Observational evidence for anisotropic solar wind turbulence on fluid and kinetic scales

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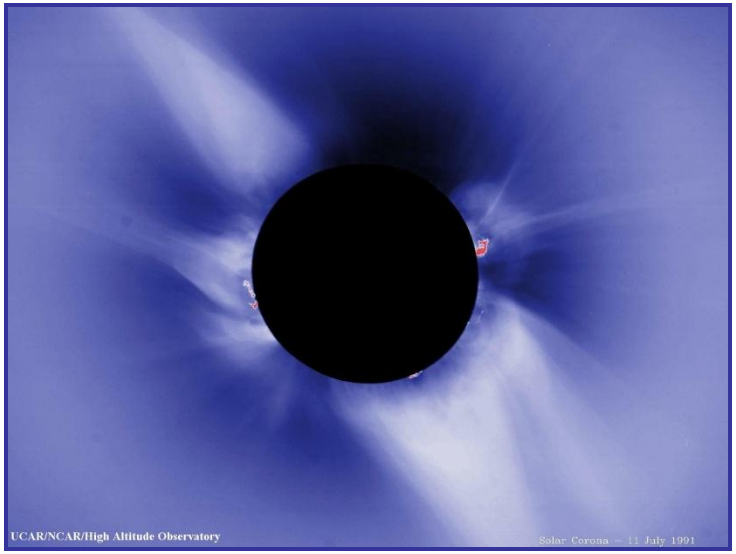
Thanks to Chris Chen, Robert Wicks, Alex Schekochihin, Miriam Forman

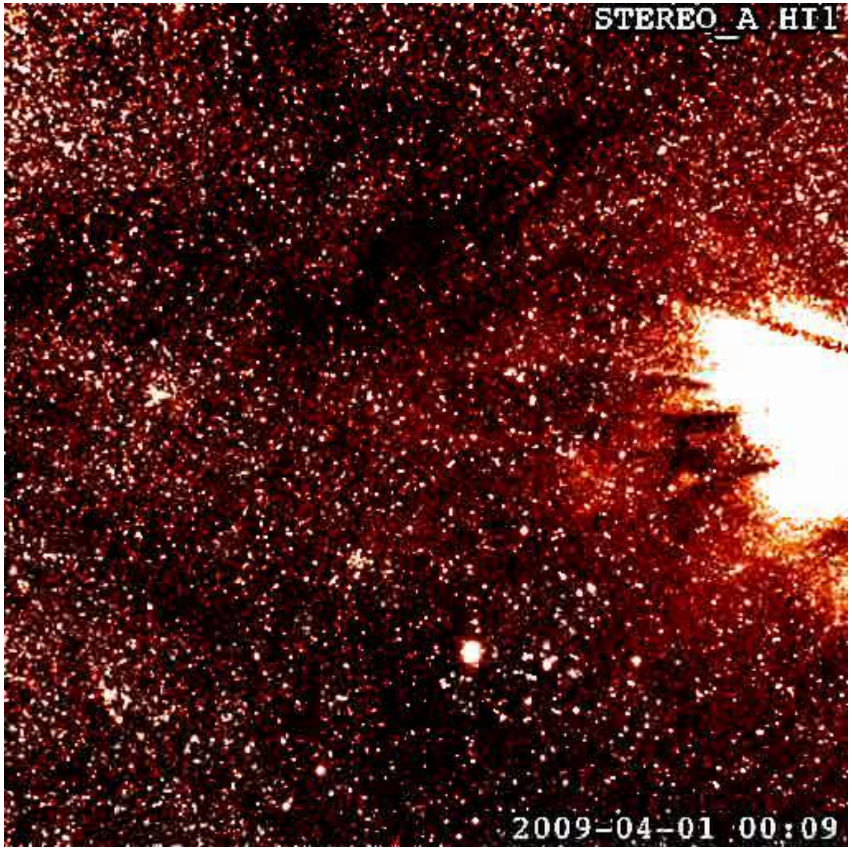
- The solar wind as a turbulence laboratory
- What we know: the basics
- MHD scale cascade
- Ion scale cascade
- Kinetics: instabilities
- Open questions



What is the solar wind?

- Collisionless, magnetised plasma
- Continual, but variable, outflow from Sun's corona
- Carries waves and turbulence from corona

- **Complex** due to solar variability, solar rotation, and in situ processes
- **Variable** on all measured scales, from sub-second $\rightarrow$ centuries



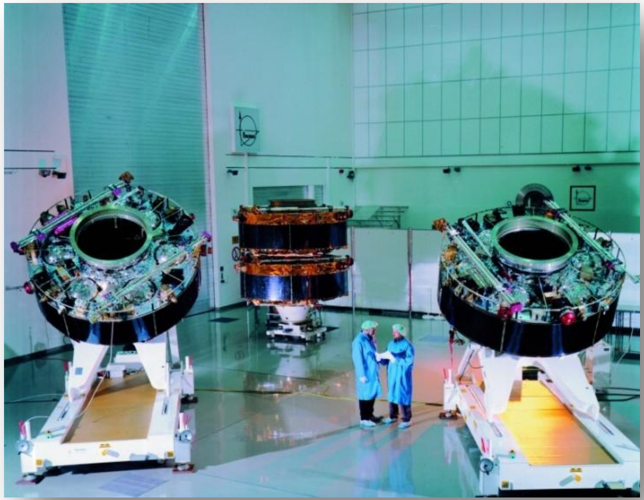
STEREO/HI

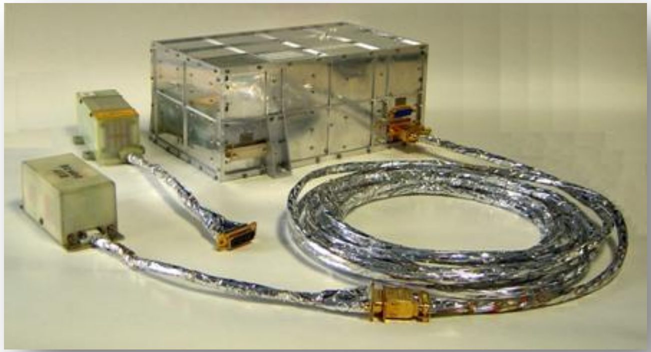
Typical solar wind parameters (near Earth)

Composition	Mostly protons, few percent alpha, small heavies
Ion temperature	$\sim 10^5$ K
Bulk speed	250-800 km/s
Alfven speed	~40 km/s
Debye length	~10m
Mean free path	~1 AU
Proton gyroradius	~100 km
Proton inertial length	~100 km
Magnetic field	~5nT
Proton beta	~ 1

Spacecraft as sensors

- Spacecraft are (mostly) test particles
- Natural fields are very small – significant spacecraft interference issues
- Typical measurements
  - Magnetic field (DC to tens Hz)
  - Electric field
  - Bulk ion properties (velocity, temperature, density)
  - Bulk electron properties (velocity, temperature, density)
  - Full plasma distributions including composition
  - Energetic particles

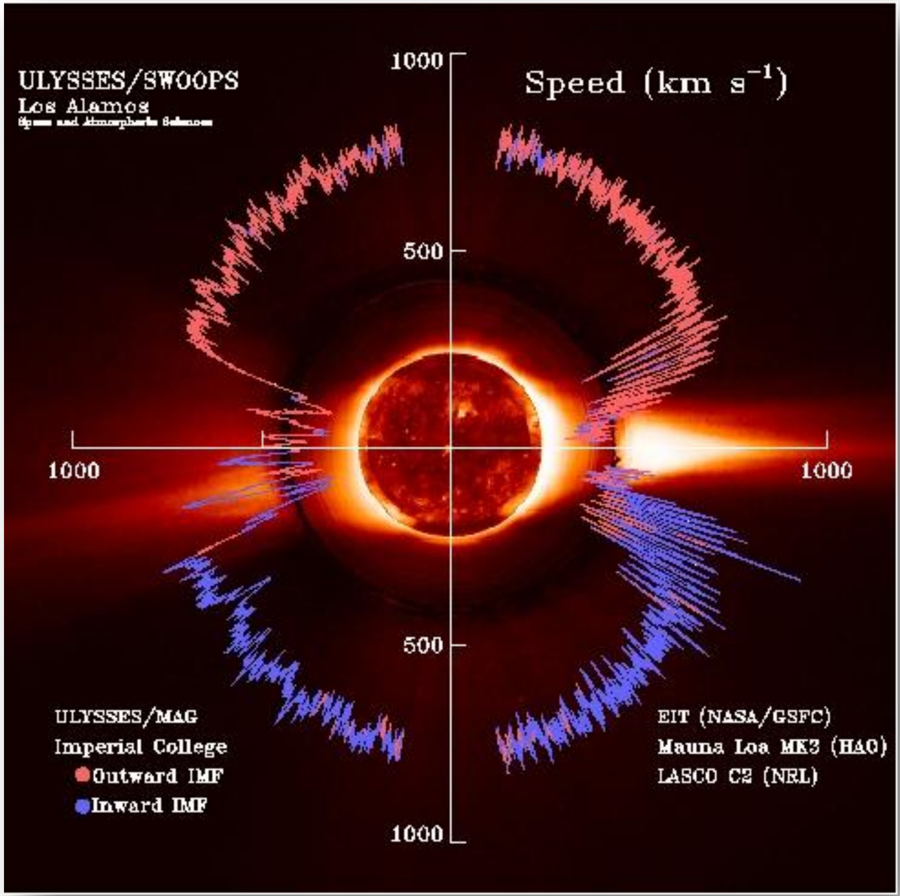




Exploring the solar system

- Spacecraft have explored most of the solar system
- None has a fully comprehensive instrument package

- Big changes in properties with distance, latitude, solar cycle
- Biggest factor is fast vs slow solar wind



