Dissipation, heating, particle acceleration and coherent structures in MHD turbulence

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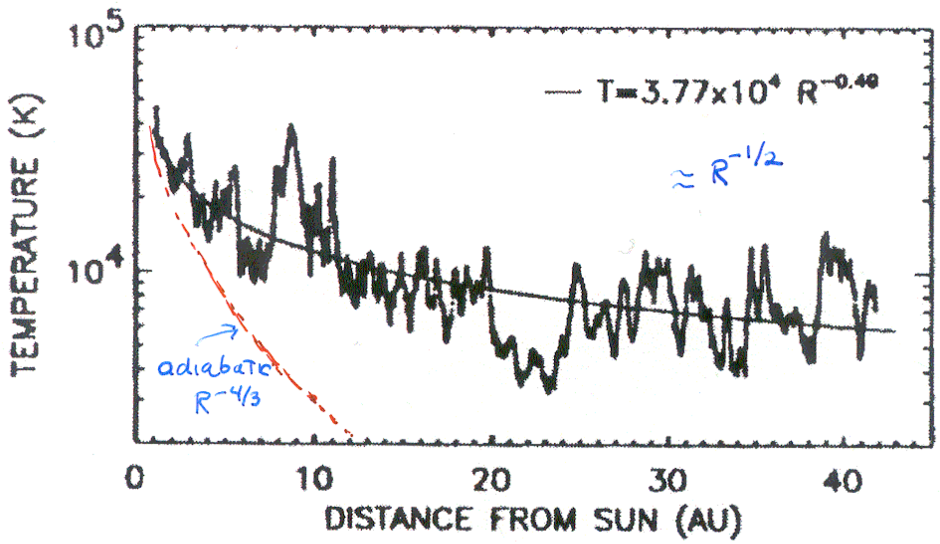
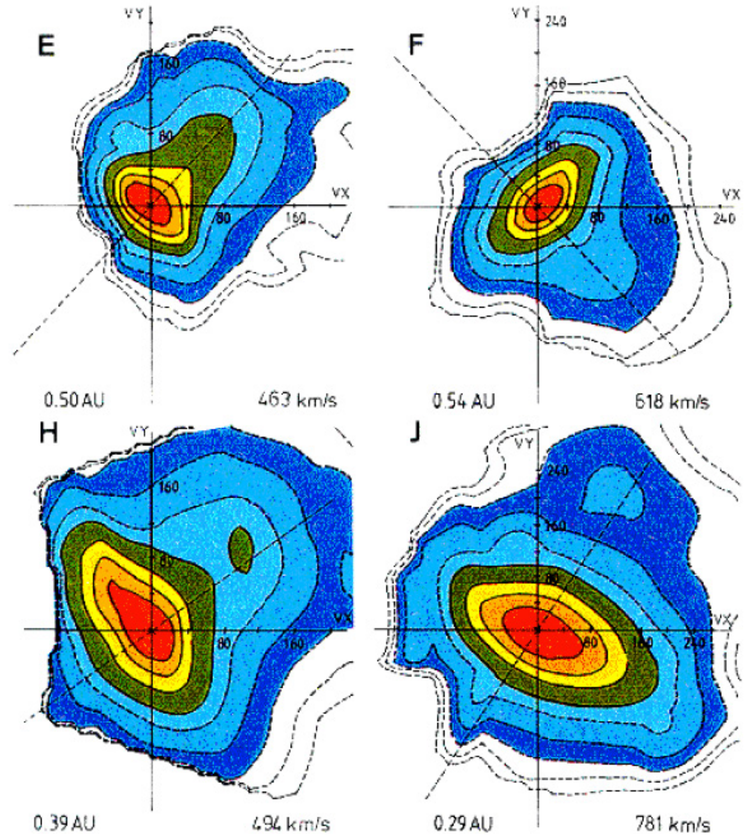
(i) Introduction

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

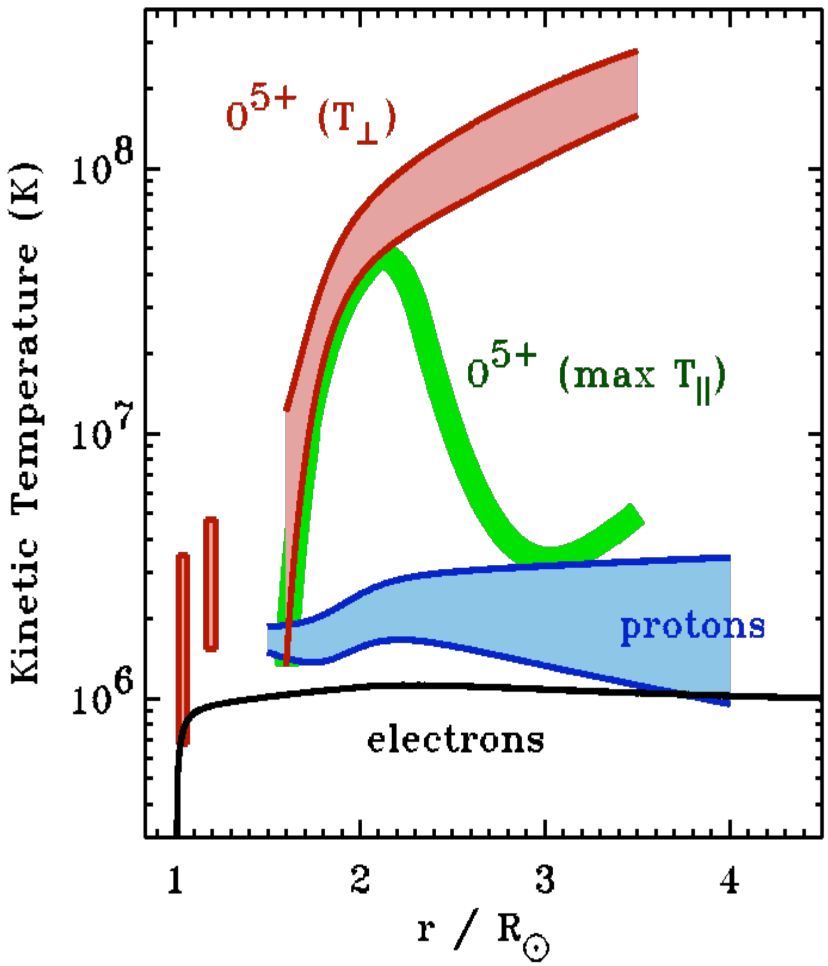


Richardson and Paularena, GRL, 1995
IMP, Voyager temperatures
(faraday cup)



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

Coronal temperatures (UVCS)



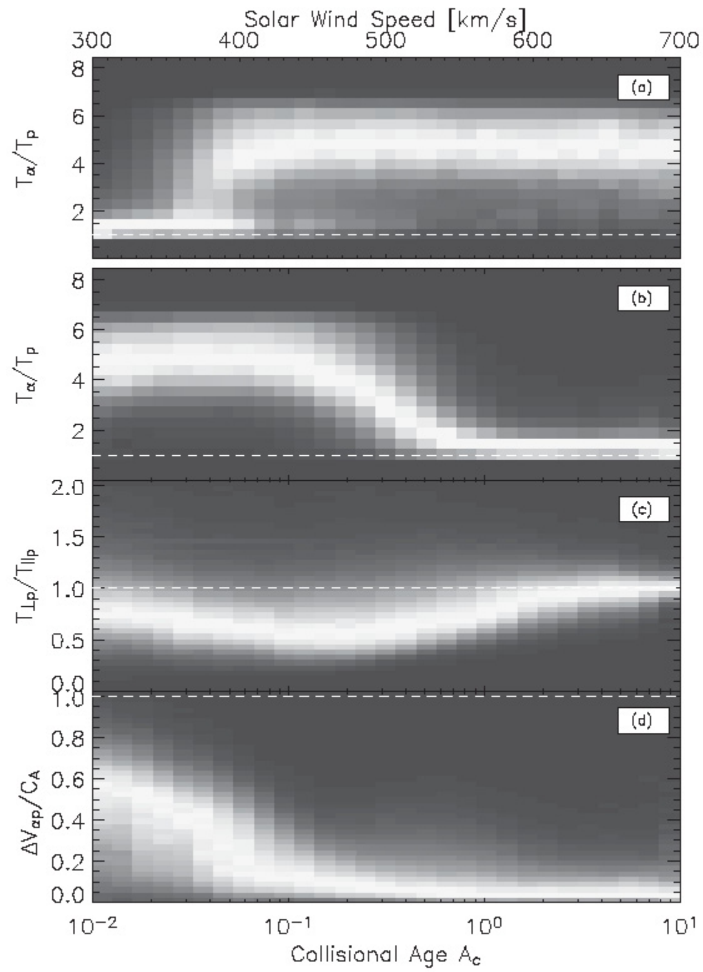
$$\left\{ \begin{array}{ccc} T_{\rm ion} \gg & T_p & > T_e \\ (T_{\rm ion}/T_p) & > & (m_{\rm ion}/m_p) \\ T_\perp & \gg & T_\parallel \\ u_{\rm ion} & > & u_p \end{array} \right\}$$

S. Cranmer, J, Kohl (UVCS)

Anisotropies: evidence for cyclotron reonance?

