Computing the Reconnection Rate in Turbulent Kinetic Layers

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Major Uncertainties in Reconnection ?

- Current understanding is based mostly on 2D simulations. *How does reconnection really work in 3D?*

- Influence of turbulence ?

  Matthaeus & Lamkin, 1985,1986
  Lazarian and Vishniac, 1991
  Kim & Diamond, 2001
  Kowal et al, 2009
  Loureiro et al, 2009

  Chaotic 3D magnetic fields?

  Eyink, Lazarian & Vishniac, 2011
  Guo, Dimond & Wang, 2012
  Eyink et al 2013
  Boozer 2012, 2013

- Do these effects fundamentally alter reconnection?

- Role of kinetic effects in collisionless regimes?

- System size dependence → Large vs asymptotically large?

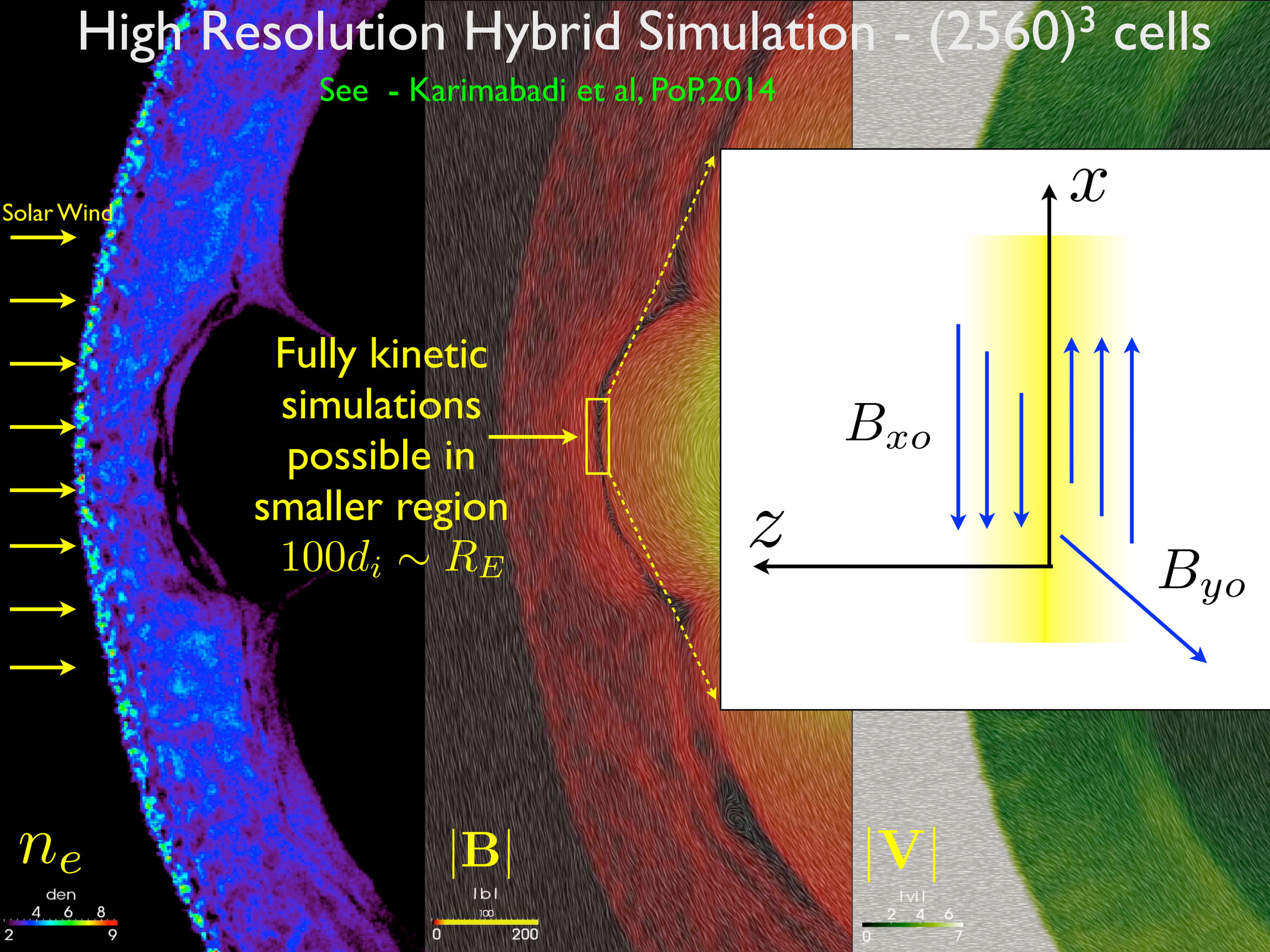
- Earth's magnetosphere is a nice reality check

Magnetic Reconnection in the Magnetosphere

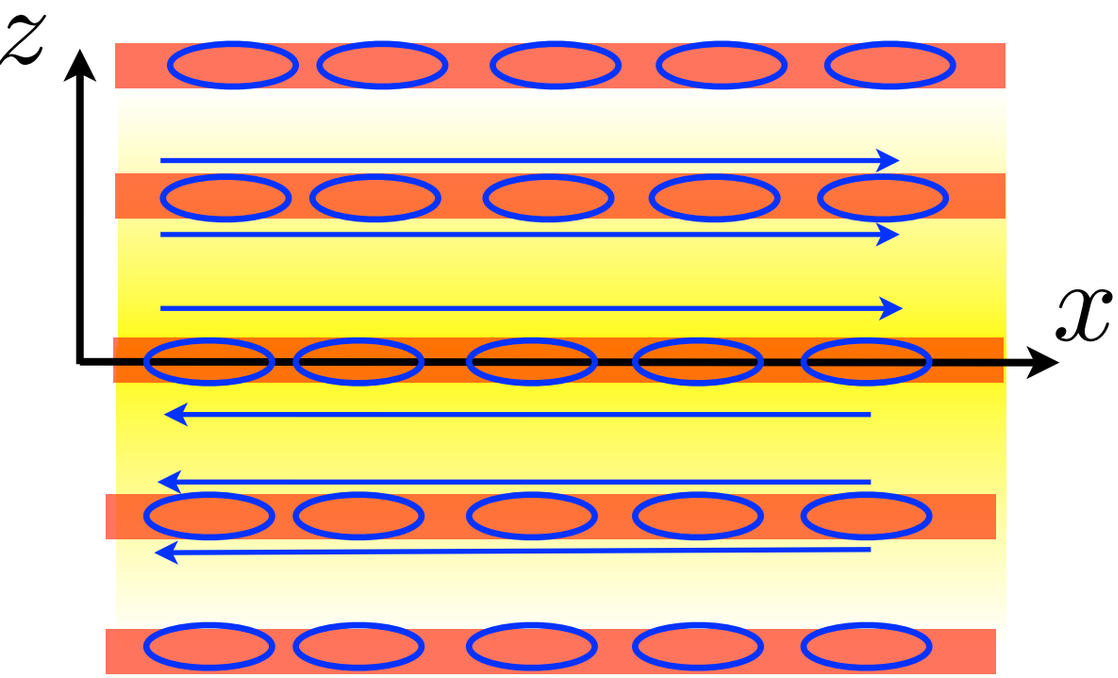
- Onset occurs in ion-scale current layers
- Nonlinear evolution produces electron layers
- Electron physics is a main focus of MMS mission
- Layers potentially unstable to: tearing → islands, +velocity shear & streaming instabilities ...
- Tearing islands from 2D are really flux ropes in 3D which can interact and drive turbulence
- Influence on reconnection rate & mixing ?
- We are studying these issues with large-scale kinetic simulations - both hybrid and **fully kinetic**

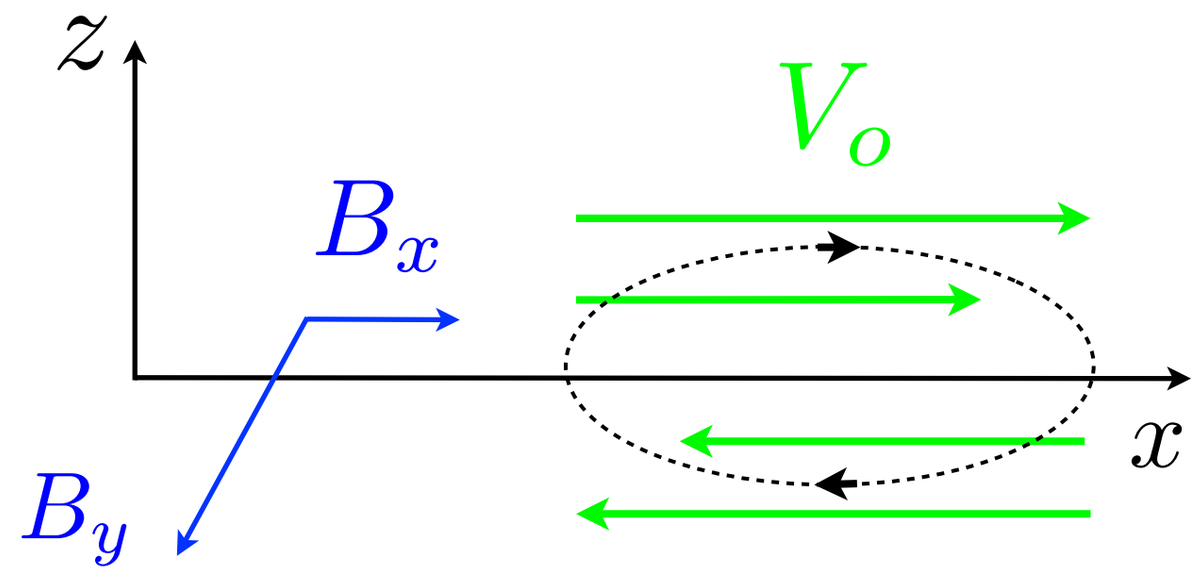
High Resolution Hybrid Simulation - $(2560)^3$ cells

