Observations of Electron Scale Turbulence

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Basic Spatial Electron Scales:

- Spatial scales:
  - Electron gyroradius: $\rho_e = v_{perp} / \Omega_e$
  - Electron inertial length scale $\lambda_e = c/\omega_{pe}$
  - Debye length $\lambda_D = (\varepsilon_0 k_B T_e / n_e e^2)^{1/2}$
- Spatial scales (solar wind, foreshock, magnetosheath same order of magnitude):
  - $\rho_e = 1\text{-}2 \times 10^3$ m
  - $\lambda_e = 1\text{-}2 \times 10^3$ m
  - $\lambda_D = 10$ m

Basic Temporal Electron Scales:

- Temporal scales:
  - Gyrofrequency: Ω_{ce} =e B /m_e
  - Electron plasma frequency: $\omega_{pe} = (n_e\, e^2/m_e\, \varepsilon_0\,)^{1/2}$
- Typically values for $f=\omega/2\pi$ (solar wind, foreshock, magnetosheath: values same order of magntiude)
  - f_{ce} = 2-4 x 10^2 Hz
  - f_{pe} = 1-4 x 10^4 Hz
- Scales are Doppler shifted to frequencies in solar wind by: $\omega = \mathbf{k}\,.\mathbf{v}_{flow}$ if $v_{phase} << v_{flow}$
  - $f_{\rho e}$= 0.5-1 x 10^2 Hz
  - $f_{\lambda e}$ = 0.5-1 x 10^2 Hz
  - $f_{\lambda D}$ = 5 x 10^3 Hz

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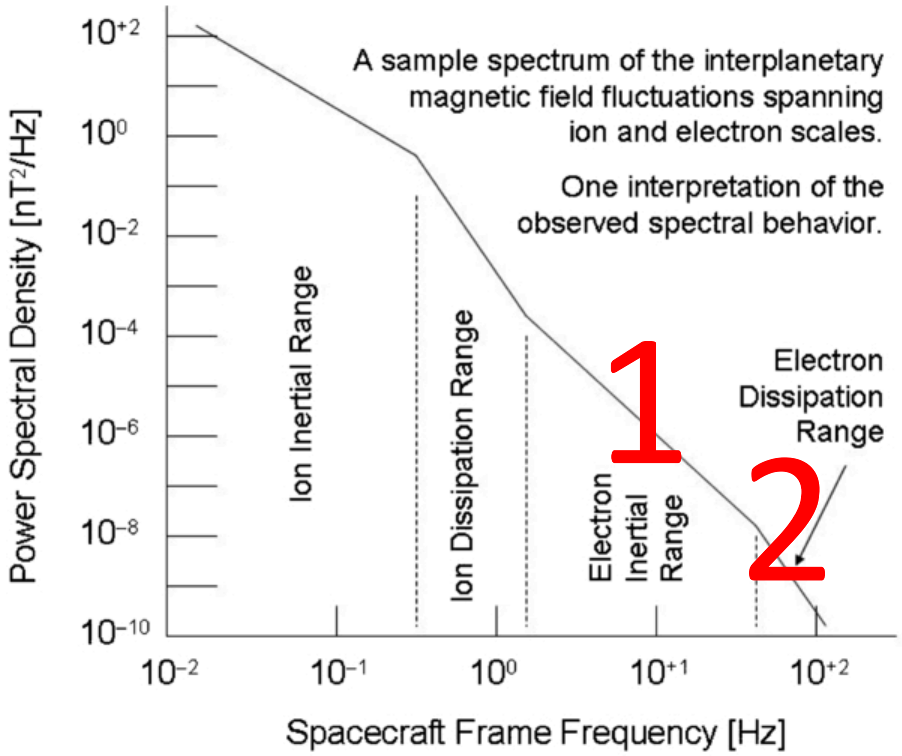
  - $f_{\lambda D}$ = 5 x 10^3 Hz

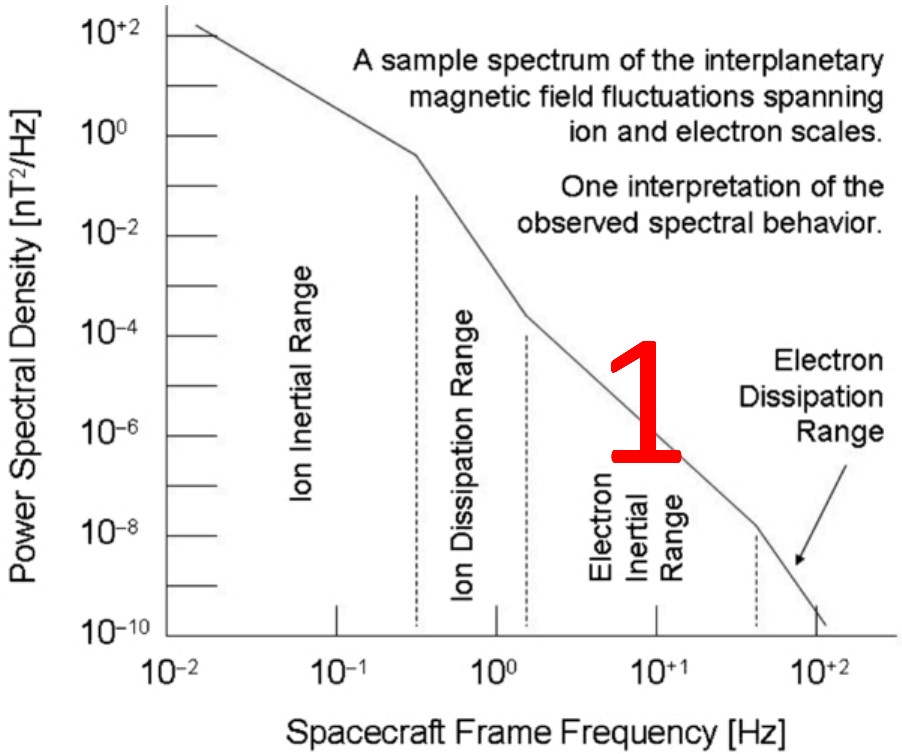
What is electron scale turbulence?
In this talk: f $\gtrsim$ 3 Hz, i.e. > ion scales



