Propagation of Reconnection Energy Away from the X-line and its Relationship to Onset

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Shay, Drake, Eastwood, Phan, *Physical Review Letters*, Super-Alfvenic propagation of substorm reconnection signatures and Poynting flux, Vol. 107, 065001, 2011.

- So, Ignoring my better judgement...

Magnetic Reconnection Generalized to Turbulent Systems

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Overview

- Basic Magnetic Reconnection
- Asymmetric Magnetic Reconnection
- Turbulent Magnetic Reconnection
- Conclusions

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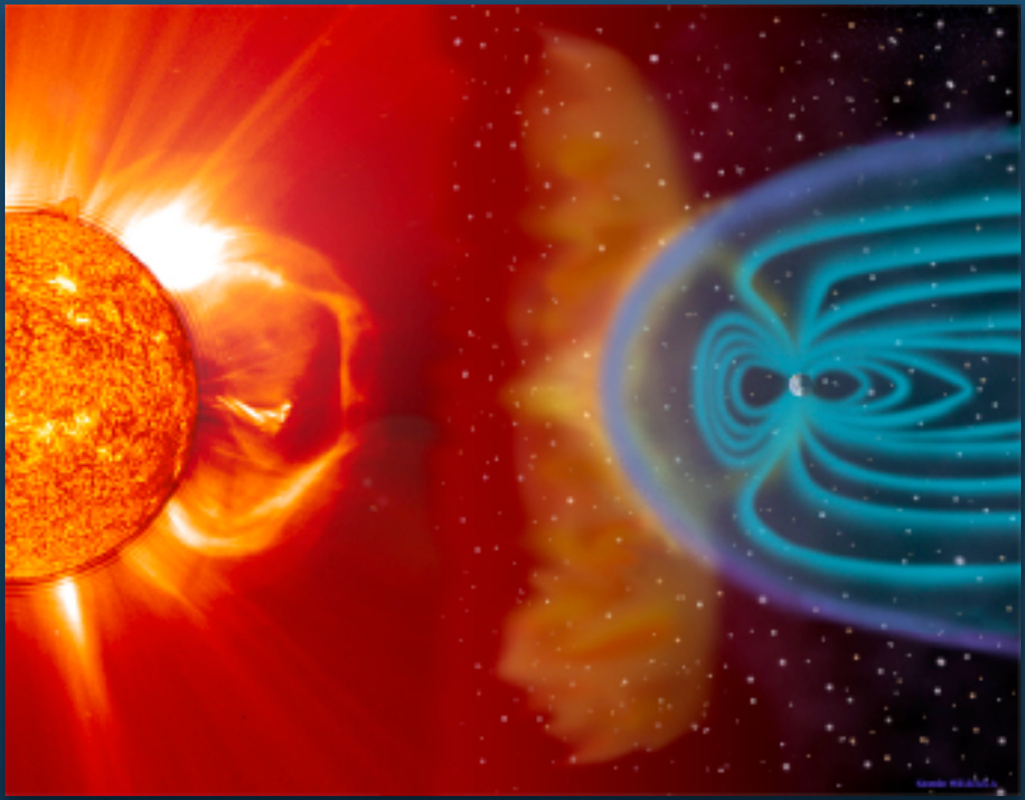
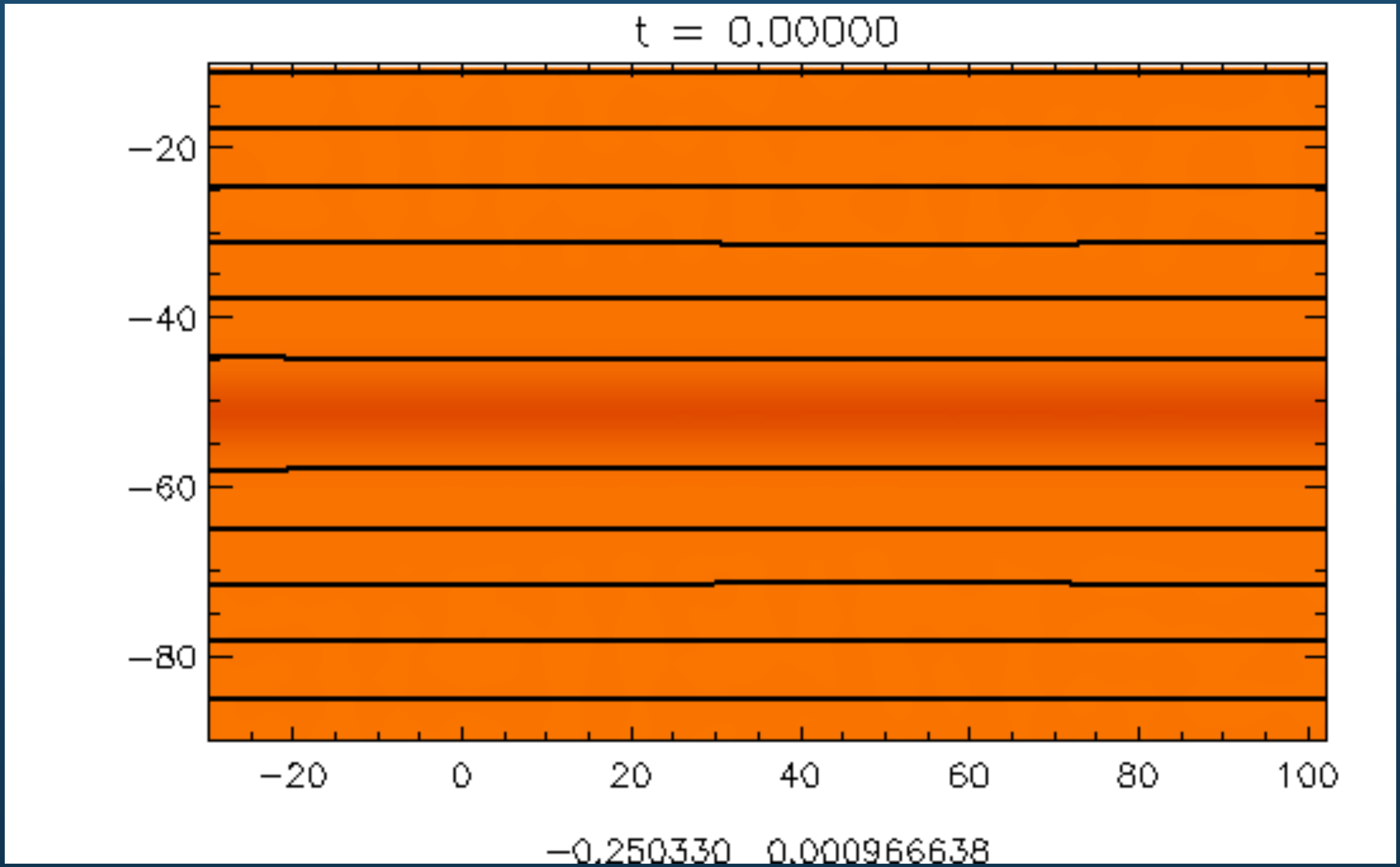
Space Weather

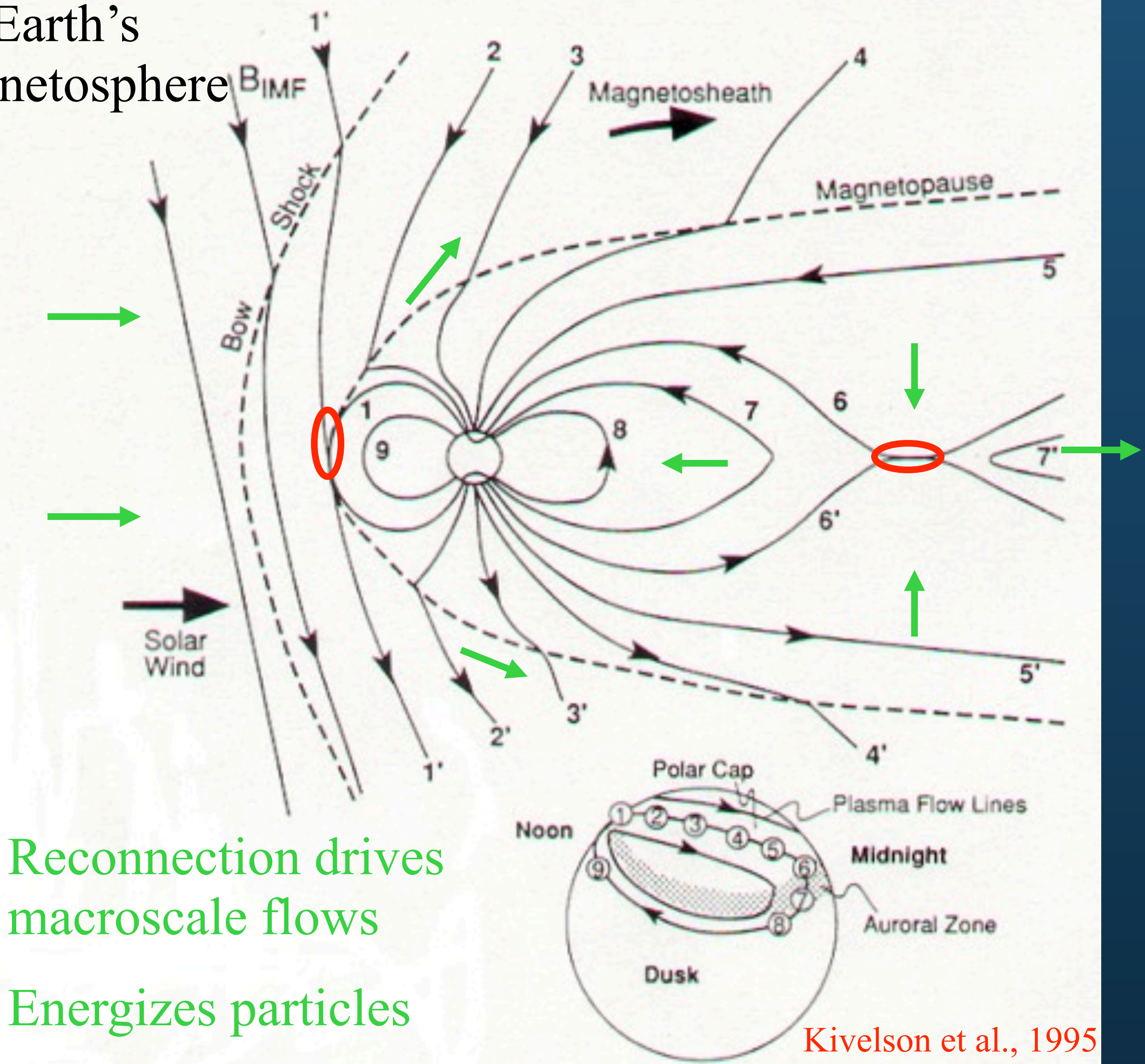


- The nature of changing environmental conditions in space.
  - Plasma: A gas of charged particles.

