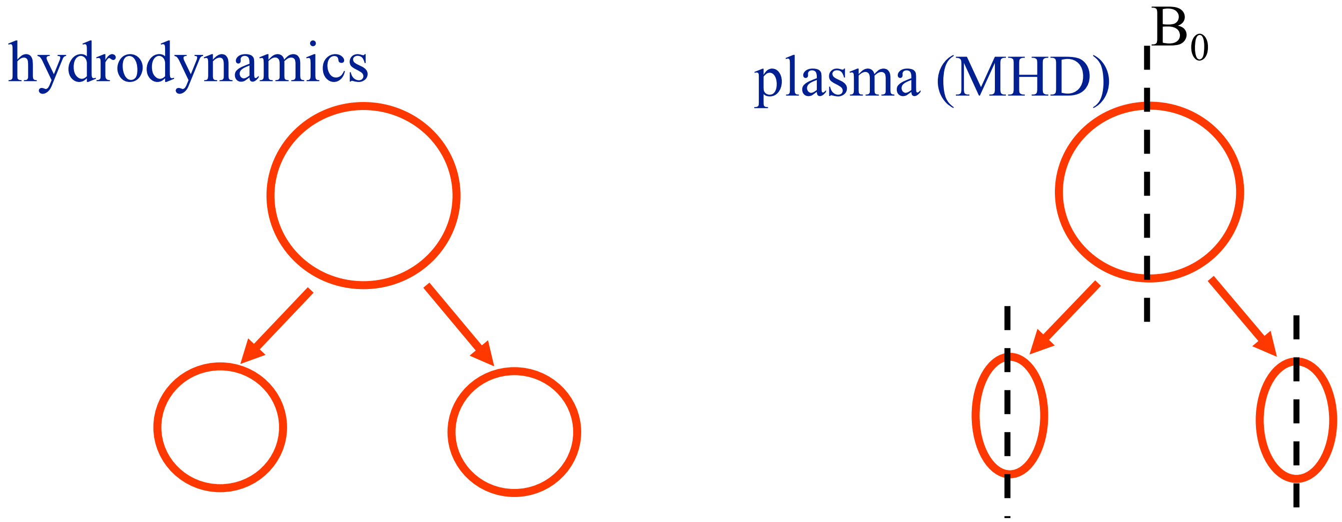
Space plasma turbulence from proton to sub-electron scales

Olga Alexandrova
olga.alexandrova@obspm.fr

LESIA, Observatoire de Paris

Turbulence in space plasmas

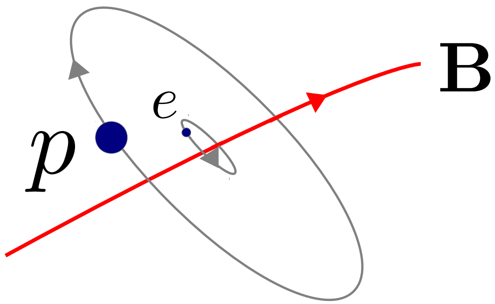


1. Presence of a mean magnetic field B_0 leads to an anisotropy of turbulent fluctuations
2. Plasma waves: Alfven, magnetosonic, mirror, wistlers, kinetic Alfven waves (KAW), etc… (wave turbulence)
3. No collisions : m.f.p. ~ 1 AU
4. In plasmas there is a number of characteristic space and temporal scales

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

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) :

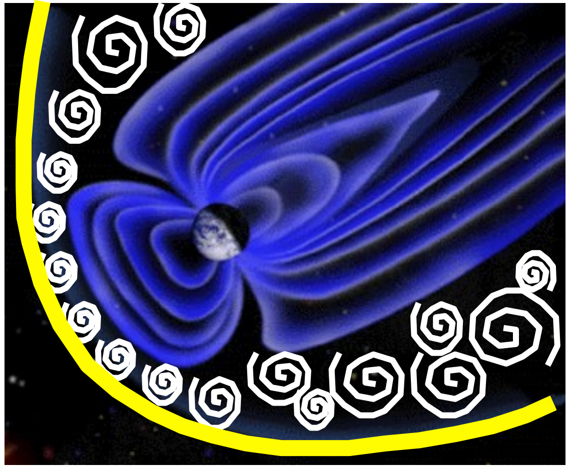
$$\lambda_{i,e} = \frac{c}{\omega_{pi,e}} \; ; \; \omega^2_{pi,e} = \frac{4\pi n e^2}{m_{i,e}}$$

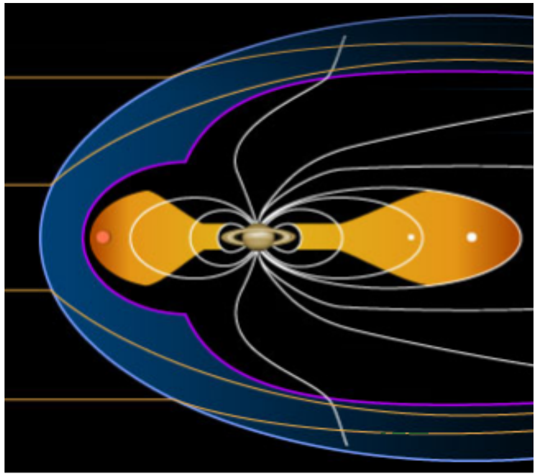
- Debye length λ_D (sphere of influence of a given test charge in a plasma); at L>λ_D plasma is quasi-neutre :

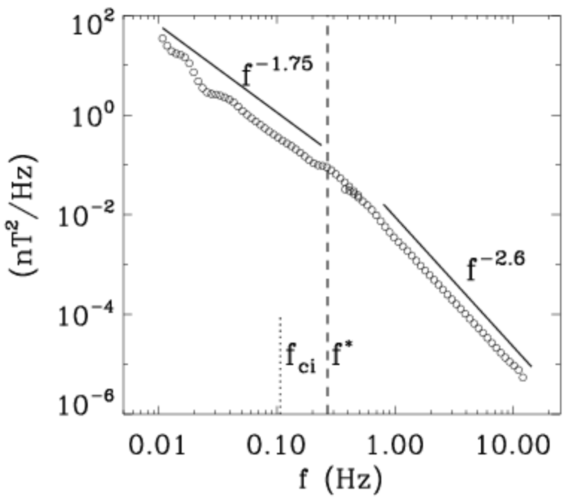
$$\lambda_D^2 = \frac{k_B T}{8\pi n e^2}$$

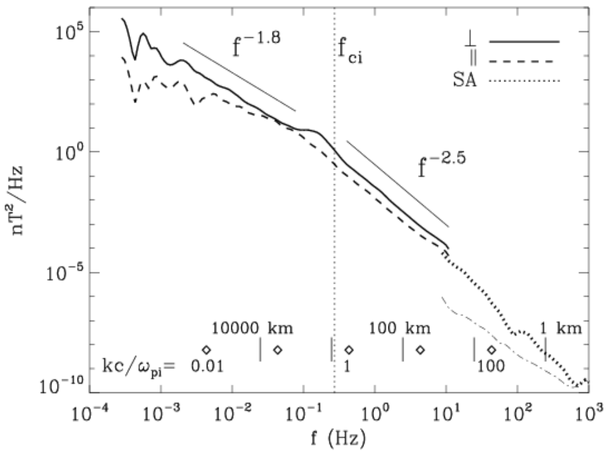
Plasma Turbulence in the Heliosphere

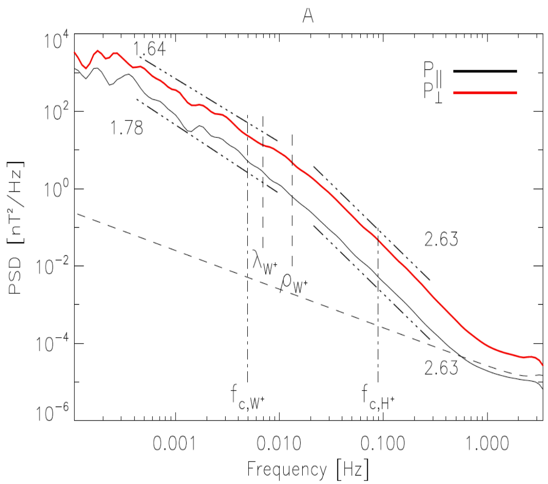
In situ measurements in the solar wind and planetary magnetospheres show omnipresence of plasma turbulence.





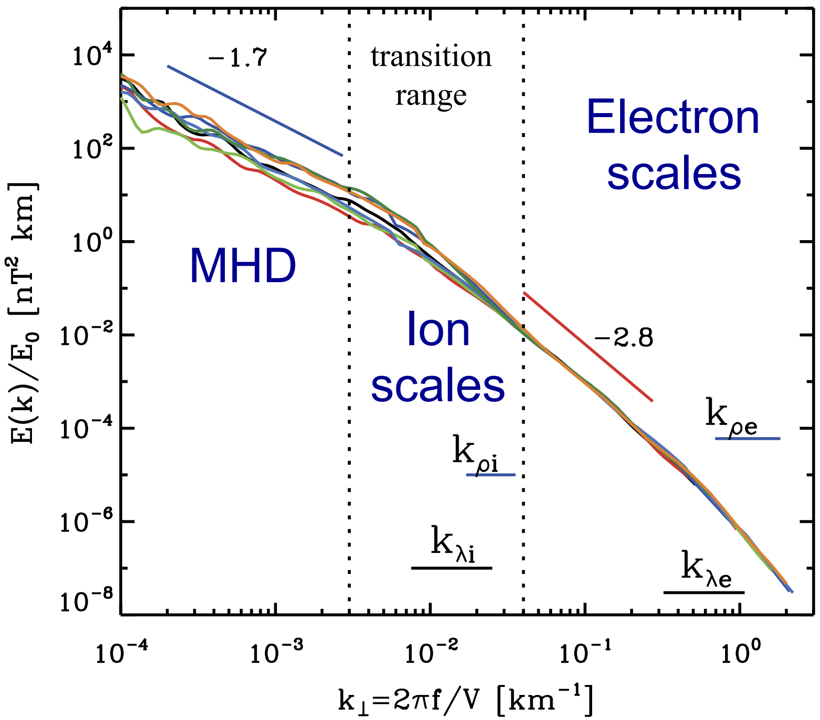






[Alexandrova et al. 2008, APJ; Von Papen et al. 2014, JGR]

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



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

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

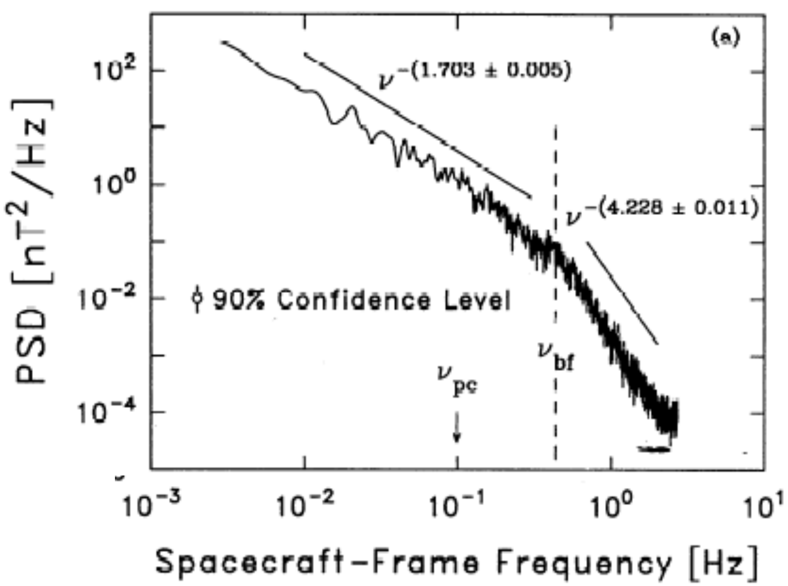
1. Ion scales

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

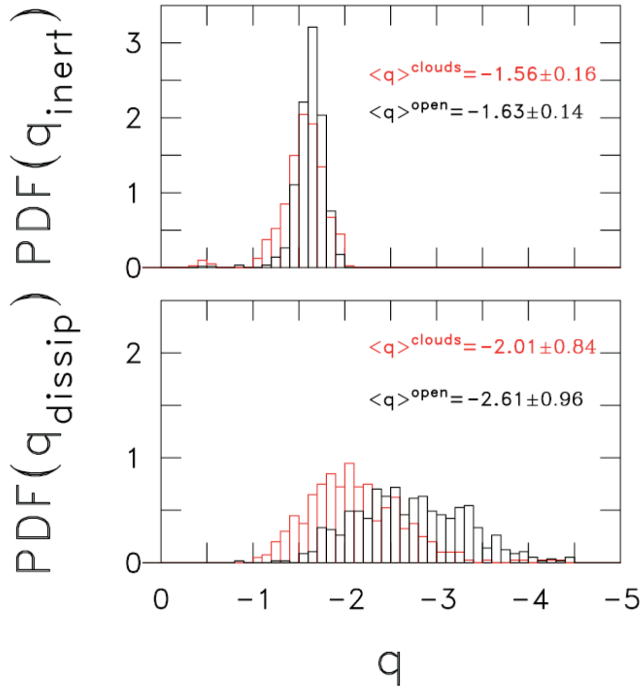
Turbulence around ion scales

Magnetic field spectrum

[Leamon et al,1998]