Anisotropies in Tp
And Talpha

vs. speed and
Vs. collisional age



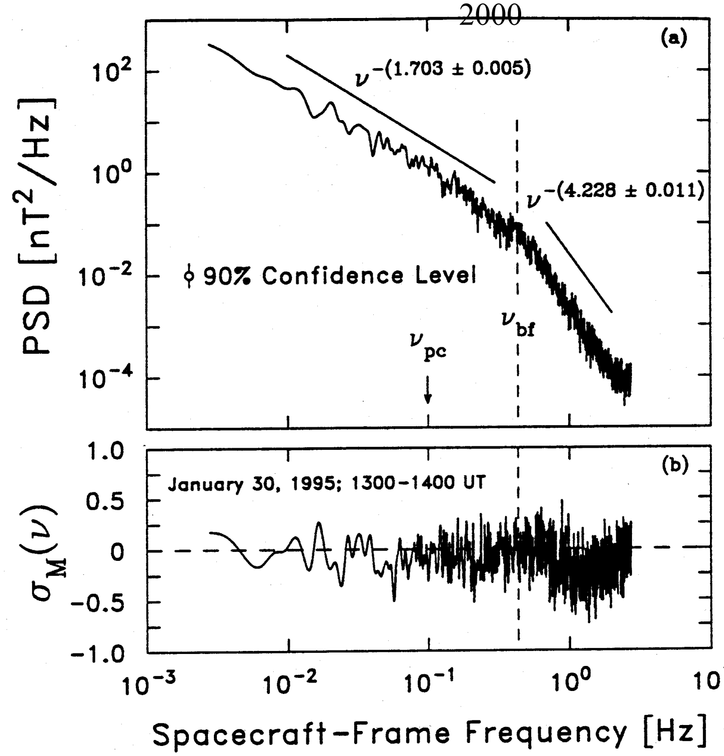
From Kasper et al, PRL 2008

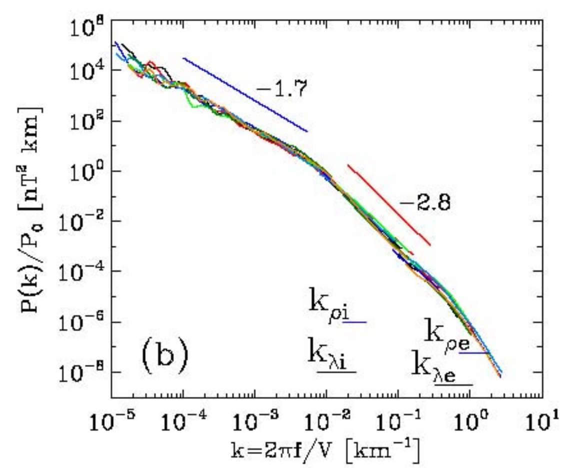
Solar Wind Dissipation

- 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

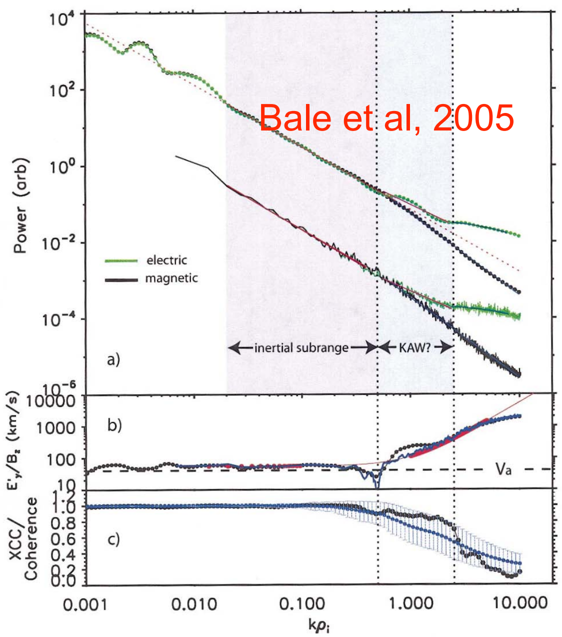
Leamon et al, 1998, 1999, 2000

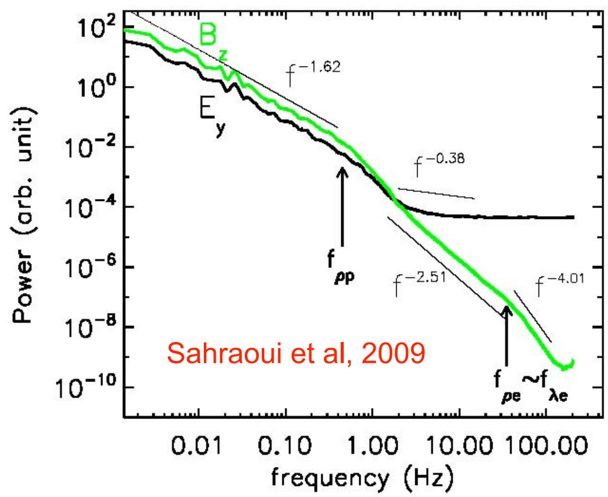


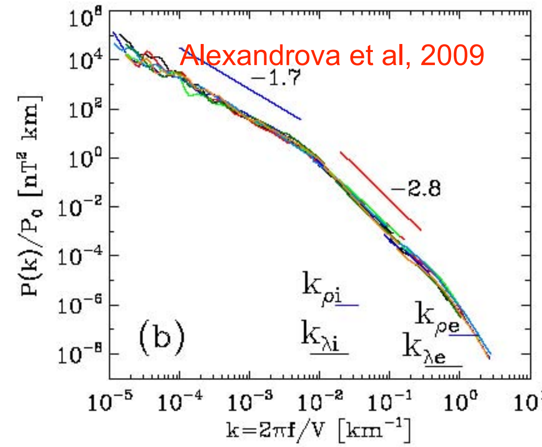


Alexandrova etal, PRL 2009

(ii) Major scientific questions







- Is there dissipation at ion scales?
- In region between ion and electron scales: is there dissipation, cascade, dispersion?
- What is the nature of dissipation at electron scales?
- Is kinetic scale activity preferentially low frequency?
- Is the activity at MHD scales and/or kinetic scales akin to interacting waves?
- Are there any signatures of waves?
- are homogenous linear Vlasov predictions, e.g., damping rates, correct, or useful?
- Where is the entropy actually generated and how? (collisions? Effective collisions?)

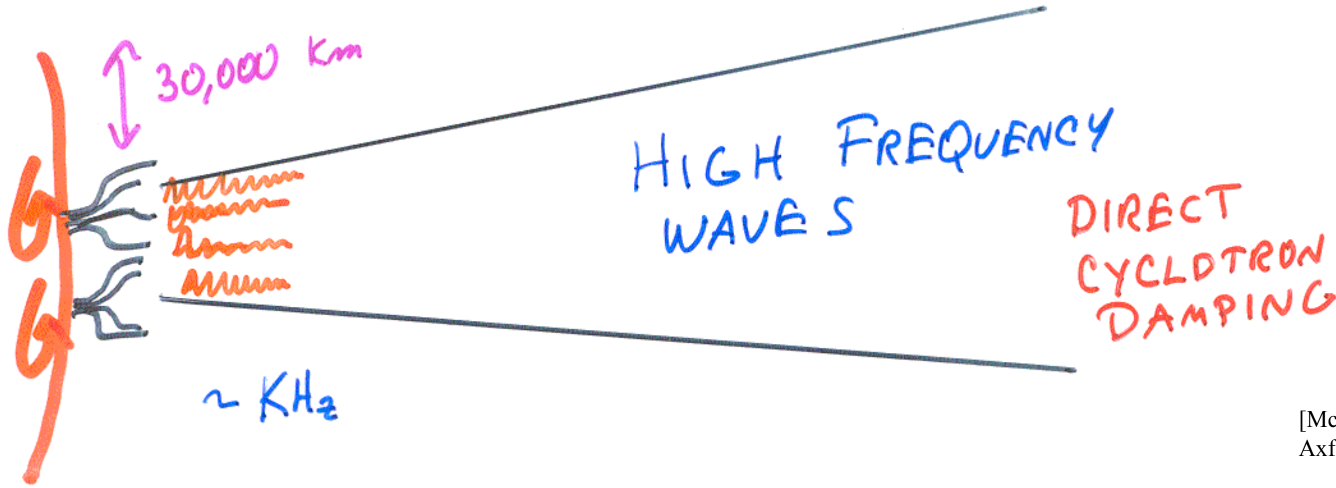
(ii) More major questions

dissipation mechanisms can be…

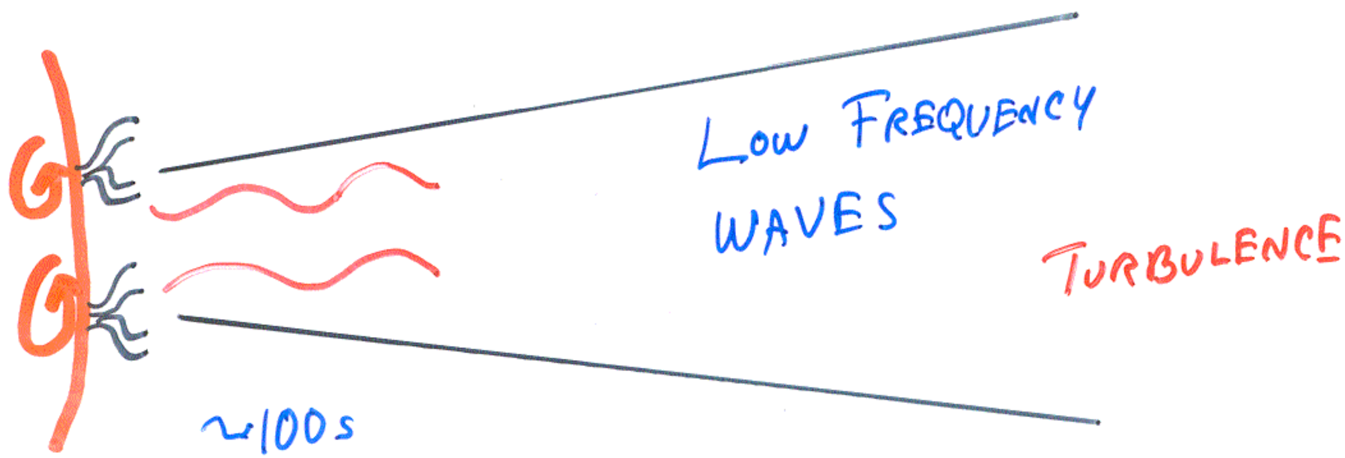
Homogenous (e.g., cyclotron damping, Landau damping)
or
Inhomogeneous (current sheets, reconnection, vortices → coherent structures)

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

(ii) Questions and issues



[McKenzie et al, 1995;
Axford and McKenzie, 1997]

