Dynamical Processes in Space Plasmas
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POWER ANISOTROPY OF SOLAR WIND FLUCTUATIONS FROM LARGE TO SMALL SCALES

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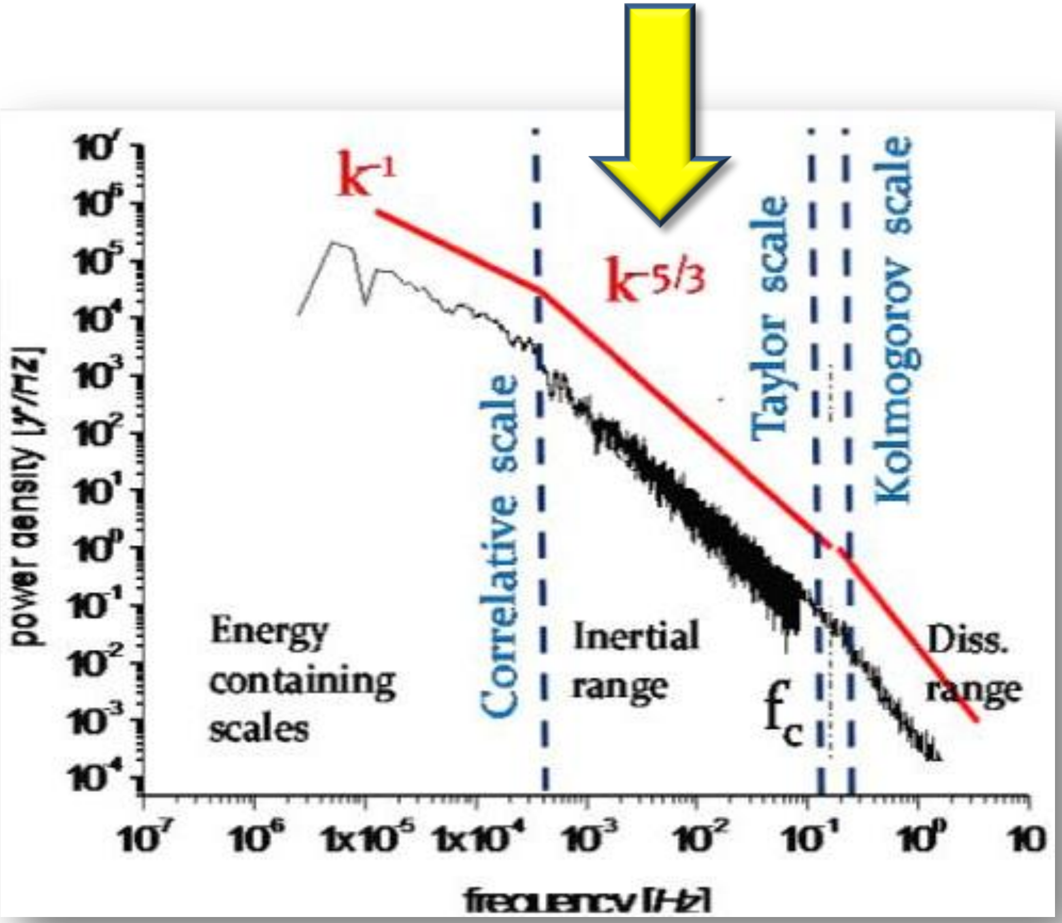
Looking at power anisotropy in the inertial range

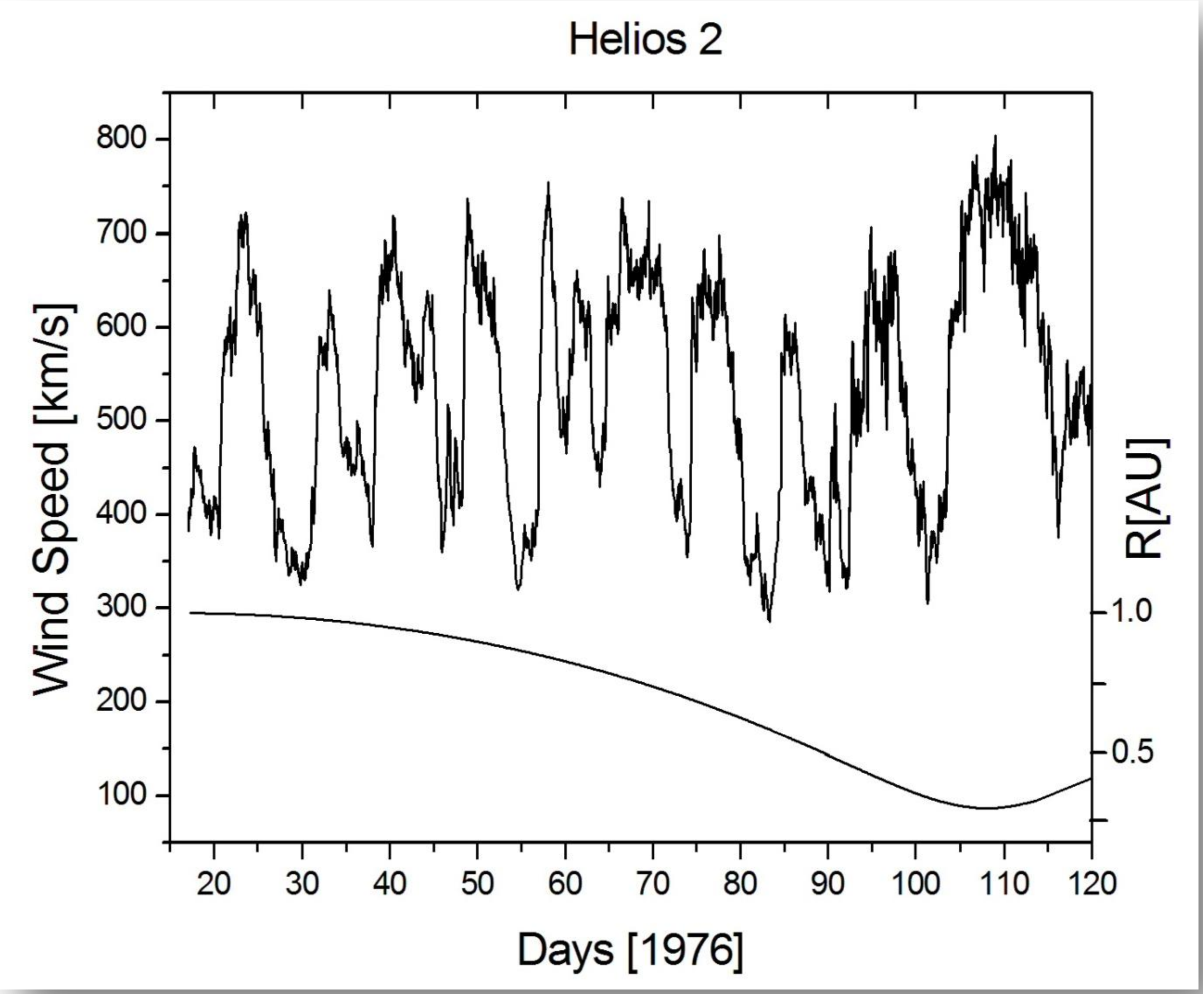


Interplanetary magnetic field power density spectrum

- Correlative Scale/Integral Scale:
  - the largest separation distance over which eddies are still correlated.
- Taylor scale:
  - The scale size at which viscous dissipation begins to affect the eddies.
  - it marks the transition from the inertial range to the dissipation range.
- Kolmogorov scale:
  - The scale size that characterizes the smallest dissipation-scale eddies

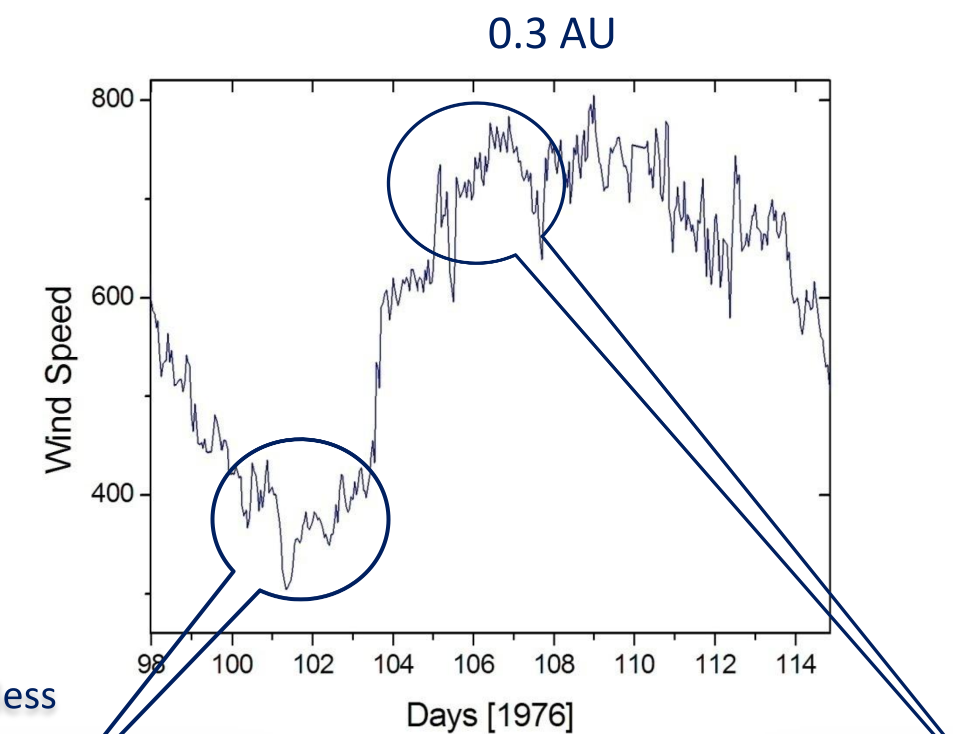
Corr. scale ~ 1 hr
Taylor scale ~ few seconds

Taking a look at fast and slow wind observed in the Ecliptic

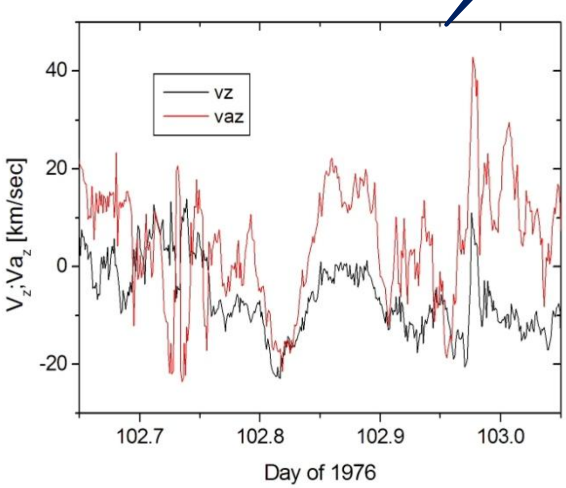


Fast and slow wind alternates in the Ecliptic

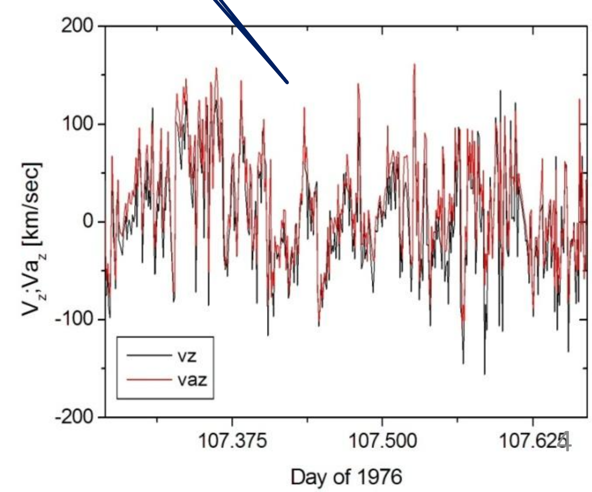
Fast and Slow wind fluctuations are generally different

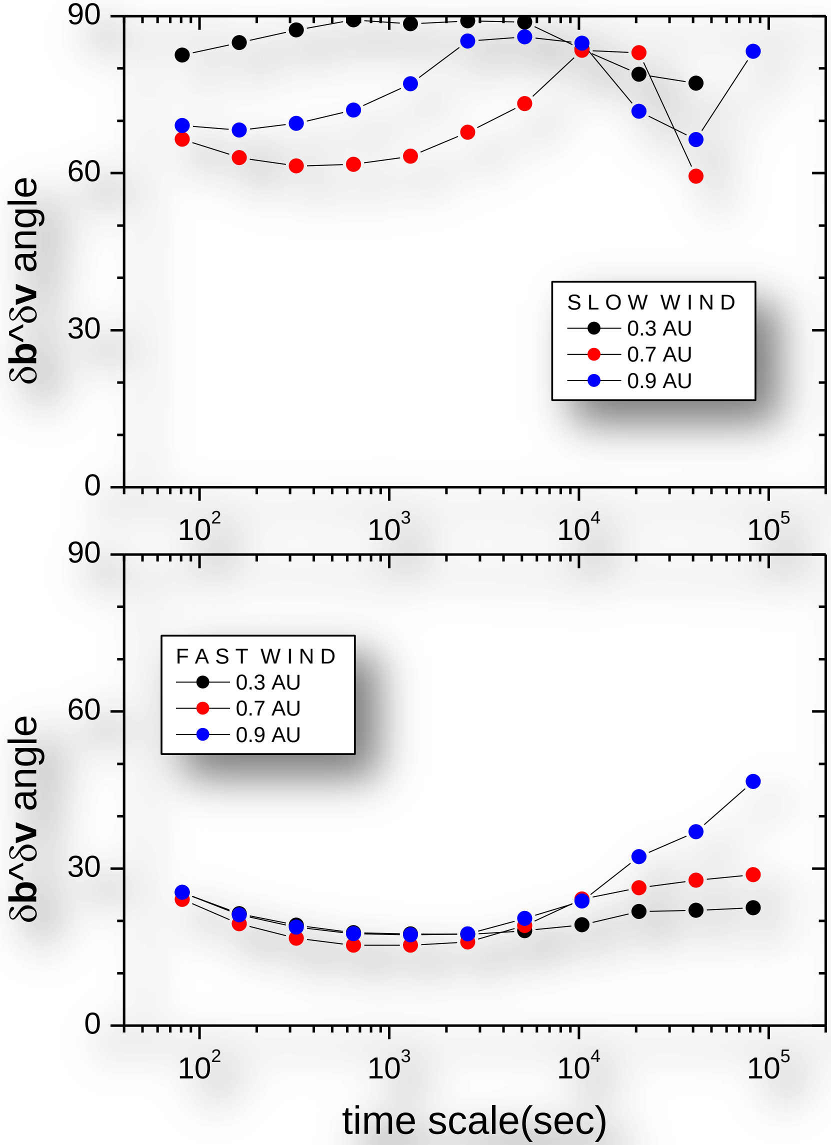


<u>Slow wind:</u>
fluctuations much less Alfvénic



<u>Fast wind:</u>
fluctuations strongly Alfvénic





Helios 2 observations

δB-δV alignment vs scale and heliocentric distance

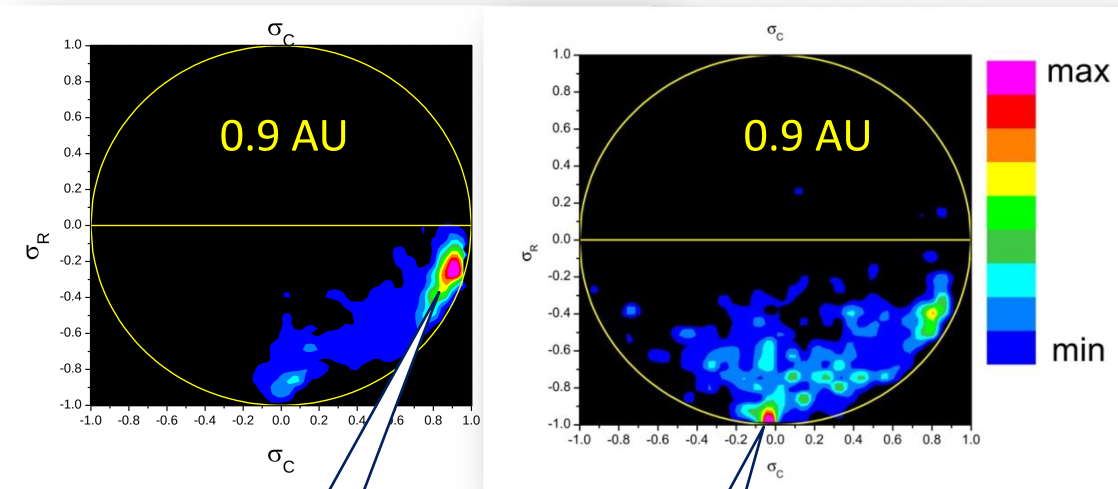
$$\hat{\theta}_\tau = \cos^{-1}\left\langle \frac{\Delta\vec{V}_\tau(t)\cdot\Delta\vec{B}_\tau(t)}{\left|\Delta\vec{V}_\tau(t)\right|\left|\Delta\vec{B}_\tau(t)\right|}\right\rangle_t$$

