
1 August 2008
Kochenevo, Russia
Photo by Hartweg Leuthen

# 3D Wavevector spectrum of solar wind turbulence: the holy grail

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# Motivation

1. Solar wind turbulence is an important testing ground for theories of turbulence in collisionless astrophysical plasmas.
2. We know that turbulent dynamics are organized by the mean magnetic field $B_0$.
3. However, we do not know the 3D wavevector spectrum of the fluctuating fields.
4. This is a long-standing unsolved problem.

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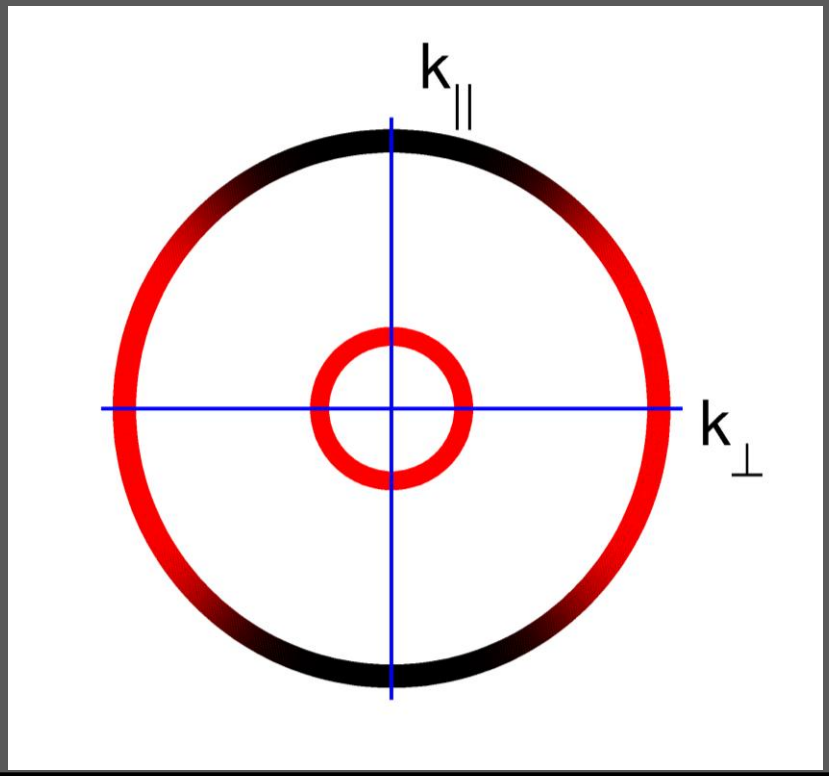
**Simulations of incompressible MHD turbulence show that the energy cascade is primarily perpendicular to the mean magnetic field $B_0$**



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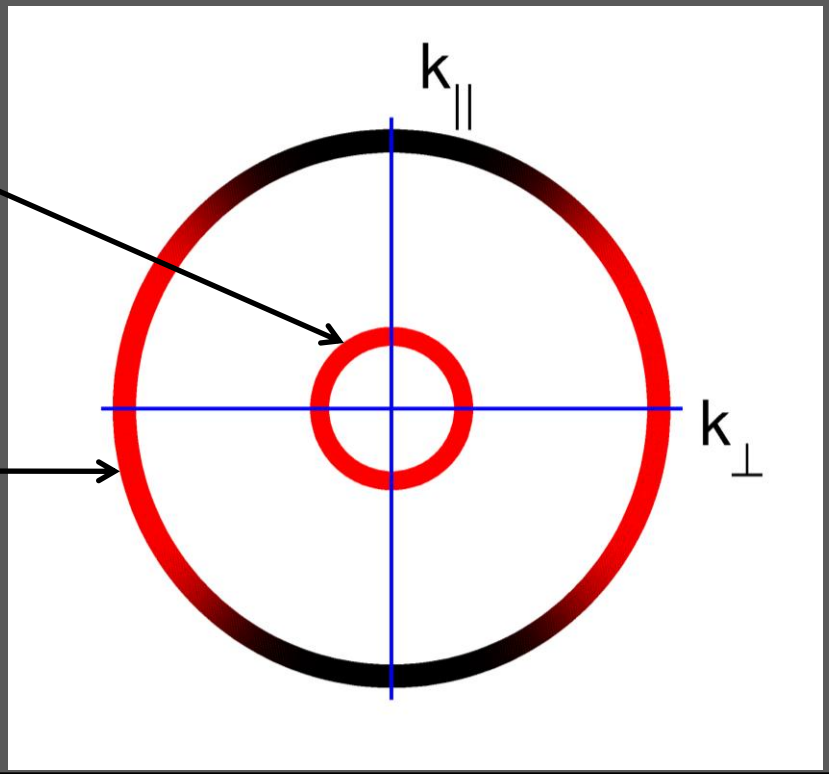
**Isotropic at large scales**

**Anisotropic at small scales**




**Anisotropy of the 3D wavevector spectrum**

# Anisotropic theories of Incompressible MHD Turbulence

1. Goldreich & Sridhar (1995)
2. Energy spectrum has different power law exponents parallel and perpendicular to $B_0$.
3. Perpendicular energy spectrum: $E_\perp \propto k_\perp^{-5/3}$
4. Parallel energy spectrum: $E_{||} \propto k_{||}^{-2}$
5. Support for this comes from numerical simulations

# Anisotropic Scaling of Magnetohydrodynamic Turbulence

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(Received 23 July 2008; published 24 October 2008)

We present a quantitative estimate of the anisotropic power and scaling of magnetic field fluctuations in inertial range magnetohydrodynamic turbulence, using a novel wavelet technique applied to spacecraft measurements in the solar wind. We show for the first time that, when the local magnetic field direction is parallel to the flow, the spacecraft-frame spectrum has a spectral index near 2. This can be interpreted as the signature of a population of fluctuations in field-parallel wave numbers with a $k_{\|}^{-2}$ spectrum but is also consistent with the presence of a "critical balance" style turbulent cascade. We also find, in common with previous studies, that most of the power is contained in wave vectors at large angles to the local magnetic field and that this component of the turbulence has a spectral index of $5/3$.

