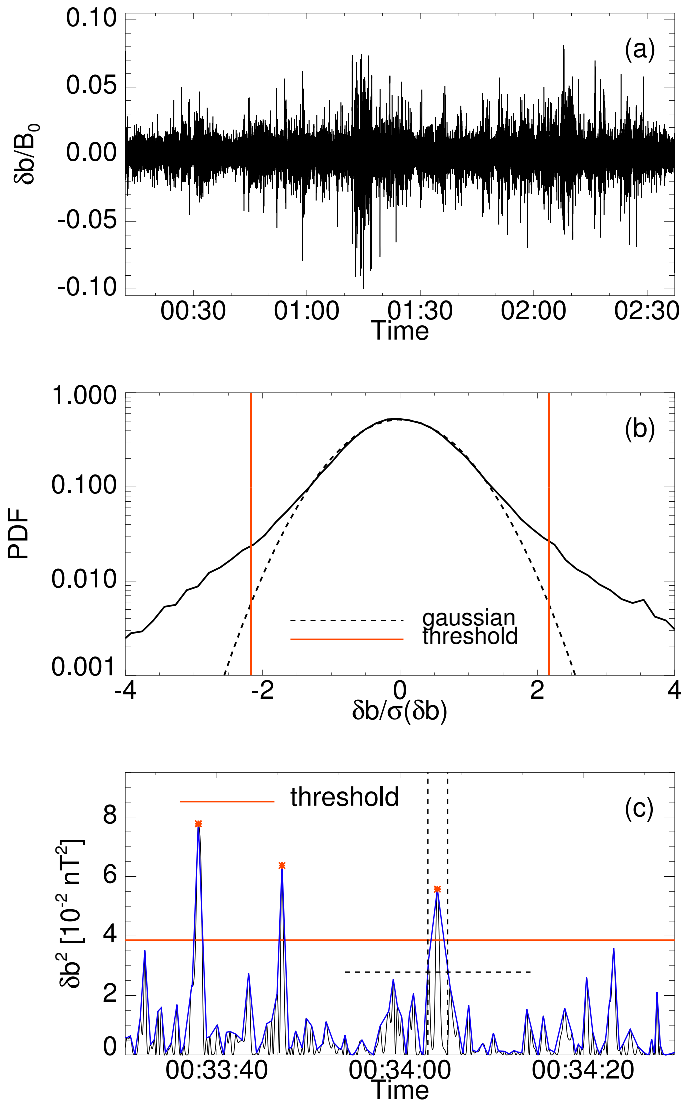
S : total power spectral density (PSD) of magnetic fluctuations;

$S_{||}$: spectrum of compressible fluctuations

$S_{||}/S$: level of compressibility, increases at ion scales (in agreement with Alexandrova et al. 2008, Hamilton et al. 2008, Kiyani et al. 2013)

Magnetic fluctuations around ion scales (slow wind)

[Perrone et al., 2016, APJ]



Let's consider $\delta B_{||}/B_0$ at ion scales

$$\delta b_i(t) = \frac{\delta j \delta t^{1/2}}{C_\delta \psi_0(0)} \sum_{j=j_1}^{j_2} \frac{\tilde{\mathcal{W}}_i(\tau_j, t)}{\tau_j^{1/2}}$$

- Parallel to B_0 fluctuations, δb, are non-Gaussian / 2h of data.
- Heavy tails correspond to ~600 intermittent events .
- **What is the nature of these events?**

Compressible structures: magnetic solitons

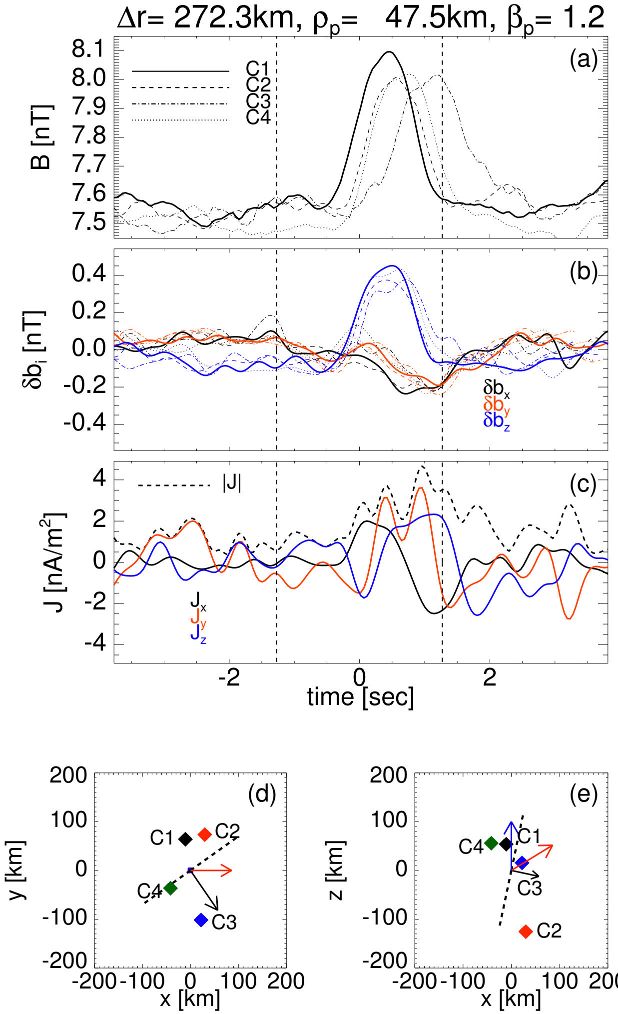
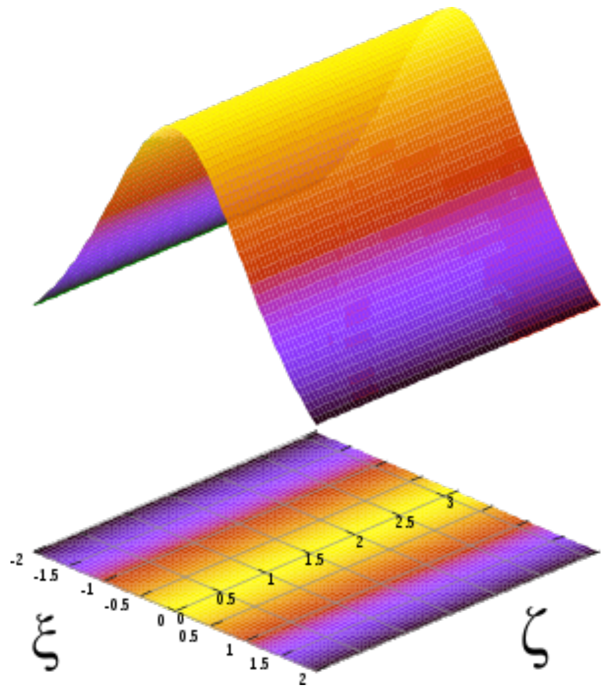


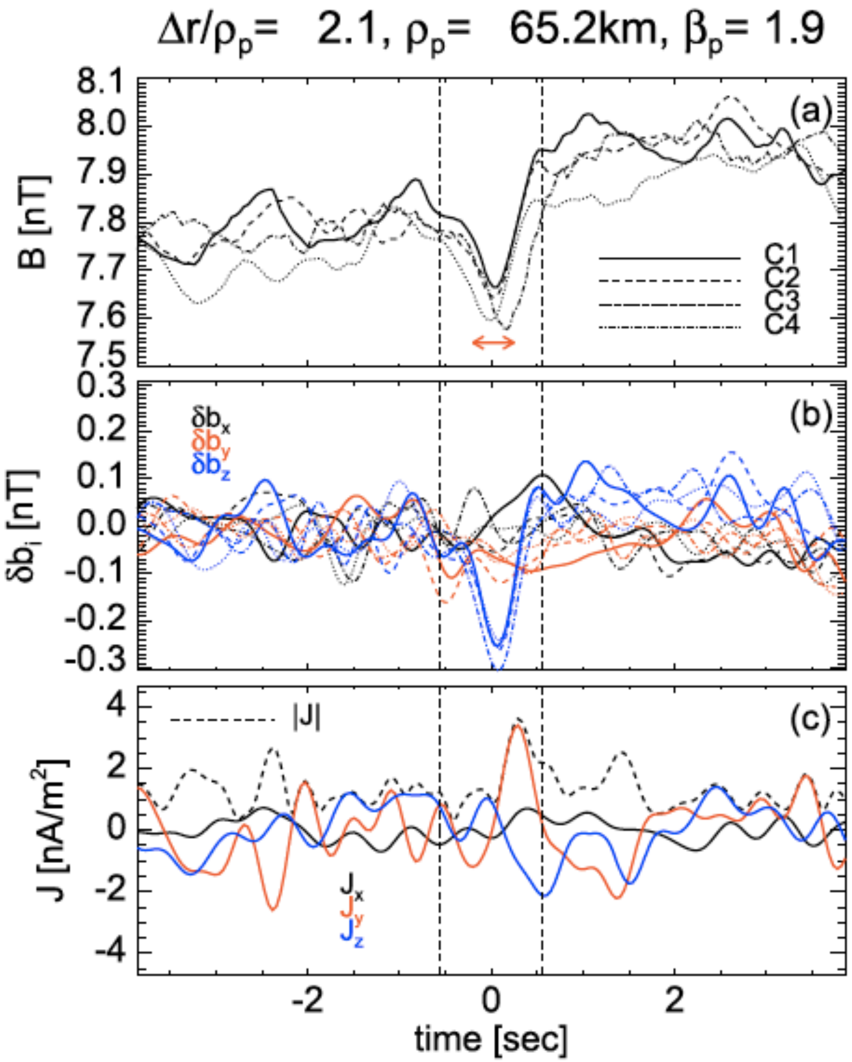
FIG. 5.— Example of linearly polarized compressible soliton-like structure, centered at 02:10:42.5 UT. The panels are the same as in Figure 4.

[Perrone et al., 2016, APJ]

- Magnetic solitons (β_p~1.2), $V_\phi=V_f \sim V_{th}$



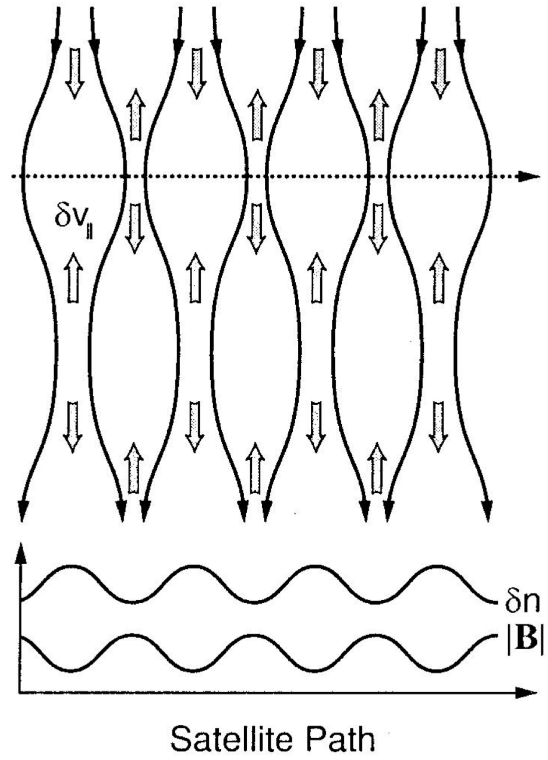
Compressible structures: magnetic holes



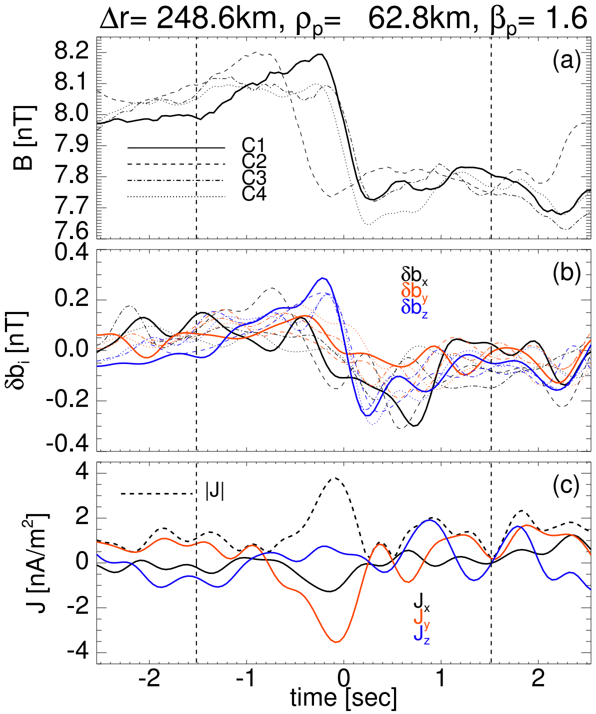
[Perrone et al., 2016, APJ]

- Magnetic holes (β_p~2), V_ϕ=0, $T_{perp}/T_{||}$>1

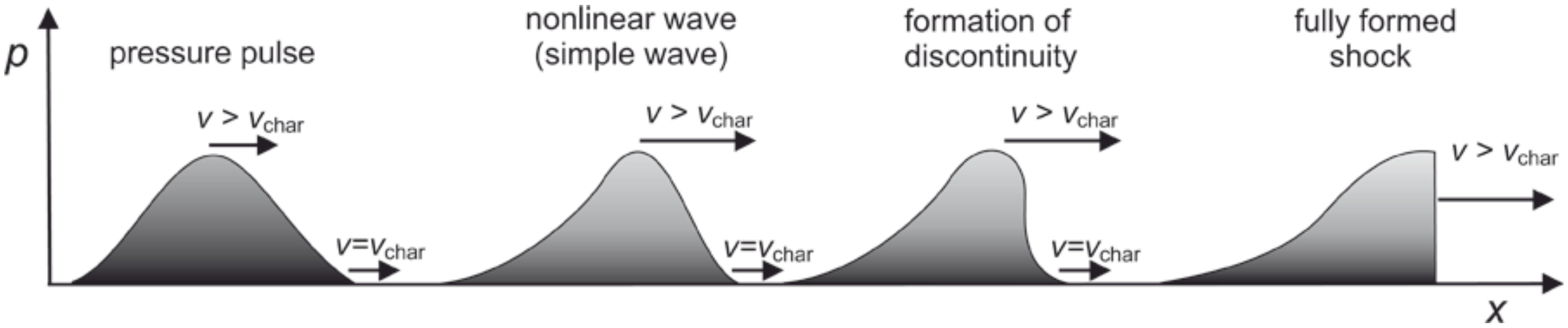
=> NL evolution of mirror instability ?



