2292-6

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The role of turbulence in the solar wind

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The role of turbulence in the solar wind

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Why turbulence in astrophysics and space physics?

- Cross scale couplings
  - Dynamical couplings across wide ramge of space and time
- Space weather and prediction
  - Stochastic behavior
  - Spatial and temporal complexity
- Mapping of field lines and transport of charged particles:
  - Influence of randomness
  - Influence of structure
  - nonGaussian statistics (rare events)

- Variability in space and time: unavoidable influence on predictability
  - Finite correlation time and correlation length
  - Deterministic chaos – sensitivity to ICs, BCs and driving
  - “1/f noise”

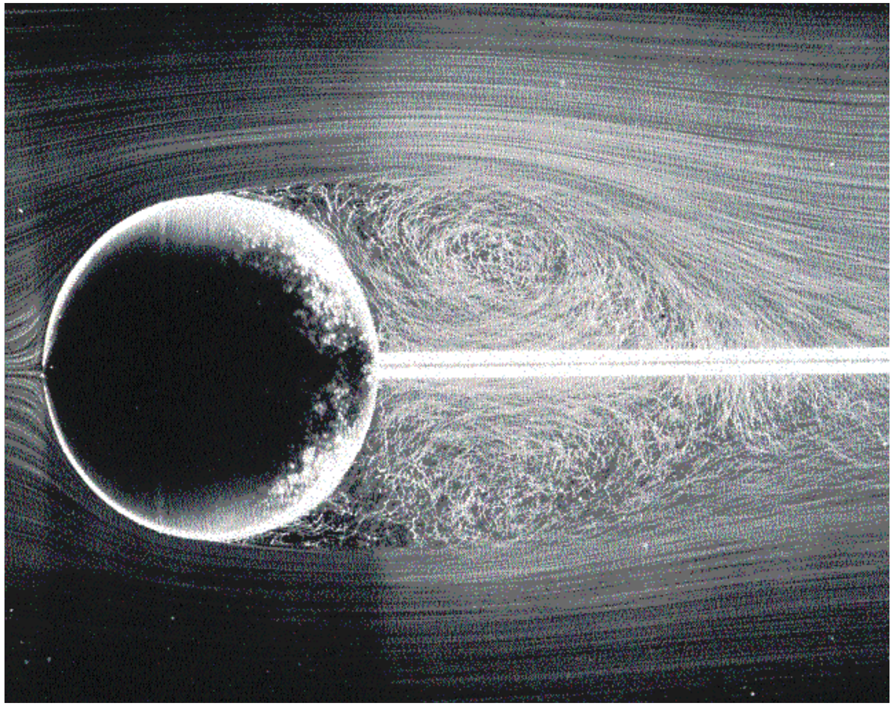
- Modification of coupling strengths, rates, diffusion coefficients
  - Heating
  - Mixing
  - Drag
  - Transport across boundaries (e.g., reconnection)

I: Solar wind turbulence: context

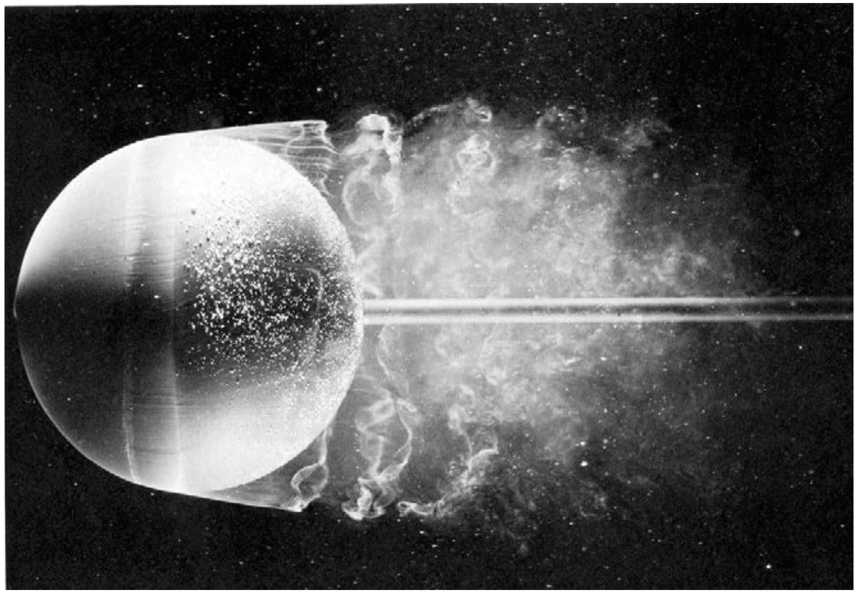
VanDyke, An Album of
Fluid Motion

Mean flow and fluctuations

- In turbulence there can be great differences between mean state and fluctuating state
- Example: Flow around sphere at R = 15,000



Mean flow

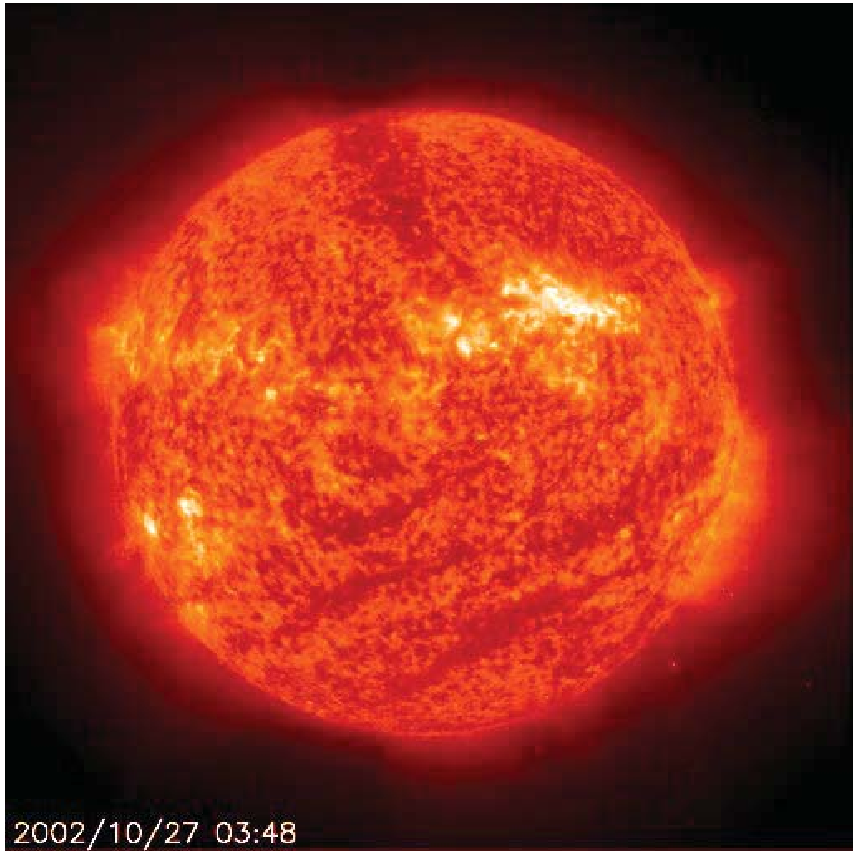


Instantaneous flow

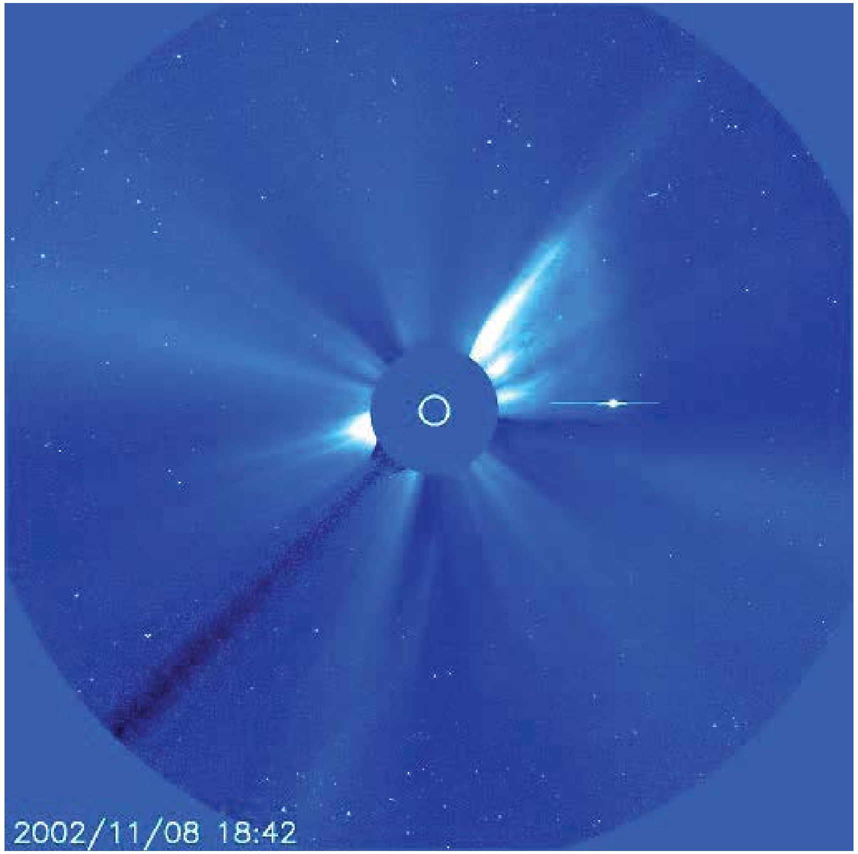
Activity in the solar chromosphere and corona: *SOHO spacecraft*

Origin of the solar wind

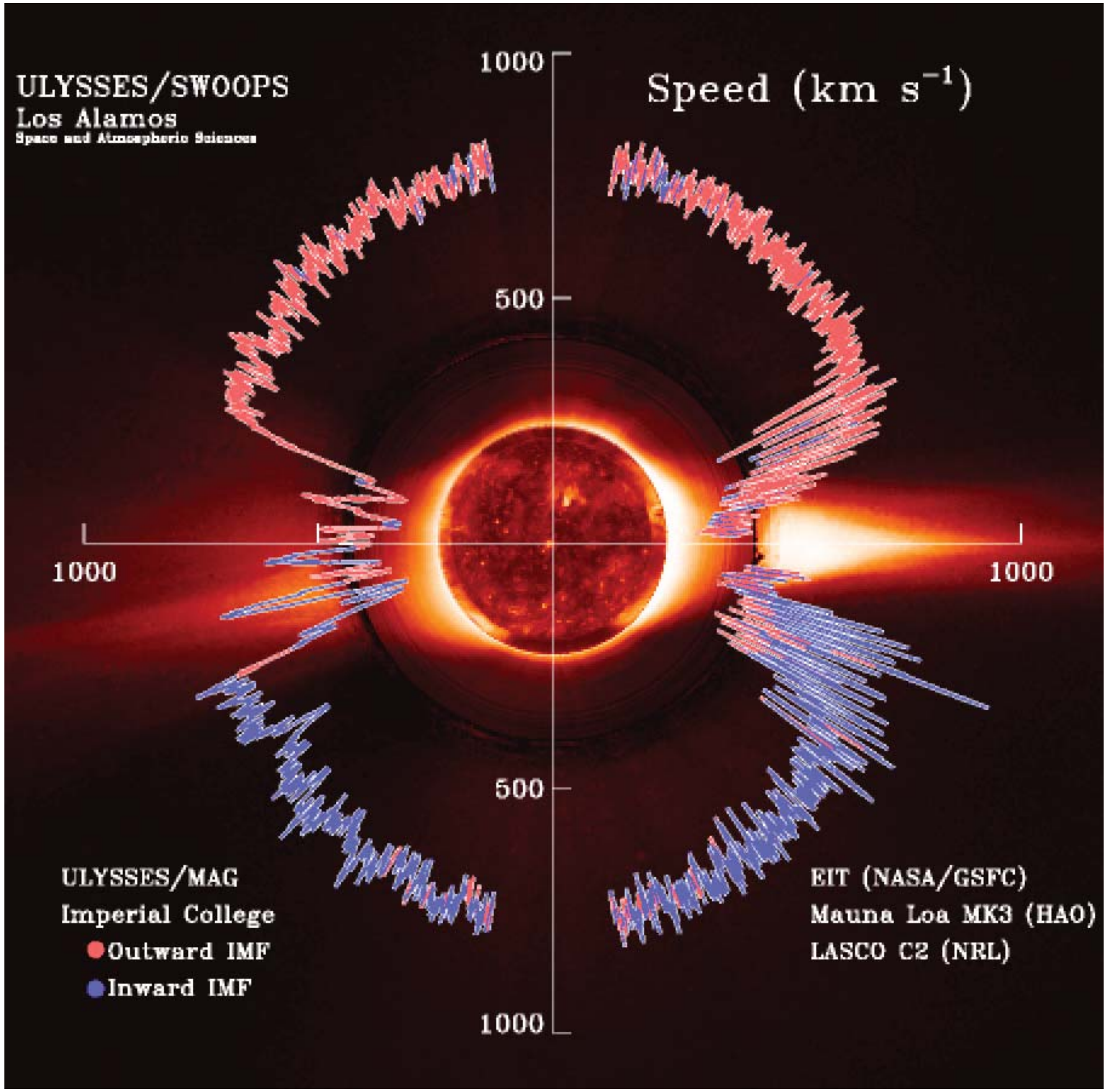
UV spectrograph: EIT 340 A



White light coronagraph: LASCO C3



Large scale features of the Solar Wind: *Ulysses*



- High latitude
  - Fast
  - Hot
  - steady
  - Comes from coronal holes

- Low latitude
  - slow
  - “cooler” (40,000 K @ 1 AU)
  - nonsteady
  - Comes from streamer belt j

McComas et al, GRL, 1995

II. Turbulence

- Hydrodynamics
  - wide range of scales --Reynolds number
  - energy decay – vonKarman
  - energy cascade – Kolmogorov\ Oubukov

- MHD
  - Energy, cross helicity, magnetic helicity (at least TWO fields)
  - Parameter space- - alfven ratio; kinetic helicity,
  - Multiple characteristic scales (correlation scales, etc)

- Plasma & kinetic effects
  - Hall, aniso pressure, kinetic damping…

Hydrodynamic turbulence

- Incompressible
- Homogeneous
- Fourier decomposition

Turbulence: nonlinearity and cascade

$$\frac{\partial \underset{\sim}{V}}{\partial t} \sim \underset{\sim}{V}\cdot\nabla \underset{\sim}{V} \xrightarrow[\text{FOURIER}]{} \frac{\partial V_\alpha(\underset{\sim}{k})}{\partial t} \sim \sum_{\underset{\sim}{r}+\underset{\sim}{p}=\underset{\sim}{k}} C_{\alpha\beta\gamma}\, \underbrace{V_\beta(\underset{\sim}{r})\, V_\gamma(\underset{\sim}{p})}_{NL}$$

"Triad interaction"

CHARACTERISTIC PROCESSES

line stretching, vortex coalescence,
reconnection . . .

ORDER → CHAOS

ergodicity, mixing

CHAOS → ORDER

coherent structures

intermittency

Turbulence and examples of fluid plasmas

hydro → MHD ← liquid metals

MHD ← plasma (collisions,

or $\Omega_{cyclotron} >> \Omega_{plasma}$)

2D Hydro ← plasma ($\Omega_{plasma} << \Omega_{cyclotron}$)

solar corona → MHD

solar wind → MHD

interstellar medium → MHD

Ionospheric plasma (e.g., auroral) → 2D hydro

Incompressible MHD

- Variables velocity $\boldsymbol{v}$ magnetic field $\boldsymbol{B} = \boldsymbol{B}_0 + \boldsymbol{b}$

  <B>$= \boldsymbol{B}_0$ mean

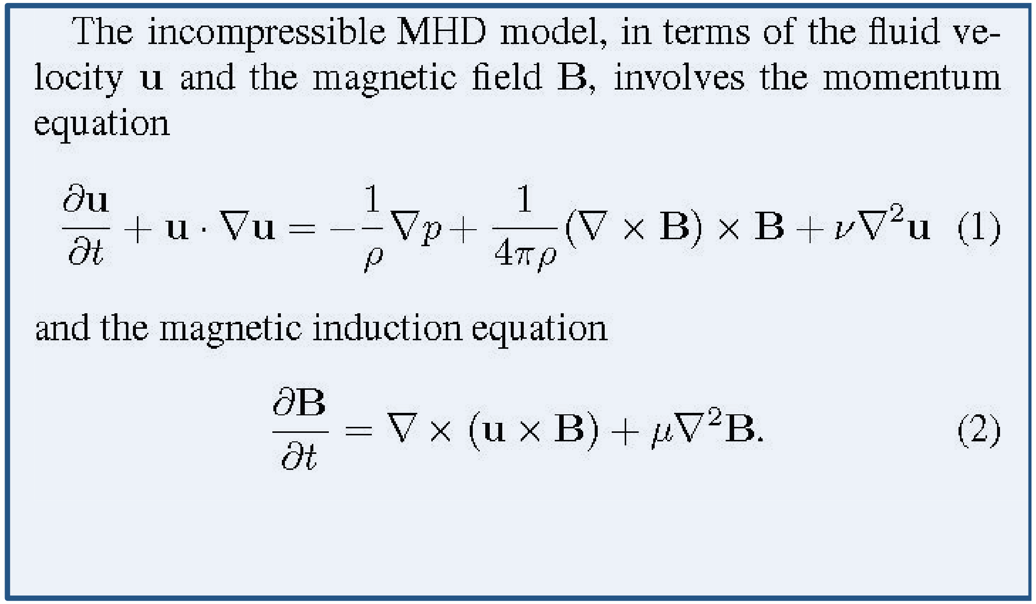
- Incompressible for “same reasons” as in hydro

  $\rho = const.$ $\nabla \cdot \boldsymbol{v} = 0$

- Lorentz force $(\nabla \times \boldsymbol{B}) \times \boldsymbol{B} = \boldsymbol{J} \times \boldsymbol{B}$ in momentum equation

- Ohm’s Law $\boldsymbol{E} = -\boldsymbol{v} \times \boldsymbol{B} + \mu \boldsymbol{J}$ + … (plasma…caution!)

Distinctive effects in MHD



The incompressible MHD model, in terms of the fluid velocity $\mathbf{u}$ and the magnetic field $\mathbf{B}$, involves the momentum equation

$$\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u} = -\frac{1}{\rho}\nabla p + \frac{1}{4\pi\rho}(\nabla \times \mathbf{B}) \times \mathbf{B} + \nu \nabla^2 \mathbf{u} \quad (1)$$

and the magnetic induction equation

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{u} \times \mathbf{B}) + \mu \nabla^2 \mathbf{B}. \quad (2)$$

- Two fields and multiplicity

of length scales

- Anistropy/propagation

$$\frac{\partial \mathbf{z}_\pm}{\partial t} \mp \mathbf{V_A} \cdot \nabla \mathbf{z}_\pm = -\mathbf{z}_\mp \cdot \nabla \mathbf{z}_\pm - \frac{1}{\rho}\nabla P + \mu \nabla^2 \mathbf{z}_\pm$$

- Multiple ideal invariants/direct/inverse cascades (see also “quasi-invariants”)
- Dimensionless parameters

There are numerous reasons to doubt that MHD turbulence admits the same sort of “universality” that hydro does.