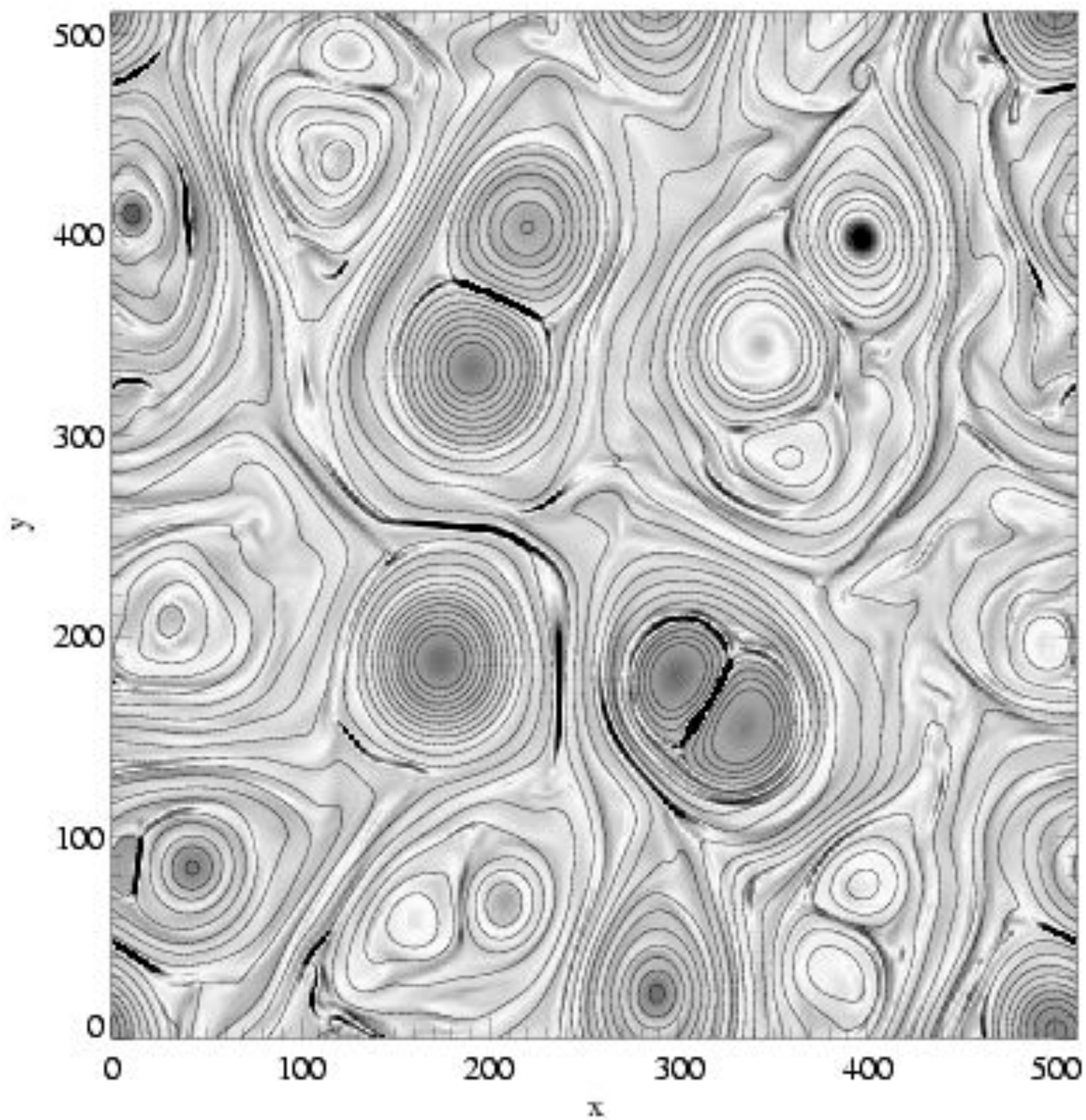


High and low f

(iii) approaches

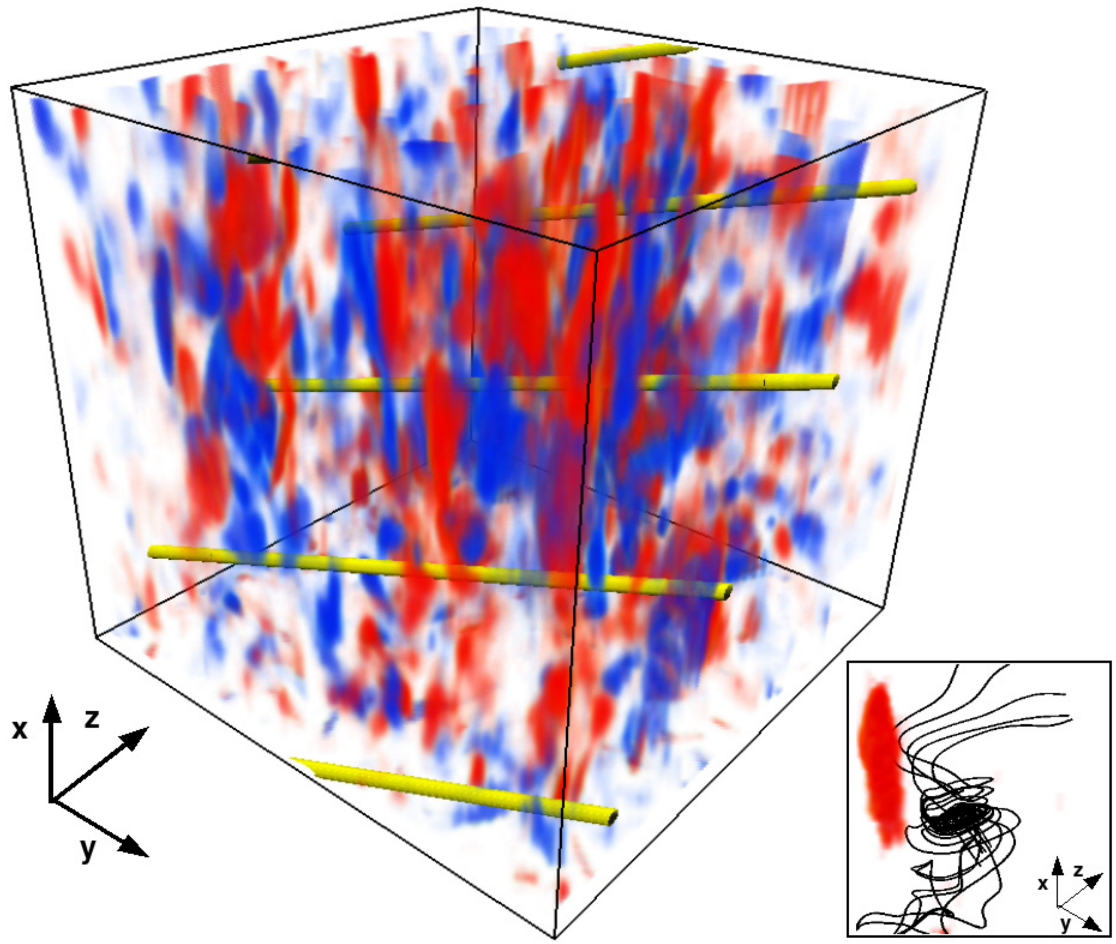
Decaying two-dimensional turbulence: islands, reconnection, current sheets

512^2 spectral method simulation



starting with
Fyfe and Montgomery, 1976
Fyfe et al, 1976, 1977

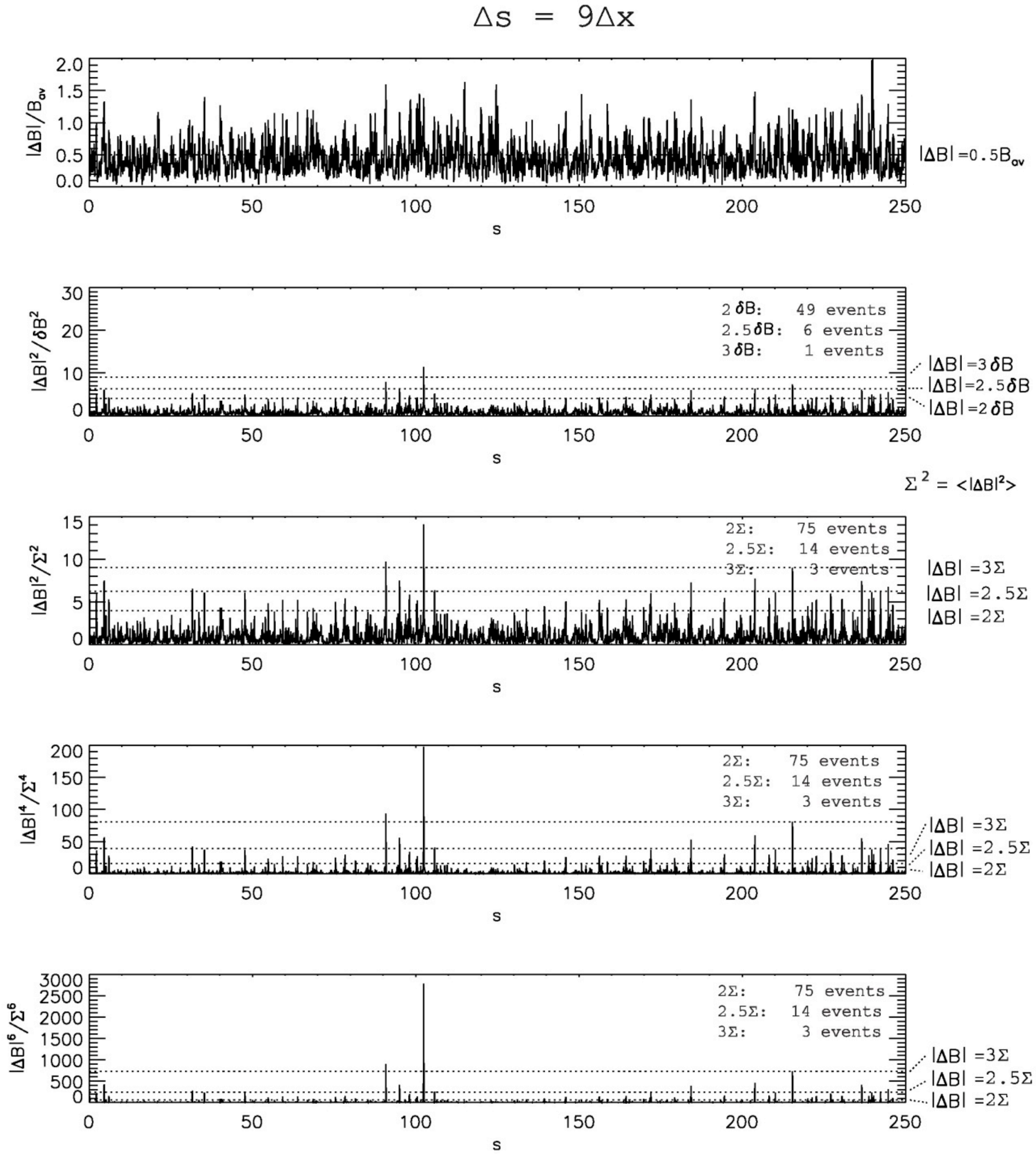
3D MHD compressible simulation with mean B_0