Compressible structures: shocks



- Shocks : $\beta_p \geq 1$, $Mach_f = 3$



Current sheets

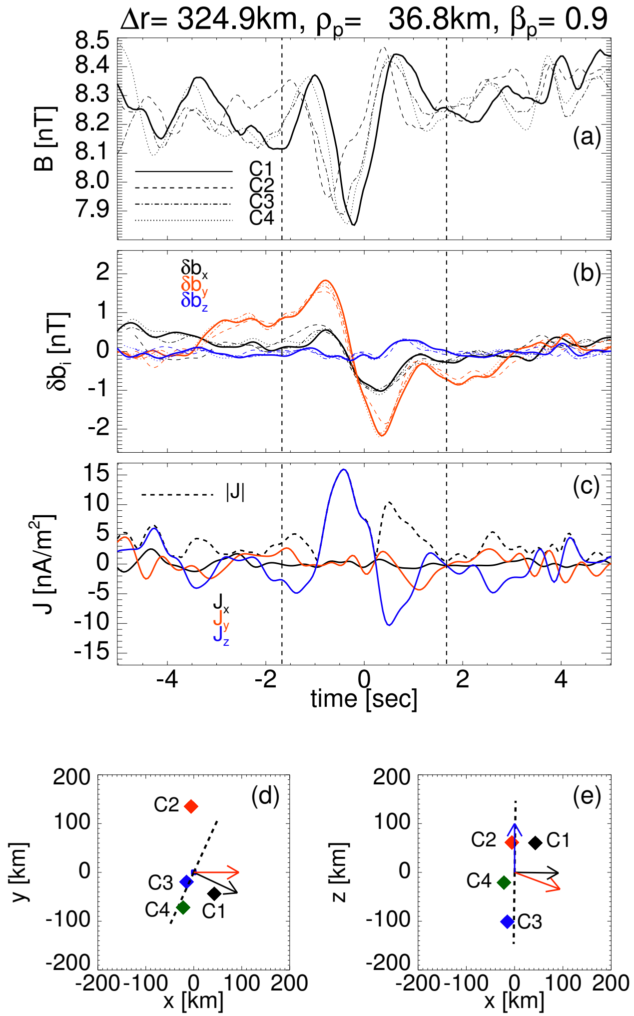
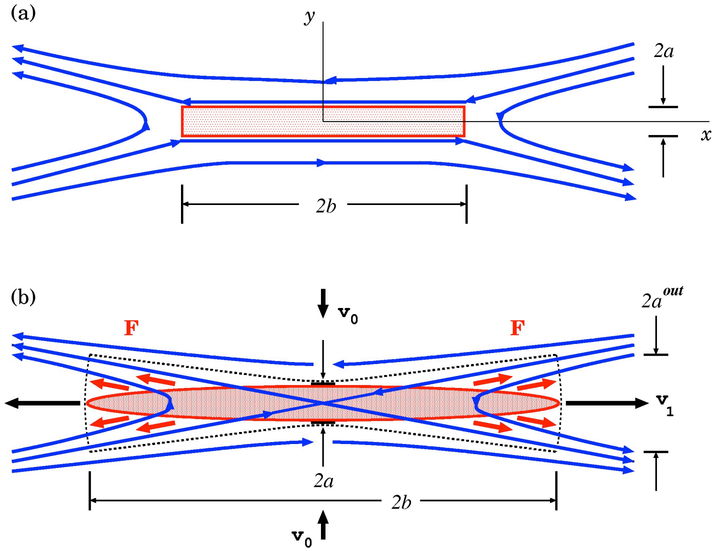


FIG. 7.— Example of a current sheet, centered at 01:07:37.8 UT. The panels are the same as in Figure 4.

- Current sheets with $\delta B_{perp} >> \delta B_{||}$ ($\beta_p \leq 1$), $V_\phi=0$
- reconnection sites?



[Perrone, Alexandrova et al., 2016, APJ]

Alfven vortices and compressible 'vortices'

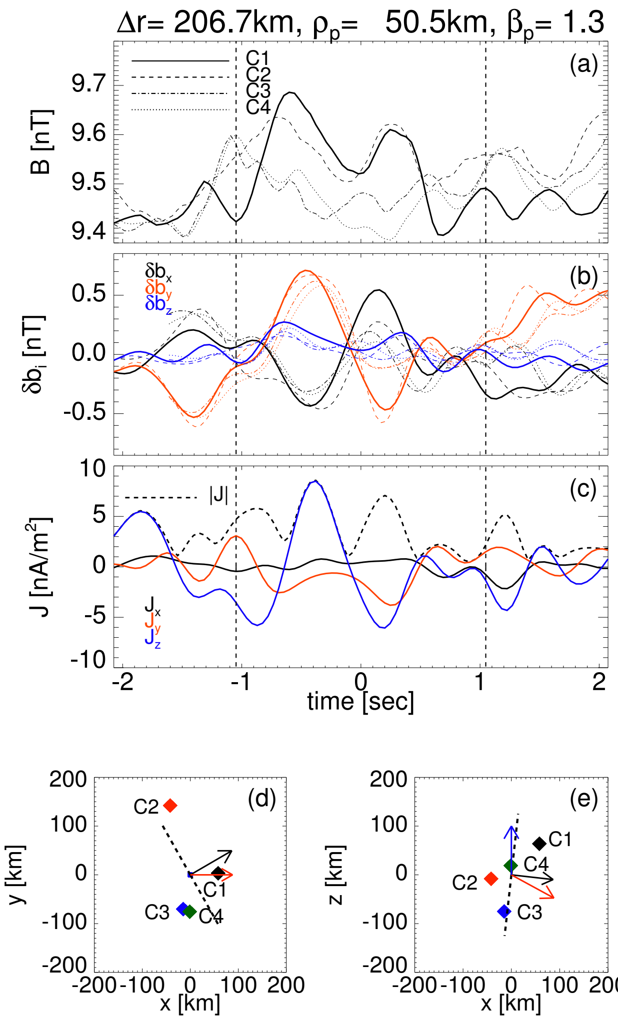
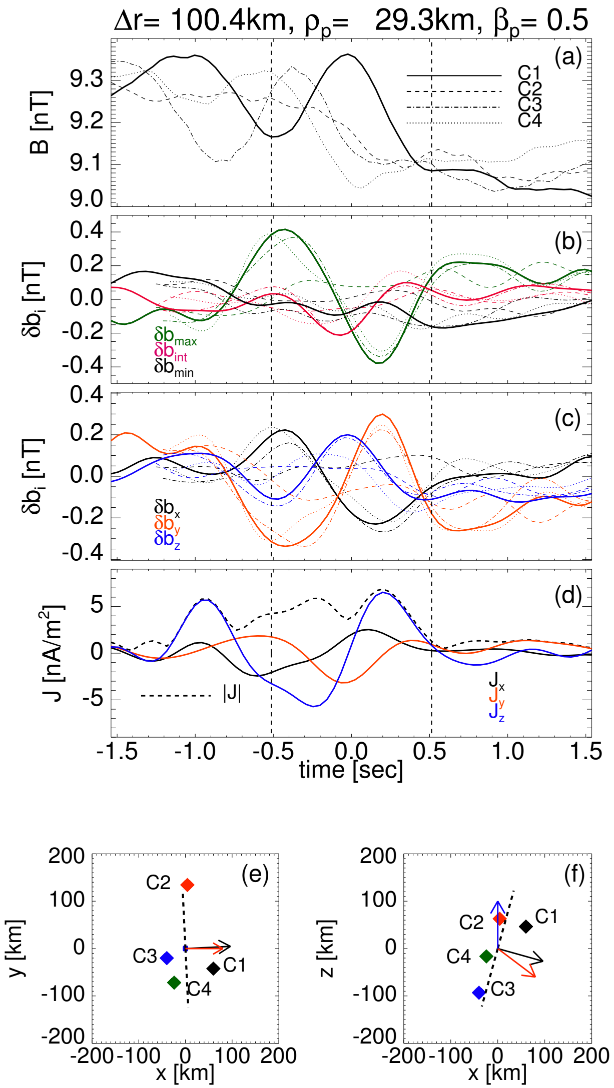


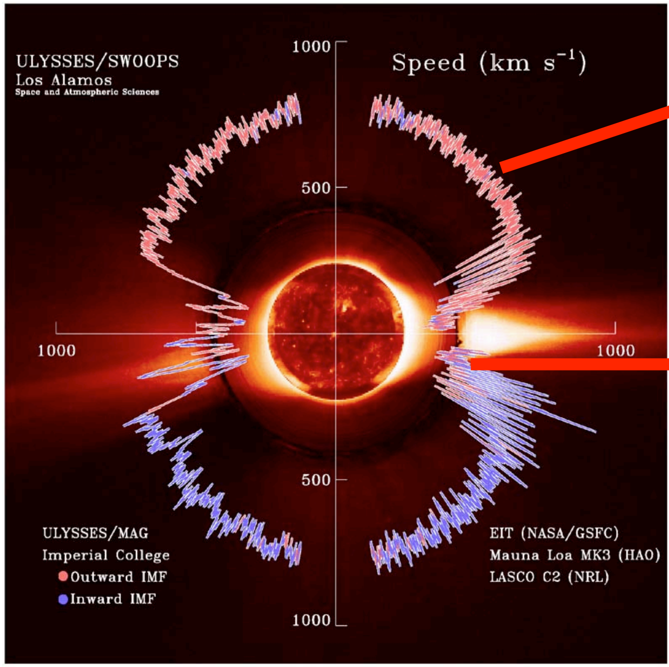
FIG. 8.— Example of Alfvén vortex-like structure, centered at 0:49:58.5 UT. The panels are the same as in Figure 4.



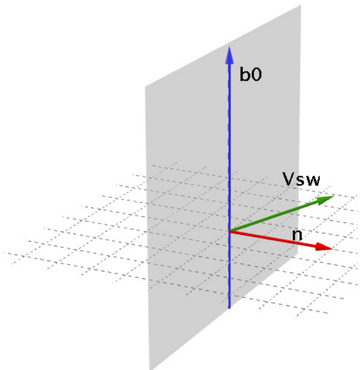
- Alfven vortex like structures with $\delta B_{perp} >> \delta B_{||}$ (β_p~1.2), $V_\phi \in [0.5, 2]V_A$

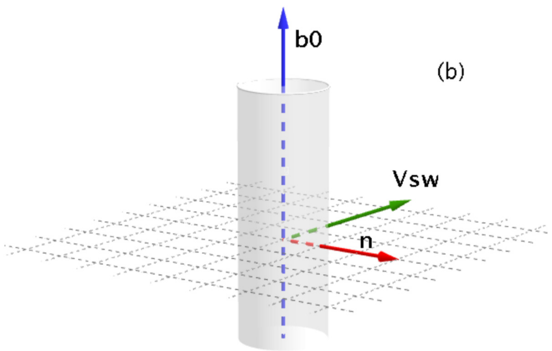
- Compressible vortex like structures with δB_{perp}~$\delta B_{||}$ (V_ϕ=0, or $\in$ [1, 4]V_A)

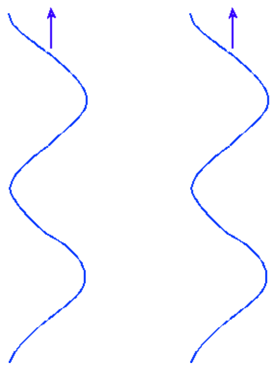
Nature of turbulence around ion scales in the fast and slow solar wind



- Fast wind: Alfvenic structures with high amplitudes ($\delta B/B>0.5$) and k_{perp} + Alfven (IC) waves of small amplitudes with $k_{||}$.
- Slow wind: mixture of compressible (solitons and shocks) and Alfvenic (current sheets and vortices) coherent structures with small amplitudes $\delta B/B \sim 0.1$ and quasi-perp wave vectors ($k_{perp} \gg k_{||}$).





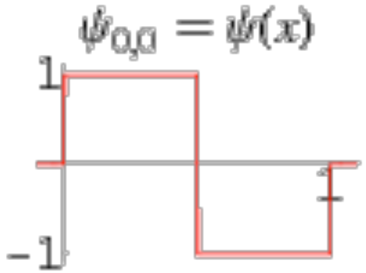


Lion et al., 2016, ApJ
Perrone et al., 2016, ApJ
Roberts et al., 2016, JGR

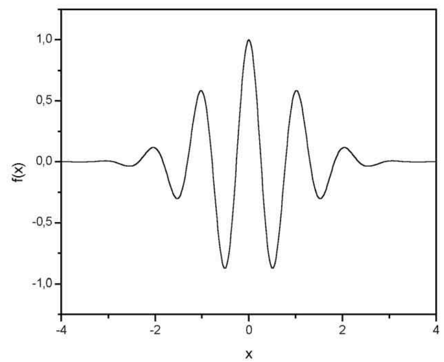
Wavelets is a powerful tool to detect coherent structures !

- Haar wavelets (Step function ~ structure functions) => planar coherent structures
- Morlet wavelets => cylindrical structures, solitons, ect…

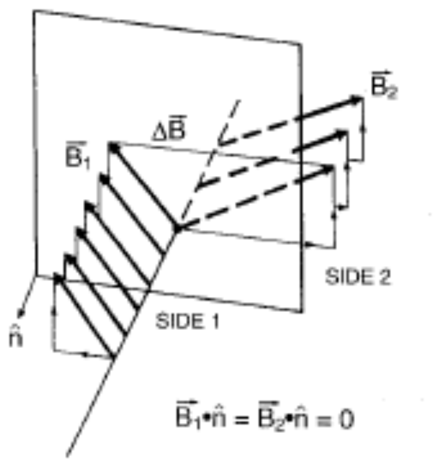
Haar:



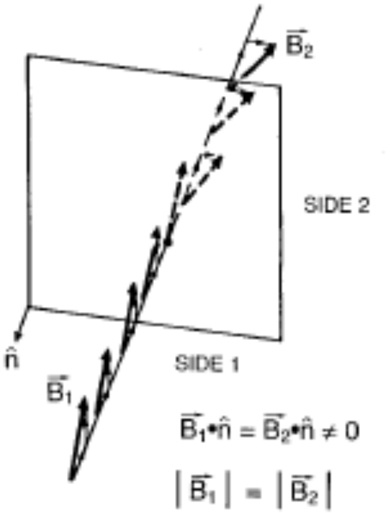
Morlet:

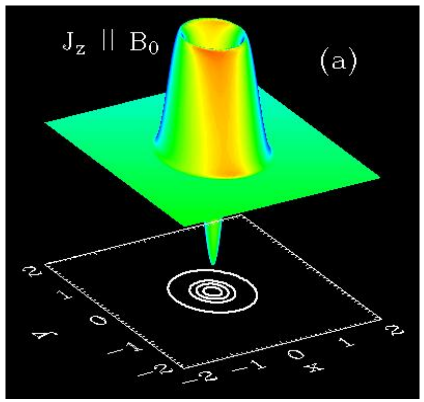


TANGENTIAL DISCONTINUITY



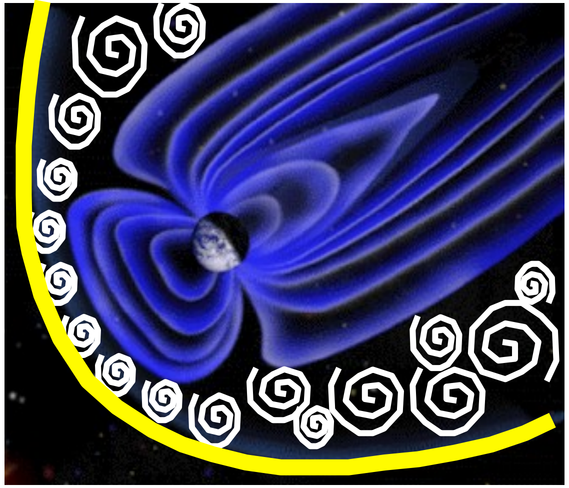
ROTATIONAL DISCONTINUITY

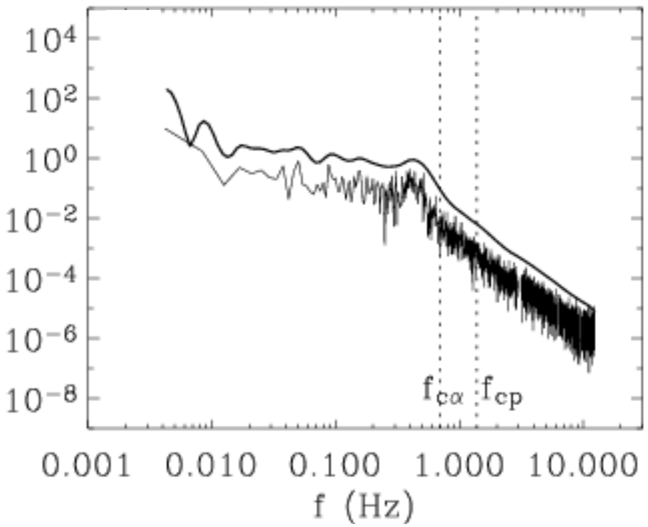


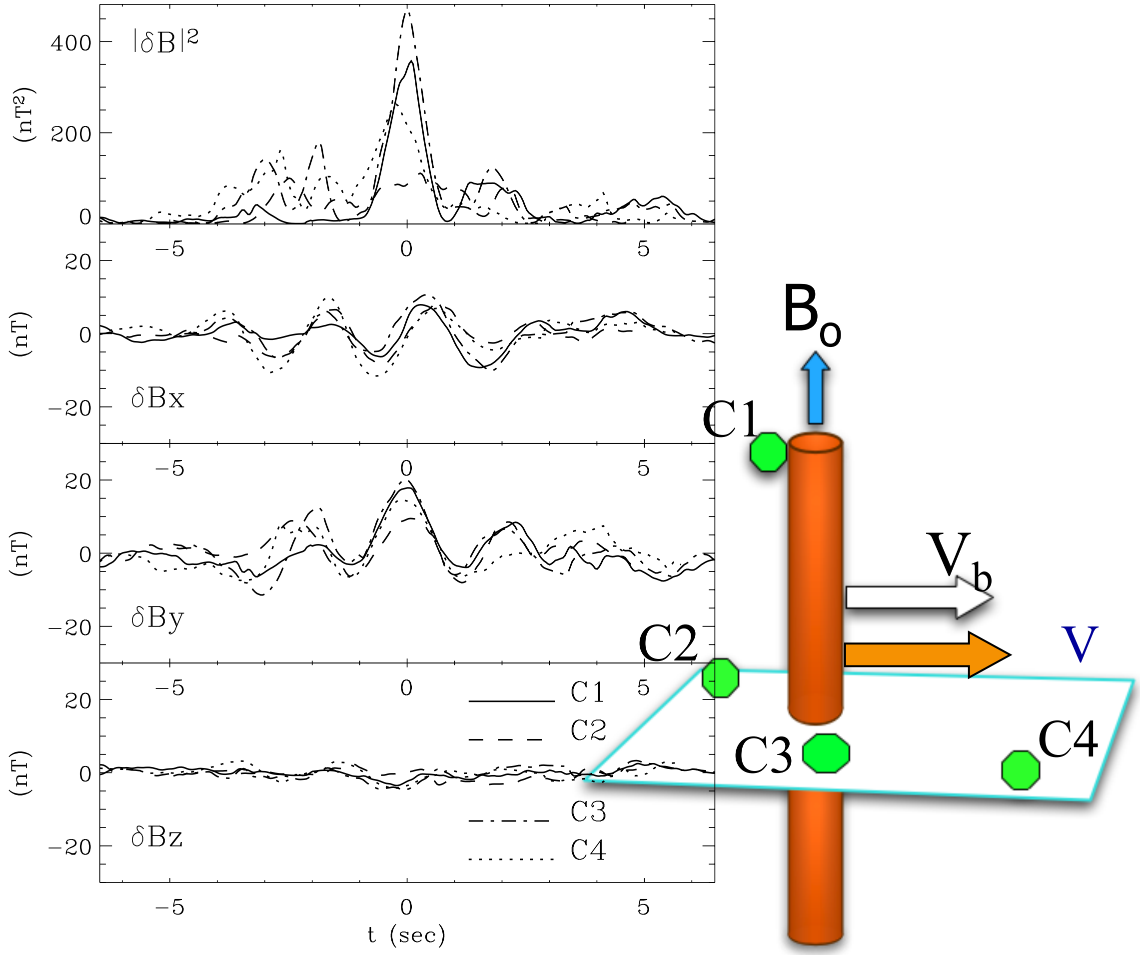


Alfven vortices: important ingredients of space plasma turbulence!

Ex: downstream of the Earth's bow shock



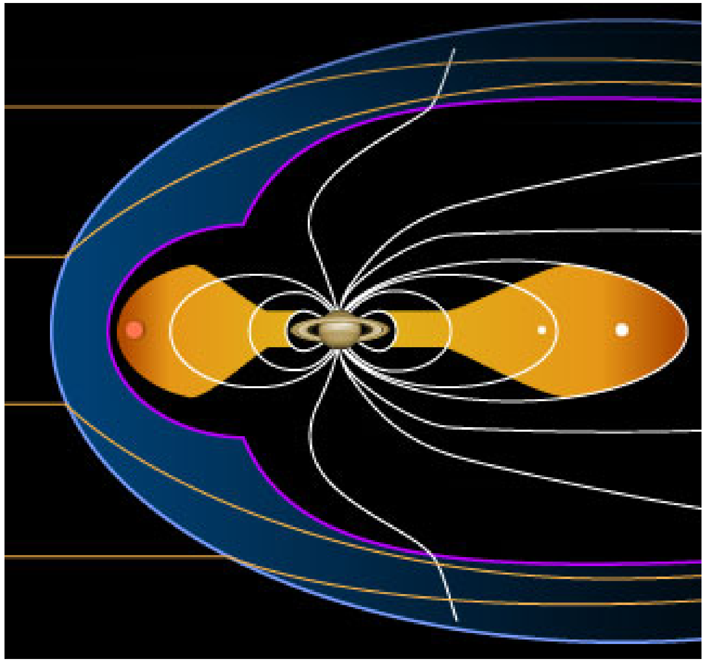


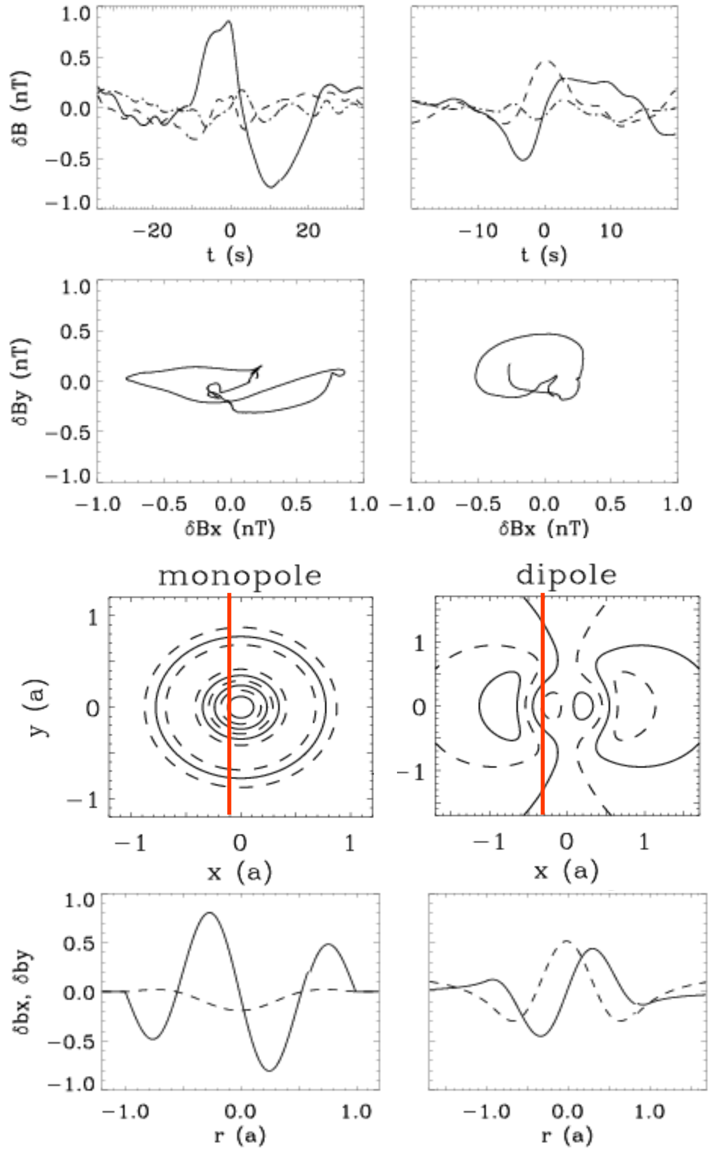


[Alexandrova et al. 2006, JGR]

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

Alfven vortices in the Saturn's Magnetosheath (*Cassini* observations)





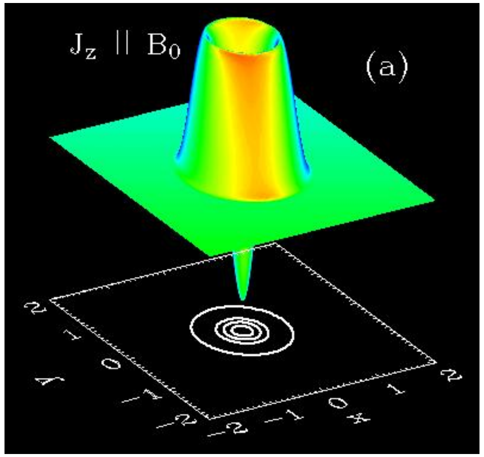
[Alexandrova & Saur, 2008, GRL]

- $B_{IMF} = 0.3$ nT
- $B_{msh} = 1.2$ nT
- $n_{msh} \sim 0.5$ cm^{-3} (Voyager-2)
- $V_{b,msh} \sim 130$ km/s (Voyager-2)
- $c/\omega_{pi} \sim 300$ km
- Mach ~ 15

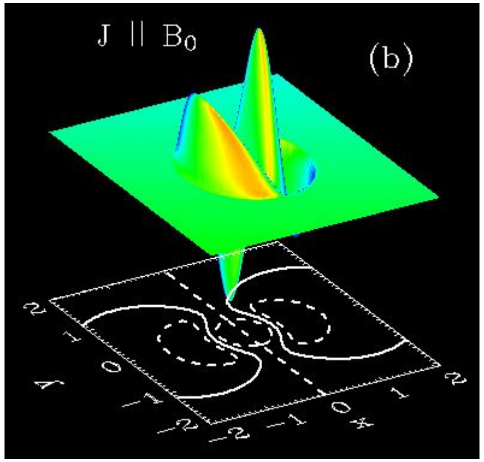
Alfvén vortices ~ 2D HD vortices

$$\boxed{\Psi = \xi A; \quad \xi = \frac{u}{B_{0y}}} \quad = \quad \boxed{\delta V_\perp / V_A = \xi \delta B_\perp / B_0}$$

Vector potential, A, ~ to stream function ⇒
field lines || stream lines & current || vorticity



Monopole ~ force free current, standing structure



Dipole ~ two inversed currents, propagates

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

[Petviashvilli & Pokhotelov, 1992]

Localized solutions of 2D incompressible Navier-Stokes equation

$$\partial_t \omega + (\delta \mathbf{V}_\perp \cdot \nabla)\omega = 0$$

ω - vorticity & Ψ - stream function

$$\omega = \nabla \times \delta \mathbf{V}_\perp = -\Delta \Psi \; ; \;\; \delta \mathbf{V}_\perp = -\nabla \times \Psi$$

Particular case:

slow variations & vorticity is localized in a circle of the radius *a*

$$\begin{cases} \Delta \Psi + k^2 \Psi + c = 0, \quad r < a \\ \Delta \Psi = 0, \quad r \geq a \end{cases}$$

- Helmholtz's equation

- Laplace's equation

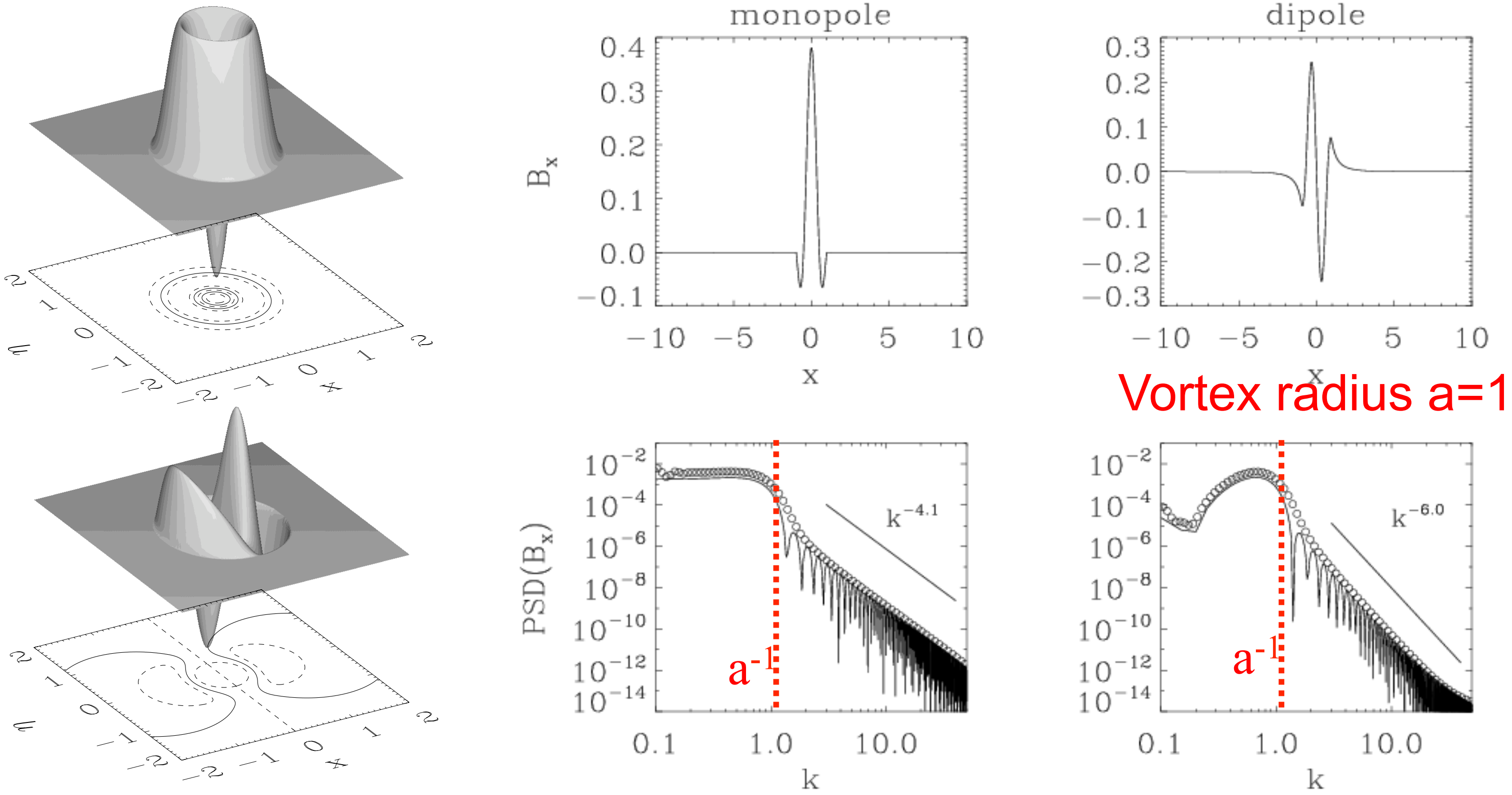
monopole

$$\begin{cases} \Psi = \boxed{\Psi_0 (J_0(kr) - J_0(ka))} + \boxed{ux\left(1 - \frac{2}{kr}\frac{J_1(kr)}{J_0(ka)}\right)}, \; r < a \\ \Psi = a^2 u \frac{x}{r^2}, \; r \geq a. \end{cases}$$

dipole

Spectral properties of Alfvén vortices

$$\frac{\partial_z}{\nabla_\perp} \sim \frac{\partial_t}{V_A \nabla_\perp} \sim \frac{\delta B_z}{\delta B_\perp} \sim \frac{\delta V_z}{\delta V_\perp} \sim \frac{\delta B_\perp}{B_0} \sim \frac{\delta V_\perp}{V_A} \sim \varepsilon.$$ [Petviashvilli & Pokhotelov, 1992]



- 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)

[Alexandrova 2008,NPG]

Applicability of Alfven vortex model in the solar wind?

- Amplitudes are too big in the fast wind
- Compressible component in the slow wind

Models for other structures ?

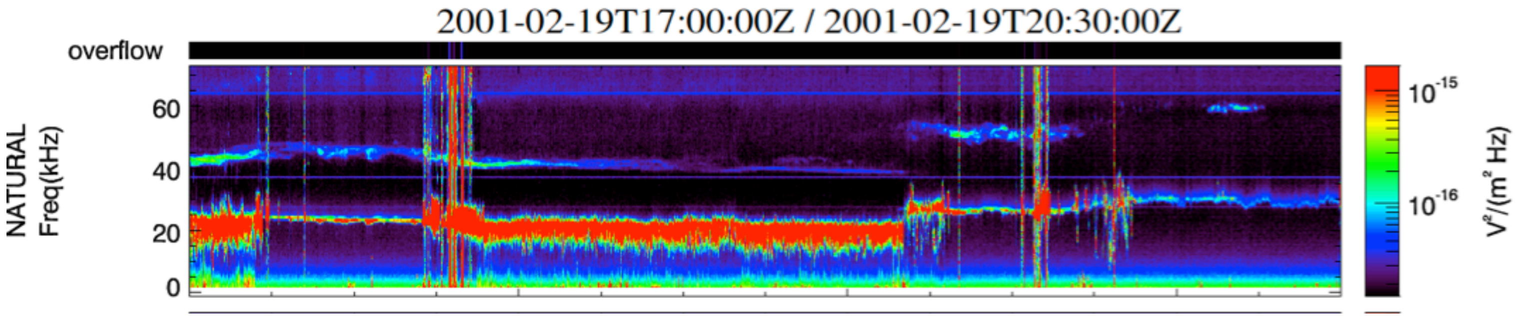
- compressible vortices ?
- Solitons
- Holes …

  - Particle acceleration/trapping in these structures?
    - MMS/THOR measurements?

