Nature of Solar Wind Turbulence at Kinetic Scales

Christopher H K Chen
www.imperial.ac.uk/people/christopher.chen

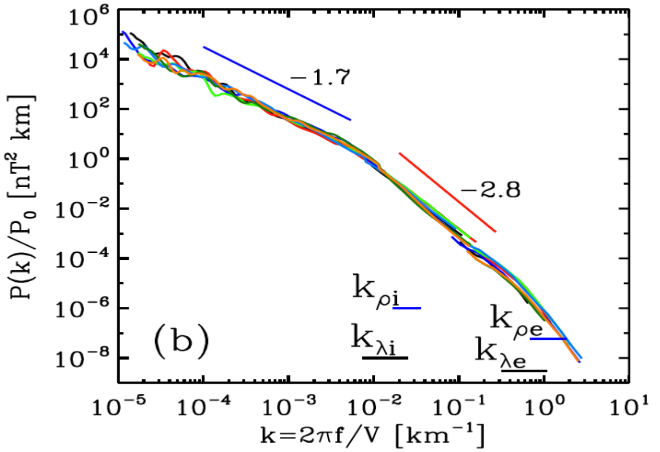
Topics

- 1. Nature of kinetic scale turbulence (Chen et al. 2013 PRL)
- 2. Transition scale from MHD to kinetic range (Chen et al. 2014 GRL)
- 3. Magnetic rotations in the kinetic range (Chen et al. 2015 MNRAS)

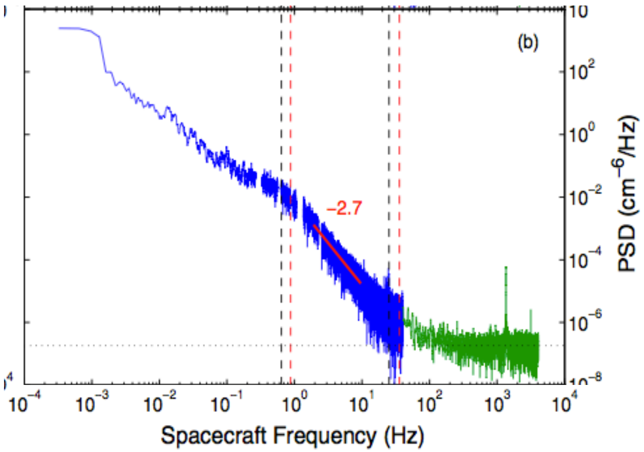
1. Nature of Kinetic Scale Turbulence

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 (Howes et al. 2011 PRL)
  - intermittency, 2D sheets: -8/3 spectrum (Boldyrev et al. 2012 ApJL)
  - compressibility (Alexandrova et al. 2008 ApJL)
  - other possibilities...
- But what is the nature of this turbulence?



Alexandrova et al. 2009 PRL



Chen et al. 2012 PRL

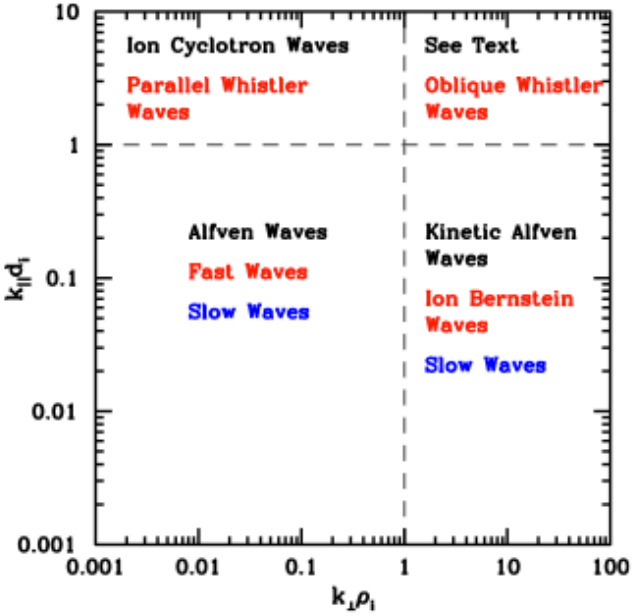
Possible Waves at Kinetic Scales

- Solar wind fluctuations have properties similar to linear waves, suggesting relevance of linear term, e.g. critical balance

