Solar Wind Turbulence

Presentation to the Solar and Heliospheric Survey Panel
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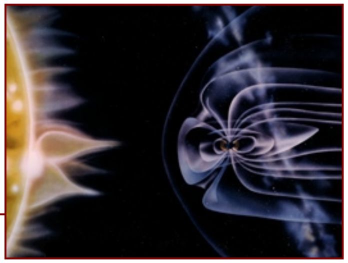
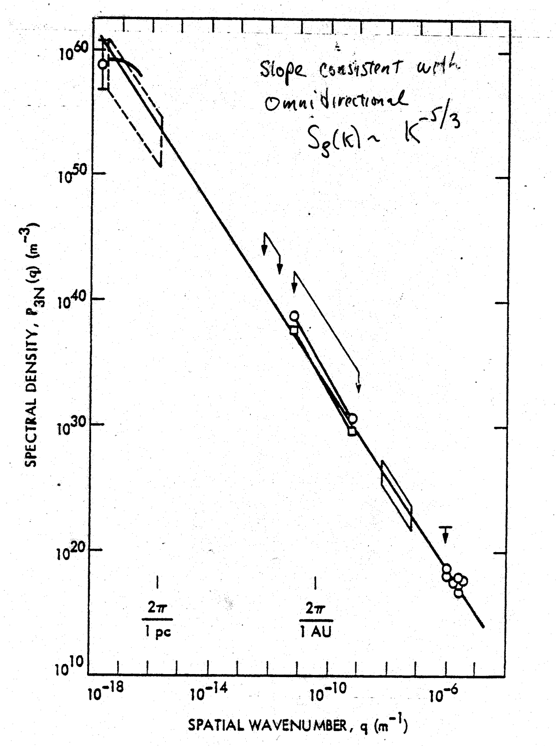
- Overview
  - Context and SH Themes
- Scientific status and Progress (last 10-20 years)
- Major Issues and Questions
  - Programs
  - Observations
  - Theory

Turbulence is a pervasive element in "Overarching Research Themes"

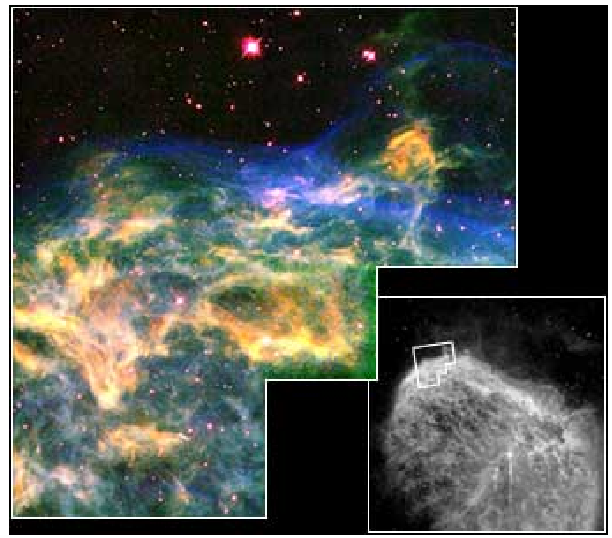


- Origins of solar magnetic fields, solar atmosphere, solar wind; why is there a heliosphere?
- Structure of the heliosphere and the Earth's plasma environment: the transport of energy and matter throughout
- Couplings between solar activity and the terrestrial environment: climate, space weather effects, predictions, societal impacts
- The Sun, planetary magnetospheres, and the heliosphere as astrophysical objects
- Fundamental plasma physical processes:reconnection; turbulence; dissipation; acceleration, trapping, scattering of particles; non-linear dynamical aspects of these phenomena

Solar Wind Turbulence: an example of a frequently encountered Astrophysical Phenomenon



- **Turbulence in Interstellar Medium from scintillation data**

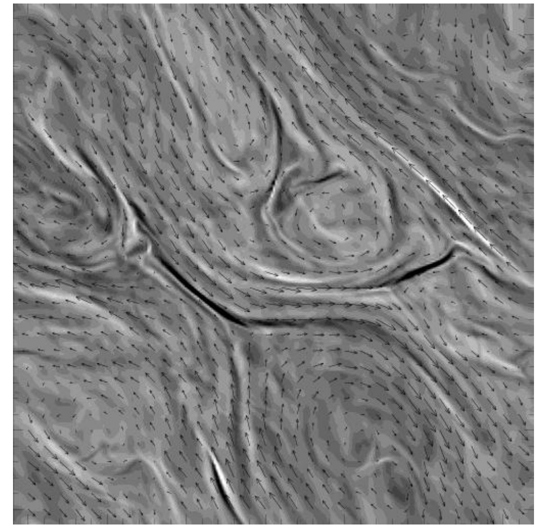


Crescent Nebula: turbulence driven by a 2000 km/s stellar wind?

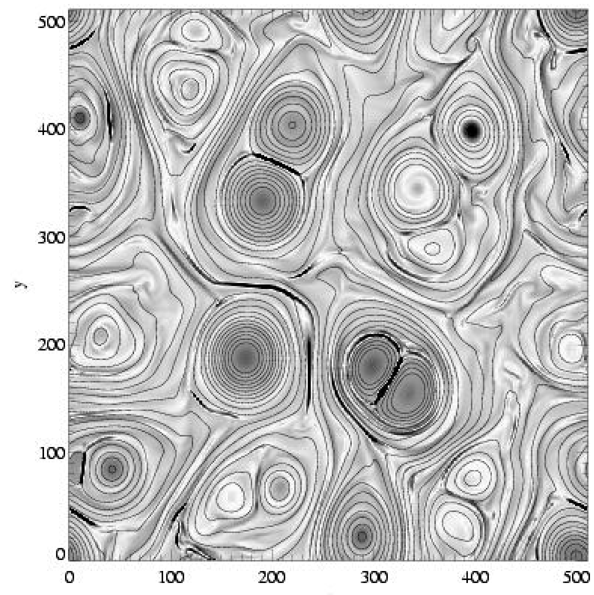
Understanding SW turbulence may help understand many astrophysical phenomena: stellar winds, galactic dynamo, cosmic ray propagation, supernova remnants, galaxy formation, cooling flows, accretion......