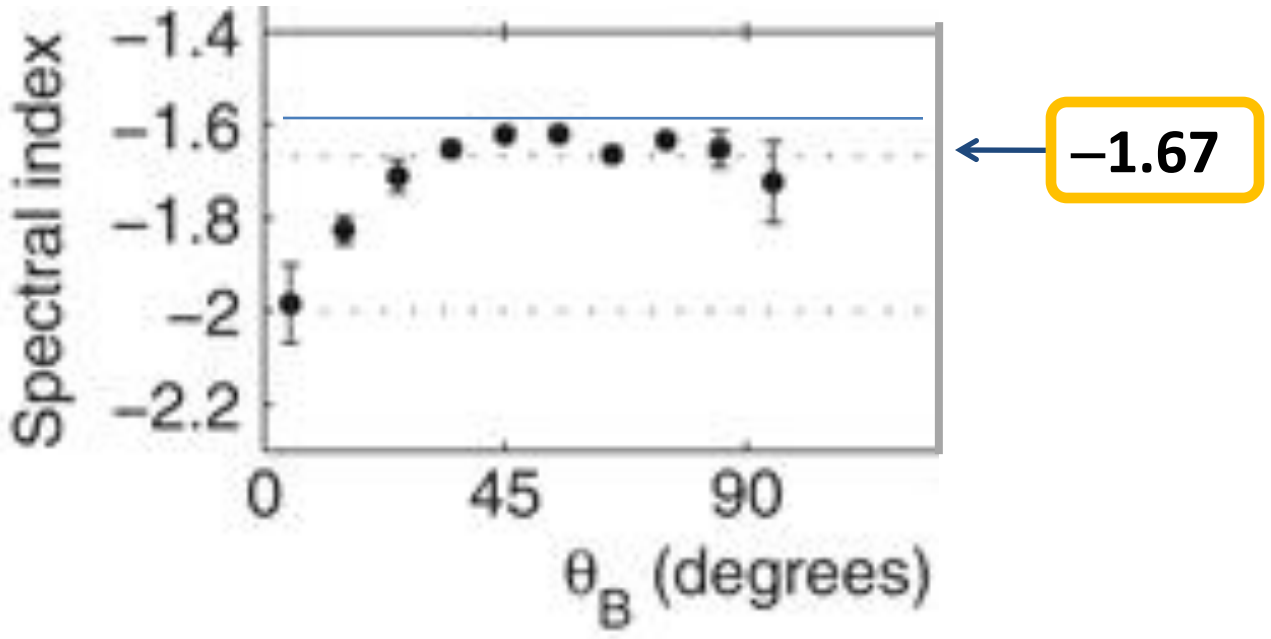
DOI: 10.1103/PhysRevLett.101.175005 PACS numbers: 52.35.Ra, 52.30.Cv, 95.75.Wx, 96.50.Bh

Magnetized plasmas fill most of the Universe and in many regions turbulence plays an important role in the transport of energy and momentum and the acceleration and scattering of charged particles. Many aspects of plasma turbulence remain poorly understood, however. Here we present results on one of these, the anisotropy of

cal balance" framework [14], turbulent energy evolves towards wave vectors where the shear and Alfvén time scales are balanced and most power resides in wave vectors where $\tau_S \leq \tau_A$, i.e., $k_{\|} \leq k_{\perp}^{2/3} \epsilon^{1/3} V_A^{-1}$.