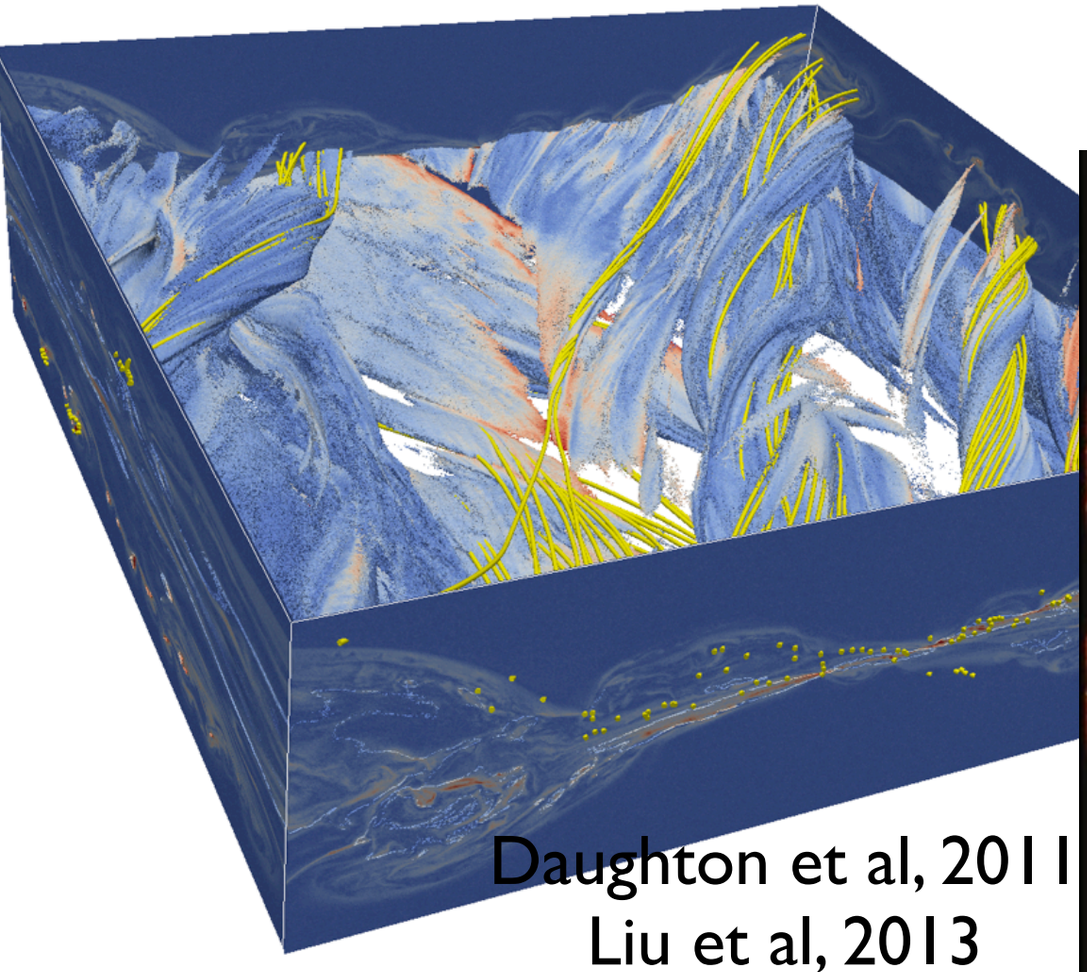
See - Karimabadi et al, PoP,2014



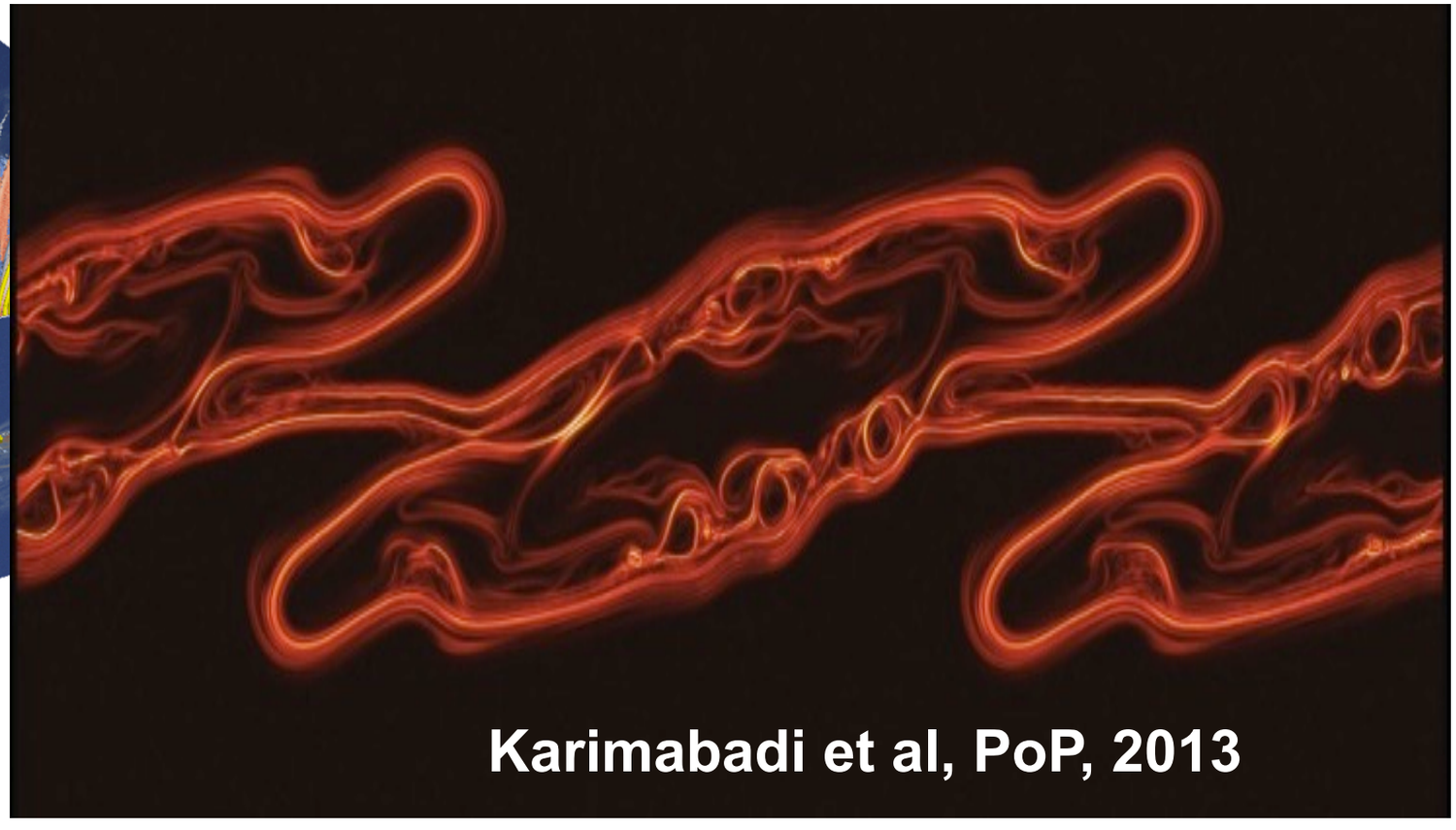
Mechanisms to Drive Turbulence at Magnetopause







Daughton et al, 2011
Liu et al, 2013



Karimabadi et al, PoP, 2013

How to compute 3D reconnection rate?

$$\frac{d\Phi}{dt} \propto \int_{s_1}^{s_2} E_{\|} ds$$

- Find topological separators

Global Magnetosphere	→	Dorelli & Bhattacharjee, 2009 Haynes & Parnell, 2010 Komar, Cassak et al, 2013
Local Kinetic Simulation ?	→	Olson & Dorelli ..., 2014

- GMR = Generalized Magnetic Reconnection, *Hesse et al.*, 2005

Wendel et al., 2013 → Open BC

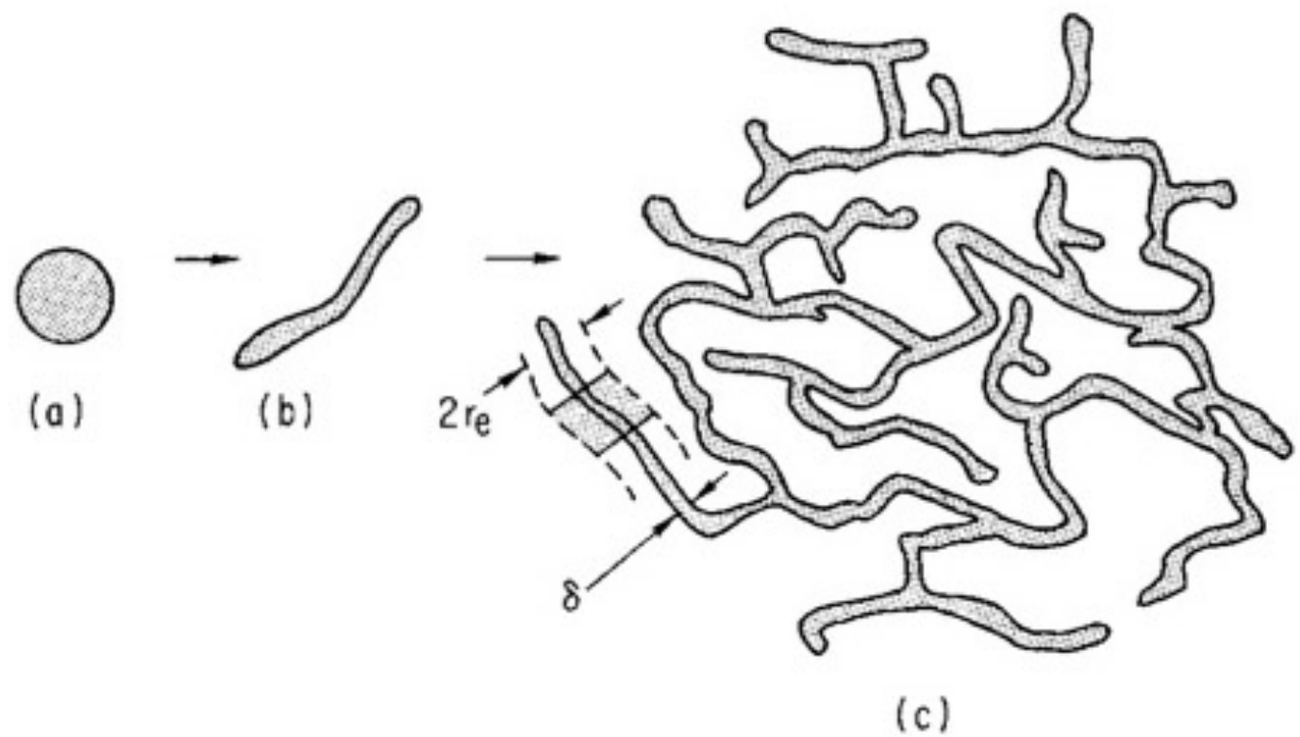
Yi-Hsin Liu, et al., 2013 → Double Periodic

Finn et al., 2013 → Line-tied

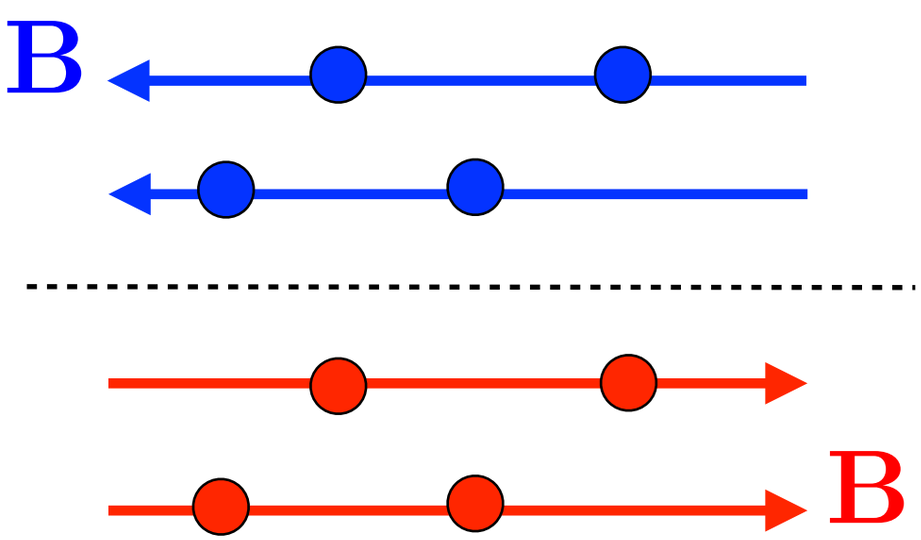
- Generalized Flux Function - Yeates & Hornig, 2011

