Modern challenges in Nonlinear Plasma Physics
Solar and interplanetary plasmas – Summary

“ I am a friend of the accordion player, the student of Giuseppe Verdi ” (P. Cargill, L. Vlahos)

Coronal structure and non-linear dynamics: waves/turbulence

Beyond MHD: reconnection /acceleration/ wave-particle interactions.

Coherent Structures, instability and CMEs

Priest - NL plasma physics in the Corona:

*** Fundamental aspects plasma physics** --

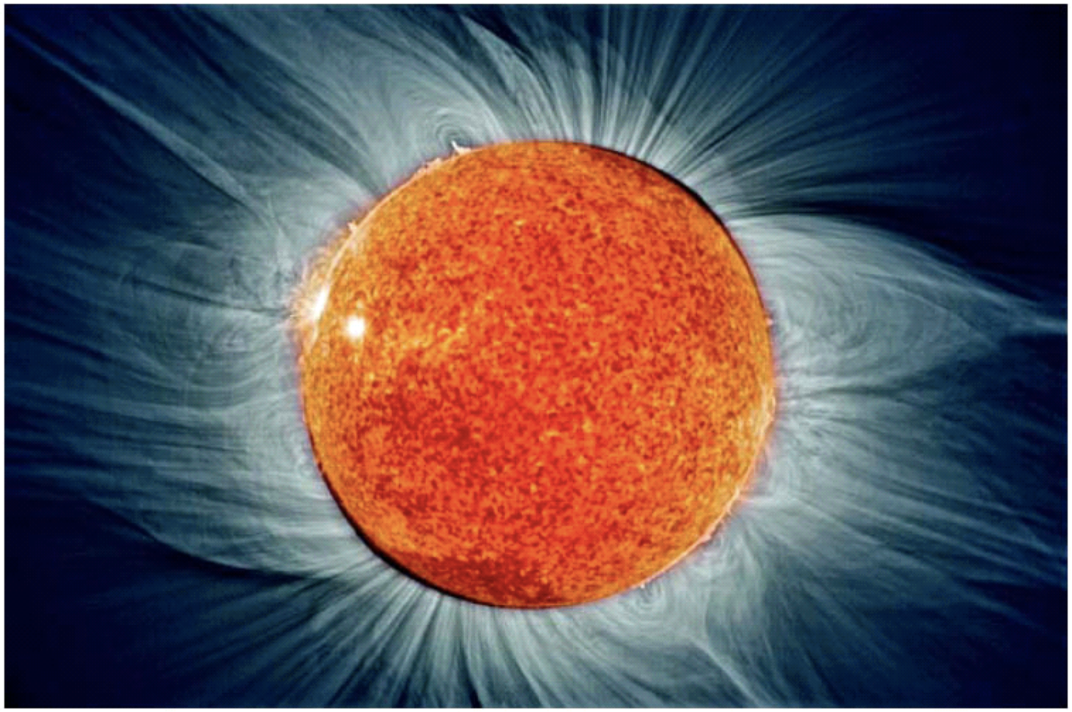
Particle acceleration, shock waves, instabilities, waves, reconnection

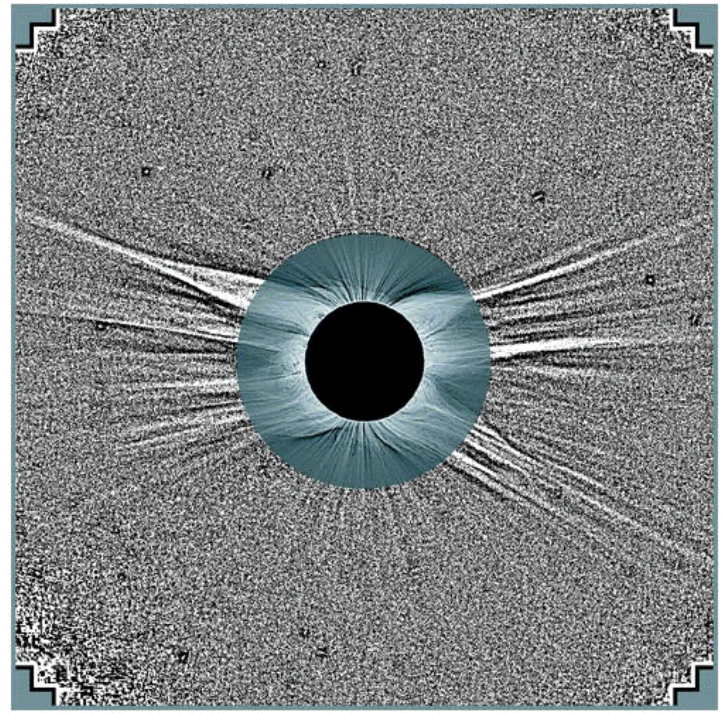
*** Subtle coupling:**

macroscopics (MHD) <----->
microscopics (kinetic plasma physics)

* MHD: global environment --
Microscopics --
transport coefficients & particle acceleration

Coronal fine structure and its evolution into the solar wind



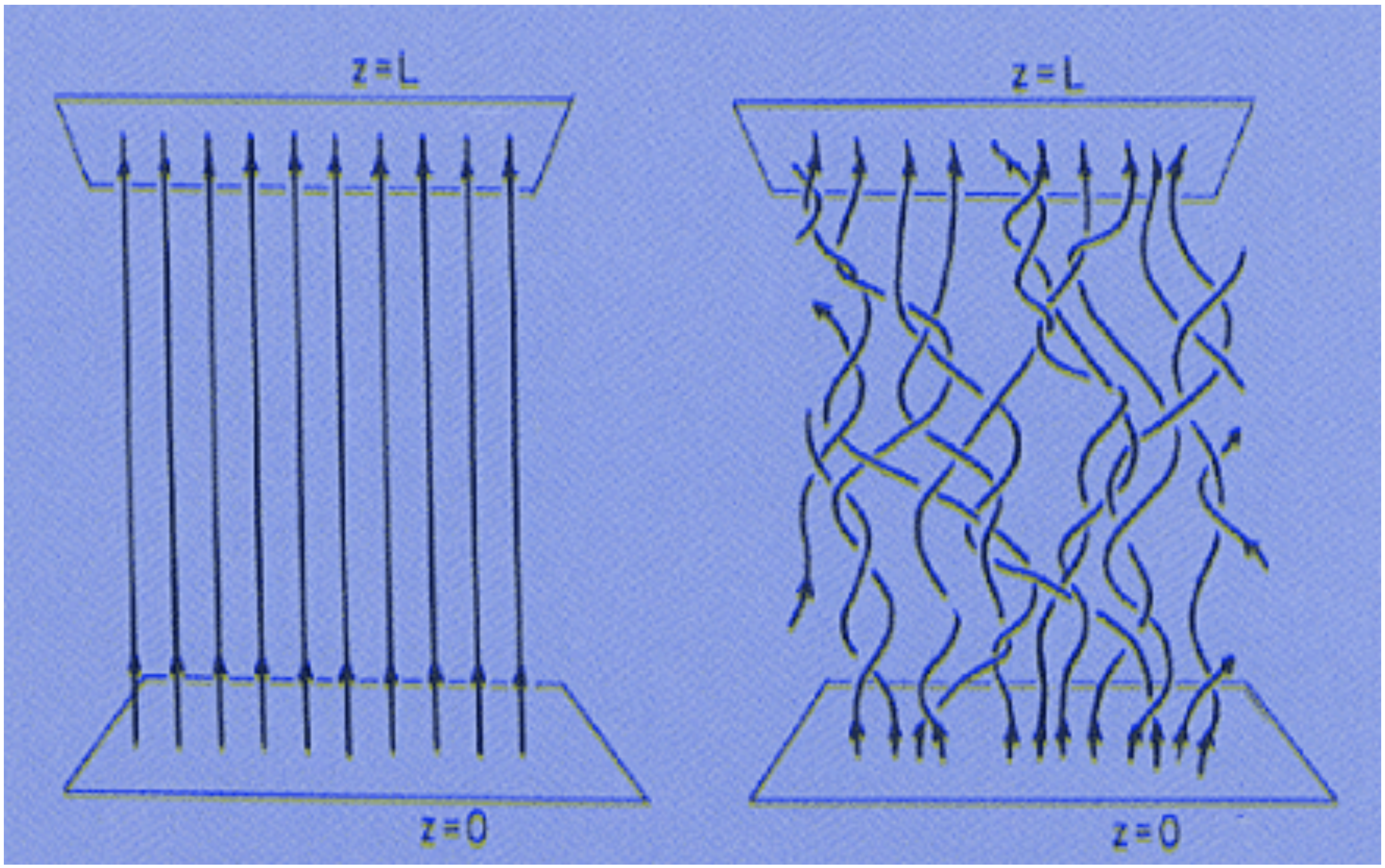


(a) White light eclipse 2007 March 29 corona made by a 1600 mm telescope in Libya and *SOHO EIT He II (30.4 nm). The resolution of the image is 1-2” and its effective* wavelength within 400 - 650 nm. (b) Edge-enhanced Druckmüller-Aniol eclipse picture Lybia, 2006, cropped at r 1/4 2:2 Rs joined to a LASCO C2 image recorded at 10:46 UT. An unsharp mask has been applied to the LASCO white-light image by subtracting from it a smoothed version of itself. Image rotated about 30o cc compared to (a), From Pasachoff et al. (2007) andWang et al. (2007).

