Nature of Kinetic Scale Solar Wind Turbulence

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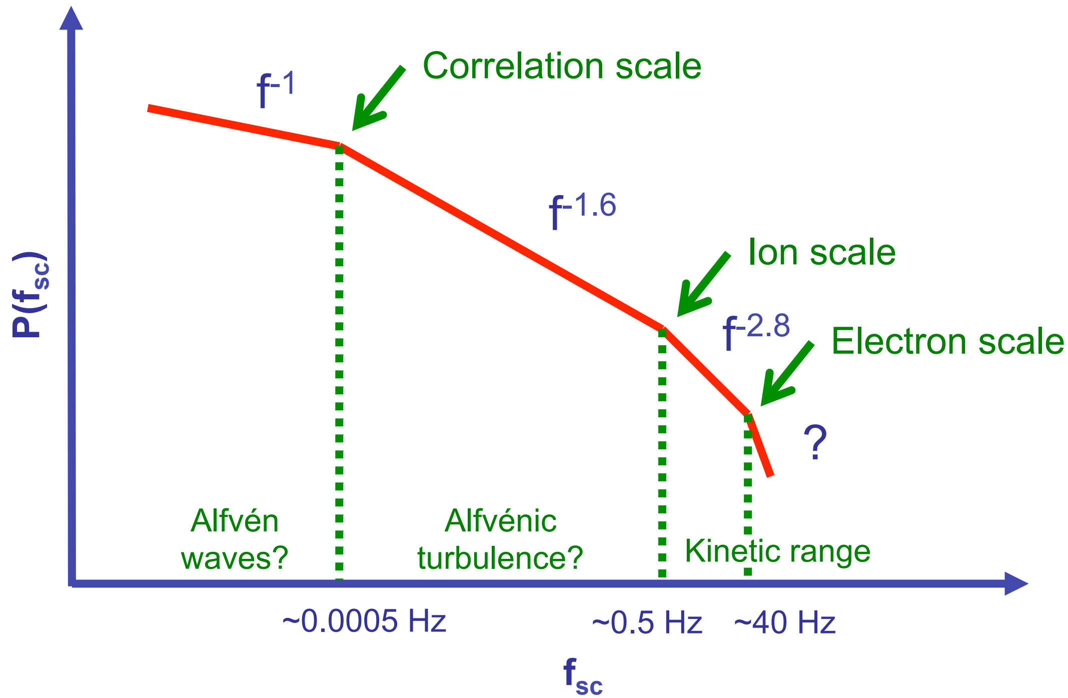
Topics

- At what scale is the transition from MHD to kinetic scale turbulence?
- What type of turbulence is present in the kinetic range?
- What are the properties of the rotation angles in the kinetic range?

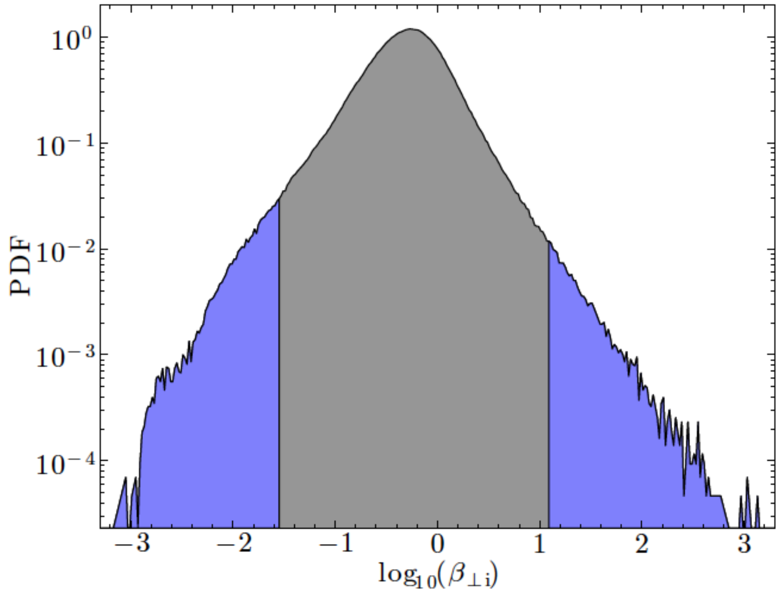
Solar Wind Magnetic Spectrum

- Solar wind spectrum of magnetic fluctuations shows several ranges
- Breaks are present at kinetic scales
- It is thought that here the turbulence is dissipated
  - heats solar wind
  - possibly heats corona
- Understanding the microscales associated with the breaks will help understand this physics



