The solar wind power spectrum observed from Cluster: insights in three dimensions and at sub ion scales

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Guest starring the joint ESTEC-ESAC Heliophysics group

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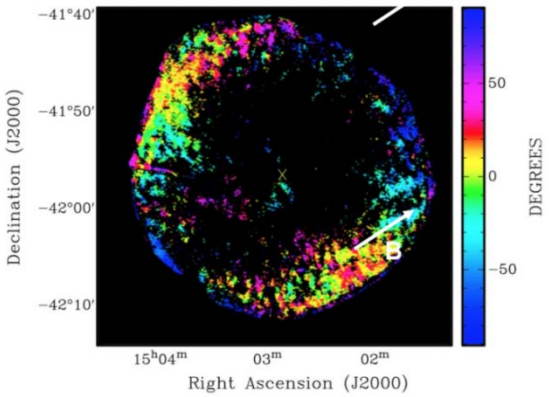
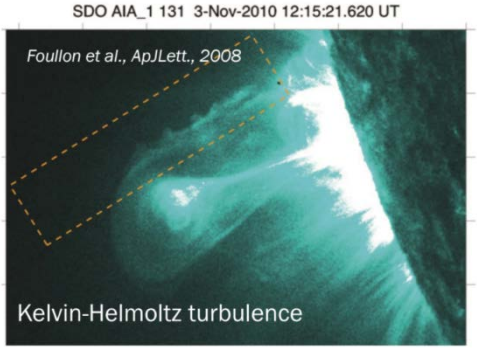
Outline

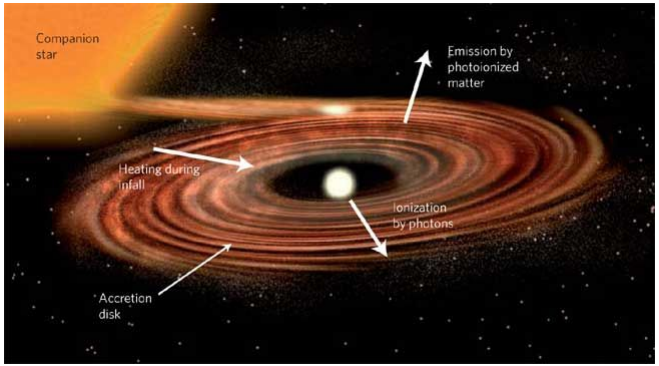
1. Introduction to turbulence. Huge range of scales involved!
2. How is Cluster still helping our understanding.
3. Three dimensional structure of solar wind turbulence at proton scales.
4. Shape of the power spectrum at electron scales

Why study turbulence? Understanding astrophysical and terrestrial plasmas

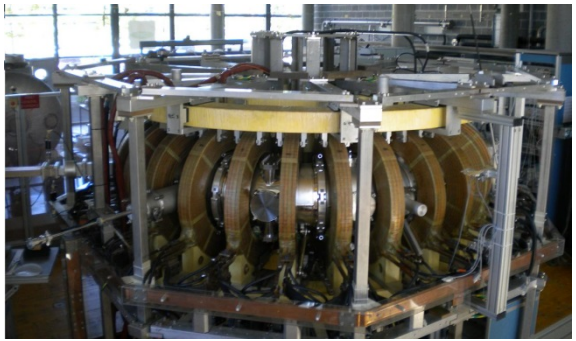


Reynoso et al., ApJ, 2013





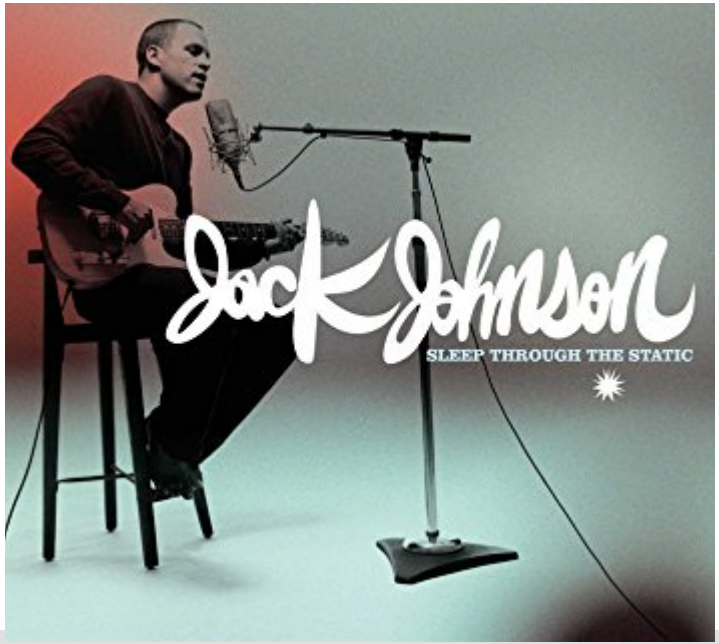
Drake 2009



TORPEX fusion rector, Credit EPFL

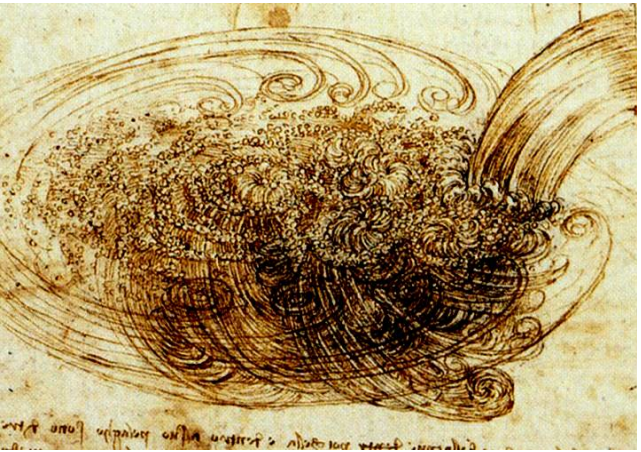
What is Turbulence? A musician's definition…

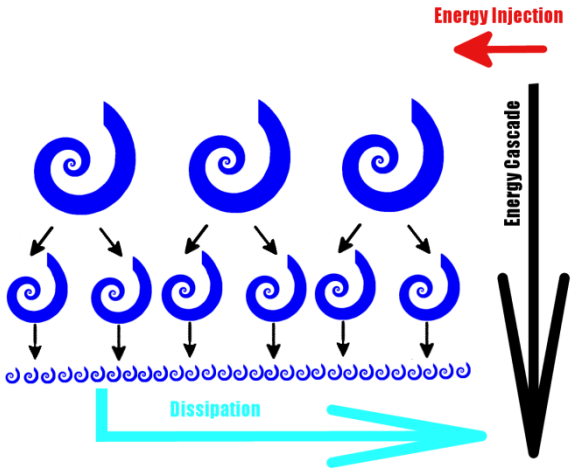
- Turbulence is like a sigh I can't help but overthink…

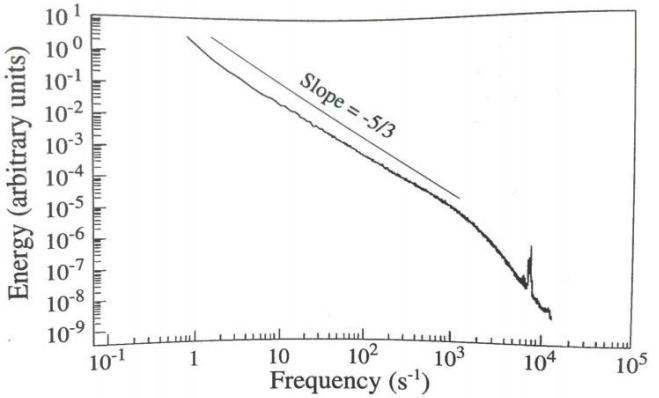


What is Turbulence? A more useful definition…

- Turbulence is like a sigh I can't help but overthink…
- Disordered fluctuations over a large range of time/length scales







What is Turbulence?

