Waves and turbulence in the solar wind

Tim Horbury

PG Lectures

- Turbulence: the basics
- Turbulence in plasmas: MHD scales
- The solar wind context
- Open questions

What is turbulence?

- Fluid phenomenon
- Nonlinear energy transfer between scales
- Occurs when inertial forces dominate viscous forces
- Important in many engineering problems

Early Concepts

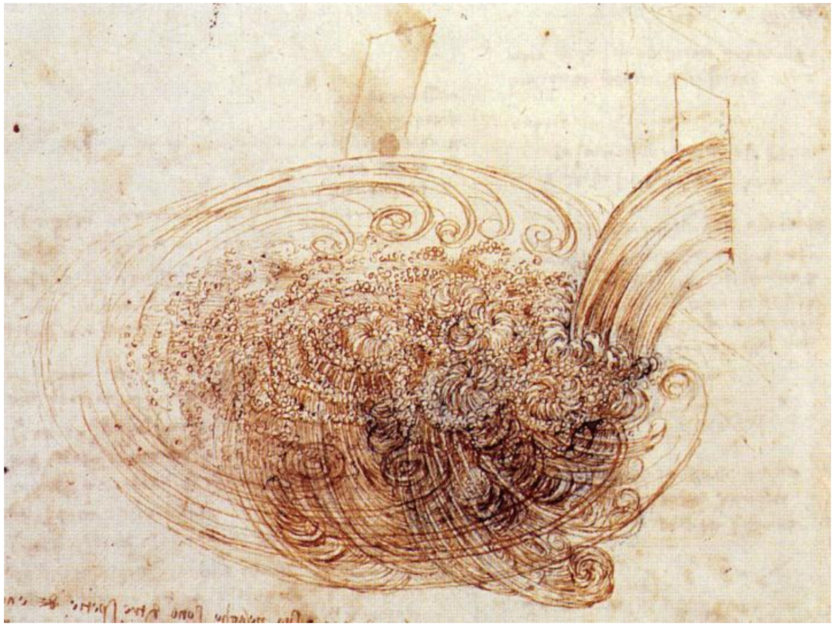
- "… the motion of the surface of the water … has eddying motions, one part of which is due to the principal current, the other to random and reverse motion"

  → Reynolds decomposition:

  $$\mathbf{u} = \mathbf{u}_0 + \delta\mathbf{u}$$

- "large things are rotated only by large eddies and not by small ones, and small things are turned by both small eddies and large"

  → Cascade of eddies

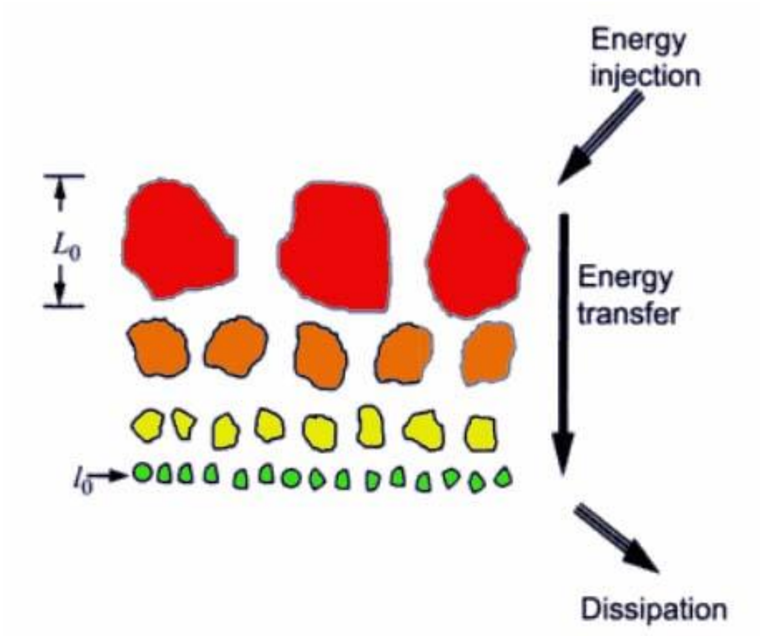


da Vinci 1510

The Richardson cascade

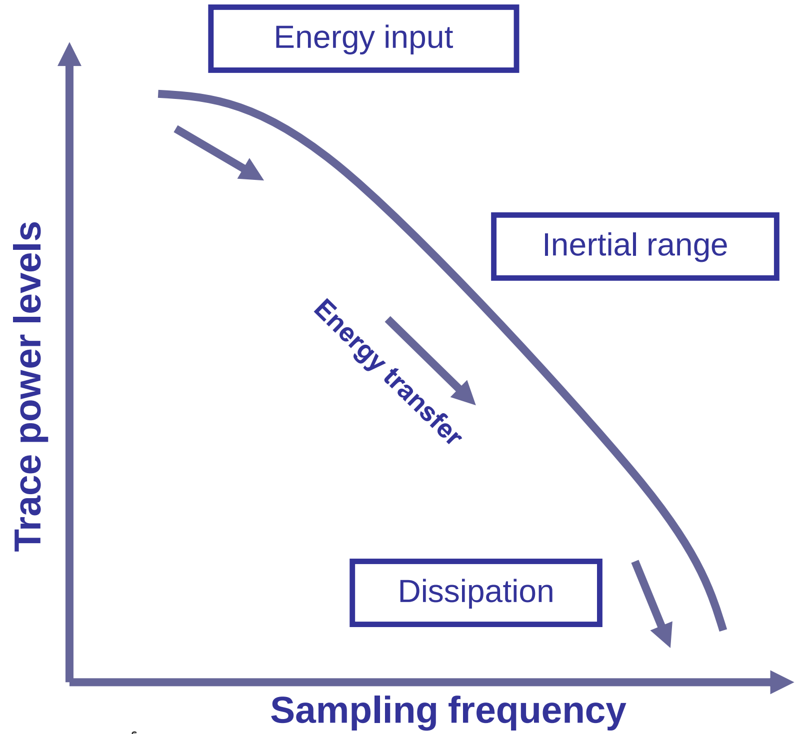
Bigger whirls have little whirls,
That feed on their velocity;
And little whirls have lesser whirls,
And so on to viscosity.

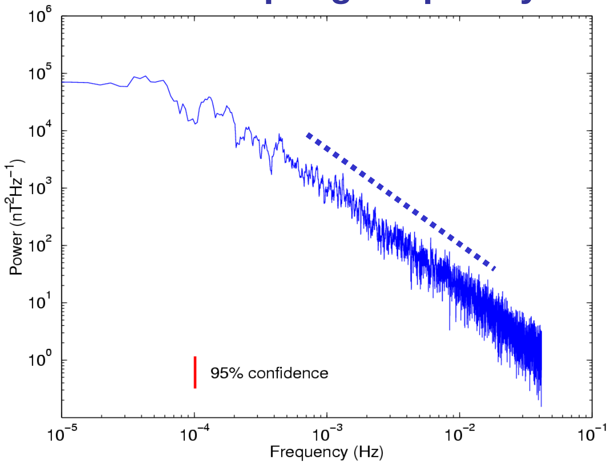
Lewis Fry Richardson, 1920



The inertial range

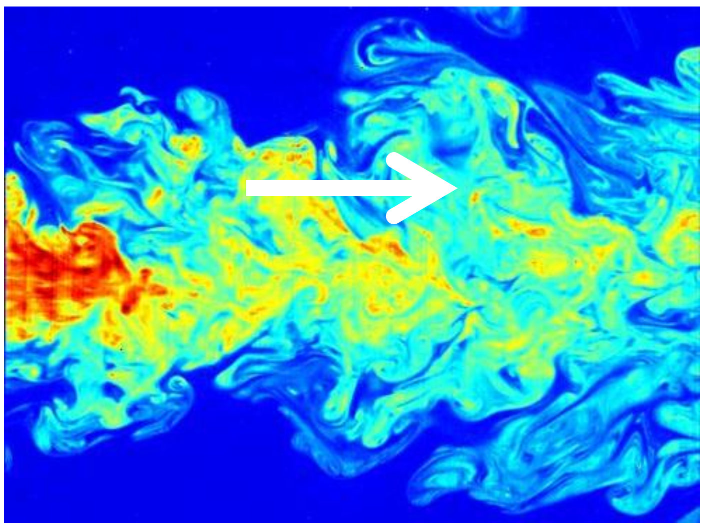
- If energy input is steady, and far from dissipation scale, have a steady state → **Inertial range**
- K41: $k^{-5/3}$ spectrum
- We observe this in hydrodynamic fluids
- Note: energy transfer rate is analytic in hydrodynamics



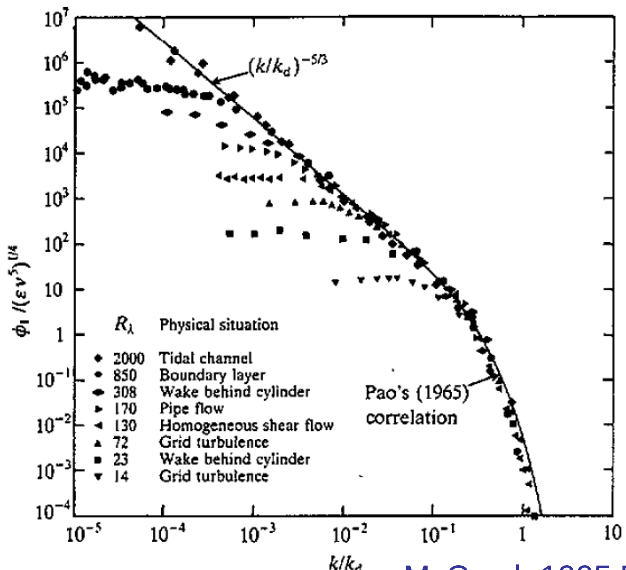


Measuring the Power Spectrum

- Taylor (1938)
  - if bulk flow is faster than turbulent motions
  - can measure velocity at fixed point
  - measured time variations correspond to spatial variations in the flow