Determining The Ion Break Scale

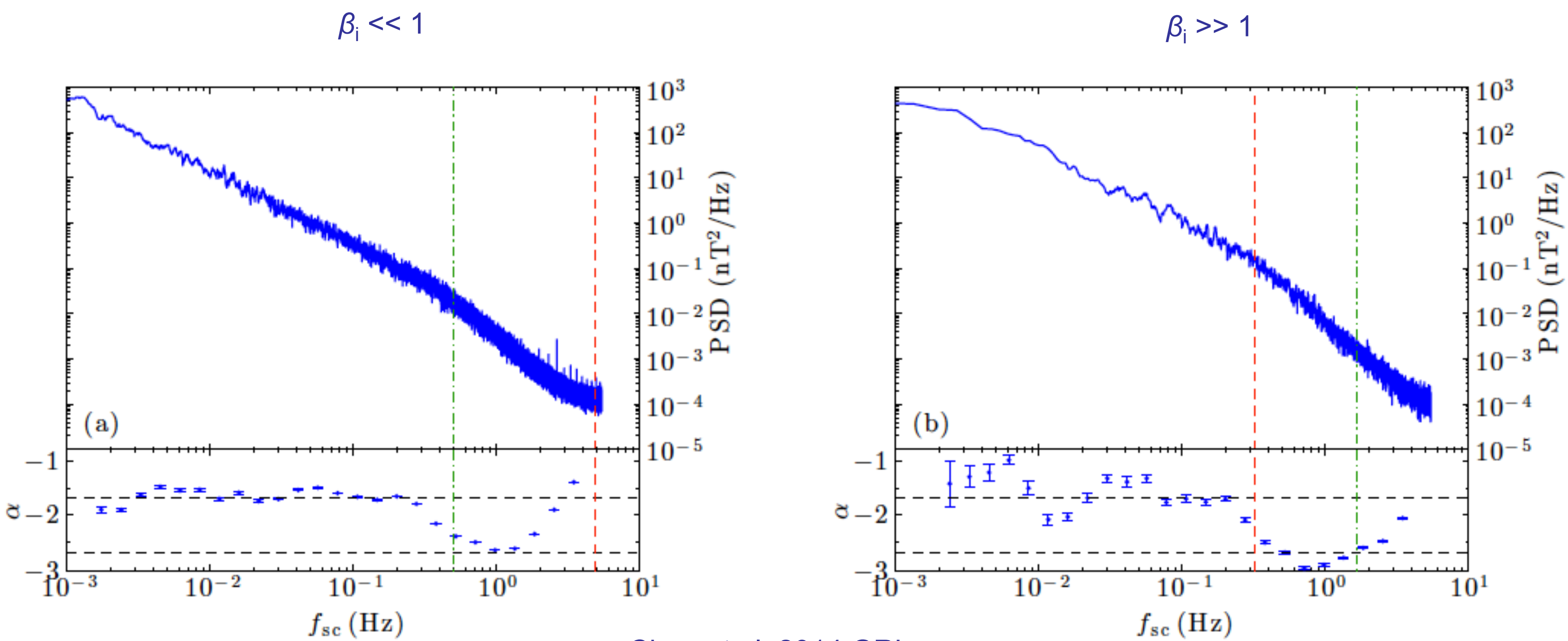
- So which scale is associated with the break?
  - Kinetic Alfvén wave dispersive/damping scale ρ_i
  - Hall MHD transition d_i (current sheets?)
  - (also others...)
- Previous studies have come to differing conclusions (Leamon, Smith, Markovskii, Perri, Bourouaine, Bruno)
- $d_i = \rho_i/\sqrt{\beta_i}$ so at $\beta_i \sim 1$ (typical for 1 AU) these are the same so can't be distinguished
- 20 years *Wind* data to find rare occasions when $\beta_i << 1$ and $\beta_i >> 1$