As the wind expands turbulence evolution and compressive effects decouple δB-δV in fast wind

[see literature in Tu and Marsch 1995, Bruno and Carbone 2005]

MHD turbulence in terms of σ_R and σ_C (scale of 1hr)

FAST WIND SLOW WIND



$$\sigma_C = \frac{e^+ - e^-}{e^+ + e^-} = \frac{2 < v \cdot b >}{e^v + e^b}$$

$$\sigma_R = \frac{e^v - e^b}{e^v + e^b}$$

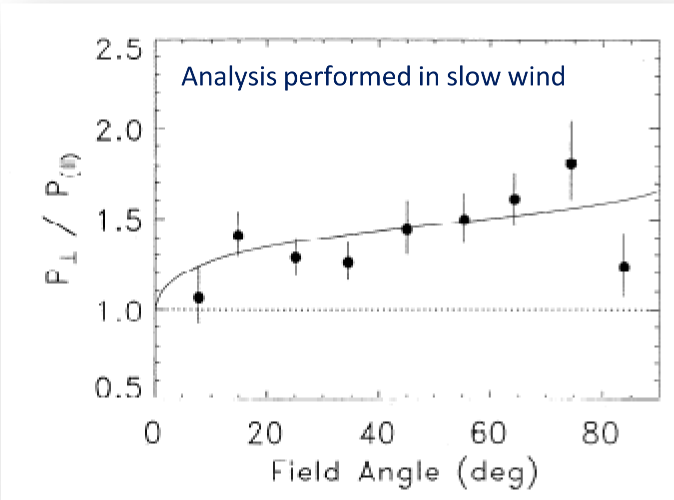
$$\sigma_C^2 + \sigma_R^2 \leq 1$$

Alfvénic population

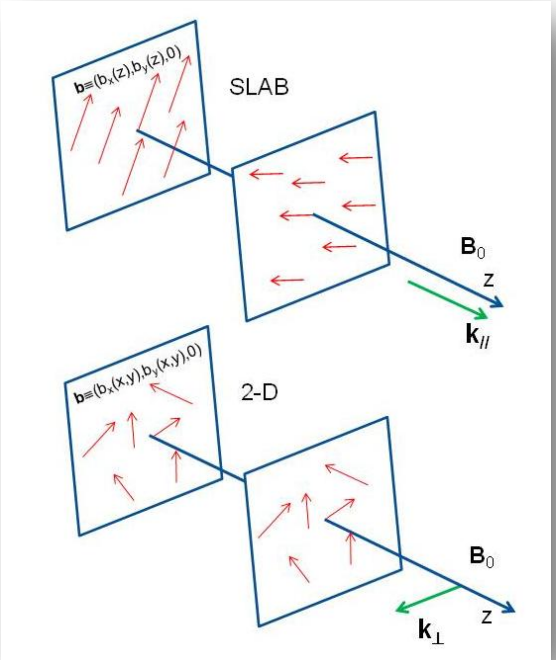
Advected structures with magnetic energy excess

This difference affects the power anisotropy

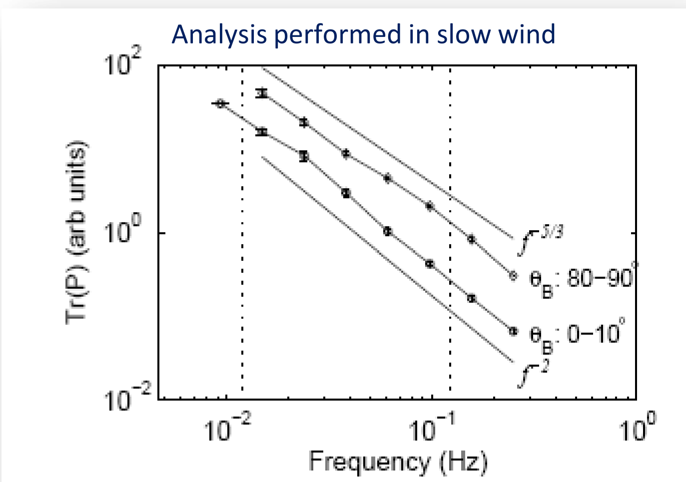
First anisotropy study in terms of $k_\perp$ and $k_{//}$ in the solar wind by Bieber et al., 1996



$K_\perp$ dominates on $k_{//}$ as we analyze directions at larger angles with magnetic field



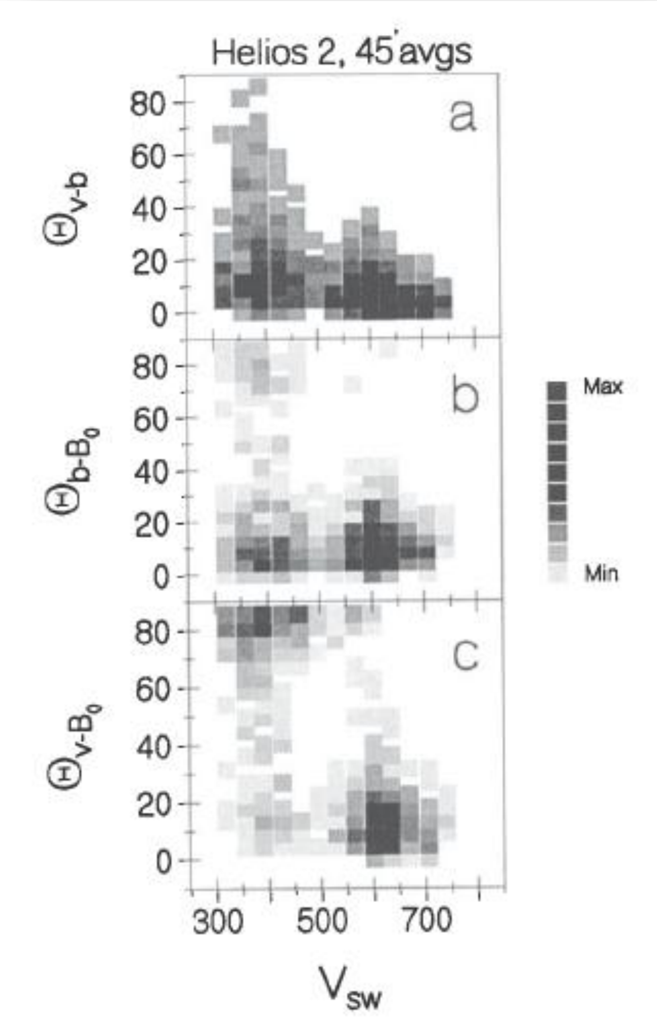
Turbulence made of 2D+SLAB [references!!]



Similar results by Horbury et al., 2008

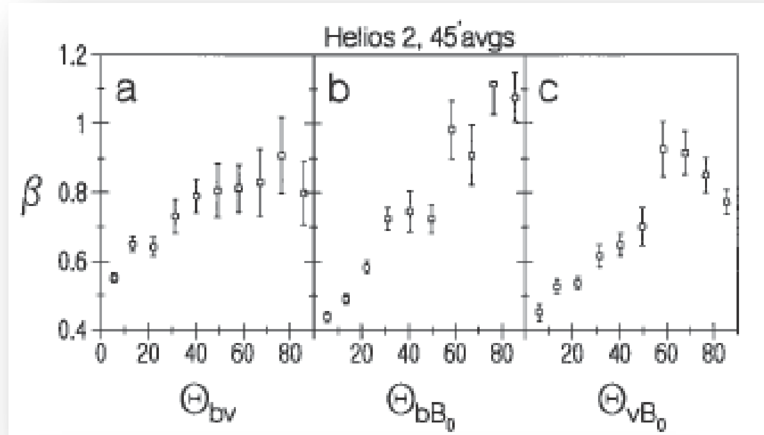
Thus, the slab turbulence due to Alfvénic fluctuations would be a minor component of interplanetary MHD turbulence (in slow wind)

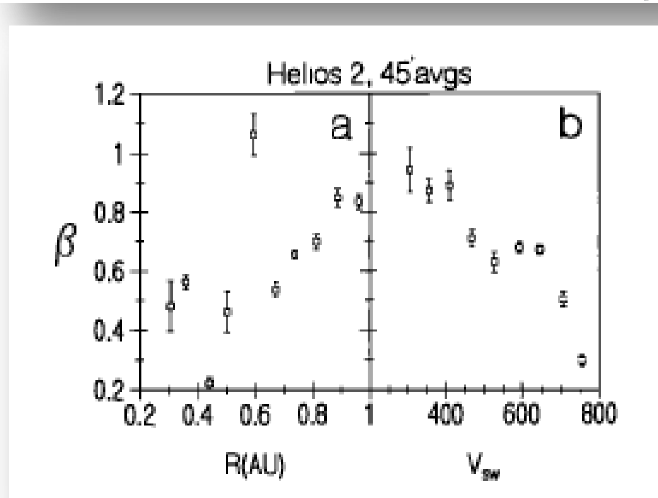
Minimum variance analysis by Klein et al., 1993



[Klein et al., 1993]

Compressive effects play a role in δB-δV decoupling

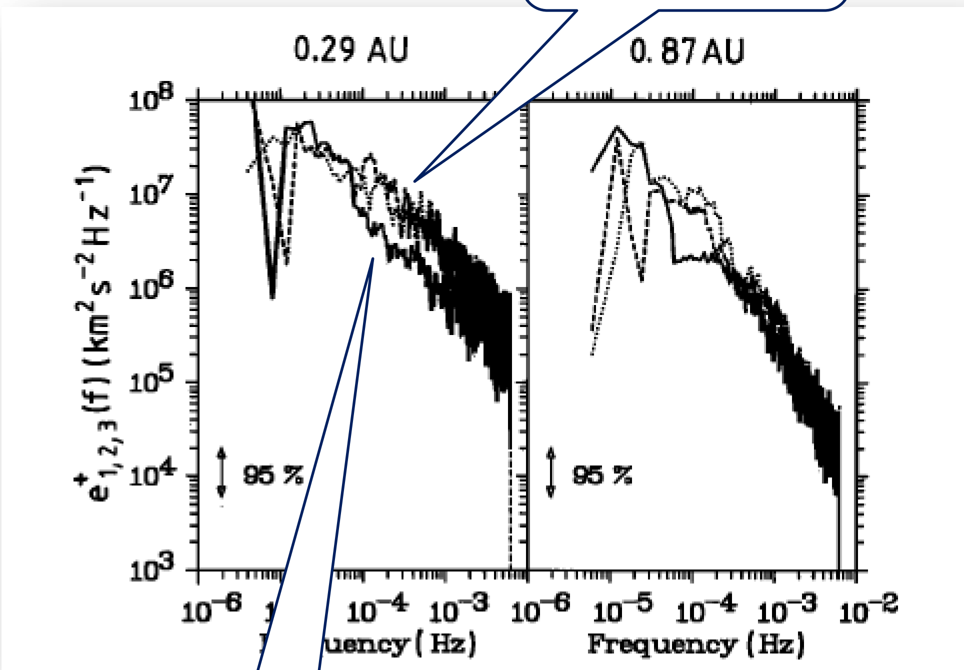


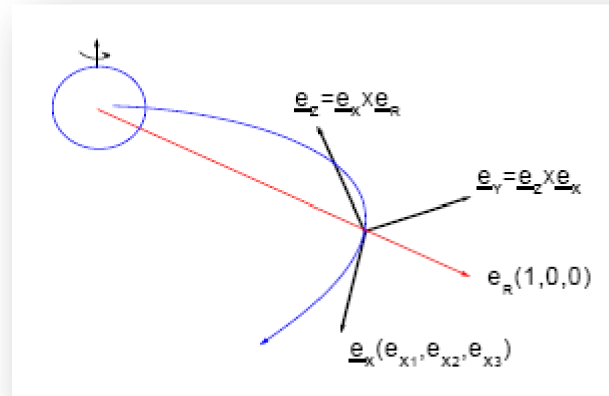


Within fast and Alfvénic wind the minvar direction lies around the mean field
[Bruno et al., 1985]