Magnetic Reconnection: Simplistic 2D



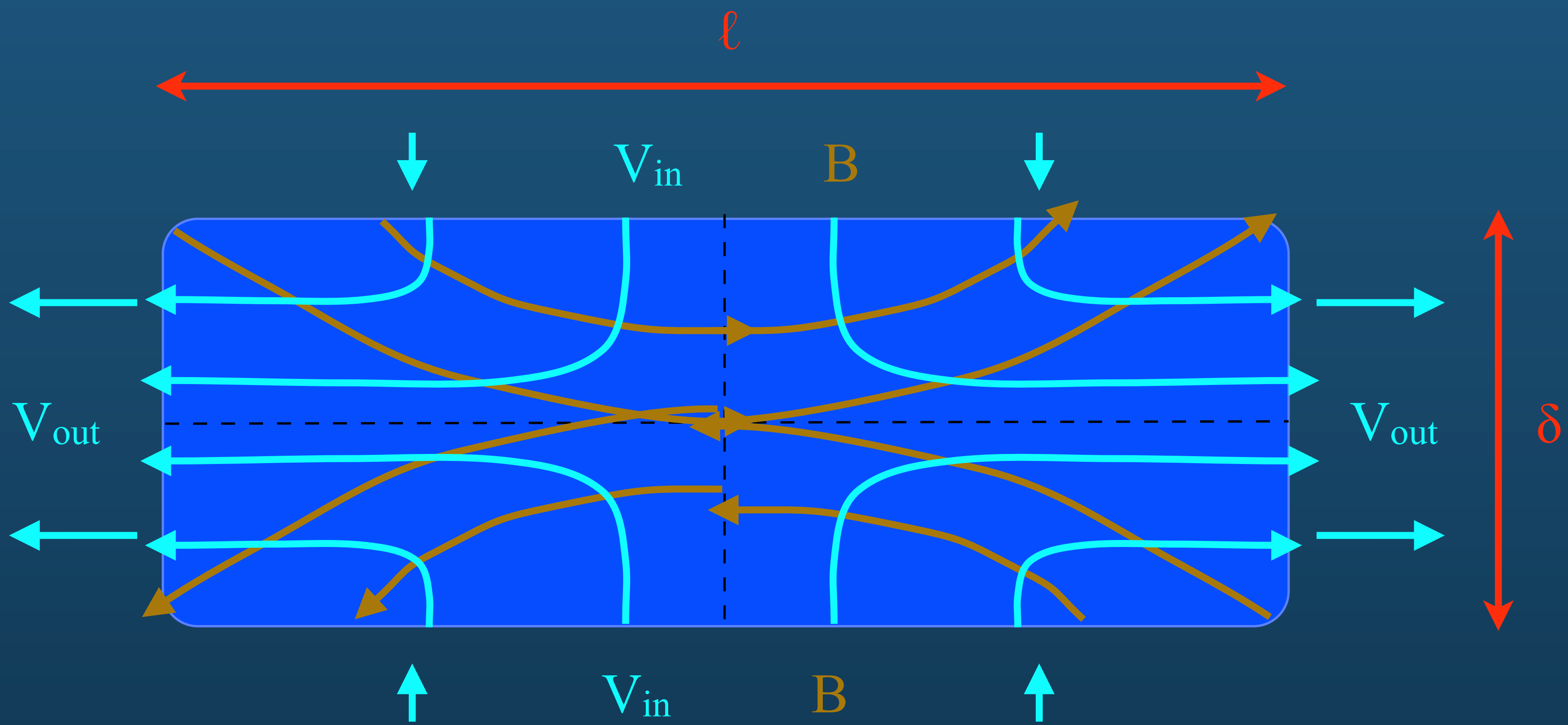
Earth's Magnetosphere



Reconnection drives macroscale flows

Energizes particles

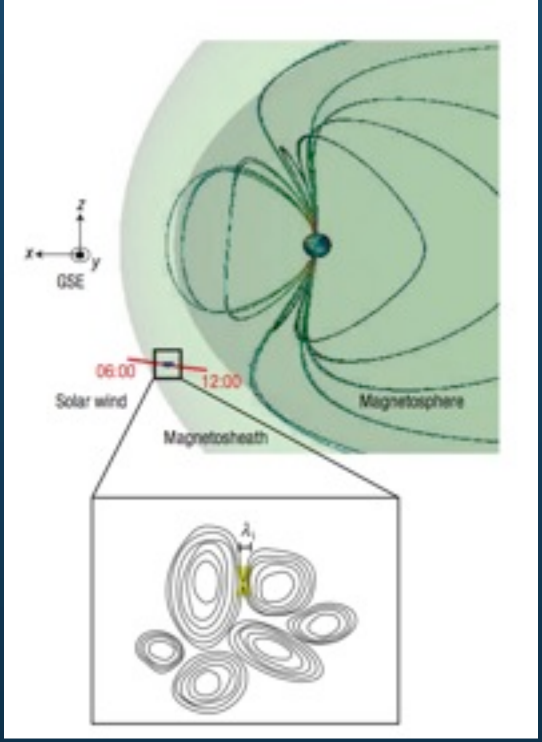
Reconnection Rate



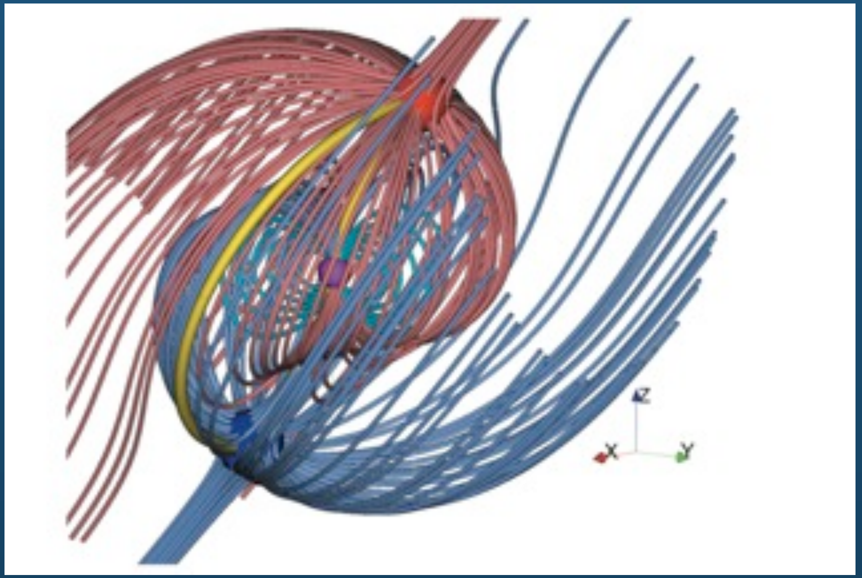
- Reconnection Rate: $V_{in} \sim (\delta/\ell)\, c_A$
- Conservation of Mass
  $m_i\, n\, V_{in}\, \ell \sim m_i\, n\, V_{out}\, \delta$
- Conservation of Energy
  $\frac{B^2}{8\pi} V_{in} \ell \sim \frac{1}{2} m_i n V_{out}^2 (V_{out}\delta)$
  $V_{out} \sim \sqrt{\frac{B^2}{4\pi m_i n}} \sim c_A$
- Reconnection Rate: $\frac{V_{in}}{V_{out}} \sim \frac{\delta}{\ell}$
- Last 10 years: $\delta/\ell \sim O(0.1)$
  $E_{\text{out-of-plane}} \sim V_{in} B$

Complex Reconnection

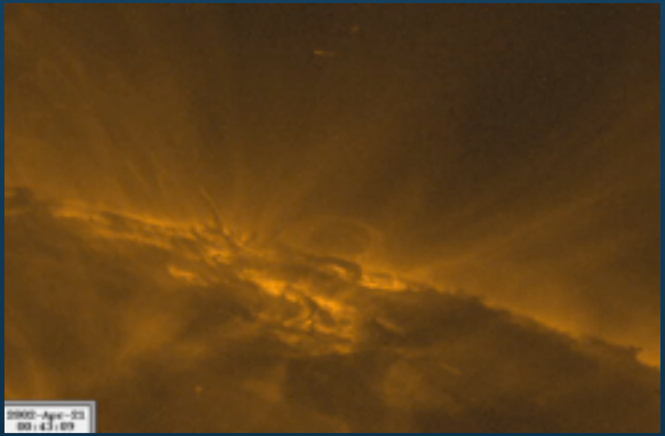
- Reconnection not so simple
  - Not quasi-steady
  - Not 2D



Retino et al., 2007



Dorelli et al., 2007



Trace Data

Overview

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- Asymmetric Magnetic Reconnection
- Turbulent Magnetic Reconnection
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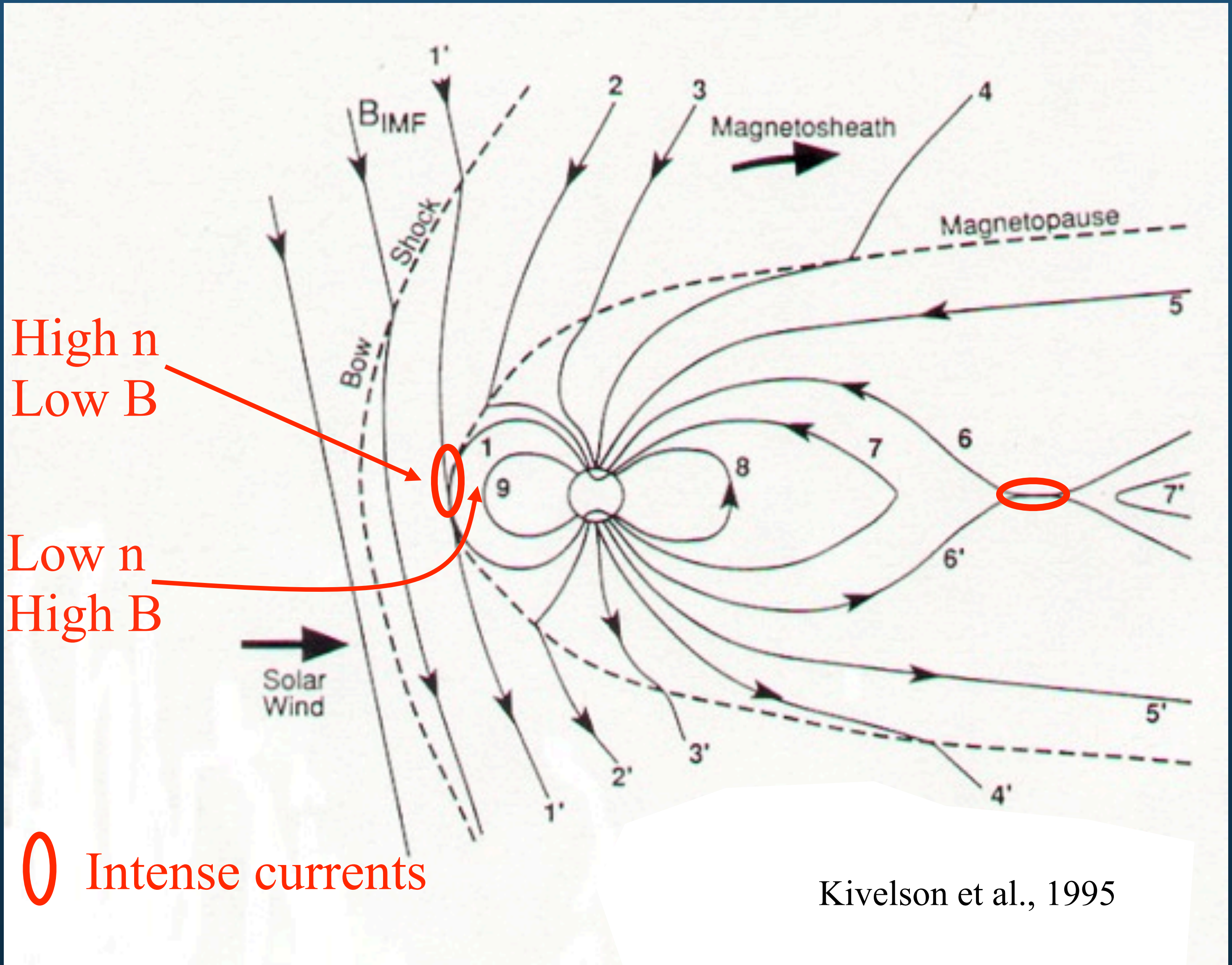
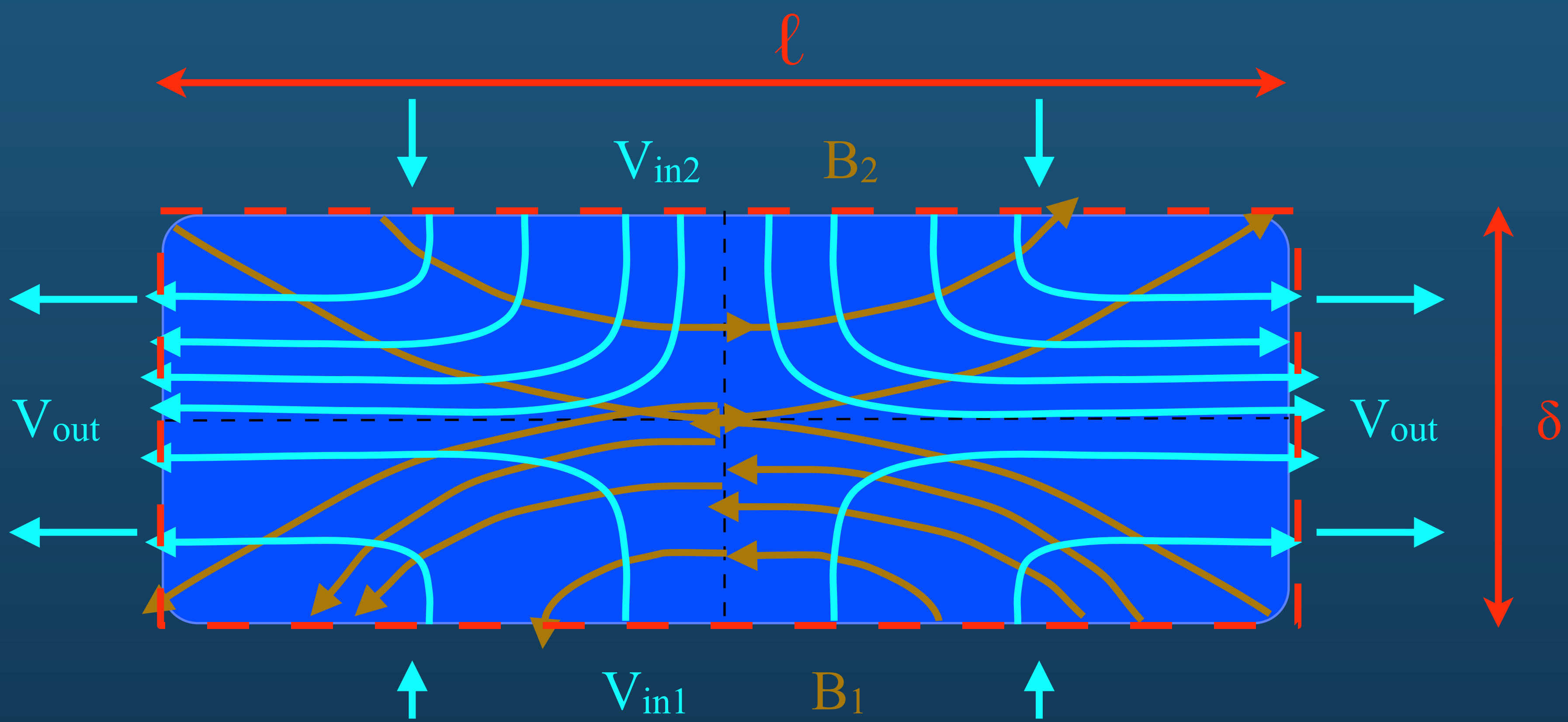
Asymmetric Magnetic Reconnection



Kivelson et al., 1995

Asymmetric Diffusion Region



- Use conservation equations again
  - Integrate MHD equations over area.