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

e.g., Tsurutani and Smith, Burlaga…



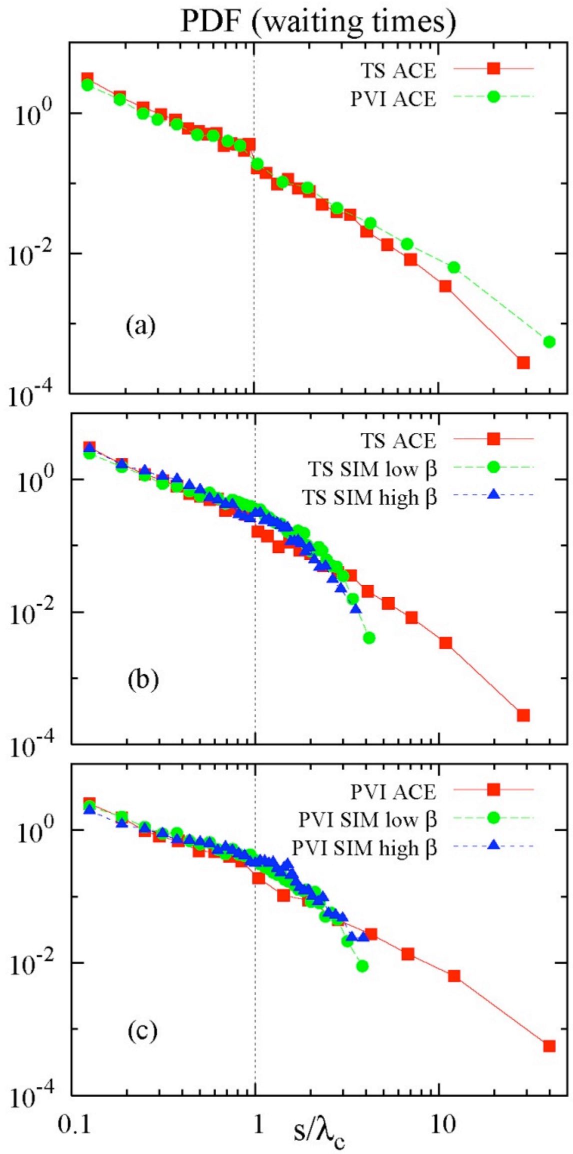
$Q(t) = |\Delta_s \mathbf{B}|^2/\Sigma^2$

$Q^2(t)$

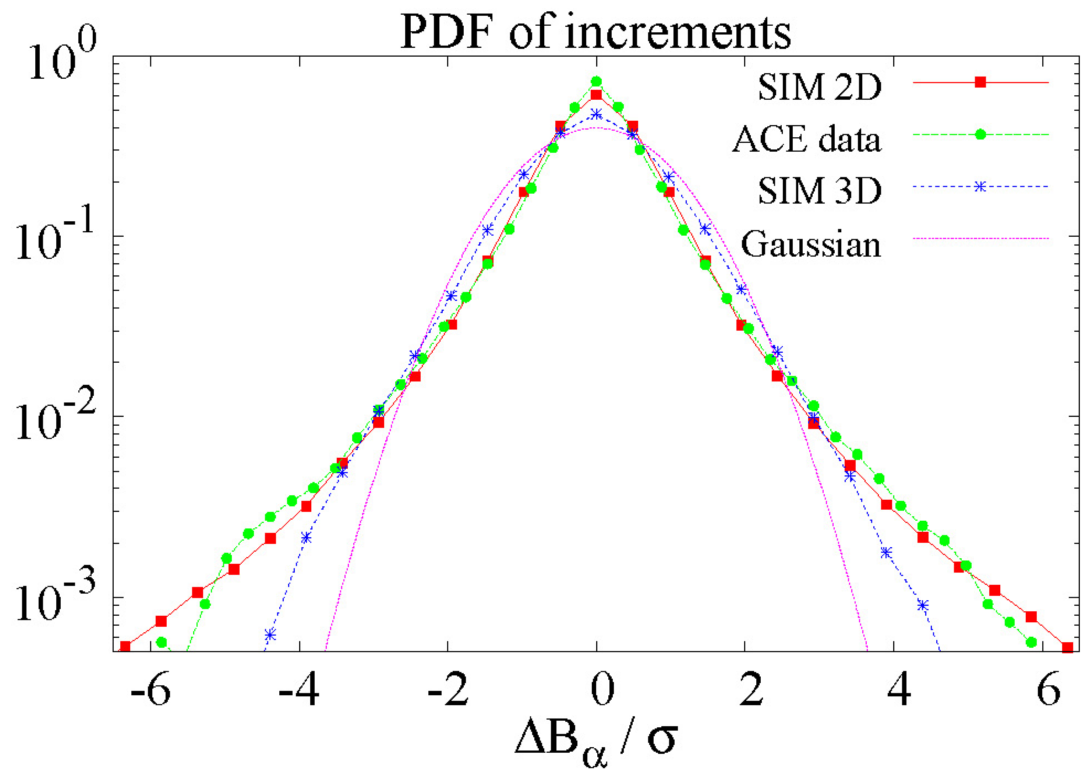
$Q^4(t)$

Intermittency time series related to intermittency measures

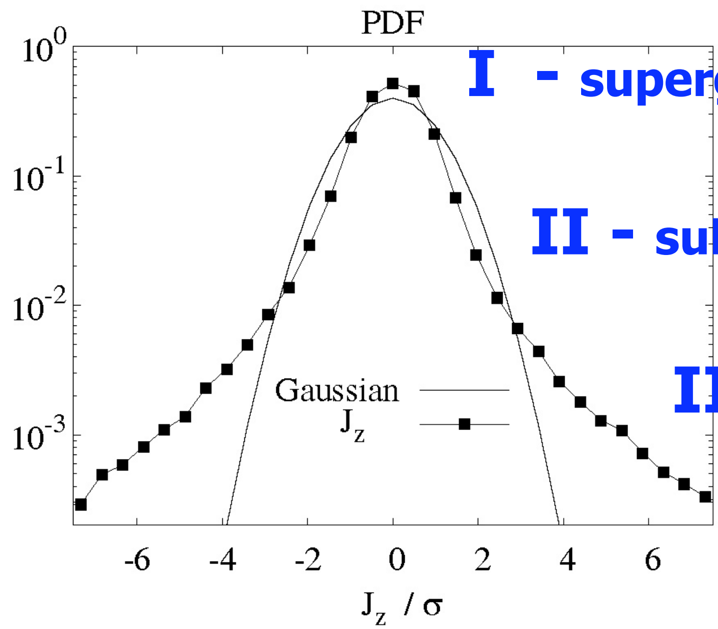
Comparison of waiting times and increment PDFs from SW-ACE and CHMHD turbulence simulation



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



Intermittency and the spatial organization of current



I - supergaussian

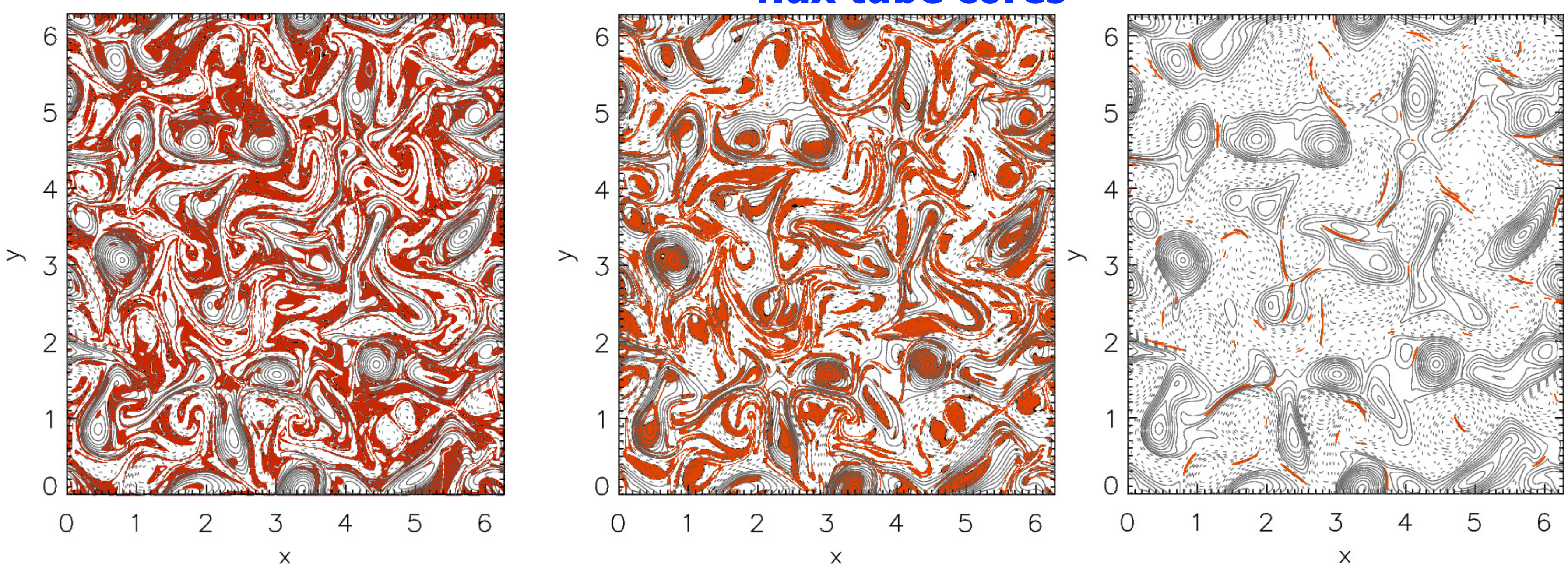
II - subgaussian

III - supergaussian

I - weak, supergaussian current lanes

II – subgaussian flux tube cores

III – supergaussian current sheets



Turbulence and current sheets in the magnetosheath (Retino et al Nature Phys. 2007)