Turbulence as a fundamental physical process

- Turbulence: complex nonlinear flow/motion of fluid or plasma
- Typically involves broad range of space and time scales
- Nonlinear processes include: cascade, enhanced transport, mixing and dissipation
- Macro vs. Micro: Turbulence interacts with large scale flow and structure; also interacts with microscopic or kinetic processes; connects inhomogeneous processes with “homogeneous” processes.”
- Large scale plasma: MHD
- Coherent vs. random features: self-organization, relaxation and chaos



Wave driven quasi-2D MHD turbulence

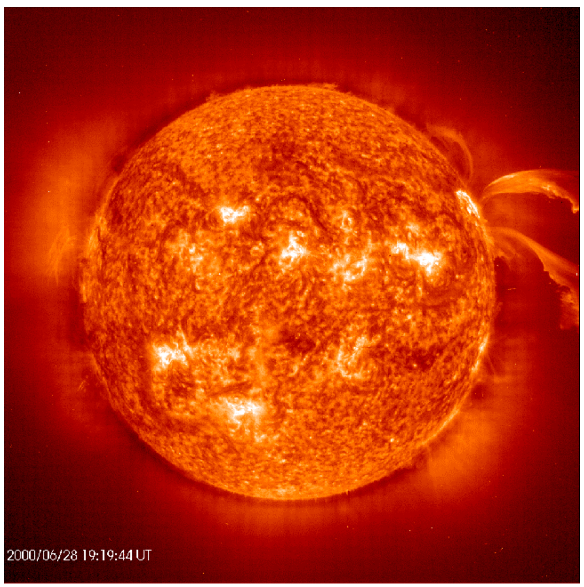


Decaying 2D MHD turbulence:
electric current density and magnetic field

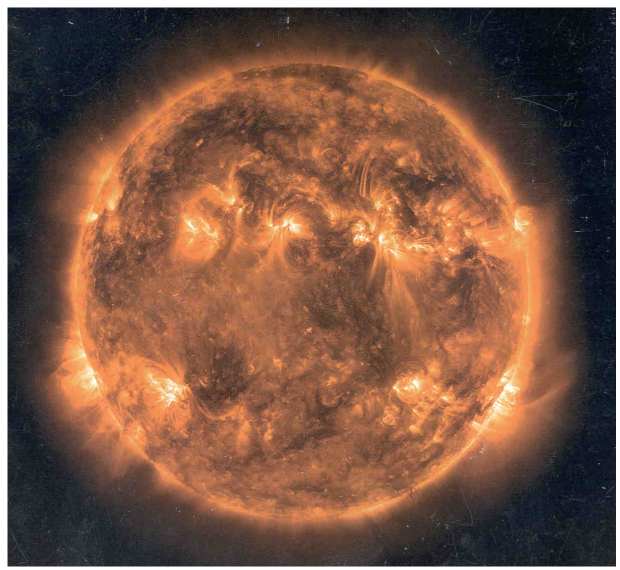
Turbulence is involved in the origin of Solar Magnetic Field, Coronal Heating, Acceleration of Solar Wind

- Turbulent Dynamo
- Coronal Heating driven by wave propagation and reflection

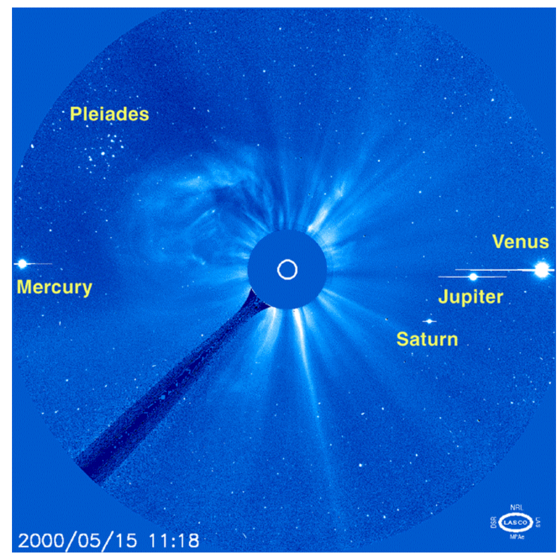
- **Complex dynamics of lower solar atmosphere: flares, CMEs, etc, may involve nonlinear MHD effects, turbulent reconnection, cascade**...



EIT/SOHO



TRACE

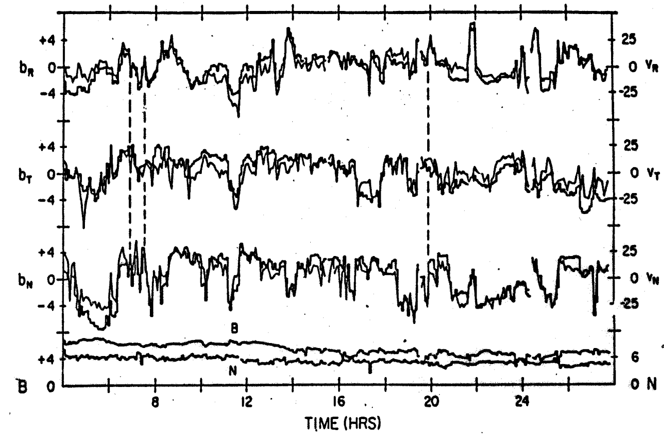


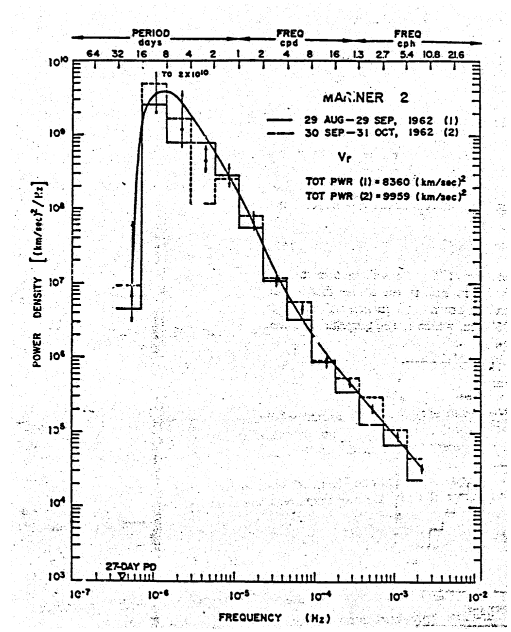
Lasco/SOHO

Two paradigms: Waves vs. turbulence

- Some features are wavelike
  - Alfvenic fluctuations, v-b correlation and small magnitude fluctuations
  - WKB similarities (however…)
  - “fossil” turbulence
- Some features are turbulence-like
  - powerlaw spectra
  - amplitudes consistent with wave-wave couplings
  - evolution of other quantities...

