Rapid Measurement of Density Fluctuations in the Solar Wind (Implications for Turbulence Models)

STEREO SWG

Meredith, NH

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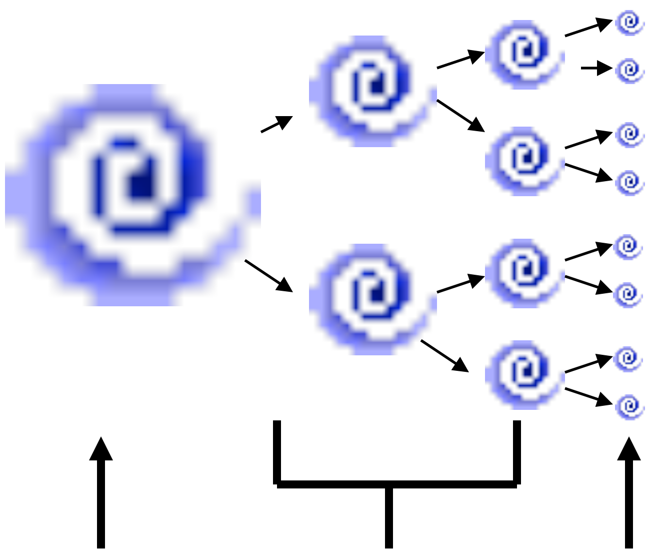
General Turbulence

Fluid Turbulence

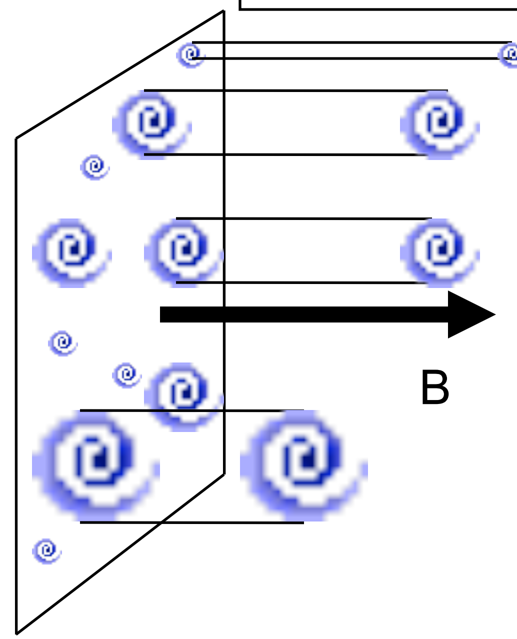


Injection | Inertial | Dissipation

$$E(k) \propto C\ \epsilon^{2/3}\ k^{-5/3}$$

- $E(k)$ → Energy Density
- ϵ → Energy Cascade Rate
- k → Inverse Fluctuation Scale Size

Plasma Turbulence



Elongation of eddies:

Dissipation in perpendicular direction 1st

Inertial:

- Separate but equal timescales || and ⊥ to B

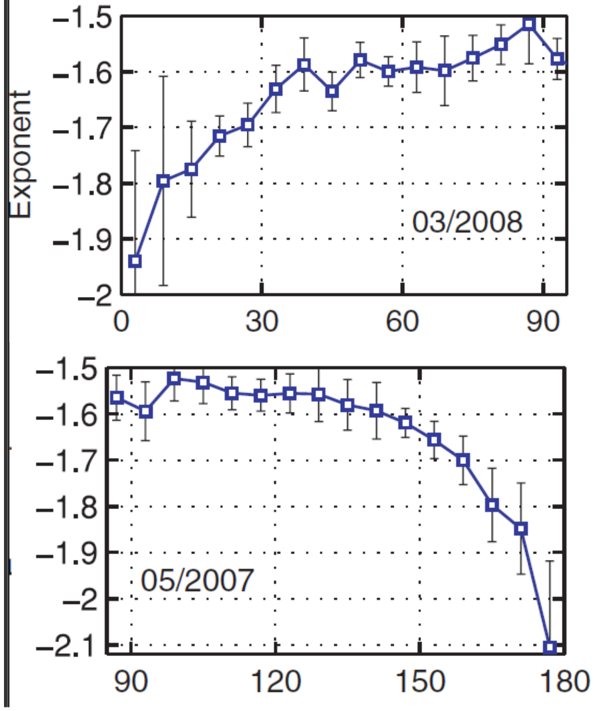
(Critical Balance Model –
Goldreich and Sridhar 1995)