Here we suggest a new approach which exploits the following connection:

Mixing of magnetic field lines ⟷ Mixing of electrons across layer



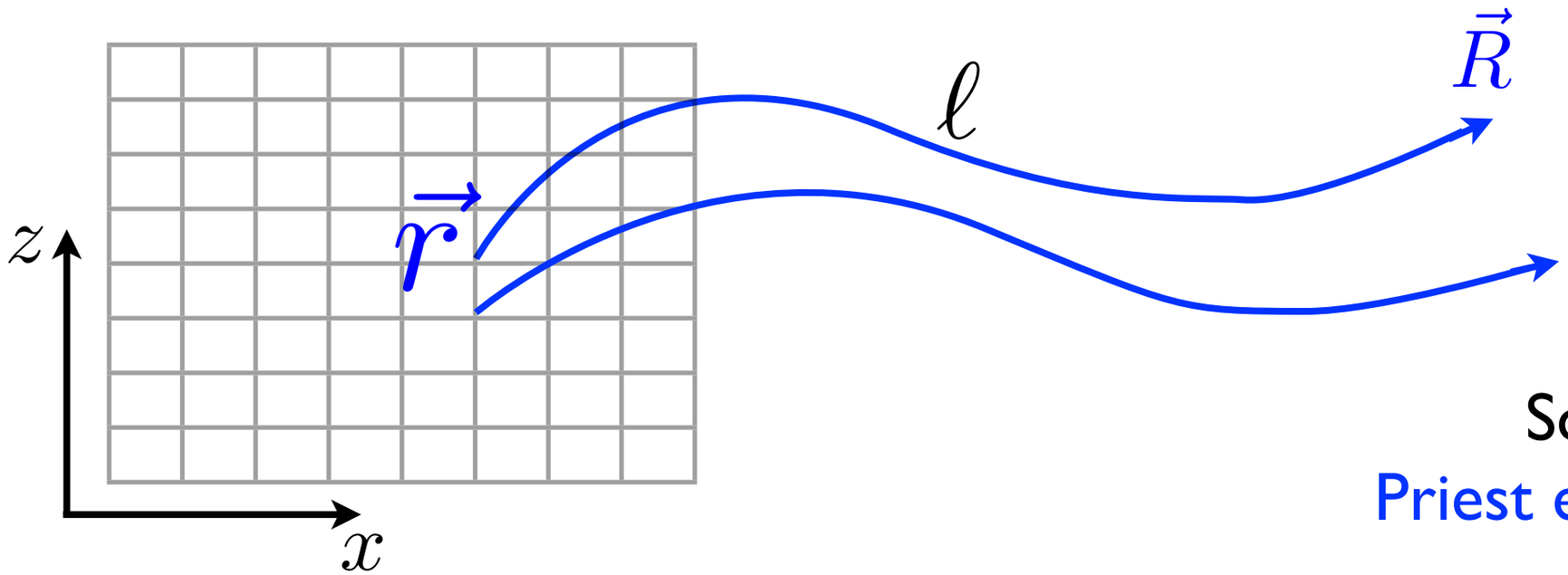
Rechester & Rosenbluth PRL, 1978



Mixing Fraction

$$\mathcal{F}_e = \frac{n_e^{bot} - n_e^{top}}{n_e^{bot} + n_e^{top}}$$

How to Quantify Structure of 3D Field ?

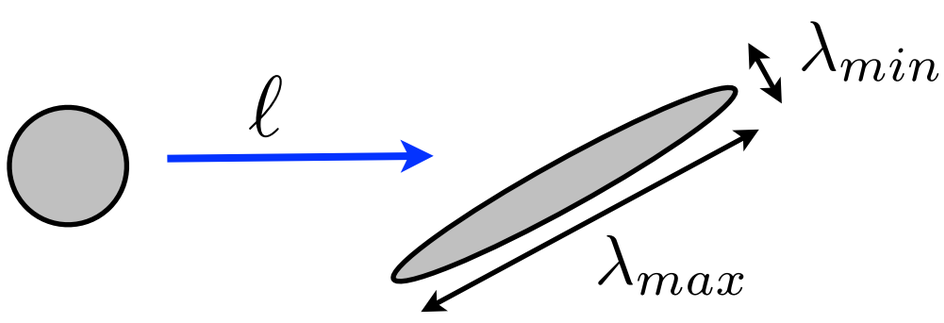


$$\mathbf{J} = \frac{\partial \vec{R}}{\partial \vec{r}}$$

Squashing Factor -
Priest et al, 95, Titov et al, 02

Displacement Tensor

$$\mathbf{D} = \mathbf{J}\mathbf{J}^{\mathbf{T}} \xrightarrow{\text{eigenvalues}} Q \approx \left(\frac{\lambda_{max}}{\lambda_{min}}\right) = \mathrm{e}^{2\sigma(\ell)}$$



$$\frac{\lambda_{max}}{\lambda_{min}} = \mathrm{e}^{2\sigma(\ell)}$$

Lyapunov exponent
see - Boozer PoP 13

$$k_L \equiv \lim_{\ell \to \infty} \frac{\sigma(\ell)}{\ell}, \quad \text{where}$$

$$\sigma(\ell) \equiv \lim_{\delta_0 \to 0} \ln\left(\frac{\delta(\ell)}{\delta_0}\right)$$

Example #1 - Subsolar magnetopause

Asymmetric Layer

$$n_{bot} = 8n_{top} \qquad T_i = 2T_e$$

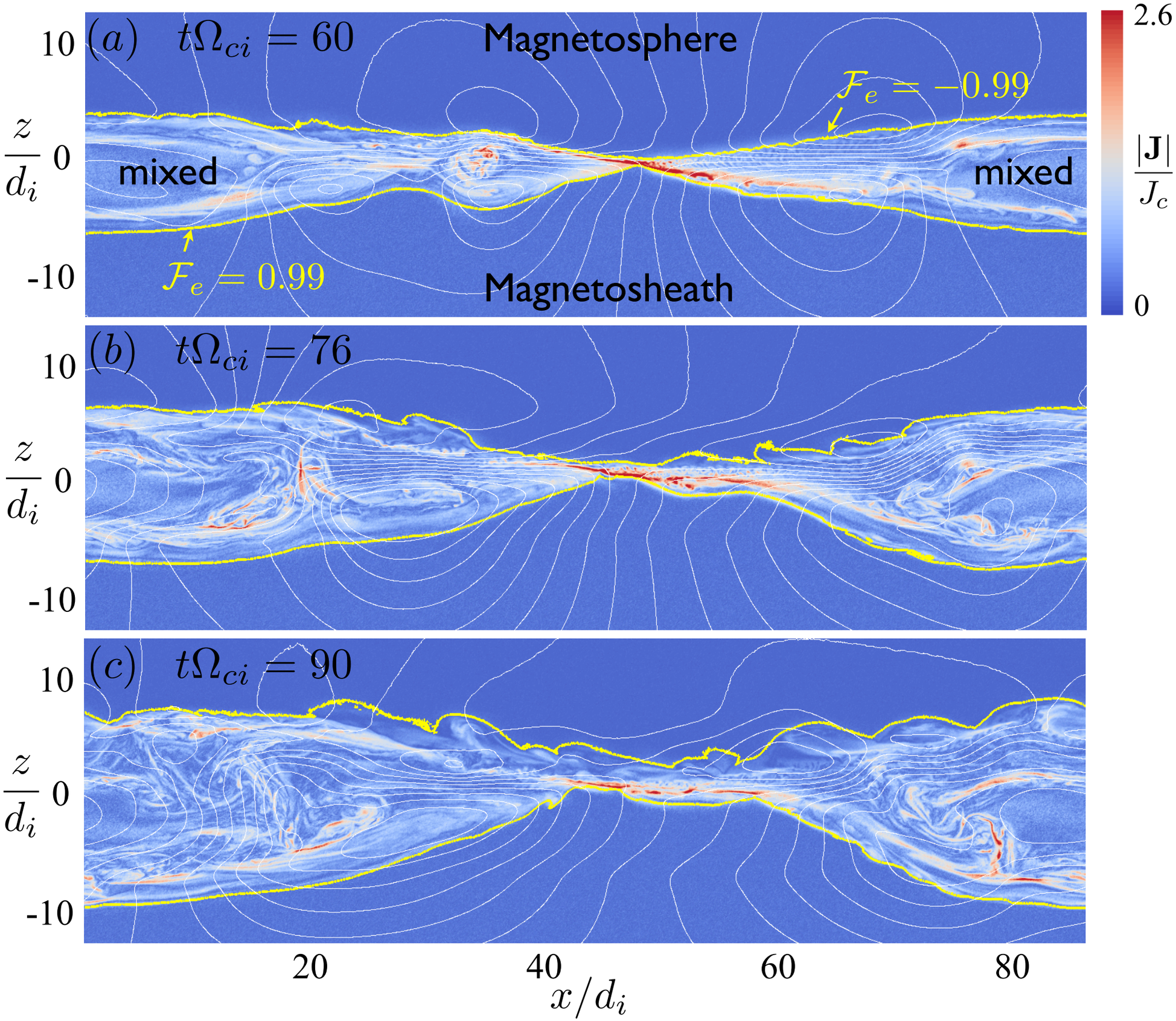
$$L_x \times L_y \times L_z = 85d_i \times 85d_i \times 35d_i$$