“Alfvenic fluctuations”





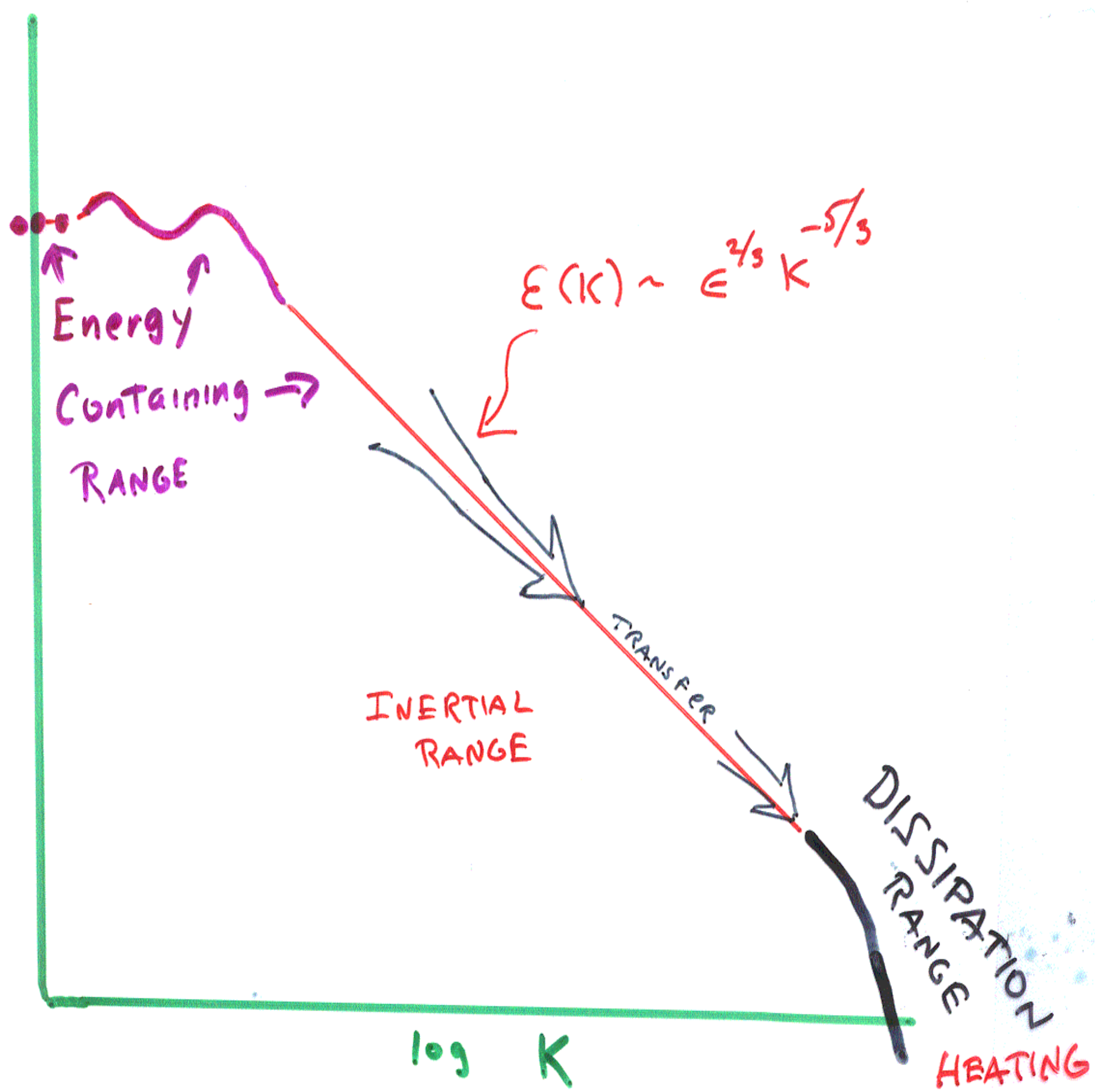
Turbulence “-5/3” spectrum

During the past 20 years considerable evidence has accumulated that the solar wind is an example of an active turbulent MHD medium.

- Spectra and the Cascade Picture (however, see sweep picture)
- Radial evolution
  - energy
  - cross helicity (Alfvenicity)
  - Alfven ratio (KE/ME)
  - density fluctuations
- Latitudinal structure (Ulysses): higher cross helicity, slower evolution
- Transport
- Anisotropies and Symmetries
- Injection of turbulence energy
  - source region
  - shear at stream interfaces
  - pickup ions
- Dissipation mechanisms
  - interface between MHD and kinetic processes
  - cyclotron absorption (sweep, "parallel cascade")
  - $k_\perp$ processes: Landau, KAW, small scale reconnection
- Simulation
- Applications (particle scattering)

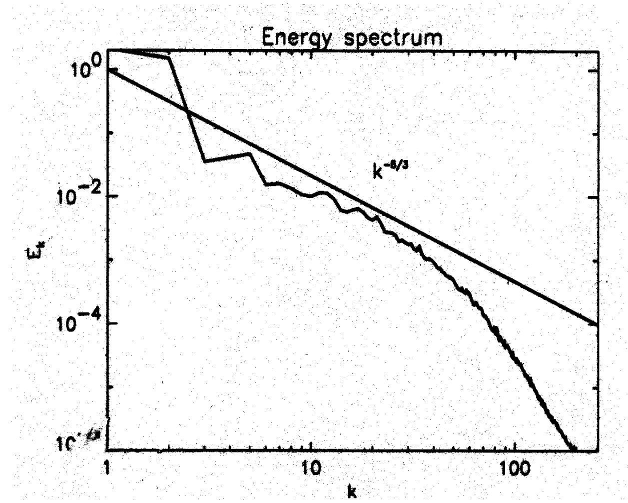
Solar Wind as *a "Natural Laboratory for Studying MHD Turbulence"*

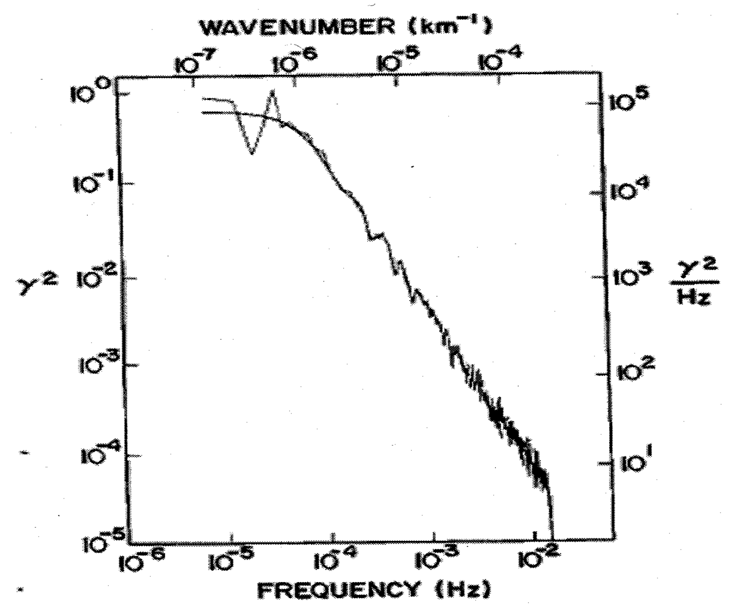
Cascade of Energy: simplified picture of homogeneous turbulence



Turbulence Spectra and Cascades

- "Kolmogoroff spectra": -5/3
- self similar dynamics
- Cascade: transfer of energy from large scale to small
- Suggests or Implies
  - quasi steady state
  - source and sink
  - turbulent heating
  - turbulent transport/dissipation (heat, tracers, particles…)