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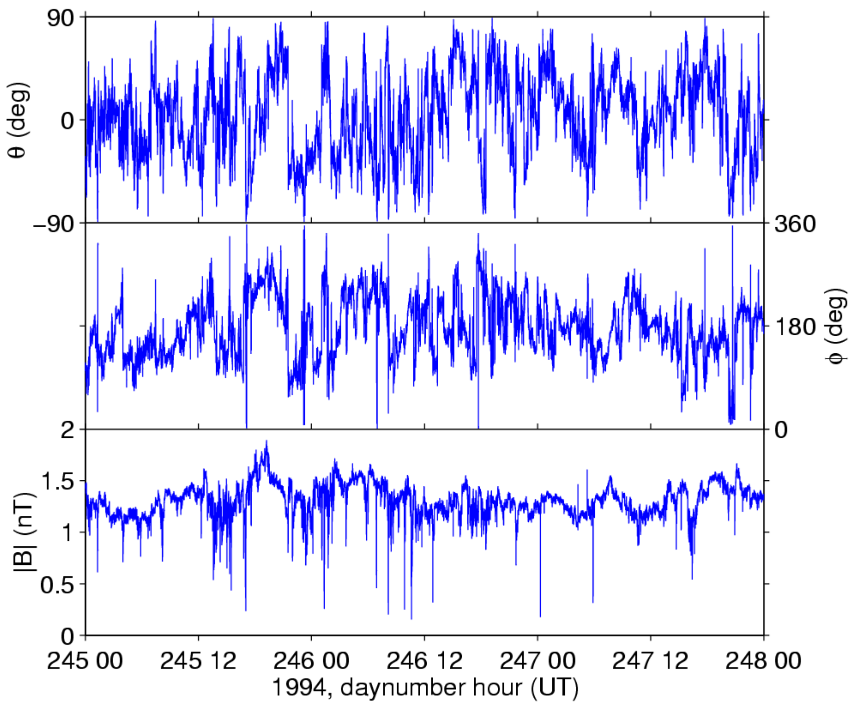
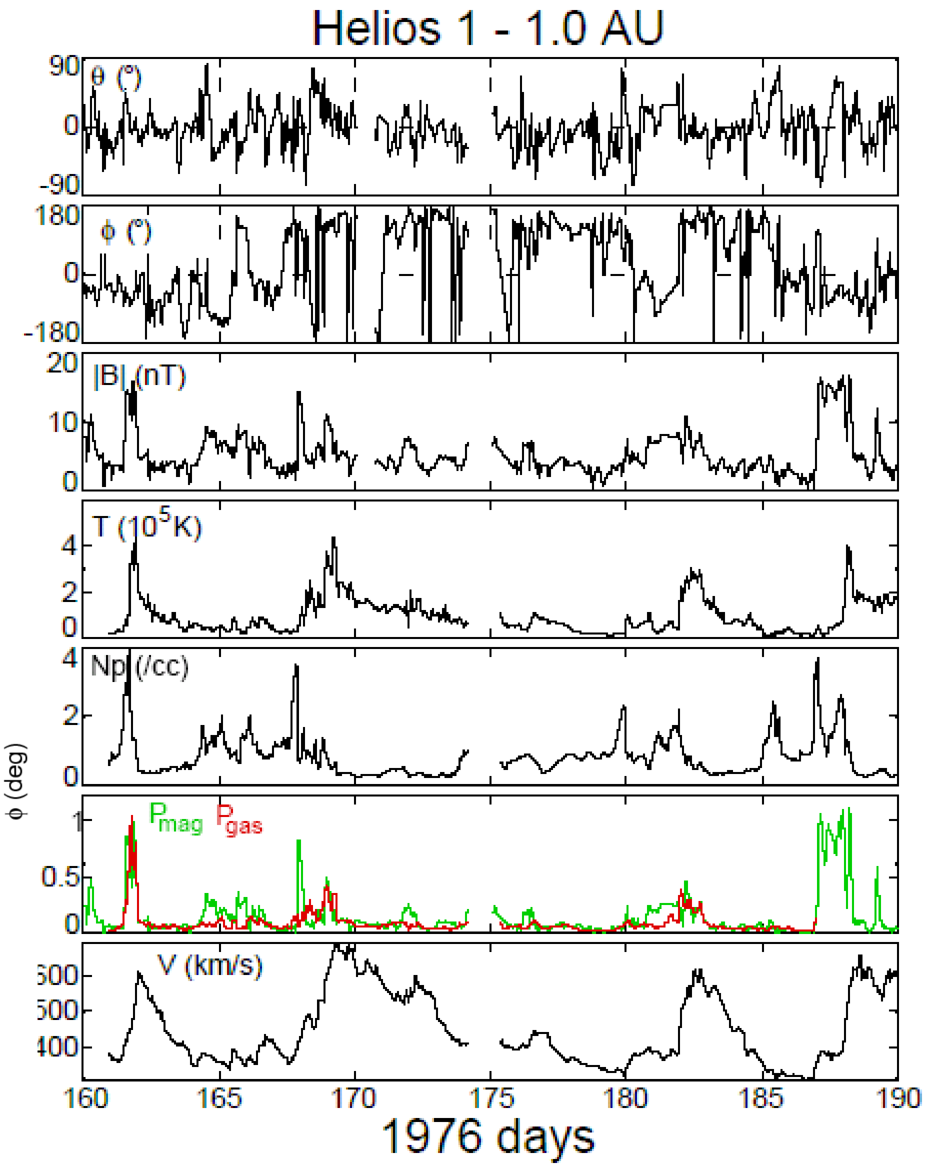
Typical conditions at 1.0 AU

- Individual streams last a few days
- Always need to consider the context





Interpreting spacecraft measurements

- In the solar wind (usually),

$$V_A \sim 50 \text{ km/s}, \; V_{SW} > \sim 300 \text{ km/s}$$

- Therefore,

$$V_{SW} >> V_A$$

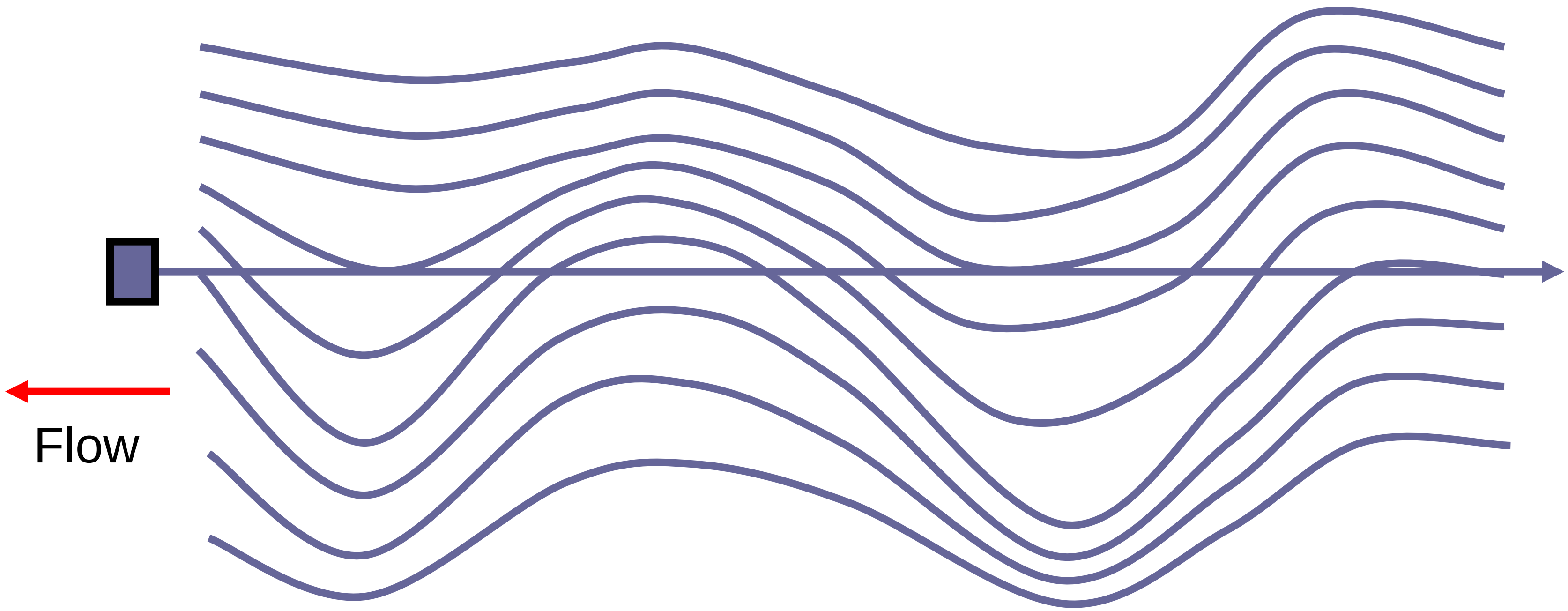
- **Taylor's hypothesis**: time series can be considered a spatial sample
- We can convert spacecraft frequency *f* into a plasma frame wavenumber *k*:

$$k = 2\pi f \,/\, V_{SW}$$

- Almost always valid in the solar wind
- Makes analysis much easier
- Not valid in, e.g. magnetosheath, upper corona, kinetic scales(?)

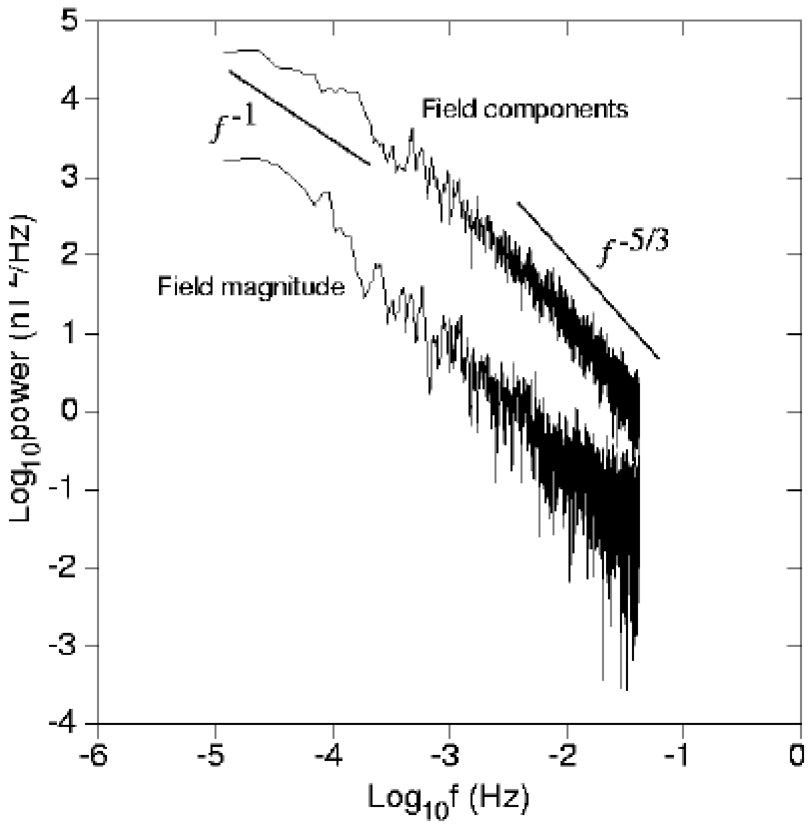
Interpreting spacecraft measurements

- Solar wind flows radially away from Sun, over spacecraft
- Time series is a one dimensional spatial sample through the plasma
- Measure variations along one flow line



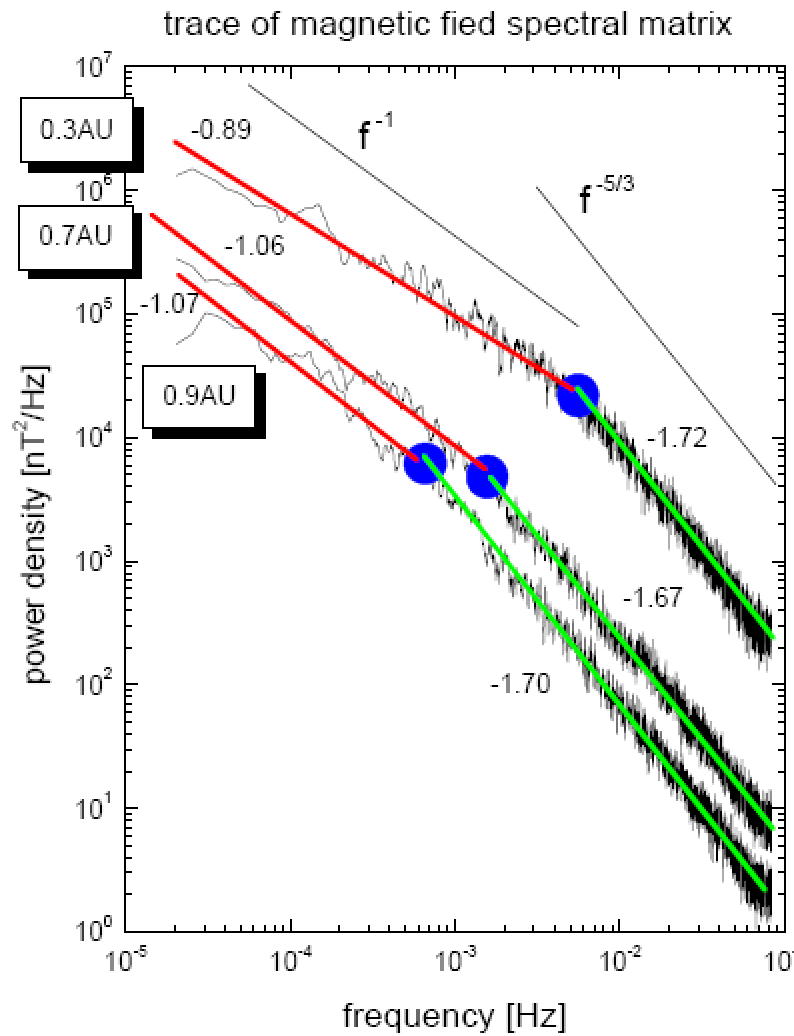
Things we know: power spectrum

- Extended fluid scale inertial range
- Magnetic field power spectrum:
  - $f^{-5/3}$
- Inertial range covers $\sim 10^2$ in scale
- Components much higher power than magnitude
  - Largely non-compressive



Active turbulent cascade in fast wind

- Bavassano et al (1982)
- Fast wind: “knee” in spectrum
- Spectrum steepens further from the Sun
- Evidence of energy transfer between scales: **turbulent cascade**



