Imbalanced turbulence in the solar wind: Observations and Theory

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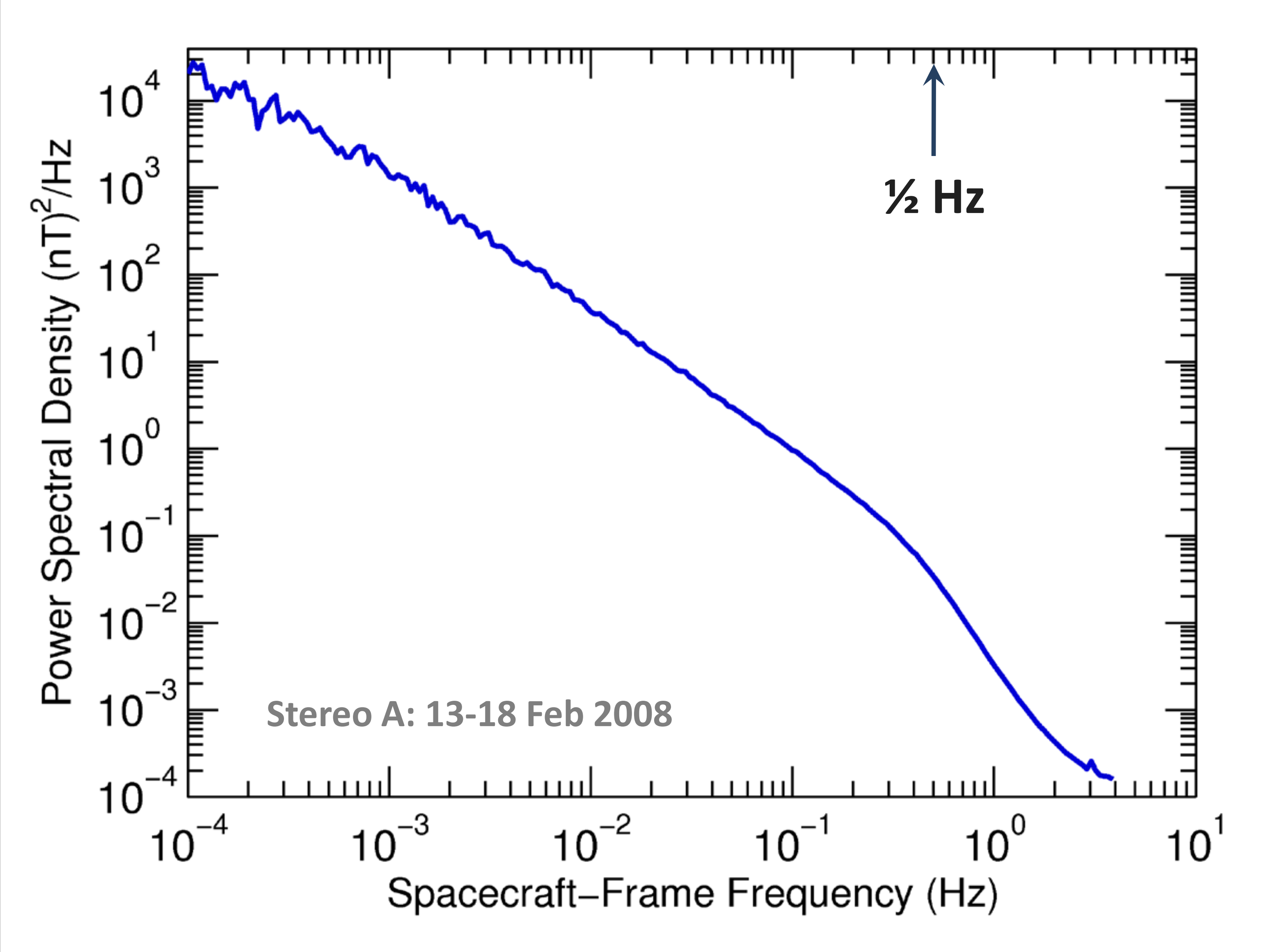
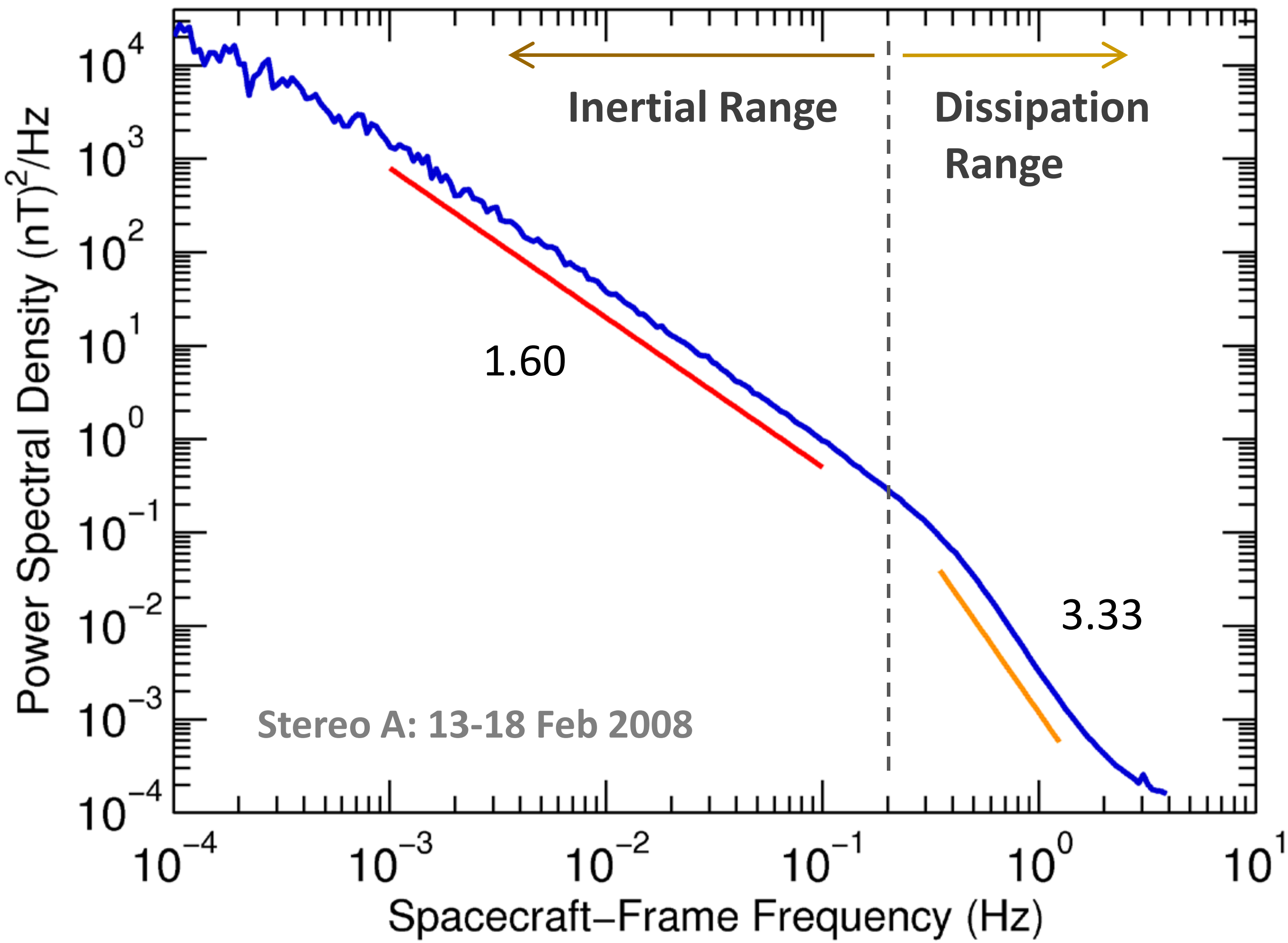
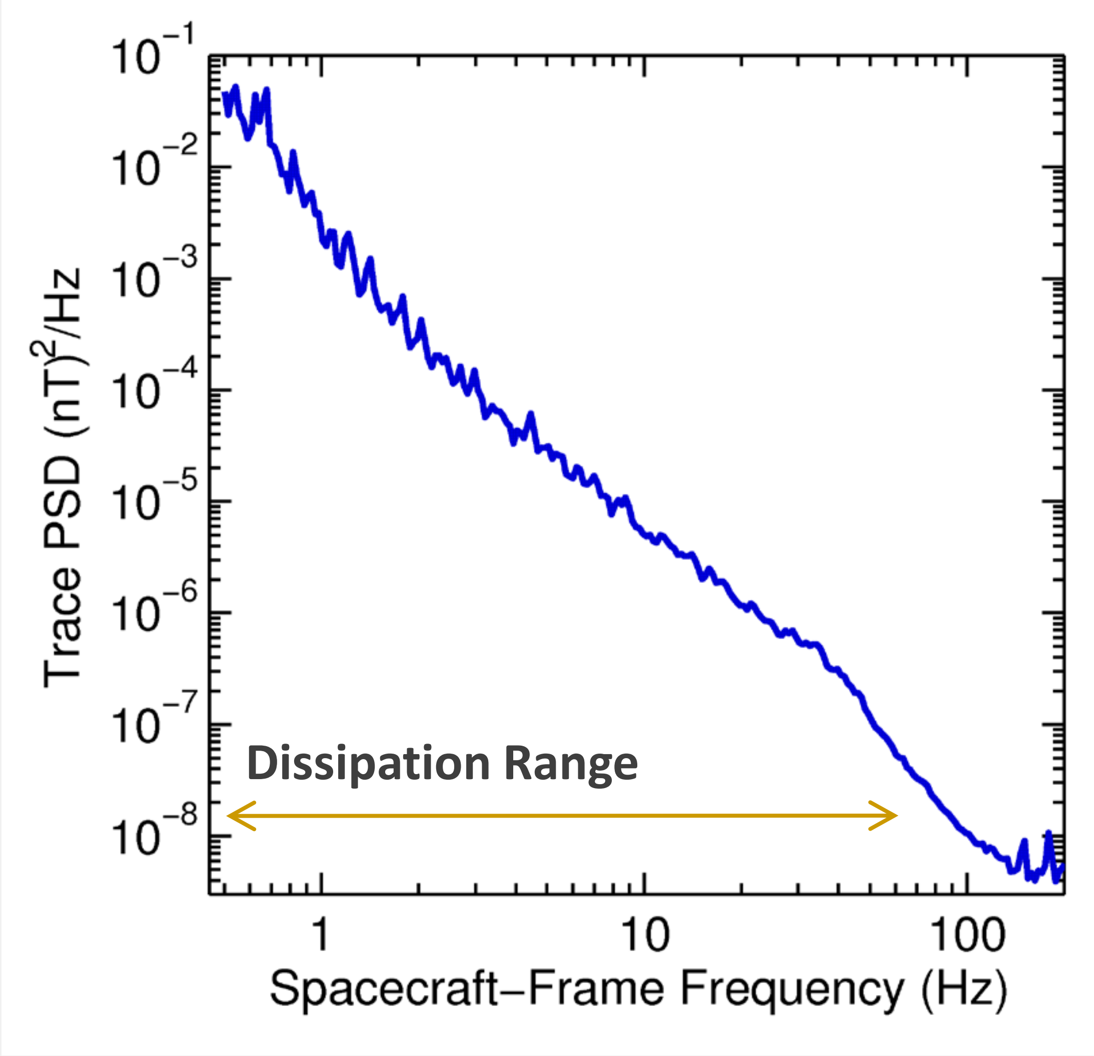
Spectrum of magnetic field fluctuations in the solar wind



Spectrum of magnetic field fluctuations in the solar wind



Cluster search coil magnetometer spectrum



19 Mar 2006

145.6 seconds;

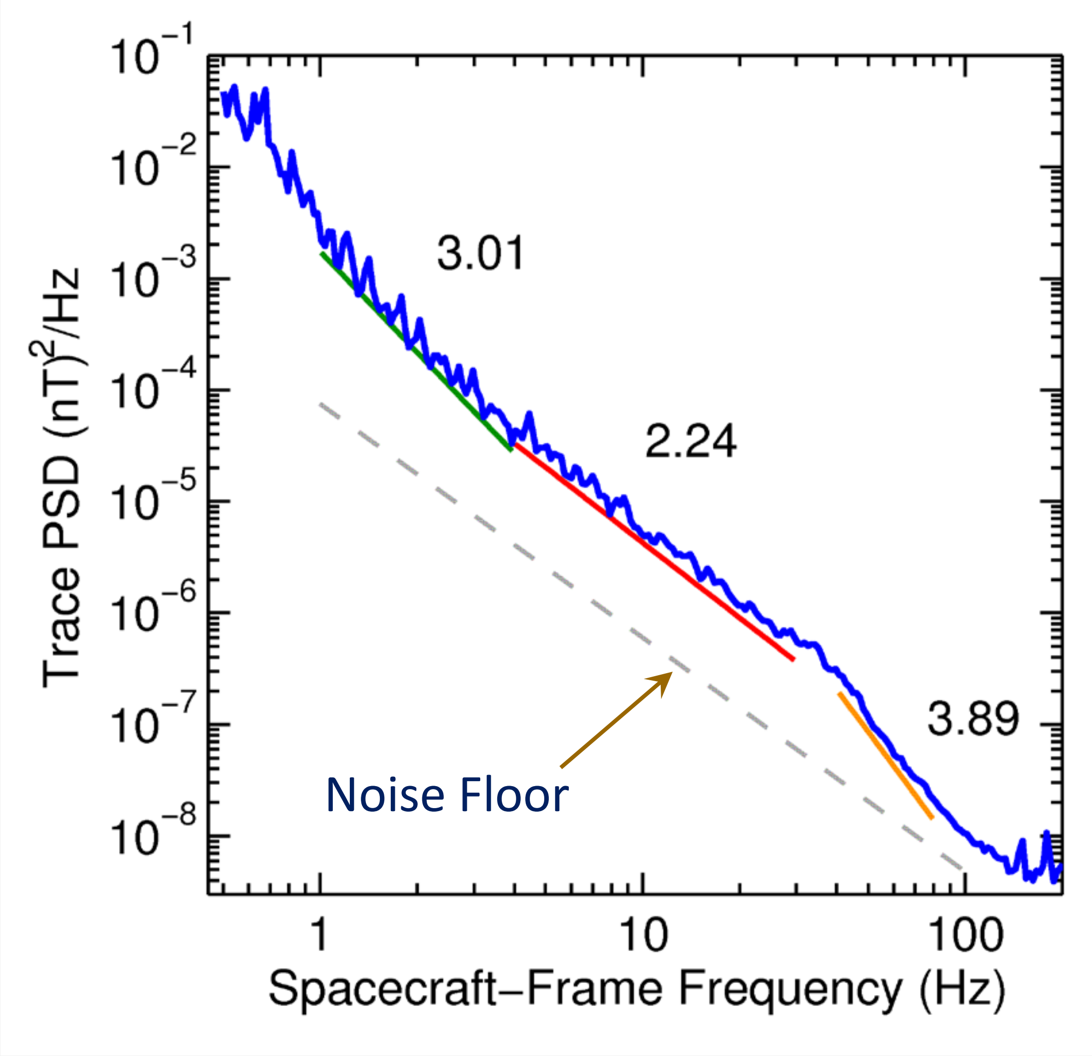
near apogee;

450 Hz burst

mode data.

