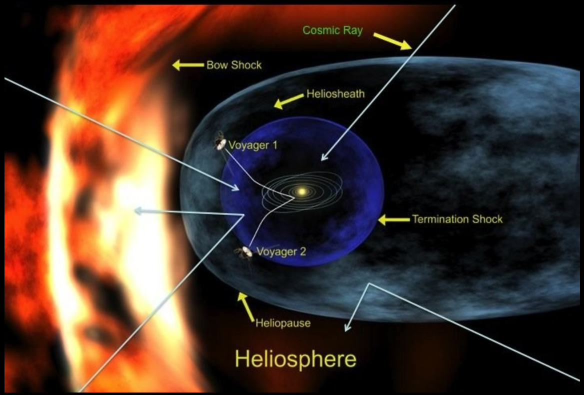
Turbulence Observations in Heliospheric Space Plasmas

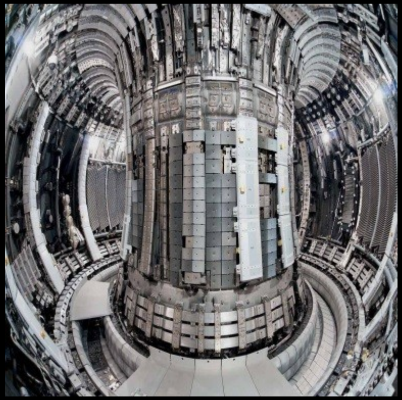
2. Overview on solar wind

Luca Sorriso-Valvo

Nanotec/CNR, Rende, Italy

Why study Solar Wind turbulence?





Has effect on the Earth: Space Weather
- Triggers reconnection, substorms, aurorae, …

Helps understanding solar processes
- Signature of coronal heating, …

Relevant for energetic particle transport and acceleration
- Controls cosmic rays throughout the solar system

Helps understanding astrophysical plasmas
- Stellar formation, jets, intergalactic medium, …

Relevant for laboratory plasmas
- Reduces confinement in fusion devices

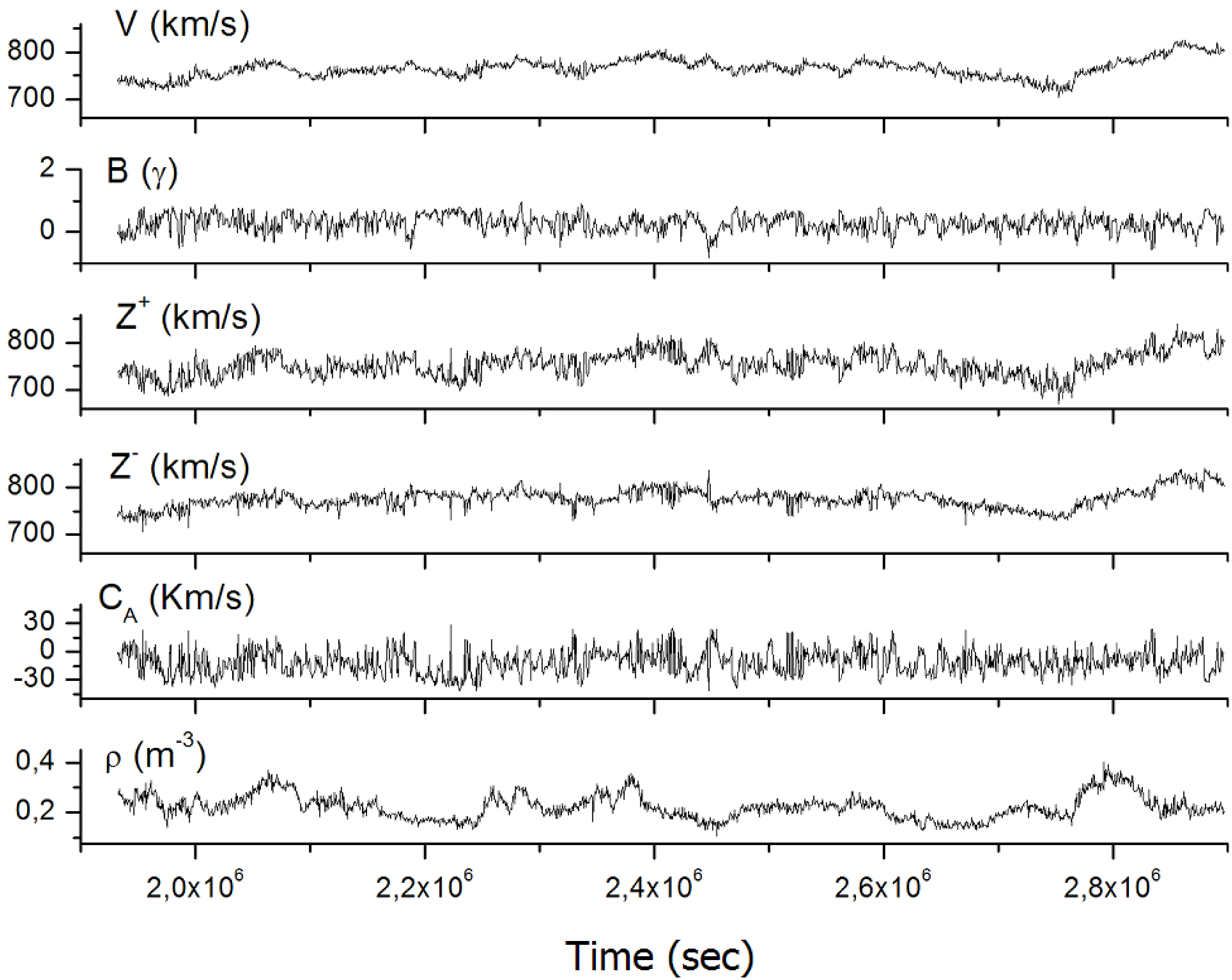
Turbulence as a universal phenomenon

Comparison with hydrodynamics and complex flows

Fundamental plasma processes
- Dissipation of energy, magnetic reconnection, propagation of waves, .

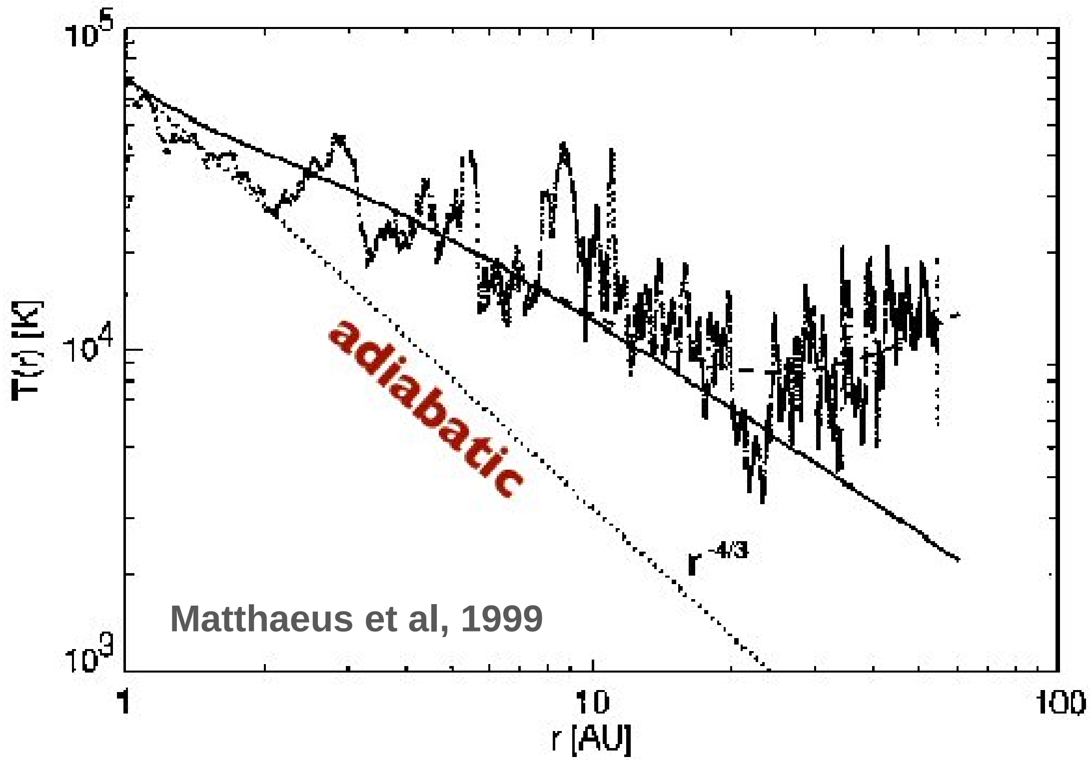
Bruno & Carbone, Liv. Rev. Solar Phys., 2005/2013;
Alexandrova et al., Space Sci. Rev., 2013;
Matthaeus & Velli, Space Sci. Rev., 2011

The solar wind as a wind tunnel



Early results: solar wind heating

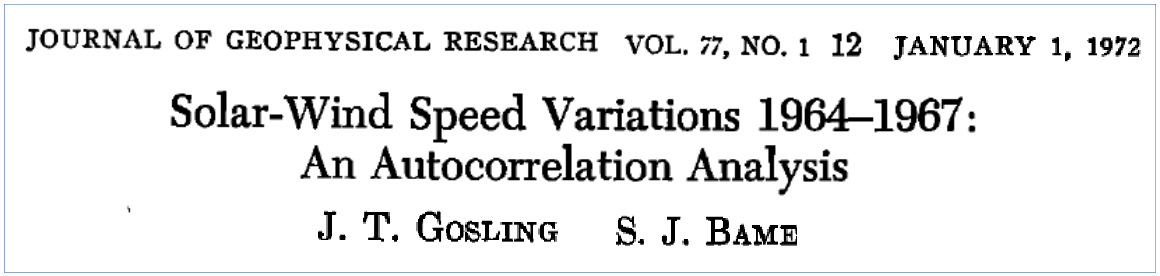
Measured solar wind temperature decreases radially less than expected from adiabatic expansion: something is heating the plasma.
A candidate: dissipation of energy at the bottom of a turbulent cascade.
Just one of many observations motivating the study of turbulence.



$T \sim T_0(r_0/r)^\xi$ $\quad$ $\xi \,\theta\, [0.7 \quad 1]$ $\quad$ (Estimate using Voyager radial profile)

Autocorrelation function

Examples of Autocorrelation function in the solar wind


JOURNAL OF GEOPHYSICAL RESEARCH VOL. 77, NO. 1 12 JANUARY 1, 1972

Solar-Wind Speed Variations 1964–1967:
An Autocorrelation Analysis

J. T. GOSLING S. J. BAME

Recurrence scale: 28 day (solar rotation)

Correlation scale: ~ a few days

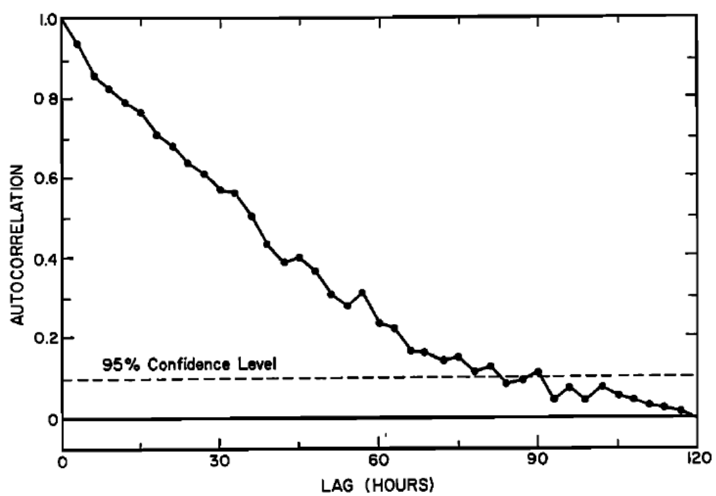


Fig. 11. Autocorrelation of Vela 2 and 3 data near zero lag using 3-hour averages of the data July 1964 to December 1967. Significant correlations extend out to a lag of about 75 hours.

Vela 2 and Vela 3 data, 1964-1967

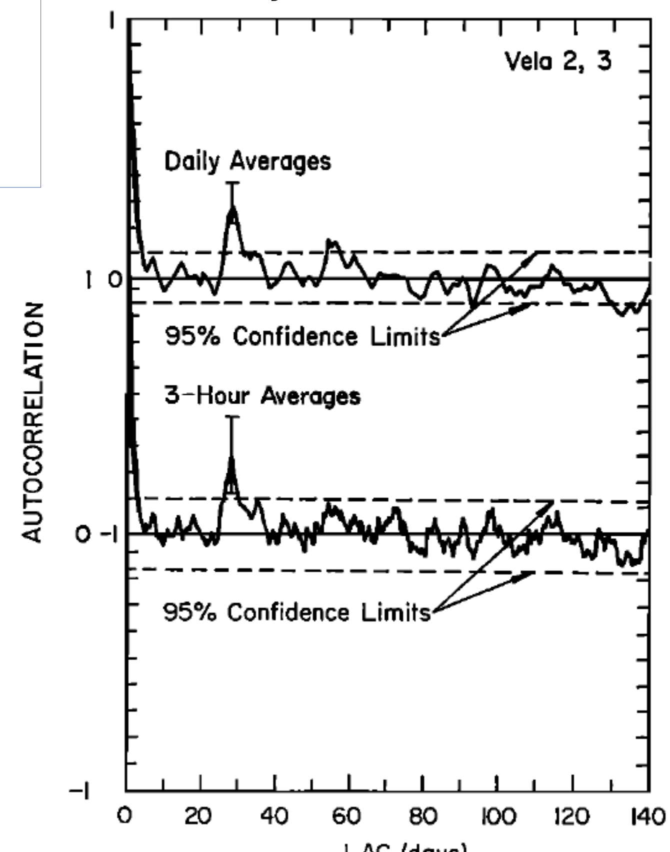


Fig. 2. Autocorrelation of the solar-wind flow speed for the interval July 1964 to December 1967 using daily averages (upper curve) and 3-hour averages (lower curve).

Autocorrelation function/2

Examples of Autocorrelation function in the solar wind

PRL **95,** 231101 (2005) PHYSICAL REVIEW LETTERS week ending 2 DECEMBER 2005

Spatial Correlation of Solar-Wind Turbulence from Two-Point Measurements

W. H. Matthaeus,[1] S. Dasso,[2] J. M. Weygand,[3] L. J. Milano,[1] C. W. Smith,[4] and M. G. Kivelson[3]

Combined dataset from ACE and Wind at different distances (lags)

TABLE I. Summary of data intervals used for this analysis.

Data set	Separation (R_E)	Length	Number
ACE-Wind	20–350	2 d	264
Cluster (I)	0.44–1.21	2–16 h	30
Cluster (II)	0.024–0.042	1–35 h	102

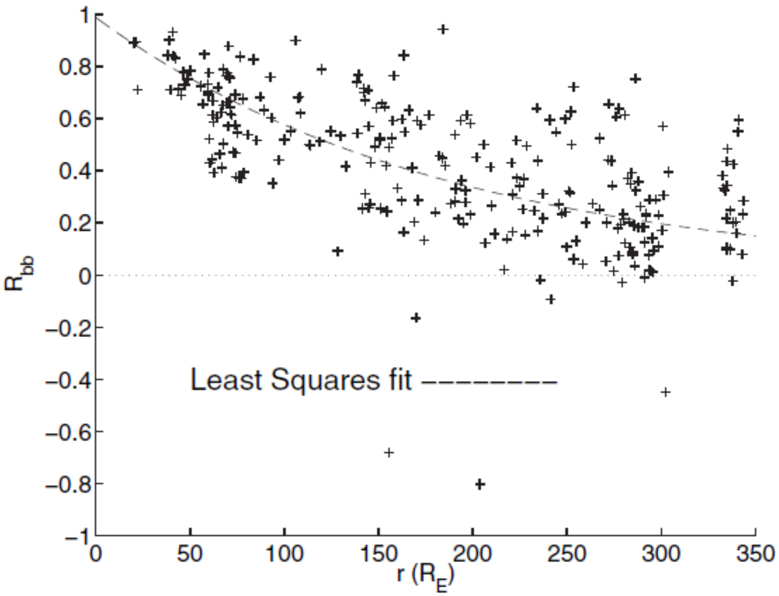


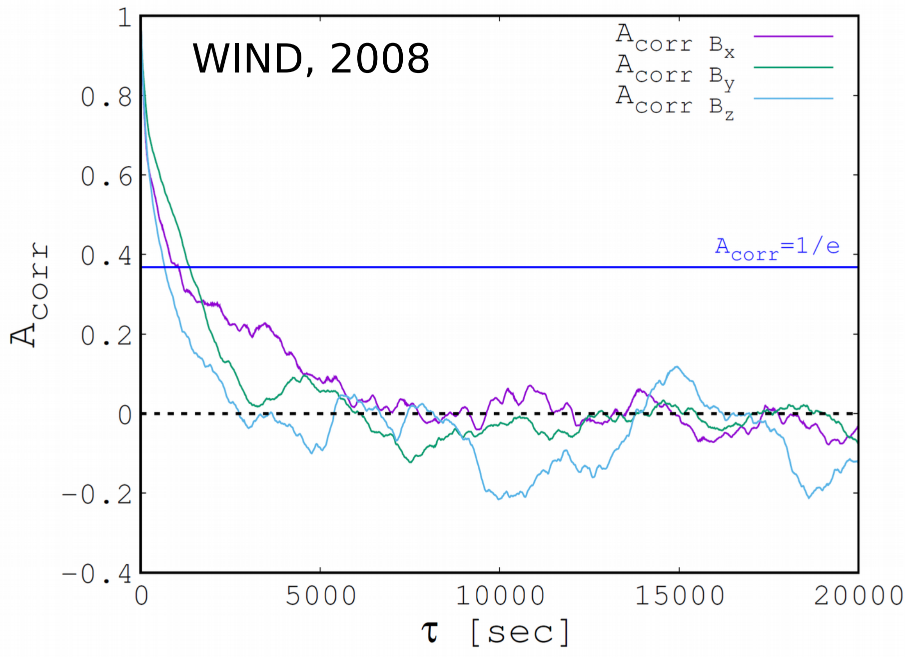
FIG. 1. Estimates of correlation function $R(r)$ from 264 ACE-Wind samples, for separation distances 20–350 R_E. A fit to a constrained [$R_{bb}(0) = 1$] exponential (dashed line) gives correlation scale $\lambda_c = 186 R_E$.