$$2920 \times 2920 \times 1200 \text{ cells} \qquad B_g = 1$$

$$2 \times 10^{12} \text{ particles} \qquad m_i/m_e = 100$$

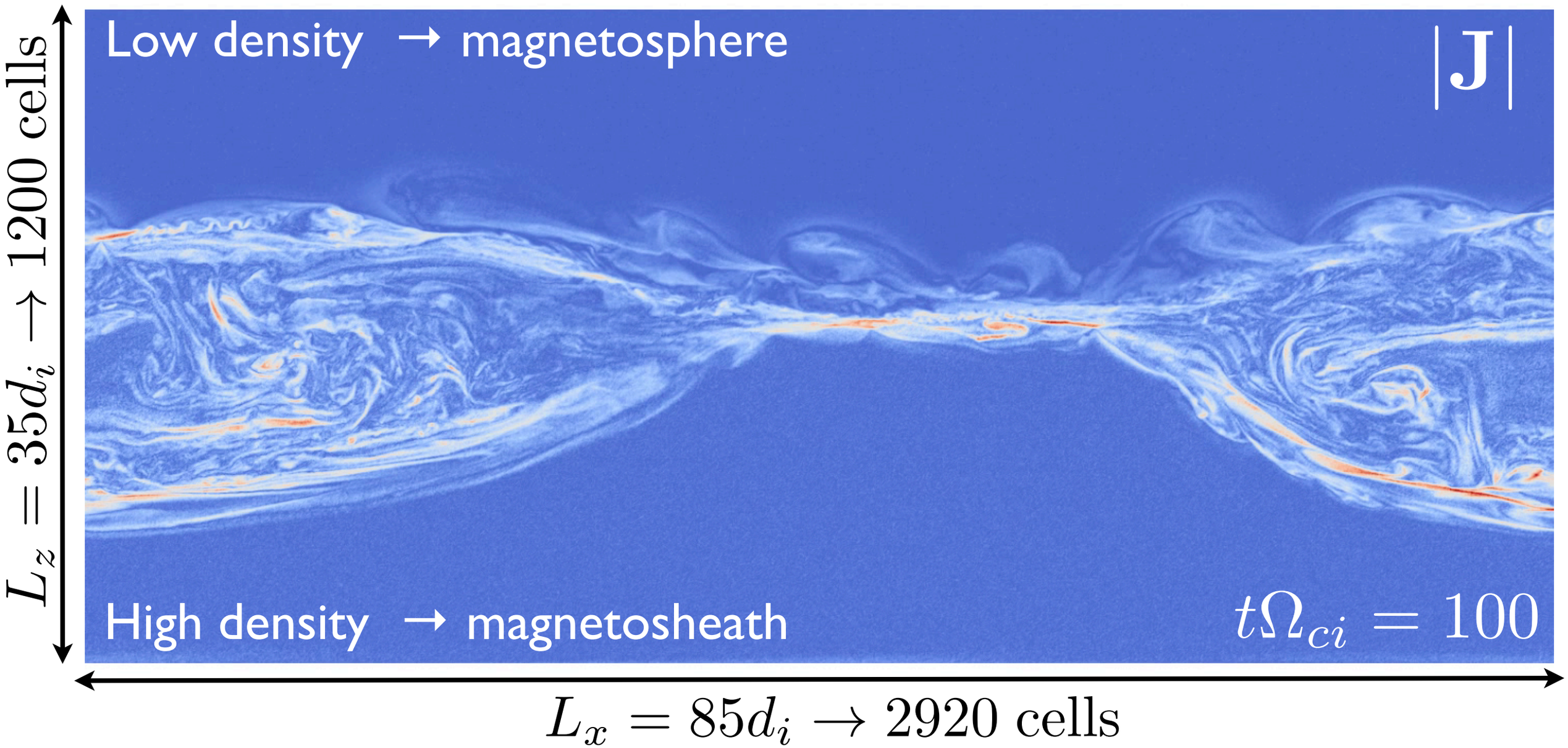
Periodic BC in X and Y

Time Evolution of Current Density & Mixing Surface

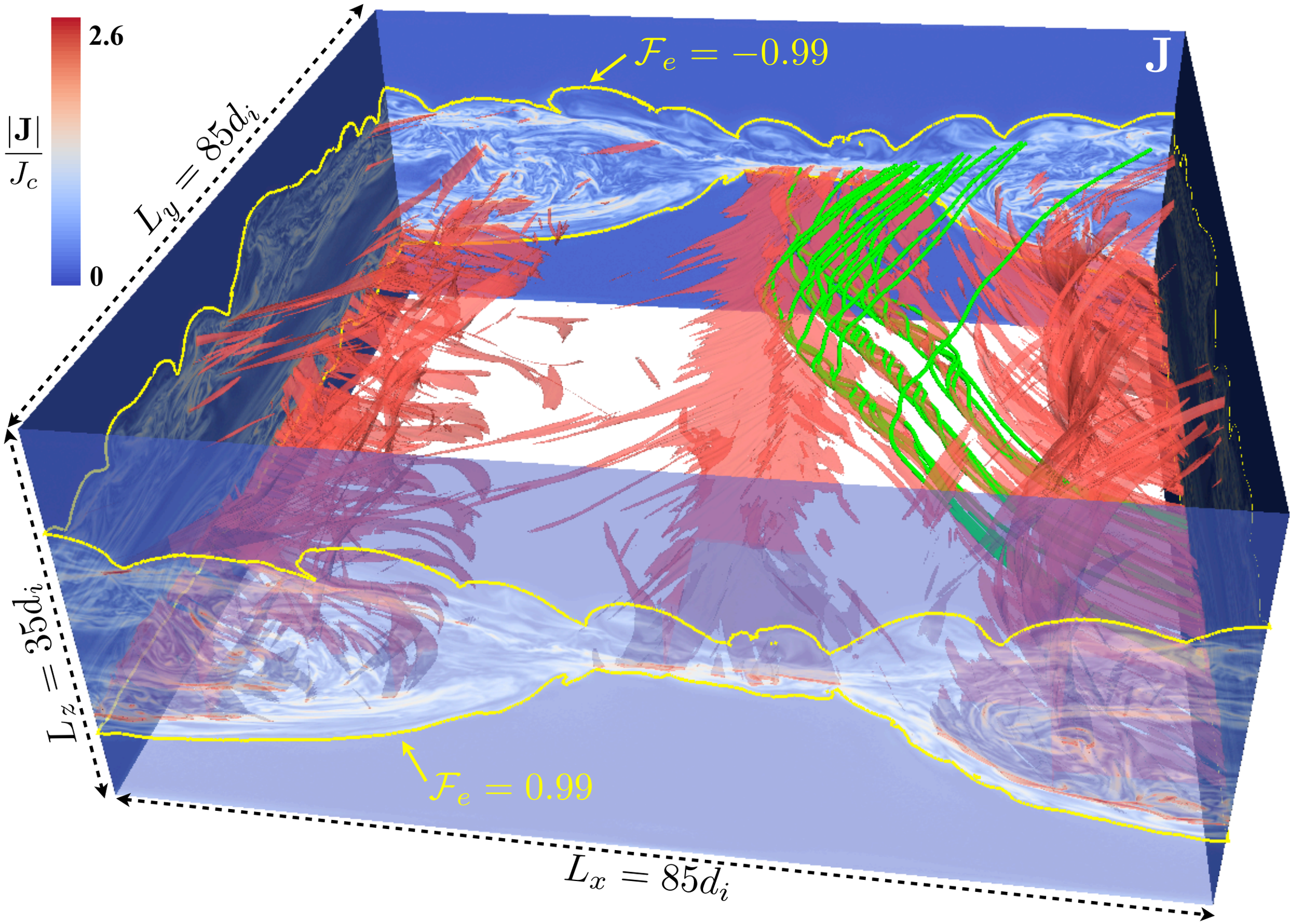


3D Structure of Current Density

Moving slice in y-direction at **fixed** time

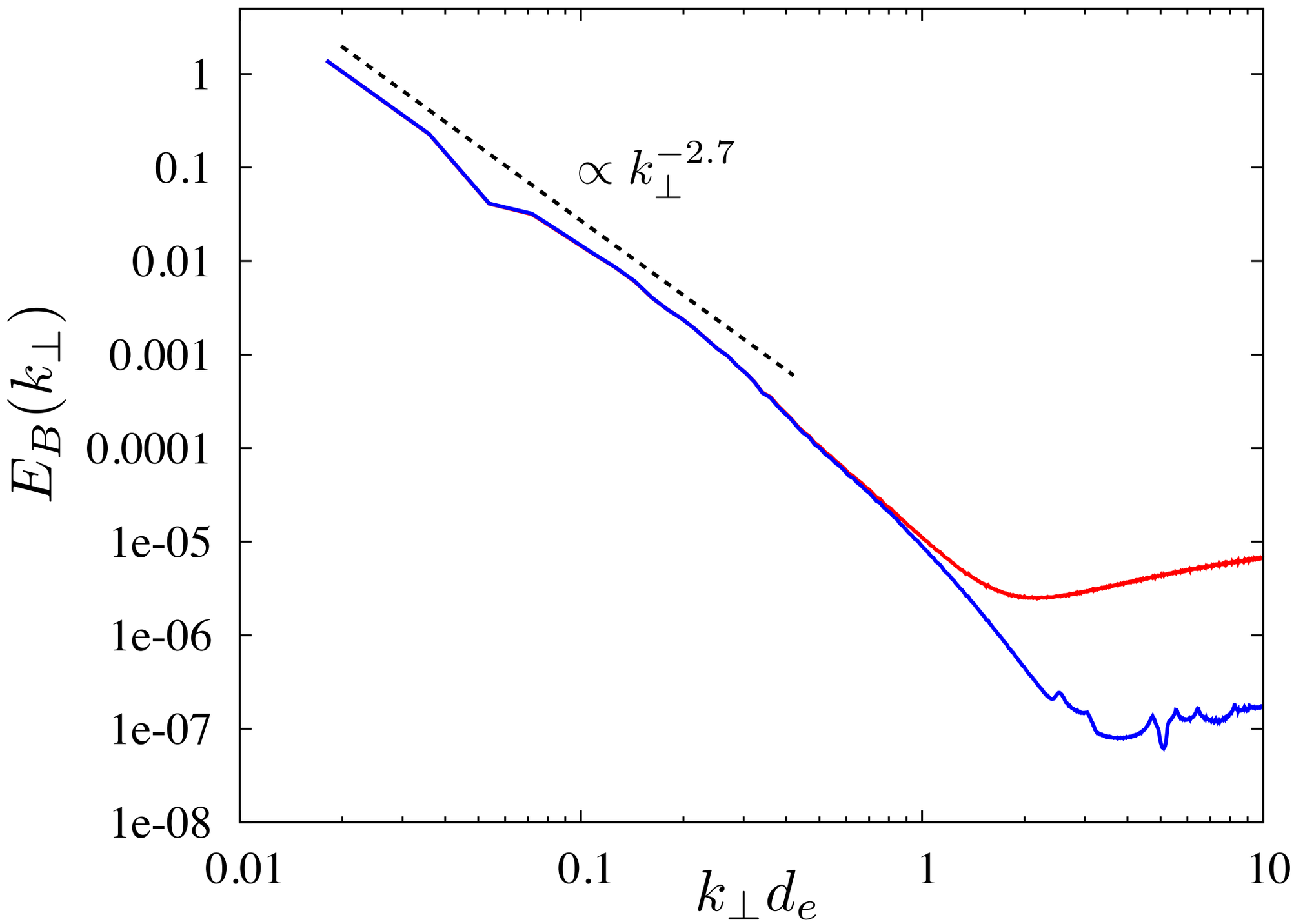