Nonlinear (incompressible) MHD

Velocity fluctuation v
Magnetic fluctuation b
Mean magnetic fld B_0

$\nabla \bullet v = 0$
$\nabla \bullet B = 0$
$B = B_0 + b$

Momentum

$$\frac{\partial \mathbf{v}}{\partial t} = - v \bullet \nabla v + J \times B + \nu \nabla^2 v$$

Induction

$$\frac{\partial \mathbf{b}}{\partial t} == - \mathbf{v} \bullet \nabla \mathbf{b} \underbrace{+ \mathbf{b} \bullet \nabla \mathbf{v}}_{\text{nonlinear}} \underbrace{+ B_0 \bullet \nabla \mathbf{v}}_{\text{linear}} \; \mu \nabla^2 \mathbf{v}$$

$$\boldsymbol{b}(\boldsymbol{x}) = \int d^3k \, \boldsymbol{b}(\boldsymbol{k}) \, e^{\,ik\bullet x}$$

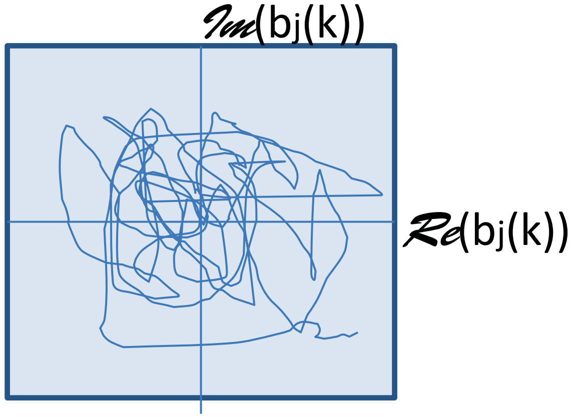
$$\partial \boldsymbol{b}(\mathbf{k})/\partial t \sim \sum_{\boldsymbol{k}=\boldsymbol{r}+p} \boldsymbol{b}(\boldsymbol{r})\boldsymbol{v}(\boldsymbol{p})$$

$$\mathbf{b}(\mathbf{k},t) \sim |\mathbf{b}(k,0)| e^{\,i\omega t}$$

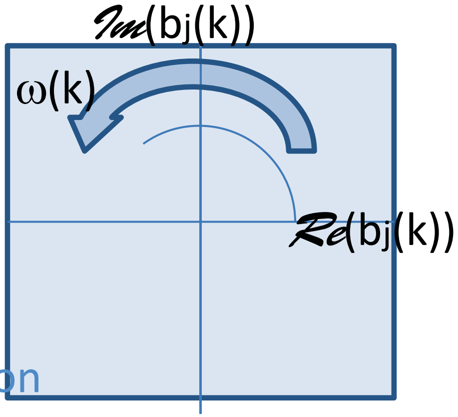
Cross scale couplings: chaos
Random walk in phase space
→ "turbulence"

eigenmodes (independent)
systematic rotation in
phase space → "waves"

Trajectory in time
of a Fourier mode
in strong
turbulence



pure wave
Fourier mode
ω(k): dispersion
relation



III. Similarity decay of energy: simple but powerful theories:

Energy decay in turbulence

Wind tunnel measurements of energy vs. distance (time)

Batchelor and Townsend, 1949

$$dE/dt \sim -u^3/L$$

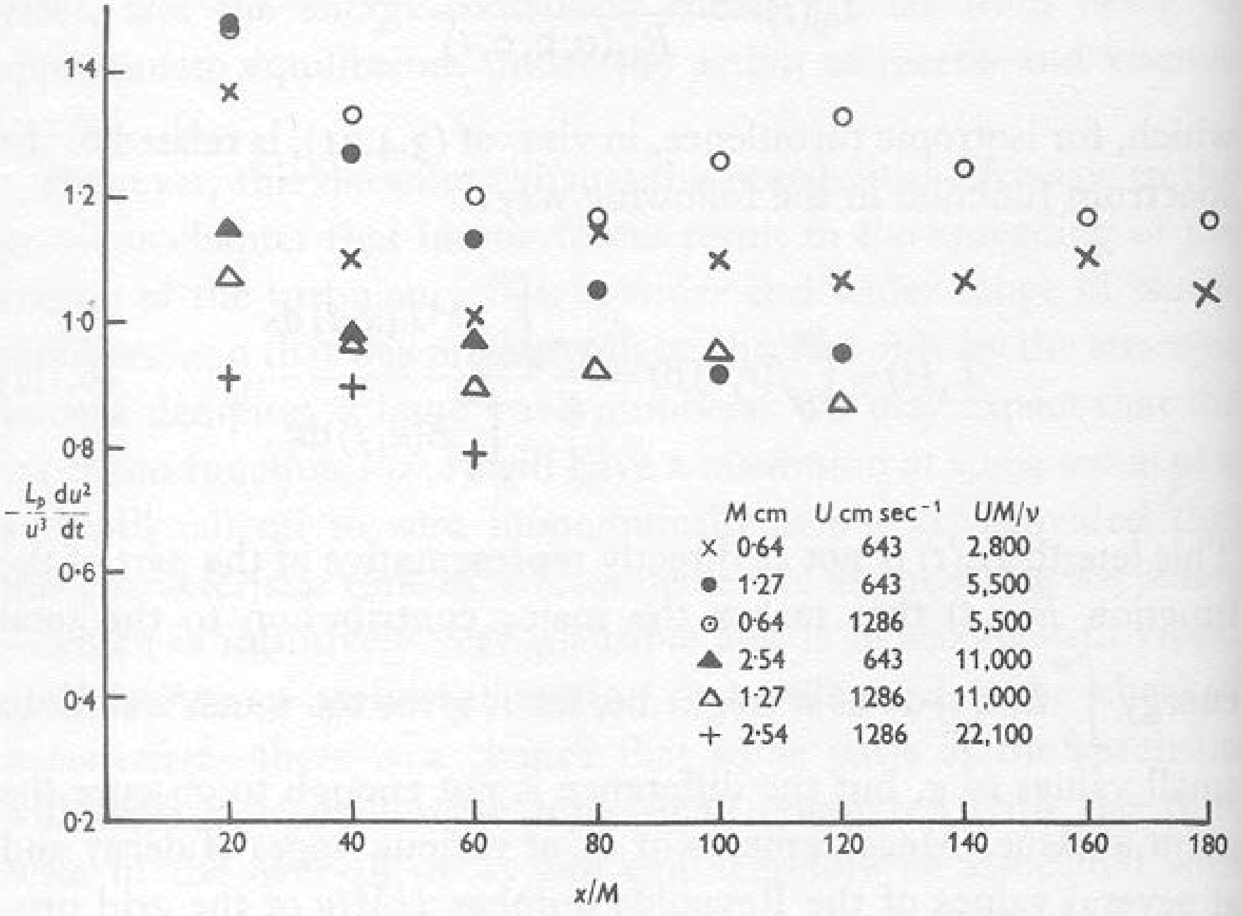


Fig. 6.1. The empirical relation $\frac{du^2}{dt} = -A\frac{u^3}{l}$.

Energy decay (decay of direct cascaded quantity)

- vK-H ideas
  - energy dissipation independent of R, Rm
  - 3rd order law (Pouquet and Politano, 1998)

    NB mean magnetic field does not appear in VKH eqns!

- `Similarity decay equations’
  - Isotropic
  - Anisotropic:

    4 length scales, and it appears they cannot be indedendent

$$\frac{dZ_+^2}{dt} = -\alpha_+ \frac{Z_+^2 Z_-}{L_+}; \qquad \frac{dZ_-^2}{dt} = -\alpha_- \frac{Z_+ Z_-^2}{L_-}$$

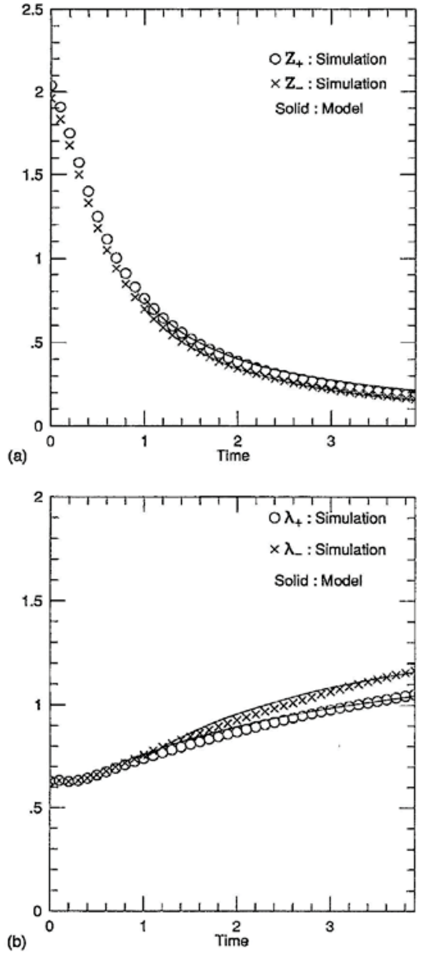
$$\frac{dL_+}{dt} = \beta_+ Z_-; \qquad \frac{dL_-}{dt} = \beta_- L_+$$

Wan et al, JFM 2011 submitted

Isotropic MHD-vKH decay (2 length scales)

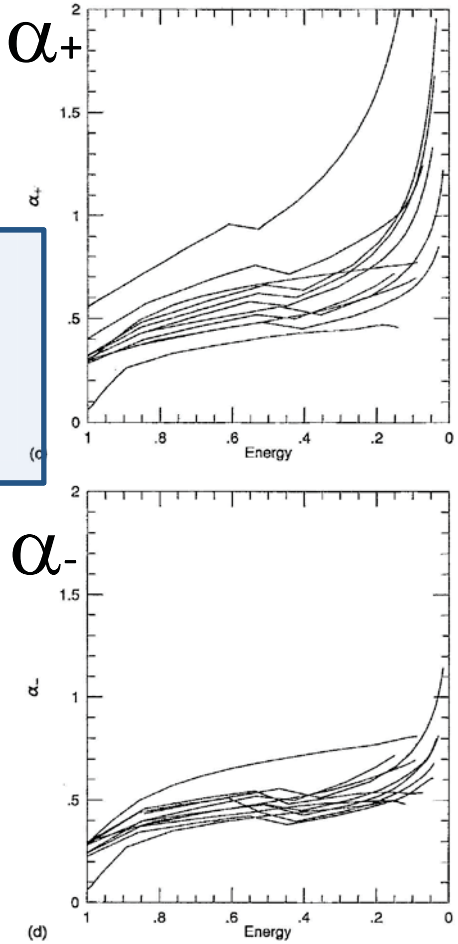
- An example

Set of simulations results



$$\frac{dZ_+^2}{dt} = -\alpha_+ \frac{Z_+^2 Z_-}{L_+}; \qquad \frac{dZ_-^2}{dt} = -\alpha_- \frac{Z_+ Z_-^2}{L_-}$$

$$\frac{dL_+}{dt} = \beta_+ Z_-; \qquad \frac{dL_-}{dt} = \beta_- L_+$$



Hossain et al, PoF ,1995
See also Biskamp, MHD turbulence

Energy→

IV. Correlations and spectra

- Hydro and MHD naturally give rise to a *heirarchy* of correlations
- 1st order -- Means
- 2nd order – correlations, spectra, structure fns.
- Higher order correlations (structure fns…)

Basic relationships:

- Ergodic theorems: replace ensemble averages by space and/or time averages

- Fourier transform relationship between correlation fns. & spectra

“Required reading”: G. K. Batchelor, Theory of Homogeneous Turbulence
Monin & Yaglom: Statistical Fluid Dynamics v 1&2

Kolmogorov 1941

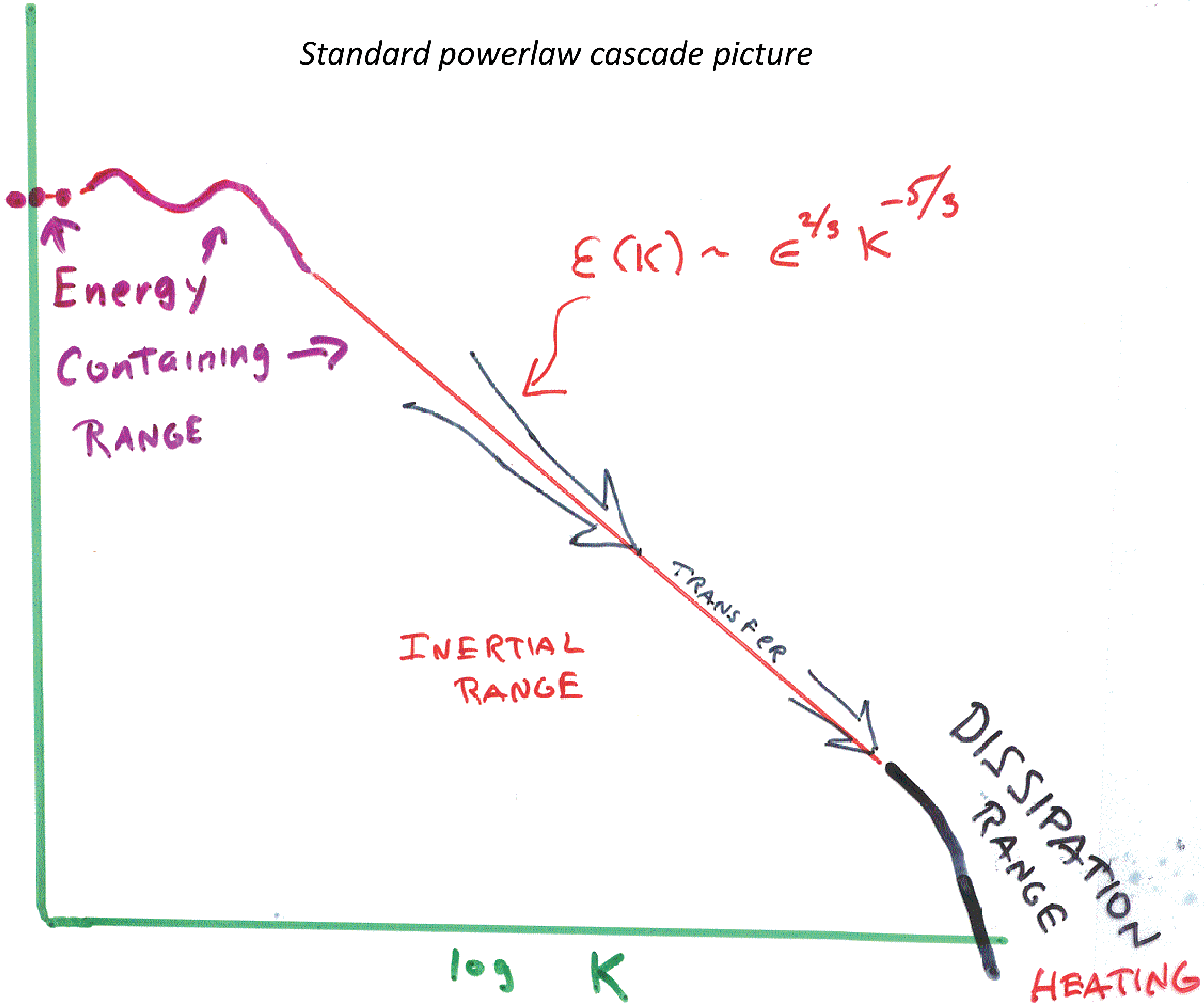
- Widely separated energy containing scale L and dissipation scale η $L/\eta >> 1$
- Energy flux across scales should be independent of scale in this "inertial range"
- u_k^2 = energy per unit mass near wavenumber k
- $t_{nl}(k)$ = nonlinear time scale at wavenumber k → $1/(k\,u_k)$
- ε_k = energy flux across shell of radius k → $\varepsilon_k = \dfrac{u_k^2}{t_{nl}(k)} = \varepsilon$

Indepdendent of k!

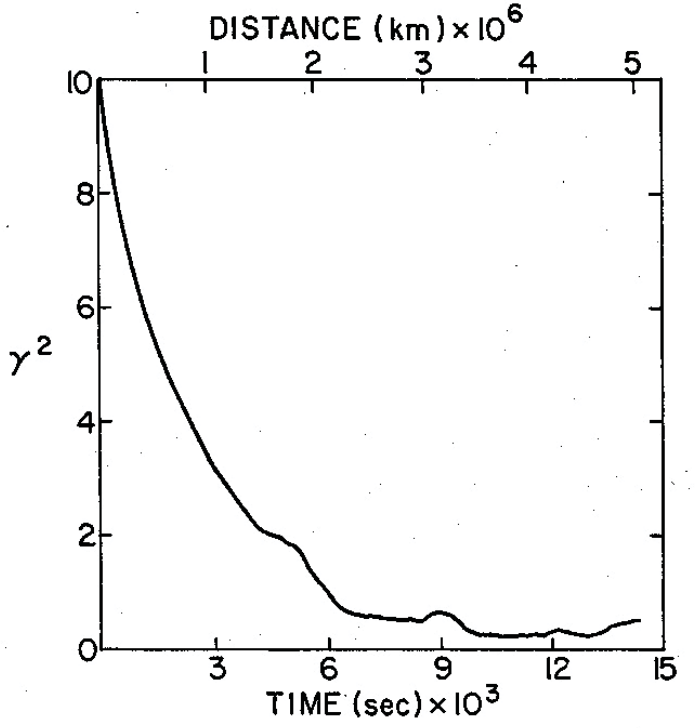
Then… $E(k) = u_k^2 / k = C\,\varepsilon^{2/3}\ \ k^{-5/3}$

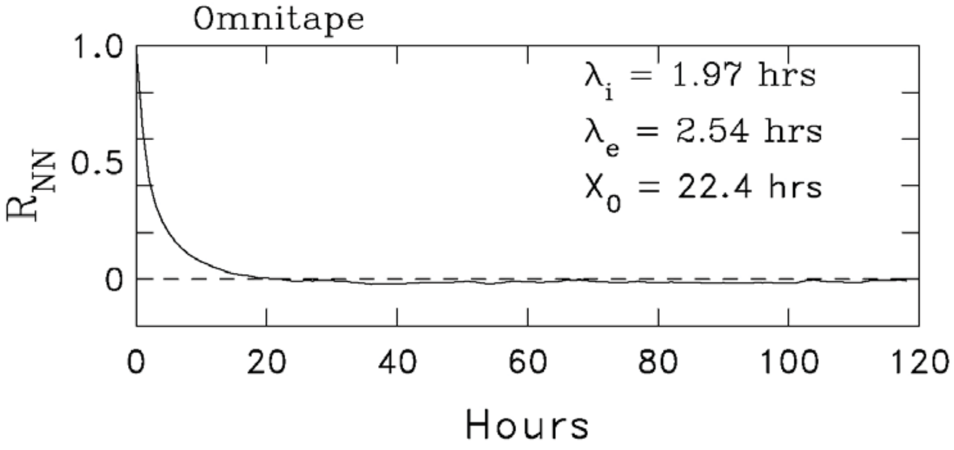
… the Kolmogorov spectrum

Standard powerlaw cascade picture



Solar wind magnetic field autocorrelation function at 1 AU:
1 s/c & frozein in flow





Tr(R) from 4 days of
Voyager data

R_{NN} from 30+ years of
OMNI data

Spectral method simulations of MHD turbulence

- Fourier spectral methods provide high order accuracy for computing accurate cascade dynamics (homogenous Turbulence

- Examples of 2D incompressible MHD at varying resolution and Reynolds number

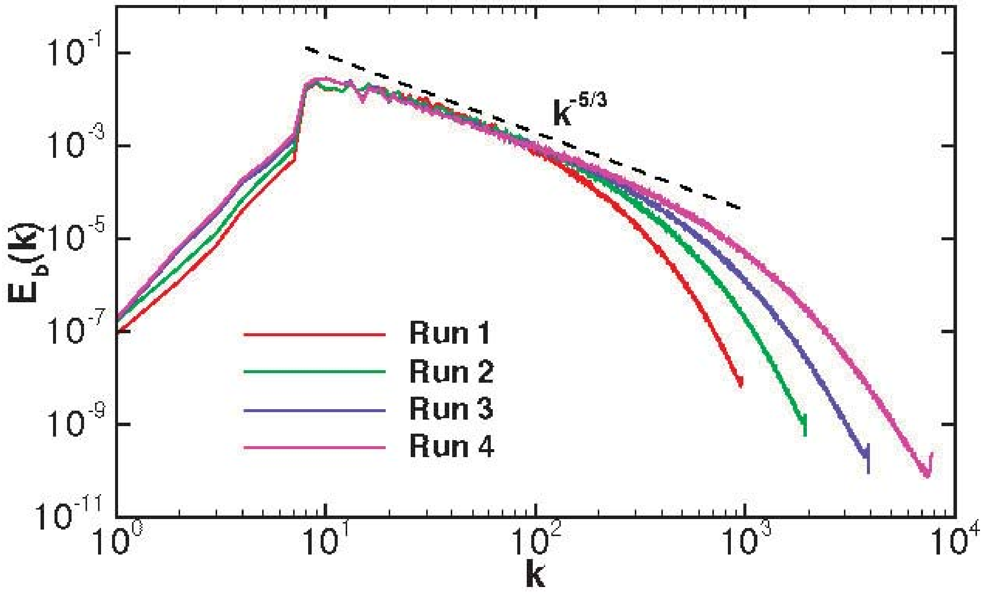


TABLE I: Parameters for the first set of simulations with $k_0 = 15$ and initial k-band [8,40].