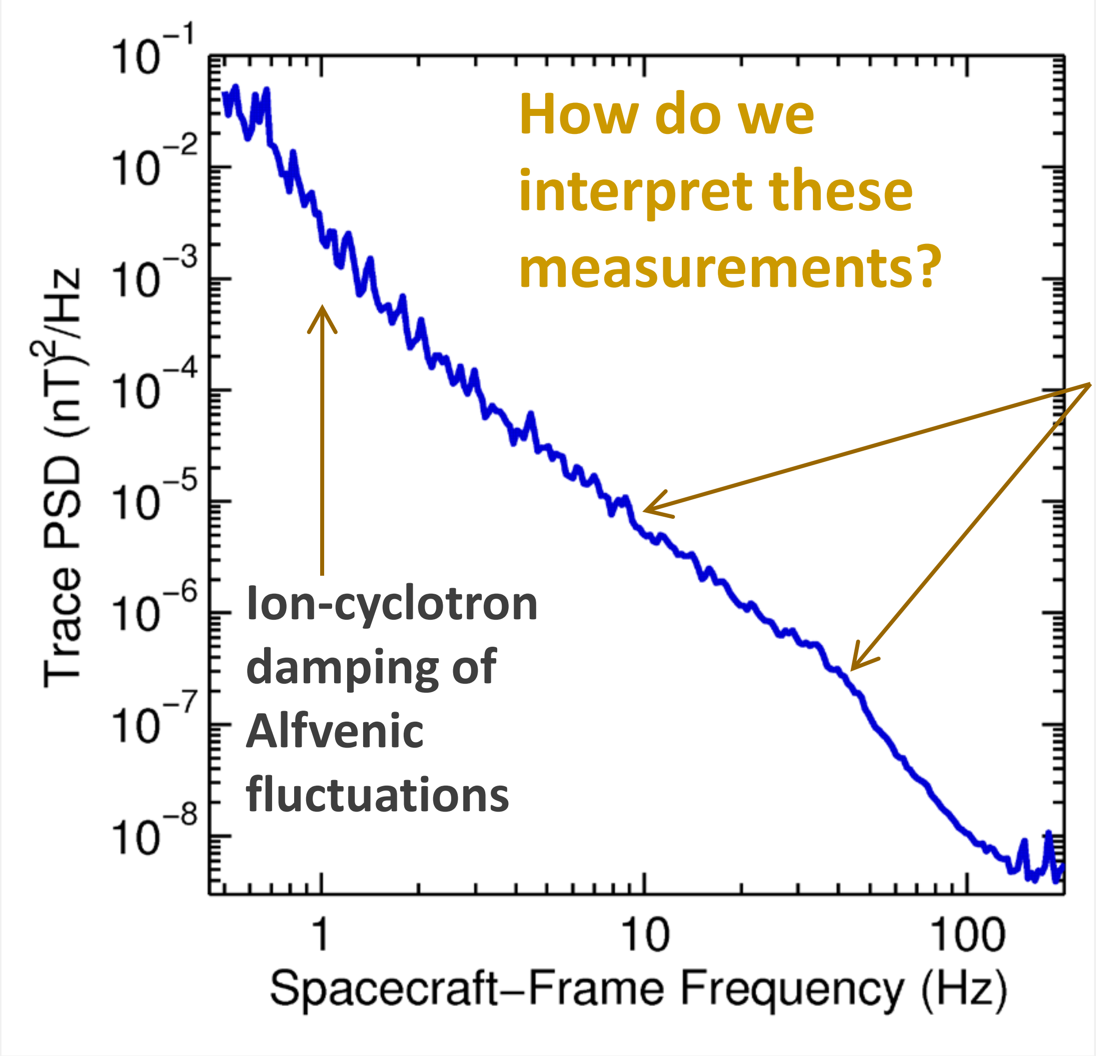
1st reported by Sahraoui et al. PRL 2009.

Cluster search coil spectrum



19 Mar 2006 near apogee; 450 Hz burst mode data; 145.6 second interval.

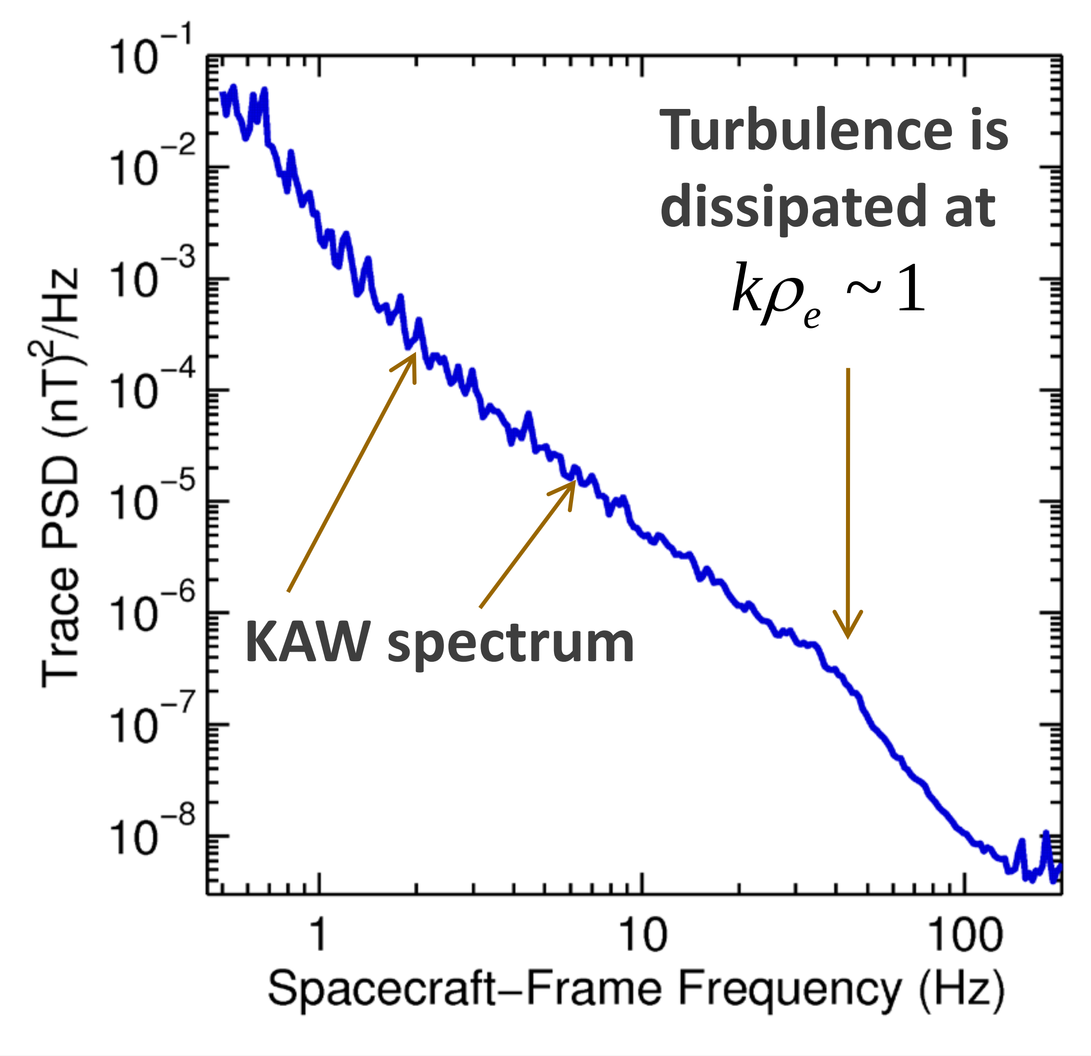
Cluster search coil spectrum



Denskat, Beinroth, & Neubauer (1983)
–IC damping
–Whistler spectrum

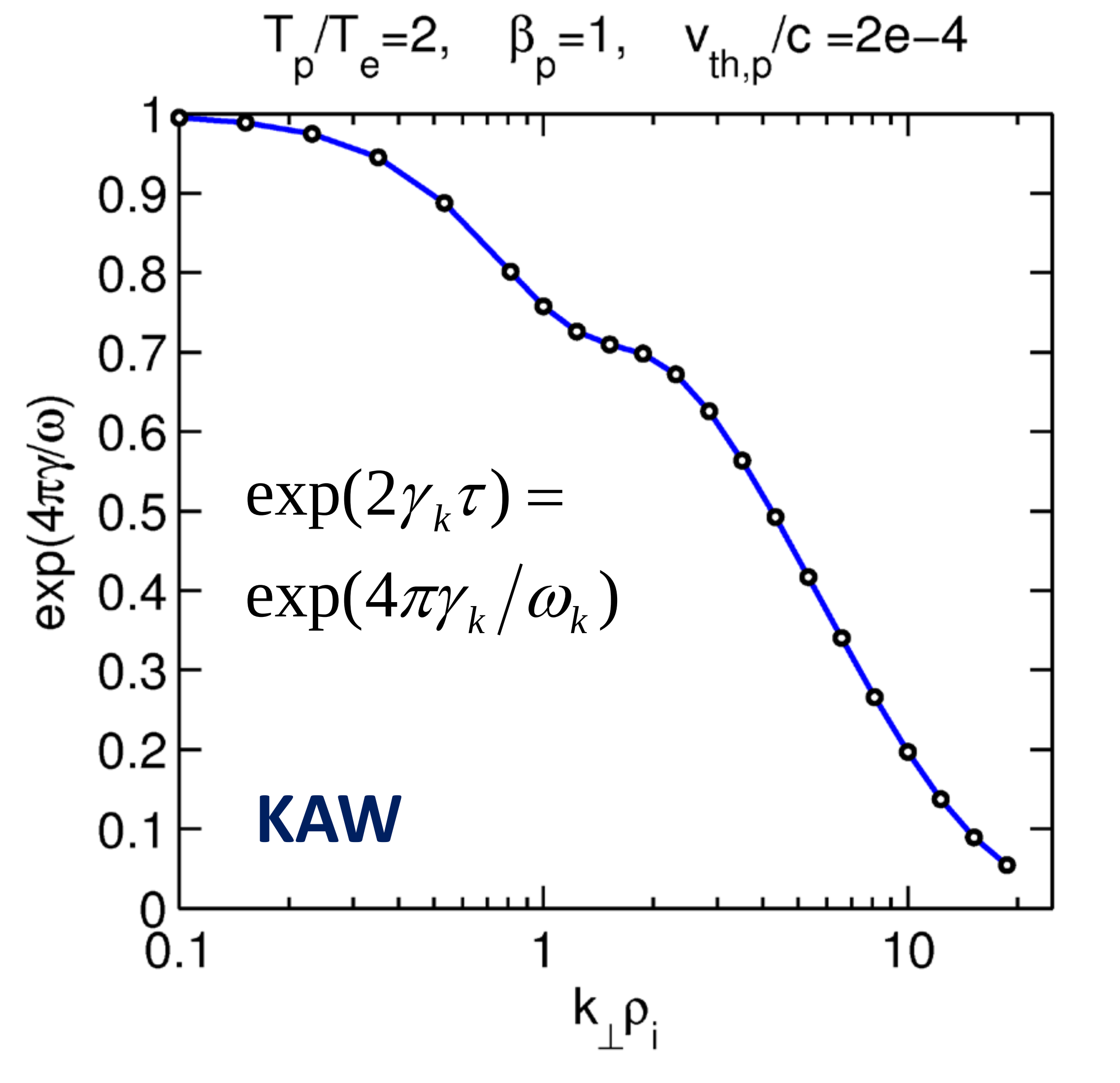
Leamon, Smith, Ness, & Wong (1998)
–Kinetic Alfven Waves (KAWs)