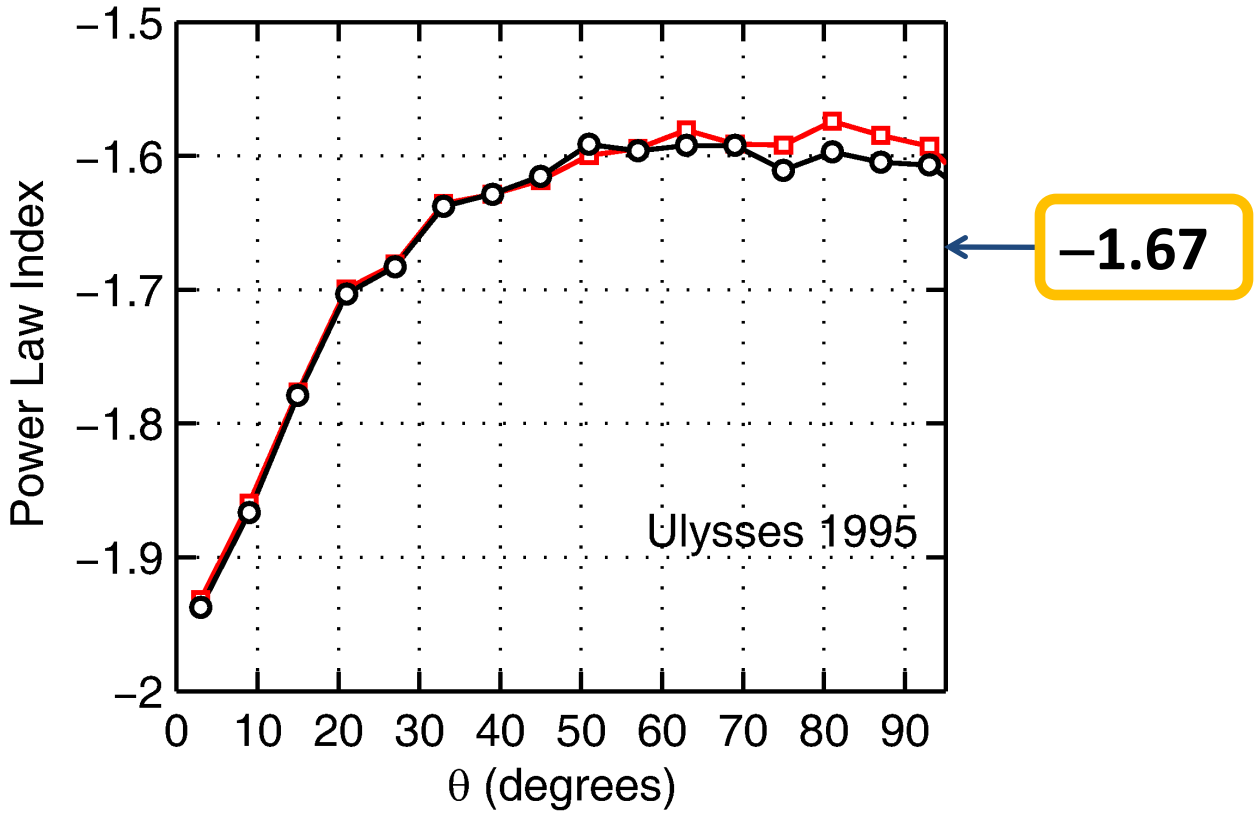
The solar wind is a unique environment in which to study space plasma turbulence: it is relatively accessible

# Horbury's results for the spectral index




Ulysses magnetic field: 1 second data, 30 day interval (1995)

# Verification of Horbury's results (?)



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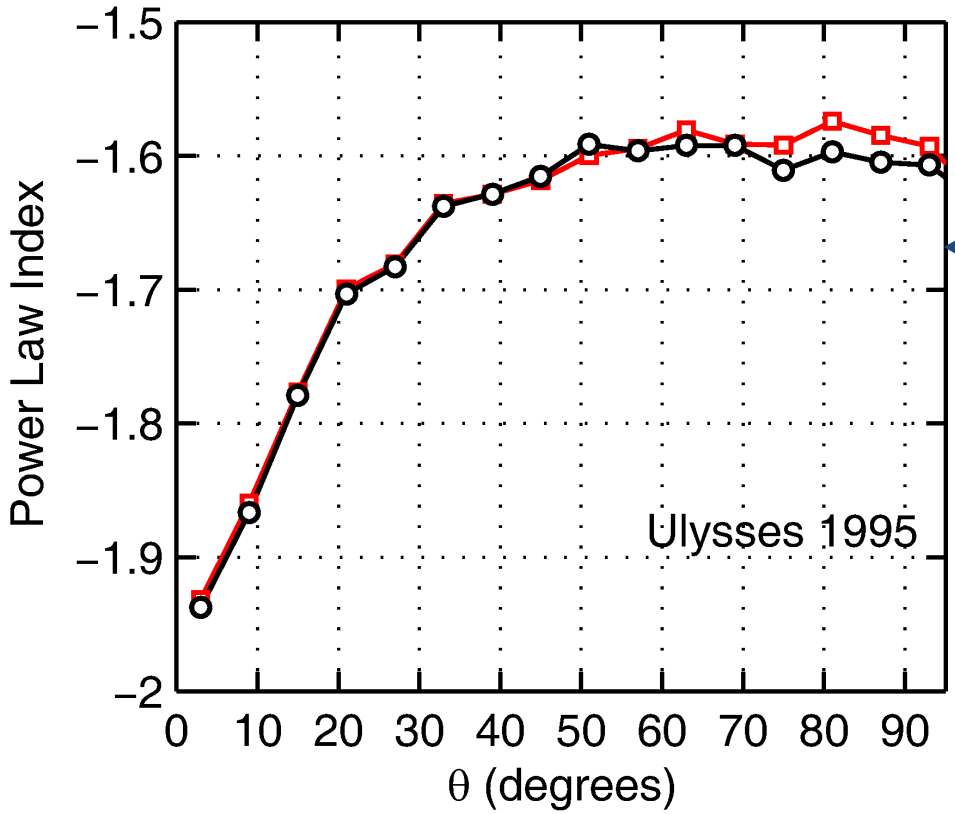