Fukushima & Westerweel 2007



McComb 1995 RPP

Turbulence in plasmas

Neutral fluids

- Motion described by Navier-Stokes equations

→ Hydrodynamics

- Energy transfer by velocity shear

Plasmas

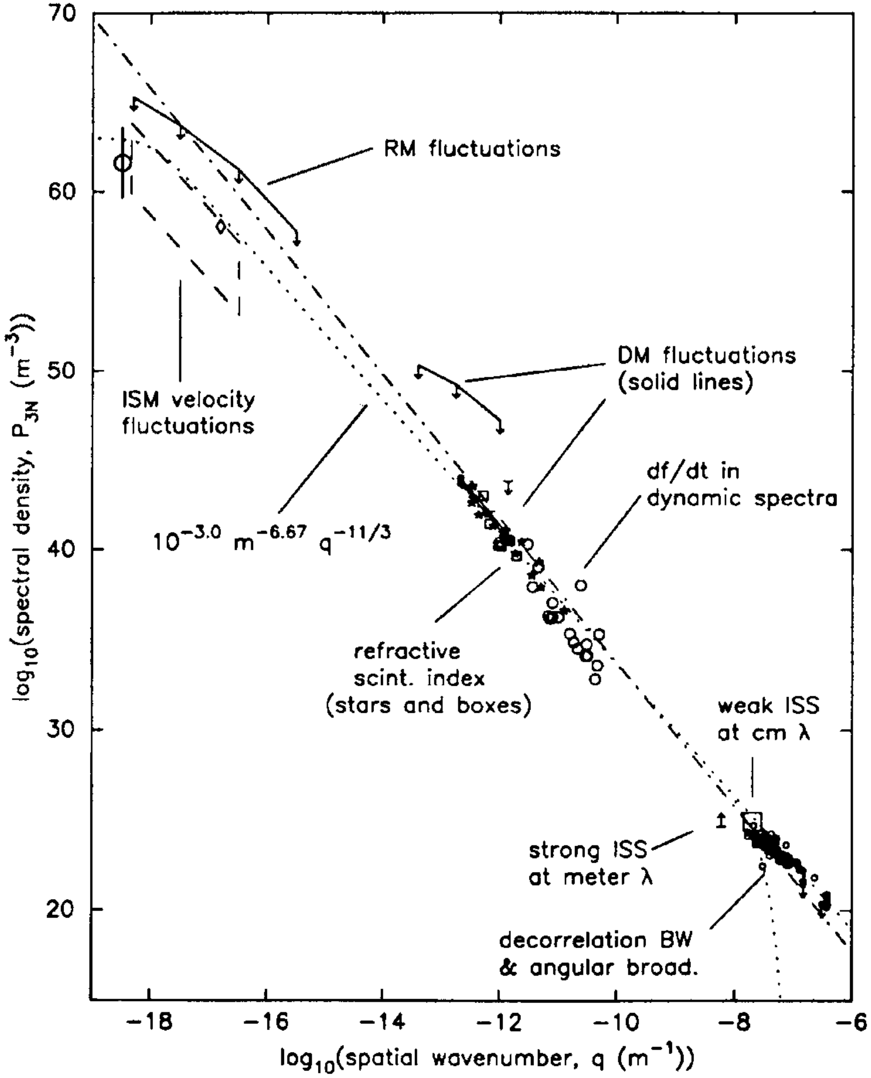
- On sufficiently large scales, can treat plasma as a fluid

→ Magnetohydrodynamics

- Multiple, finite amplitude waves can be stable
- Presence of a **magnetic field**
  - Breaks isotropy
  - Key difference to neutral fluids

“The great power law in the sky”

- Measure interstellar density fluctuations using scintillations
- Consistent with Kolmogorov scaling over many orders of magnitude



Why study waves and turbulence in the solar wind?

Effect on the Earth

- Can trigger reconnection, substorms, aurorae, …

Understanding solar processes

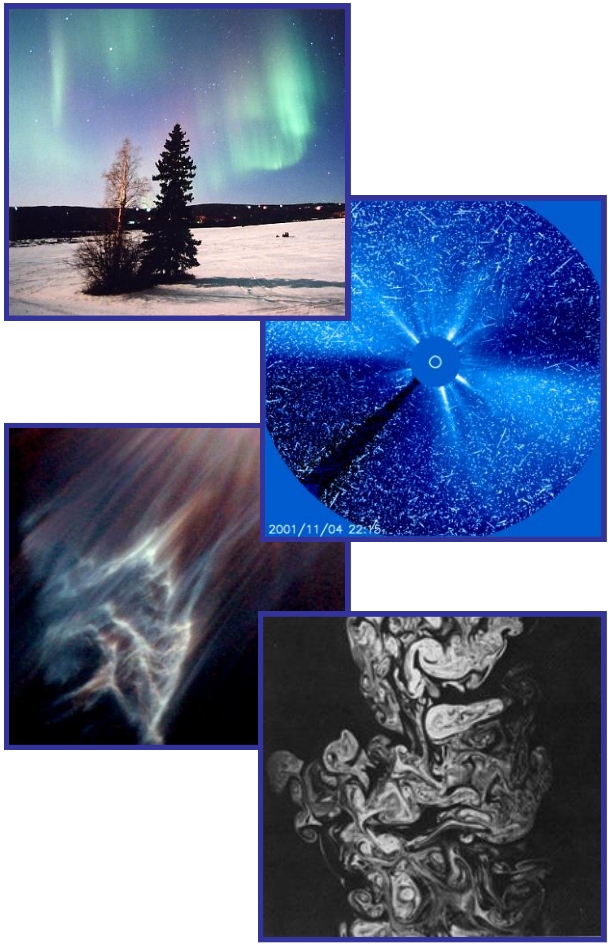
- Signature of coronal heating, etc.

Application to other plasmas

- Astrophysics: particle propagation
- Dense plasmas: transport

Turbulence as a universal phenomenon

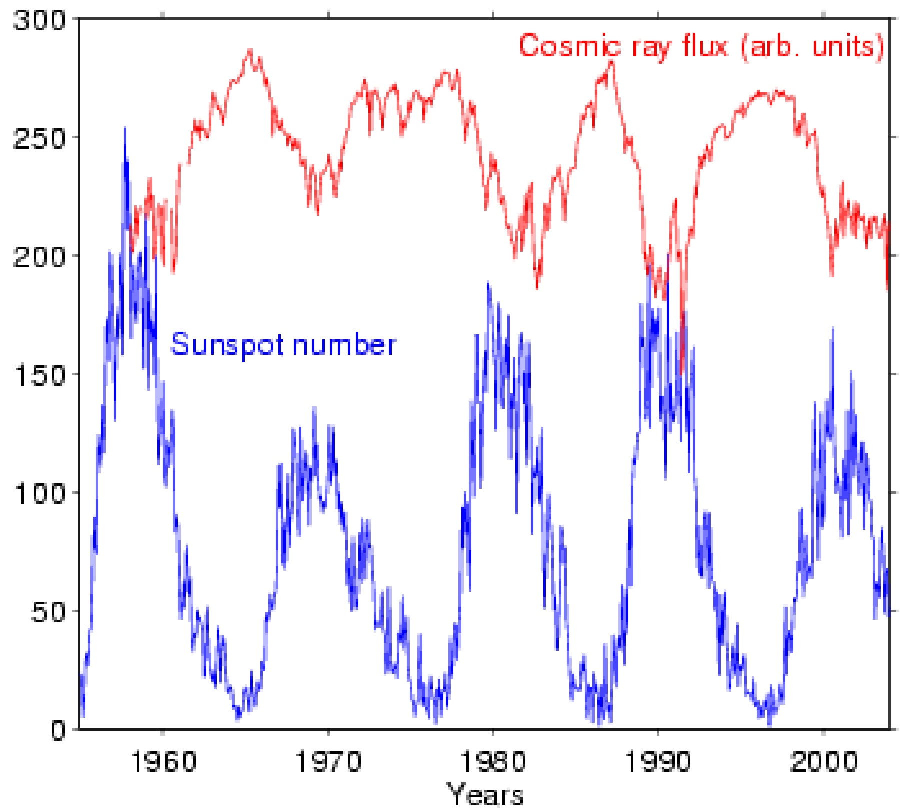
- Comparison with hydrodynamics



D. Vier/SoHO/Hubble/Dimotakis et al

Cosmic rays and the solar cycle

- Cosmic ray flux at the Earth is modulated by the solar cycle
- This is due to variations in the **magnetic barrier** in the solar system
- **Waves and turbulence** in the solar wind form a key part of this barrier



Solar wind as a turbulence laboratory

- Characteristics
  - Collisionless plasma
  - Variety of parameters in different locations
  - Contains turbulence, waves, energetic particles
- Measurements
  - In situ spacecraft data
  - Magnetic and electric fields
  - Bulk plasma: density, velocity, temperature, …
  - Full distribution functions
  - Energetic particles