$$R_m^{\rm eff} = \left(\frac{\lambda_c}{\lambda_T}\right)^2 \approx 230\,000.$$

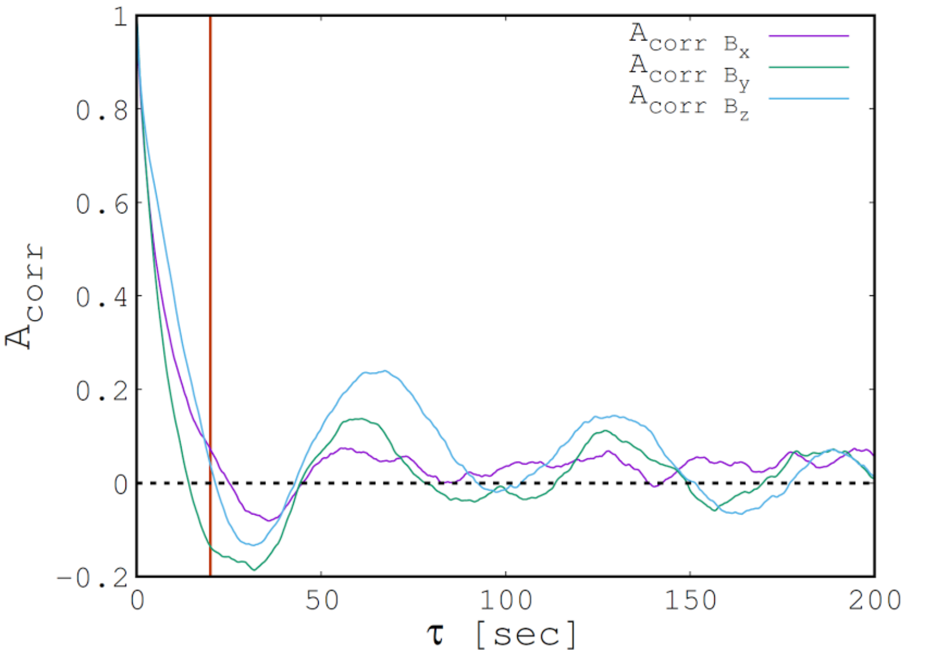
Autocorrelation function/3

Examples of Autocorrelation function in the solar wind (WIND data) and in the magnetosheath (MMS data)

Solar wind @1AU
Estimated correlation timescale~1h
Strongly variable: ranges from ~30min to ~12h in the literature



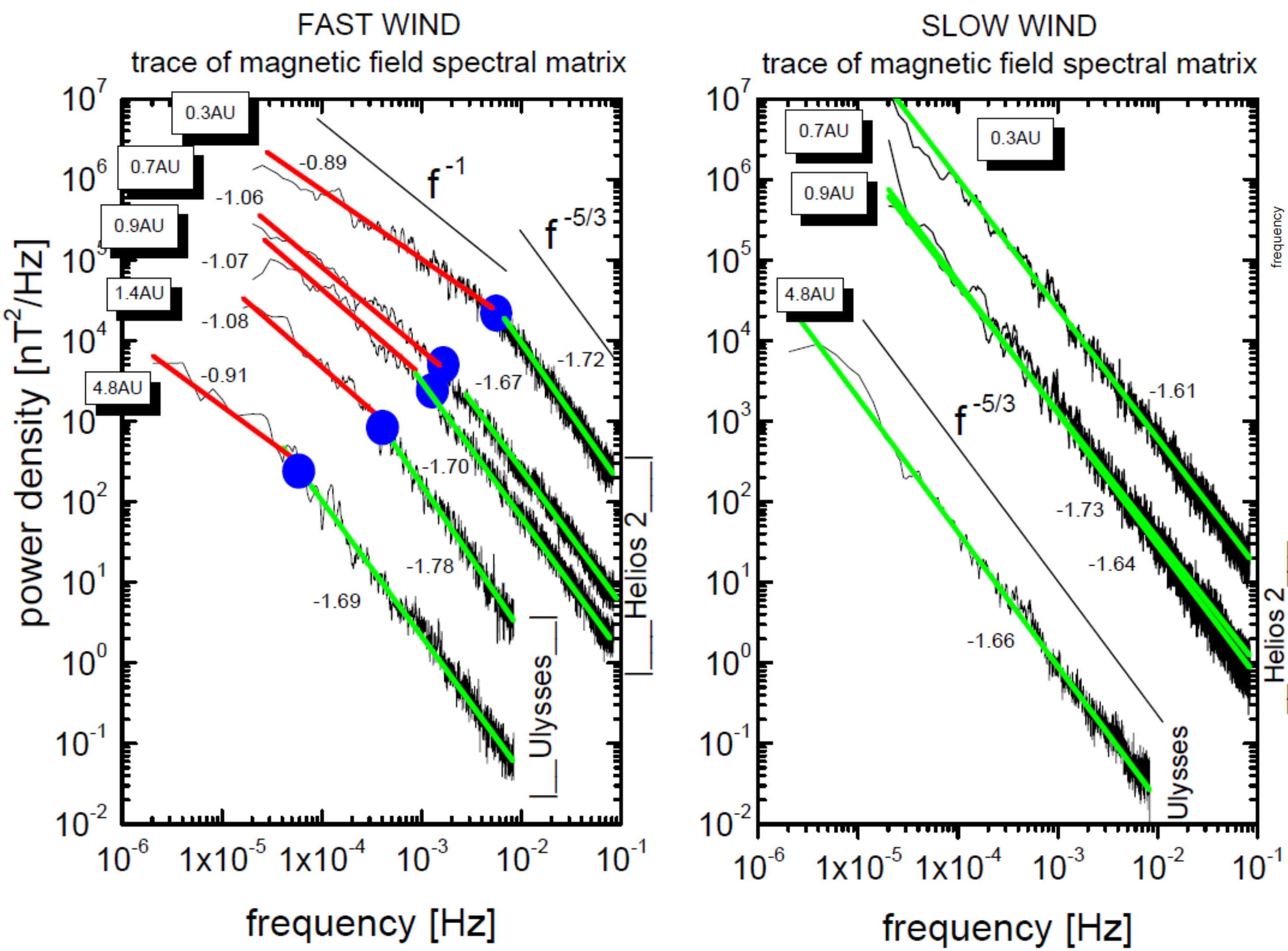
Magnetosheath with KHI
Estimated correlation timescale ~20sec
Estimated KH roll-up: ~70sec

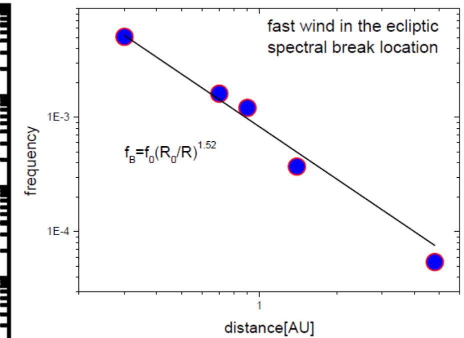


Panebianco, in preparation

Spectra

Magnetic spectra: turbulent solar wind ($f^{-5/3}$). Evidence of radial evolution in Fast wind. 1/f range: uncorrelated (Alfvénic?) fluctuations?



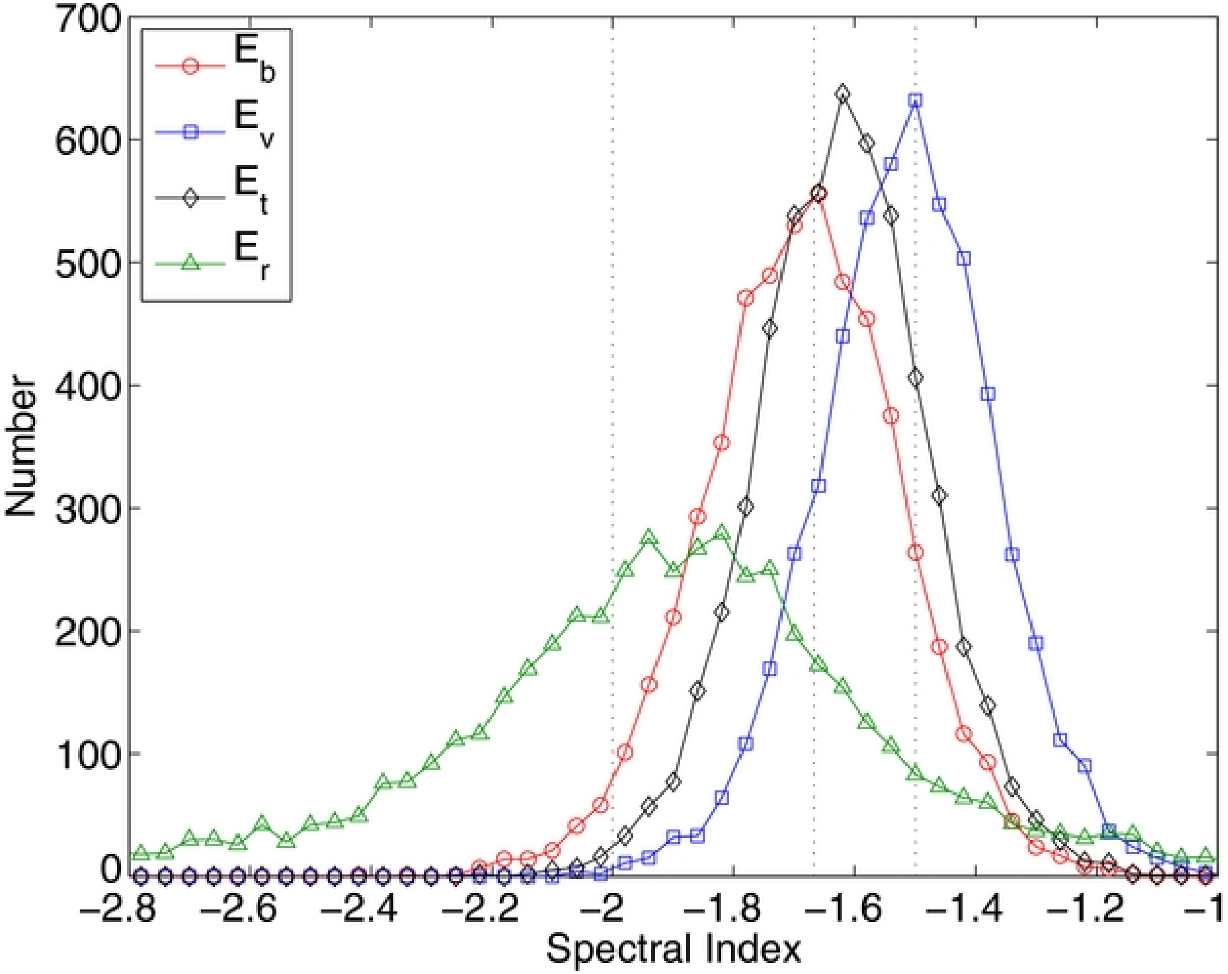


Alfvénic and compressive turbulence, radial evolution and other trends: see *Bruno & Carbone Liv. Rev. Sol. Phys, 2013* for a survey.

Bruno & Carbone 2013

Spectra/2

Variety of spectral indexes are observed:
sensitivity to “junk” fluctuations? Physics of the cascade?



WIND, 2004-2009; Chen et al., 2013

Spectra/3

....and they depend on SW parameters

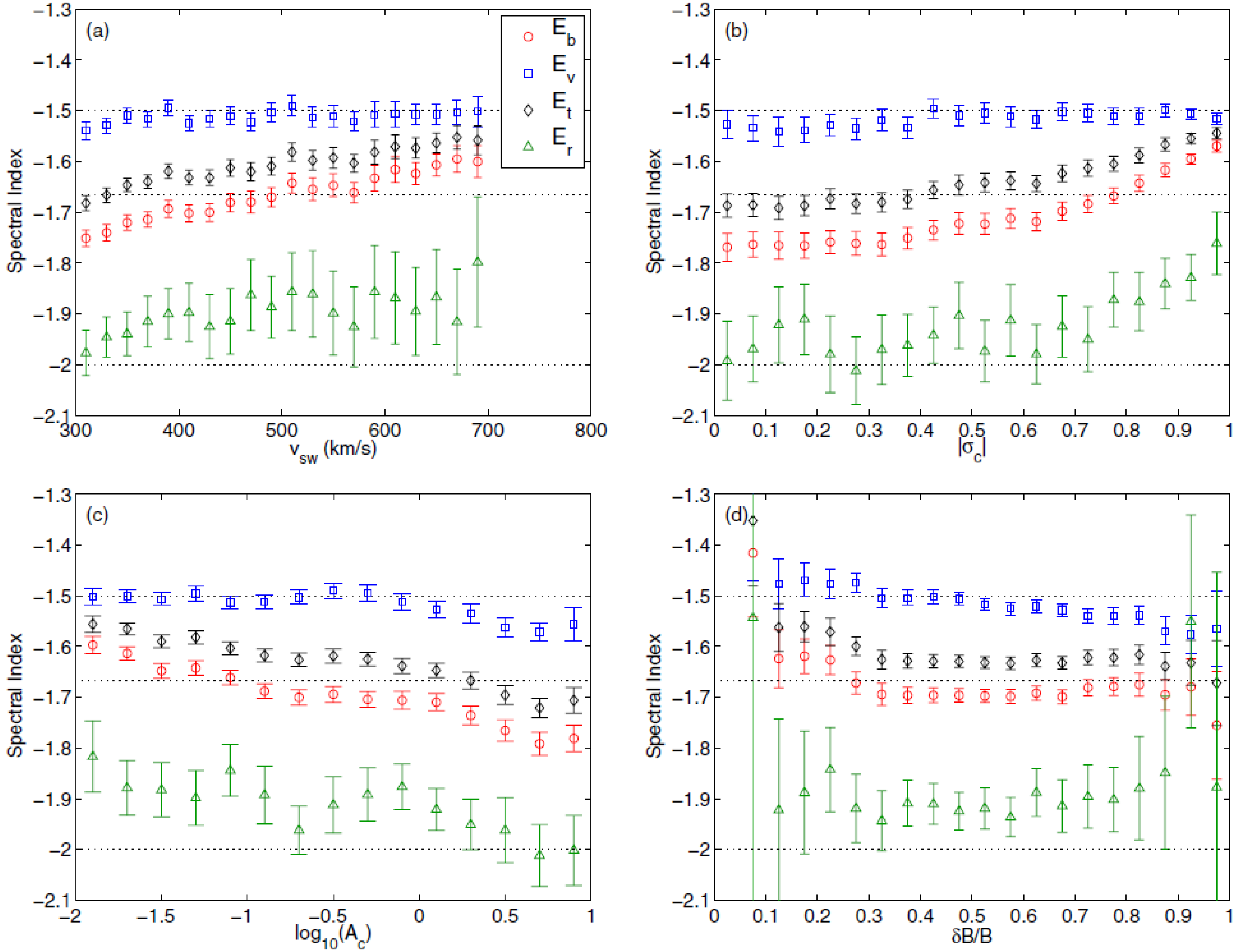
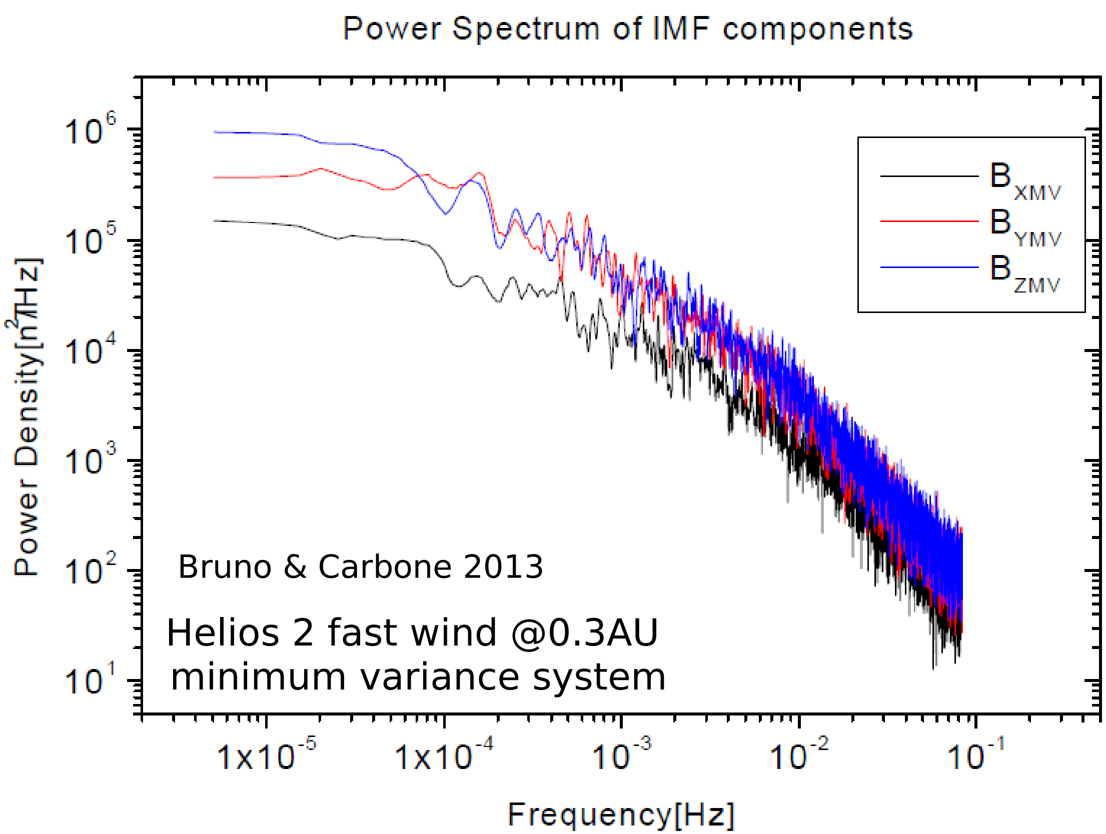


Figure 5. Dependence of spectral indices on (a) solar wind speed v_{sw}, (b) magnitude of imbalance $|\sigma_c|$, (c) collisional age A_c, and (d) fluctuation amplitude $\delta B/B$. The error bars represent 2 standard errors of the mean. The black dotted lines correspond to different spectral index predictions.
(A color version of this figure is available in the online journal.)