Coronal Heating Models

Parker's classical Nanoflare Model

by braiding (1972)

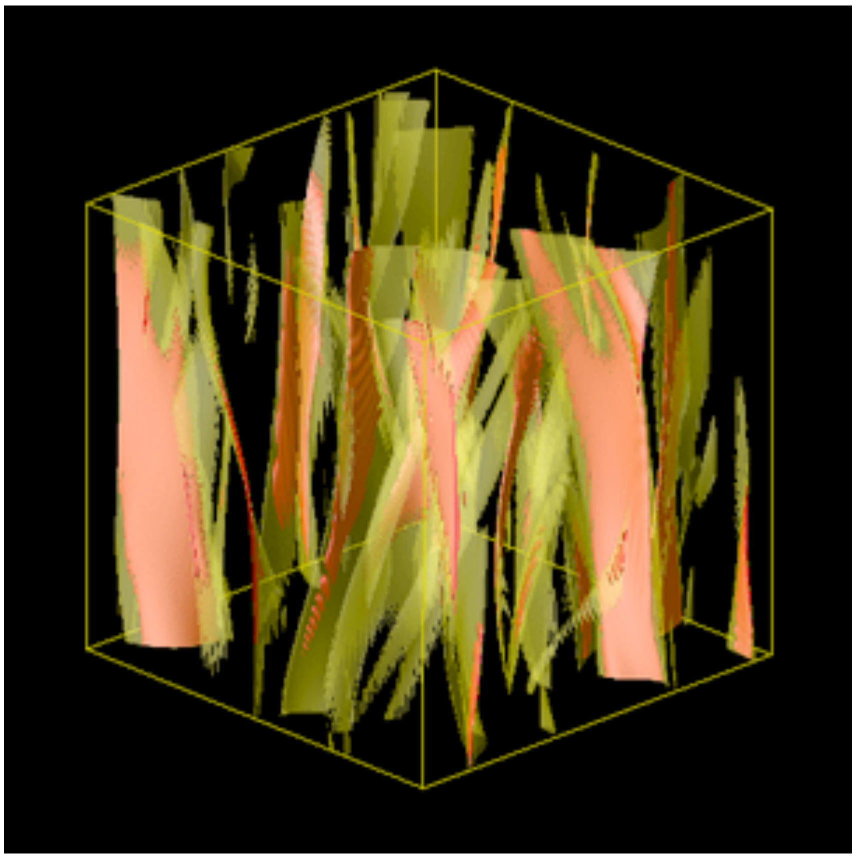


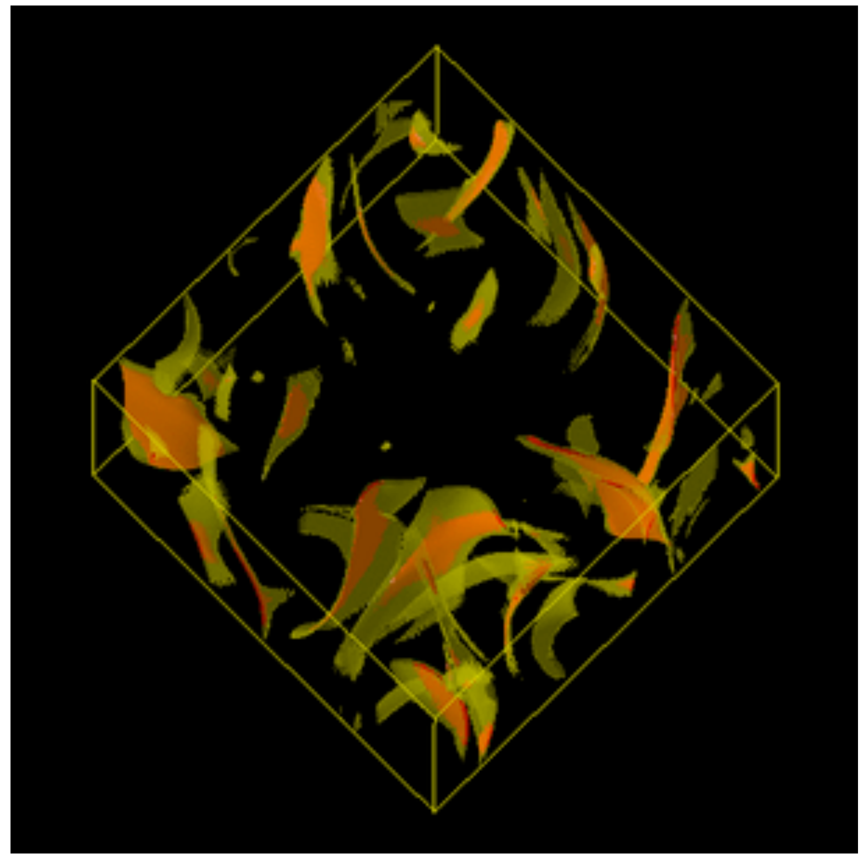
Initial B uniform / motions braiding

Full RMHD simulations

J^2/R

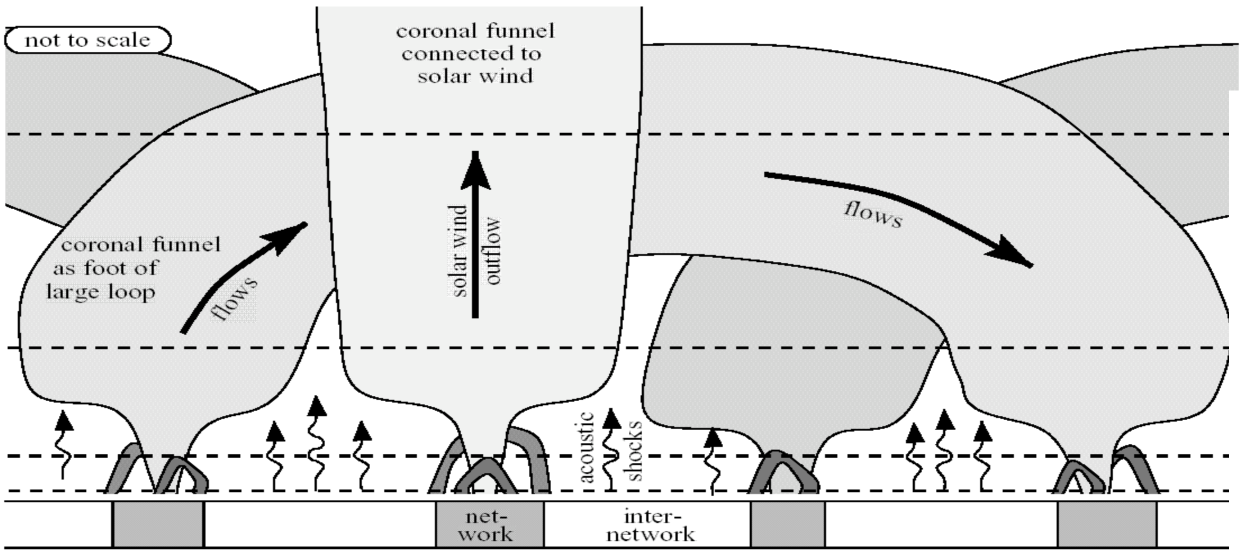
Red = 1000   Yellow = 350   Max = 2.7×10^4 min = 0



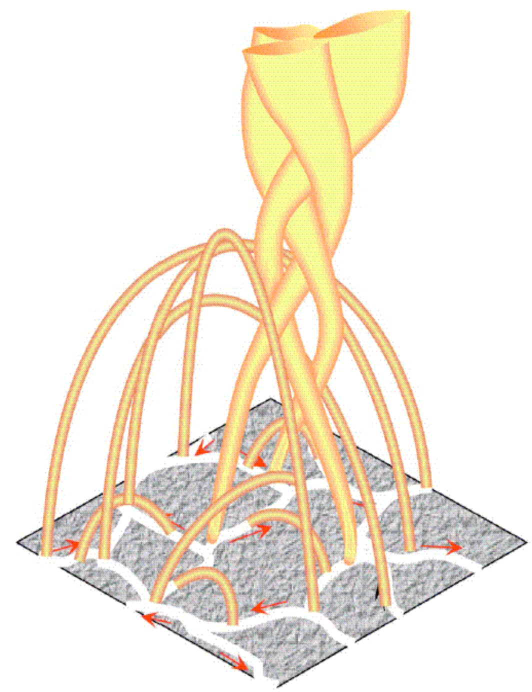


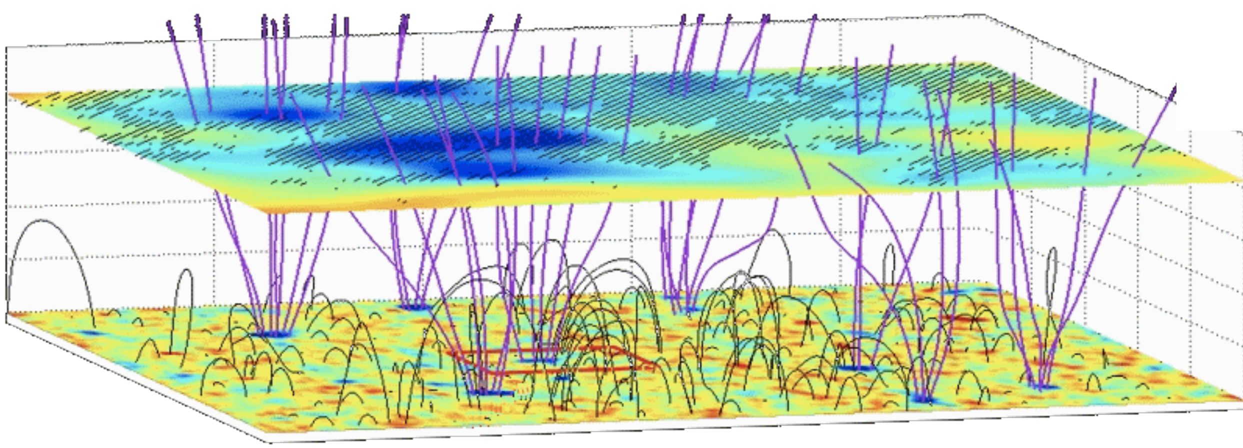
Boundary layer at the Coronal Base

Peter (2001)



Fisk (2005)





Tu et al. (2005)