Flux Ropes in Asymmetric Reconnection Layers

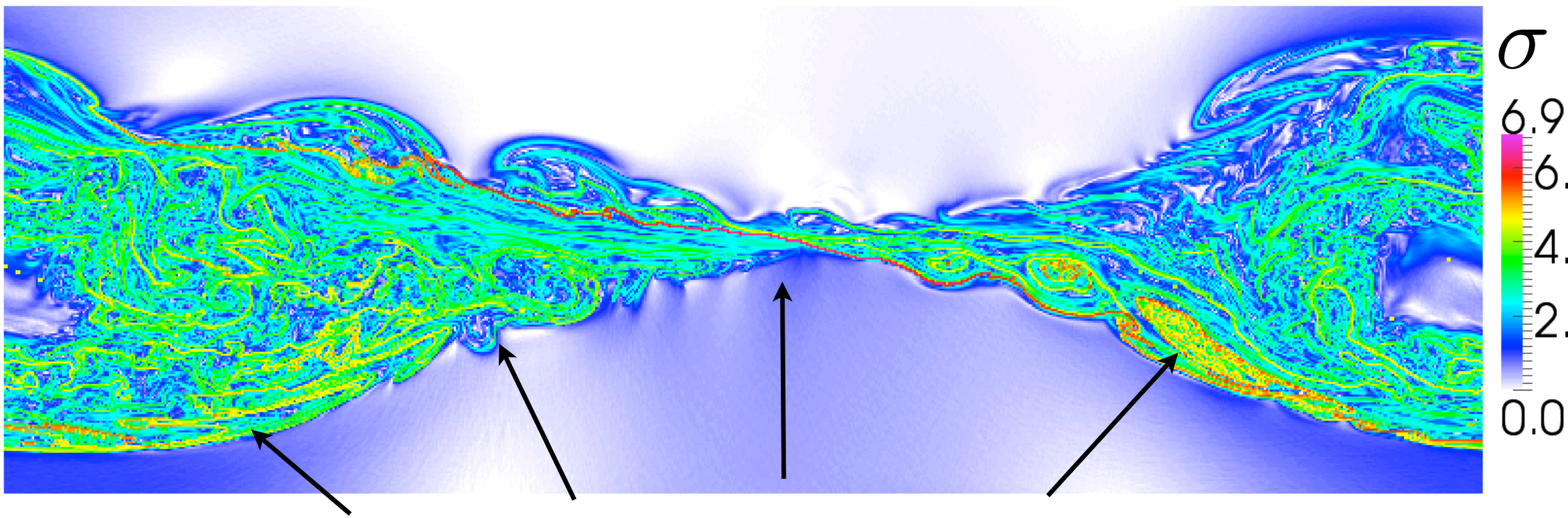


Daughton et al, 2014

Energy Spectrum of Magnetic Field



Field Line Exponentiation in Forward Direction

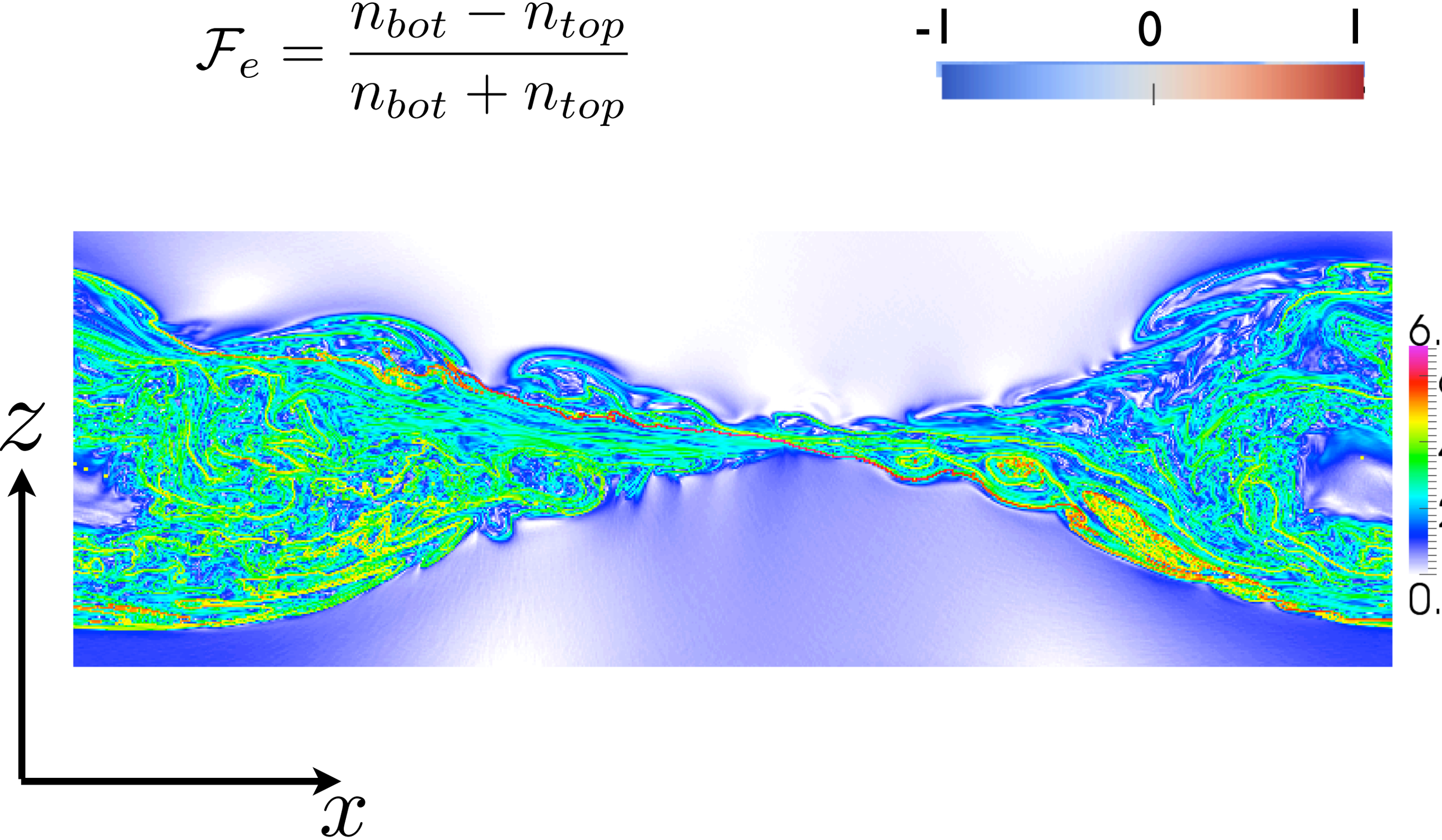


Sharp boundary between smooth & chaotic field

Separatrix Surface

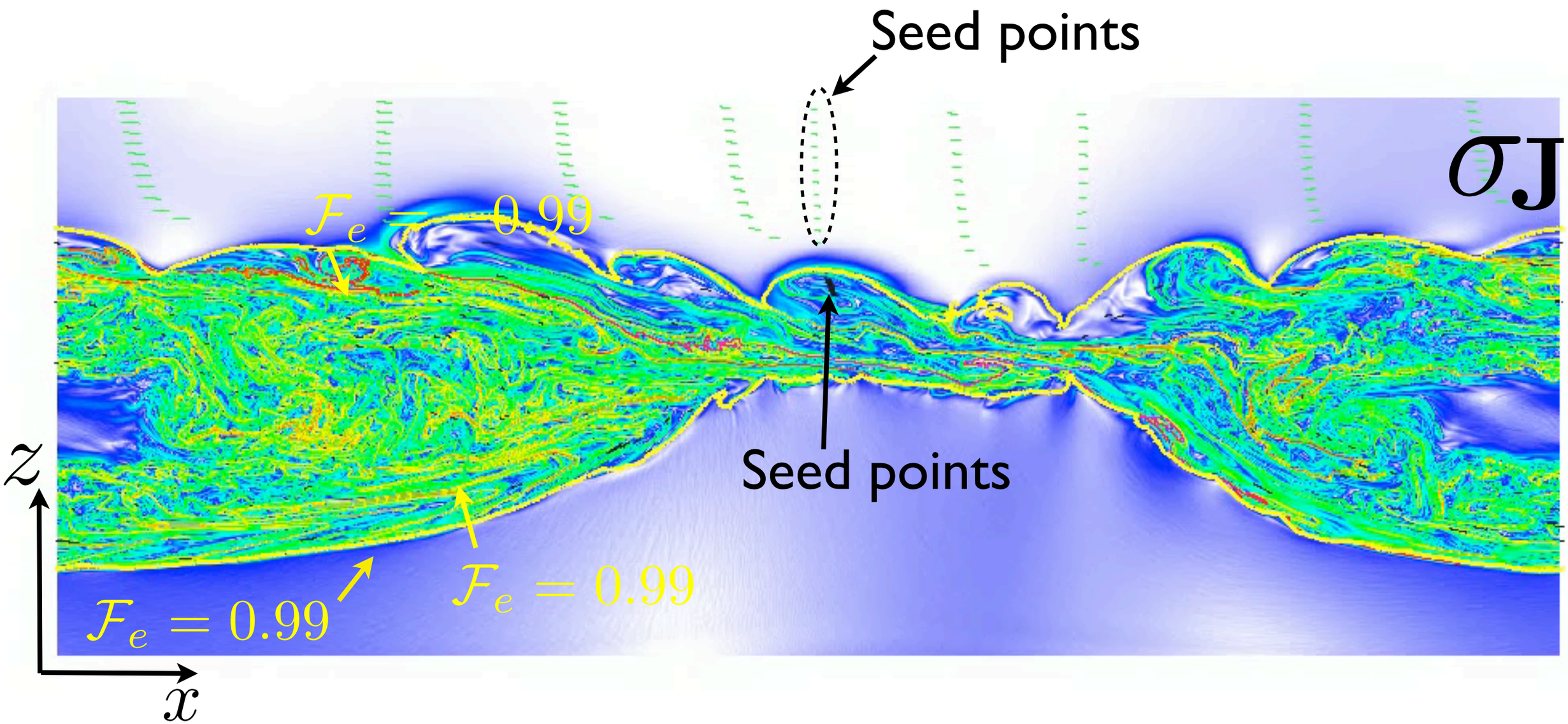
Correlation between Mixing & Stochastic Field