WIND, 2004-2009; Chen et al., 2013

Spectra/4: anisotropy

Unlike neutral flows, MHD turbulence is anisotropic (B). Components transverse to the mean magnetic field have more power, and spectral exponents depend on the k-B_0 angle.
Also predicted by MHD simulations: convection of Alfvénic fluctuations decorrelates and inhibits the nonlinear interactions in the || direction.
Not sufficient to explain observed anisotropy (see e.g. Oughton, 1994)



Variance anisotropy: $\delta B_\perp \neq \delta B_{||}$
Power anisotropy: $P(k_\perp) \neq P(k_{||})$
Wavevector anisotropy: $k_\perp \neq k_{||}$
Spectral index anisotropy: $\alpha_\perp \neq \alpha_{||}$
Imbalance: $E^+ \neq E^-$

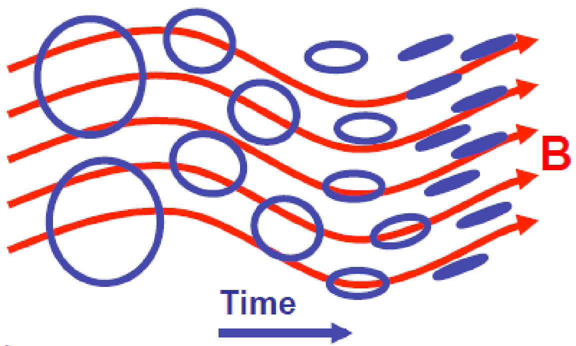
[Horbury, Wicks & Chen 2012 SpaceSciRev]

Spectra/5: anisotropy

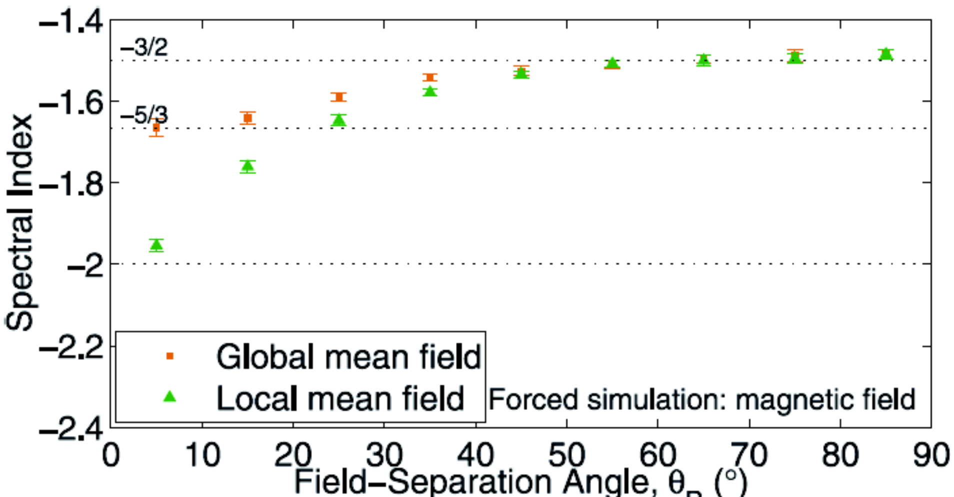
Critical balance [Goldreich & Sridhar, 1995]*:*

$\tau_A \approx \tau_{NL} \;\rightarrow\; k_{||} \sim k_\perp^{2/3}$ (eddies get elongated) $\rightarrow E(k_\perp) \sim k_\perp^{-5/3},\; E(k_{||}) \sim k_{||}^{-2}$

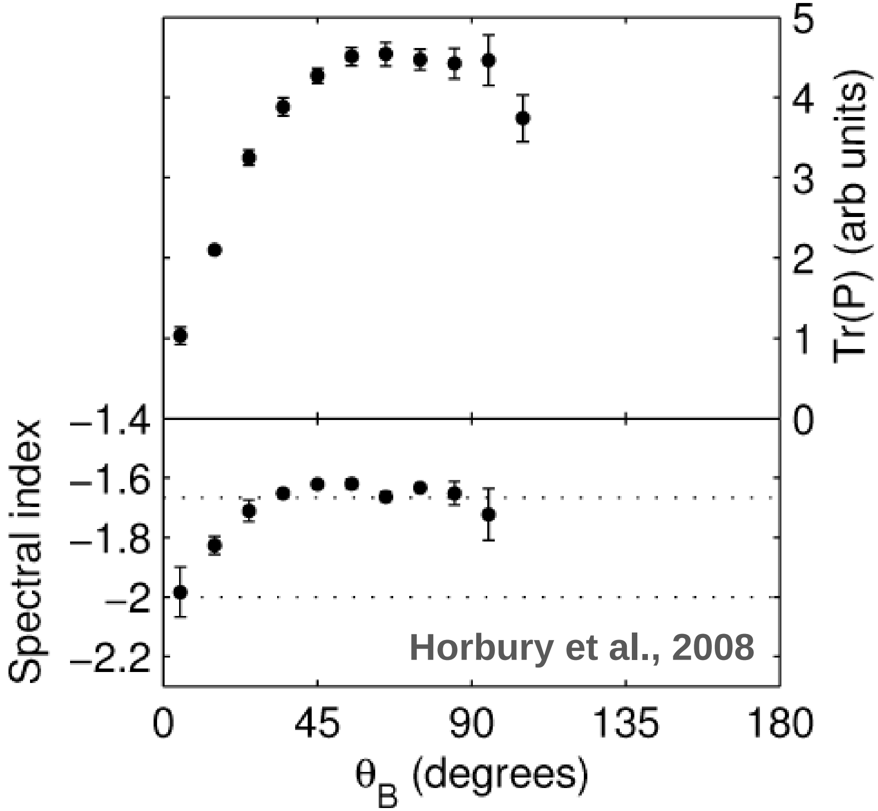
Observed spectral exponents seem to confirm the prediction.



Caveat: use of wavelet-based locally defined, scale-dependent mean magnetic field. Is this OK?



Chen et al. 2011 MNRAS



Spectra/6: anisotropy

The Uncertainty of Local Background Magnetic Field Orientation in Anisotropic Plasma Turbulence

F. Gerick, J. Saur, and M. von Papen

Published 2017 June 26

The Astrophysical Journal, Volume 843, 5

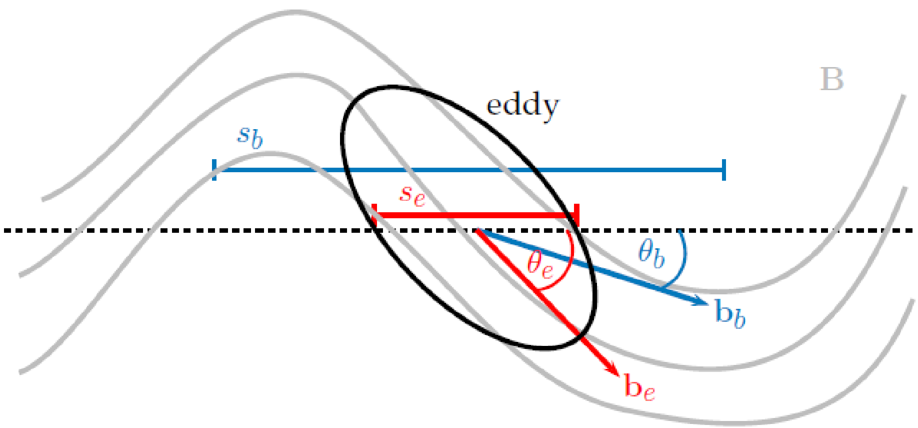


Figure 1. Schematic representation of the orientation of an eddy with respect to the orientation of two different background fields averaged at the scale of the eddy s_e and averaged at some larger scale s_b.

a gradual change of the spectral anisotropy from local to global field

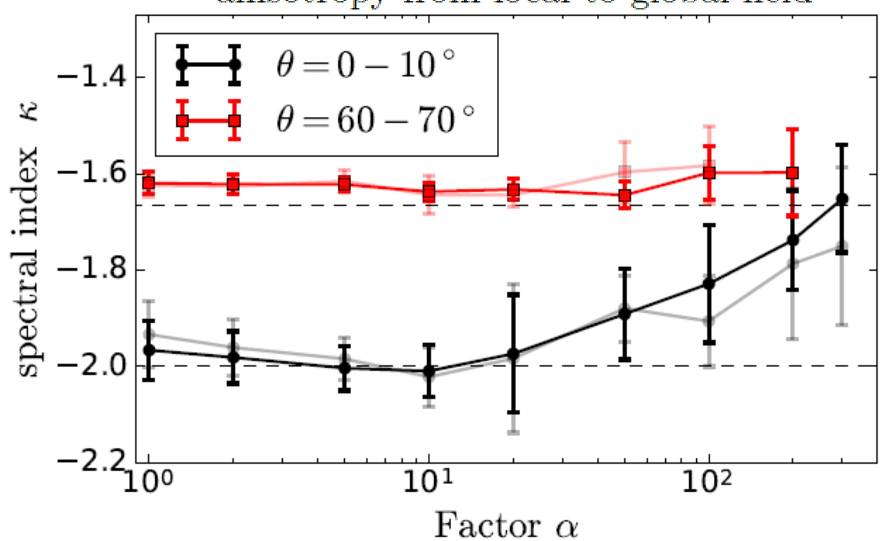
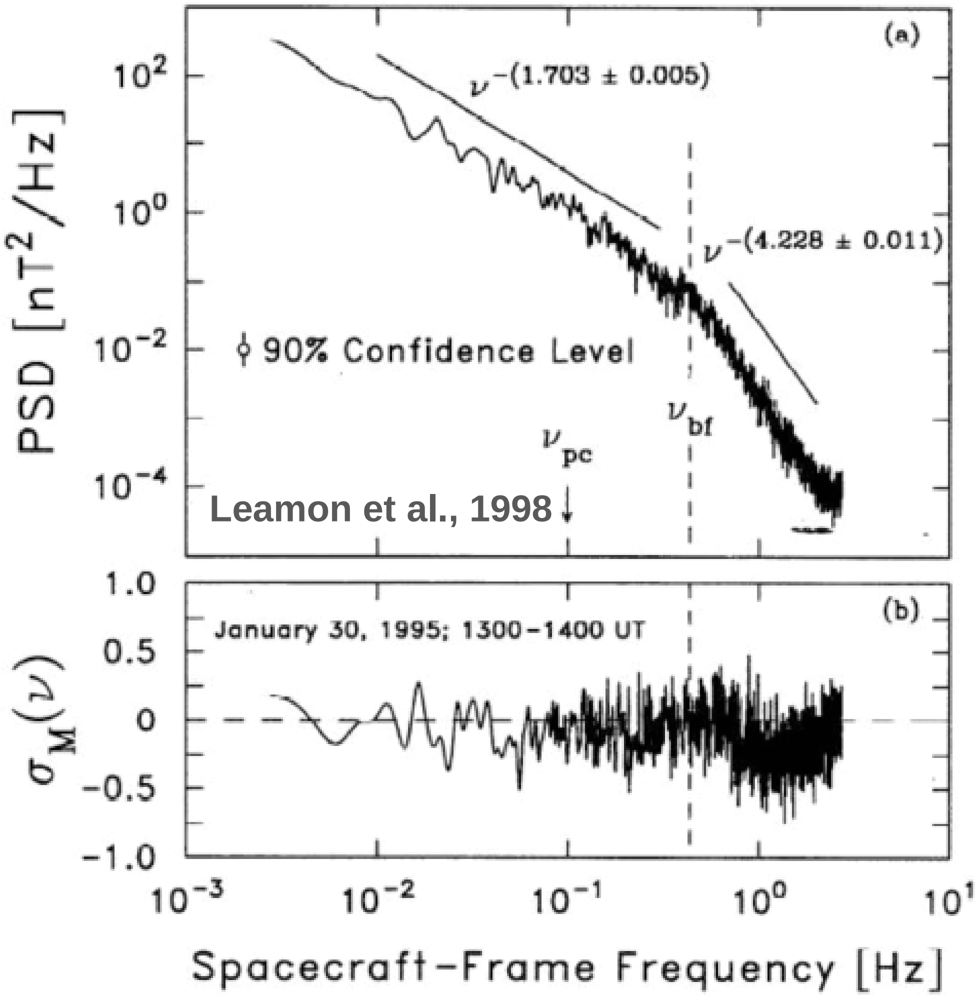


Figure 5. Spectral index κ at θ=0–10° and θ=60–70° as a function of increased averaging width by the factor α . Error

Open questions: How to define (local or global) B_0 in a turbulent flow with fluctuations at all scales? Meaningful in terms of theoretical models? ~Lagrangian turbulence? OK in time series? Mixing longitudinal and transverse fluctuations?

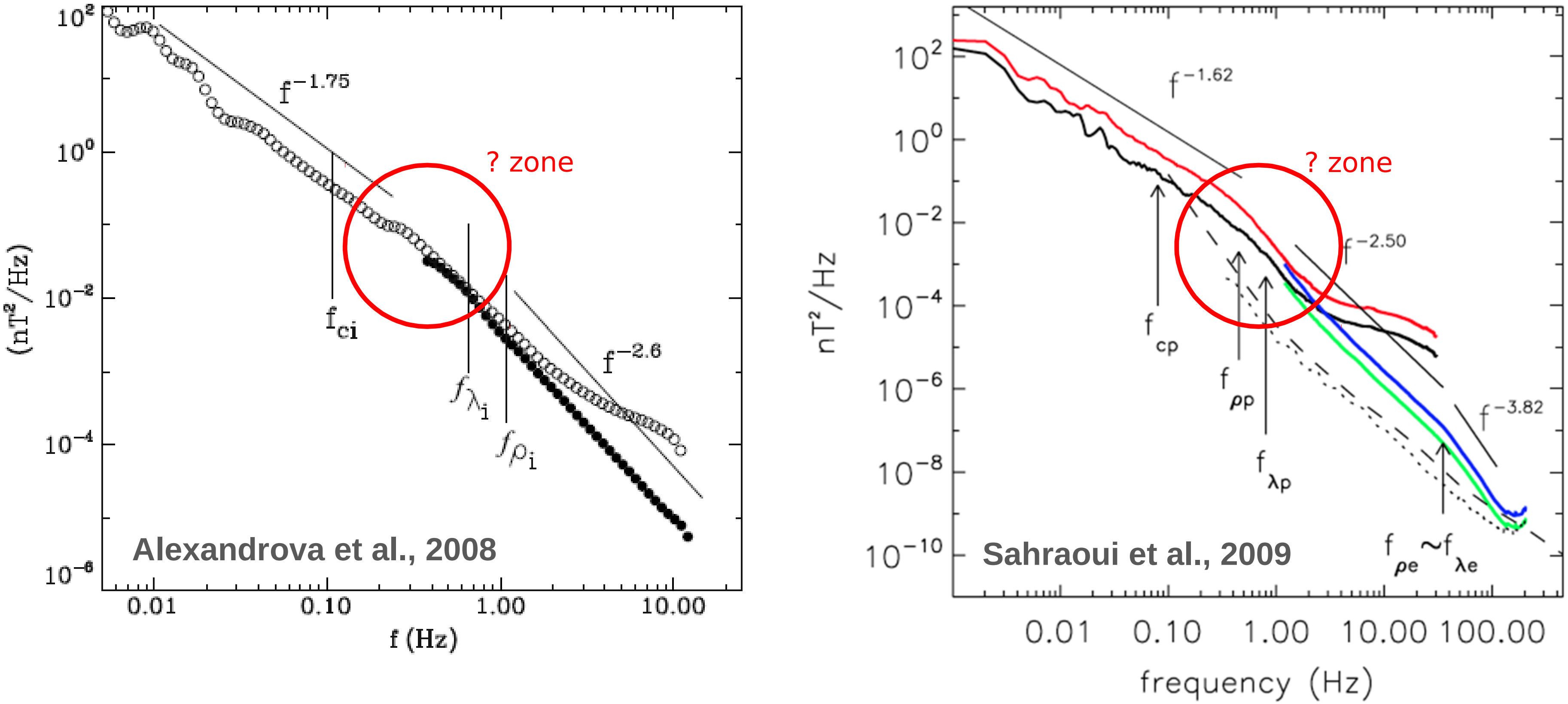
Spectra/7: high frequency

Early observations of high frequency spectra showed a secondary power-law range, with very variable spectral index [2-4] (claim of dissipation range).



Spectra/7: high-freq exponents

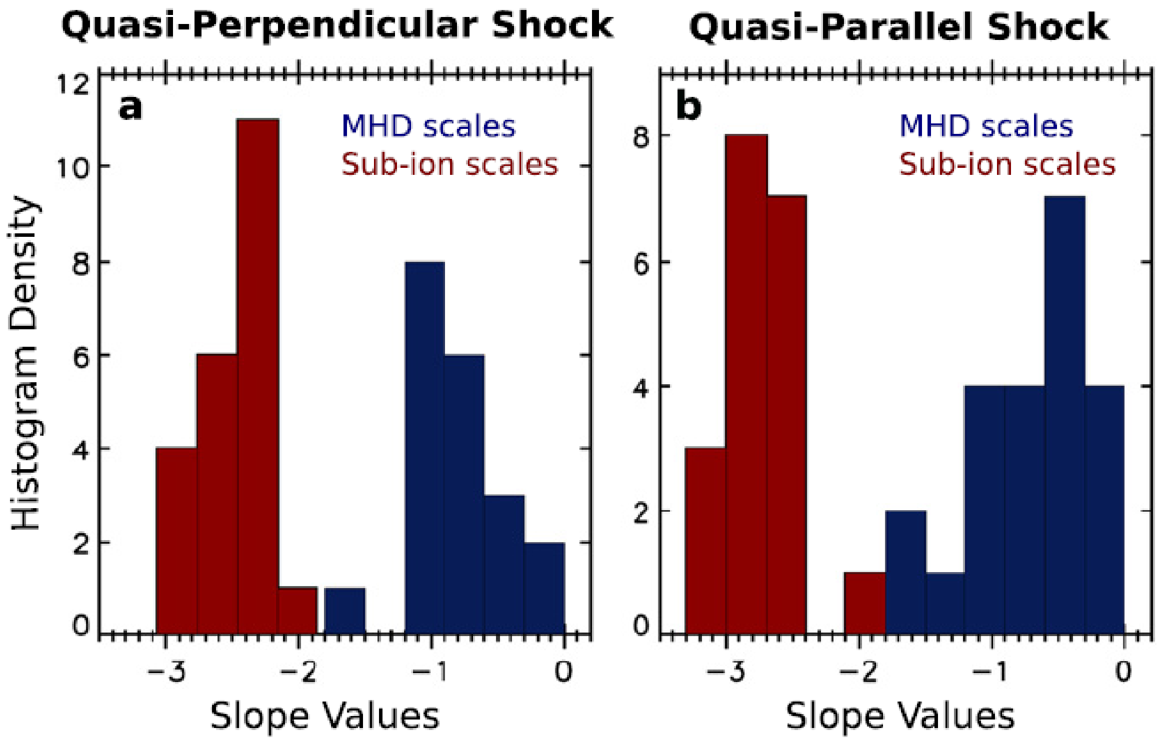
There is now a certain amount of agreement about the spectral properties after the ion-scale break [~2.5-2.8, 7/3, 8/3...]. Something more complicated happens in the transition zone.