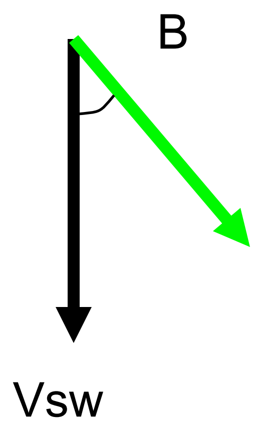
Dispersion/Dissipation (below ion gyroscale):

- Single fluid approx. breaks down
- Ion Landau damping available
- Kinetic Alfven wave cascade?

(Gyrokinetic Model - Schekochihin et al. 2009)

Previous Observations





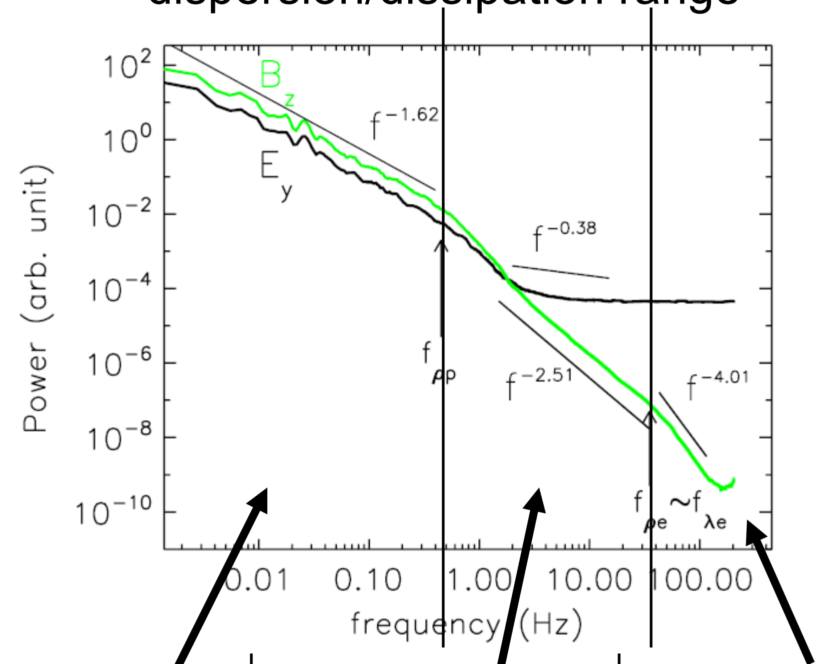
STEREO observations (Podesta 2009) match predicted anisotropy of B spectral index in <u>inertial</u> range

From GS: [$k_{||} \sim k_{\perp}^{2/3}$]
therefore:

$E_{n,B}(k_{||}) \sim k_{||}^{-2}$

$E_{n,B}(k_{\perp}) \sim k_{\perp}^{-5/3}$

Cluster observations (Sahraoui et al. 2009) match predicted B-field scaling into dispersion/dissipation range



Inertial	Dispersion	Dissipation
$E(k_{\perp}) \sim k_{\perp}^{-5/3}$ (GS/GK Predicted)	$E(k_{\perp}) \sim k_{\perp}^{-7/3}$ (GK Predicted)	$E(k_{\perp}) \sim k_{\perp}^{-?}$

Previous Observations

Maximum Frequencies of Turbulent Fluctuations Measured (spacecraft reference frame):

Magnetic Field	200 Hz (Sahraoui et al. 2009) Cluster
Electric Field	10 Hz (Bale et al. 2005) Cluster
Density	16 Hz (Celnikier et al. 1987) ISEE

Simultaneous E, B, and n measurements at frequencies up to 200 Hz needed to test turbulence theories

STEREO Measurements

<u>Langmuir frequency tracking:</u>

A technique for rapidly measuring plasma density

(7.7 Hz – 152 Hz): An unexplored density turbulence regime!