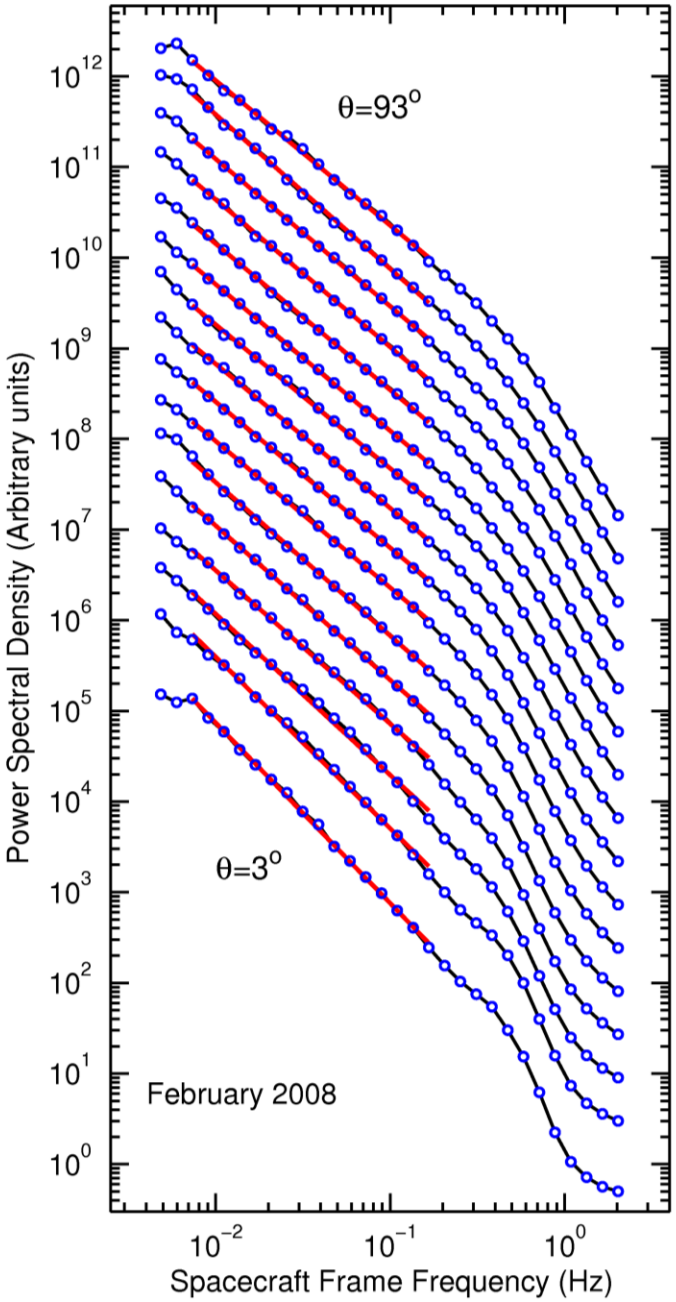

**−1.67**

**High-speed streams in ecliptic plane should have same behavior**

Power spectra at different angles θ to the magnetic field

Red lines are linear least-squares fits

The slope is the power-law index




Stereo A

Fluxgate magnetometer