Smith et al. 2012

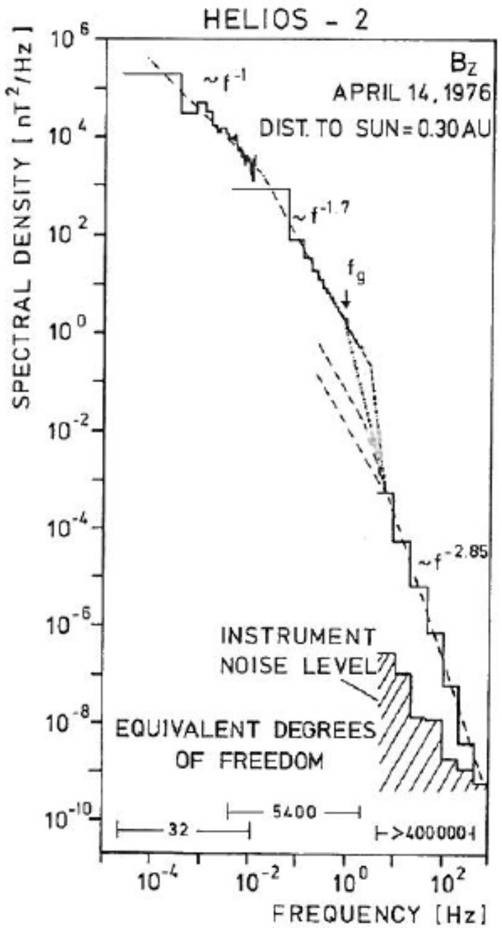
1. Observations: Electron inertial range

3 Hz < f < [$f_{\rho e}$, $f_{\lambda e}$] = ~50 Hz



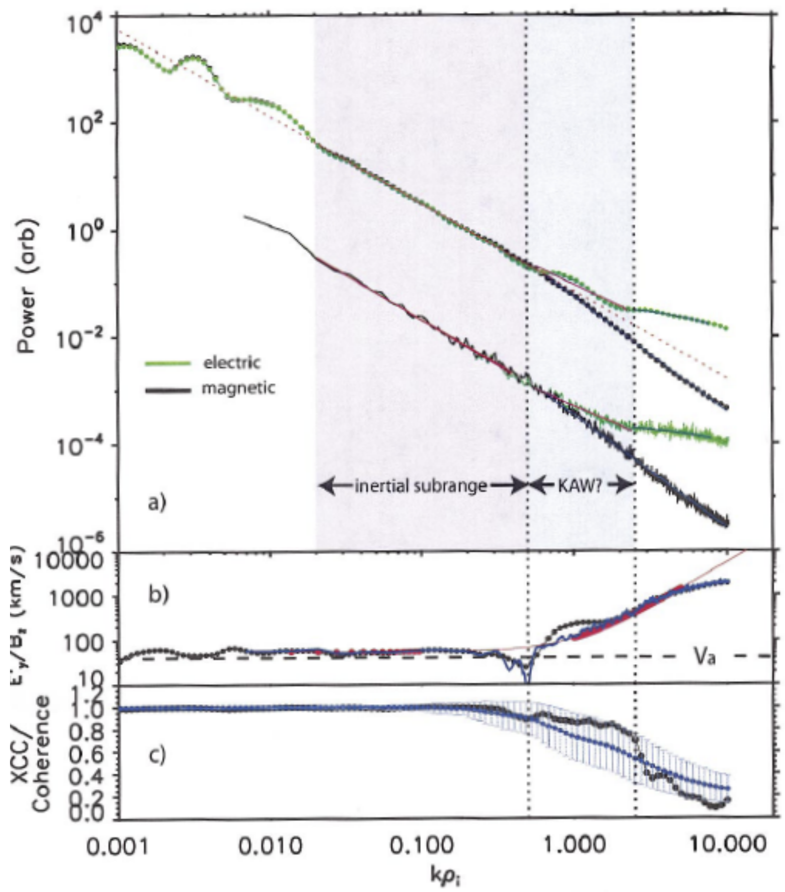
Smith et al. 2012

Helios Measurements (Denskat et al. 1983)



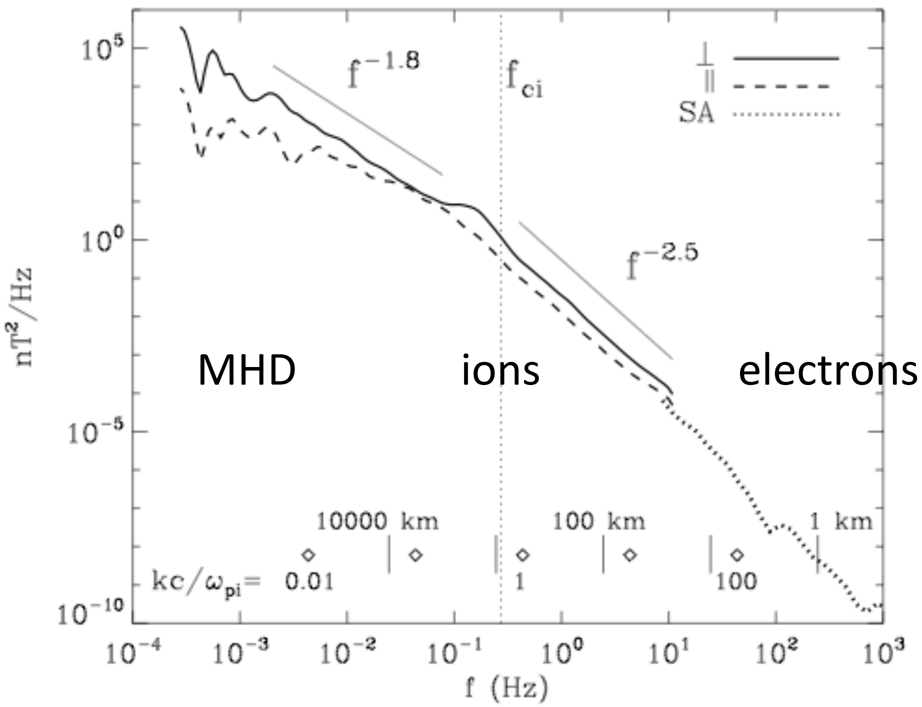
- Magnetic field measurments within solar wind between 0.3 and 1.0 AU
- Helios 2 fluxgate and search coil magnetometer
- Slope of spectra ~1.7 approx constant within $4x10^{-3}$ Hz to 2 Hz.
- Spectral break around gap between 2 Hz and 4.7 Hz
- Displacement of power spectral density between 2 Hz and 4.7 Hz probably due to damping of Alfven waves near the proton and alpha-particle cyclotron frequencies
- For f > 4.7 Hz spectral indicies in the range of ~3 are observed.

Cluster: Solar wind observations around ion scales (Bale et al. 2005)



- $k\rho_i$ <0.45: magnetic and electric spectrum with α=-1.7
- $0.45 < k\rho_i < 2.5$: electric field $\alpha = -1.26$ and magnetic field $\alpha = -2.12$
- $k\rho_i$ >2.5 electric spectrum $\exp(-k\rho_i/12.5)$
- E/B-Ratio fits $v0(1+ (k\rho_i)^2)$, see red curve in b). This is consistent with kinetic Alfven waves for $k\rho_i$.