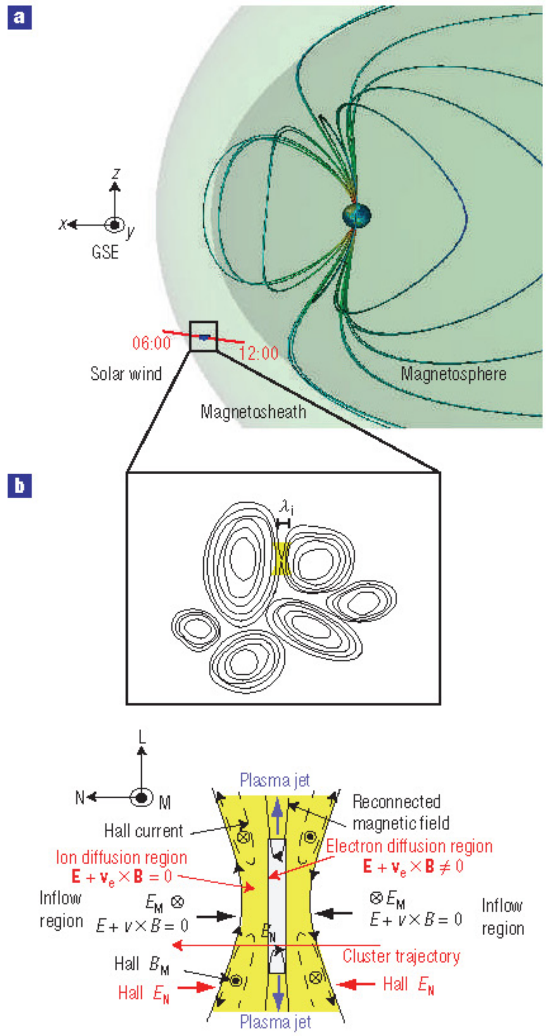
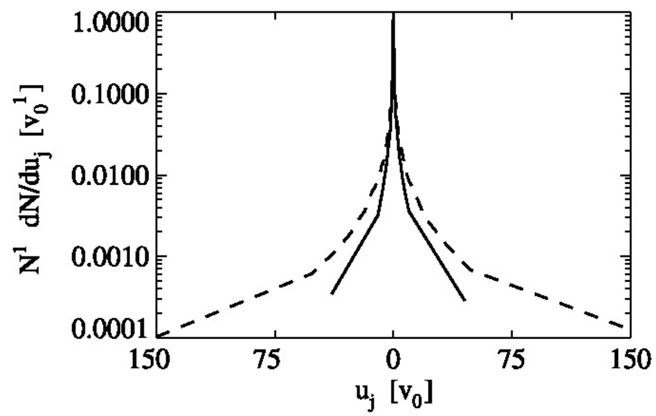


Figure 1 The quasi-parallel bow-shock crossing. a, Spacecraft orbit (red line). **b**, Schematic diagram of the current-sheet formation between magnetic islands and of magnetic reconnection in the current sheet. GSE: geocentric solar ecliptic coordinate system.

- Cluster data
- Analyzed large number of current strictures with high res data
- Consistent with reconnecting current sheets between turbulent magnetic islands or flux tubes

Test particles (p and e) in MHD with B0/dB ~10

Current density and field lines



Proton distributions
At two early times (~1 Tnl)

Par-perp directions 2 perp directions

-------------------------- ------------------------------

→ Highly anisotropic turbulence with current channels aligned with B0

→*Cascade, anisotropy and intermittency properties of the turbulence have a significant influence on the acceleration*

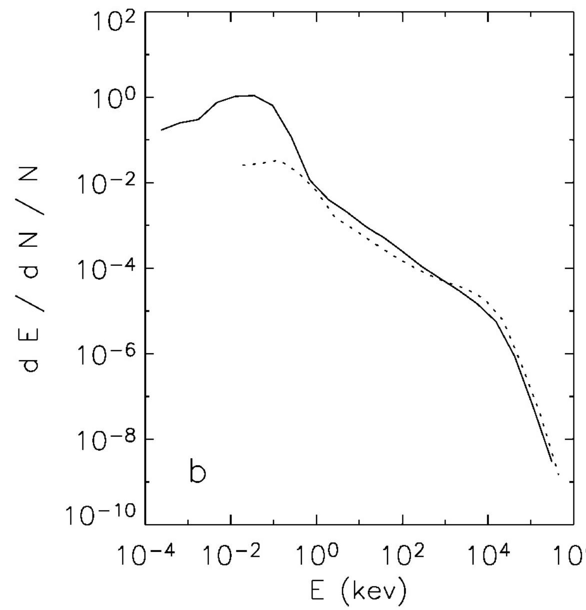
Test particles are accelerated by the turbulent electric fields in MHD and HMHD.

•Is acceleration the same for all types of test particles? NO…

•Both turbulent inductive field and parallel electric field participate, but in different proportions for p and e and Hvy-Ions
(Dmitruk and WHM, 2005; Turkmani et al, 2005)

•Are magnetic moments conserved? Mostly yes, but not for the particles with large energy changes (e.g., Lehe et al, 2009) Is this controversial?

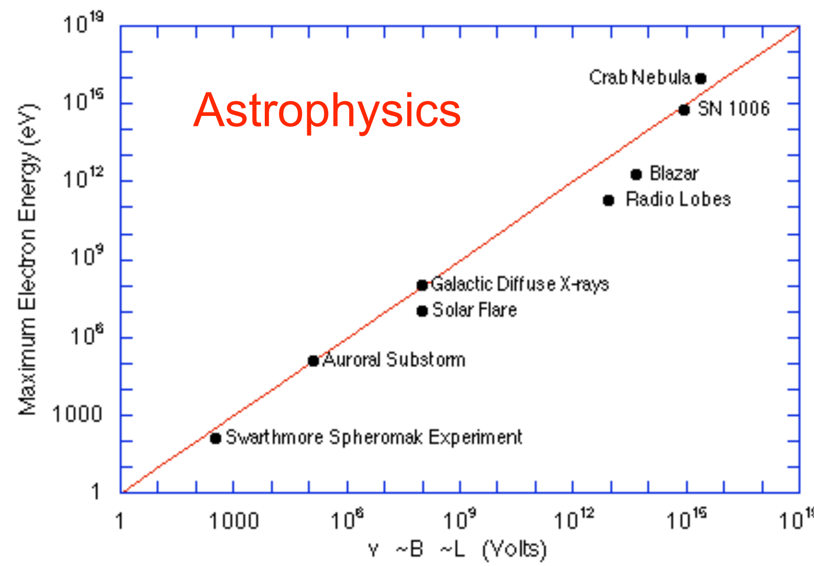
▪Do test particles provide clues about how particles are accelerated self consistently?



Test particle electron distribution after t=0.1 of turbulence evolution Turkmani et al, ApJ, 2005

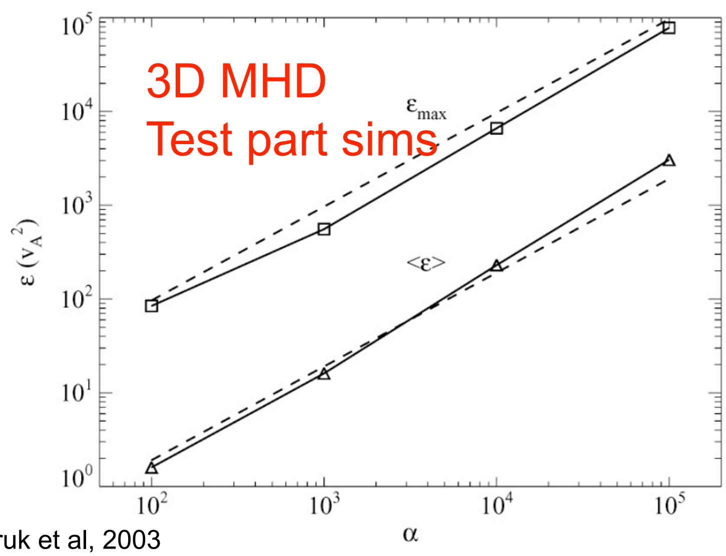
Particle acceleration and V-B-L scaling in astrophysics, turbulence simulation and experiments:
maybe everything is not shock acceleration

- Max Energy ~ vBL
- Mean and Max Energy scalings ir turbulence simulations
- Swarthmore Spheromak experiment