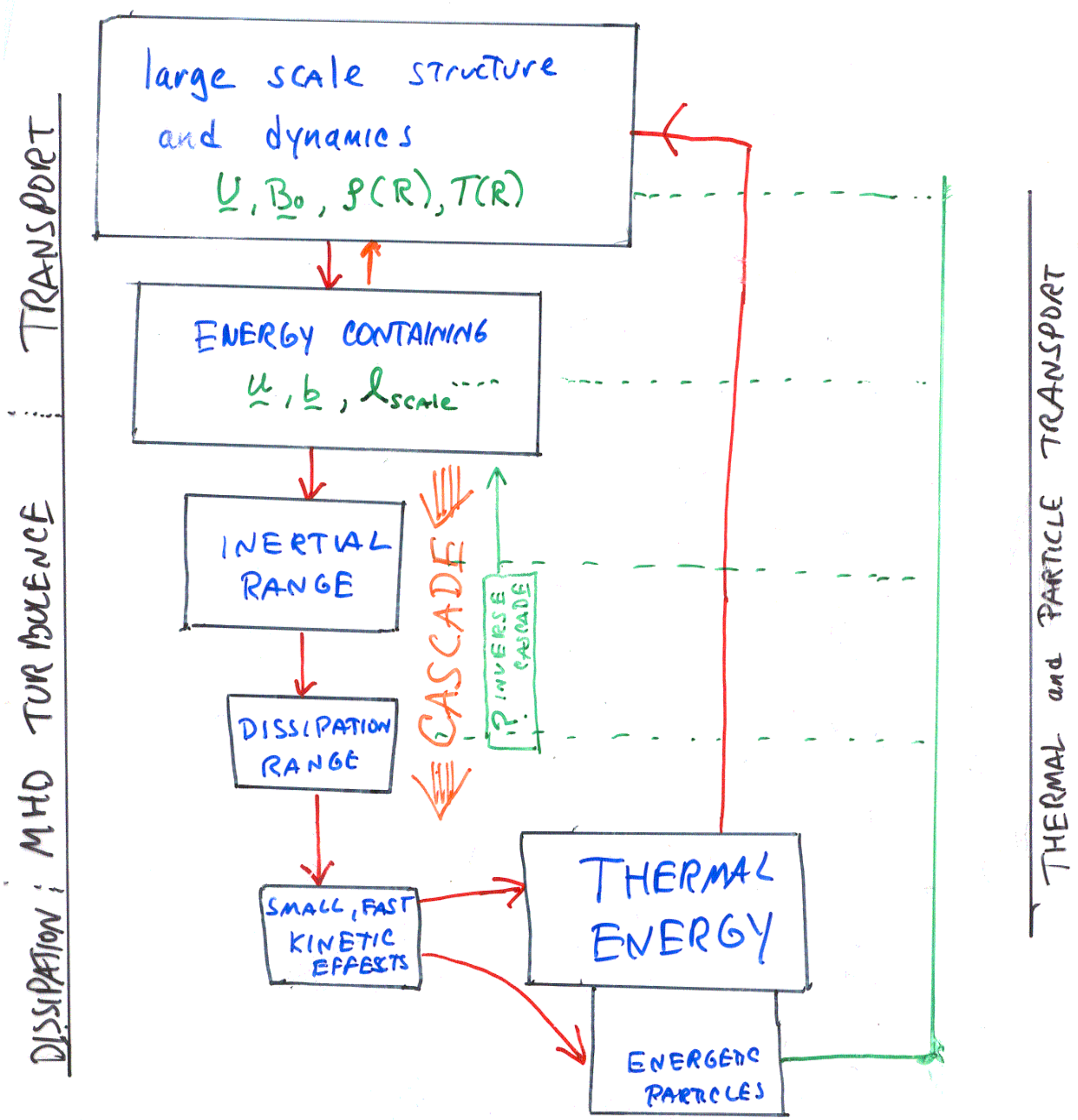


$$\varepsilon \approx -(Z_+{}^2 Z_- + Z_-{}^2 Z_+)/\lambda$$

$$\Rightarrow \; -Z^3/\lambda$$

$$\eta \approx \delta u \bullet \lambda$$

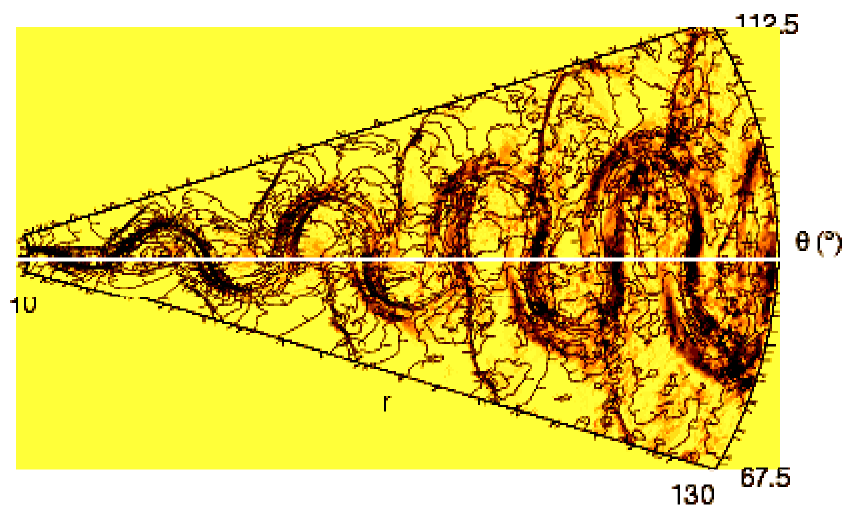
Turbulence Couplings in inhomogeneous plasma



Inhomogeneous SW Turbulence

- Transport Theory
  - large and small scales “separated” by <…>
  - “Non WKB” includes interacting fluctuations, “zero frequency” hydrodynamic modes
  - MECS: Mixing, Expansion, Compression and Shear
  - models for the local cascade effects
- Direct Numerical Simulation
  - Has become powerful enough to span macroscopic and meso-turbulence scales.

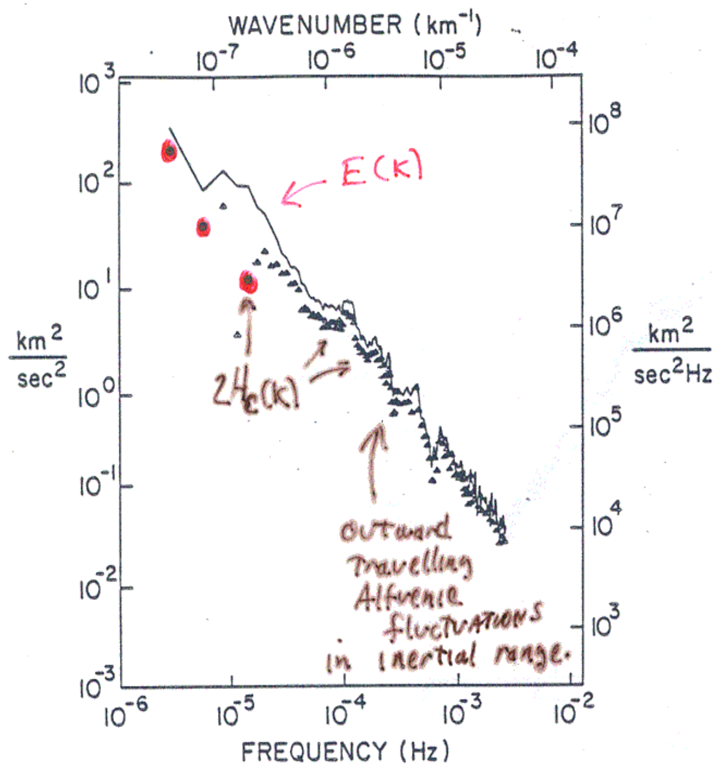
B-magnitude and vorticity from simulation of stream interaction and vortex street formation in the outer heliosphere (Goldstein et al, 2001)