From observed magnetograms - construct coronal field lines

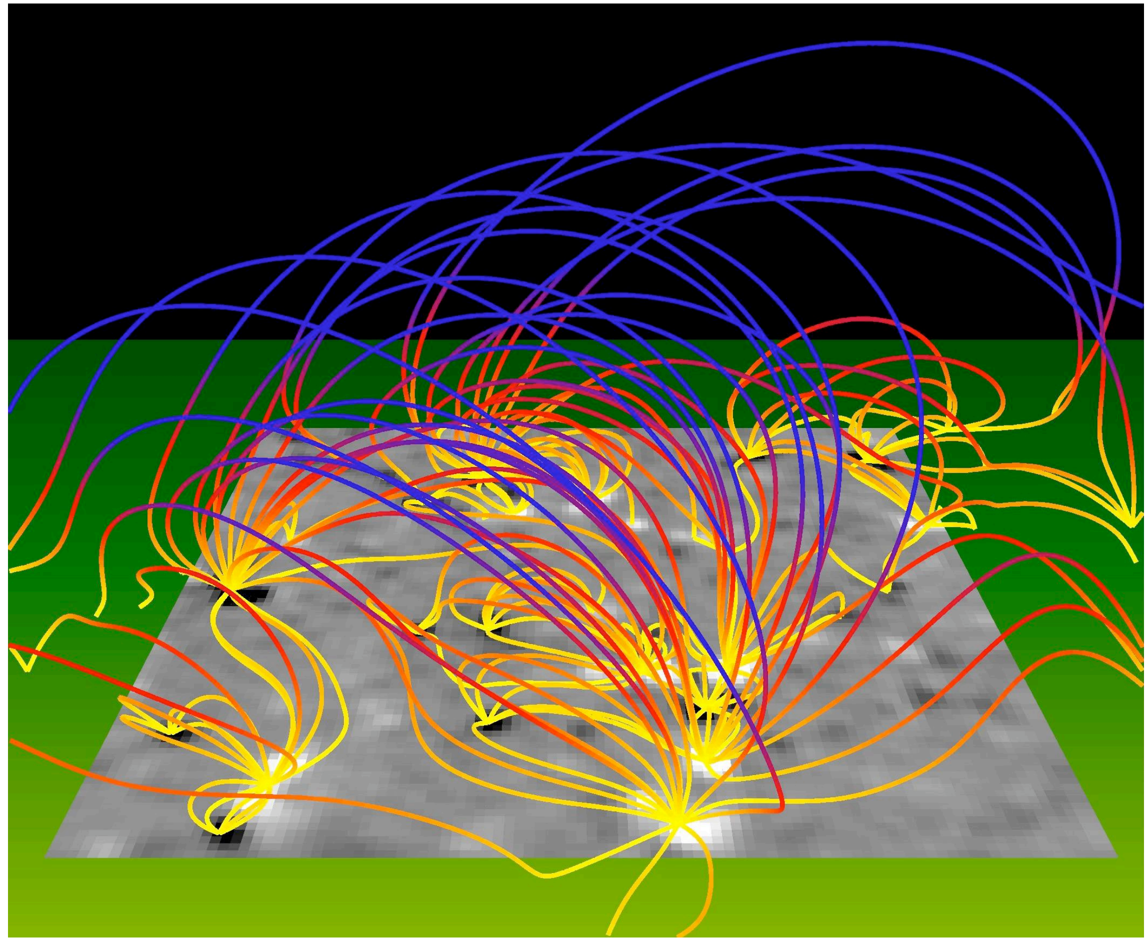
- each source connects to 8 others

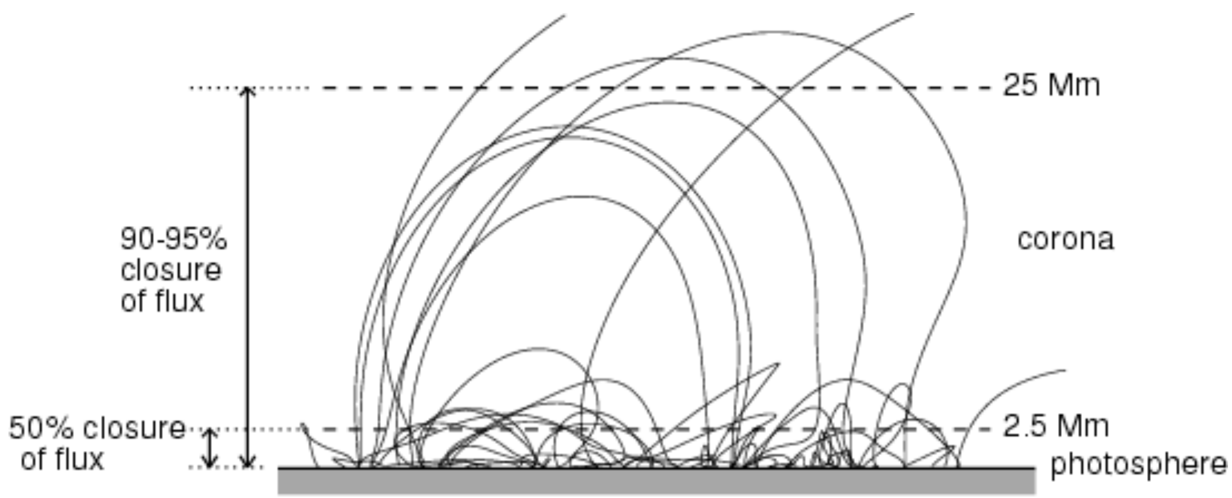
Time for all field lines to reconnect **only 1.5 hours**

→ more complexity & heating low down

? describe structure

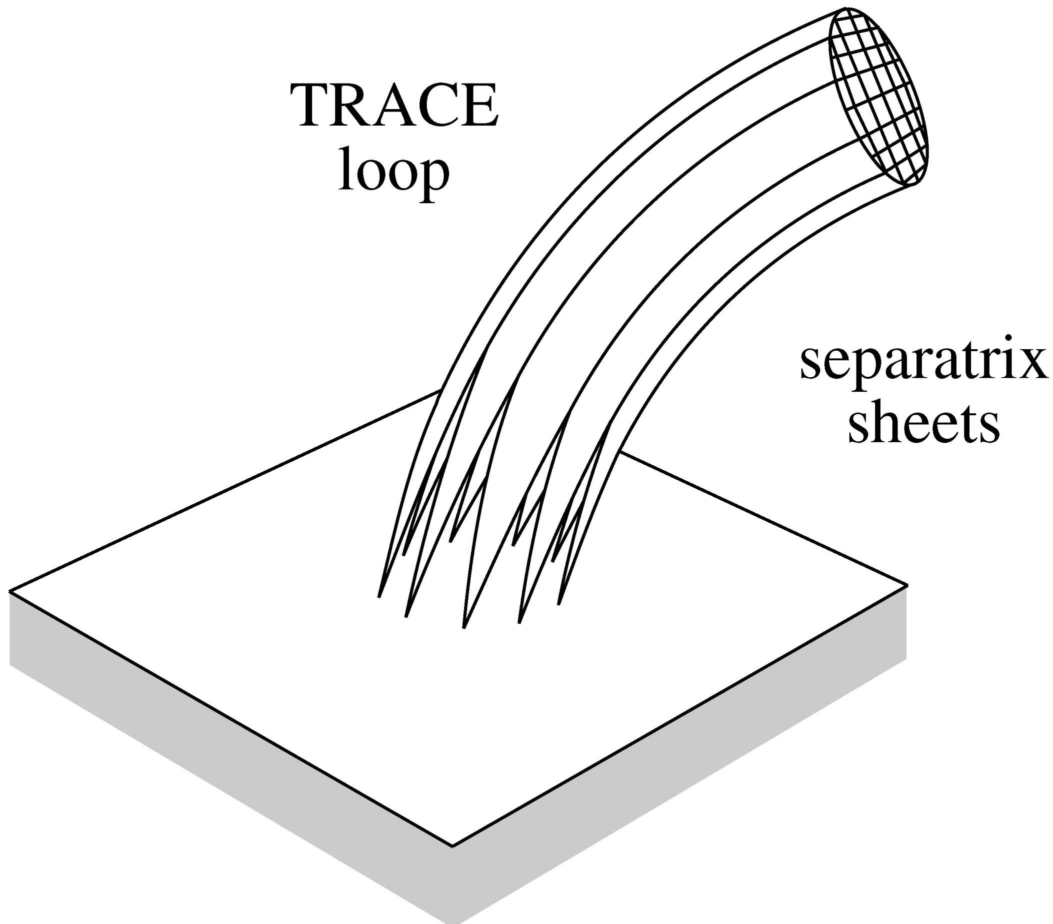
? nature of reconn^n





TRACE Loop

Reaches to surface in many footpoints.



Separatrices form web in corona

Conclusions for turbulence models:

Numerical simulations of the Parker scenario are beginning to shed light on some features of forced MHD turbulence. The scenario may apply to localized regions of the quiet sun or active regions, where a global confining field is present.

It has also been applied recently (Dmitruk et al. 2000) to open field line regions where reflections from gradients act as a confining cavity….but RMHD breaks down?

Numbers are not bad: 2 10^5 erg/cm^2/s

Dissipation, must quite generally, involve kinetic effects, since the E-fields required for this dissipation are 7 orders of magnitude greater than the Dreicer field

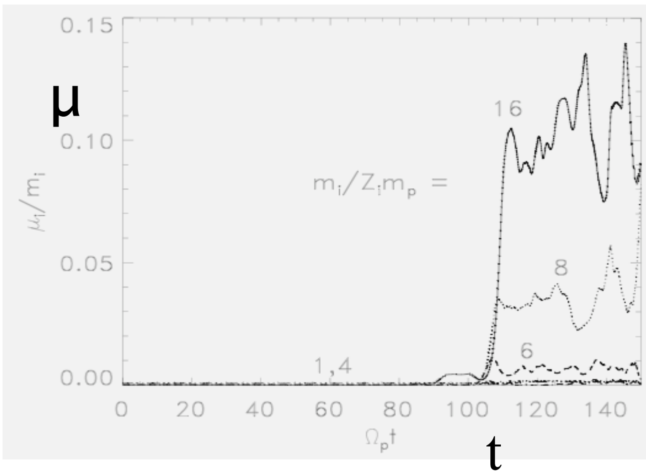
The value of the Dreicer electric field for typical values of coronal plasma parameters $n=10^9$ cm^{-3}, $T=10^6$ K (the Coulomb logarithm L~20) is $E_D=10^{-7}$ statvolt/cm [Mangeney 1999].

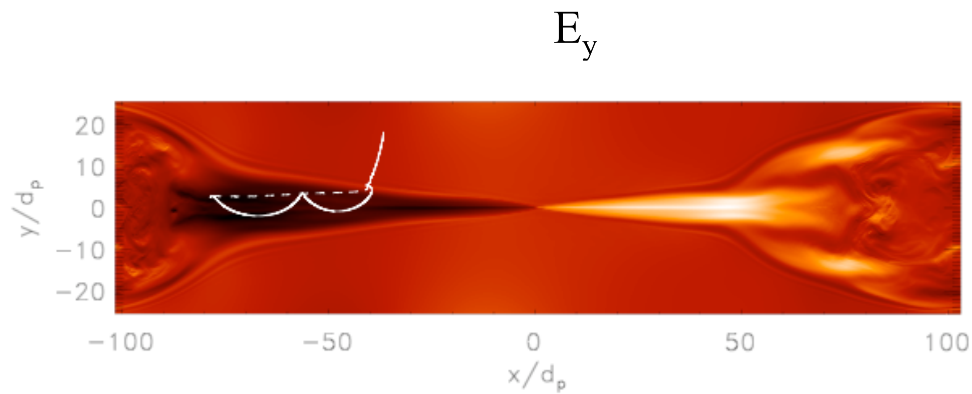
Average heat flux, lost F ~ 10^6 $erg/cm^2/sec$, E=h j. height H and surface S the volumetric heating rate is then e = F/H implying that $h j^2 f= e$ where f is a filling factor giving the fraction of the volume over which currents effectively dissipate.