- At MHD scales turbulence is predominantly polarised as Alfvén waves, $r_A = \delta v^2/\delta b^2 \sim 1$ (Belcher & Davis 1971 JGR)

- At kinetic scales we have: ion cyclotron waves, kinetic Alfvén waves, whistler waves, ion Bernstein waves, etc.

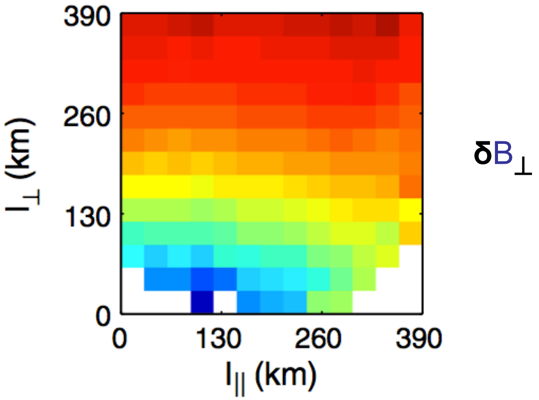
- How can we determine which are relevant for the solar wind?

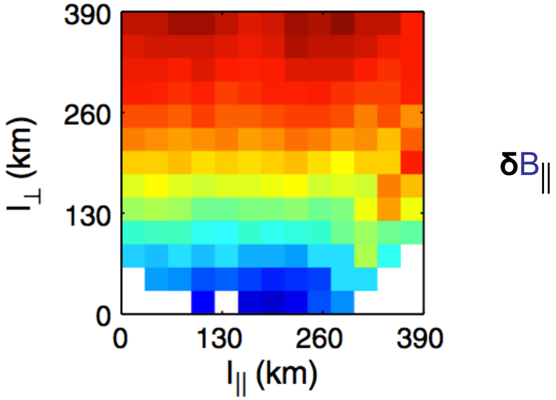


TenBarge et al. 2012 ApJ

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

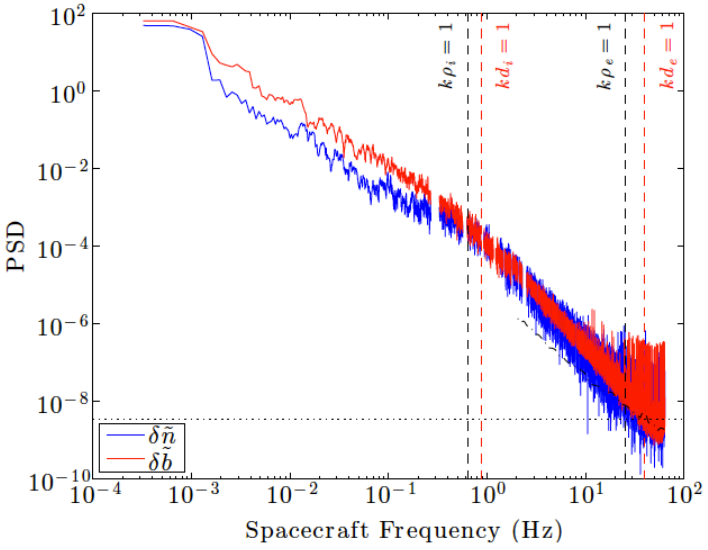
KAW vs Whistler Turbulence

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

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

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

- Check with THEMIS / ARTEMIS data
- Kinetic Alfvén ratio $r_{KAW} = \delta\tilde{n}^2/\delta\tilde{b}_\perp^{\,2} \sim 1$ → predominantly kinetic Alfvén turbulence
- In fact, magnetic energy slightly dominates (effect of non-linear terms?)