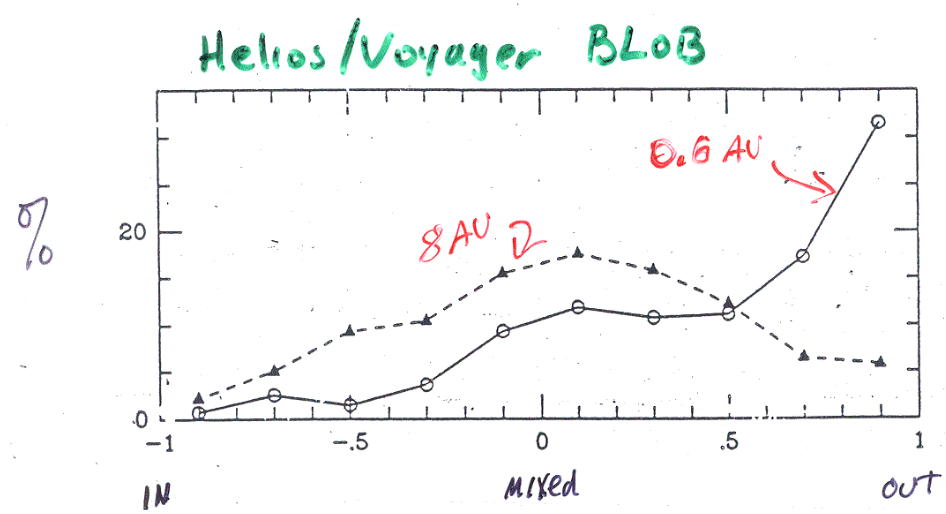


Radial Evolution of Alfvenicity

- At Helios orbit, mostly outward travelling Hc in inertial range -- evidence for solar origin of fluctuations
- Systematic reduction in preponderance of outgoing fluctuations at larger **R**

- By 2-3 AU nearly equal inward and outward (low latitudes)
- Similar effect at Ulysses latitude, but slower
- **Evidence for (non-WKB) evolution -- due to shear driving or expansion effects**