- The only **collisionless plasma** we can **sample directly**

Interpreting spacecraft measurements

- In the solar wind (usually),

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

- Therefore,

$$V_{SW} >> V_A$$

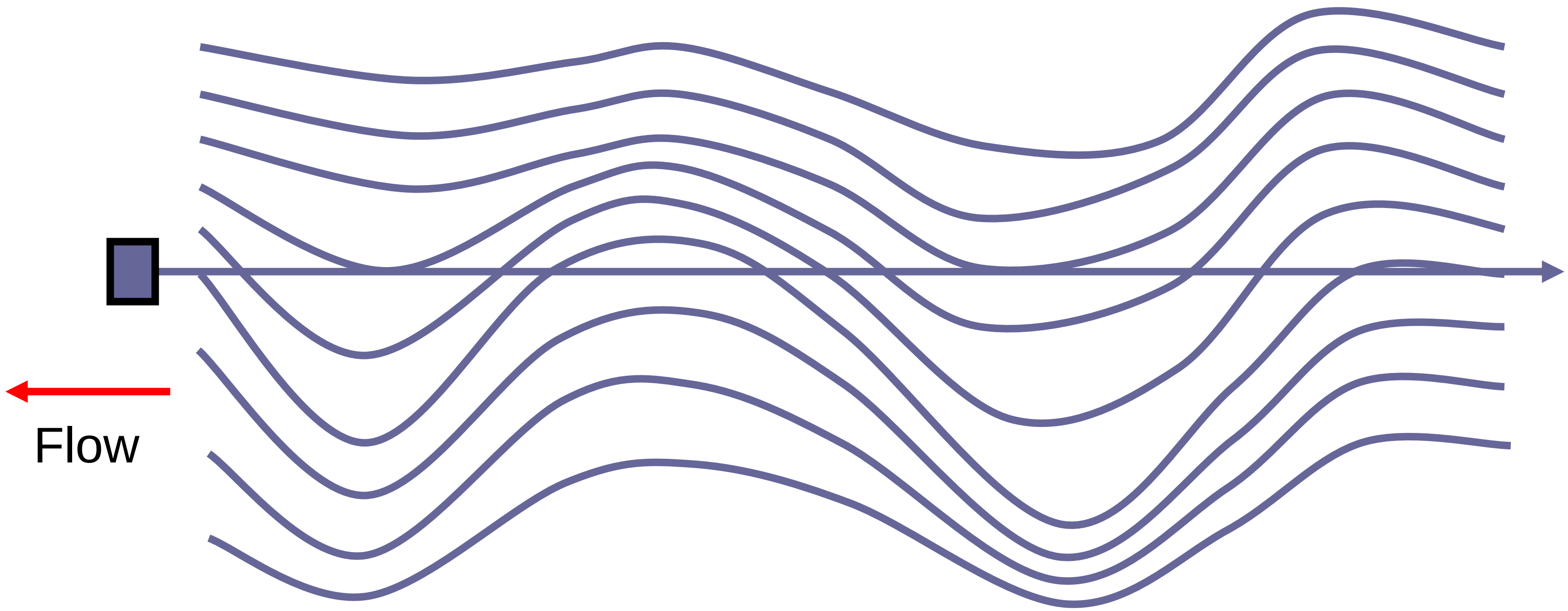
- **Taylor's hypothesis**: time series can be considered a spatial sample
- We can convert spacecraft frequency *f* into a plasma frame wavenumber *k*:

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

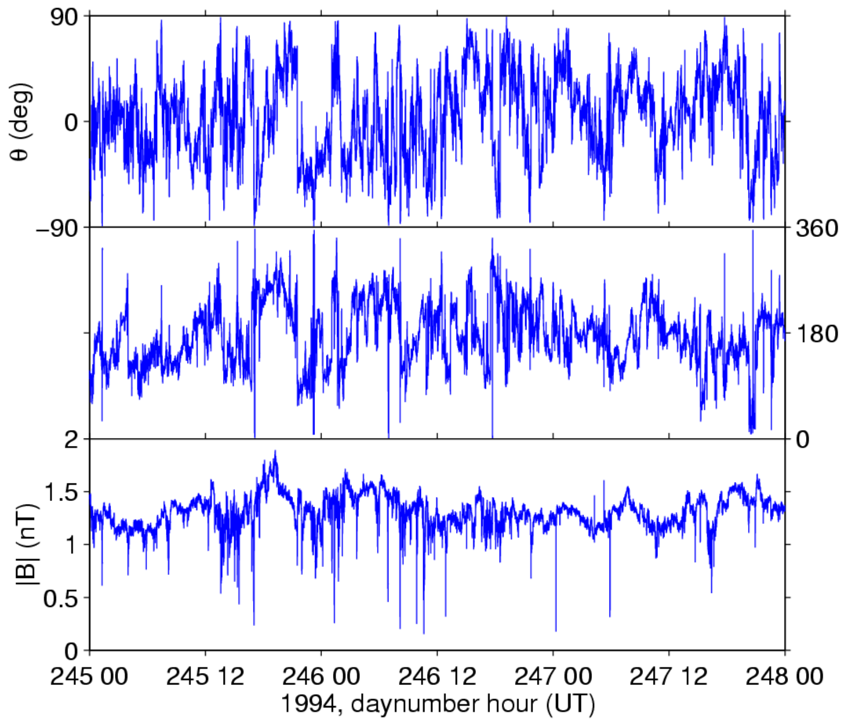
- Almost always valid in the solar wind
- Makes analysis much easier
- Not valid in, e.g. magnetosheath, upper corona