Chen et al. 2013 PRL

Implications of KAW Turbulence

- Similar results seen in simulations (Chen et al. 2013 PRL, Boldyrev et al. 2013 ApJ, Franci et al. 2015 ApJL)
- Consistent with transition from anisotropic Alfvenic MHD range
- 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 ApJL)
  - efficiency of cyclotron damping is reduced (Schekochihin et al. 2009 ApJS)

2. Ion Break Scale

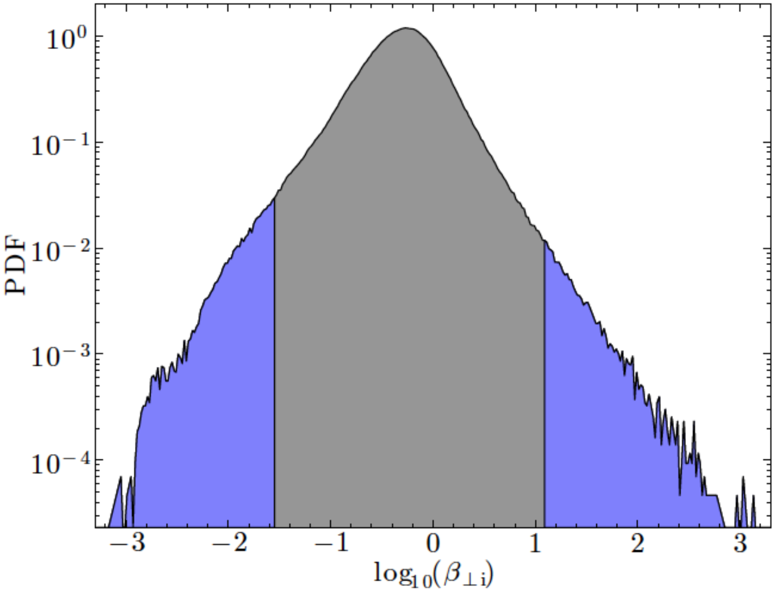
Ion Break Scale

- So which scale is associated with the break?
  - Kinetic Alfvén wave dispersive/damping scale ρ_i
  - Hall MHD transition d_i (current sheets?)
  - Others: cyclotron damping scale, gyrofrequency, ...

- Previous studies came to different conclusions
  - Leamon et al. 2000: d_i and oblique propagation
  - Smith et al. 2001: d_i at low beta
  - Markovskii et al. 2008: combination of scale and amplitude
  - Perri et al. 2010: no theoretical scale
  - Bourouaine et al. 2012: d_i assuming strong anisotropy
  - Bruno et al. 2014: cyclotron damping scale

High and Low Beta Intervals

- Difficulty in distinguishing scales is that they are similar at 1 AU
- $d_i = \rho_i/\sqrt{\beta_i}$ so at $\beta_i \sim 1$ these are the same
- We look for intervals with $\beta_i \ll 1$ and $\beta_i \gg 1$ so that they are measurably different
- 20 years *Wind* data to find these rare occasions
- Low beta intervals mostly in CMEs, but display long -5/3 range so can study microphysics as in non-CME wind