Observations ofvery fine scale structure in the corona would seem to indicate that it must be fairly small, say f~ 0.1. Then

$E = h j =(he/f)^{1/2}$. Taking a volume of height 10^5 km and typical coronal values for the resistivity, one obtains E~ 1 statvolt/cm……

J. Drake Particle acceleration during magnetic reconnection Pickup threshold: guide field





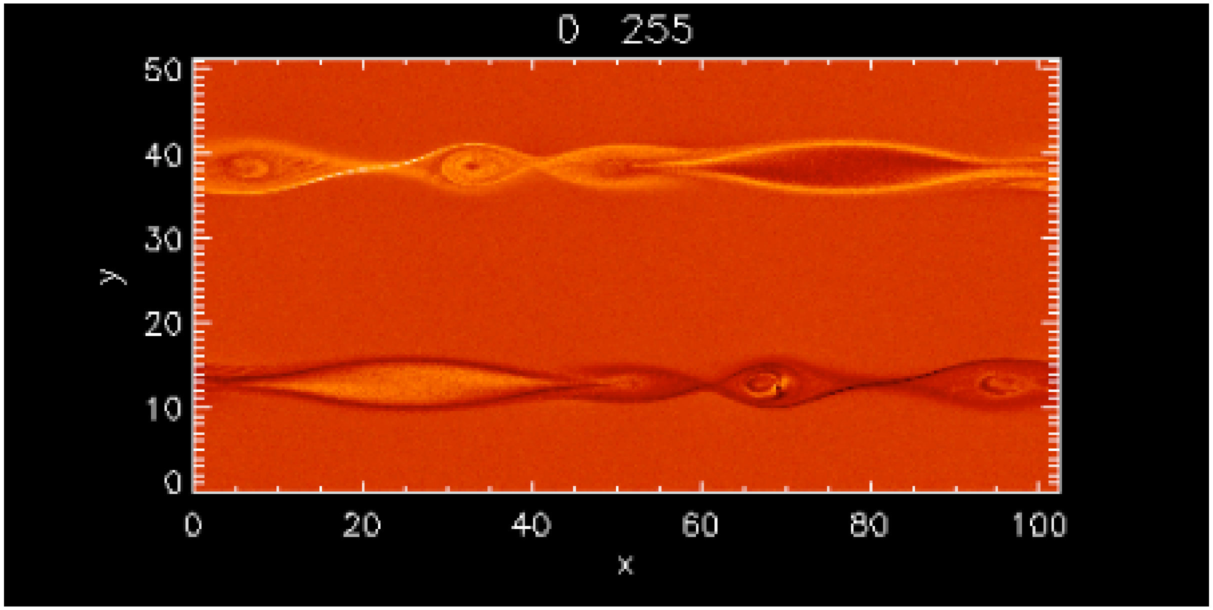
$B_{z0} = 5.0$

- Protons and alpha particles remain adiabatic (μ is conserved)
- Only particles behave like pickup particles gain significant energy ⇒ threshold for pickup behavior

$$\frac{v_{iy}}{\Delta} \approx \frac{0.1 c_{Apx}}{\rho_{sp}} > \Omega_i \Rightarrow \frac{m_i}{Z_i m_p} > 10 \frac{c_{ps}}{c_{Apx}}$$

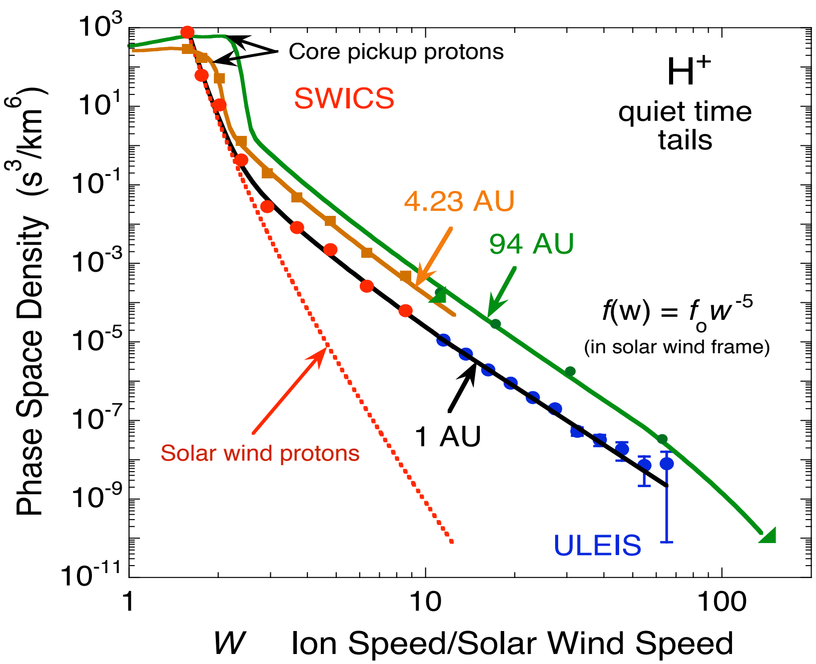
For a given ion mass and charge this is a threshold in the reconnecting magnetic field B_x

A multi-island acceleration model



- A single x-line line model can not explain the high fraction of energy going into electrons and ions in flares
  - Parallel electric fields are strongly localized around the x-line -- energetically unimportant
- Narrow current layers spawn multiple magnetic islands in reconnection with a guide field
  - Must abandon the classical single x-line picture!!

Universal super-Alfvenic ion spectrum in the quiet solar wind



Fisk and Gloeckler, 2006

- Proton spectra of the form f v^{-5} are observed throughout the heliosphere

Conclusions

• High energy particle production during magnetic reconnection involves the interaction with many magnetic islands

– Not a single x-line

• Ion interaction with the reconnection exhaust seeds them to super-Alfvenic velocities.

– Ions that act as pickup particles as they enter reconnection exhausts gain most energy

• M/Q threshold for pickup behavior

• Gain a thermal velocity given by the Alfven speed

• Wind and ACE observations support this picture

• Interaction with reconnection exhausts should enable energetic ions to be accelerated through Fermi contraction

• M/Q threshold for pickup behavior is a possible explantation of impulsive flare heavy ion abundance enhancements

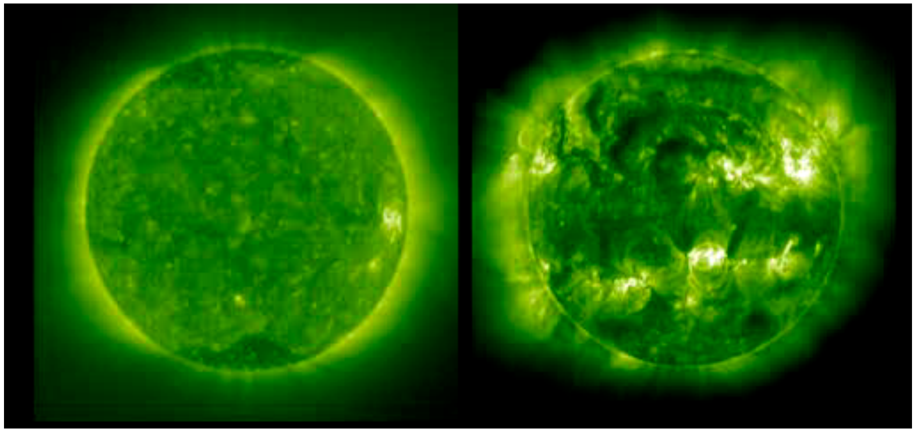
Conclusions (cont.)

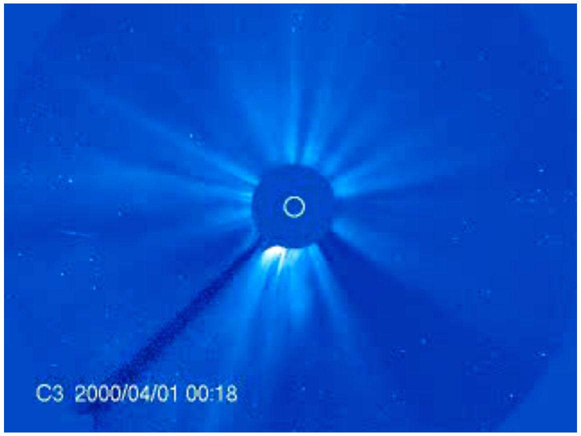
- The sectored heliospheric field is compressed as it approaches the heliopause
  – Collisionless reconnection inevitably onsets and dissipates the sectored field energy
- Enormous reservoir of energy
- Preferential heating of pickup particles
- Efficient heating of pickup ions through magnetic island contraction
  – Balance of contraction drive and convective loss yields powerlaw solutions
  – Spectral indices are controlled by the approach to firehose stability
- Minority ions have similar spectra to the main He and H
- Background protons are strongly heated and have spectra similar to those seen by Fisk/Gloeckler

The solar wind as a turbulence laboratory (S. Chapman)

SOHO-EIT image of the corona
at solar minimum and solar maximum

SOHO- LASCO image
of the outer corona
near solar maximum





I: coronal signature has scaling properties
II: solar wind has intermittent (multifractal) inertial range of turbulence
III: in-situ observations span inertial range,
dissipation/dispersion range and lower k

Multifractal inertial range turbulence- examples

$$S_p = <| x(t+\tau) - x(t) |^p > \sim \tau^{\xi(p)}, \text{ plot } \log(S_p) \text{ vz. } \log(\tau) \text{ to obtain } \xi(p)$$

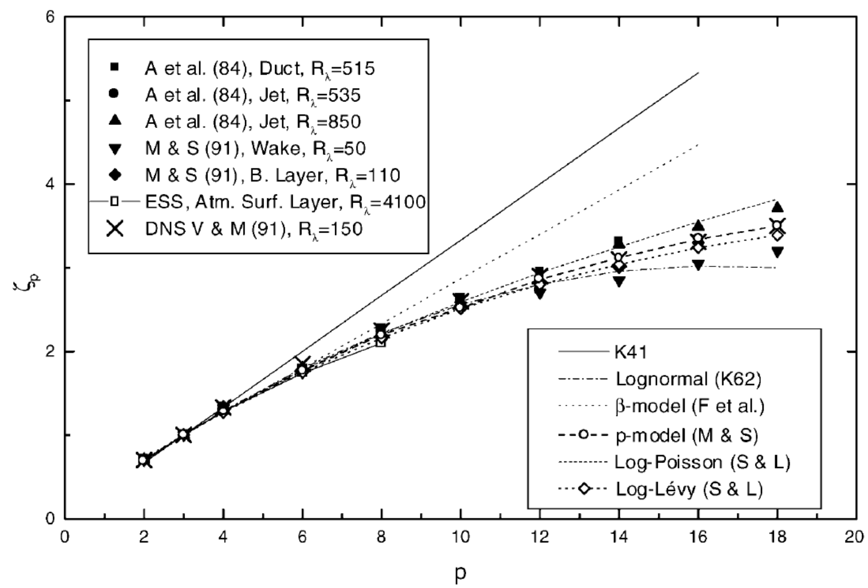
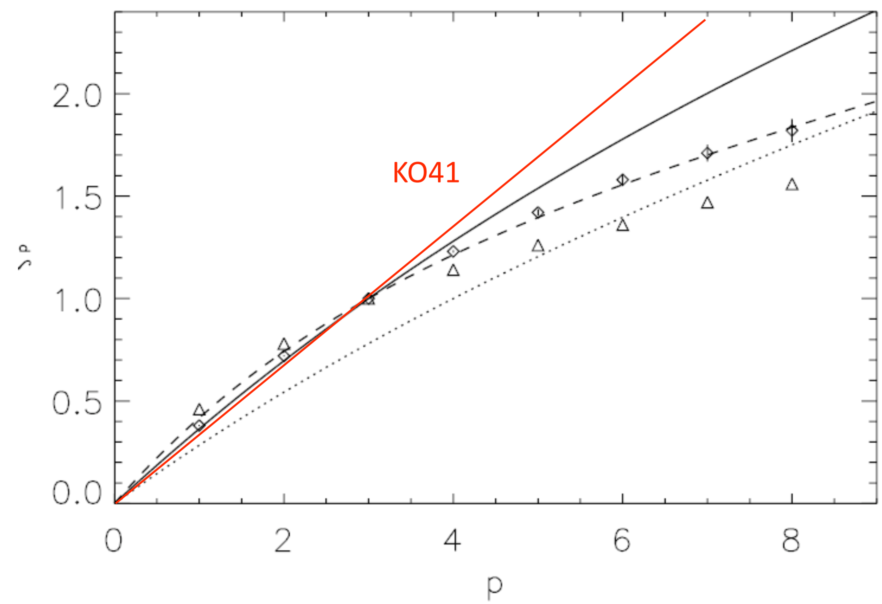


Fig. 11. Power-law exponents ζ_p of the structure functions as a function of the order p, together with the values predicted by K41 and the various intermittency models of Table 1.