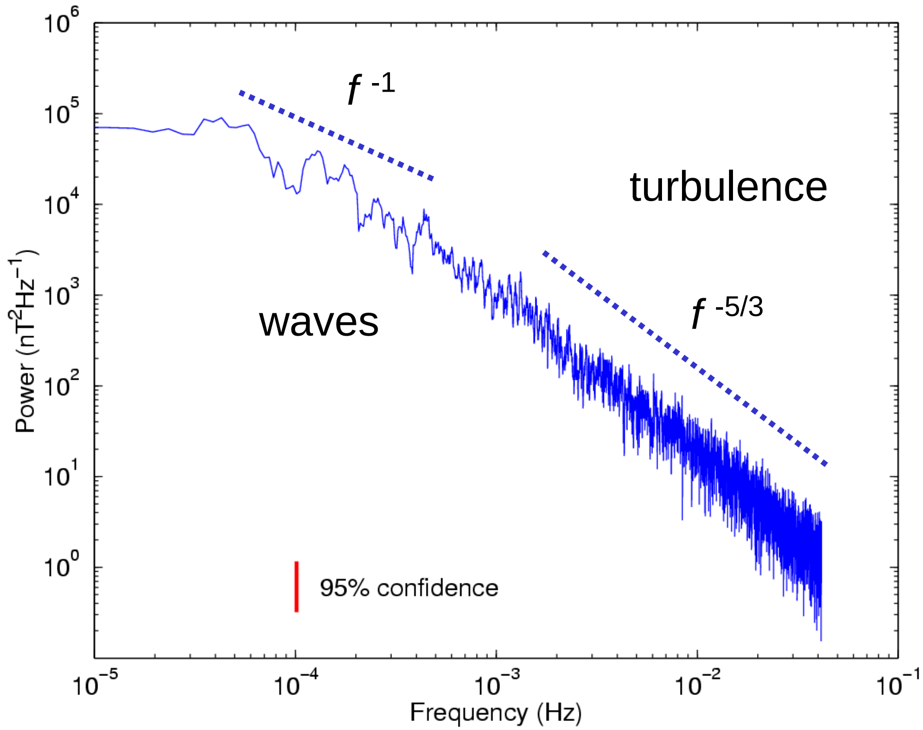
Interpreting spacecraft measurements

- 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



The turbulent solar wind





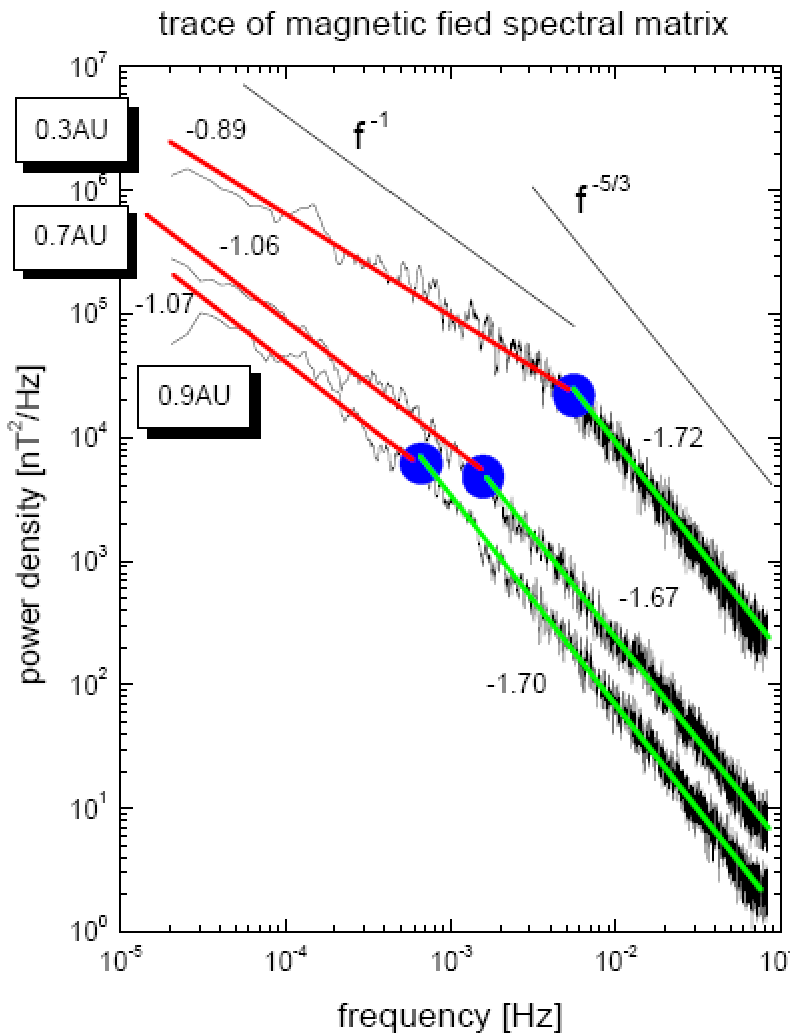
- Fluctuations on all measured scales

Power spectrum

- Broadband
- Low frequencies: f^{-1}
- High frequencies: $f^{-5/3}$

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**

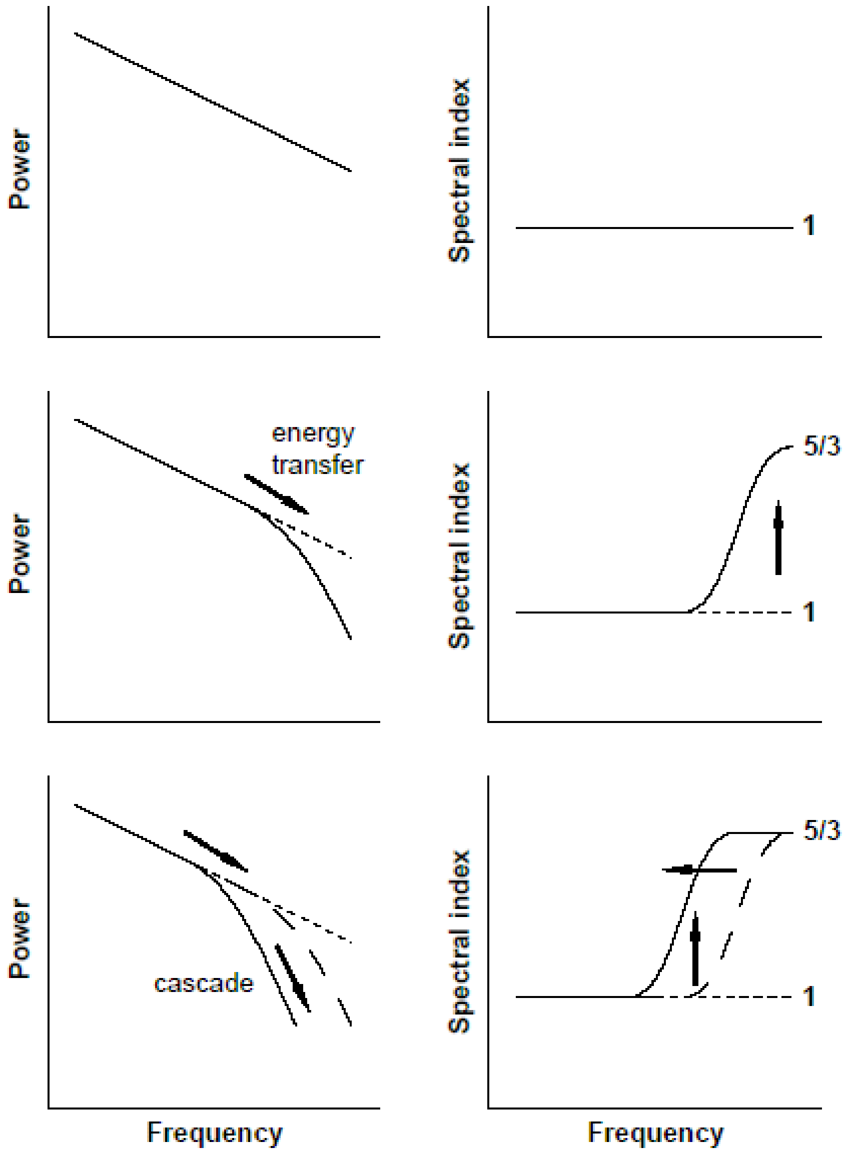


after Bavassano et al 1982

Interpretation

- Initial broadband 1/f spectrum close to Sun
- High frequencies decay, transfer energy
- Spectrum steepens
- Progressively lower frequencies decay with time (distance)
- Breakpoint in spectrum moves to lower frequencies

- **Breakpoint is the highest frequency unevolved Alfvén wave**



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Alfvén waves

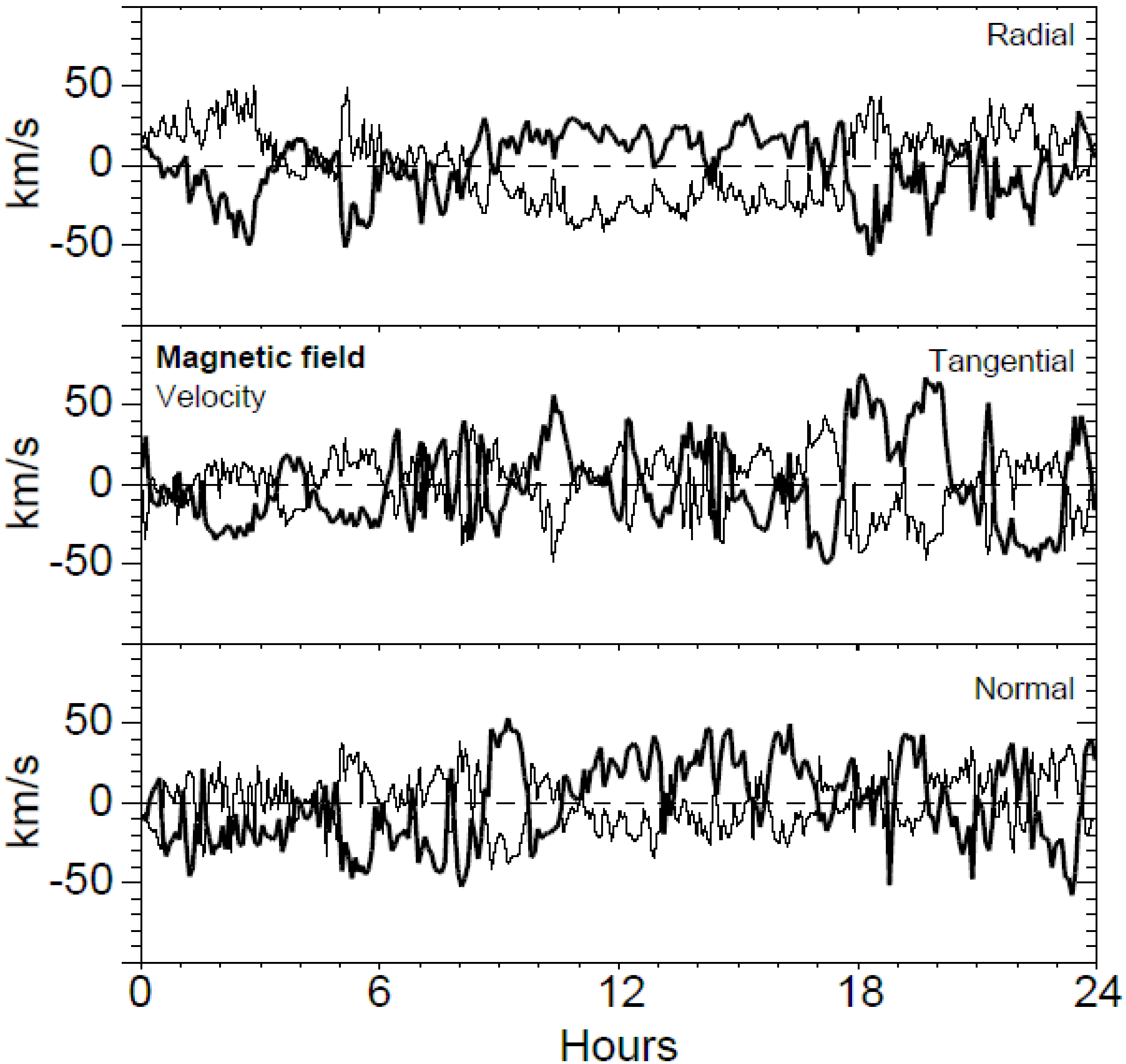
Field-parallel Alfvén wave:

- B and V variations anti-correlated

Field-anti-parallel Alfvén wave:

- B and V variations correlated

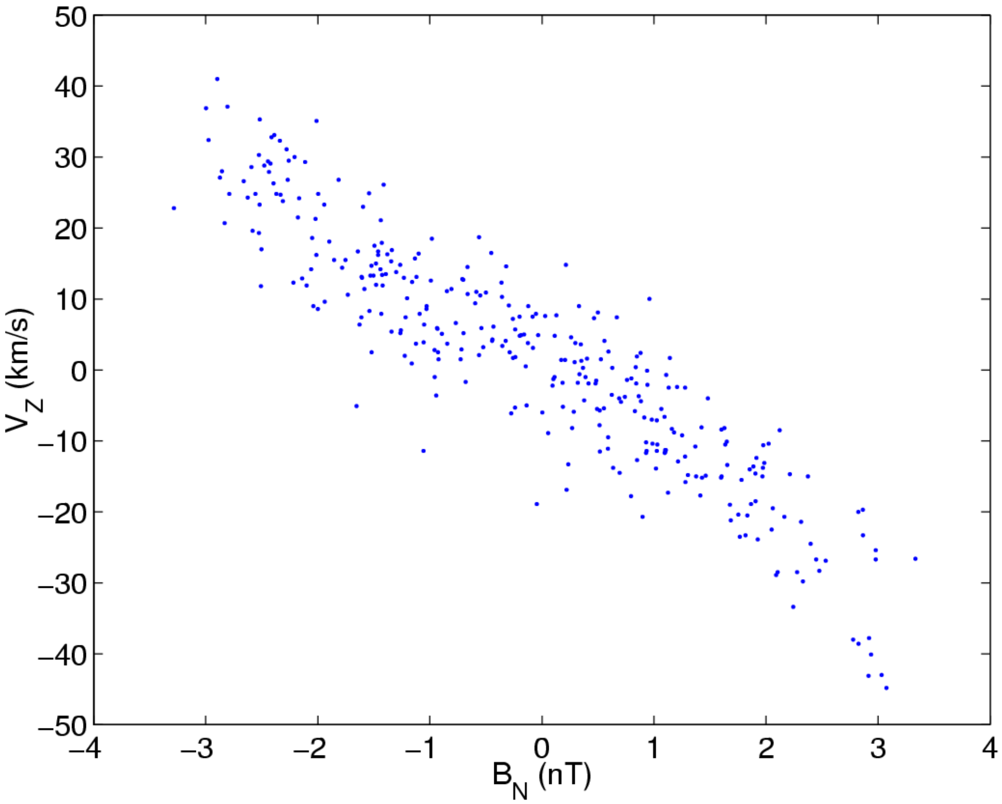
- See this very clearly in the solar wind
- Most common in high speed wind



Propagation direction of Alfvén waves

- Waves are usually propagating **away** from the Sun

Average magnetic field anti-sunward
Negative correlation
Propagating parallel to field
Propagating **away** from Sun in plasma frame



