# PAC 2005 Recommendations

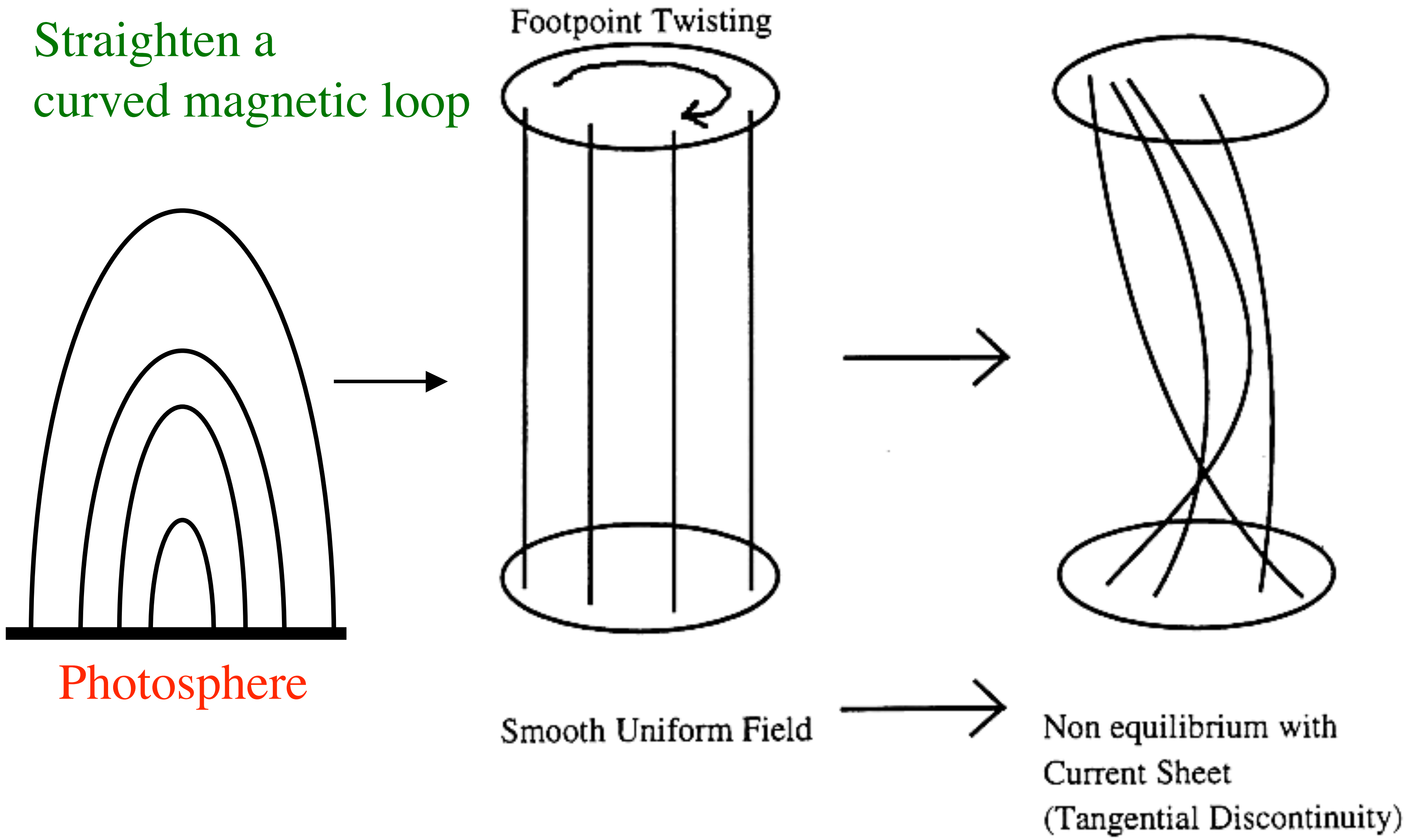
"….*At this point, the coupling of the laboratory results to theory and to astrophysics is not yet well developed*. *This seems particularly promising in the area of impurity or minority ion heating*. It might be interesting to see how heating compares to the turbulent flux of energy to small scales (this may be deduced from the fluctuation spectrum with some theoretical assumptions). *We recommend that CMSO develop further connections to scientific work on theory and observations regarding such phenomena in solar-heliospheric physics*. Specific questions include whether the dynamics on MST might also be present in the solar wind, and if so how one might detect it? The theoretical work needs to proceed to quantitative predictions, doubtless subject to assumptions, that can be compared with trends in the data."

## Part 2
## Coronal/Solar Wind Heating

Research at CMSO encompasses two types of heating mechanisms:

- A flux-tube tectonics model, driven by the magnetic carpet of the Sun. This is inspired by Parker's "nanoflare" model involving the formation of thin current sheets in complex magnetic topologies. This mechanism applies to heliocentric distances $r \leq 1.5\ R_S$.
- Nonlinear waves and turbulence in open magnetic flux tubes emerging from coronal holes that heat the fast solar wind at distances $r \geq 2\ R_S$.