[Smith et al., 2006]



- There exist a spectral “break” close to ion scales
- Spectral variability at sub-ion scales: no universal behavior?
- Attention: less than 1 decade is measured…

Turbulence around ion scales

Ion moments spectra

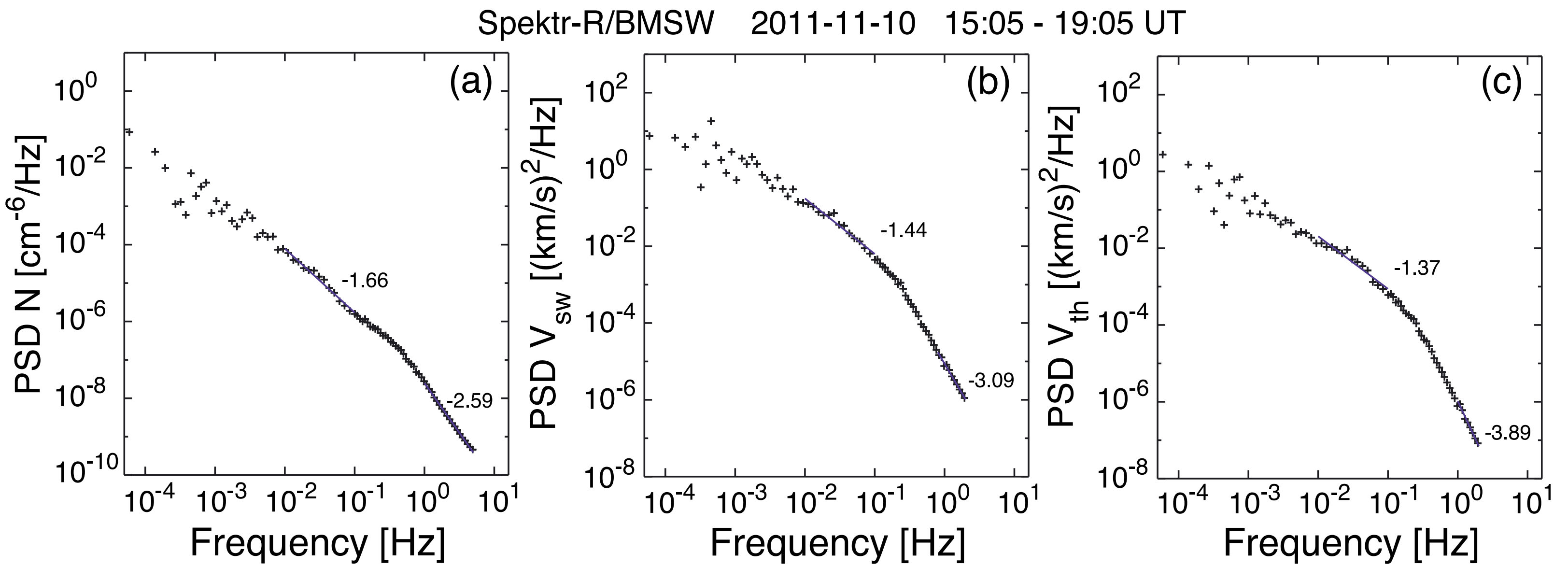
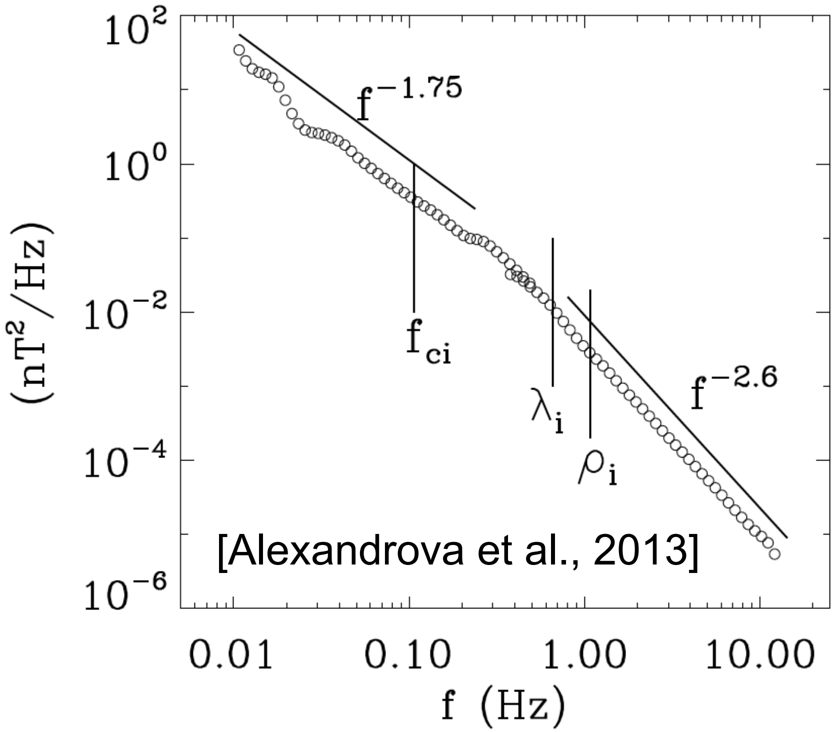


Fig. 10 Spectra of ion moments, (**a**) density, (**b**) velocity, (**c**) ion thermal speed, up to ~ 3 Hz as measured by *Spektr-R*/BMSW (Bright Monitor of Solar Wind) in the slow solar wind with $V_{sw} = 365$ km/s and $\beta_p \simeq 0.2$. Figure from Šafránková et al. (2013)

[Safrankova et al, 2013, PRL], see as well Chris Chen's talk

Which ion scale is responsible for the break?



Time scale

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

Spatial scales

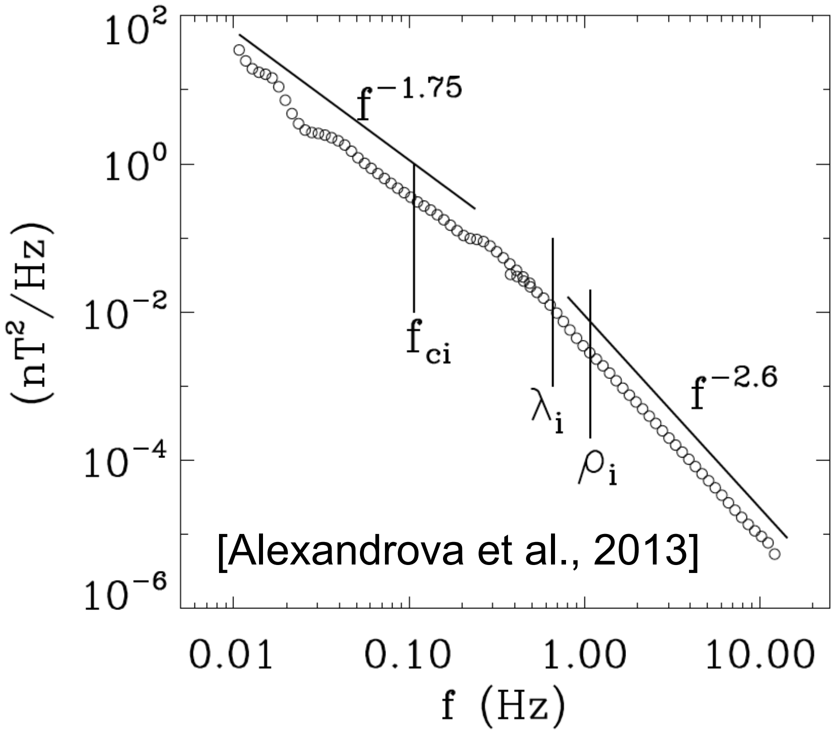
$$\rho_i = \frac{V_{\perp i}}{\Omega_{ci}} \ ; \ \lambda_i = \frac{c}{\omega_{pi}} = \frac{V_A}{\Omega_{ci}}$$

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?



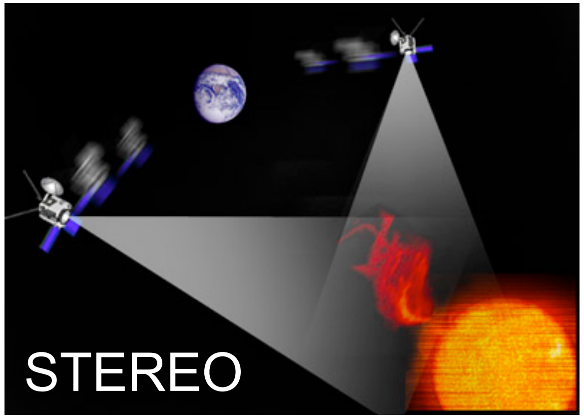
- Leamon et al. 2000 : λ_i
- Perri et al. 2010 : any of the scale/ combination of scales
- Bourouaine et al. 2012: λ_i
- Alex. S. (Gyro kinetics) : ρ_i
- Bruno et al. 2014: resonant k of parallel Alfven waves
- Chen et al. 2014: beta dependent.

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

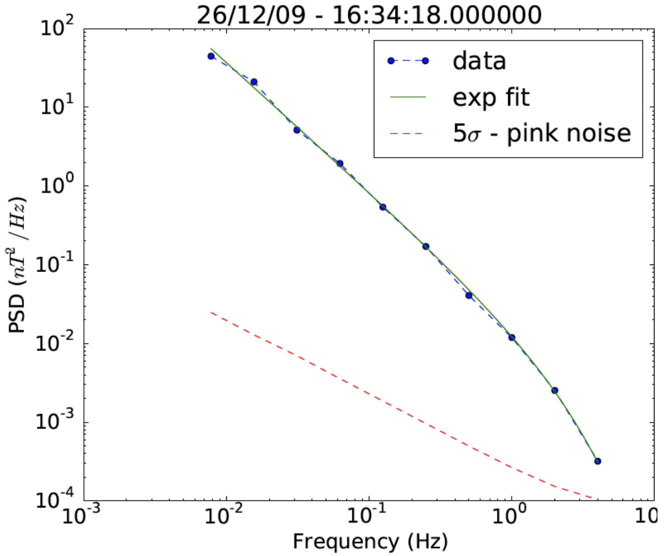
⇒ The largest characteristic ion scale “breaks” turbulent spectrum [Chen et al. 2014].

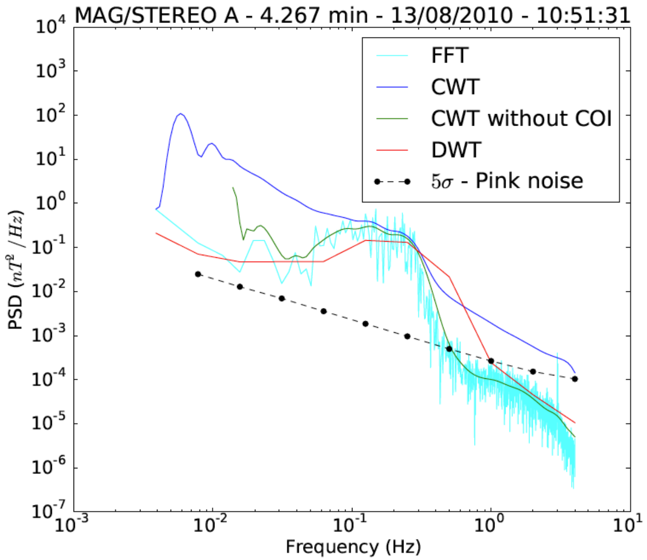
Statistical study of ion transition

A tentative to make a large statistical study with 6 years of STEREO mission measurements in the solar wind shows that the break point itself is not well defined.