What is going on at electron scales?

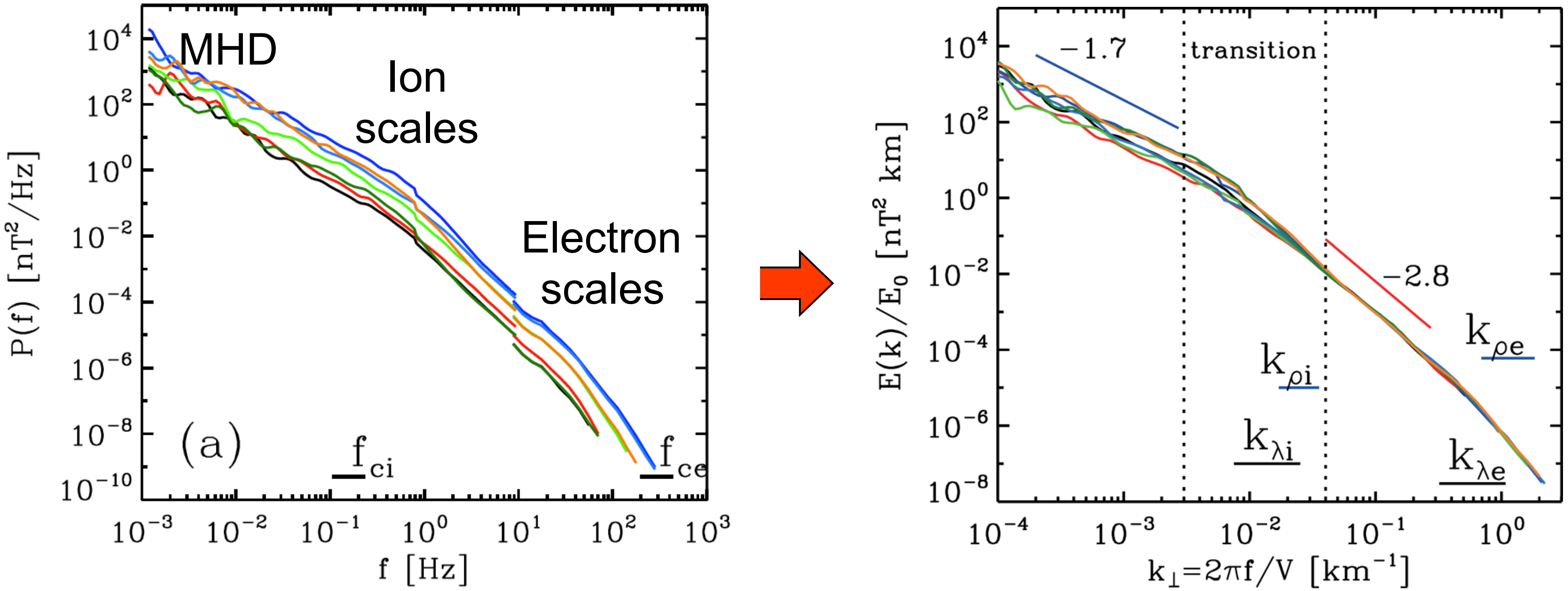
- Cluster mission : the most sensitive instrumentation (mag. spectrum up to 400 Hz).

- Cluster is devoted to magnetospheric research => spend short time intervals in the solar wind/orbit.



Turbulent spectrum between MHD and electron scales (Cluster measurements)

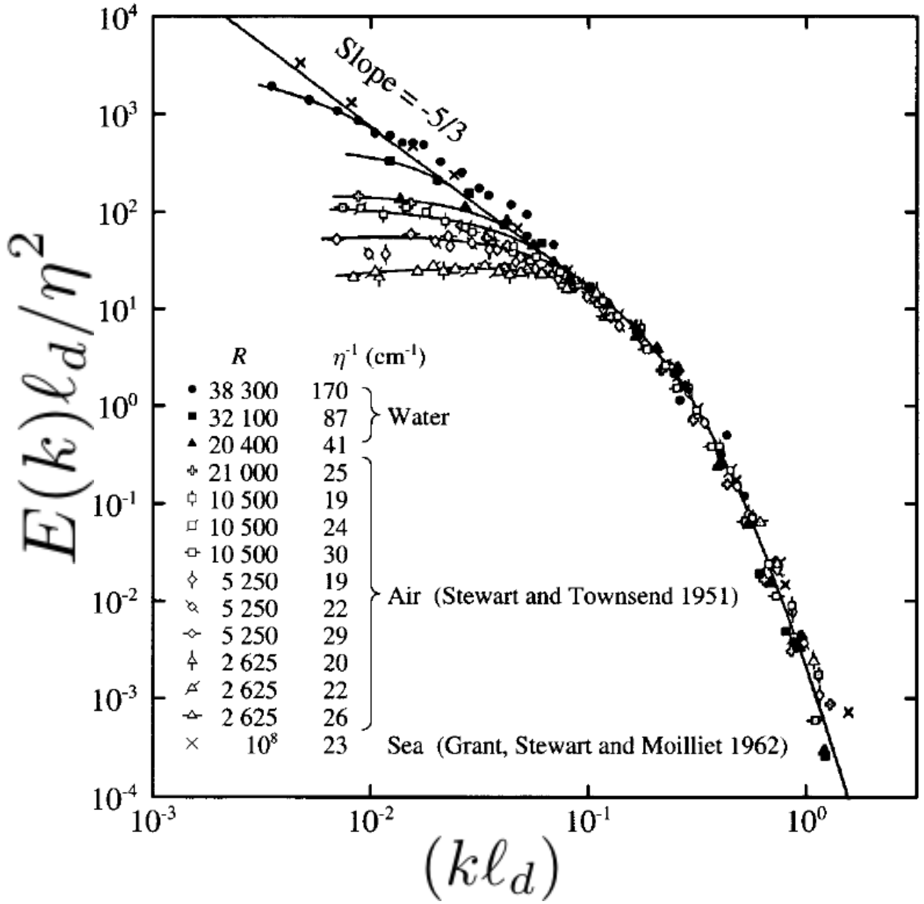
[Alexandrova et al. 2009, PRL; 2013, SSR]



- General spectra at MHD and between ion and electron scales ($\sim k^{-2.8}$).
- Spectral variability around ion scales depends on coherent structures types and presence of ion instabilities [e.g. Matteini+'07, Bale+'09, Lion+'16, Perrone+'16, Roberts+'16].
- End of the cascade? Dissipation scales?

Universal Kolmogorov's function:

Frisch, Turbulence: the legacy of Kolmogorov, 1996



$$E(k)\ell_d/\eta^2 = F(k\ell_d)$$

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

ℓ_d: dissipation scale

η: viscosity

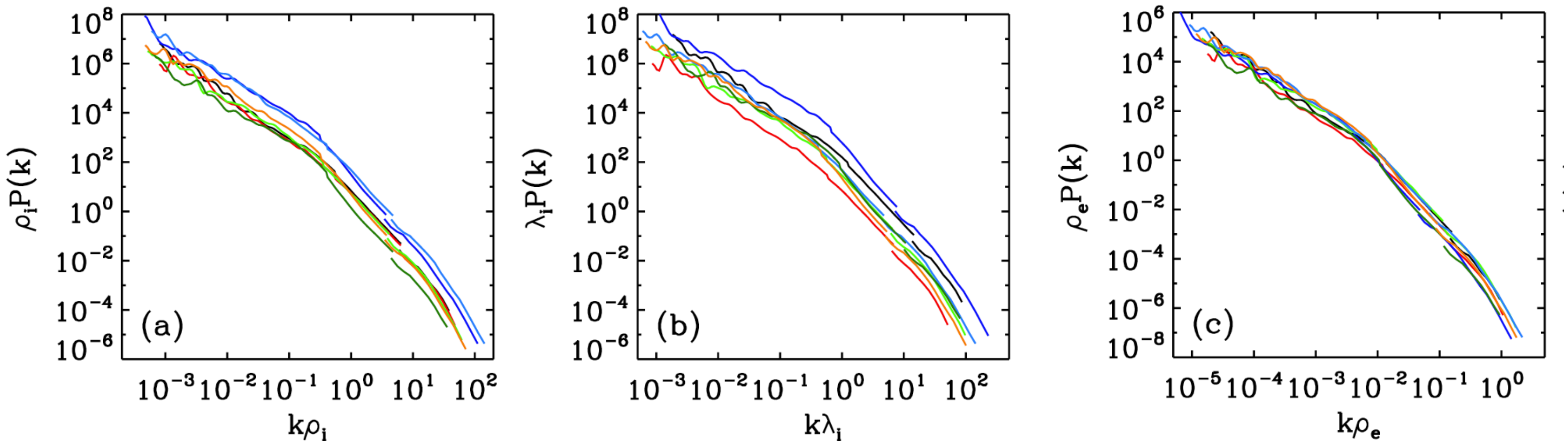
In HD turbulence, this normalization collapses spectra measured under different conditions.

Dissipation scale?

Universal Kolmogorov's function: $\boxed{E(k)\ell_d/\eta^2 \sim (k\ell_d)^{-5/3}}$

Let us try to apply this kind of normalization for sw spectra and for different candidates for the dissipation scale ld:

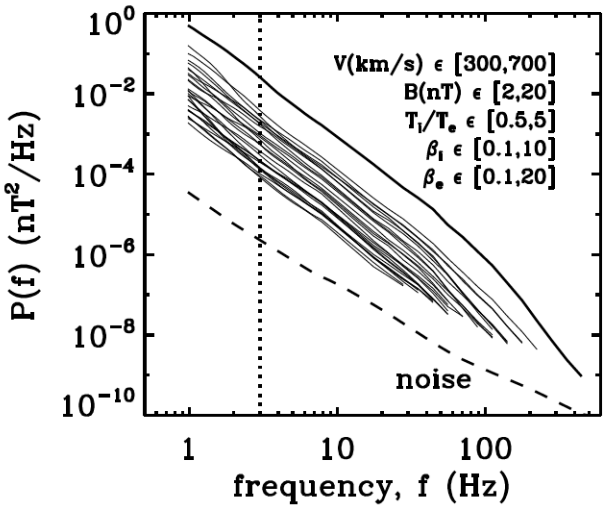
$$\ell_d = \rho_{i,e}, \lambda_{i,e}$$

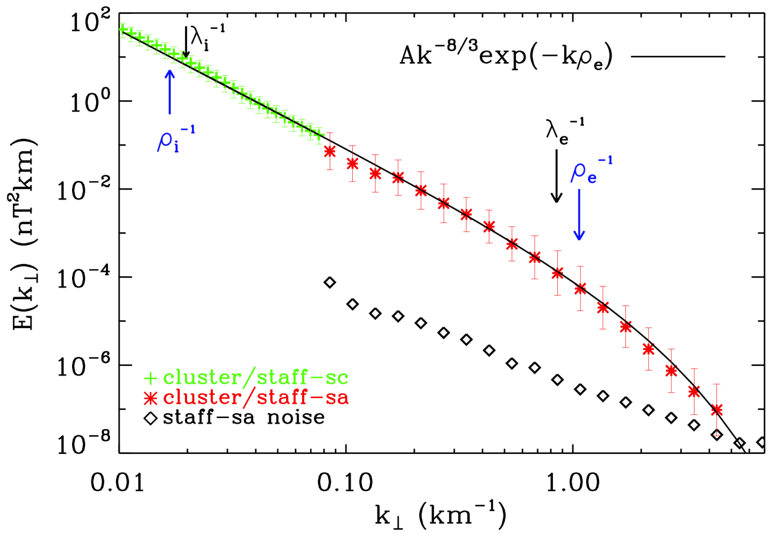


- Assumption: η=Const
- $k\rho_i$ & $k\lambda_i$ - normalizations are not efficient for collapse
- $k\rho_e$ normalization bring the spectra close to each other.

$\rightarrow$ $\boxed{\ell_d \sim \rho_e}$ [Alexandrova et al., 2009, PRL]

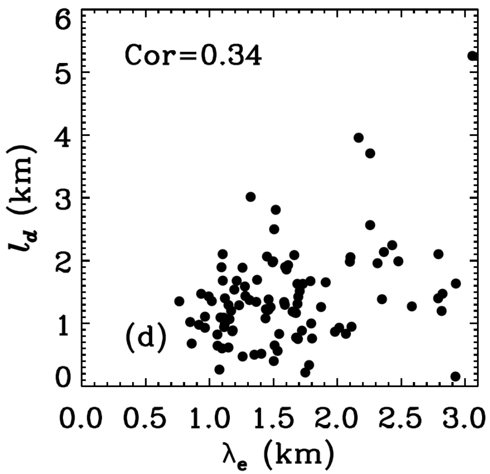
Spectrum at kinetic scales and dissip. scale

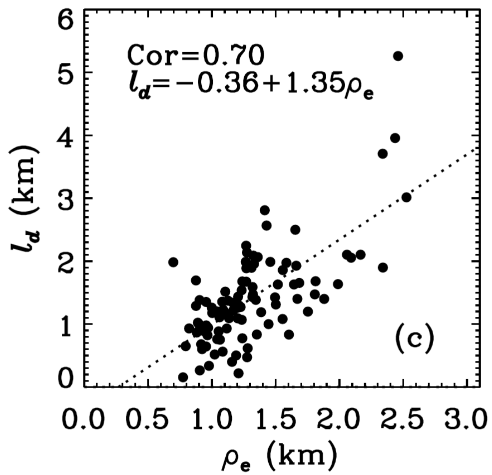




$$\boxed{E(k) = Ak^{-\alpha}\exp(-k/k_d)}$$

[Chen, Doolen, et al., 1993, PRL]



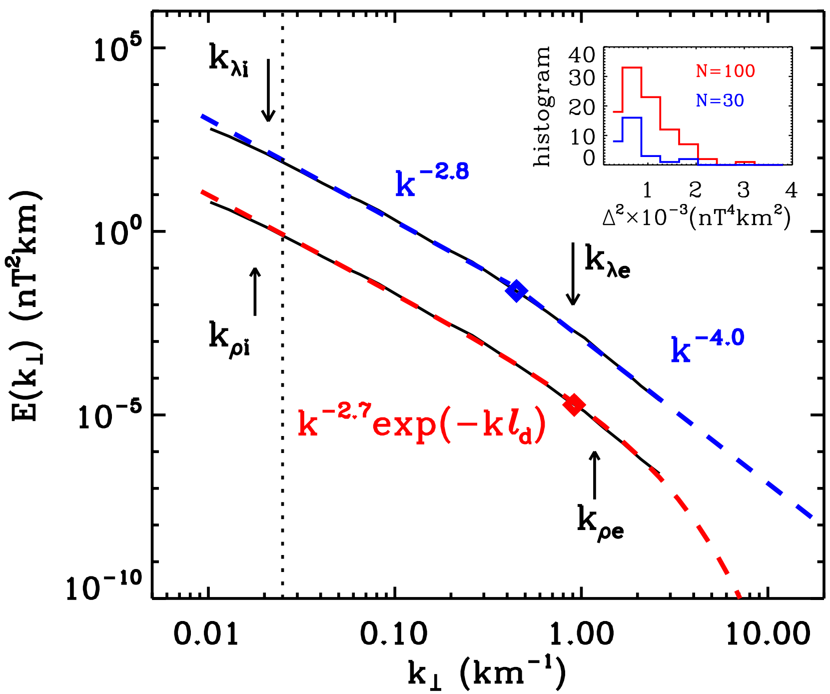


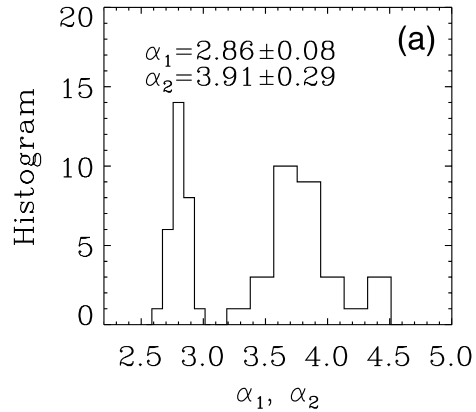
$$\boxed{\ell_d \sim \rho_e}$$

[Alexandrova et al., 2012, APJ]