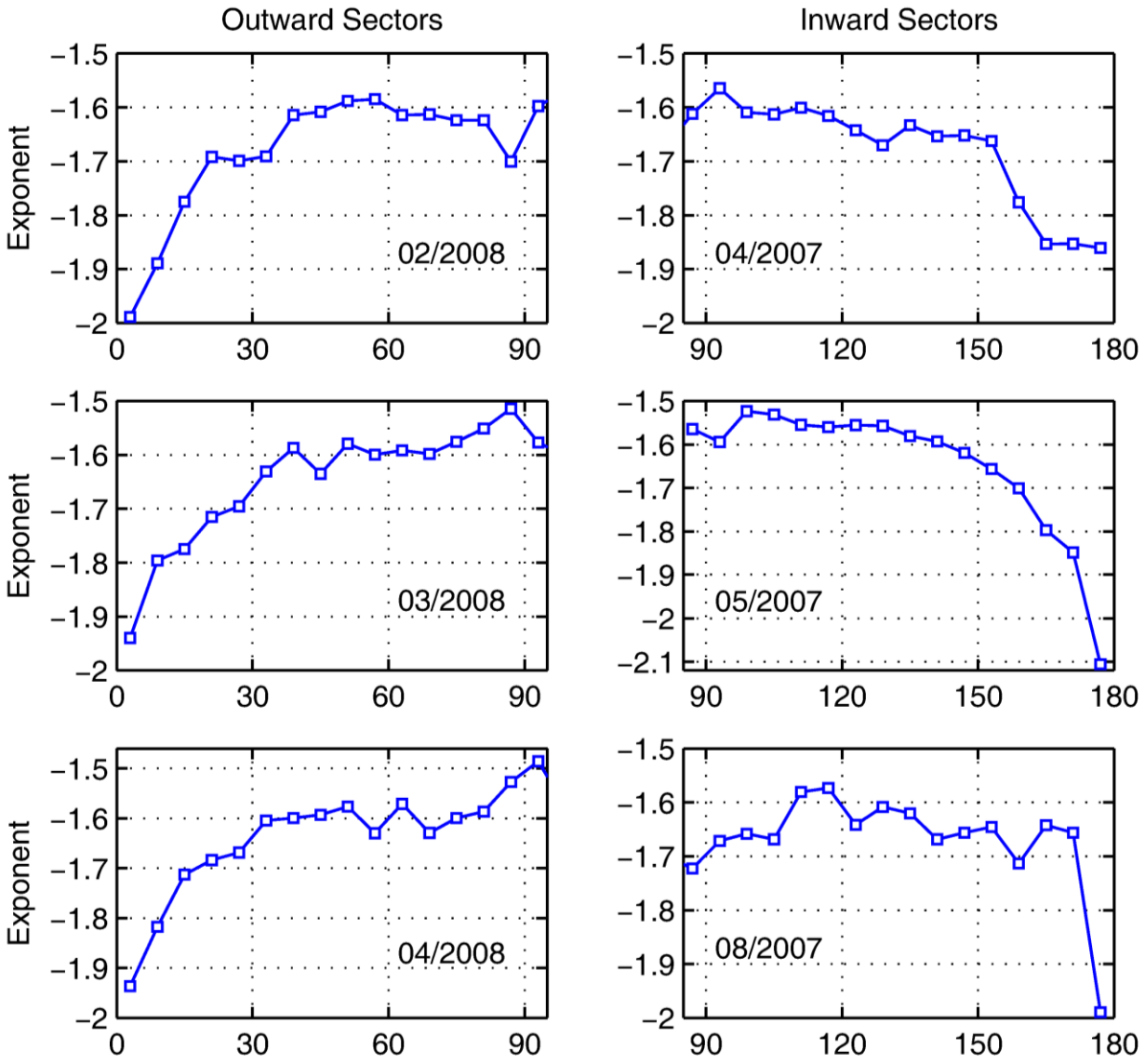
8 vectors per second

High-speed stream

5 day interval

**Stereo data**

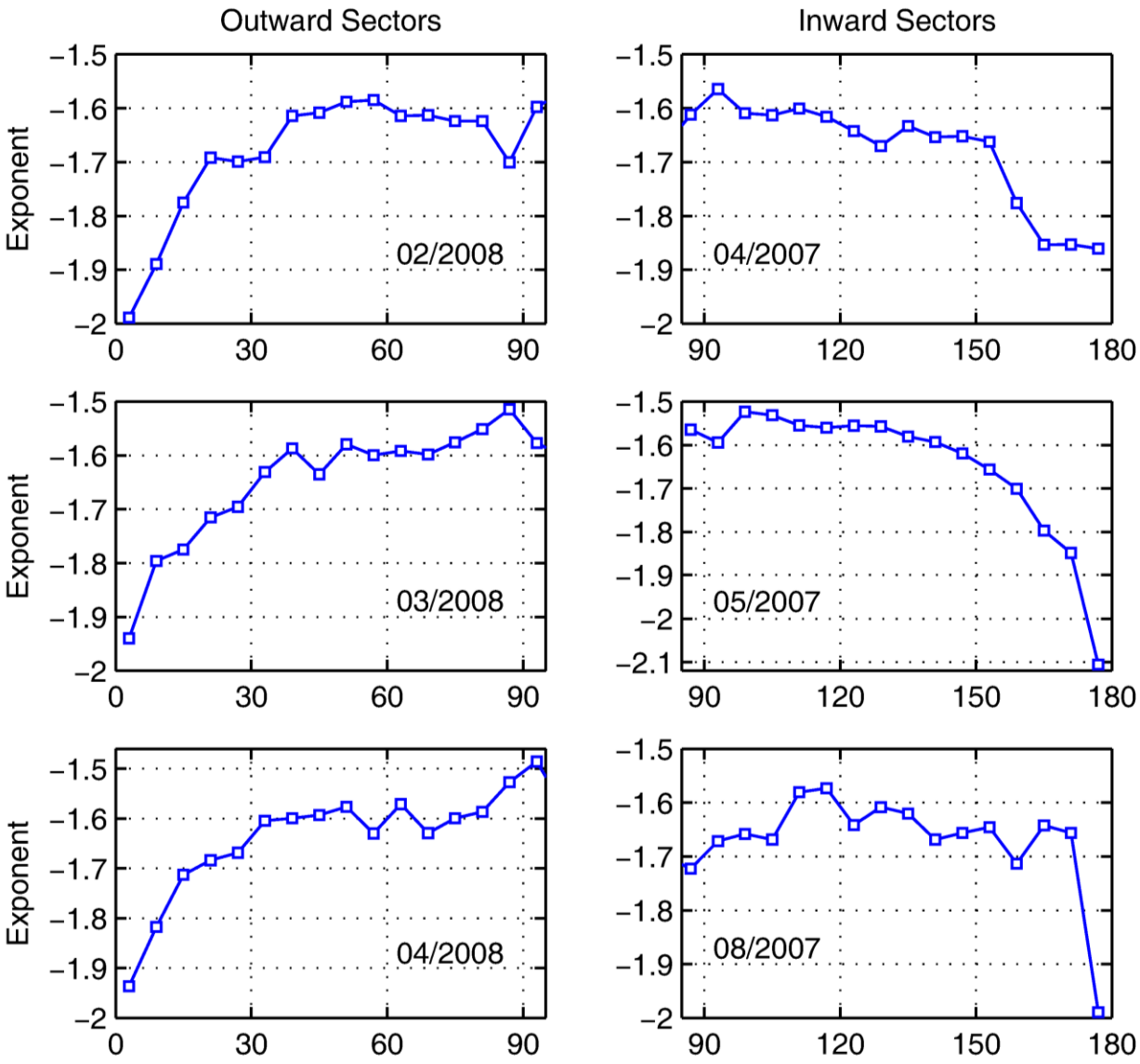
**High-speed streams**



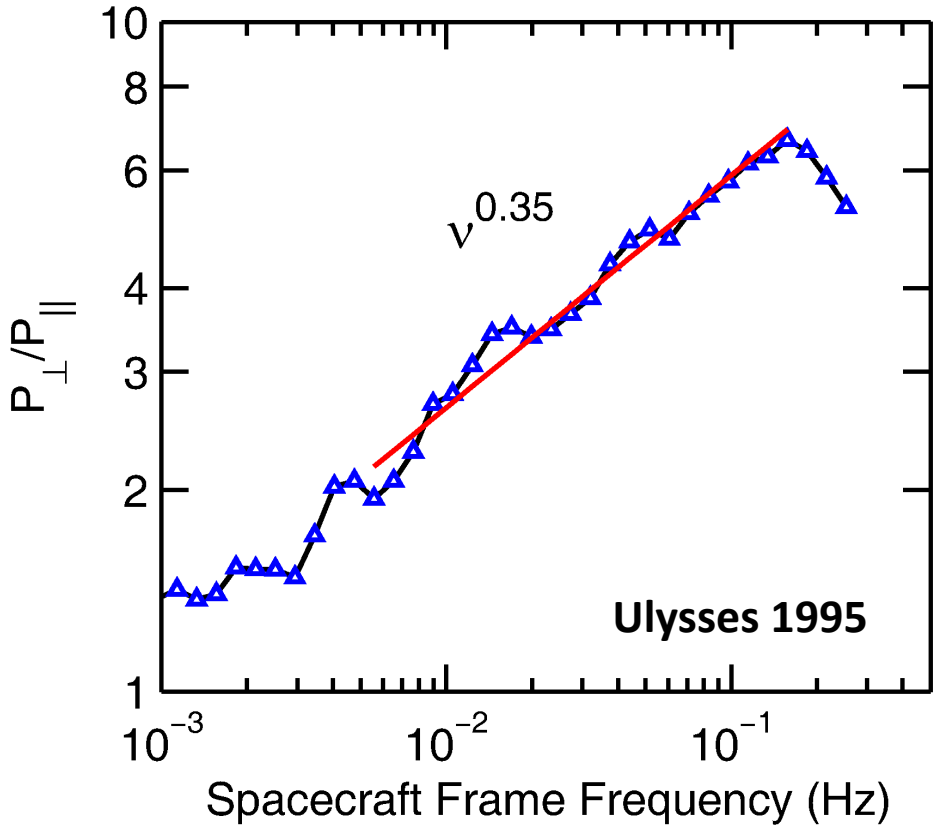
**Good News:**
**Same trend found in 9 of 9 intervals studied.**