Caveat: very short samples, ergodicity might be violated.

Spectra/8: high-freq exponents

There is now a certain amount of agreement about the spectral properties after the ion-scale break [~2.5-2.8, 7/3, 8/3…]. Something more complicated happens in the transition zone.



Hadid et al., APJL 2015

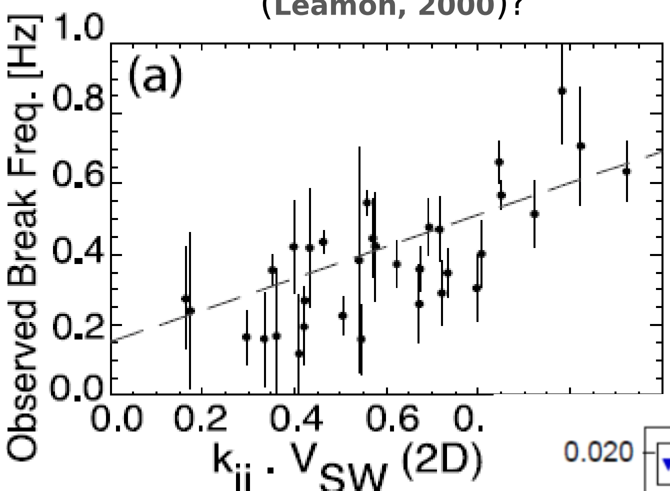
Caveat: very short samples, ergodicity might be violated.

Spectra/9: spectral break

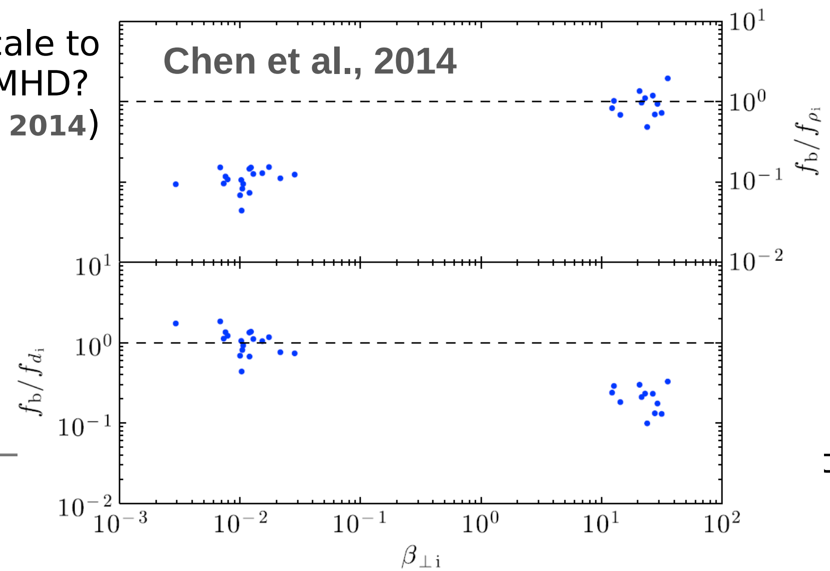
[or f_b *vs* f_{ci} *vs* $f_{\lambda i}$ (Hall) *vs* $f_{\rho i}$ (kinetic Alfvén turbulence) *vs* f_r (Alfvén waves resonance)...]

Disagreement on the location of the spectral break f_b (important to understand which processes end the MHD cascade).

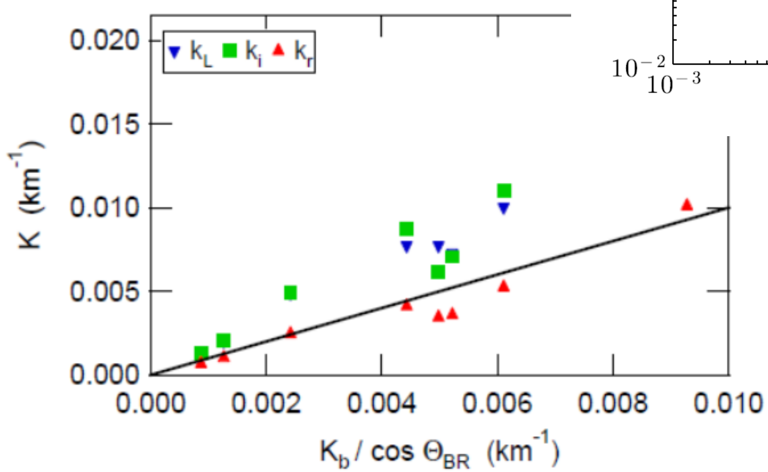
Ion inertial length (**Leamon, 2000**)?



The first scale to break MHD? (**Chen et al., 2014**)

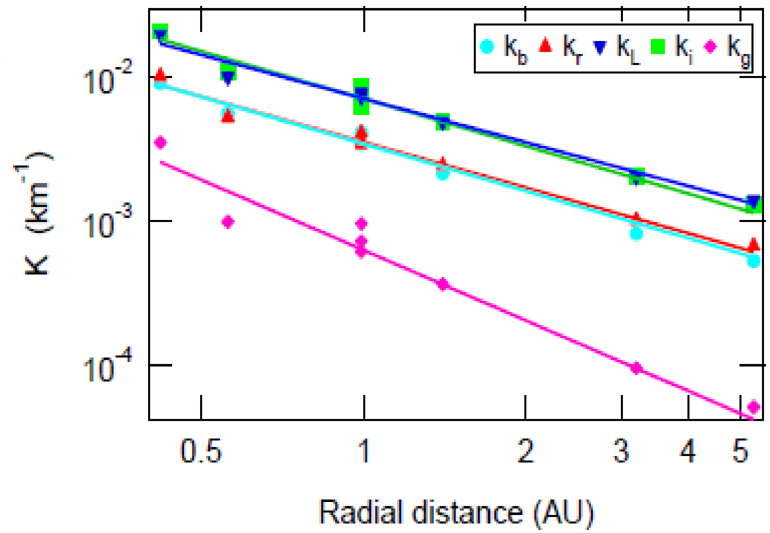


Resonance condition for ||-propagating Alfvén waves? (**Bruno & Trenchi, 2014**)

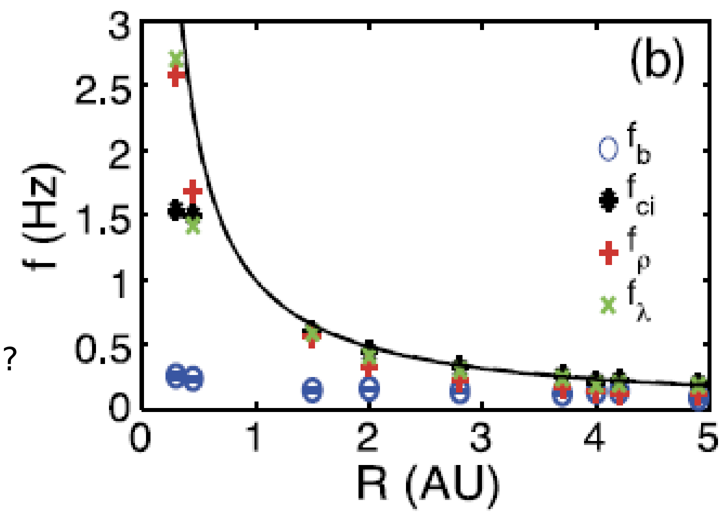


Spectra/10: spectral break/2

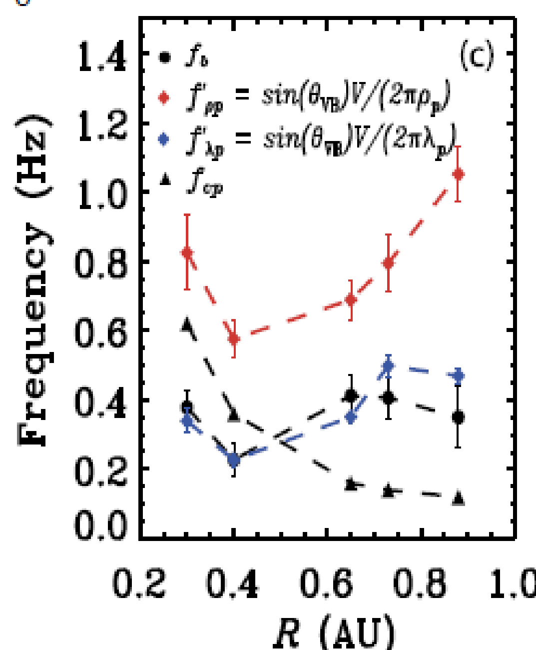
Radial distance evolution of the spectral break:
even more controversial data.



Decreasing (Messenger/Wind/Ulysses alignment)?
Bruno & Trenchi 2014



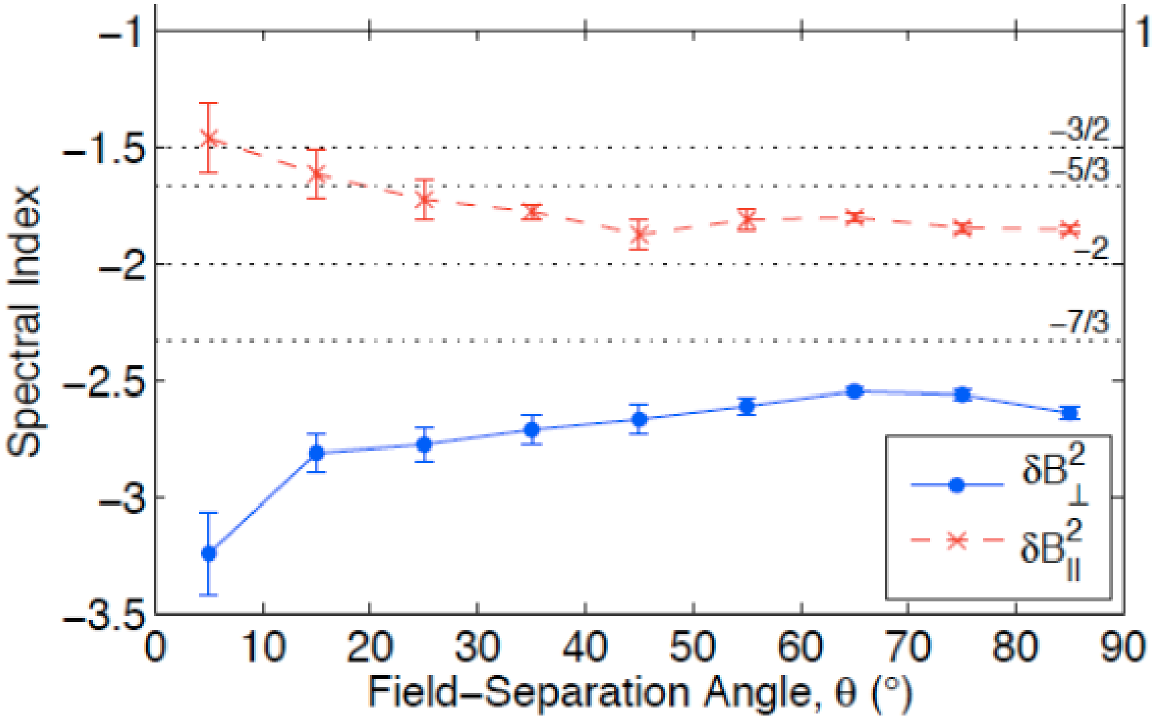
Constant Helios2+Ulysses)?
Perri et al., 2010



Increasing?
Bourouaine et al., 2012

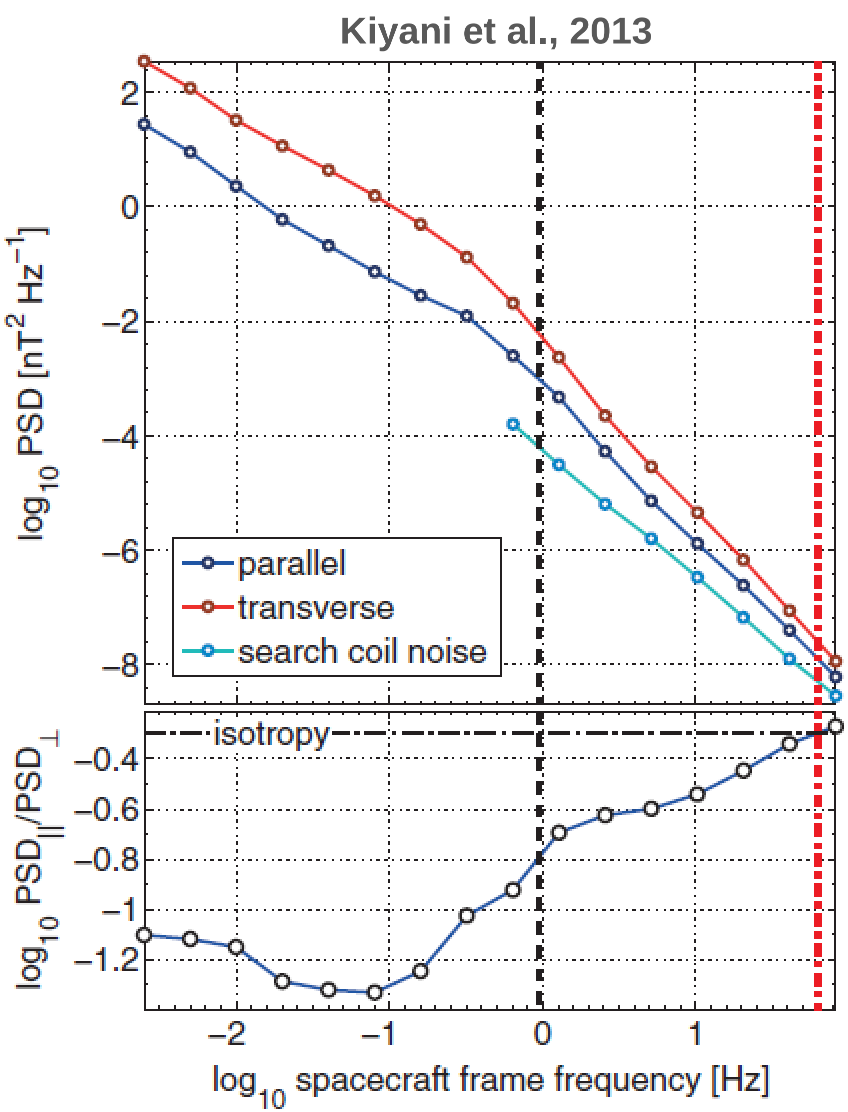
Spectra/11: high-freq anisotropy

And of course spectra are anisotropic at kinetic scales

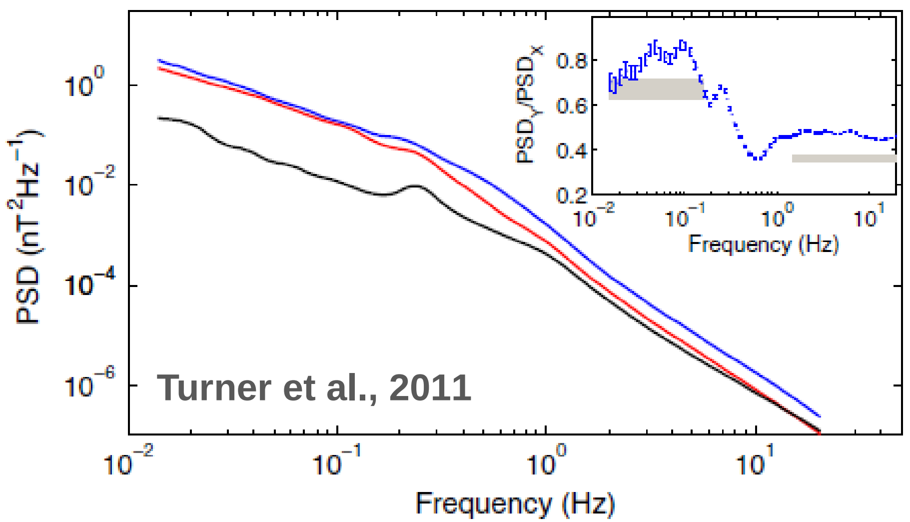


Chen et al. 2010 PRL

Spectra/(n-1): compressive



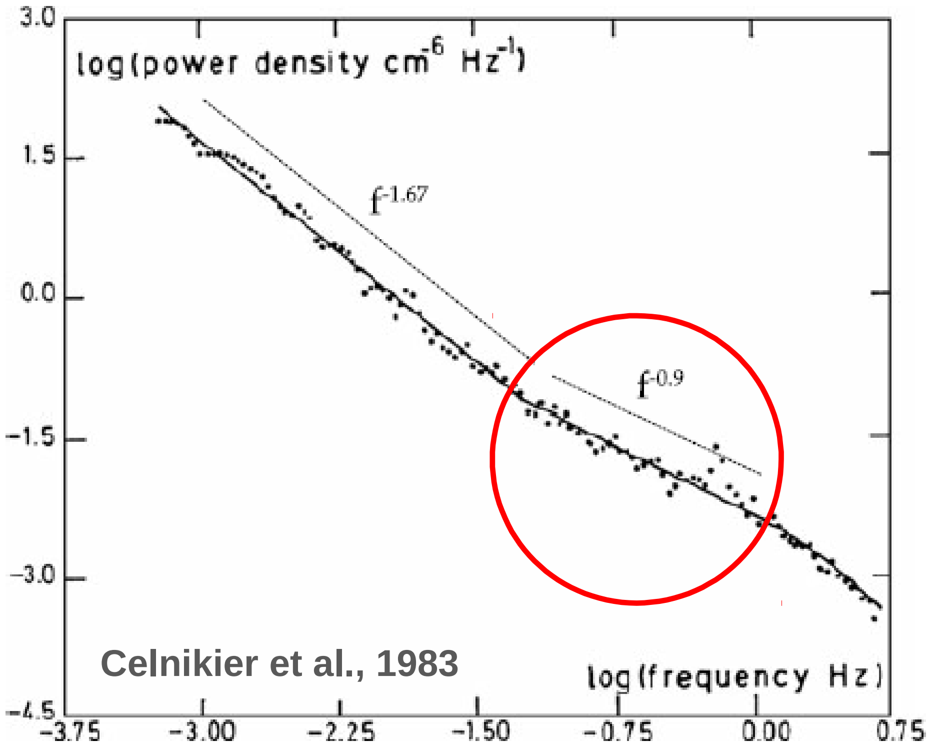
Consistently with several models, magnetic fluctuations become more compressible at small scales. Typical relative power in $\delta B_{||}$ increases from 5% to 30% [**Salem et al., 2012**].