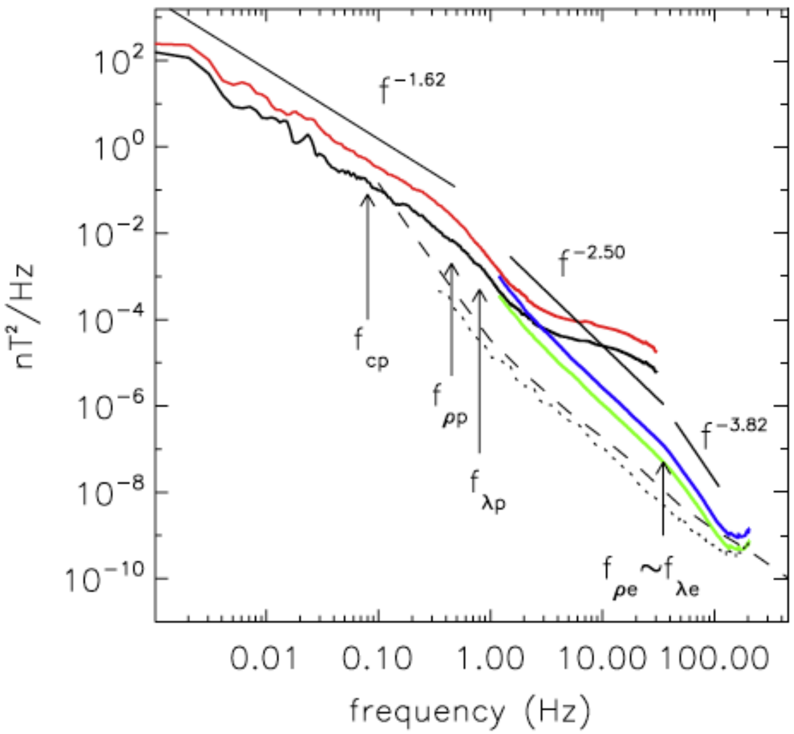
Cluster: Magnetosheath up to electron scales
(Alexandrova et al. 2008)



- Spectral knee at ion scales ~0.3 Hz and curvature around 50 Hz; emission of parallel whistler waves at 100 Hz
- Between ion and electron scales [$0.2k\,\lambda_i$, $50\,k\,\lambda_i \approx 1.2k\,\lambda_e$]:
  - $B_\perp$ and $B_{||}$: α=-2.5

Cluster: Foreshock up to electron scales

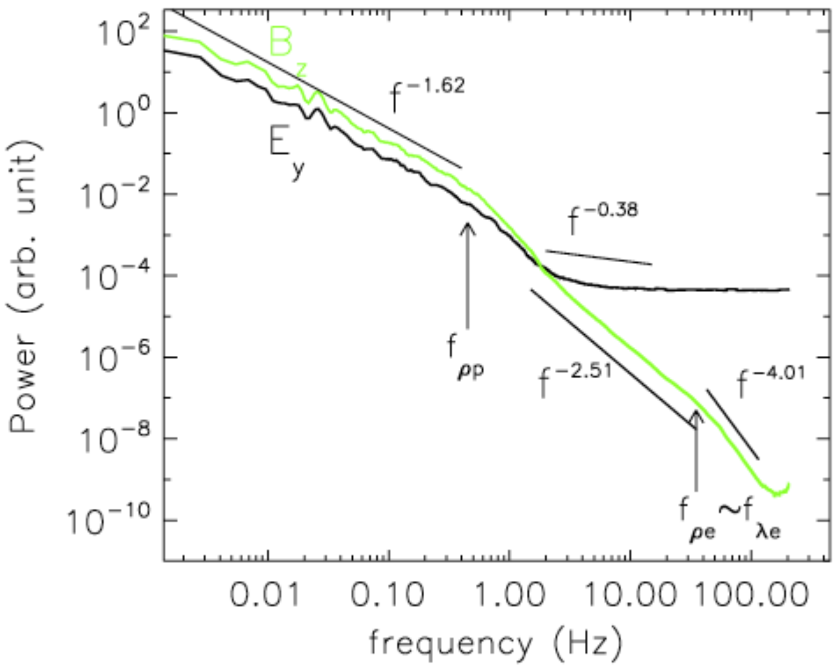
Sahraoui et al. 2009



B_{perp}: FGM (red)
B_{para}: FGM (black)
B_{perp}: STAFF-SC burst (blue)
B_{para}: STAFF-SC burst (green)

- Two breakpoints at 0.5 Hz and 35 Hz.
- Spectral behavior between ion and electron scales
  - $f^{-2.5}$
- Breakpoints fit well with Doppler-shifted: proton and electron gyro-scales

Cluster: Foreshock (Sahraoui et al. 2009)

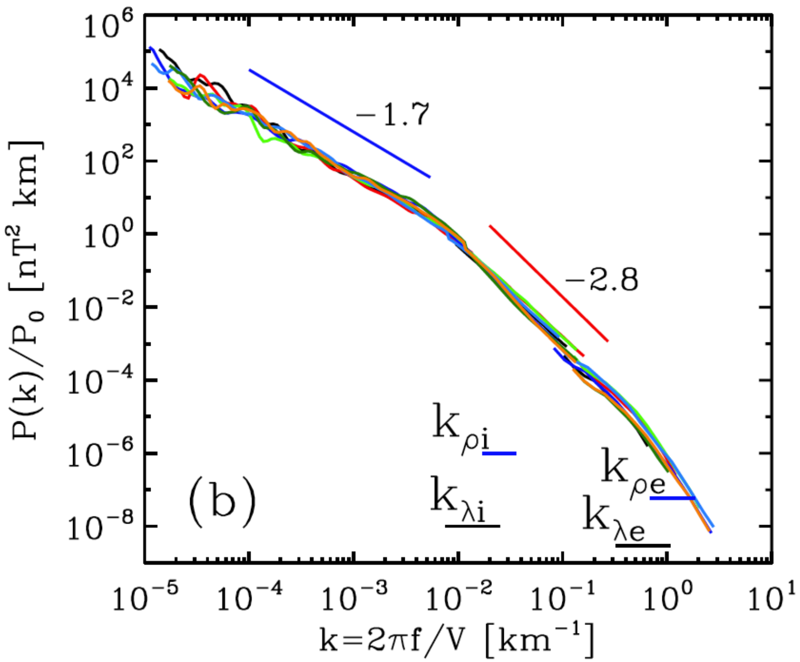


B_z : FGM and STAFF-SC (green)
E_y : EFW (black)