$$\mathcal{F}_e = \frac{n_{bot} - n_{top}}{n_{bot} + n_{top}}$$



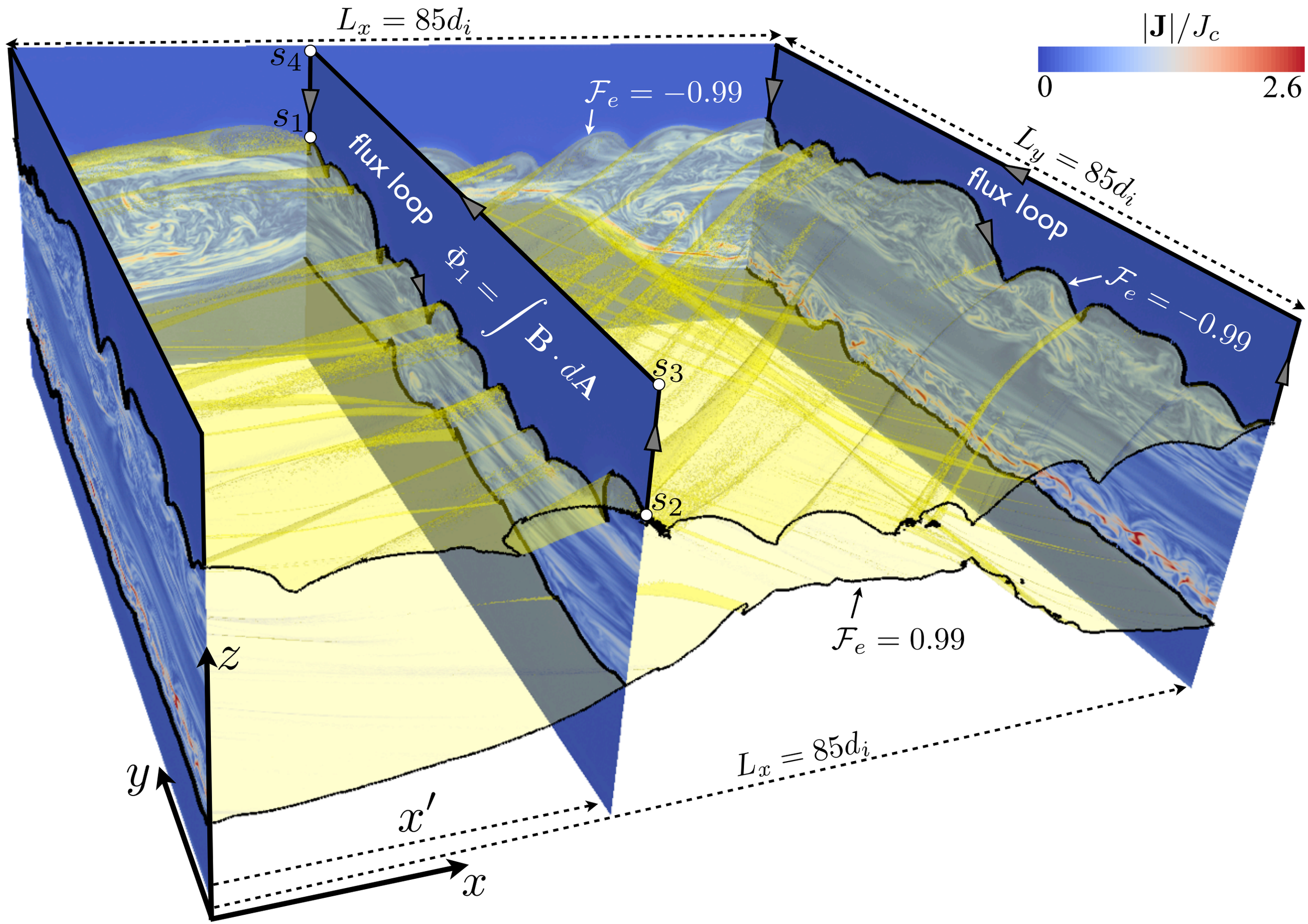
Very good correlation!

