Kinetic Scale Turbulence in the Solar Wind

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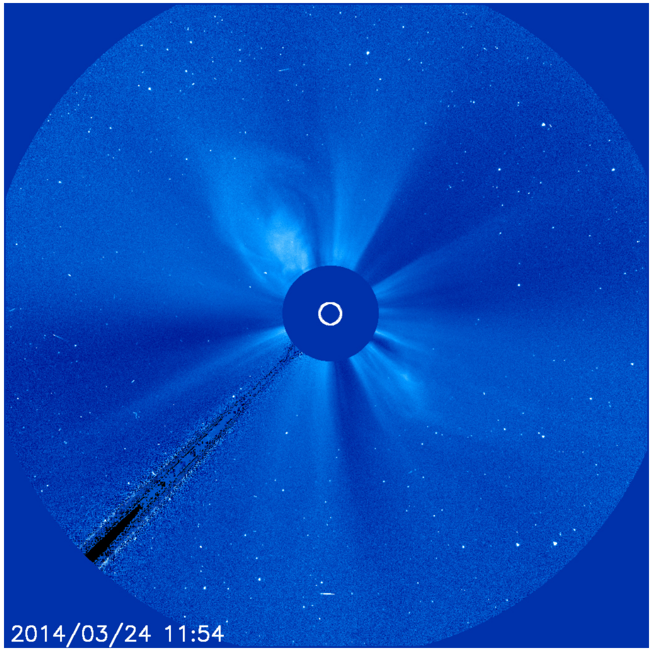
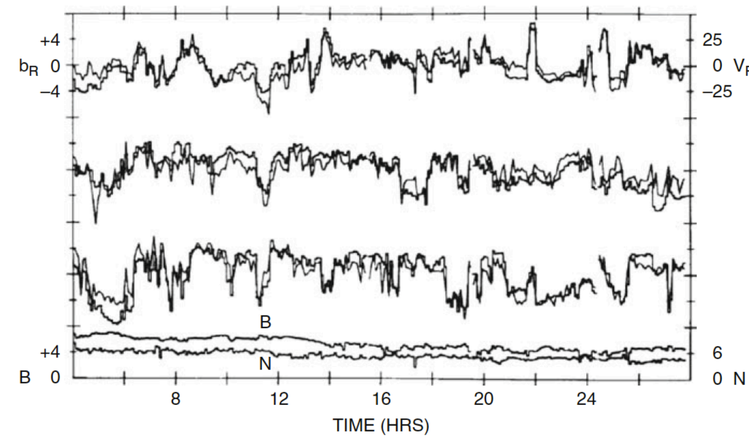
The Solar Wind

- Mainly H (96%) and He (4%) plasma, with small fraction of heavy ions
- Highly collisionless (on turbulence scales)
- mfp ~0.5AU >> ρ_i ~70km >> ρ_e ~2km >> λ_D ~8m
- $\beta \sim 1$, $T_p \sim T_e$
- Supersonic. Taylor hypothesis: measured frequency spectrum → k spectrum
- Lots of (non-turbulent) structure
- Expands non-adiabatically, extra heating