Formalize Conservation Laws

- Write MHD in conservative form (ρ = mass density, v = flow velocity, B = magnetic field, P = pressure, E = electric field,

$$\mathcal{E} = \frac{1}{2}\rho v^2 + \frac{P}{\gamma - 1} + \frac{B^2}{8\pi}$$

= total energy)

  – Integrate over closed surface.

$$\frac{\partial \rho}{\partial t} = -\vec{\nabla}\cdot\left(\rho\vec{v}\right)$$

$$\frac{\partial}{\partial t}\left(\rho\vec{v}\right) = -\vec{\nabla}\cdot\left[\rho\vec{v}\vec{v} + \left(P + \frac{B^2}{8\pi}\right)\overleftrightarrow{I} - \frac{\vec{B}\vec{B}}{4\pi}\right]$$

$$\frac{\partial \mathcal{E}}{\partial t} = \vec{\nabla}\cdot\left[\left(\mathcal{E} + P + \frac{B^2}{8\pi}\right)\vec{v} - \frac{\left(\vec{v}\cdot\vec{B}\right)}{4\pi}\vec{B}\right]$$

$$\frac{\partial \vec{B}}{\partial t} = -c\vec{\nabla}\times\vec{E}$$

$$\Rightarrow$$

$$\int d\vec{S}\cdot\left(\rho\vec{v}\right) = 0$$

$$\int d\vec{S}\cdot\left[\rho\vec{v}\vec{v} + \left(P + \frac{B^2}{8\pi}\right)\overleftrightarrow{I} - \frac{\vec{B}\vec{B}}{4\pi}\right] = 0$$

$$\int d\vec{S}\cdot\left[\left(\mathcal{E} + P + \frac{B^2}{8\pi}\right)\vec{v} - \frac{\left(\vec{v}\cdot\vec{B}\right)}{4\pi}\vec{B}\right] = 0$$

$$\int d\vec{S}\times\vec{E} = 0$$

General Diffusion Region

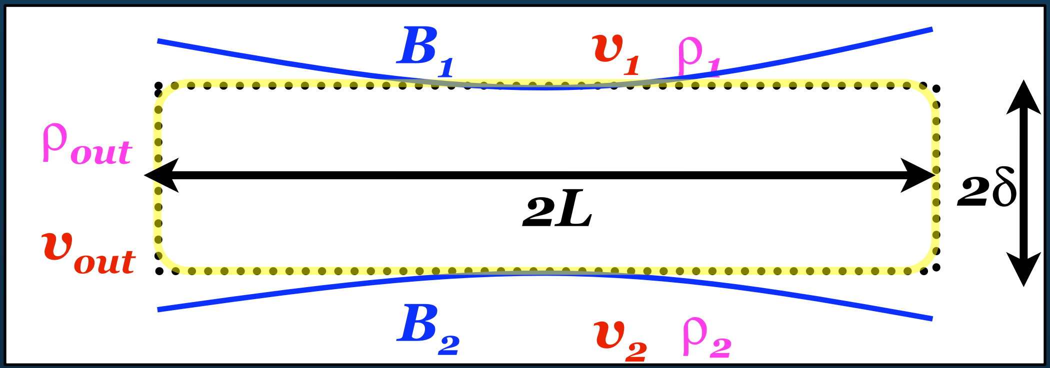
- Steady state diffusion relation (not L = D)
- Integrate conservation relations

Conservation of mass $\left(\rho_1 v_1 + \rho_2 v_2\right) L \sim \left(\rho_{out} v_{out}\right) 2\delta$

Conservation of momentum Pressure Balance

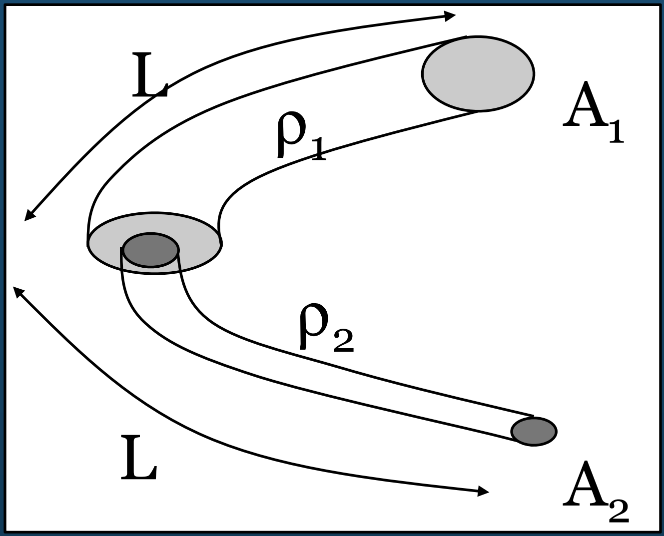
Conservation of Energy $\left(\frac{B_1^2}{8\pi} v_1 + \frac{B_2^2}{8\pi} v_2\right) L \sim \left(\frac{1}{2} \rho_{out} v_{out}^2\right) v_{out} 2\delta$

$\partial B/\partial t = 0$ $v_1 B_1 \sim v_2 B_2$



Asymmetric Scaling Relations

- Assume reconnected flux tubes mix and conserve total volume.
  - Each flux tube contains same amount of flux:
    - $B_1A_1 \sim B_2A_2$



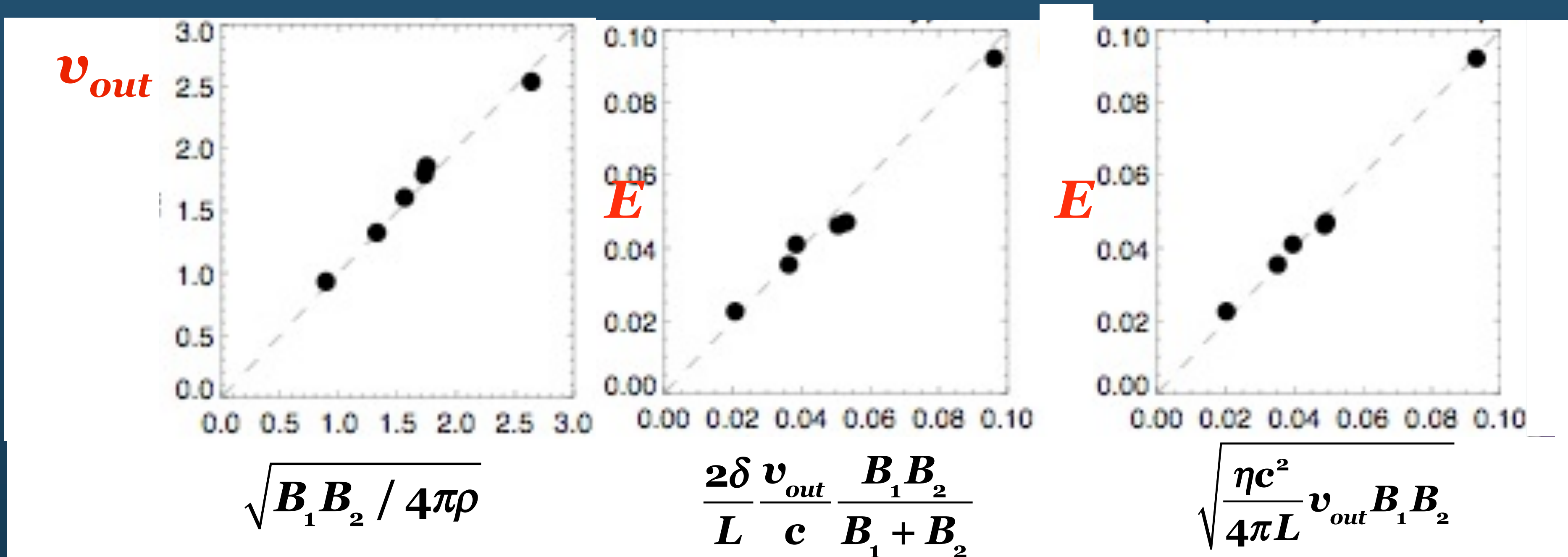
$$\rho_{out} \sim \frac{M}{V} \sim \frac{\rho_1 A_1 L + \rho_2 A_2 L}{A_1 L + A_2 L}$$

$$\Rightarrow \quad \rho_{out} \sim \frac{\rho_1 B_2 + \rho_2 B_1}{B_1 + B_2}$$

$$v_{out}^2 \sim \frac{B_1 B_2}{4\pi\rho_{out}} \quad \text{and} \quad E \sim \frac{1}{c}\left(\frac{2B_1B_2}{B_1+B_2}\right) v_{out}\frac{\delta}{L}$$

Verification of Scaling

- Scaling laws for outflow speed v_{out} and reconnection rate E in terms of geometry and upstream parameters tested



- Very good agreement
- Other studies find agreement:
  - Borovsky and Hesse, 2007 (anomalous resistivity MHD)
  - Birn et al., 2008 (Anomalous resistivity MHD)
  - Borovsky et al., 2008 (Global MHD)
  - Pritchett, 2008 (Kinetic PIC)