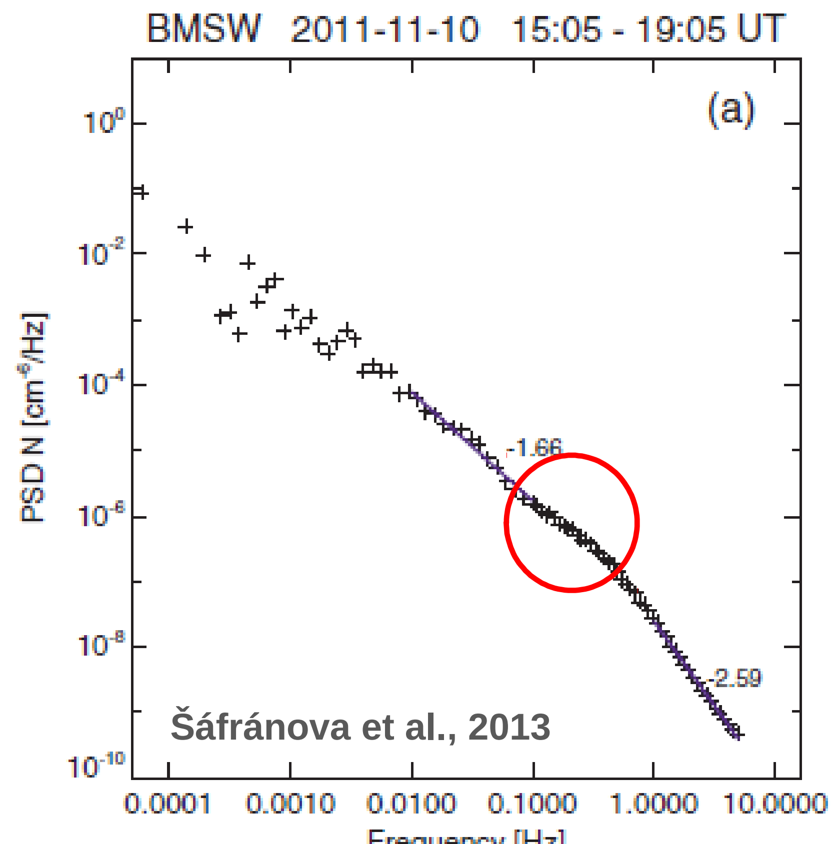
Spectra/(n): density

Density fluctuations are enhanced (shallower spectra) in the transition range, where compressive magnetic fluctuations also start to enhance.

Electron density

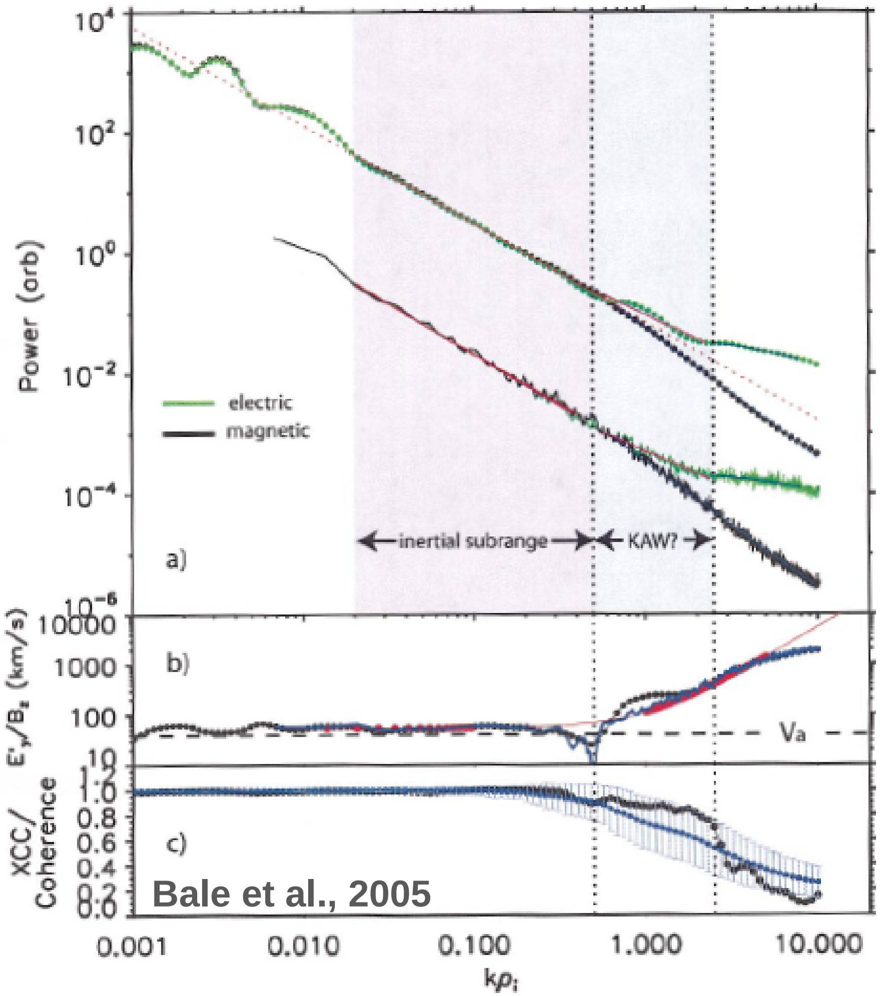


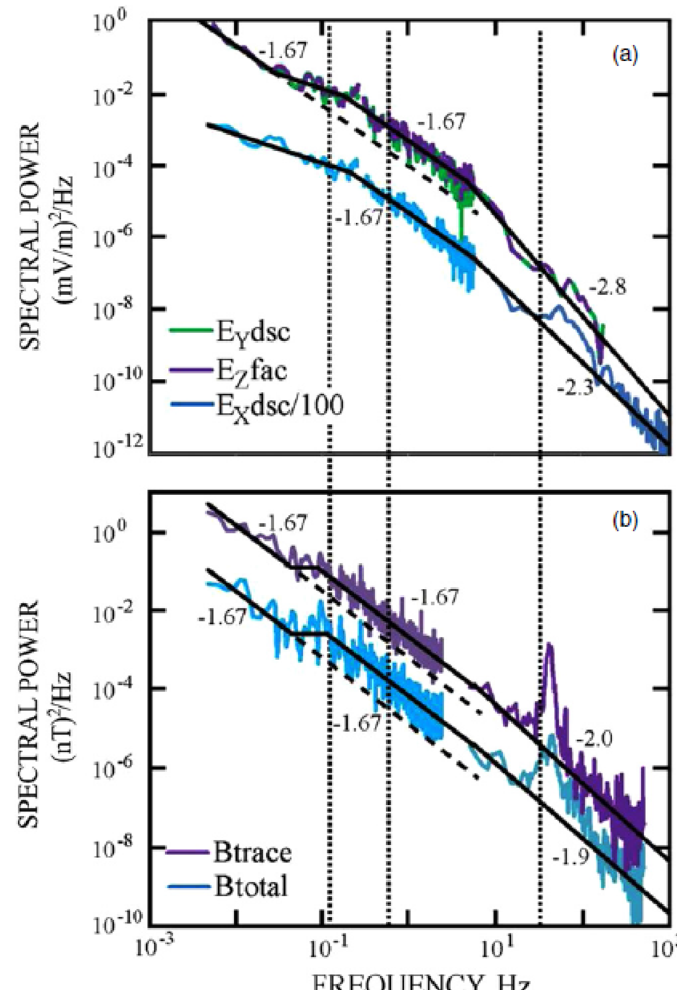
Ion density [Spektr-R]



Spectra/(n+1): electric field

Electric field measurements show a spectral flattening above the ion-scale break, where it decouples from the magnetic field. Parallel electric field also show more power than expected. In the inertial range, it couples to B in the s/c frame, and to velocity in the plasma frame. At small sales: faster decay.

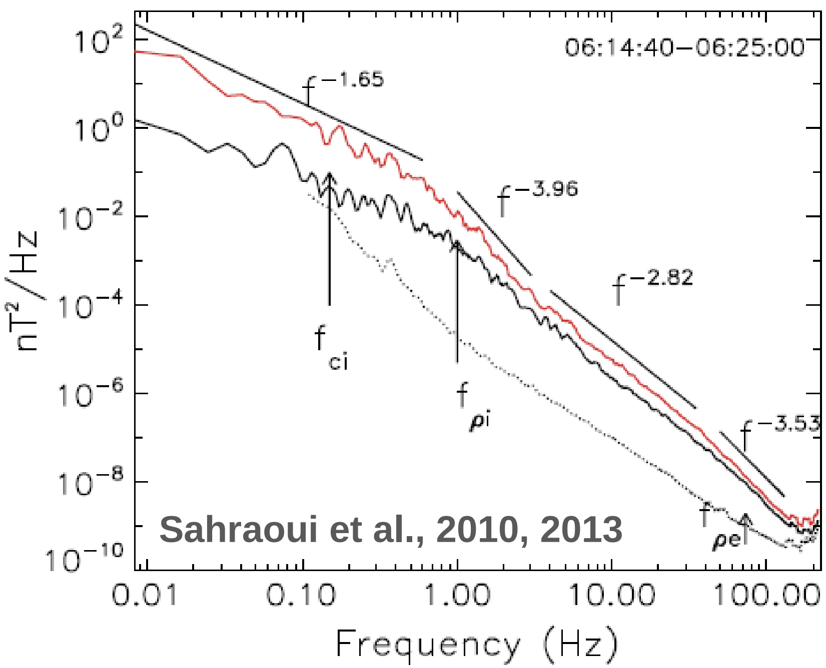


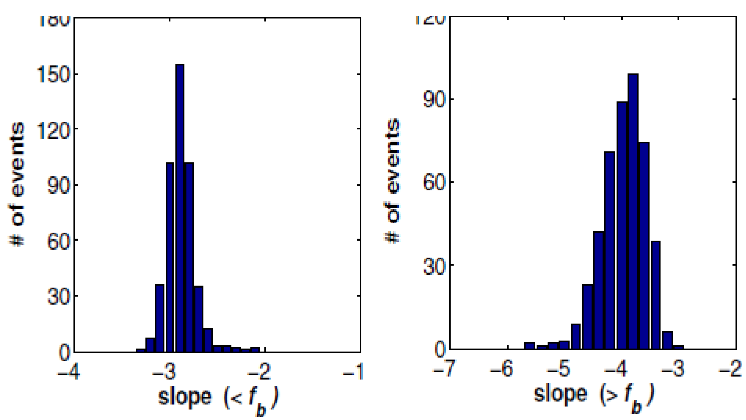


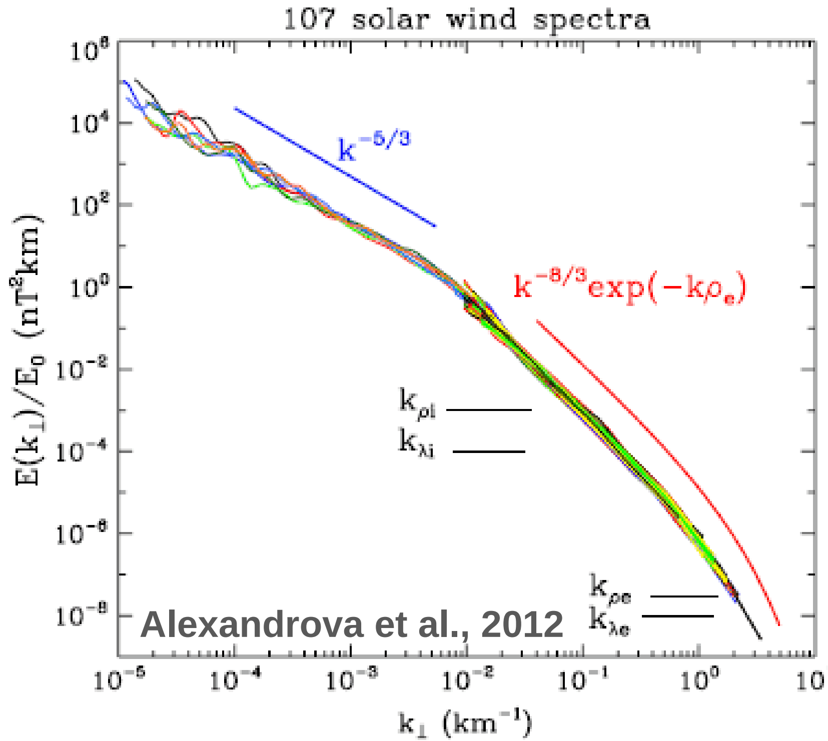
Mozer & Chen, 2013

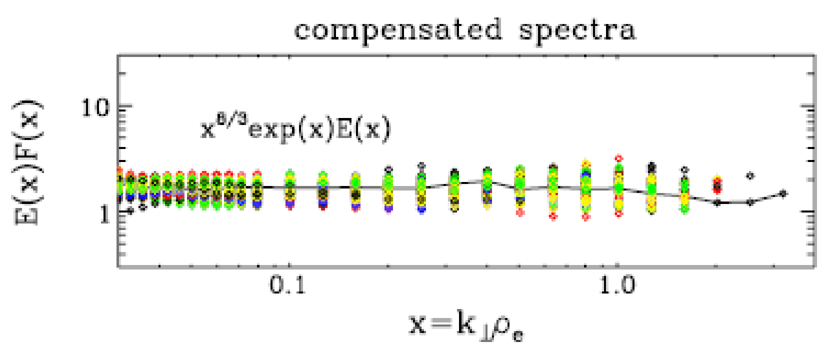
Spectra/∞: electron scale

A second break occurs at electron scales. The spectral shape after the break is debated, but limited data resolution and steep decrease don't allow an answer.



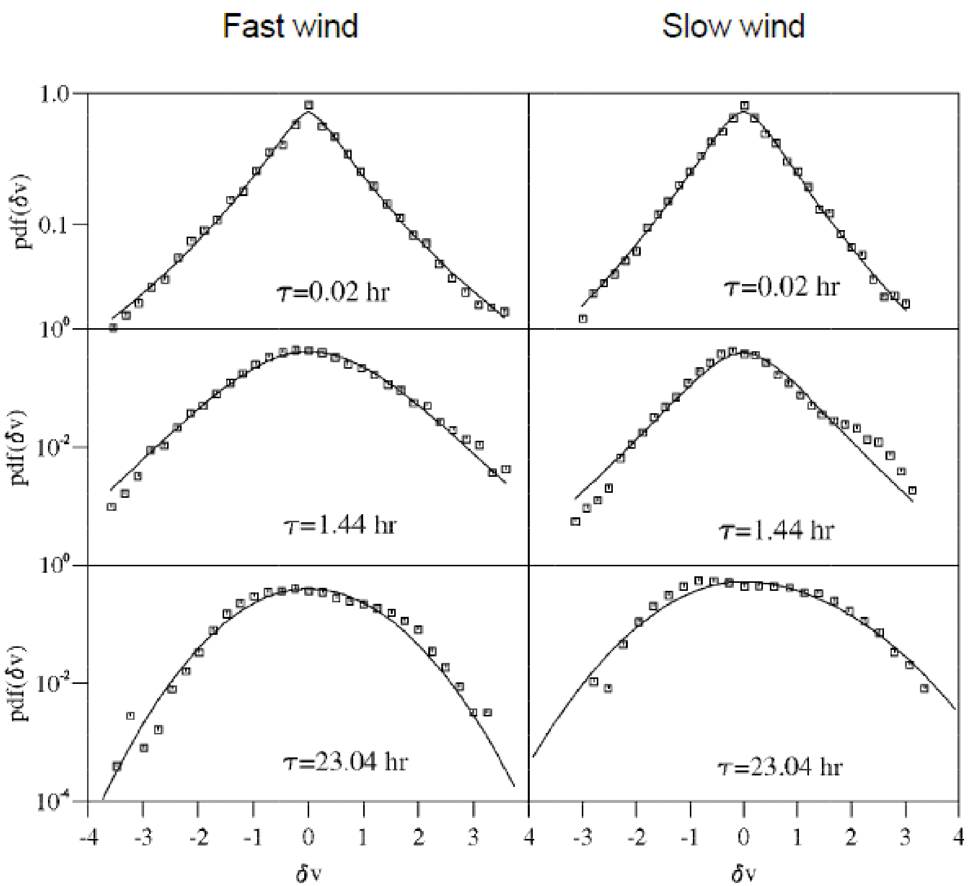




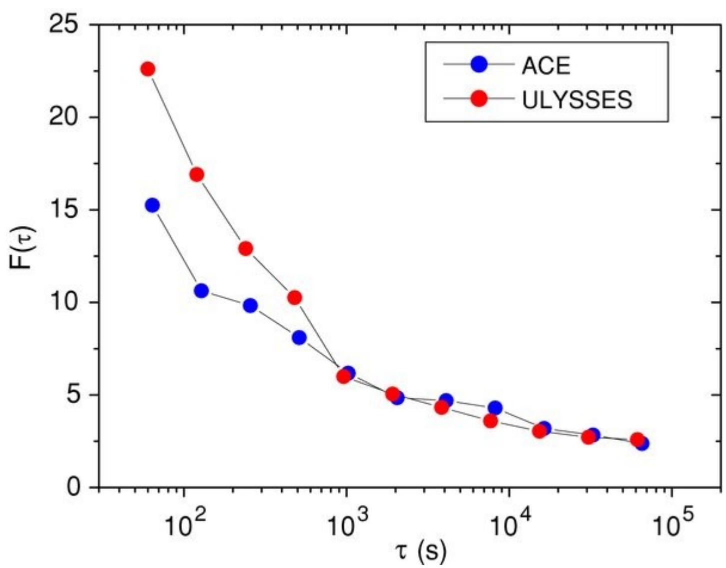


Intermittency

SW turbulence is highly intermittent:
energy is transferred on concentrated small scale structures.