Most of time we have a smooth transition and sometime spectral bumps related to emissions of monochromatic Alfven waves :



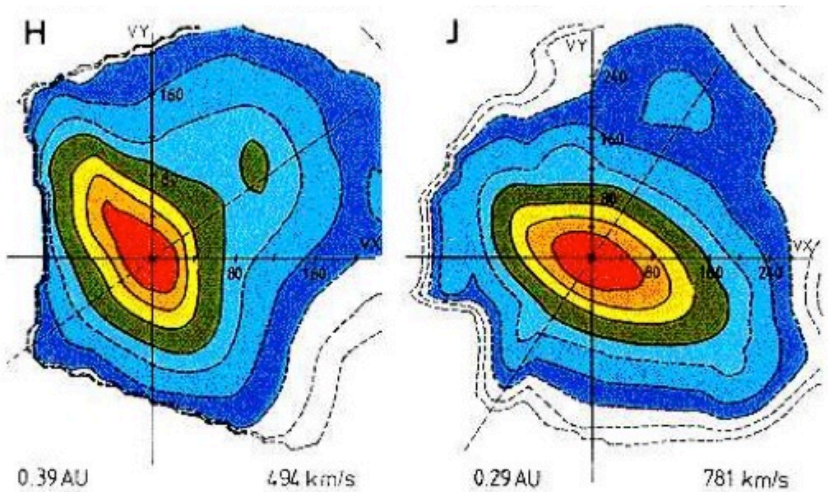


[Lion, Alexandrova, et al., in prep., 2015]

Ion instabilities

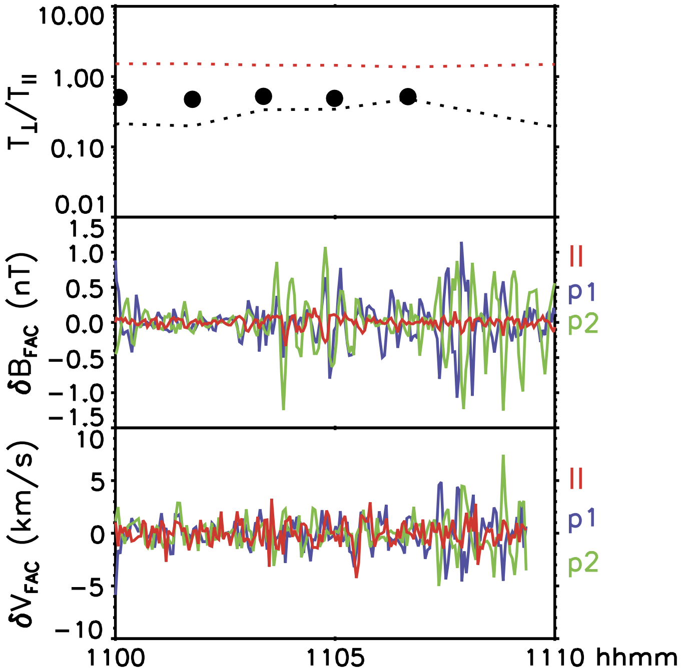
- ion distribution functions $f(V_i)$ are anisotropic =>
- ion temperature anisotropy instabilities develop to isotropy $f(V_i)$
- => quasi-monochromatic waves at a frequency/scale close to ion scales

[Marsch et al. 1983]

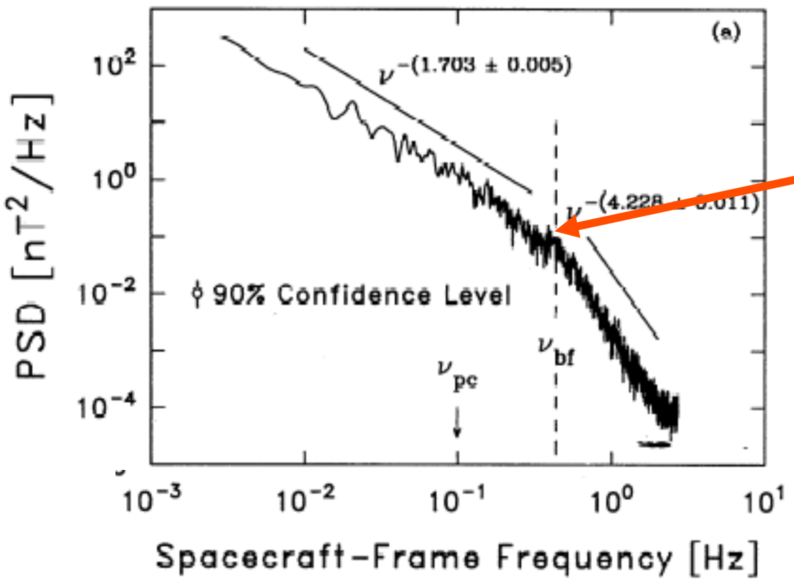


$$T_{i\perp} \neq T_{i\|}$$

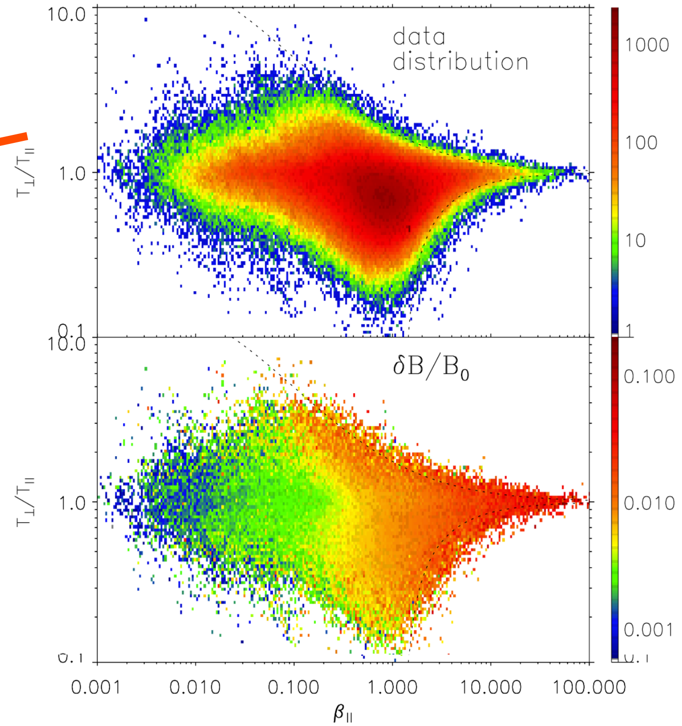
[Alexandrova et al. 2013]



Ion instabilities are at ion scales



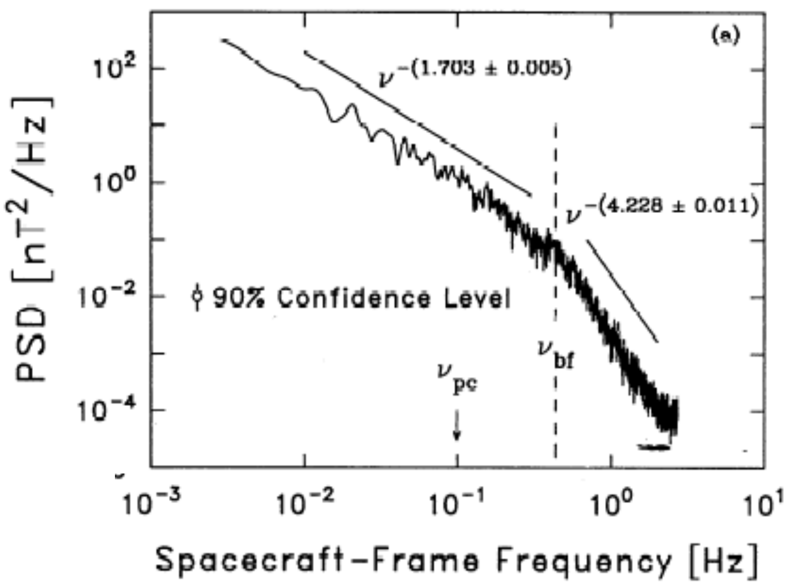
[Bale et al. 2009, PRL]



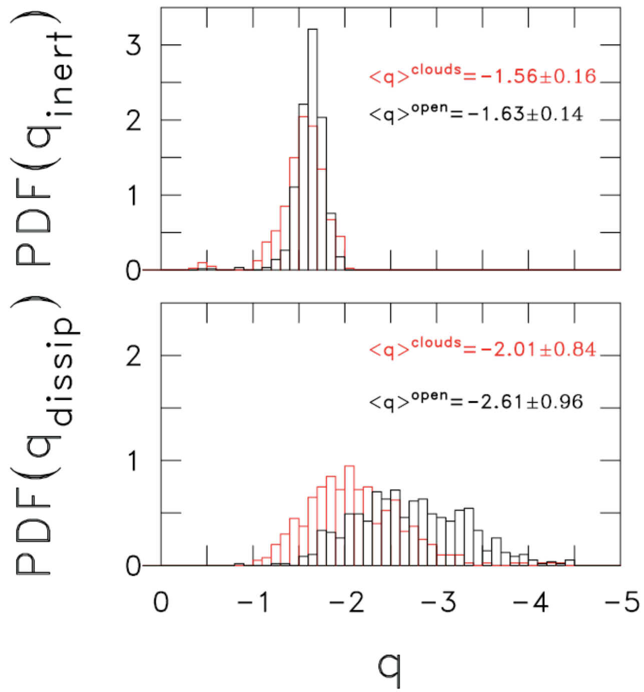
- At ion scales: superposition of 2 different phenomena, turbulence and ion temperature anisotropy instabilities.

Non-universal spectrum around ion scales

[Leamon et al,1998]



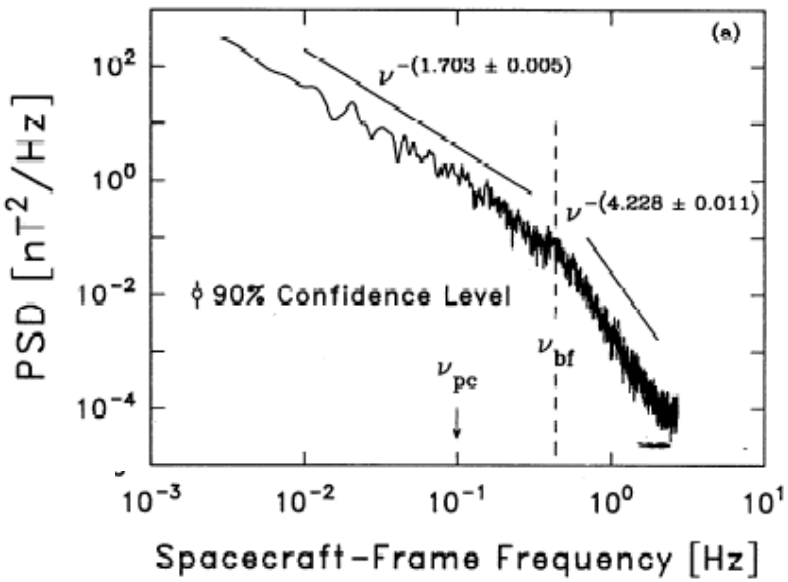
[Smith et al., 2006]

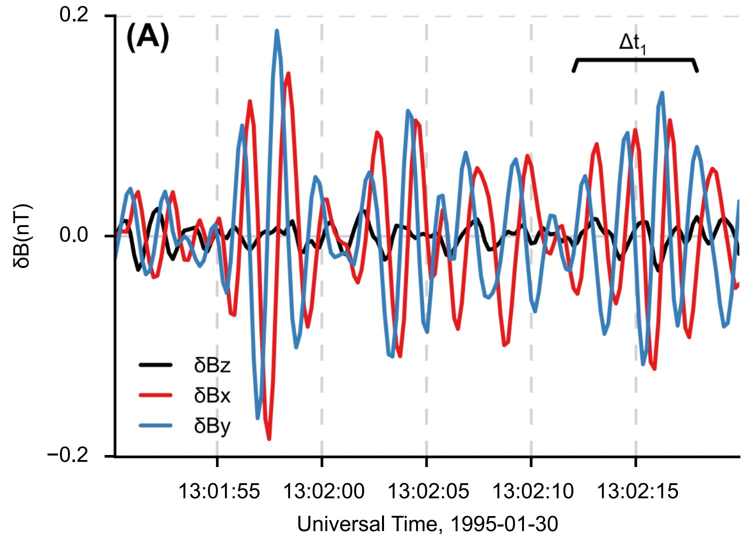


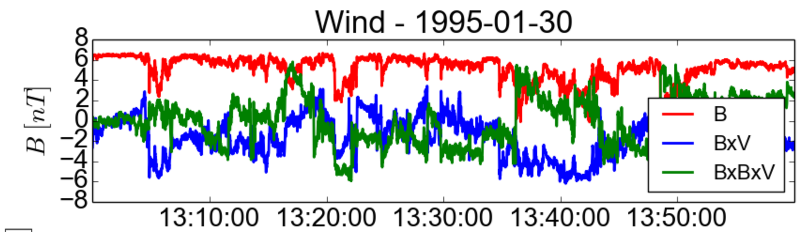
Do ion instabilities explain completely non-universality of the spectra just after the break?