Z ± power in the mean-field reference system by Marsch and Tu, 1990

Perpendicular components





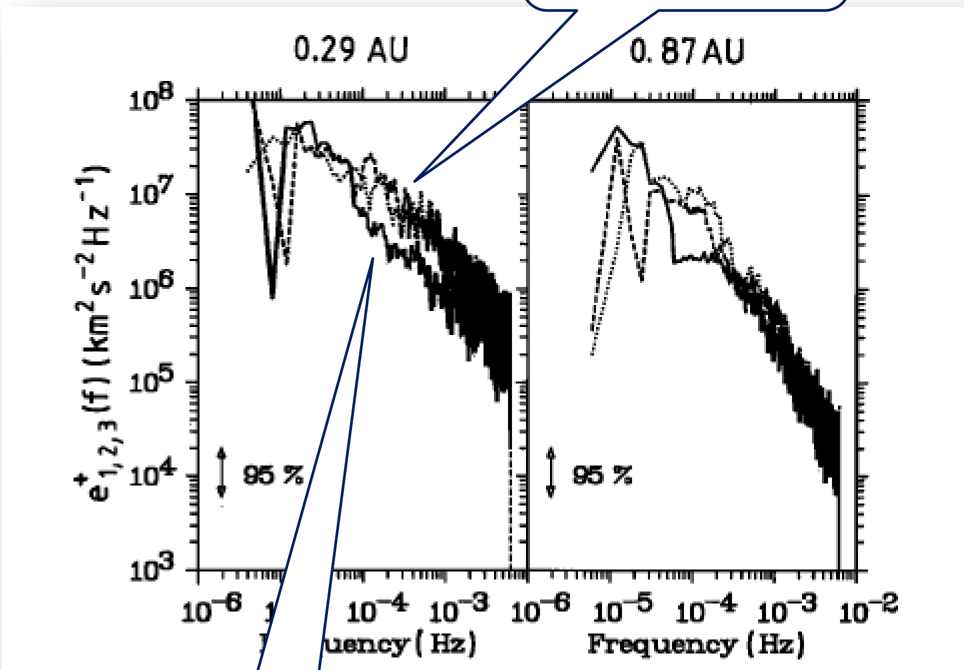
[Marsch and Tu, 1990]

Parallel component

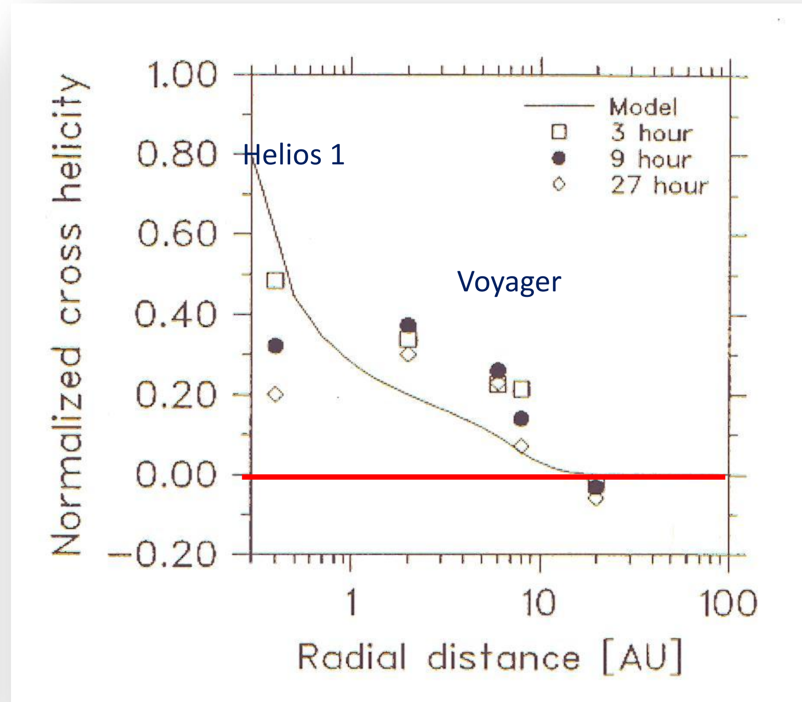
$Z^{\pm}$ power in the mean-field reference system by Marsch and Tu, 1990

Perpendicular components

$$\sigma_c = \frac{e^+ - e^-}{e^+ + e^-}$$



[Marsch and Tu, 1990]



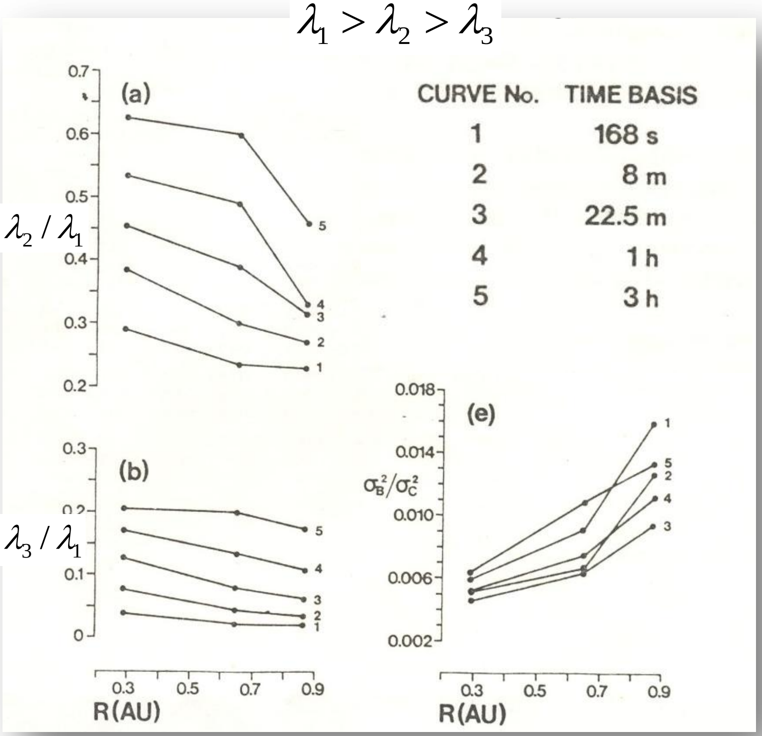
[Adopted from Matthaeus et al., 2004]

Parallel component

As the wind expands, the anisotropy decreases with decreasing the Alfvénic character of fluctuations
Turbulence becomes more isotropic

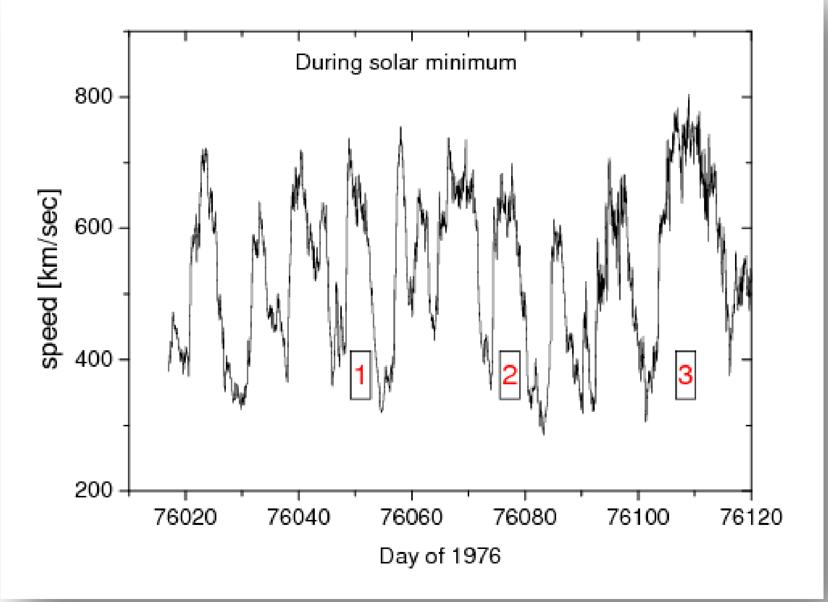
At odds with previous results was the analysis by Bavassano et al., 1982

$\lambda_1 > \lambda_2 > \lambda_3$



[Bavassano et al., 1982]

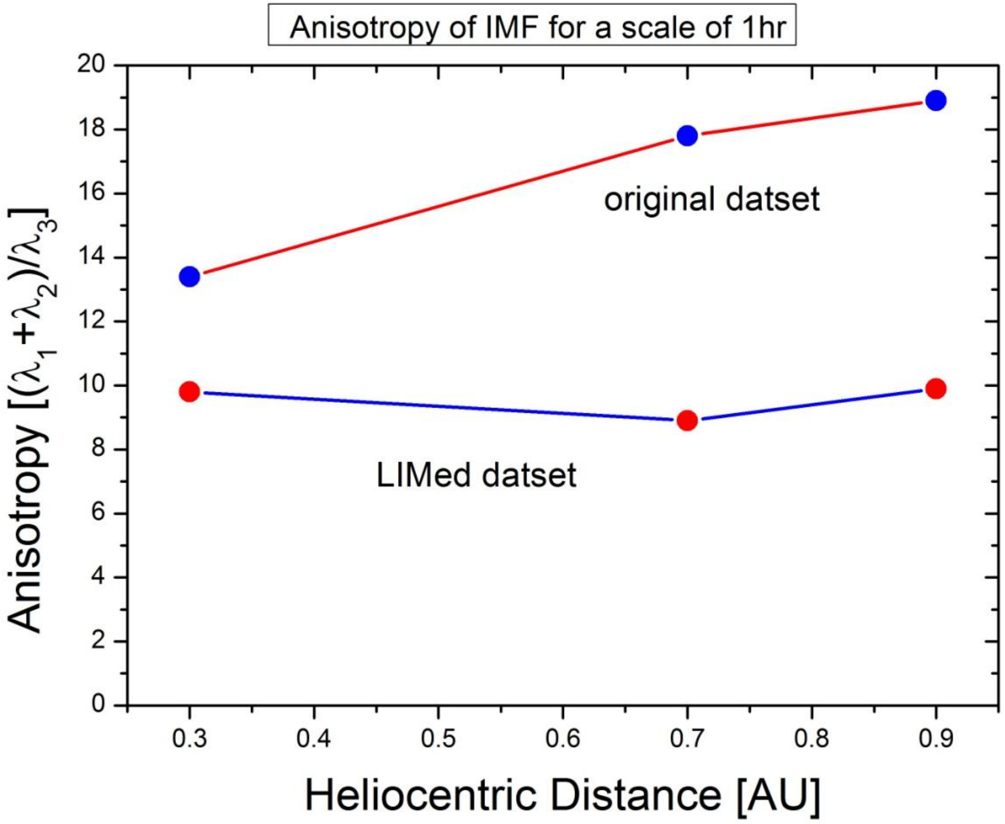
Analysis performed with the same corotating stream observed at different heliodistances



- Anisotropy of magnetic field fluctuations increases with heliocentric distance
- Field compressibility increasese with heliocentric distance

Previous studies (Marsch and Tu, 1990, Klein et al., 1991) showed that fluctuations become more isotropic during wind expansion

This appearent contraddiction was solved removing intermittent events from |B|, i.e. the most compressive events outside a normal distribution



[adapted from Bruno et al., 1999]

Local Intermittency Measure technique
(Farge et al., 1990; Farge, 1992)
based on wavelet decomposition

$$< LIM^2(\tau,t) >_t = \frac{< w^4_{\tau,t} >_t}{< |w_{\tau,t}|^2 >^2_t} \equiv FF(\tau)$$

The Flatness Factor of the wavelet coefficients at a given scale τ, i.e. *LIM²*, is equivalent to the Flatness Factor *FF* of data at the same scale τ (Meneveau, 1991)

Thus, values of *FF(τ)>3* allow to localize events which lie outside the Gaussian statistics and cause *Intermittency*.

Some remarks

Compressive events increase intermittency

Intermittent events can increase the power anisotropy of fluctuations

Then: compressive events might play a role in power anisotropy

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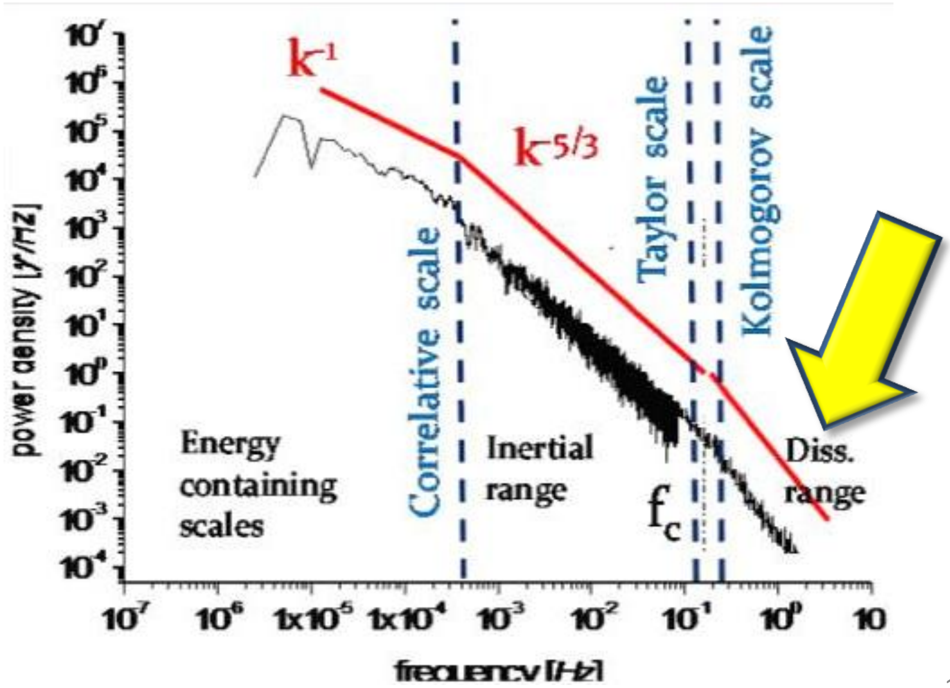
Compressive events increase intermittency

Intermittent events can increase the power anisotropy of fluctuations

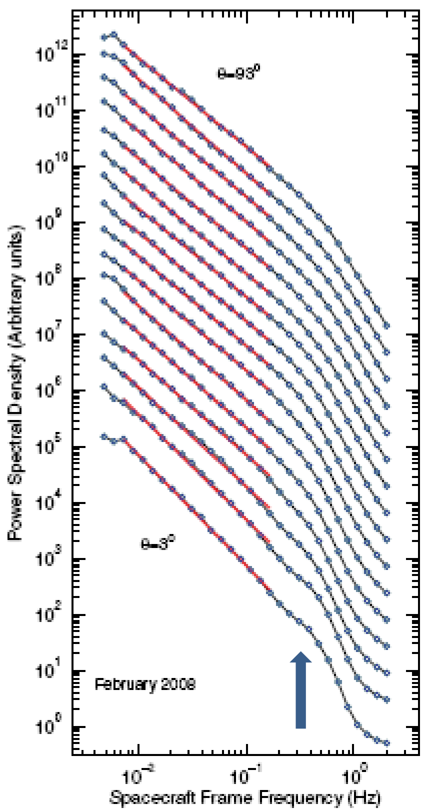
Then: compressive events might play a role in power anisotropy

With this in mind, we look at power anisotropy beyond f_C

[Leamon et al., 1998, 1999, Bale et al., 2005, Hamilton et al., 2008, Podesta, 2009, Sahraoui et al., 2009, etc…]