IG. 4. Scaling exponents ζ_p^+ for 3D MHD turbulence (dia-ıonds) and relative exponents ζ_p^+/ζ_3^+ for 2D MHD turbulence riangles). The continuous curve is the She-Leveque model ζ_p^{SL}, the dashed curve the modified model ζ_p^{MHD} (7), and the dotted line the IK model ζ_p^{IK}.

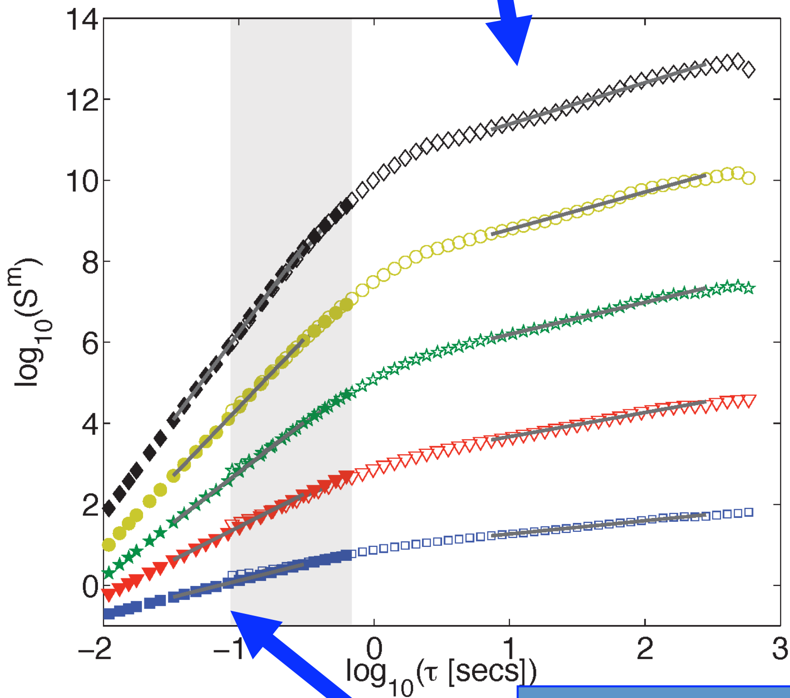
Lab Fluid experiments,
Anselmet et al, PSS, 2001

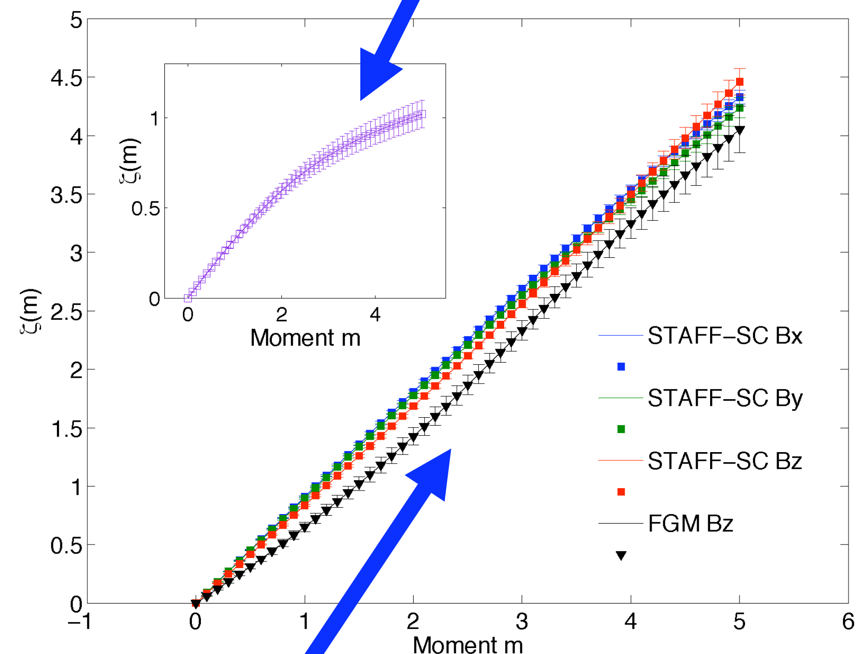
2 and 3D MHD simulations
Muller & Biskamp PRL 2000

How large can we take p? *See eg Dudok De Wit, PRE, 2004*

$$S_p = \langle | x(t+\tau) - x(t) |^p \rangle \sim \tau^{\xi(p)}, \text{ plot } \log(S_p) \text{ vz. } \log(\tau) \text{ to obtain } \xi(p)$$

Inertial range- multifractal



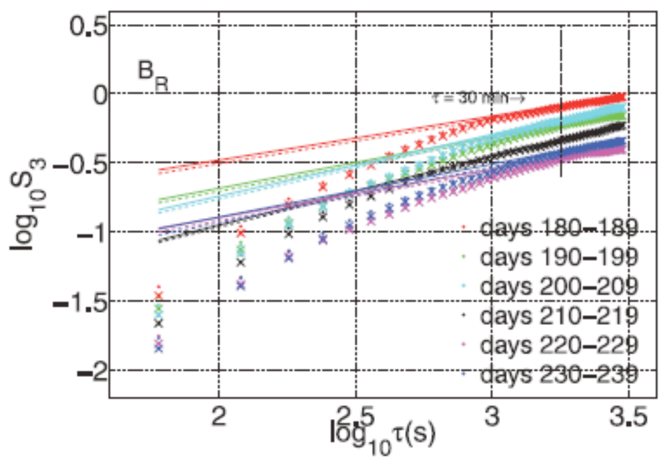


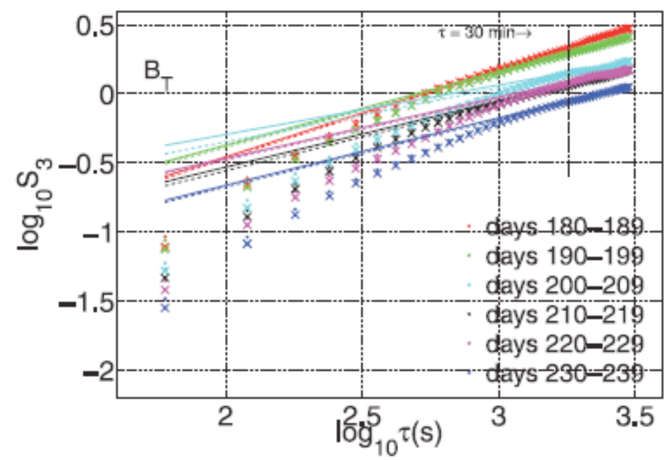
Dissipation range- fractal

CLUSTER STAFF and FGM shown overlaid.

Kiyani, SCC et al PRL submitted 2009

Evolving turbulence-
Quiet, fast polar solar wind: 1995 North polar pass, solar min, ULYSSES





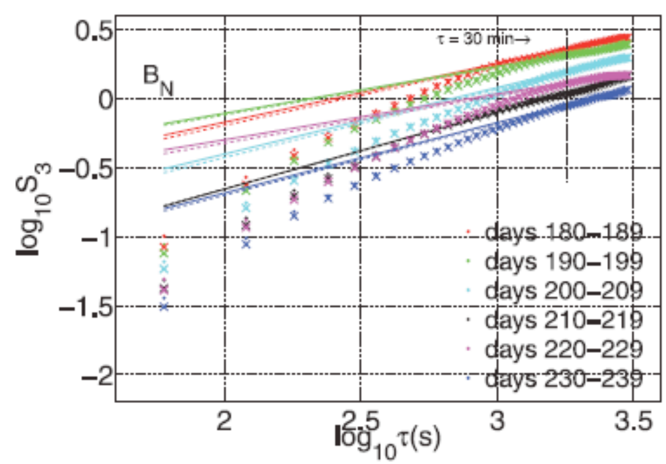
IR turbulence- expect

$S_3 \sim \boldsymbol{\tau}^{\xi(3)}$

i.e. straight line on log-log plot

not quite seen here!

$1/f$ is actually $1/f^{\gamma}$



Nicol, SCC et al ApJ 2008, SCC et al, ApJL 2009

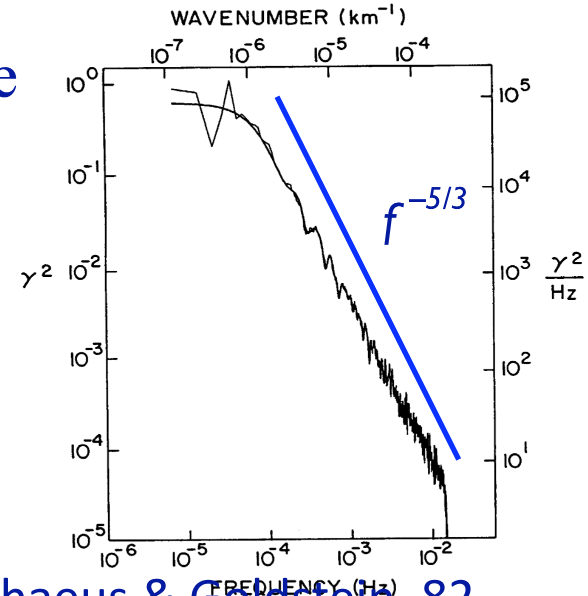
F. Sahraoui Solar wind turbulence

High resolution Cluster data to analyze small scale SW turbulence

A new inertial range below ρ_i

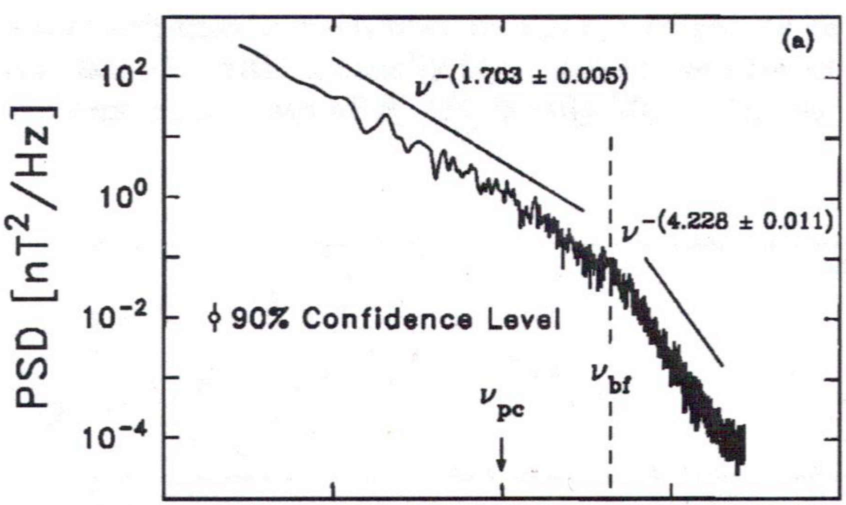
1. *First evidence of a dissipation range @ ρ_e*
3 *(KAW turbulence*

What happens to the energy at and below the ion scale ?