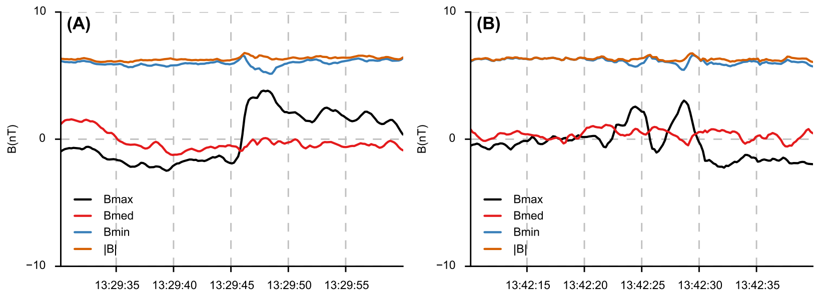
‘Typical’ solar wind spectrum : revisited

[Lion et al, 2015, to be submitted]





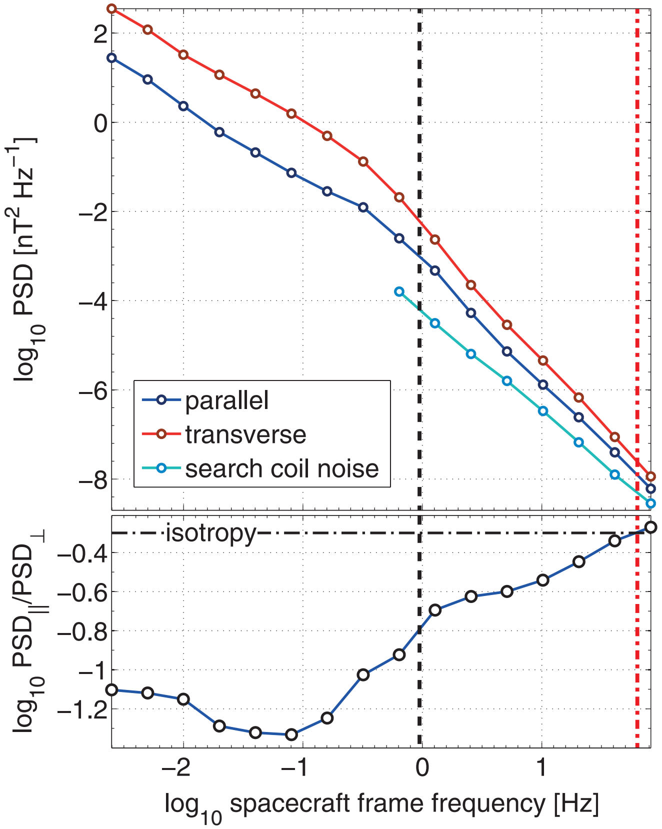


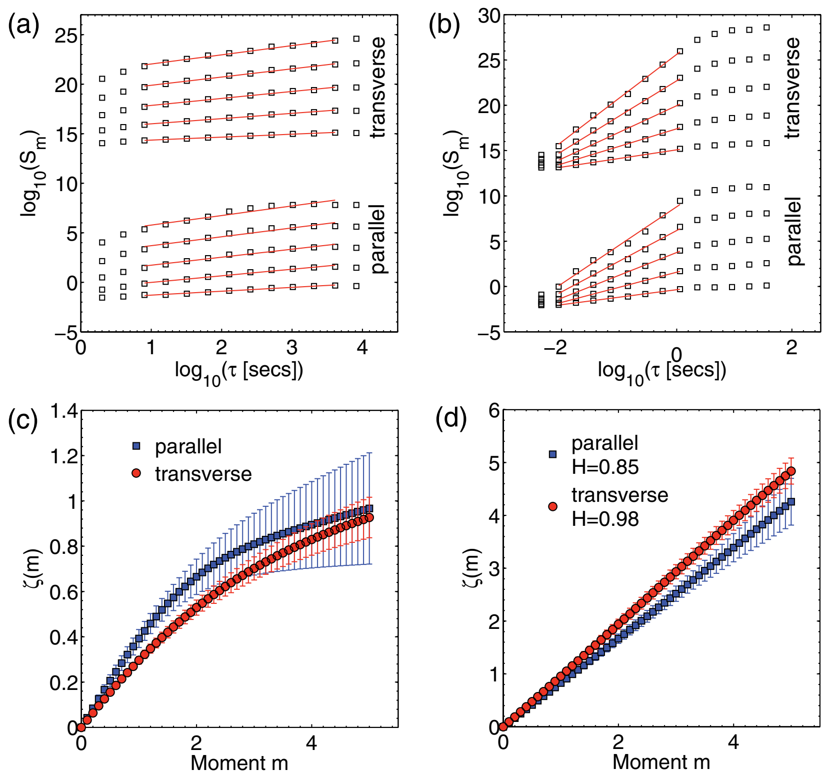


A particular combination of waves and coherent structures gives a clear break, otherwise, variable spectral shape, smooth transition, ect….
(see as well the talk of Denise Perrone)

Compressibility and intermittency

The Astrophysical Journal, 763:10 (13pp), 2013 January 20



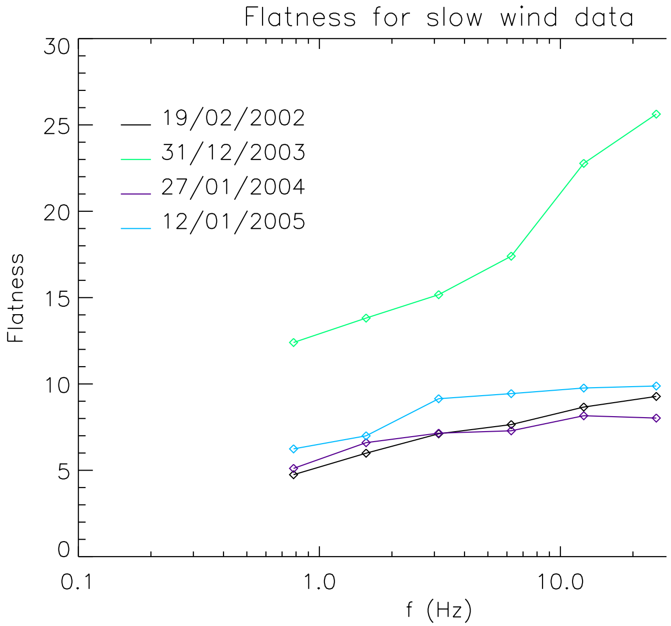


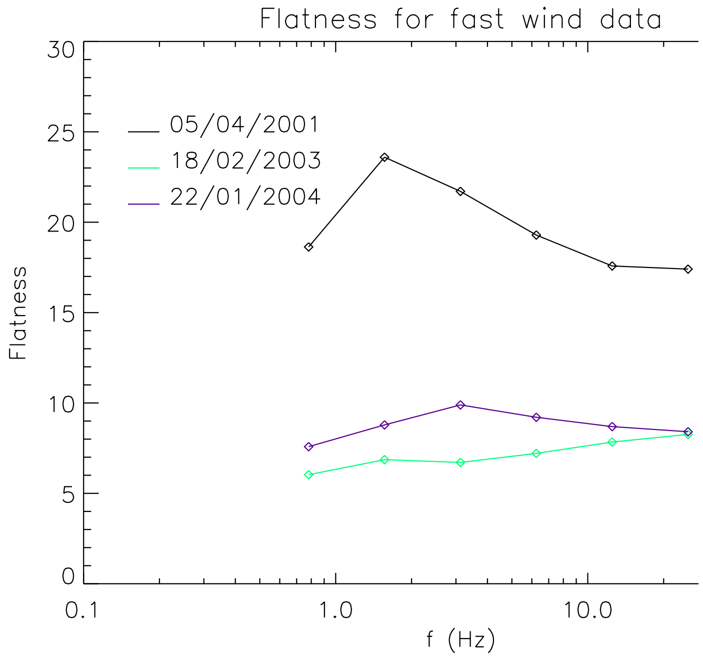
magnetic field. The *m*th order wavelet structure function (Farge & Schneider 2006) is given by

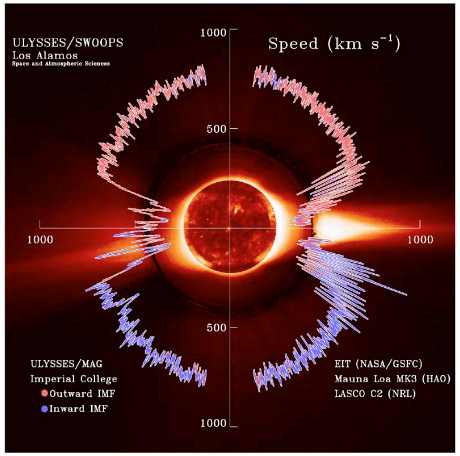
$$S^{m}_{\|(\perp)}(\tau) = \frac{1}{N}\sum_{j=1}^{N}\left|\frac{\delta B_{\|(\perp)}(t_j, \tau)}{\sqrt{\tau}}\right|^{m}, \qquad (7)$$

[Kiyani et al. 2013, APJ]

Intermittency at sub-ion scales in slow and fast winds





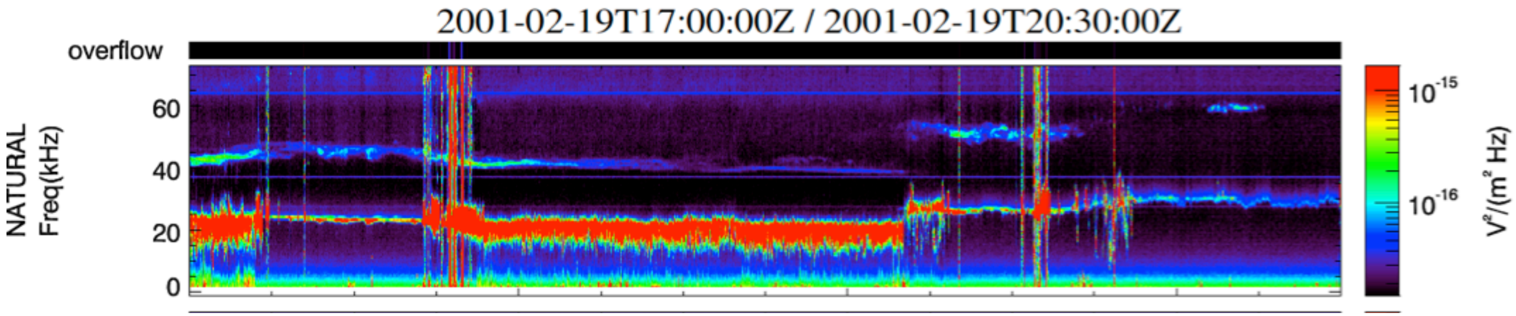


[C. Rossi, in preparation, 2015]

What is going on at electron scales?