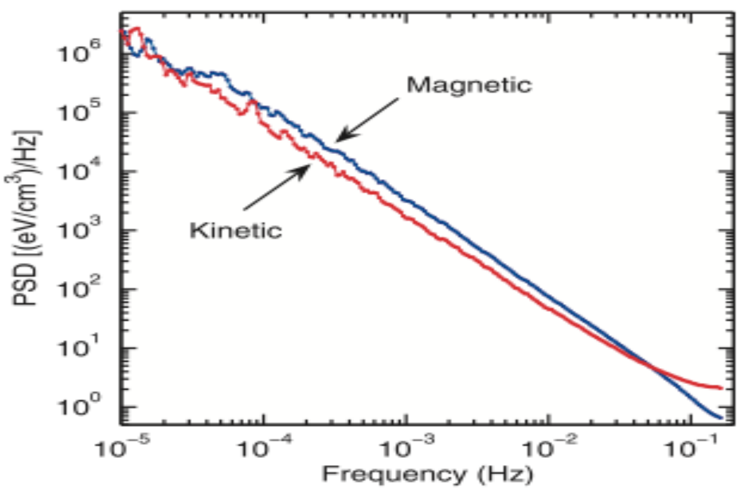


MHD Scale Turbulence

- Predominantly Alfvénic (90% of energy)
- Residual energy $\delta v^2/\delta b^2 = 0.7$
- Power spectra with index ≈ -5/3 or -3/2
- Anisotropic ($k_\perp > k_{||}$), with steep parallel spectrum $E(k_{||}) \propto k_{||}^{-2}$
- Cascade rate matches T profile
- Active Alfvénic turbulence seems most plausible explanation



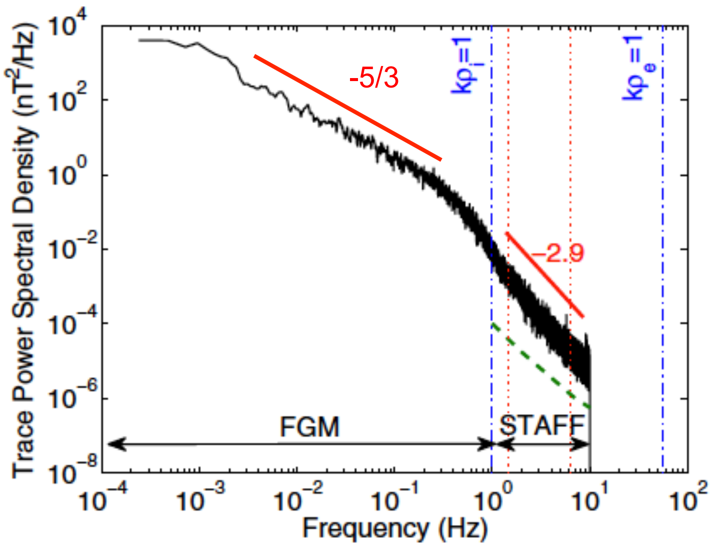
Belcher & Davis 1971 JGR



Podesta et al. 2007 JGR

Turbulence at Kinetic Scales

- What happens at kinetic scales?
- Further cascade? Damping? Heating? Kinetic scale structures? Instabilities?
- B steepens at ion scales ~ 0.5 Hz
- Power law indicates at least some energy to further cascade
- Only recently been able to examine this in detail, with new measurements

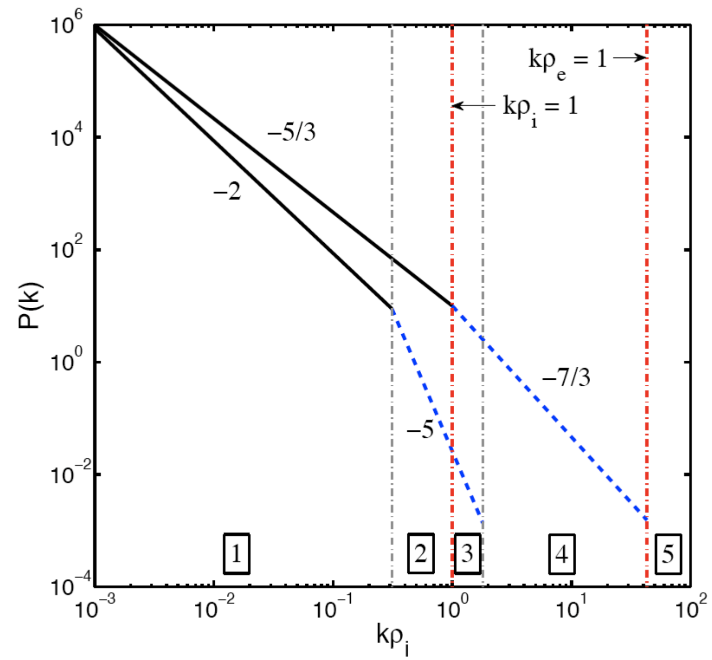


Chen et al. 2010 PRL

Cascade Pre(post)dictions

- Apply K41 to relevant fluid equations
  - $E_B(k) \sim k^{-7/3}$ Vainshtein 1973 SovPhysJETP
- Apply critical balance
  - $k_{\|} \propto k_{\perp}^{1/3}$
  - $E_B(k_{\|}) \sim k_{\|}^{-5}$