# Parker's Model (1972)



# A theorem on Parker's model

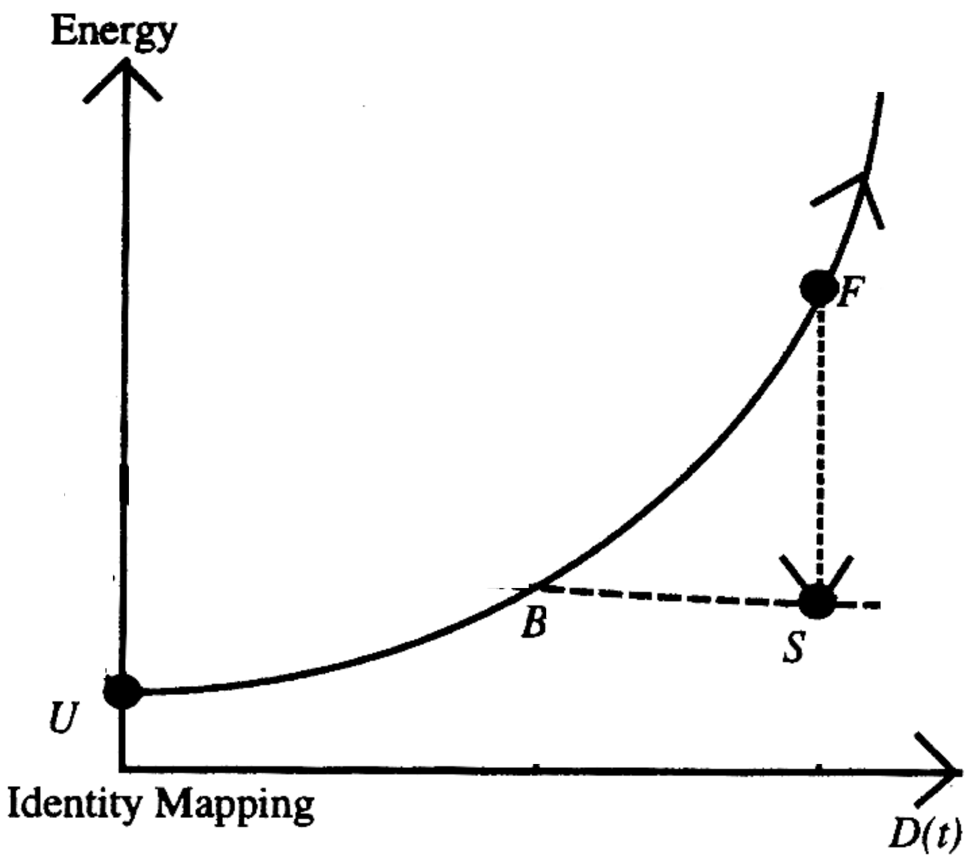
For any given footpoint mapping connected with the identity mapping, there is at most one smooth equilibrium.

Caveat: A proof based on *reduced* MHD equations, periodic boundary condition in $\mathbf{x}_{\perp}$

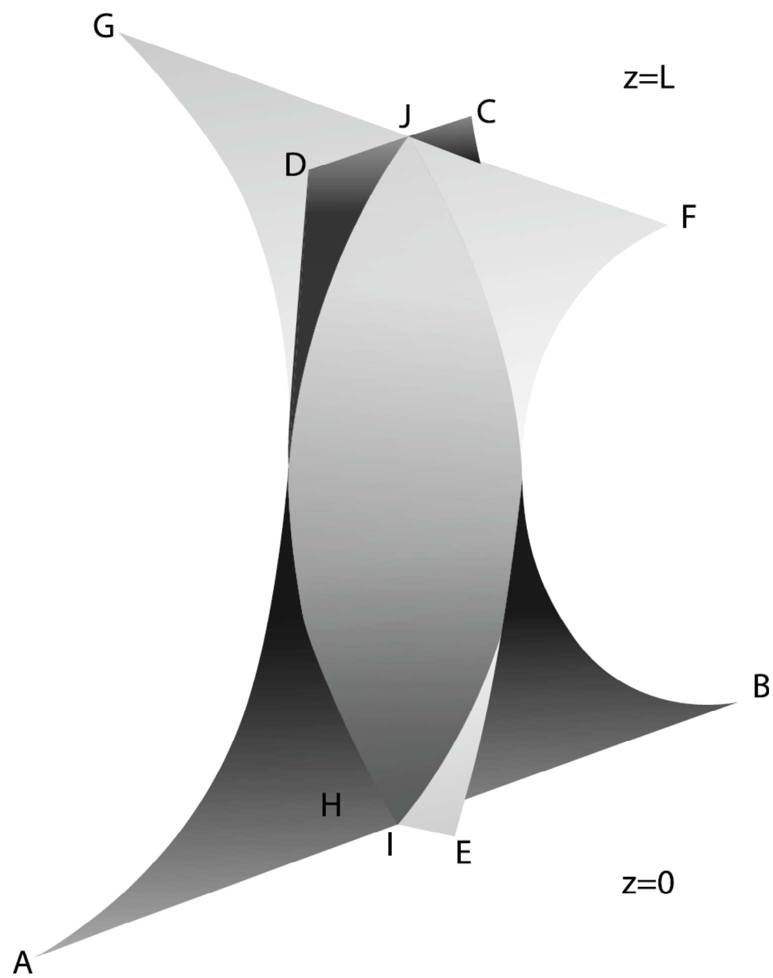
[Ng and Bhattacharjee 1998; also recent related results by Aly 2005 and Low 2006]

# Implication

An unstable but smooth equilibrium cannot relax to a second smooth equilibrium, hence must have current sheets.



## A current sheet topology in line-tied geometry (Ng and Bhattacharjee 2007)




Currents sheets tend to form where the Jacobian of the mapping tends to be most distorted: referred to as Quasi-Separatrix Layers.

# Tectonics model of coronal heating

- A tectonics model of coronal heating, driven by the magnetic carpet, has been proposed [*Priest, Heyvaerts and Title,* 2002].

- Heating is provided by dissipation and reconnection via current sheets at separatrix (or quasi-separatrix) surfaces between neighboring cells due to photospheric footpoint motion.

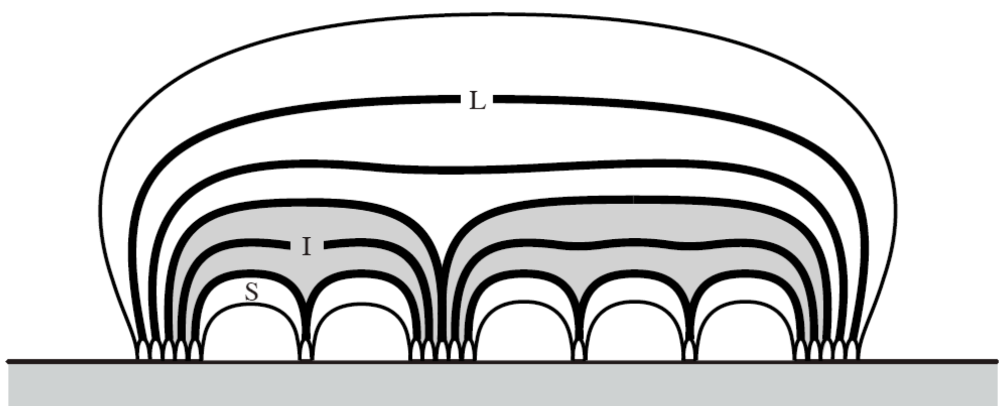



FIG. 3.—Schematic representation of the tectonics of the solar corona, showing separatrix current sheets (*thick curves*) along the boundaries of small loops (S) and both within and on the boundaries of intermediate (I) and large (L) loops. Each loop consists of one or several elementary flux tubes, each of which is bounded by a current sheet and linked to a discrete source in the photosphere.