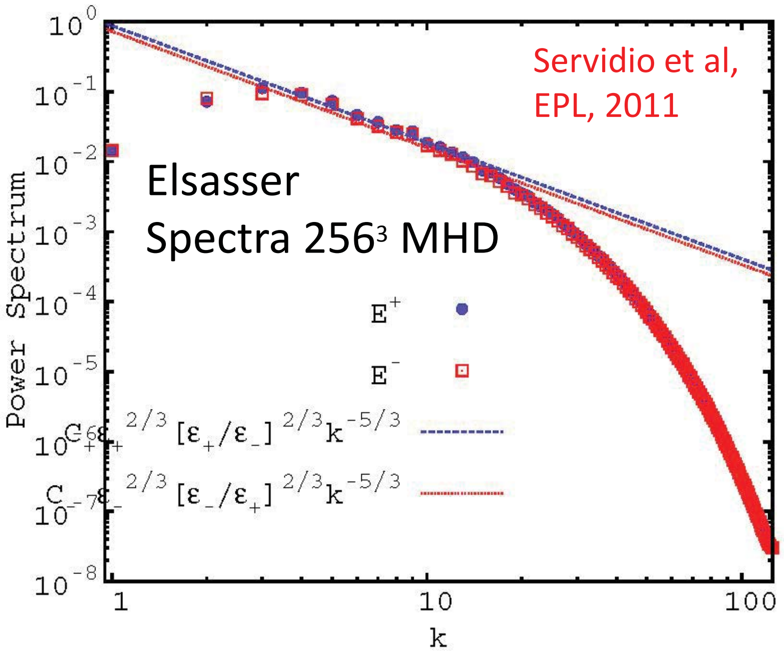
Run	Grid	ν,η	Peak time	K_{max}/K_{diss}	X
Run 1	2048^2	0.00045	0.14	3.1	963
Run 2	4096^2	0.00015	0.20	3.0	1279
Run 3	8192^2	0.000055	0.30	3.0	2971
Run 4	16384^2	0.000022	0.35	3.1	7945

- Theory

  K41 & I-Kr65

- Simulation →

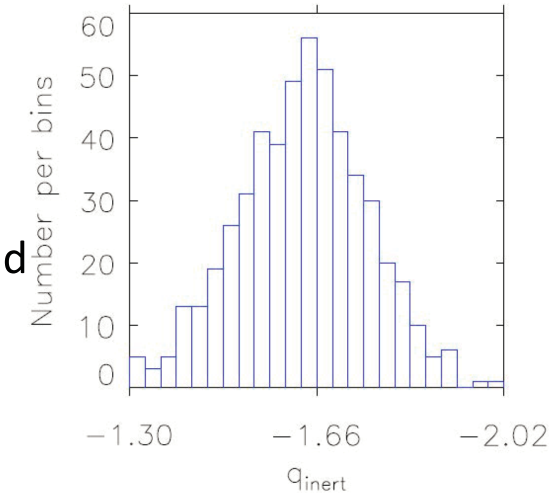
- Solar wind observation

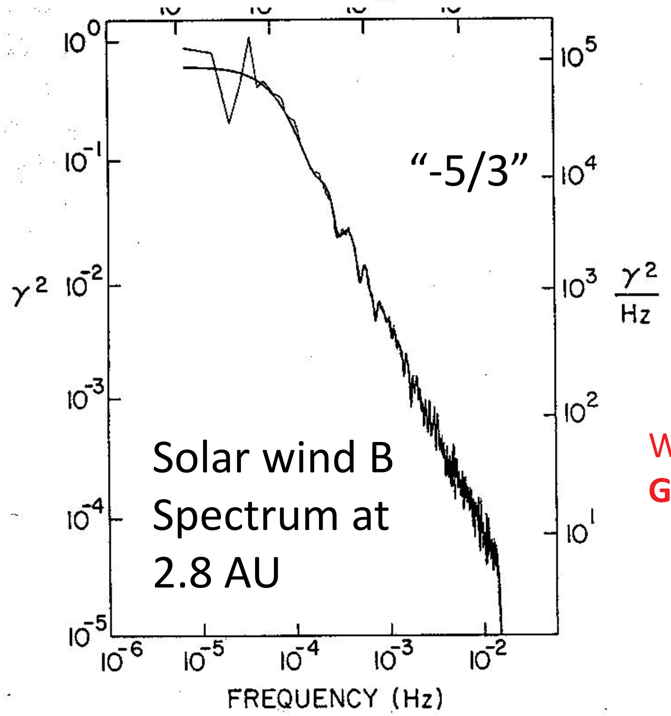


Servidio et al, EPL, 2011

Elsasser Spectra 256³ MHD

But if you look at many intervals, there's a broad distribution of powerlaws (Vasquez et al, 07





"-5/3"

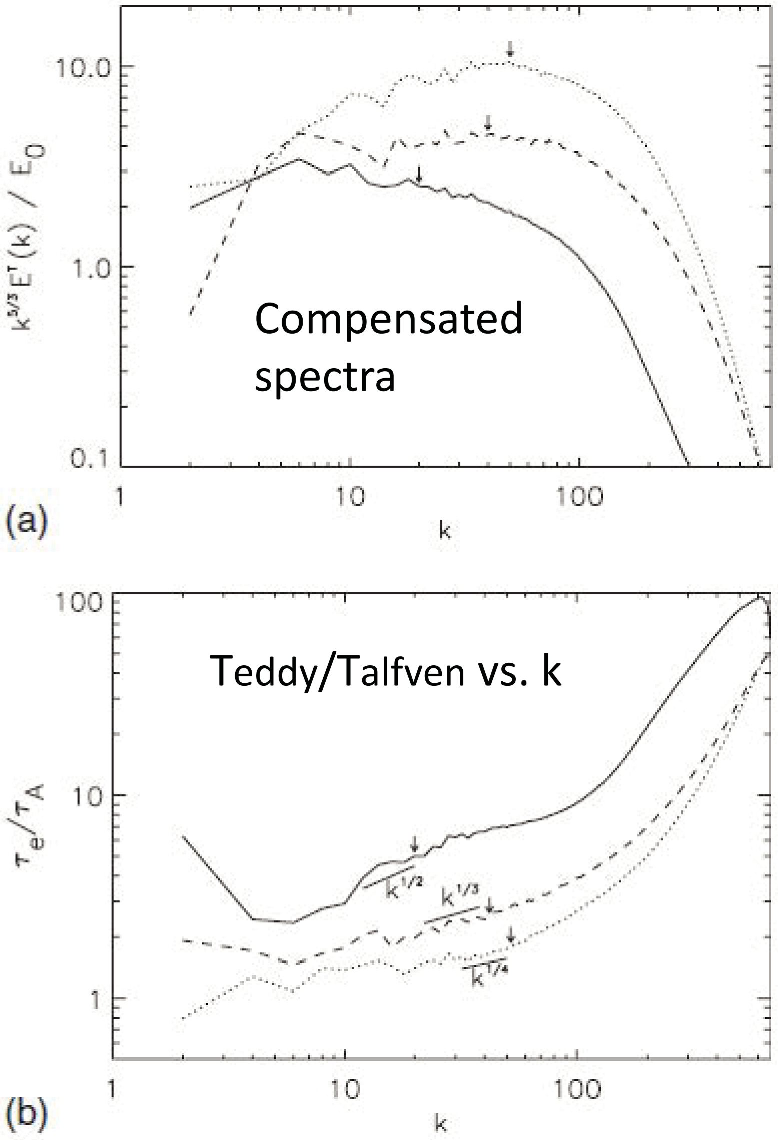
Solar wind B Spectrum at 2.8 AU

WHM & **Gol**dstein, 1982

MHD spectra are highly variable!

In simulations
AND solar wind

- Lee at al (PRE, 2010) showed that initial conditions with same E, Hc and Hm, and same initial spectra can *evolve very differently* →
- The reason for this is not agreed upon
- May point to role of the structure of 4th order moments (Wan et al JFM 2011, submitted) ; if these are nonuniversal then MHD is not universal.
- NB: B_0 and 4th order correlations do not enter third order law, so anisotropy at 3rd and 4th order may be very important



Compensated spectra

Teddy/Talfven vs. k

More than one cascaded quantity – when more than one ideal quadratic invariant (conserved flux in k-space)

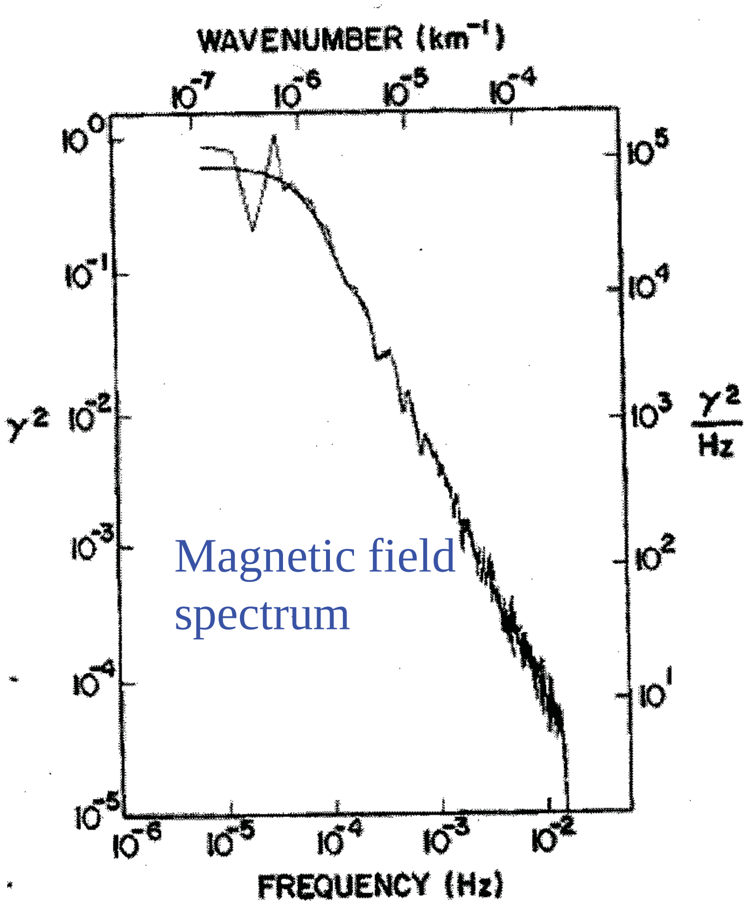
- *Direct and inverse cascades*

- Signaled by "Bose condensation' in modified thermodynamic limit in Gibbs ensemble statistical mechanics of the Fourier-Galerkin model
- 2D hydro: E inverse; enstrophy direct (Kraichnan PoF 1967)
- 3D MHD: Hm inverse; energy direct (Frisch et al)

  [Hc 'hybrid'] (Stribling and Matthaeus, 1991)
- 2D MHD: mean square magnetic potential inverse; energy direct (Fyfe&Montgomery, 1976)
- 2D Guiding center plasma: electric potential inverse; mean square charge density direct Seyler et al PoF (1975, 1976

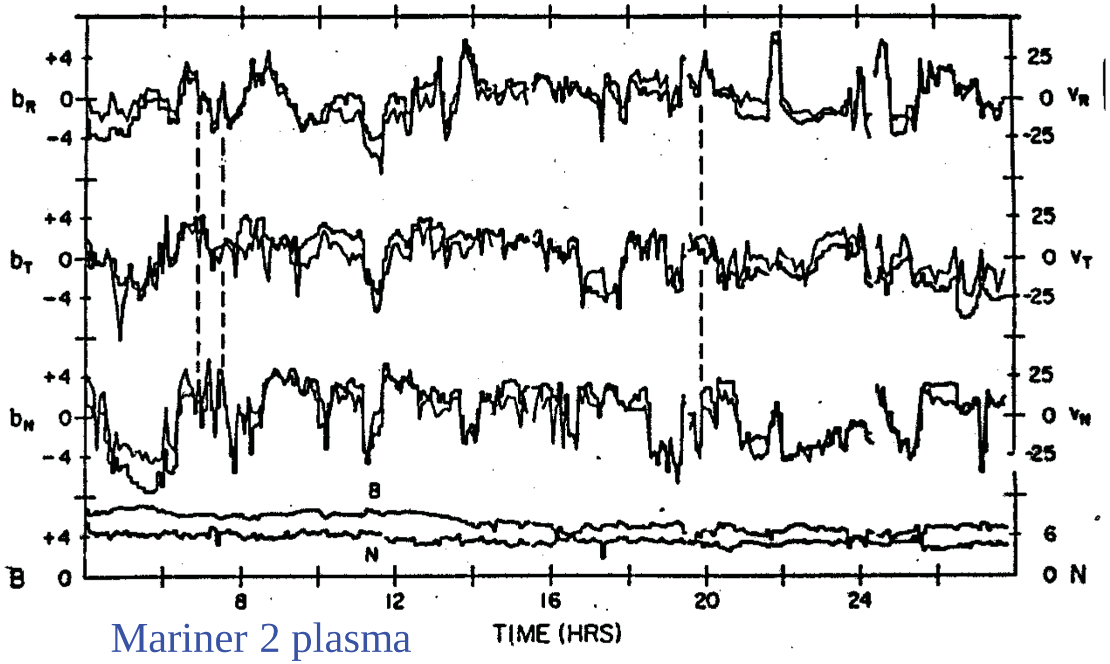
Solar wind: indications of both turbulence and wave-like properties:

- MHD-like features
- Powerlaws
- “Alfvenic fluctuations”



Magnetic field spectrum

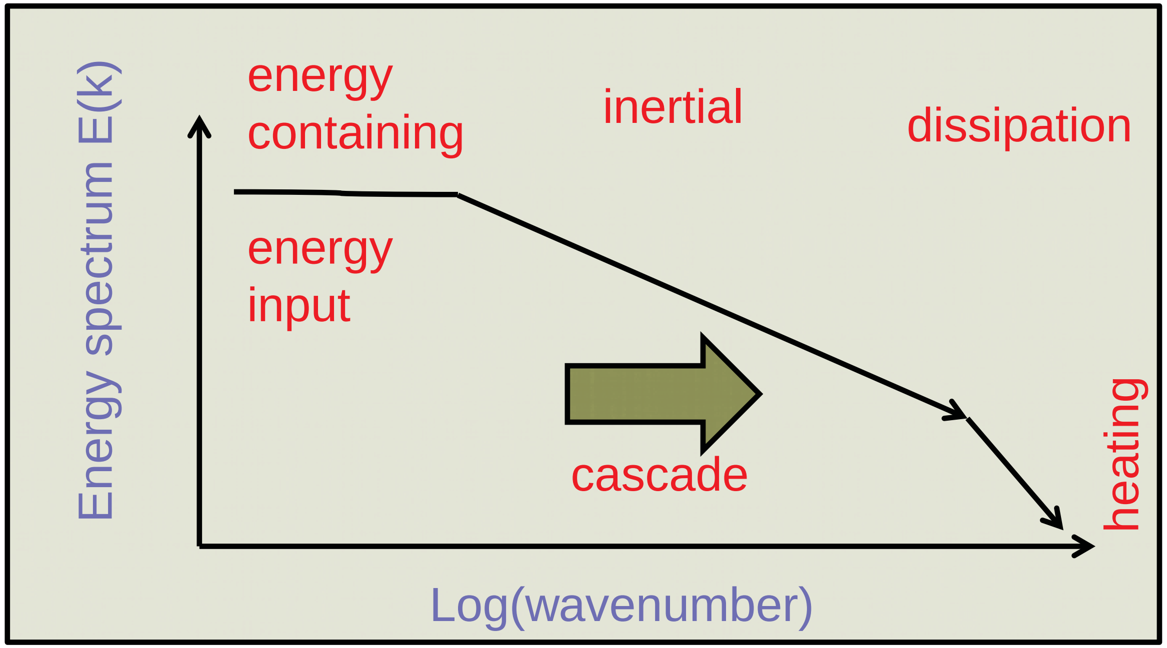
SW at 2.8 AU: Matthaeus and Goldstein



Mariner 2 plasma and magnetic field data

Belcher and Davis, JGR, 1972

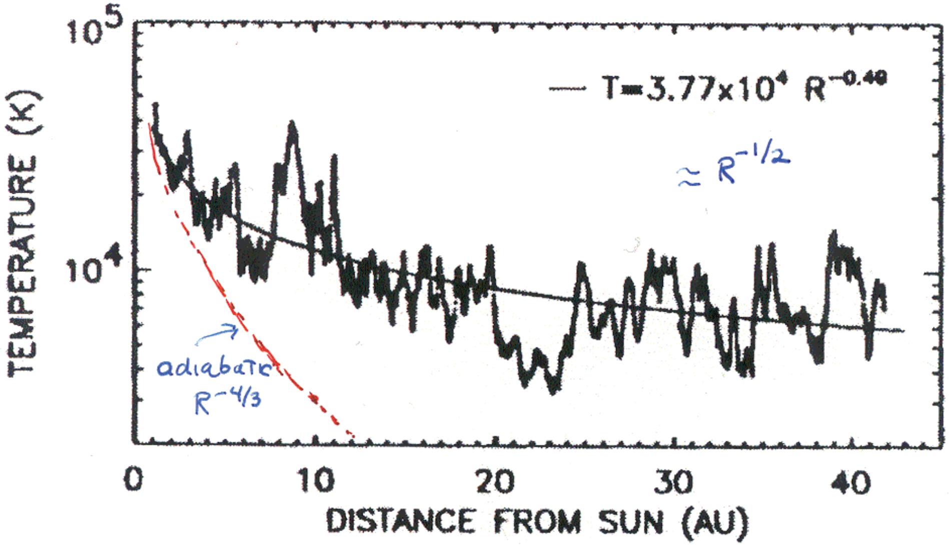
“standard” turbulence spectrum



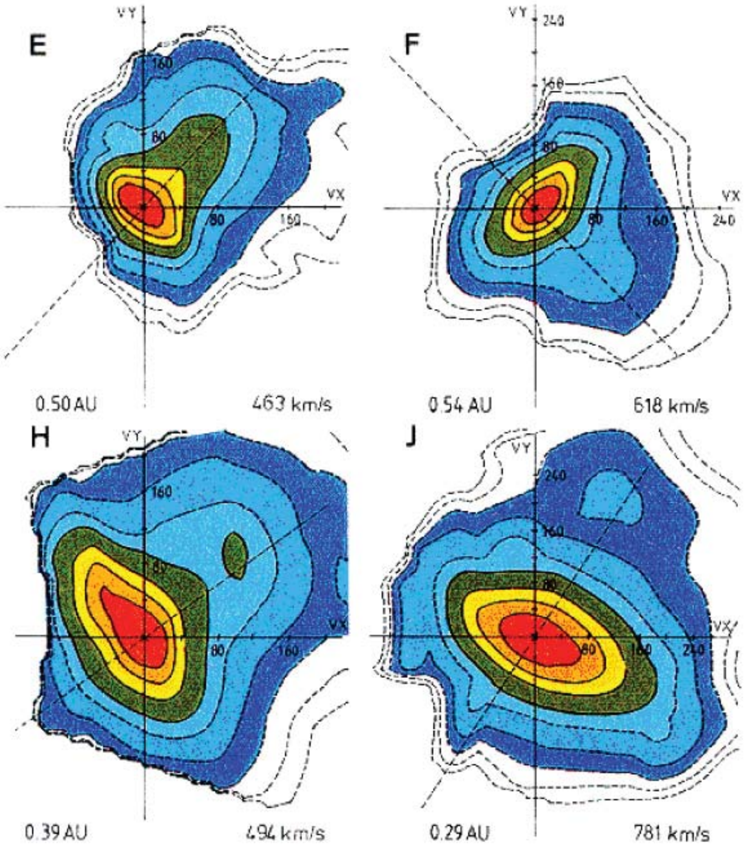
- **Dissipation:** conversion of (collective) fluid degrees of freedom into motions into kinetic degrees of freedom
- **Heating:** increase in random kinetic energy
- **Entrop**y increase: irreversible heating

V. Turbulence gives heating

Solar wind proton temperatures:
nonadiabatic and anisotrpic (fast wind)



Richardson and Paularena, GRL, 1995
IMP, Voyager temperatures
(faraday cup)



Marsch, Helios proton distributions
From L.Rev Solar Phys. 2006

- The solar wind is "too hot" at 1 AU
- <u>The solar wind is "too hot" at 30 AU</u>
- <u>The corona is "too hot" at 2 Rs</u>

Coleman, 1968
Tu et al, 1988

Matthaeus et al., 1999

McKenzie, Axford et al 1996
Dmitruk et al, 2002
+ …

Phenomenological decay models with cross helicity
(for use in dynamic alignment regimes)

$$Z_{\pm}^2 = \langle |\mathbf{u} \pm \mathbf{b}|^2 \rangle$$

- MHD phenomenologies:
  decay of Elsasser energi

  - Kolmogoroff-like

$$\frac{dZ_+^2}{dt} = -\alpha \frac{Z_+^2 Z_-}{\lambda} \qquad \frac{dZ_-^2}{dt} = -\alpha \frac{Z_-^2 Z_+}{\lambda}$$

  - Kraichnan-like

$$\frac{dZ_+^2}{dt} = -\alpha \frac{Z_+^2 Z_-^2}{V_A \lambda} \qquad \frac{dZ_-^2}{dt} = -\alpha \frac{Z_+^2 Z_-^2}{V_A \lambda}$$

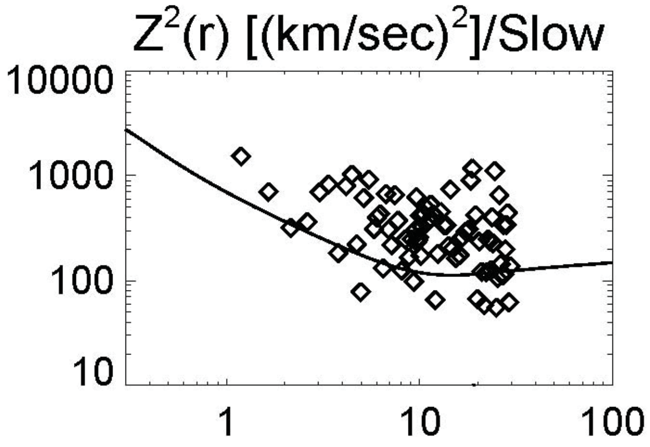
- Embed the turbulence phenomenology in a non-WKB transport theory (energy, cross helicity, correlation scale) with expansion, reflection ("mixing"), driving by shear and pickup ions. Feed turbulent dissipation into internal energyequation.