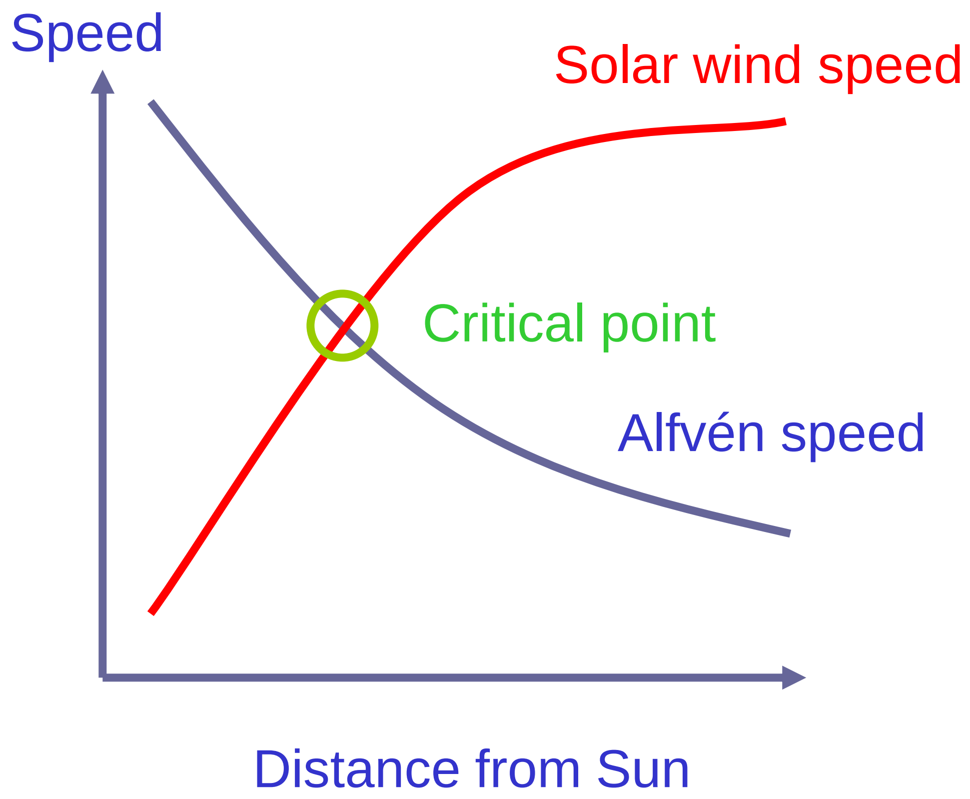
Dominance of outward-propagating waves

- Solar wind **accelerates** as it leaves the corona
- Alfvén speed **decreases** as field magnitude drops

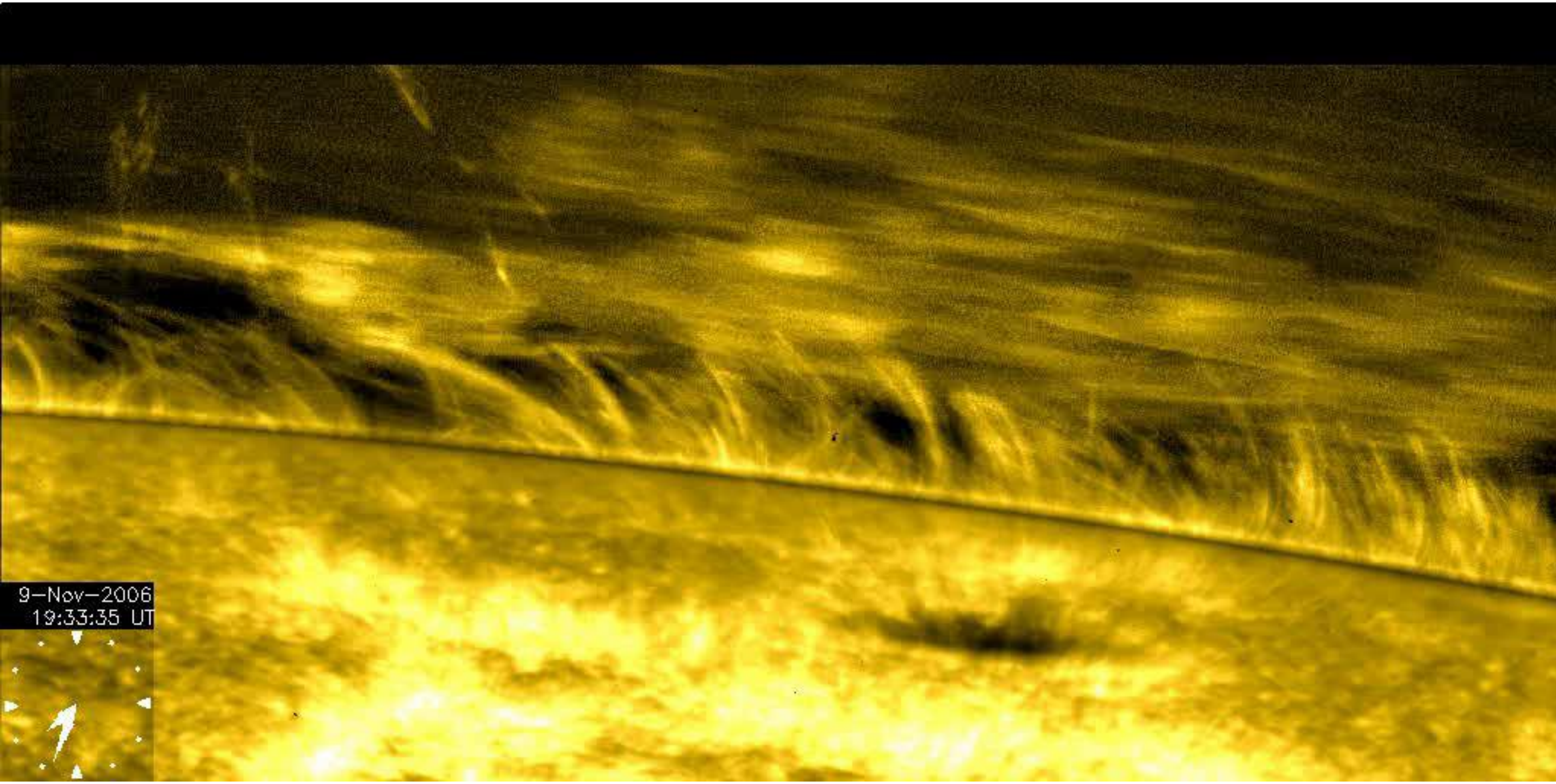
- Alfvén critical point: equal speed (~10-20 solar radii)
- Above critical point, all waves carried outward

Therefore,

- Outward-propagating low frequency waves **generated in corona!**



Waves and motion in the chromosphere



Currently interesting questions

- Anisotropy: what is the effect of the magnetic field?
- Kinetic scales: how is energy transferred and dissipated below the ion gyroscale?
- Turbulent structures: does plasma turbulence generate discrete structures?

Importance of the magnetic field

- Magnetic field is often used for turbulence analysis

- Precise measurement
- High time resolution
- Low noise

- For MHD scales, this is often sufficient
- (but more about velocity later...)

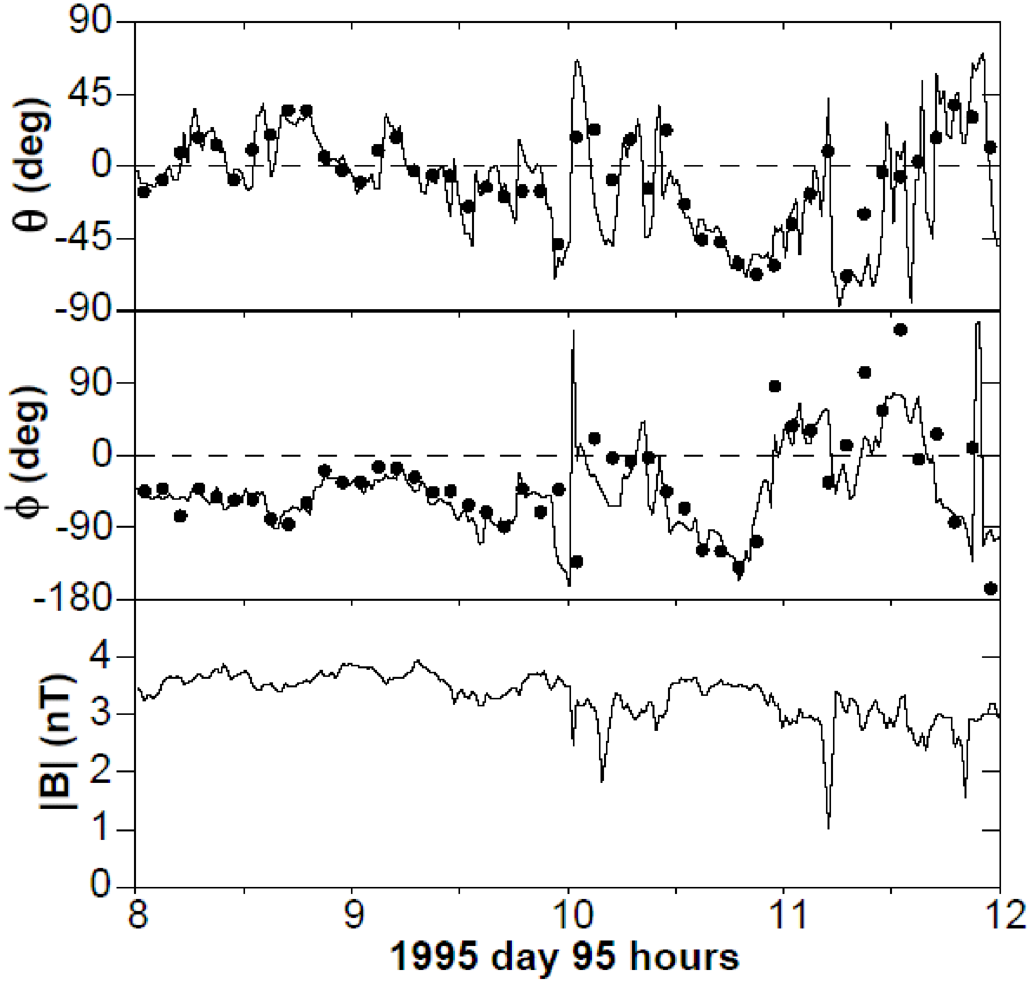
- For kinetic scales, have to be more careful