Entire spectrum is caused by KAW cascade



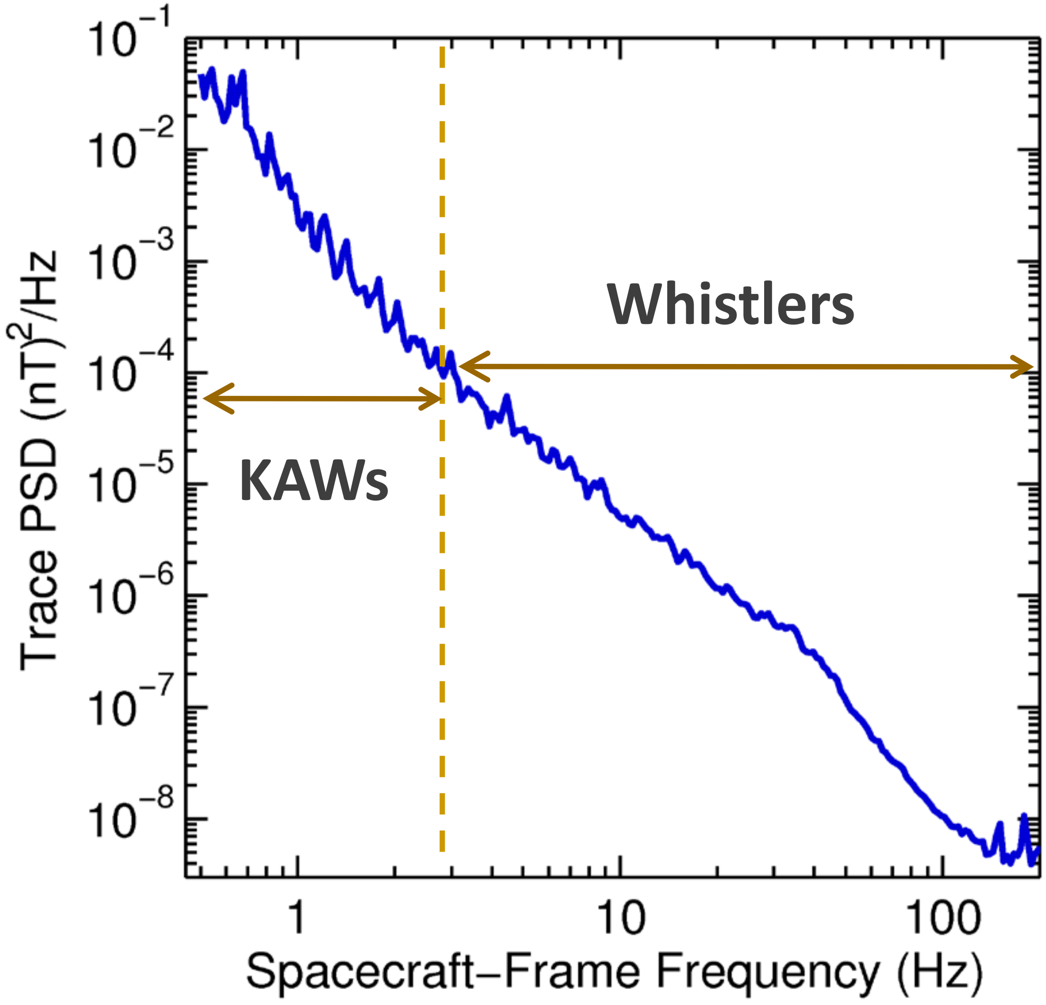
Damping of KAWs must be small in the range from $k_\perp \rho_i$=1 to $k_\perp \rho_e$=1 (Sahraoui et al. 2009)

Energy attenuation in one wave period



The electron gyro-radius scale is $k_\perp \rho_e$=1, or, $k_\perp \rho_i$=60.

Cluster search coil spectrum



Whistler waves likely play a role at high frequencies

See Podesta et al., ApJ 712, 685-691 (March 2010), for a detailed analysis

Part 2

Inertial range physics:
Anisotropy of solar wind fluctuations

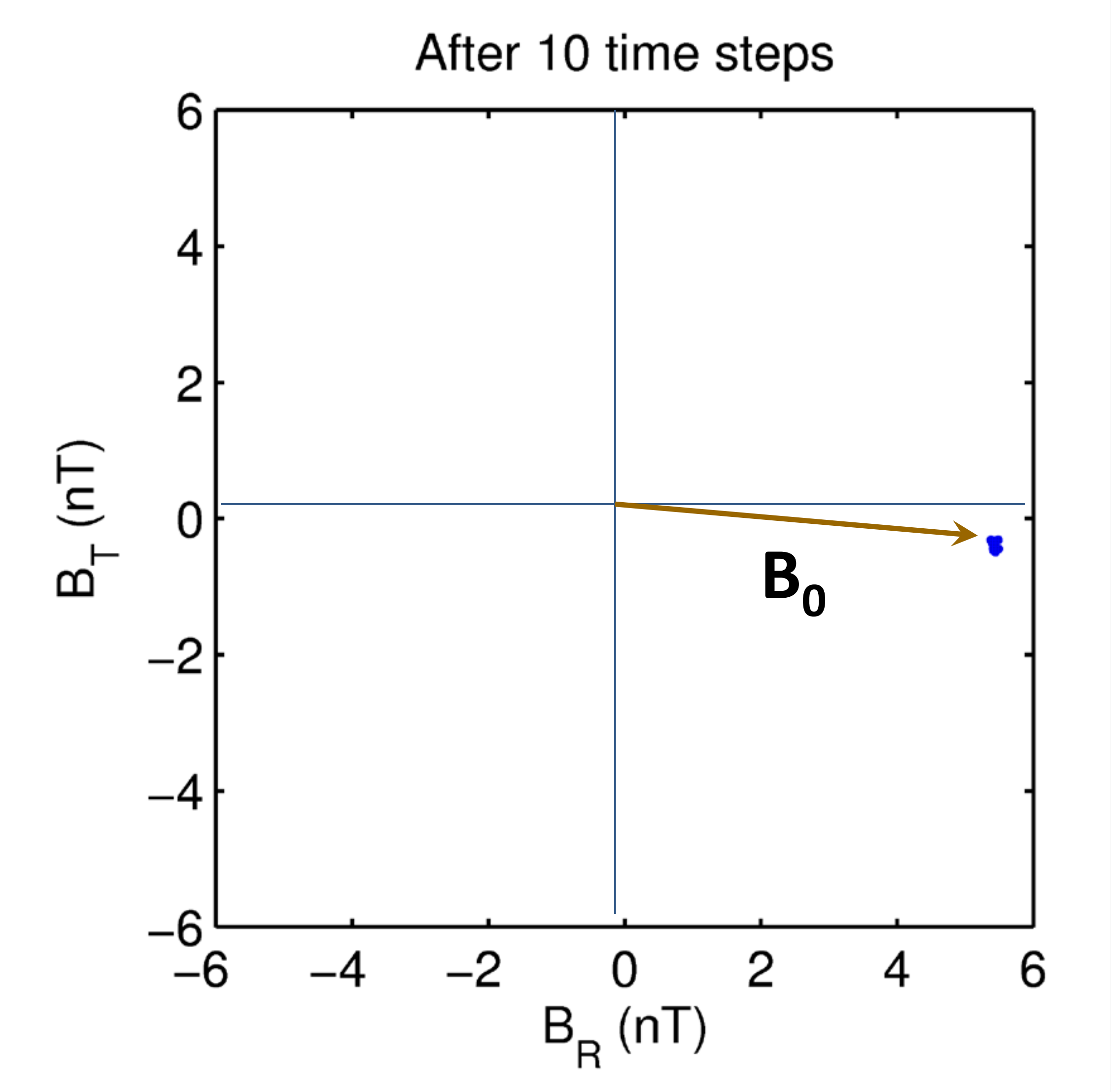
Horbury, Forman, & Oughton,
PRL 101, 175005 (2008)

Tessein, Smith, et al., ApJ 692:684–693 (2009)

Podesta, ApJ 698:986–999 (2009)

Measurements of the power-law scaling parallel and perpendicular to B_0

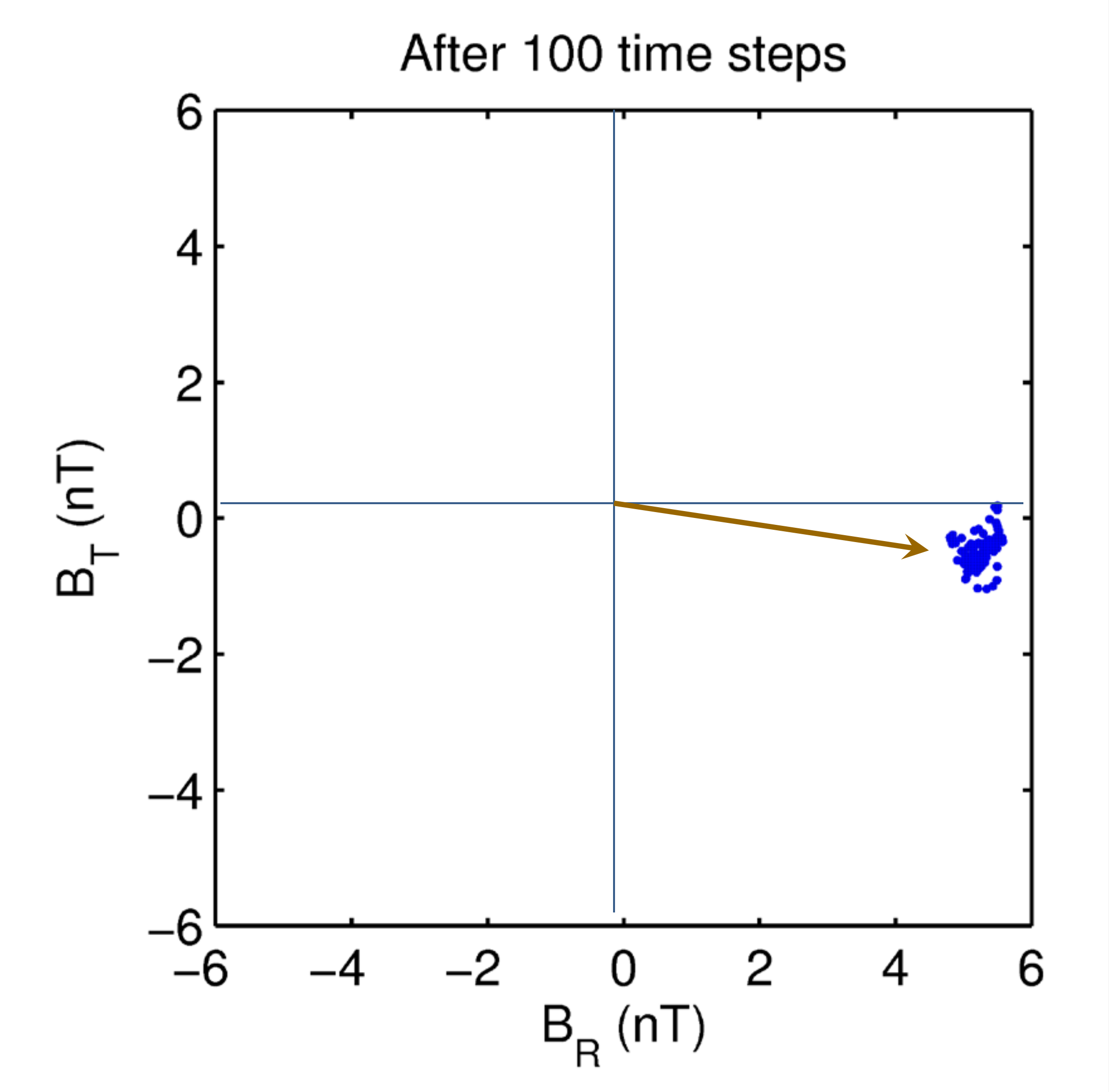
Trace out the tip of the vector B_0 in time



Projection of B_0 onto a plane.

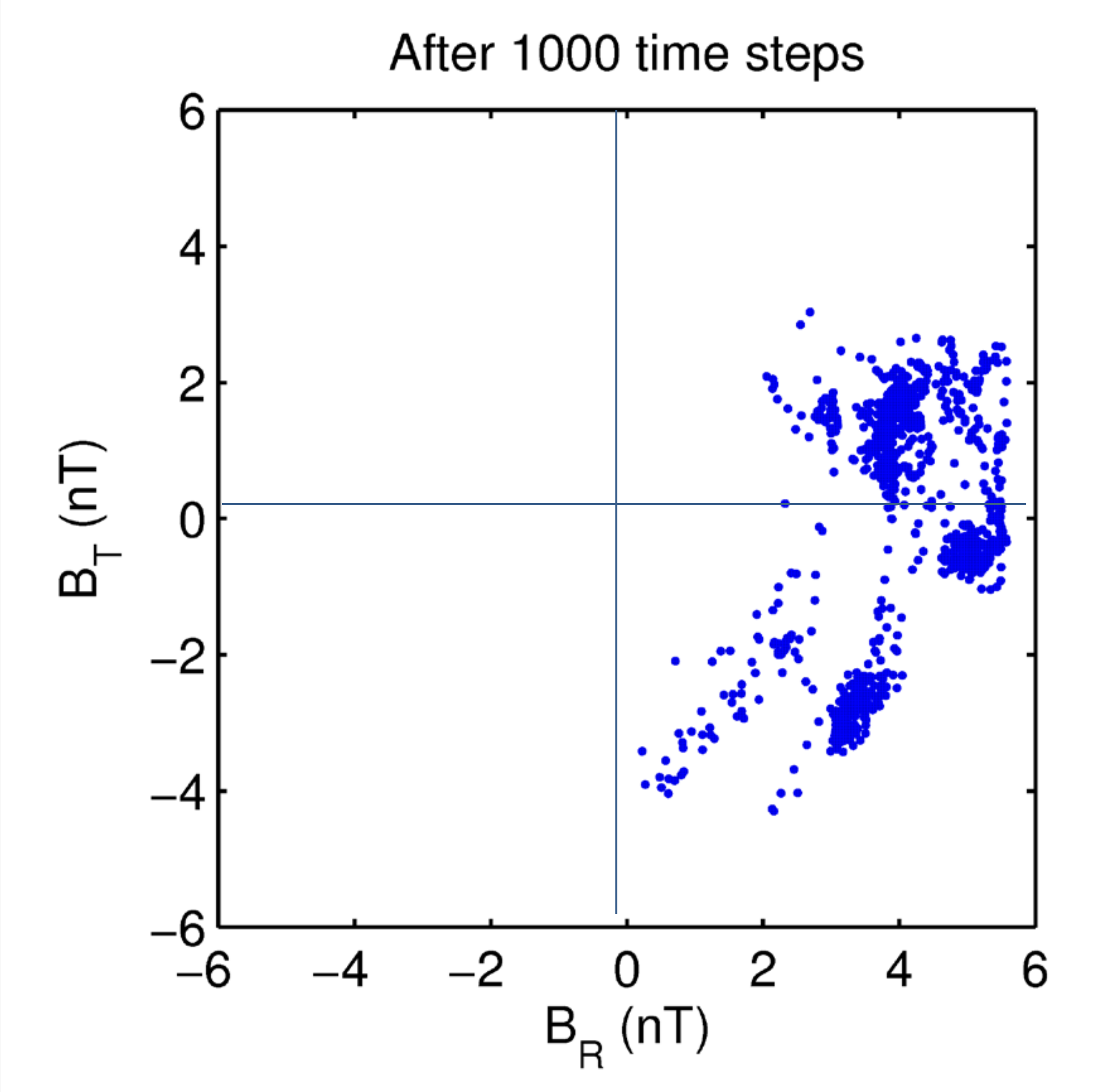
Note: B_0 is the **local** mean magnetic field