Chen et al. 2014 GRL

Break Scale at Low and High β_i

- 2 examples: high and low β_i
- Break occurs at the larger of the scales



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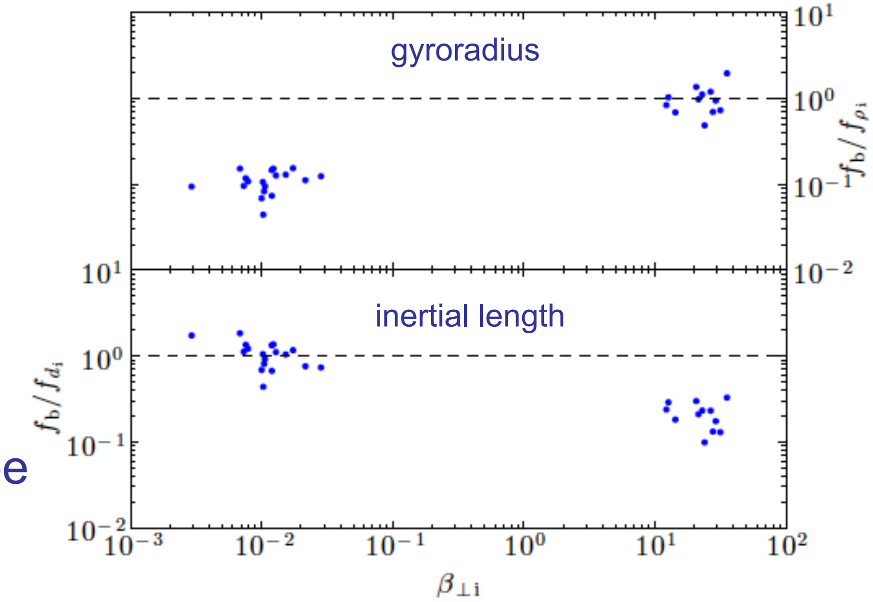
Statistical Study

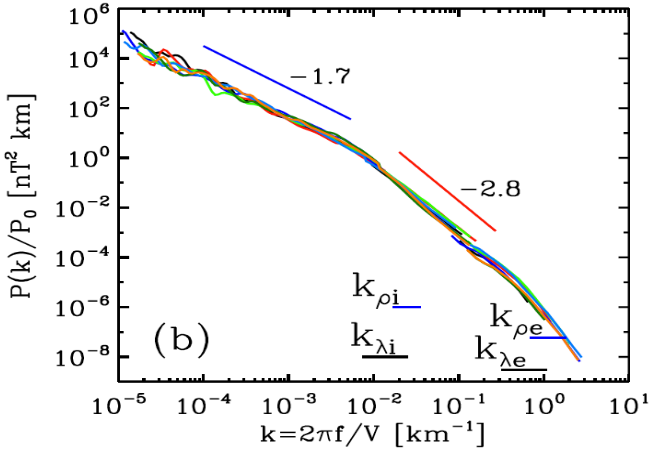
- Break at larger of ρ_i and d_i
  - ρ_i consistent with dispersive scale
  - but d_i is not
- Possibilities
  - ρ_s for dispersive scale at low β_i (but out by a factor of 5)
  - electron Landau damping (but this it not strong at these scales)
  - cyclotron resonance (but shouldn't be important for $k_\perp >> k_{||}$)
  - alternative dissipation process
  - non-thermal distributions



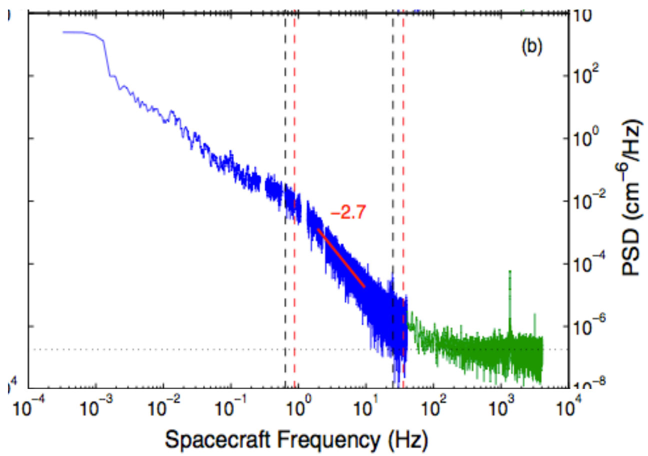
Chen et al. 2014 GRL

Turbulence in the Kinetic Scale Range

- Magnetic spectrum has spectral index ≈ -2.8 in kinetic range
- Recently have been able to measure density spectrum: -2.75 ± 0.06
- Steeper than -7/3 pure cascade:
  - electron Landau damping
  - intermittency, 2D sheets: -8/3 spectrum (Boldyrev et al. 2012 ApJL)
- But what is the nature of this turbulence?