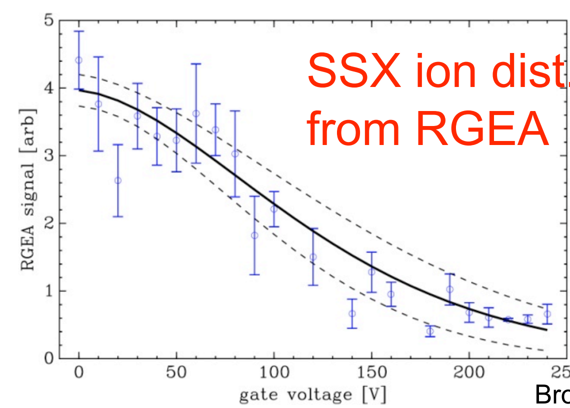


ere v is the typical velocity, B is the typical magnetic field, and L is the typical system size

from K. Makishima, "Energy non-equipartition processes in the Universe." 1999



Dmitruk et al, 2003



Brown et al, 2001

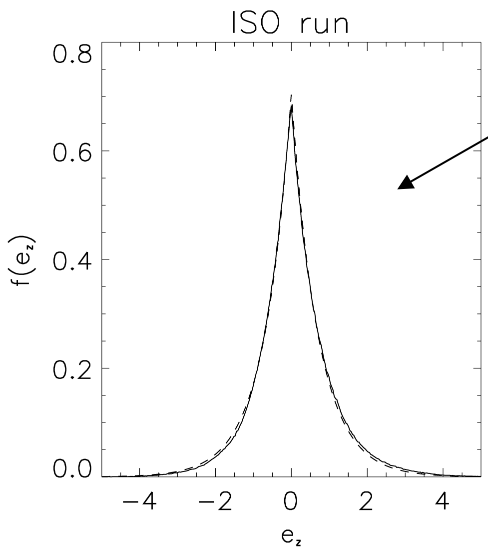
VBL~ $\alpha\ \lambda\, E$ ~ alpha * E-correlation * typical electric field)

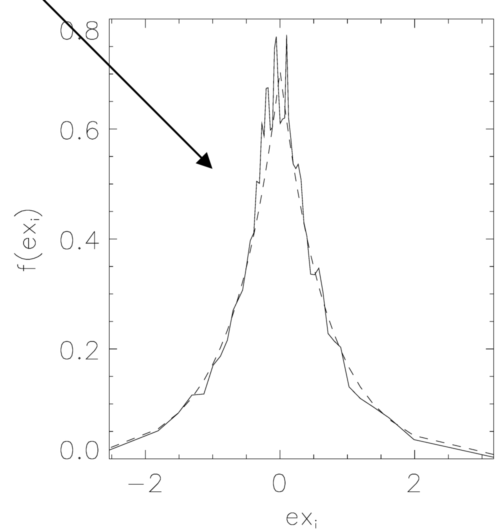
Statistics of the induced electric field

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

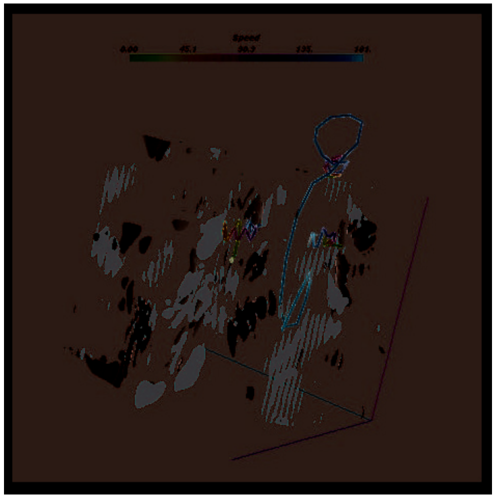




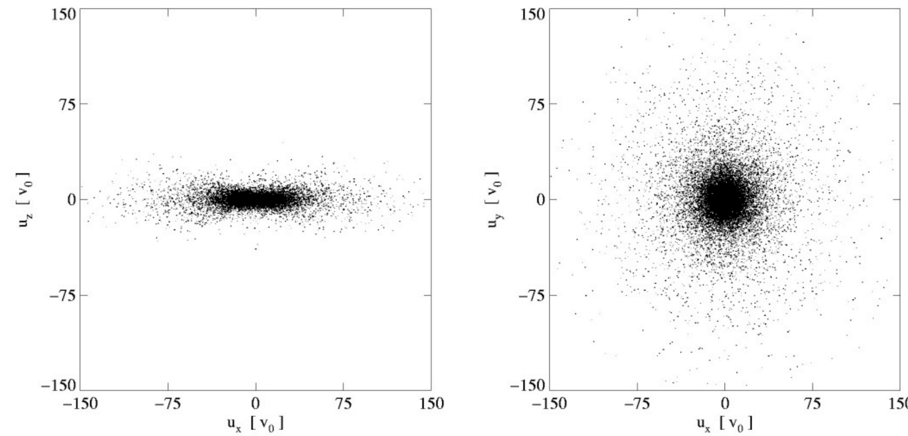
Spectral MHD simulation
t = 3

30 years of 1 hour SW data

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



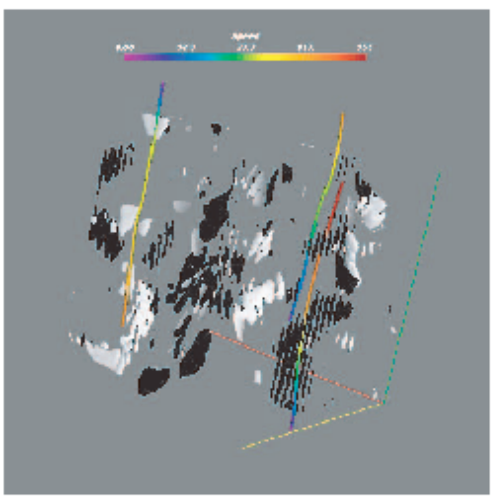
protons

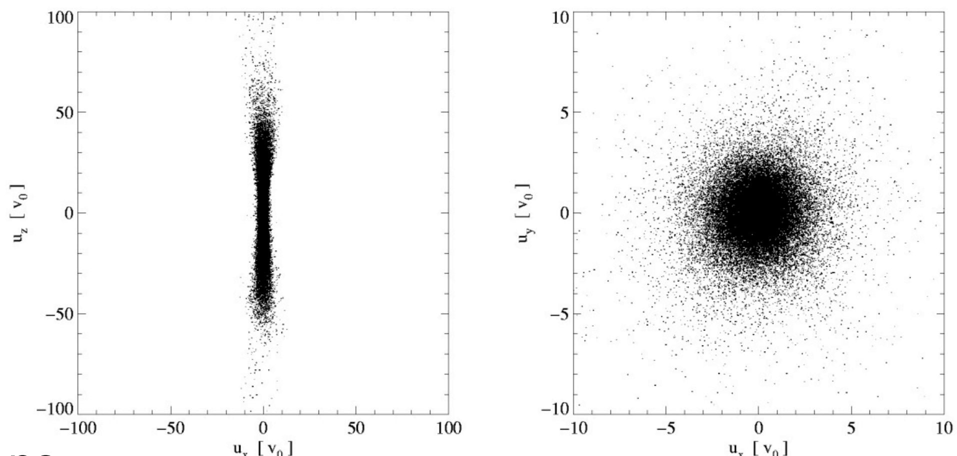


B_0 direction

perp plane

Trajectories and current structures



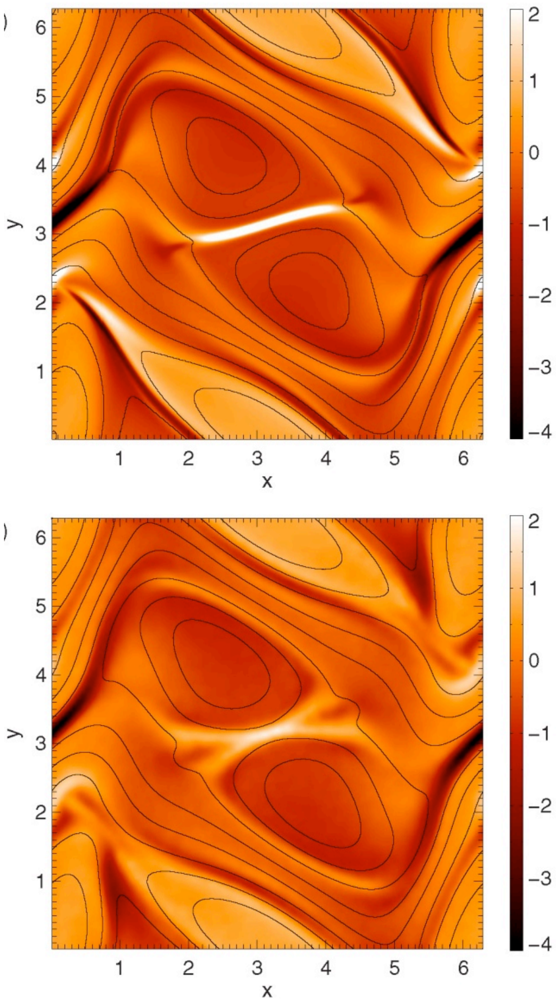


electrons

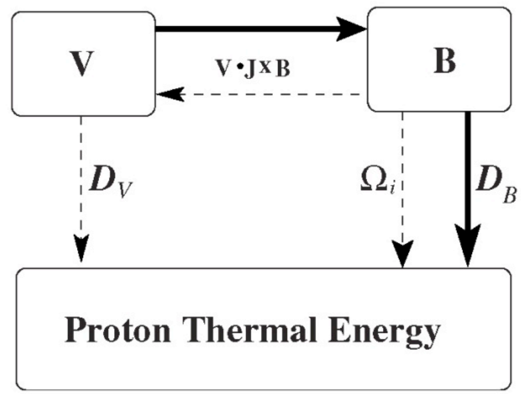
Dmitruk et al, 2004

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

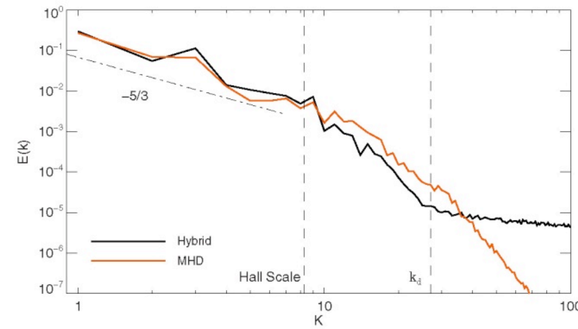
MHD and hybrid B, J



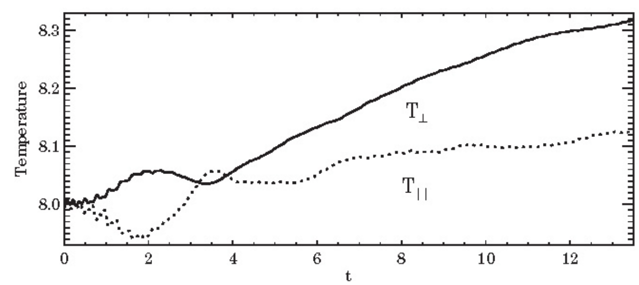
Energy flow



Spectra: MHD and hybrid



Perpendicular heating! (no standard cyclotron resonance)