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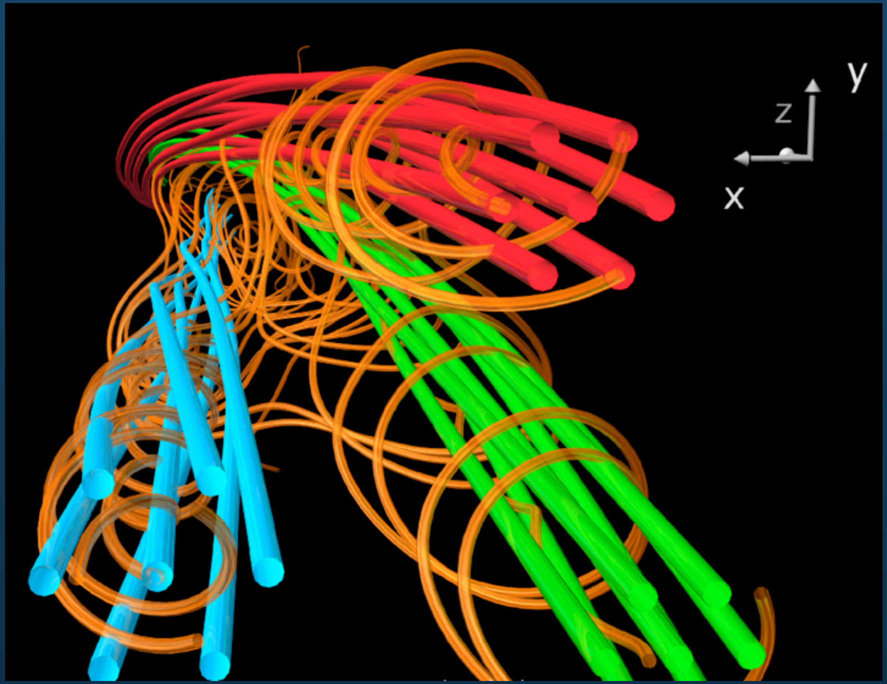
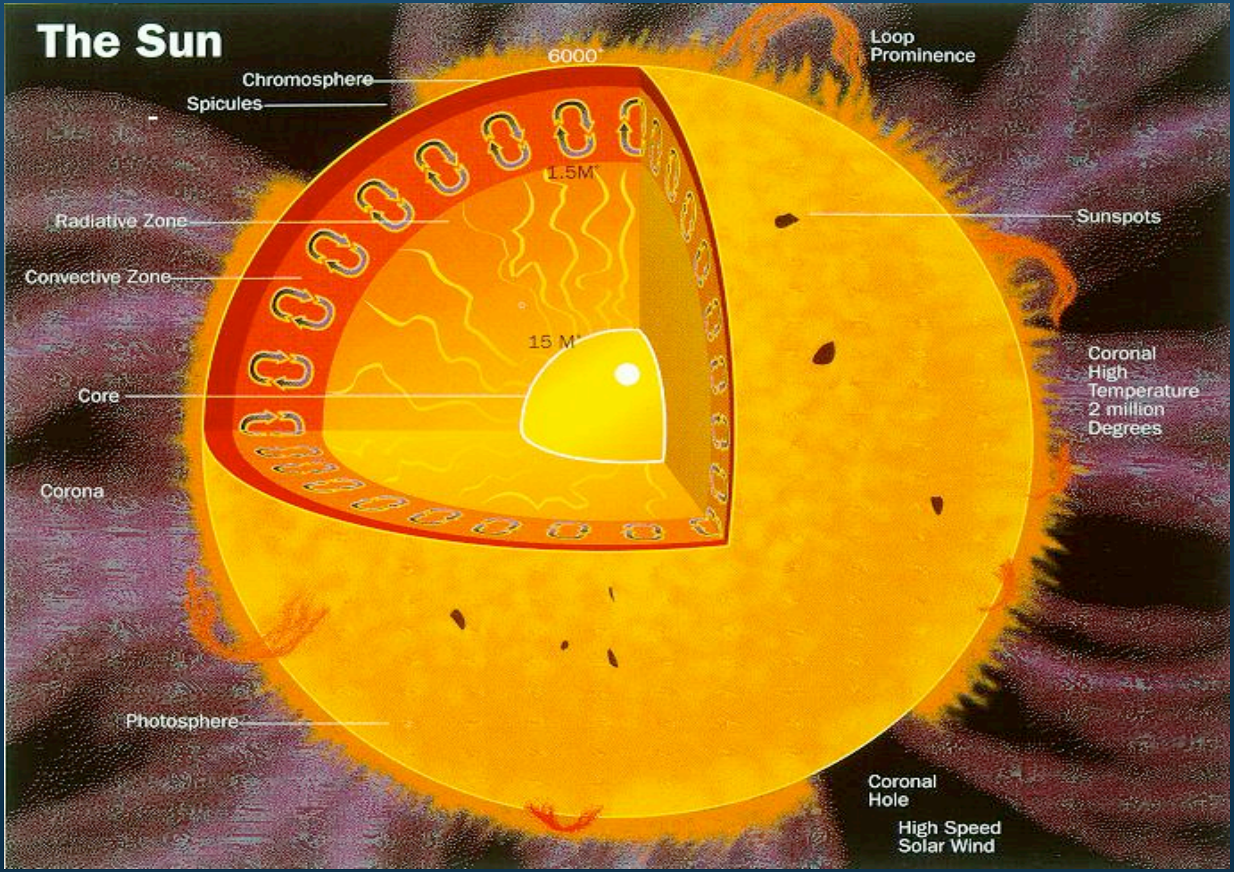
Laboratory Flux Ropes

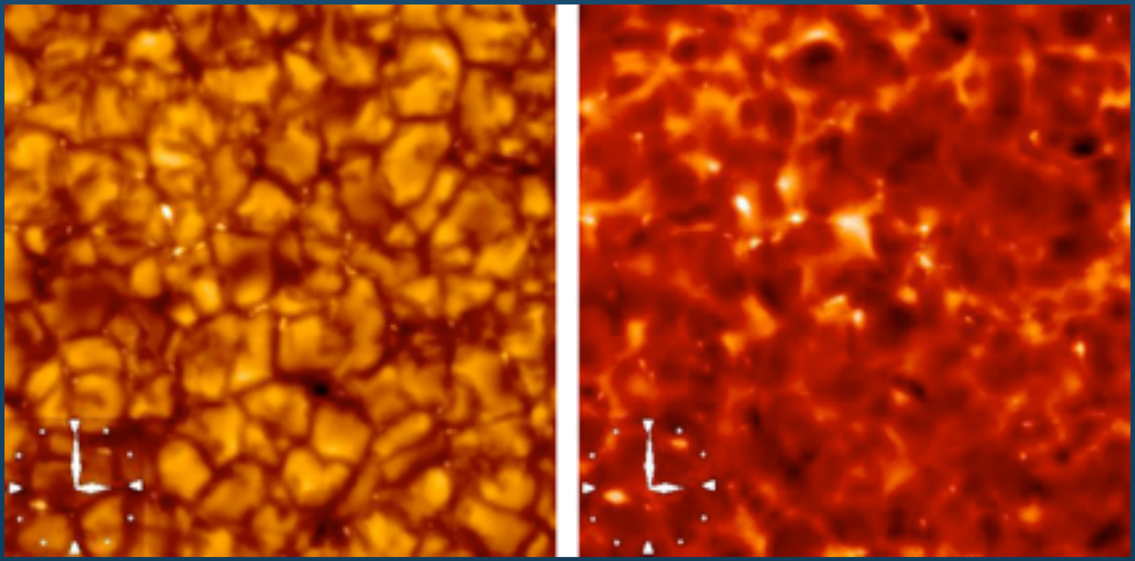
- Large Plasma Device (LAPD)
  - Gekelman, Carter, et al., 2012
- Measurements of magnetic flux ropes



Solar Structure



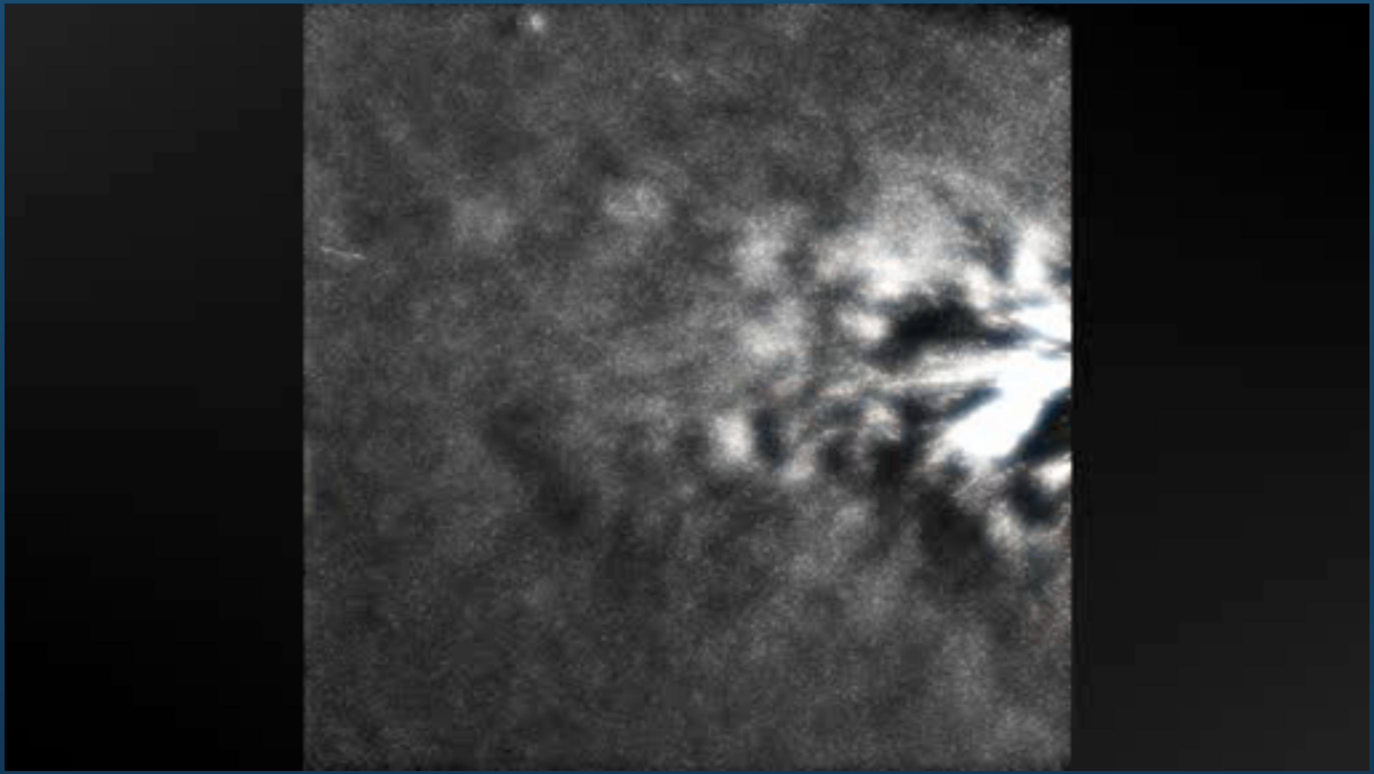
Solar Turbulence



Hinode (G-band 430nm and Ca II H 397nm)

- Granules
  - 1000km across
  - Convection cells across entire sun

The Solar Wind



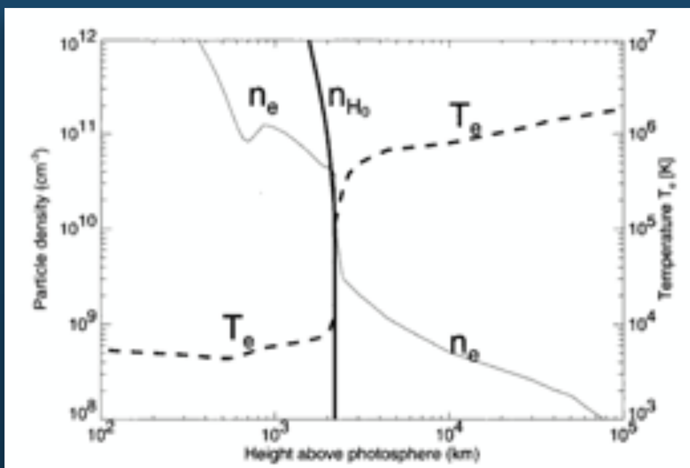
STEREO Spacecraft

630-730nm

- Continuous wind
  - Supersonic
  - Magnetic Field

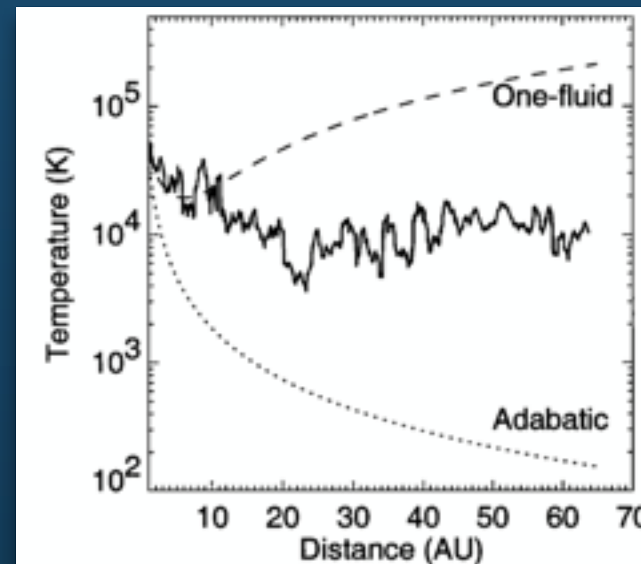
Plasma Heating - Magnetic Dissipation?

- Something is heating the solar corona



Model of Photosphere/Corona Transition
"Physics of the Solar Corona,"
Aschwanden, 2005.

