Magnetic fields in the Universe V
Octobre 5-9 2015

Observations of solar wind turbulence (from MHD to electron scales)

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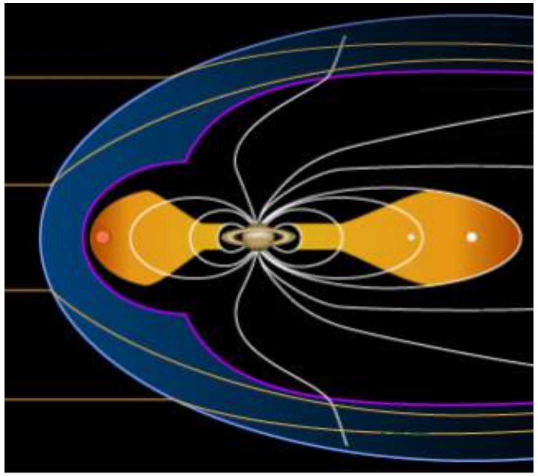
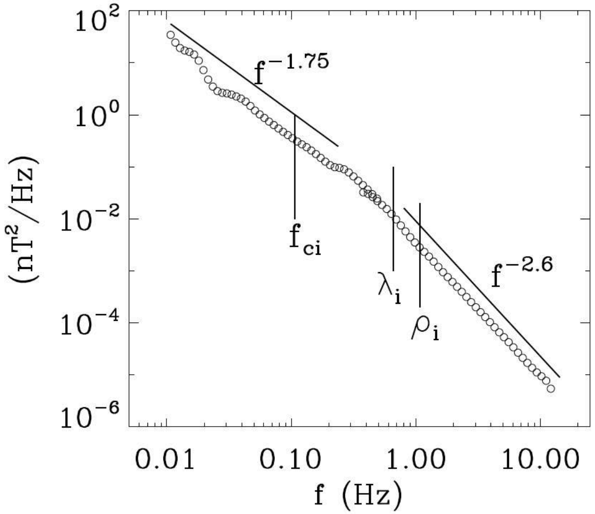
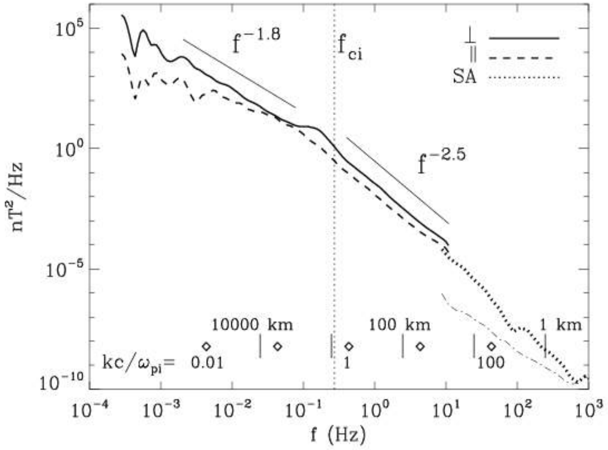
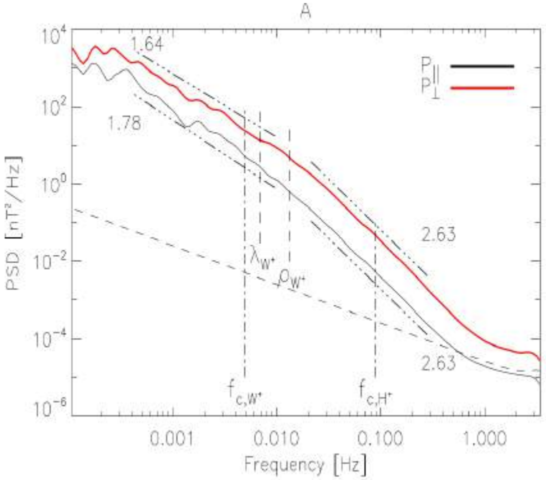
Plasma Turbulence in the Heliosphere

In situ measurements in the solar wind and planetary magnetospheres show omnipresence of plasma turbulence.



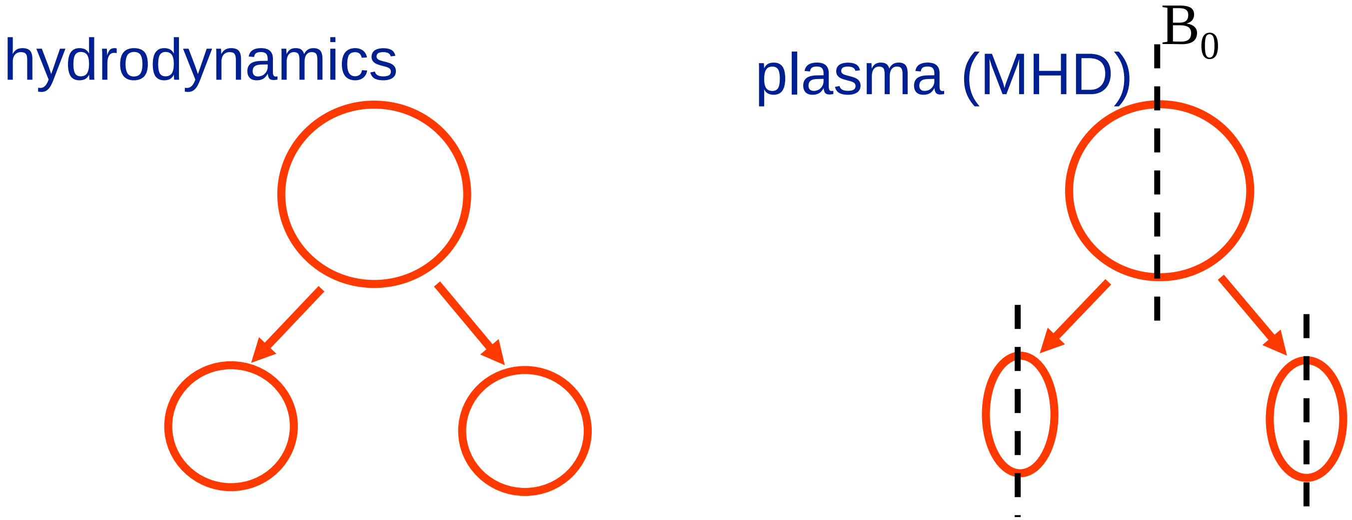






[Alexandrova et al. 2013, 2008, Von Papen et al. 2014]

Turbulence in space plasmas



hydrodynamics

plasma (MHD)

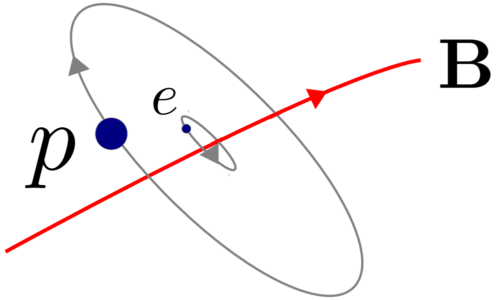
B_0

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.

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

Typical plasma scales in the solar wind

- Larmor radius (ρ_i ~100 km, ρ_e~1 km) and cyclotron frequency ($\Omega_{ci}/2\pi$ ~0.1Hz, $\Omega_{ce}/2\pi$ ~200Hz) 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, which is close to $\rho_{i,e}$ in plasma with $\beta=nkT/(B^2/2\mu_0)$~1) and plasma frequency (ω_p) :

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

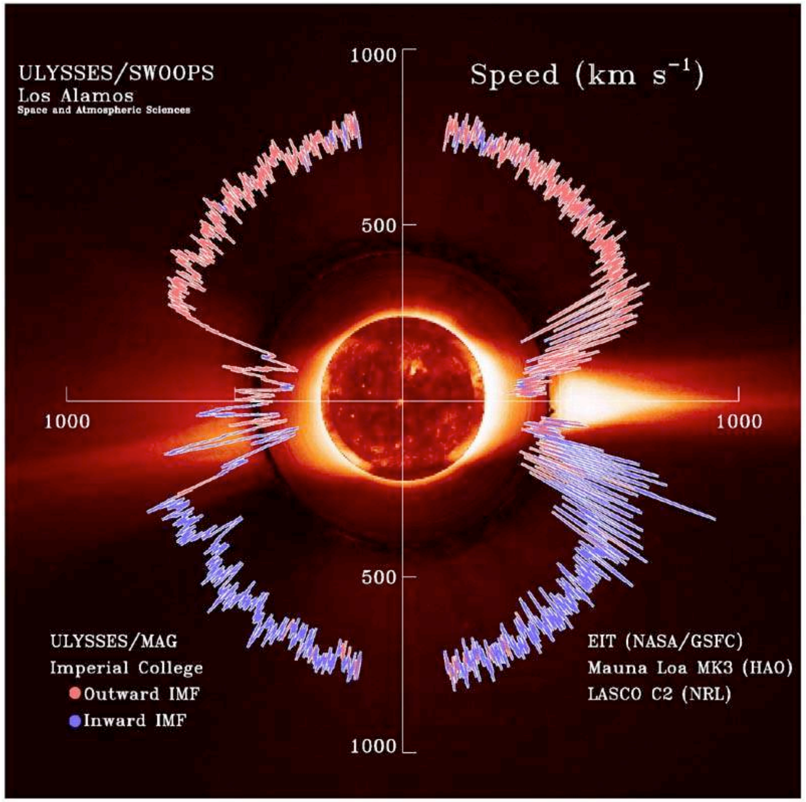
- Debye length λ_D~10m (sphere of influence of a given test charge in a plasma); at L>λ_D plasma is quasi-neutre :

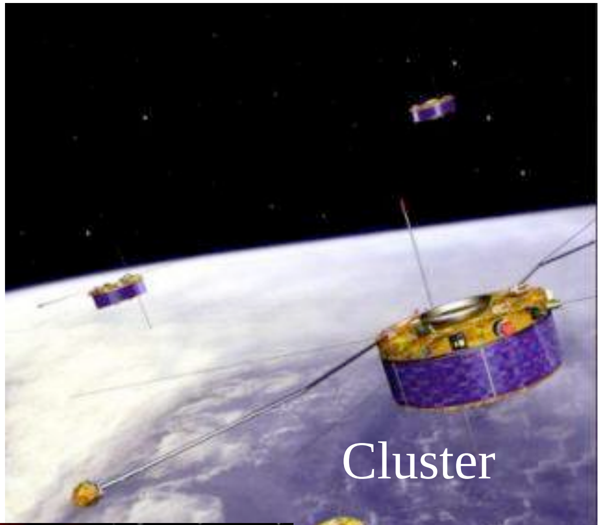
$$\lambda_D^2 = \frac{k_B T}{8\pi n e^2}$$

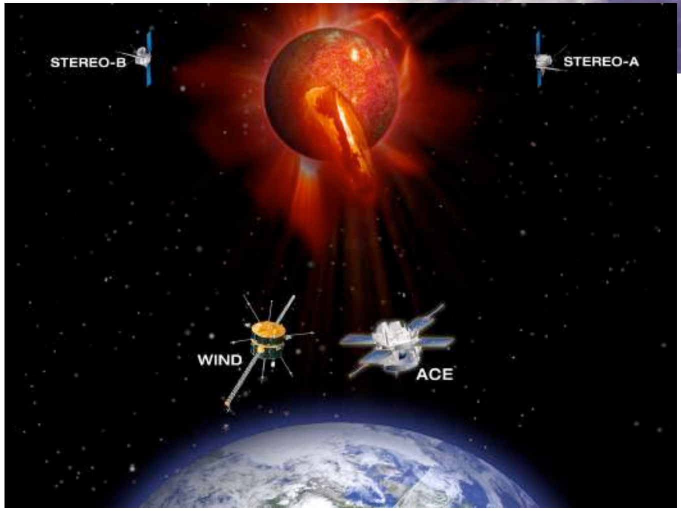
- Satellite size ~ 1-2 m.

The solar wind

one of the best and the closest laboratory for astrophysical plasma turbulence.