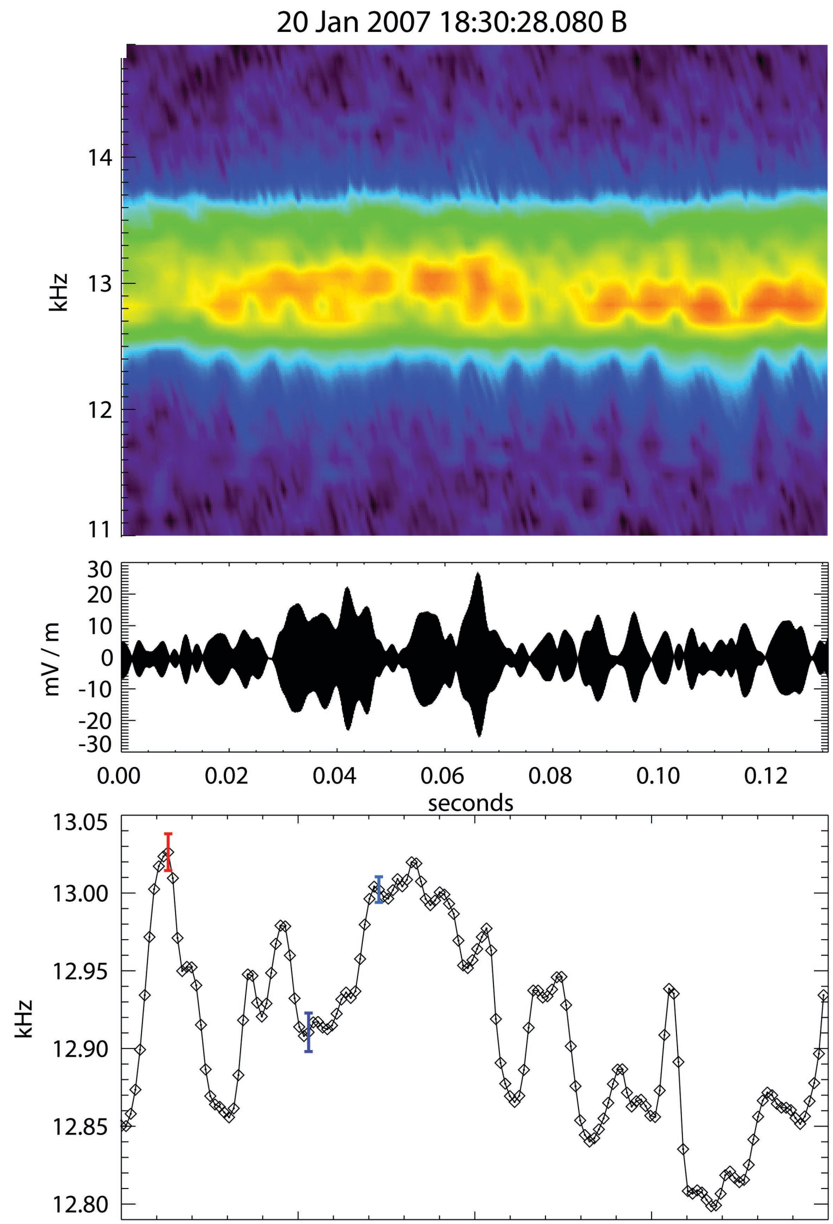
STEREO high cadence E Langmuir wave captures (125 KS/sec)