[*Priest, Heyvaerts and Title,* 2002]

# Reduced MHD simulations

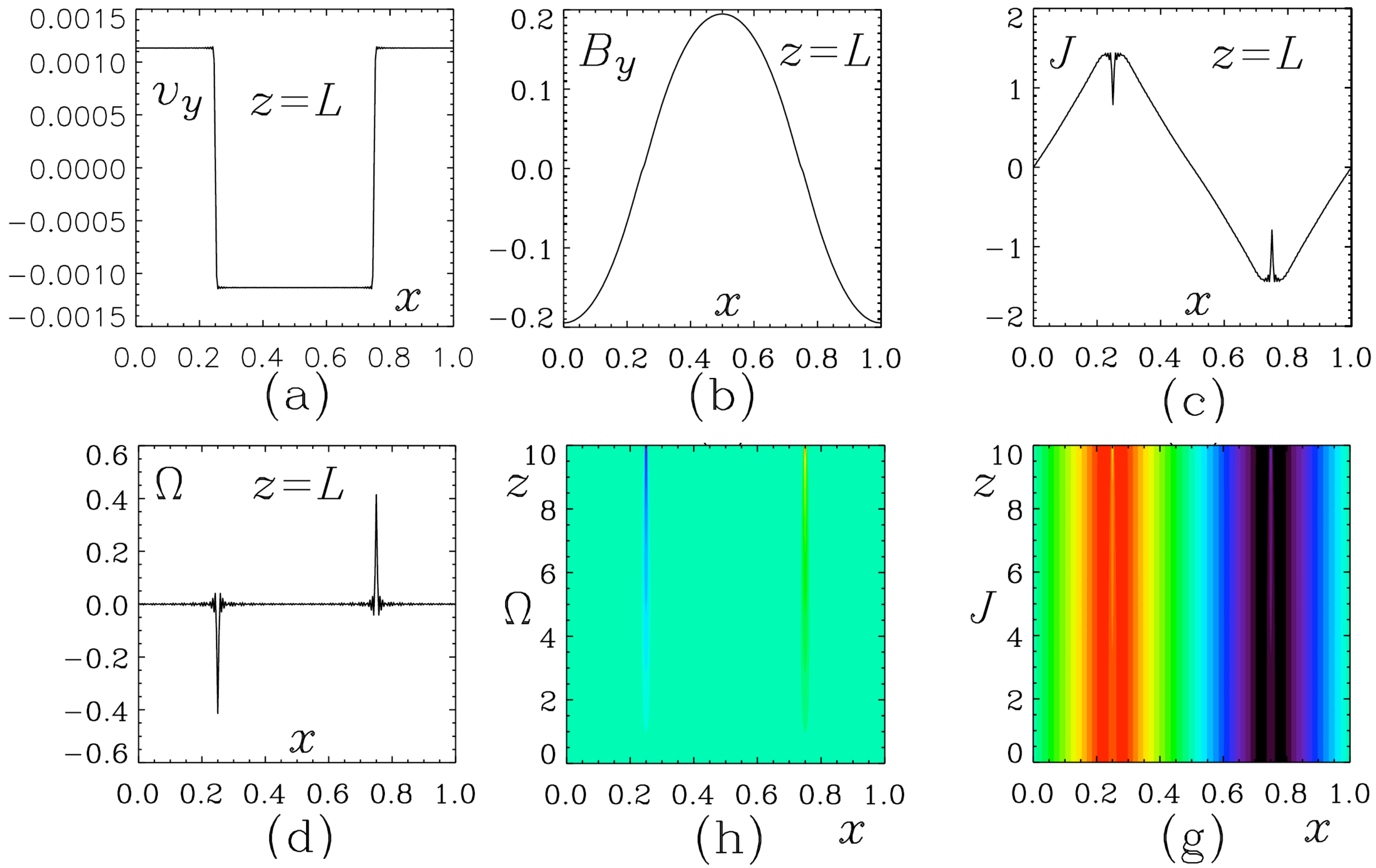
• Only one transverse coordinate ($x$) so that nonlinear terms are identically zero. Revisit the scaling results of Priest et al. (2002). Nonlinear dynamics, involving instability and reconnection, is deliberately excluded as a first step.

• Periodic boundary conditions along *x*, line-tied along *z.*

• Random footpoint drive, with a coherence time $\tau_{\mathrm{coh}}$.

[Ng and Bhattacharjee 2007]

# Random drive --- typical fields




$\eta = 5\times10^{-6}$ $\nu = 10^{-5}$ $L = 10$ $\tau_{\mathrm{coh}} = 1000 \sim 0.1\tau_r$