Spectral shape: 2 alternatives approachs

[Alexandrova et al., 2012, APJ]

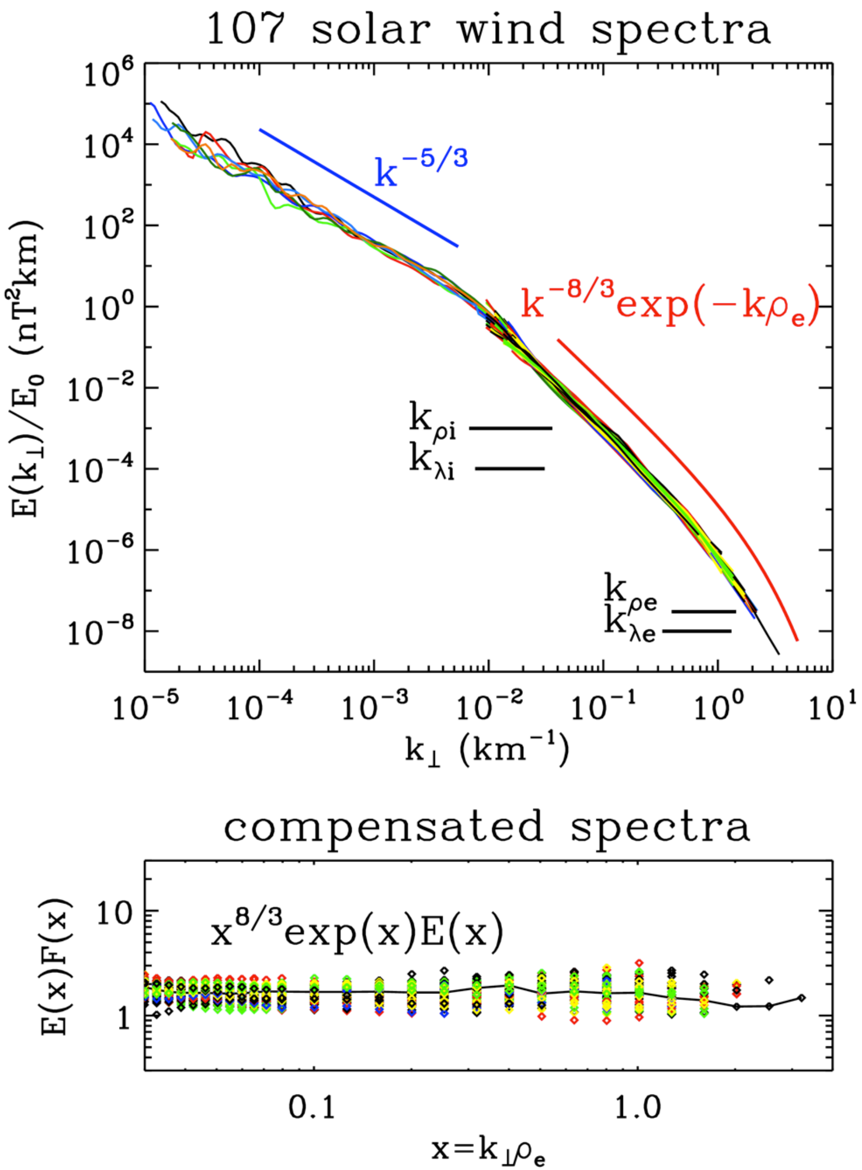




[Alexandrova et al., 2012, APJ] Sahraoui et al. [2013] show similar results.

- small dispersion for α_1 around 2.86 and high dispersion for α_2
- Exponential-model has 3 free parameters (A,α,l_d)
- 2-power-law model has 5 free parameters ($A_1,\alpha_1,A_2,\alpha_2,k_{break}$)

General spectrum at kinetic scales



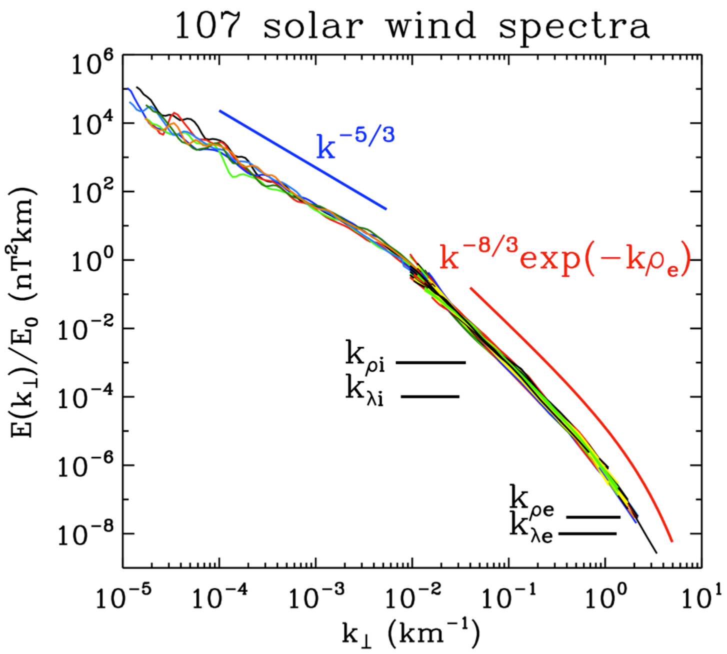
- For different solar wind conditions we find a general spectrum with "fluid-like" roll-off at electron scales [Alexandrova+'12].
- Electron Larmor radius seems to play a role of the dissipation scale in collisionless solar wind [Alexandrova +'09,12; Sahraoui+10,13]

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

Explanation of this spectrum?

General spectrum at kinetic scales

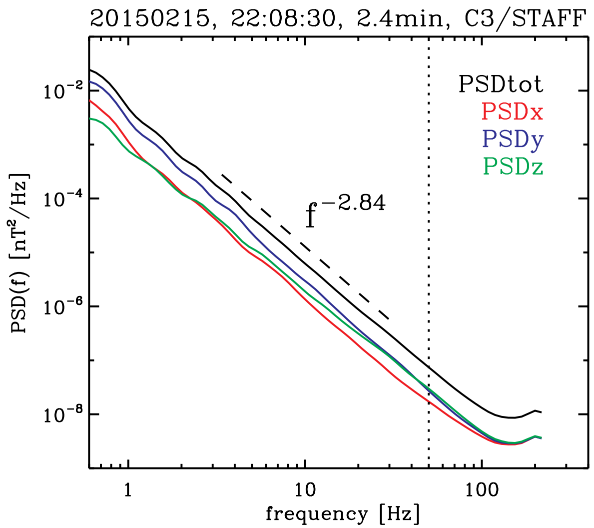
Understanding of the spectrum at kinetic scales is still an open issue…

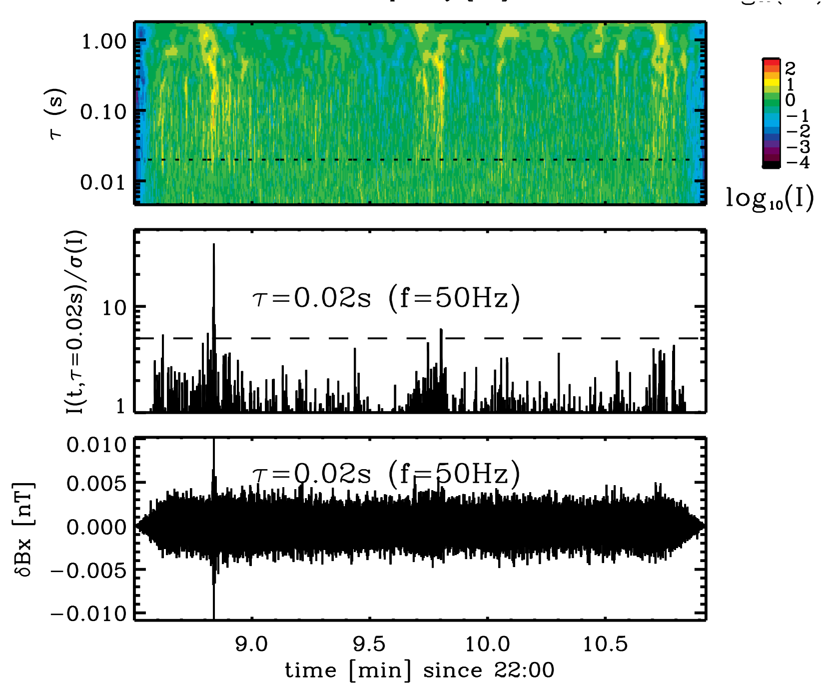


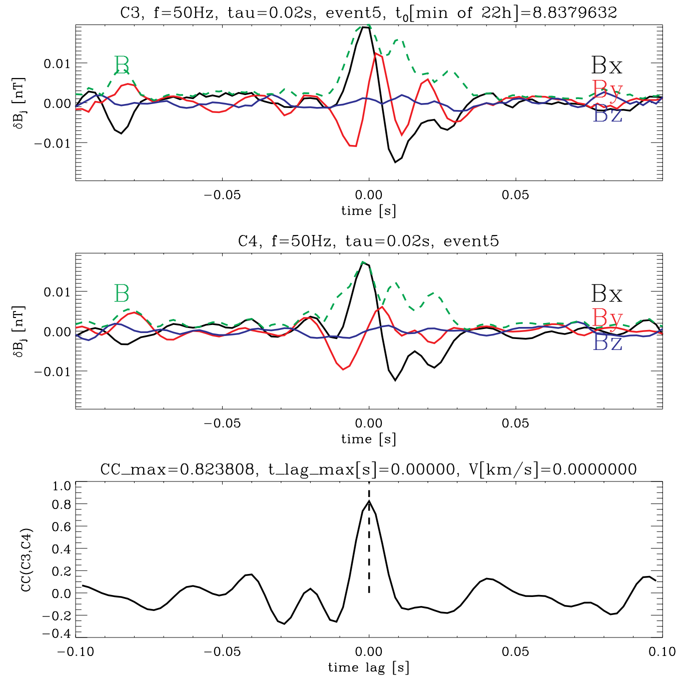
- $k_{perp}^{-8/3}$ spectrum between ion and electron scales can be explained by :
  - q-perp whistler turbulence with a weak parallel energy transfer [Galtier+'05]; see EMHD simulations of Meyrand & Galtier'13.
  - compressible Hall MHD [Alexandrova+08]
  - compressible NL Kinetic Alfven waves fluctuations [Boldyrev and Perez'12];
  - Hybrid simulations of Franci et al. 2015
  - Landau-fluid model (dissipation of KAW with oblique k) c.f. T. Passot lecture.
  - …

- Exponential roll-off:
  - Cascade model with ~k^2 damping term (dissipation via linear Landau damping of KAW's) [Howes et al. 2006, 2011]
  - Low viscosity + strong gradients => usual dissipation term is at work?

Nature of solar wind sub-ion scales turbulence ?



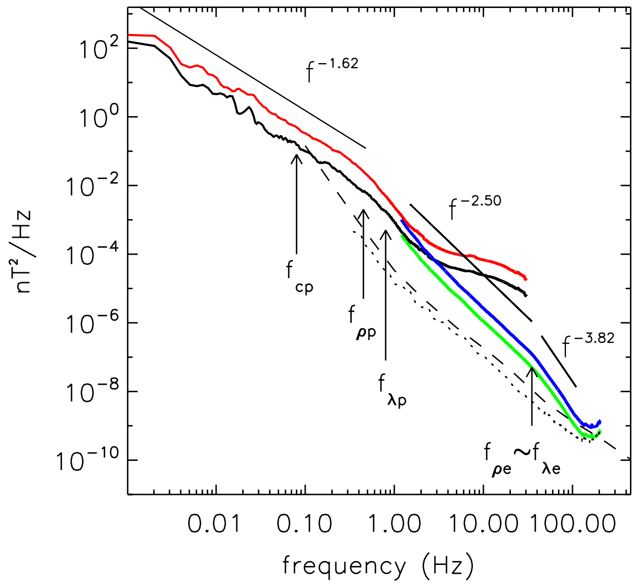




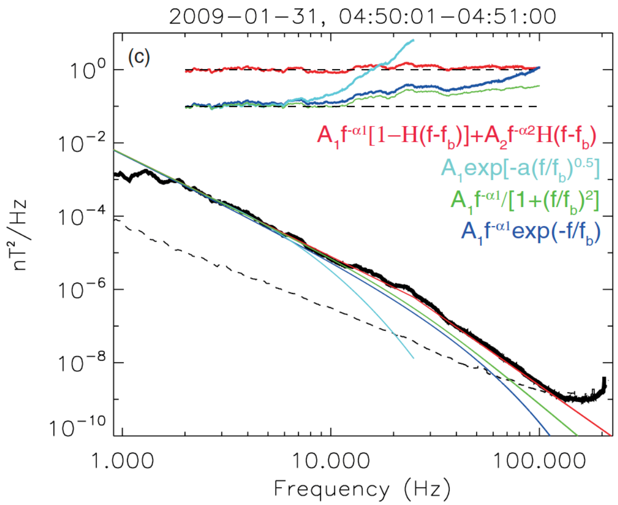
- Example of intermittent structure at scales close to electron scales (10 km): Kinetic Alfven vortex ?
- Signature of strong turbulence..
- General ? c.f. Chen et al.: KAW turbulence ?