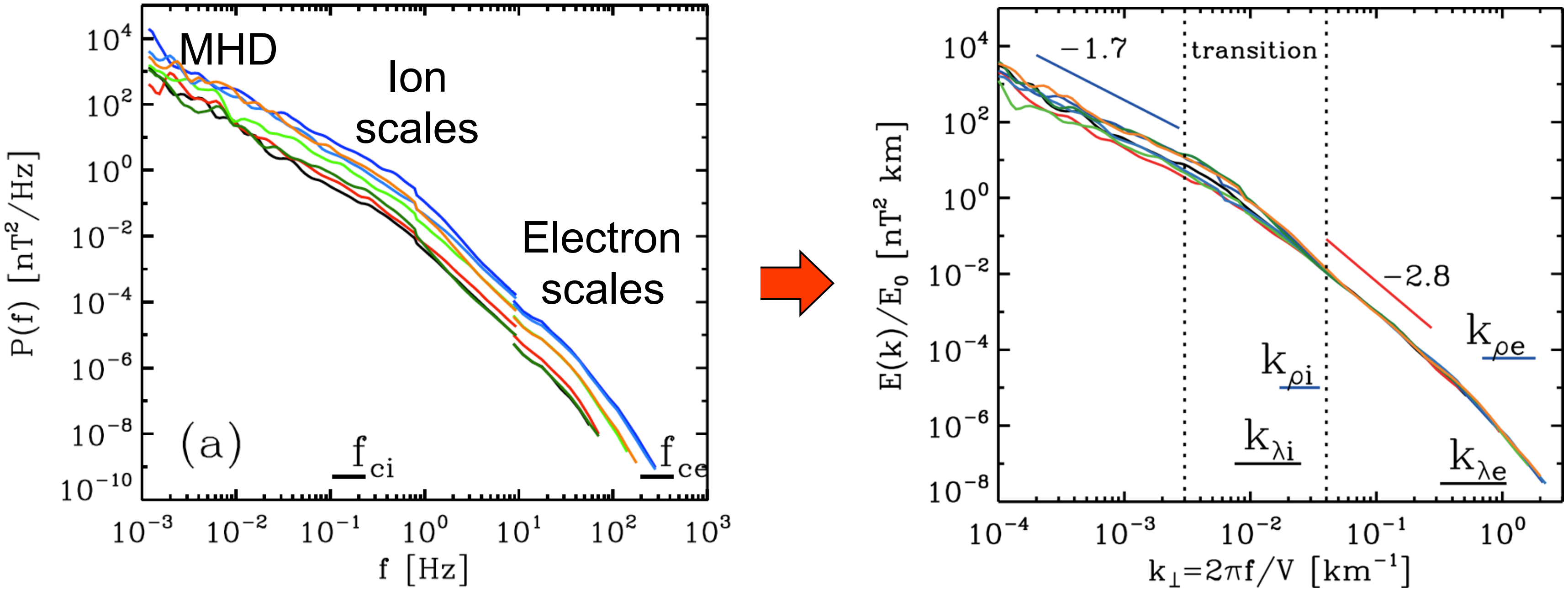
- Cluster mission : the most sensitive instrumentation (mag. spectrum up to 400 Hz).

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



Turbulent spectrum up to electron scales

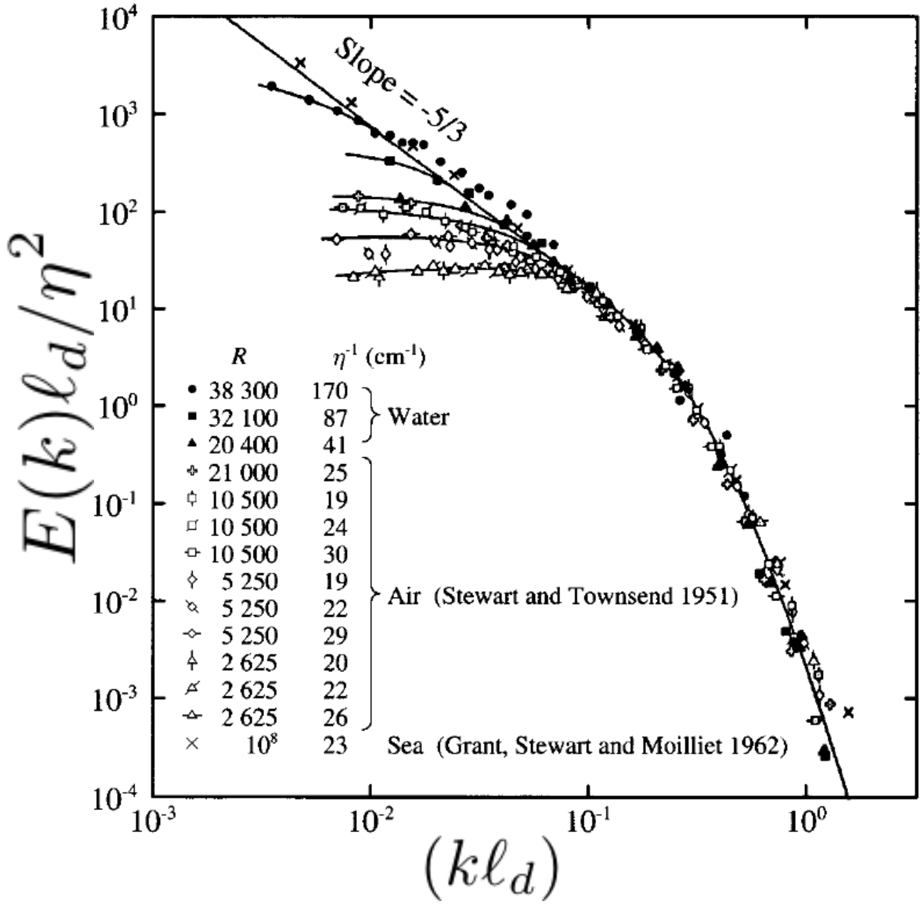
[Alexandrova et al. 2009, PRL; 2013, SSR]



- General spectra at MHD and between ion and electron scales (~$k^{-2.8}$).
- Spectral variability around ion scales due to presence of ion instabilities [e.g. Matteini+'07, Bale+'09], and coheren structures [Lion+'15, soon]
- End of the cascade? Dissipation scales?

Universal Kolmogorov's function:

Frisch, Turbulence: the legacy of Kolmogorov, 1996



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

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

ℓ_d: dissipation scale

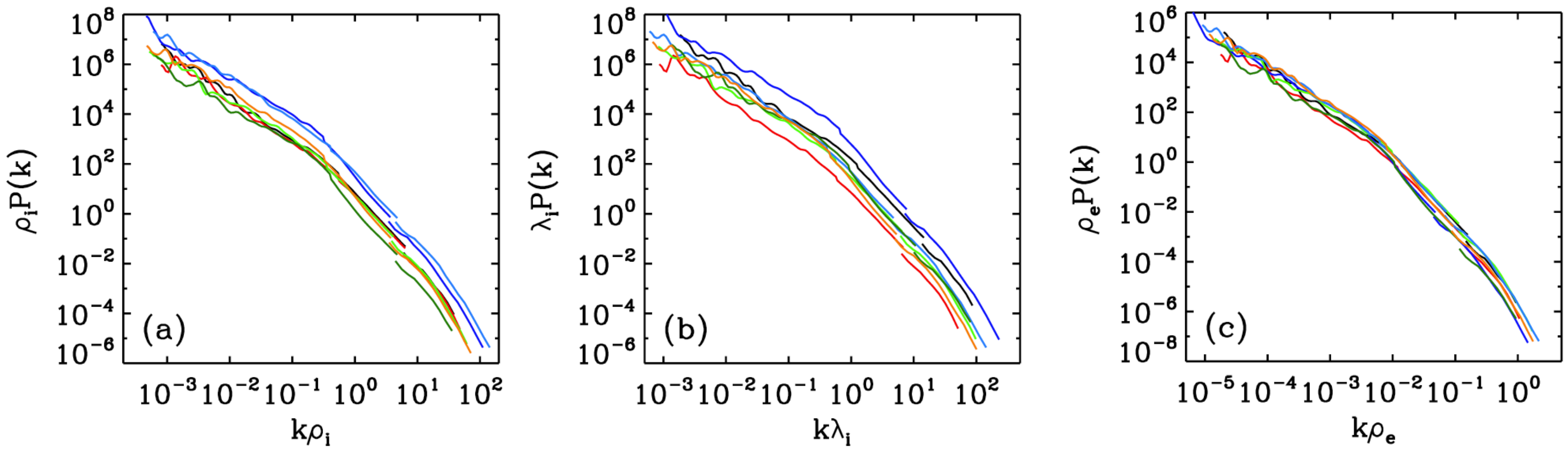
η: viscosity

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

Dissipation scale?

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

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

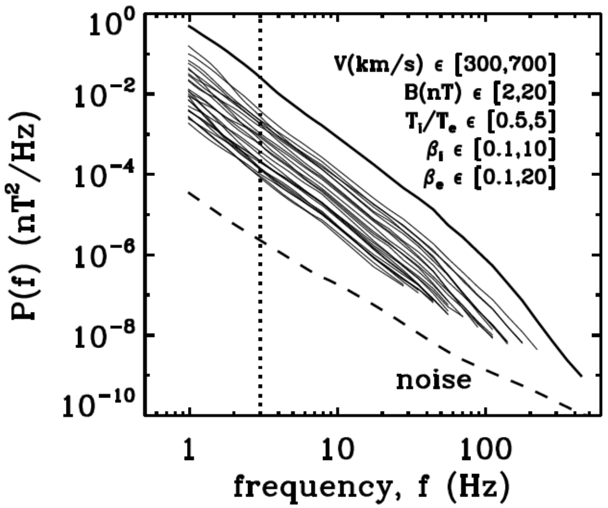


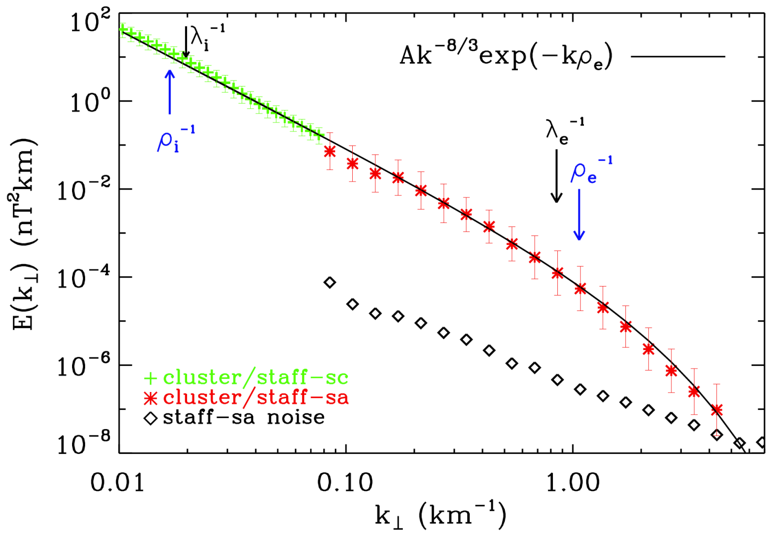
- Assumption: η=Const
- $k\rho_i$ & $k\lambda_i$ - normalizations are not efficient for collapse
- $k\rho_e$ normalization bring the spectra close to each other.