↓ Sliding window Fourier analysis

$$\omega_L^2 = \omega_p^2 + 3v_{th}^2 k_L^2$$

↓ Error analysis

$$n_e = \omega_p^2 m_e e_0 / q_e^2$$



Density Power Spectrum

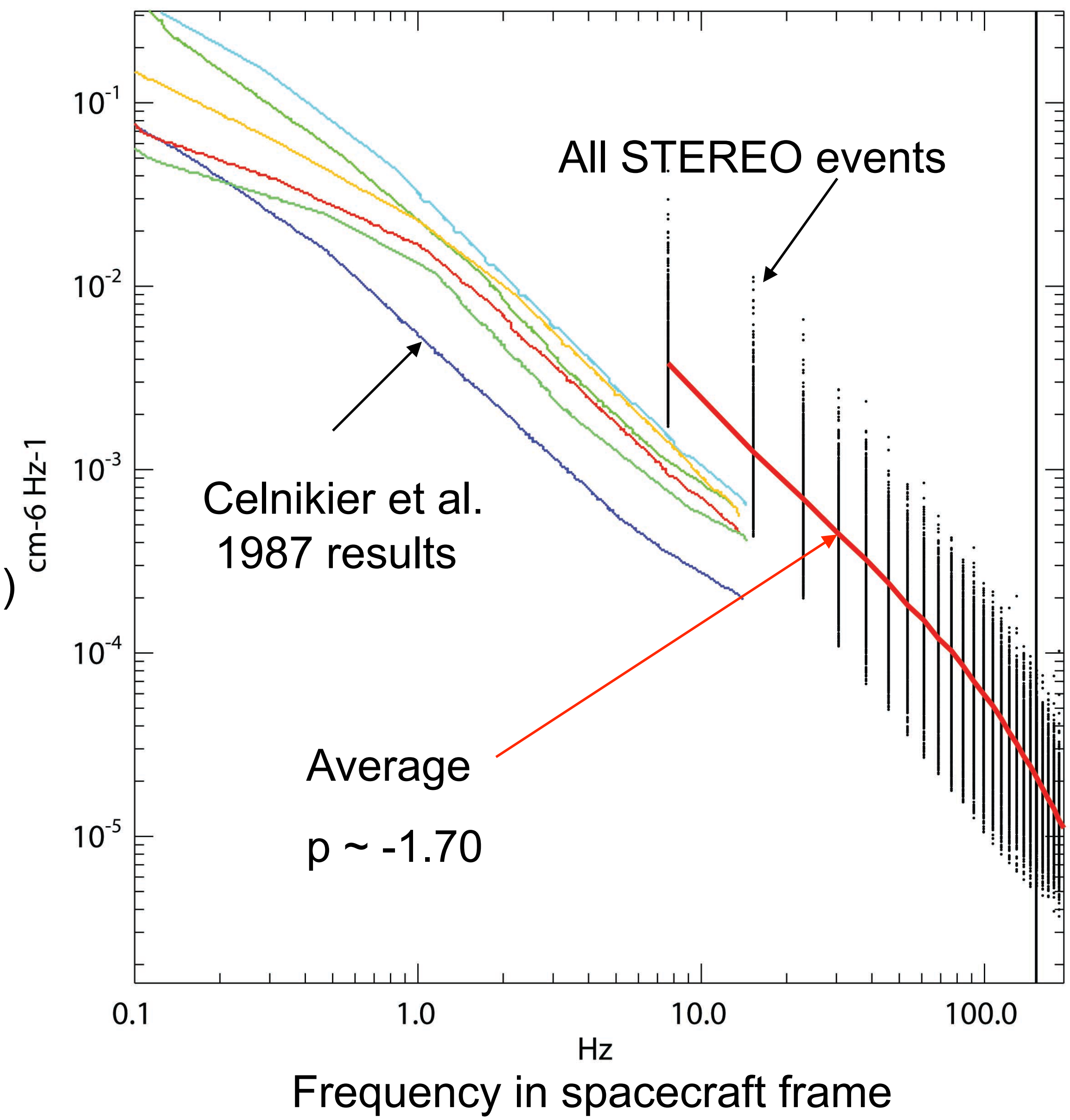
Lowest freq.

(1 / 130ms) ~ 8 Hz

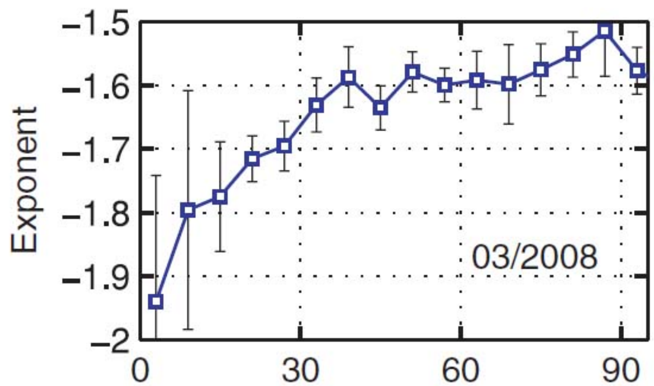
Highest freq. set by Fourier analysis (Bieber et al. 1993) and window overlap limit ~ 152 Hz

Large range of solar wind conditions sampled (~1200 events)