# Random drive --- heating rate

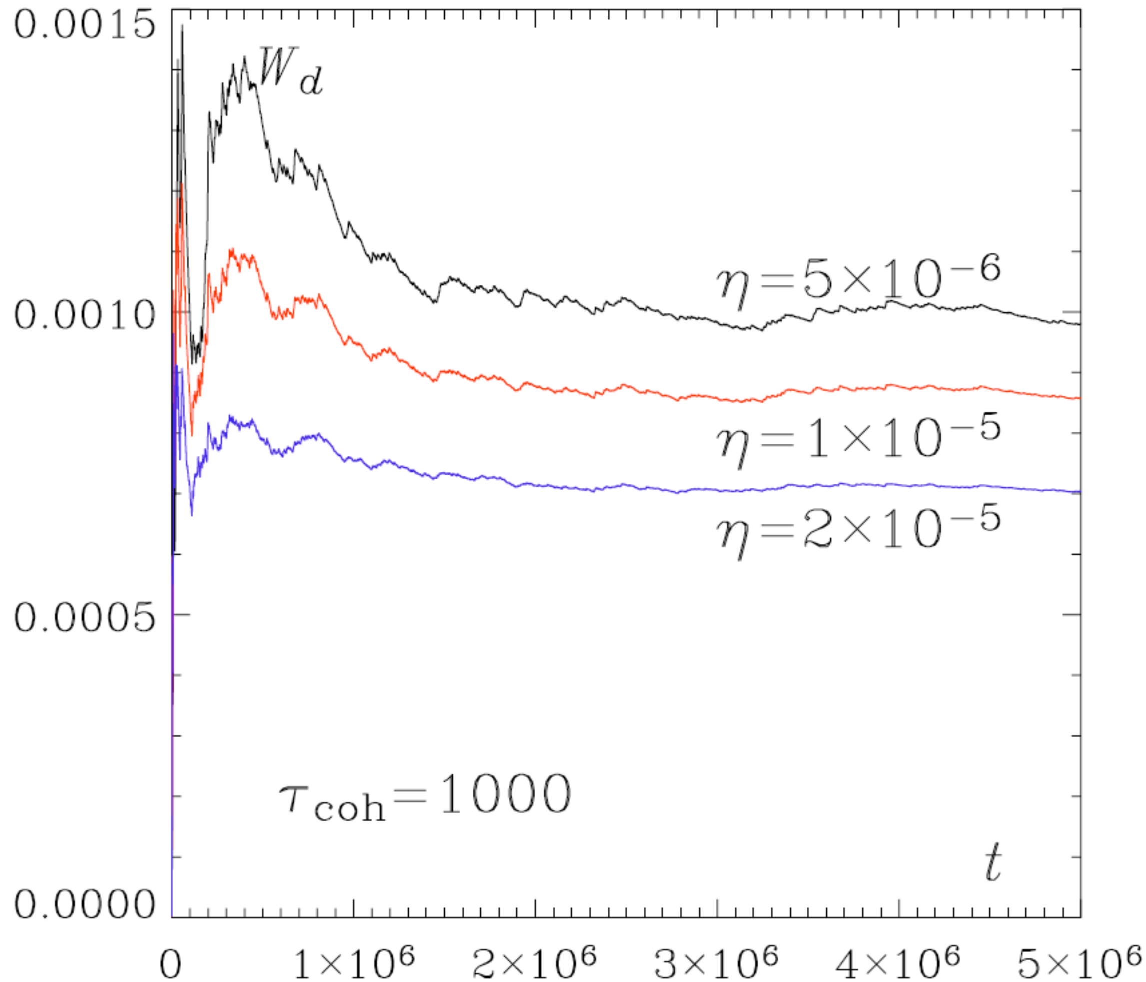
$$\overline{W}_d(t) \equiv \frac{1}{t}\int_0^t W_d(t')dt' = \frac{1}{t}\int_0^t \int \left[\eta J^2(\mathbf{x},t') + \nu \Omega^2(\mathbf{x},t')\right] d^3x\,dt'$$

$\nu = 10^{-5}$

$L = 10$

$\tau_{\mathrm{coh}} = 1000 \sim 0.1\tau_r$

- Average heating rate decreases when $\eta$ increases. Dependence a little weaker than $1/\eta$.



# Random drive --- heating rate/small $\tau_{\rm coh}$

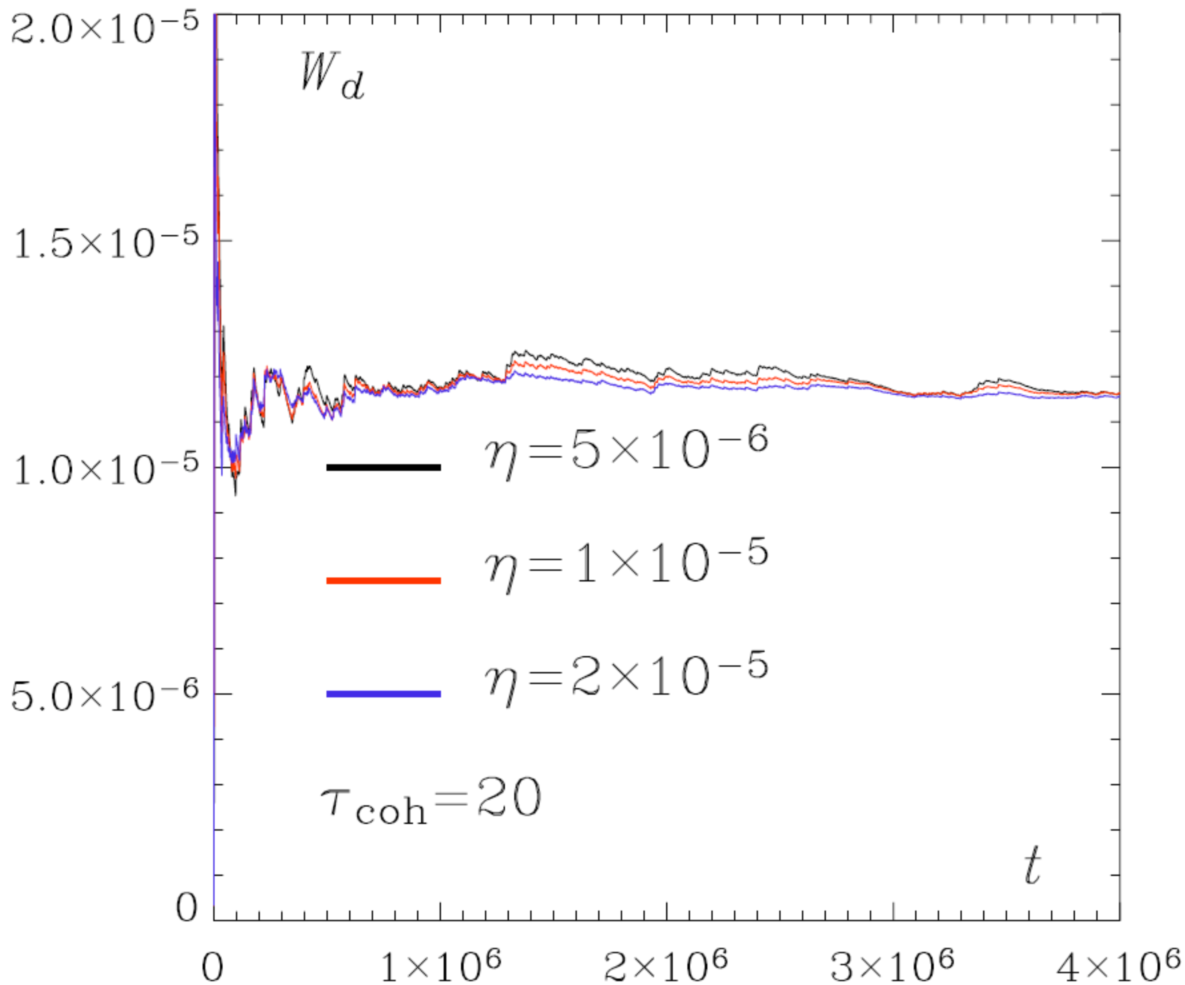
$$\overline{W}_d(t) \equiv \frac{1}{t}\int_0^t W_d(t')dt' = \frac{1}{t}\int_0^t \int \left[\eta J^2(\mathbf{x},t') + \nu \Omega^2(\mathbf{x},t')\right] d^3x dt'$$