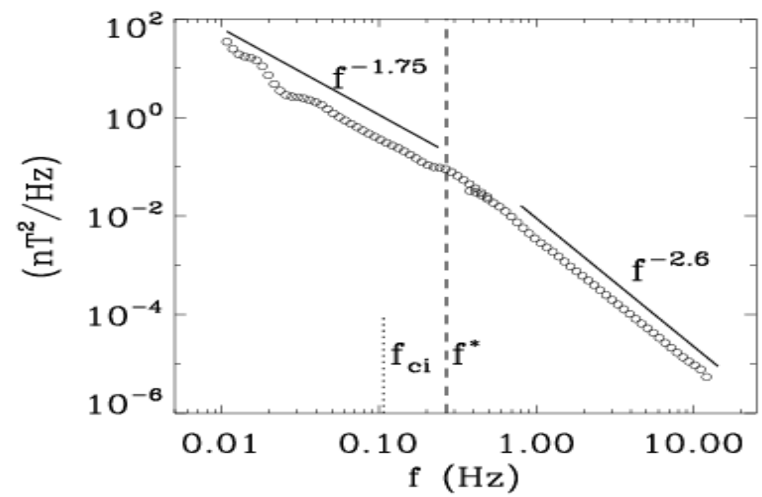
Matthaeus & Goldstein, 82

Dissipation at f_{ci} (or ρ_i)



Leamon *et al.* 98; Goldstein *et al.* JGR, 94

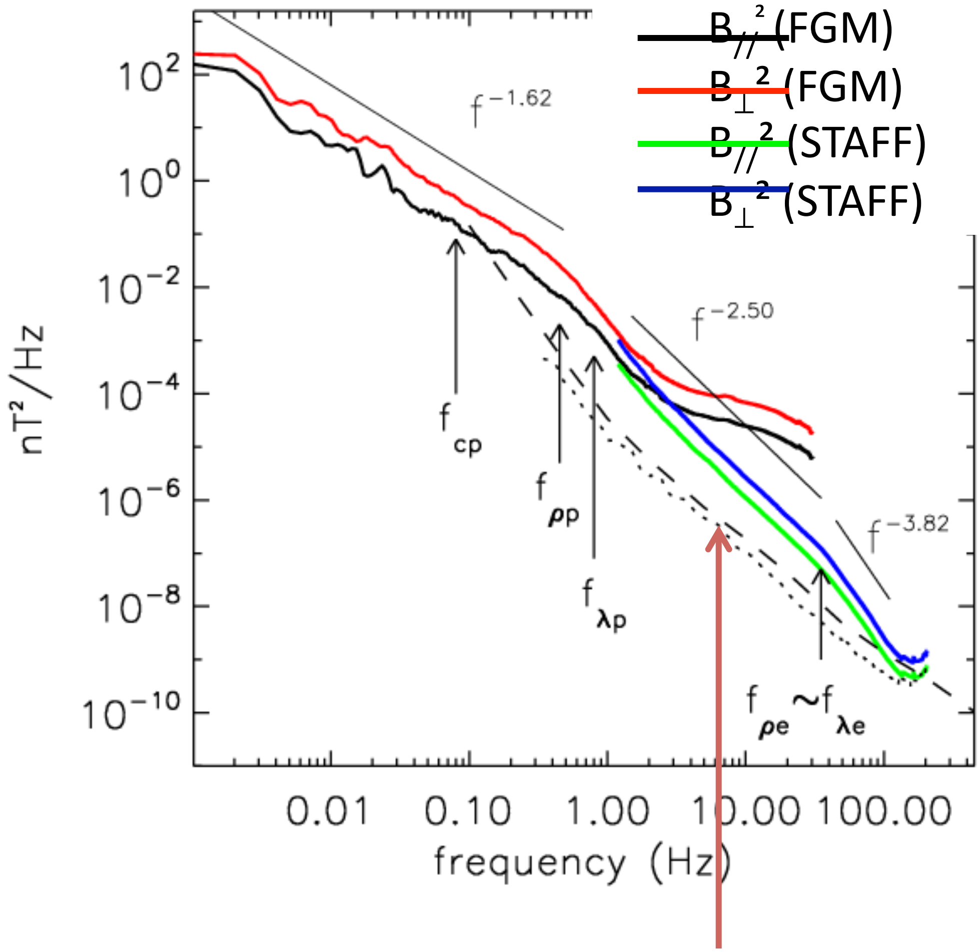
Cascade below f_{ci} (or ρ_i)



Alexandrova *et al.*, 08, Bale *et al.*, 05

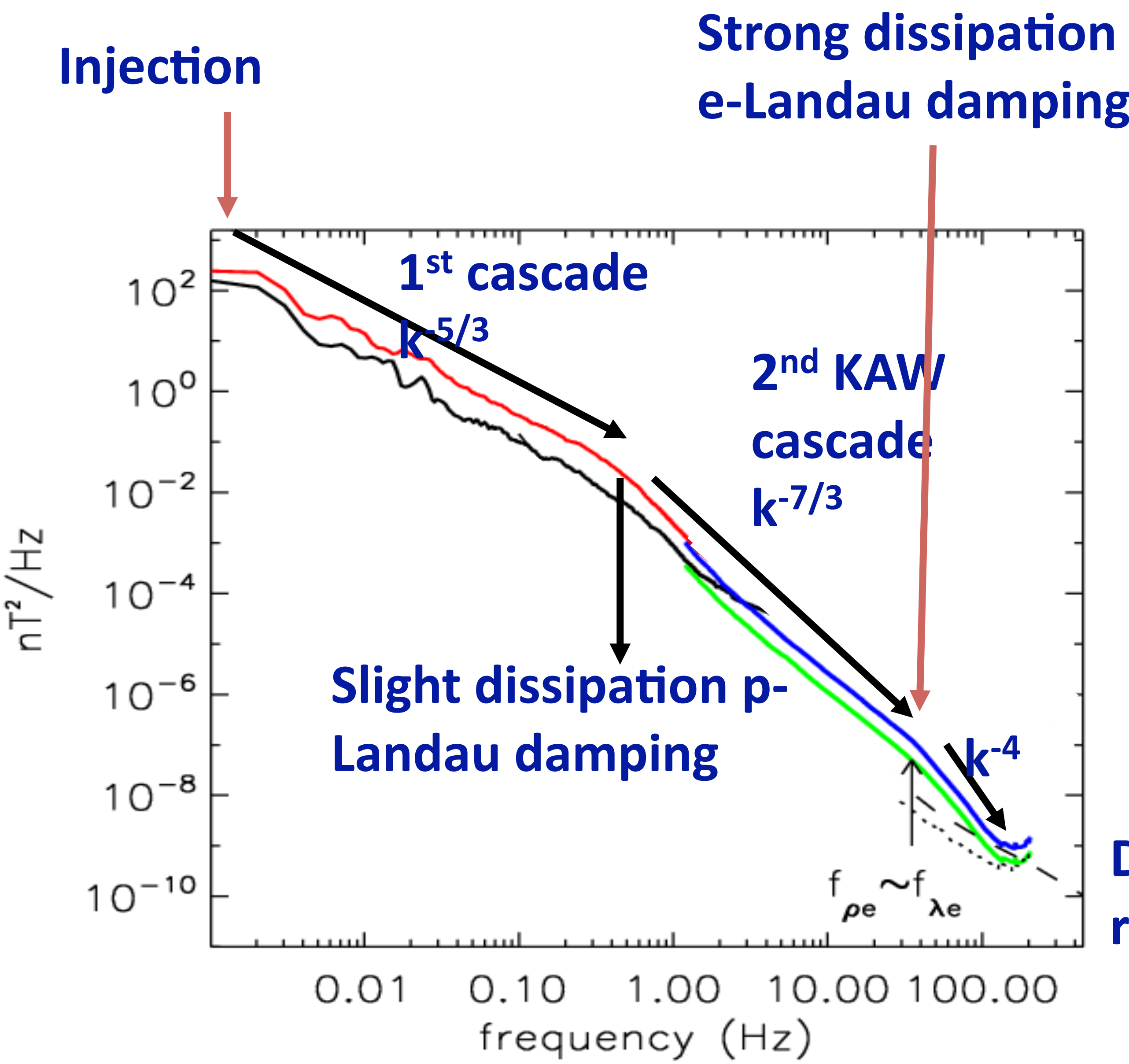
High resolution magnetic field data from FGM and STAFF-SC

1. **Two breakpoints, corresponding to r_i and r_e, are observed.**
2. **A clear evidence of a new inertial range ~ $f^{-7/}$ below r_i**
3. ***First evidence of a dissipation range ~ f^{-4} a electron scale r_e***