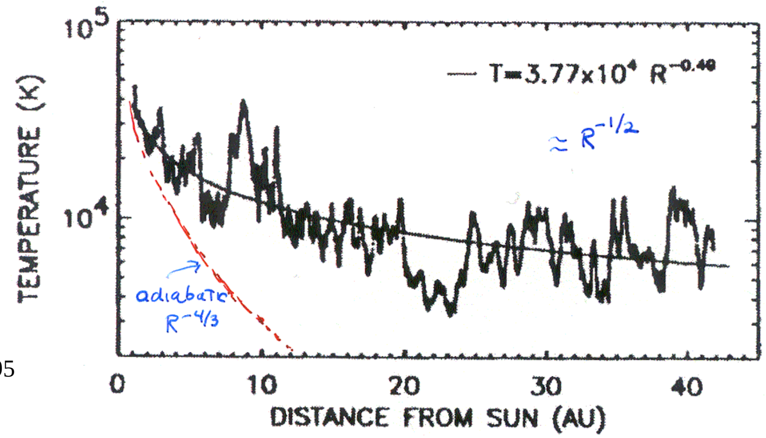




Roberts et al, 1987

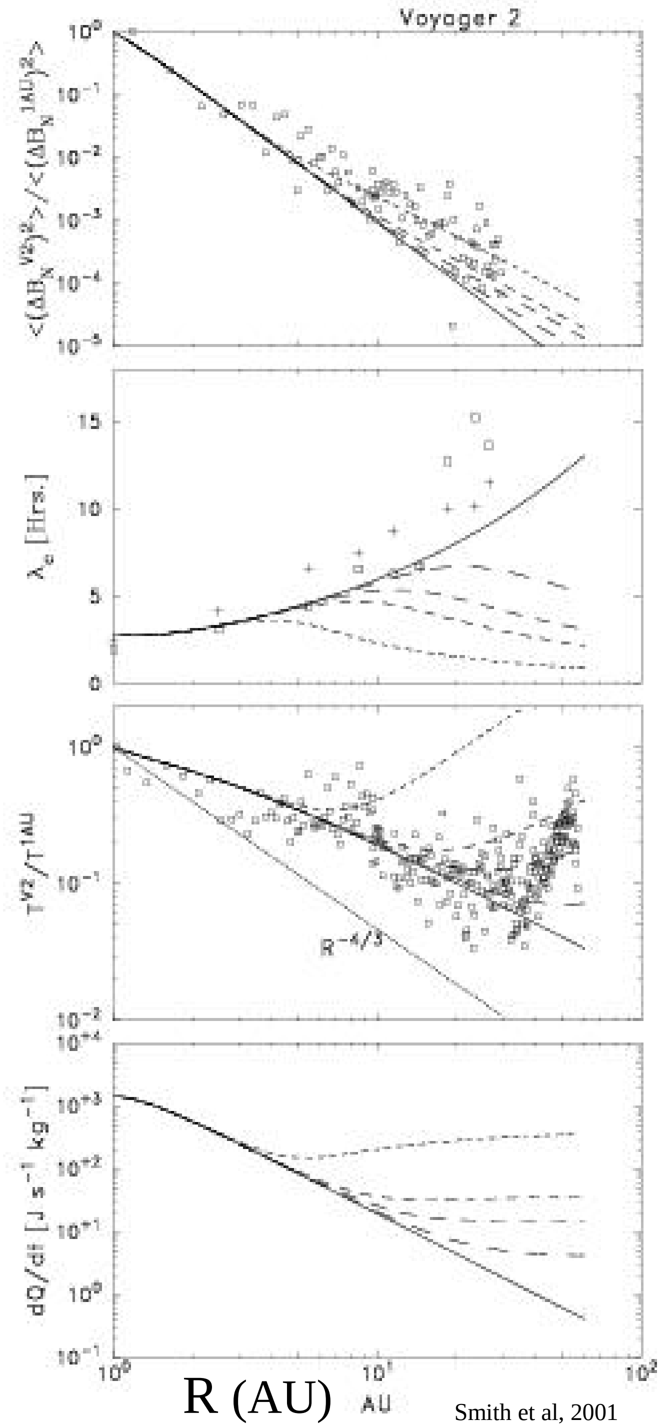
Radial Evolution and Heating

- Solar Wind protons are highly nonadiabatic



Richardson et al, 1995

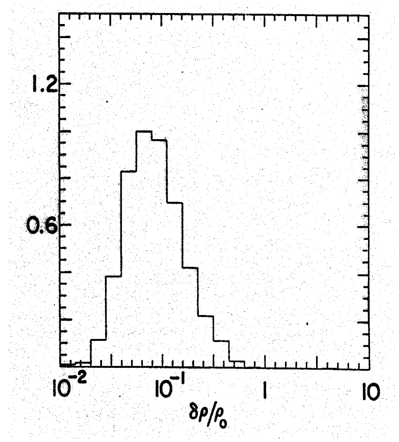
- Transport/MHD turbulence model seems to explain many features, based upon
  - quasi-2D cascade
  - shear driving
  - variable effects of pickup ions

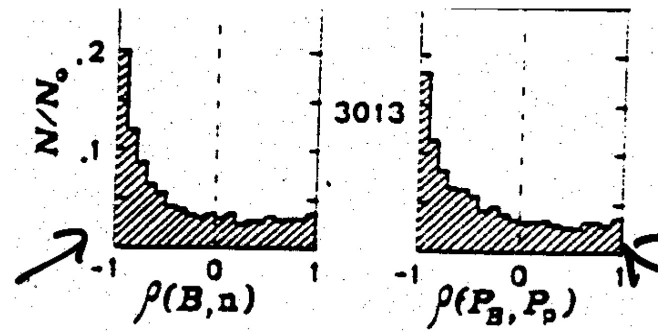


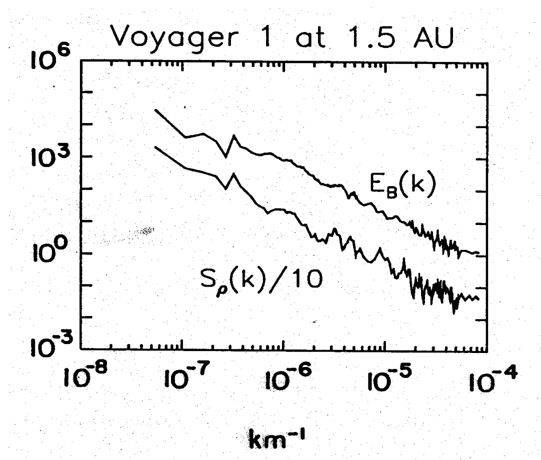
Smith et al, 2001

Distinctive Density Correlations in SW Turbulence

- Density fluctuations are small, on average ~1/10
- Density - magnetic field strength anti-correlations -- “Pressure balance”
- Density spectrum tends to follow magnetic field spectrum
- MHD waves can explain some of this, but nearly incompressible MHD turbulence seems to explain more...

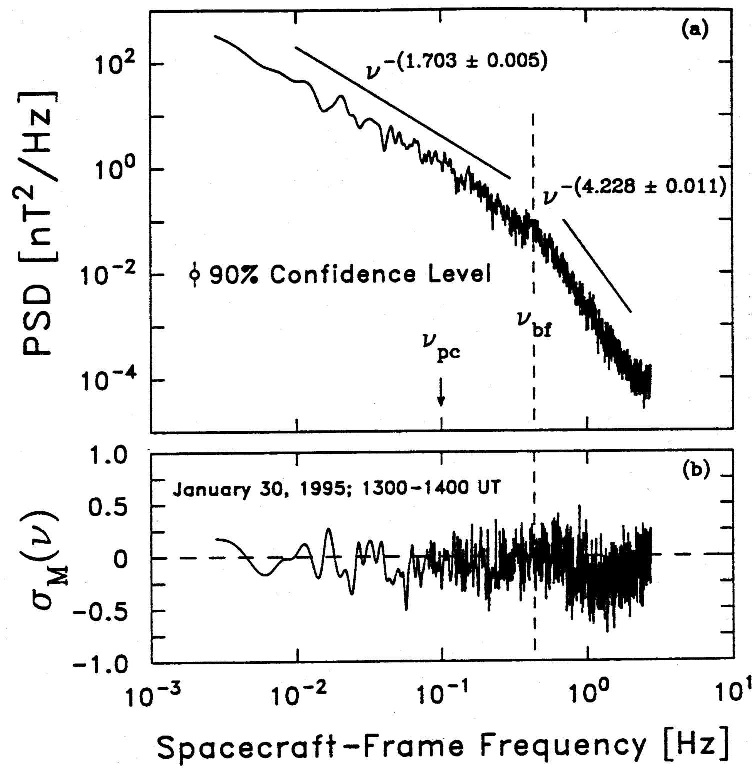






Dissipation

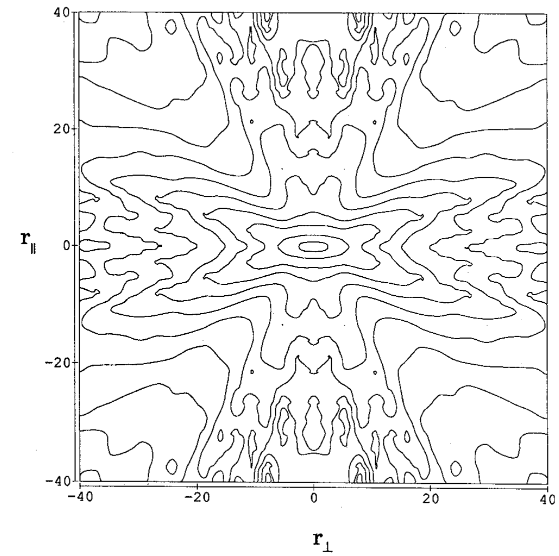
- Interface between MHD and kinetic processes
- End product of the cascade: Channel for deposition of heat
- steepening near 1 Hz (at 1 AU) -- breakpoint scales best with ion inertial scale
- Helicity signature
- Appears inconsistent with solely parallel resonances
- both k_{par} and $k_{\perp}$ are involved