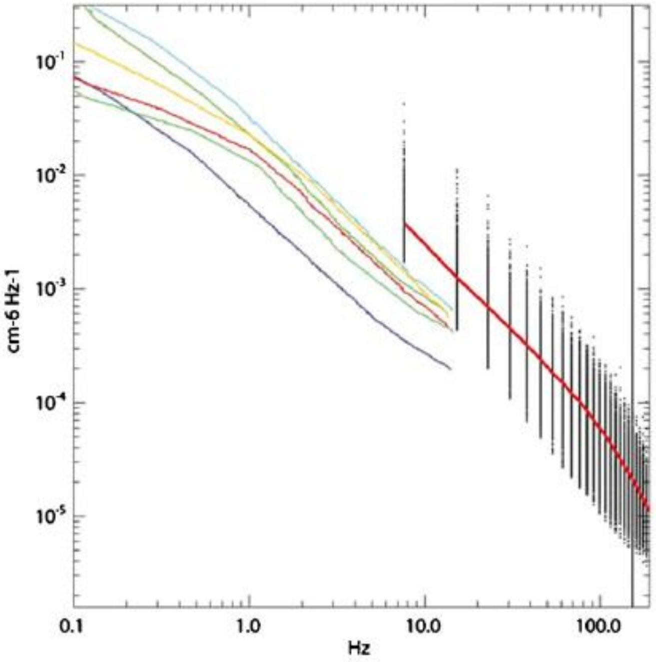
after Bavassano et al 1982

Density spectrum

- Malaspina et al., Ap. J., v.711, 322, 2010
- See also Celnikier et al., Astron. Astrophs., v.181, 138, 1987

- Broadband density spectrum
- Evidence for break at ion gyroscale

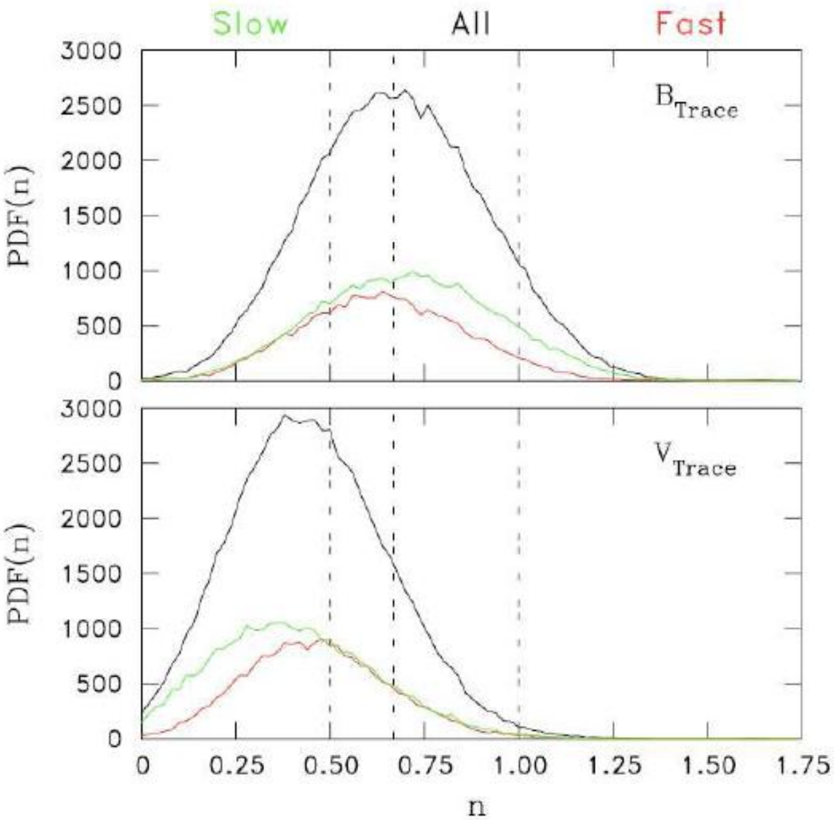
- Behaviour as a passive scalar on MHD scales?



Velocity vs magnetic field scaling

- Magnetic field has 5/3 spectral index
- Velocity has 3/2 spectral index (Podesta, 2009)

- Physical cause of this effect?
  - Related to Alfvenicity?



Tessein et al., 2009

Alfvén waves

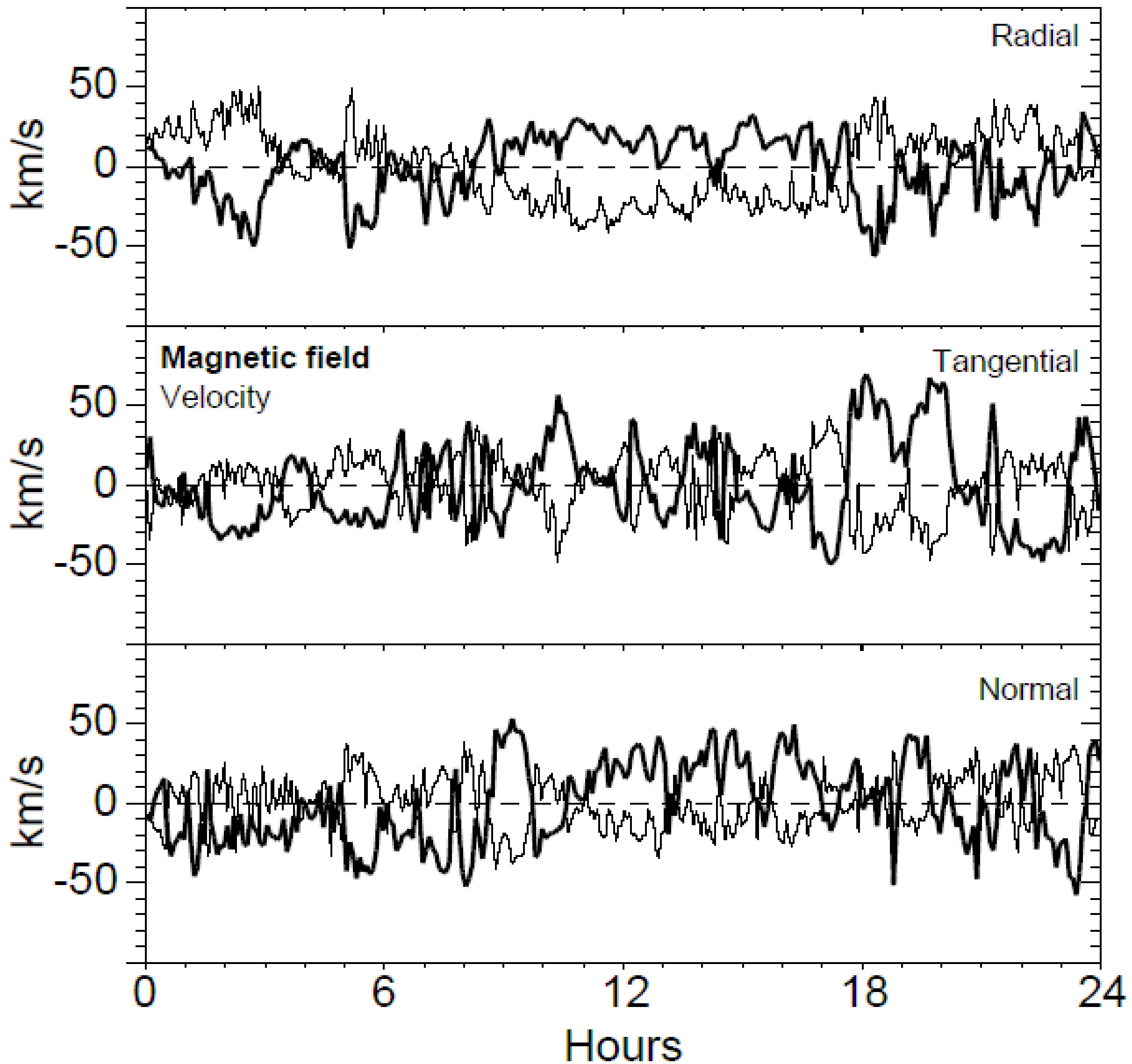
Field-parallel Alfvén wave:

- B and V variations anti-correlated

Field-anti-parallel Alfvén wave:

- B and V variations correlated

- See this very clearly in the solar wind
- Most common in high speed wind



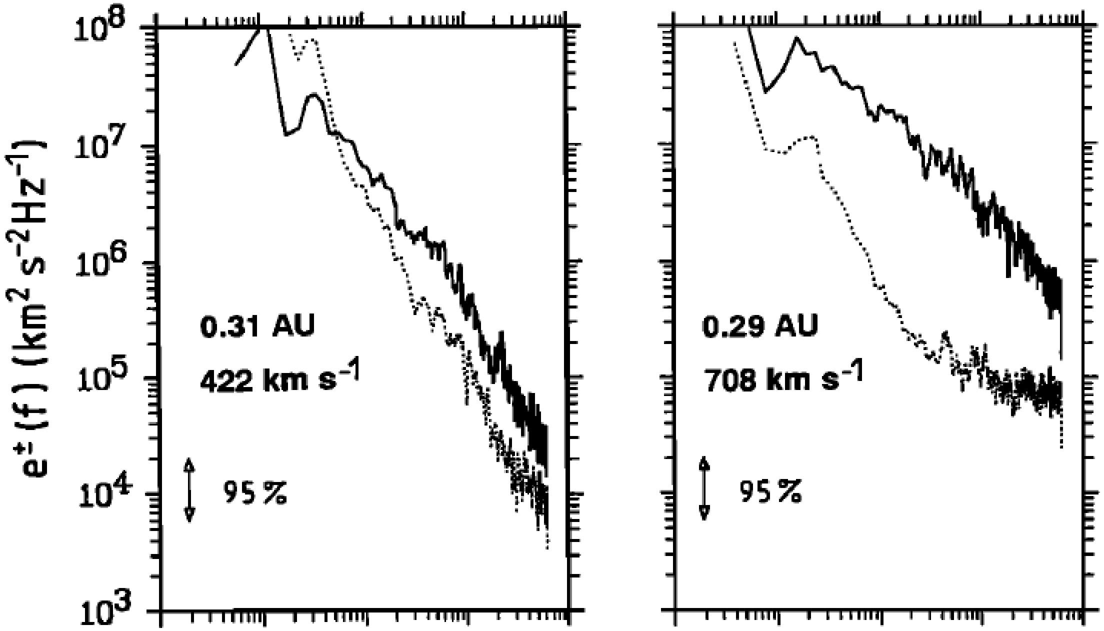
Elsasser variable power spectra

Fast wind

- Imbalanced, dominant outward component
- “Diamond” spectrum

Slow wind

- More balanced on average
- Longer inertial range



Marsch and Tu, JGR, 1990

- **Solar wind often shows significant imbalance**

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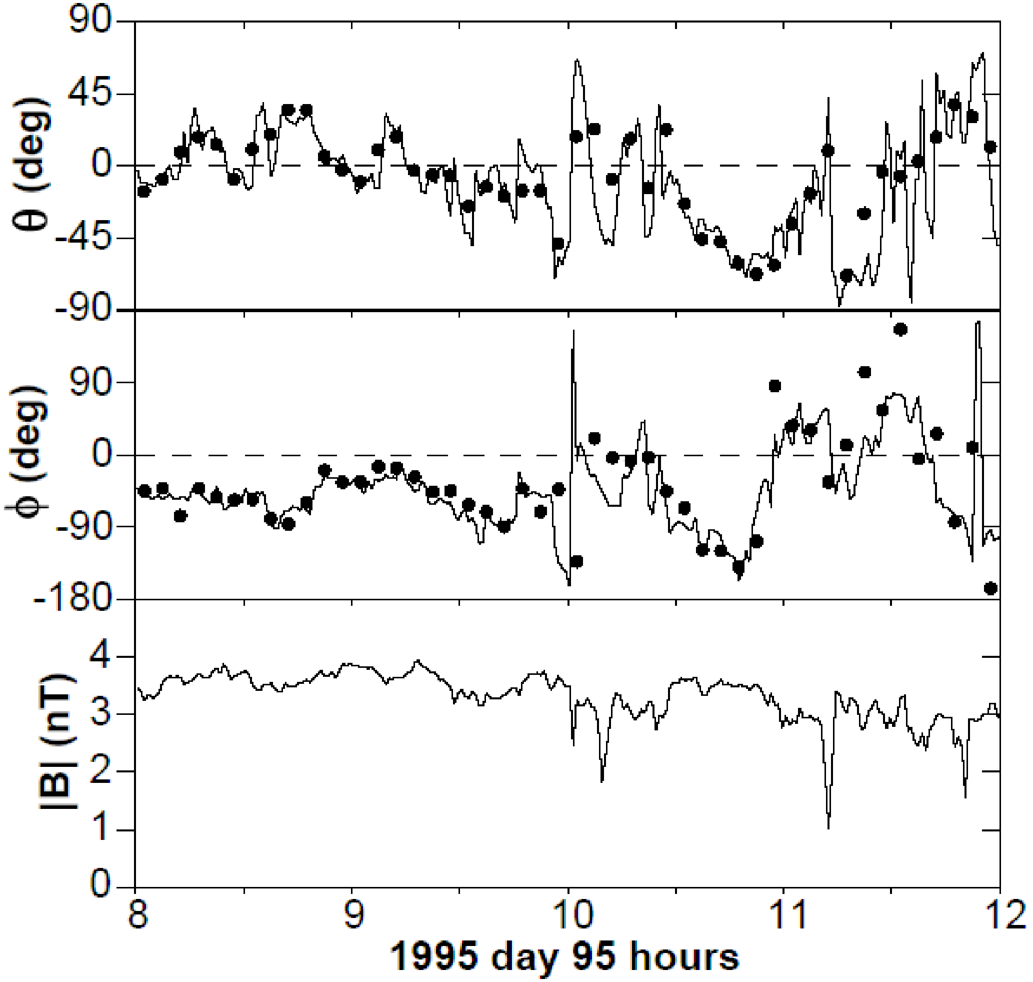
Field-aligned anisotropy