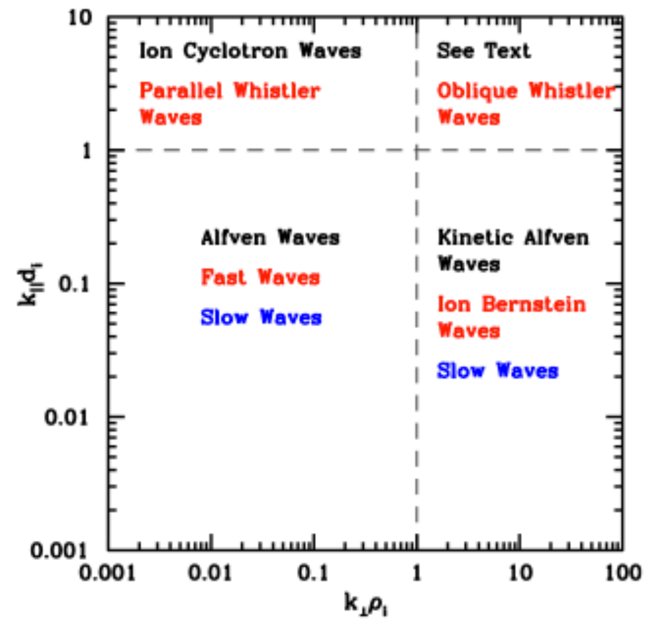
Alexandrova et al. 2009 PRL



Chen et al. 2012 PRL

Possible Waves at Kinetic Scales

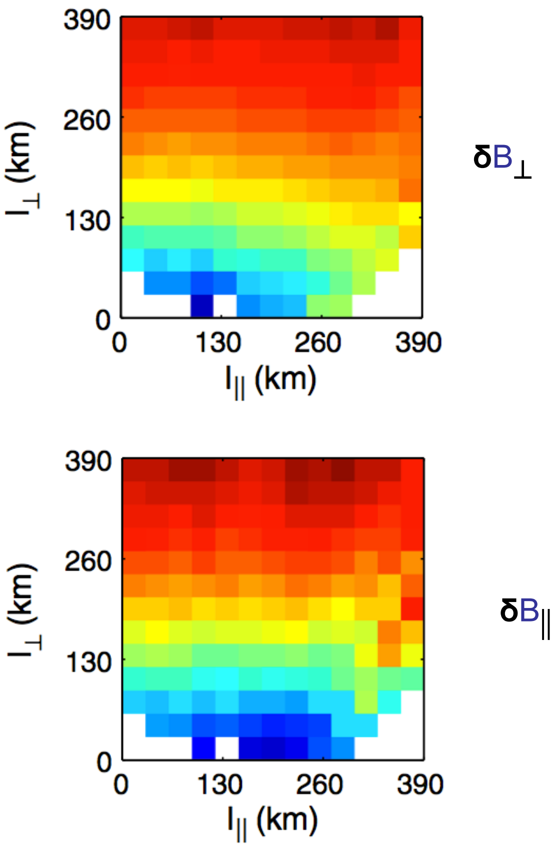
- Turbulence theory, e.g. critical balance, suggests that linear physics is relevant in non-linear turbulence
- At MHD scales turbulence is predominantly polarised as Alfvén waves ($r_A \sim 1$)
- At kinetic scales we have: ion cyclotron waves, kinetic Alfvén waves, whistler waves, ion Bernstein waves, etc.
- How can we determine which are relevant for the solar wind?