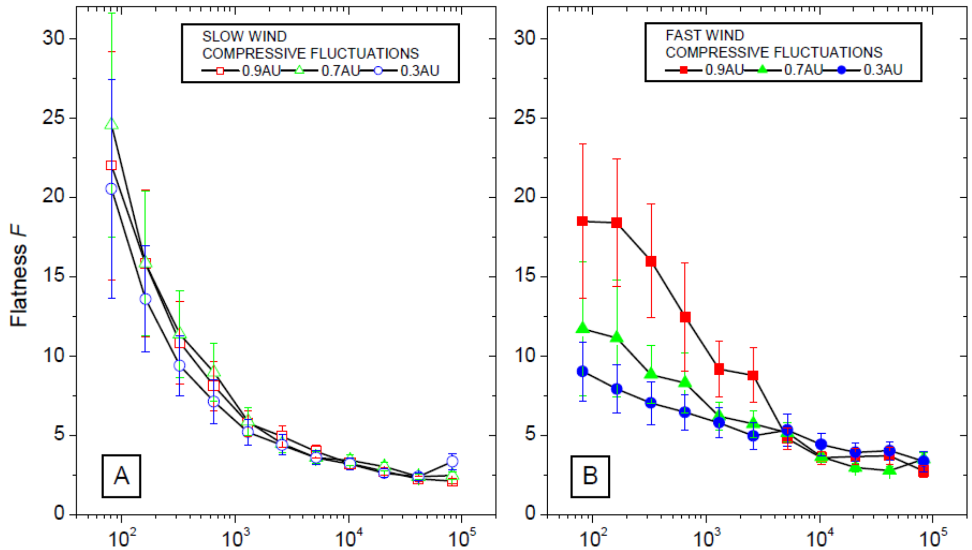
- Generation of small scale structures
- Depends on SW speed, radial distance, solar activity, and more generally on SW conditions.
- Good agreement with multifractal models for intermittent turbulence



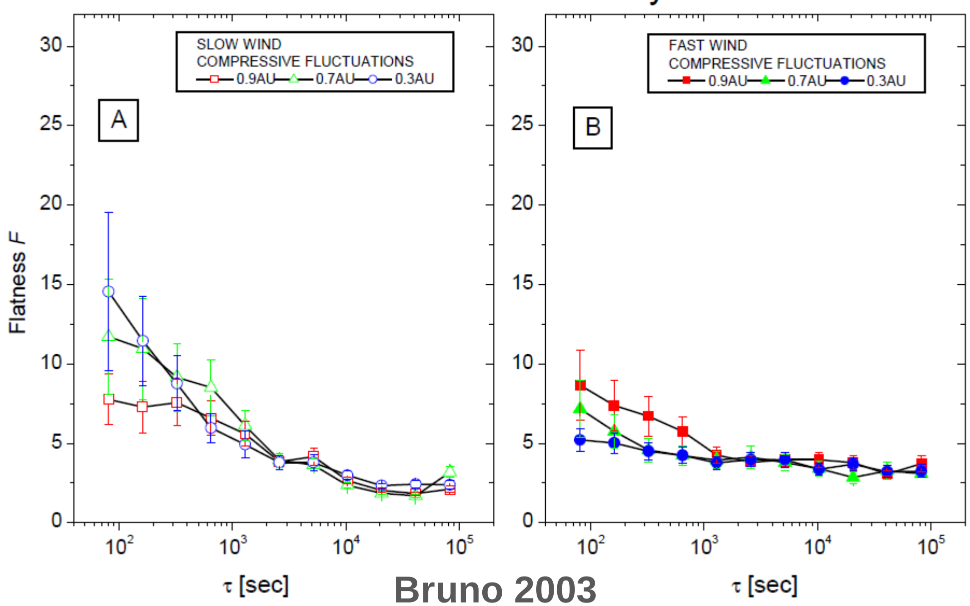
Burlaga 1991; Marsch & Tu 1994; Carbone 1996; Horbury 1998; Sorriso-Valvo 1999, 2000; …

Intermittency/2: radial evolution

Interplanetary Magnetic Field



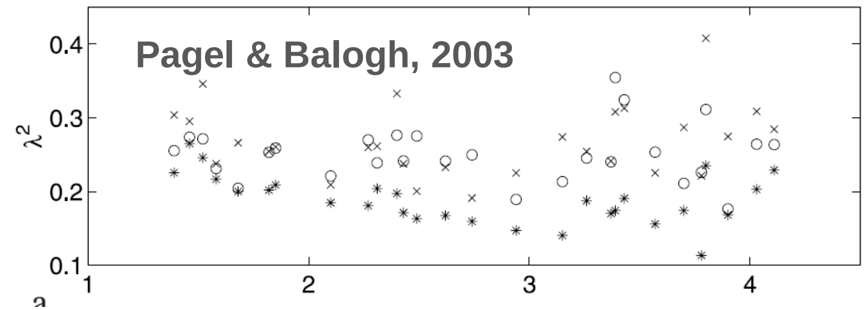
Solar Wind Velocity



Bruno 2003

PDF fitting parameter, related with the kurtosis

λ^2 and σ_0^2 at τ=T

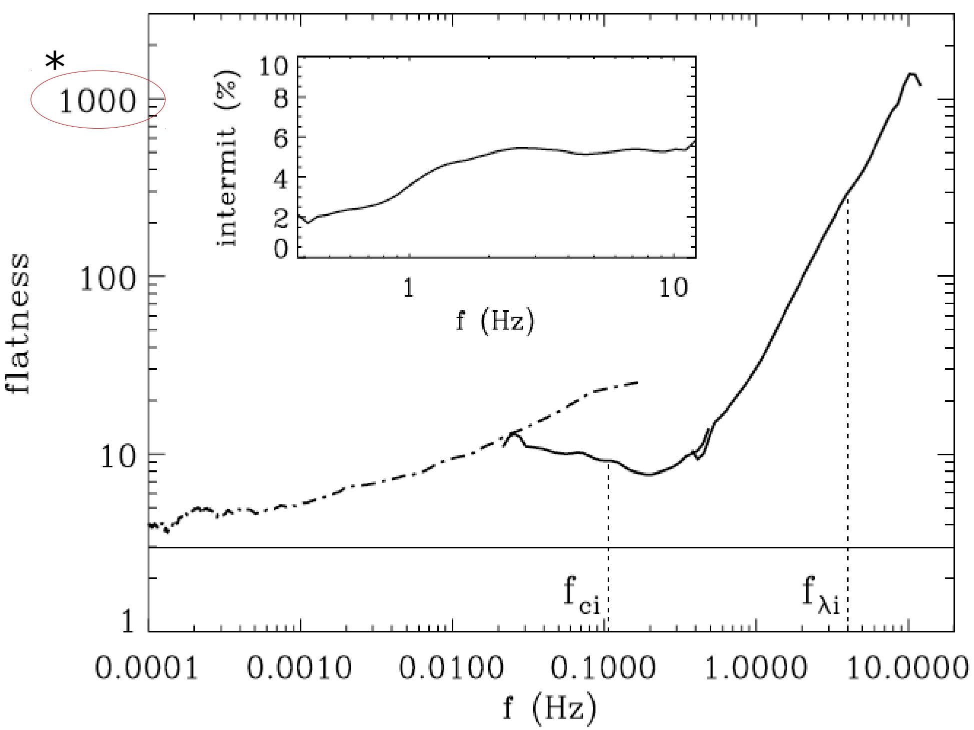


Radial increase of intermittency may be the result of developing turbulence, or decrease of uncorrelated (Alfvénic) fluctuations (in fast wind).

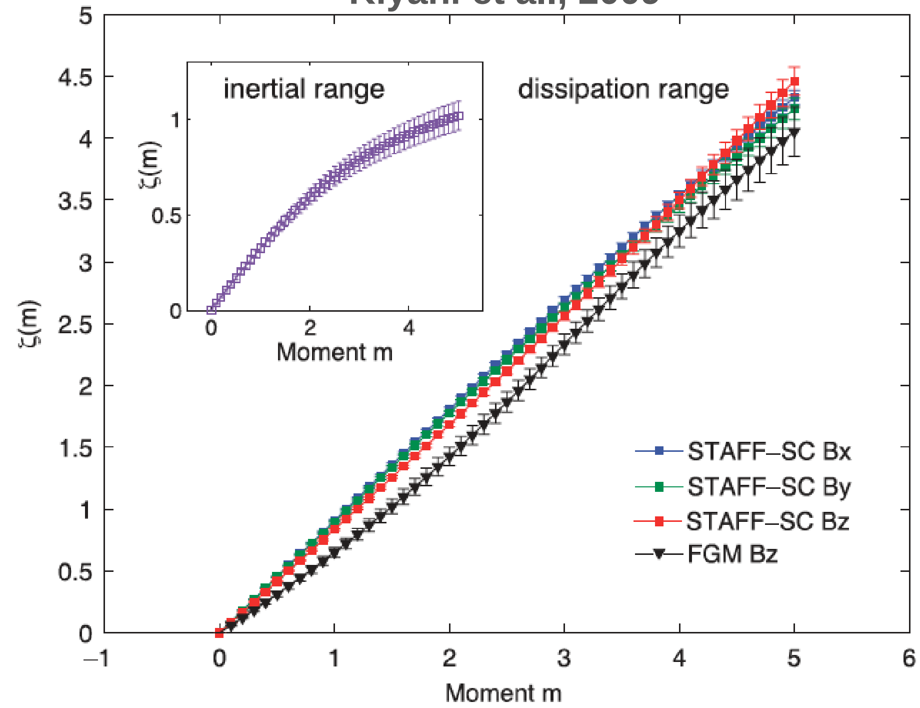
Intermittency/3: small scale

Intermittency at high frequency is more variable: some SW samples show increase of Flatness (typically with a small flattening/decrease around the spectral break, suggesting phase re-organization), or linear scaling of the structure functions (no intermittency). It is probably a very local property.

Alexandrova et al., 2008



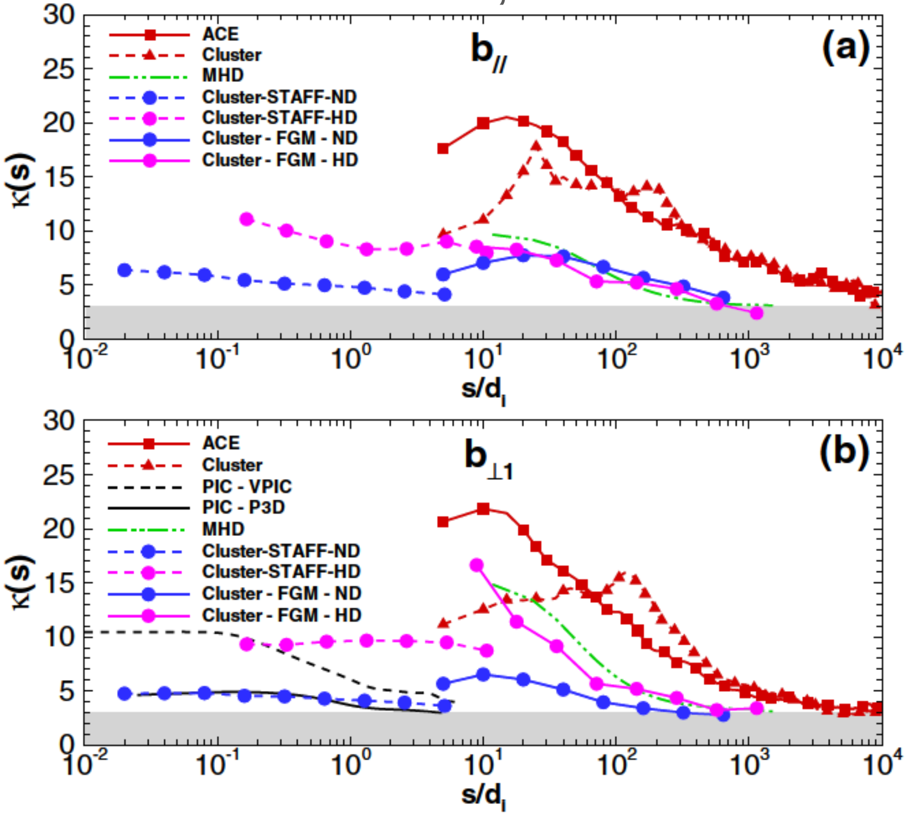
Kiyani et al., 2009



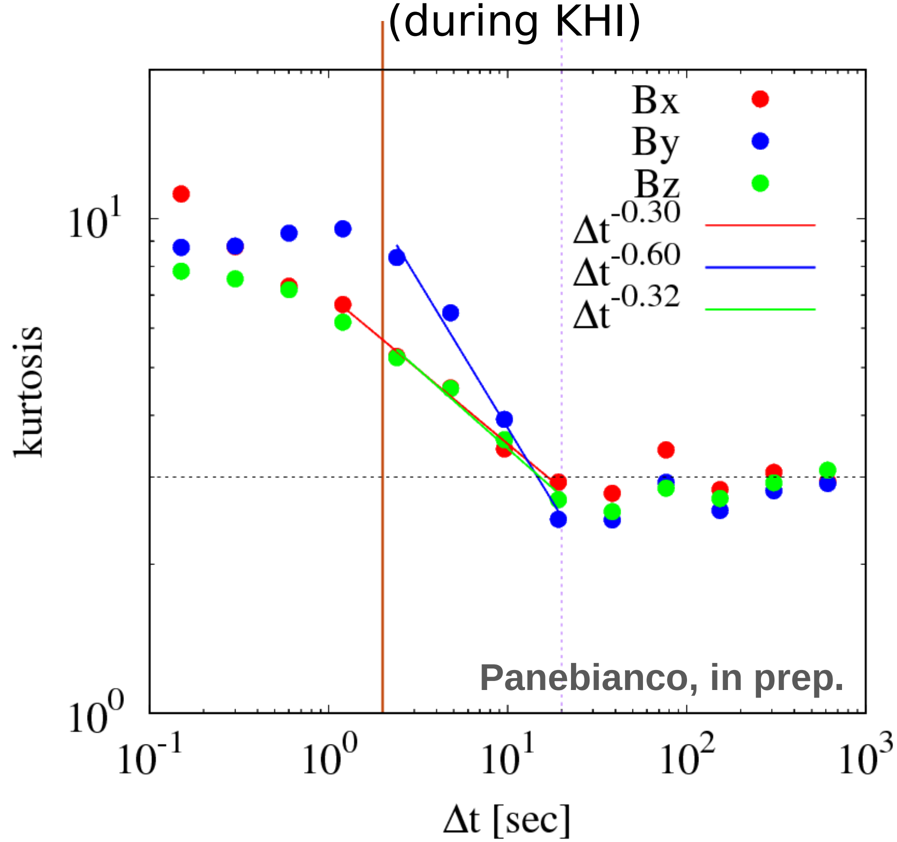
Gives information about the nonlinear character of the high frequency energy cascade, and on formation of smaller scale structures.

Intermittency/4: small scale

Wu et al., 2013



MMS magnetic field data
in the magnetosheath
(during KHI)



Intermittency/5: structures

Intermittency highlights the enhanced presence of small scale magnetic structures in solar wind turbulence. These structures have been described and studied in several works **[Tsurutani & Smith, 1979; Tu & Marsch, 1995]**.

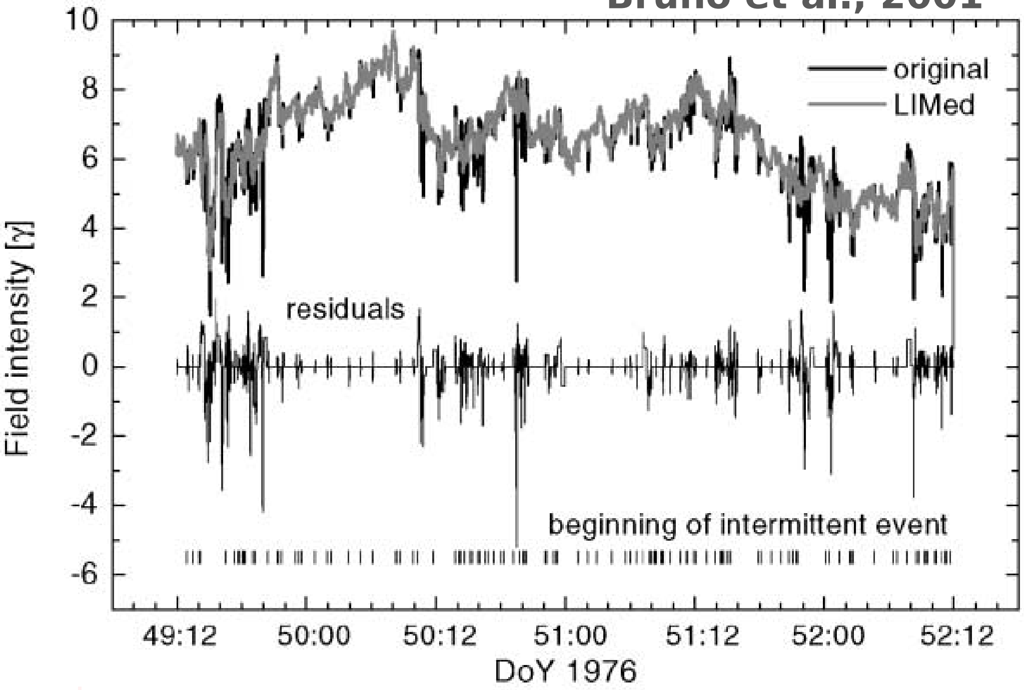
Detection techniques are based on **wavelet** power threshold (e.g. the Local Intermittency Measure)

[Veltri & Mangeney 1999; Bruno 2001]

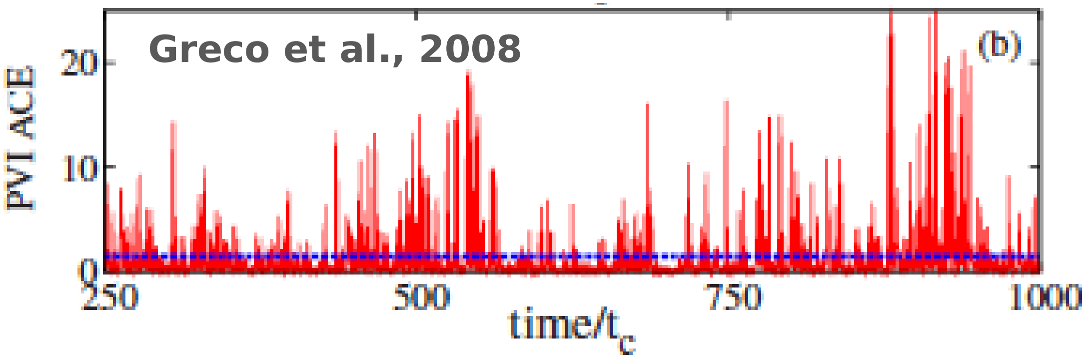
or **variance** threshold (PVI)

[Greco 2008; Greco & Perri, 2014].