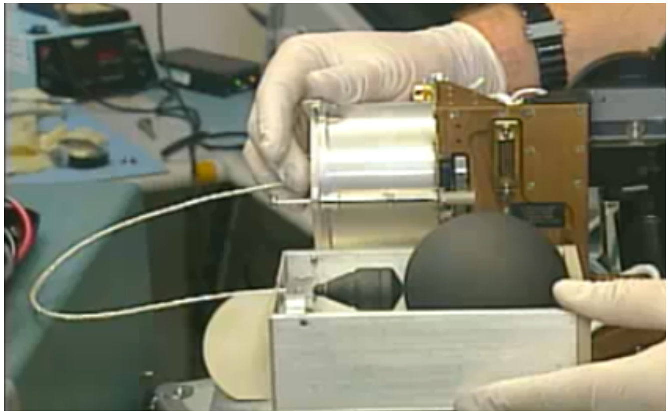
  Cho & Lazarian 2004 ApJL
- With intermittent 2D structures
  - $E_B(k_{\perp}) \sim k_{\perp}^{-8/3}$ Boldyrev & Perez 2012 ApJL
- Also some weak turbulence predictions (but may be non-universal)

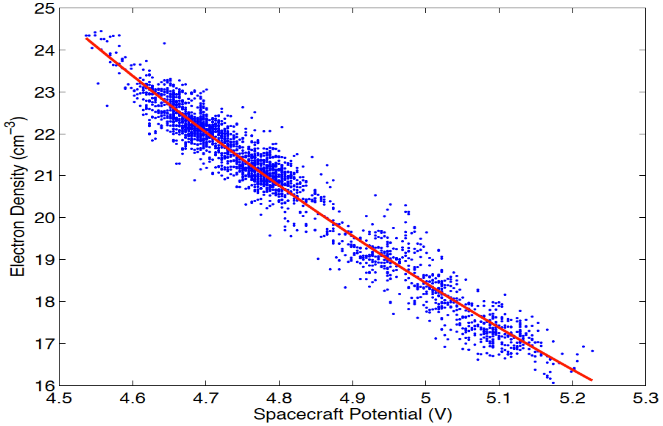


Chen et al. 2010 ApJL

Measuring Density Fluctuations

- Need more than B
- Can now measure density at high resolution (Pedersen 1995 AnGeo)
  - s/c in sunlight emits photoelectrons and charges positive
  - also attracts electrons from plasma, reaching equilibrium current balance
  - higher density → larger return current → spacecraft less positive
- S/c potential measured with biased probes

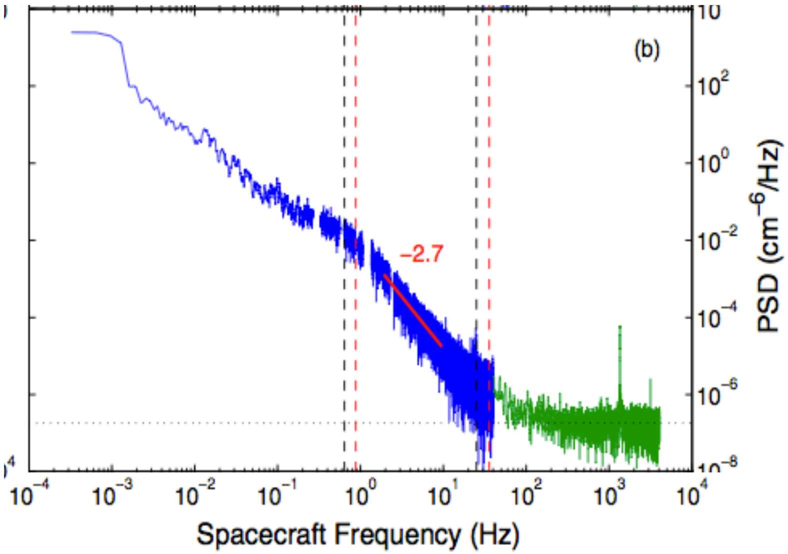




Chen et al. 2012 PRL

Density Spectrum

- First measurement of density spectrum at kinetic scales
- Mean spectral index is -2.75 ± 0.06
- Matches B spectrum of -2.8, consistent with a KAW cascade
- Steeper than -7/3 pure cascade, closer to -8/3 intermittent theory
- Steepening could also be due to damping