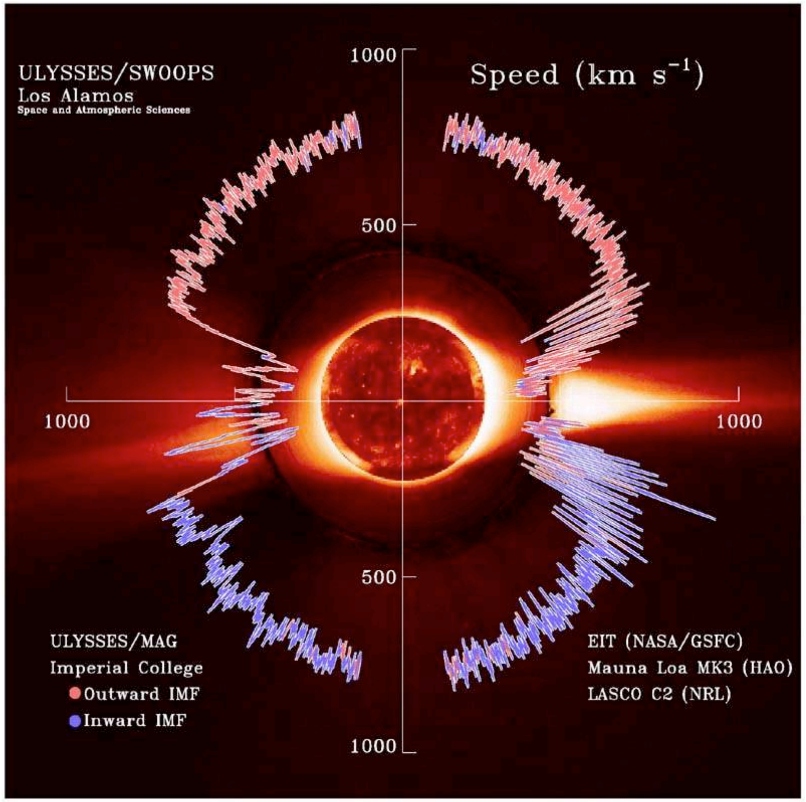




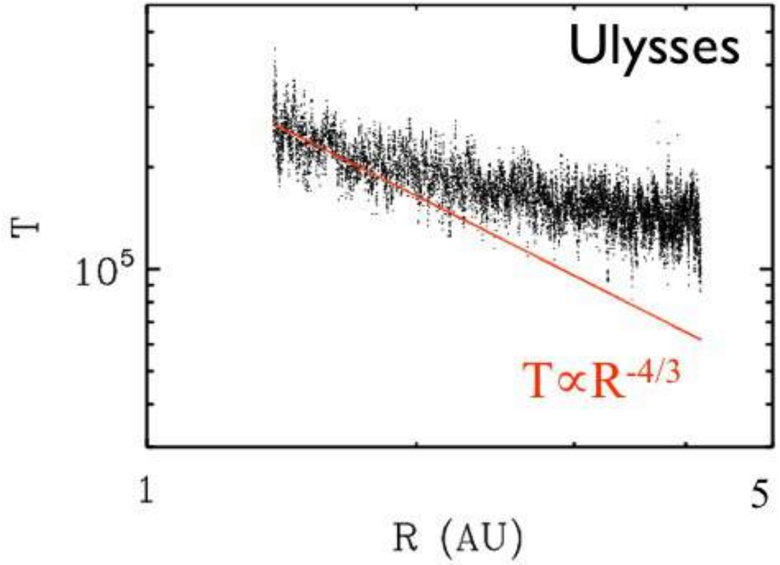


Two components, Slow and Fast streams.
Slow wind: V = 300-400 km/s, n=7 cm-3, Tp=2.10^{5}K
Fast wind: V = 600-800 km/s, n=3 cm-3, Tp=5.10^{5}K

The solar wind



[Image credit: Lorenzo Matteini]

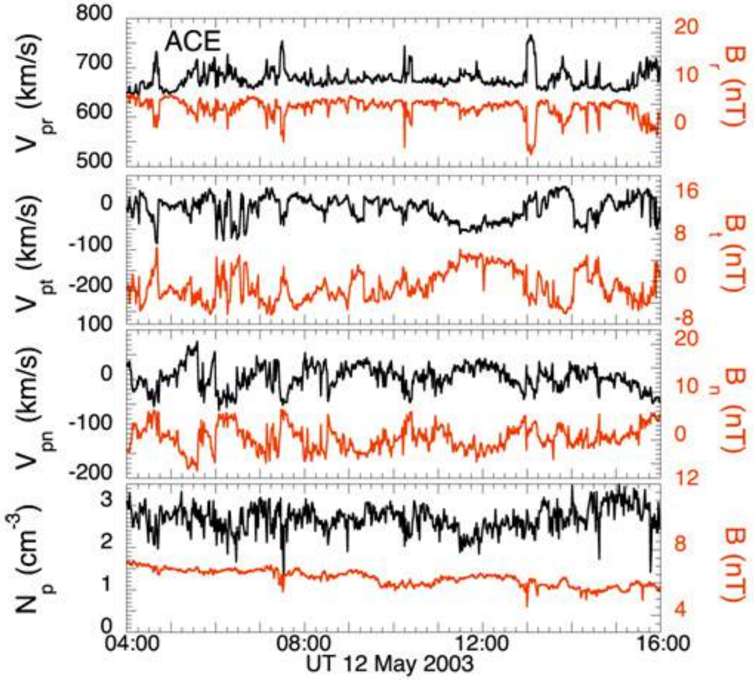


Wind temperature decays less than adiabatic (~$R^{-4/3}$)

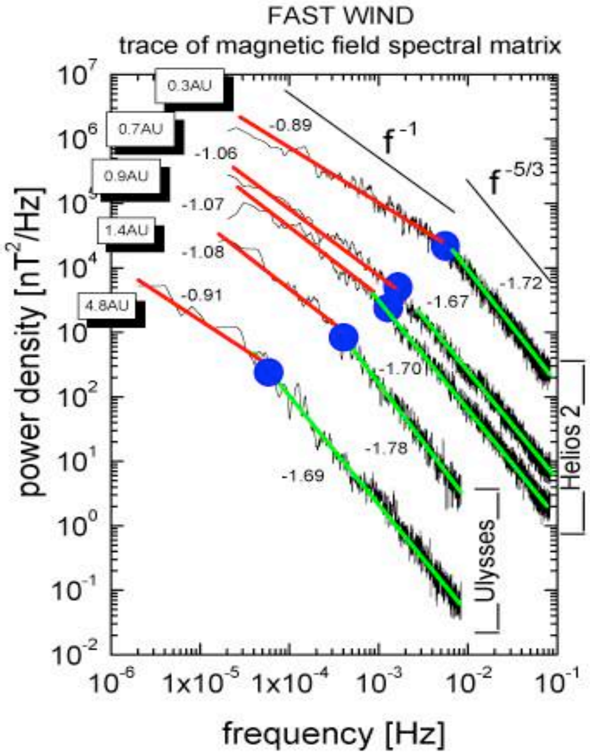
Turbulence dissipation may explain the solar wind heating [e.g. Vasquez et al. 2007; Sorriso-Valvo et al. 2007; Macbride et al. 2008; Smith et al. 2009; Cranmer et al. 2009; Marino et al. 2012; Wu et al. 2013, …]

Solar wind Turbulence and Alfven waves

[Gosling et al., 2009; Balcher & Davis 1977]

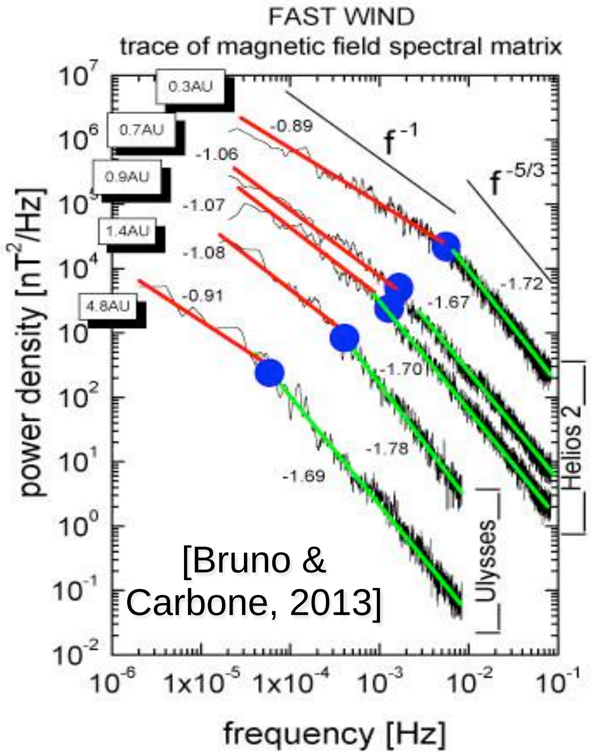


[Bruno & Carbone, 2013]



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

Starting point of the Kolmogorov spectrum



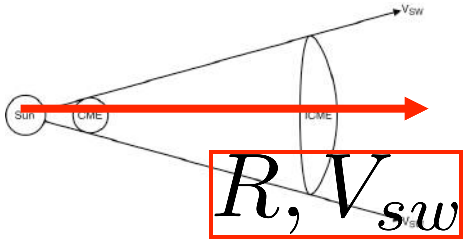
[Bruno & Carbone, 2013]

- The solar wind expansion time:

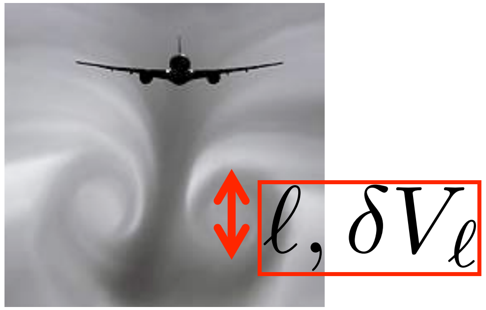
$$\tau_{exp} = R/V_{sw}$$

- The eddy-turnover time:

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



R, V_{sw}

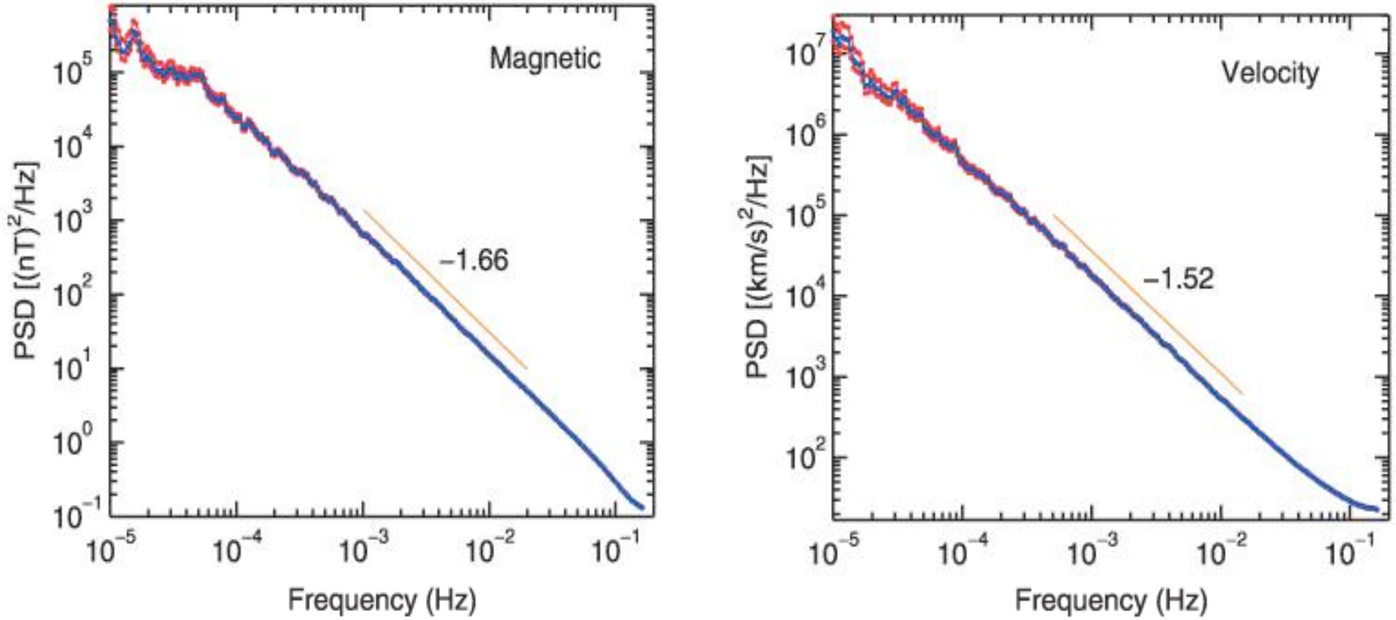


$\ell, \delta V_{\ell}$

- 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

In a case of a pure alfvenic turbulence magnetic and velocity spectra should be the same, but in the solar wind it is not the case:



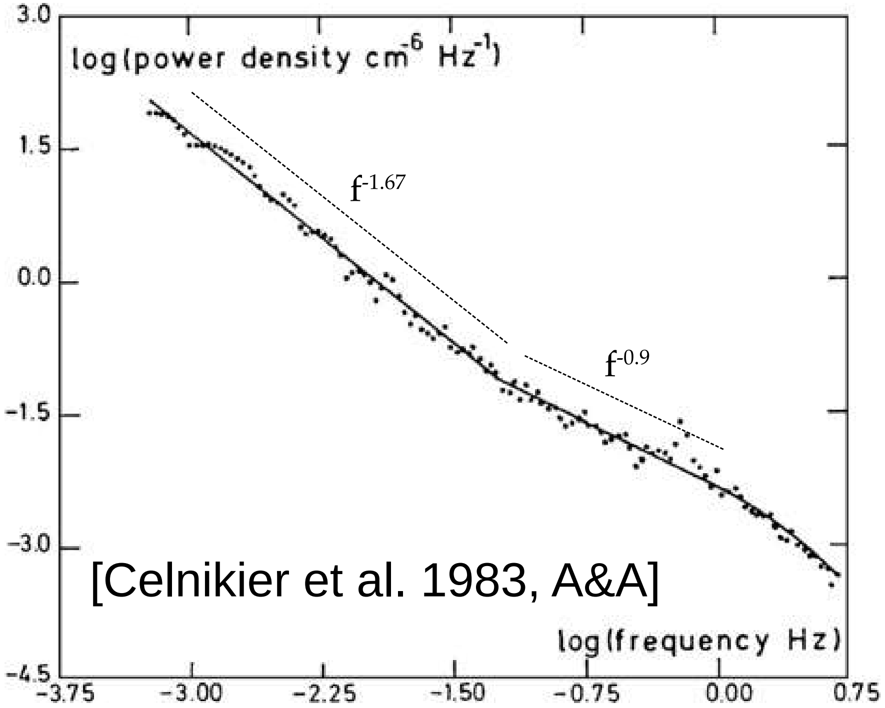
[Podesta et al., 2007; Salem 2000, PHD]

Why?

- Local dynamo process (Grappin et al., 1983) ?
- Solar wind expansion ? V-B alignment (see talk of S. Boldyrev)?
- Compressibility ?

Solar wind turbulence is compressible

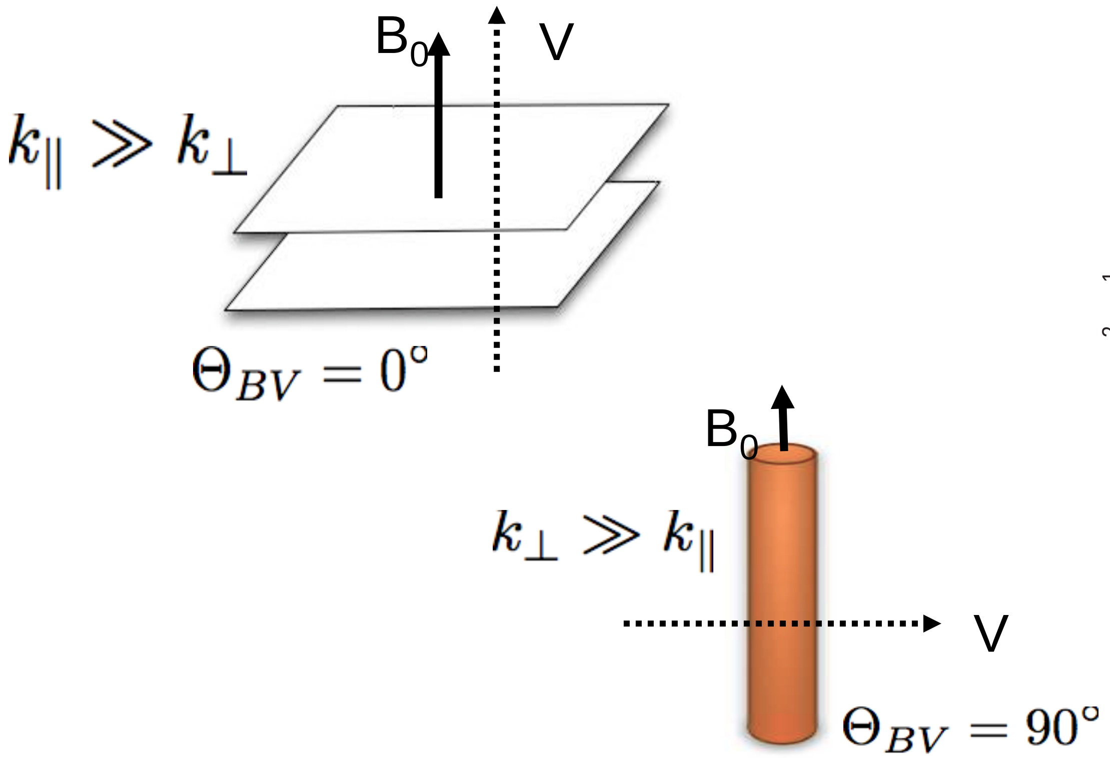
Spectrum of electron density fluctuations in the solar wind as measured by ISEE 1 & 2. See as well Chen et al. 2013.

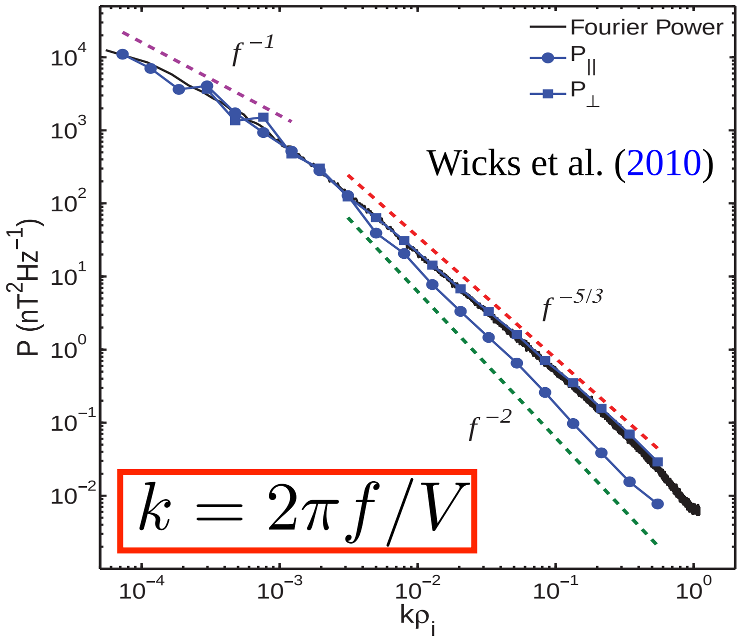


[Celnikier et al. 1983, A&A]

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

Anisotropy of turbulent fluctuations at MHD scales





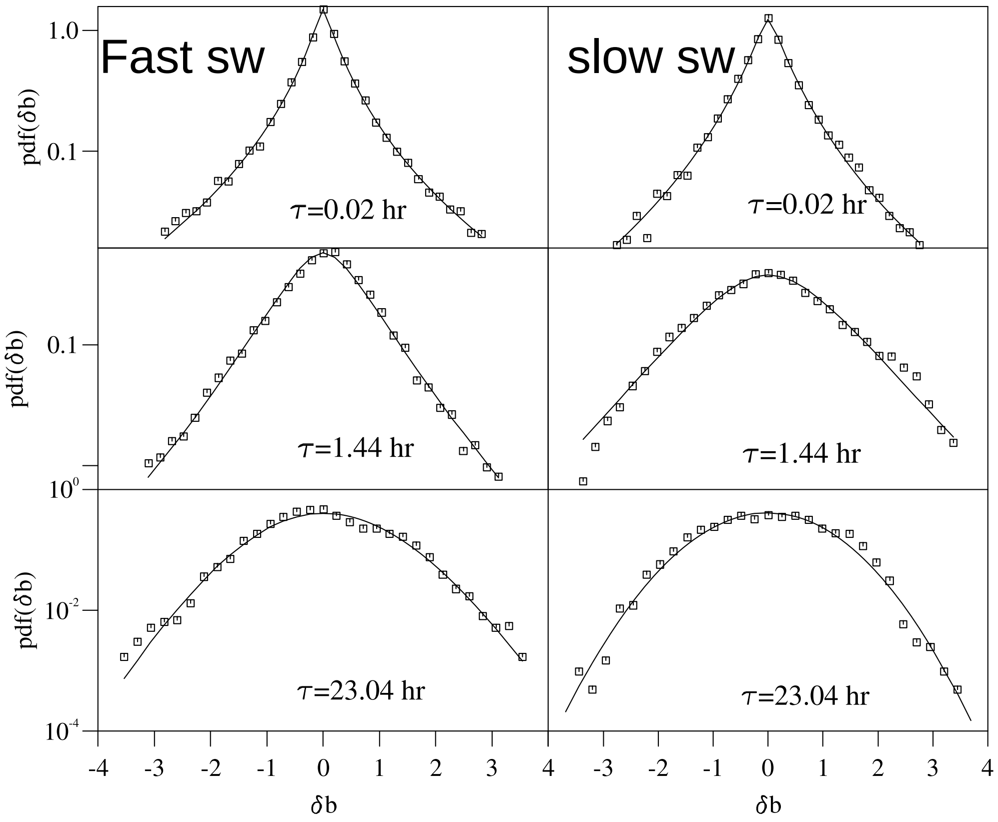
- Alfvénic turbulence of Goldreich and Sridhar, 1995 is based on the idea of a balance between linear Alfvén time (along B_0) and non-linear time (in plane perp. to B_0):

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

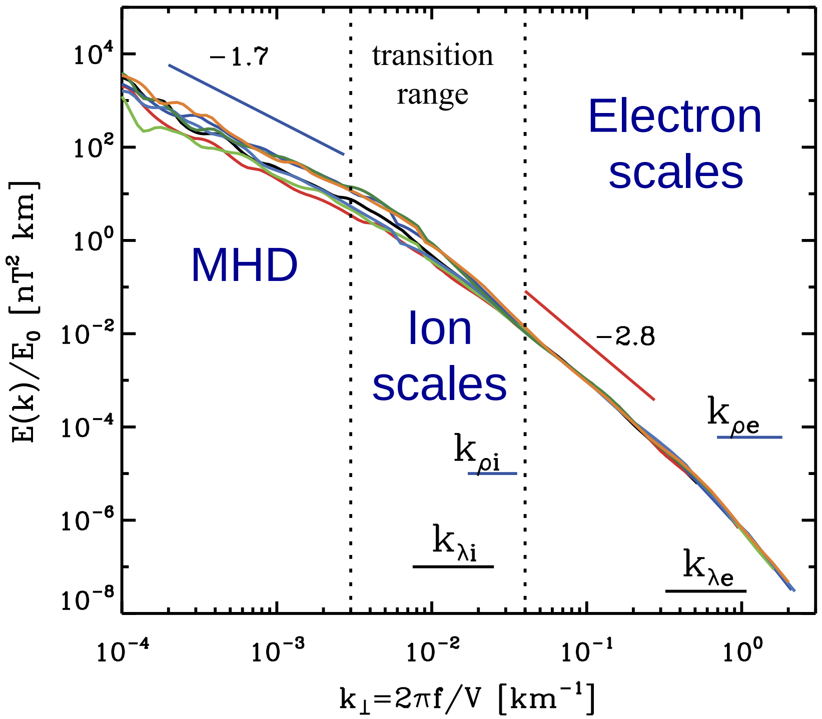
$$\boxed{P(k_\perp) \sim k_\perp^{-5/3}\ ;\ P(k_\parallel) \sim k_\parallel^{-2}}$$