Trace out the tip of the vector B_0 in time



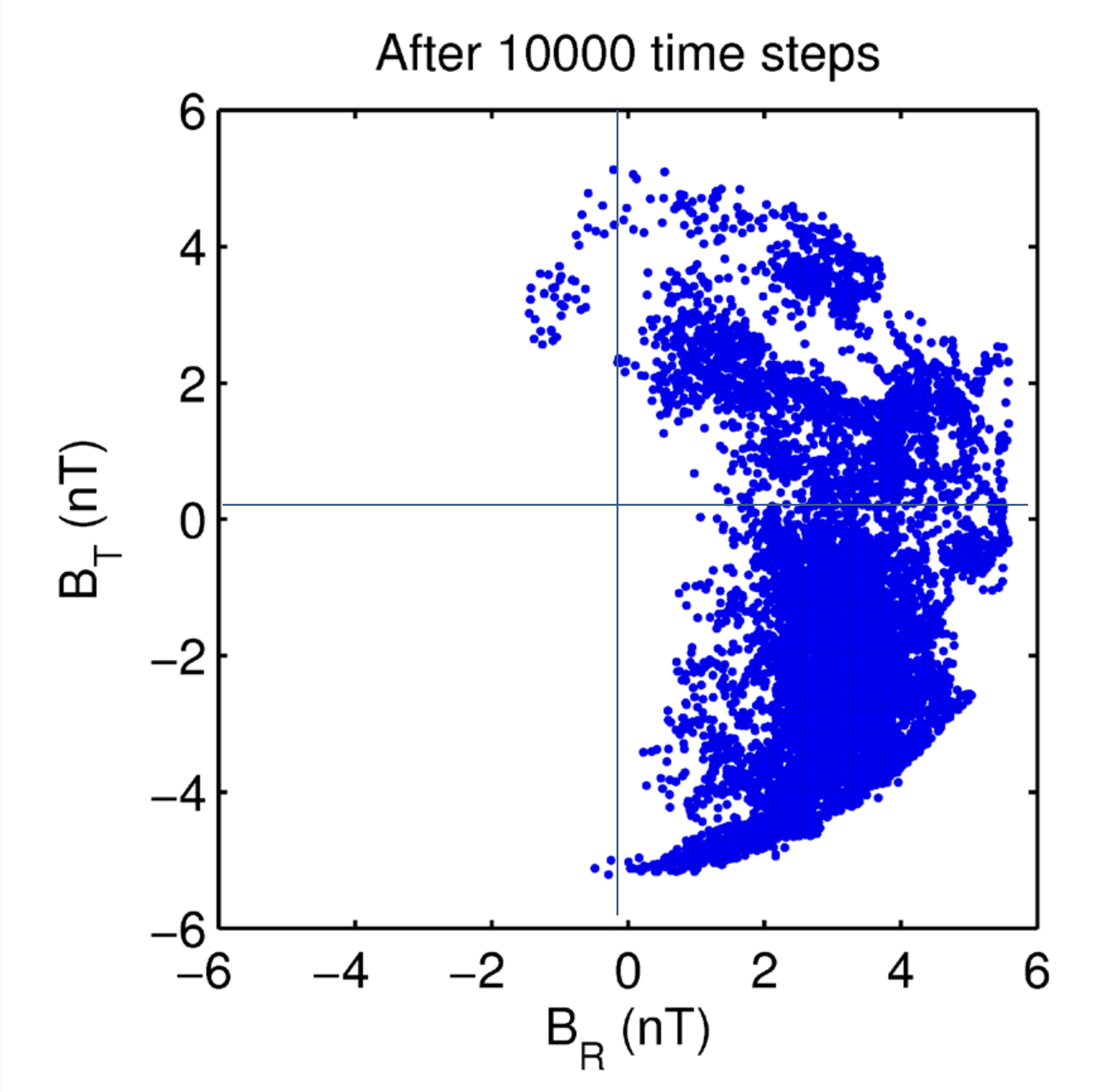
Projection of B_0 onto a plane.

Trace out the tip of the vector B_0 in time



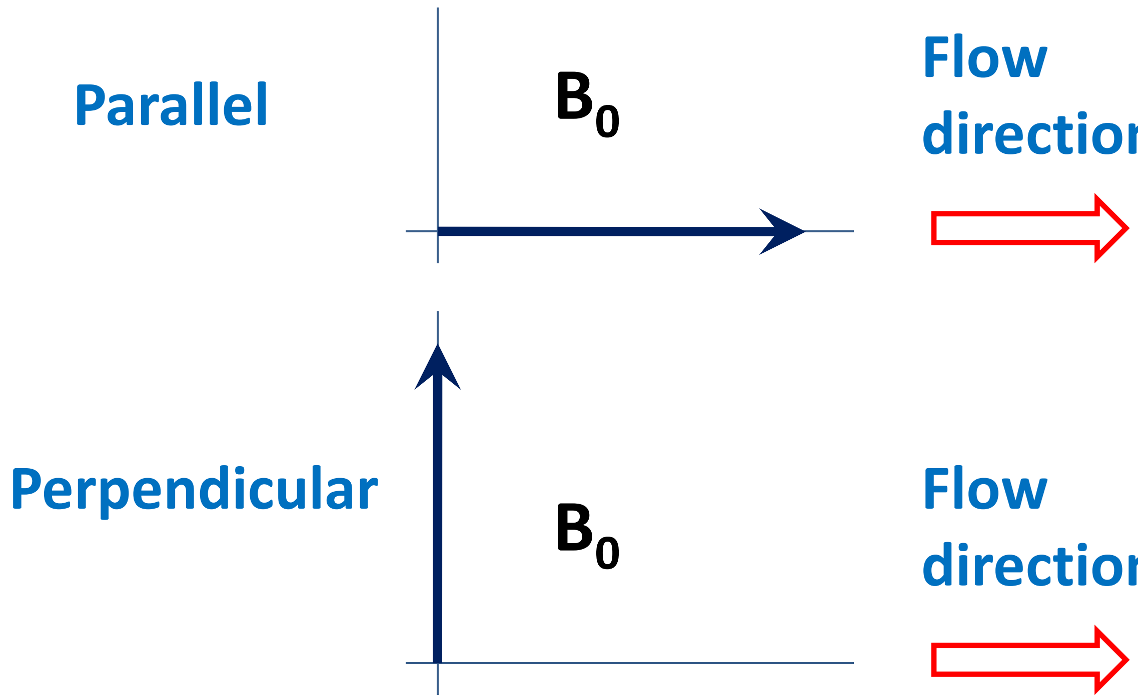
Projection of B_0 onto a plane.

Direction of B_0 is highly variable



Projection of B_0 onto a plane.

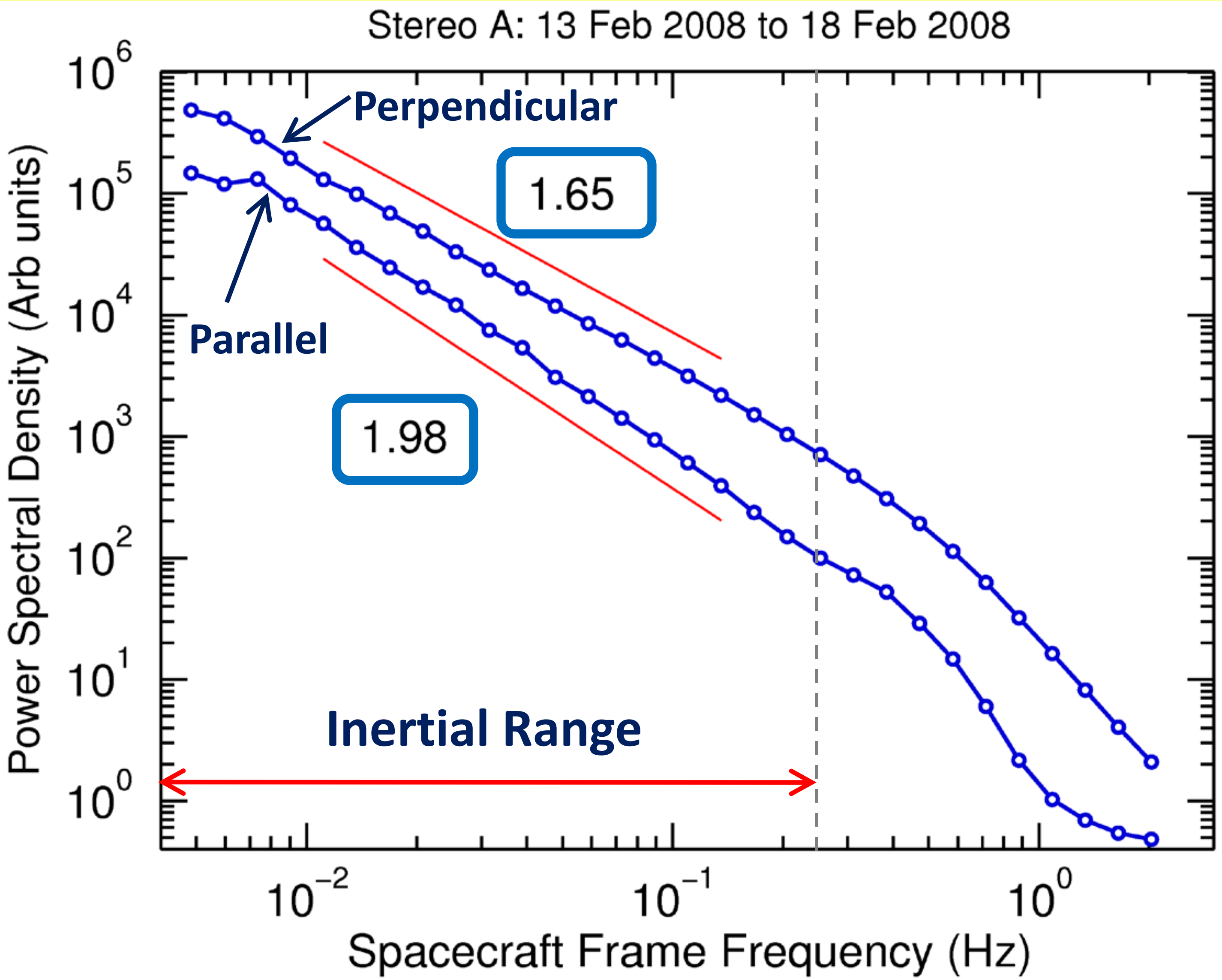
Make measurements when B_0 is directed parallel or perpendicular to the flow



Fluctuations evolve slowly compared to the sweeping time

What we measure: $$(\delta B)^2 = \left\langle \left| \mathbf{B}(\mathbf{x}+\mathbf{r}) - \mathbf{B}(\mathbf{x}) \right|^2 \right\rangle$$

Spectra parallel and perpendicular to B_0



Premature to conclude solar wind obeys the anisotropic 5/3 scaling of GS95

- There exist magnetic field observations by other groups showing perpendicular scaling closer to 3/2
- Observations suggest that scaling laws for the magnetic field B may not be unique in the solar wind
- So far, measurements of anisotropy have not included velocity fluctuations which usually scale like 3/2
- The scaling of the total energy, kinetic plus magnetic, usually lies between 3/2 and 5/3.
- There is good reason to believe the Boldyrev 3/2 scaling should apply to solar wind turbulence at 1 AU