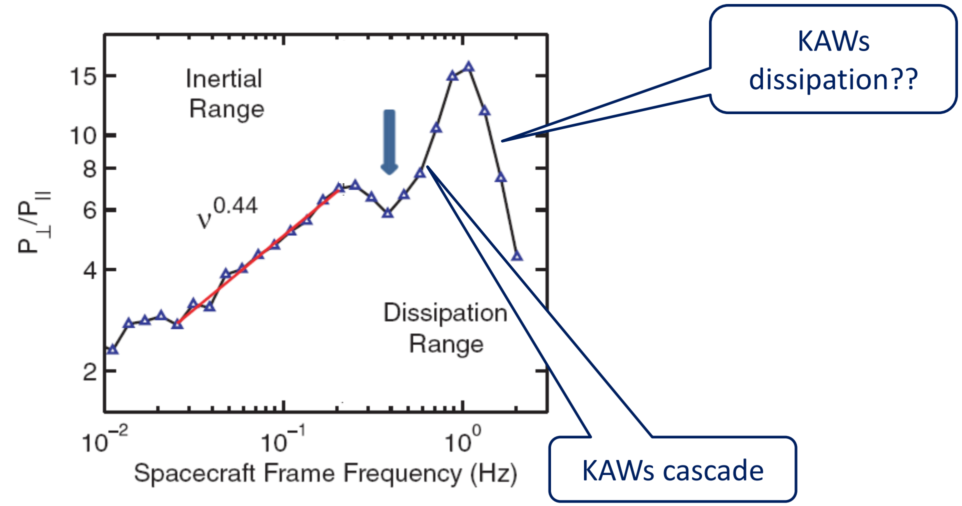


Power anisotropy study from Podesta, 2009



[curves arbitrarily shifted vertically]

[θ angle between local mean field and radial direction]



<u>Inertial range:</u>

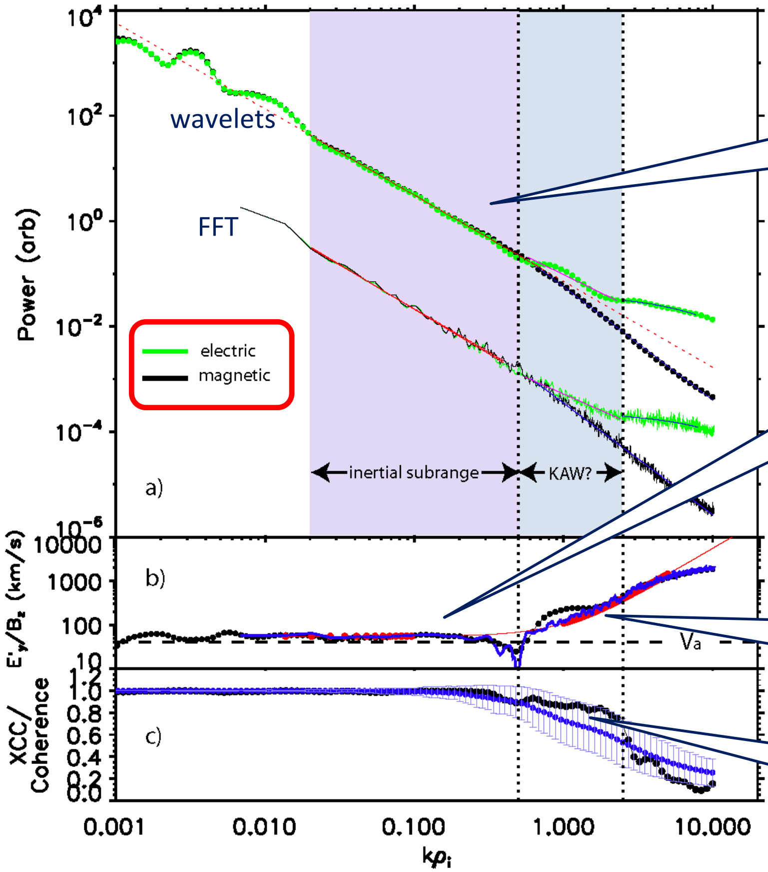
- energy cascade directed primarily perpendicular to the mean mag field [Shebalin et al., 1983; Oughton et al., 1994; Matthaeus et al., 1996]
- power anisotropy increaseses with wavenumber

<u>“Dissipation” range:</u>

- The new cascade (KAWs) starts at **$k\rho_i$~ 1** [i.e. <u>$\nu_{S/C}$ ~ 0.5Hz</u>, in this case] when the fkuid-like behavior breaks down
- power anisotropy increaseses with wavenumber
- The second peak marks beginning of KAWs dissipation?

Observational evidence for Alfvén waves – KAWs transition in the solar wind

[Bale et al., 2005, Cluster data]



electric field and magnetic field $k^{-5/3}$ inertial sub-range is observed up to $k\rho_i \sim 1$ (Electric spectrum arbitrarily offset to overlap magnetic spectrum)

the wave phase speed in this regime is shown to be consistent with the Alfvén speed

The red curve approximates the dispersion relation for KAWs ($v_\Phi \sim k^2\rho_i^2$). For whistler waves ($v_\Phi \sim k\rho_i$). it would run much lower for $k\rho_i > 1$ [Bale et al., 2005]

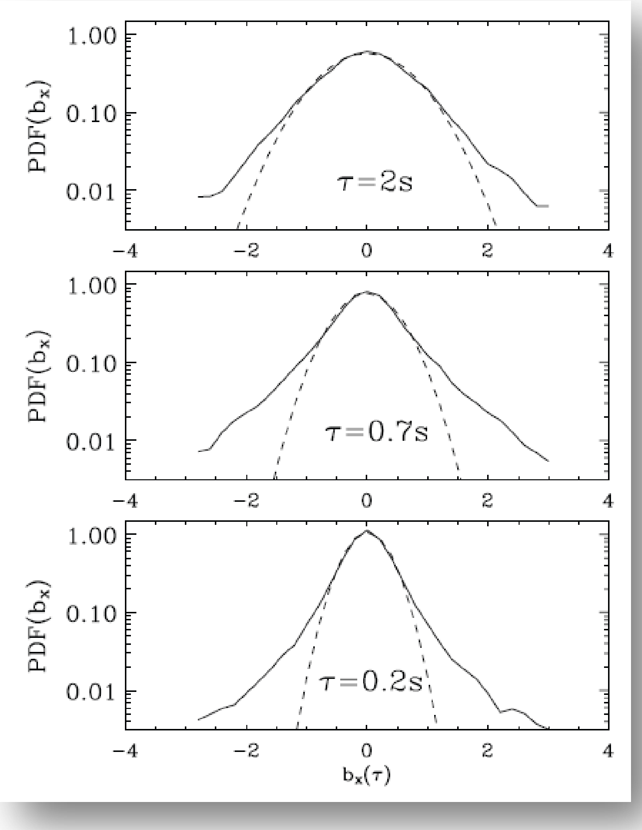
Good correlation between the electric and magnetic power (as black dots) and good cross-coherence of Ey with Bz (as blue dots) suggest KAW

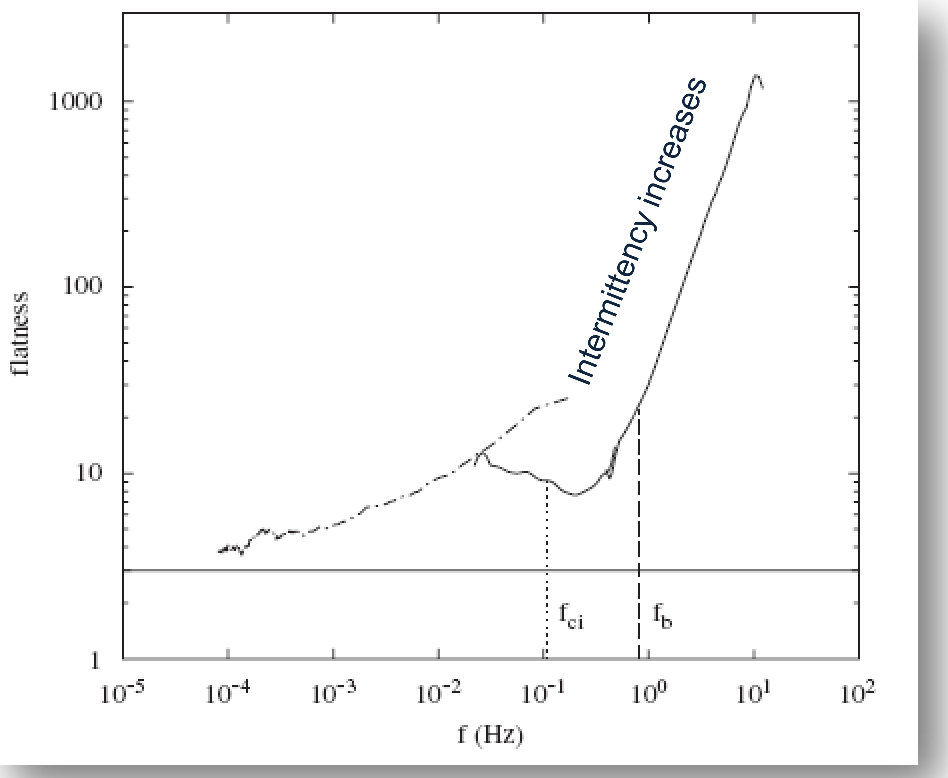
$$\rho_{i,e} = V_{th_{i,e}} / \omega_{ci,e}$$

$$\lambda_{i,e} = V_{A_{i,e}} / \omega_{ci,e}$$

Moreover, Sahraoui et al., 2009 extended the study to the electron gyroscale where they identified dissipative processes of KAWs

Study by Alexandrova et al., 2008, 2009 using Cluster magnetic observations beyond f_{ci}



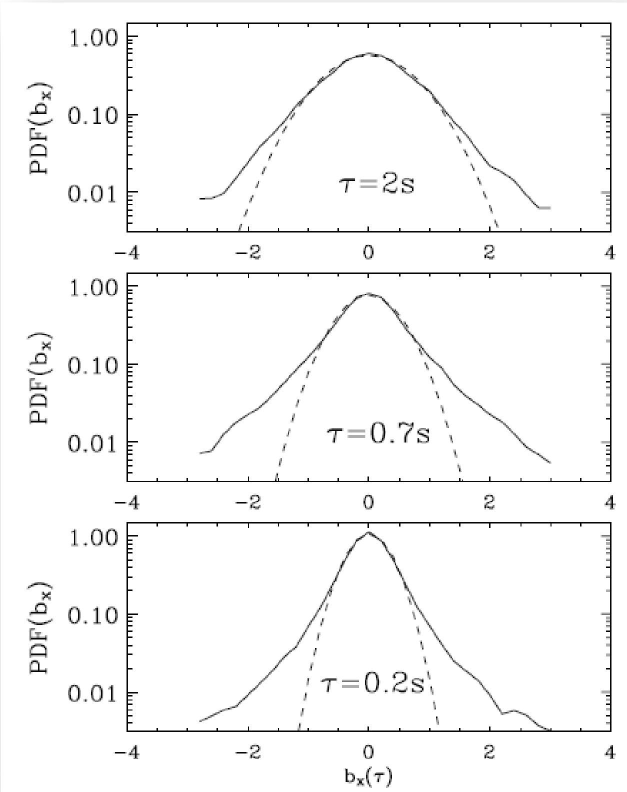


(Alexandrova et al., 2008, 2009)

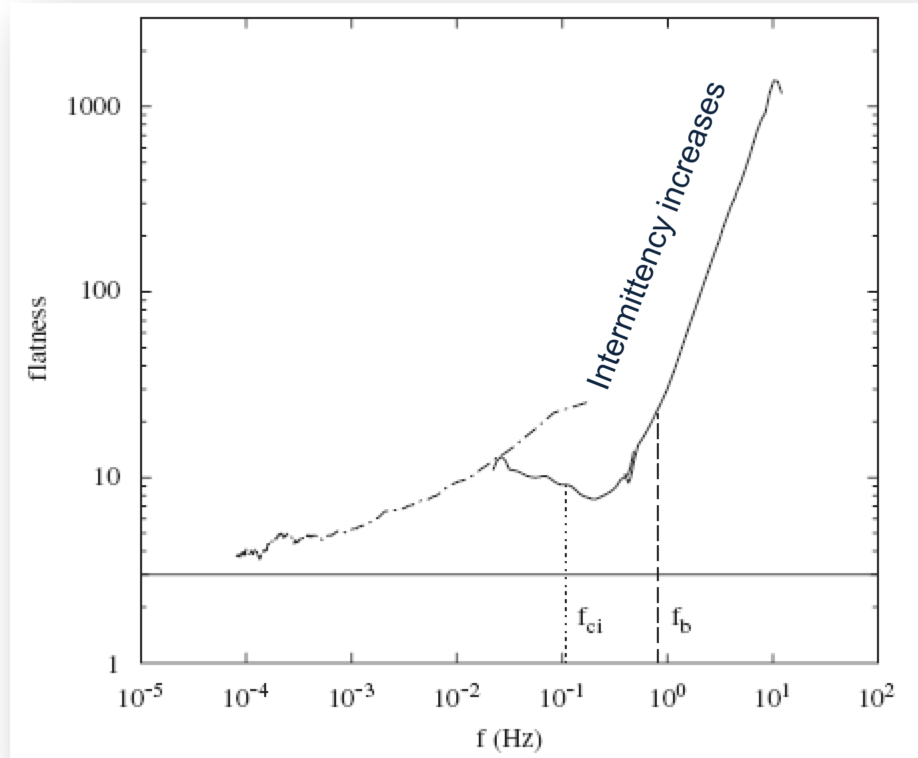
The presence of a power-law spectrum (instead of a rough exponential cutoff) and the increase of intermittency suggest the presence of a new cascading range (Stawicki et al., 2001, Bale et al., 2005, Sahraoui et al., 2006, 2009)

The cascade has a compressible character. Compressibility seems to govern the spectral index $k^{-7/3+2\alpha}$ where α is the compressibility (Alexandrova et al., 2008, 2009)

Study by Alexandrova et al., 2008, 2009 using Cluster magnetic observations beyond f_{ci}



(Alexandrova et al., 2008, 2009)



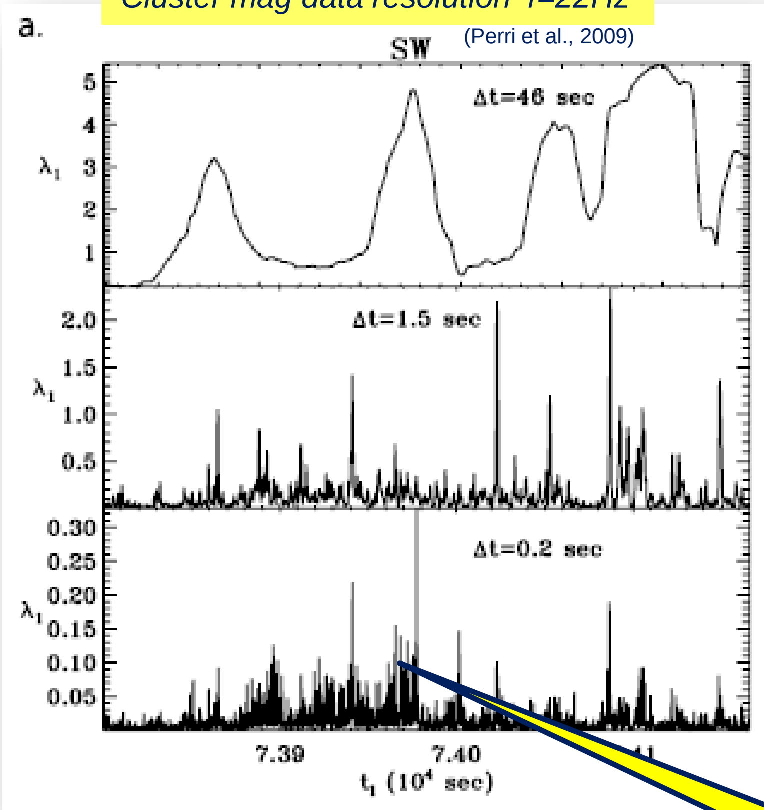
(Alexandrova et al., 2008, 2009)