- B scales as $k_\perp^{-2.51}$
- E scales as $k_\perp^{-0.38}$ (but close to noise level)
- Scaling is consistent with kinetic Alfven waves (KAW)
- Authors show additionally that second break point is consistent with damping of KAW:
  $\gamma/\omega_r \approx 1$ for $k\,\rho_e \approx 1$

Cluster: Solar wind (Alexandrova et al. 2009)

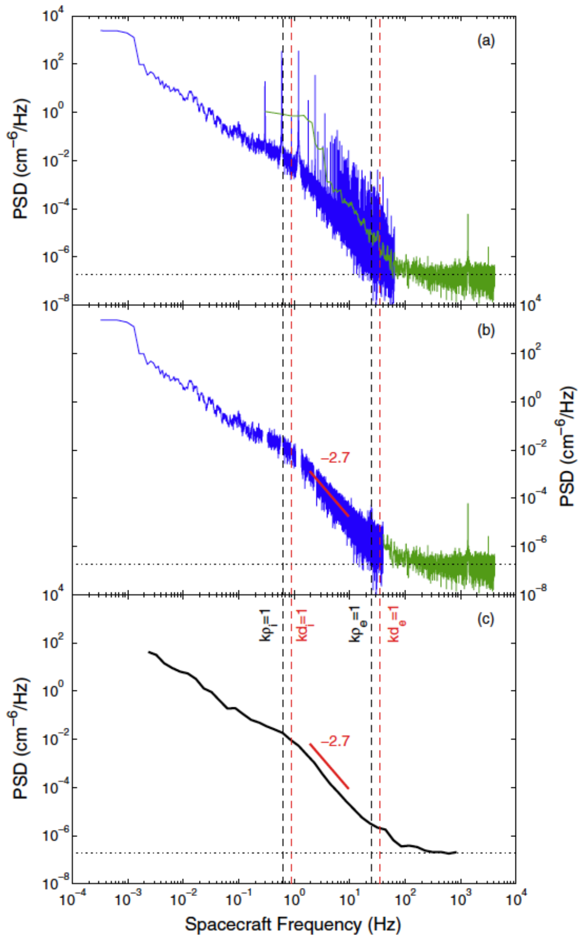
$$V \in [360, 670] km/s,\ \beta_i \in [0.4, 2],\ \beta_e \in [0.2, 1.6],\ \Theta_{BV} \in [65, 85]^\circ$$



- Cluster Mag-Observations with FGM, STAFF-SC and STAFF-SA in f=[1×10^{-3}, 3×10^{2}] Hz
- Under different plasma conditions the spectrum:
  - $k^{-2.8}$ power law between ion and electron scales

Artemis: Electron density fluctuations

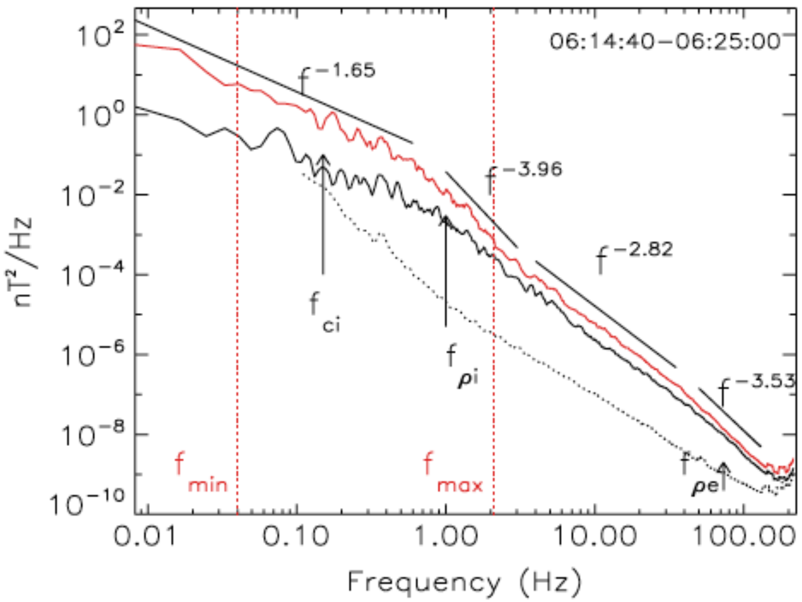
(Chen et al. 2012)



- Slow solar wind
- α=-2.7 within within 3 < k ρ_i < 15
- α=-2.75 ± 0.06 from a statistical study of 16 intervals.

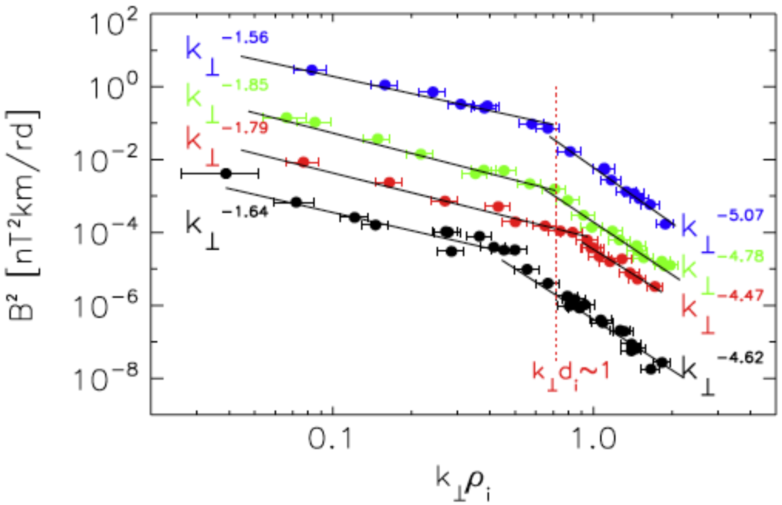
Cluster: Solar wind up to electron scales

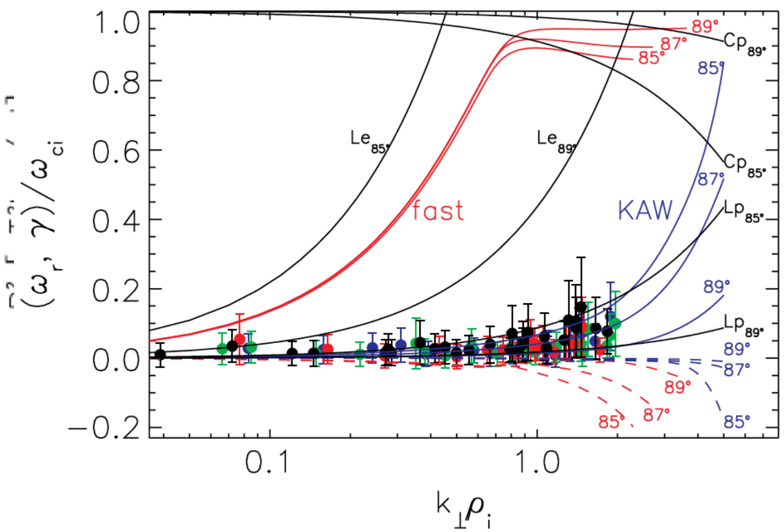
(Sahraoui et al. 2010)