$\nu = 10^{-5}$

$L = 10$

$\tau_{\rm coh} = 20 \sim 0.002\tau_r$

- Average heating rate almost independent of $\eta$ .



# Random drive --- transverse *B*/small $\tau_{\text{coh}}$

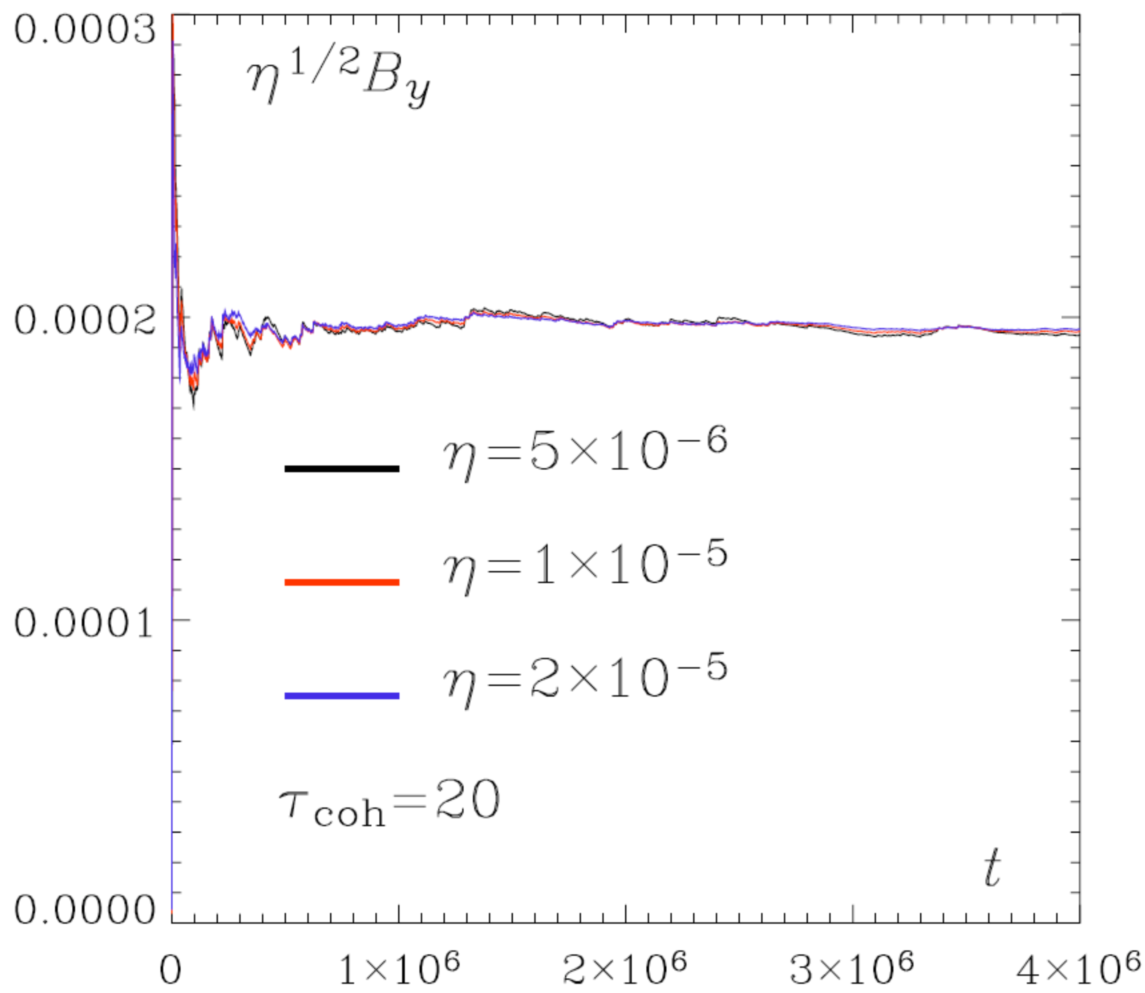
$$\overline{B}_y(t) \equiv \left[\frac{1}{t}\int_0^t \int B_y^2(\mathbf{x},t')d^2x dt'\right]^{1/2}$$

$\nu = 10^{-5}$

$L = 10$

$\tau_{\text{coh}} = 20 \sim 0.002\tau_r$

- $\overline{B}_y$ has almost a $\eta^{-1/2}$ dependence.



# Summary

♦ A tectonics model of coronal heating in the magnetic carpet [*Priest, Heyvaerts and Title,* 2002] is considered using 2D RMHD simulations.

♦ It is shown numerically and by scaling analysis that for a random footpoint driving, the heating rate $<H>$ is independent of $\eta$ .