→ $\ell_d \sim \rho_e$

[Alexandrova et al., 2009, PRL]

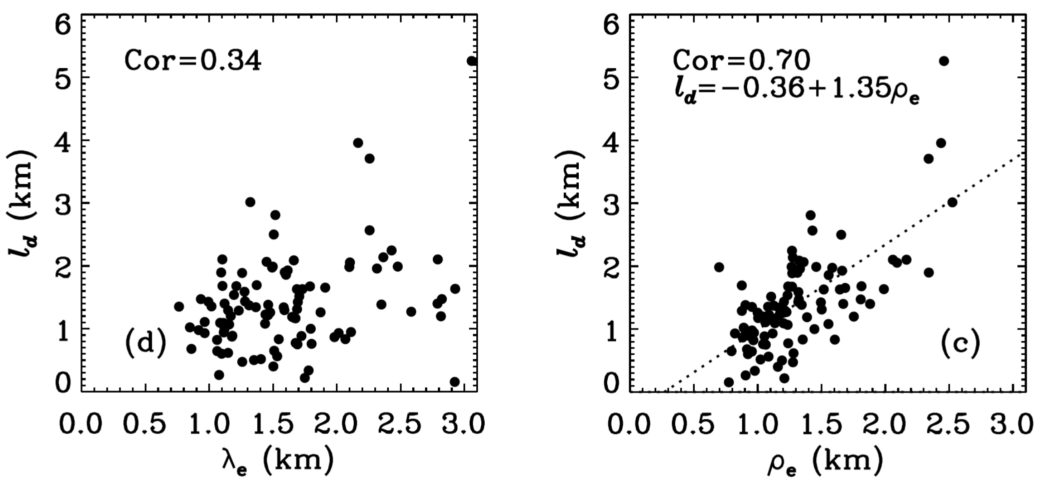
Spectrum at kinetic scales and dissip. scale





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

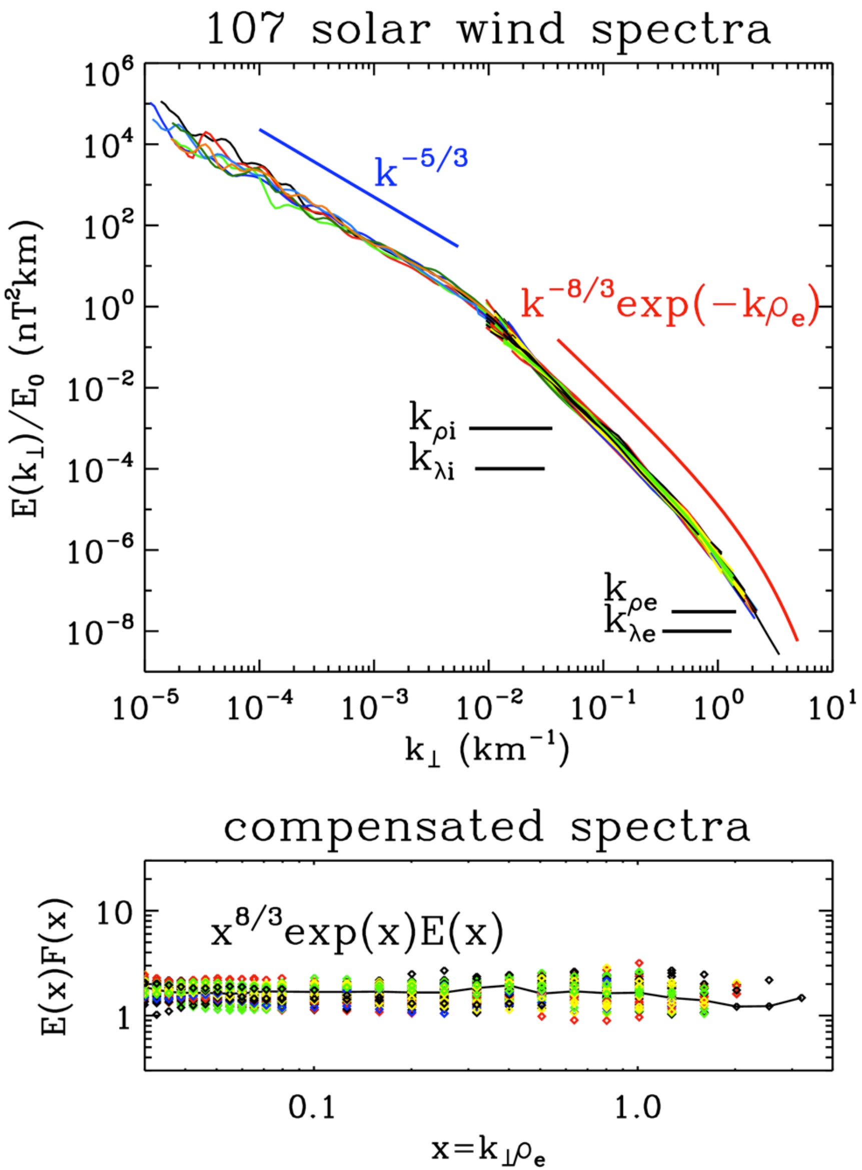
[Chen, Doolen, et al., 1993, PRL]



$$\ell_d \sim \rho_e$$

[Alexandrova et al., 2012, APJ]

General spectrum at kinetic scales



- For different solar wind conditions we find a general spectrum with "fluid-like" roll-off spectrum 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]

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

[Alexandrova et al., 2012, APJ]

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

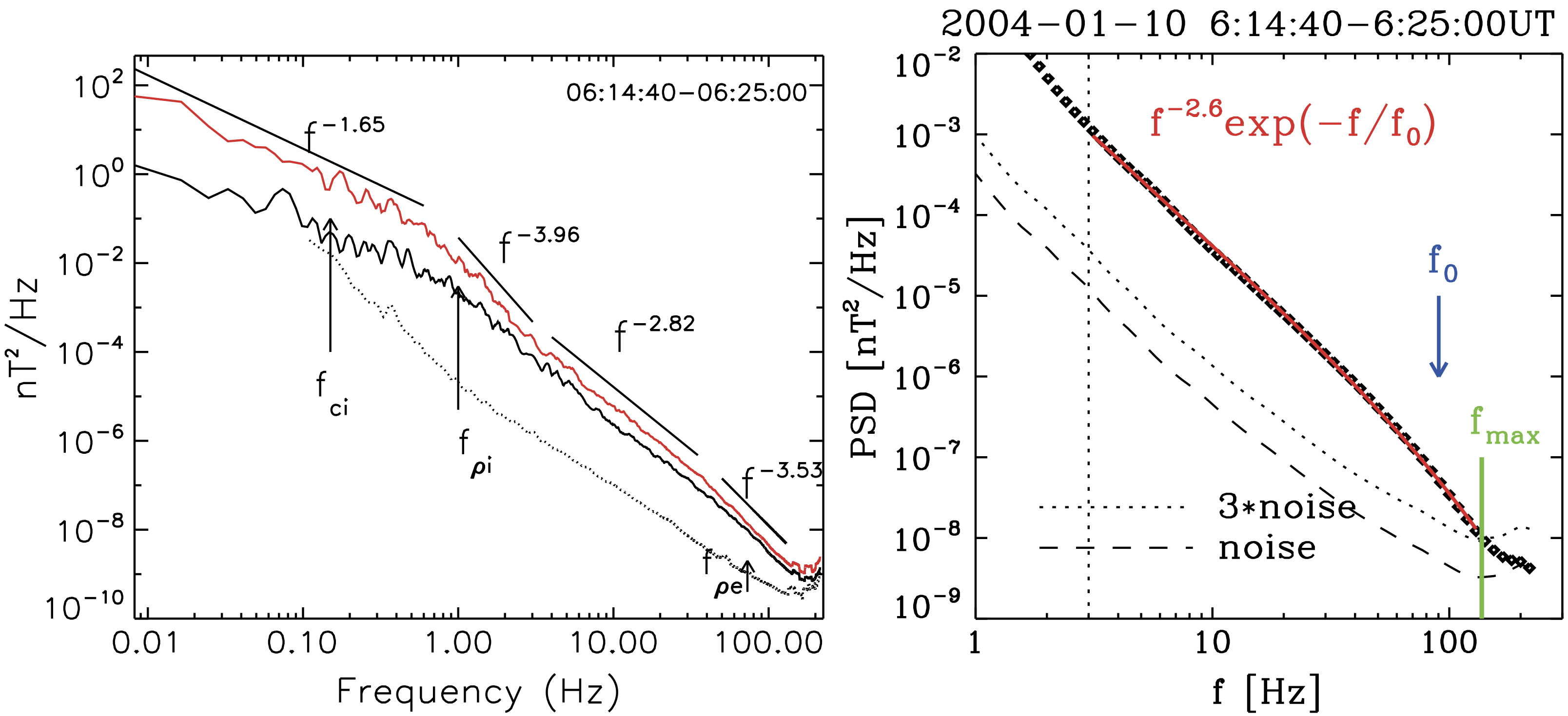


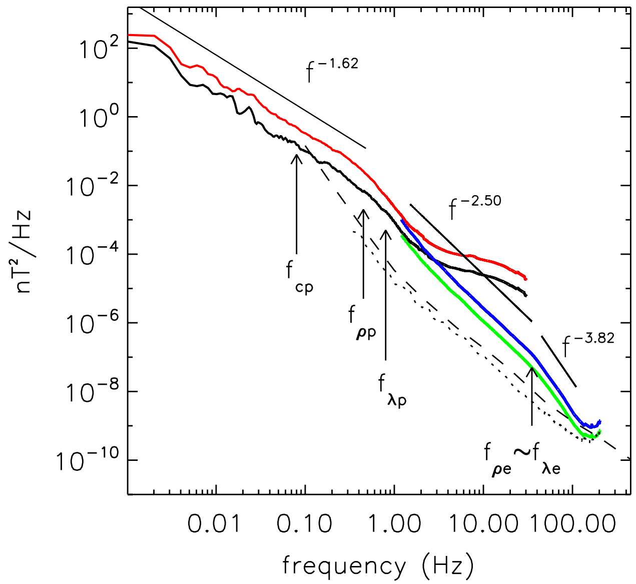
Fig. 18 (*Left*) Magnetic spectrum from Sahraoui et al. (2010), compared with $\sim f^{-2.8}$ for $4 \leq f \leq 35$ Hz and with $\sim f^{-3.5}$ for $50 \leq f \leq 120$ Hz, the break frequency is around 40 Hz. (*Right*) A zoom on the high frequency part of the spectrum on the left, fitted with $\sim f^{-2.6}\exp(-f/f_0)$, the exponential cut-off frequency $f_0 = 90$ Hz is close to the Doppler shifted ρ_e, $f_0 \simeq f_{\rho_e} = V_{sw}/2\pi\rho_e$. This last fitting function is equivalent to the model (7) for wave vectors

[Sahraoui et al., 2010, PRL]

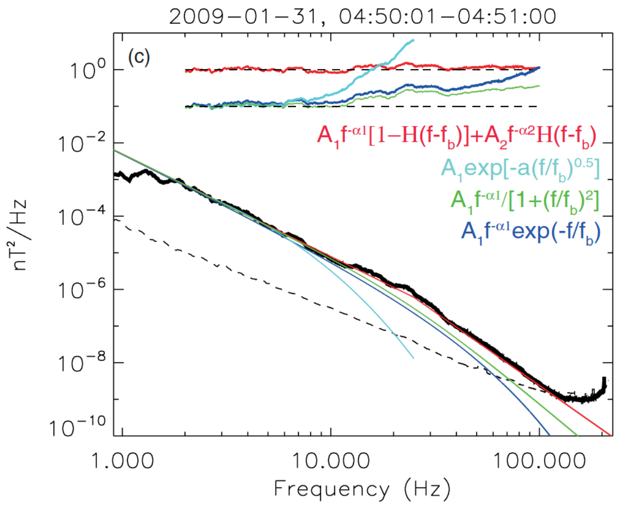
[Alexandrova et al. 2013, SSR]

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

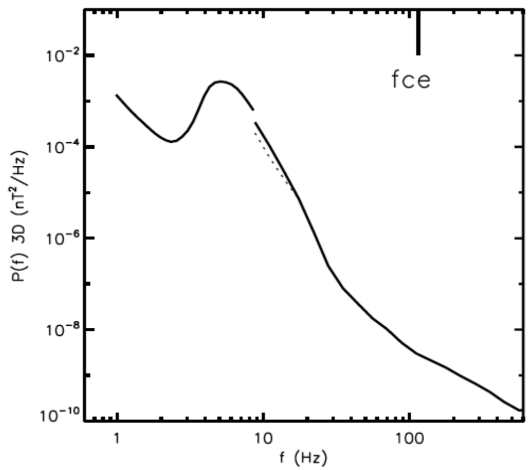
Observation of spectral break of bosse at electron scales:



[Sahraoui et al., 2009]