Hollweg, 1999:

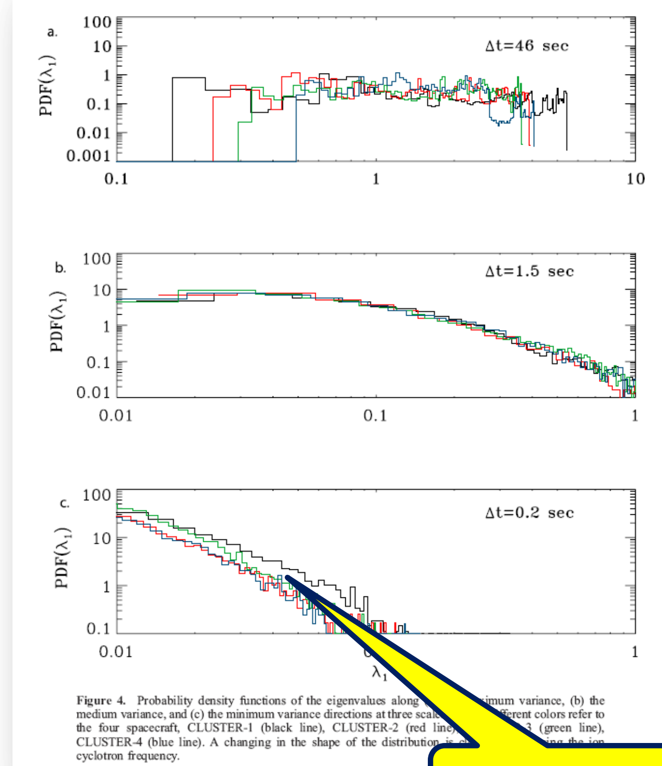
- KAW becomes strongly compressive when $k\rho_i \sim 1$.
- The compression is accompanied by a magnetic field fluctuation $\delta B_{\parallel}$ such that the total pressure perturbation $\delta p_{tot} \approx 0$

Perri et al., 2008, 2009, performed a minimum variance study in this frequency range, focusing on the anisotropy of the fluctuations

Cluster mag data resolution f=22Hz



(Perri et al., 2009)



(Perri et al., 2009)

Intermittent behavior

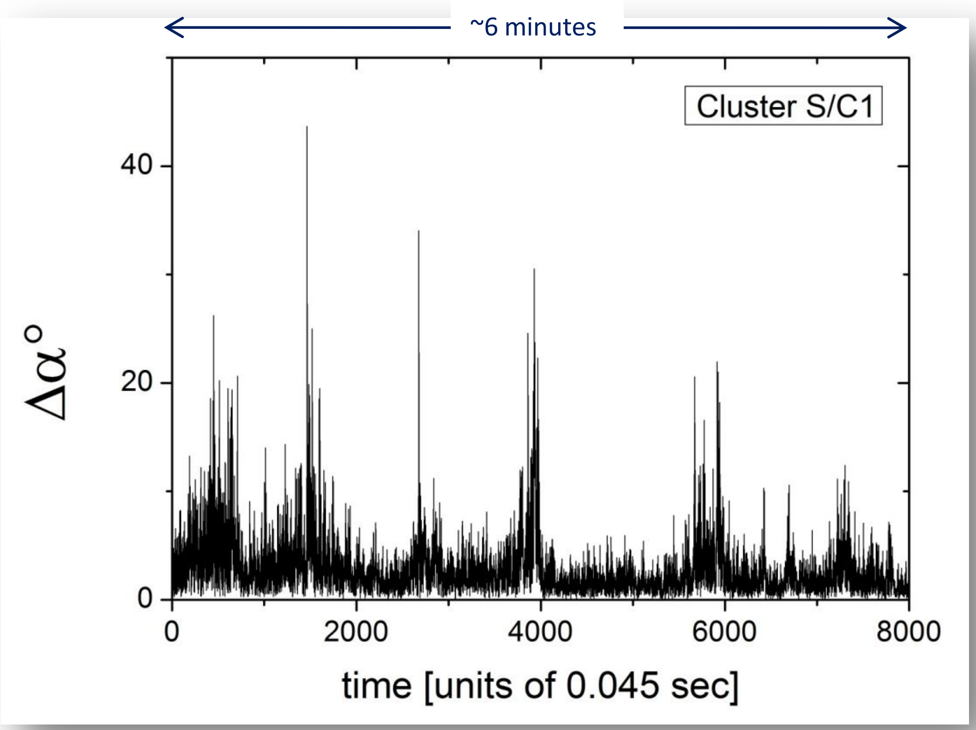
Power law

Time series and probability distribution function for the ***max eigenvalue*** at three different scales (46s, 1.5s, 0.2s)

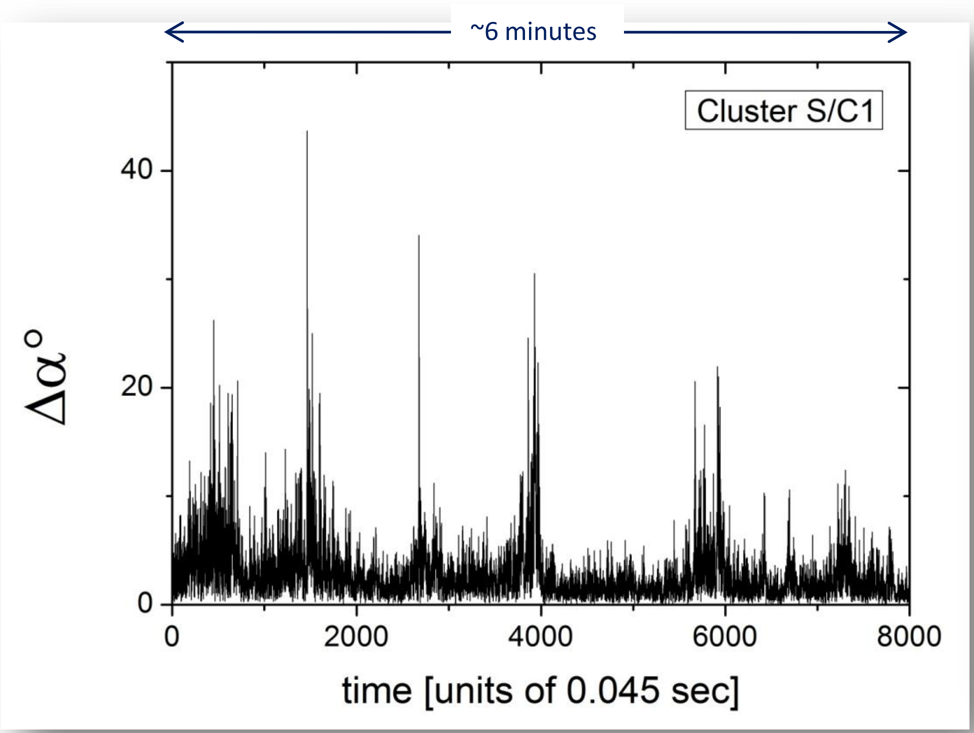
What is the possible mechanism to reproduce this behavior?

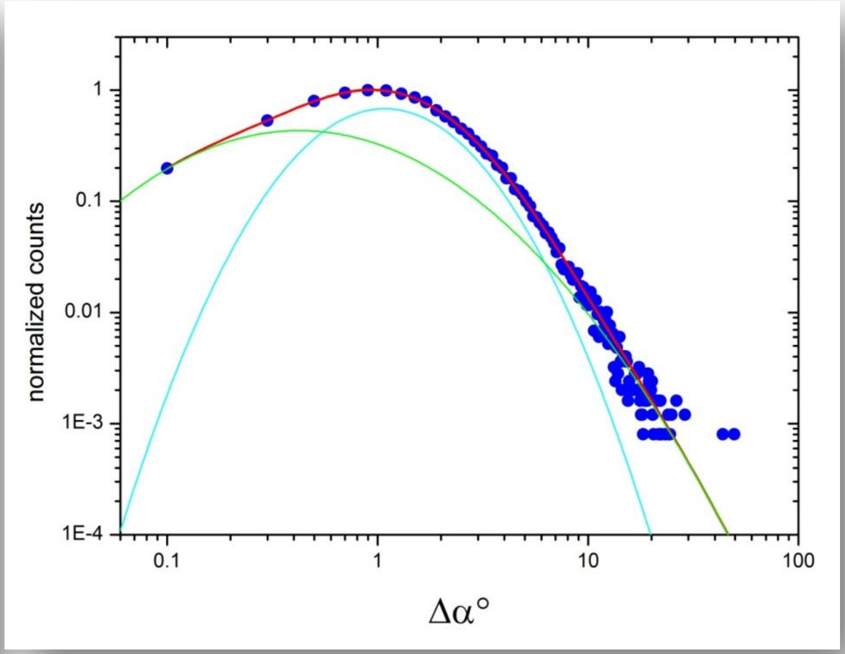
- The PDFs evolve with the scale, becoming power laws at scales smaller than the ion cyclotron scale.
- Similar behaviour for the other eigenvalues

Looking at the distribution of angular fluctuations of B vector on a time scale of 0.045 sec (i.e.22Hz)



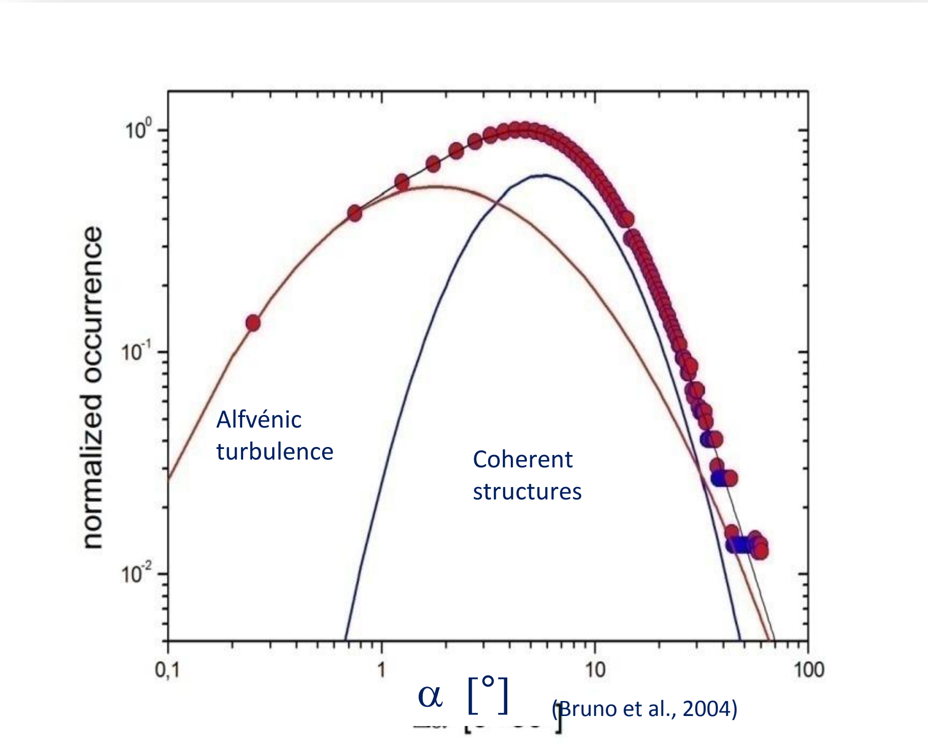
Looking at the distribution of angular fluctuations of B vector on a time scale of 0.045 sec (i.e.22Hz)