- Below break point near [0.4,1] $k_\perp \rho_i$: steep scaling (transition region): $k_\perp^{-4.5}$
- Electron inertial range $k_\perp^{-2.8}$

Cluster: Solar wind k-filtering in ion transition region
(Sahraoui et al. 2010)

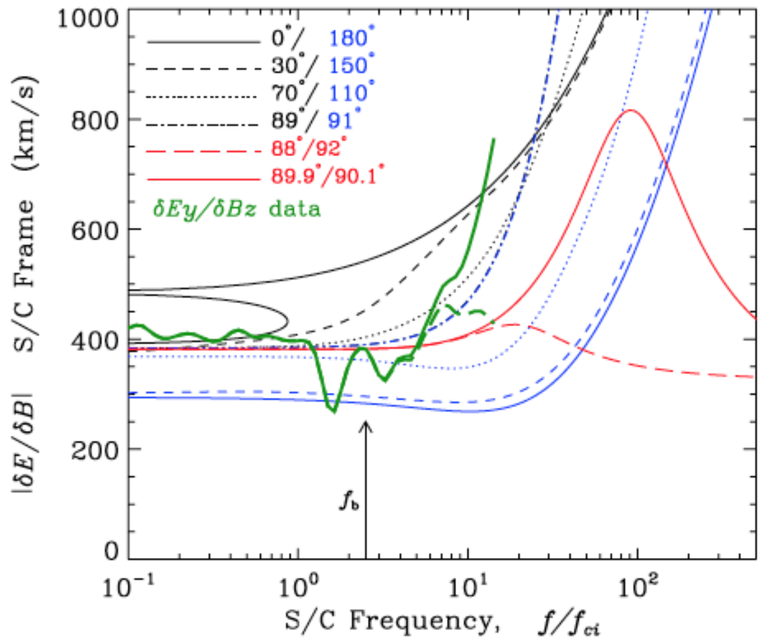


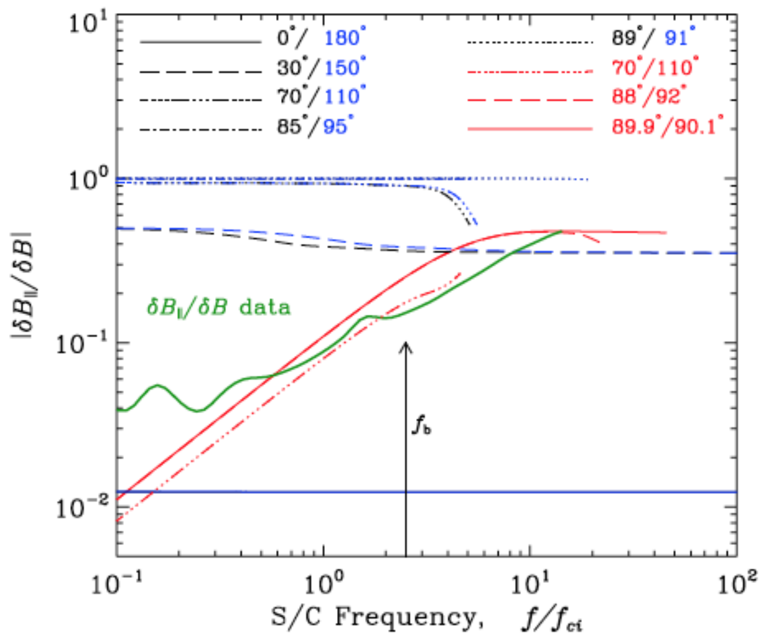


- Transition region (up to 2 Hz, ~ $k_\perp \rho_i$ ~2)
- Cascade is carried by highly oblique kinetic Alfven waves.
- Observations follow KAW dispersion relationship within [0.04,2] $k_\perp \rho_i$ (see also Salem et al. 2012)
- The (k,omega) observations are also in agreement with convected (or slowly propagating) coherent structures with $k_\perp >> k_{||}$ and $\omega \approx 0$ (Roberts et al. 2013).

Ratio δE/δB and $\delta B_{||}/\delta B$

(Salem et al. 2012)

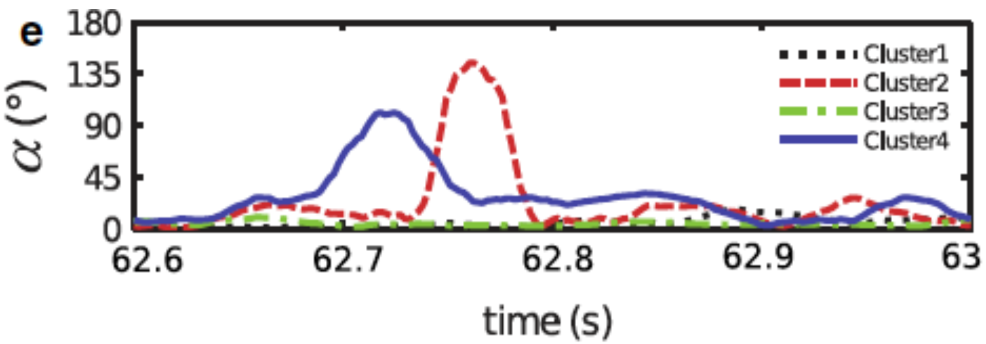




Data are consistent with kinetic Alfven waves with nearly perpendicular wavevectors