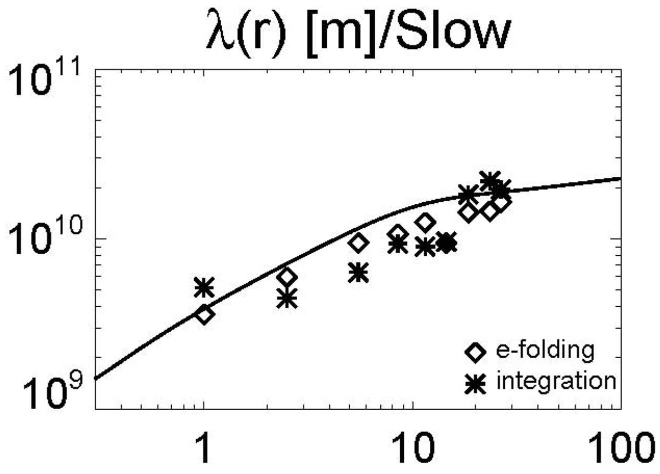
- See Breech et al, 2008 and references therein; Ng and Bhattacharjee, 2007

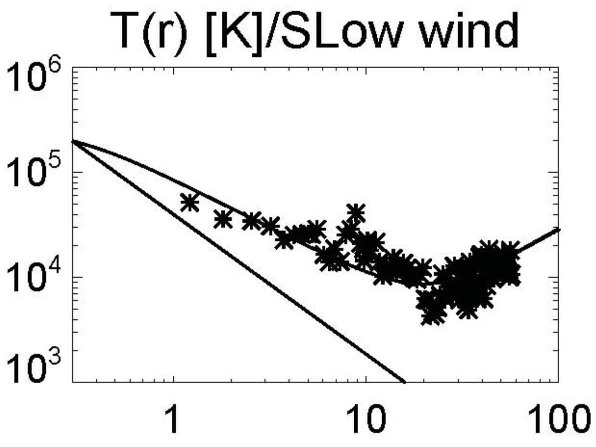
- For electrons and protons separately – see Breech et al, 2009; Cranmer et al,, 2009

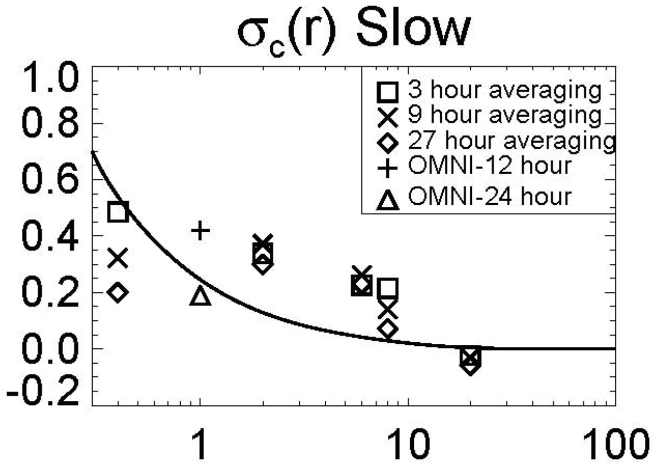
Transport model:
low latitude wind and comparison with Voyager data

Csh = 1.5

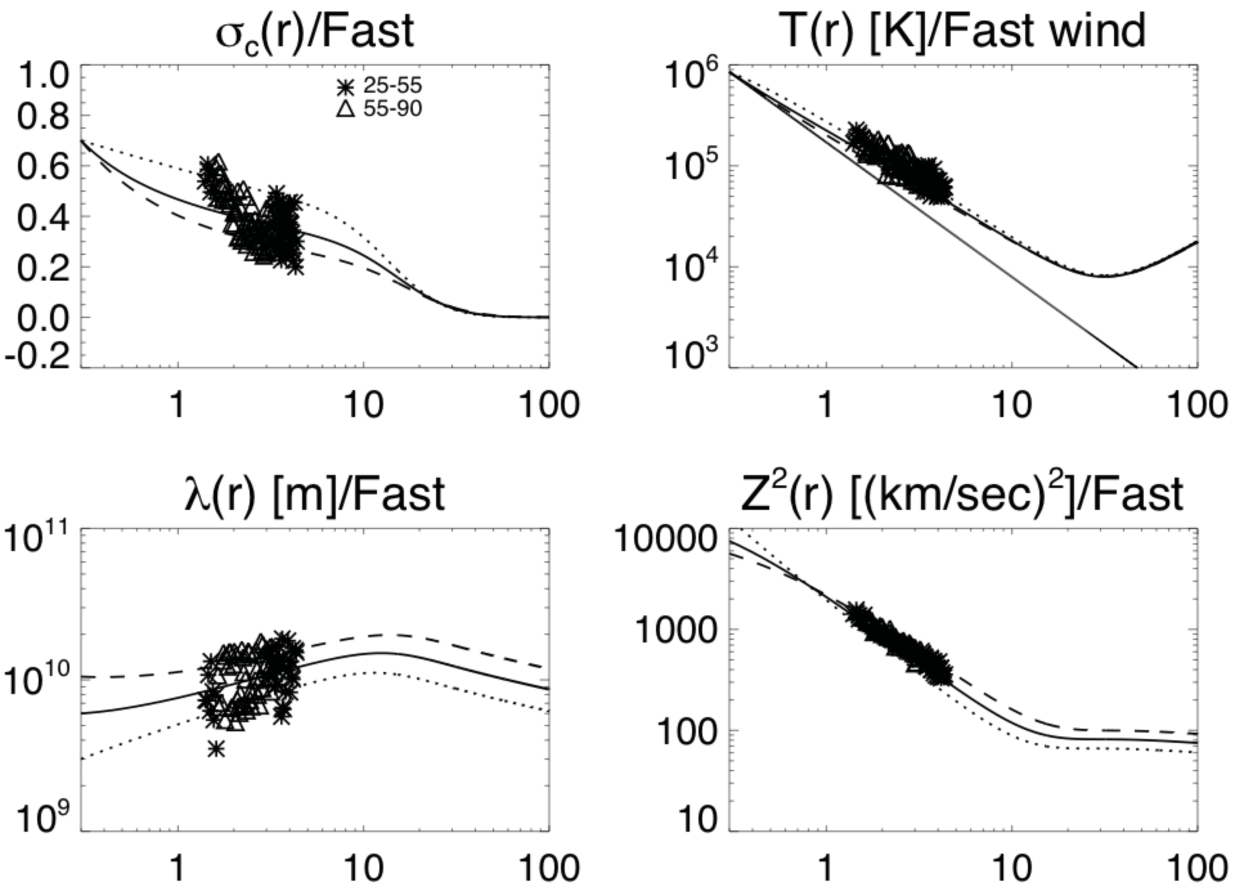








Transport model: high latitude parameters and Ulysses data

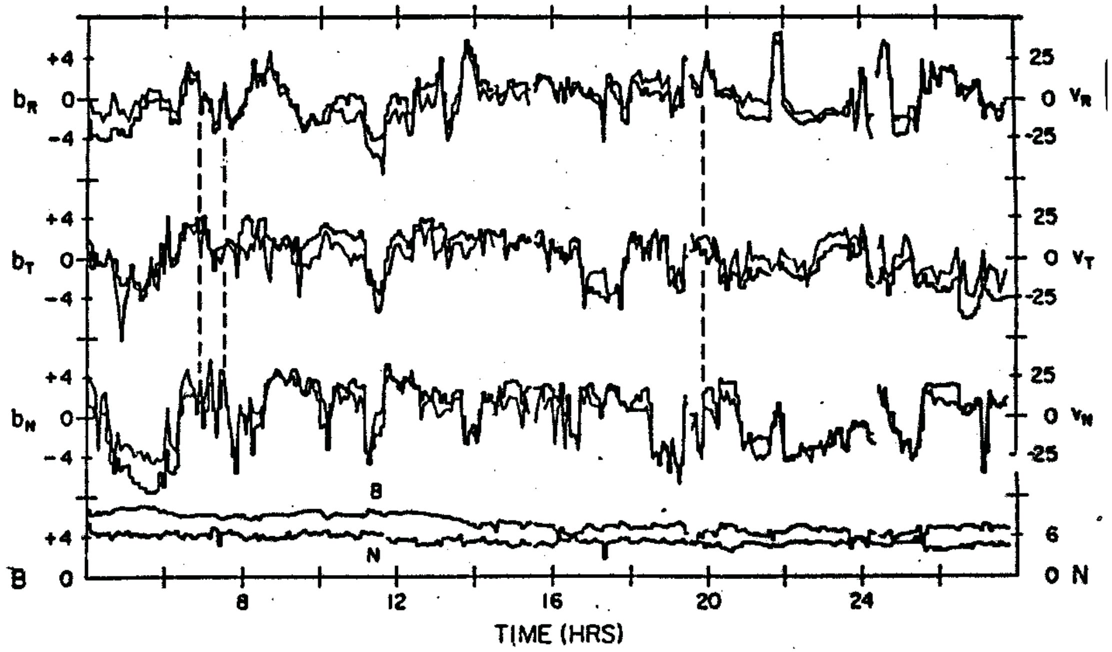


C_{sh} = 0.5

Matches data fairly well.

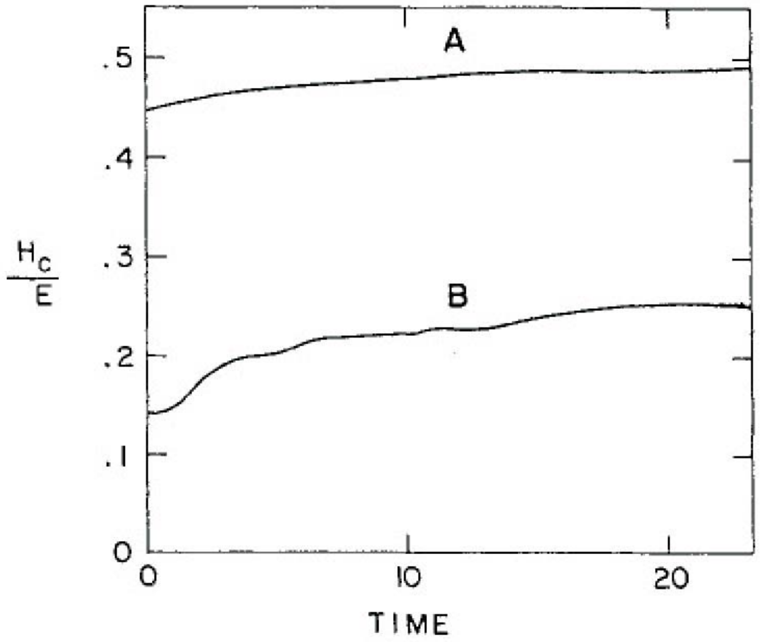
VI. Relaxation and correlations

Turbulence causes/processes alfvenic fluctuations – and other relaxation processes



σ_c = 2 Hc /E tends to increase in time

Theory based on Kraichnan 65 ideas: Dobrowolny et al, 1980



2D: Matthaeus et al, 1983

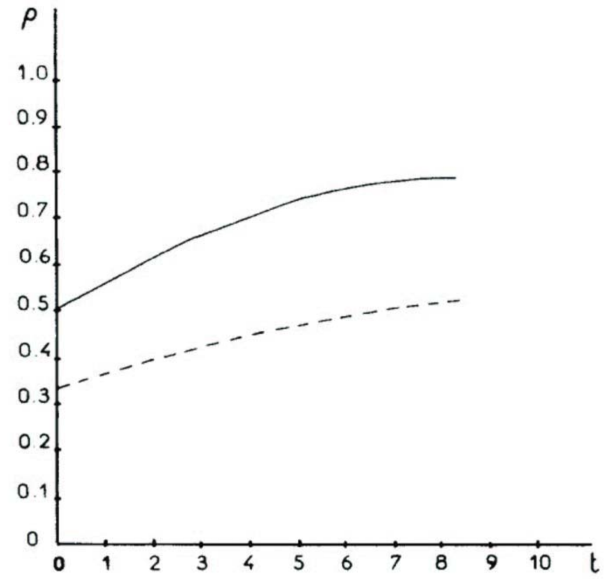
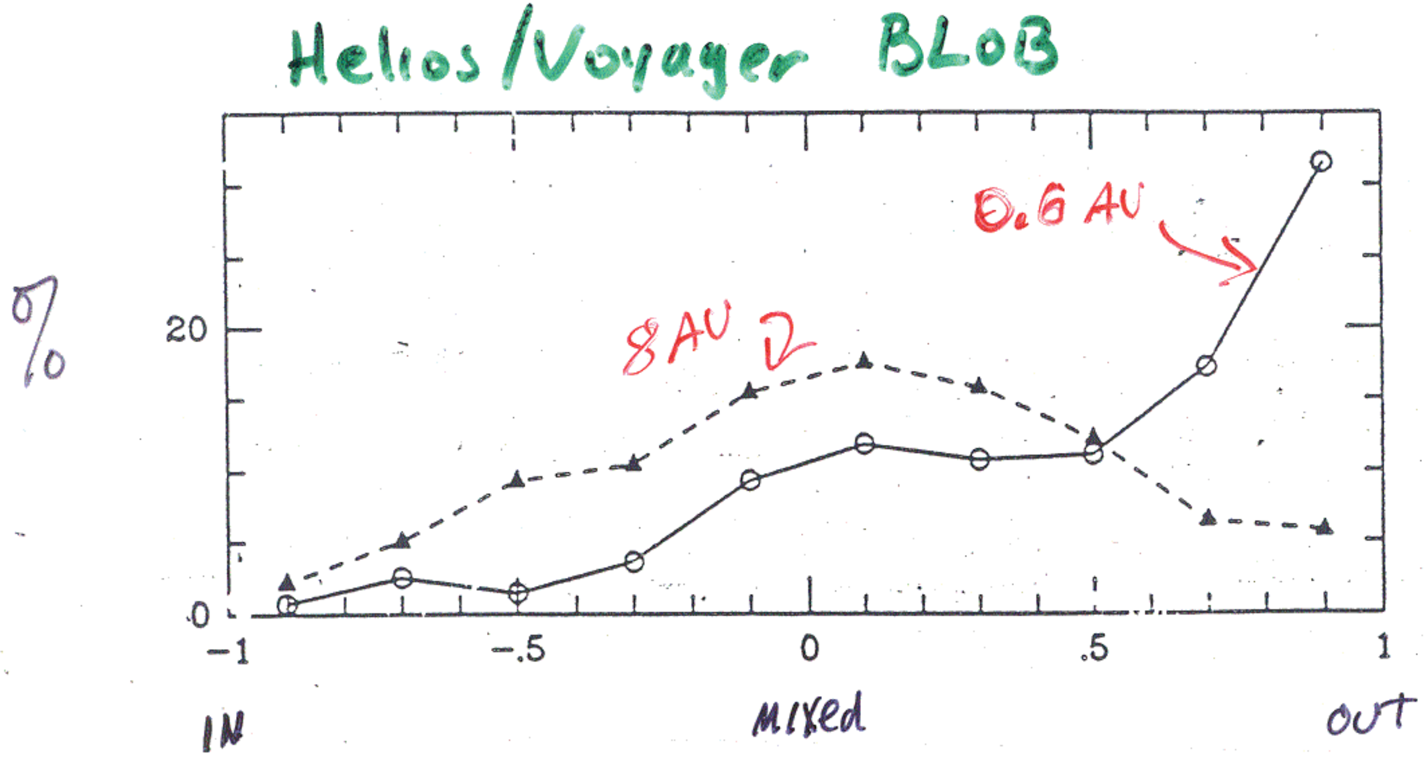


FIG. 1. Evolution of the correlation coefficient ρ defined in Eq. (1.1). Dashed line, random initial conditions (same conditions as in Fig. 2); solid line, Orszag-Tang vortex (conditions described in Fig. 3).

3D: Pouquet et al 1986

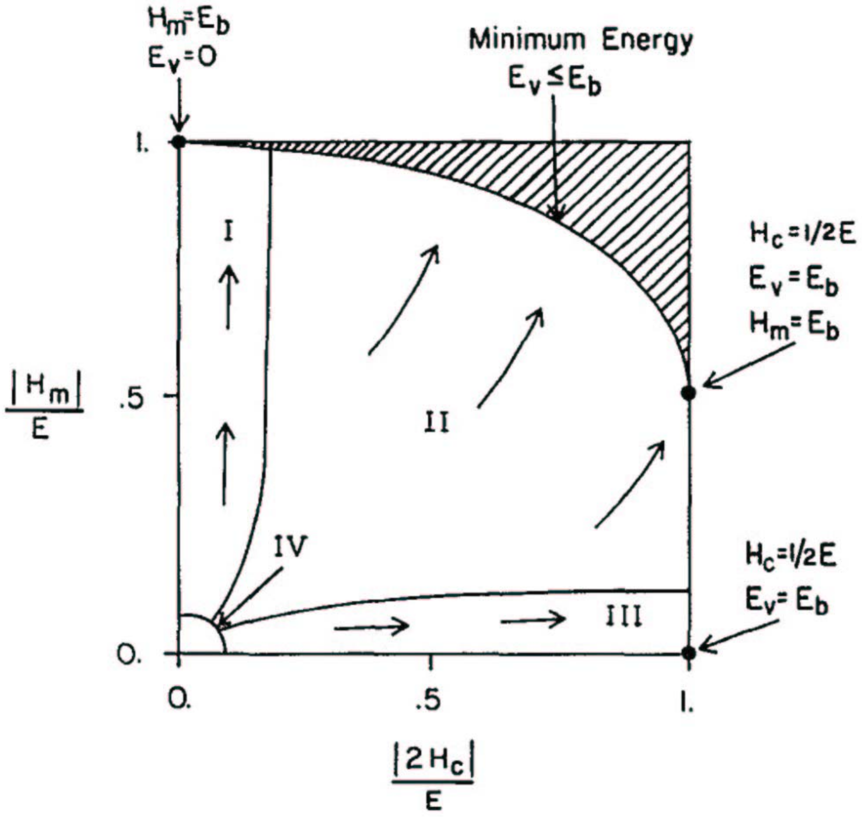
Decrease of Alfvenicity with heliocentric distance



Roberts et al, 1987b

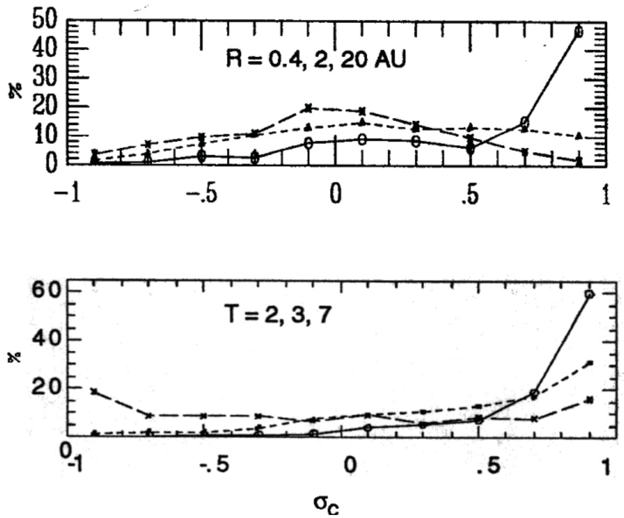
σ_c does not always increase!

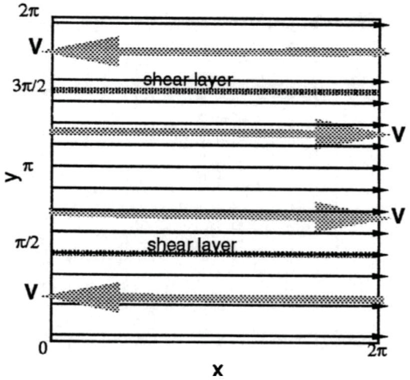
General picture of global turbulent relaxation: A balance of competing processes



Ting et al 1986;
Stribling and Matthaeus, 1992

Simulations in which cascade is driven by large scale shear show decreasing cross helicity





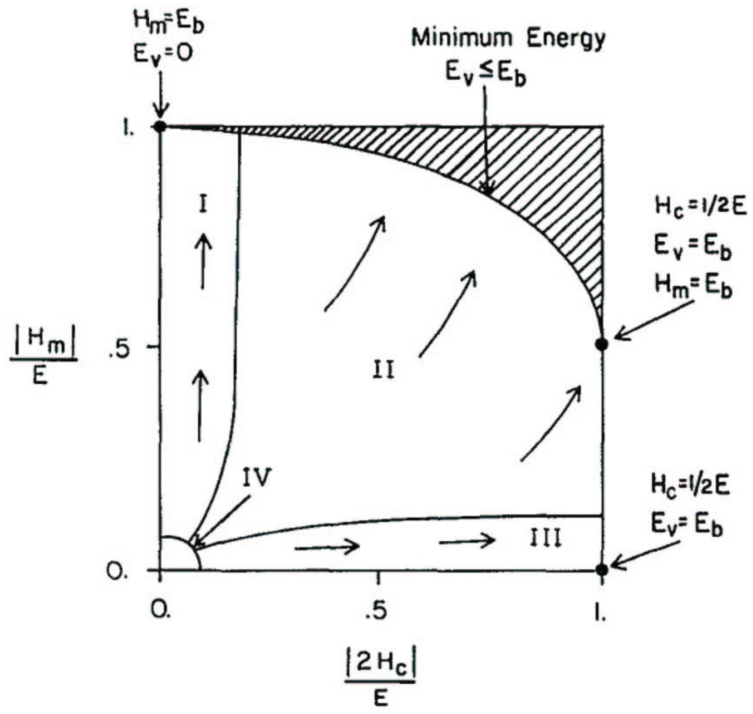
Roberts et al, JGR 1992

ALFVENIC FLUCTUATIONS:
Global and local relaxation:
Beltrami, force free, Alfven alignments:

$$\delta \int \left[\left(|\mathbf{v}|^2 + |\mathbf{b}|^2 \right) - 2\alpha \mathbf{v} \cdot \mathbf{b} - \phi \mathbf{a} \cdot \mathbf{b} \right] d^3x = 0$$

in which constant magnetic helicity and constant cross helicity are imposed constraints. Here, α and ϕ are Lagrange multipliers, $\mathbf{a}$ the potential vector, and $\mathbf{b} = \nabla \times \mathbf{a}$. The Euler-Lagrange equations imply that