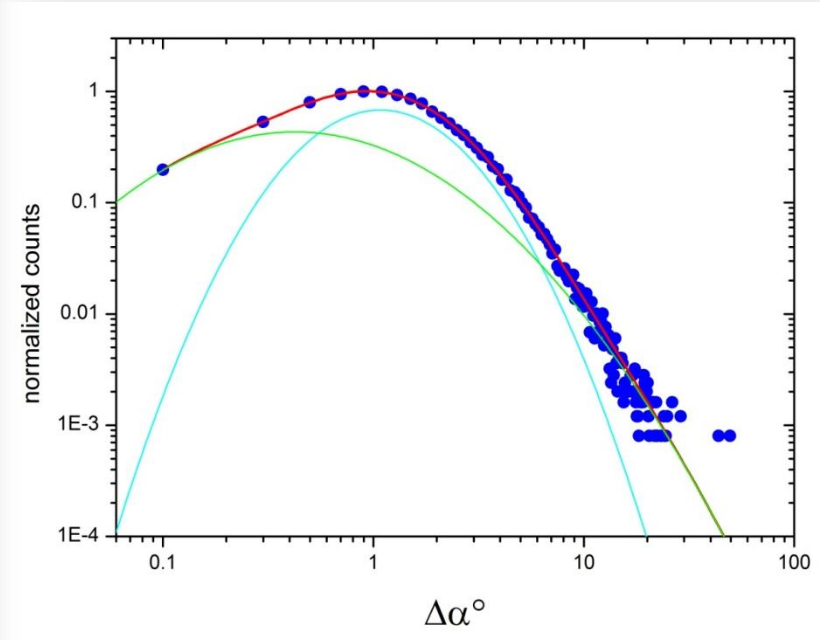




Distribution obtained from Cluster 1,2,3,4 data at the time scale of 0.045s

Same type of distribution at larger scales, within the inertial range

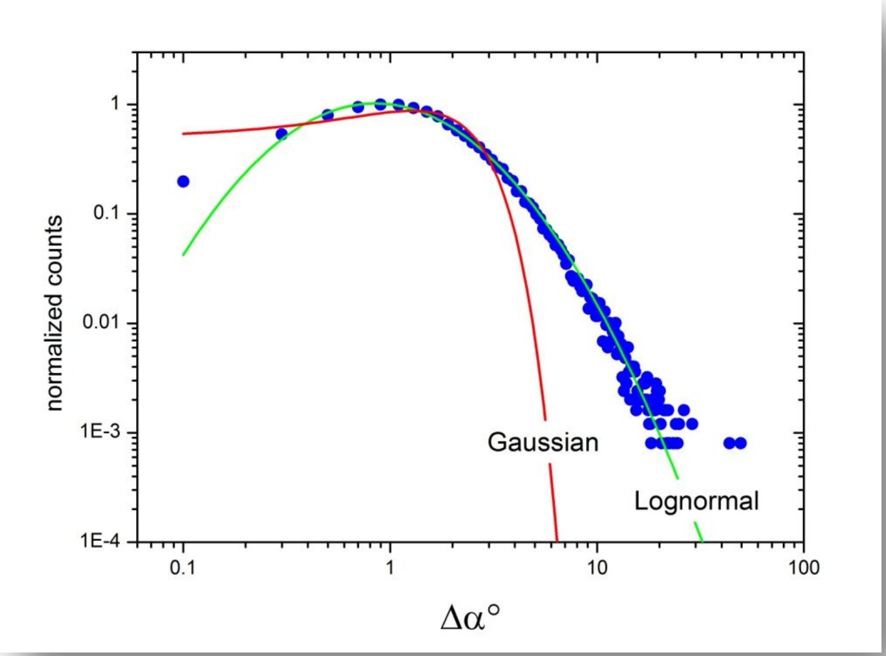


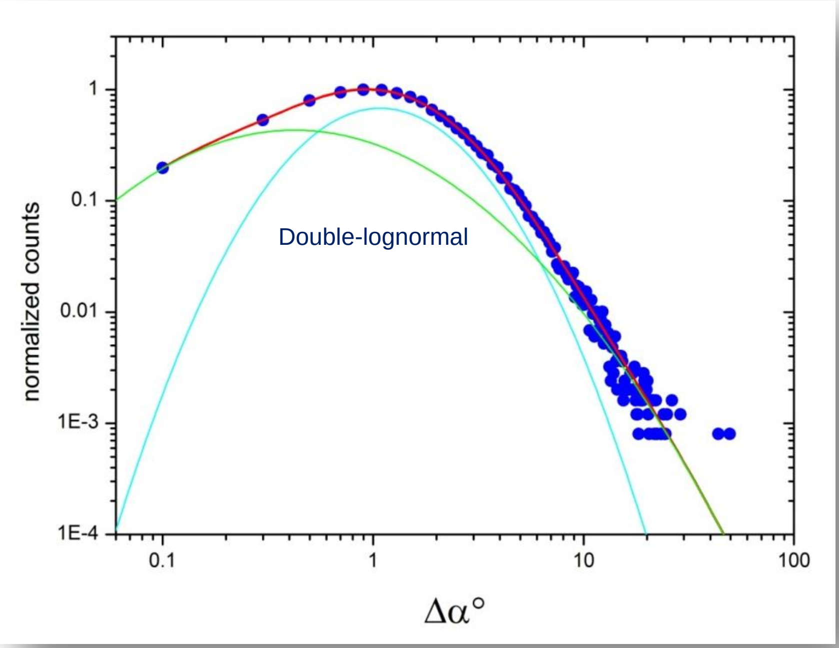


Distribution obtained from Helios data at the time scale of 6s

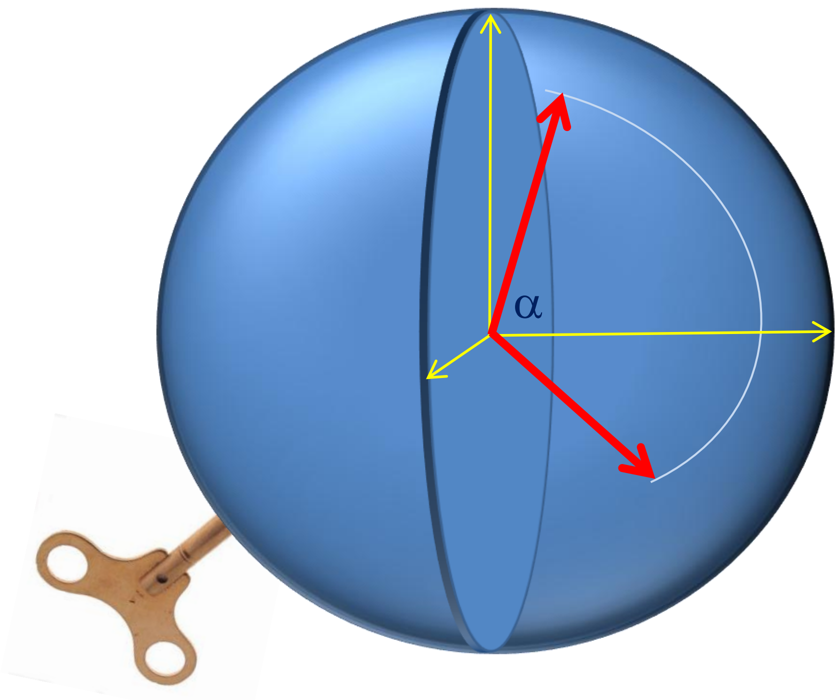
Distribution obtained from Cluster 1,2,3,4 data at the time scale of 0.045s

The double-lognormal is the best fit

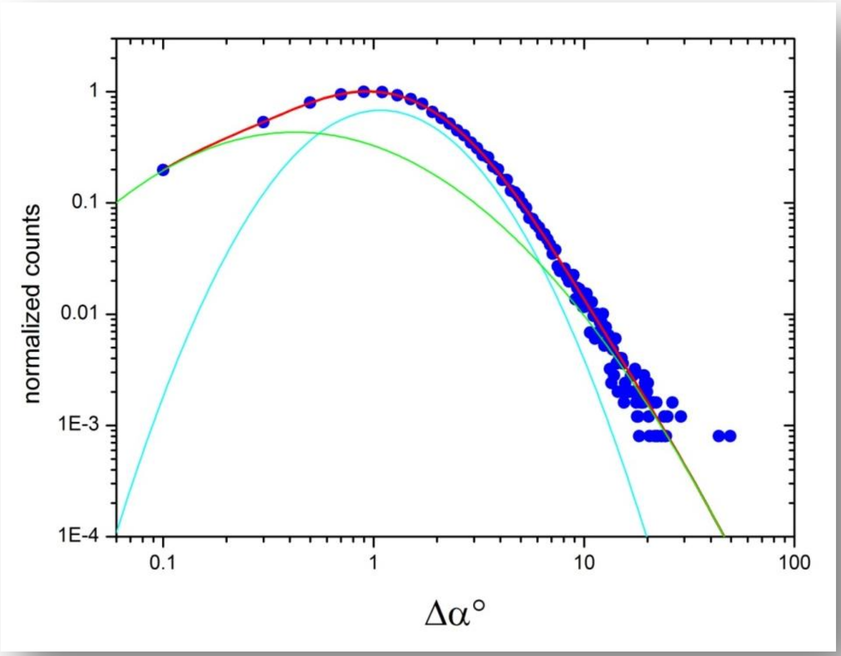




A Toy Model to reproduce Cluster observations

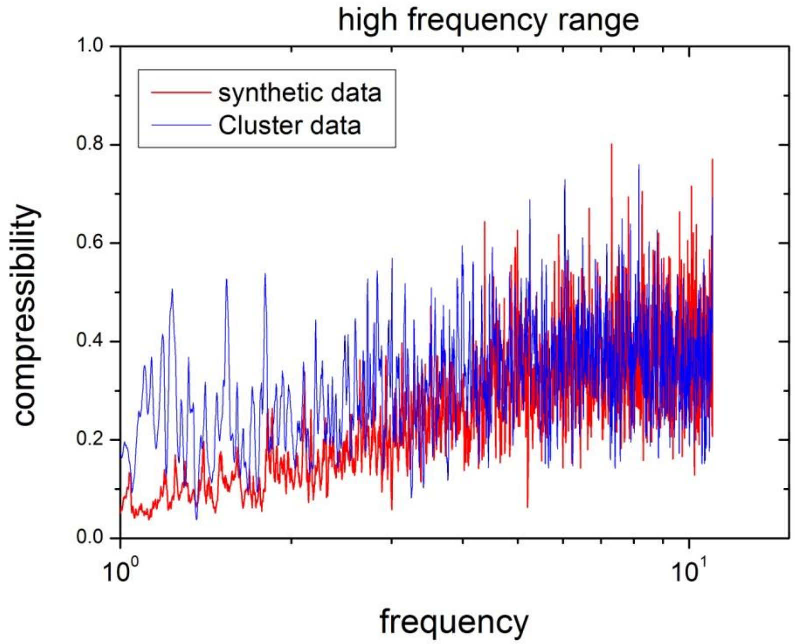


We allow the tip of a vector to move randomly on the surface of a sphere. The distribution of the angle α between 2 successive orientations of the vector follows the double-lognormal distribution obtained from Cluster observations



Distribution obtained from Cluster 1,2,3,4 data at the time scale of 0.045s

- moreover, we added compressions in the field intensity
- we tried to reproduce the same compressive level found in real data (similar spectra)
- compressions revealed to play an important role in this toy model (see next slides)

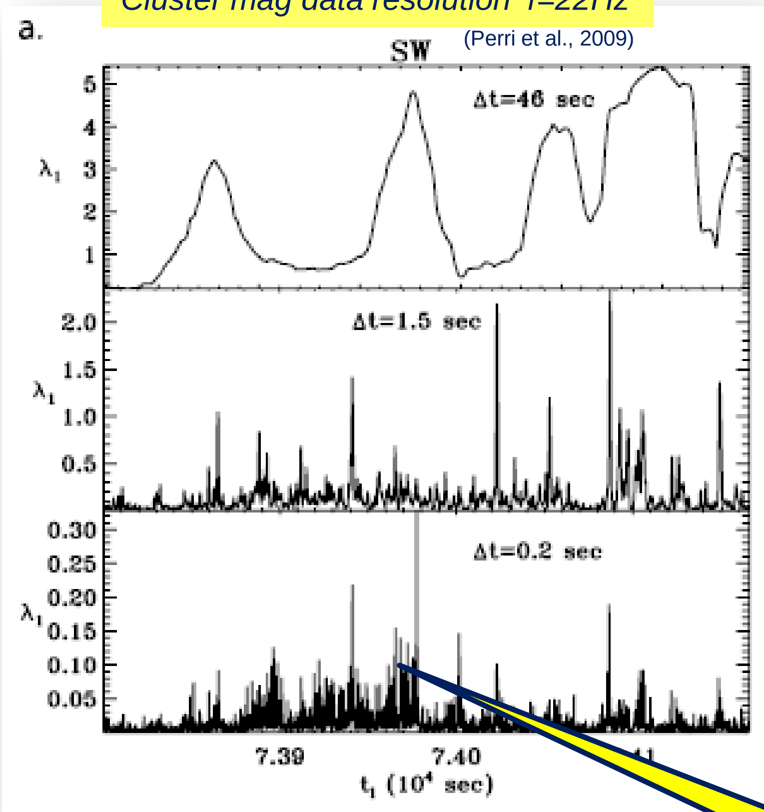


Compressibility(f) $\equiv S_{|B|}(f)/S_C(f)$

Compressions added:
$\sigma_{|B|}/\langle|B|\rangle \sim 3\%$

minimum variance study by Perri et al., 2008, 2009

Cluster mag data resolution f=22Hz



Time series and probability distribution function for the ***max eigenvalue*** at three different scales (46s, 1.5s, 0.2s)

Intermittent behavior

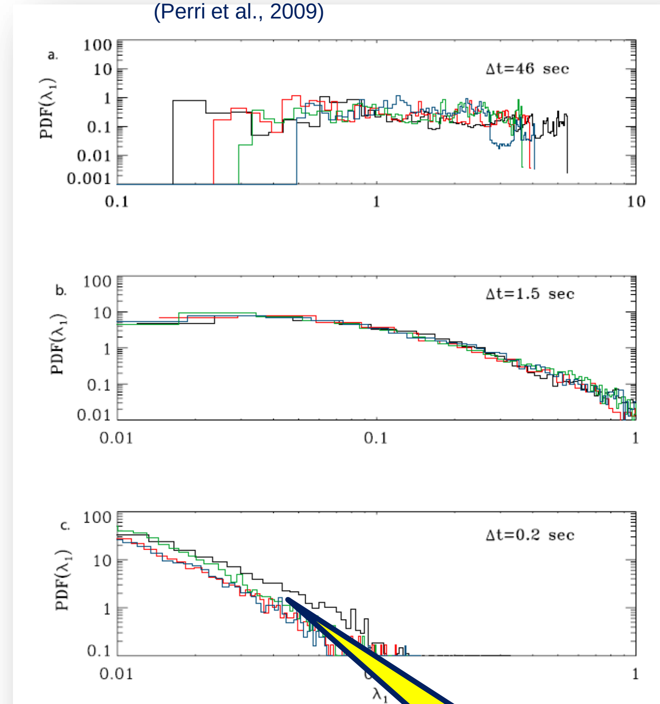
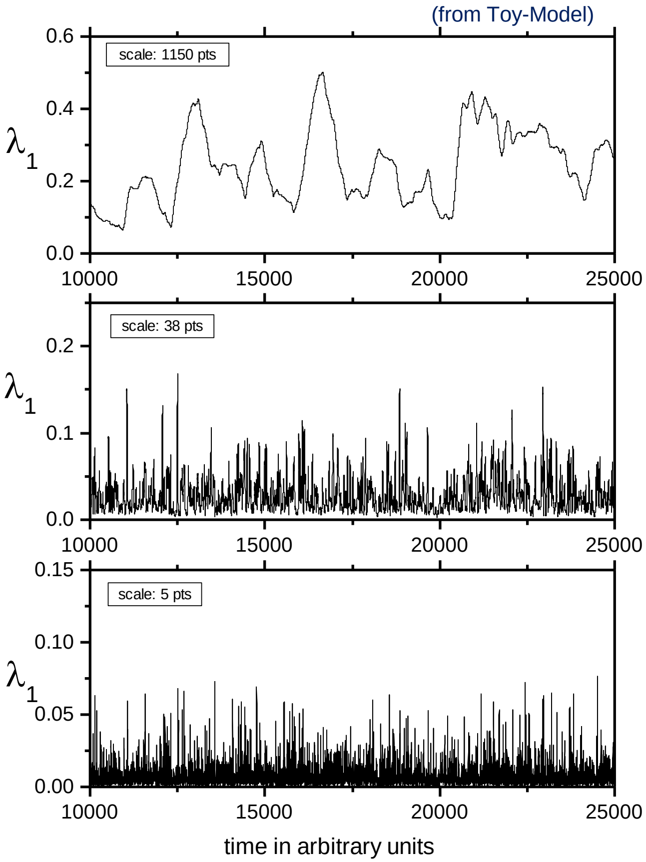


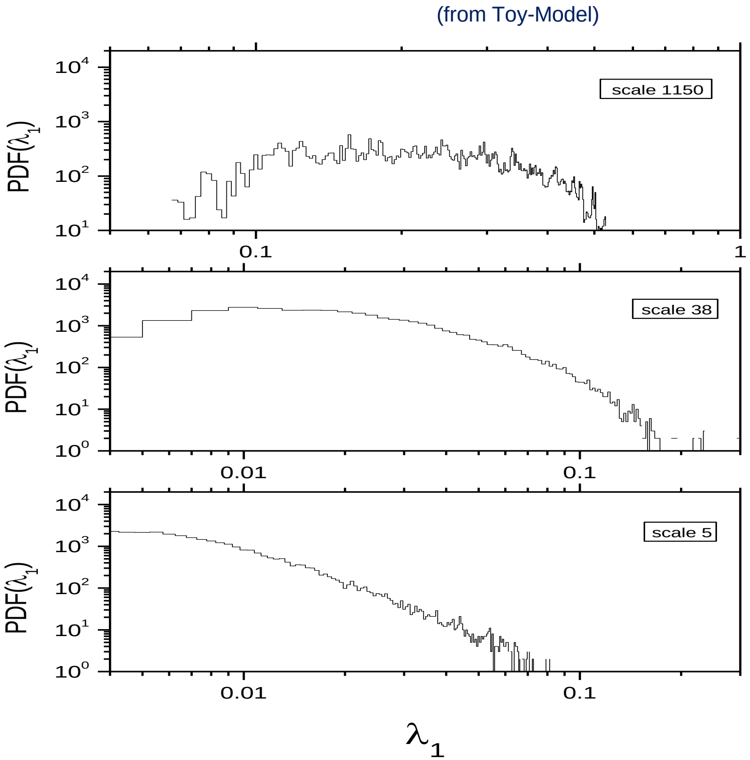
Figure 4. Probability density functions of the eigenvalues along ... imum variance, (b) the medium variance, and (c) the minimum variance directions at three scale... fferent colors refer to the four spacecraft, CLUSTER-1 (black line), CLUSTER-2 (red line), ...3 (green line), CLUSTER-4 (blue line). A changing in the shape of the distribution ... the ion cyclotron frequency.