Current sheets/discontinuities

Perri et al. 2012

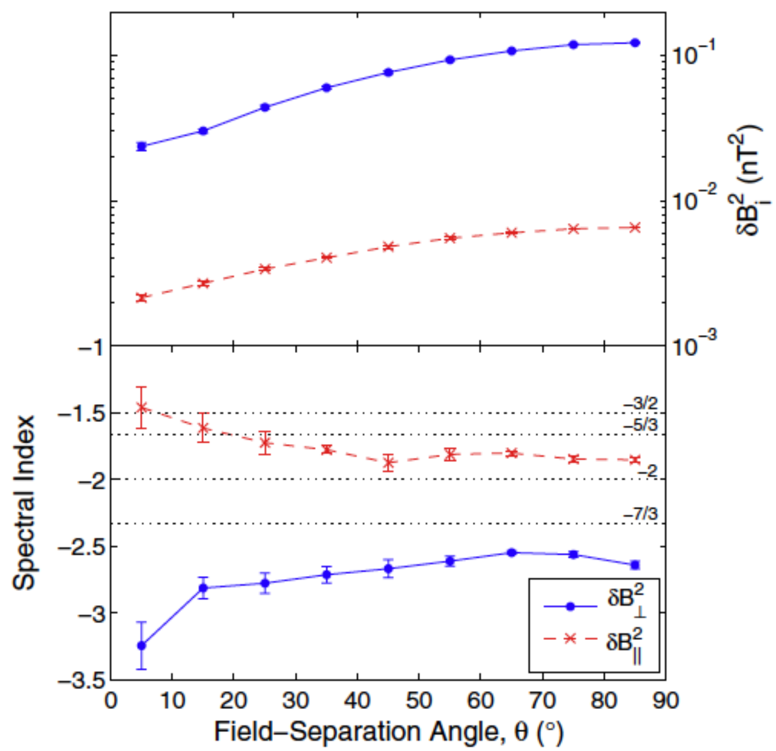


$$\alpha(t, \tau) = \arccos\left(\frac{\mathbf{B}(\mathbf{t}) \cdot \mathbf{B}(\mathbf{t} + \tau)}{|\mathbf{B}(\mathbf{t})||\mathbf{B}(\mathbf{t} + \tau)|}\right).$$

- Cluster observations of thin current sheets in plane perpendicular to B
- Observed on scales between proton and electron gyroradius
- Might be signs of intermittency and localized areas of turbulent dissipation

Anisotropy between ion and electron scales

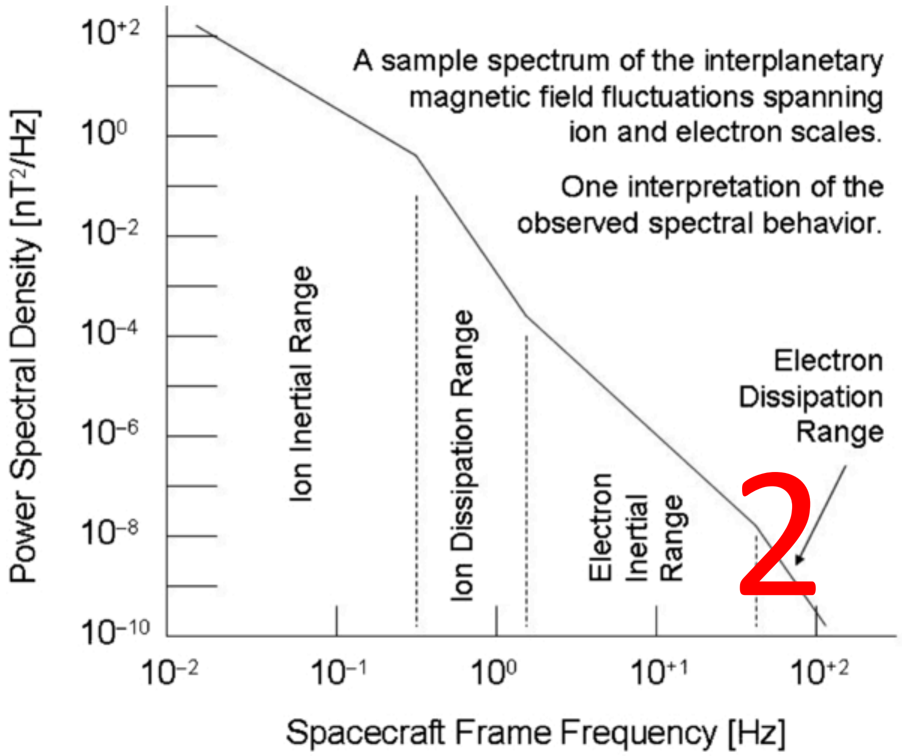
Chen et al. 2010



- Measurements between k ρ_i and k ρ_e
- $(B_\perp / B_{||})^2 \approx 0.05$
- Spectral index for $B_\perp$ at small Θ steepens consistent with critical balanced cascade (KAW or Whistler turbulence)
- Spectral index for $B_{||}^2$ is less consistent with predictions.

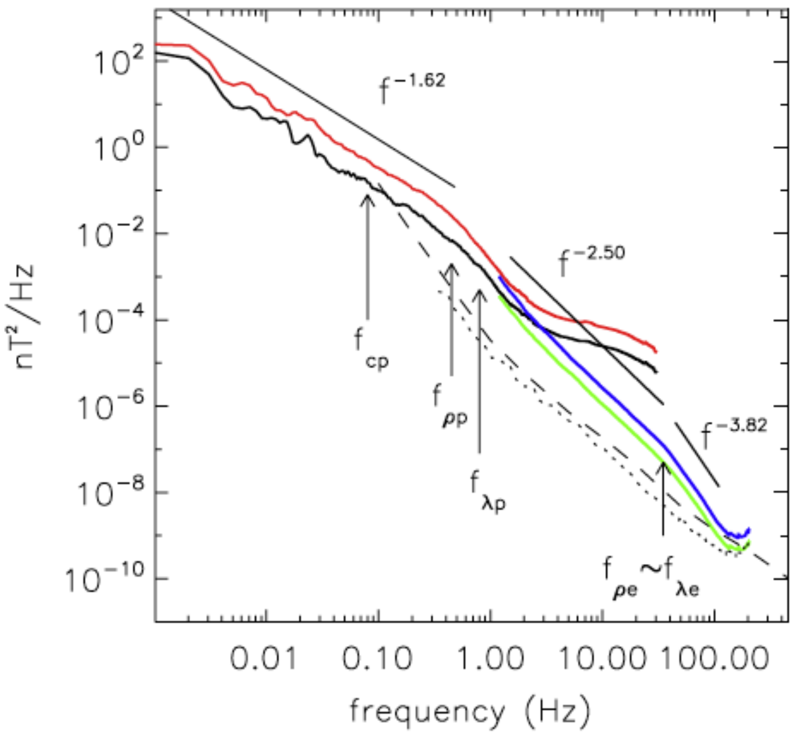
2. Observations: Electron dissipation range