- Something is heating the solar wind

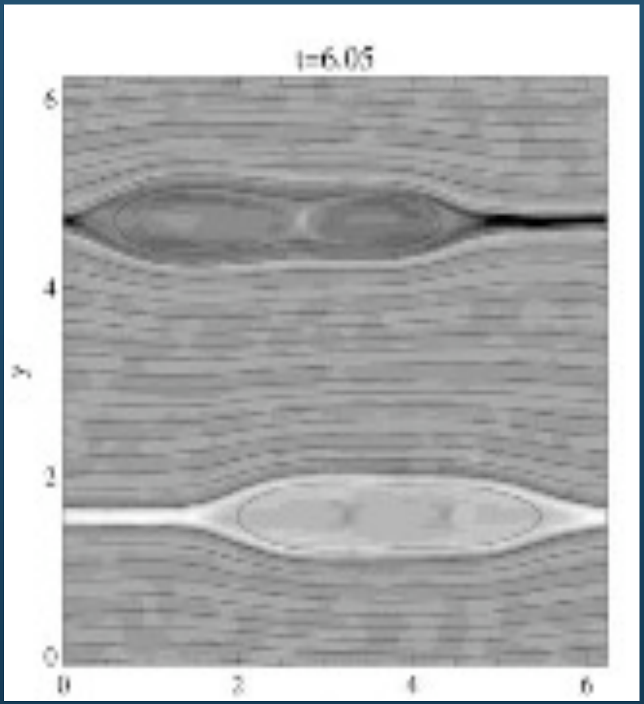


Wang et al., JGR, 106, 29401, 2001

Turbulent Reconnection

- System-sized current sheets with turbulence generated or added.
  - Matthaeus et al., 1986, 2003.
  - Malara et al., 1992
  - Kliem, 1995
  - Lazarian and Vishniac, 1999
  - Lapenta, 2008
  - Loureiro, 2009
- Typically see increases in reconnection rate due to turbulence (externally imposed and generated locally)
- Question: What are the properties of magnetic reconnection in a fully turbulent system?

Current

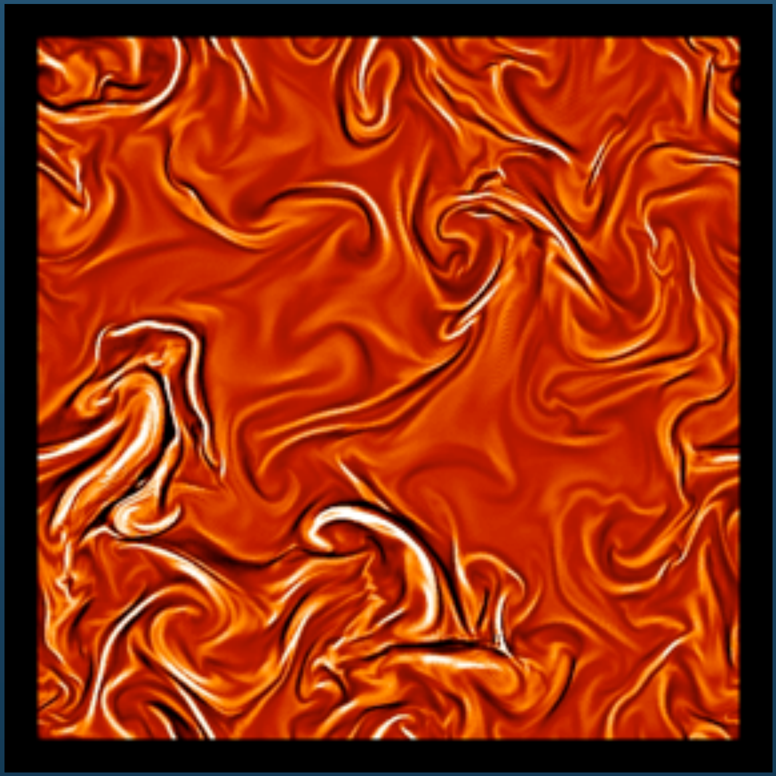


Dmitruk et al., 2003

Turbulent Reconnection

- Not well understood
- What is the nature of reconnection in turbulence?
- How do we describe it?
- How fast is turbulent reconnection?

- Different from Self-Generated Reconnection During Turbulence
  - This turbulence generates the reconnection.



2D MHD Turbulence Simulations

$$\frac{\partial \omega}{\partial t} = -(\boldsymbol{v}\cdot\boldsymbol{\nabla})\omega + (\boldsymbol{b}\cdot\boldsymbol{\nabla})\, j + R_\nu^{-1}\nabla^2\omega$$

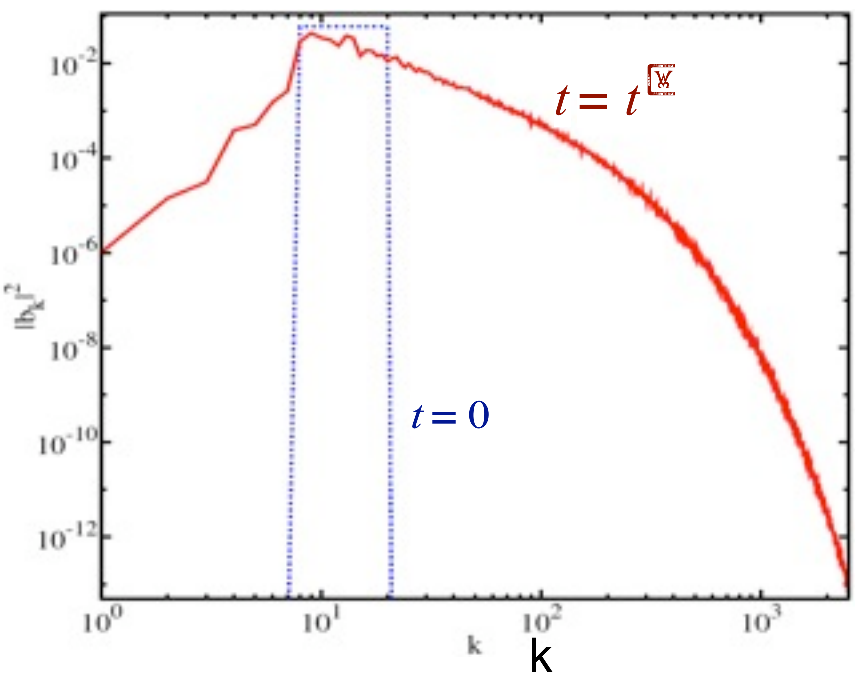
$$\frac{\partial a}{\partial t} = -(\boldsymbol{v}\cdot\boldsymbol{\nabla})a + R_\eta^{-1}\nabla^2 a$$

where: $\boldsymbol{b} = \boldsymbol{\nabla} a \times \hat{z}$, $\boldsymbol{v} = \boldsymbol{\nabla}\phi \times \hat{z}$, $j = -\nabla^2 a$, $\omega = -\nabla^2\phi$

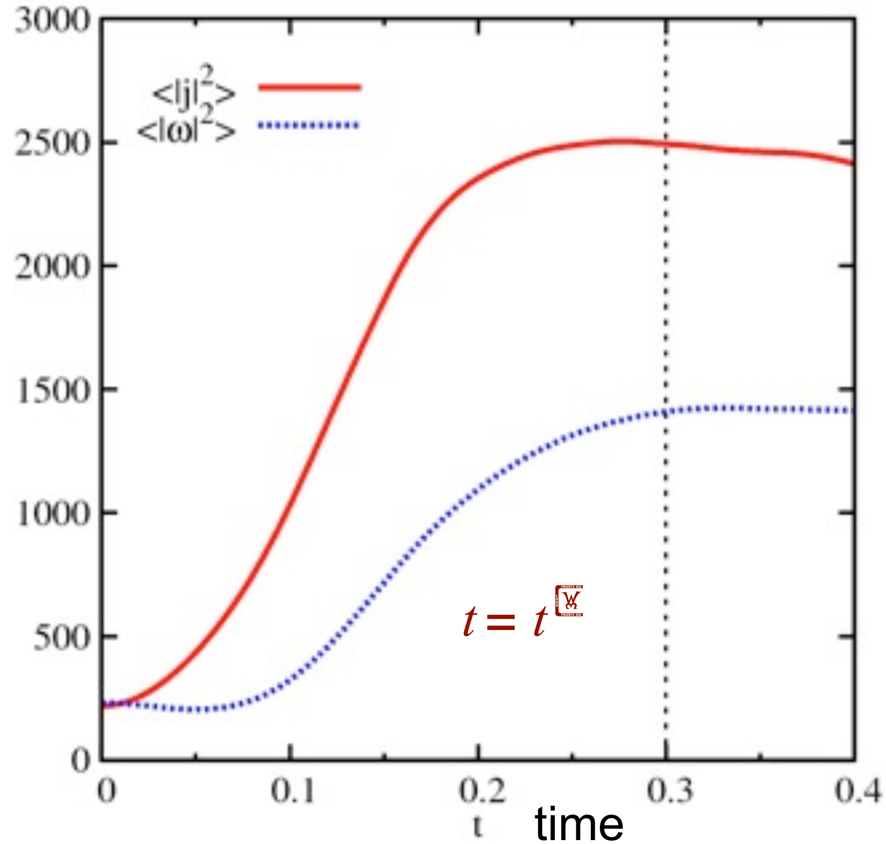
- Dealiased (2/3 rule) pseudo-spectral code.
- Resolution up to 8192^2 grid points
- $R_\eta = R_v = 5000$.
- Total Energy: $E = (½) \langle v^2+b^2 \rangle \sim 1$

2D MHD: Direct Numerical Simulations

Power Spectrum of B



Current and Enstrophy



- Energy is initially in $5 \leq k \leq 30$ (k in units of $1/L_0$)

2D MHD Turbulence Simulations

Color: J
Contours: a (gray: a>0, black: a<0)
Note: a = A (out of page)

(Only 1/40 of the box is shown)

- Intermittent J structures
- Magnetic dissipation
  - Plain Diffusion
  - Magnetic Reconnection
    - Notice x-lines!
- Magnetic Topology
  - Extremum (critical points) of a
  - O-lines:
    - Minimum and Maximum
  - X-lines:
    - Saddle points

Hessian Theory

- Study the Hessian of a to find extremum(critical points)
- Hessian: $$H^a_{i,j}(\mathbf{x}) = \frac{\partial^2 a}{\partial x_i \partial x_j}$$
- Critical points: $$x^* \rightarrow \nabla a = 0$$