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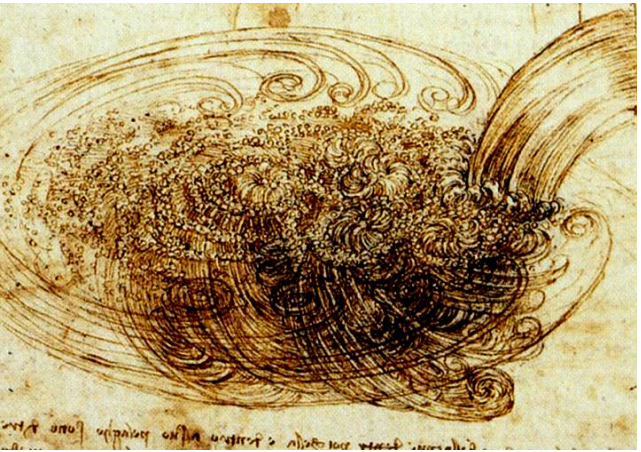
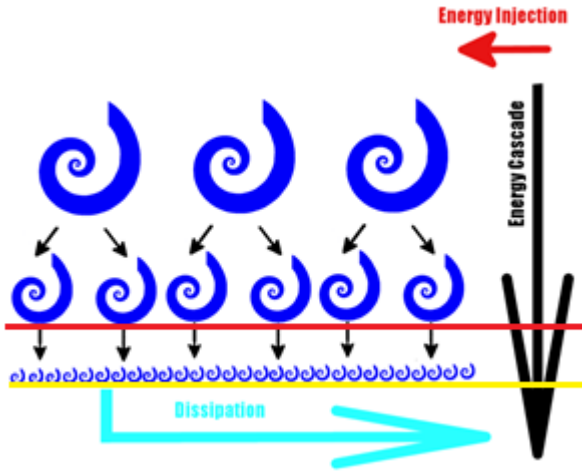
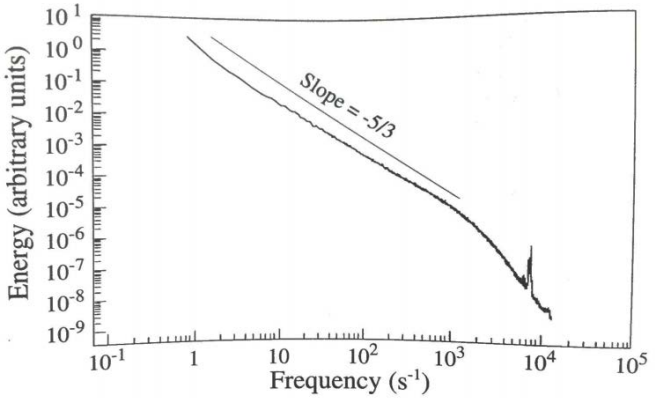


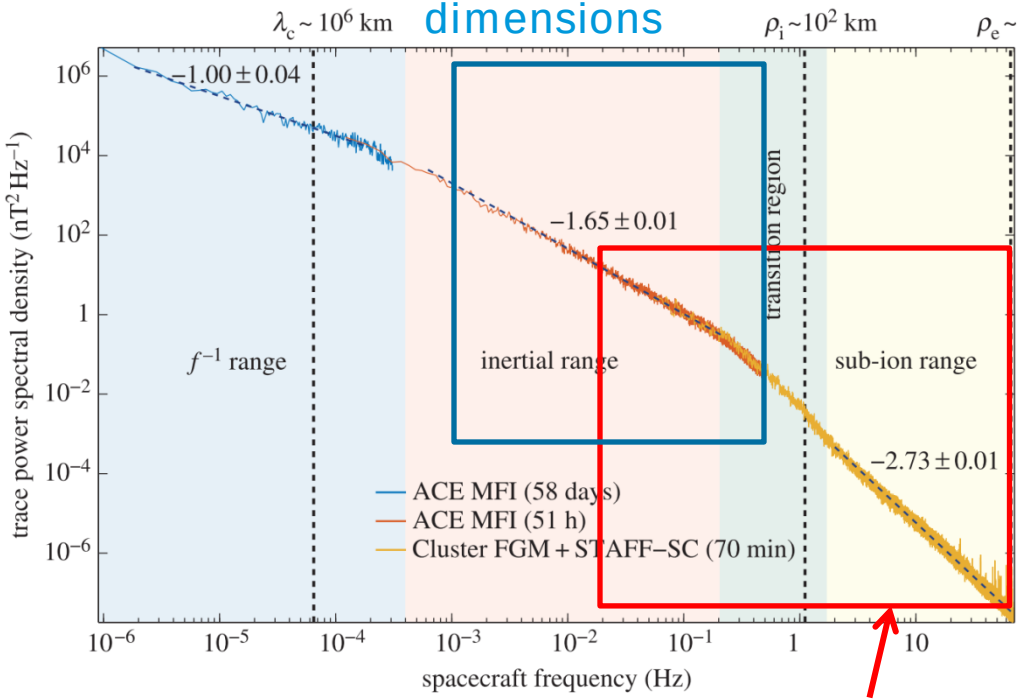




Spectrum of magnetic fluctuations

Part 1 Three dimensions

- Several different particle species (α, protons, electrons some heavy ions)
- Presence of a large scale magnetic field-> Anisotropy
- Several different length scales possible!!
- Spectrum considerably more complex