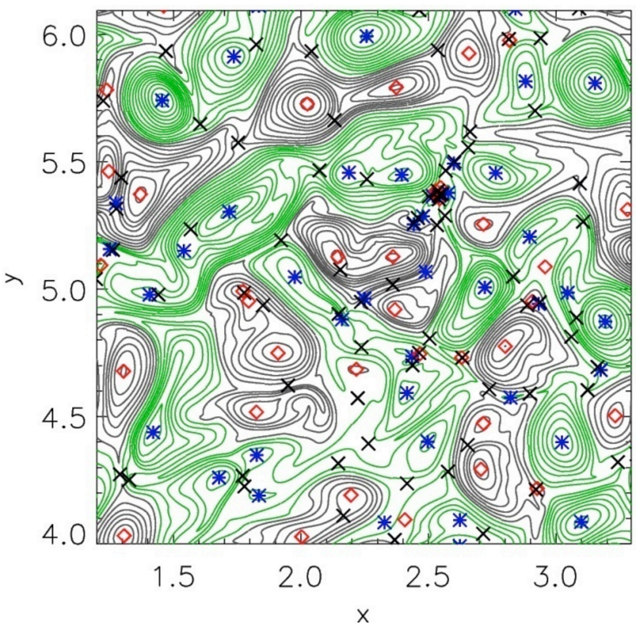


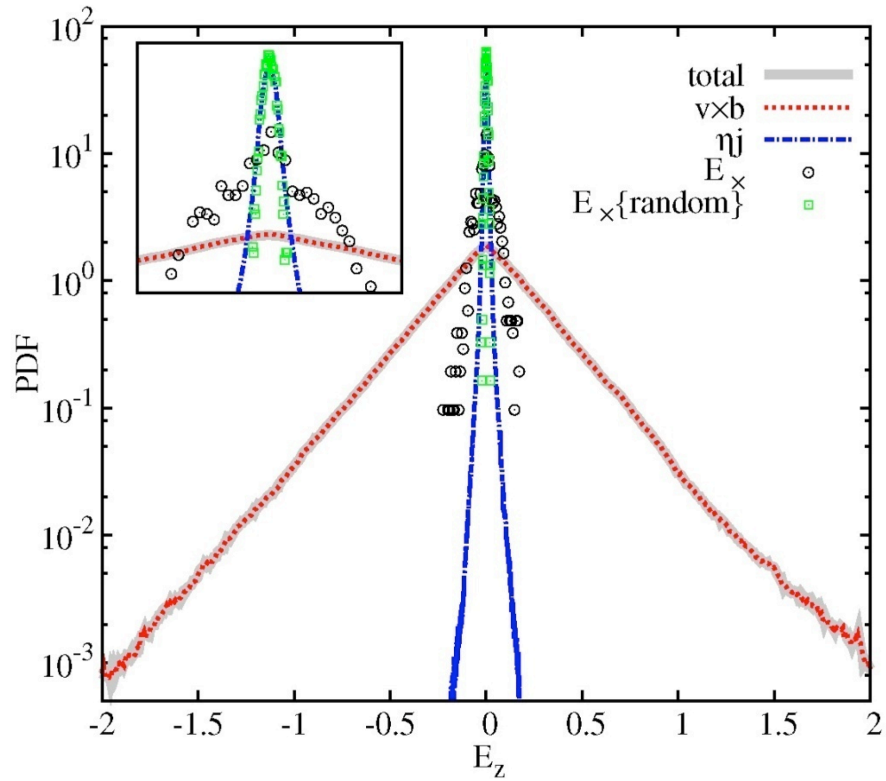
PHYSICS OF PLASMAS **16**, 032310 (2009)

Kinetic dissipation and anisotropic heating in a turbulent collisionless plasma

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

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!

Related issue: are there any kind of recognizable "waves" in turbulence?

Eulerian frequency spectra

- 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

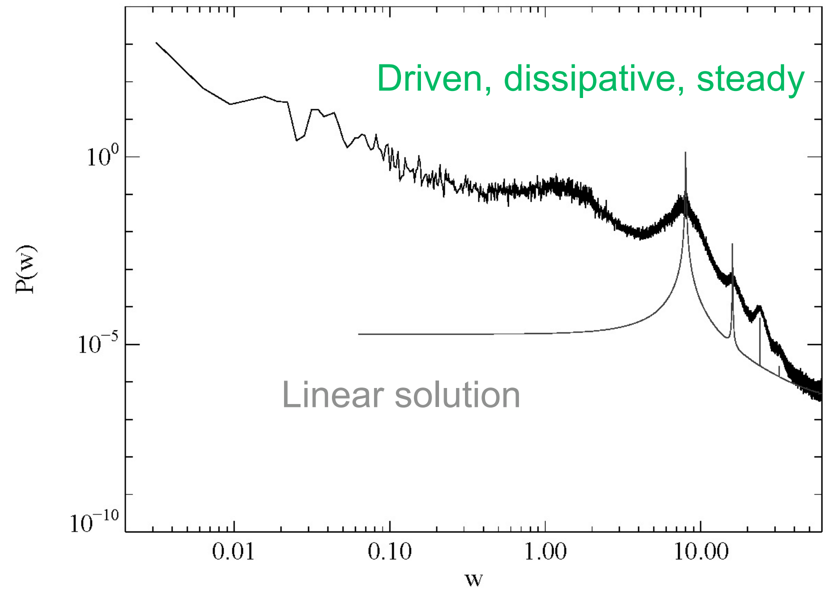
  – for *ANY* value of imposed magnetic field B0 !

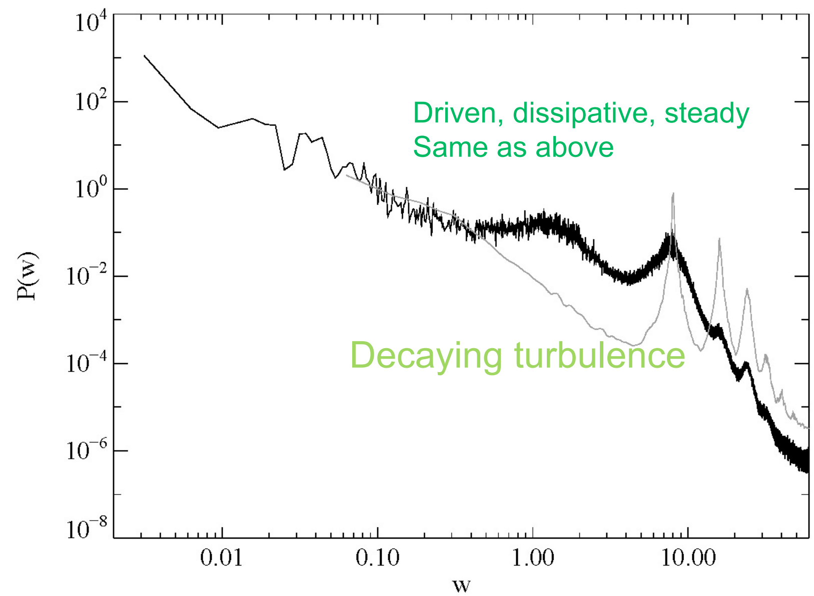
- Shown are Eulerian frequency spectra (one point) with B0=8, for :
  - driven steady case
  - decaying (energy renormalized) turbulence

- 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





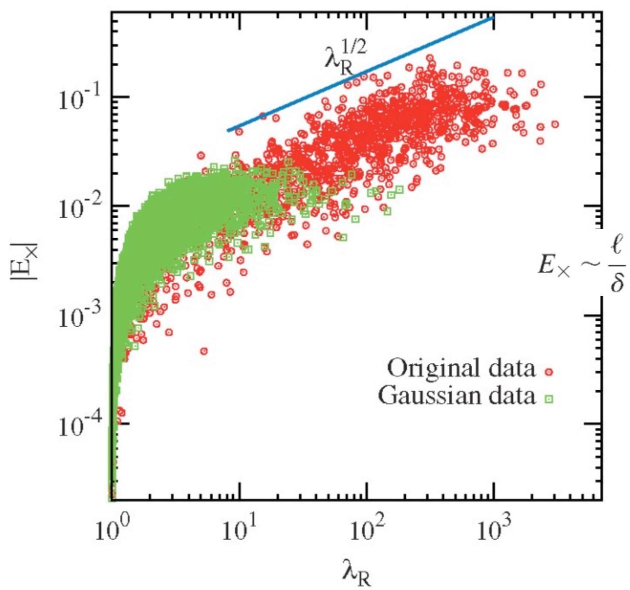
There are many outstanding issues/questions that need to be addressed using a broad range of methodologies and approaches:

- heating of the corona
- Distributed heating of the solar wind
- Origin of the kinetic signatures
- 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