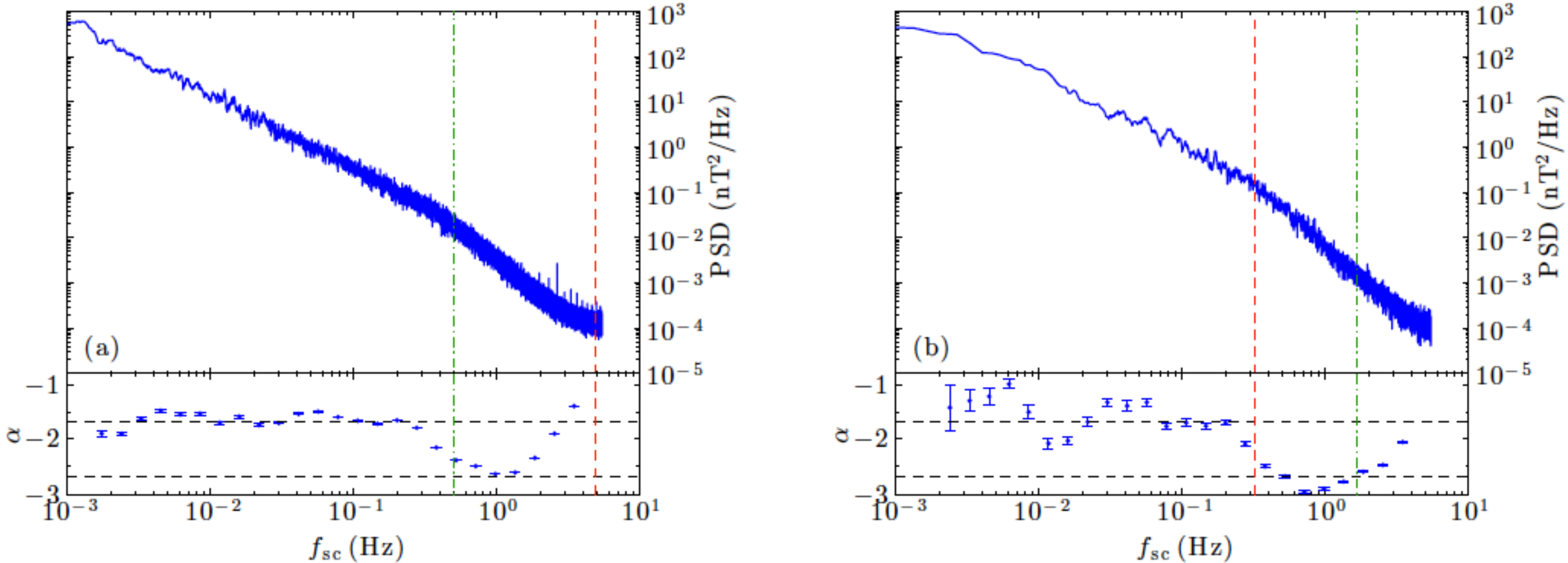
Chen et al. 2014 GRL

Break Scale at Low and High β_i

- 2 examples: high and low β_i
- Break occurs at the larger of the scales
- Note: clear break not always seen (only in 55% of cases)

β_i << 1

β_i >> 1

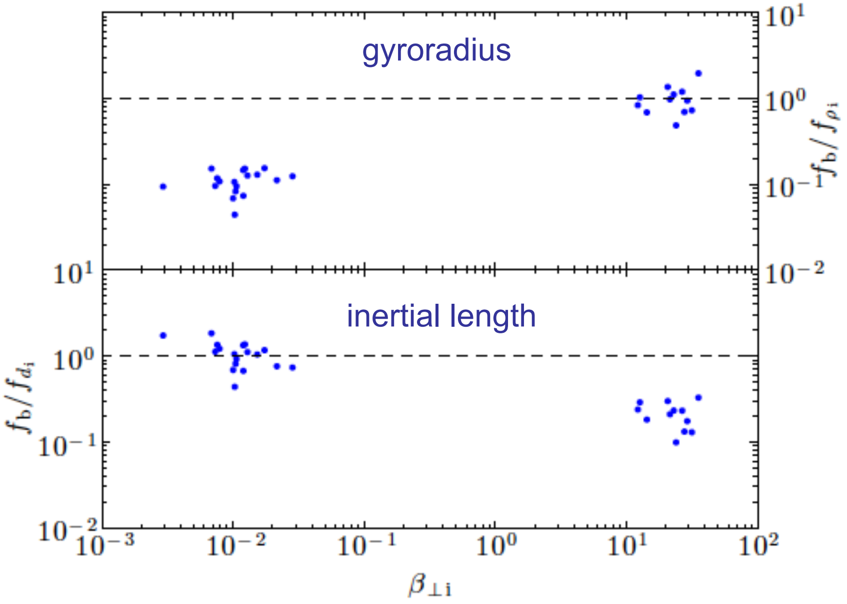


Chen et al. 2014 GRL

Statistical Study

- Break at larger of ρ_i and d_i
  - ρ_i consistent with KAW dispersion
  - 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