TenBarge et al. 2012 ApJ

Anisotropy at Kinetic Scales

- First step is to determine the anisotropy
- Multi-spacecraft *Cluster* measurement between ion and electron scales
- Power contours are elongated in parallel direction
  - anisotropic eddies
  - $k_\perp > k_\parallel$
- Suggests that one of the oblique electromagnetic modes is dominant
  - kinetic Alfvén wave
  - oblique whistler wave



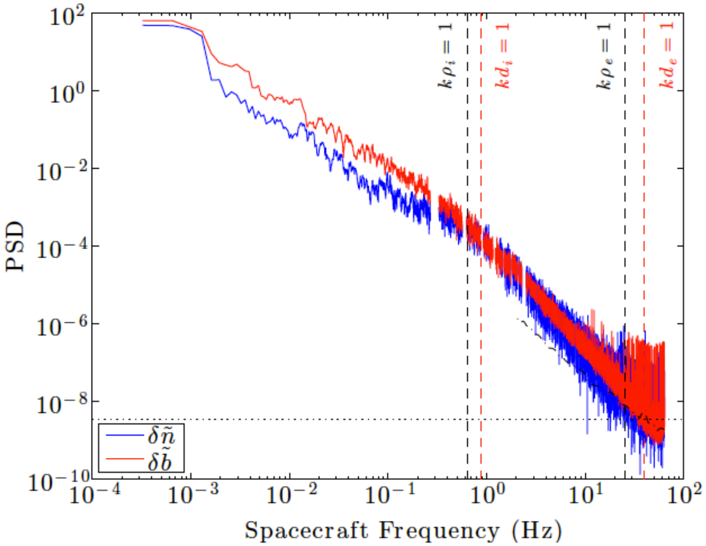
Chen et al. 2010 PRL

KAW vs Whistler Turbulence

- Similar in many ways but:
  - whistler: $\delta\tilde{n}^2/\delta\tilde{b}_\perp{}^2 << 1$ (ions stationary)
  - KAW: $\delta\tilde{n}^2/\delta\tilde{b}_\perp{}^2 = 1$

$$\tilde{n} = \left(1+\frac{T_i}{T_e}\right)^{\frac{1}{2}} \frac{v_s}{v_A}\left[1+\left(\frac{v_s}{v_A}\right)^2\left(1+\frac{T_i}{T_e}\right)\right]^{\frac{1}{2}} \frac{n_e}{n_0}$$

$$\tilde{\mathbf{b}} = \mathbf{B}/B_0$$



Chen et al. 2013 PRL

- Data show kinetic Alfvén ratio $\delta\tilde{n}^2/\delta\tilde{b}_\perp{}^2 \sim 1$ → predominantly kinetic Alfvén turbulence
- In fact, magnetic energy slightly dominates (effect of non-linear terms?)

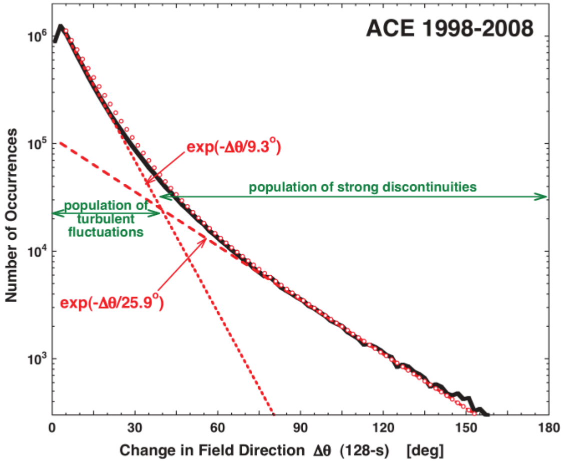
Implications of KAW Turbulence

- Similar results seen in simulations (Chen et al. 2013, Boldyrev et al. 2013, Franci et al. 2015)
- Consistent with transition from anisotropic Alfvenic MHD range
- Consistent with bump in density spectrum at ion scales
- Further evidence that linear physics can determine (to order unity) field relationships in strong turbulence
- KAW turbulence is low frequency
  - Taylor's hypothesis can be used (Klein et al. 2014)
  - cyclotron damping is questionable as a heating mechanism (Schekochihin et al. 2009)