Kiyani et al. 2015

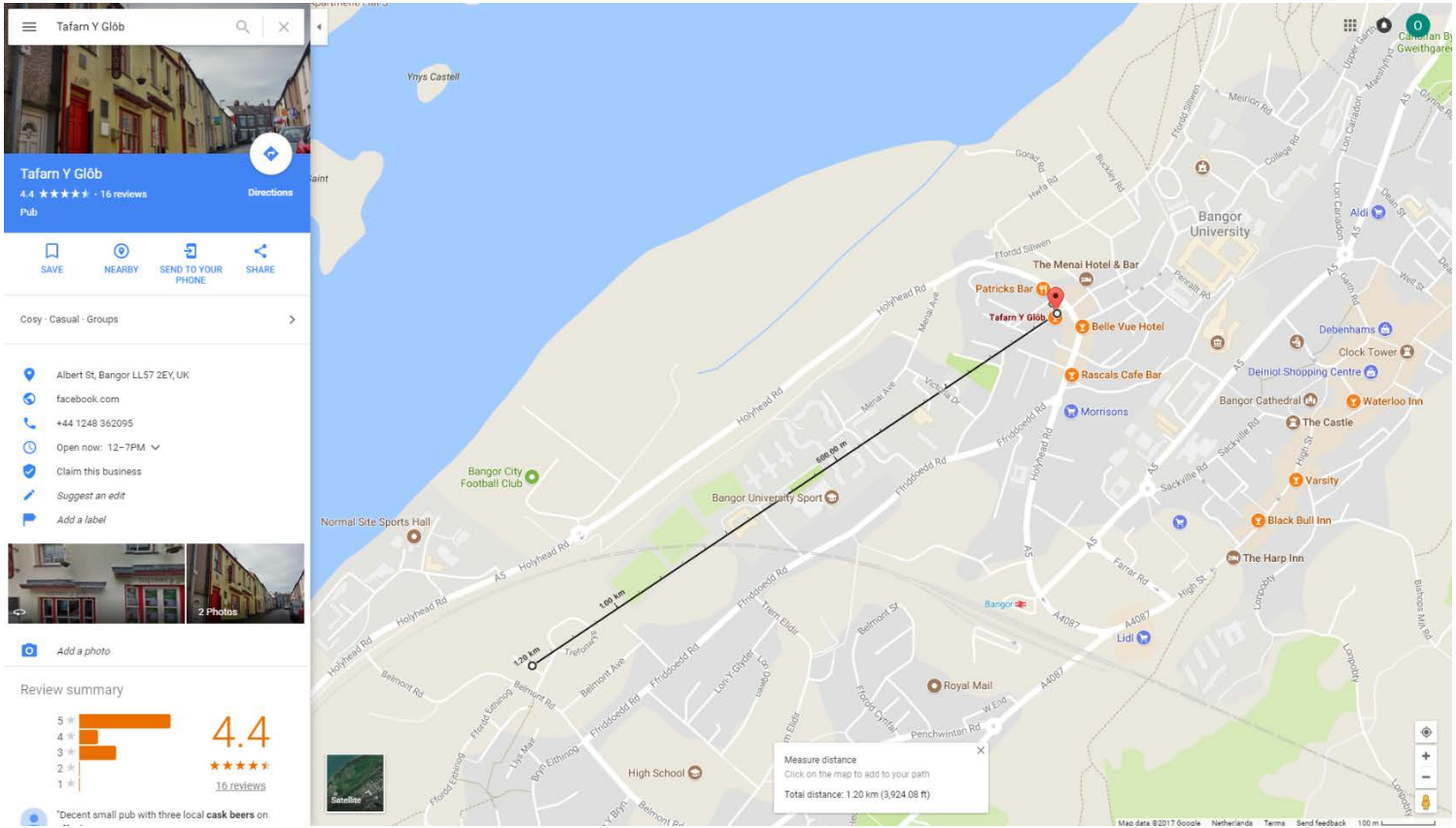
Part 2 The shape here!

What can we learn from Cluster?

1. Three dimensional structure of Turbulence

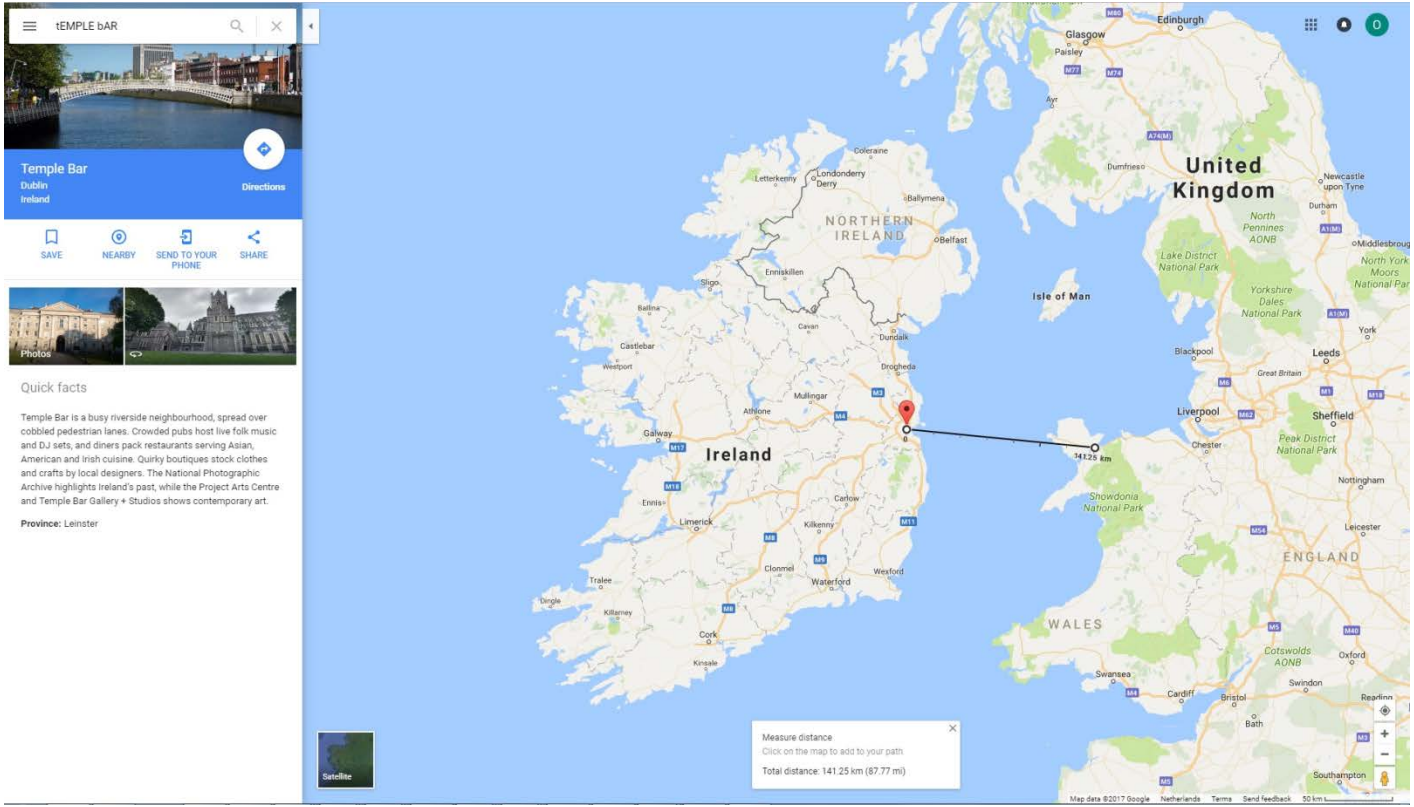
- Multiple sampling points
- Variation of tetrahedron size
- Inter-spacecraft distances vary from a few kilometers(between a pair). To 100s of km with tetrahedron to 10000km (can you explain that to me using pubs?)