- Power levels tend to be perpendicular to local magnetic field direction
  $\rightarrow$ **anisotropy**

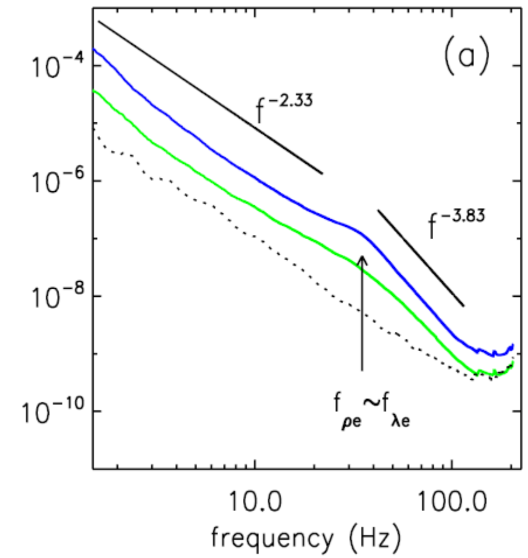
- Dots: local minimum variance direction
- Track large scale changes in field direction

- Small scale turbulence “rides” on the back of large scale waves

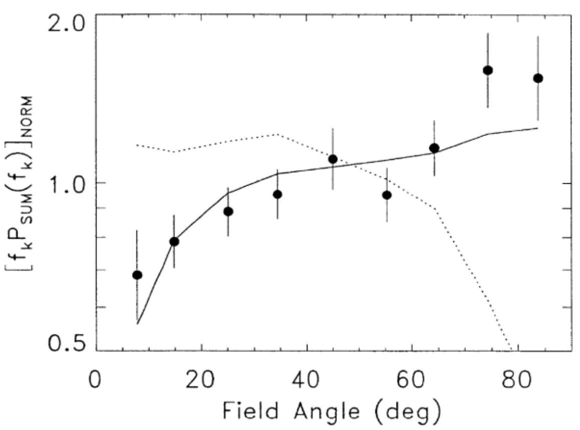


Types of anisotropy

- Variance anisotropy
  - $\delta B_\perp > \delta B_{||}$ (e.g. Belcher and Davis, 1971)
- Wavevector anisotropy
  - Different energy in wavevectors in different directions (e.g. Bieber et al., 1996)
- Scaling anisotropy
  - Different power laws in different directions
- Anisotropy of energy transfer
  - Turbulent cascade can have different rates in different directions
- "Imbalance"
  - Parallel/anti-parallel propagation of Alfvénic turbulence

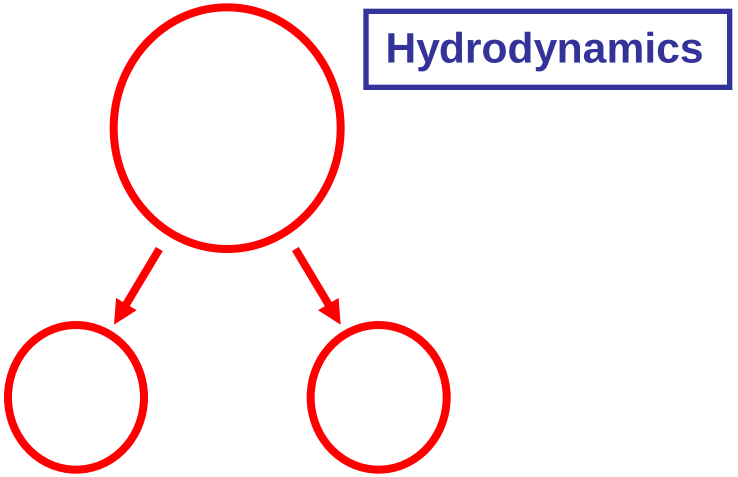


Sahraoui et al., 2009



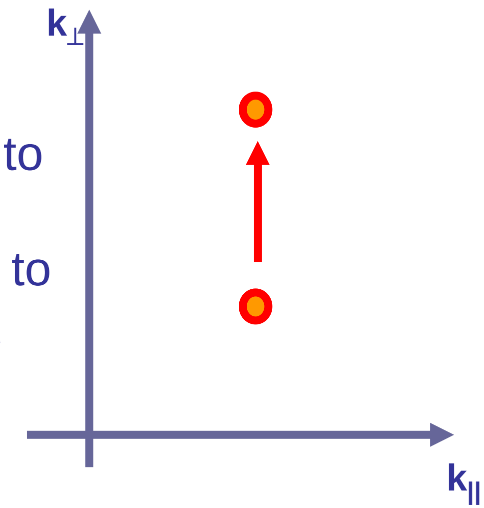
Bieber et al., 1996

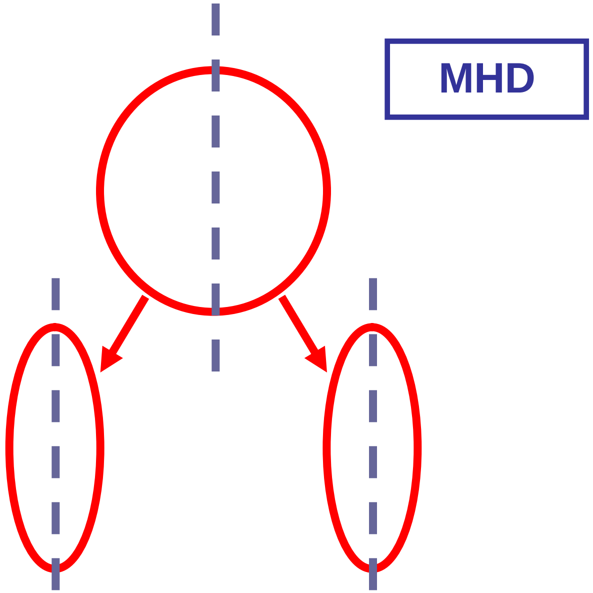
Anisotropic energy transfer



Wavevectors

- Energy tends to move perpendicular to magnetic field





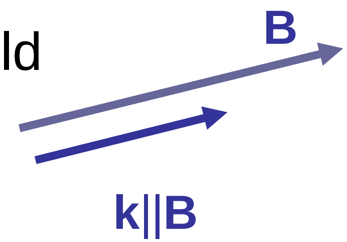
Eddies

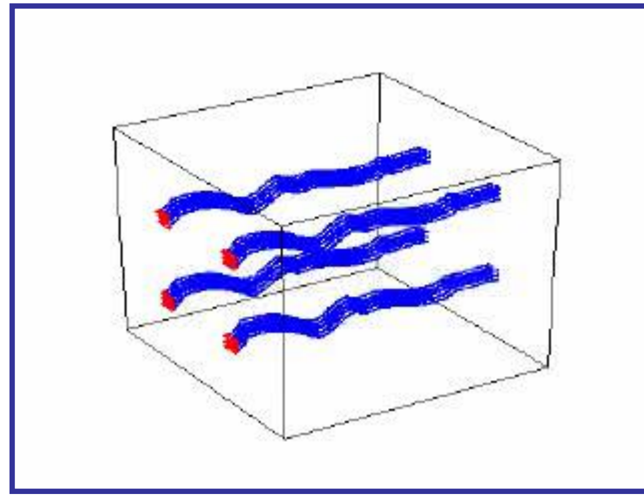
- On average, tend to become smaller perpendicular to field
- Results in long, fine structures along the magnetic field

Anisotropy and 3D magnetic field structure

Slab

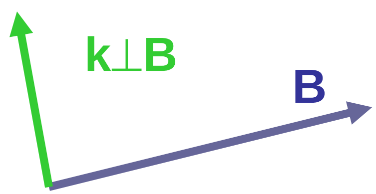
- Plane waves
- Infinite correlation length perpendicular to magnetic field
- Flux tubes stay together

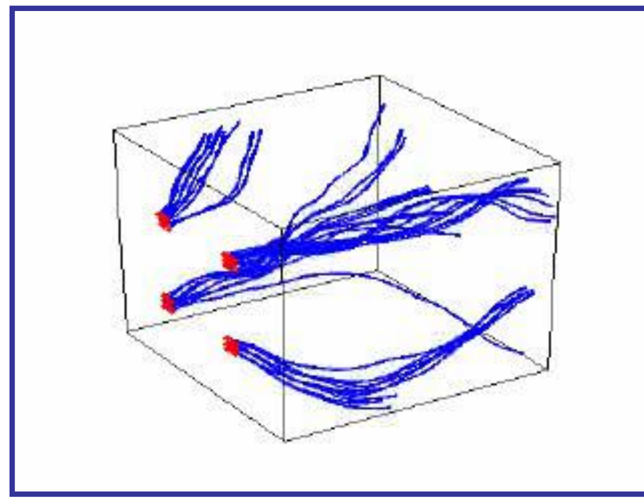




2D (+slab)

- Finite perpendicular correlation length
- Flux tubes “shred”

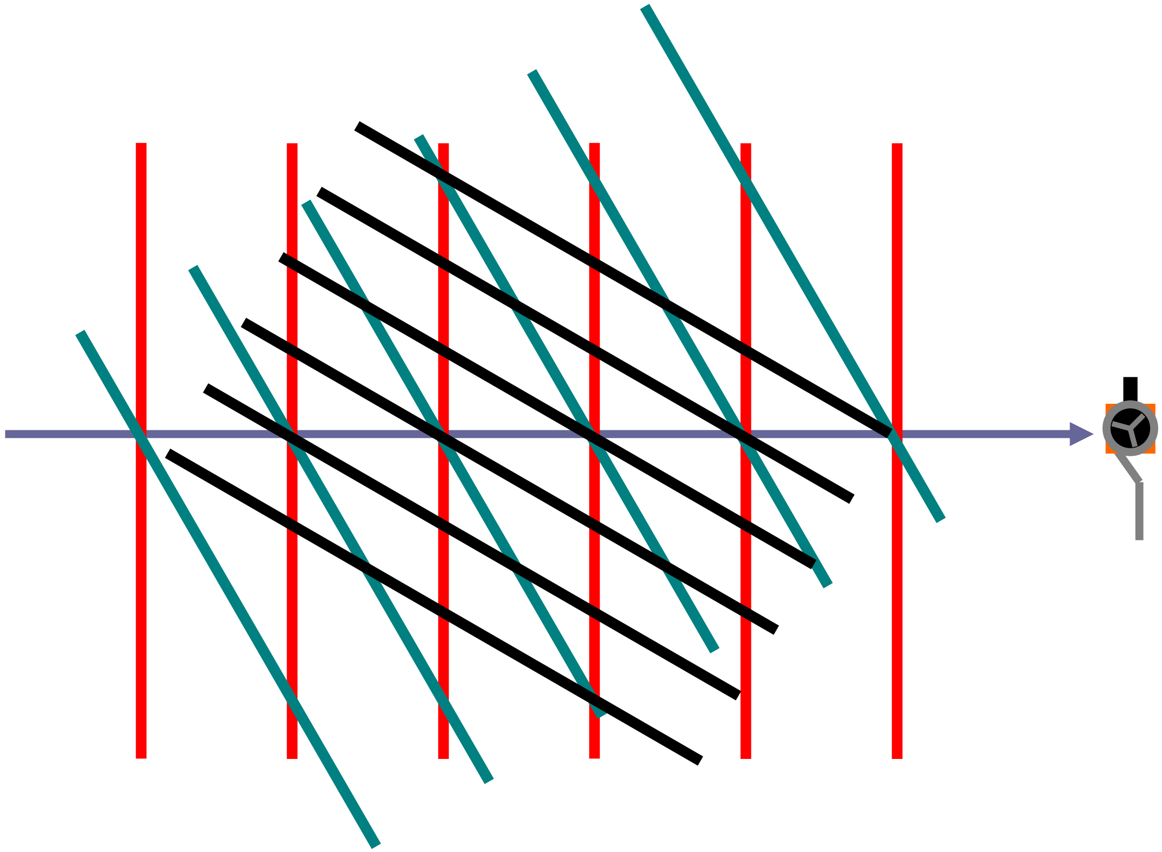




→ Important consequences for particle transport

Measuring anisotropy: reduced spectrum

- For a given spacecraft frequency f, this corresponds to a flow-parallel scale $\lambda = V_{SW} / f$
- …and a flow-parallel wavenumber $k_{||} = 2\pi f / V_{SW}$
- But sensitive to all waves with $k \cdot V_{SW} = 2\pi f$