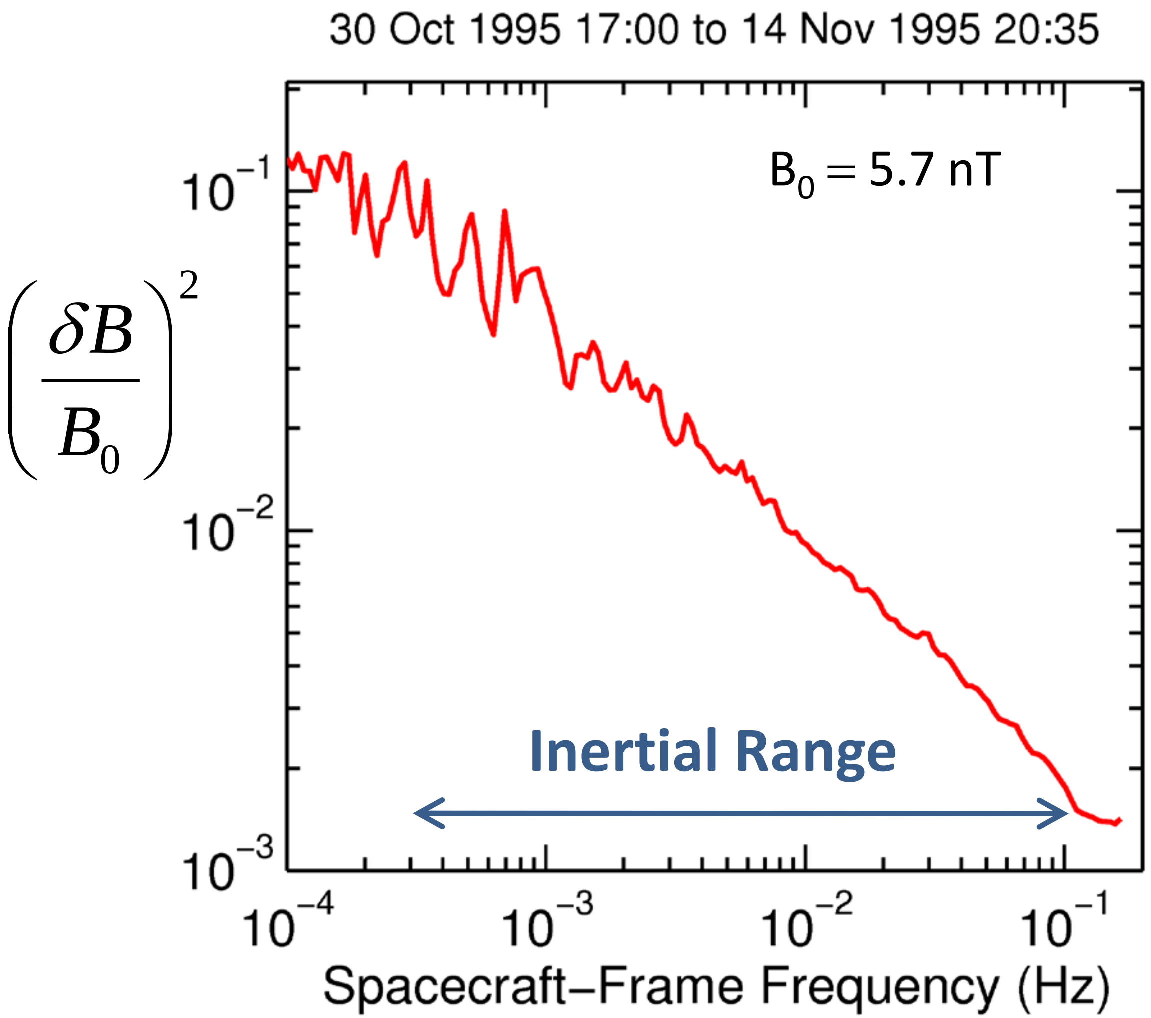
Why should the Boldyrev 3/2 scaling apply?

1. There is evidence for scale dependent alignment in the solar wind, at least at the largest inertial range scales (Podesta et al., JGR, **114, A01107, 2009**)
2. The solar wind is not strongly magnetized in the sense that $\beta << 1$, typically $\beta \sim 1$, however, observations show that at inertial range scales

$$(\delta B)^2 << B_0^2$$

3. This is the criteria for the applicability of Boldyrev's theory (Boldyrev, ApJ, 626:L37–L40, 2005)

Typical values of $(\delta B/B_0)^2$ at 1 AU



Measurements by the Wind spacecraft

Note:

$$(\delta B)^2 = f P_B(f)$$

where P_B is the trace power spectral density of B.

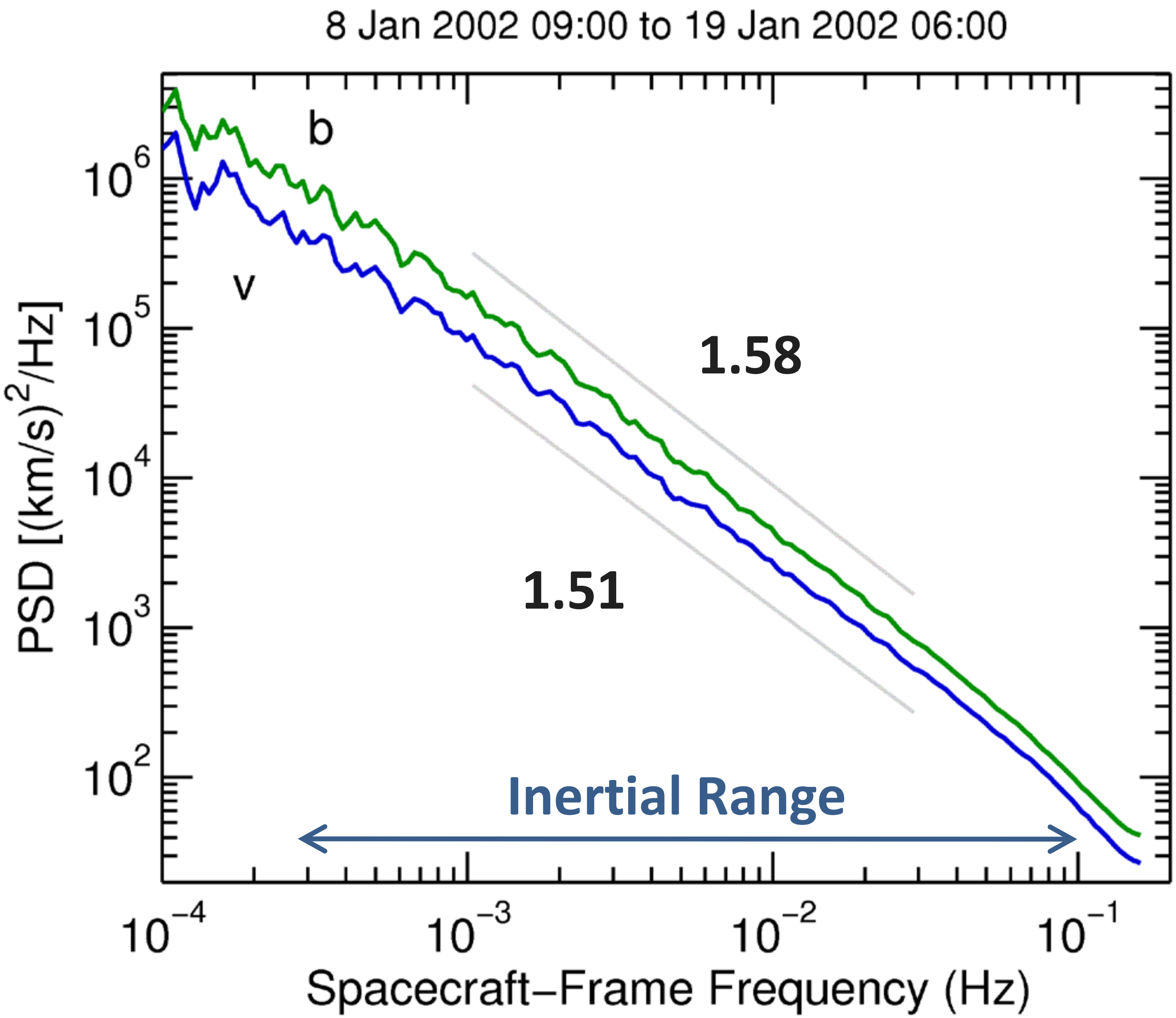
Part 3

Power spectra of velocity and magnetic field fluctuations using traditional Fourier techniques (no perp/para decomposition)

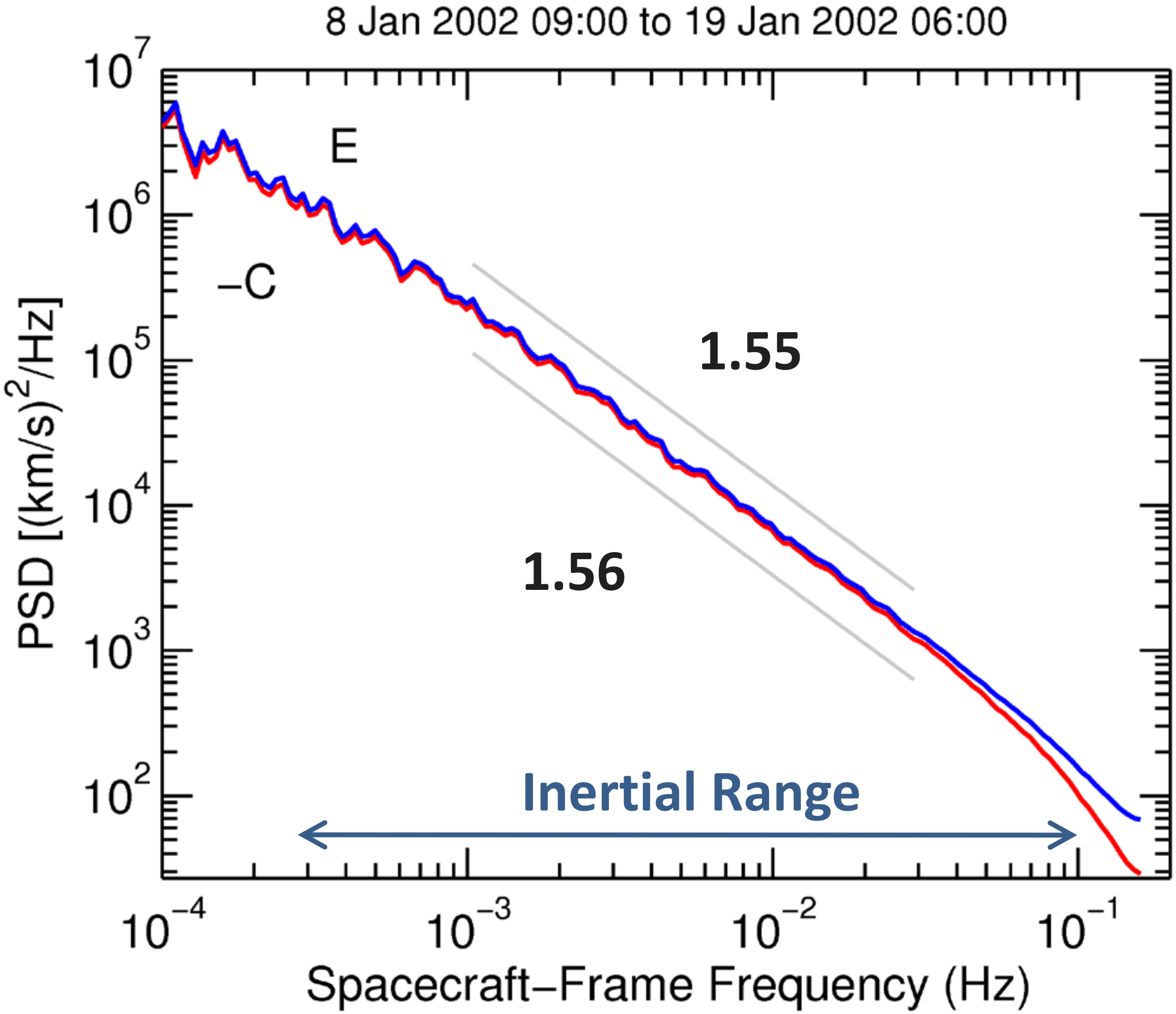
Total energy spectrum, kinetic plus magnetic, and cross-helicity spectrum

The Wind spacecraft, launched in 1994, is the 1st to provide simultaneous plasma and magnetic field measurements capable of spanning the entire inertial range.

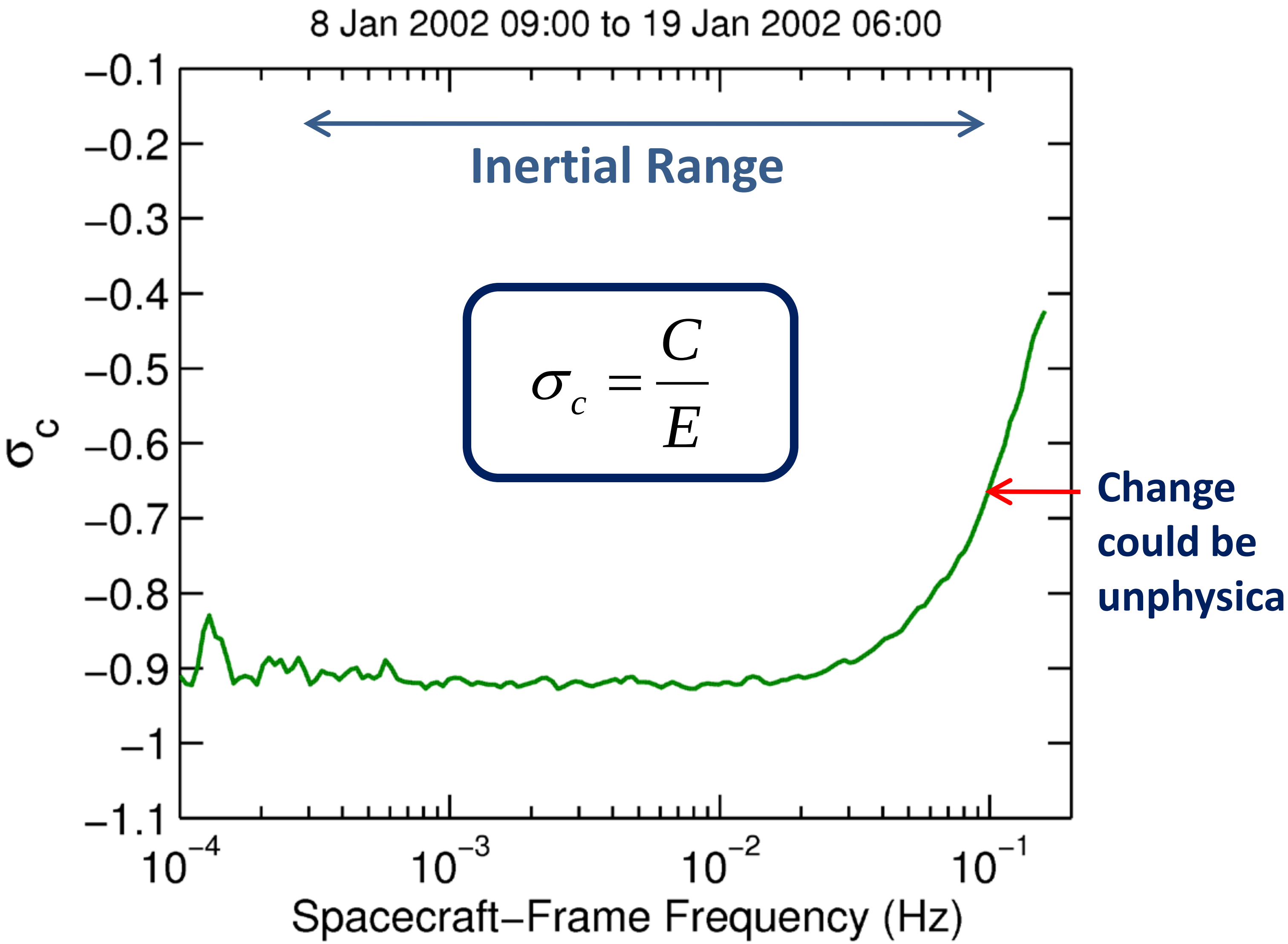
Velocity and magnetic field spectra at 1 AU