(iv) Major payoff in understanding dissipation, coherent structures and acceleration: along with cascade, these link the system across wide ranges In space and time-scales

extras

Reconnection rates (X-point electric fields) in MHD turbulence

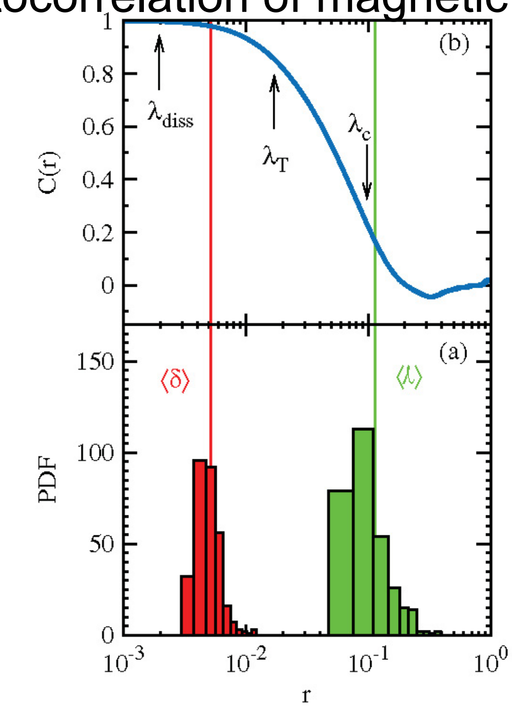


Distribution vs l/δ

(ASPECT RATIO
OF DIFFUSION REGION)

$$\lambda_R = (l/\delta)^2$$

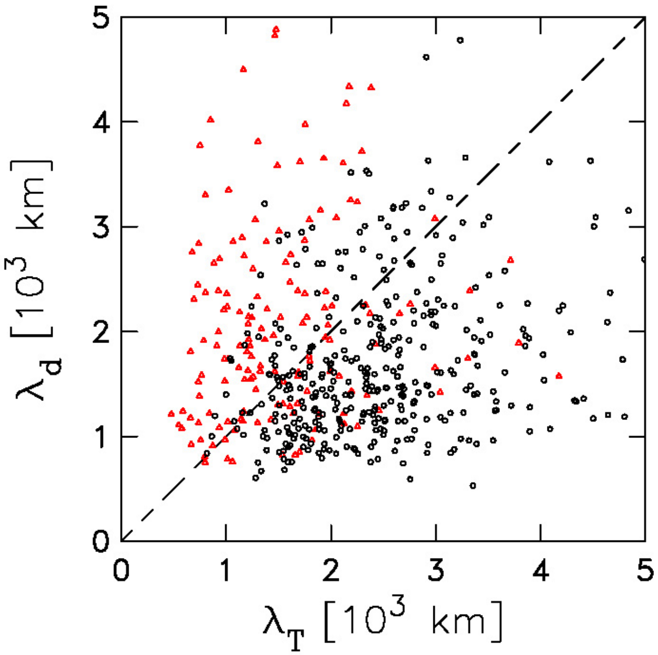
Distribution relative to
Autocorrelation of magnetic field



Thickness
between
Taylor and
dissipation
scales

Length ~
Distributed about
Correlation
scale

Dissipation scale and Taylor scales (ACE at 1 AU)



◊ $\lambda_T > \lambda_d$ cases are like hydro

→ $\lambda_T < \lambda_d$ *cannot* occur in hydro, it is a *plasma* effect.

Further study of the relationship between these curves may provide clues about *plasma dissipation*

clouds: red

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

- MHD phenomenologies: decay of Elsasser energi

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

- 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

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

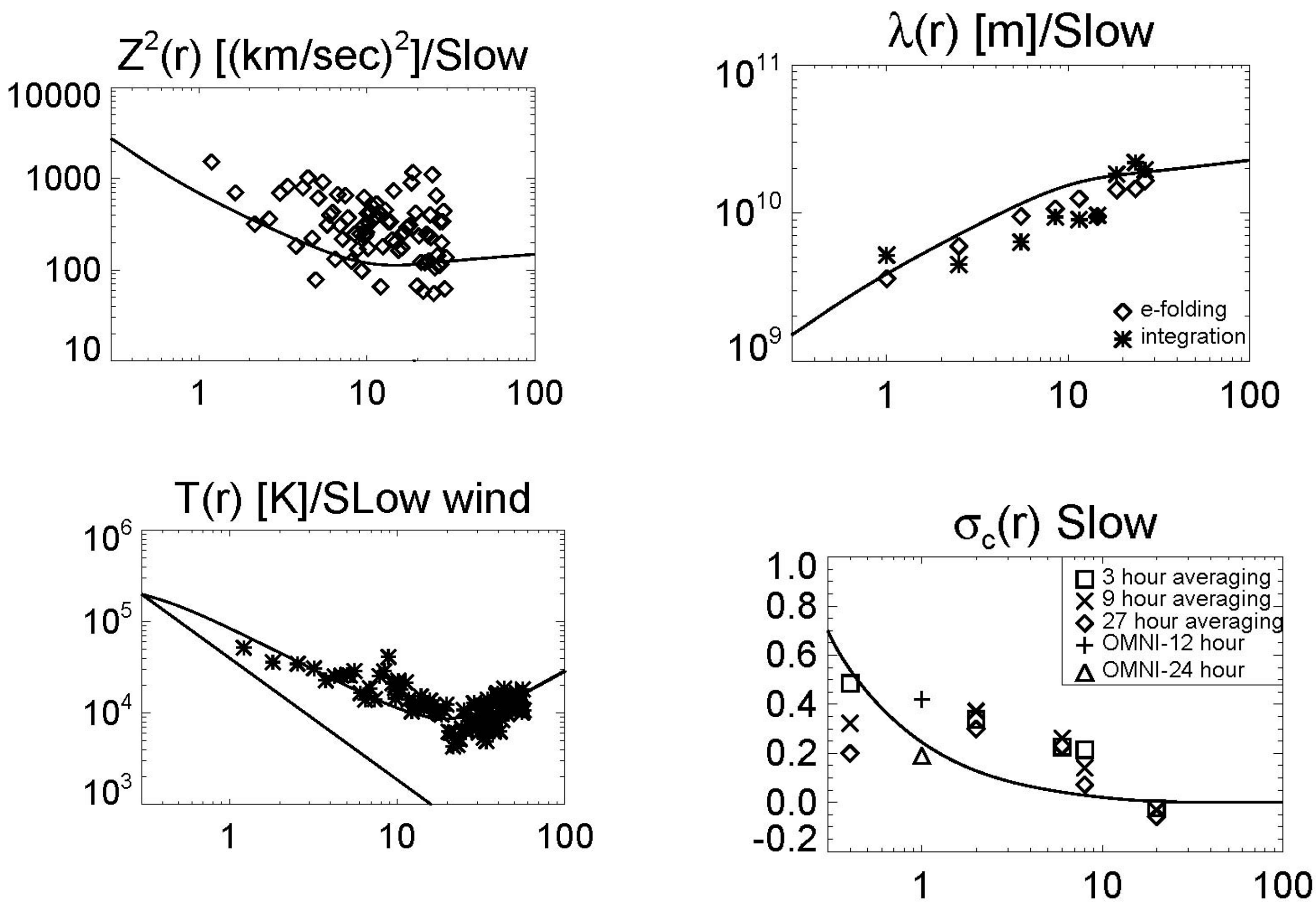
- But for ***similarity solution,*** one needs TWO LENGTH

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

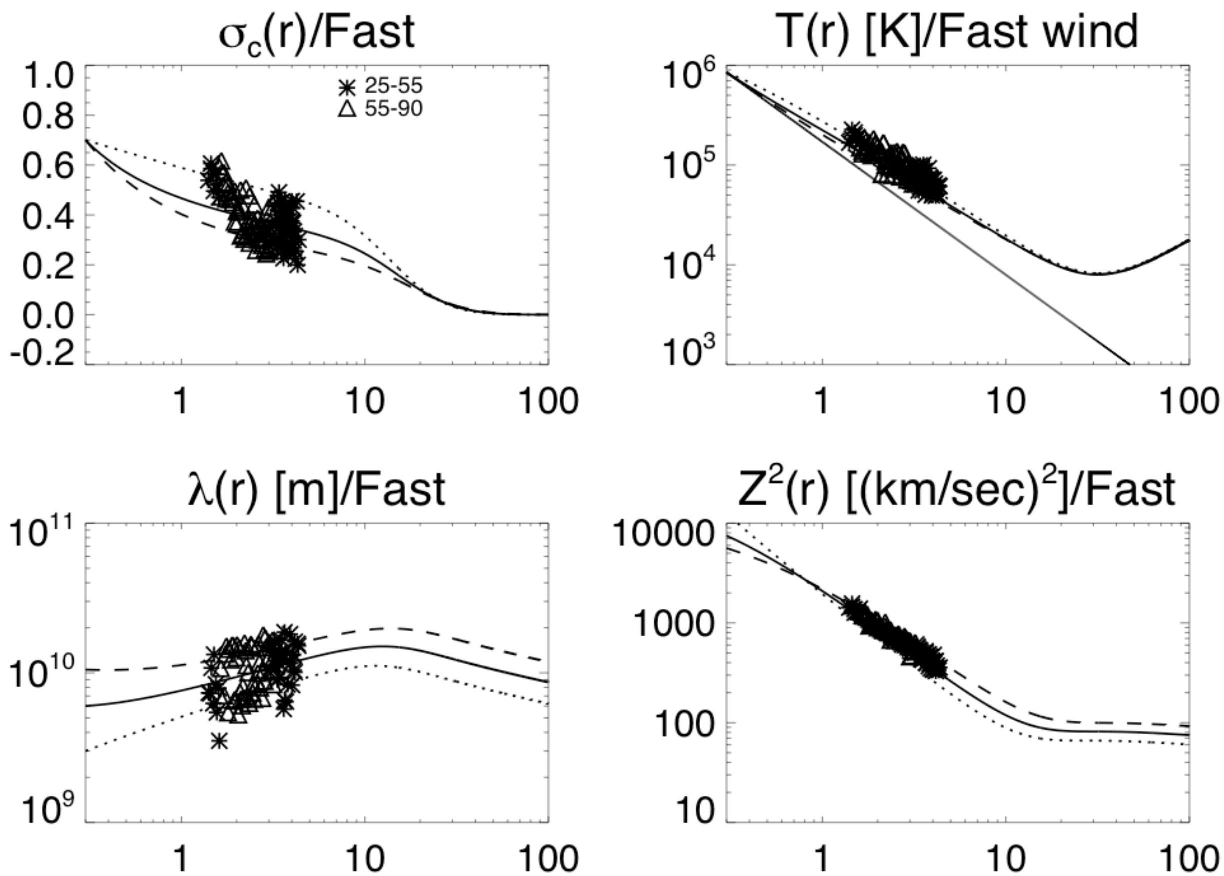
See Breech et al, 2008 and references therein; also Ng and Bhattacharjee, 2007

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.