1km (electron scales) scale



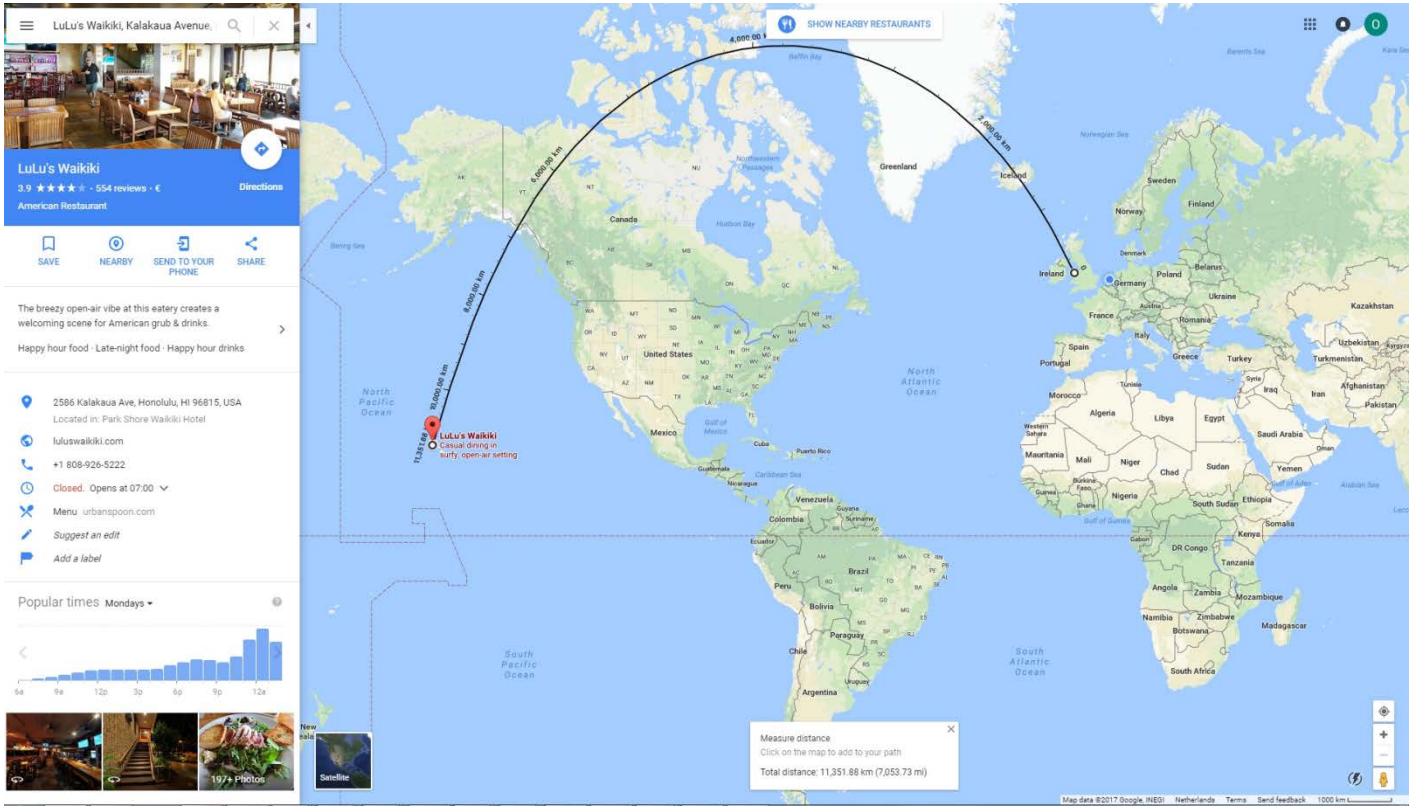
Distance from my mum's house to Tafarn y Glôb!

100km (proton scales) Scale



Distance from Y Glôb to Temple Bar

10000km (fluid scales) scale



Distance from Y Glôb to Lulu's

Correlation length 100 times larger!

What can we learn from Cluster?

1. Three dimensional structure of Turbulence

- Multiple sampling points
- Variation of tetrahedron size
- Inter-spacecraft distances vary from a few kilometers. To 100s of km with tetrahedron to 10000km (can you explain that to me using pubs?)

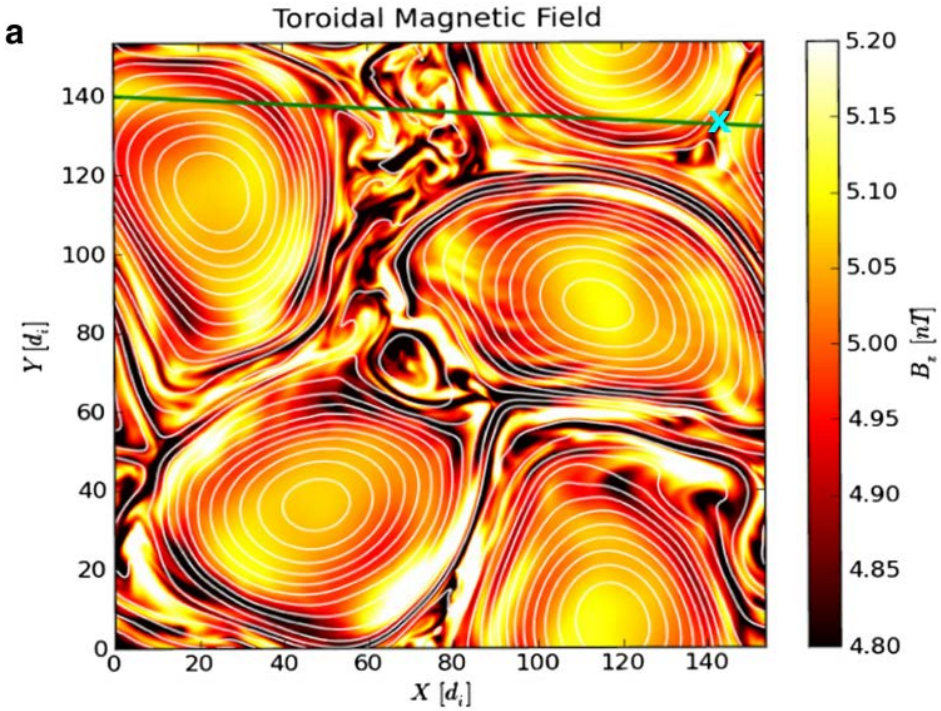
2. Extremely sensitive Search Coil magnetometer

- Very small dt means we can study very small lengths along the sampling direction
- Still the best (most sensitive) magnetometer out there!