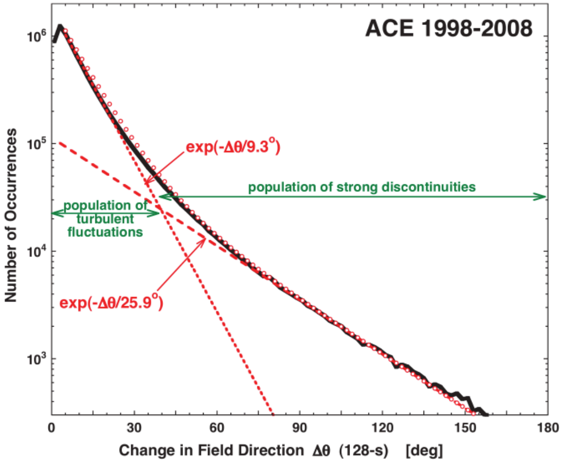
Chen et al. 2014 GRL

3. Magnetic Rotations in Kinetic Range

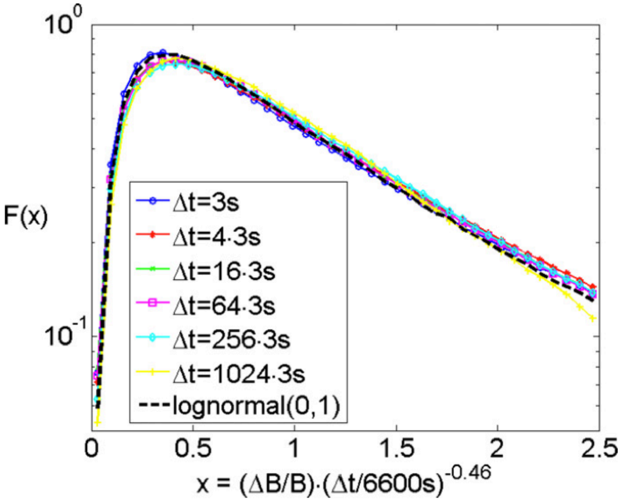
Magnetic Field Rotations

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

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



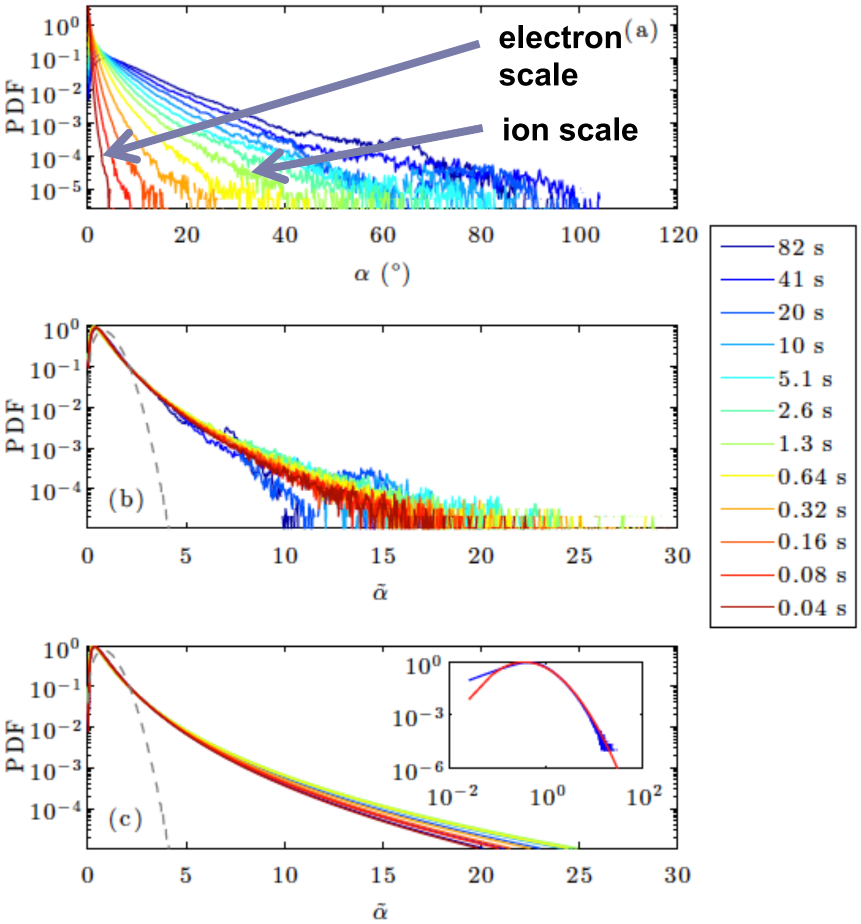
Borovsky 2010 PRL



Zhdankin et al. 2012 ApJL

Rotations at Kinetic Scales

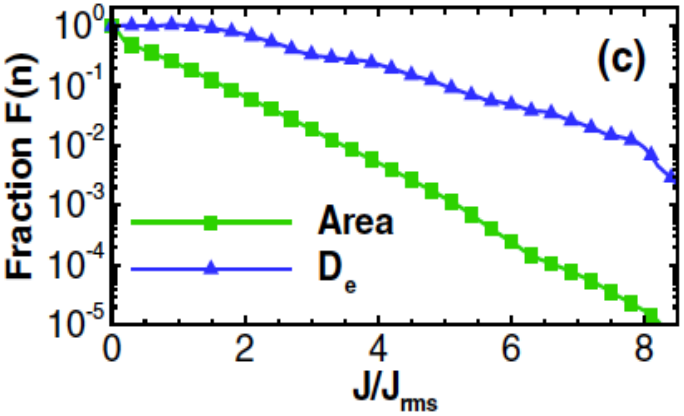
- Use combined FGM/STAFF Cluster data, 7 hour interval clear of foreshock
- Angles become small quickly from ion to electron scales
- Distribution is non-Gaussian but almost self-similar (like components)