Intermittency of turbulent fluctuations within the MHD inertial range

[Sorriso-Valvo et al. 1999, Dudok de Wit et al. 2013]



Solar wind turbulent spectrum of magnetic fluctuations at MHD-Ion-Electron scales



[Alexandrova, Chen, Sorriso-Valvo, Bale, Horbury, 2013 Space Science Rev, open access]

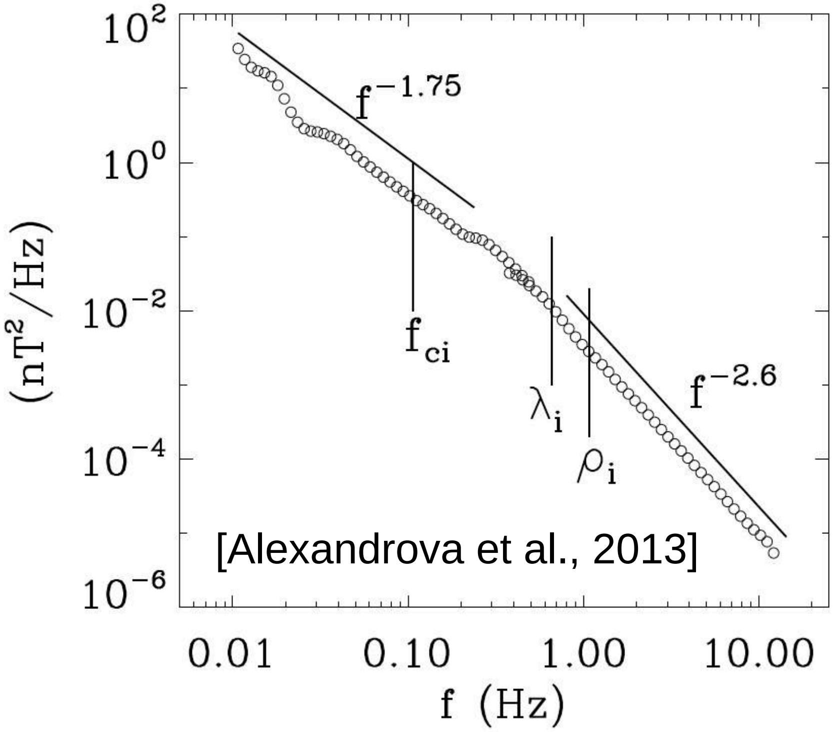
1. What is going on close to ion and electron scales?
2. Which plasma scale is responsible for the ion break?
3. Which plasma scale plays the role of the dissipation scale?
4. Physical mechanisms?
5. Nature of turbulent fluctuations : waves or strong turbulence?
6. …

Turbulence at kinetic scales

1. Ion scales

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

Which ion scale is responsible for the break?



[Alexandrova et al., 2013]

Time scale

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

Spatial scales

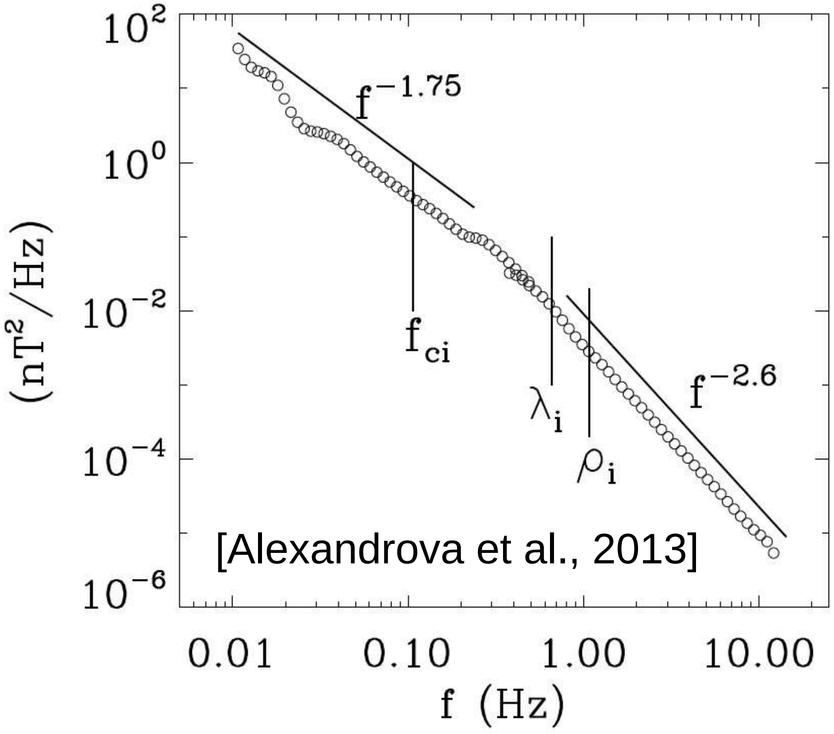
$$\rho_i = \frac{V_{\perp i}}{\Omega_{ci}} \ ; \ \lambda_i = \frac{c}{\omega_{pi}} = \frac{V_A}{\Omega_{ci}}$$

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?



[Alexandrova et al., 2013]

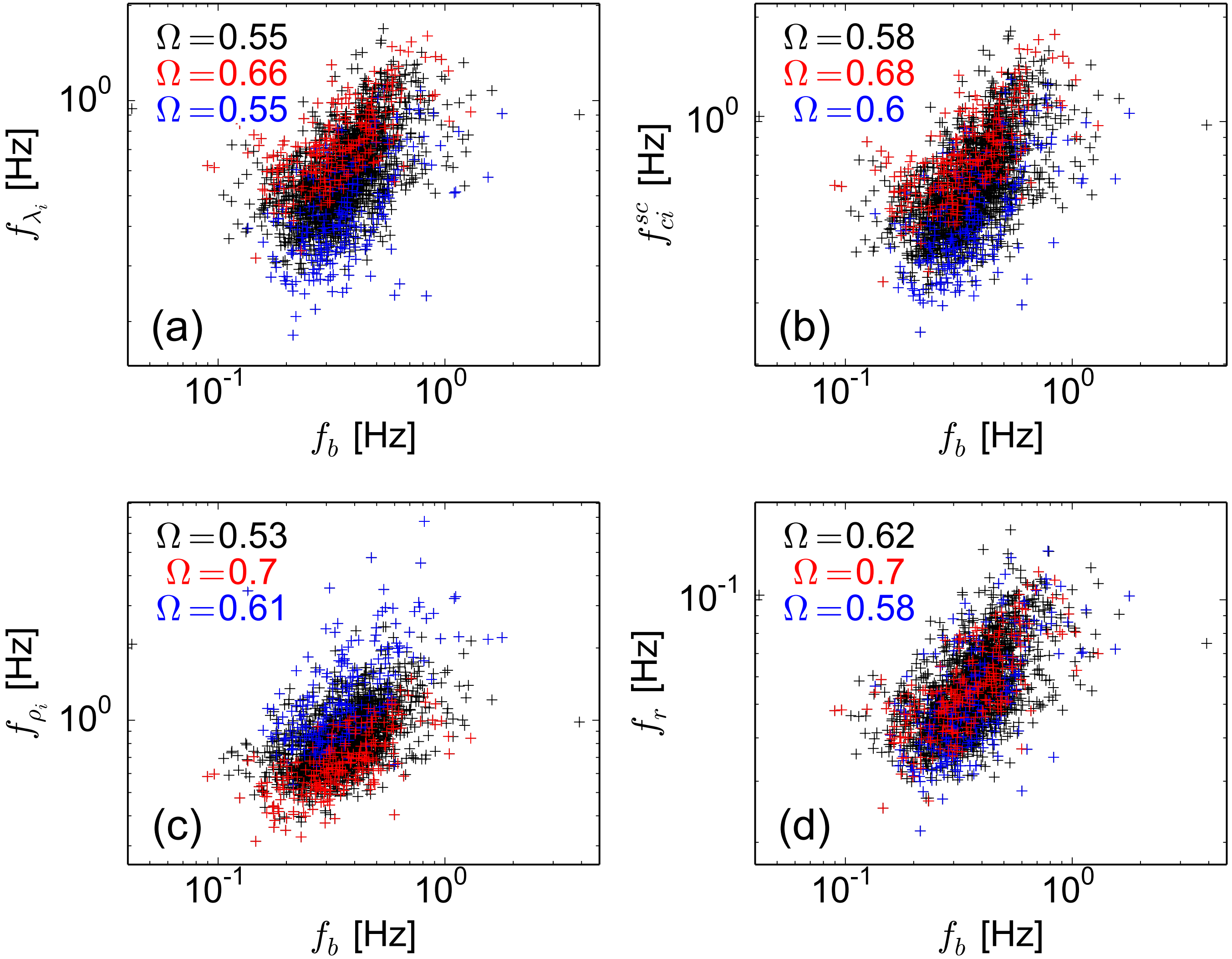
- Leamon et al. 2000 : λ_i
- Schekochihin et al. 2009: ρ_i
- Perri et al. 2010 : any of the scale/ combination of scales
- Bourouaine et al. 2012: λ_i
- Bruno et al. 2014: resonant k of parallel Alfven waves
- Chen et al. 2014: beta dependent.

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

⇒ The largest characteristic ion scale “breaks” turbulent spectrum [Chen et al. 2014].

All scales correlates well with f_b...

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

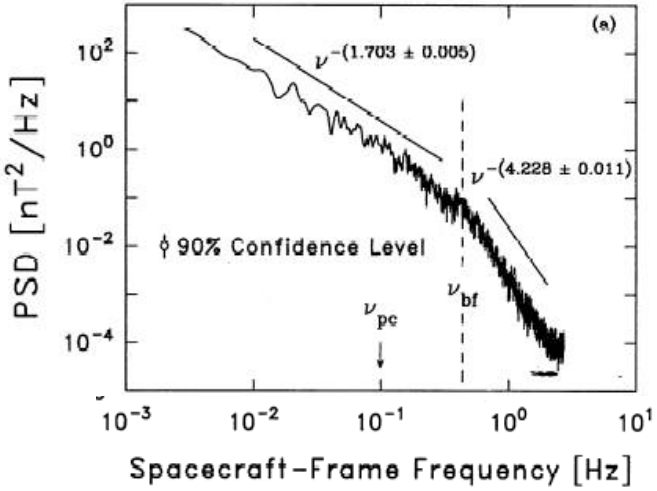


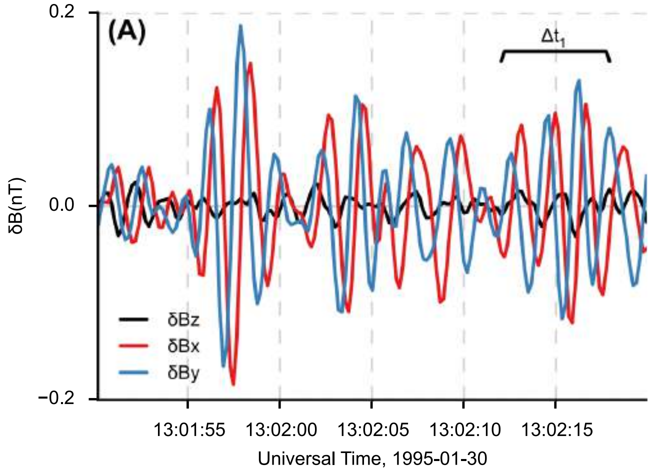
Red: high $\beta p > 1$
Blue: low $\beta p < 0.2$
Black: all data

⇒ No ONE scale (ONE physical phenomena) to explain the ion transition ?