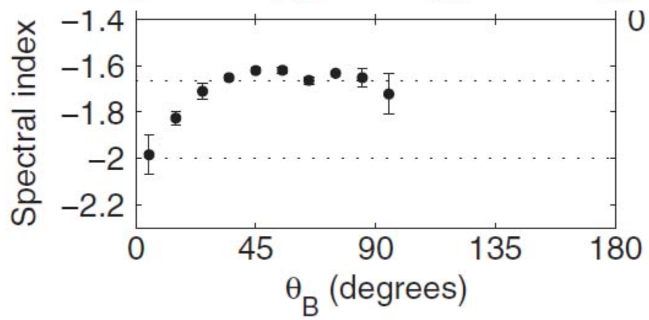
Spectral power within factor of 2 from Celnikier et al. 1987 results, using an independent technique!



Anisotropy Observations

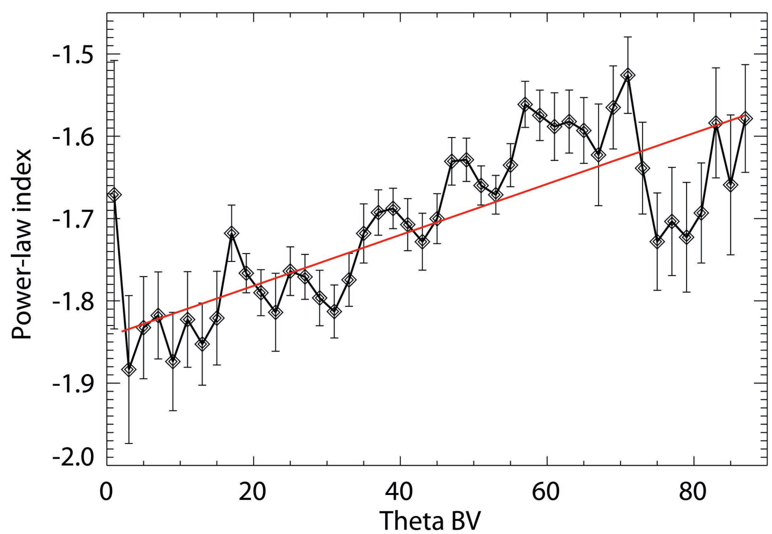


STEREO B turbulence
Podesta 2009



Ulysses B turbulence

Horbury 2008



STEREO n

turbulence

→ Dispersion range anisotropy

→ -1.90 to -1.60 with θ

(expected for <u>inertial</u> range?)

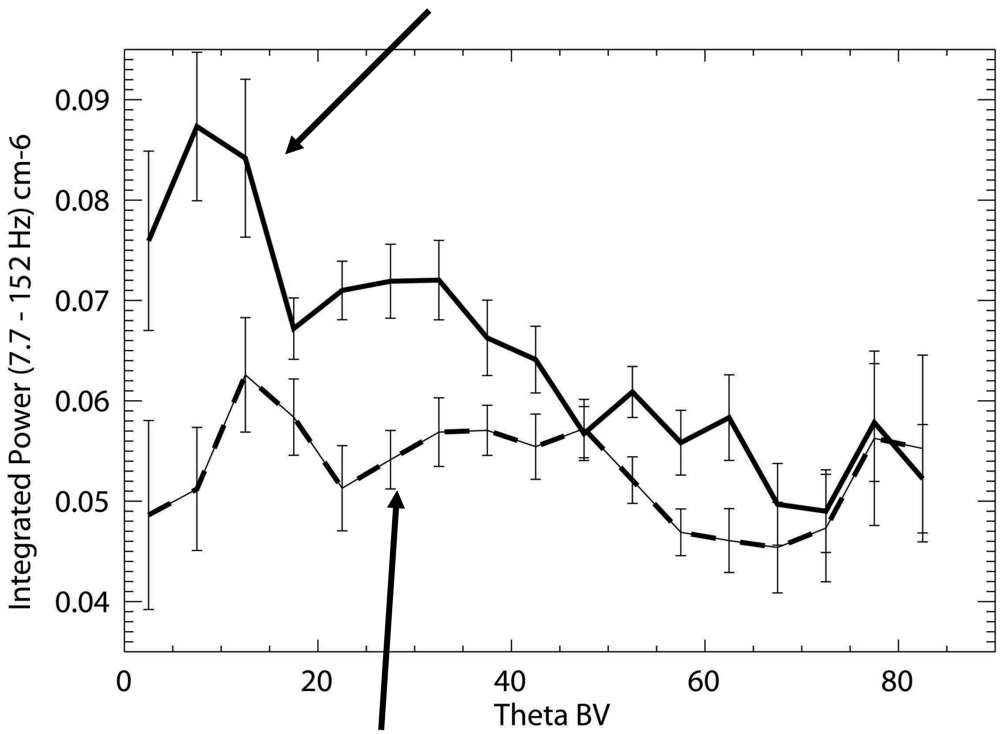
→ -11/ 3 to -7/ 3 expected for <u>dispersion</u> range (by GK theory)