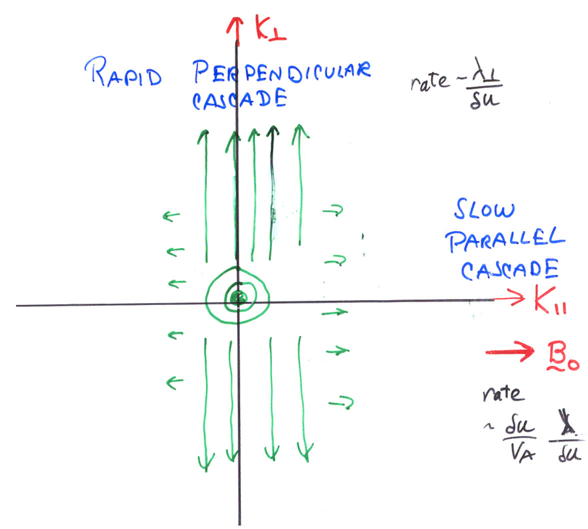
Leamon et al, 1998

Anisotropy and symmetry

- SW turbulence "sees" at least two preferred directions:
  - radial (expansion)
  - local mean magnetic field $\mathbf{B}_0$
- Several observational studies confirm lack of isotropy
- Multicomponent models: each with fixed symmetry
- Two/Three component "slab" + quasi-2D + "structures" model seems to cover most of the constraints:
  - scattering theory
  - direct observations
  - "Maltese cross"
  - Weakly Compressible MHD theory
- Slab component: waves/origin of SW
- quasi-2D component: consistent with simulations, theory and lab experiments.
- Structures: smaller parallel variance piece (phase mixing, compressible simulations, "5:4:1", NI Theory)
- Symmetry/Anisotropy has <u>*major impact*</u> on transport, heating, couplings to kinetic effects, diffusion, etc...



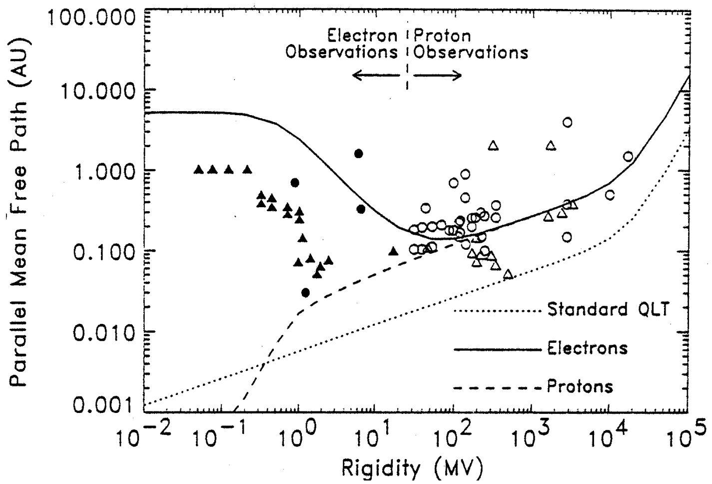
Maltese Cross



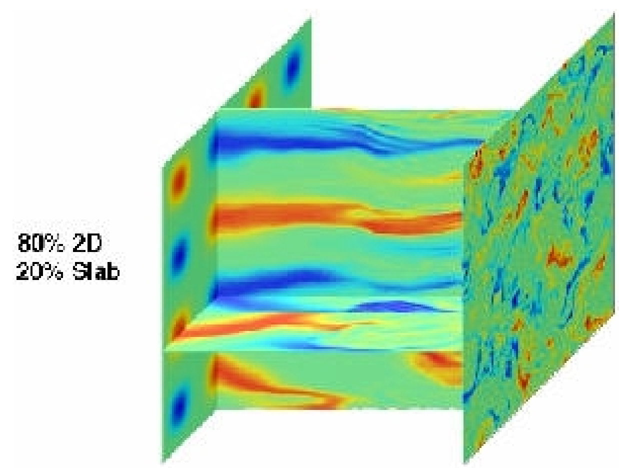
Simulations and Theory suggest that perpendicular cascade is much faster than parallel

Two Examples of the effects of anisotropic turbulence: quasi 2D ingredient

- **Charged Particle diffusion**
- 2D part doesn't participate strongly in parallel scattering
- dynamical effects control parallel diffusion of low energy particles, introduce a speed effect (e vs. p)

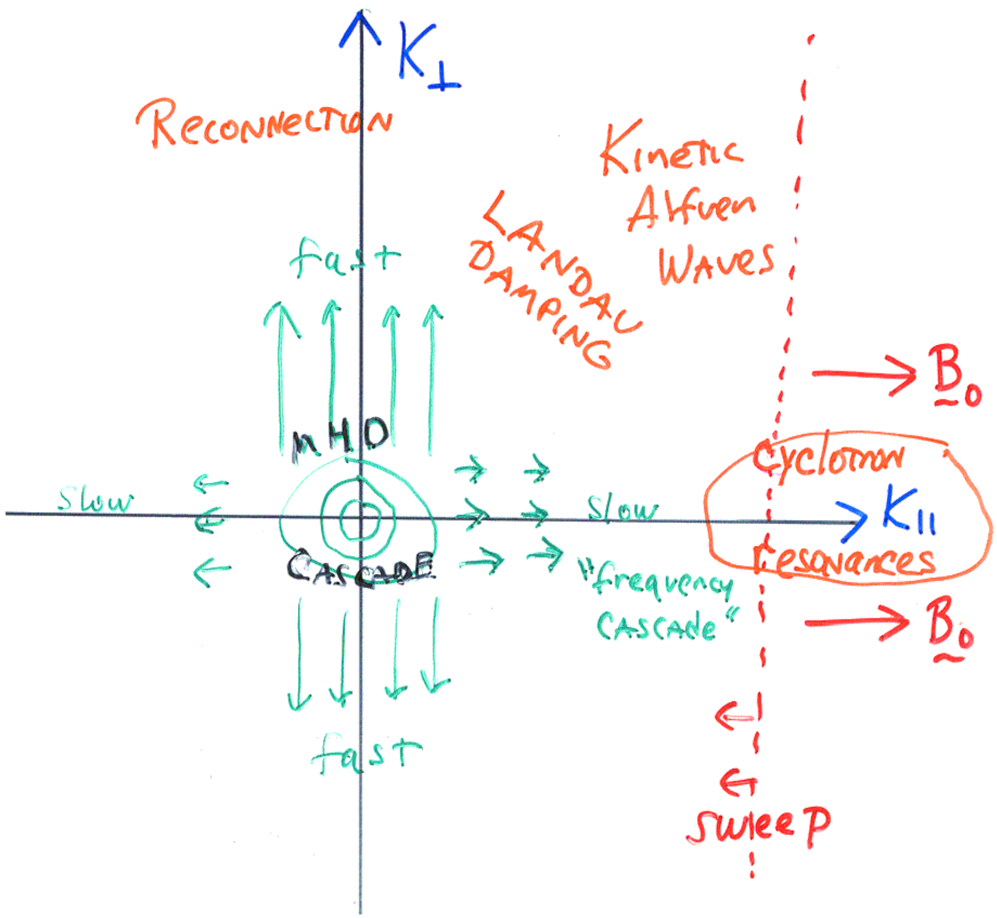


- **Field Line Diffusion/Random Walk**
- Quasi-2D part introduces as "hydrodynamic" character to field line mixing (non-quasilinear scaling**)**
- Flux surfaces shred and mix like ink in water