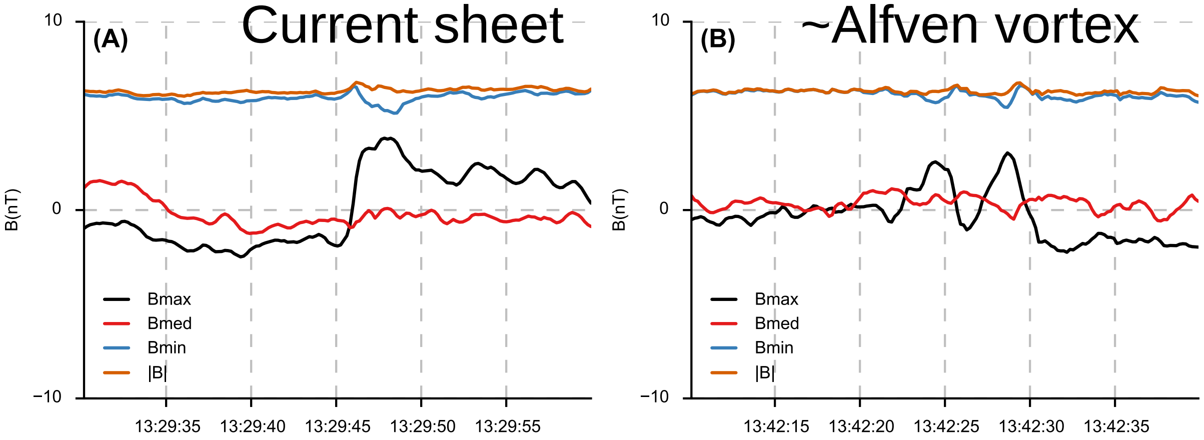
Ion scales: superposition of different phenomena

[Leamon et al. 1998]

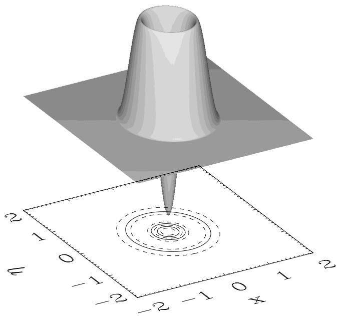




Monochromatic Alfven waves at freq~f_{ci} with $k_{||}$ (generated by AIC instability).

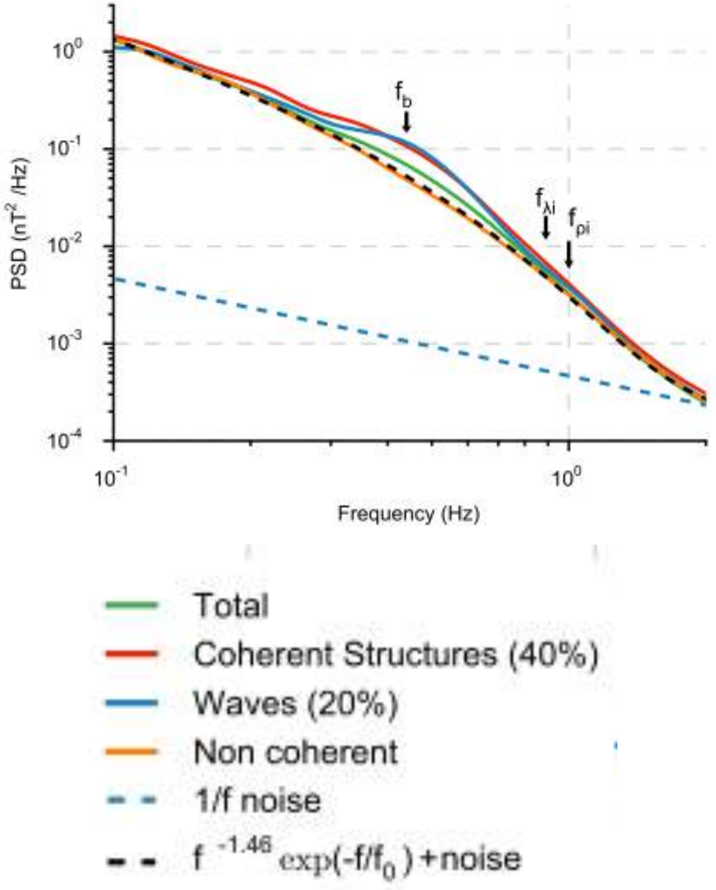


Localized spatial structures with k_{perp} at scale ~ ion Larmor Radius



[Lion et al, 2015, submitted to APJ]

Solar wind spectrum around ion scales
(conclusions based on a case of a fast sw stream)



It consists of
- 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.

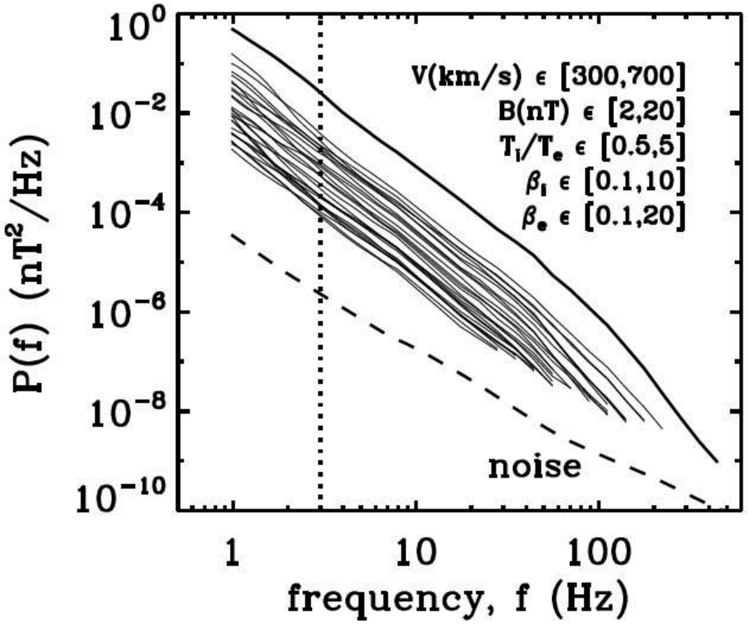
⇒These results may explain spectral variability around ion scales.

[S. Lion, O. Alexandrova, A. Zaslavsky, 2015, submitted to APJ]

Turbulence at kinetic scales

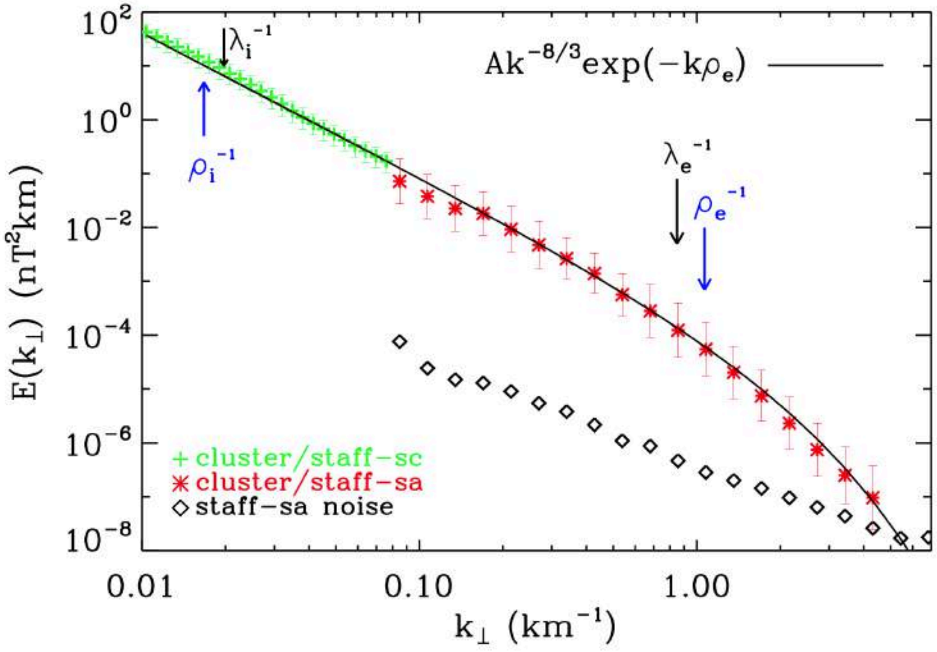
2. Electron scales

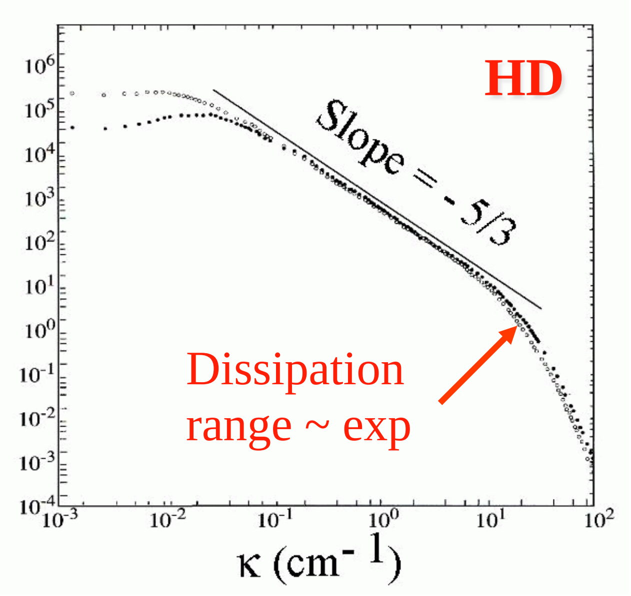
Cluster mission : the most sensitive instrumentation (magnetic spectrum up to 400 Hz, i.e. scales ~300m).



Turbulent spectrum at electron scales: dissipation range?!

[Alexandrova et al., 2012, APJ]





- In HD turbulence, dissipation range can be described by [Chen et al., 1993, PRL] :

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

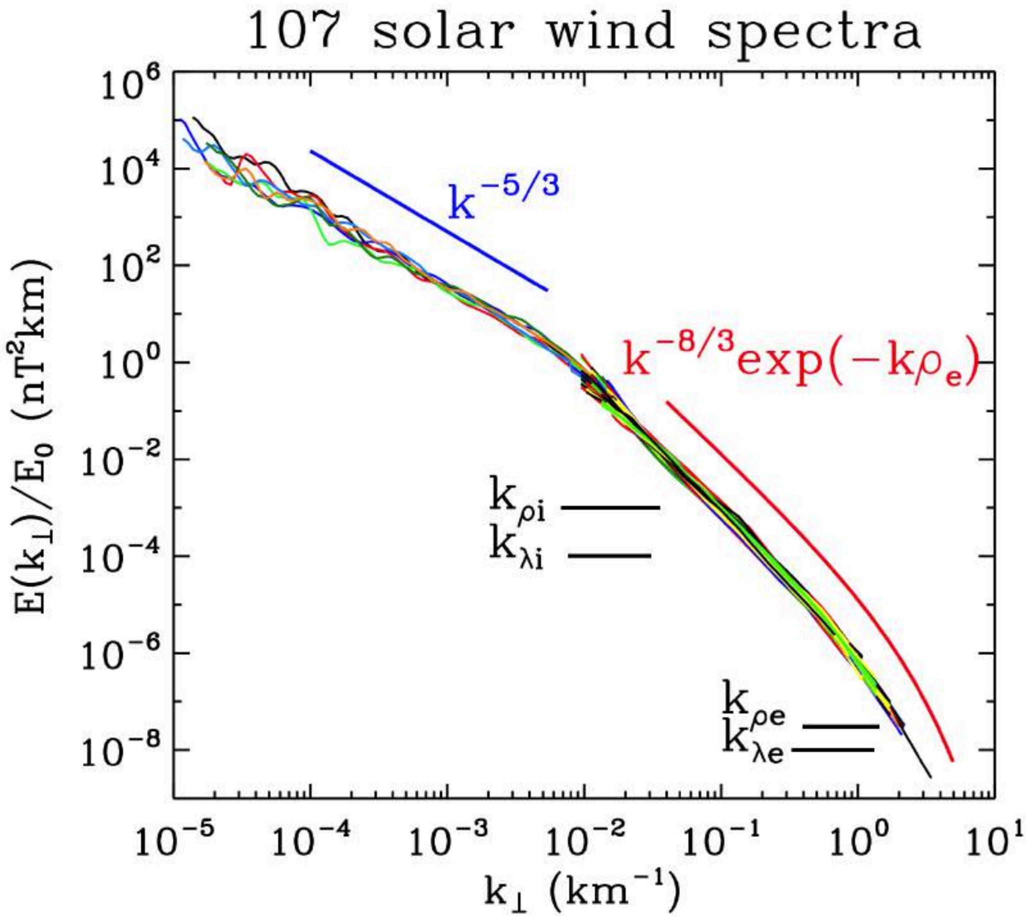
- In solar wind turbulence, we find a similar law :