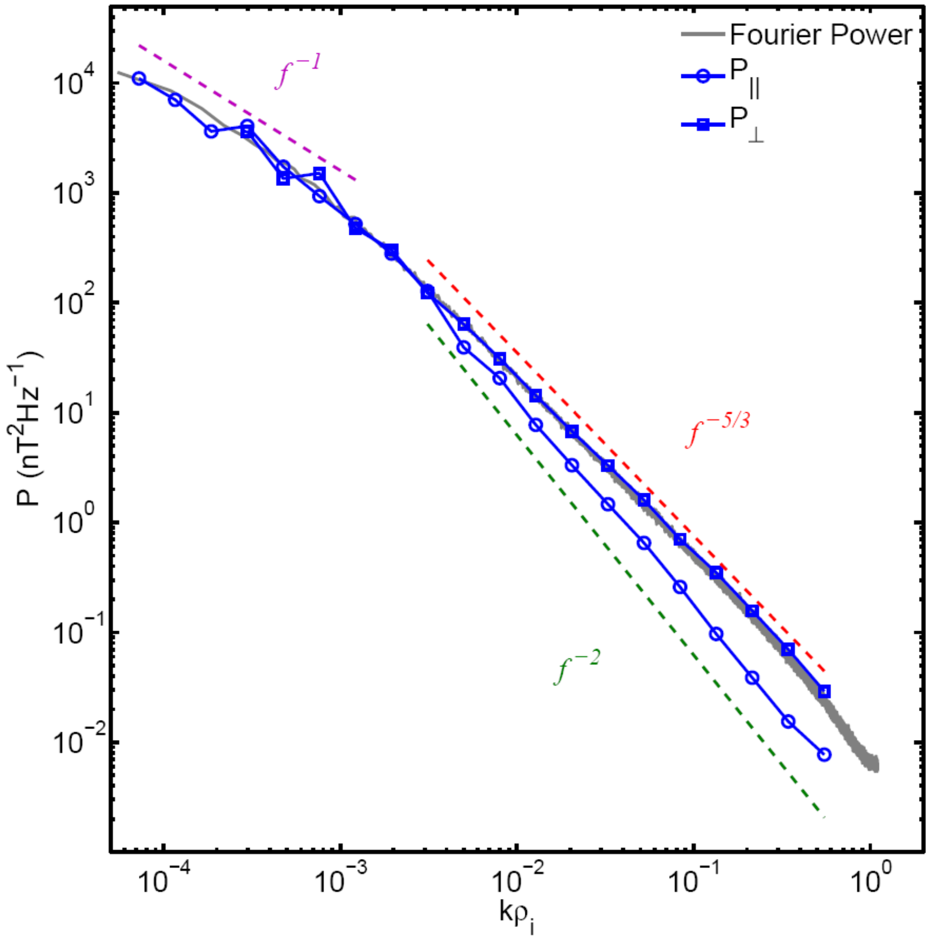
→ "reduced spectrum"

Power anisotropy

- Significant power anisotropy in the inertial range
- Power anisotropy seems to be generated through cascade

- Note: isotropy at the "outer scale"

- Wicks et al., Mon. Not. Roy. Astron. Soc., 2010



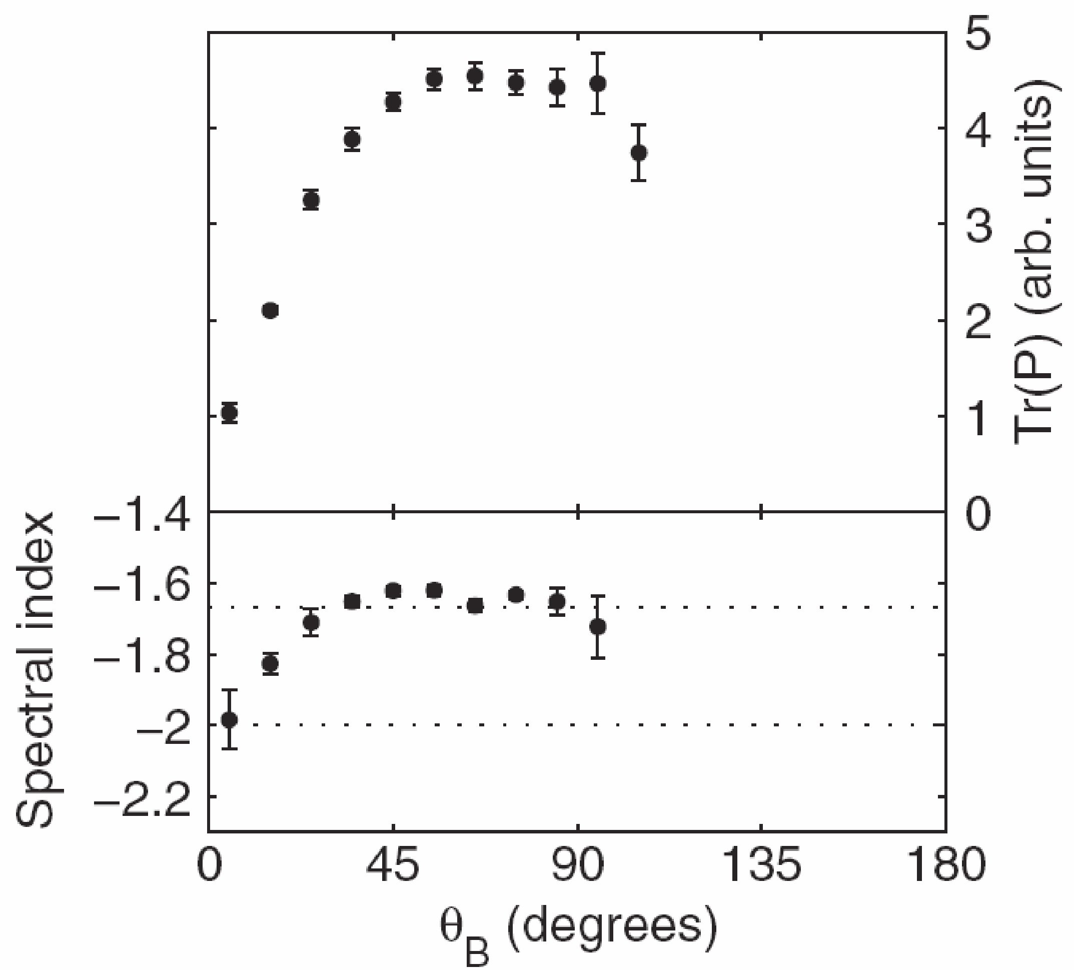
Consistency with critical balance

Inertial range

- 5/3 spectral index perpendicular to field
- 2 spectral index parallel to field

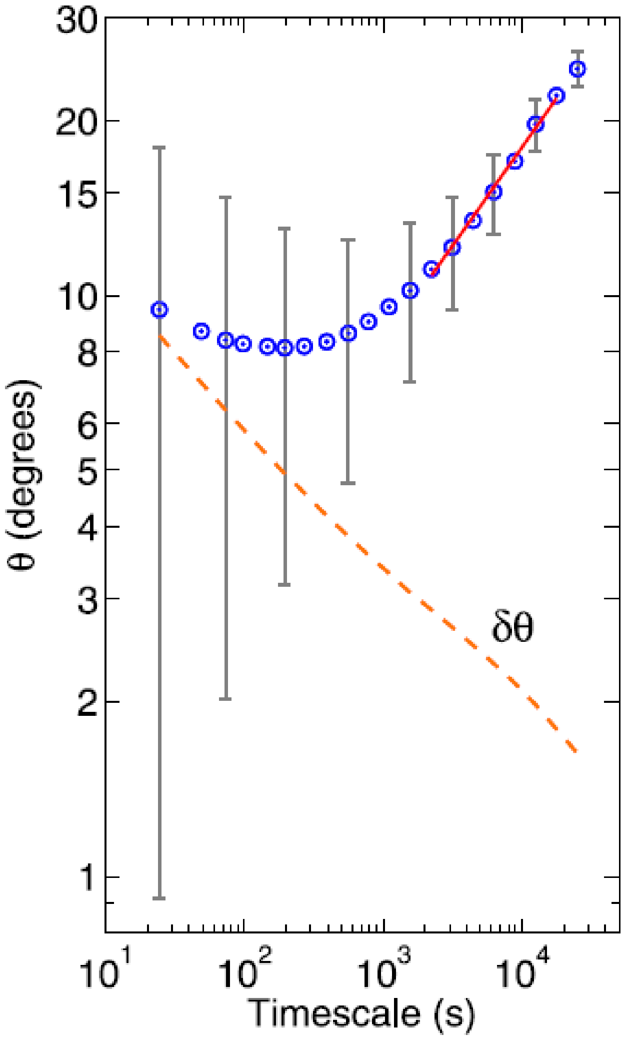
- Consistent with critical balance
- Other explanations are possible!

- Horbury et al., 2008

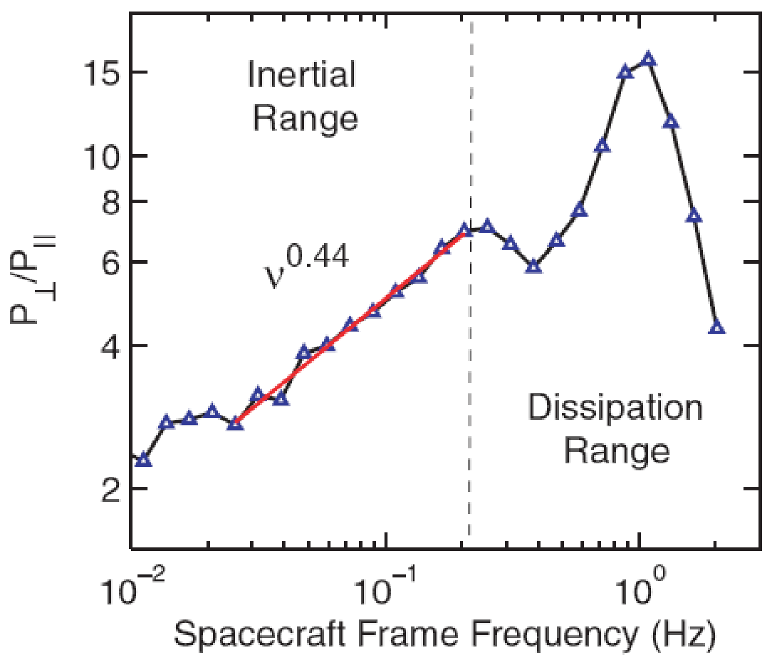


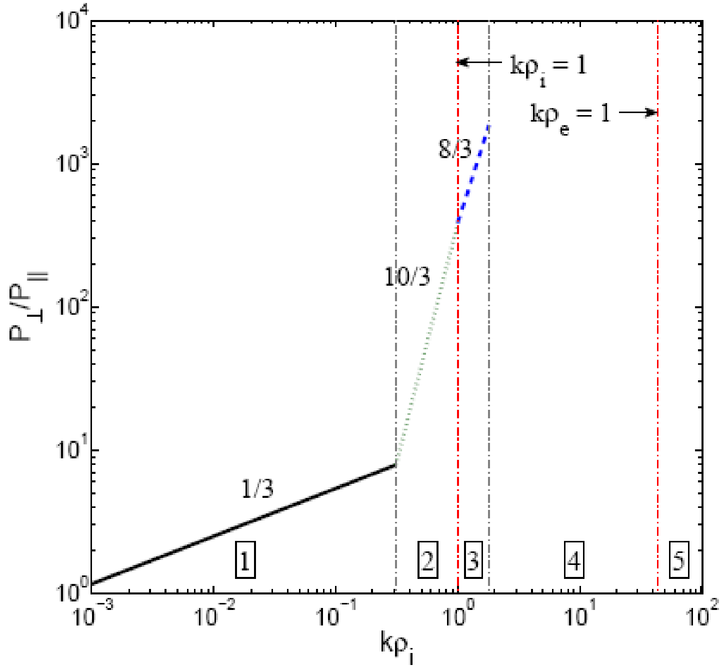
Dynamic alignment in the solar wind?