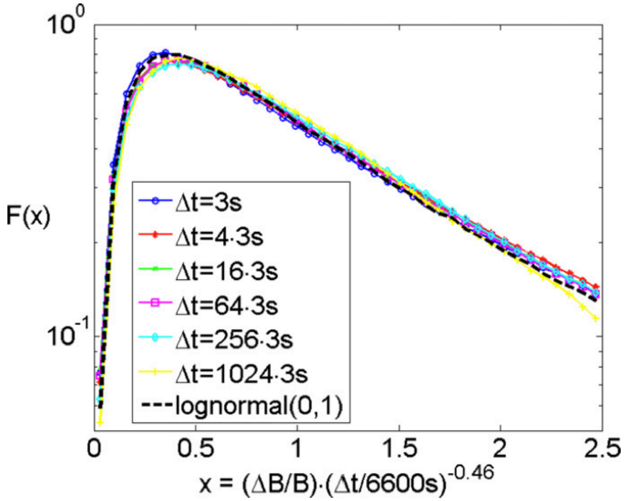
Magnetic Field Rotation Angles

$$\alpha(t,\tau) = \cos^{-1}\left[\frac{\mathbf{B}(t)\cdot\mathbf{B}(t+\tau)}{|\mathbf{B}(t)||\mathbf{B}(t+\tau)|}\right]$$

- Distribution of magnetic field rotation angles in MHD range
- Sometimes divided into turbulence + discontinuities (non-turbulence?)
- When cast as dB/B distribution is claimed to be scale-invariant log-normal rotations
- What about in the kinetic range?
- And what does this imply about possible heating mechanisms?



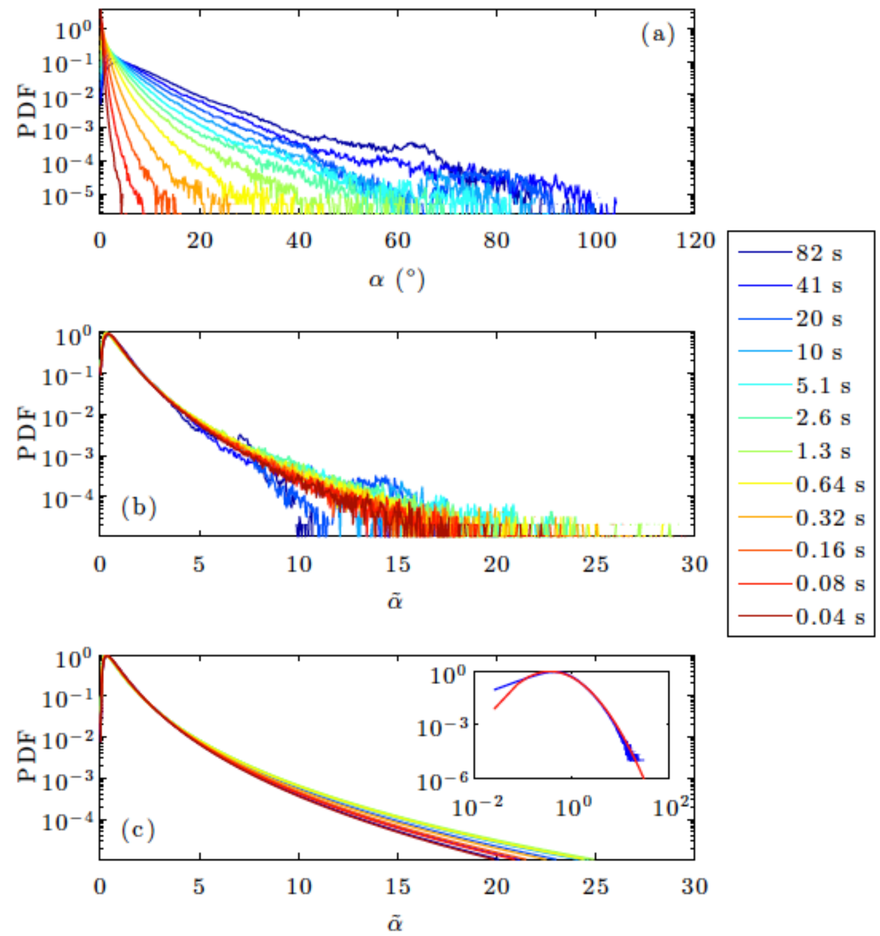
Borovsky 2010 PRL



Zhdankin et al. 2012 ApJL

Angle Distributions at Kinetic Scales

- Use combined FGM/STAFF Cluster data, 7 hour interval clear of foreshock
- Angles become small quickly from ion to electron scales
- Distribution is almost self-similar
- Kurtosis can't be measured directly so log-normal fits were performed
- Fits generally do well (better than double exponential) although still underestimate small angles