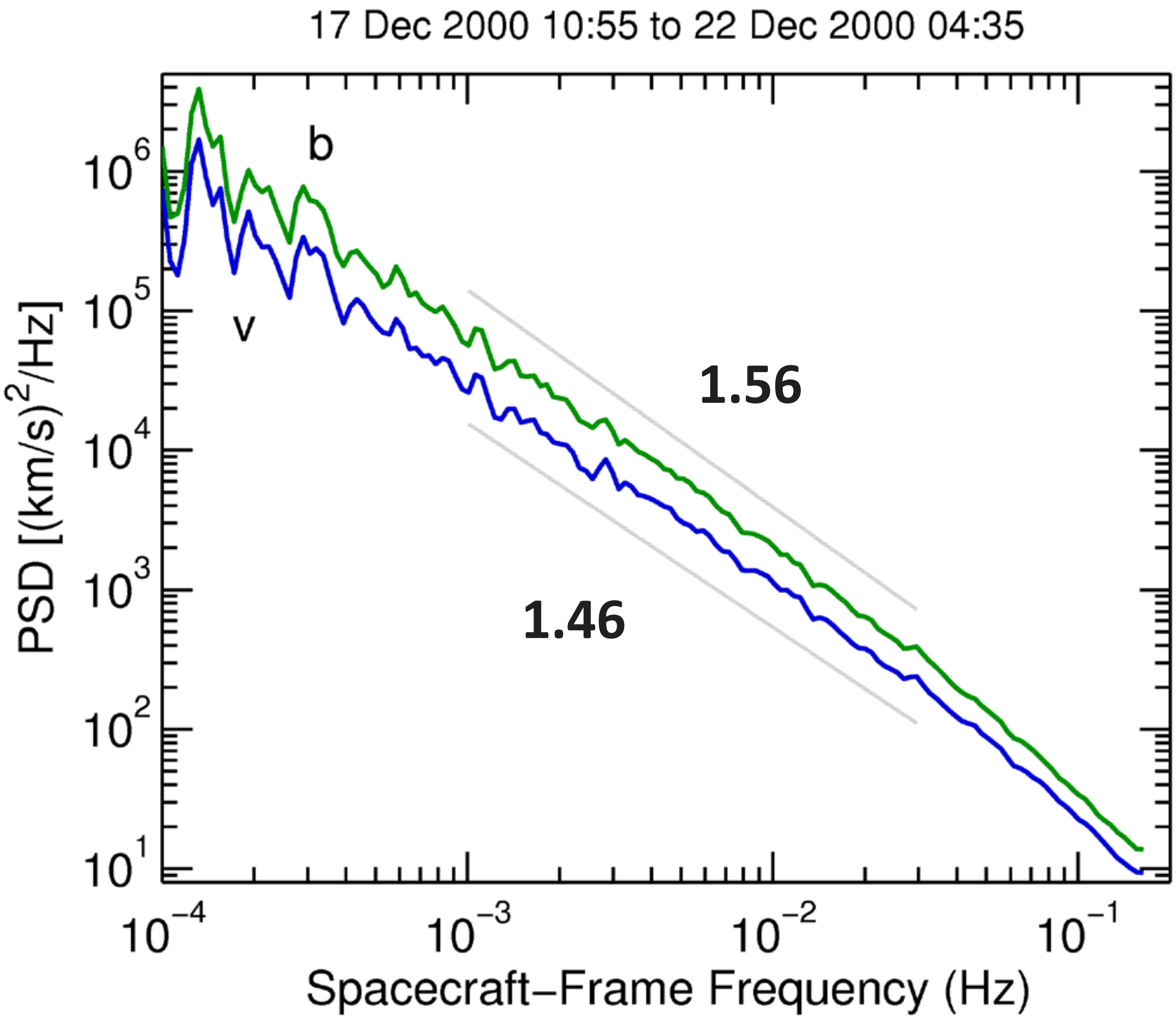
Energy and cross-helicity spectra at 1 AU



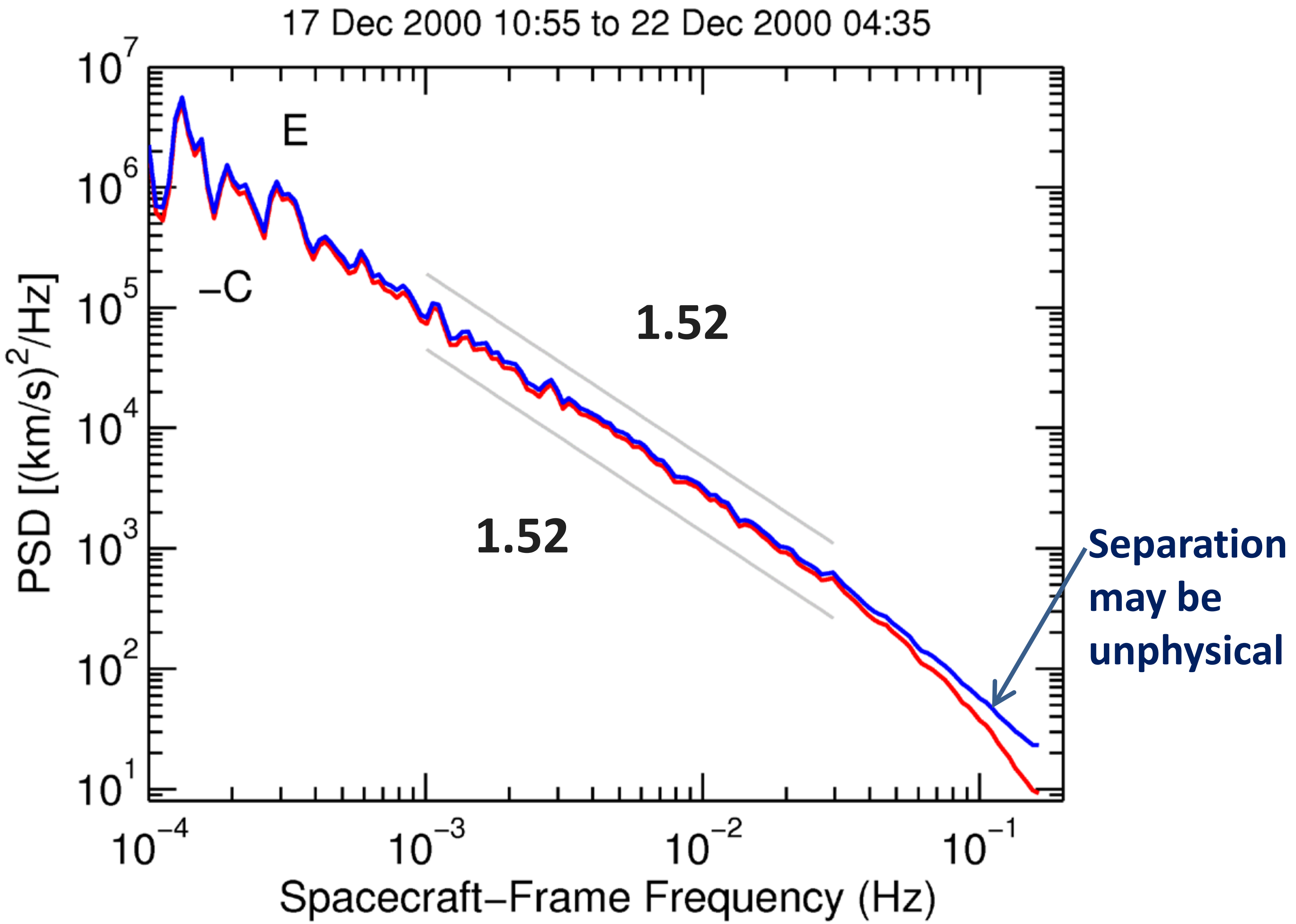
Normalized cross-helicity spectrum at 1 AU