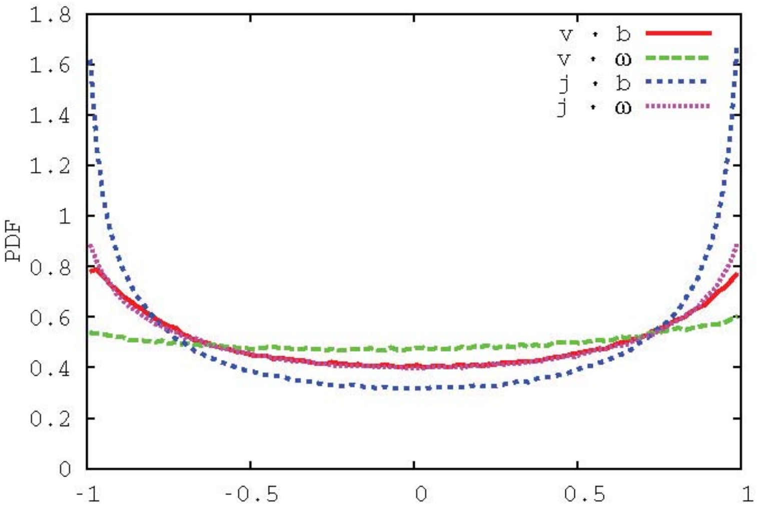
$$\mathbf{v} = \alpha \mathbf{b} = \frac{\alpha\phi}{1-\alpha^2}\mathbf{j} = \frac{\phi}{1-\alpha^2}\omega \qquad (1)$$



Local rapid relaxation causes several types of correlation
- non-Gaussian statistics, intermittency
- coherent structures/ discontinuities

→PATCHES

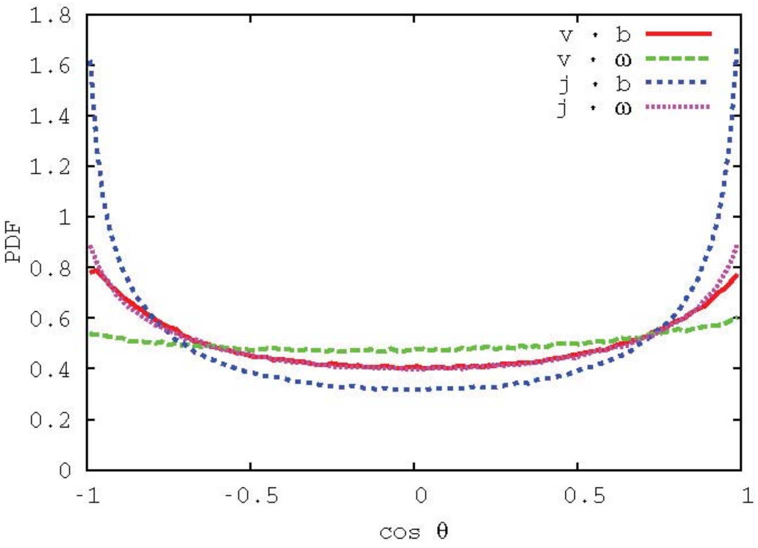
e.g. local alfvenic alignment



Hydrodynamic antecedent: cos θ
“local Beltramization” (Kraichnan, 1987):

local relaxation and suppression of nonlinearity: Beltrami, force free, Alfven alignment:

$$\mathbf{v} = \alpha \mathbf{b} = \frac{\alpha\phi}{1-\alpha^2}\mathbf{j} = \frac{\phi}{1-\alpha^2}\omega$$

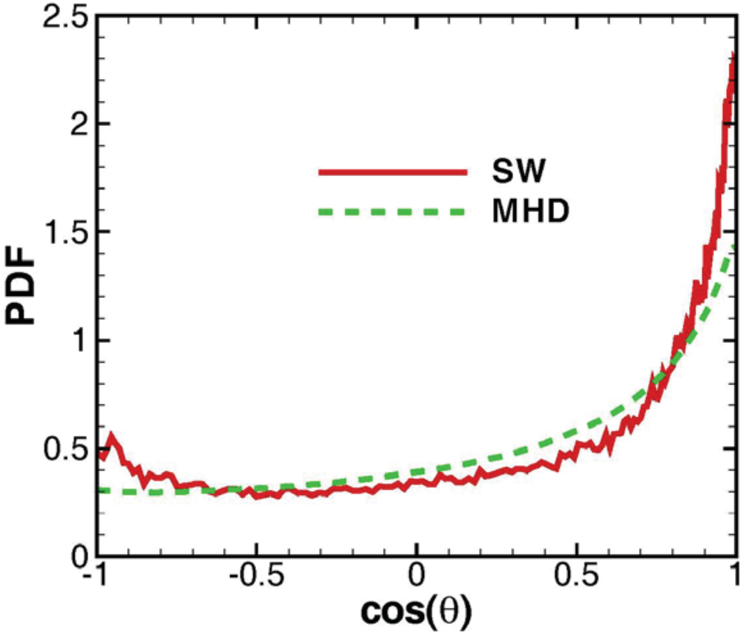


Local rapid relaxation implies:
- several types of correlation
- suppression of nonlinearity
- non-Gausian statistics□intermittency
- coherent structures/ discontinuities

Hydrodynamic antecedent:
“local Beltramization” :

R.H. Kraichnan and R. Panda, *Phys. Fluids* (1988);
R.B. Pelz, V. Yakhot, S.A. Orszag, L. Shtilman and E. Levich, *Phys. Rev. Lett.* (1985); R.M. Kerr, *Phys. Rev. Lett.* (1987).

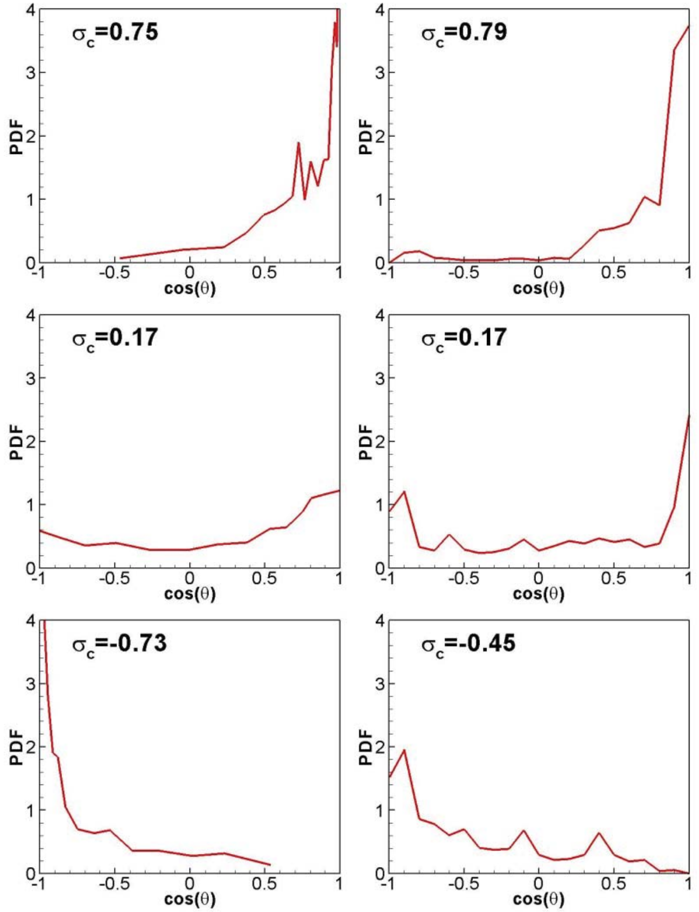
- Analysis of patches of Alfvenic correlations- SIMs and SW
- Distributions of cos(θ_{vb})
- Global statistics & statistics of linear subsamples (~1-2 correlation scales)
- SW and 3D MHD SIM (512^3)
- Global Alfvenicity $\sigma_c \approx 0.3$



- For a specified sample size, can get highly variable Alfvenicity (see Roberts et al. 1987a,b)
- Same effect in SW and in SIMs!

10 hr SW samples

Linear SIM samples



Osman et al, ApJ, 2011b

Turbulence causes distinctive correlations

- E.g., nonequipartition

Alfven ratio $r_A(k) = E_v(k)/E_b(k)$

- rA ~ 1 inner heliosphere
- rA ~1/2 r> 1 AU
- rA ~ ½ in inertial range of MHD simulations

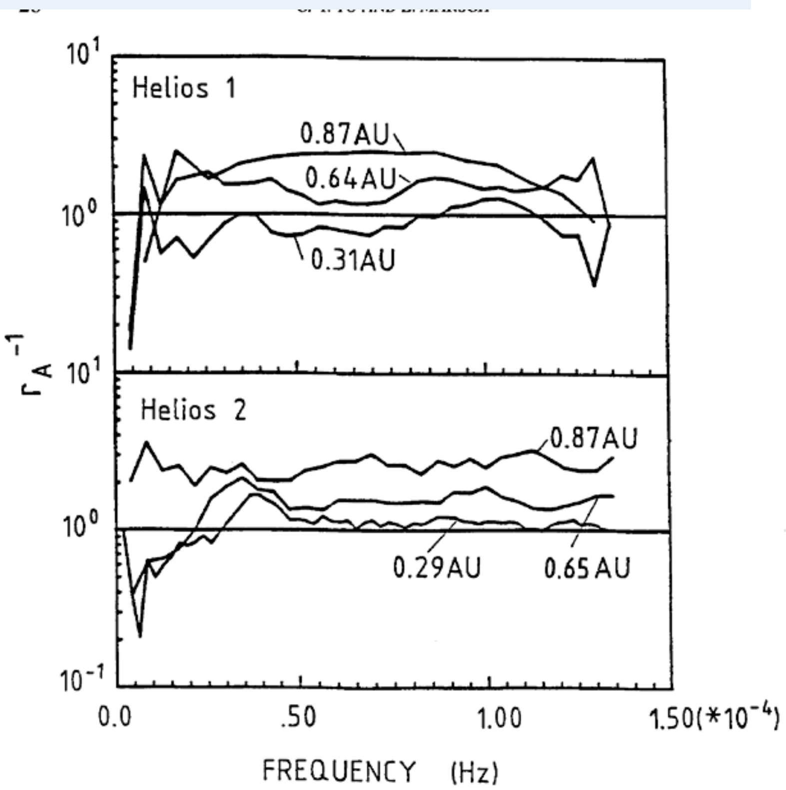


Fig. 2-6. The inverse of the ratio $r_A = E_v(f)/E_b(f)$ versus frequency as computed at different heliocentric distances for Helios 1 (upper panel) and Helios 2 (lower panel). The distances are indicated at each curve (adopted from Bruno *et al.*, 1985).

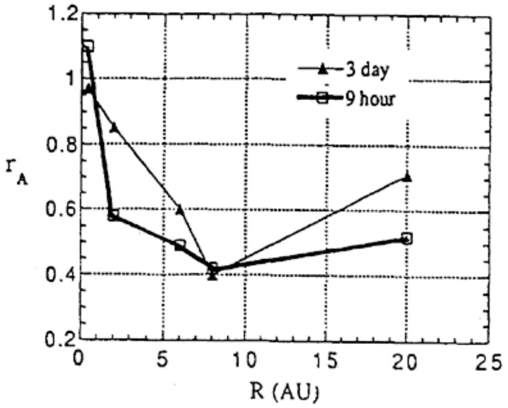
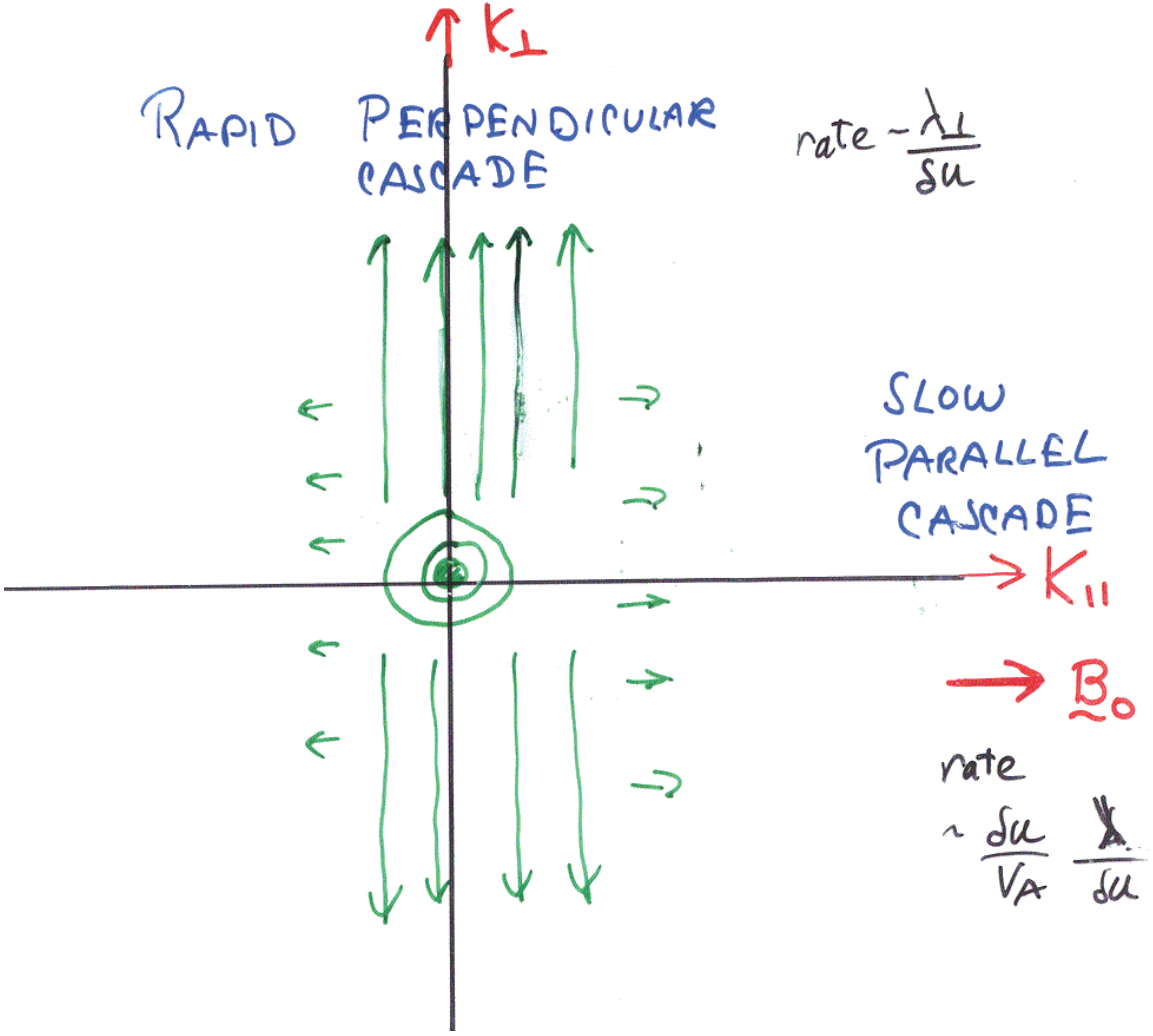


Fig. 2-8. The Alfvén ratio (for the non-radial components of the velocity and magnetic field fluctuations) as a function of heliocentric distance. The data used are from Helios 2, 1977 near 0.4 AU, from the Voyager 2, 1977 near 2 AU, and from Voyager 2, 1985 near 20 AU (adopted from Roberts *et al.*, 1990).

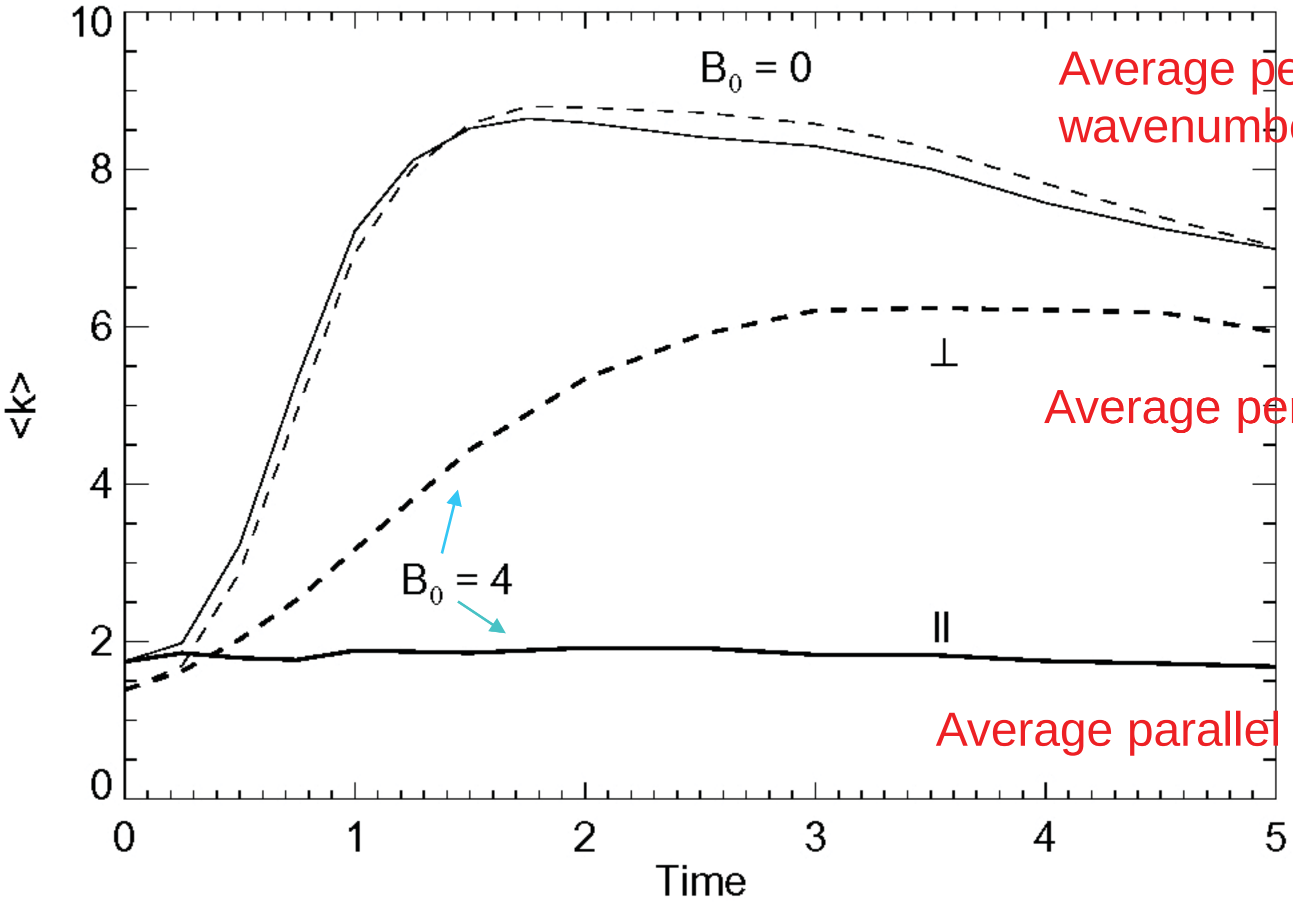
Suggestion: rA < 1 due
To current sheet formation

VII. Turbulence produces anisotropy

- Variance anisotropy
- Spectral anisotropy


$k_\perp$
RAPID PERPENDICULAR CASCADE
rate $\sim \frac{\lambda_\perp}{\delta u}$
SLOW PARALLEL CASCADE
$k_\parallel$
$\underset{\sim}{B}_0$
rate
$\sim \frac{\delta u}{V_A} \frac{\lambda}{\delta u}$

Spectral anisotropy in MHD



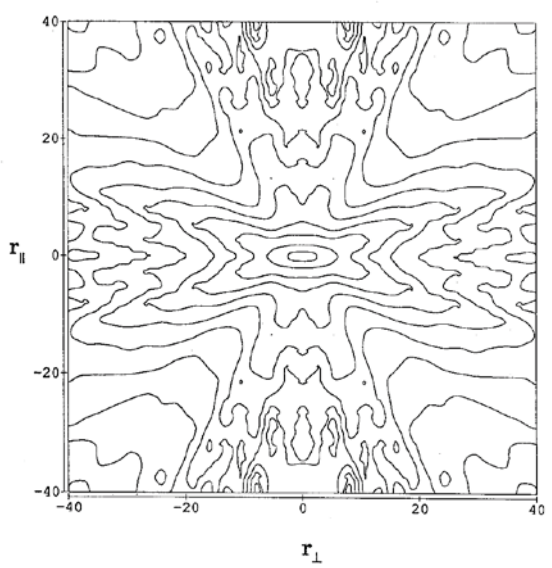
Average perp and par wavenumbers almost equal

Average perp wavenumber

Average parallel wavenumber

Solar wind fluctuation geometry

- “Maltese cross” – two component model
- Slab + 2D
- Cosmic ray scattering parallel mean free paths → 20% slab - 80% 2D
- NI MHD Theory –20% - 80%
- Direct measurement → 20 % - 80%



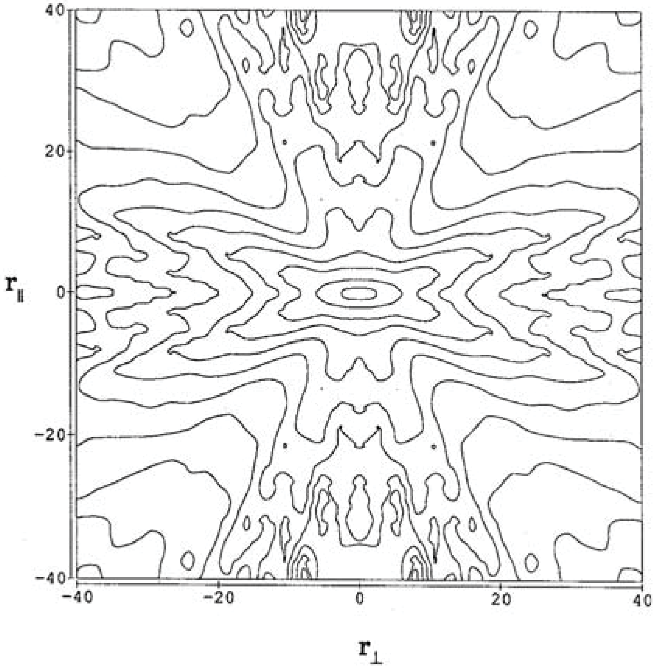
A significant fraction (~80%) of the fluctuation energy is in highly oblique (70+ deg) modes