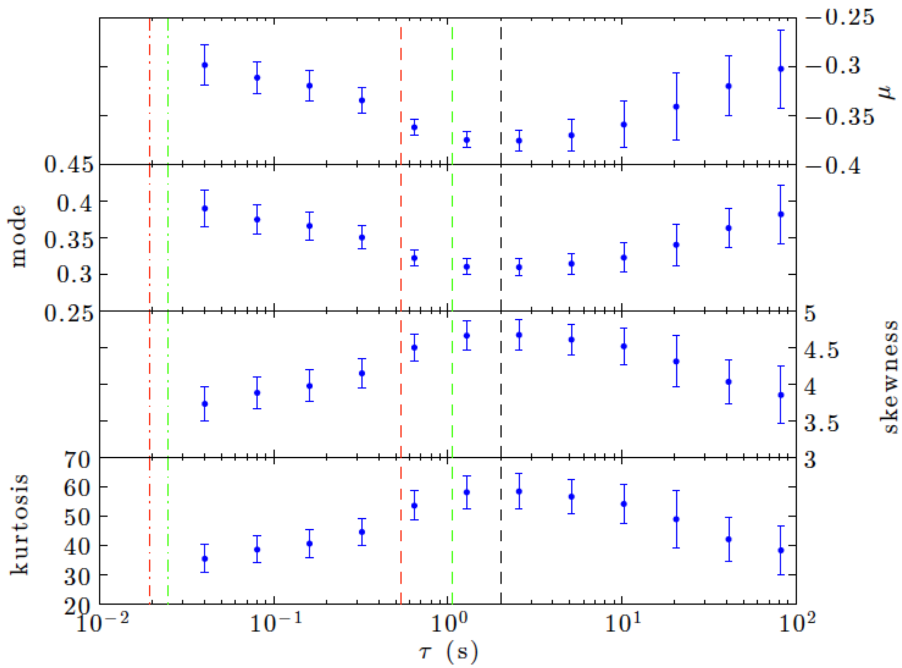


Chen et al. 2015 MNRAS (submitted)

Log-Normal Fits

$$f(x) = \frac{1}{x\sigma\sqrt{2\pi}} \exp\left[-\frac{(\ln x - \mu)^2}{2\sigma^2}\right]$$

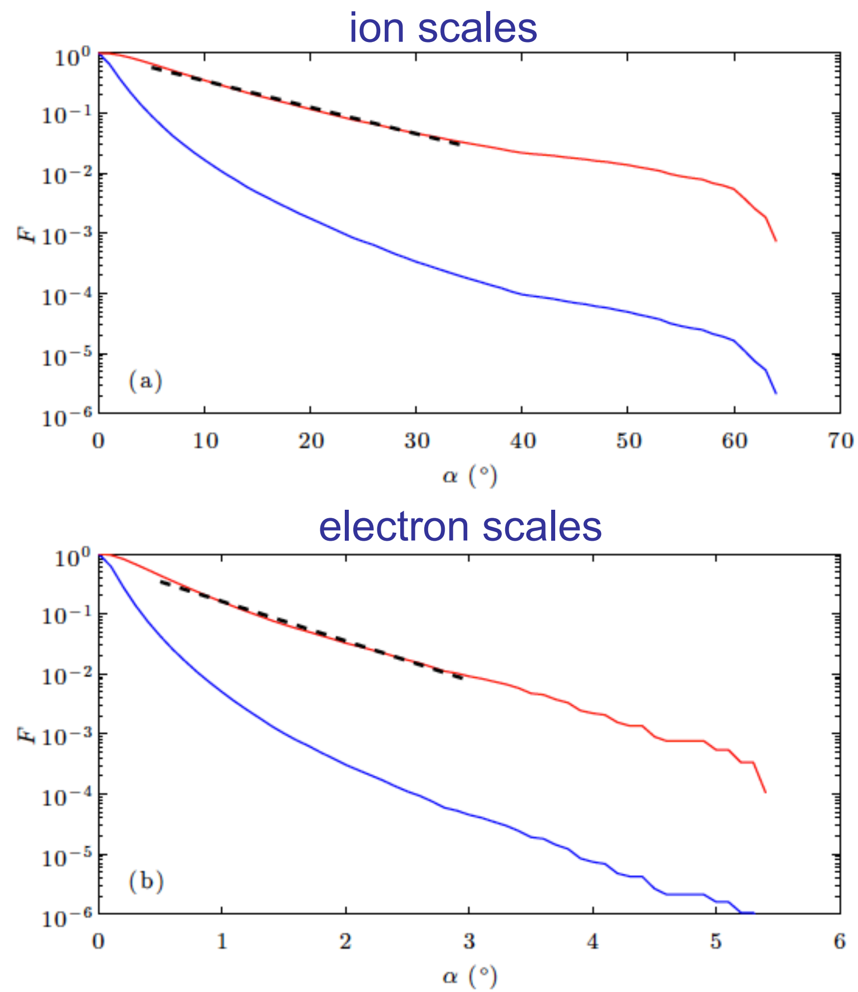
- Fit parameters from log-normal fits
- Error bars are standard deviations from 7 non-overlapping sub-intervals
- Changes with scale are small but statistically significant
- Behavior matches that of the magnetic field component fluctuations (peaks at ion scales)