$[f_{\rho e}, f_{\lambda e}] = \sim 50 \text{ Hz} \leq f$

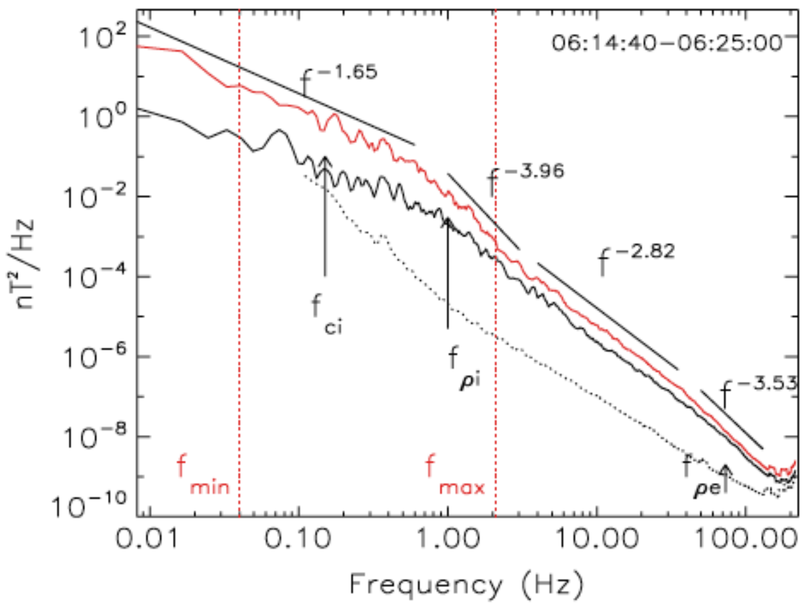


Smith et al. 2012

Electron Dissipation: Power law



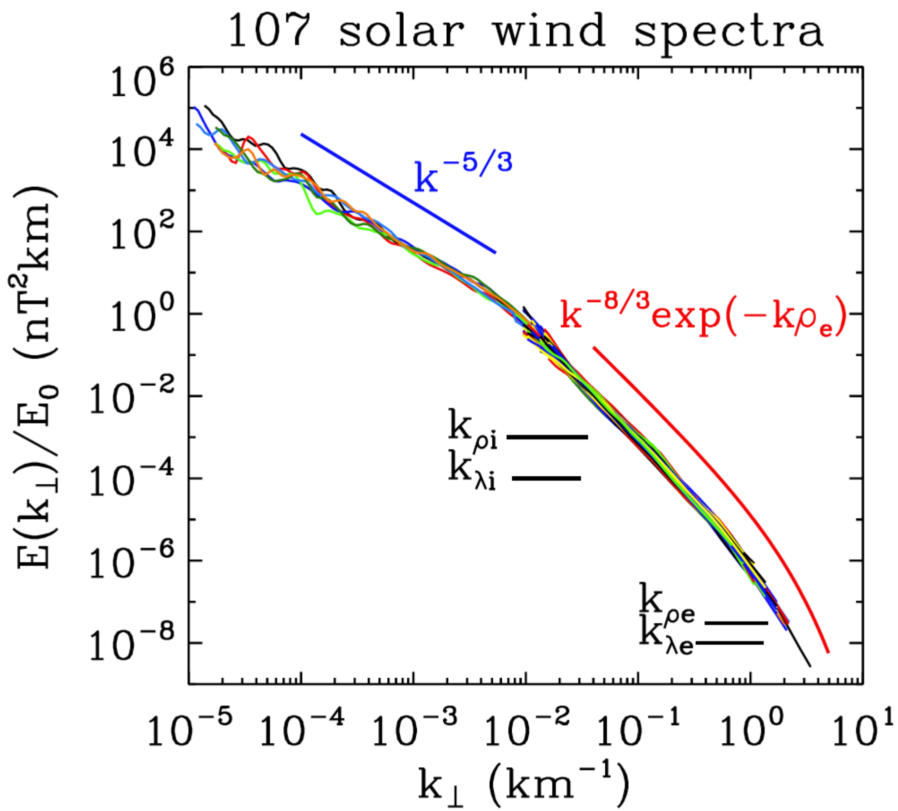
- Sahraoui et al. 2009 (Foreshock)
- $f^{-3.82}$ (electron scales)
- Breakpoint ~ at Doppler-shifted electron gyro-scales and electron inertial length.

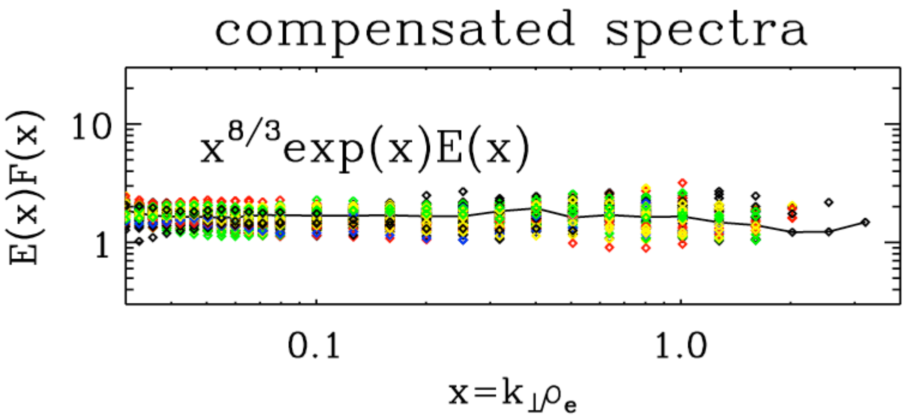


- Sahraoui et al. 2010 (Solar wind)
- $f^{-3.5}$ (electron scales)
- Breakpoint ~35 Hz, Doppler-shifted electron gyro-scales ~ 80 Hz.