- Distribution is quite well fit to log-normal, only small changes in fit parameters with scale
- May be related to distribution of energy dissipation in the plasma (Sorriso-Valvo, Zhdankin, ...)



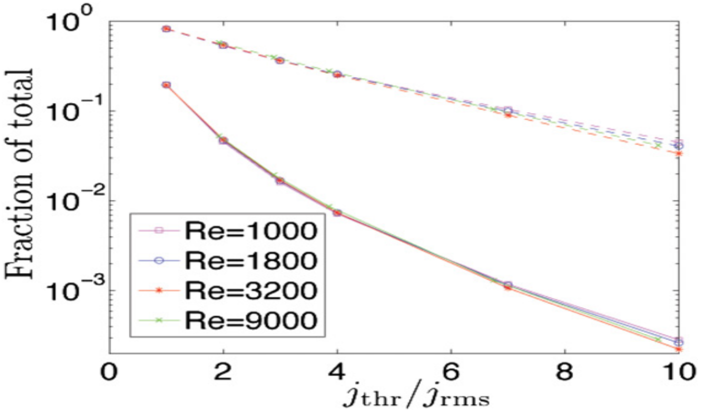
Chen et al. 2015 MNRAS

Intermittent Energy Dissipation

- Recent simulations have shown the intermittent nature of energy dissipation
  - Wan et al.: 2D PIC
  - Zhdankin et al.: 3D MHD
- Dissipation concentrated at current structures in both simulations
- Shape of curves contains information about nature of dissipative structures
  - 2D: volume fraction is ~exponential
  - 3D: energy fraction is ~exponential