Define: $$\lambda_R \equiv \frac{\lambda_{max}}{\lambda_{min}}$$

Connection to Diffusion Region $$\lambda_R \approx \sqrt{\frac{\ell}{\delta}}$$

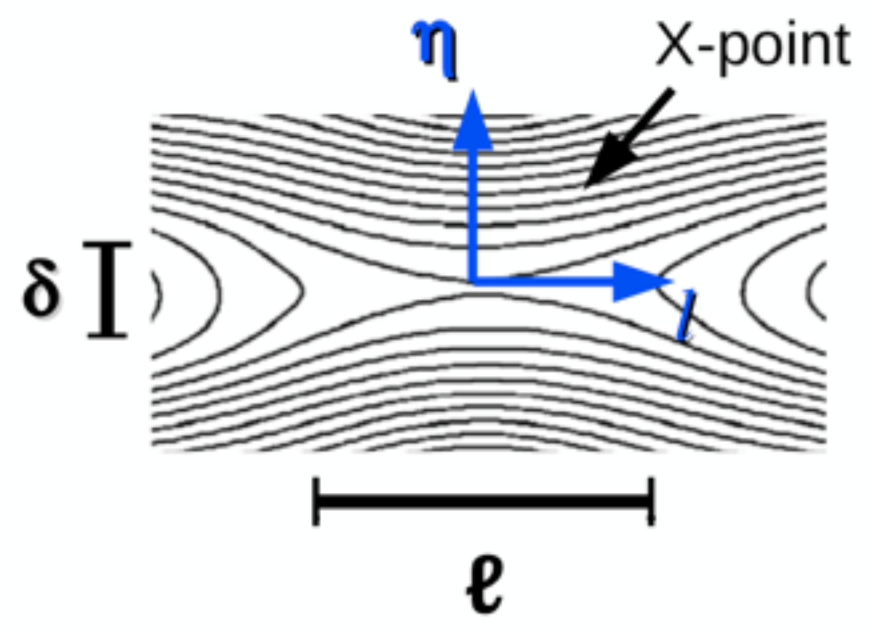
eigenvalues

eigenvectors

$$\lambda_{\max} = \frac{\partial^2 a}{\partial \eta^2}$$

$$\lambda_{\min} = \frac{\partial^2 a}{\partial l^2}$$

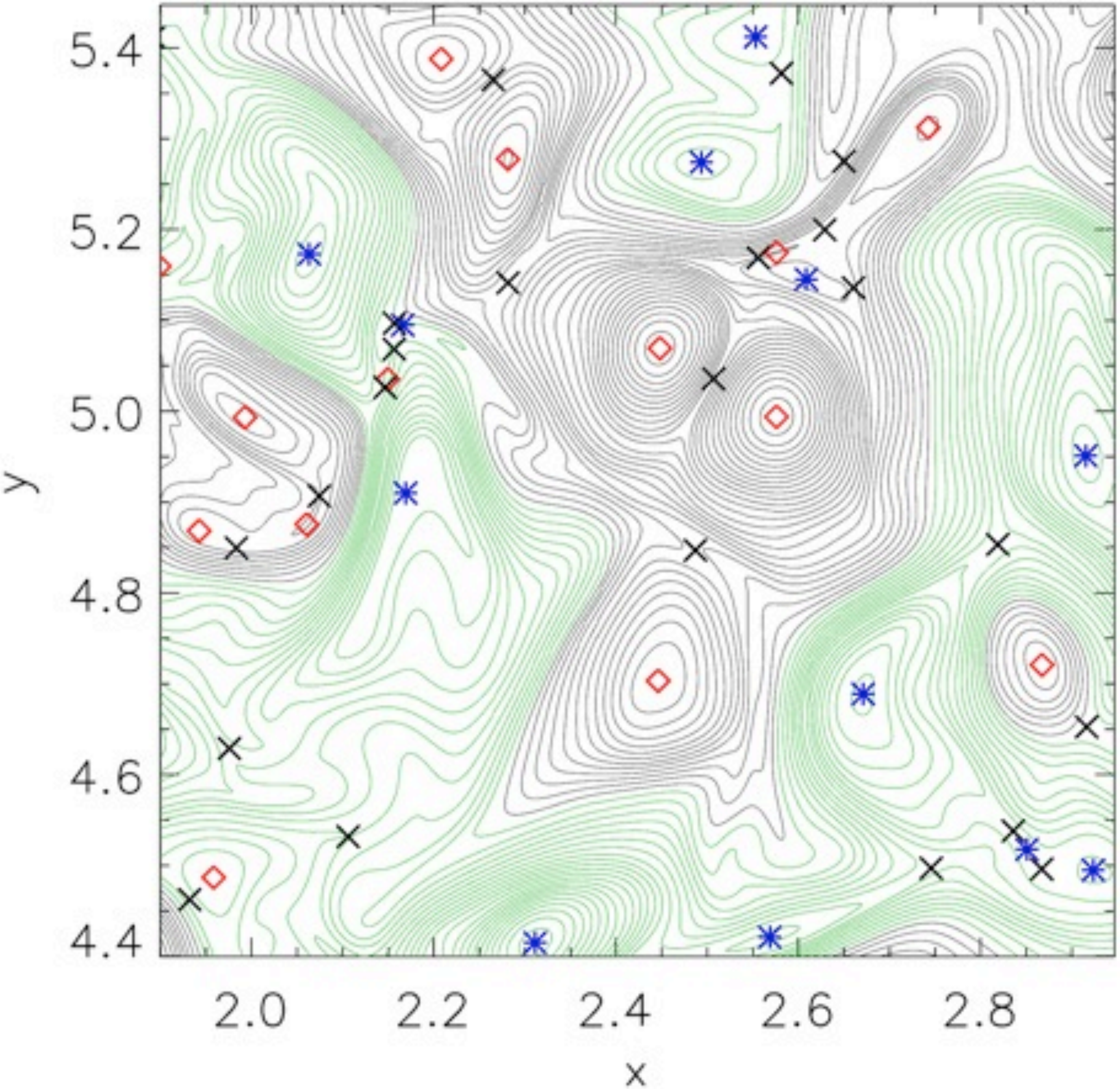
$$\left\{ \vec{\mathbf{S}}_\eta, \vec{\mathbf{S}}_l \right\}$$



D. Biskamp, *Magnetic Reconnection in Plasmas* (Cambridge Univ. Press, Cambridge, 2000).

S. Rana, Surface *Topological Data Structures* (John Wiley & Sons, Chichester, England, 2004).

Critical Points in Turbulence



Magnetic potential *a* and critical points

a > 0

a < 0

maximum ✳

minimum ◇

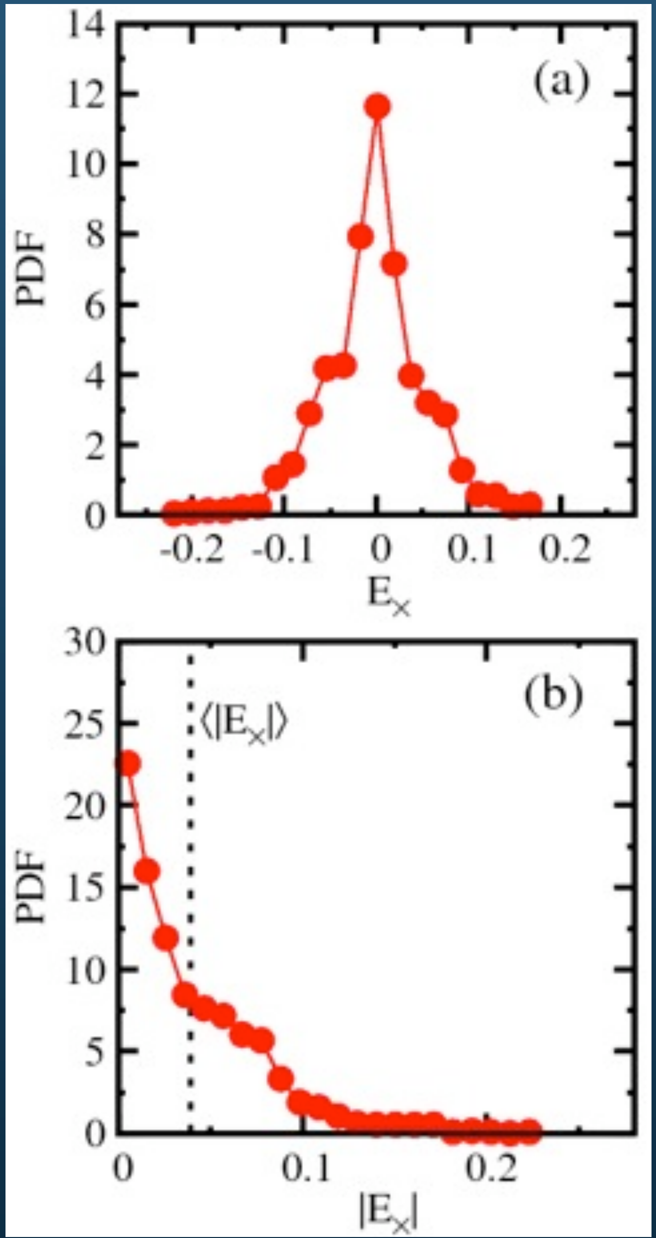
X-point x

Distribution of Reconnection Rates

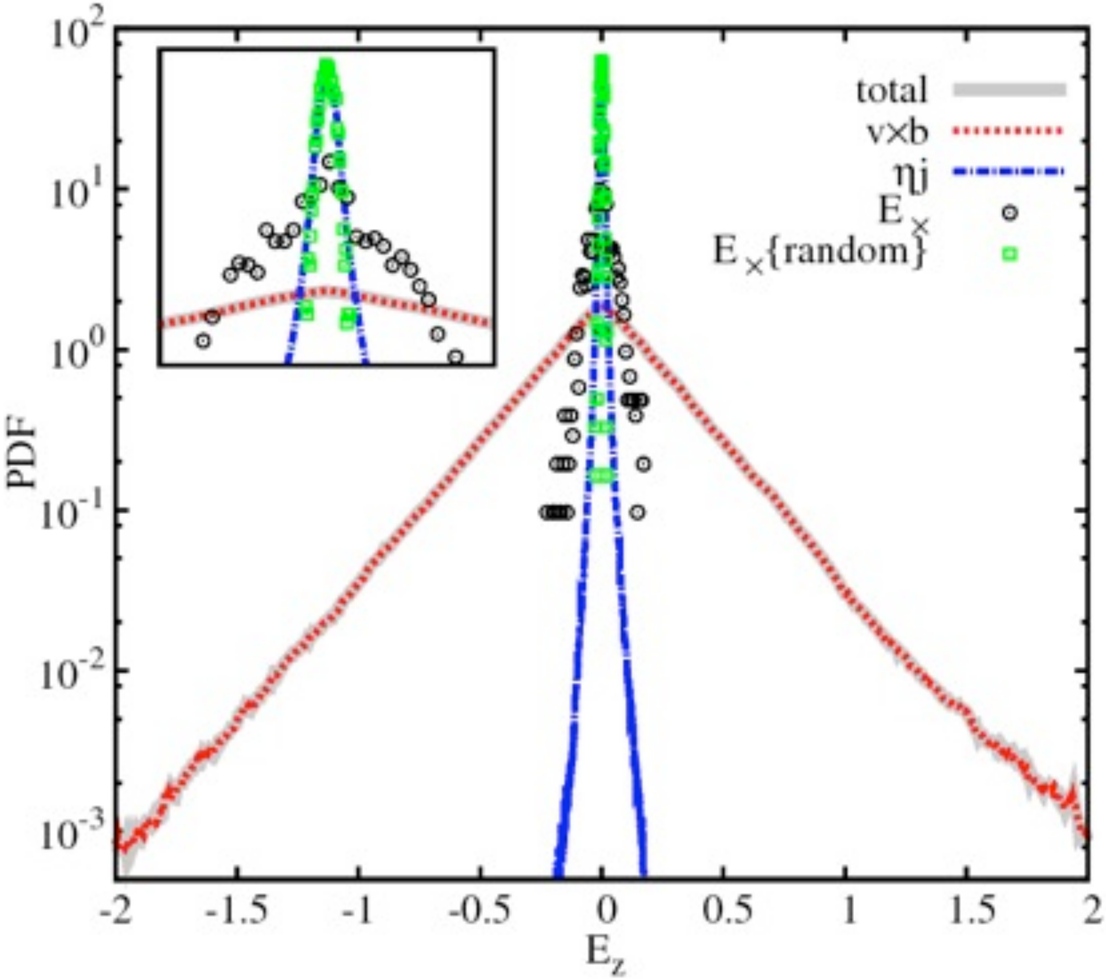
$$\dot{a} = R_\mu^{-1} \nabla^2 a \,|_{\times-\mathrm{point}} = -E_\times$$

Normalized to the root mean-square magnetic fluctuation δb^2_{rms}

- Reconnection rates are broadly distributed
- Turbulence can be viewed as a sea of reconnecting islands with different reconnection rates.



Statistics of the Electric Field



How much of electric field *contributes* to reconnection?

$$E = -\frac{v}{c} \times b + \eta\, j$$

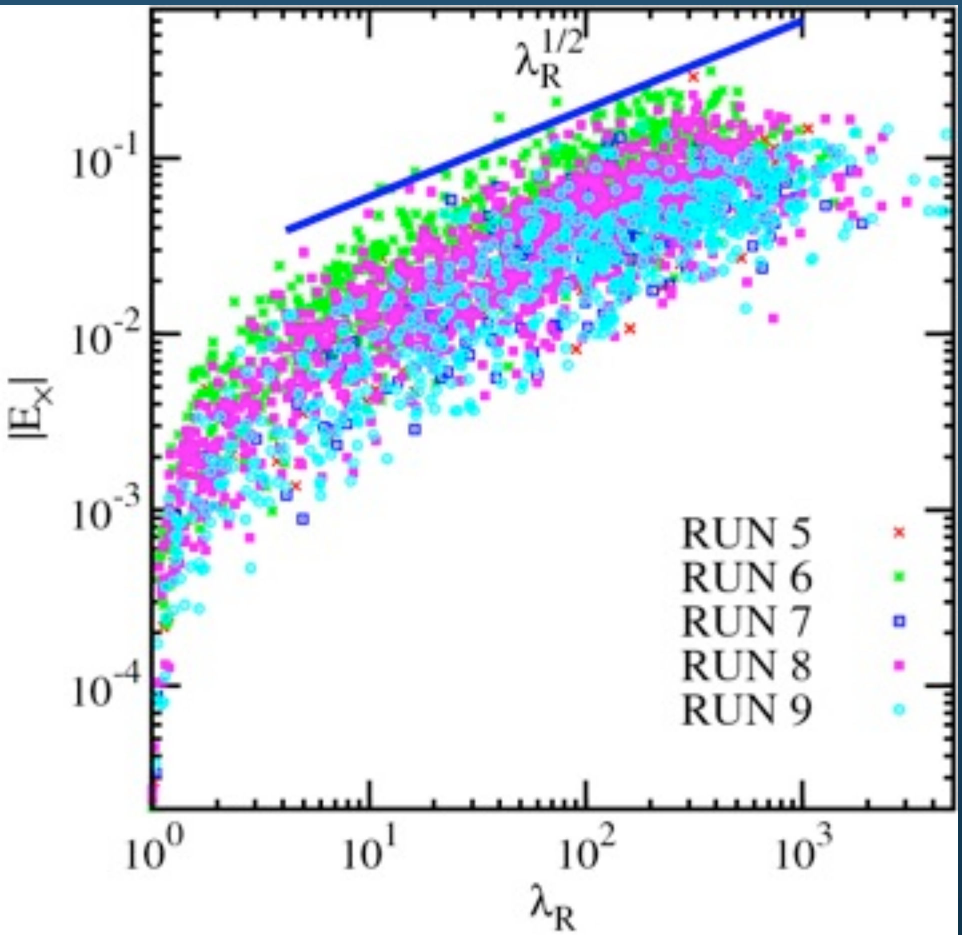
PDF($E_{v\times b}$) is typical of solar wind plasmas