Bruno et al., 2001



$$\mathrm{PVI}_{\Delta t,t} = \frac{|\Delta \mathbf{B}(t,\Delta t)|^2}{\langle |\Delta \mathbf{B}(t,\Delta t)|^2 \rangle},$$

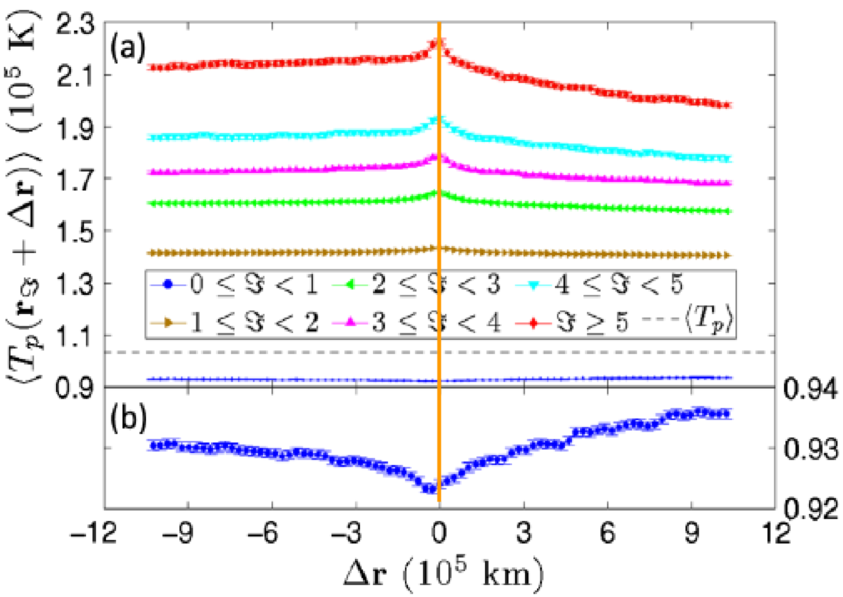


$$\mathrm{LIM}_{\Delta t,t} = \frac{|\tilde{b}_{\Delta t,t}|^2}{\langle |\tilde{b}_{\Delta t,t}|^2 \rangle_t},$$

Heating and acceleration near intermittent structures

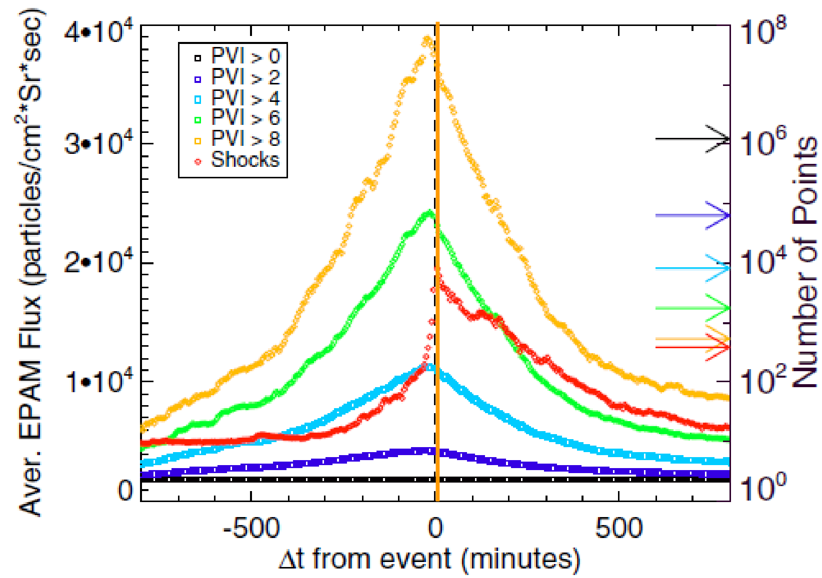
Enhanced heating near PVI structures

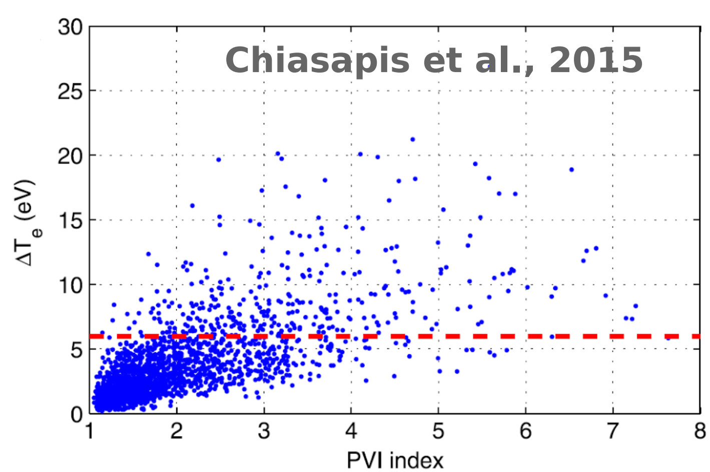
[Osman et al., 2012]



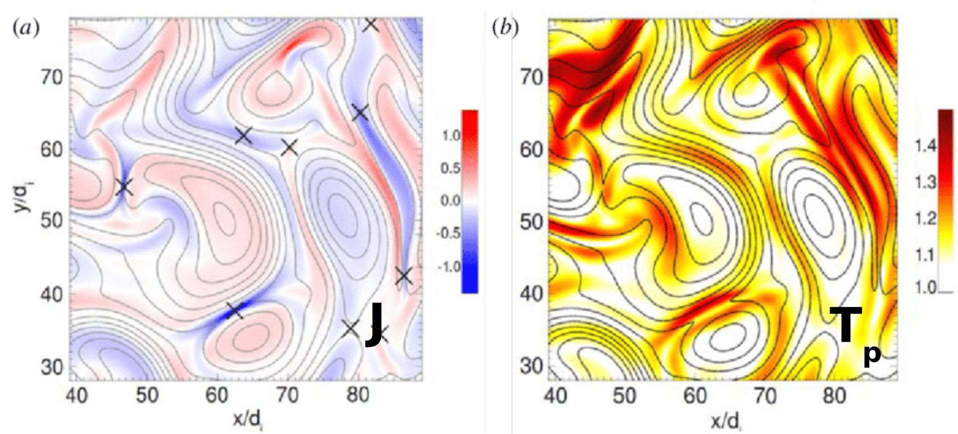
Enhanced SEP near PVI structures

[Tessein et al., 2013]





Servidio et al., 2012



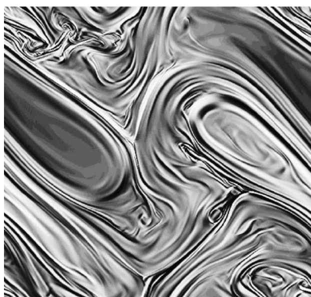
Third-order moment scaling law

Fluids - Yaglom law: linear scaling of the 3rd order moment: $\Delta v_l^3 = -4/5\varepsilon l$

MHD - Politano-Pouquet law: linear scaling of the *mixed* 3rd order moment.

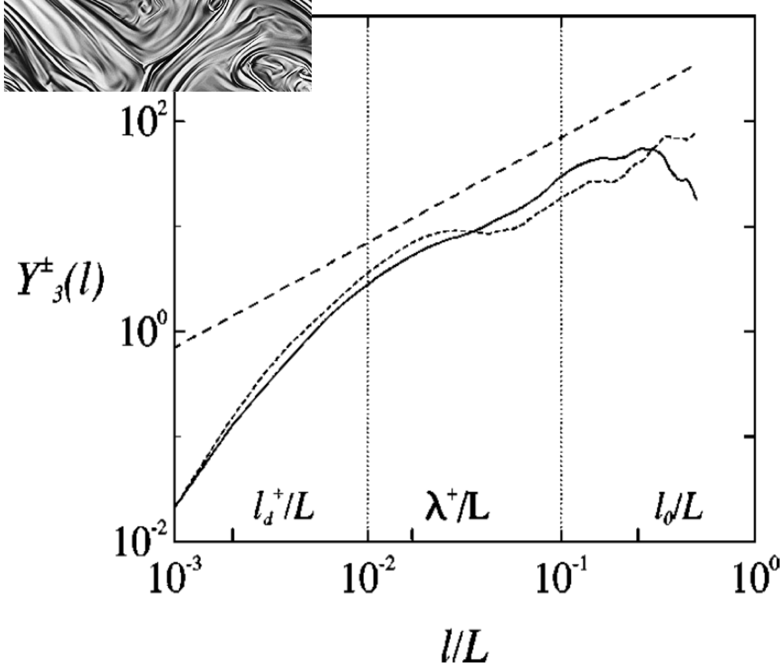
$$Y^{\pm}(\ell) = \langle |\Delta \mathbf{z}^{\pm}(\ell;\mathbf{x})|^2 \Delta z_R^{\mp}(\ell;\mathbf{x}) \rangle = -\frac{4}{3}\varepsilon^{\pm}\ell$$

$$Z^{\pm}(\mathbf{x},t) = \mathbf{v} \pm \frac{\mathbf{B}}{\sqrt{4\pi\rho}}$$



2D-MHD simulations

Sorriso-Valvo et al., 2002



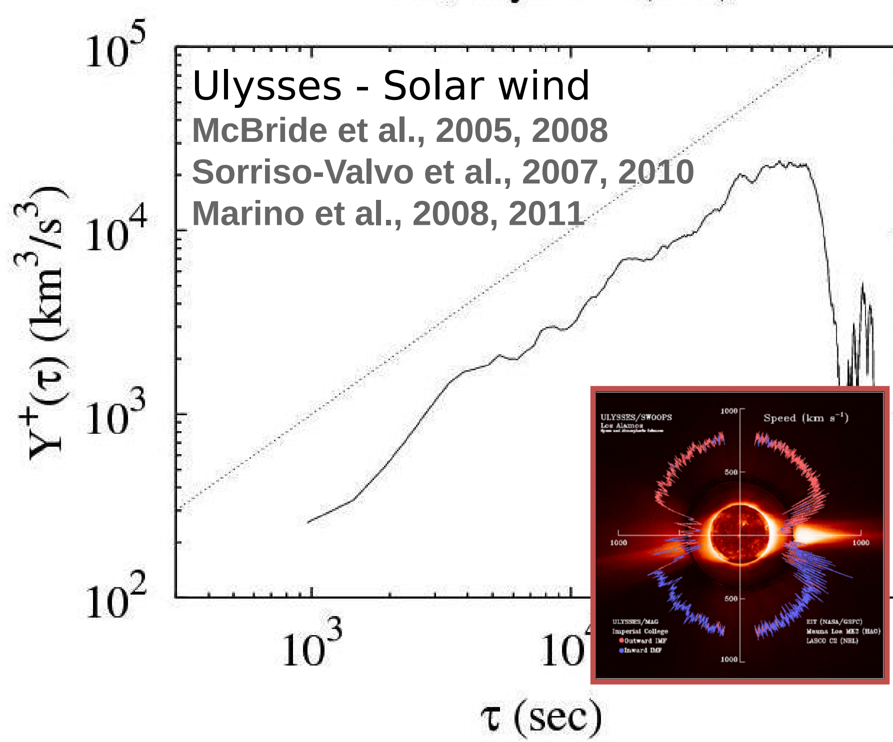
1997, days 1-9 (fast)

Ulysses - Solar wind

McBride et al., 2005, 2008

Sorriso-Valvo et al., 2007, 2010

Marino et al., 2008, 2011



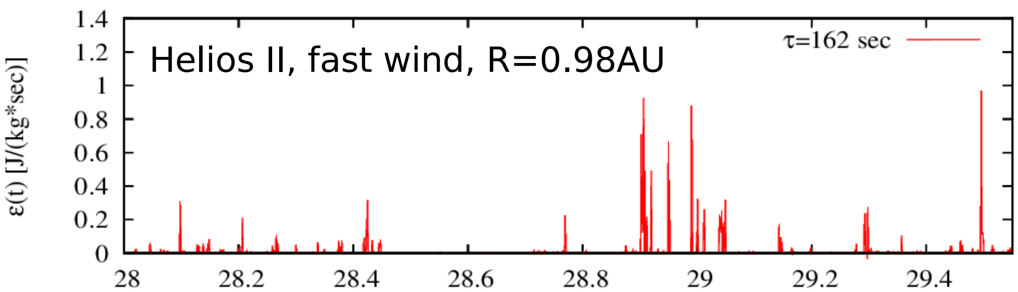
Mean and local energy transfer rate

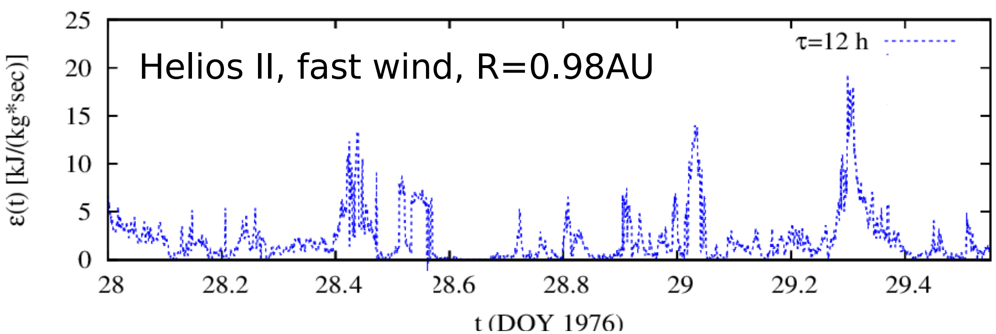
Politano-Pouquet: first measurement of the mean energy transfer rate: $2\varepsilon = \varepsilon^{+} + \varepsilon^{-}$

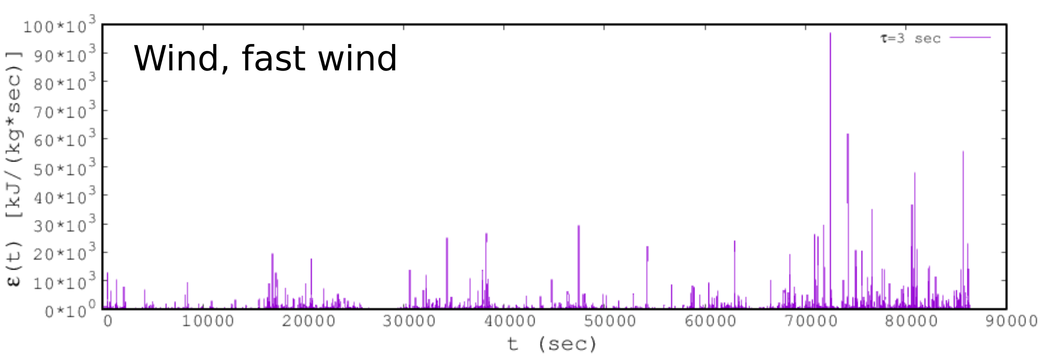
$$Y^{\pm}(\ell) = \langle |\Delta \mathbf{z}^{\pm}(\ell;\mathbf{x})|^2 \Delta z_R^{\mp}(\ell;\mathbf{x}) \rangle = -\frac{4}{3}\varepsilon^{\pm}\ell$$

Taylor hypothesis

$$\boxed{\epsilon_{\tau}^{\pm}(t) = \left| \frac{|\Delta z^{\pm}(t)\,|^2\,\Delta z_R^{\mp}(t)}{\tau\,\langle v \rangle} \right|}$$