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

General spectrum at electron scales

[Alexandrova et al., 2012, APJ]

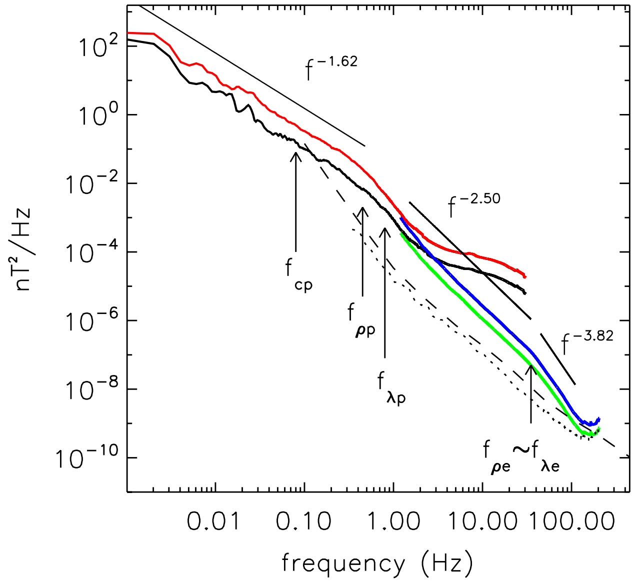
$$\boxed{E(k) = Ak^{-8/3}\exp(-k\rho_e)}$$



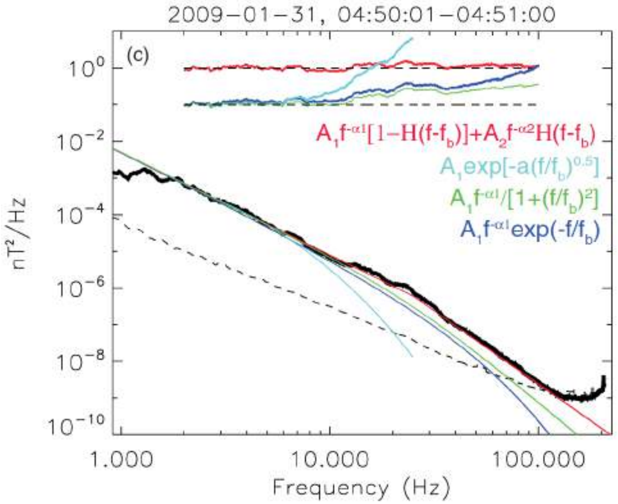
Electron Larmor radius ρ_e plays the role of the dissipation scale in collisionless solar wind turbulence.

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

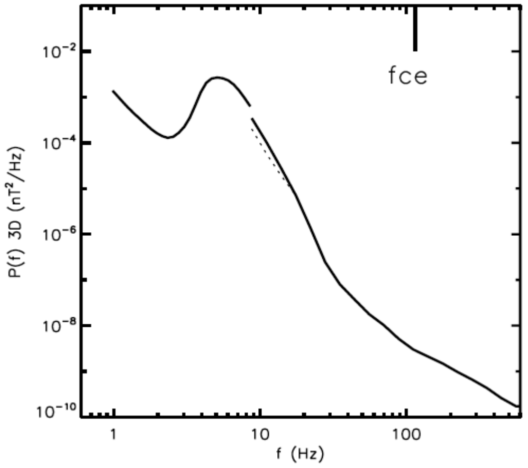
Observation of spectral break of bosse at electron scales:



[Sahraoui et al., 2009]



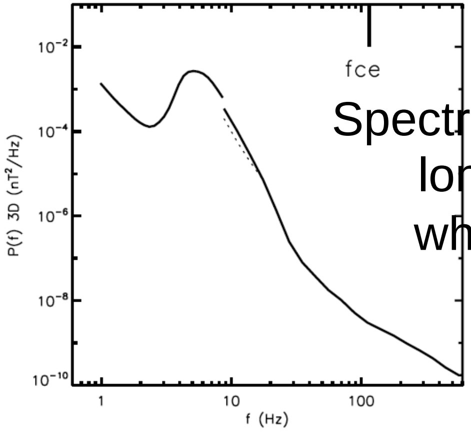
[Sahraoui et al., 2013]



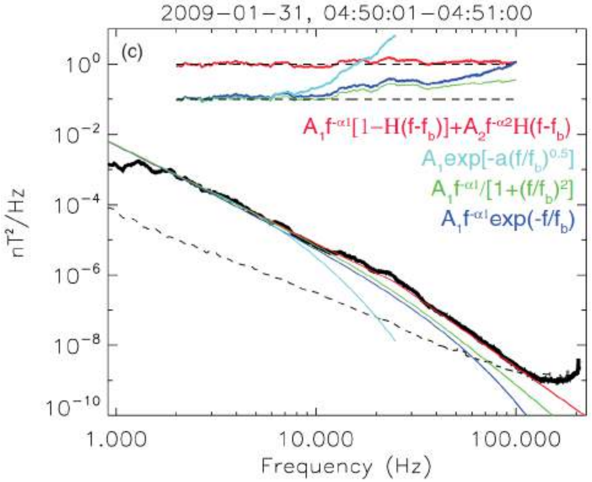
[Lacombe et al. 2014]

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

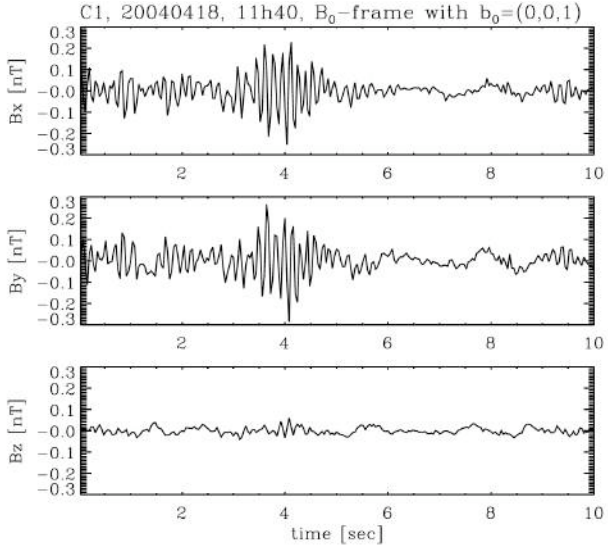
Examples of quasi-monochromatic whistler waves in the solar wind (5-10% of data)

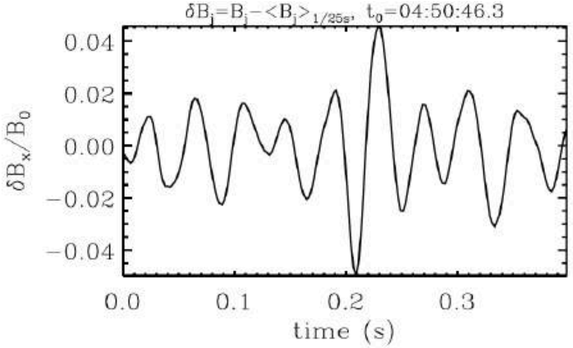


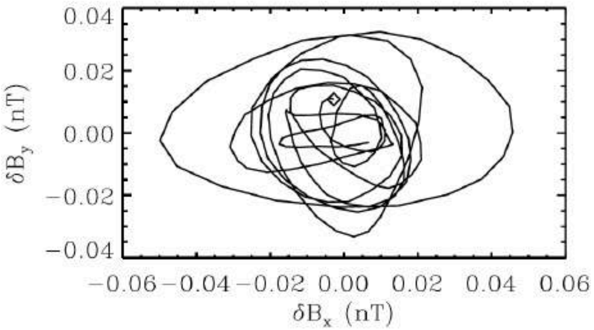
Spectral bump = long-live whistlers



[Sahraoui et al. 2013]: spectral break is due to sporadic whistlers







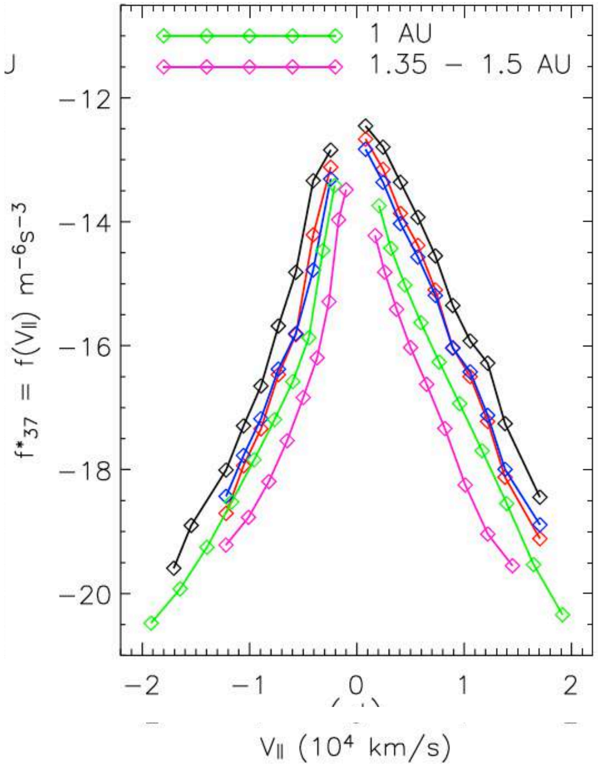
[Lacombe et al. 2014]

Phase-diff. between Bx and By:

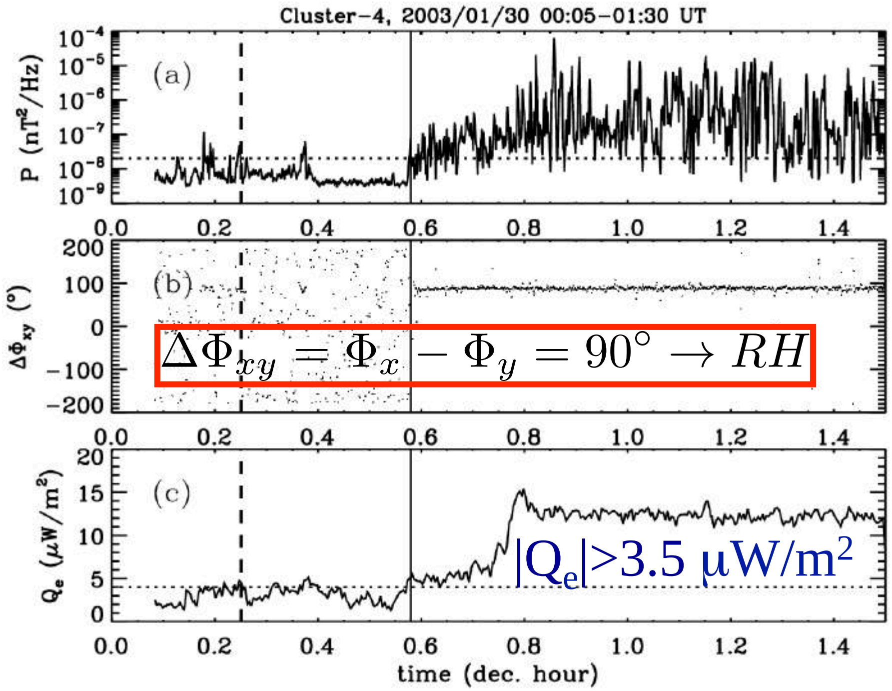
$$\boxed{\Delta\Phi_{xy} = \Phi_x - \Phi_y = 90^\circ}$$

Whistlers appear for high electron heat flux

[Maksimovic et al. 2005]



[Lacombe et al. 2014, APJ]



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

$|Q_e| > 3.5\ \mu W/m^2$

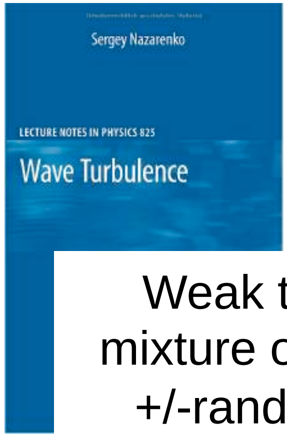
$$Q_e = \int \frac{m}{2}\mathbf{U}U^2 f(v)d^3v, \quad \mathbf{U} = \mathbf{v} - <\mathbf{v}>$$

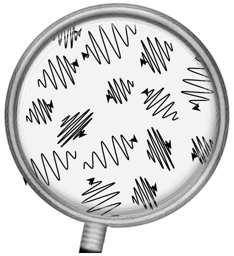
Electron heat flux, Q_e, is a measure of the asymmetry of the electron distribution function $f(v_e)$. In the solar wind it is present for $f(v_{e\|})$.