Wan et al. 2012 PRL

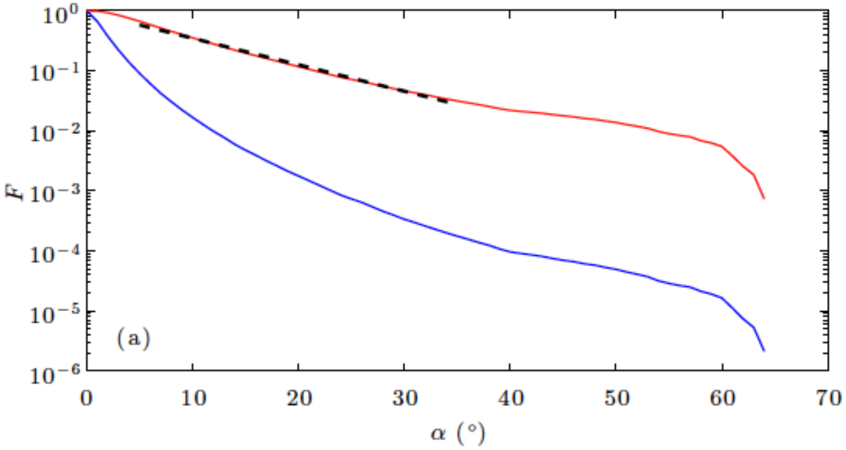


Zhdankin et al. 2014 ApJ

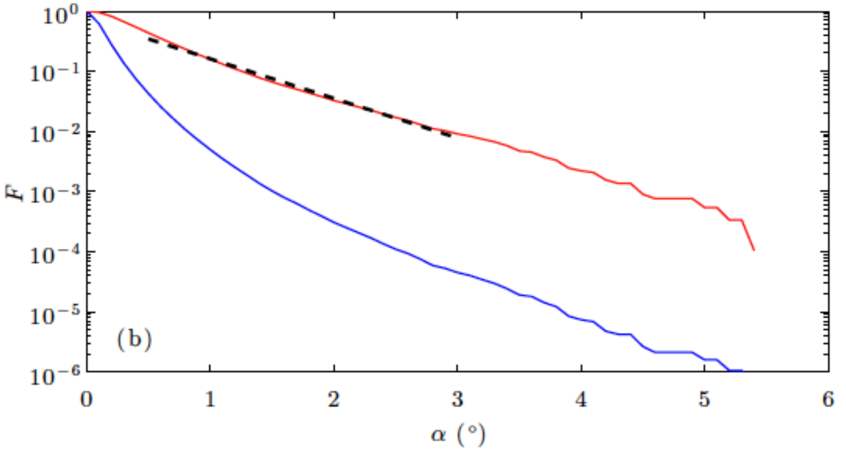
Energy Fractions in Solar Wind

- Fraction of fluctuations with angles > α (blue), fraction of energy ($|\delta \mathbf{B}|^2$) in those angles (red)
- Energy drops exponentially, not much in large angles (α > 30°)
    - e-folding 9.8° at ion scales
    - e-folding 0.66° at electron scales
- Since α ~ δB/B ~ j, plots can be a proxy for dissipation fraction
- Shape is more similar to the 3D MHD simulations (full dimensionality required to reproduce dissipative structures?)

ion scales



electron scales



Chen et al. 2015 MNRAS

Summary

- 1. Kinetic scale fluctuations are predominantly anisotropic kinetic Alfvén turbulence, implications for cascade physics and dissipation

- 2. 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

- 3. Rotation angles in kinetic range remain log-normal, almost self-similar, but not a significant amount of energy in large angles, intermittent dissipation proxy similar to 3D MHD simulations, more comparisons needed