Examples of different (non-universal) spectra at electron scales

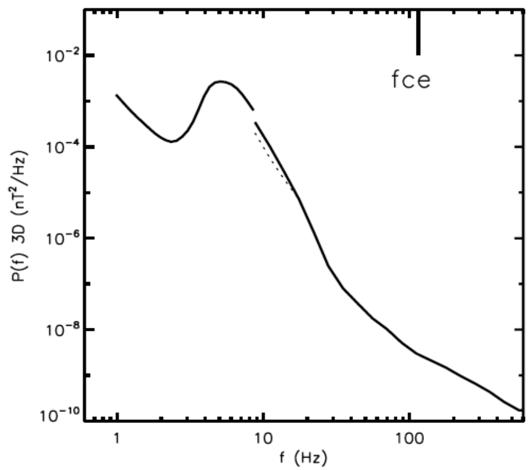
Observation of spectral break or bump at electron scales:



[Sahraoui et al., 2009]



[Sahraoui et al., 2013]

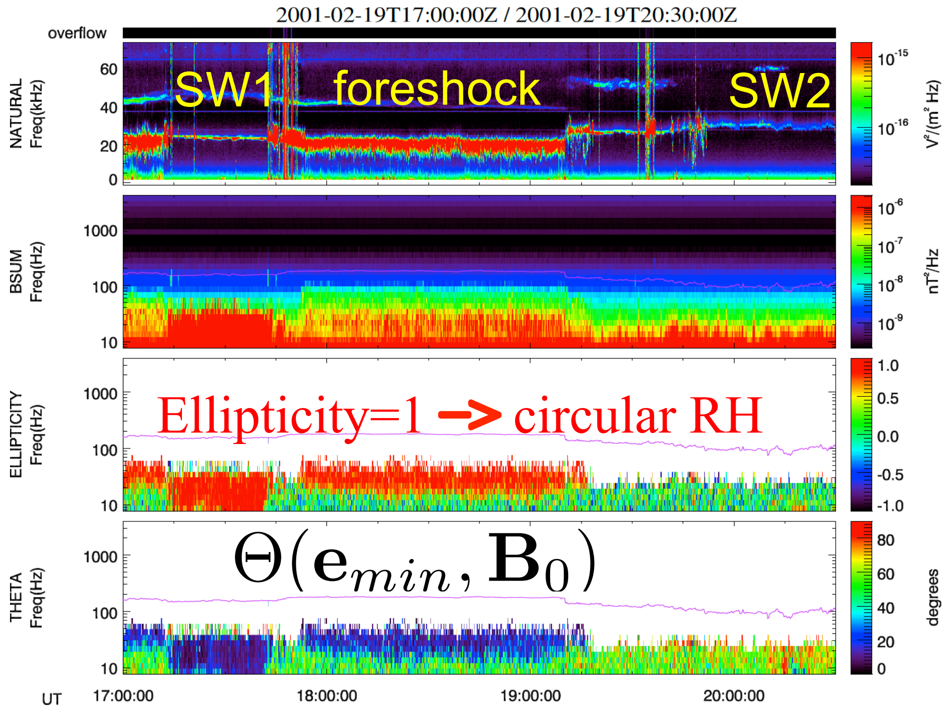


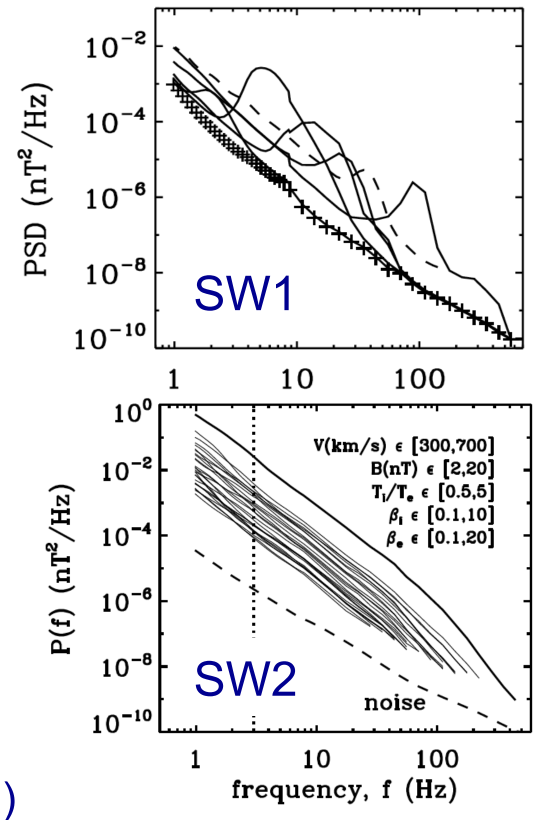
[Lacombe et al. 2014]

These non-universal features are due to appearence of quasi-monochromatic whistler waves in parallel propagation (with $k||B_0$).

Methodology of data selection

1. Cluster/Whisper measures electric field fluctuations around the plasma frequency (check for bow-shock connection)
2. Cluster/STAFF-SA: magnetic fluctuations within the (8Hz,4kHz) range, polarization and propagation direction

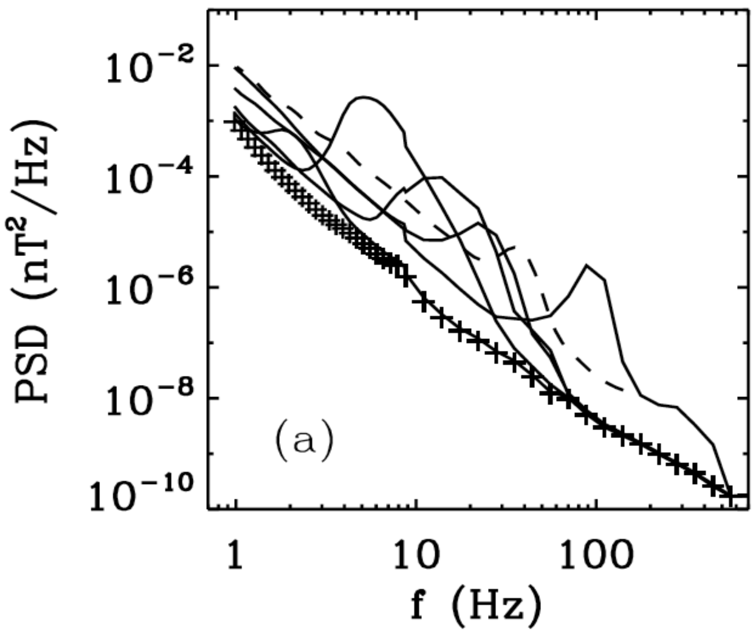


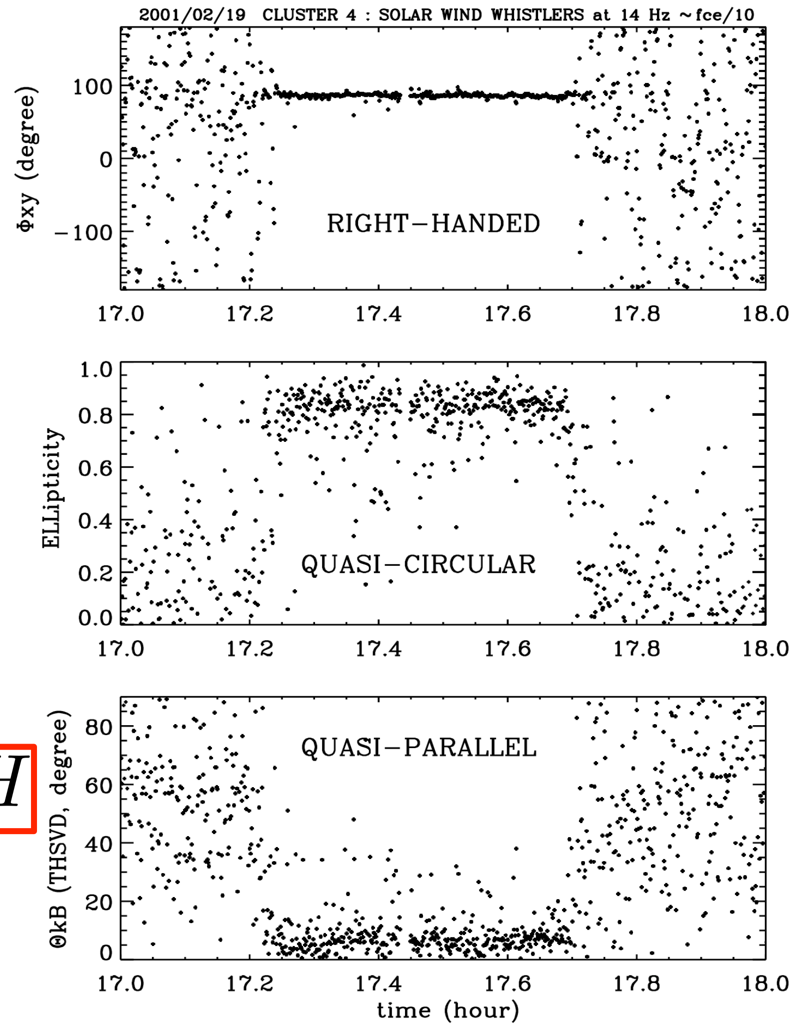


- Polarized fluctuations => spectra with bumps (10% of data)
- Non-polarized fluctuations => permanent (or background) turbulence (90% of data, Alexandrova et al. 2012, 2013)
- Permanent turbulence + sporadic polarized fluctuations => “intermediate” spectral shape (breaks, small bumps, …)

Polarized fluctuations
(spectra with bumps, knees, breaks...)

[Lacombe et al. 2014]

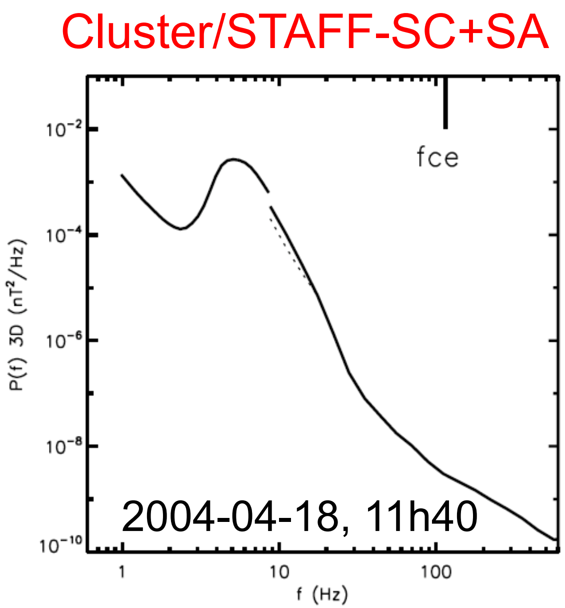


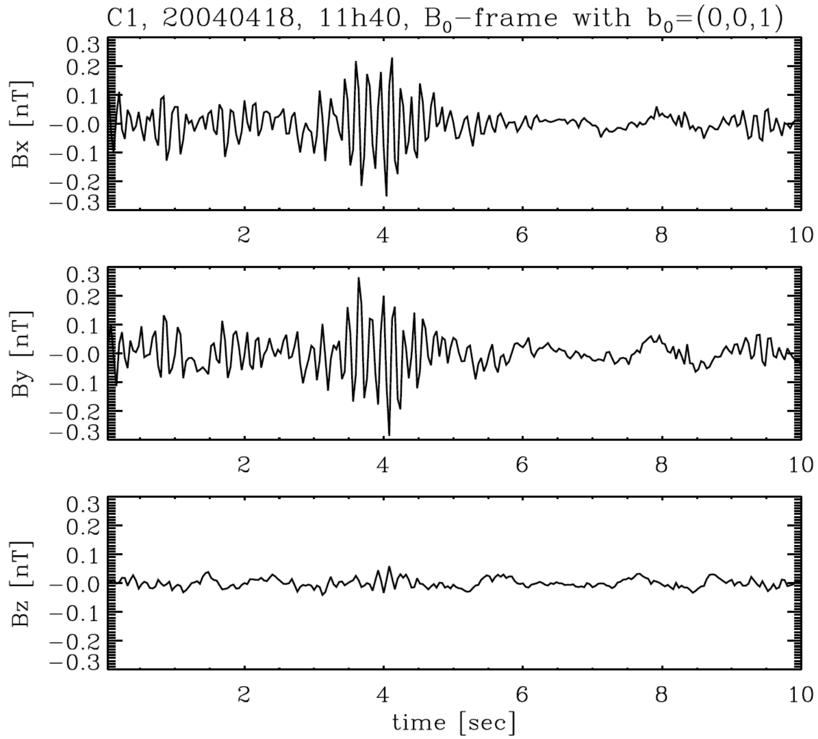


$$\boxed{\Delta\Phi_{xy} = \Phi_y - \Phi_x = 90^\circ \rightarrow RH}$$

→ **Parallel whistlers with RH-polarization**

Waveforms
(example of Cluster/STAFF-SC)

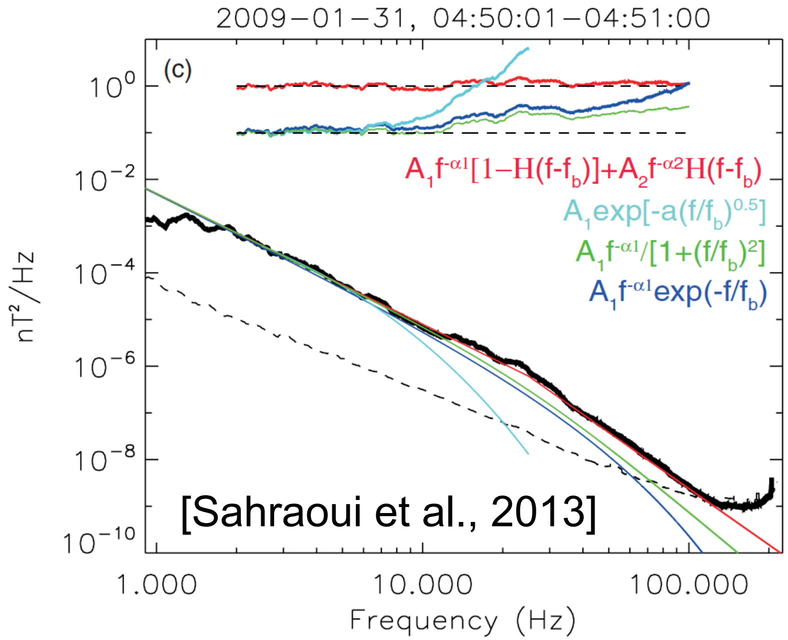


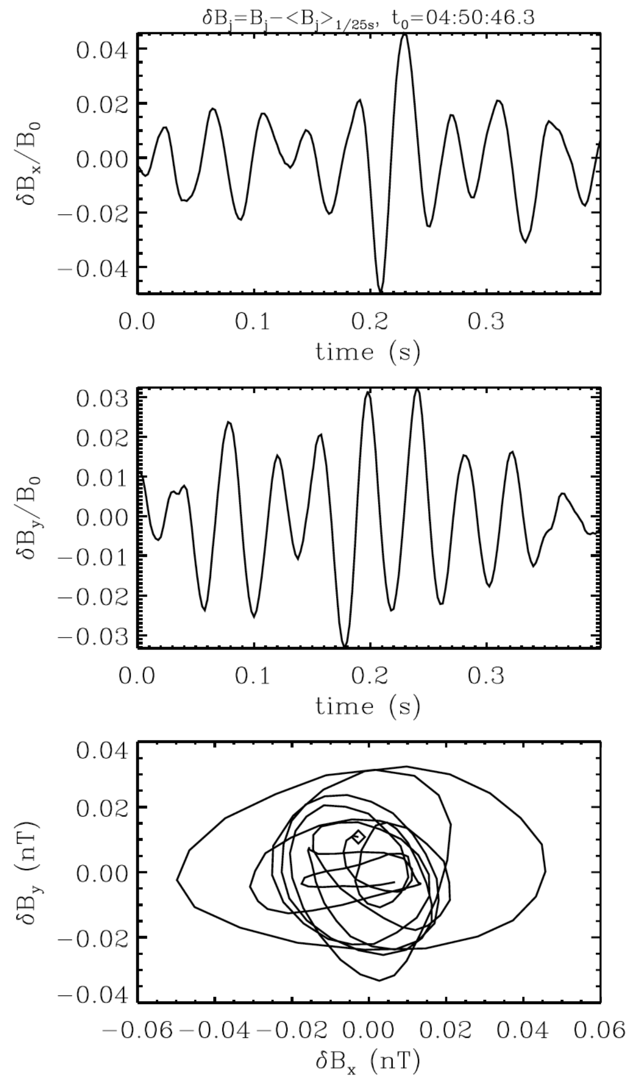


- The spectral bump at $f<f_{ce}$ is observed by both, STAFF-SC and SA;
- it corresponds to coherent wave-packets of whistlers (RH polarization):

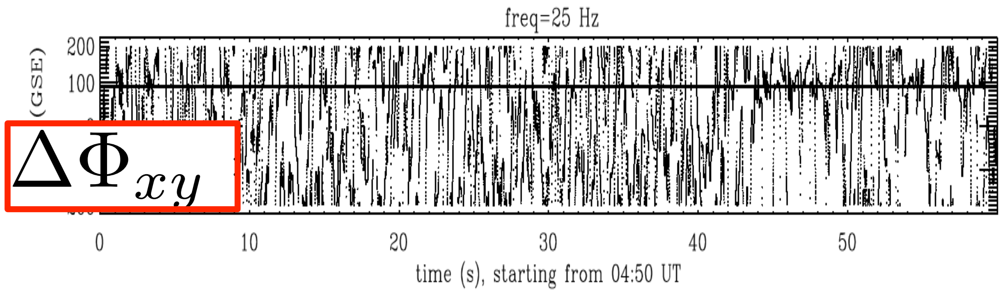
$$\boxed{\Delta\Phi_{xy} = \Phi_y - \Phi_x = 90^\circ \rightarrow RH}$$