STAFF-SC noise level

Journey of the energy through scales: 2D cascade



1. Turbulence
2. e-Acceleration
3. Heating
4. Reconnection

(R. Ghosh) Co-existence of Turbulence and Discrete Modes in the Solar Wind

The *p*- and *g*-mode in the SW controversy

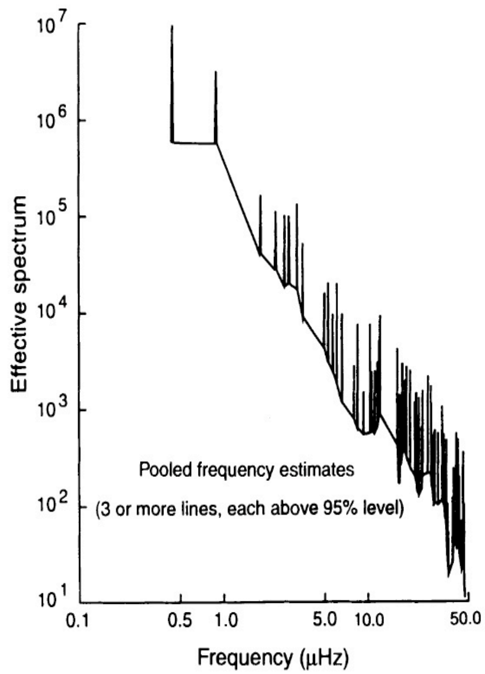
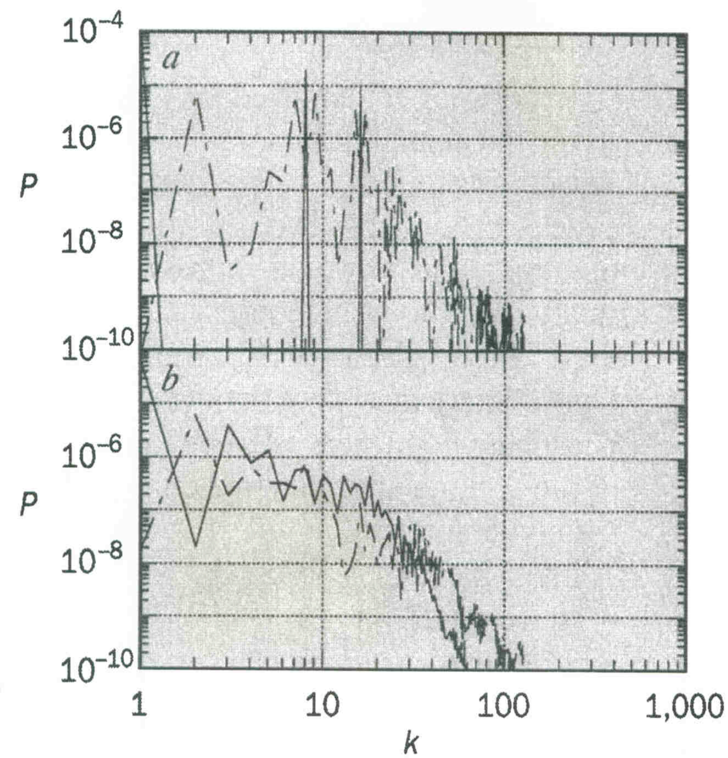


FIG. 3 Line spectrum in the *g*-mode frequency range derived from three or more frequency coincidences in the spectra of interplanetary particle fluxes.



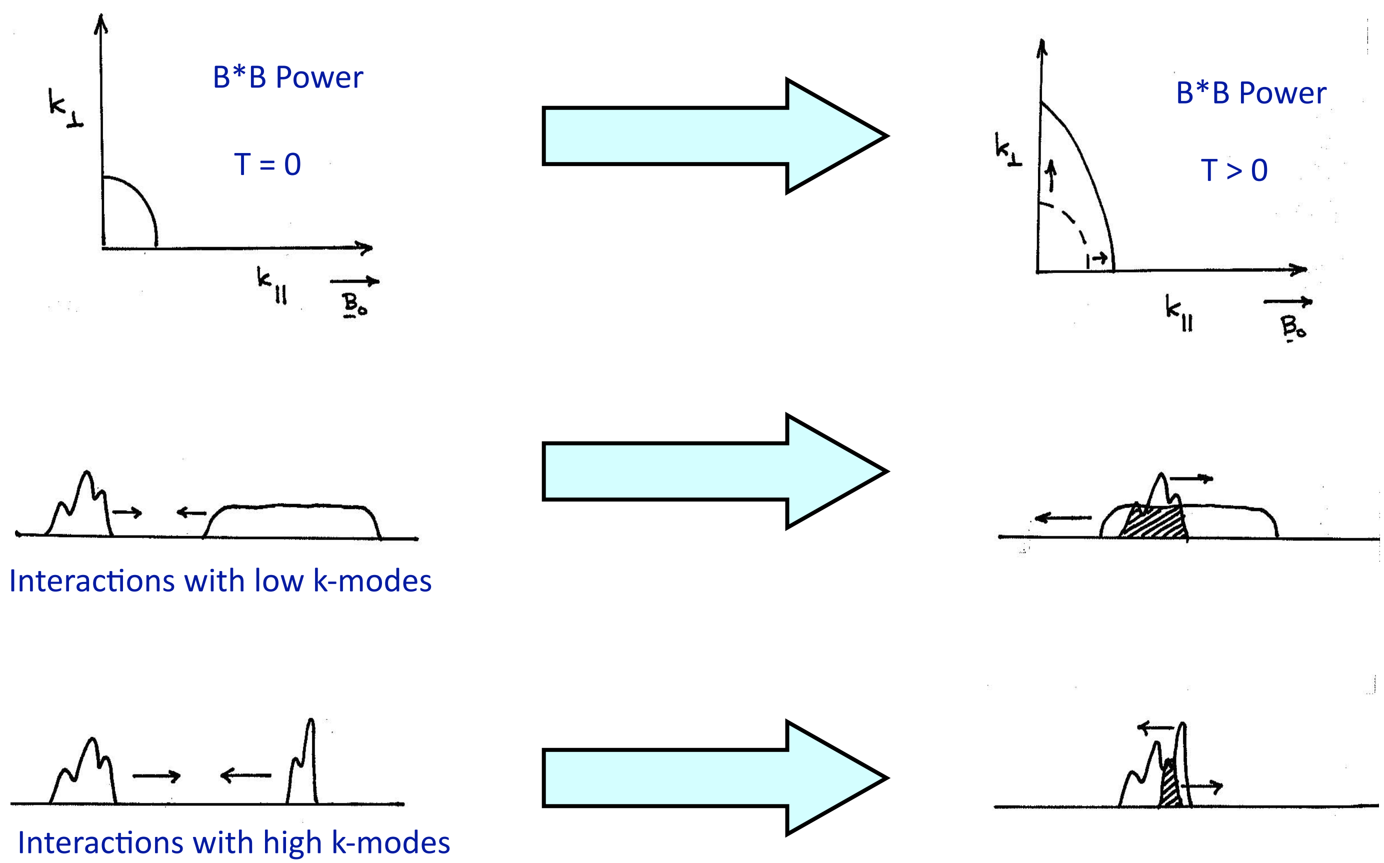
a, Power spectrum of the initial magnetic field (solid) and field magnitude (dot-dash) for a compressible MHD simulation. *b*, Same as *a* but at a later time.

Thomson et al, Nature, 376, 139 (1995)

Roberts et al, Nature, 381, 31 (1996)

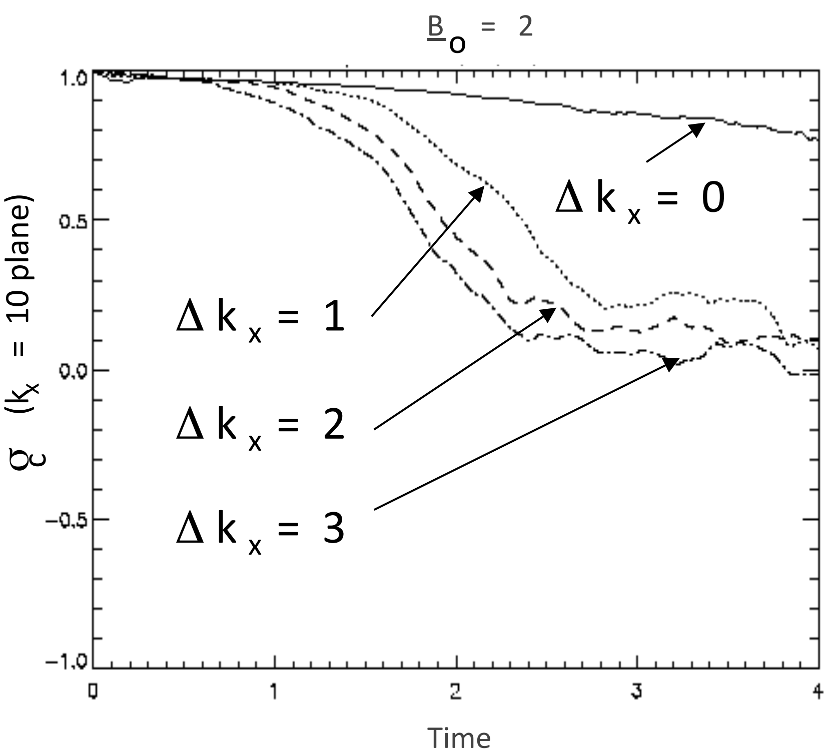
Anisotropy in MHD turbulence due to a mean magnetic field

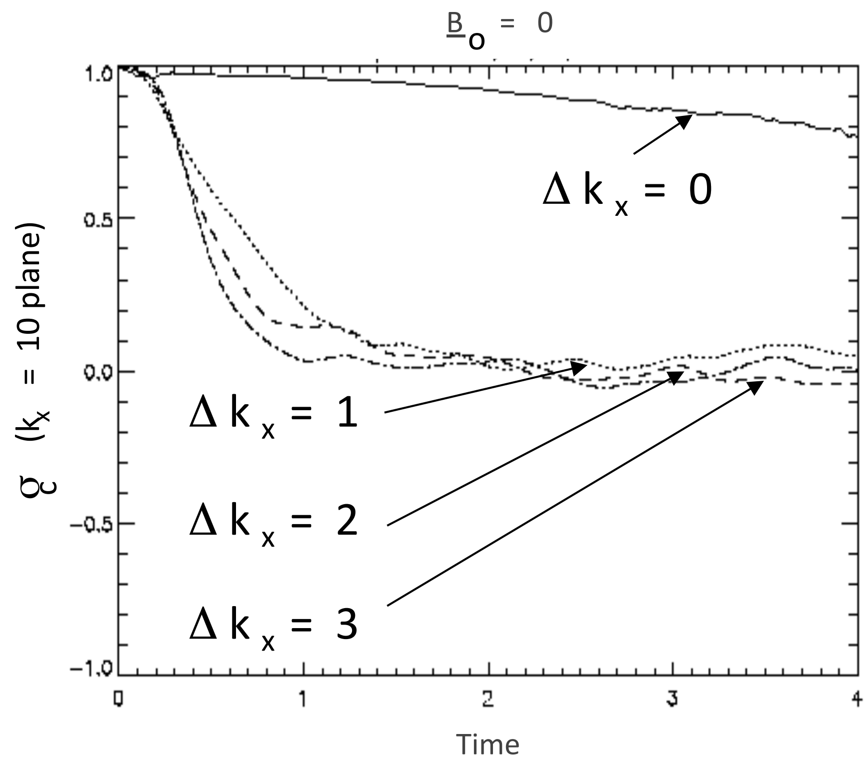
Shebalin et al, J. Plasma Phys., 29, 525 (1983)