**Bad News:**
**Power-law exponents have large error bars**

**Comparison with theory is difficult**



# Ratio $P_\perp/P_{||}$ gives sensitive test of theory

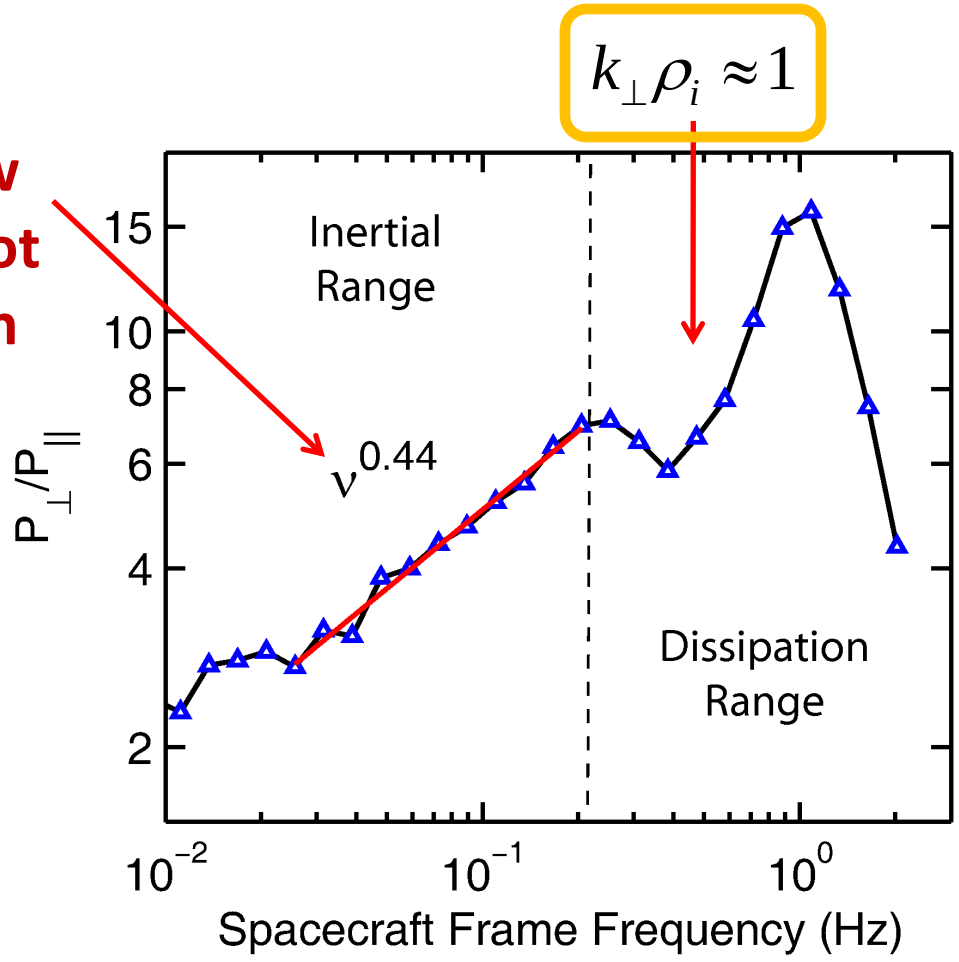



**Theory of Goldreich & Sridhar 1995 predicts**

$$\frac{P_\perp}{P_\parallel} \propto \nu^{1/3}$$

# Stereo data: High-Speed Stream, Feb 2008

**Power-law fit does