(Observed for |B|)

→ Why is density different?

Kinetic Alfven Waves?

Fast wind (> 450 km/s)



Slow wind (< 450 km/s)

- In-situ generated density fluctuations parallel to B

- Stronger in Fast Wind (solid line)

- High Ti / Te = weak KAW damping
  [Fast Wind]

- Low Ti / Te = strong KAW damping
  [Slow Wind]

- Indicates KAW cascade?
  - Coordinated particle obs. Needed

Possibly better to organize by collisional age (Kasper et al. 2008) (Bale et al. 2009)

Summary

- Frequency-tracking technique to measure rapid electron density fluctuations

- Some results agree with prior turbulence observations / models:
    - Good agreement with (Celnikier et al. 1987) results
    - Strong anisotropy
    - hints of kinetic Alfven waves (?)

- Some results do not match:
    - Scaling does not match GK model predictions in dispersion range

- What exactly is going on at dispersion/dissipation scales?

    Need coordinated B-field, E-field, and N at high cadence for more rigorous tests

End

Error Analysis

$$\omega_L = \omega_p \left(1 - \frac{3T_e}{v_b^2 m_e}\right)^{-\frac{1}{2}} \left(1 + \frac{v_{sw}}{v_b} cos(\theta_{Bv})\right)$$

Te variation (negligible?)

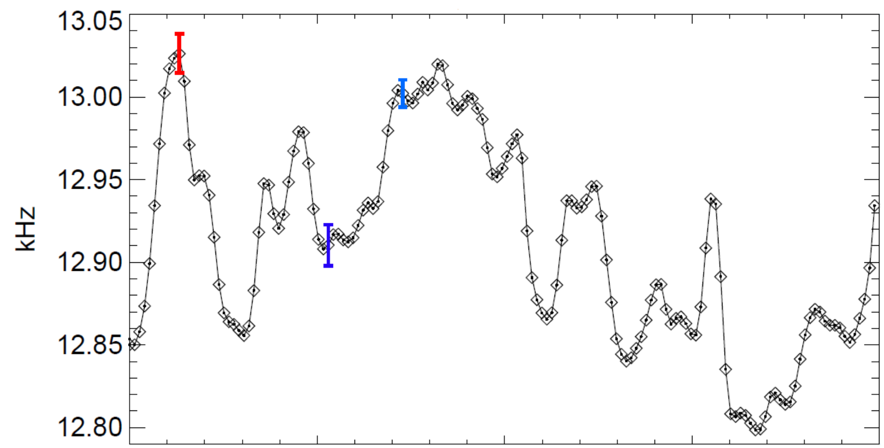
Vsw variation (5% variation)

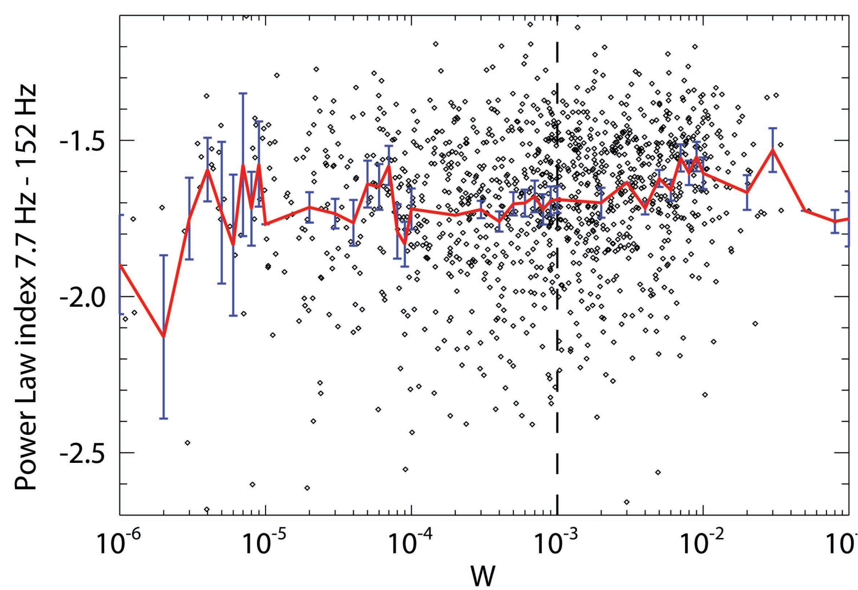
θ variation (2% variation)