Directly test boundaries by following field lines

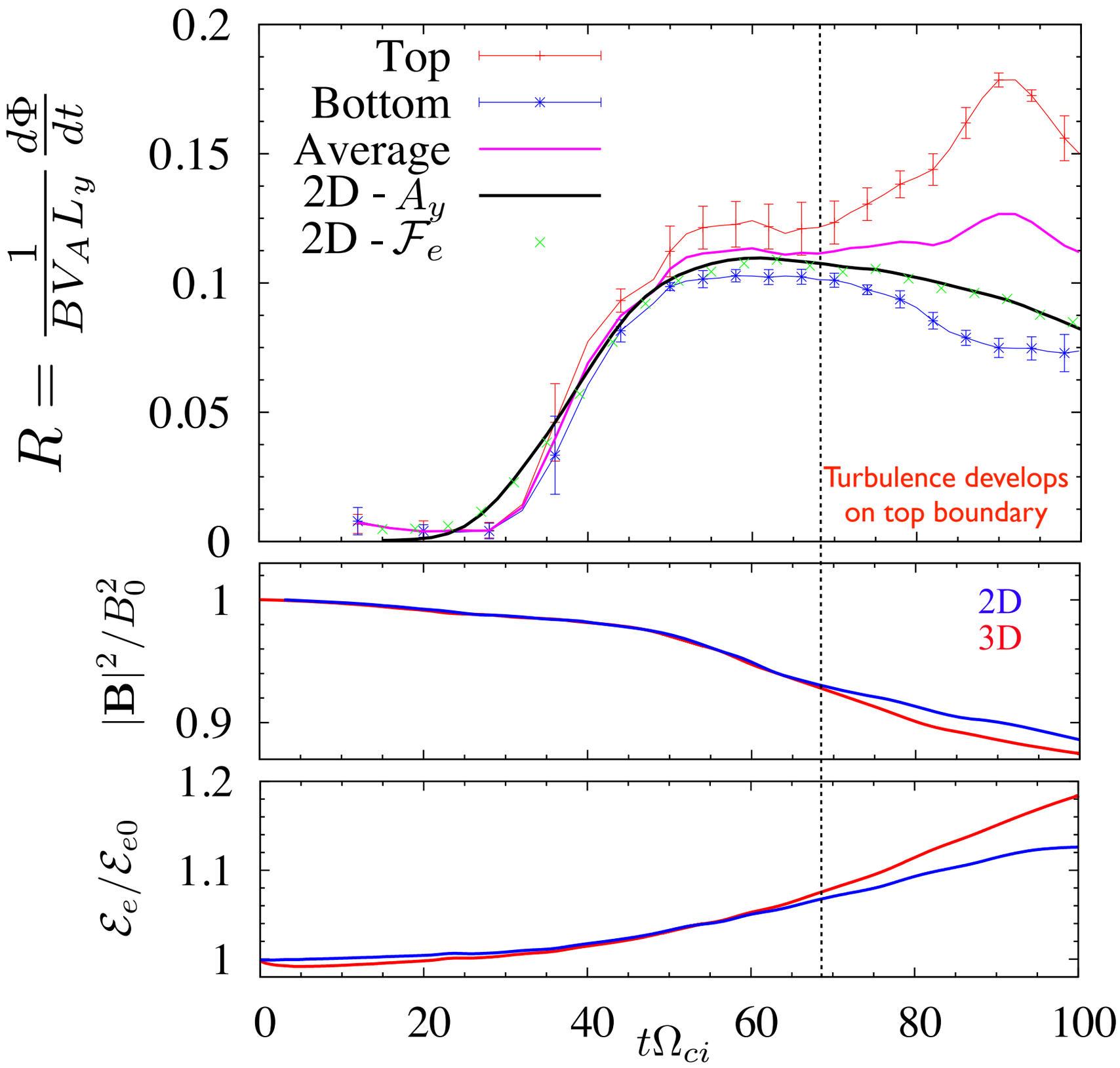


Mixing fraction also well correlated with current density

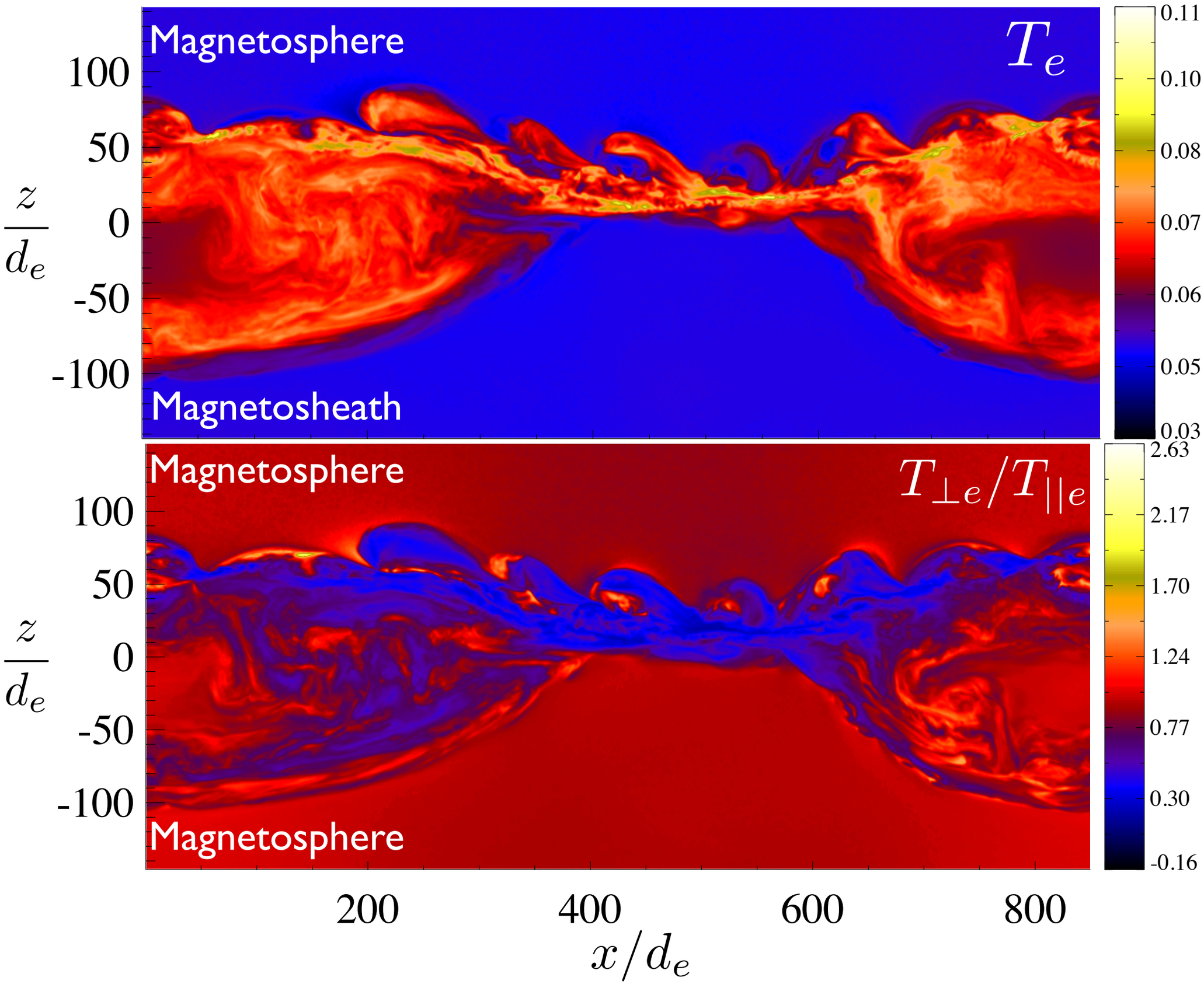
Topologically there are 3 Regions



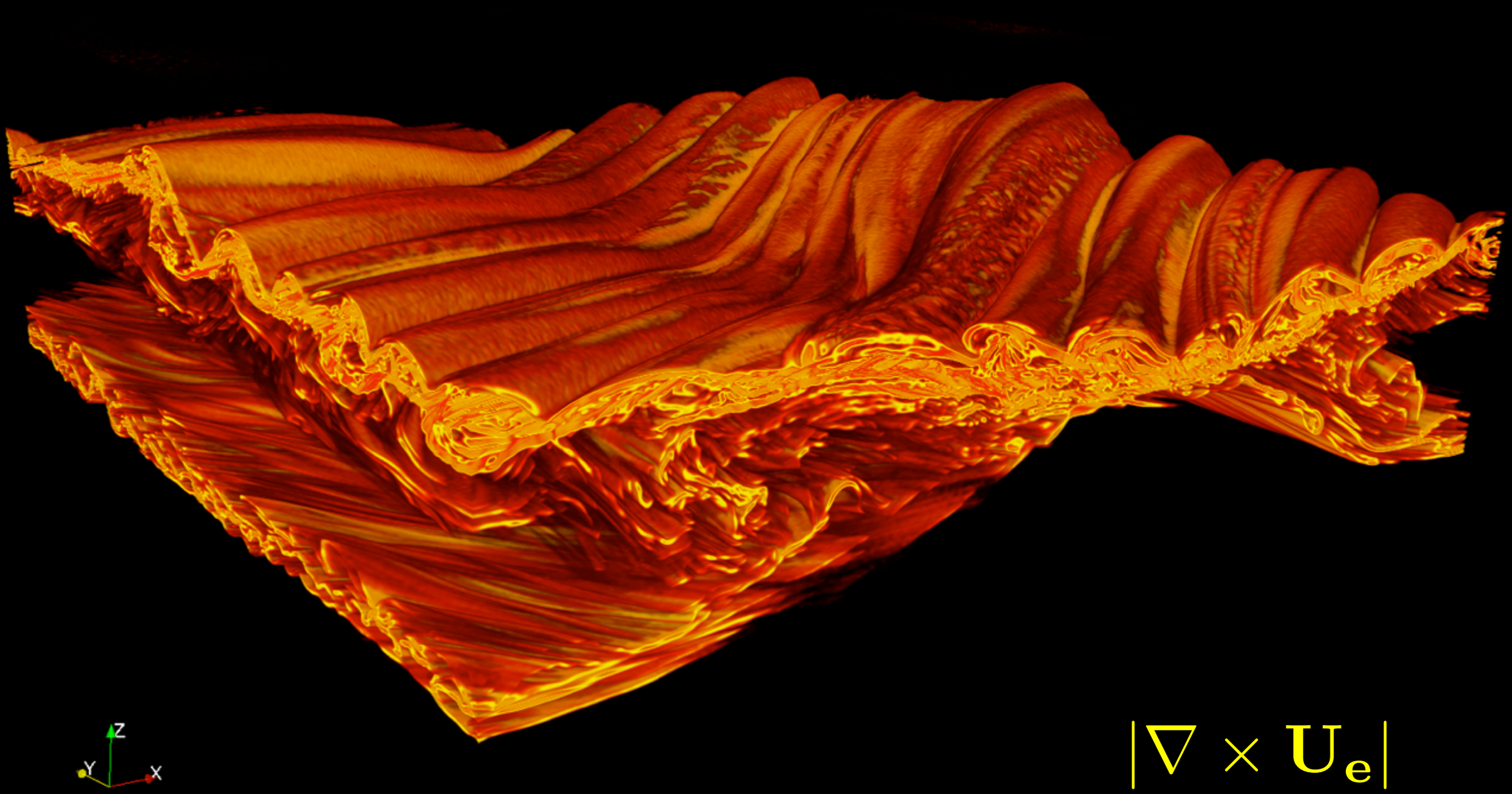
Time Evolution of 3D Reconnection Rate



Boundaries evident in electron moments

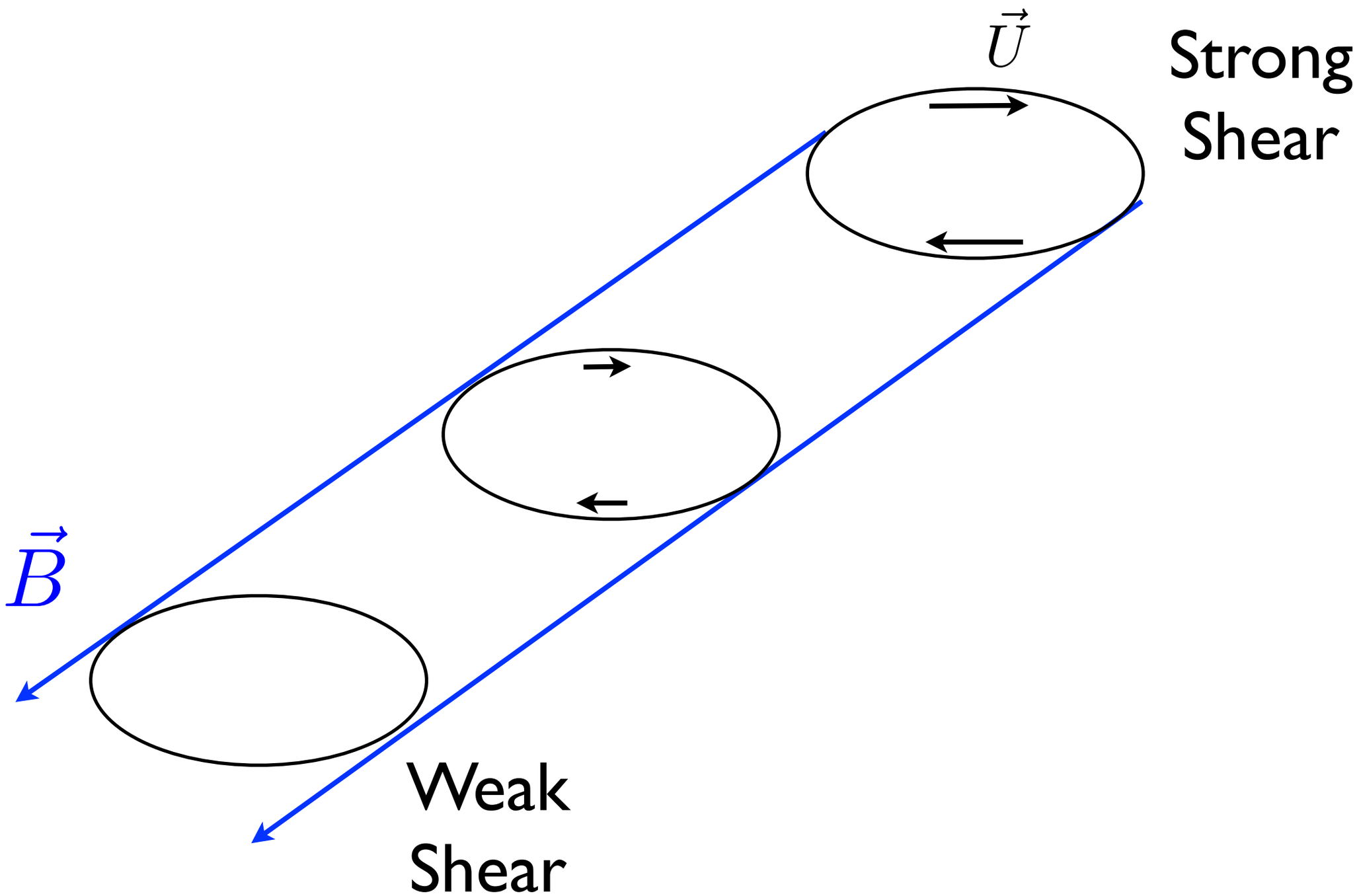


Isosurface of vorticity - Vortex Tubes