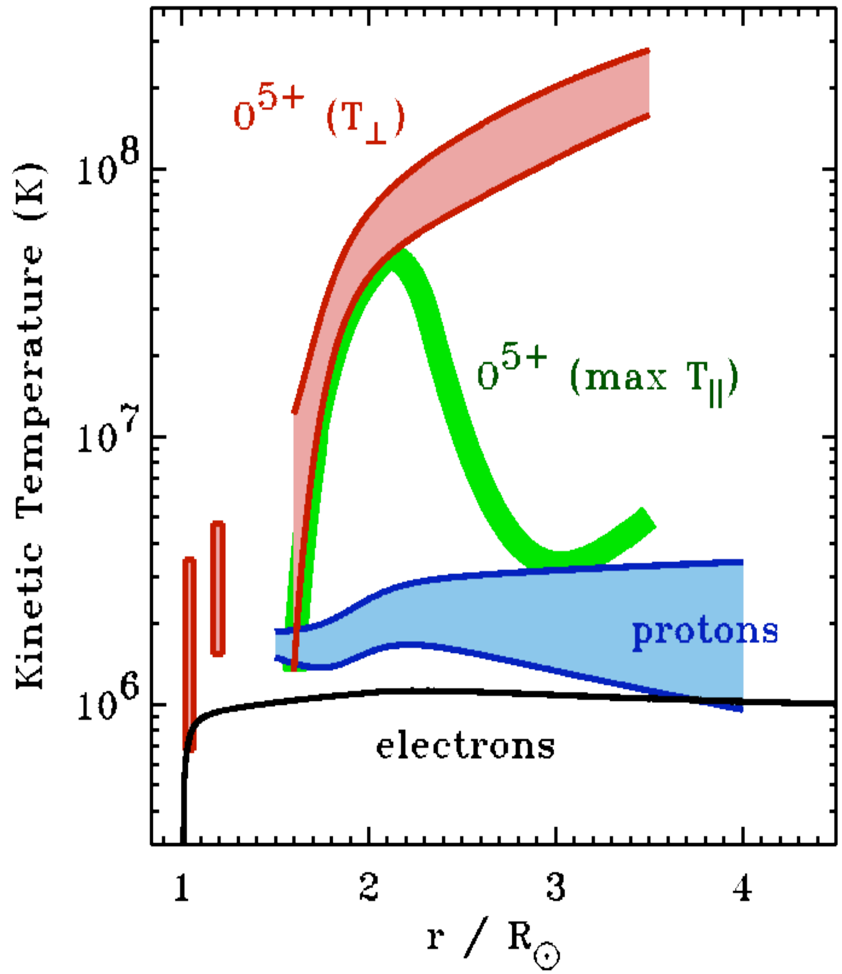
♦ In less constrained geometry, the growth of $B_y$ would be limited by instabilities or reconnection. Thus, this is a process for producing $B_y$ for eventual dissipation by reconnection and/or secondary instabilities.

# The impact of UVCS/SOHO

UVCS has led to new views of the collisionless nature of solar wind acceleration. Key results include:

- The fast solar wind becomes **supersonic** much closer to the Sun (~2 $R_s$) than previously believed.
- In coronal holes, heavy ions (e.g., $O^{+5}$) both flow **faster** and are **heated** hundreds of times more strongly than protons and electrons, and have **anisotropic temperatures**. (e.g., Kohl et al. 1997,1998)

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



# Weak MHD turbulence

Alfvén effect: cascade develops only if two Alfvén wave packets propagating in opposite directions collide

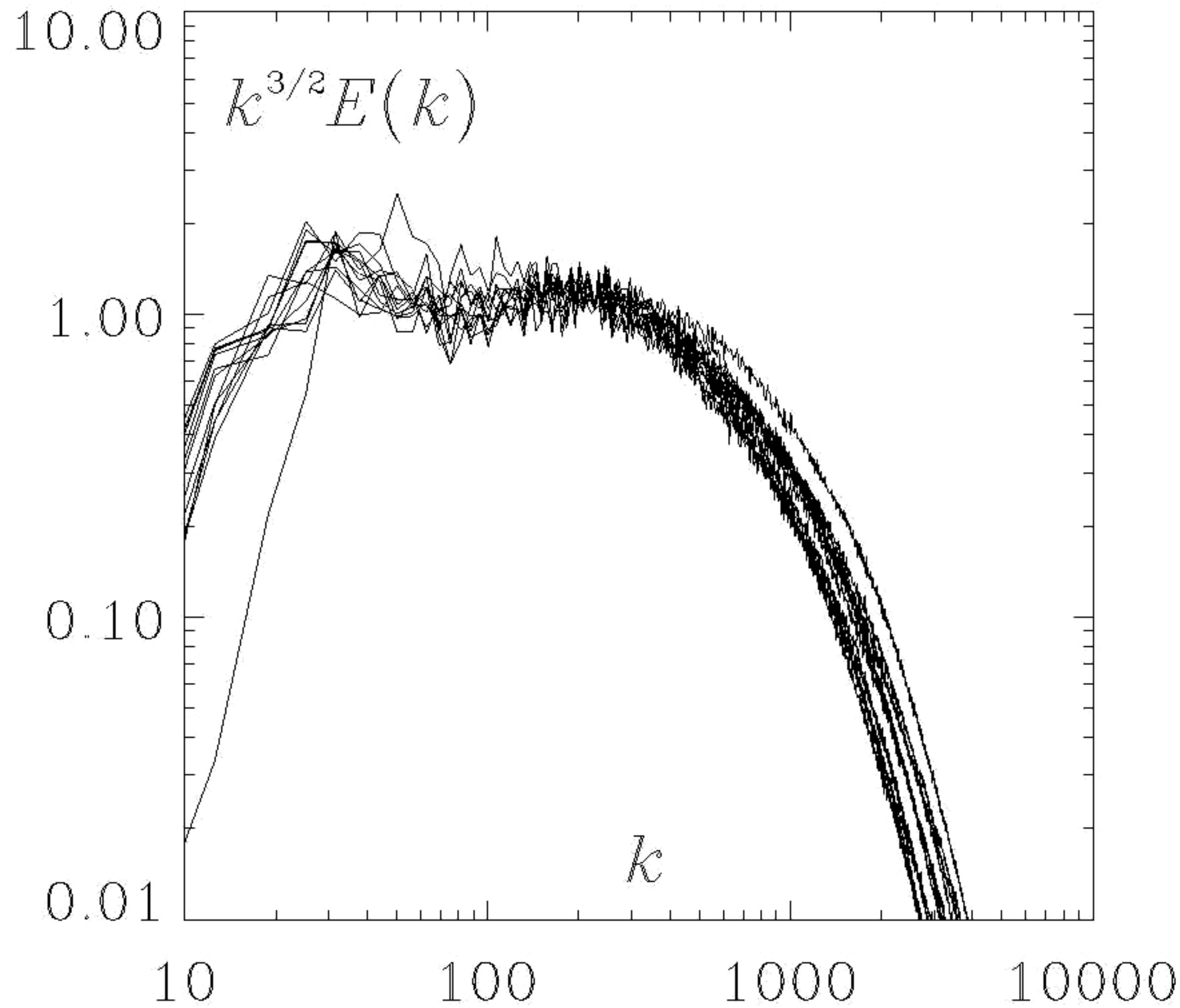
- Weak turbulence: $\chi \equiv k^{1/2} E_k^{1/2} V_A^{-1} = v_k / V_A << 1$
- Time scales:
    - ♦ Eddy turn-over time $\tau_N \sim 1/kv_k$
    - ♦ Alfvén time $\tau_A \sim 1/kV_A = \chi\tau_N << \tau_N$
    - ♦ Energy cascade time $\tau_E \sim \tau_A / \chi^2 = \tau_N / \chi >> \tau_N$