Field-aligned anisotropy

- Power levels tend to be perpendicular to local magnetic field direction
- → **anisotropy**

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

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



Anisotropy of energy transfer

Neutral fluid

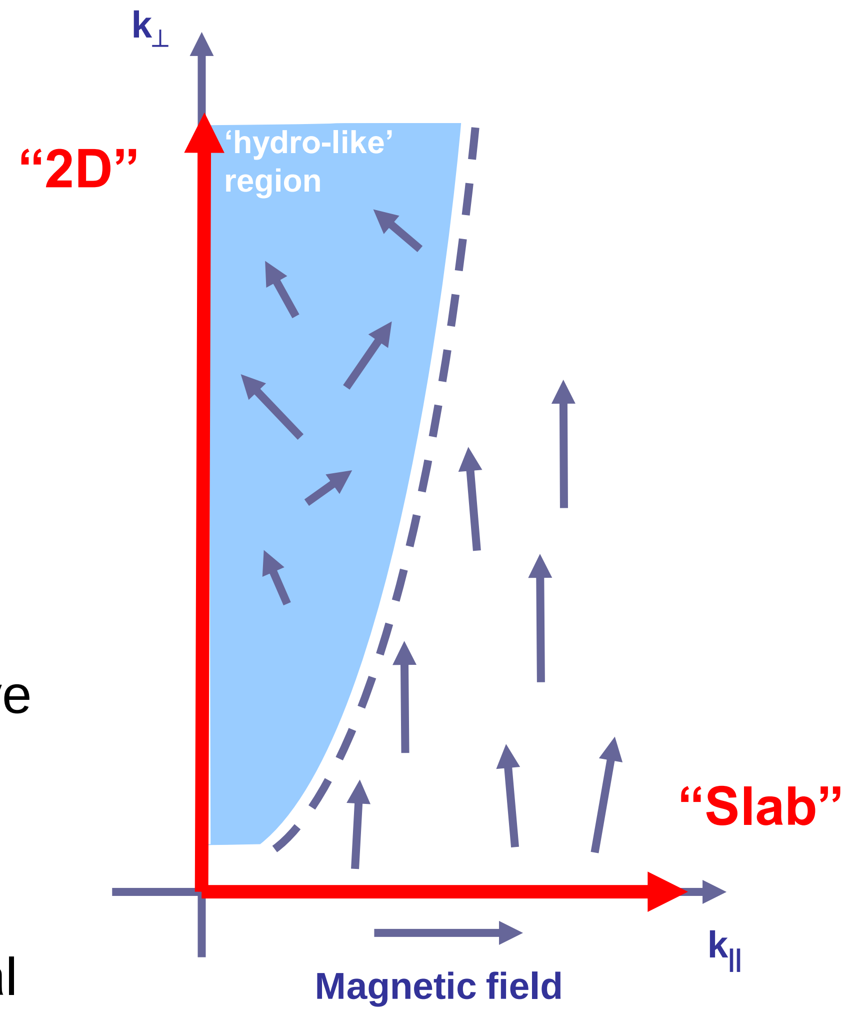
- No preferred direction
  $\rightarrow$ isotropy

Plasmas

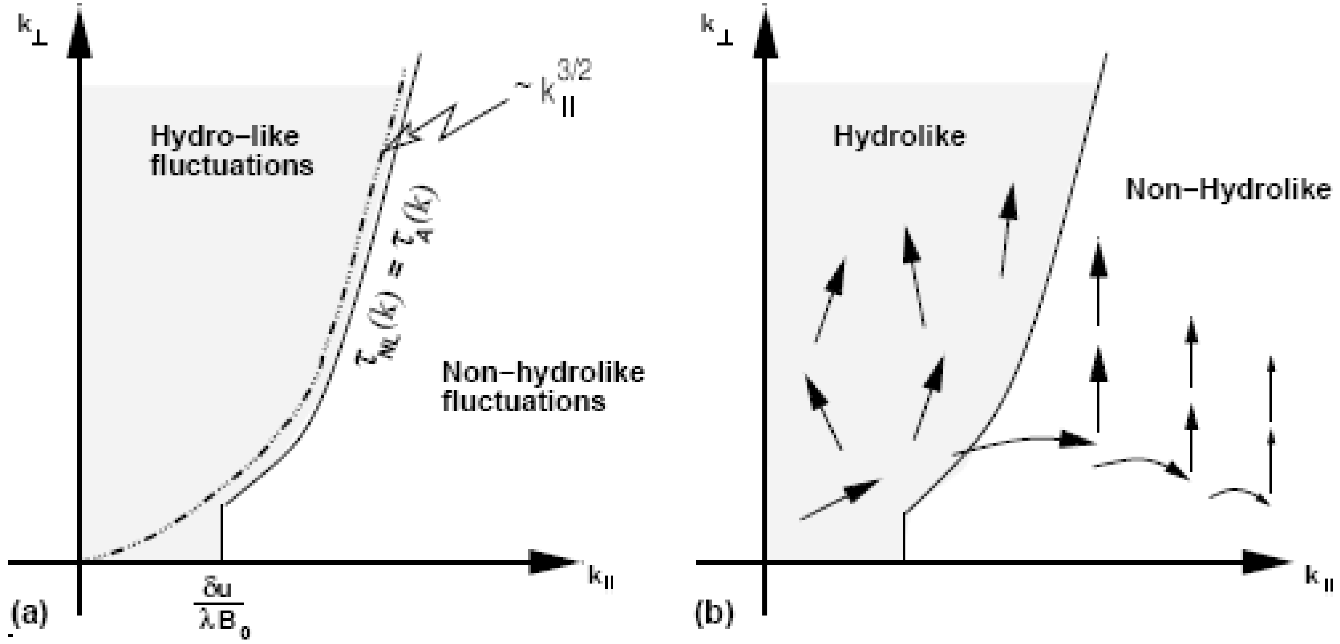
- Magnetic field breaks symmetry
  $\rightarrow$ **anisotropy**

- Shebalin (1983): power tends to move **perpendicular** to magnetic field in wavevector space

- Goldreich and Sridhar (1995): "critical balance" region close to $k_{||}=0$

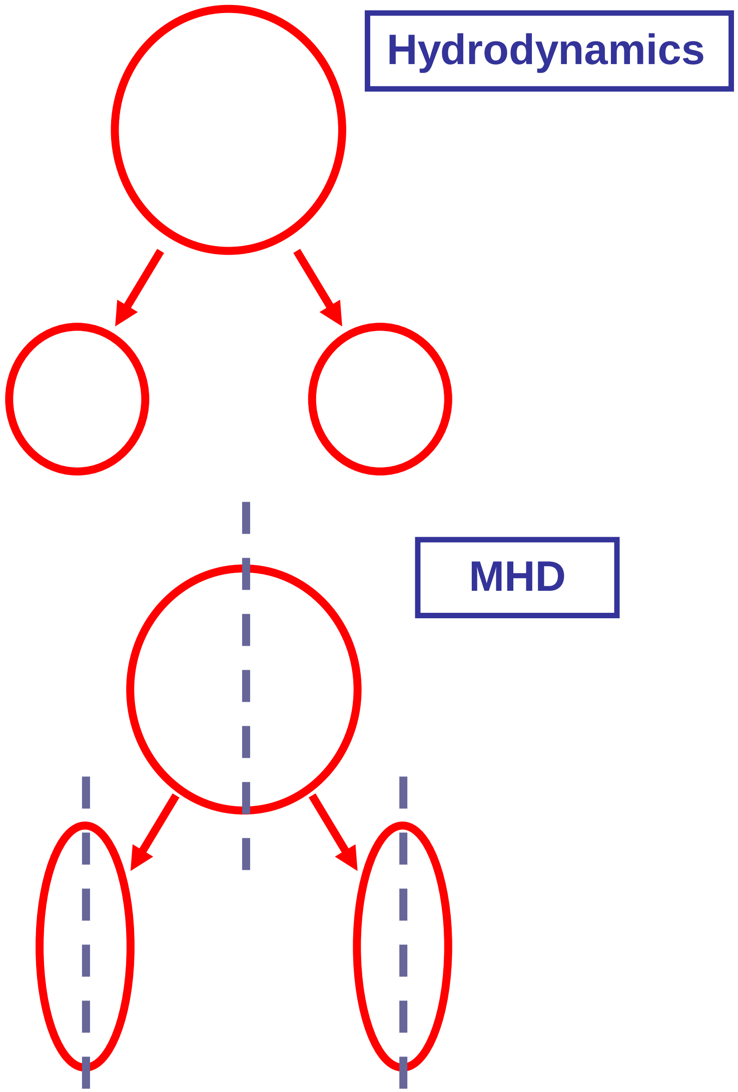


Critical balance



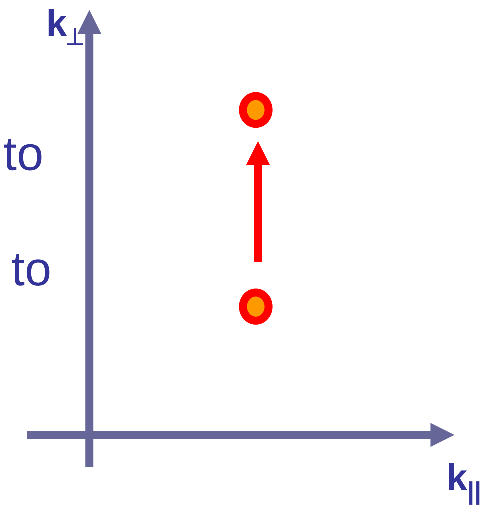
- Goldreich and Sridhar, 1995
- Balance of Alfven and nonlinear timescales
- Distinguish hydro-like and MHD-like regimes
- What is nature of cascade around this regime?