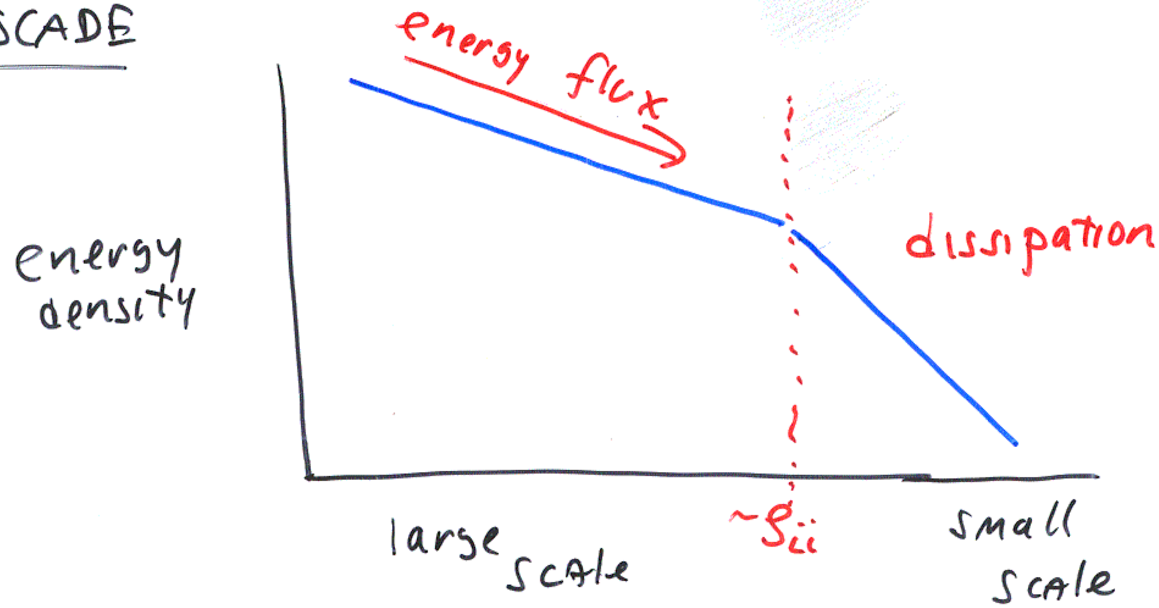


Dissipation (Revisited): effects of anisotropic cascade

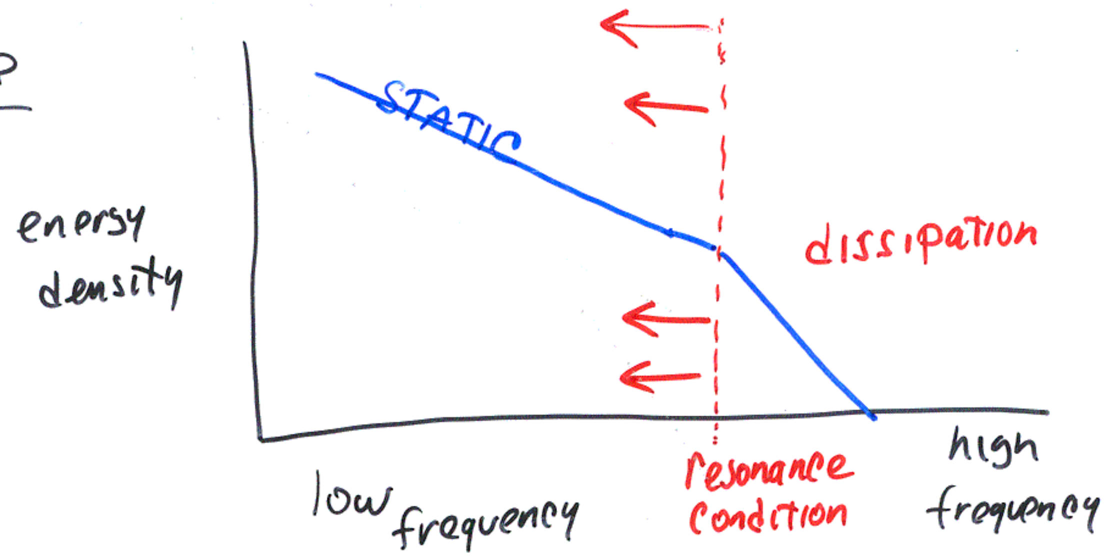
- Parallel cascade is weak so frequency replenishment is weak
- quasi-2D and oblique dissipation processes are supplied substantial energy/time
- sweep is effective but limited by available fluctuation power
- KAW and nonlinear quasi-2D processes require further investigation.



CASCADE



SWEEP



Summary of Progress in Solar Wind Turbulence

- Perhaps the best studied form of MHD/plasma turbulence
- conceptual connections and physical similarities to solar, coronal, ISM turbulence
- *In situ* studies, simulation and theory have revealed a number of features about cascase, anisotropy, cascade, radial and latitudinal evolution, dissipation
    - BUT THERE IS A LOT MORE TO LEARN
- Progress has been made in
    - Application to heating in SW and corona,
    - transport in the heliosphere
    - simulation of meso-scale processes
    - interactions with pickup ions
    - scattering of charged particle
        - modulation is a problem that has “got it all.”

Some Questions and Challenges

- How is turbulence generated and transported *throughout the entire heliosphere?*
- Dynamical turbulence effects, and the associated question: How does turbulence participate (directly and indirectly) in acceleration of suprathermal and high energy particles?
- The modulation problem
- The coronal heating problem
- The role of turbulence in accelerating the solar wind, and the origin of the fluctuations themselves.
- The problem of the interaction of the solar wind and turbulence with pickup ions of interstellar origin
- A complete understanding of the geometry and symmetry of turbulent fluctuations, and its influence on the properties of the IMF.
- The interface between kinetic and MHD fluctuations: solar wind heating and dissipation.
- What does SW turbulence tell us about astrophysics?
- Role in Space Weather and CME dynamics
- Use of the SW for development of fundamental knowledge of turbulence.

Big Picture and Goals

- MHD scale turbulence is involved in transport of energy and particles throughout the heliosphere from the convection zone and corona to the heliopause.
  - *It is involved in every one of the "overarching themes."*
- Understand the turbulence itself, how it is distributed and how it evolves.
- Understand how SW/heliospheric turbulence affects important macroscopic processes:
  - dynamo, heating of the corona, transport of solar and galactic cosmic rays, macroscopic solar wind, structure of the heliosphere and its interaction with the ISM.

SW Turbulence: Programs and Observations

- Solar Probe
- Interstellar Probe
- Multispacecraft observations: specific missions (Cluster II) and targets of opportunity (Wind, ACE…)
- Cruise mode of planetary exploration missions can be well outfitted with relatively inexpensive in situ plasma and field instruments.
- High time resolution plasma and MAG instruments
- Nanosats? Plasma Turbulence Explorer?
- Coordination of imaging (e.g., STEREO) and/or remote sensing (IPS) and in situ observation.
- A strong multidisciplinary Theory Program
- Commitment to support of advanced computational physics research (not computer science only)