Example of sporadic whistlers





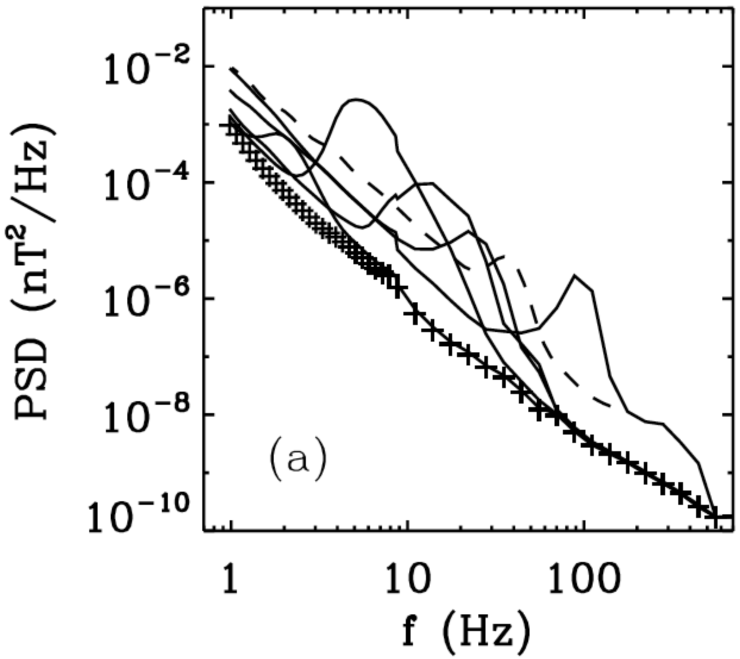
Phase difference in the plane perp to B_0 around 90^o is a signature of whistlers:

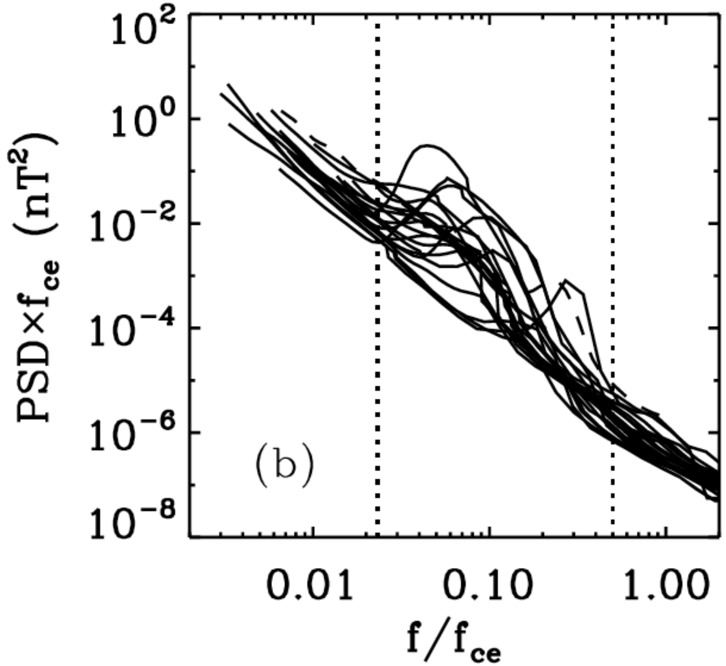


Permanent turbulence + sporadic whistler waves => spectral break/knee at the frequency of whistlers

Magnetic spectra with long-lived whistlers

10 minutes spectra



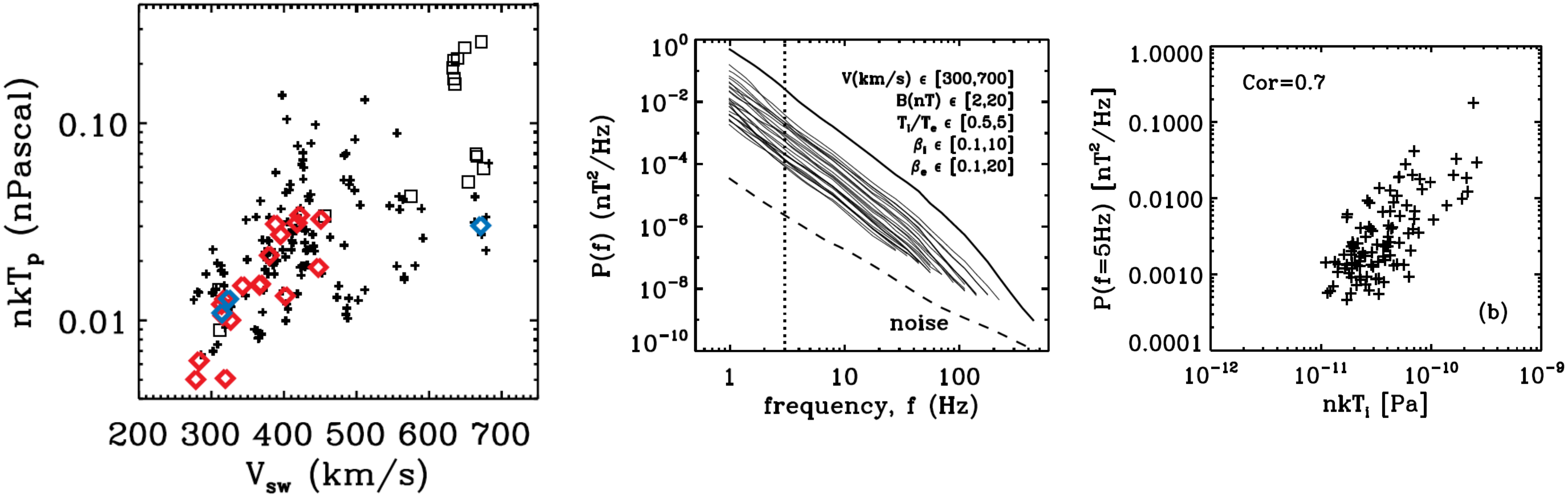


- f/f_ce normalization is more appropriate
- Spectral bumps are observed between the lower hybrid frequency sqrt(f_{ce}*f_{ci}) and 0.5f_{ce}
- These frequencies are typical of whistler mode waves.

When do we observe whistler waves in the SW?

Whistlers are more visible when the background turbulence has low intensity.

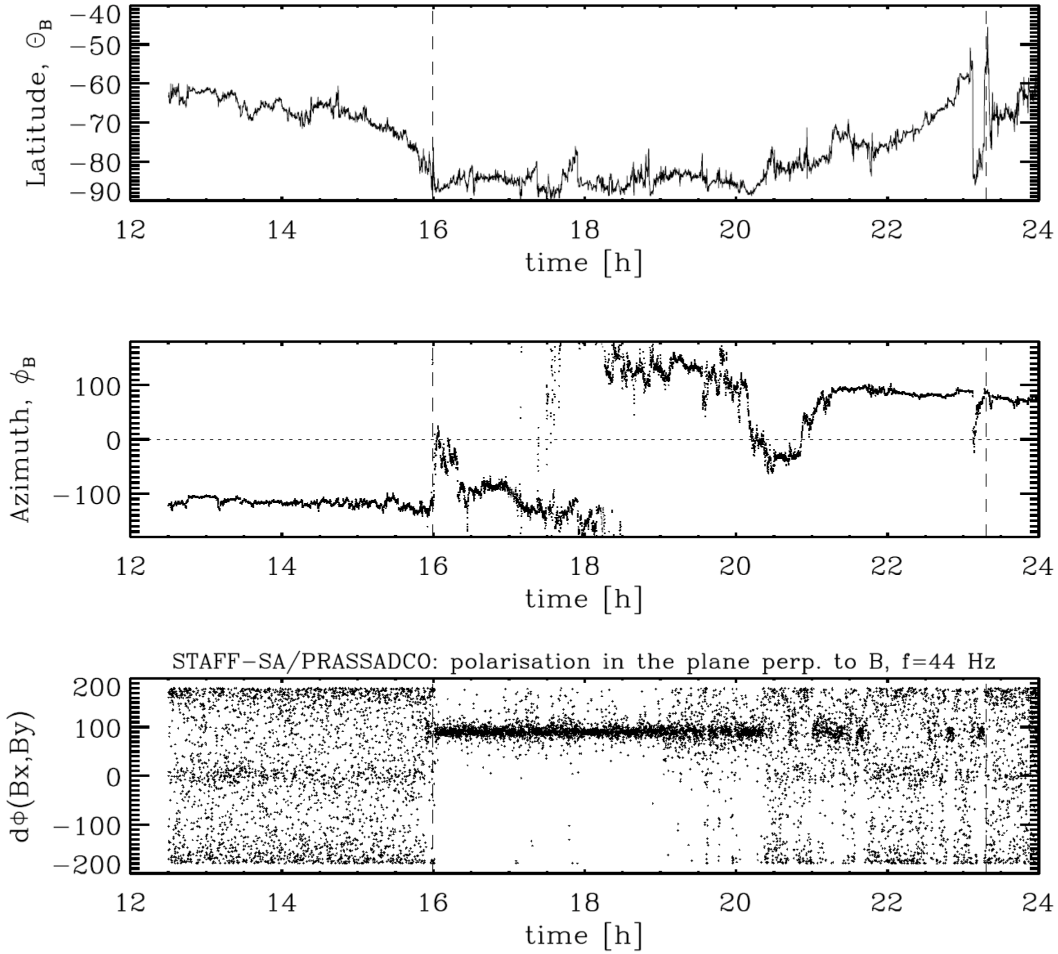
[Alexandrova et al. 2013, SSR]

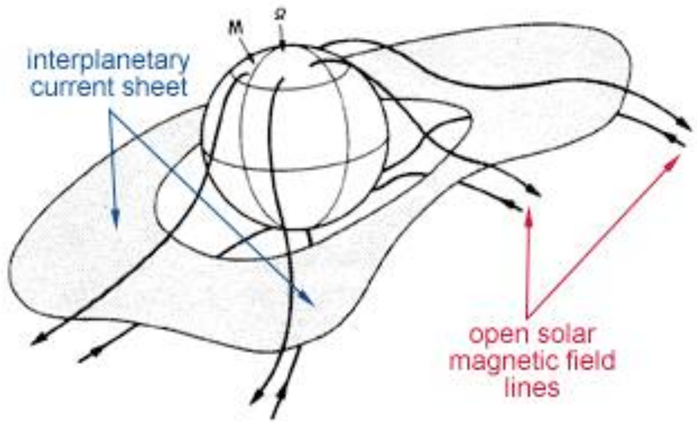


- The whistlers are only observed for low proton thermal pressure nkT_p and for low V_{sw}.
- Indeed, the level of background turbulence is proportional to nkT_p, and as well to V_{sw} (stronger Doppler shift for higher V_{sw}).
- So, the whistlers are probably "occulted" by the strong turbulence at high nkT_p and high V_{sw}.

Variations of IMF orientation and appearance of whistler waves

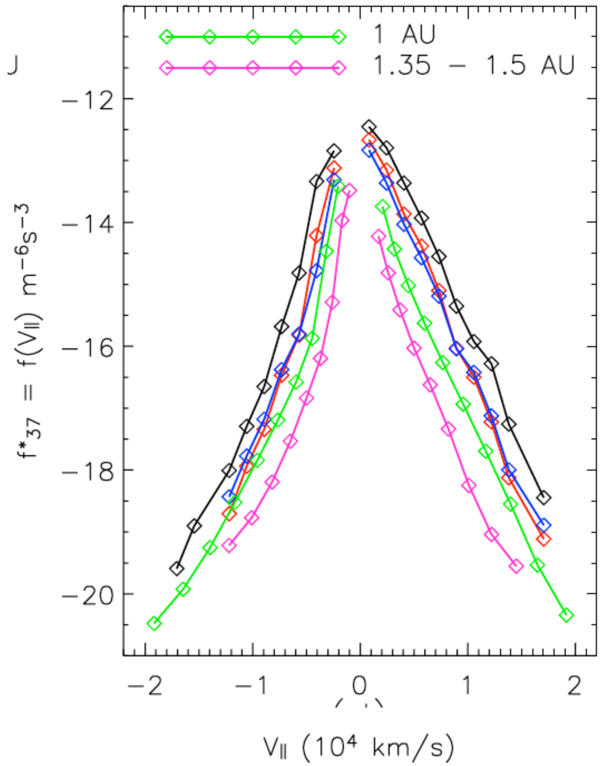
Cluster, free solar wind, 2001-04-22



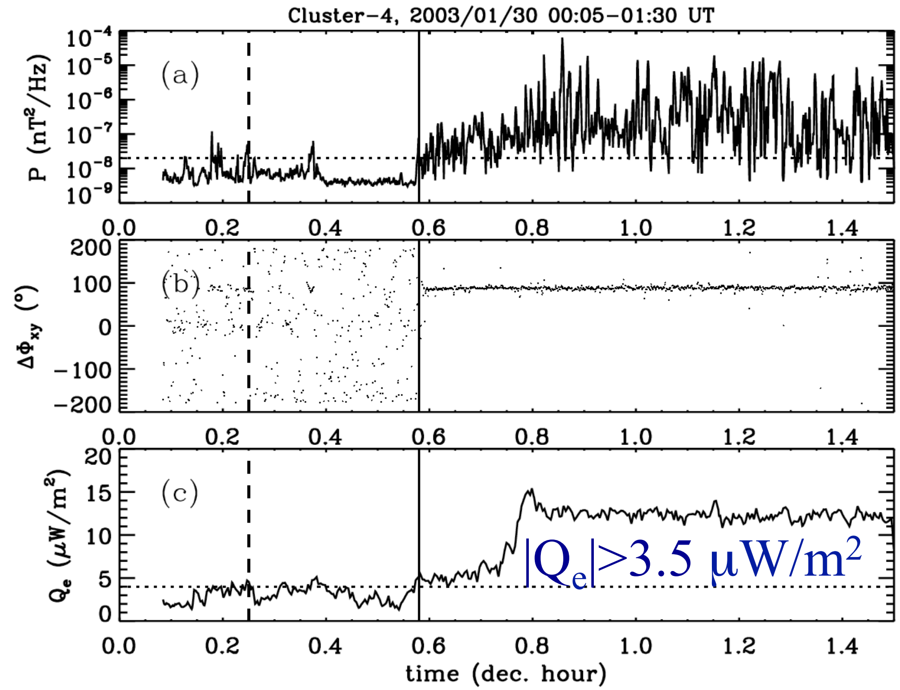


Role of the electron heat flux

[Maksimovic et al. 2005]



[Lacombe et al. 2014, APJ]



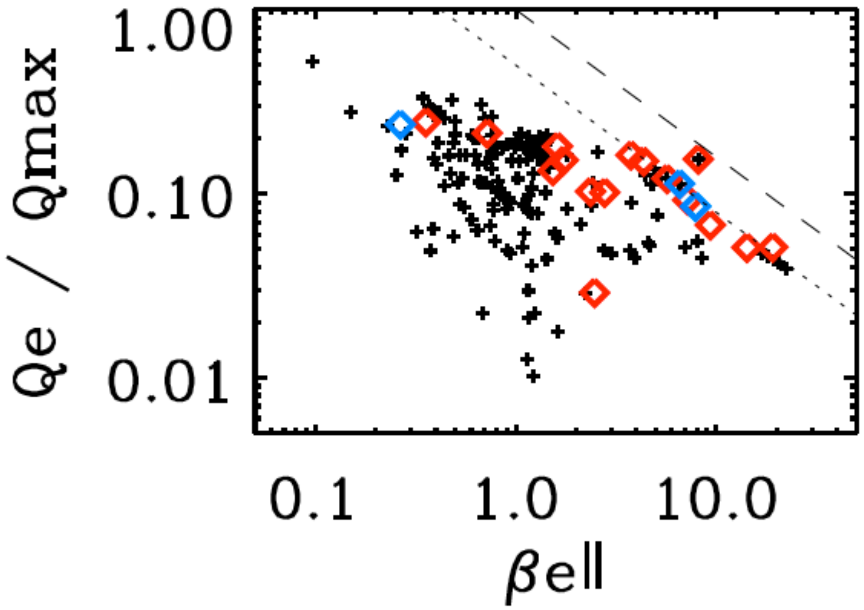
$$Q_e = \int \frac{m}{2} \mathbf{U} U^2 f(v) d^3 v, \quad \mathbf{U} = \mathbf{v} - <\mathbf{v}>$$

Electron heat flux, Q_e, is a measure of the asymmetry of the electron distribution function $f(v_e)$. In the solar wind it is present for $f(v_{e||})$.

Case study: We find that whistlers grow with increasing of Q_e.