Three dimensional Structure

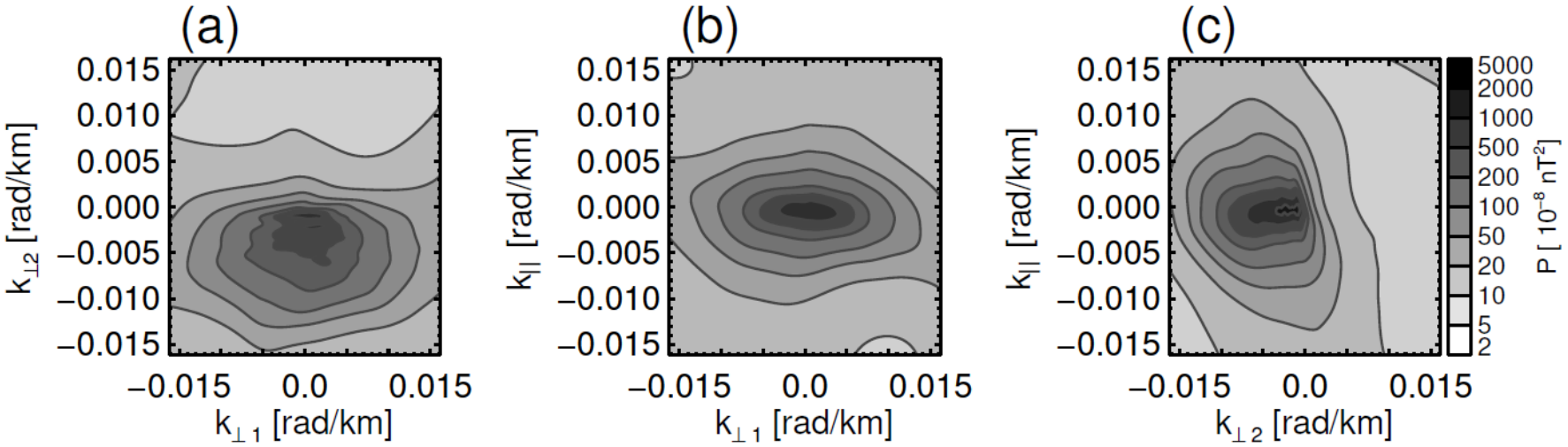
Single Spacecraft

- Assumption that fluctuations do not evolve in the time it takes to sample them (Taylor's frozen in flow hypothesis)
- 1-D cut through the plasma on the velocity (sampling) direction
- Assume a direct relation between frequency and wavenumbers
- Warning! Not valid for low flow speed, fast fluctuation speeds.
- We need multi-point measurements to be able to determine the power spectrum in 3 dimensions in wavenumber space
- Can we do better with multiple spacecraft?



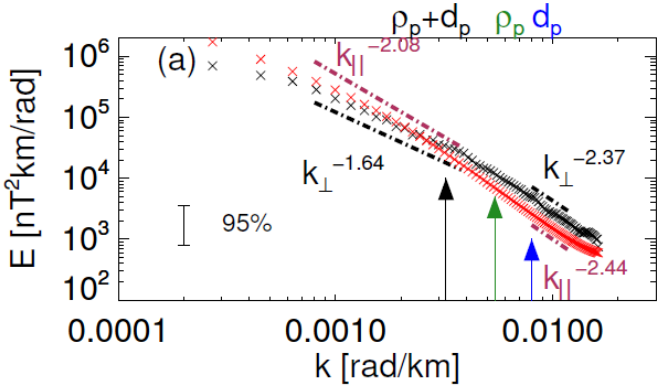
Perri et al 2012

What is the three dimensional structure of turbulence?

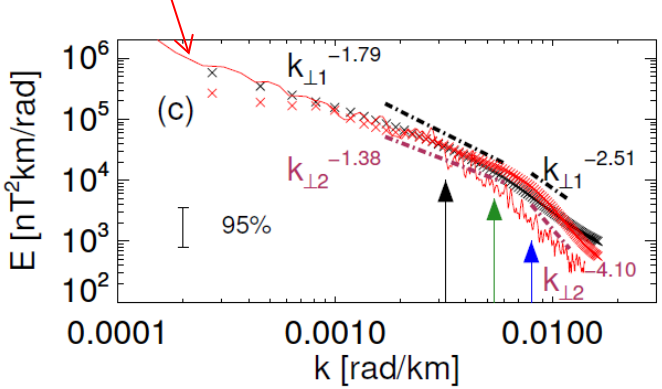


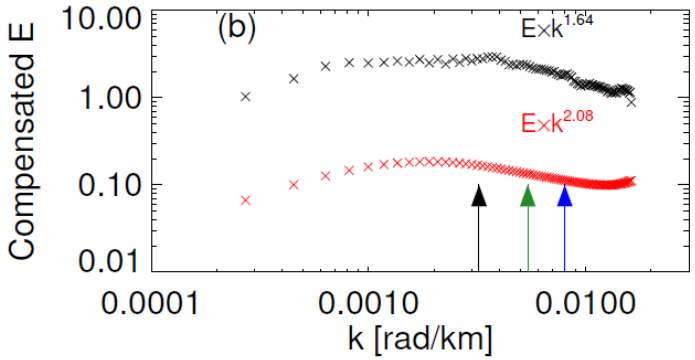
By comparing fluctuations at different Cluster spacecraft we can obtain a three dimensional distribution of power in inverse space!