vb variation (3% variation)

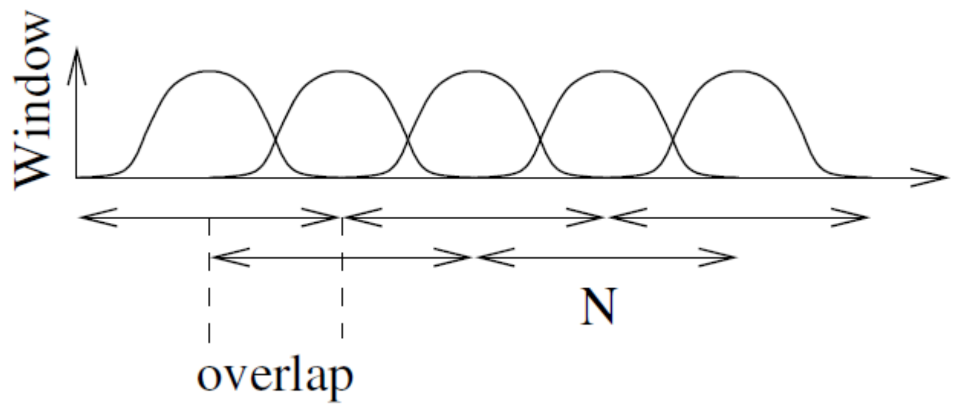
Ponderomotive effects
(small trend, within error)

Ratio of electric to kinetic energy
> 10^{-3} for millisecond durations,
(sometimes)

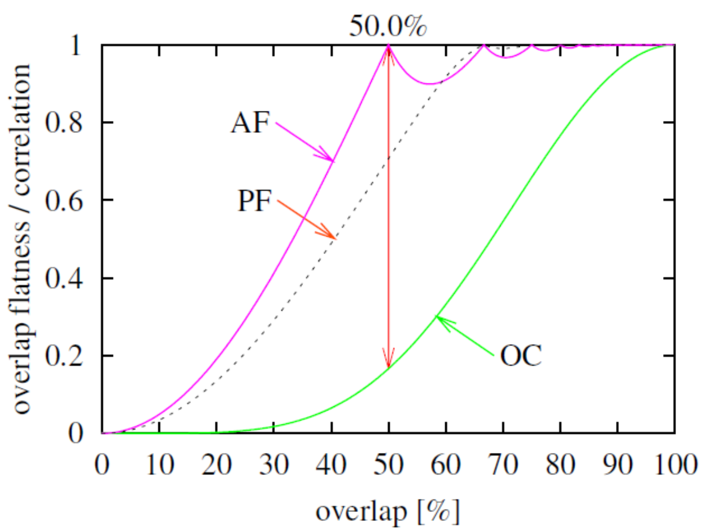




Error Analysis (overlap)



Heinzel et al. 2002



N τ	Overlap with 0 τ (r)	OC	$f_{Nyquist}$ (Hz)
1	90	94	610
2	80	77	304
3	70	55	203
4	60	33	152
5	50	17	122

Figure 9 *Overlap characteristics of the Hanning window.*

Why Study SW Turbulence?

- No generally accepted model of magnetized plasma turbulence
  - Analogy to fluid turbulence does not apply since DC magnetic field separates parallel and perpendicular scales
  - How are electric, magnetic, and density turbulence related?
  - What mechanism governs small scale dissipation?
  - What about intermittency?

- Longstanding Questions
  - What causes heavy ion preferential heating? (ion-cyclotron waves?)
  - What causes coronal heating / acceleration? (Kinetic Alfven waves?)