Milano *et al. PRE* (2002), Breech *et al.* JGR(2003)

$$E_{v\times b} > E_\times > E_{\eta j}$$

- In General: Convection > Reconnection > Diffusion

R. Rate Geometry Dependence



- Highest R. Rates scale with diffusion region geometry

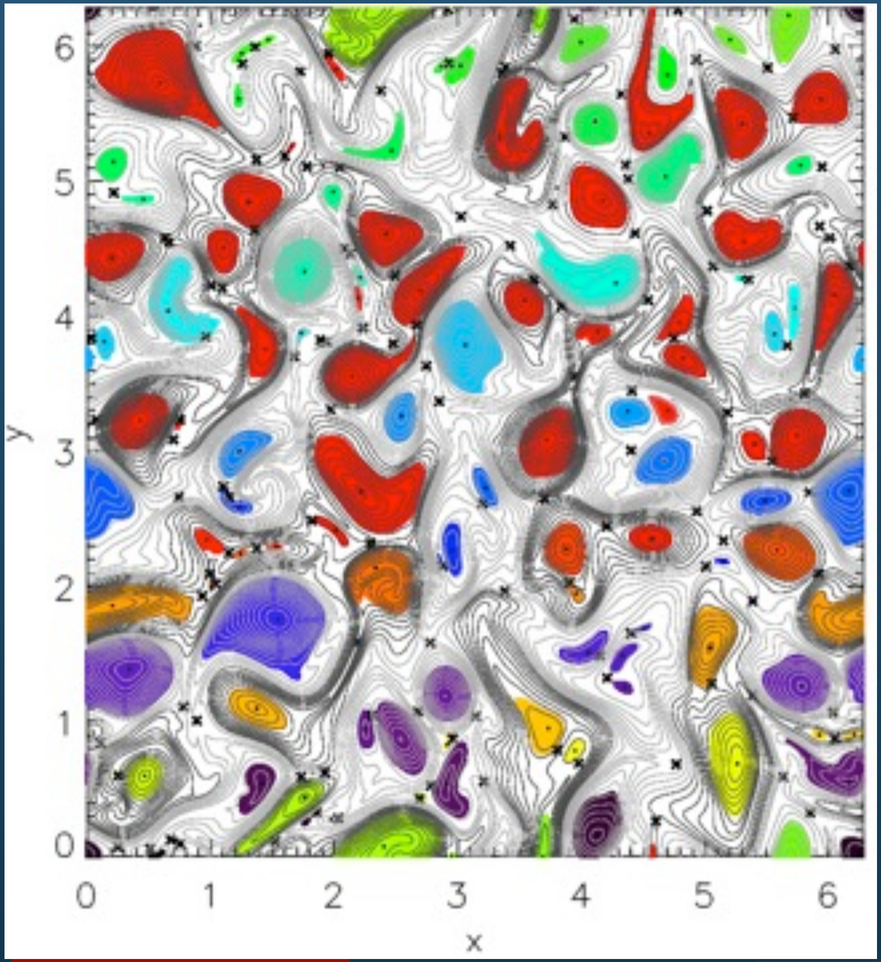
$$\lambda_R \equiv \frac{\lambda_{max}}{\lambda_{min}}$$

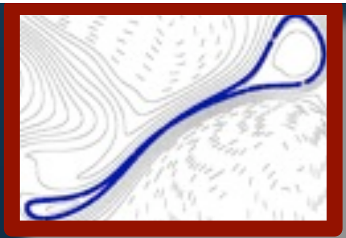
$$\text{Since } \frac{\delta}{D} \equiv \frac{\delta}{\ell} \approx \sqrt{\frac{1}{\lambda_R}}$$

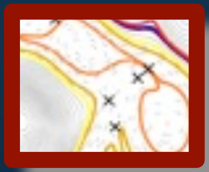
$$E_\times \sim \frac{D}{\delta}$$

- At first glance:
  - Opposite of normal Reconnection prediction!

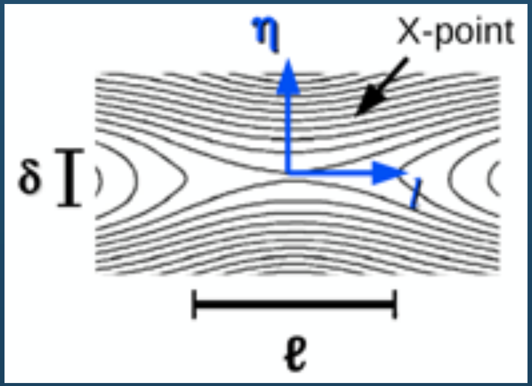
Complexity of Reconnection







- How do we characterize this complex reconnection?
  - Hessian Eigenvalues



  - Examine each x-line
    - Determine δ,ℓ, and B
    - E_X(th.) vs. E_x (exp.)

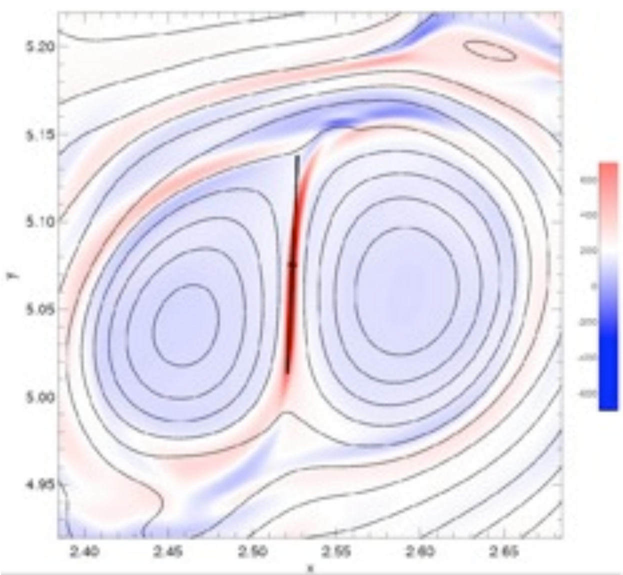
Dimensions of the Diffusion Region

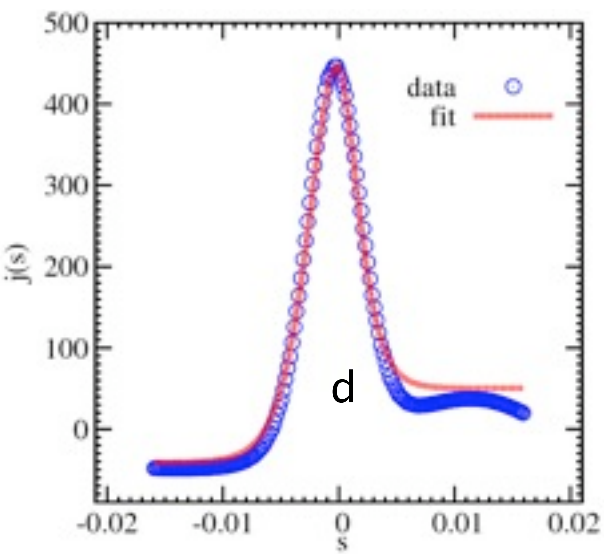
- Hessian eigenvectors
  - Fit determines δ, B_{up1}, B_{up2}

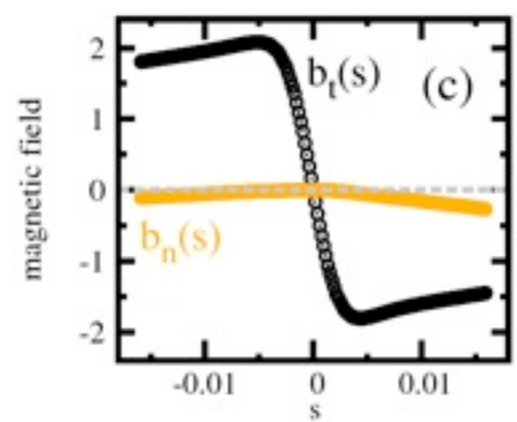
$$J_z = A_1\, sech^2\left(\frac{s-s_0}{\delta_1}\right) \quad \{s \geqslant s_0\}$$

$$J_z = A_2\, sech^2\left(\frac{s-s_0}{\delta_2}\right) \quad \{s < s_0\}$$

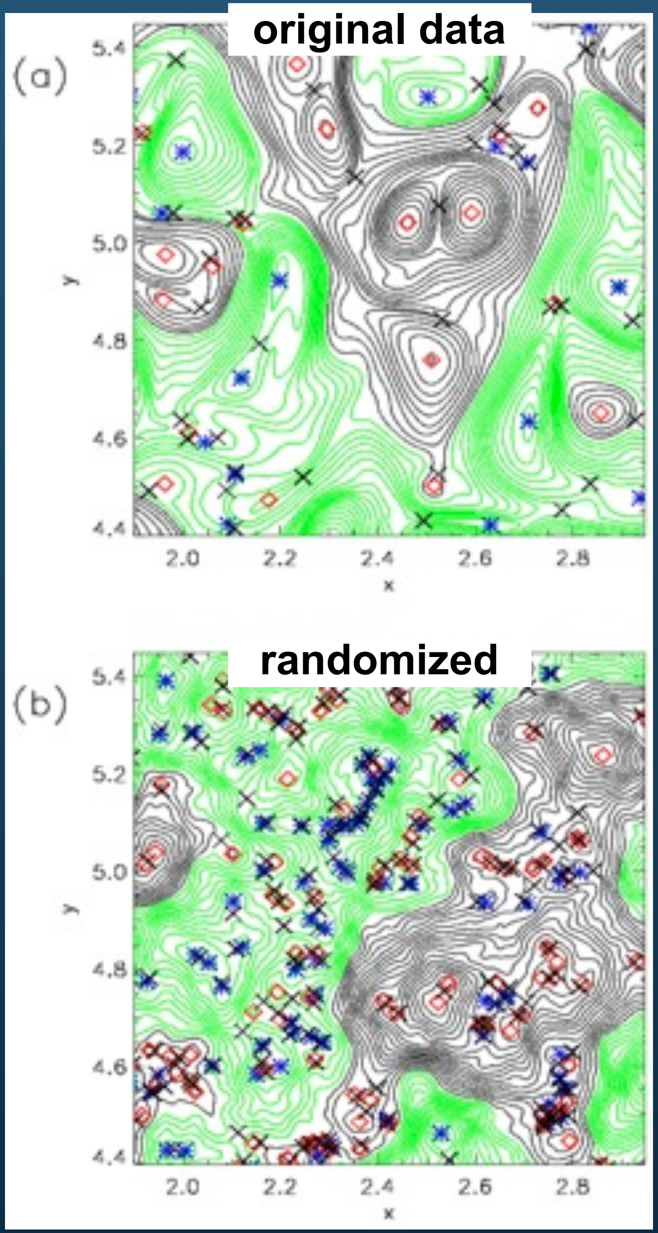
$$\ell \simeq \delta \sqrt{\frac{\lambda_{max}}{\lambda_{min}}}$$