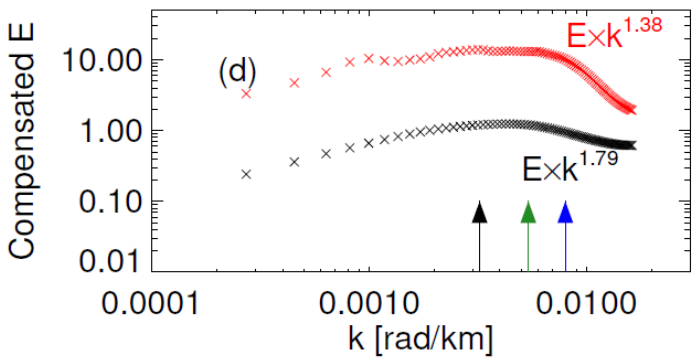
Spectra obtained



Line from TH points from MSR

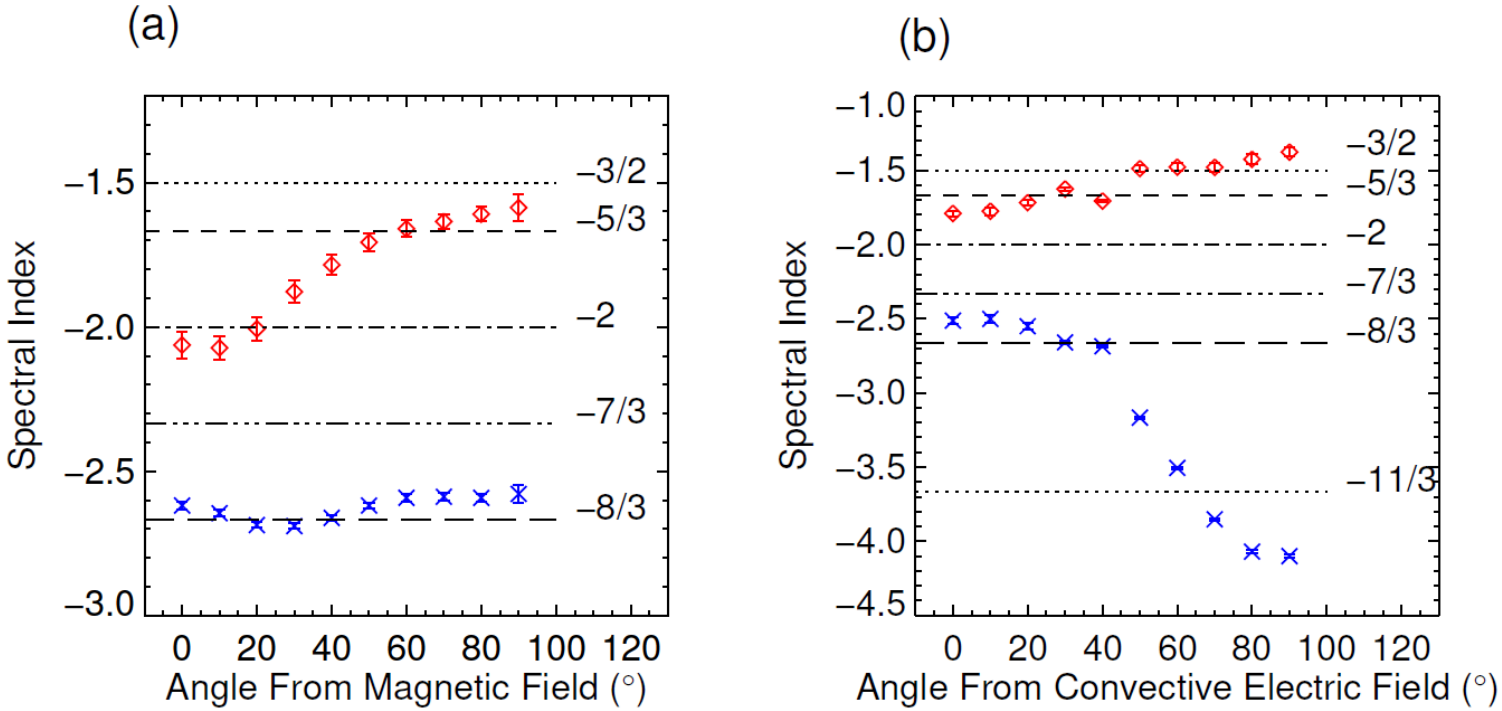






Evolution of the spectral index

Integration performed in cylindrical coordinates to get a average index in the perpendicular direction



Summary 1

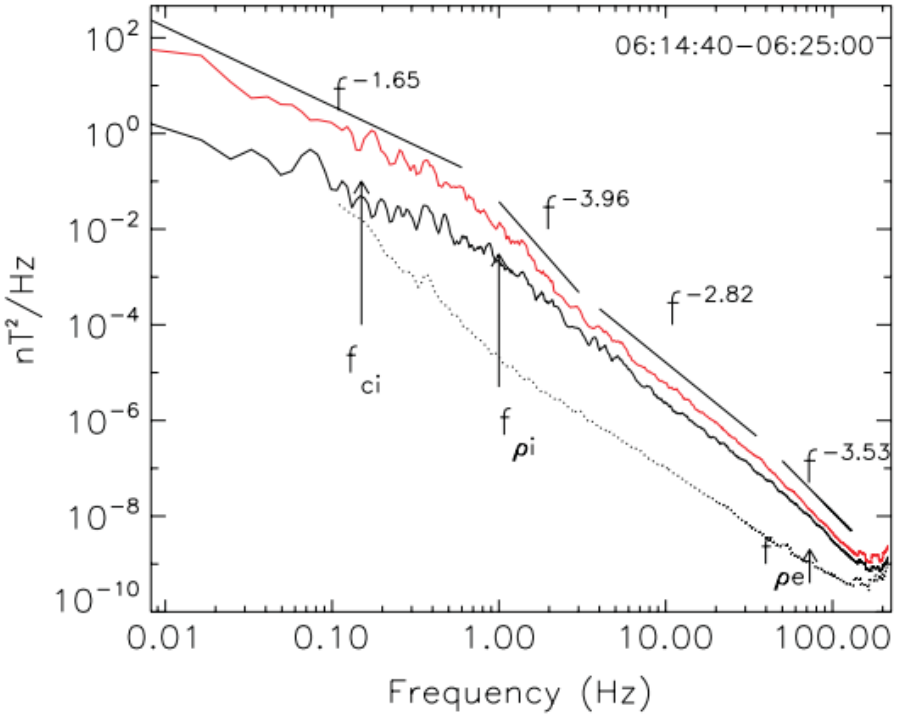
- We have obtained spectral indices in the parallel/perp direction consistent with the ‘critical balance’ hypothesis. With a single interval of solar wind plasma
- Anisotropy with respect to th
- Agyrotropy of the spectra in perpendicular direction??

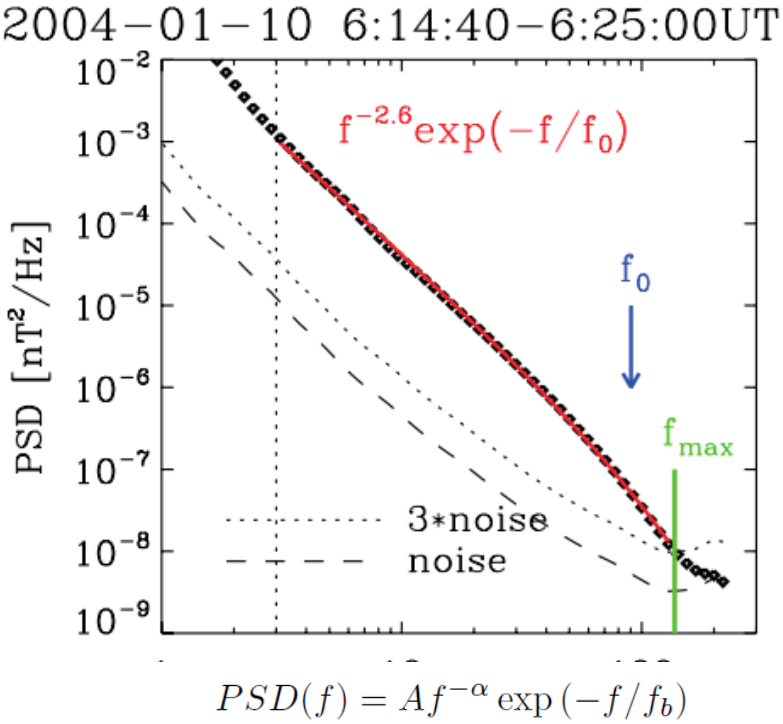
1. Radial expansion
2. Fewer waves excited upstream
3. Sampling effect
4. Preferred directions for dissipation

- At sub ion scales the turbulence becomes more isotropic. Can be explained generally in the framework of Two fluid MHD i.e. Hall effect (Kiyani et al 2013)

Spectrum at electron scales!