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

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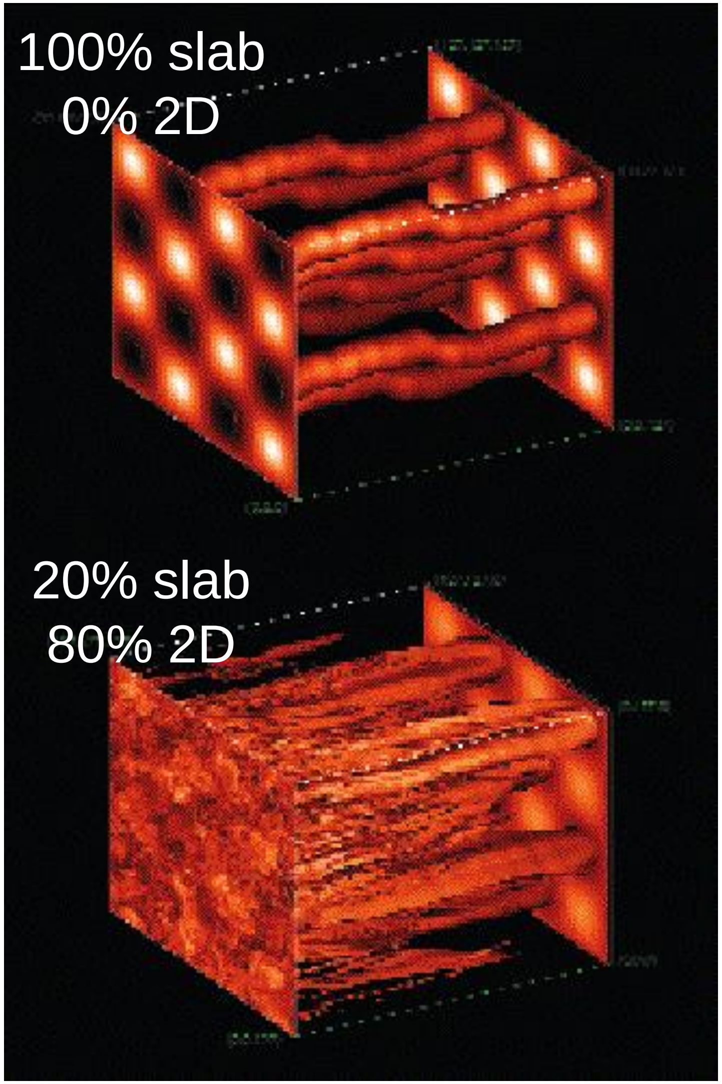
Anisotropy and 3D field structure

- Wavevectors **parallel** to the field: long correlation lengths perpendicular to field ("slab")
- Wavevectors **perpendicular** to the field: short correlation lengths perpendicular to field ("2D")

- Mixture of slab and 2D results in **shredded** flux tubes
- Consequences for field structure and energetic particle propagation



Matthaeus et al 1995

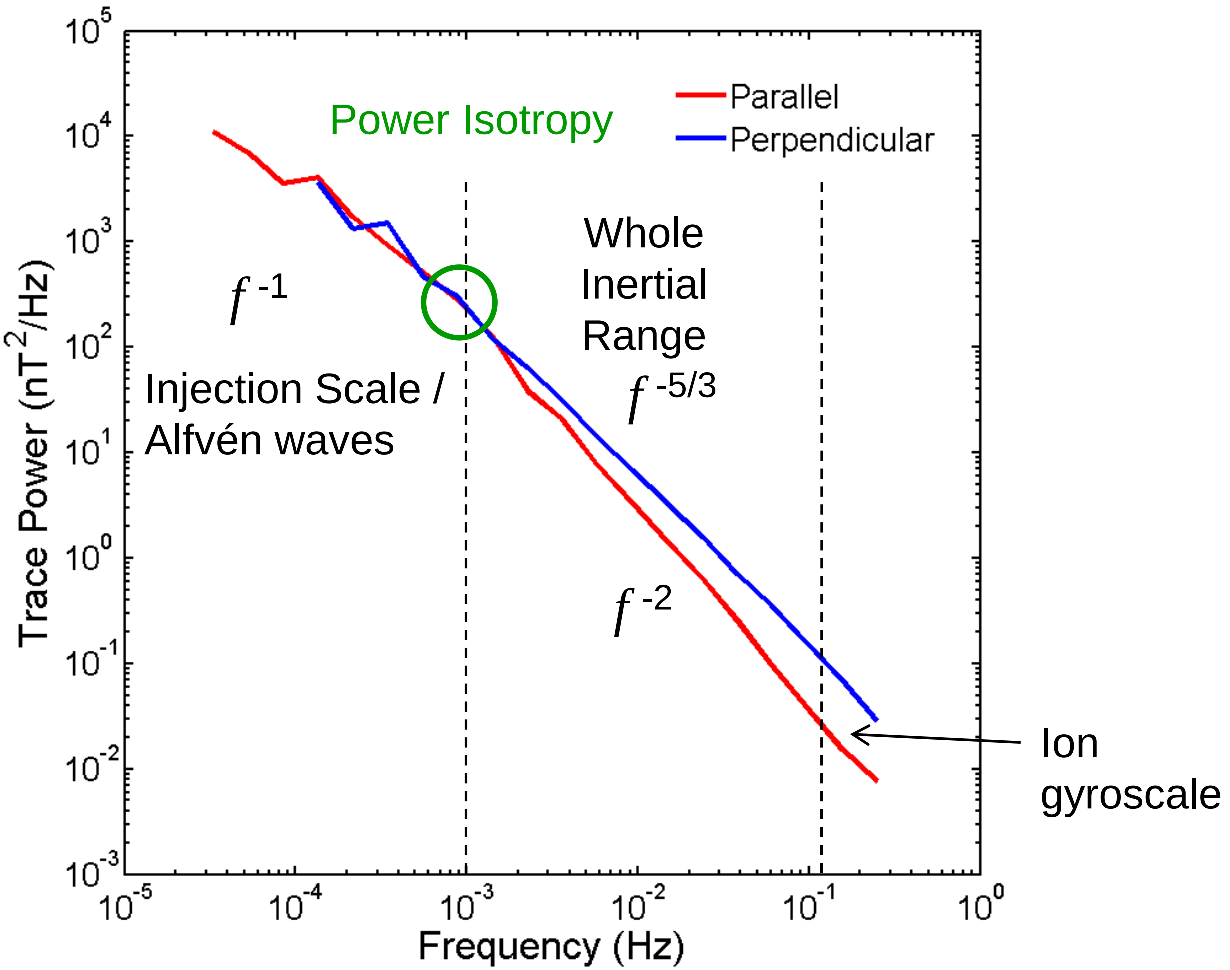
Evidence for critical balance?

- Wicks et al., 2011
- Track local magnetic field, using wavelets

- Perp spectrum: 5/3
- Parallel spectrum: 2

- This is what is predicted for reduced spectrum from critical balance

- Is this a proof of CB?



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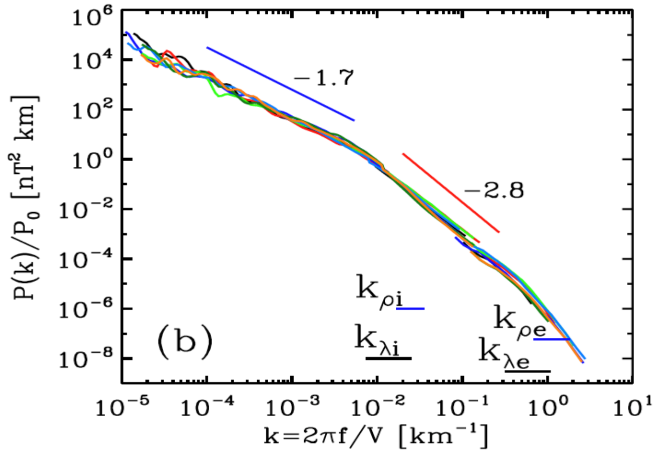
Kinetic processes

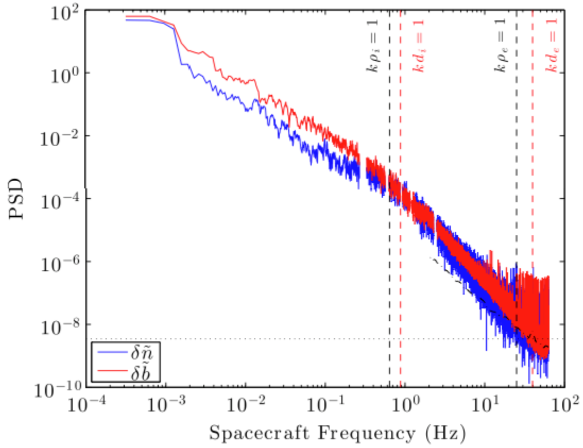
- What happens when we reach non-MHD scales?
- Kinetic processes important
- Hydrodynamics: viscosity causes dissipation
- Collisionless plasmas: no real viscosity
- What causes dissipation?
- Waves become dispersive

Spectrum at Small Scales

- What happens when cascade reaches special plasma scales, e.g., gyroradius?
- Scale invariance broken so change in power law spectrum, it steepens
- What physical processes cause this?
  - new type of cascade
  - energy dissipation
- Nature of the fluctuations
  - kinetic Alfven
  - dispersive modes
  - more compressible
  - natural extension of large scale cascade