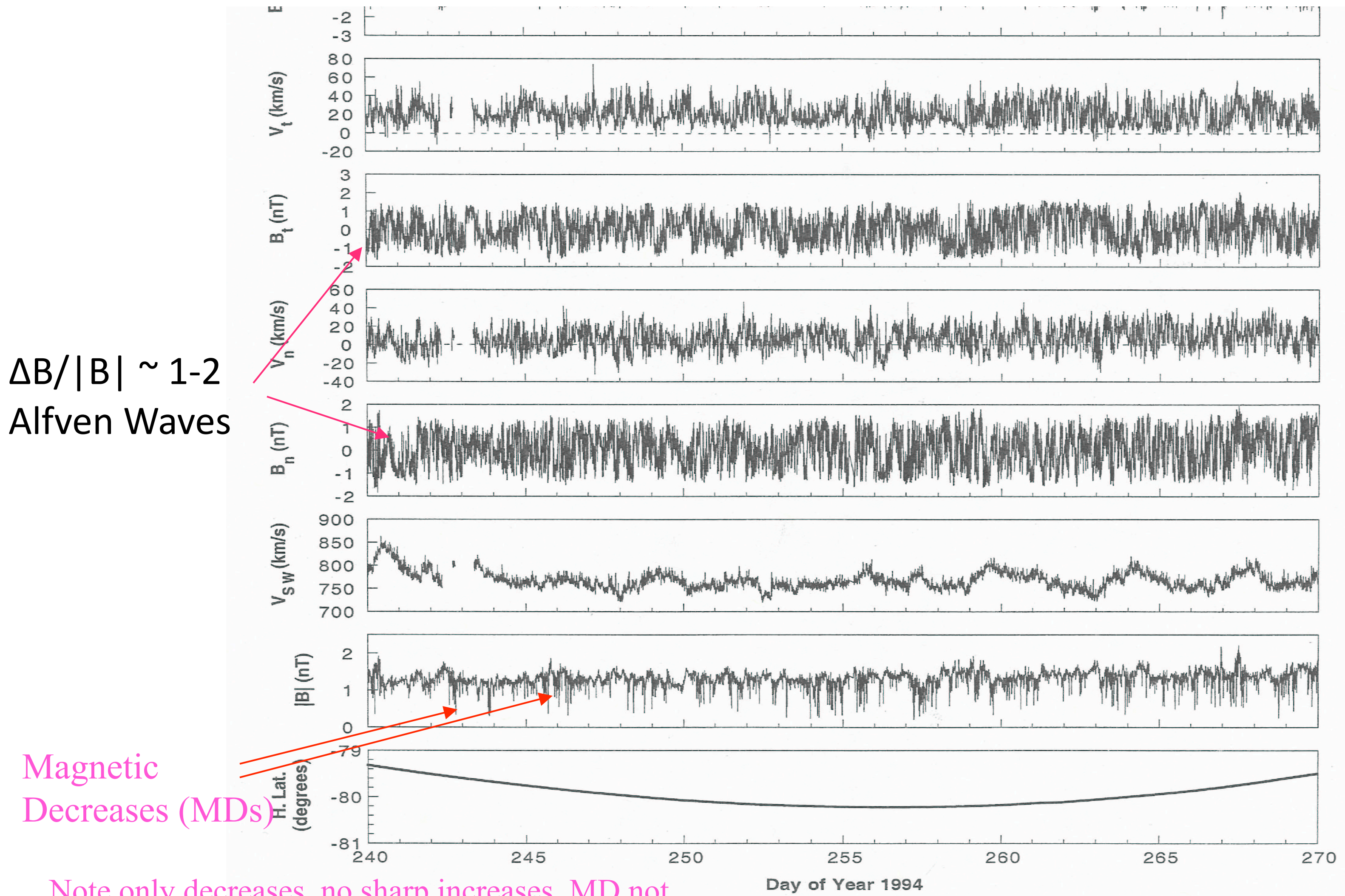
Survivability of Monochromatic Alfvénic (high cross-helicity) Mode

- Initial discrete mode $\sigma_c = \frac{2\,\underline{u} \bullet \underline{B}}{\underline{u} \bullet \underline{u} + B \bullet B} = +1$ at $k_x = 0$
- Driven 2-D turbulence with k_x bandwidths: $\Delta k_x = 0, 1, 2, 3$



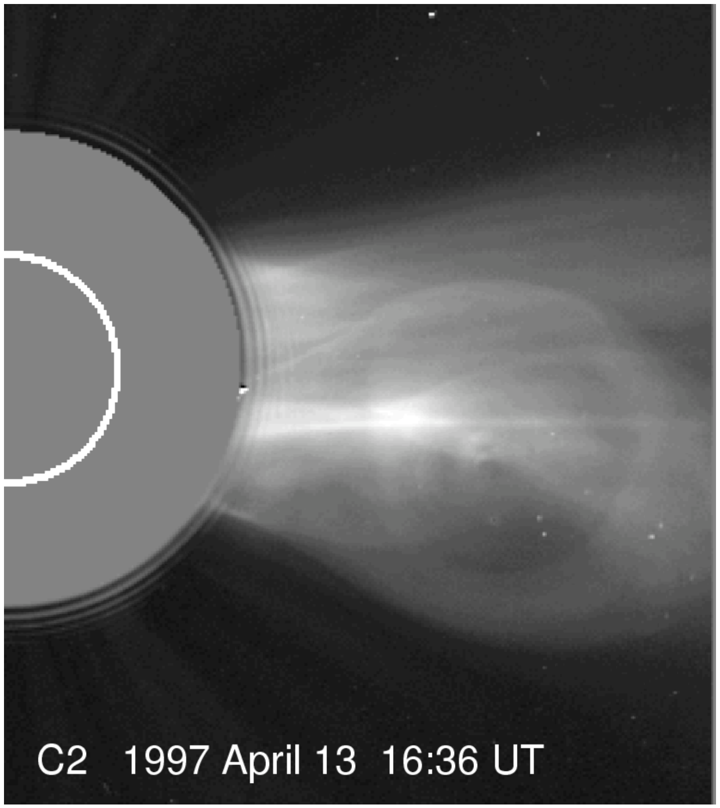


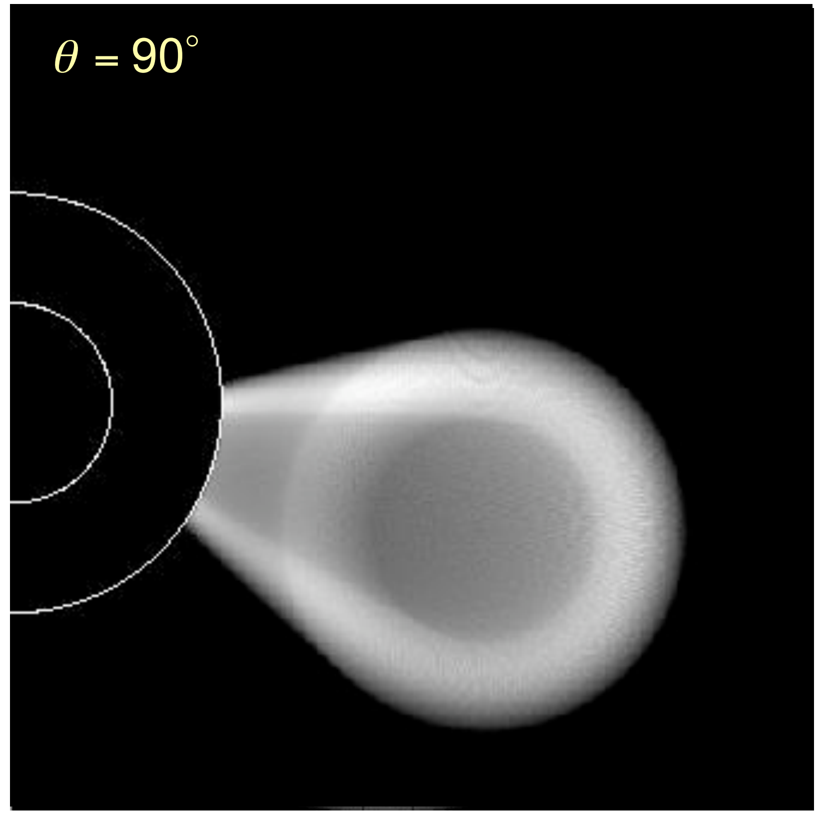
(B. Tsurutani) Mdecreases (formerly holes) in interplanetary space and mirror modes in planetary magnetosheaths and the heliosheath



Note only decreases, no sharp increases. MD not quasiperiodic

Physics of CME Expansion (J. Chen)





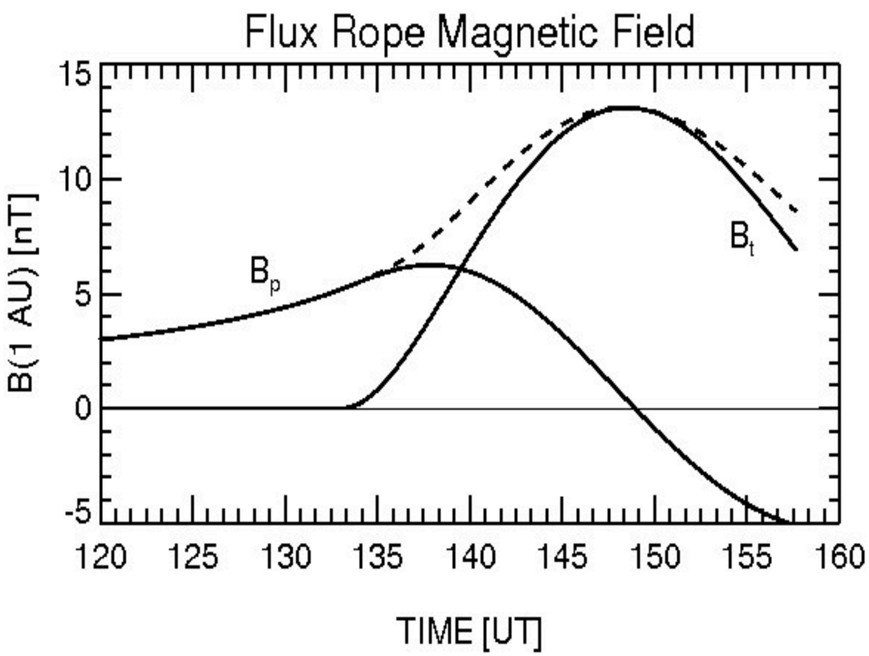
- Good *quantitative* agreement with a flux rope viewed end-on (*Chen et al.* 1997)
  - No evidence of structural changes attributable to disconnection
- Other examples of flux-rope CMEs (*Wood et al.* 1999; *Dere et al., 1999; Wu et al.* 1999; *Plunkett et al.* 2000; *Yurchyshyn* 2000; *Chen et al.* 2000; Krall *et al.* 2001; *Thernisien et al*. 2006)

PREDICTED MAGNETIC FIELD AT 1 AU

Magnetic Cloud [*Burlaga et al.* 1981]

Calculated magnetic field at 1 AU

– Comparison with IMPACT/PLAS



Dec 30