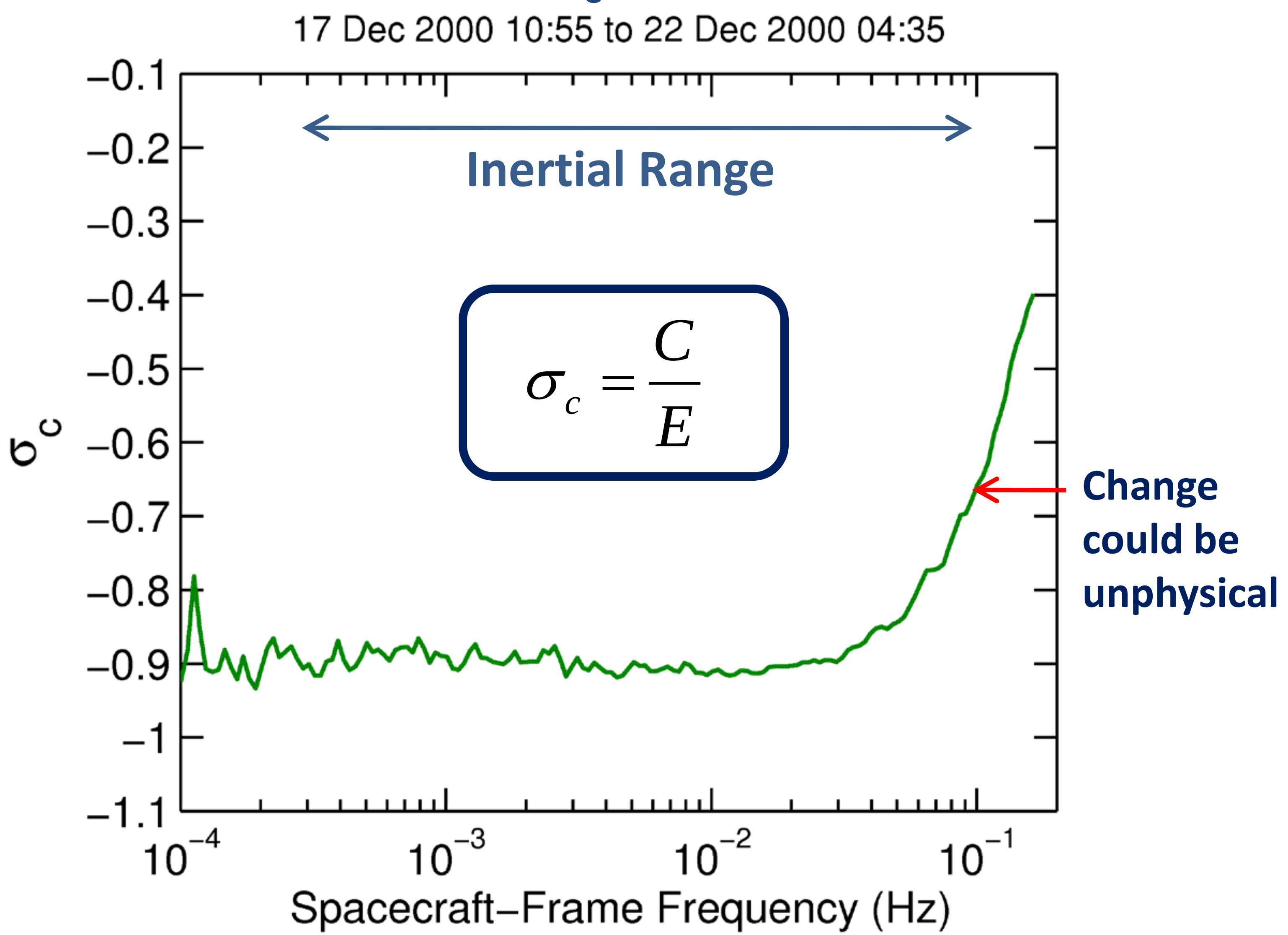
2nd example of v and b spectra at 1 AU



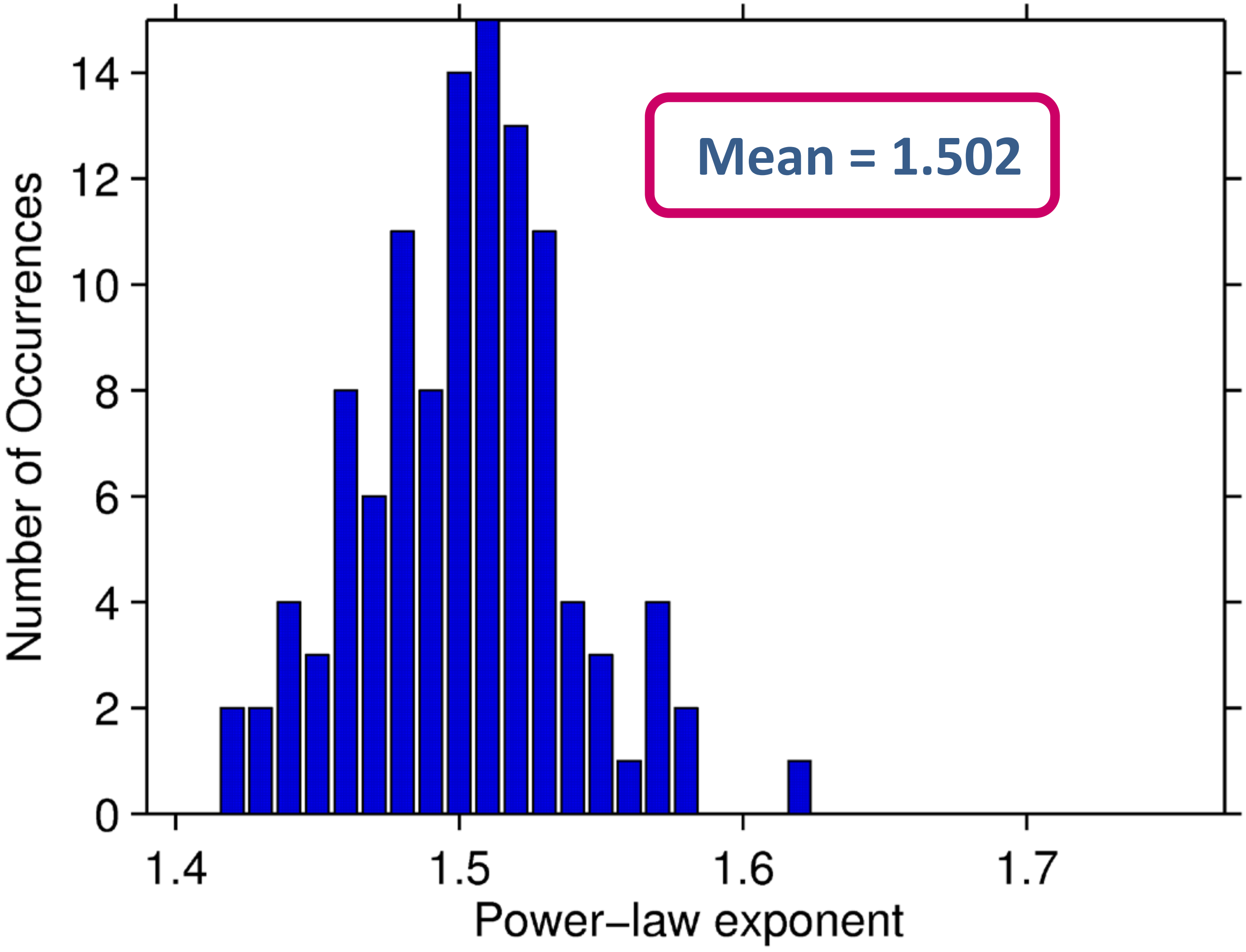
2nd example of E and C spectra at 1 AU



2nd example of σ_c spectrum at 1 AU

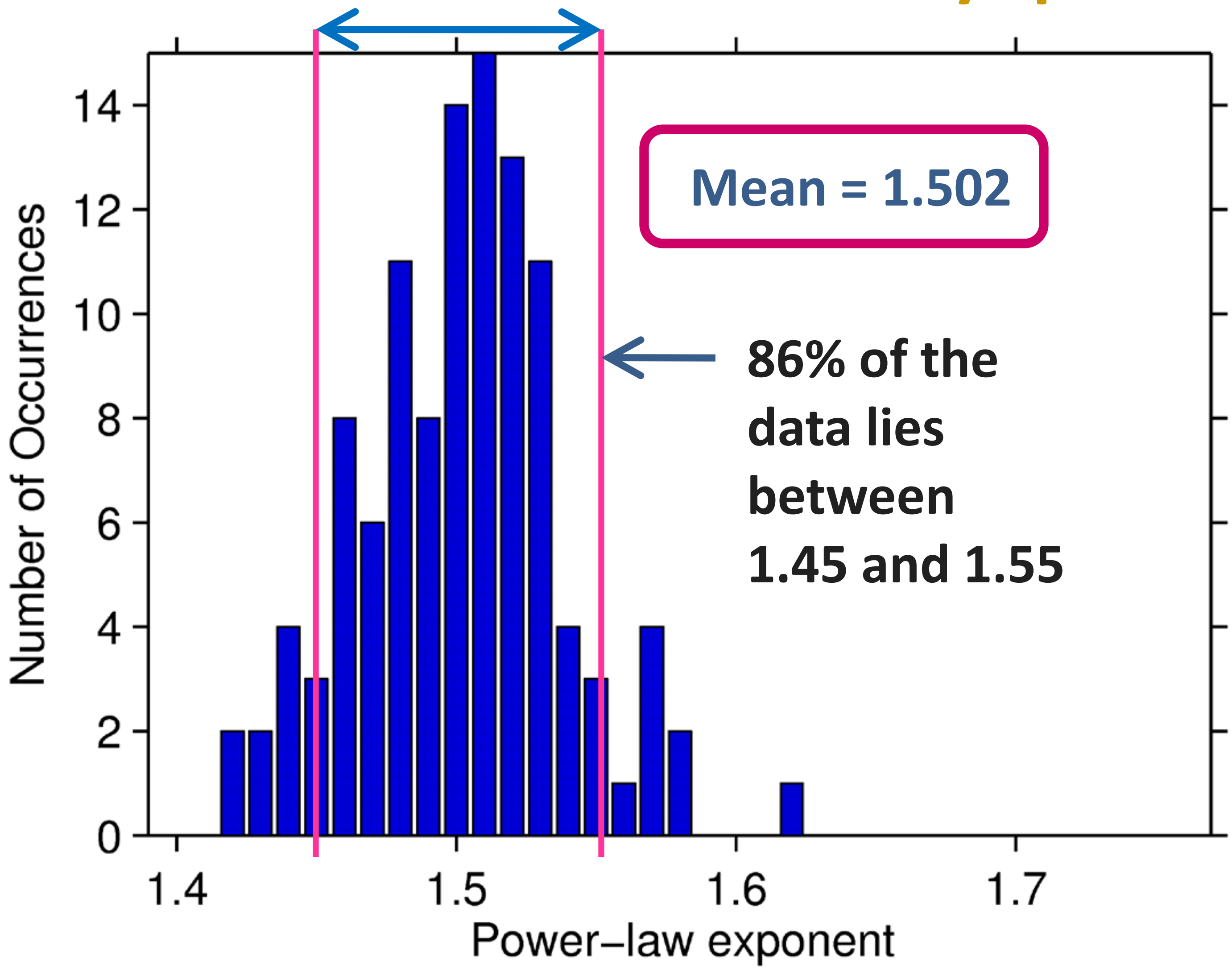


Power law indices for velocity spectrum



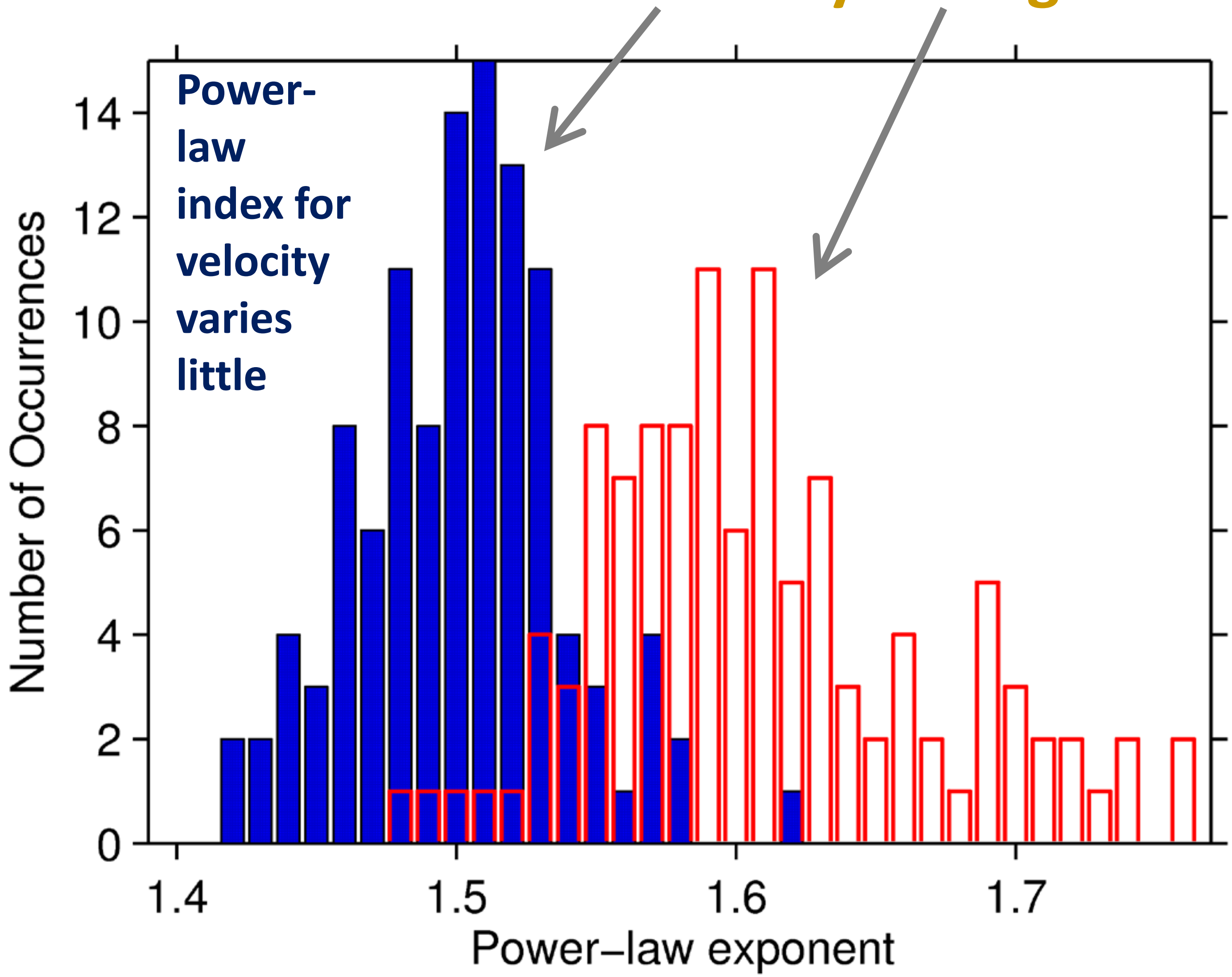
Study of 112 intervals of Wind data

Power law indices for velocity spectrum



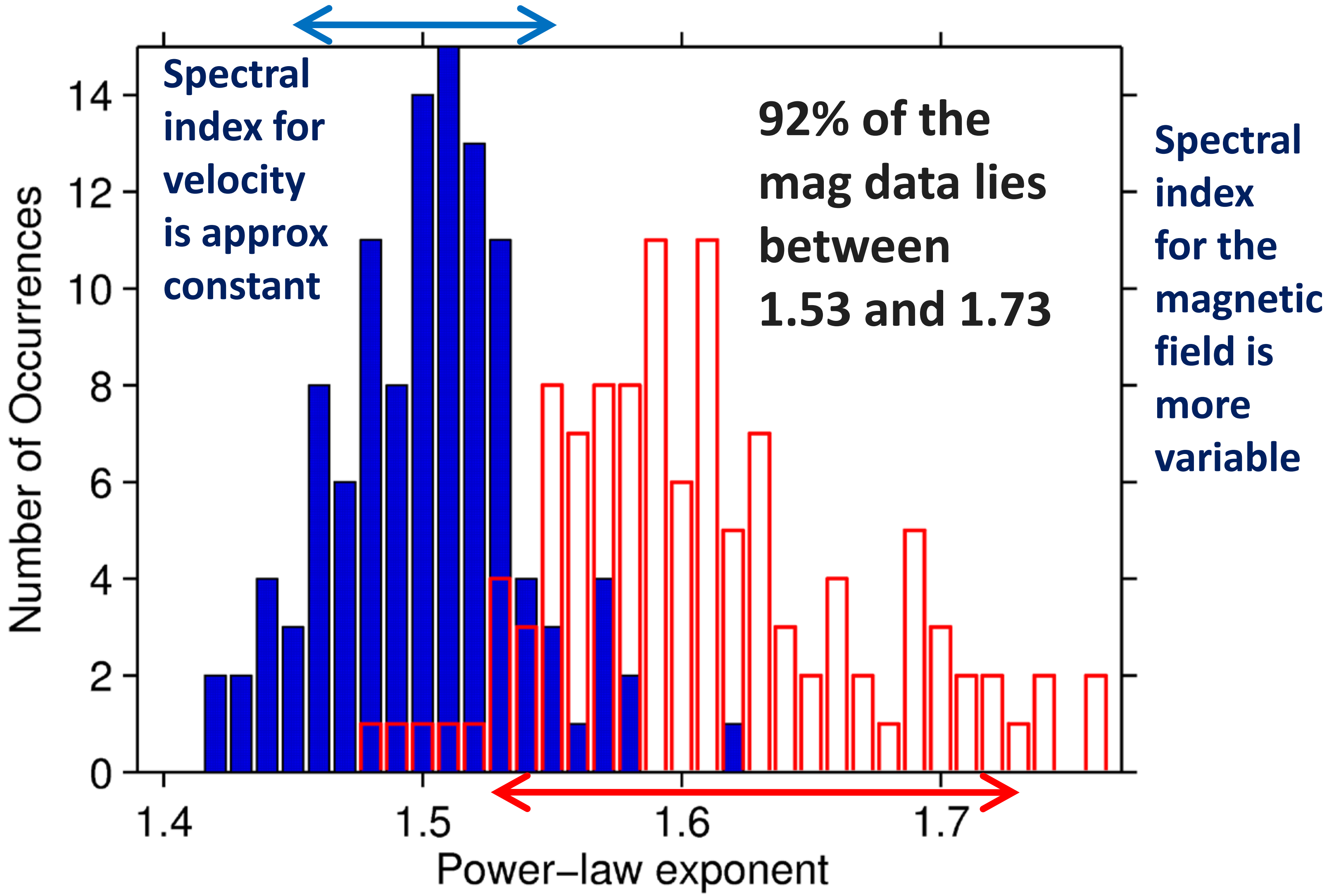
Study of 112 intervals of Wind data

Power-law indices for velocity & magnetic field

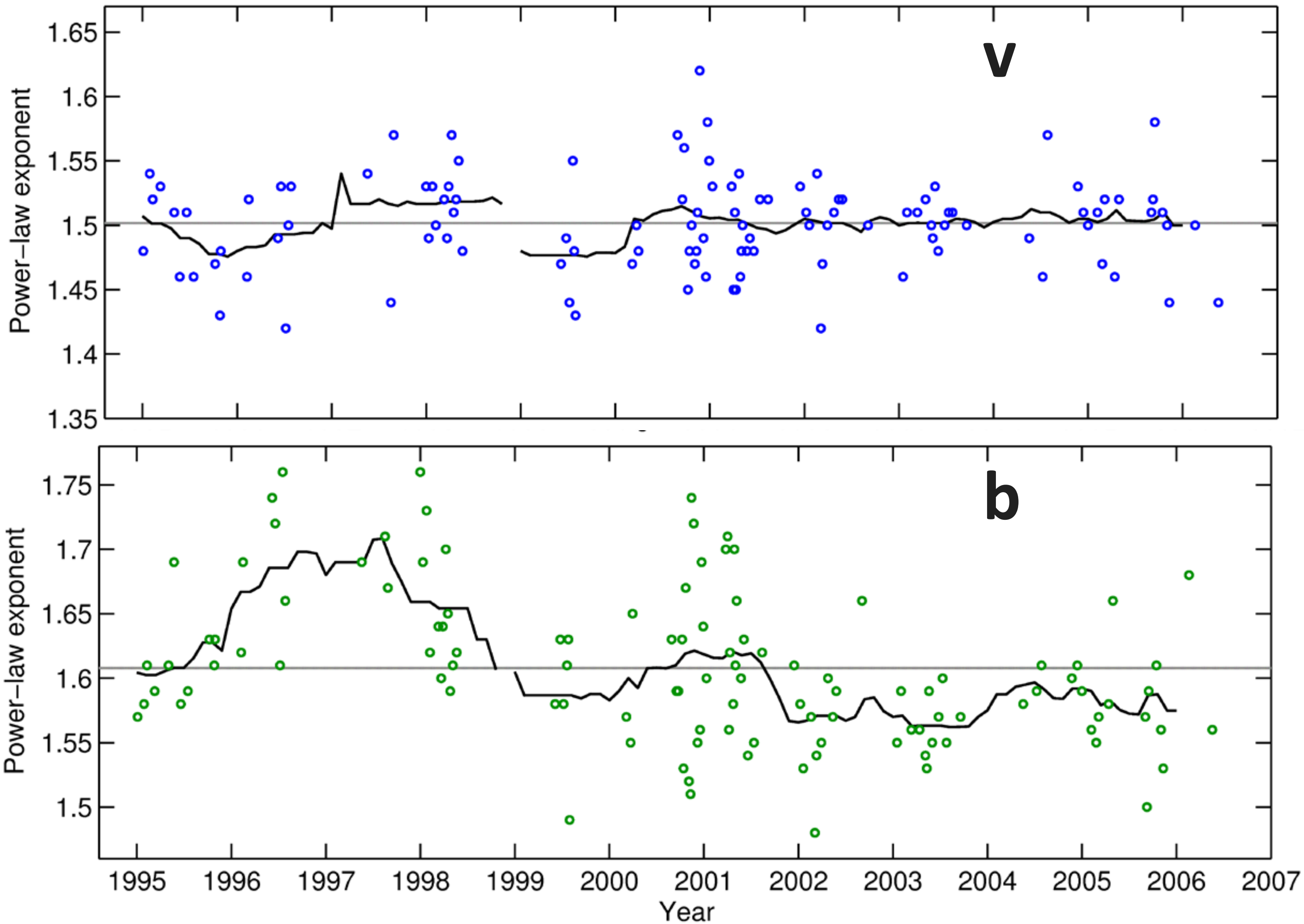


Power-law index for the magnetic field is more variable

Power-law indices for velocity & magnetic field



Power-law indices for velocity & magnetic field



Velocity spectrum has a unique and/or universal scaling law in the solar wind with a spectral exponent of **3/2**

This is consistent with results from simulations of incompressible MHD turbulence and evidence in support of the Boldyrev theory

Equipartition does not hold in the solar wind; V and B have different scaling laws.

Therefore, a complete description of inertial range physics in the solar wind must go beyond Boldyrev's theory.

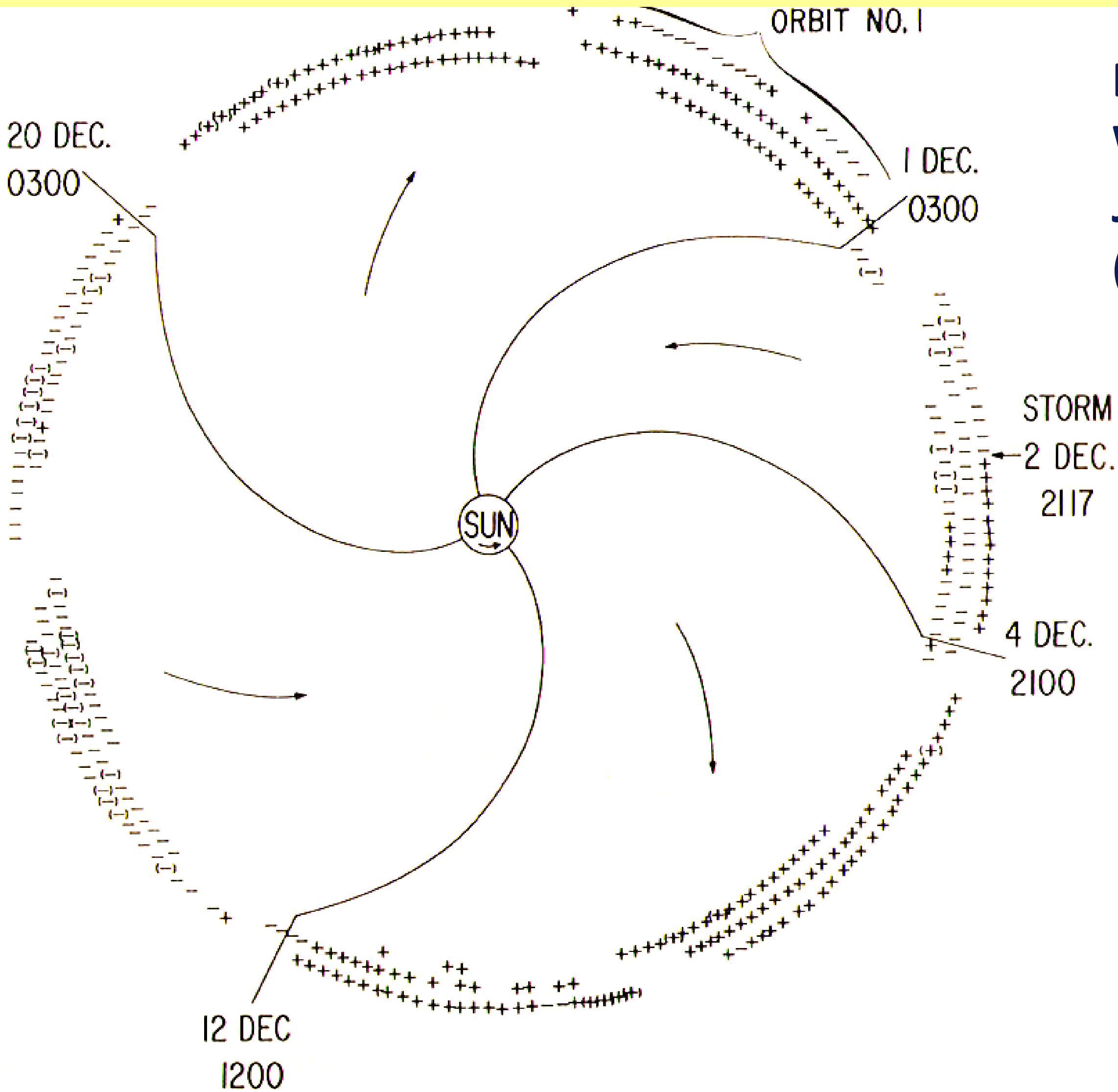
Solar Wind Observations show

1. Velocity spectrum usually exhibits ~3/2 scaling
2. Scaling of the magnetic field spectrum is more variable with values between 3/2 and 5/3+ (why does it vary?)
3. Scaling of the total energy, kinetic plus magnetic, typically lies between 3/2 and 5/3.