Maltese: Matthaeus et al, 1990
Cos Ray: Bieber et al, 1994
NI MHD: Zank and Matthaeus, 1991
Direct: Bieber et al, 1996

Spectral/correlation anisotropy

- Theory (Shebalin et al, 1983; Oughton et al 1994)
- Simulation
- Observation in SW

2D axisymmetric magnetic field correlation fn. from ~2 years Of ISEE-3 data



“Maltese Cross”

Mathaeus et al 1990

Spectral method simulation with strong B0=10 br ms

Parallel Direction →

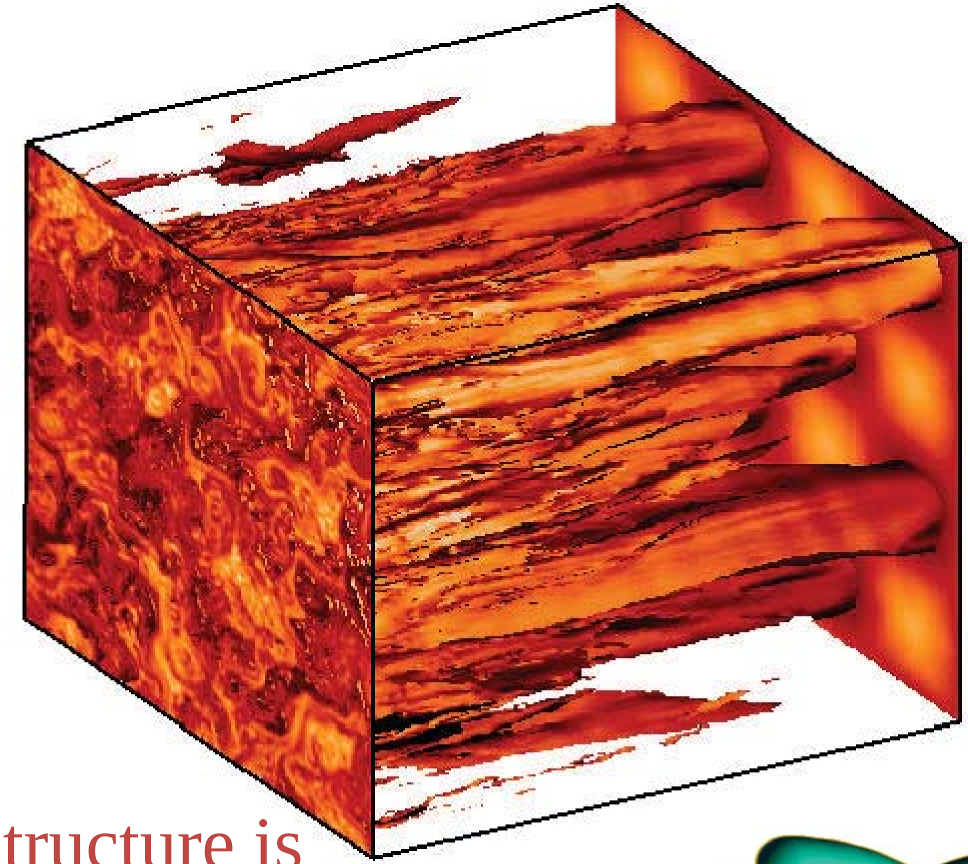
Perp plane

Dmitruk + whm, 2004

VIII. Turbulence causes complexity in the structure of the magnetic field

Nature of magnetic flux surfaces depends on turbulence, scale and local topology

A mixture of 2D and slab fluctuations in the "right" proportion



Magnetic Surfaces Composite MHD Turbulence
(80% 2D ; 20% Slab)

Matthaeus et al, 1995

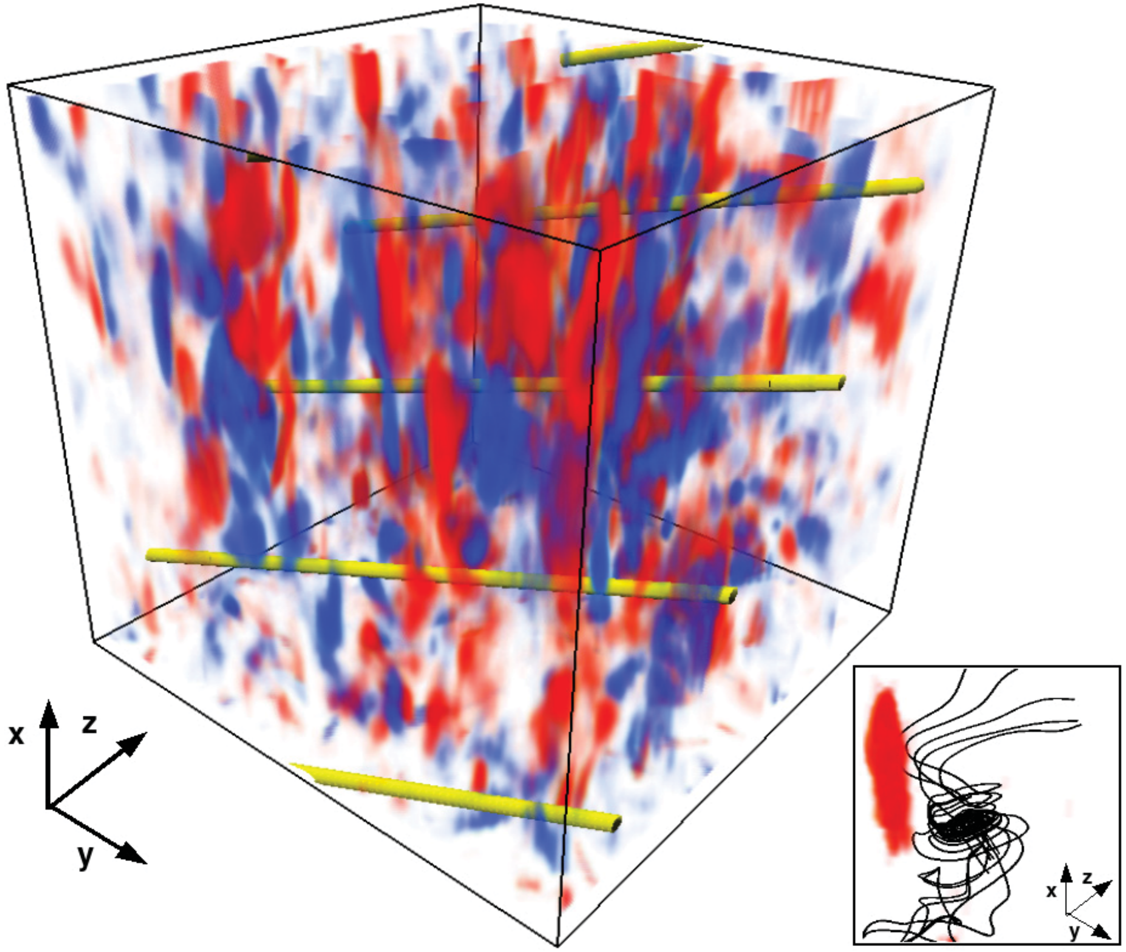
Magnetic structure is spatially complex

Compare laminar models:

Bruno et al. [2004]

IX. Turbulence accounts for discontinuities

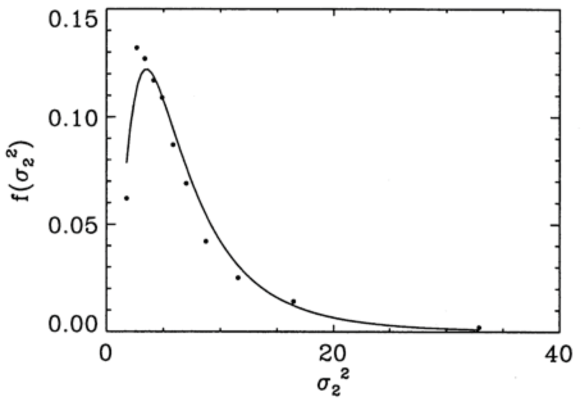
3D MHD compressible simulation with mean B_0



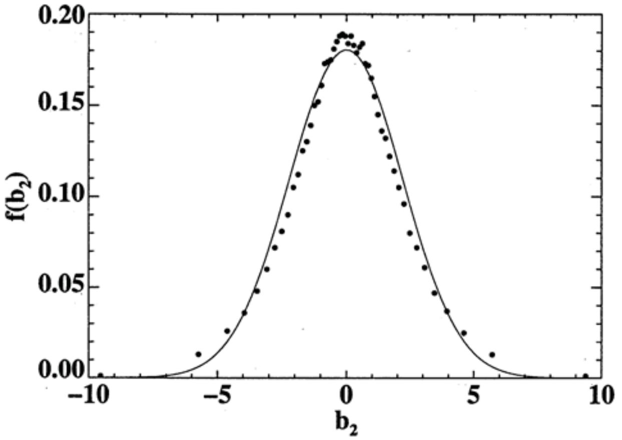
PDF of component variances

- Variances are approx. log-normal

→ Suggests independent (scale invariant) distribution of coronal sources

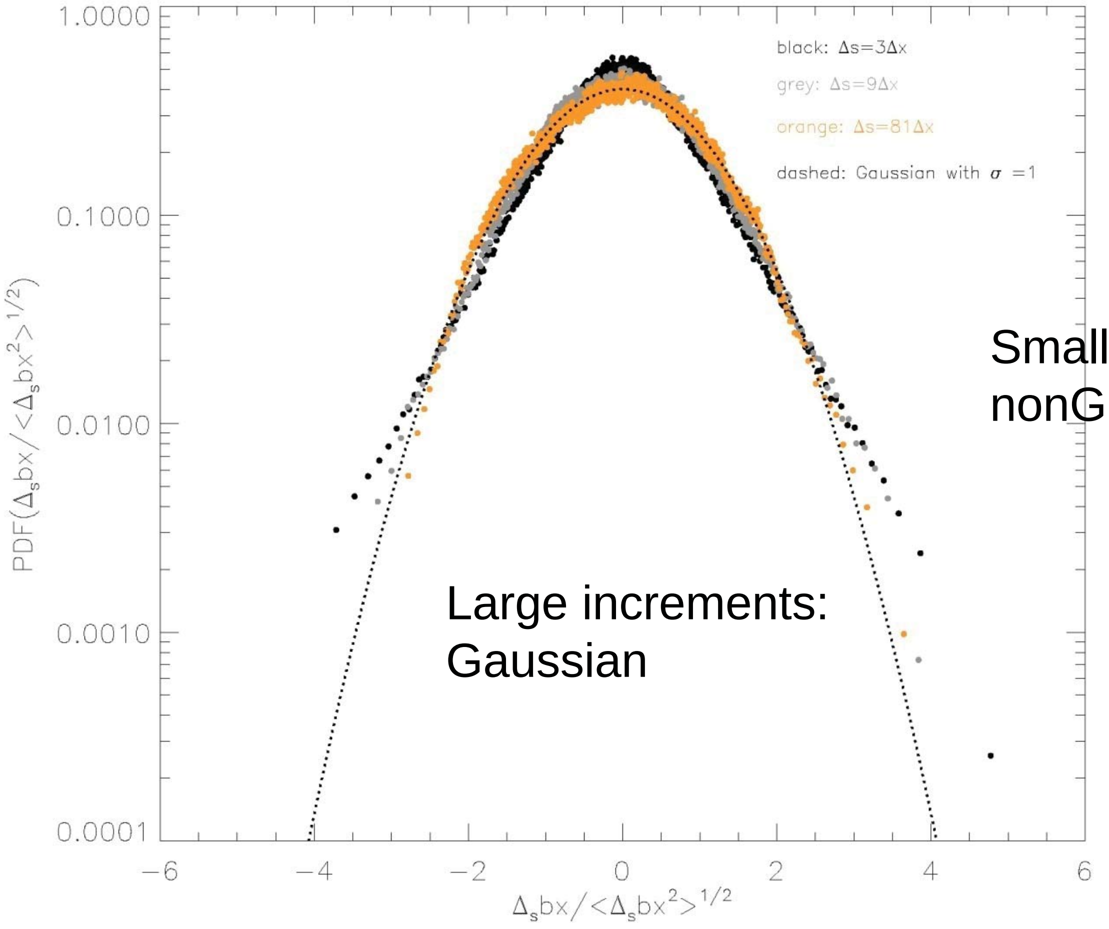


- When normalized to remove variability of mean and variance, component distributions are close to Gaussian



Padhye et al, JGR 2001; Sorriso-Valvo et al, 2001

Pdfs of increments- one magnetic field component



Small increments:
nonGaussian

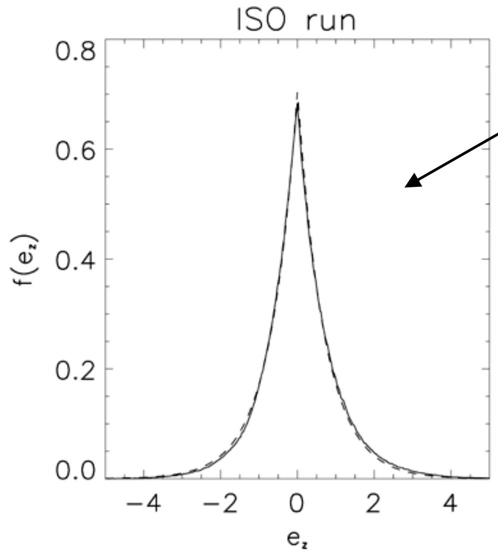
Large increments:
Gaussian

Statistics of the induced electric field

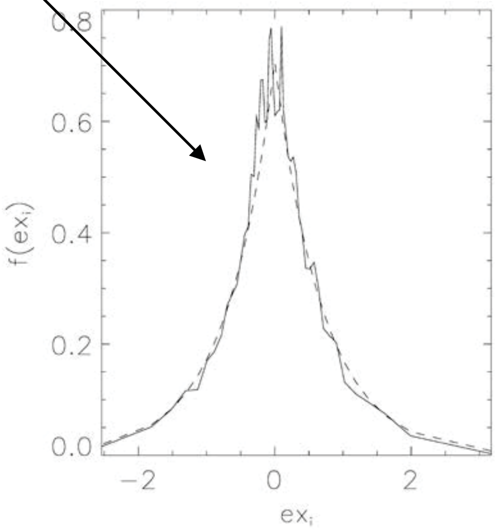
Milano et al, PRE, 2002

- For Gaussian v, b ⇒ Induced E is exponential or exponential-like
- Ind. E is localized but not as localized as the reconnection zones
- Kurtosis 6 to 9

Dashed lines are theoretical
Values for Gaussian v, b



Spectral MHD simulation
t = 3

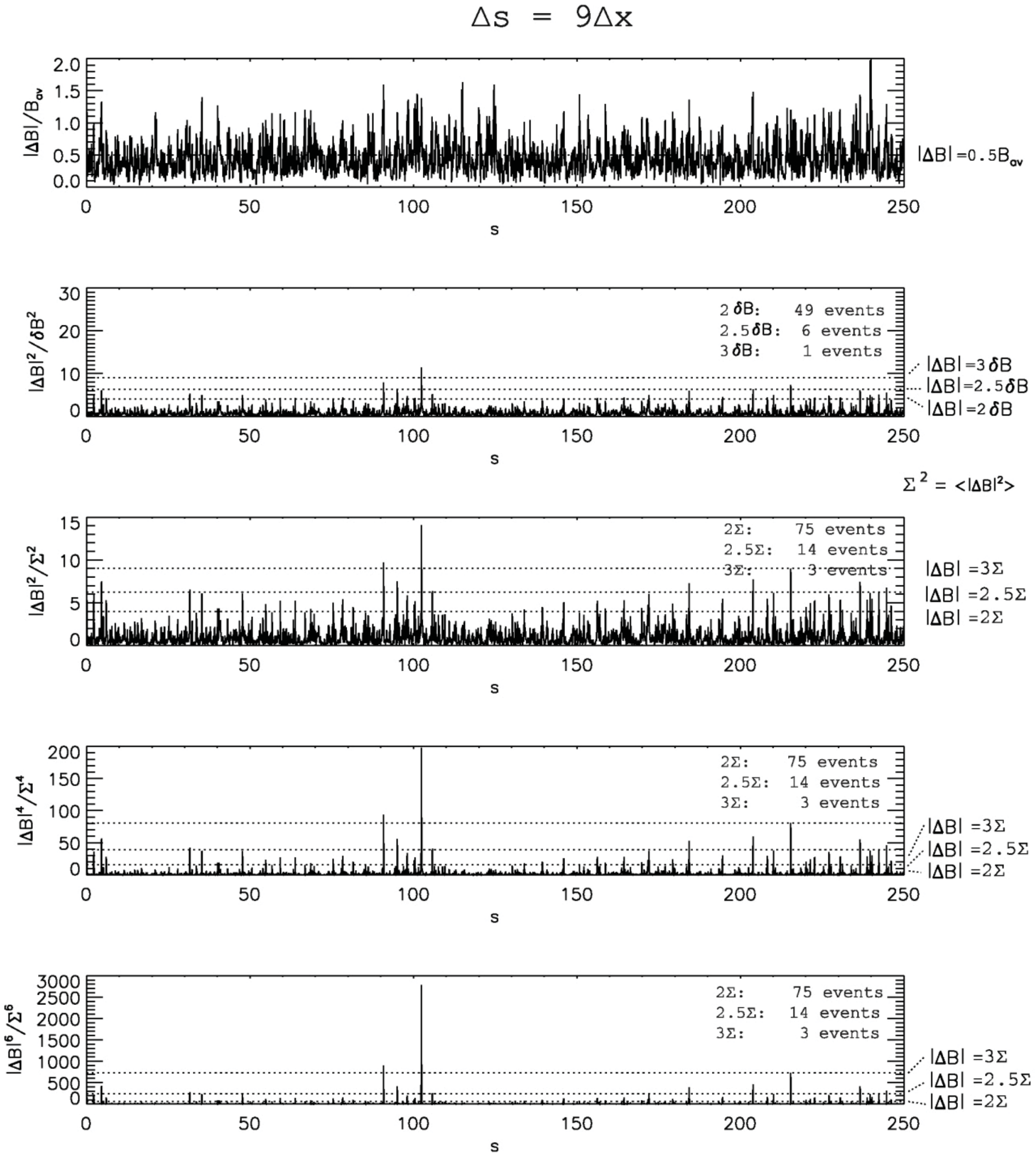


30 years of 1 hour SW data

Increments $\Delta_s \mathbf{B} = \mathbf{B}(x + s) - \mathbf{B}(x)$
Statistics of $|\Delta_s \mathbf{B}|$ for $s = 9\Delta x$ (inertial range)