Kolmogorov cascade rate: $\varepsilon_{\mathrm{K}} \sim v_k^2 / \tau_N \sim k^{5/2} E_k^{3/2}$

IK cascade rate: $\varepsilon_{\mathrm{IK}} \sim v_k^2 / \tau_E \sim \varepsilon_{\mathrm{K}} \chi \sim k^3 E_k^2 V_A^{-1} << \varepsilon_{\mathrm{K}}$

# $k^{-3/2}$ energy spectra

- overlapping spectra over a period of large scale Alfvén time



# Energy cascade rate

Fit numerical values of $E(k) = C_{\mathrm{K}}\varepsilon^{2/3}k^{-5/3} = C_{\mathrm{IK}}\varepsilon^{1/2}V_A^{1/2}k^{-3/2}$

or $\varepsilon = C_{\mathrm{K}}^{-3/2}\varepsilon_{\mathrm{K}} = C_{\mathrm{IK}}^{-2}\varepsilon_{\mathrm{IK}}$

where

$\varepsilon_{\mathrm{IK}} = k^3 E_k^2 V_A^{-1}$

by IK theory

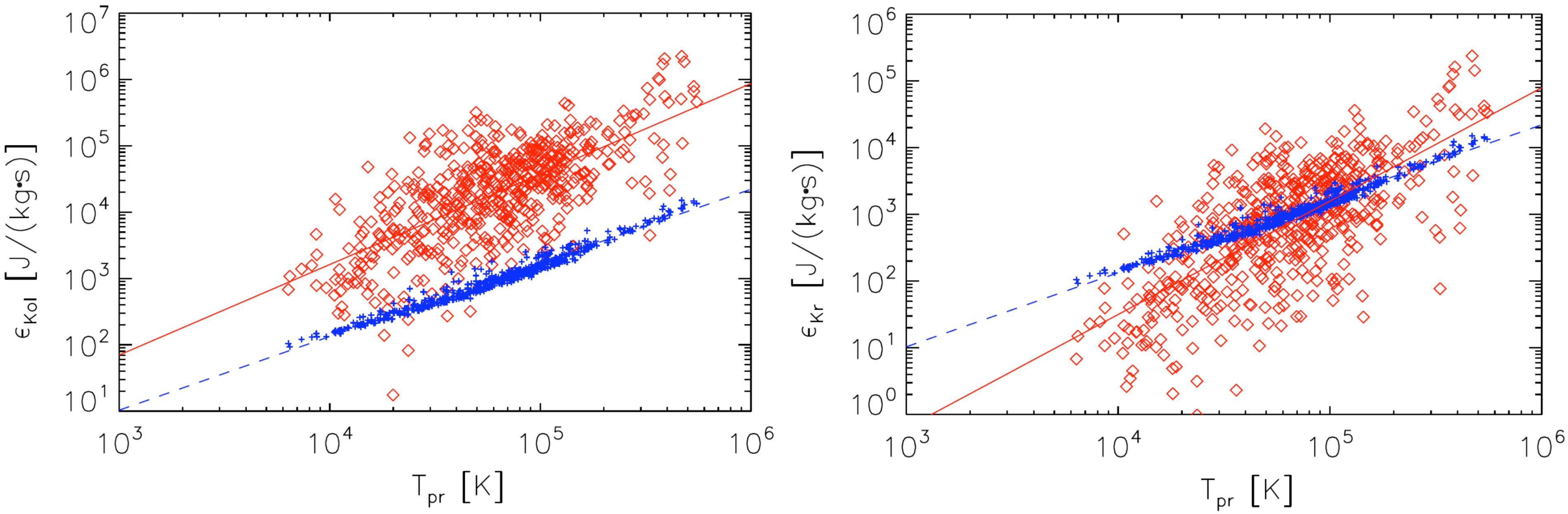
$\varepsilon_{\mathrm{K}} = k^{5/2} E_k^{3/2}$

by Kolmogorov theory

Consistent with IK theory

| | $2048^2$ | $1024^2$ |
|---|---|---|
| $C_{\mathrm{IK}}$ | 1.8 | 1.8 |
| $C_{\mathrm{K}}$ | 4.6 | 4.0 |