- Boldyrev, 2005
  - Angle between δb and δv should reduce down the cascade
- Podesta et al., J. Geophys. Res., A01107, 2009
  - Evidence for dynamic alignment in the solar wind?
- Timescale consistent with inertial range?



Transition to ion kinetic scales





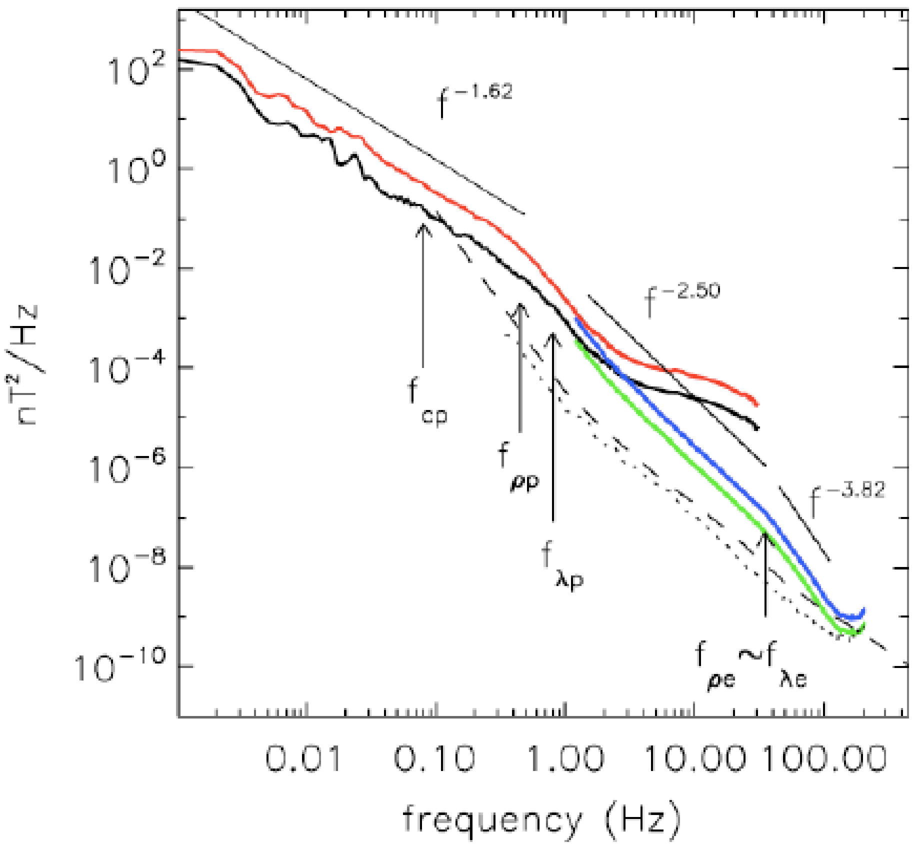
- How does anisotropy vary across the transition to ion kinetics?
- Podesta, 2009: evidence for decreased anisotropy at ion gyroscale: instabilities?
- Chen et al., 2010: predictions for scaling based on CB gyrokinetic scalings

Kinetic effects

- Multiple possible dissipation mechanisms
  - Whistlers, kinetic Alfven waves, ...
- Which one(s) is/are operating in the solar wind?

- Evidence for another power law at smaller scales

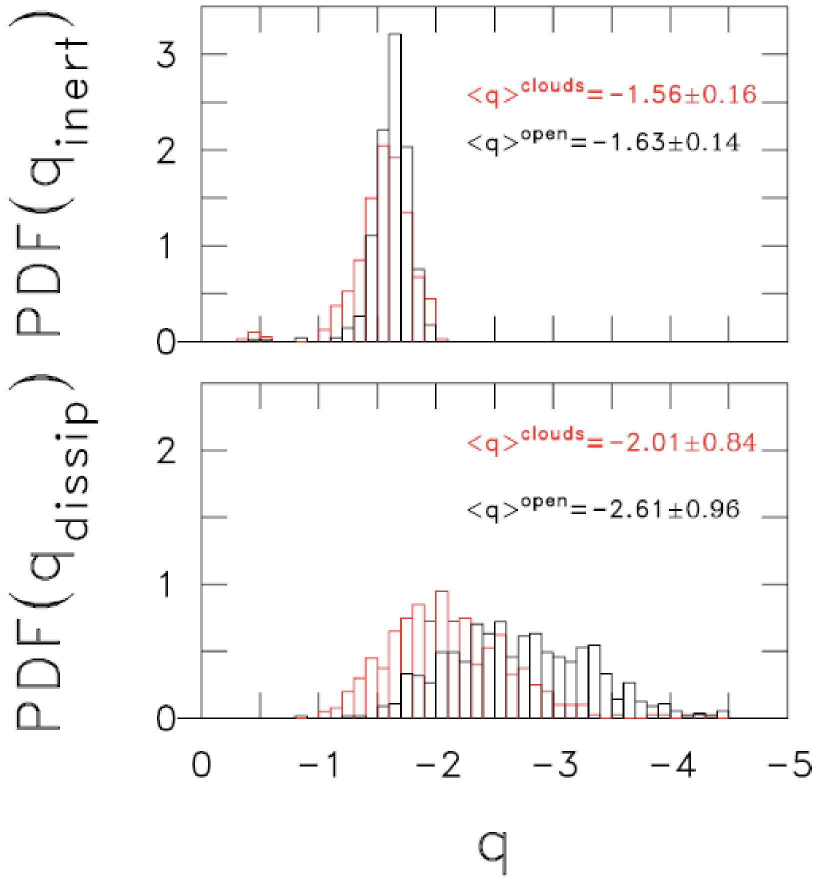
→ Continued energy transfer, not just dissipation



Sahraoui, 2009

Dispersion scale spectral index

- MHD inertial range
  - Spectral index near 5/3
- What happens in dissipation (dispersion?) range?
- Steeper spectrum
  - **Much more variable**

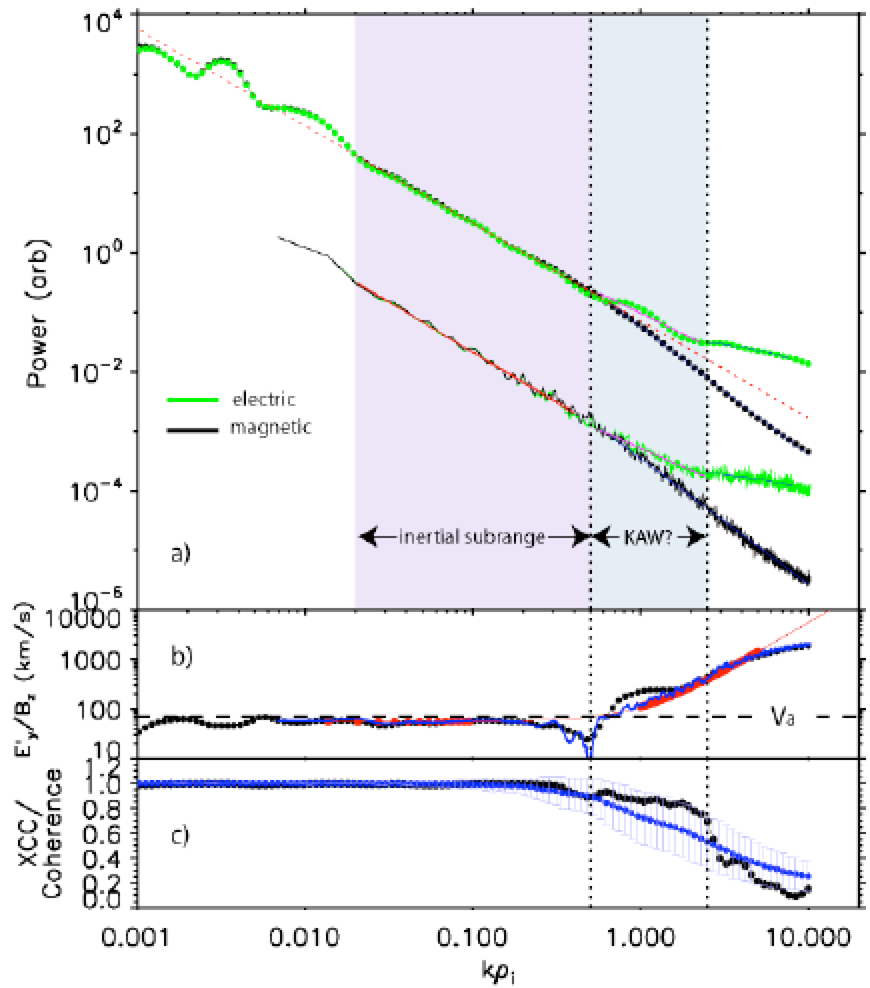


Smith et al., 2006

E and B spectrum in the kinetic regime

- Evidence for kinetic Alfven waves?

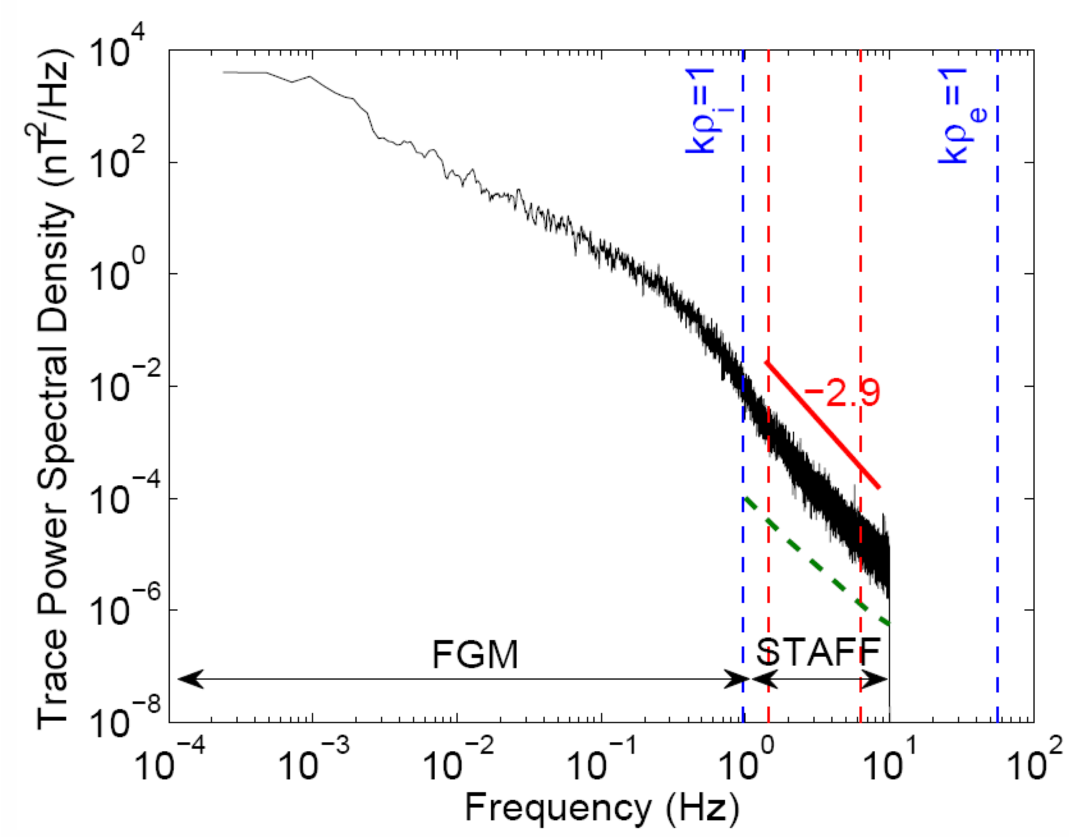
- Bale, 2005



Dissipation scales with multi-spacecraft

- Use four Cluster spacecraft on 100km scales
  - Provides information down to tens of km