4. Energy and cross-helicity have approx the same scaling so normalized cross-helicity is approx scale invariant
5. Equipartition between velocity and magnetic field does not hold so the behavior of the residual energy $E_R = E_B - E_V$ in imbalanced turbulence needs to be understood
6. No equipartition implies Boldyrev's theory does not provide a complete description of solar wind turbulence

Part 4

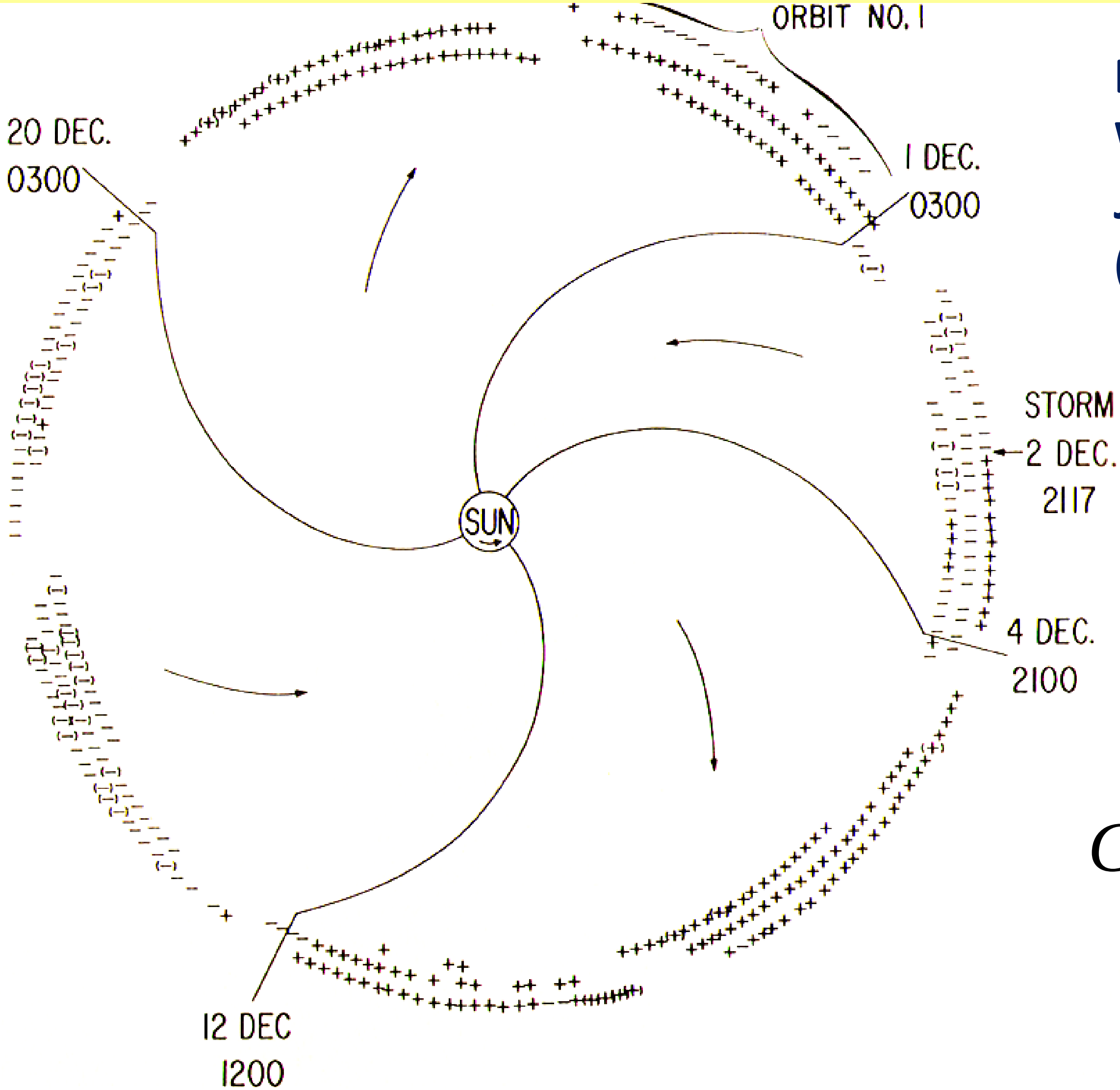
Does imbalanced turbulence exist in nature?

Magnetic sector structure in the ecliptic



Discovered by Wilcox and Ness, JGR, Vol 70, 5793 (1965)

Magnetic sector structure in the ecliptic



Discovered by Wilcox and Ness, JGR, Vol 70, 5793 (1965)

Cross-helicity depends on the volume chosen for analysis

$$C = \int_V \mathbf{v} \cdot \mathbf{b} \, dV$$

Is solar wind turbulence imbalanced?

Locally, yes. Globally, no.

What about driven, steady state, MHD turbulence in other naturally occuring systems?

Locally, yes. Globally, no.   (a conjecture)

Why? —— Independent forcing of the two Elsasser variables is not possible in MHD without introducing a fictitious force in the induction equation $\rightarrow$ Energy injection rates of $w^{\pm}$ are equal

Conclusions

Imbalanced turbulence appears to be a local phenomenon

Imbalanced turbulence may not exist on a global scale (largest system size).

Please let me know if you have good reason to believe otherwise (jpodesta@solar.stanford.edu) .