not agree with GS1995**



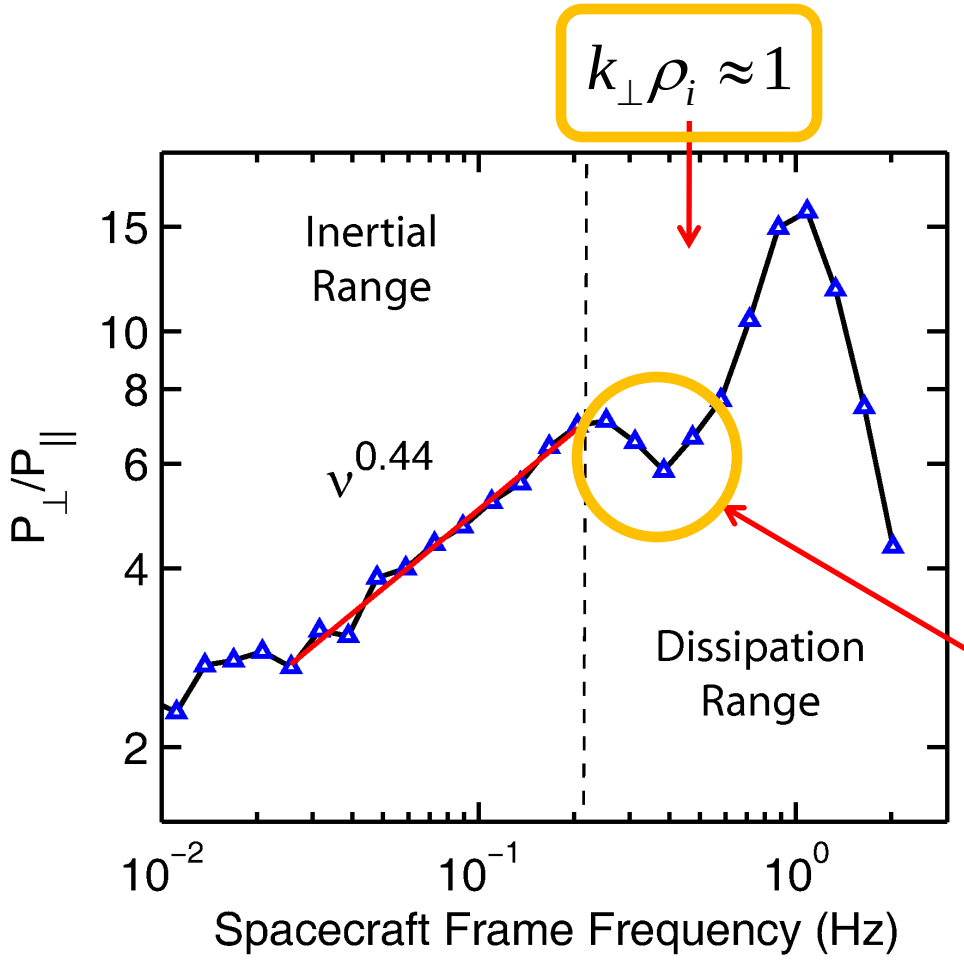

**Peak indicates Perpendicular nature of cascade in dissipation range**

**Probably the KAW cascade**

**Damping of KAWs at 2 Hz?**

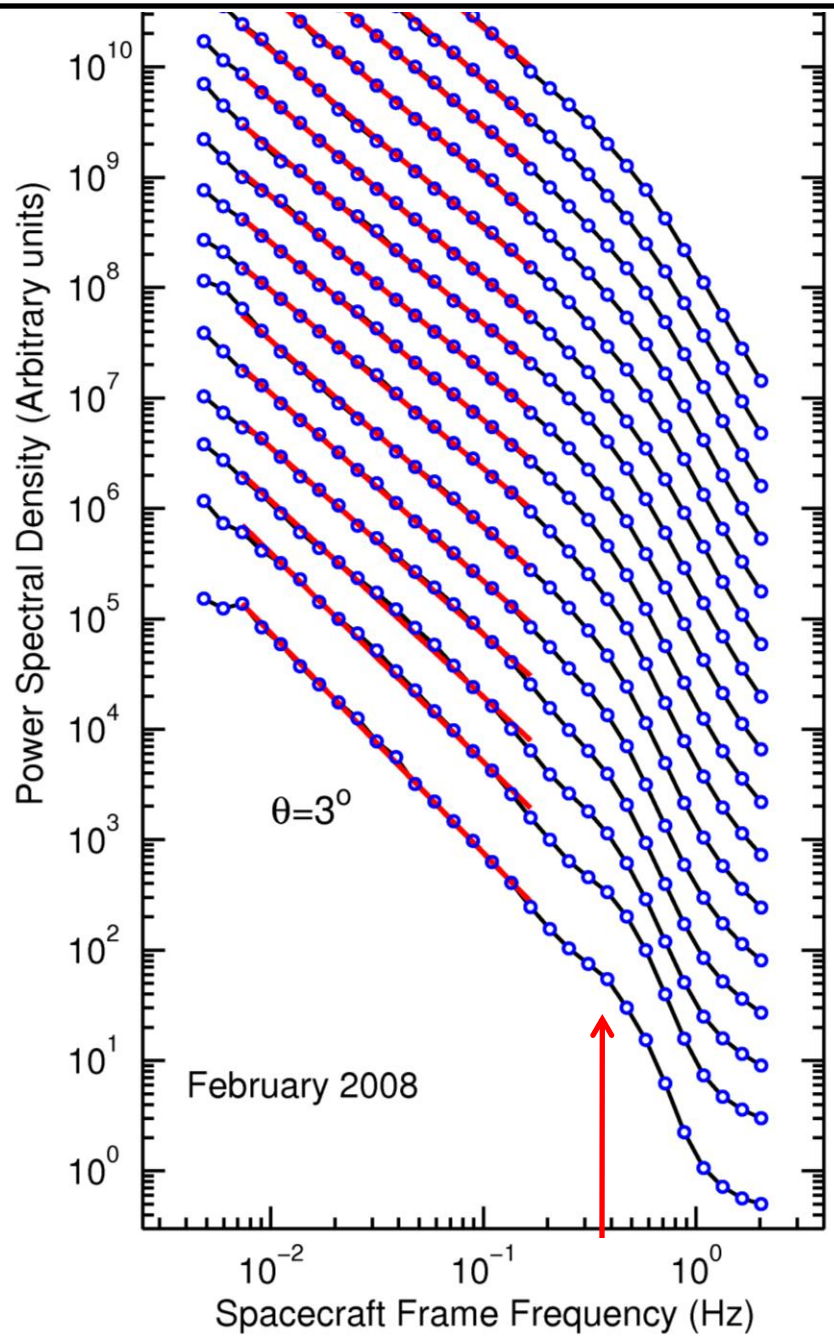
**$\gamma T \approx -1$**

# Stereo data: High-Speed Stream, Feb 2008




**Denominator increases relative to numerator**

**Enhanced