Standard statistical measures

Intermittency time series related to intermittency measures



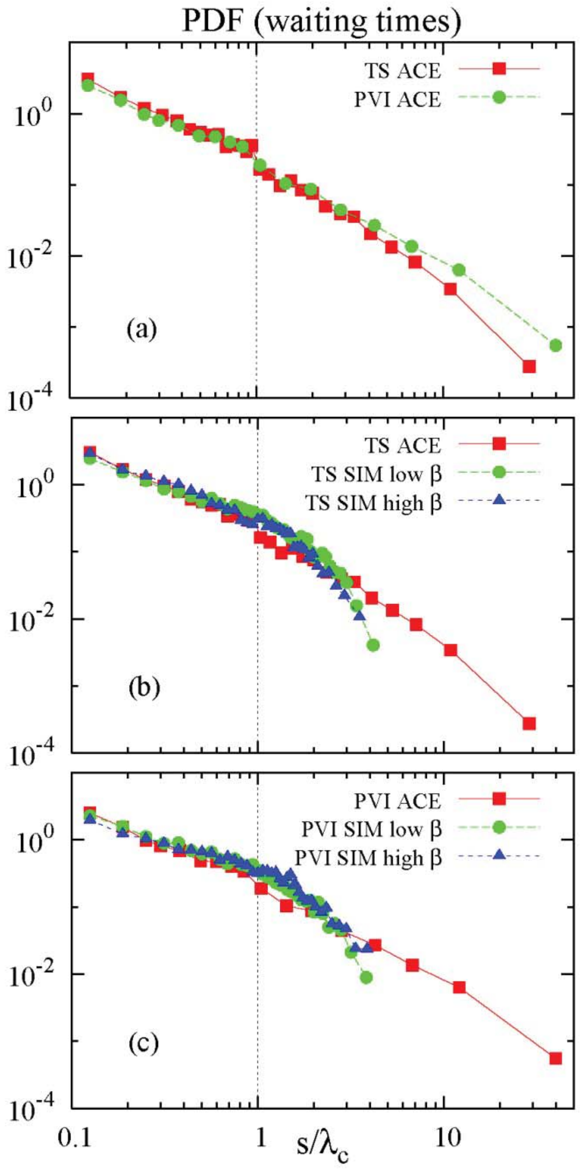
e.g.,
Tsurutani and Smith
Burlaga…

$Q(t) = |\Delta_s \mathbf{B}|^2/\Sigma^2$

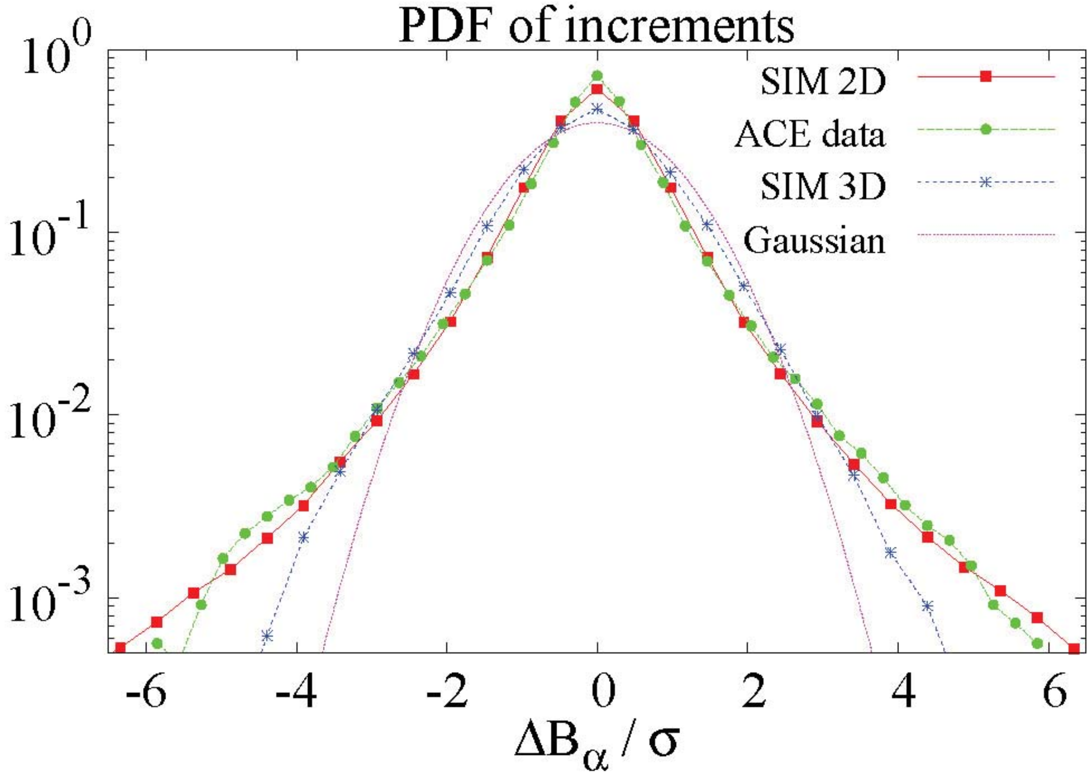
$Q^2(t)$

$Q^4(t)$

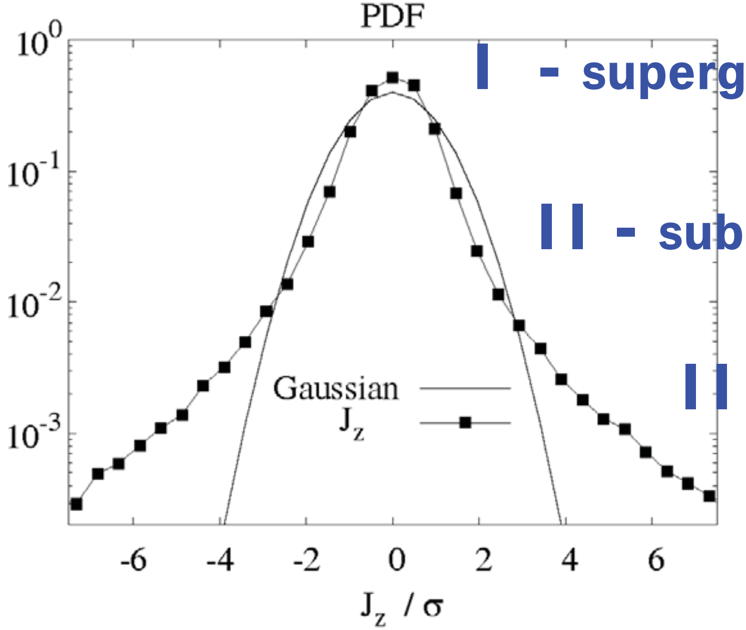
Comparison of waiting times and increment PDFs from SW-ACE and CHMHD turbulence simulation



Inertial range $\Delta_s \mathbf{B} = \mathbf{B}(t + s) - \mathbf{B}(t)$



Intermittency and the spatial organization of current

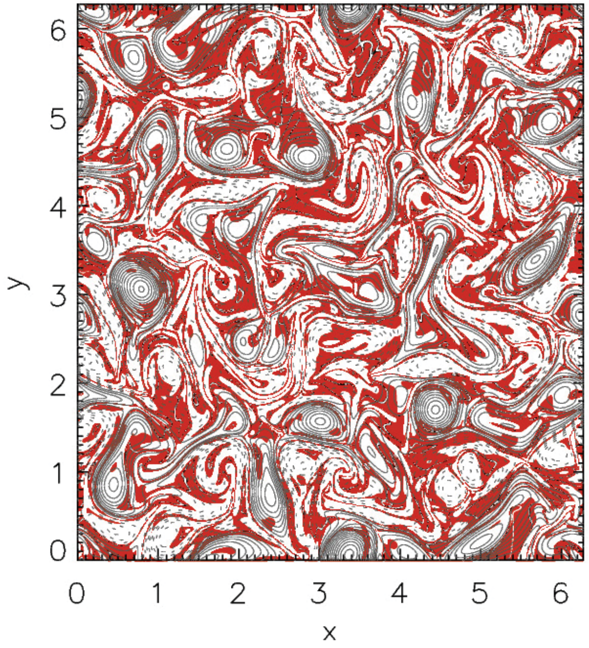


I - supergaussian

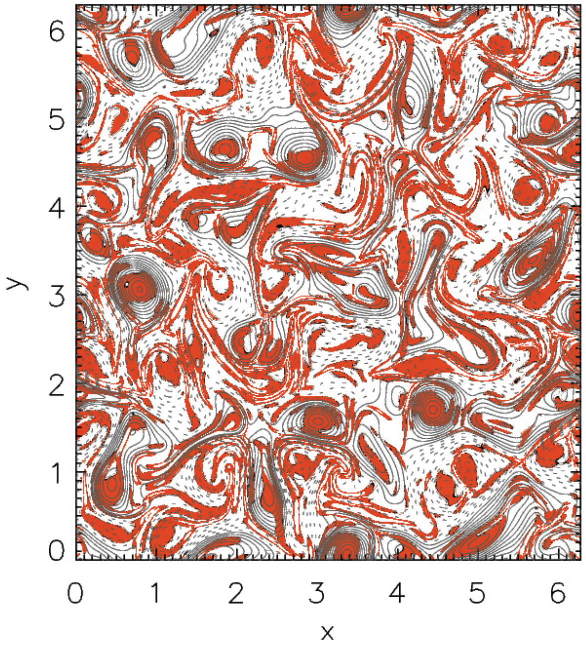
II - subgaussian

III - supergaussian

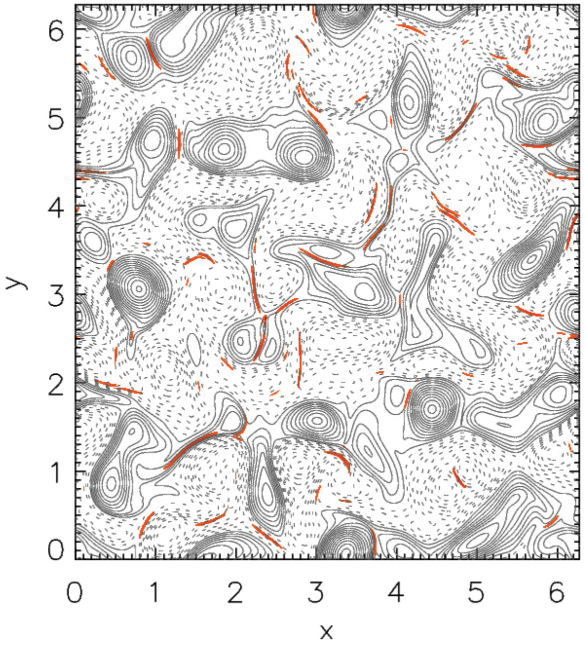
I - weak, supergaussian current lanes



II – subgaussian flux tube cores

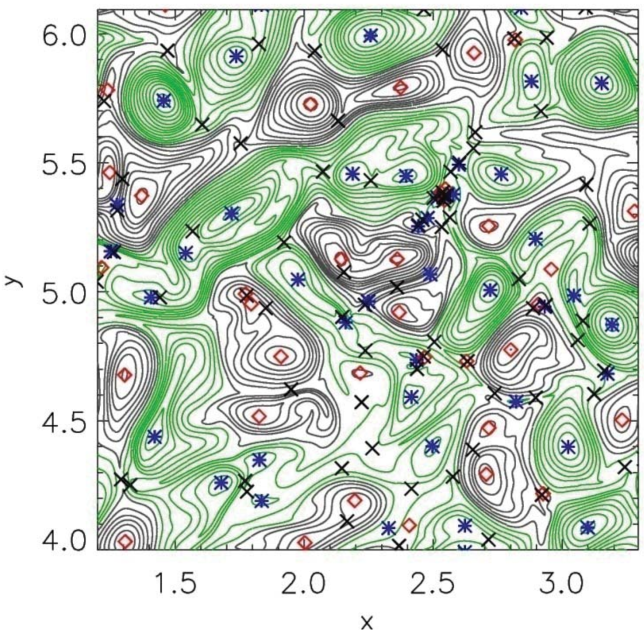


III – supergaussian current sheets



X. Turbulence regulates reconnection rates

Electric fields in turbulence and near reconnection sites



Large number of X points
and O points in a small fraction
of a large 2D MHD simulation
At moderately high Rm

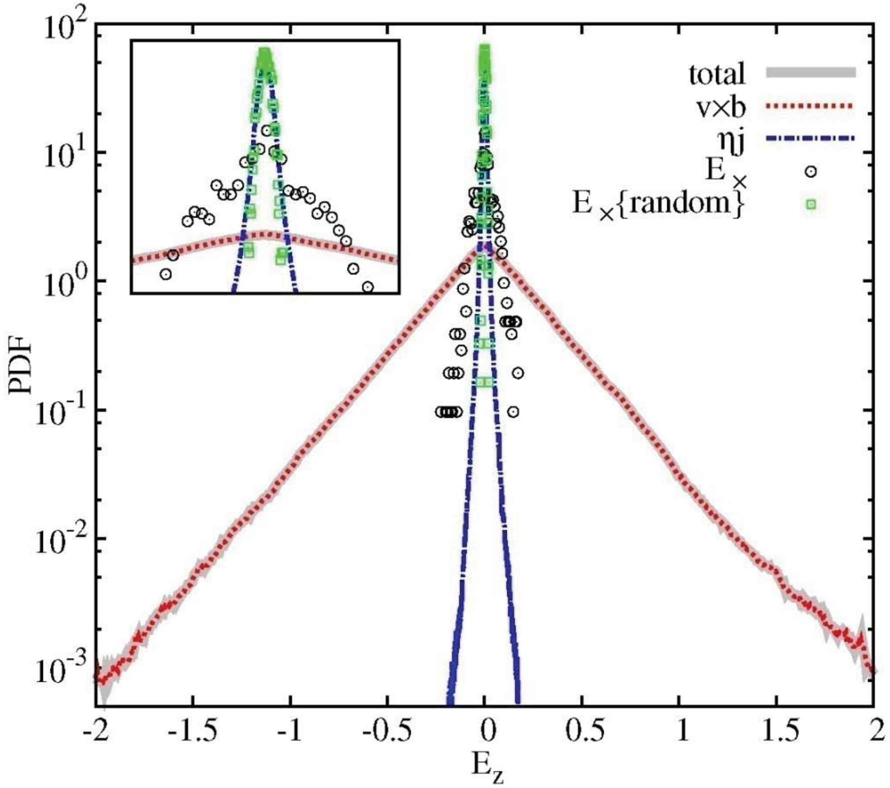


FIG. 6: PDF of the out-of-plane electric field contributions: total electric field given by the Ohms' law in the Eq. (7) (res solid-line), advective component (green dot-dashed line), diffusive (blue dotted line) part, reconnection rate (magenta solid-dotted line) and the electric field at the X-points evaluated from A_z^{Gauss} (azure dotted line). In the inset, a zoom in the core of these distributions is shown.

BIG electric fields are random inductive and away from Rec. Regions!

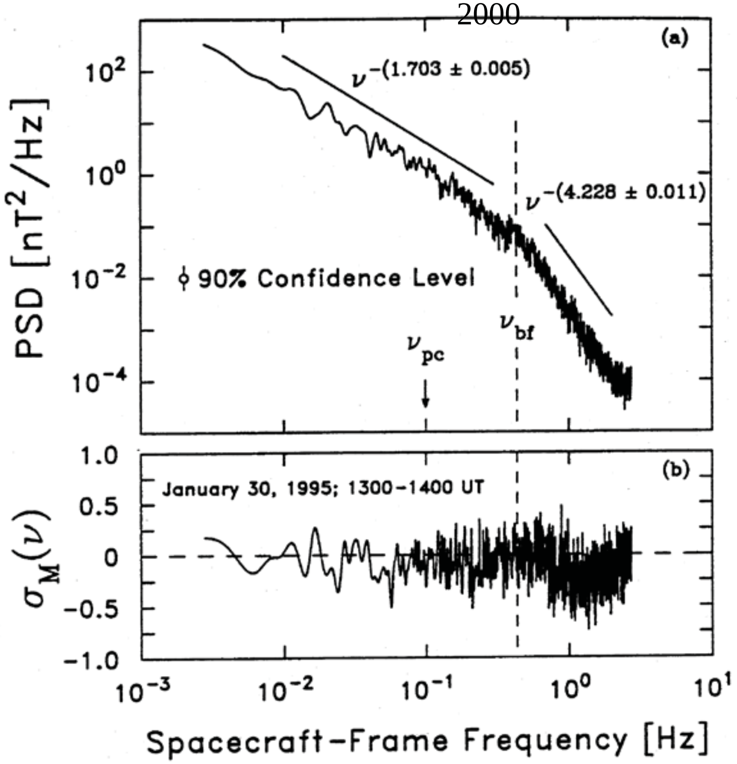
XI. Turbulence drives dissipation and small scale kinetic processes

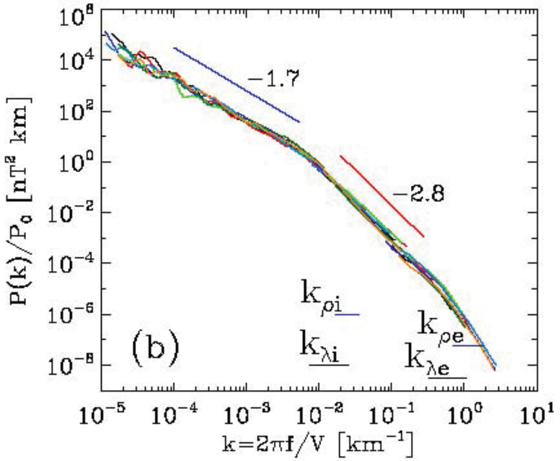
Solar Wind Dissipation

- ION SCALES: steepening near 1 Hz (at 1 AU) -- breakpoint scales best with ion inertial scale; Helicity signature → proton gyroresonant contributions ~50%; both Kpar and Kperp involved, oblique current sheets

- BETWEEN ION AND ELECTRON SCALES: steepening continues, dispersion range, kinetic Alfven waves? second inertial range?, subsequent steepening at electron scales

Leamon et al, 1998, 1999, 2000





Alexandrova etal, PRL 2009

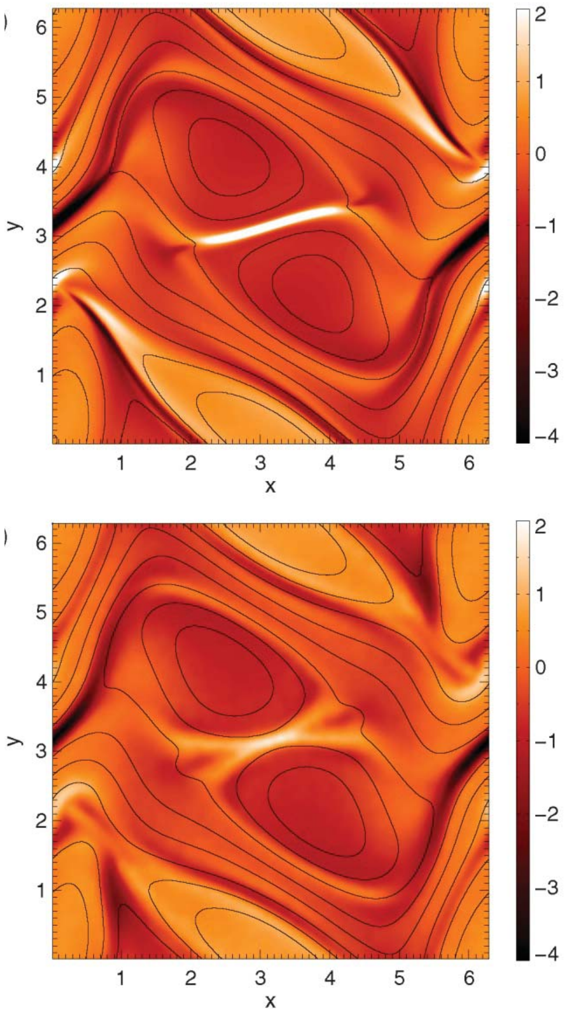
dissipation mechanisms can be…

Homogenous (e.g., cyclotron damping, Landau damping)
or
Inhomogeneous (current sheets, reconnection, vortices → coherent structures)

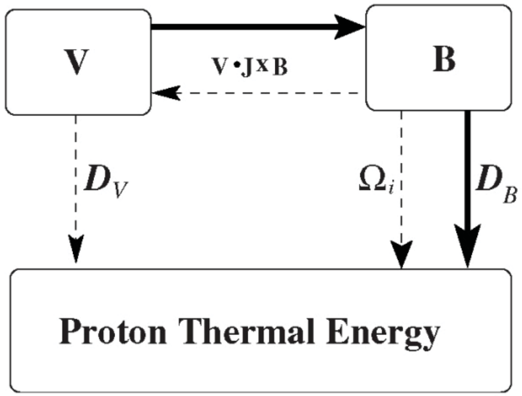
Linear (linear Vlasov theory, instabilities…)
or
Nonlinear (turbulence, nonlinear kinetic processes, particle acceleration…

Kinetic heating of ions: MHD and kinetic scale hybrid simulation (Orszag-Tang vortex)

MHD and hybrid B, J



Energy flow



V

B

V •J x B

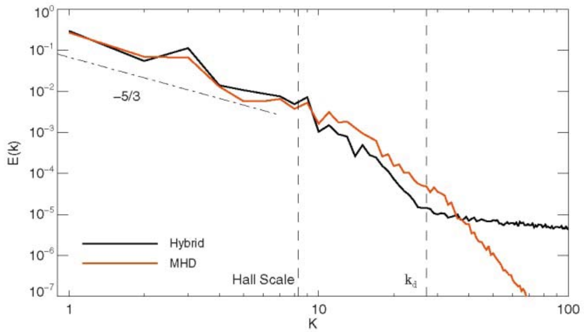
D_V

Ω_i

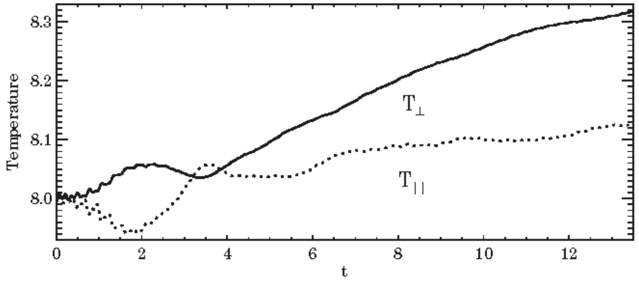
D_B

Proton Thermal Energy

Spectra: MHD and hybrid



Perpendicular heating! (no standard cyclotron resonance)



PHYSICS OF PLASMAS **16**, 032310 (2009)

Kinetic dissipation and anisotropic heating in a turbulent collisionless plasma

T. N. Parashar, M. A. Shay, P. A. Cassak,[a] and W. H. Matthaeus

Dissipation “channels”