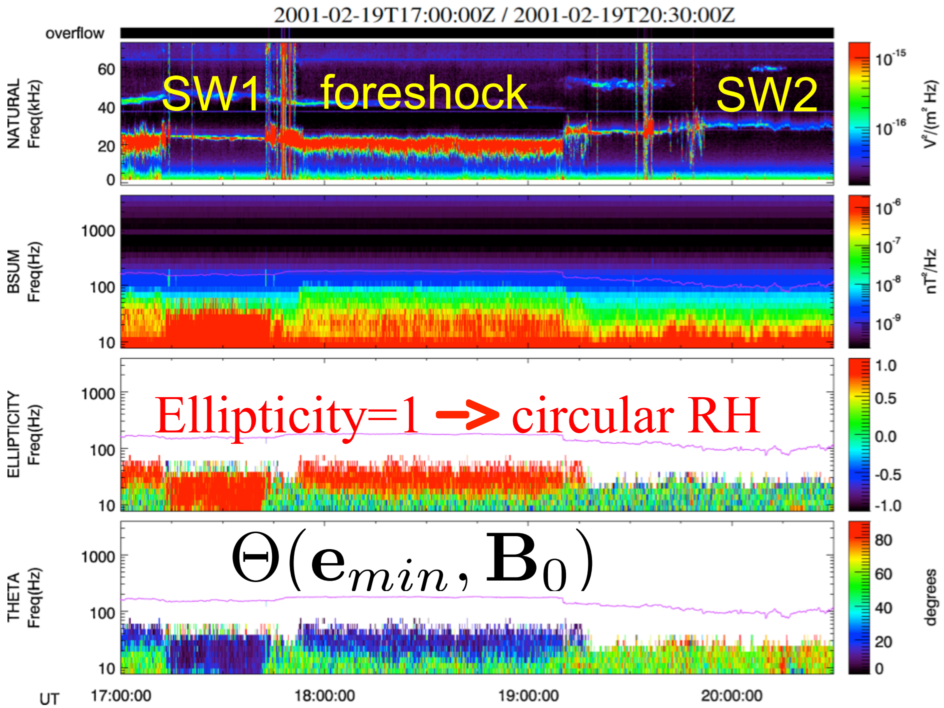
[Sahraoui et al., 2013]

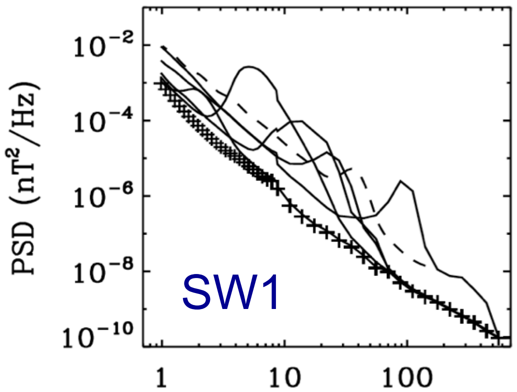


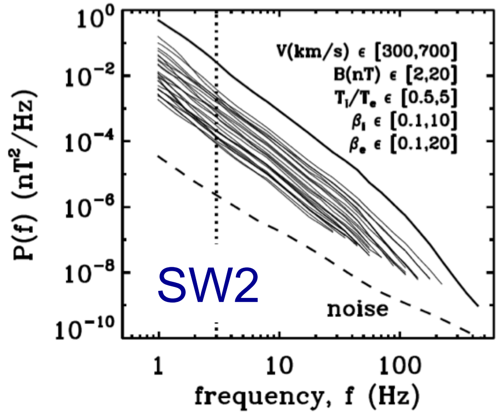
[Lacombe et al. 2014]

What do we learn from ion scales experience?!
- Are there any waves?

Importance of polarization study



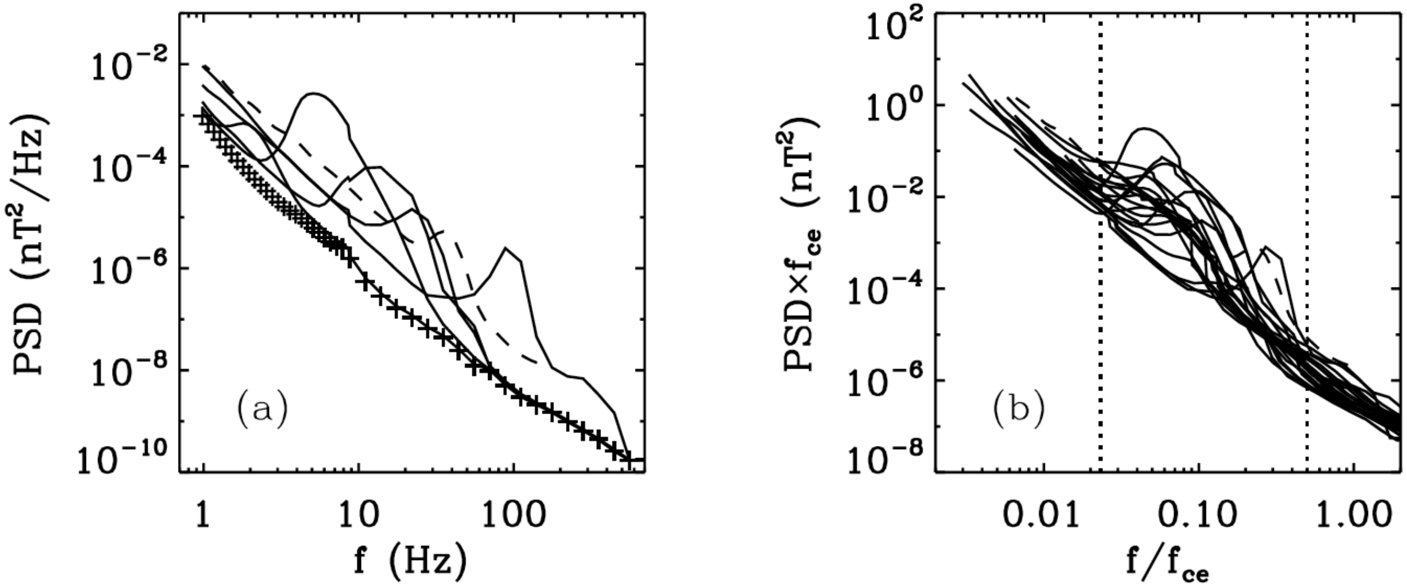




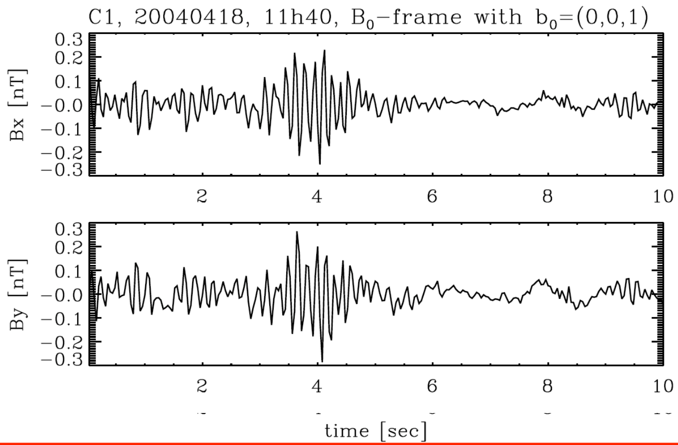
- Polarized fluctuations => spectra with bumps
- Non-polarized fluctuations => permanent (or background) turbulence
- Permanent turbulence + sporadic polarized fluctuations => "intermediate" spectral shape (breaks, small bumps, …)

- **~ Similar picture as at ion scales…**

Polarized whistler waves (spectra with bumps, breaks…)

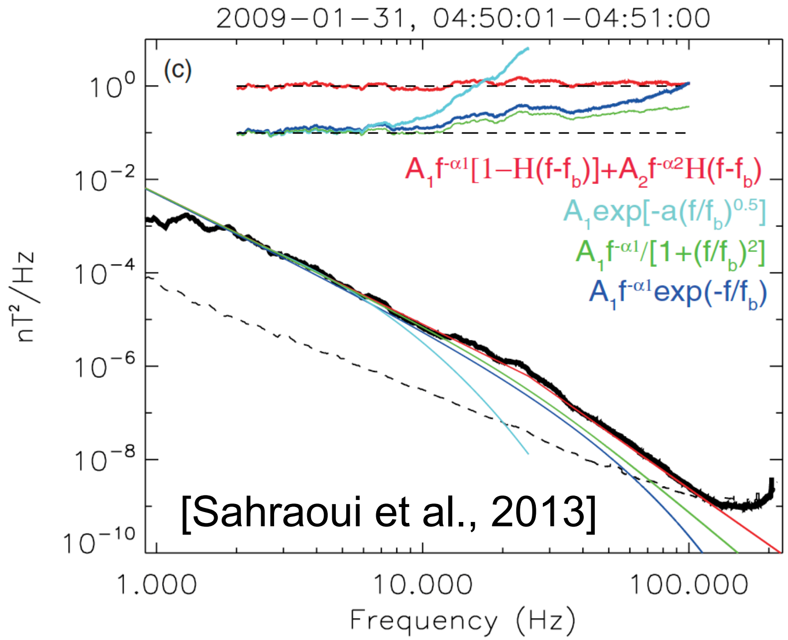


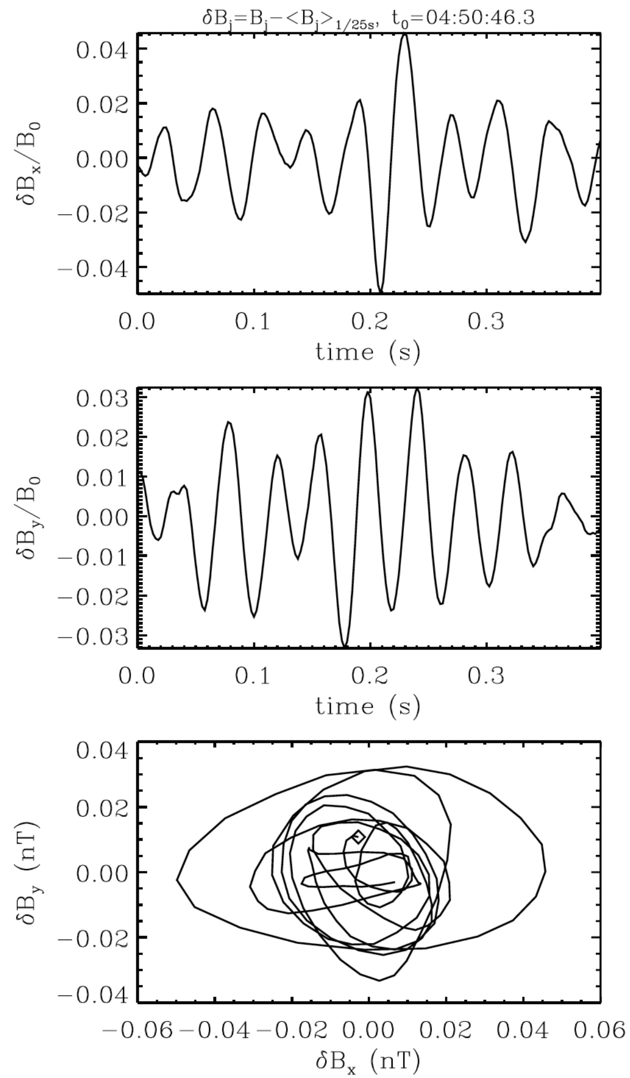
[Lacombe et al. 2014, APJ]



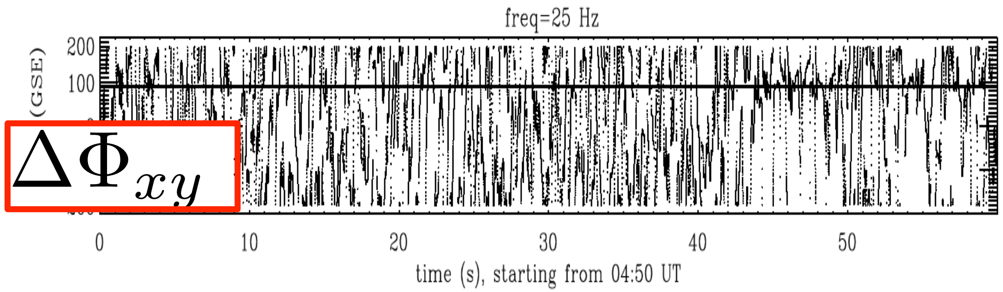
$$\Delta\Phi_{xy} = \Phi_x - \Phi_y = 90^\circ \rightarrow RH$$