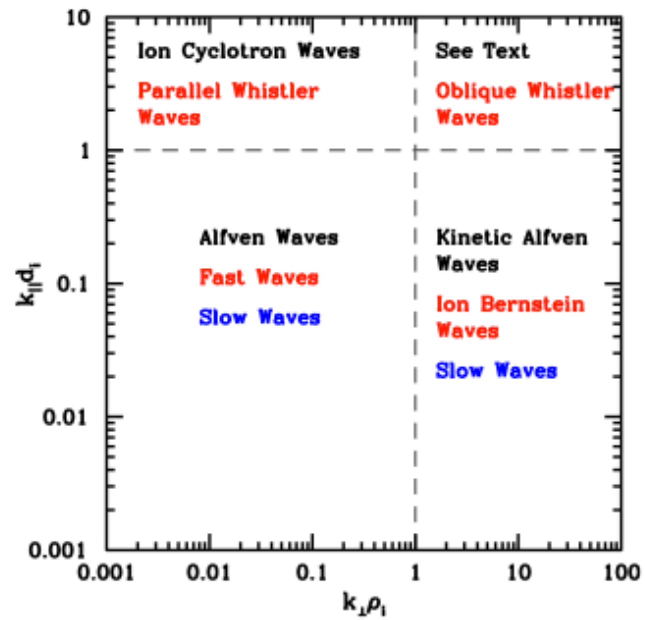
Chen et al. 2012 PRL

Nature of Kinetic Scale Turbulence

- What is the predominant type of turbulence at kinetic scales in the solar wind?

- At kinetic scales the MHD modes become
  - ion cyclotron waves (parallel)
  - ion Bernstein waves (electrostatic)
  - kinetic Alfvén waves
  - whistler waves

- Are properties of these seen in the solar wind? If so, which is dominant?

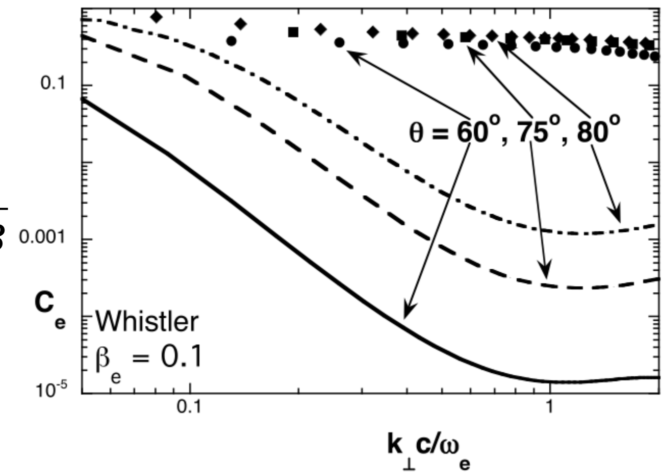


TenBarge et al. 2012 ApJ

KAW or Whistler Turbulence?

- Many properties qualitatively similar: dispersion, magnetic compressibility, helicity
- Since strong turbulence only qualitatively follows linear modes, we need a qualitative difference (Boldyrev et al. 2013 ApJ):
  - whistlers have $\omega > k_\perp v_{thi}$, so ions stationary, negligible δn
  - KAW have $\omega < k_\perp v_{thi}$, so ions fluctuate
- We use this to identify the nature of kinetic scale turbulence