Power law

- The PDFs evolve with the scale, becoming power laws at scales smaller than the ion cyclotron scale.
- Similar behaviour for the other eigenvalues

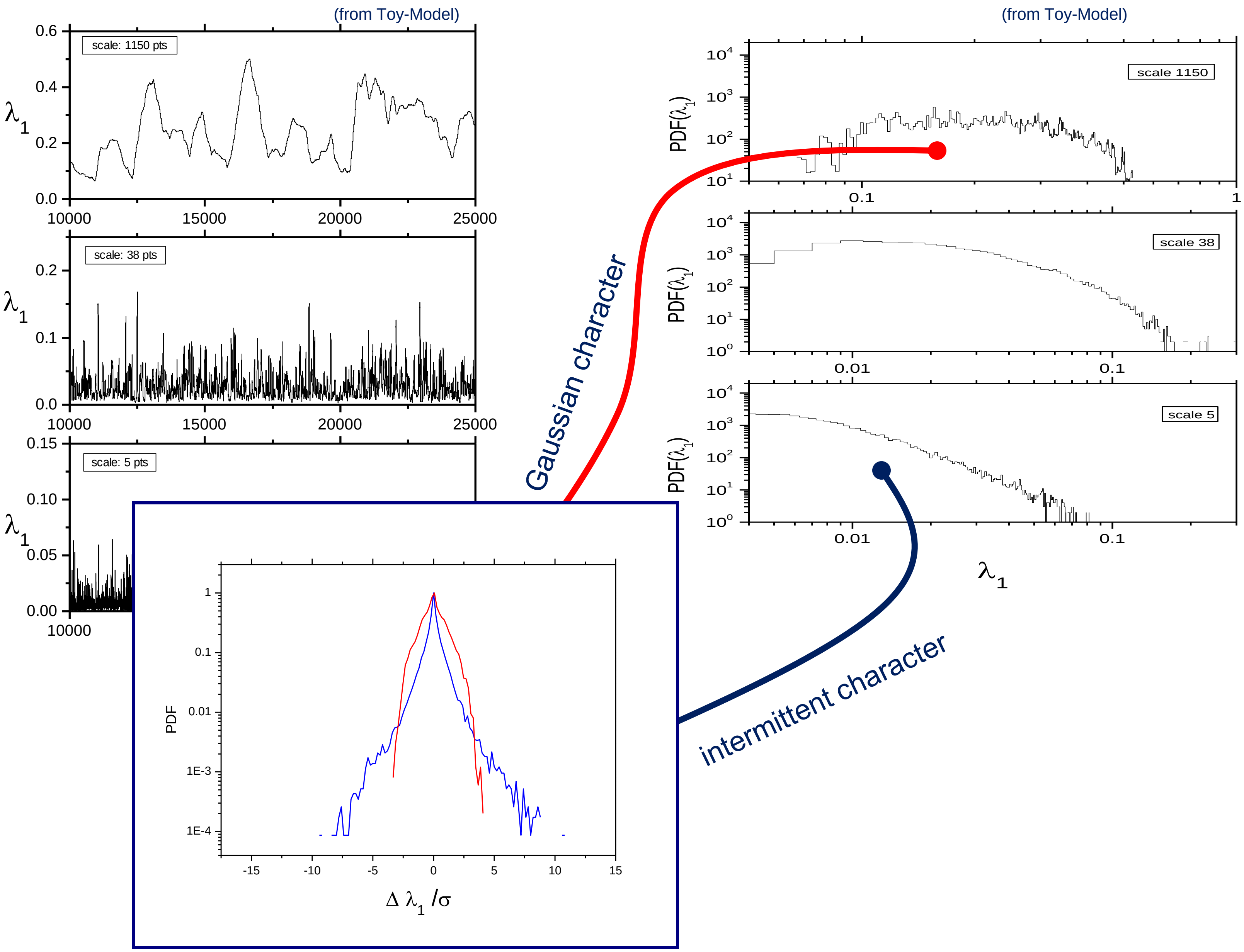
Max eigenvalue behavior from Toy Model





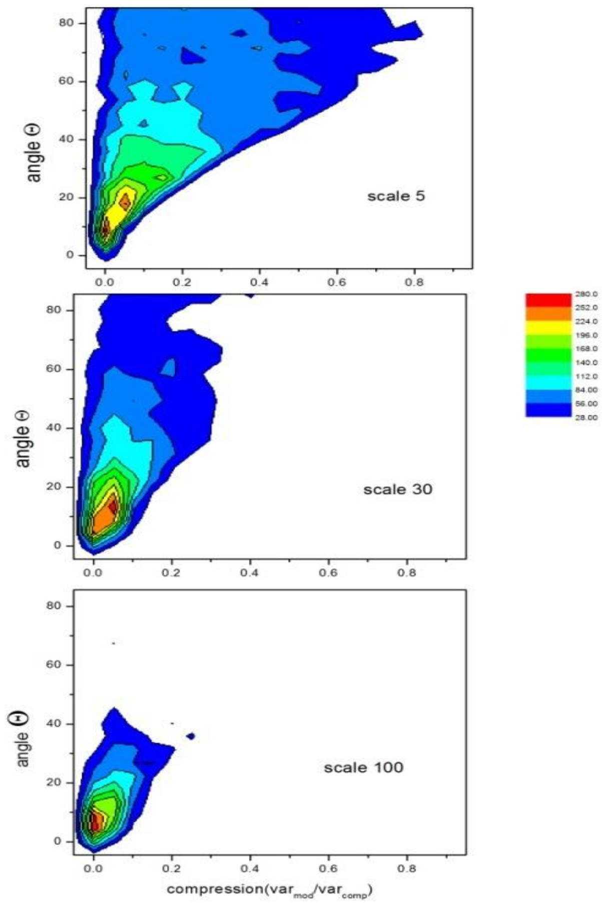
The Toy Model reproduces qualitatively the results obtained in the solar wind

Max eigenvalue behavior from Toy Model

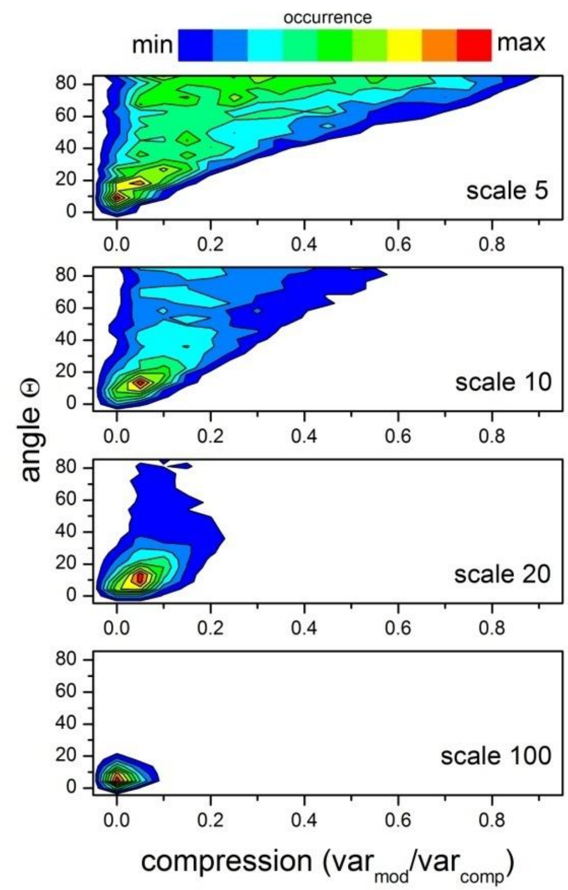


Θ distribution vs compressibility at different scales

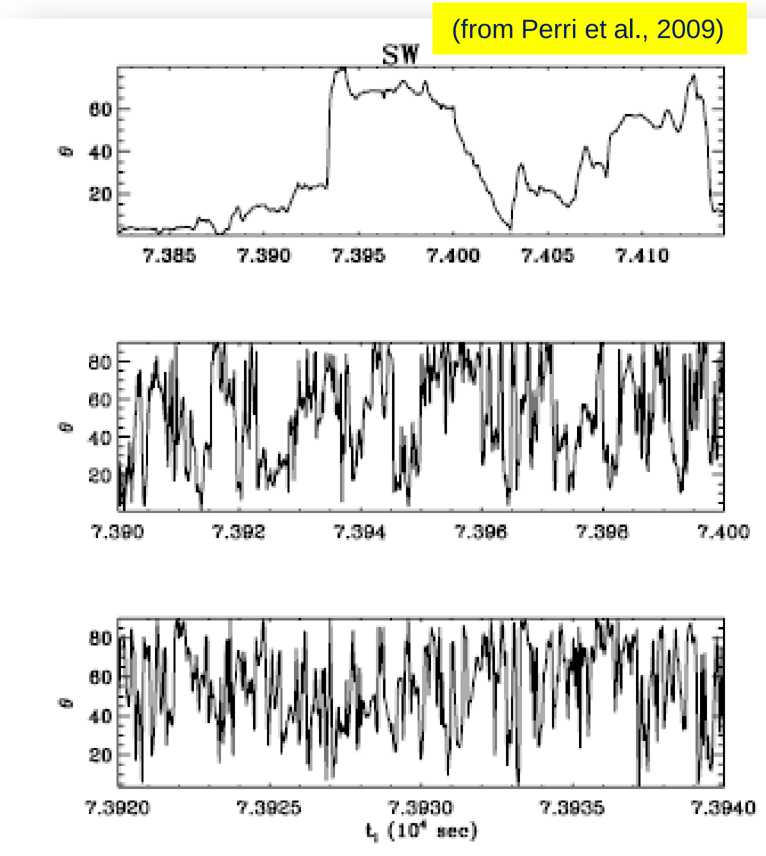
Cluster



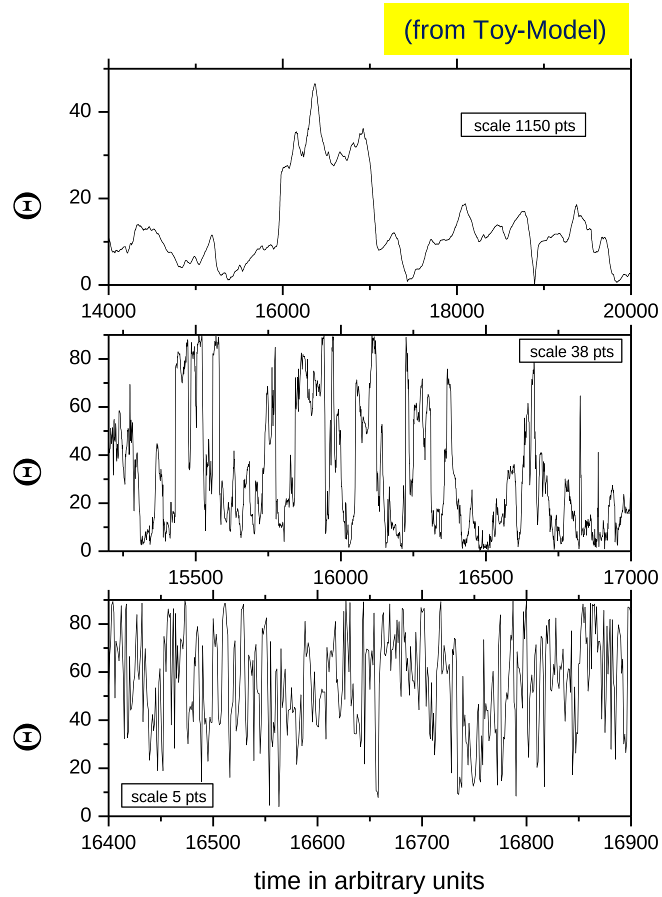
Toy Model



Time behavior of the angle Θ between minvar direction and mean field direction at three different scales.



Results from Cluster



Similar profiles obtained from toy model

PDFs in the Solar Wind

(from Perri et al., 2009)

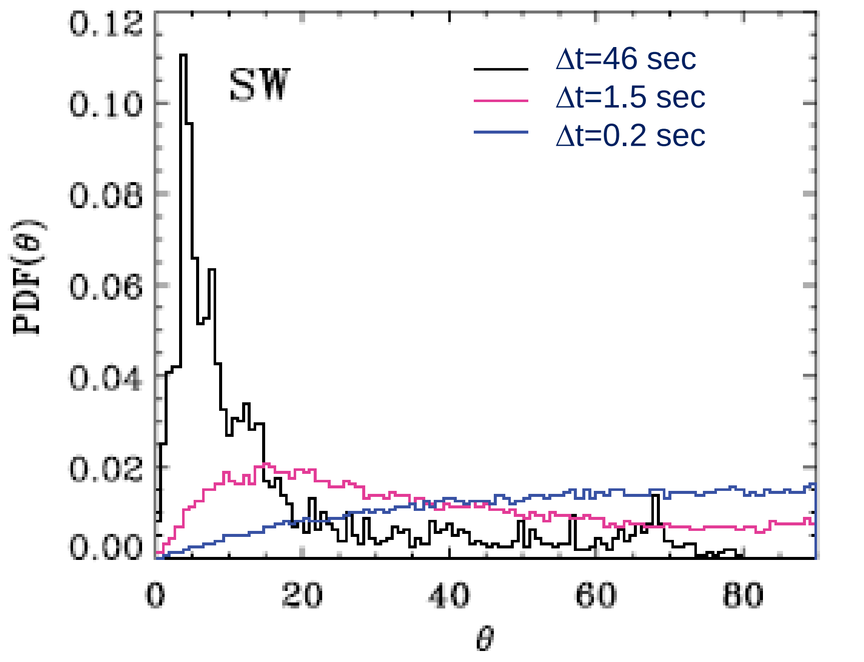
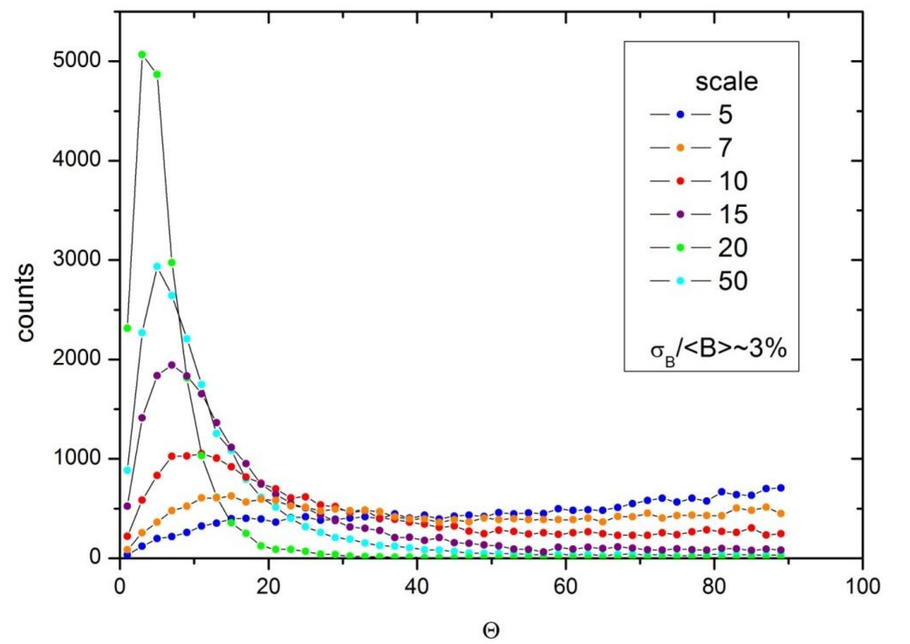


Figure 15. Probability density function of the angle θ at three scales in SW. The probability of finding a local mean magnetic field nearly parallel to the minimum variance direction increases at large scales.