Generally: necessary condition $|Q_e|>3.5$ mW/m^2

Instability related to the electron heat flux



$$Q_e = \int \frac{m}{2} \mathbf{U} U^2 f(v) d^3 v,$$

$$\mathbf{U} = \mathbf{v} - < \mathbf{v} >$$

$$Q_{max} = \frac{3}{2} m_e n_e v^3$$

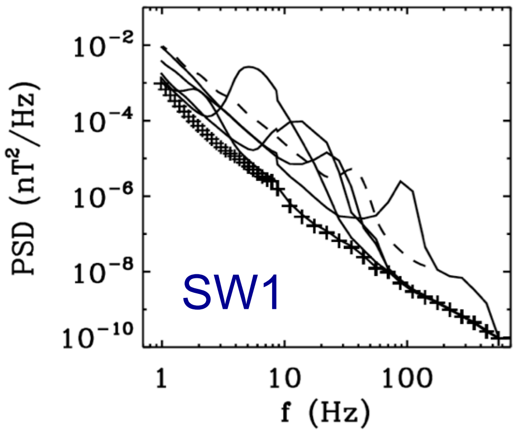
Whistlers (diamonds) are observed at the threshold for the whistler heat flux instability (dashed line, Gary et al.,99)

The whistler heat flux instability contributes to the regulation of the electron heat flux, at least for b_e>3 at 1 AU.

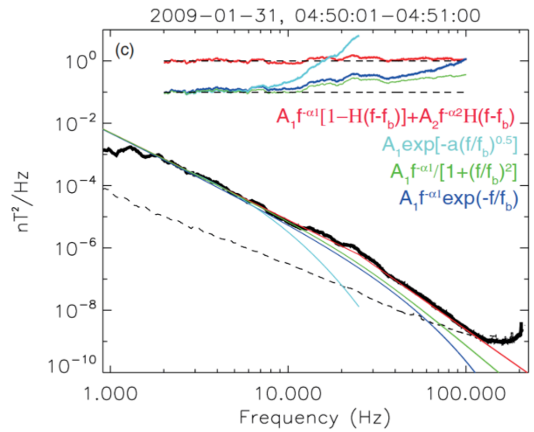
[Lacombe et al. 2014, APJ]

NB: Polarization study is crucial

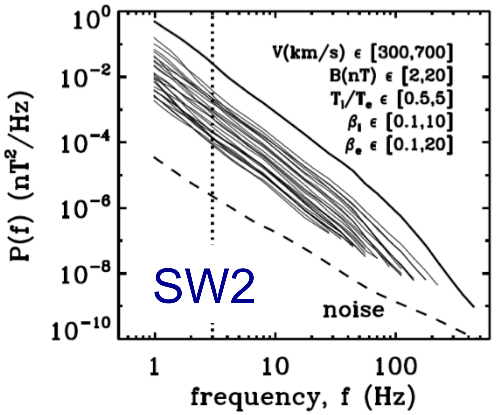
Polarized fluctuaitons

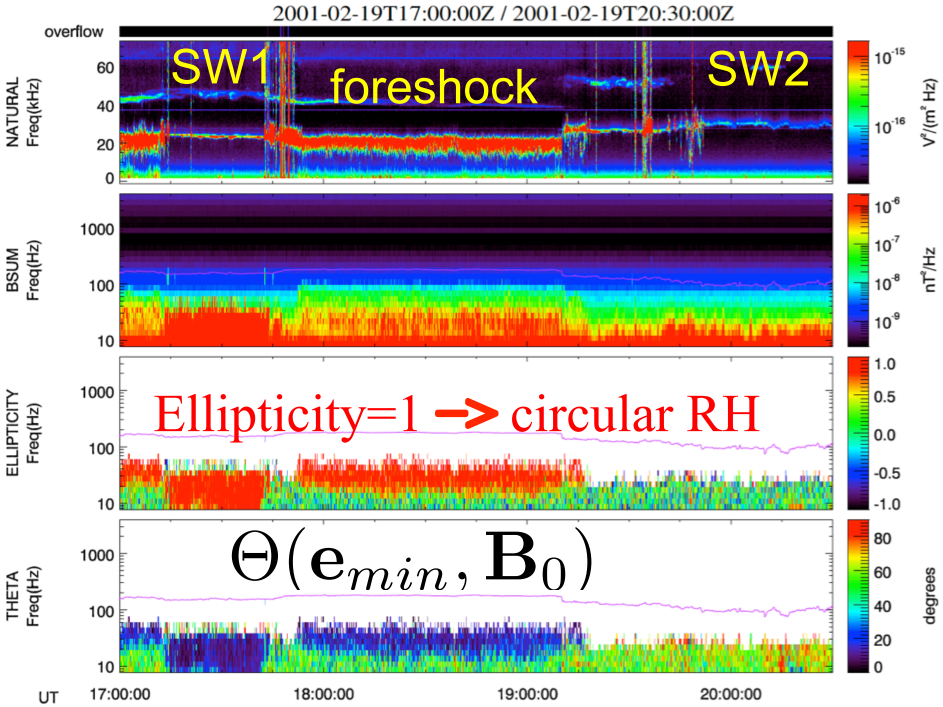


Non-polarized+polarized



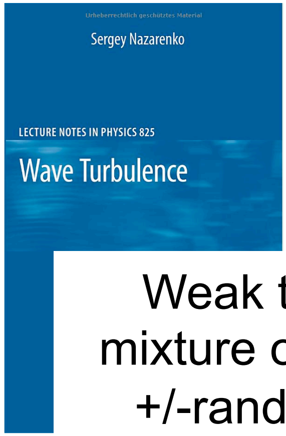
Non-polarized

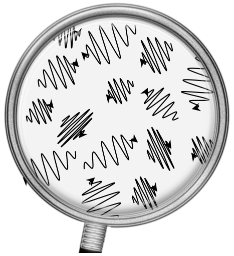




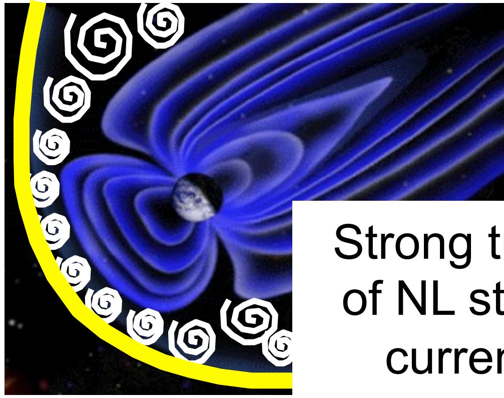
Turbulence nature: weak (or wave) vs strong

Courtesy S. Galtier

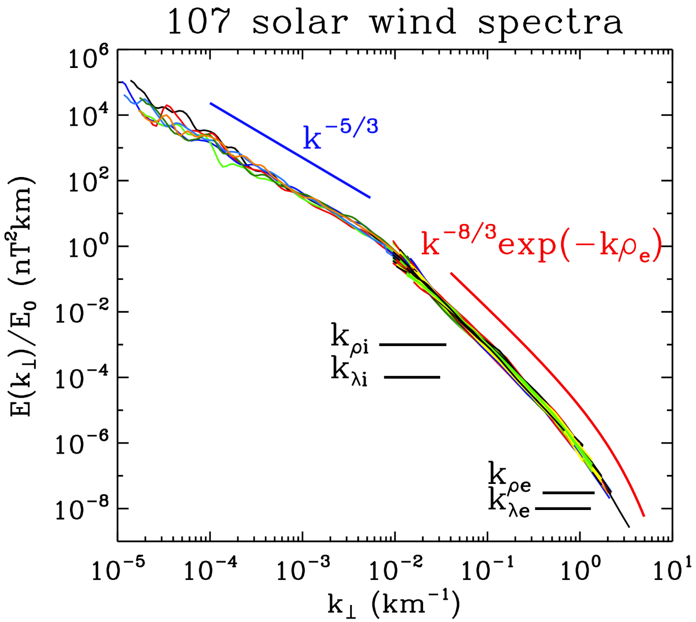




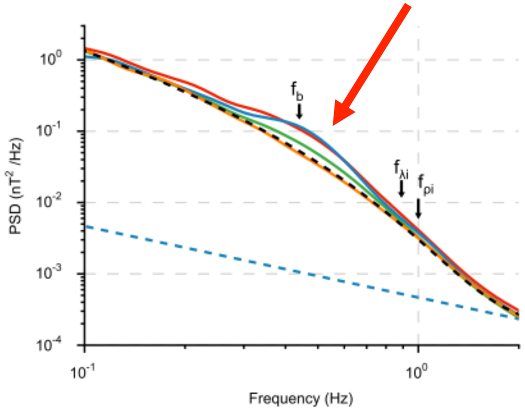
Weak turbulence: mixture of waves with +/-random phases

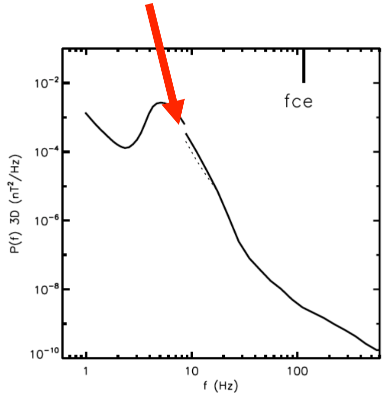


Strong turbulence: mixture of NL structures (vortices, current sheets, ect…)



Zooms around ion and electron scales:

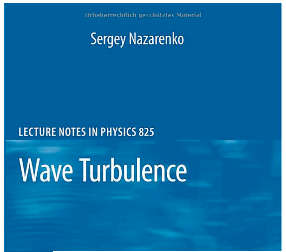


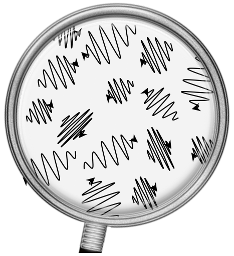


Strong turbulence within $k^{-5/3}$ and $k^{-8/3}$ ranges + waves (sometimes) at ion and electron scales.

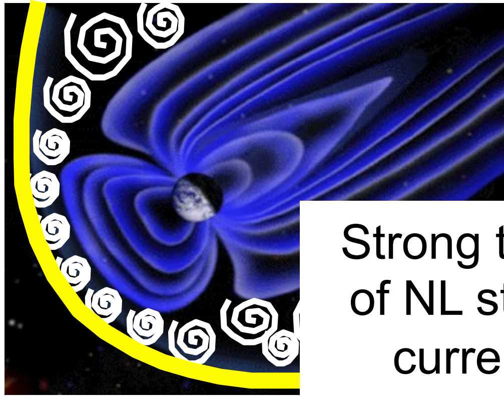
Turbulence nature: weak (or wave) vs strong

Courtesy S. Galtier



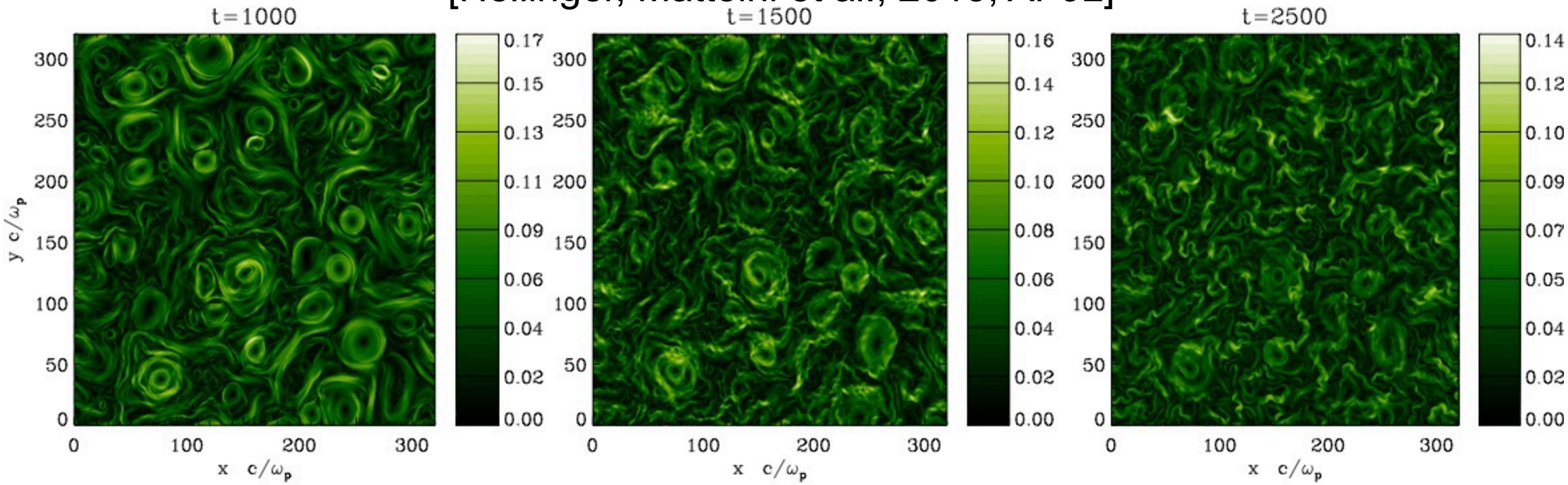


Weak turbulence: mixture of waves with +/-random phases



Strong turbulence: mixture of NL structures (vortices, current sheets, ect…)

[Hellinger, Matteini et al., 2015, APJL]



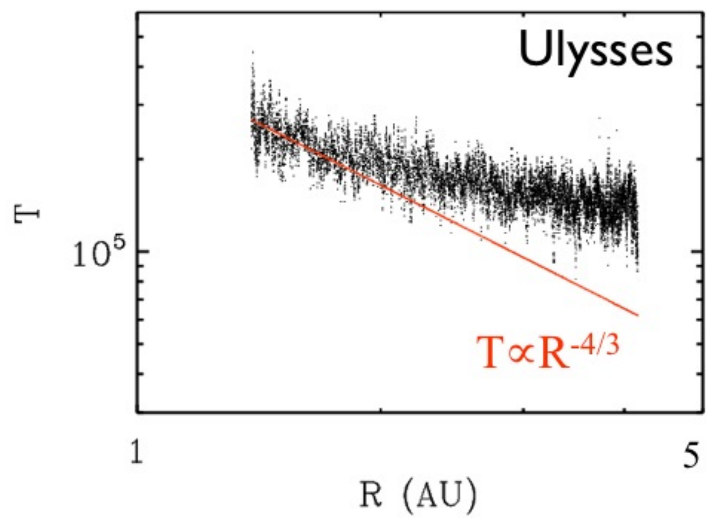
Courtesy of Lorenzo Matteini: 2D Hybrid numerical simulations showing developpment of strong turbulence (vortices) with superposed waves at ion scales.

Conclusion and discussion

- Plasma turbulence is an important ingredient in many astrophysical systems.
- Solar wind is one of the best laboratories of space plasma turbulence.
- We resolve turbulent fluctuations from MHD (10^7 km) to sub-electron scales (300 m).
- Turbulence nature: Alfven and whistler waves (with $k_{||}$), coherent structures (k_{perp}), non-coherent fluctuations (k?). KAWs?
- Evidence of energy exchange between waves and particles via instabilities (at ion and e-scales).

- But is there any dissipation of turbulent energy during this exchange?
- What is the role of coherent structures in the dissipation? Reconnection within coherent current sheets ?
- Dissipation mechanism without collisions ?
- Solar wind heating?
- …

Recent/future space missions: MMS, Solar Orbiter (ESA, 2018), Solar Probe Plus (NASA, 2018), THOR (ESA?) will answer these questions ?



‘Message to go…’

- Polarization/waveform analysis in time is very important : we can not make conclusions on the nature of turbulence by looking only at spectra !
- This approach allows us to understand the phenomena around ion scales.
- Idem for electron-scales : taking off time intervals with parallel propagating whistler waves we find more-or-less general spectrum at kinetic scales.
- At ion scales: no UNIQUE characteristic scale
- ion transition and associated phenomena (monochromatic waves, coherent structures) seems to depend on local plasma
- Background turbulence at electron scales has one clear ‘dissipation scale’ at ρ_e. (Is there equivalent scale at ion scales for the background non-polarized part of turbulence?)
- … we have still a lot of things to do ☺