# Energy cascade rate -- observations

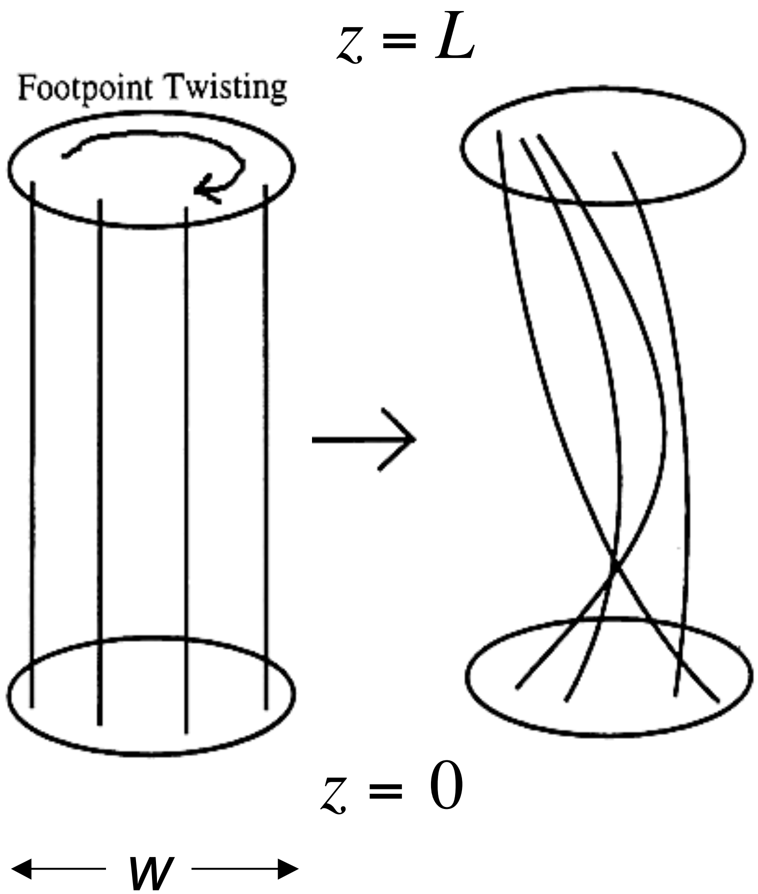


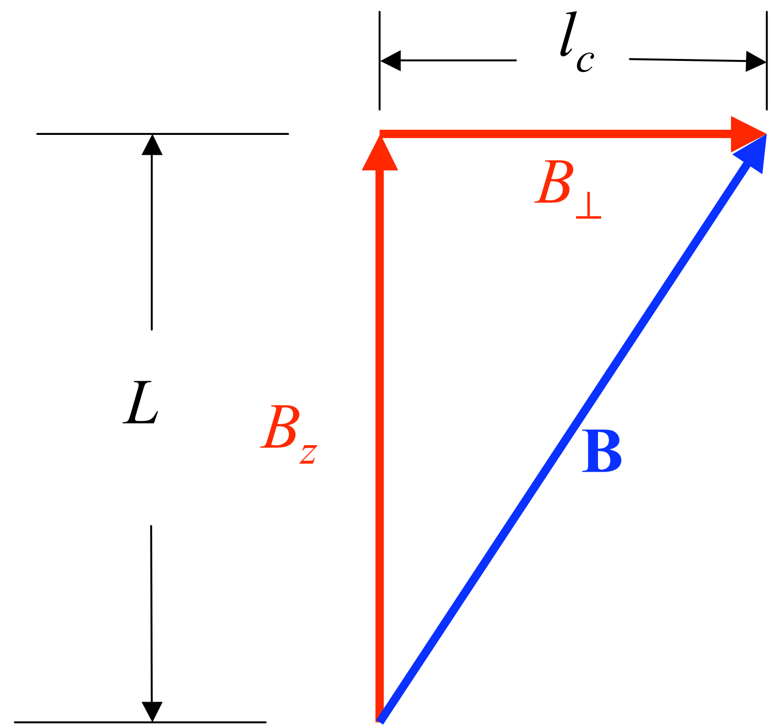

From [*Vasquez et al*. 2007, preprint], scatter plot of the Kolmogorov cascade rate (red diamonds - left), the IK cascade rate (red diamonds -right), and expected heating rate (blue crosses) as a function of proton temperature $T_{pr}$. The Kolmogorov rate exceeds the expected one by a factor of 10 or more, while the IK rate is roughly in agreement.

# Next five years

- Extend the tectonics model of coronal heating by including impulsive reconnection and secondary instability dynamics in line-tied geometry.
- Determine the contributions of waves launched from multiple small-scale reconnection sites in the supergranular network (as in the tectonics model) to solar wind heating.
- Ion heating by *anisotropic* Hall MHD turbulence in MST and the solar wind (synergistic collaboration with the Harvard CFA group under the auspices of the NASA Living with a Star program).

# $B_\perp$ from random footpoint motion



# Scaling due to random footpoint motion

If dissipation is due to Ohmic diffusion with resistivity $\eta$

$$\frac{\bar{B}_y}{B_z} \sim \frac{l_c}{L} \sim \frac{v_0}{L}\sqrt{\tau_{\text{coh}}\tau_r} \sim \frac{v_0}{L}\sqrt{\frac{\tau_{\text{coh}}\bar{w}^2}{\eta}} >> 1$$

where $l_c = v_0\sqrt{\tau_r \tau_{\text{coh}}}$ is the statistically expected distance moved by a footpoint with velocity $v_0$ in a random walk motion in a resistive time $\tau_r \sim w^2/\eta$ .

- Heating rate $\bar{W}_d \sim \eta \int \bar{J}^2 d^3x \sim \eta \bar{B}_y^2 (Lw^2)/\bar{w}^2 \sim \frac{v_0^2}{L} B_z^2 \tau_{\text{coh}} w^2$

  $\langle H \rangle \sim \frac{\bar{W}_d}{w^2}$ is independent of $\eta$.

- If $w \sim v_0 \tau_{\text{coh}}$, $\langle H \rangle \sim B_z^2 v_0 w / L$ , which is of the order of magnitude required for coronal heating.

- However, $\bar{B}_y$ is unphysically large for small $\eta$ in this case.

# Scaling due to random footpoint motion

If dissipation is due to instability/reconnection when $B_y \sim f\, B_z$

$$\frac{\overline{B}_y}{B_z} \sim f \sim \frac{v_0}{L}\sqrt{\tau_{\rm coh}\tau_E} \Rightarrow \tau_E \sim \left(fL/v_0\right)^2/\tau_{\rm coh}$$

- Heating rate $\overline{W}_d \sim \overline{B}_y^2(Lw^2)/\tau_E \sim \dfrac{v_0^2}{L}B_z^2\tau_{\rm coh}w^2$

  $\langle H\rangle \sim \dfrac{\overline{W}_d}{w^2}$ is independent of $f$ and dissipation mechanism.

- If $w \sim v_0\tau_{\rm coh}$, $\langle H\rangle \sim B_z^2 v_0 w/L$ , which is again of the order of magnitude required for coronal heating, but now without an unphysically large $\overline{B}_y$ , if instability/reconnection dissipate energy fast enough when $f \sim O(1)$.