(from Toy-Model)



Striking similarity between these PDFs and those found in the SW

PDFs in the magnetosheath

(from Perri et al., 2009)

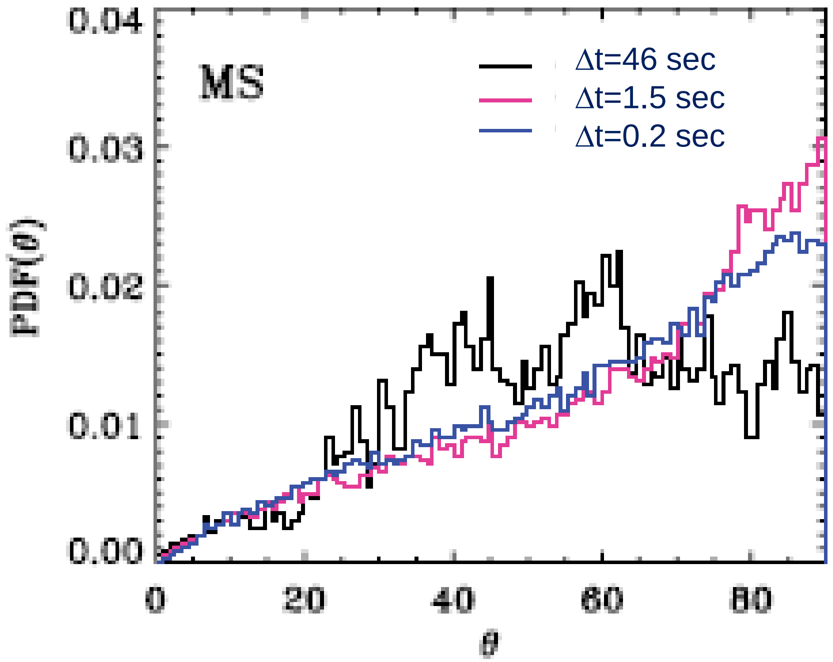
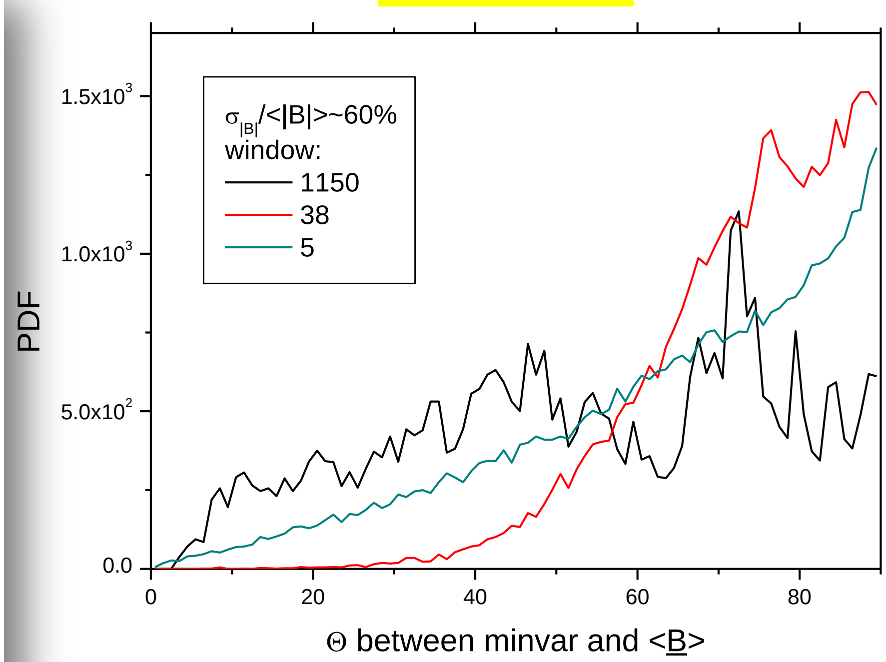


Figure 17. Probability density function of the angle θ at three scales in MS. Here at all scales the local mean magnetic field is nearly perpendicular to the minimum variance direction.

(from Toy-Model)



It is sufficient to increase the compressive level to obtain distributions similar to those recorded in the magnetosheath

The effect of compressions

(from Perri et al., 2009)

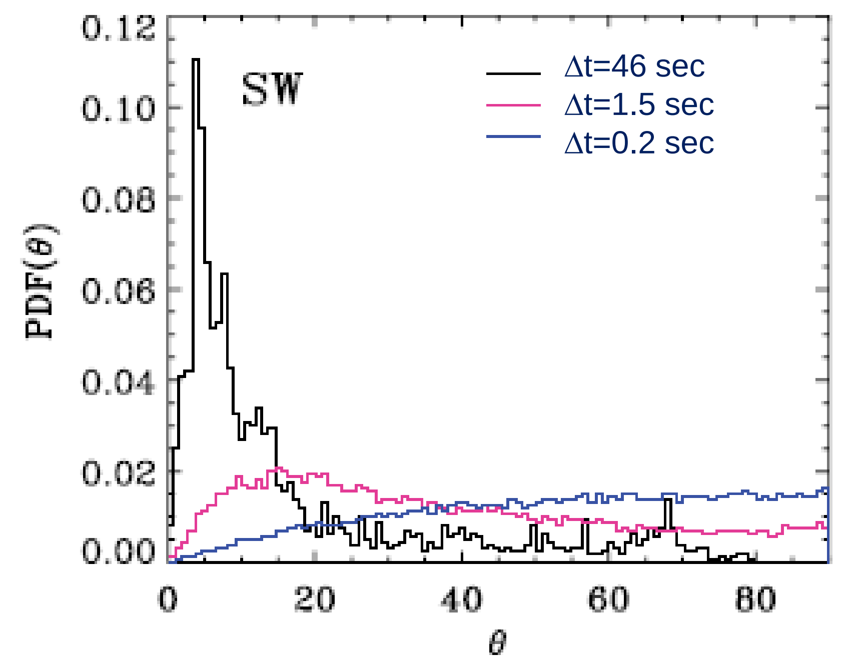
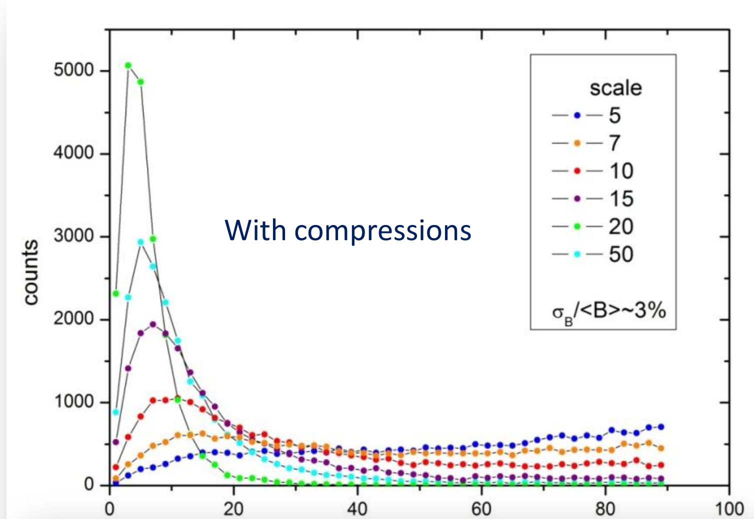
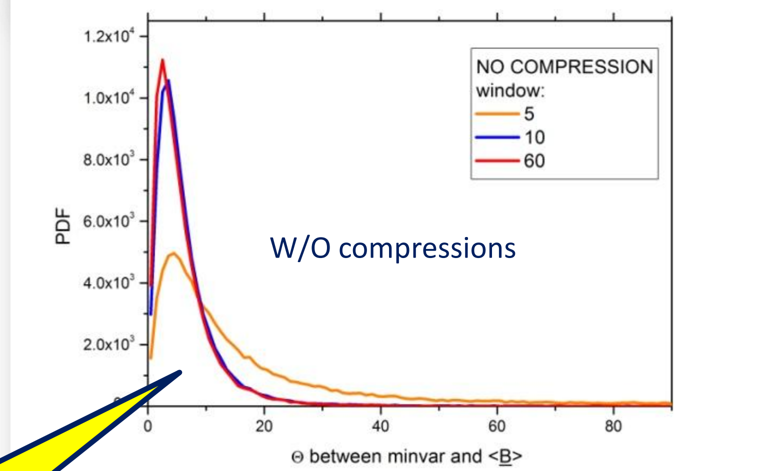


Figure 15. Probability density function of the angle θ at three scales in SW. The probability of finding a local mean magnetic field nearly parallel to the minimum variance direction increases at large scales.

(from Toy-Model)





Without compressions the toy doesn't work well

Also the type of ΔΘ distribution plays a role, the same level of compression is not longer sufficient

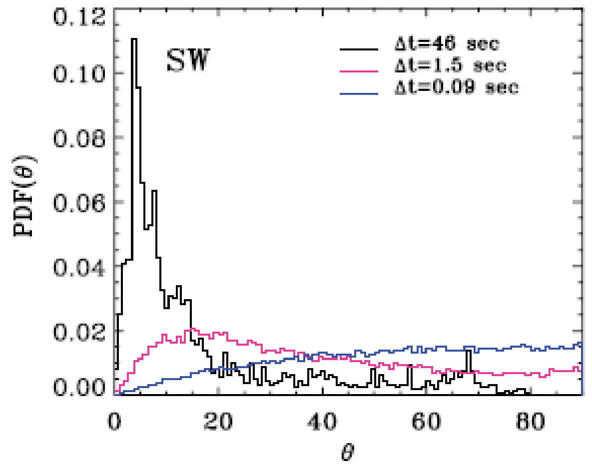
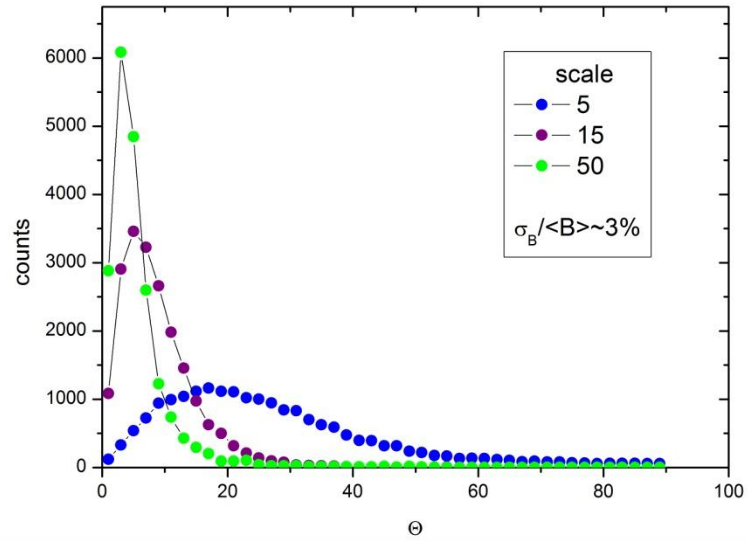
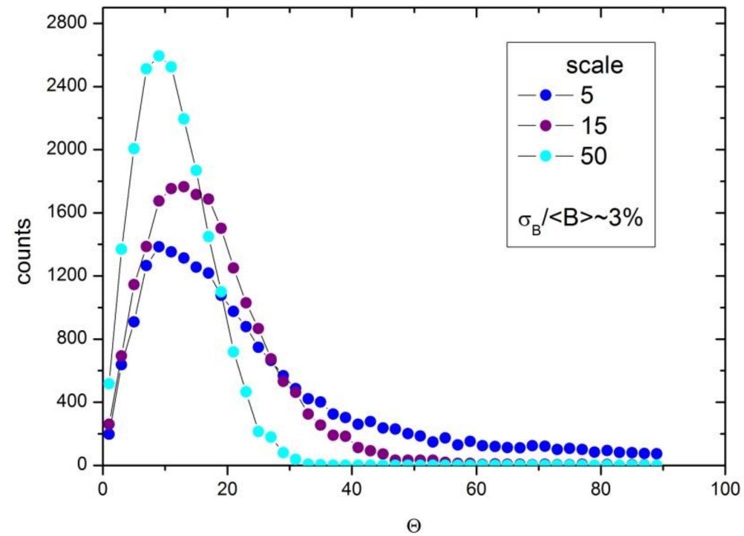


Figure 15. Probability density function of the angle θ at three scales in SW. The probability of finding a local mean magnetic field nearly parallel to the minimum variance direction increases at large scales.

ΔΘ extracted from Gaussian distribution



ΔΘ extracted from uniform distribution



Summary on power anisotropy

❖ $k^{-5/3}$ inertial range:
- Alfvénic fluctuations are mixed with advected structures
- power anisotropy ($P_{\perp}/P_{//} > 1$) increaseses with wavenumber
- Compressive events increase intermittency and affect power anisotropy

❖ Beyond the proton cyclotron freq.:
- Fluctuations show features of KAWs
- The new cascade starts at $\mathbf{k_{\perp}\rho_i \sim 1}$
- intermittency increases
- power anisotropy ($P_{\perp}/P_{//} > 1$) increaseses with wavenumber
- important role played by compressions confirmed by anisotropy studies and in agreement with the compressive character of KAWs
- A simple toy model can reproduce the minvar results only if compressions are included