Spectrum at Electron scales



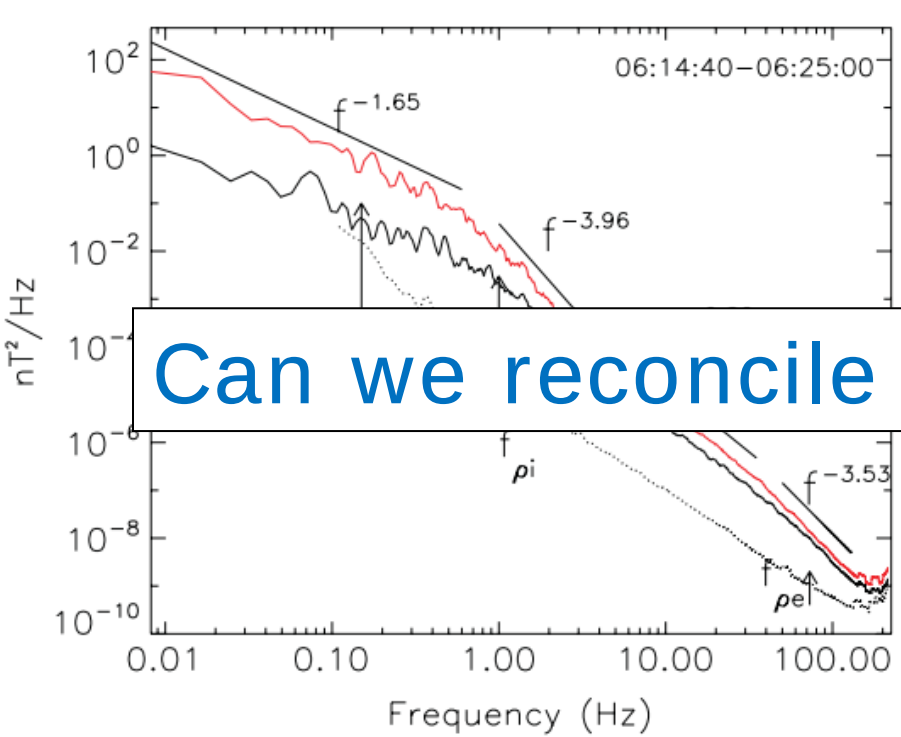


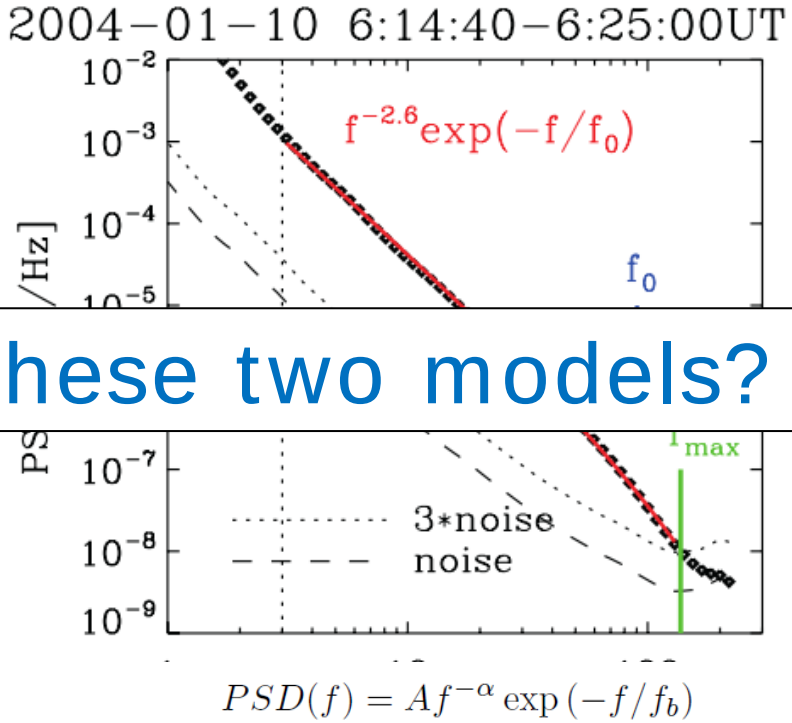
$$PSD(f) = Af^{-\alpha}\exp(-f/f_b)$$

Comparison from Alexandrova et al. 2013 SSR

$$PSD(f) = A_1 f^{-\alpha_1}(1 - H(f - f_b)) + A_2 f^{-\alpha_2} H(f - f_b)$$

Spectrum at Electron scales





Can we reconcile these two models?

$$PSD(f) = Af^{-\alpha}\exp\left(-f/f_b\right)$$

Comparison from Alexandrova et al. 2013 SSR

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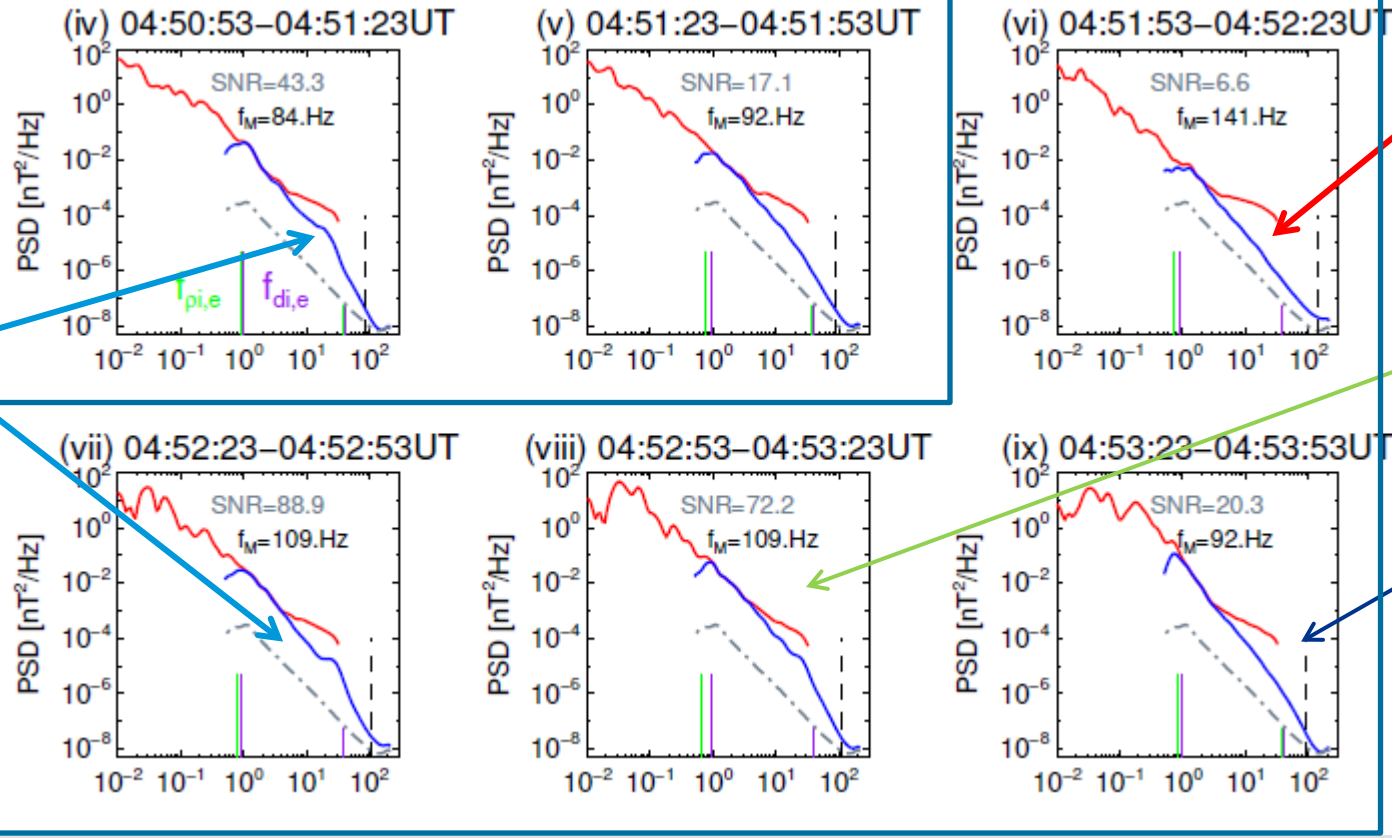
30 Second spectra- different shapes