Statistical study of turbulent spectra to a fraction of ρ_e

Alexandrova et al., 2009, 2012





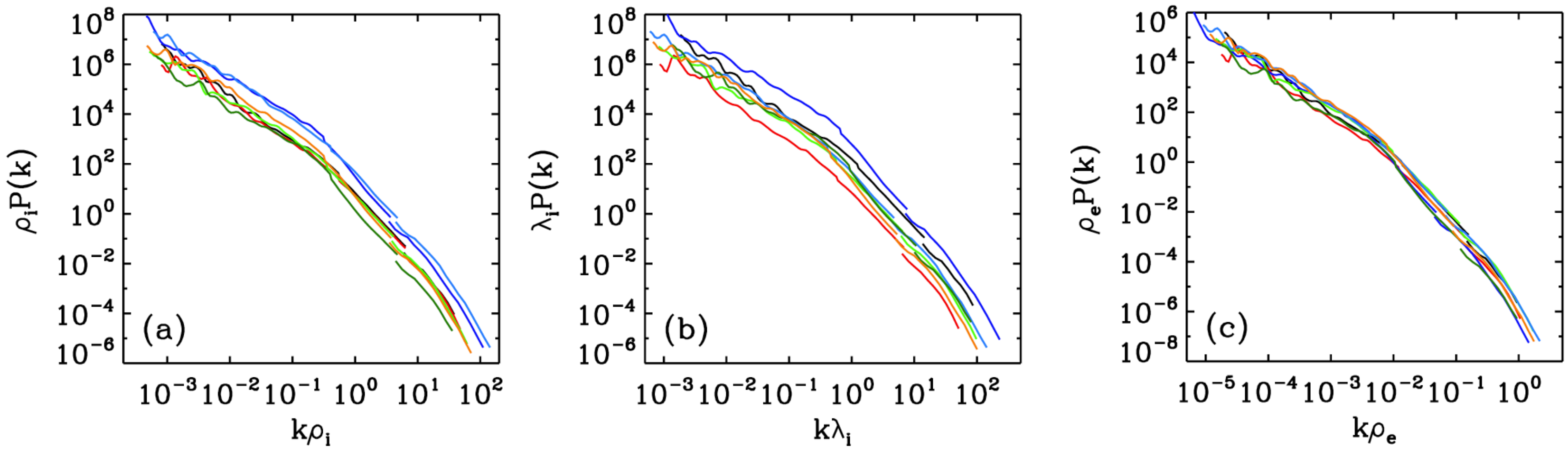
- A compensating function $x^{8/3}\exp(x)$, with $x=k\rho_e$, leads to flat compensated spectra at $k\rho_e>0.03$ and for ~2 decades in scales, corresponds to f=[3,300] Hz

- $E(k_\perp) = E_0\, k_\perp^{-8/3} \exp(-k_\perp \rho_e)$ describes well the totality of the observed spectra. E_0 is the only free parameter.

Dissipation scale and Universality?

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

In HD turbulence, this normalization collapses spectra measured under different conditions. Same scaling applied to solar wind 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.

→ $$\ell_d \sim \rho_e$$

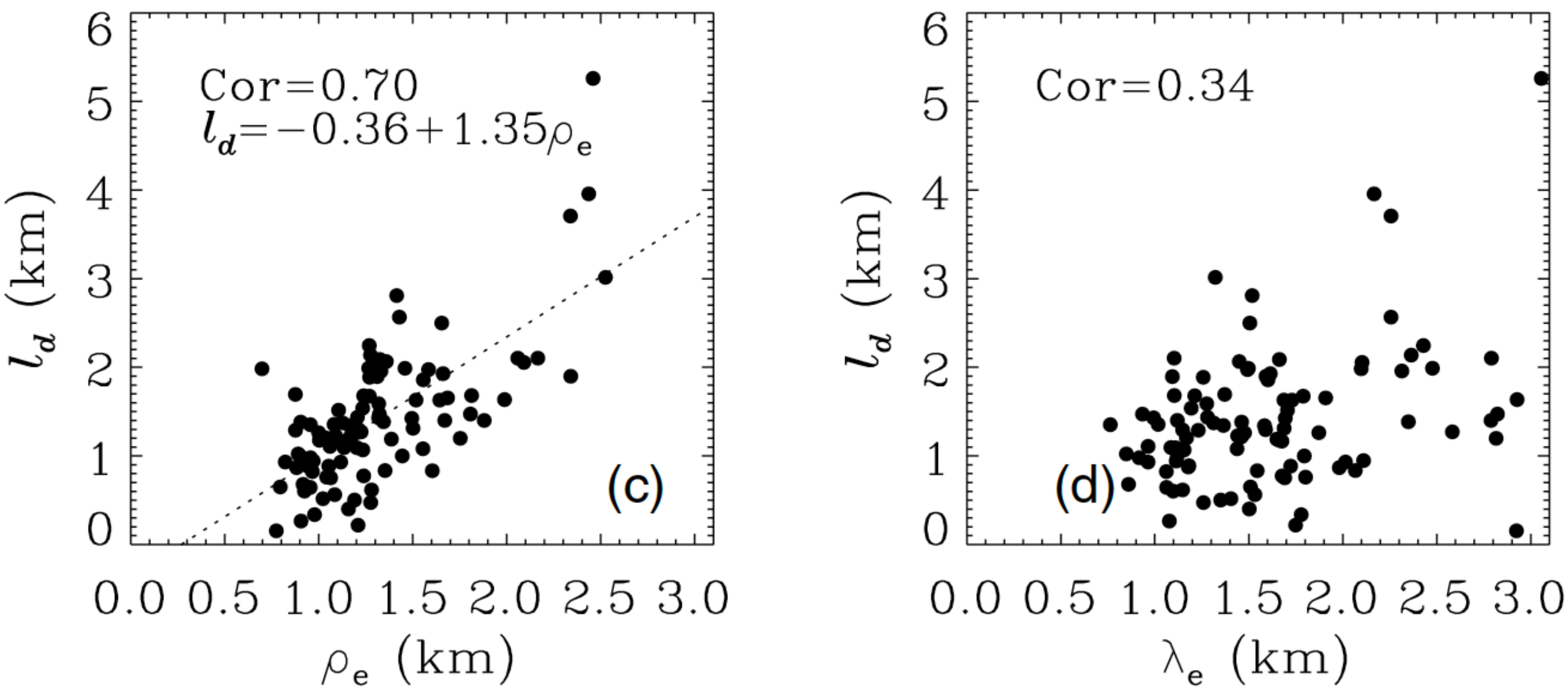
[Alexandrova et al., 2009, PRL]

What controls the dissipation Scale?

Alexandrova et al. 2012

- Fitting with the 3 parameter model

$E(k_\perp) = A\, k_\perp^{-a} \exp(-k_\perp l_d)$



l_d is well correlated with ρ_e confirming the « Kolmogorov Universal function » normalization results, Alexandrova et al. 2009.

Summary

- „Electron inertial scale“: Spectral slopes between ion and electron scales different authors
  - at f>3 Hz, all spectra are quite similar: α = 2.5 (foreshock), 2.8 (solar wind) (Sahraoui et al. 2009, 2010, Alexandrova et al. 2009, 2012)
  - Note, that 8/3~2.6 is the same as 2.8 when the exp factor is present (Alexandroval et al. 2012)
  - For E and $k_{\perp}$: α = 1.36 (Bale et al. 2005, transition region)
  - Electron density fluctuations show 2.7 spectrum (Chen et al. 2012)
- Second spectral scale most likely correlated/controlled by electron gyroradius ρ_e (Sahraoui et al. 2009,2010, Alexandrova et al. 2009, 2012)
- „Electron dissipation scale“ for $f > f_{\rho e}$: Spectrum steepenss, but no consensus is reached in the community
  - on the form of the spectral structure: Exponential (Alexandrova et al. 2009, 2012) or power law (Sahraoui et al. 2009, 2010)
  - whether it is universal or not.