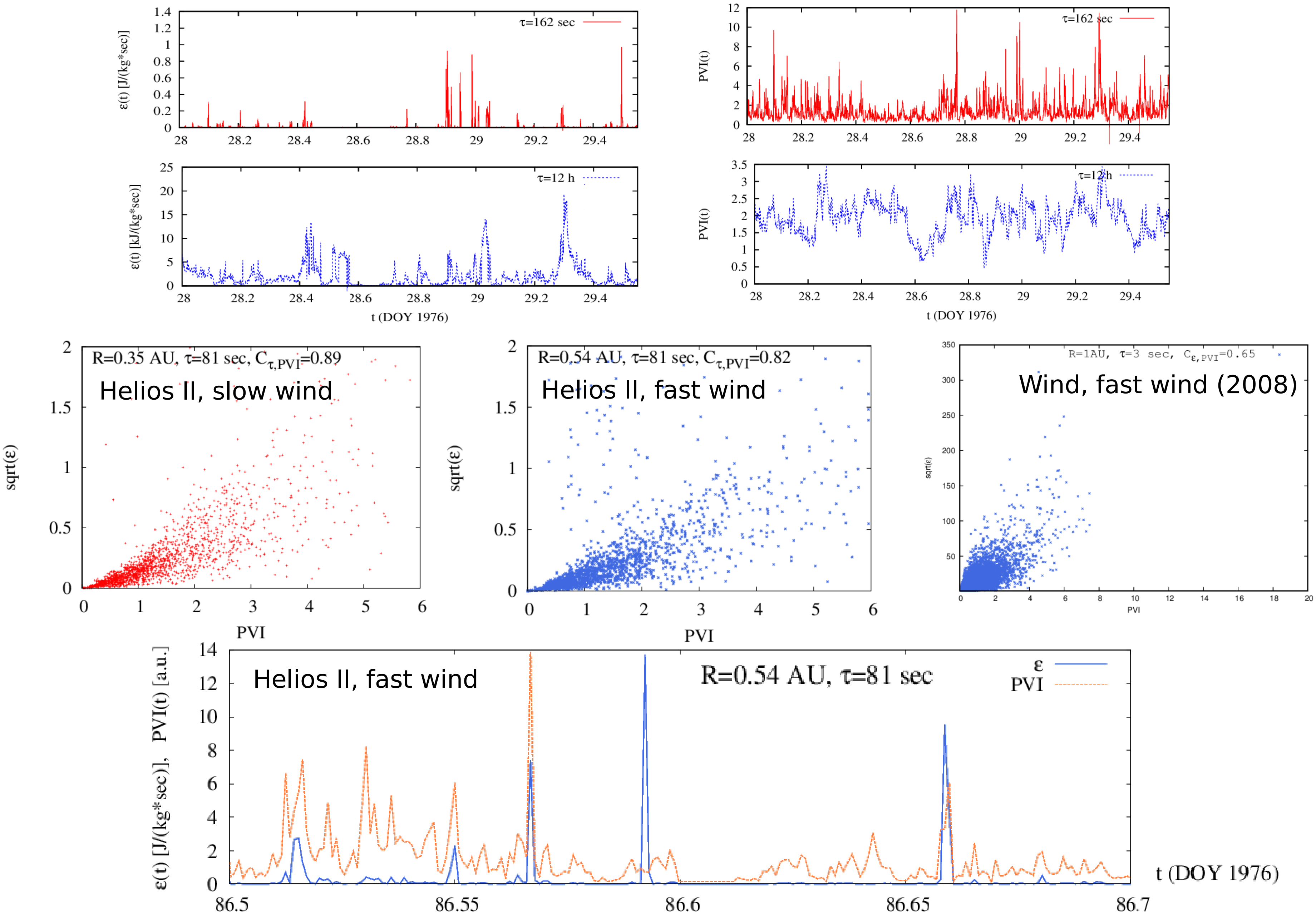


Marsch & Tu, 1997
Sorriso-Valvo et al., 2015

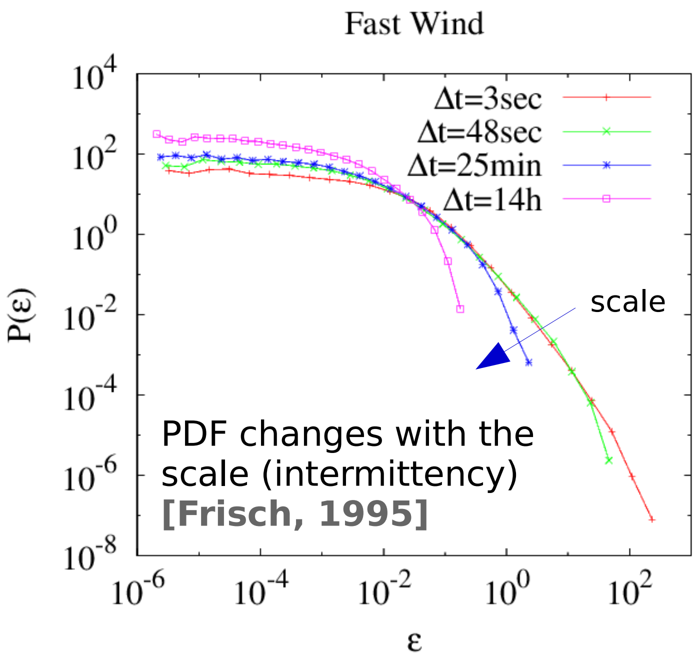
A proxy for the local energy transfer rate

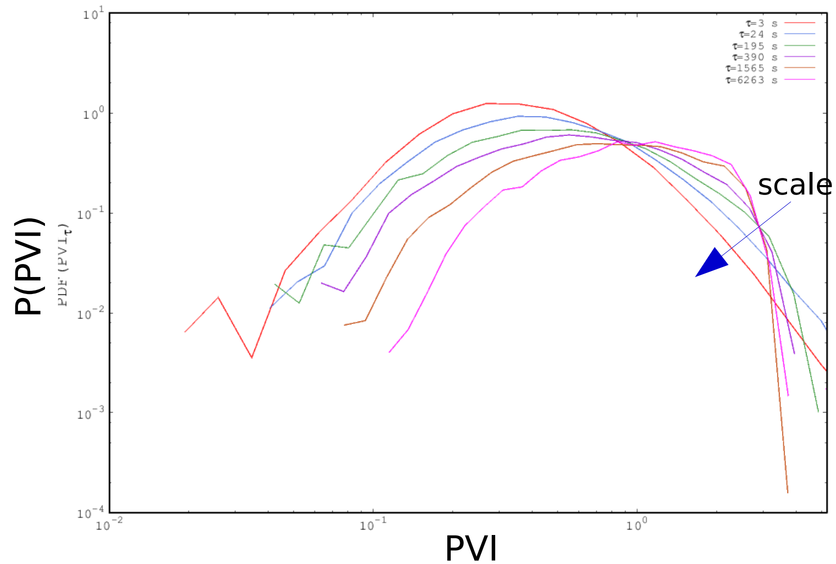
Includes velocity, magnetic field and coupled terms

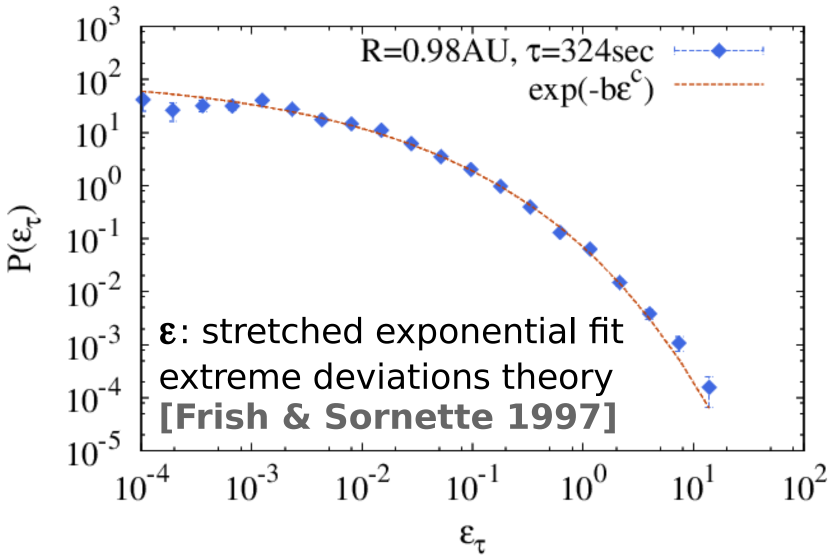
Comparison with PVI: Helios, Wind

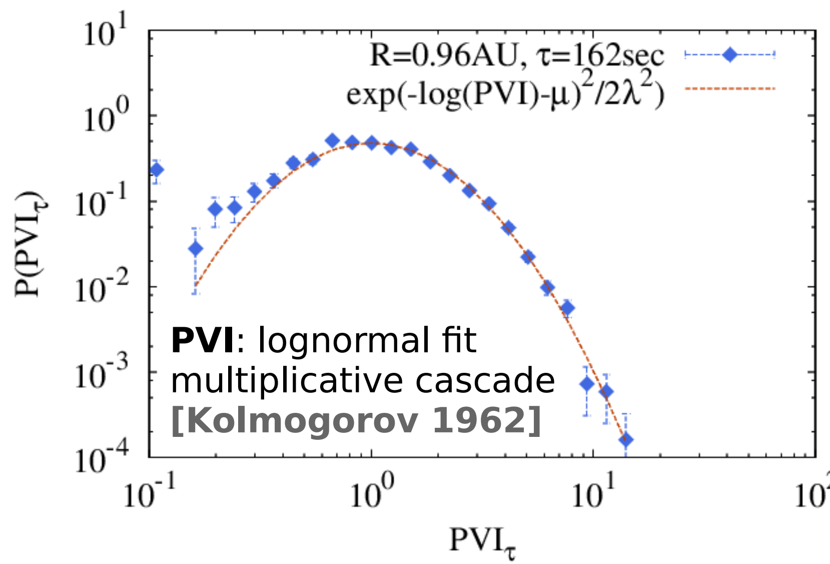


Statistical properties of proxies: PDF



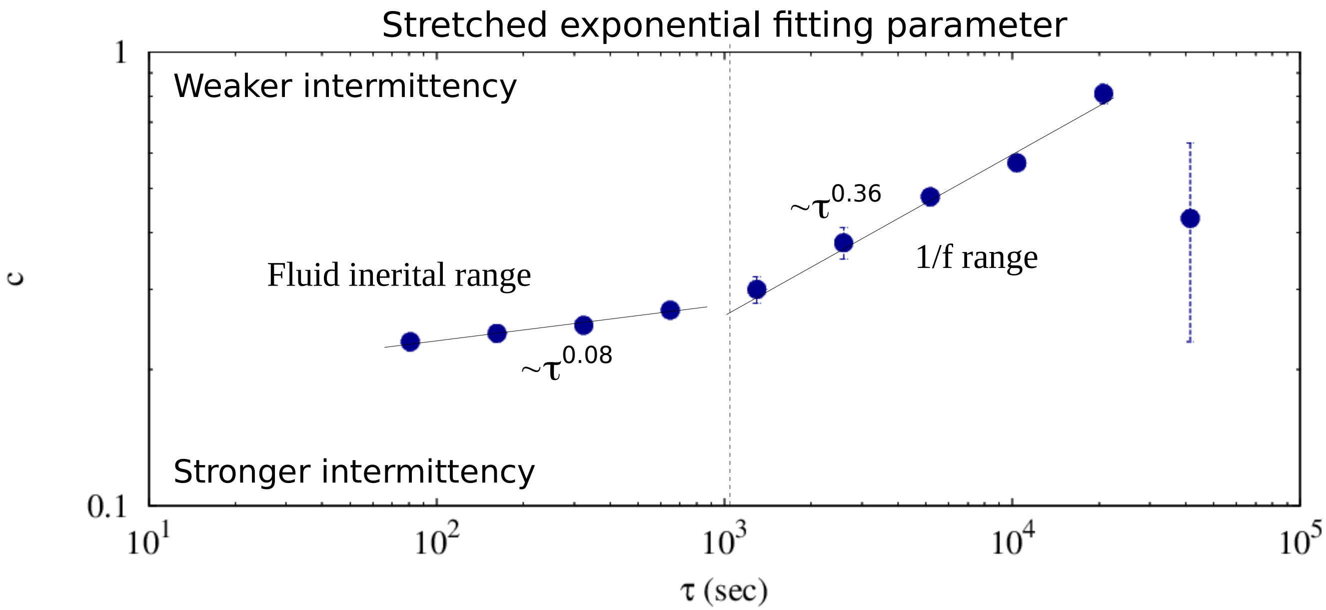






Statistical properties of proxies: scaling

Helios II, fast wind, R=0.98AU



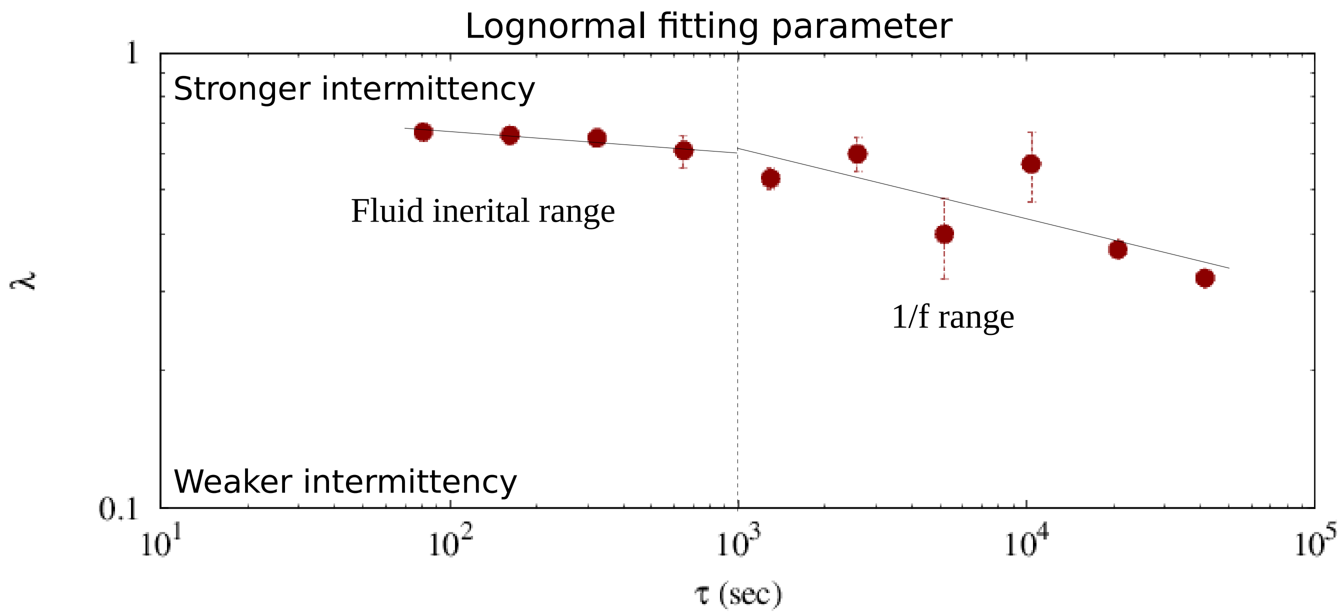
Extreme deviations theory:

scaling exponent ~1/n

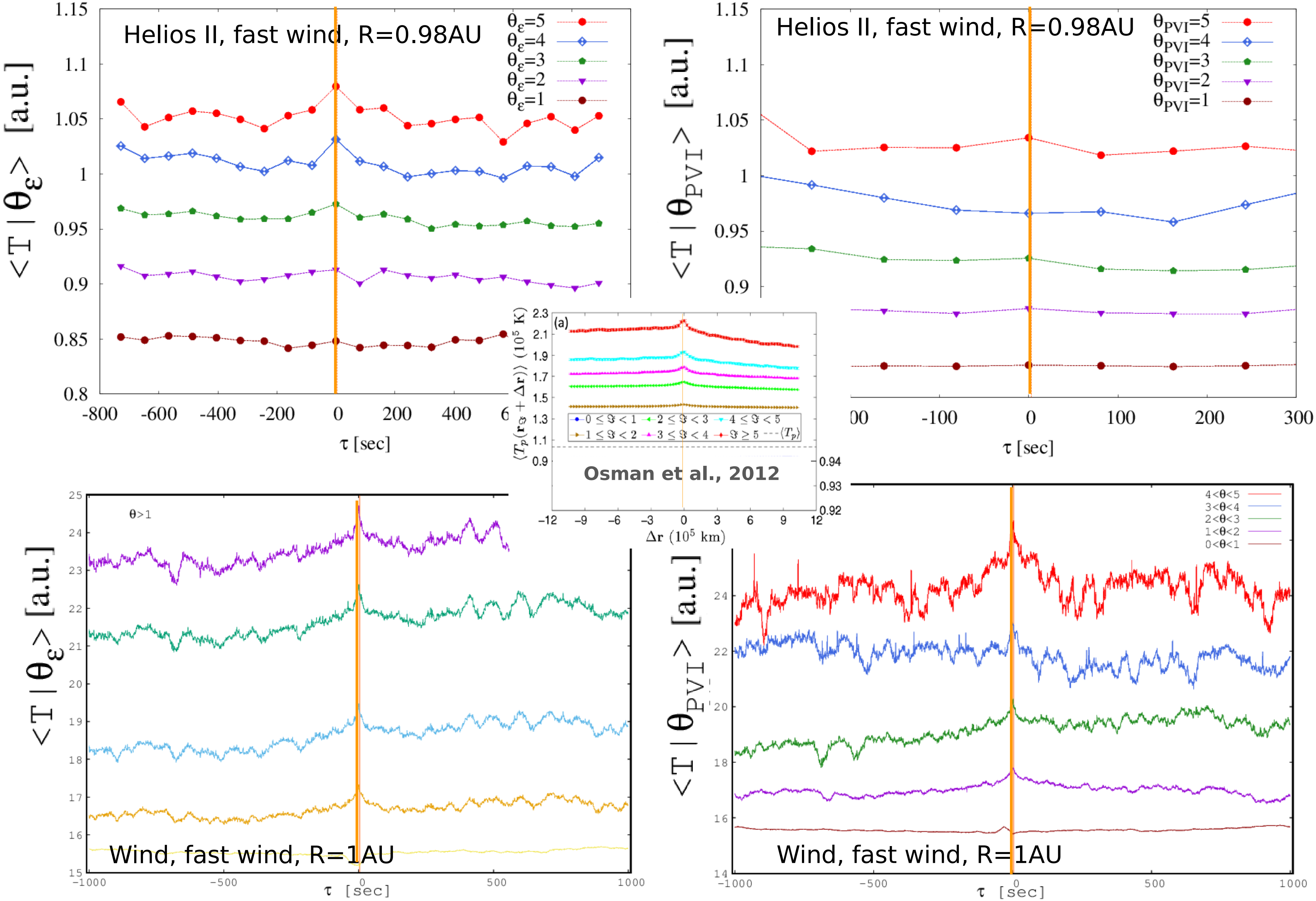
n: number of fragmentations in the cascade.

Inertial range: n~12

1/f range: n~3



Proton heating near ε and PVI structures



Summary/1

- There are many proposed mechanisms for dissipation of plasma turbulence.
  - What is the relative contribution to dissipation by each of these mechanisms?
  - How is dissipated turbulent energy divided between alphas, protons and electrons?
  - Do we need to challenge some assumptions, e.g. universality?

- What is the most appropriate theoretical framework in which to interpret dissipation range fluctuations?
  - We need to investigate the degree of nonlinearity scale-by-scale and compare to inertial range.
  - What are the most relevant wave modes and how do we distinguish between them?

Summary/2

- What are the roles of current sheets, coherent structures and intermittency in dissipation?
  - How are these structures related to magnetic reconnection?
  - What are the origins of these structures?
  - Need a more robust estimate of the relative importance of current sheets and wave modes?

- This field of work is directly relevant to new missions: NASA MMS, DSCOVR, Solar Probe+ and ESA Solar Orbiter.
  - These will help address the role of turbulent reconnection and the radial evolution of turbulence.
  - What does the plasma turbulence community need that these missions do not provide?