$$\frac{\delta n / n}{\delta B / B}$$



Gary & Smith 2009 JGR

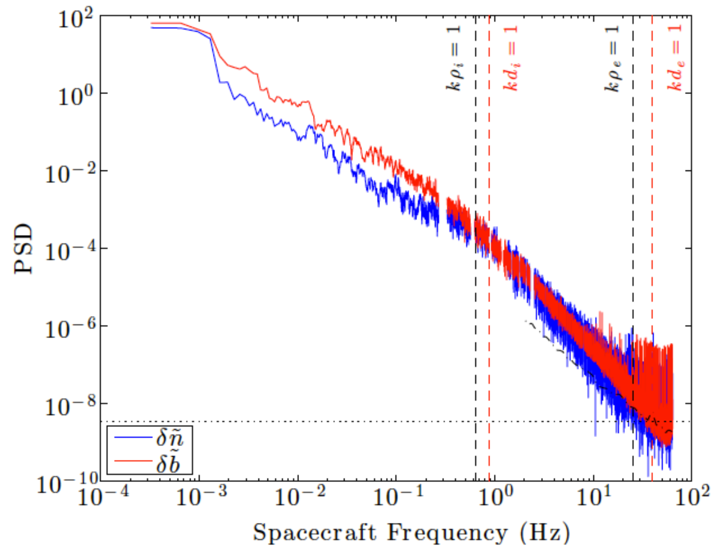
Measurements

- If we normalize the fields as

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

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

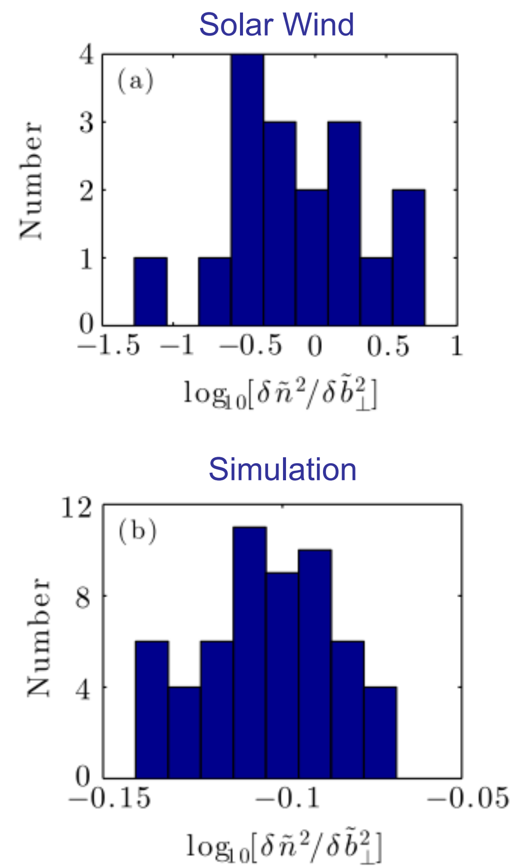
- Then
  - KAW: $\delta\tilde{n} = \delta\tilde{b}_\perp$
  - whistler: $\delta\tilde{n} \ll \delta\tilde{b}_\perp$
- Normalized spectra approx equal → predominantly kinetic Alfvén turbulence, rather than whistler