Chen et al. 2015 MNRAS (submitted)

Energy Fractions

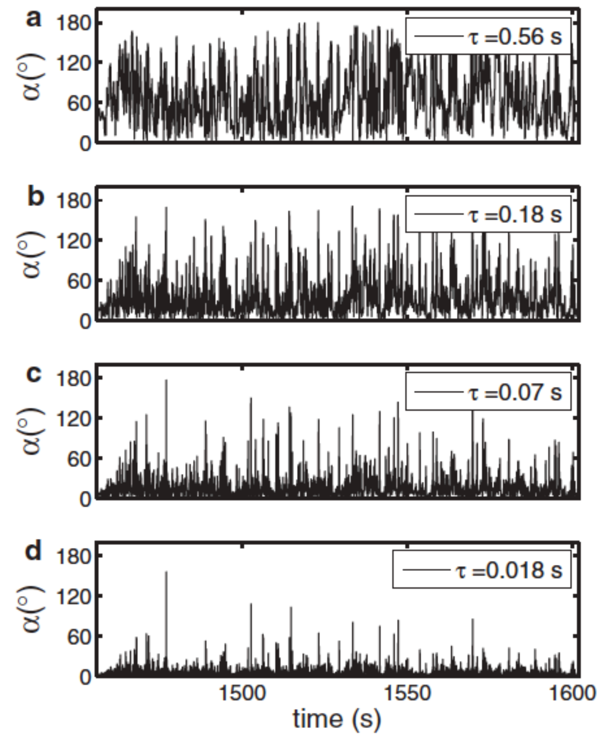
- Blue lines: fraction of fluctuations with angles > α
- Red lines: fraction of energy in fluctuations with angles > α
- Energy drops exponentially
  - e-folding 9.8° at ion scales
  - e-folding 0.66° at electron scales
- Not a significant amount of energy at large angles (α > 30°)
- Shape of these curves matches dissipation in current structures in MHD simulations (Zhdankin et al. 2014)



Chen et al. 2015 MNRAS (submitted)

Comparison to Previous Work

- Like Zhdankin et al. 2012 we find that log-normal distributions fit the data well
- But fit parameters are different (6 years of data so effects of driving?)
- Our rotation angles are much smaller than those of Perri et al 2012
- This is because they used search-coil data only, so no DC field was included
- Reconnection can be suppressed at small angles, since angles here are much smaller than thought this needs to be re-examined



Perri et al. 2012 PRL

Summary

- Spectral break occurs at the larger of ρ_i and d_i, ρ_i in agreement with dispersive scale, but fully consistent explanation for d_i still lacking
- Kinetic scale fluctuations are predominantly anisotropic kinetic Alfvén turbulence, important implications for understanding this range
- Rotation angles in kinetic range remain log-normal, almost self-similar, but there is not a significant amount of energy in large angles