Example of sporadic whistlers in the SW





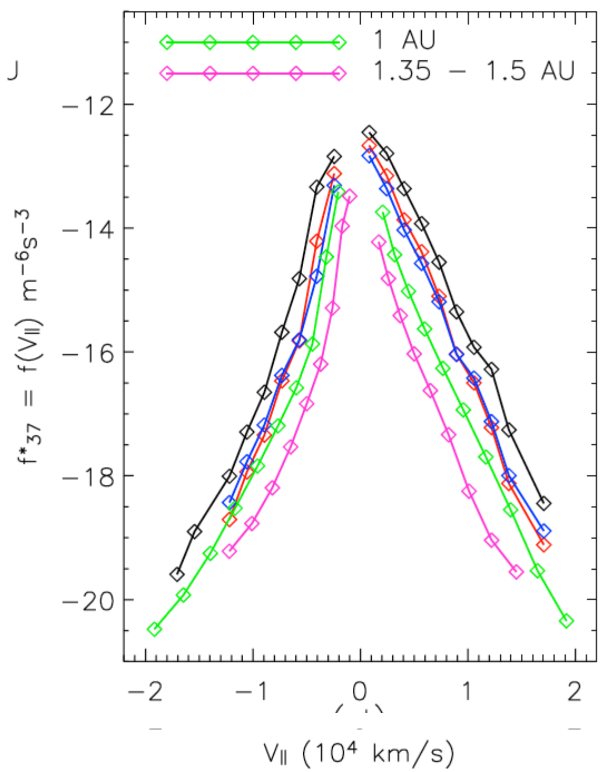
Phase difference in the plane perp to B_0 around 90^o is a signature of whistlers:



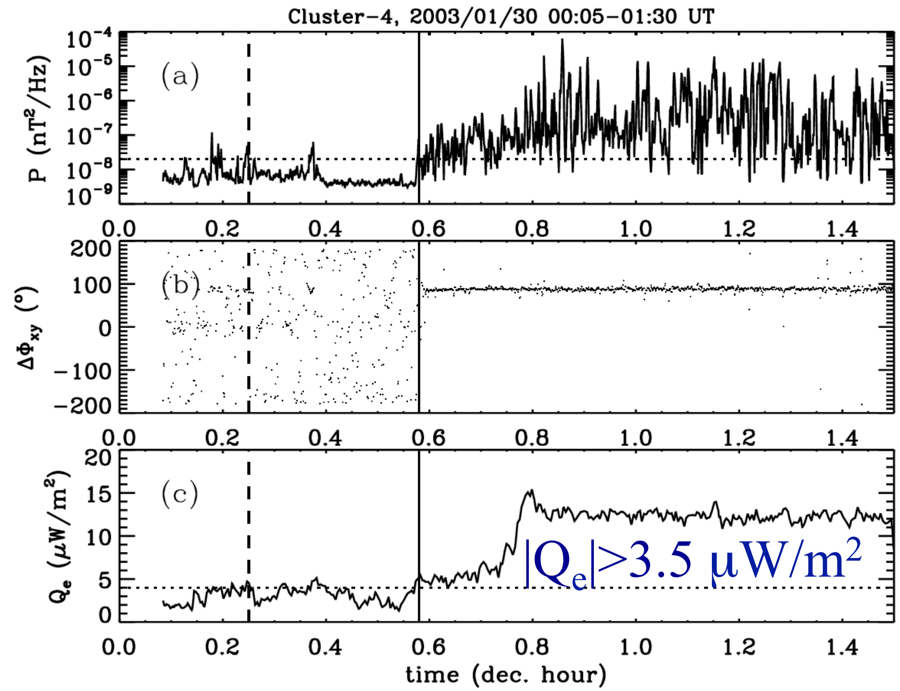
Background turbulence + sporadic whistler waves
=> spectral break/knee at the frequency of whistlers

Role of the electron heat flux

[Maksimovic et al. 2005]



[Lacombe et al. 2014, APJ]

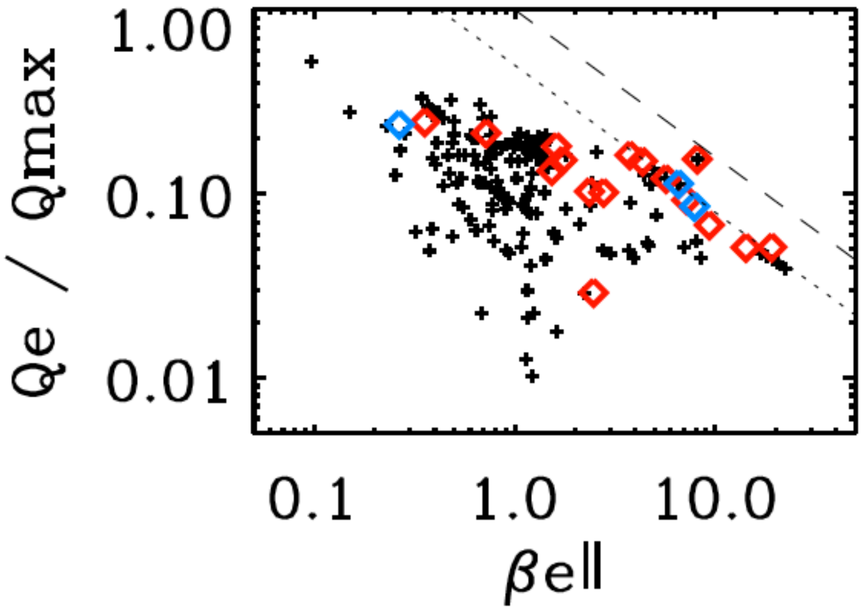


$$Q_e = \int \frac{m}{2}\mathbf{U}U^2 f(v) d^3v, \quad \mathbf{U} = \mathbf{v} - < \mathbf{v} >$$

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.

Instability related to the electron heat flux



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

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

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

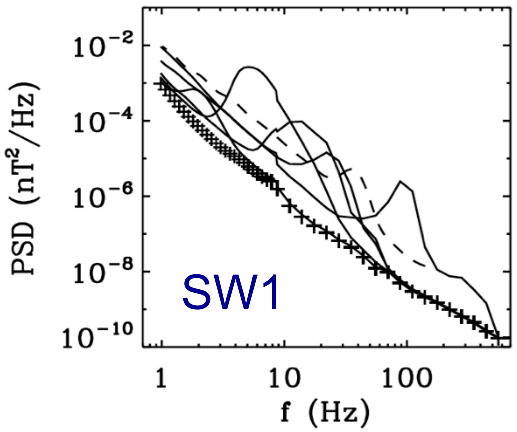
Whistlers (diamonds) are observed at the threshold for the whistler heat flux instability (dashed line, Gary et al.,99)

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

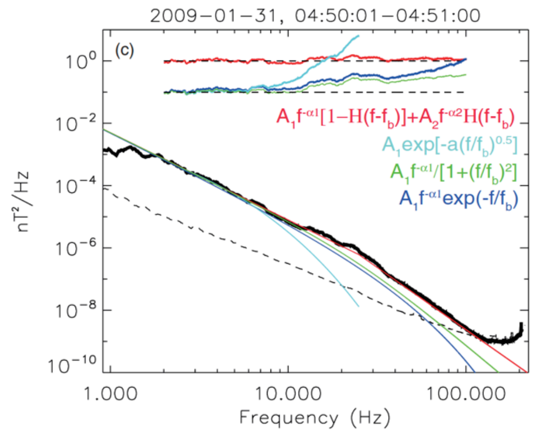
[Lacombe et al. 2014, APJ]

NB: Polarization study is crucial

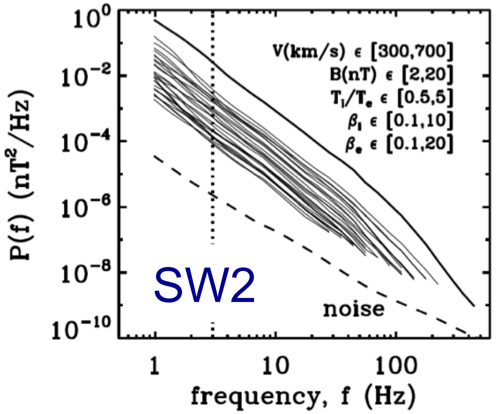
Polarized fluctuaitons

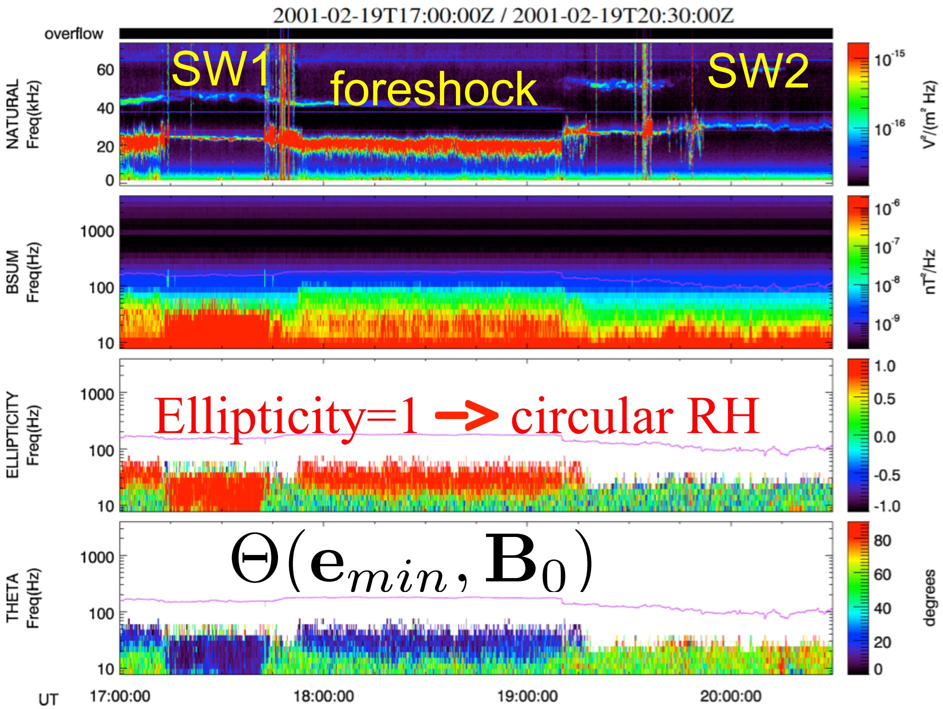


Non-polarized+polarized



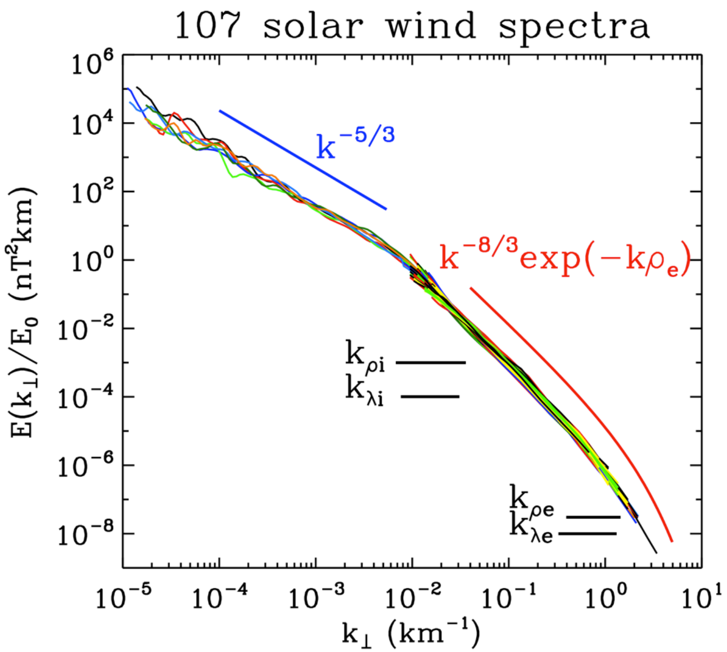
Non-polarized





General spectrum

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];
  - compressible Hall MHD [Alexandrova+08]
  - compressible NL KAW fluctuations [Boldyrev and Perez 2012];

- 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?

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?
- …