Chen et al. 2013 PRL

Comparison to Simulations

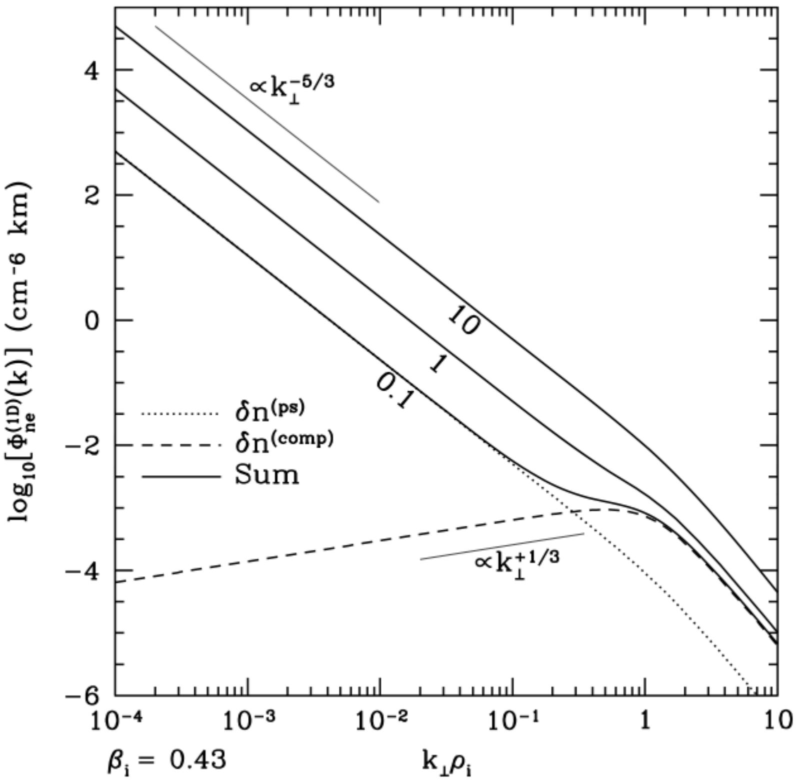
- 17 solar wind intervals available
- Slight dominance of magnetic energy, kinetic Alfvén ratio: $\delta\tilde{n}^2/\delta\tilde{b}_\perp{}^2 = 0.75$
- Compare to 512^3 simulation of kinetic Alfvén turbulence (Boldyrev, Xia, Perez)
- Again dominance of magnetic energy $\delta\tilde{n}^2/\delta\tilde{b}_\perp{}^2 = 0.79$
- Consistent with strong turbulence having *qualitative* but not *quantitative* properties of the linear modes



Chen et al. 2013 PRL

Flattening at Ion Scales

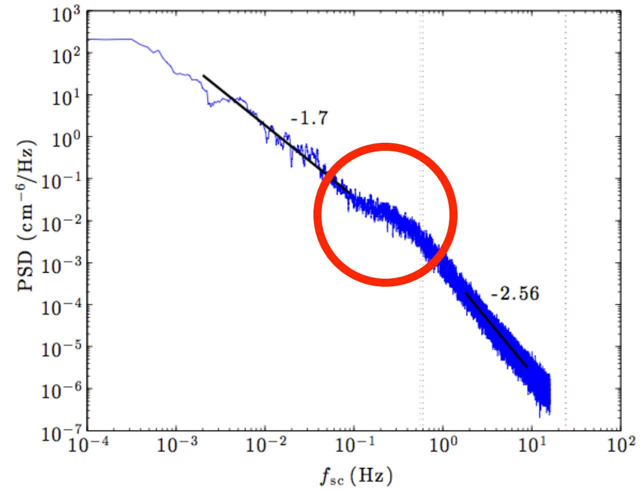
- Alfvénic turbulence becomes compressive at ion scales
- Density spectrum modeled as passive scalar + active kinetic Alfvén turbulence
- Leads to flattening in spectrum before ion scales
- Flattening is enhanced for
  - smaller passive component
  - lower β_i

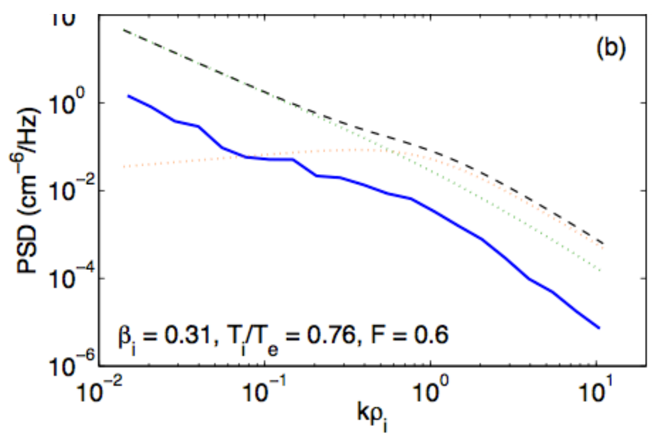


Chandran et al. 2009 ApJ

Flattening at Ion Scales

- A bump in the density spectrum is often seen at ion scales
- Compare to Chandran/Howes model of this using measured sw parameters
- Shape matches well, at different values of β_i
- Flattening enhanced at lower β_i so should show up strongly at 9.8 Rs in Solar Probe Plus measurements