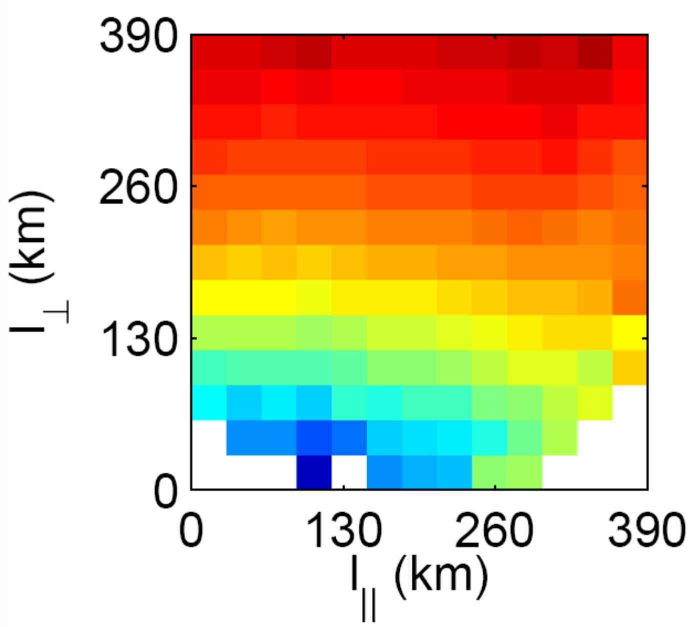
- First measurement of power and spectral index anisotropy on dissipation scales

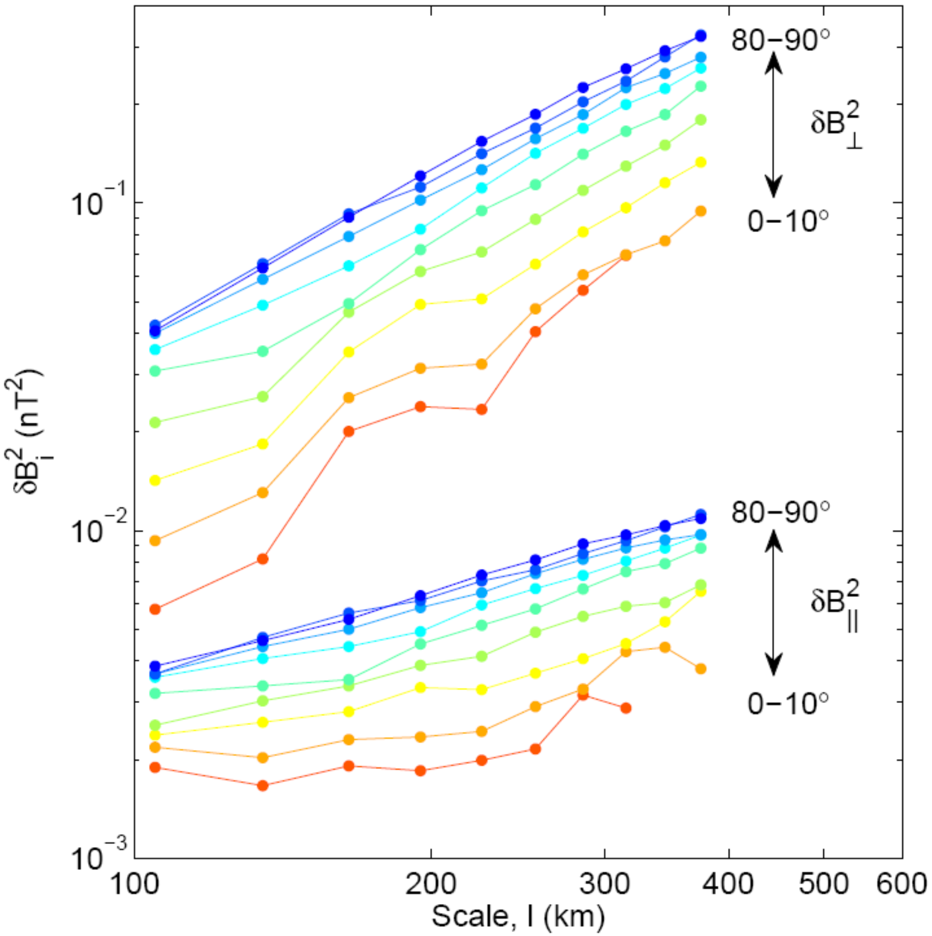


Chen et al., 2010

Multi-point structure functions

- Power law scaling on ion kinetic scales -> turbulent cascade
- Chen et al., PRL, 2010





Anisotropy on ion kinetic scales

- See power anisotropy similar to MHD scales

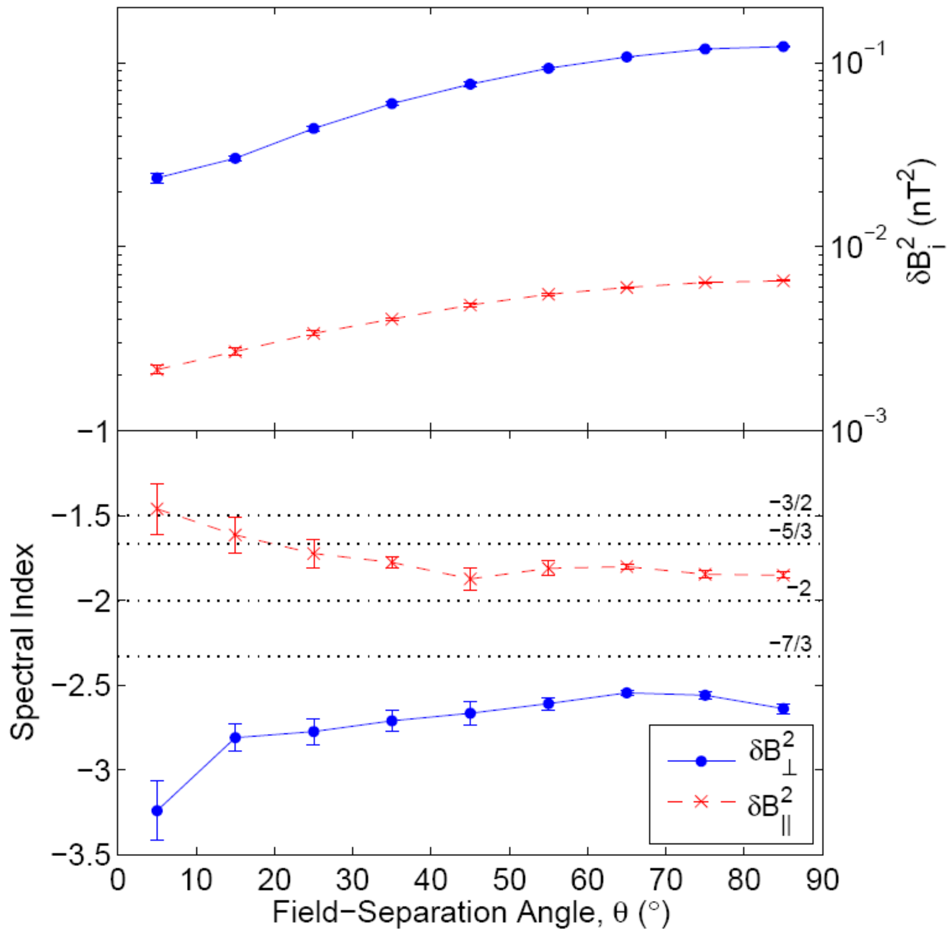
Field-perpendicular fluctuations

- Spectral index variations consistent with critically-balanced kinetic Alfven waves

Field-parallel fluctuations

- Not consistent with critically-balanced kinetic Alfven waves

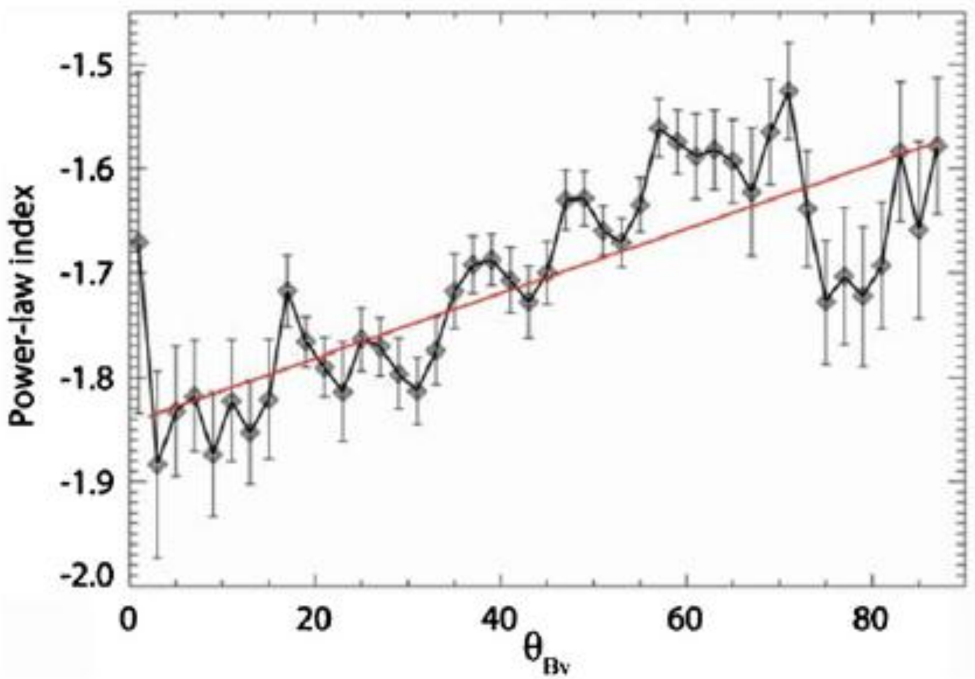
Chen et al., PRL, 2010



Anisotropic density scaling in the ion kinetic range

- Evidence for anisotropic scaling of density fluctuations
- Malaspina et al., 2010

- This is in the ion kinetic range
- Not consistent with theory?