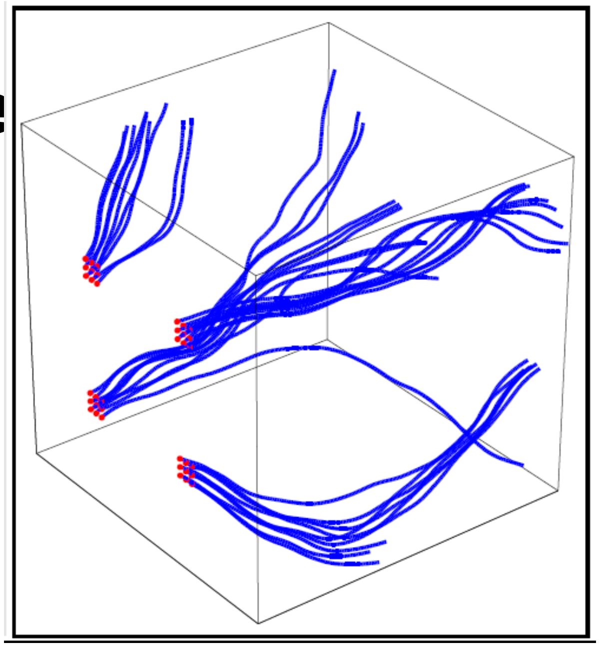


Alexandrova et al. 2009 PRL



Chen et al. 2013 PRL

Discontinuities vs turbulence

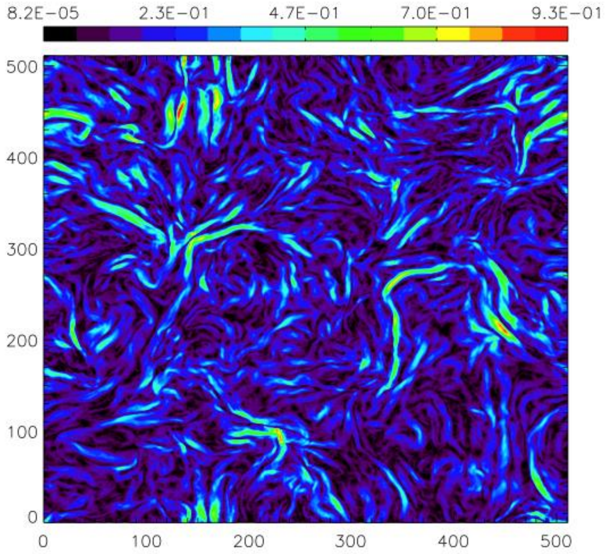


- Turbulence
  - Field-perpendicular cascade generates short scales across the field
  - Tube-like structures
  - Not topological boundaries

- Flux tubes
  - Sourced from Sun (Borovsky)
  - Topological boundary?
- How to decide?
  - Composition changes?

Intermittency & Structures

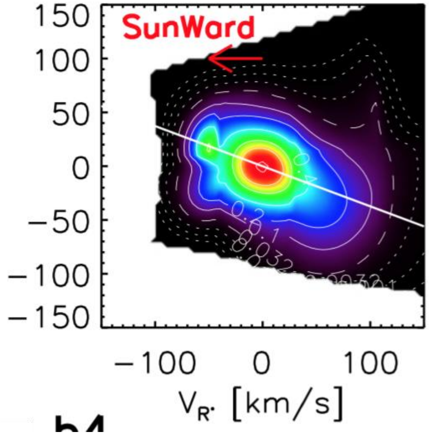
- Plasma turbulence also intermittent, but tends to generate 2D sheets
- Solar wind structures: current sheets, discontinuities, reconnection events, etc.
- Turbulence generated vs plasma boundaries



Boldyrev & Perez 2012 ApJL

Dissipation and Heating

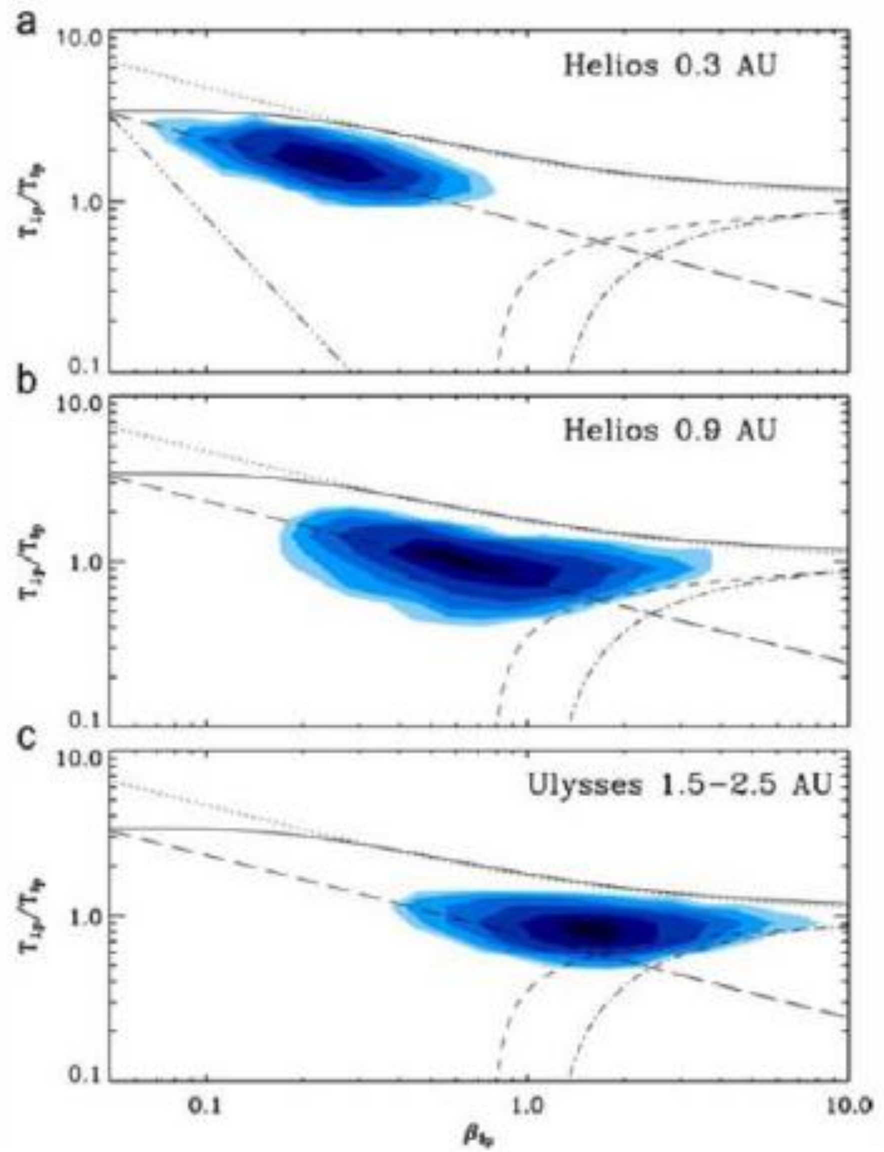
- How is the turbulent energy finally dissipated?
- How can “collisionless” plasmas be heated?
- Several mechanisms proposed
  - cyclotron damping
  - stochastic heating
  - Landau damping (+ entropy cascade)
  - reconnecting current sheets
- What constitutes irreversible heating? Are collisions required or are wave-particle interactions enough?
- These are currently some of the big questions in space plasma physics



He et al. 2015 ApJL

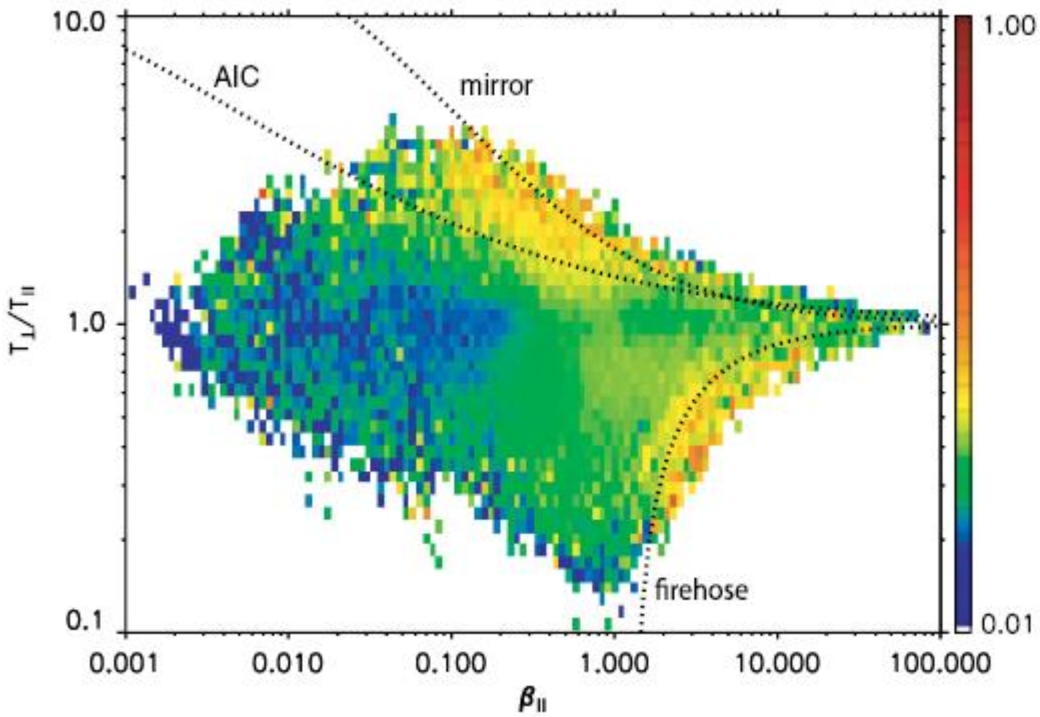
Kinetic instabilities

- Evidence for evolution of kinetic distribution limited by instabilities
- Instability thresholds for ion cyclotron (solid), the mirror (dotted), the parallel (dashed), and the oblique (dash-dotted) fire hose
- Figure from Matteini et al., 2007



Evidence for instability-generated fluctuations

- Bale et al., PRL, 2009
- Intervals near instability thresholds seem to generate fluctuations loca
- Process which keeps distributions near instabili
- What fraction of observec power is due to instabilities?



Some unanswered questions

3D structure

- What is the 3D form of the turbulence, particularly the magnetic field?
- How does this control energetic particle transport?

Dissipation

- Mechanism?
- Role of instabilities?

Coronal heating

- What can we learn about coronal conditions from the solar wind?

Summary

Anisotropy

- Perpendicular cascade
- K41-type cascade

Intermittency

- Similar to hydro

Kinetics

- Ultimate dissipation processes unclear