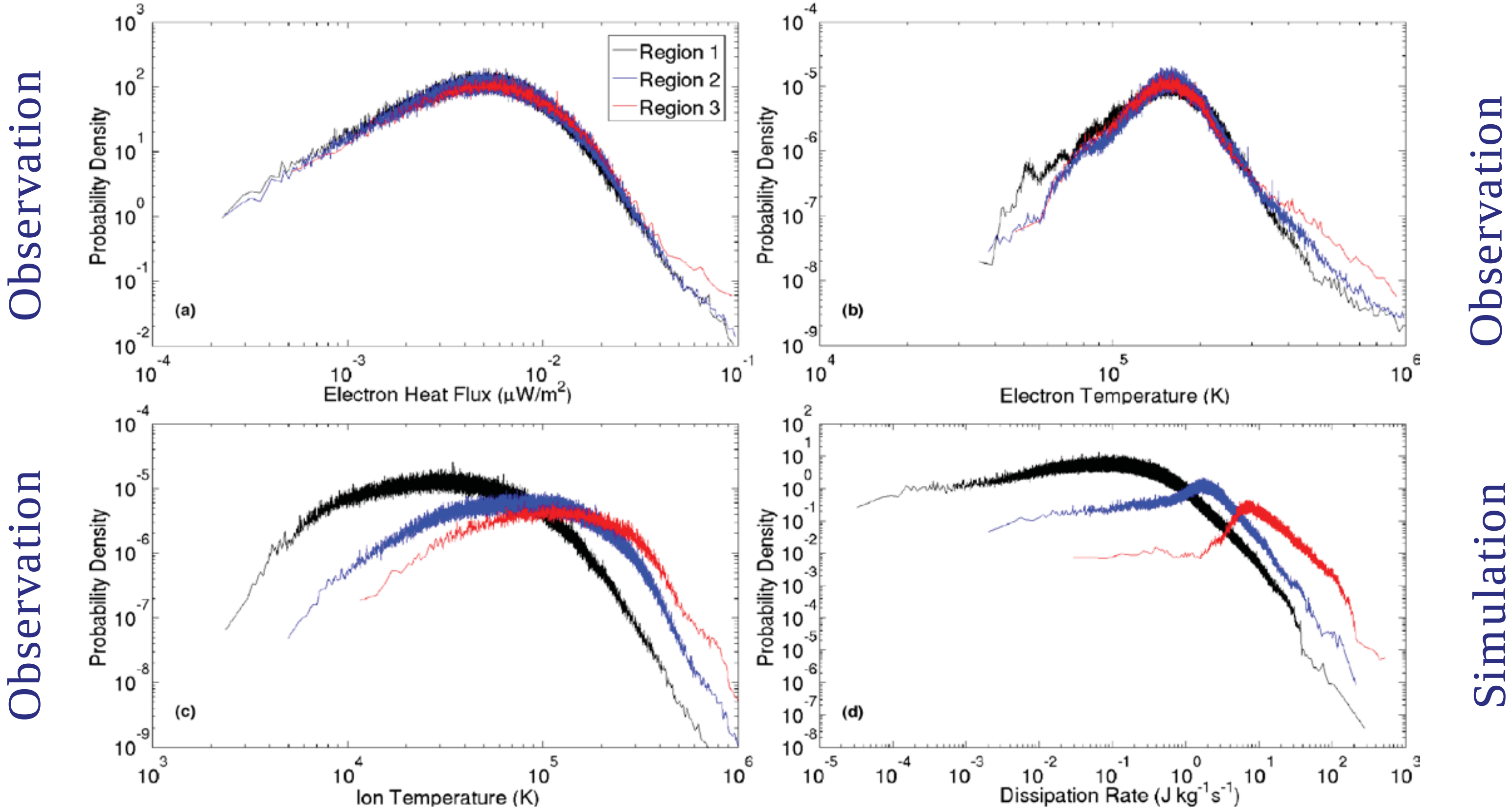
- Homogeneous
  - - landau, cyclotron (dissipation?)
  - - collisions

- Inhomogeneous
  - – Structures + kinetic response (e.g., reconnection)
  - – Current channels, reconnection, vortices (Markovsky, Hollweg)

Coherent structures are associated with enhanced heating

Red pdfs have PVI ≥4 ←→ Region 3

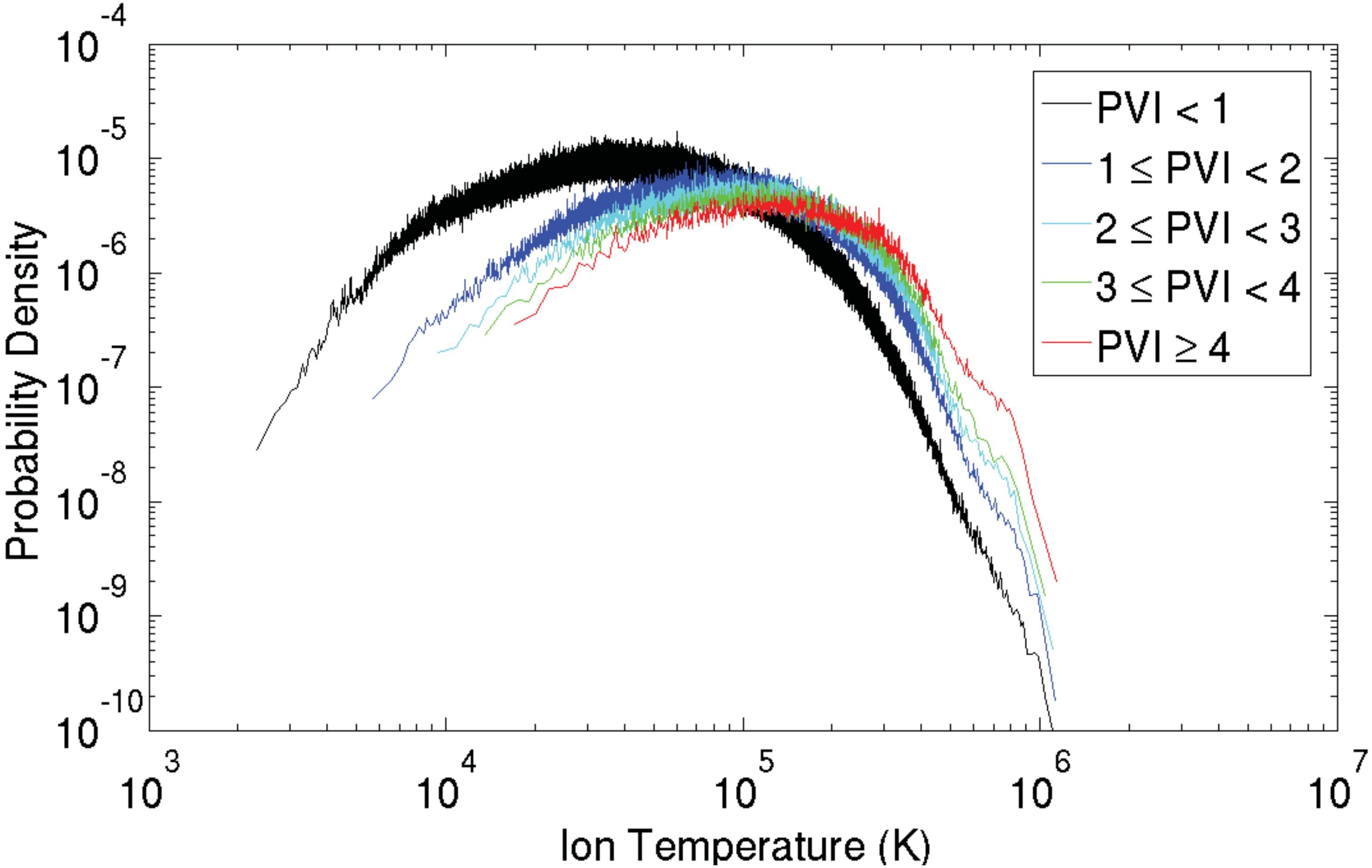
Each of the heating diagnostics is conditionally sampled so that the values associated with each of the three regions can be plotted as a separate PDF.



The red PDFs have probability densities that vanish for the lower values and are enhanced for the highest values.

Current Sheet Hierarchy

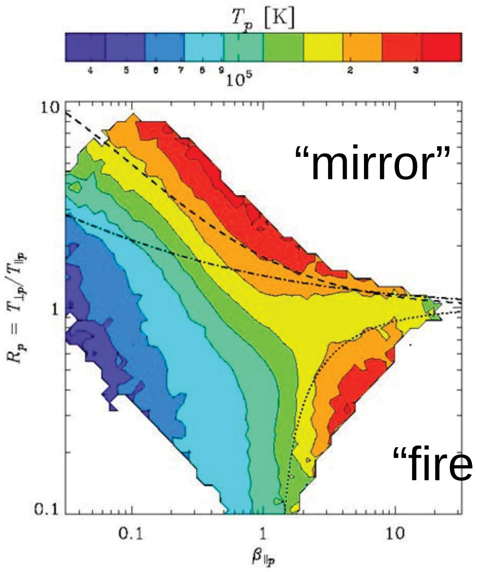
Most intense current sheets associated with largest heating



Organization of SW in ($\beta_{||}$, $T_{\perp}/T_{||}$) plane:

discontinuities are hotter and are found at limiting parameters

Distribution of Tp
in ($\beta_{||}$, $T_{\perp}/T_{||}$) plane

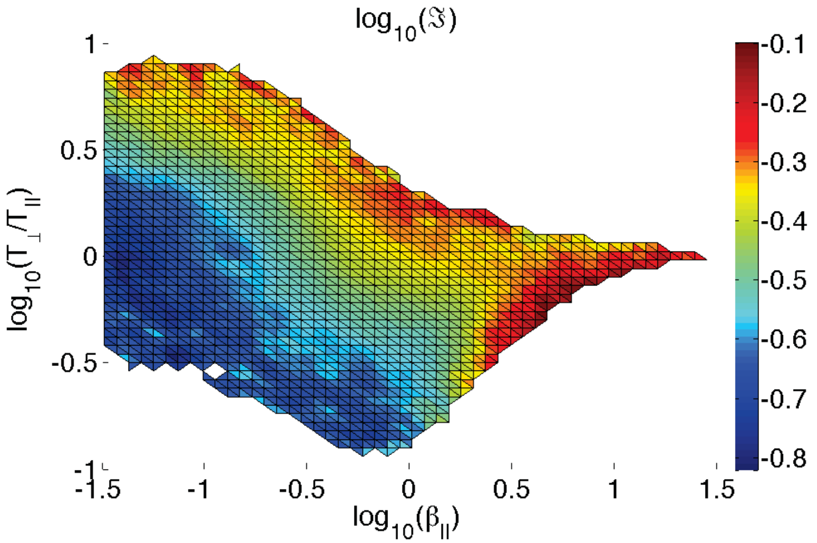


“mirror”

“firehose”

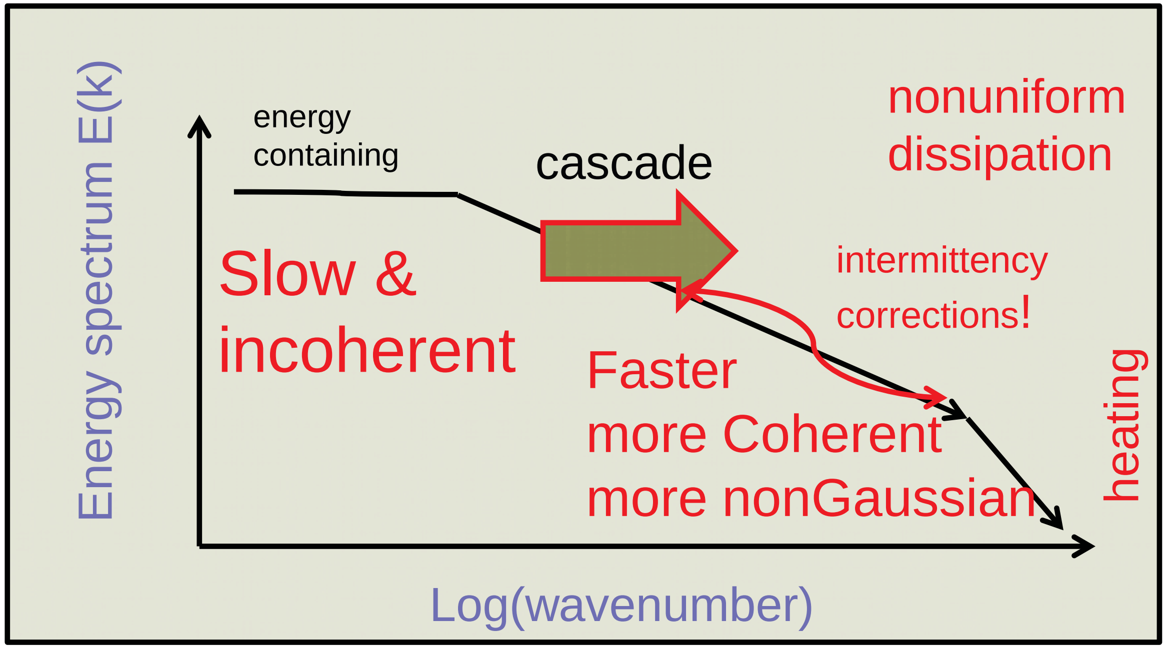
From Kasper, Maruca &Bale, 2011

Distribution of mean *PVI*
in ($\beta_{||}$, $T_{\perp}/T_{||}$) plane



From Osman et al, 2011

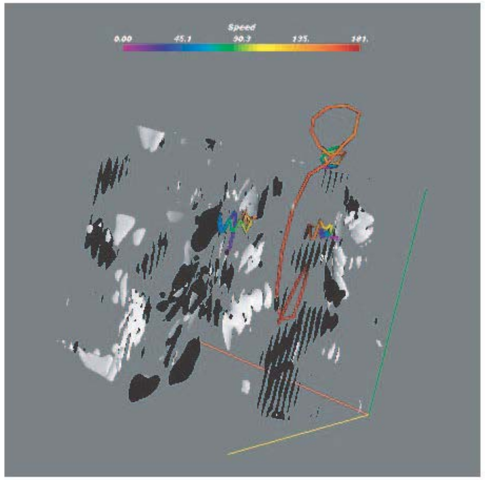
More detailed turbulence spectrum



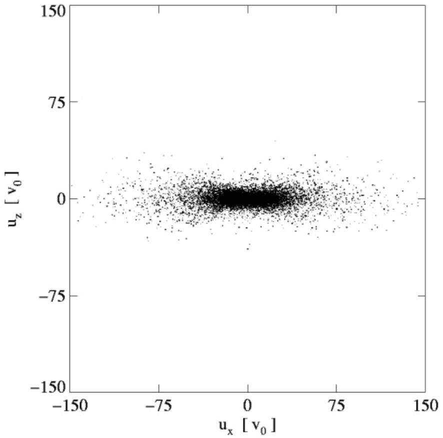
- **Cascade:** *progressively enhances nonGaussian character*
- *Generation of* ***coherent structures*** *and patchy correlations*
- *Coherent structures are sites of* ***enhanced dissipation***

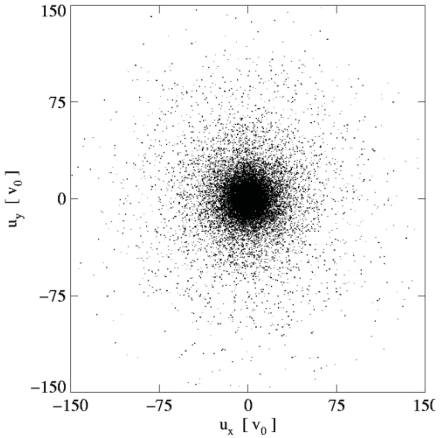
XII. Turbulence accelerates particles producing distinctive anisotropies

Test particles in MHD: distributions at short times (<crossing time of Lc)



protons

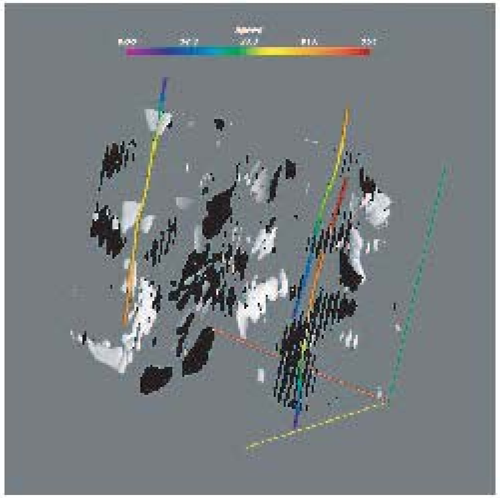


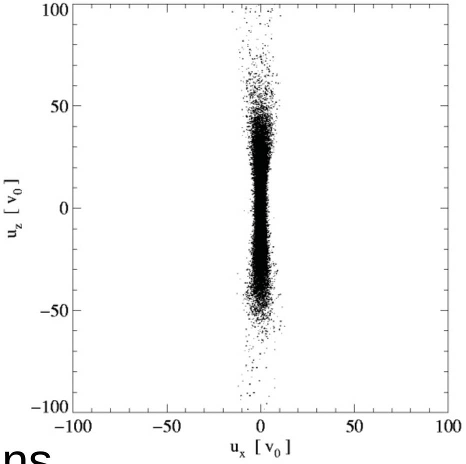


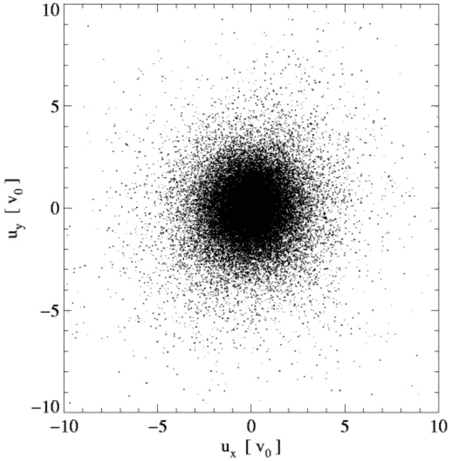
B_0 direction

perp plane

Trajectories and current structures







electrons

Dmitruk et al, 2004

XIII. Turbulence destroys wave behavior and is of a “zero frequency” nature

Are there any kind of recognizable “waves” in turbulence?

- Simulations of driven dissipative MHD with imposed DC magnetic field of varying strength show little indication of power in “waves” at frequencies that solve the dispersion relations

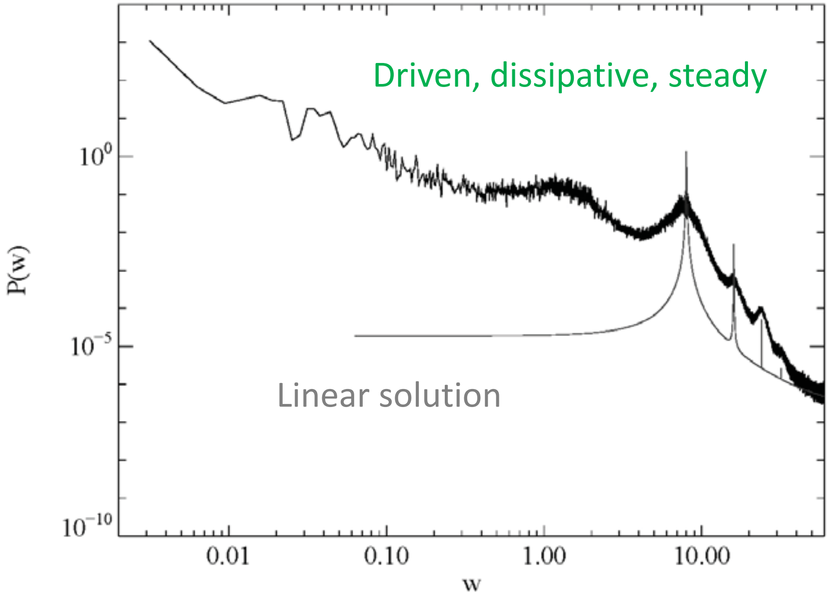
  – for *ANY* value of imposed magnetic field B0 !

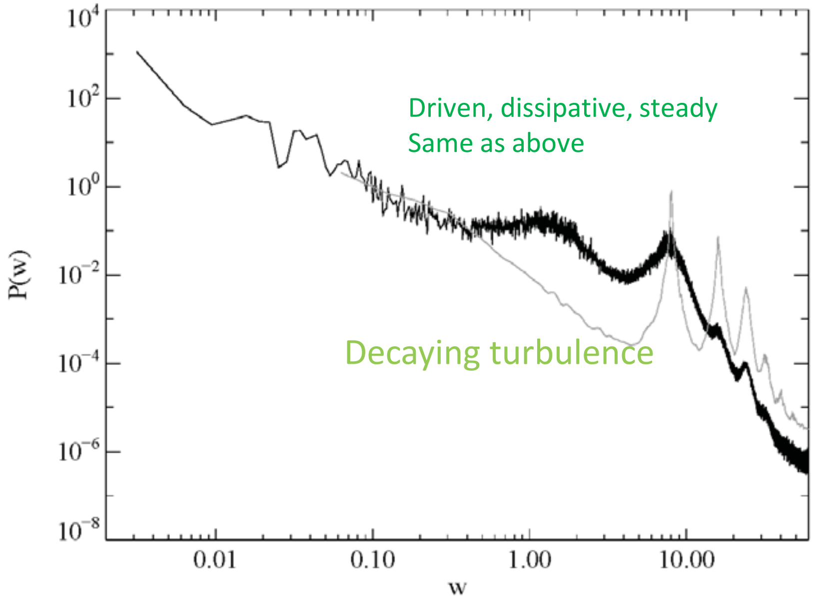
- Shown are Eulerian frequency spectra (one point) with B0=8, for :
  - driven steady case
  - decaying (energy renormalized) turbulence

- Varying dB/B0 one find no more than ~16% energy in the dispersion relation peaks,
With maximum at dB/B0 ~ ½

- See Dmitruk and Matthaeus, Phys Plasmas 2008

Eulerian frequency spectra





SUMMARY:

We are only beginning to understand the subject of turbulence in space physics and astrophysics1

There are many outstanding issues/questions involving turbulence that need to be addressed using a broad range of methodologies and approaches:

- heating of the corona
- Distributed heating of the solar wind
- Origin of the kinetic signatures
- Scattering of energetic particles
- Role/relationship to MHD scale turbulence
    - Cascade
    - Coherent structures
- Applicability of wave theory
- Applicability of linear vlasov theory
- Homogenous vs inhomogeneous dissipation
- Contributions from proton, electron and inter-p-e scales