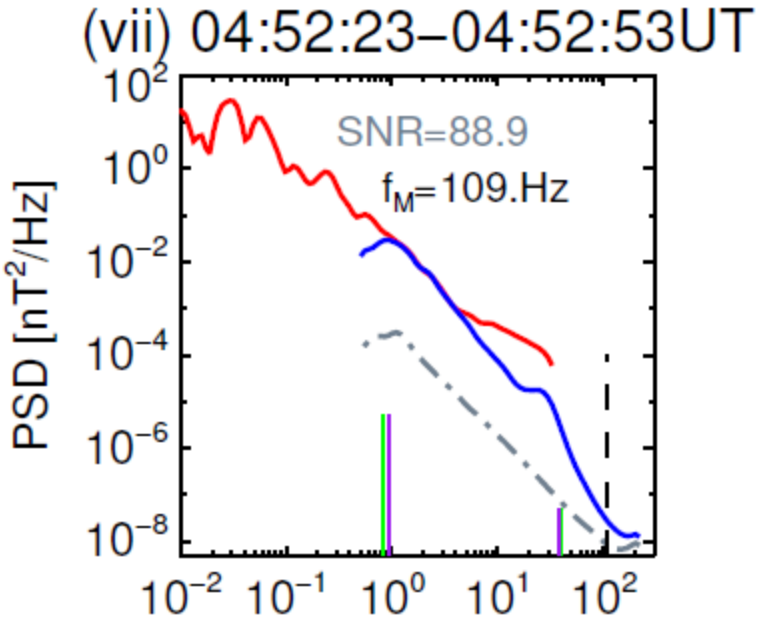
Spectral Knees

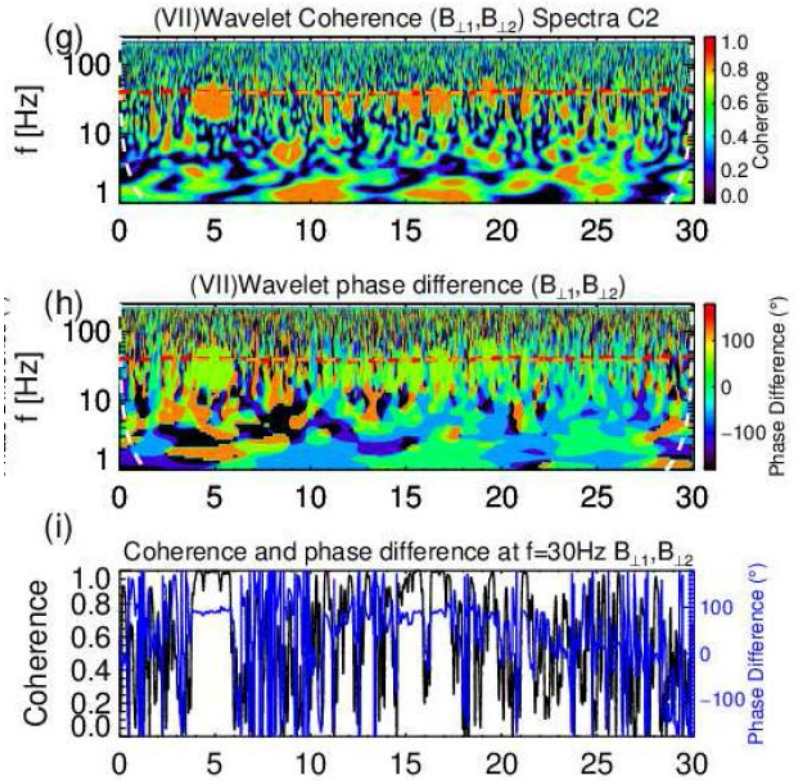
No clear break

Prominent break

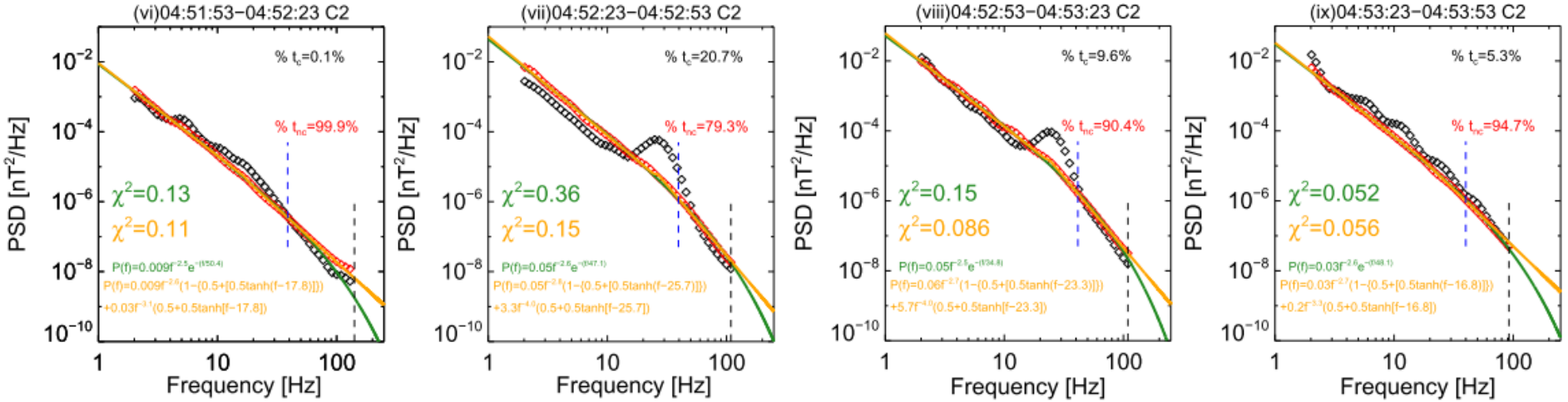
Exponential Cut-off

Wavelet coherence of spectra. Spectra VII- Clear Bump





Split into components-Black coherent, red not coherent



Set a threshold in coherence in perp1-perp2 plane and classify everything above the threshold as coherent

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$$PSD(f) = A_1 f^{-\alpha_1}(1 - H(f - f_b)) + A_2 f^{-\alpha_2} H(f - f_b)$$

Summary 2

- Spectral knee in the spectrum caused by parallel magnetosonic/whistler waves
- Spectral breaks are also caused by the same waves although they cover a smaller time. **Take home message: Check your spectrum for presence of whistler waves before doing a statistical study.**
- Break and exponential model both perform well for the incoherent component. But exponential model has fewer free parameters
- Exponential model performs slightly better when there is limited coherence/coherent structures appear.
- Background turbulence (exponential shape) + Whistler waves
- Cluster still advancing science.

Thank You!

Empty your mind, be formless, shapeless — like **water**. Now you put **water** in a cup, it becomes the cup; You put **water** into a bottle it becomes the bottle; You put it in a teapot it becomes the teapot. Now **water can flow** or it **can crash**. Be **water**, my friend.