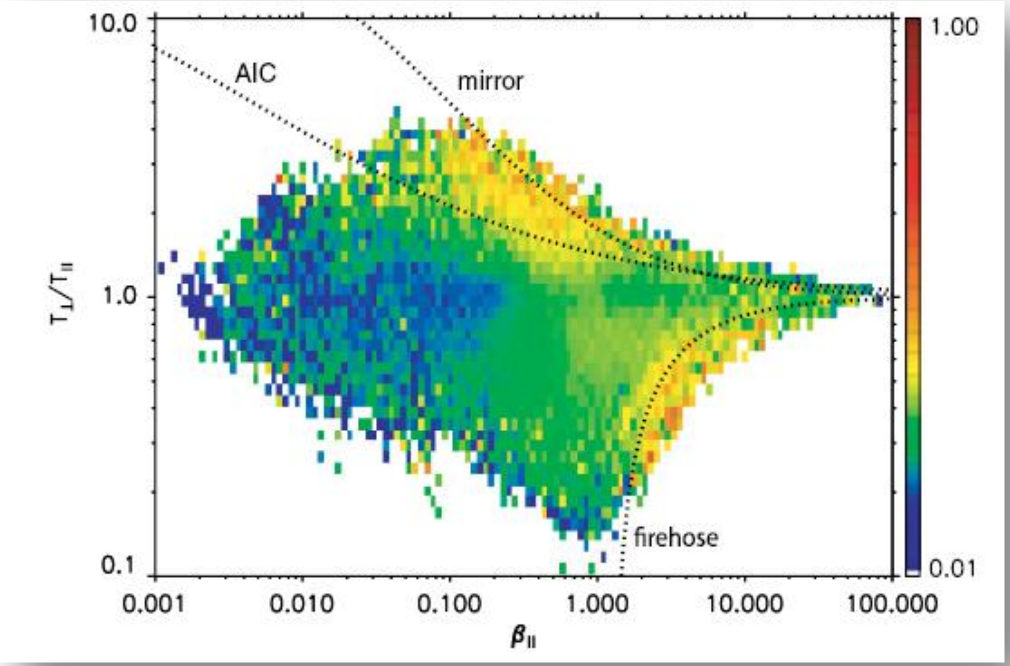


Kinetic instabilities

- Expansion of solar wind drives particle distributions towards firehose and mirror mode instabilities (Kasper, Hellinger, Matteini)

- Good evidence for generation of fluctuations on ion kinetic scales due to these

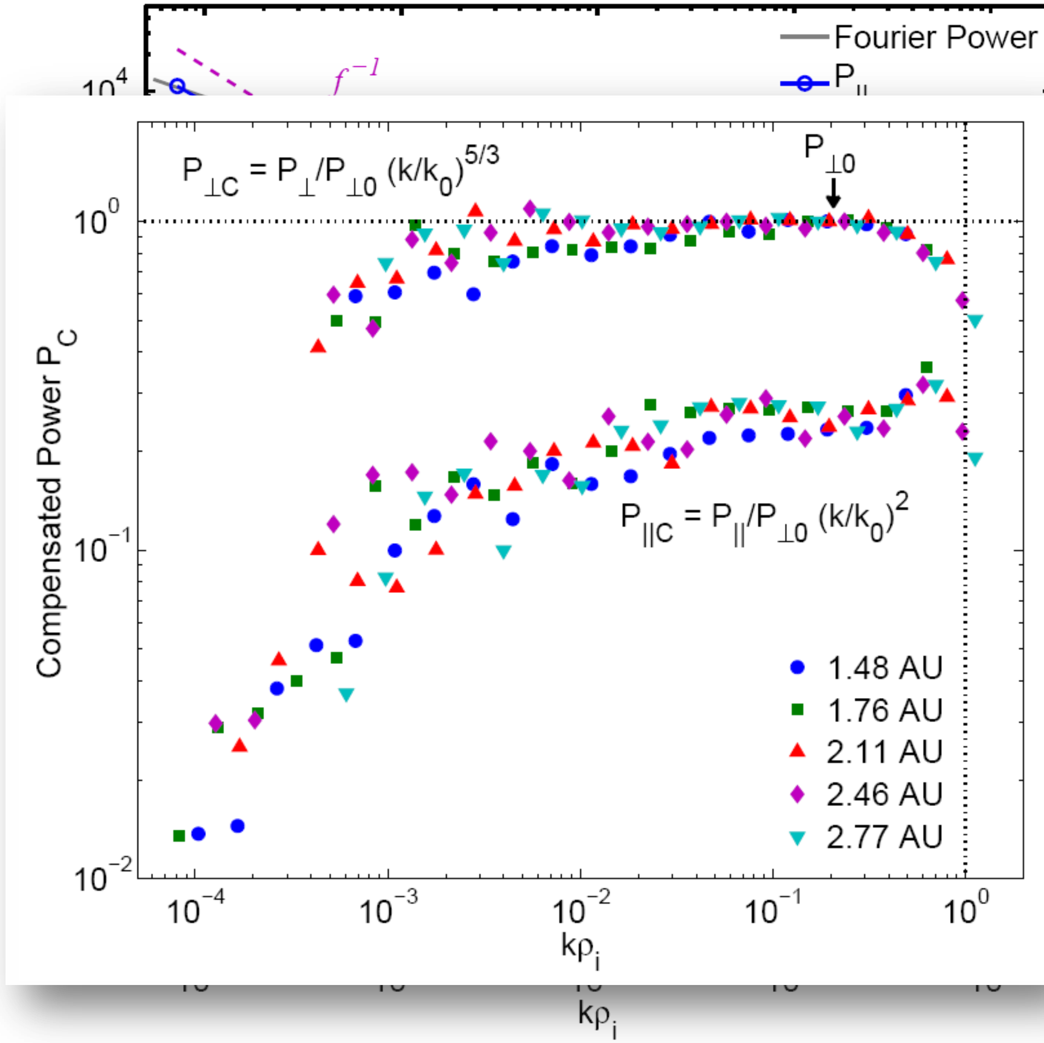
- See talks by Bale, Kasper



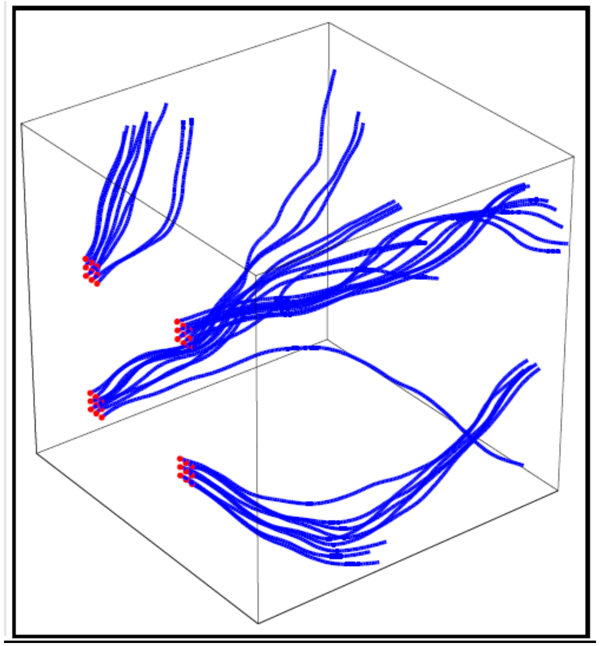
Bale et al., PRL, 2009

Evidence for firehose instability

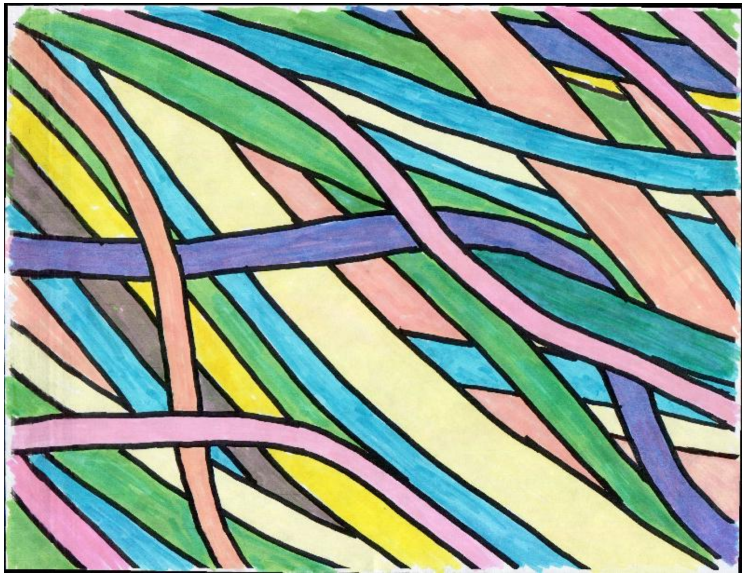
- Consistent with plasma near firehose instability
- Appears to have field-parallel wavevector
- Only visible using wavelet analysis
- Wicks et al., MNRAS, 2010



Discontinuities vs turbulence



- Turbulence
  - Field-perpendicular cascade generates short scales across the field
  - Tube-like structures
  - Not topological boundaries

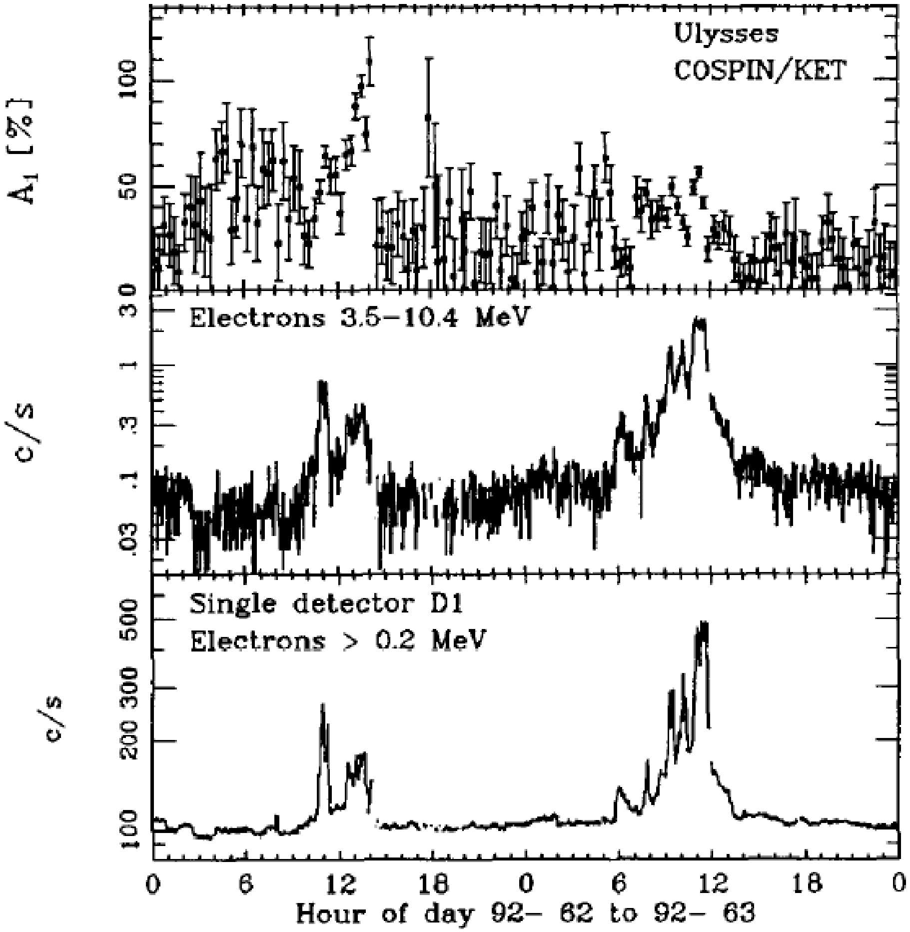


- Flux tubes
  - Sourced from Sun
  - Topological boundary?
- Solar wind is likely a combination of both at the same time

Using particles to study turbulence

- Jovian electron bursts
  - Electrons highly tied to field lines
  - Relativistic electrons are instantaneous diagnostics of connectivity
  - Seen up to several hundred million km from planet

- Evidence for very fine scale structure



Ferrando et al., 1993

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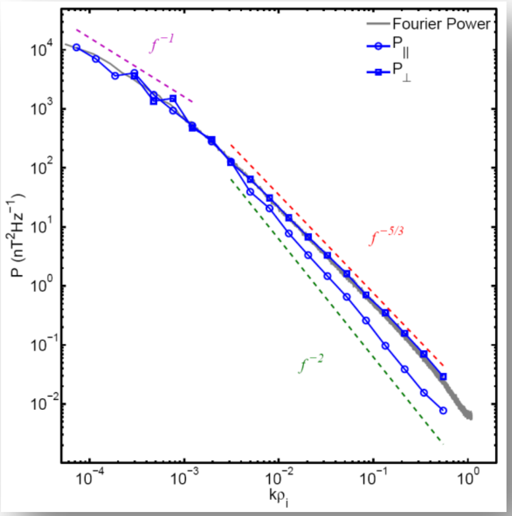
Summary and questions

- Anisotropic cascades on both MHD and ion kinetic scales
- Anisotropy in magnetic field, velocity and density, but some differences
- Evidence for kinetic instabilities, sometimes
- Imbalance is also sometimes present



Outstanding questions

- Is critical balance actually present on MHD or ion kinetic scales?
- What is the form of the ion kinetic cascade?
- What is the effect of imbalance?
- How important are instabilities and/or structures in solar wind dynamics?