We find that whistlers grow with Q_e(generation mechanism: whistler heat flux instability, see Gary et al.,99).

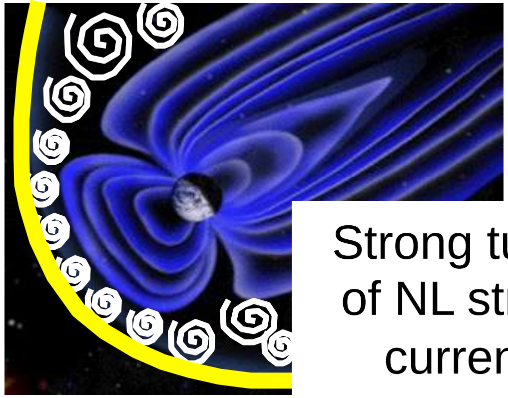
Turbulence nature: weak (or wave) vs strong

Courtesy S. Galtier

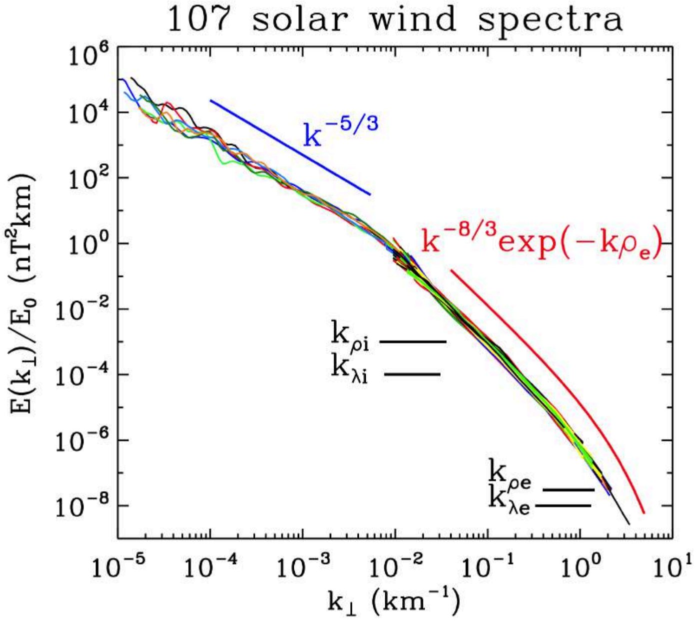




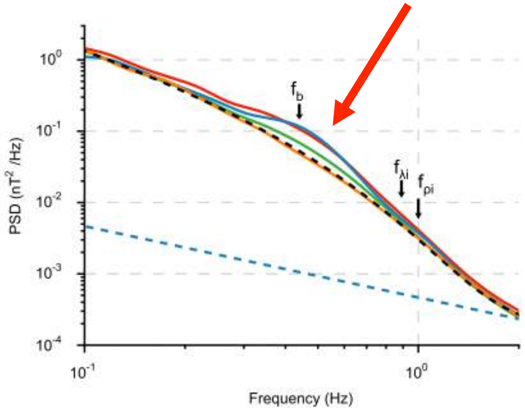
Weak turbulence: mixture of waves with +/-random phases

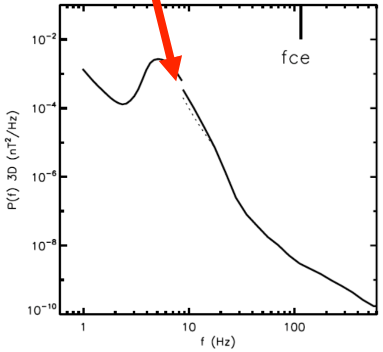


Strong turbulence: mixture of NL structures (vortices, current sheets, ect…)



Zooms around ion and electron scales:

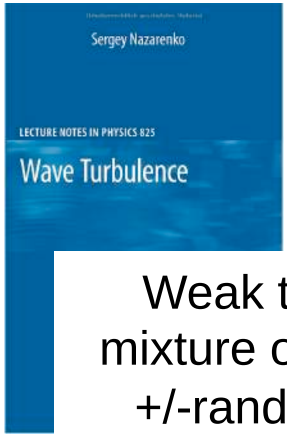




Strong turbulence within $k^{-5/3}$ and $k^{-8/3}$ ranges + waves at ion and electron scales.

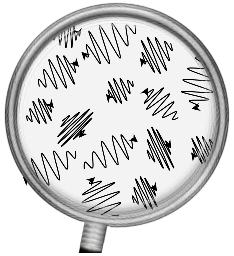
Turbulence nature: weak (or wave) vs strong

Courtesy S. Galtier

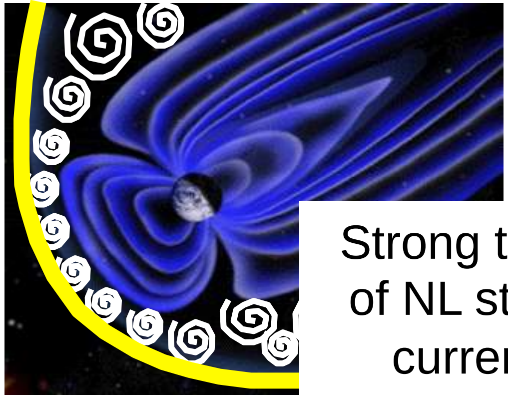

Sergey Nazarenko

LECTURE NOTES IN PHYSICS 825

Wave Turbulence

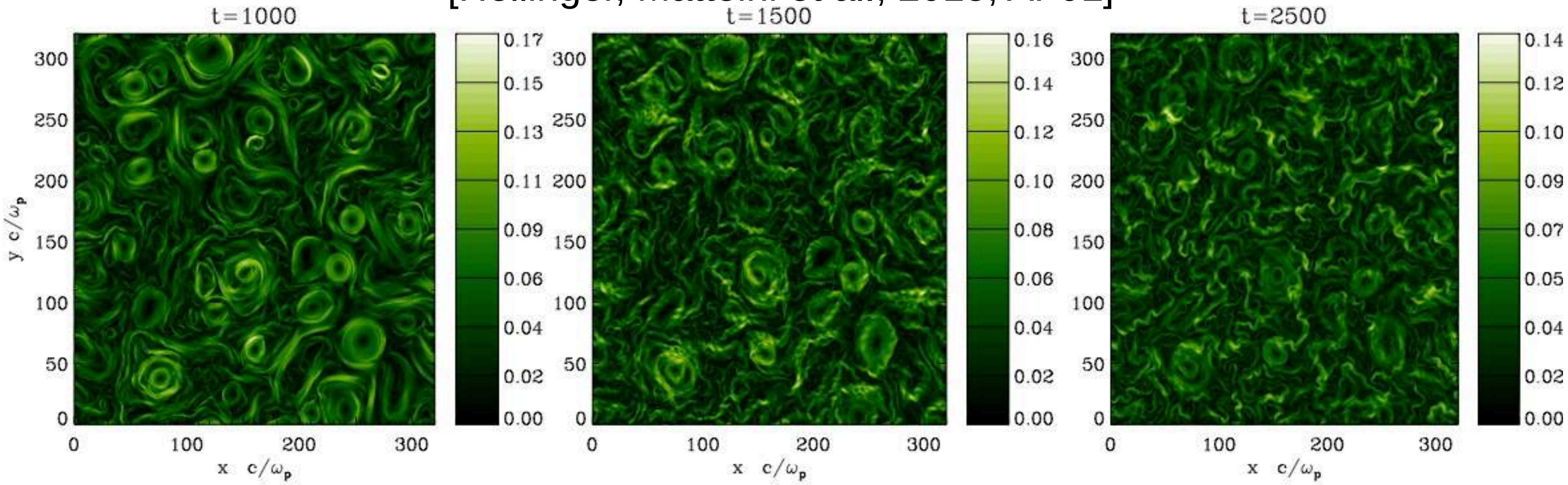


Weak turbulence: mixture of waves with +/-random phases



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

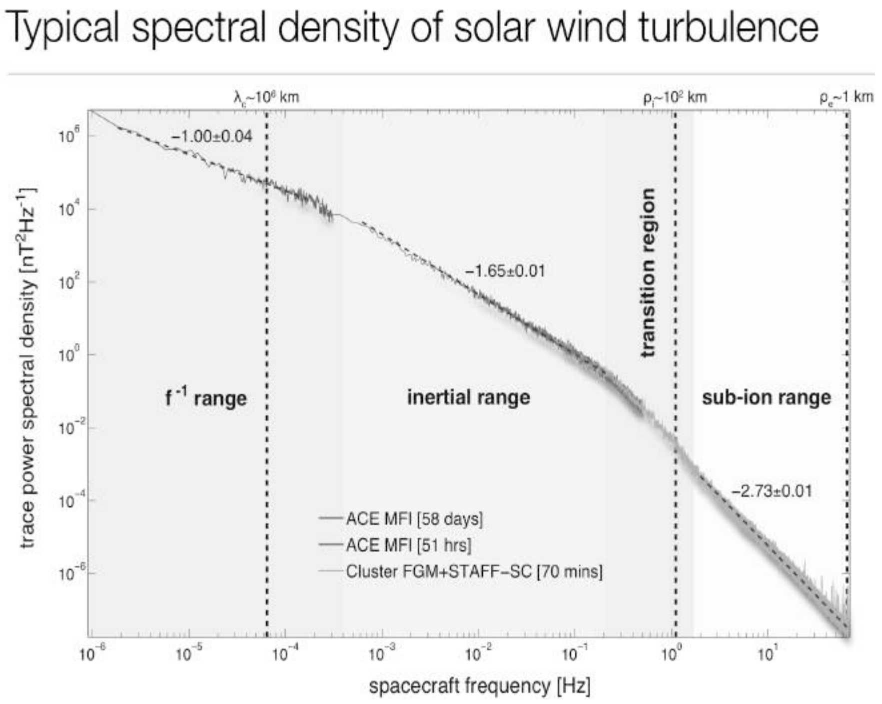
[Hellinger, Matteini et al., 2015, APJL]



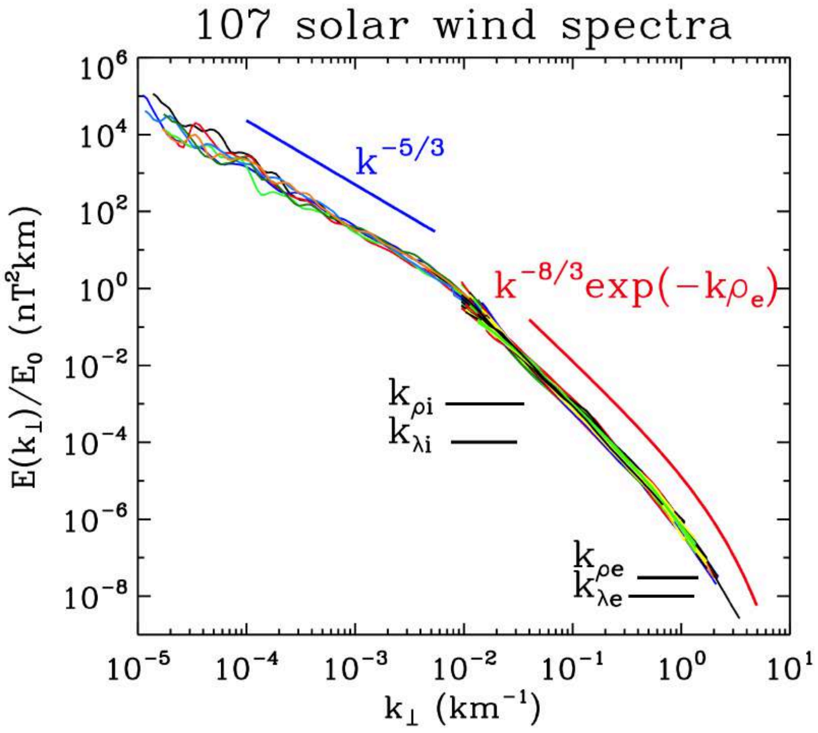
Courtesy of Lorenzo Matteini: 2D Hybrid numerical simulations showing developpment of strong turbulence (vortices) with superposed waves at ion scales.