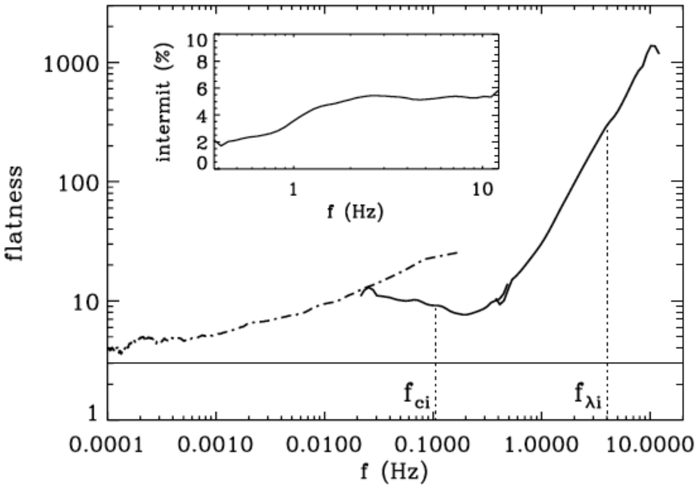




Chen et al. 2013 SW13

Kinetic Scale Intermittency

- How intermittent is kinetic scale turbulence?
- Previous B results are conflicting, so look at n
- To measure, we need high resolution time series without spin tones
- Spektr-R / BMSW can provide n_i at 31 ms
- 6 Faraday cups, simultaneously measure different points on the distribution
- Assume isotropic Maxwellian (intervals checked for this)

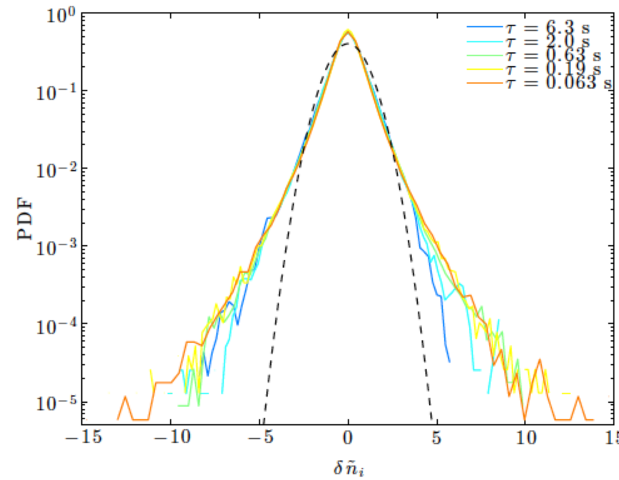


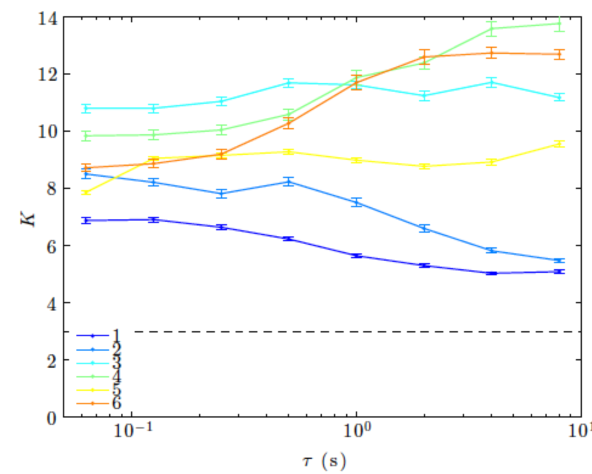
Alexandrova et al. 2008 ApJ

Šafránková et al 2013 SSR

Density Intermittency

- Fluctuations are intermittent (non-Gaussian)
- PDFs remain same shape through range
- Small differences between intervals, but no large change in K
- Matches results of (Kiyani et al. 2009 PRL), but not (Alexandrova et al. 2008 ApJ)
- Intermittency different to MHD range
- Not fully understood, could be mono-fractal turbulence, limited current sheet stability, weaker due to damping





Chen et al. 2014 ApJL (submitted)