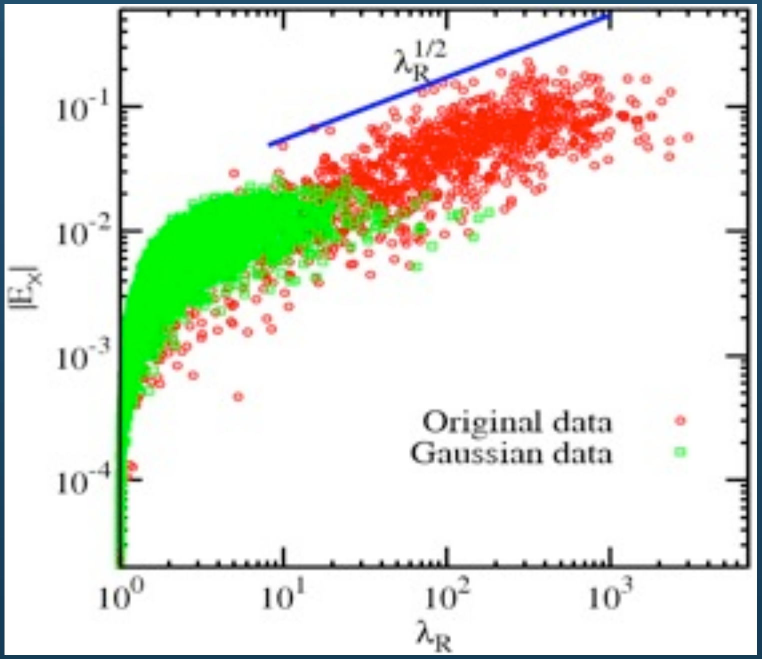




Coherence Key for Reconnection

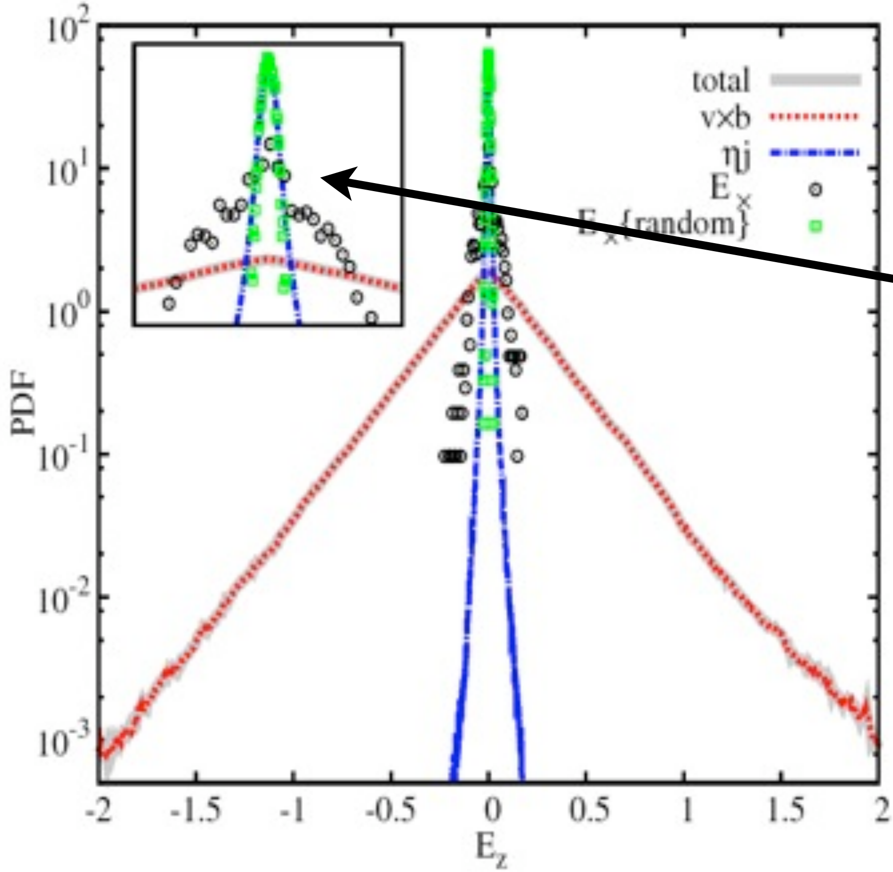


- Randomize a → slower reconnection



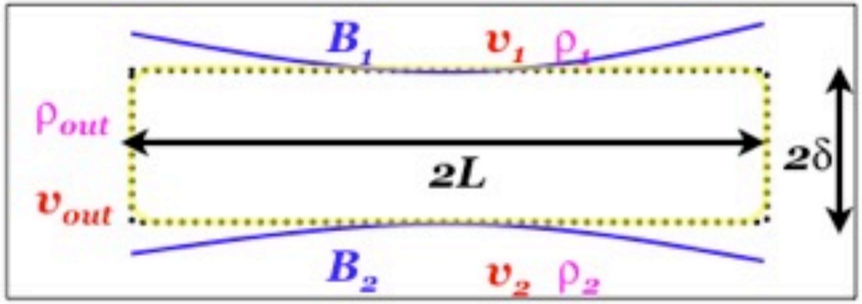
- Reconnection in turbulence not described by random phases.
  - Could lead to errors in test-particle calculations.

Coherence Key



- Intermittency
  - Current sheets
  - Non-gaussian pdfs
- Phases in k-space very important!

Asymmetric Reconnection



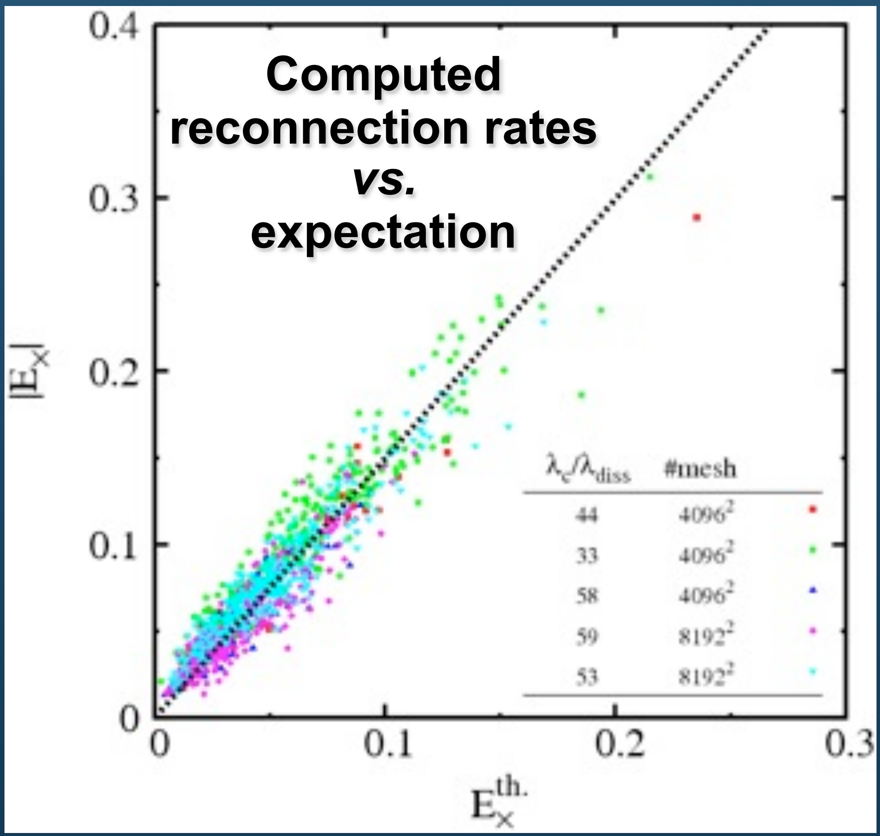
- Examine conservation laws
  - Mass density, Energy

Outflow speed $$v_{out}^2 \sim \frac{B_1 B_2}{4\pi} \frac{B_1 + B_2}{\rho_1 B_2 + \rho_2 B_1}$$

Reconnection Rate $$E \sim \frac{1}{c}\left(\frac{\rho_{out} B_1 B_2}{\rho_1 B_2 + \rho_2 B_1}\right) v_{out} \frac{2\delta}{L}$$

- Borovosky et al., 2007, Cassak and Shay, 2007, 2008, Swisdak et al., 2007, Pritchett et al., 2008.

Reconnection Rate in Turbulence



$$E_\times = \sqrt{\frac{b_1^{3/2} b_2^{3/2}}{R_\mu D}}$$

- Asymmetric Reconnection model organizes data
  - Only coherent current sheet x-lines
  - Turbulence determines SP parameters
    - B_{up}
    - D

Servidio *et al.*, Phys Rev. Lett. (2009).

- Very Surprising:
  - Remember:
  - MHD smashing islands together much faster than reconnection.
  - Sweet-Parker assumes Steady-State!
    - Yet, somehow it works.

How can quasi-steady theory be valid?

- We have limited ourselves to very actively reconnecting islands.
- What does it take to get “fast” reconnection?
  - Continuous pushing for a “long” time.
  - A quick bounce between islands won't do it.
  - Continuous pushing => “Quasi-steady” reconnection.

- Examine time dependence of reconnection rates.

Only Scratched the Surface

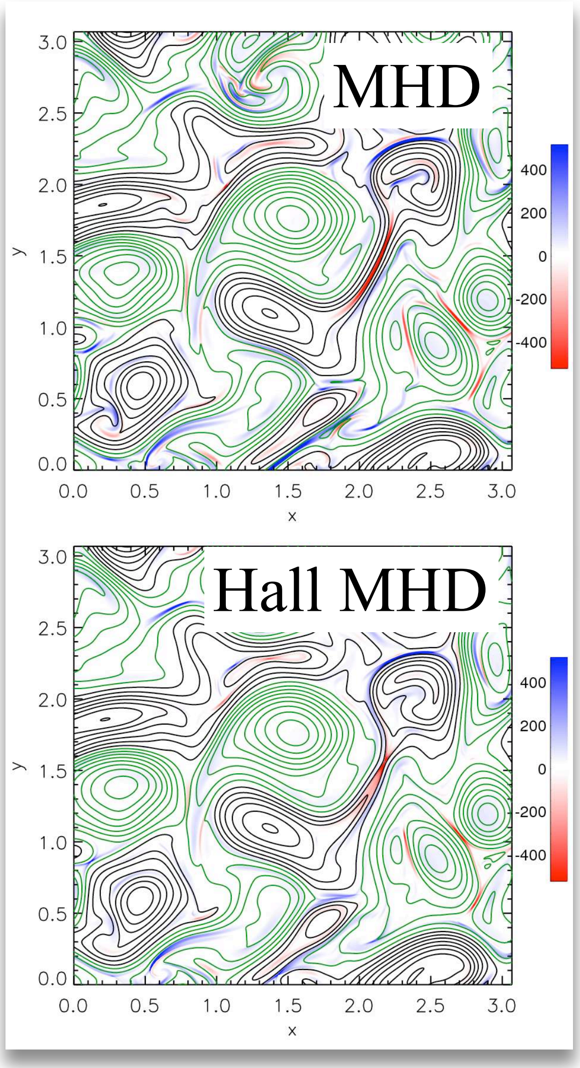
- Velocities
  - Properties
  - Viscous damping?
- Dynamic time behavior of x-lines?
  - Typical time scale for reconnection?
    - Onset, fast, decay
    - Quasi-steady assumption okay?
- Collisionless plasma
  - Hall term: Donato et al., Submitted, 2012.
- Three-dimensional simulations
- Kinetic PIC Simulations

Numerical Issues

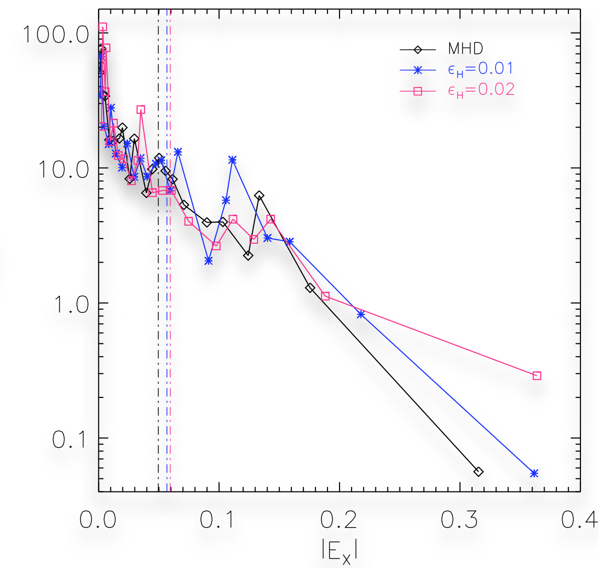
- Even harder than “simple” reconnection simulations.
  - Regular MHD:
    - $\delta_{dissipation} << L_{eddy} << L_{driving}$
  - Kinetic PIC (forget it)
    - $\delta_e << \delta_i << L_{eddy} << L_{driving\ scale}$
- MHD
  - Direct numerical simulations expense
  - Very careful to resolve dissipation
    - Will still get Energy spectra with unphysical dissipation.
- Kinetic

Hall MHD Turbulence (2D)

- Initial Study of Hall MHD Reconnection
  - Donato et al., submitted, 2012.
- Hall MHD
  - Stronger current sheets
  - Higher Rates



PDF of E_x



Kinetic PIC Smulation

- Two Dimensional Kelvin Helmholtz Simulations
  – Karimabadi et al, In Preparation, 2012.

Do We Care?

- So we need current sheets for the reconnection.
  - So?
- Key Question:
  - Are current sheets and magnetic reconnection critical to understand the dissipation in turbulence?
    - Yes! (says a believer in reconnection)
    - However
      - Dissipation in turbulence often characterized through wave analysis (random phases).

Conclusions

- Self-organization processes in turbulence produce coherent current sheets
- Hessian analysis of extrema
  - Broad range of reconnection rates
- Asymmetric Sweet-Parker analysis
  - Organizes coherent x-line current sheets
  - Very surprising (Quasi-steady theory works!)
- Robustly Reconnecting current sheets are strongly coherent
  - Random phase approximation not necessarily valid.