Discussion and Conclusion

- Solar wind is one of the best laboratories of space plasma turbulence.
- **In-situ observations: from MHD (10^7 km) to sub-electron scales (300 m).**
- At very large scales: spectrum is ~f^{-1}, Alfvenic fluctuaitons;
- MHD inertial range is dominated by k_{perp} fluctuations, with Kolmogorov's power law ;
- One decade around ion scales: superposition of turbulence and waves/ion instabilities ;
- Between ion and e-scales: small-scale inertial range ~$k_{perp}^{-8/3}$;
- One decade around e-scales: dissipation at ~ρ_e + sometimes whistler waves with $k_{||}$.


Typical spectral density of solar wind turbulence

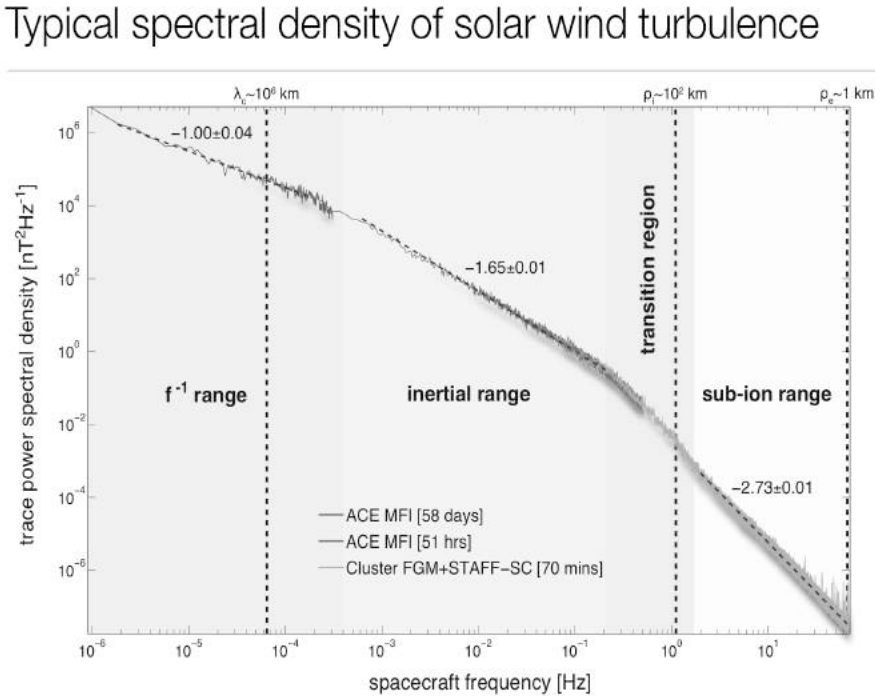
[Kiyani et al. 2015]


107 solar wind spectra

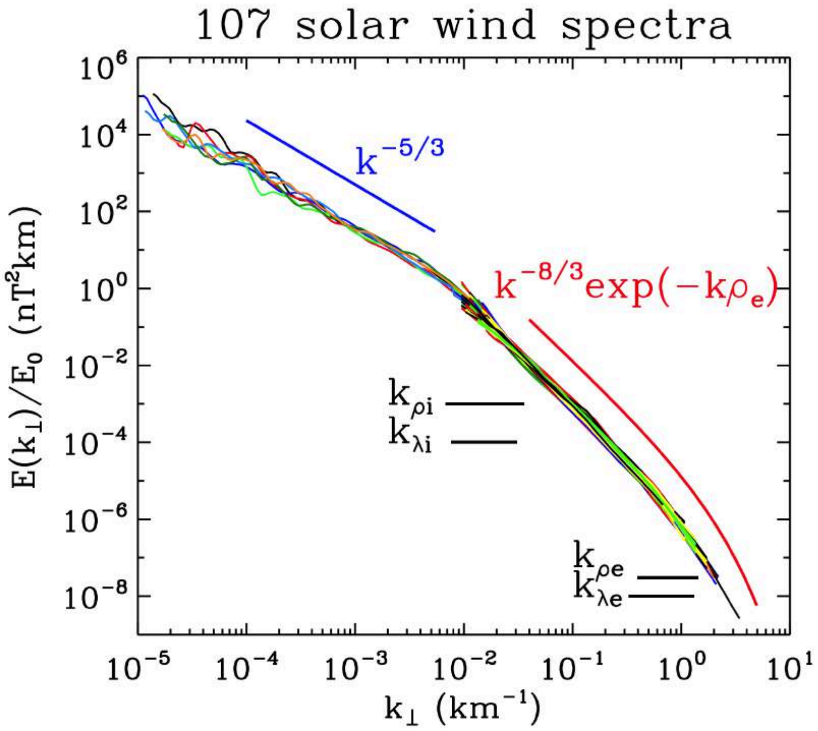
[Alexandrova et al. 2012]

Open questions

- Nature of Kolmogorov like turbulence ? Role of compressibility ?
- Physical processes at ion scales ?
- Final dissipation at electron scales ?
- Plasma heating and particle acceleration by turbulence ?
- Dissipation without collisions ?
- …



[Kiyani et al. 2015]

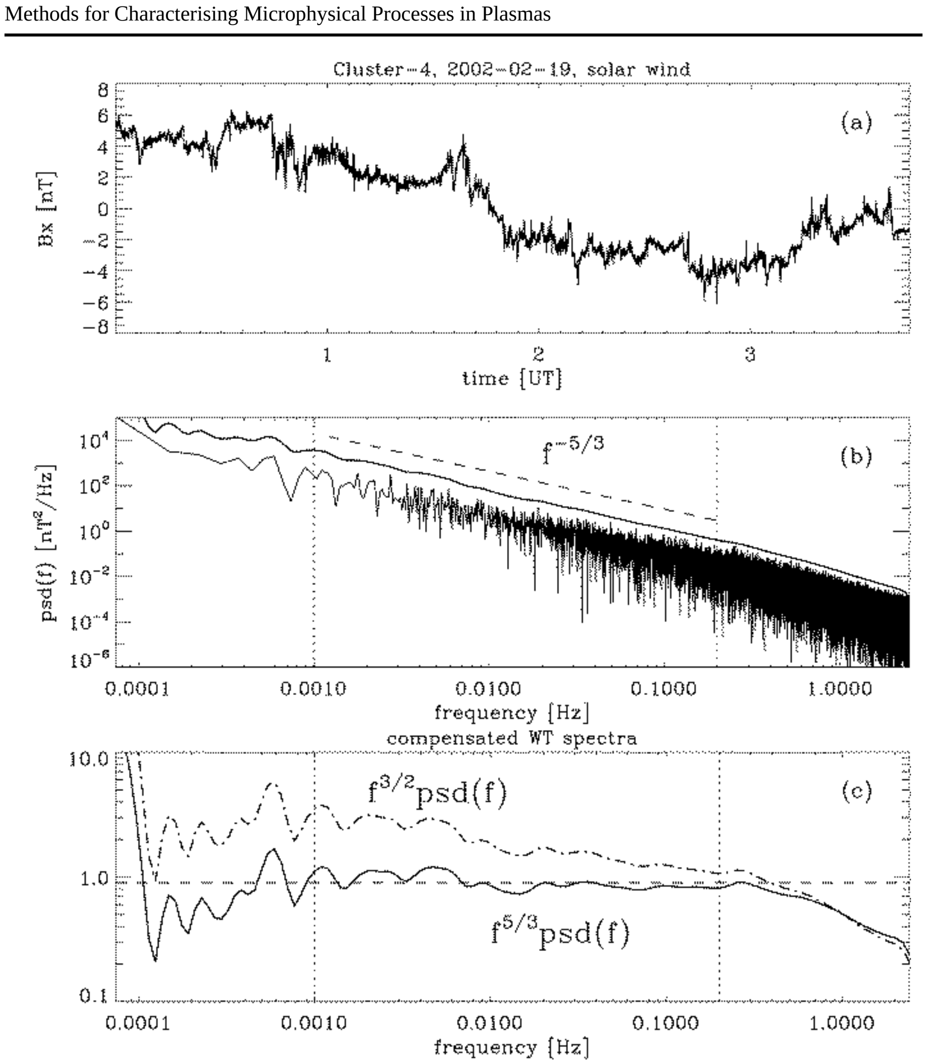


[Alexandrova et al. 2012]

Bonus

How do we measure turbulent spectra?

Satellites in-situ measurements are time series =>
Fourier (or Wavelet) transform => frequency spectra


Methods for Characterising Microphysical Processes in Plasmas

[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

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

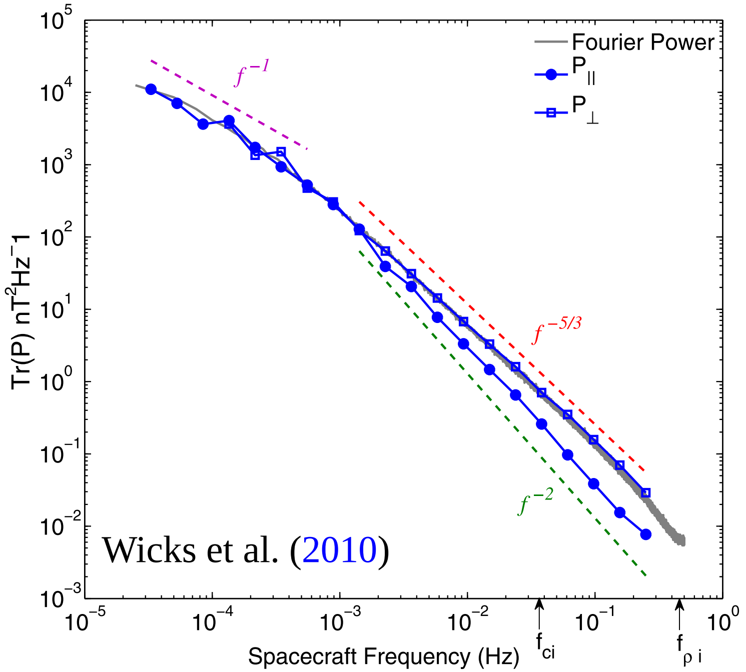
Supposing that ω_0 << k.V, (Vφ << V) :

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

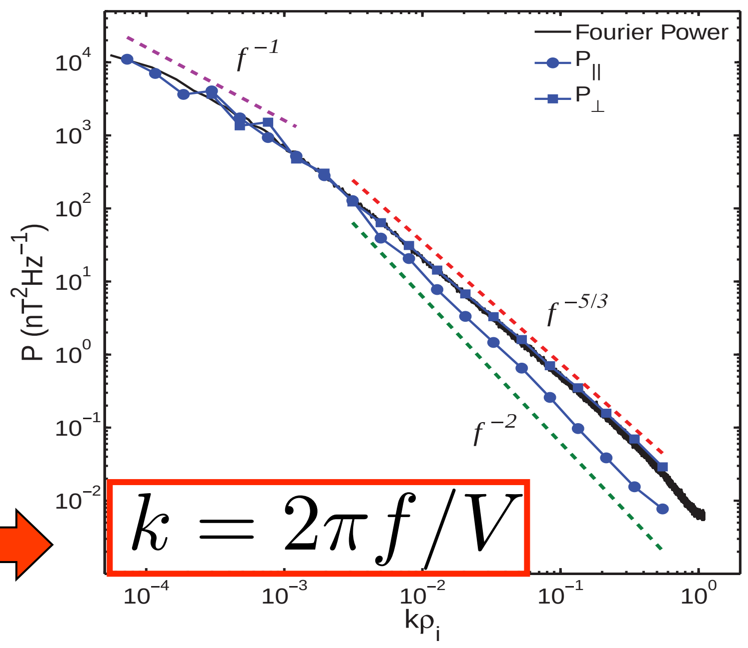
We don’t know the angle between k and V
=> assumption of k || V:

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

Anisotropy of turbulent fluctuations at MHD scales



Taylor hypothesis



$$k = 2\pi f / V$$

- Alfvénic turbulence of Goldreich and Sridhar, 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):

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

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