power in $k_{||}$ direction**




**Small bump around spectral break in the parallel spectra**

**Caused by waves propagating nearly parallel to B**

**Abrupt cutoff of instability causes rapid rise to peak (1 Hz).**

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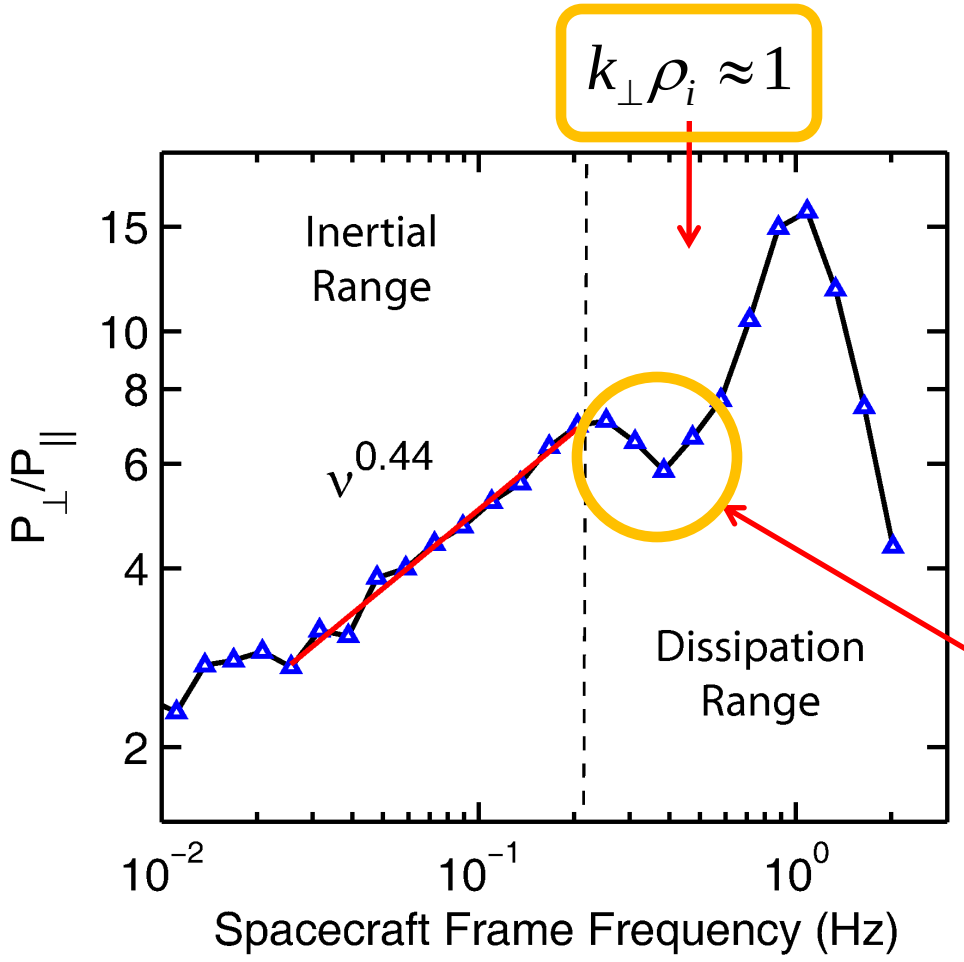


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