$$|\nabla \times \mathbf{U_e}|$$

Wrap-up of Vortex Tubes may Generate New Reconnection Sites



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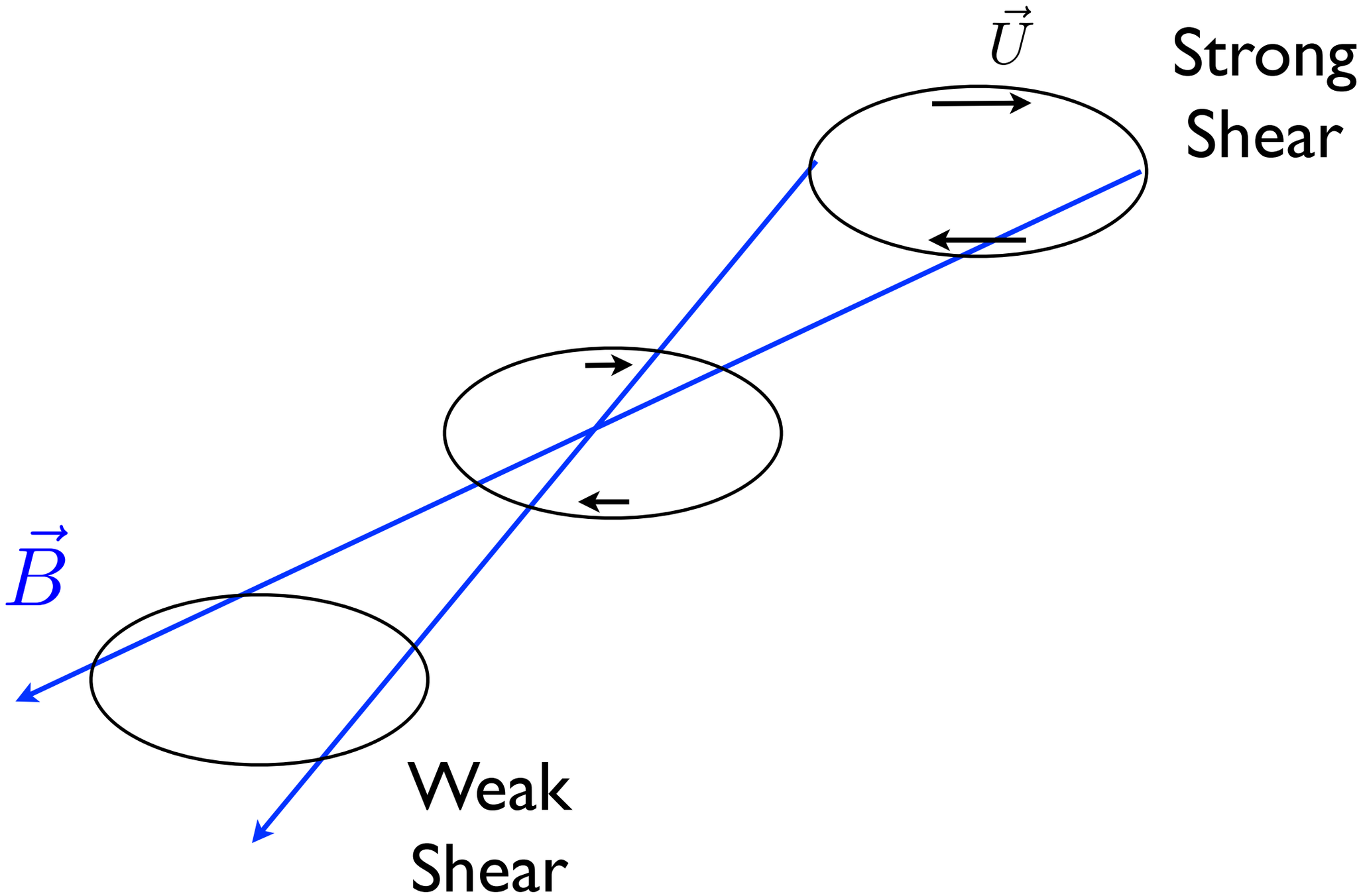
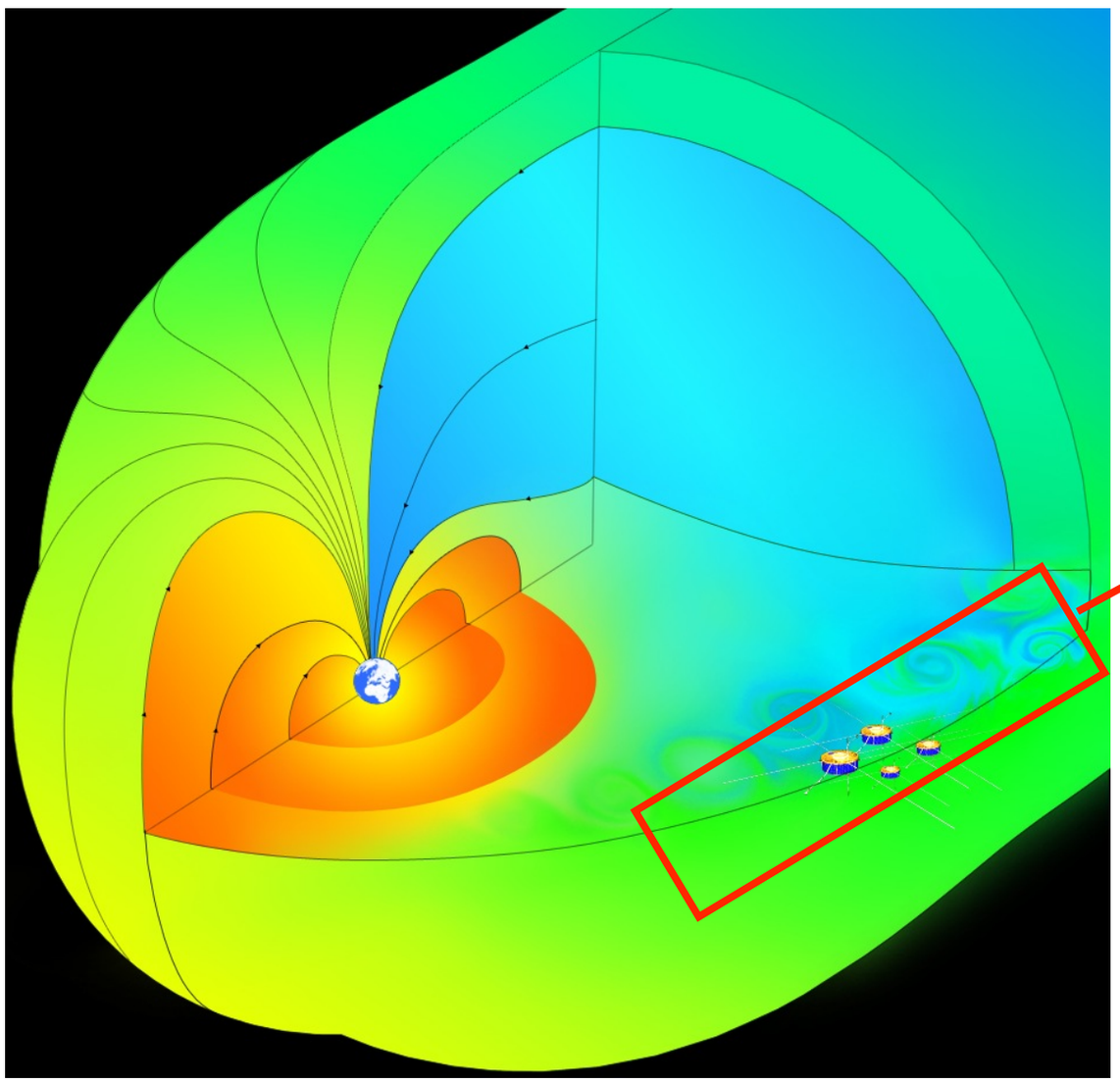
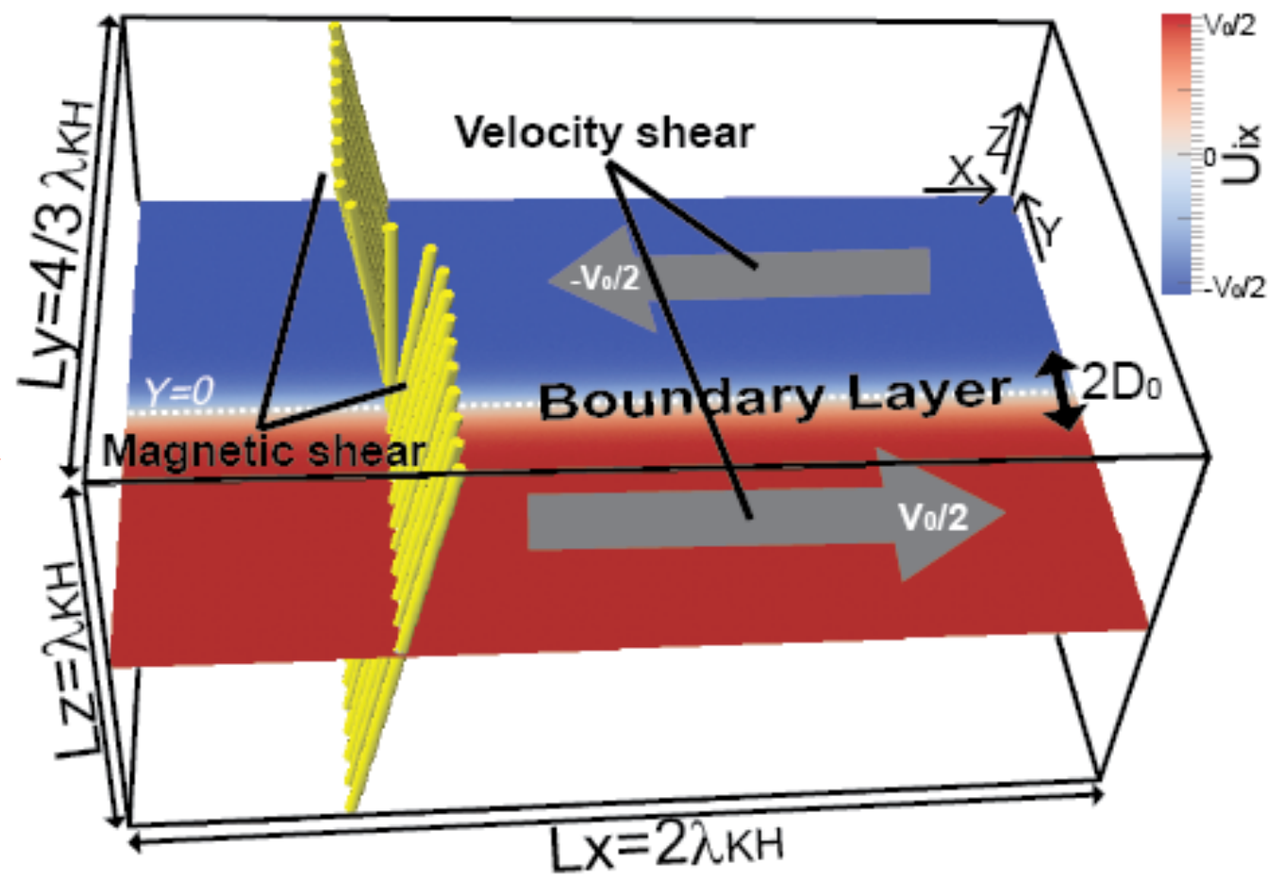


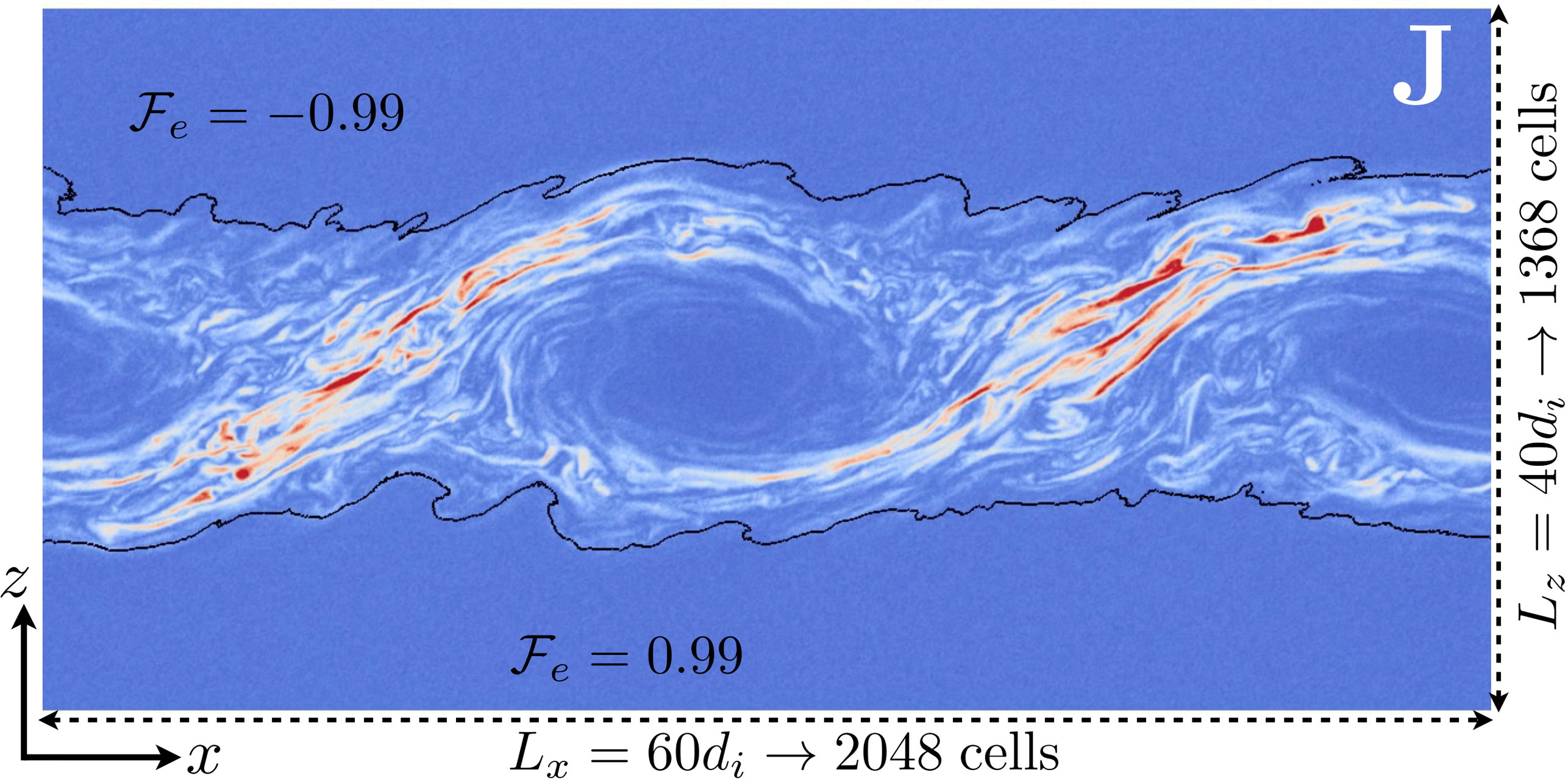
Example #2 - Vortex-Induced Reconnection

Nakamura et al, JGR, 2013
Daughton et al, PoP, 2014



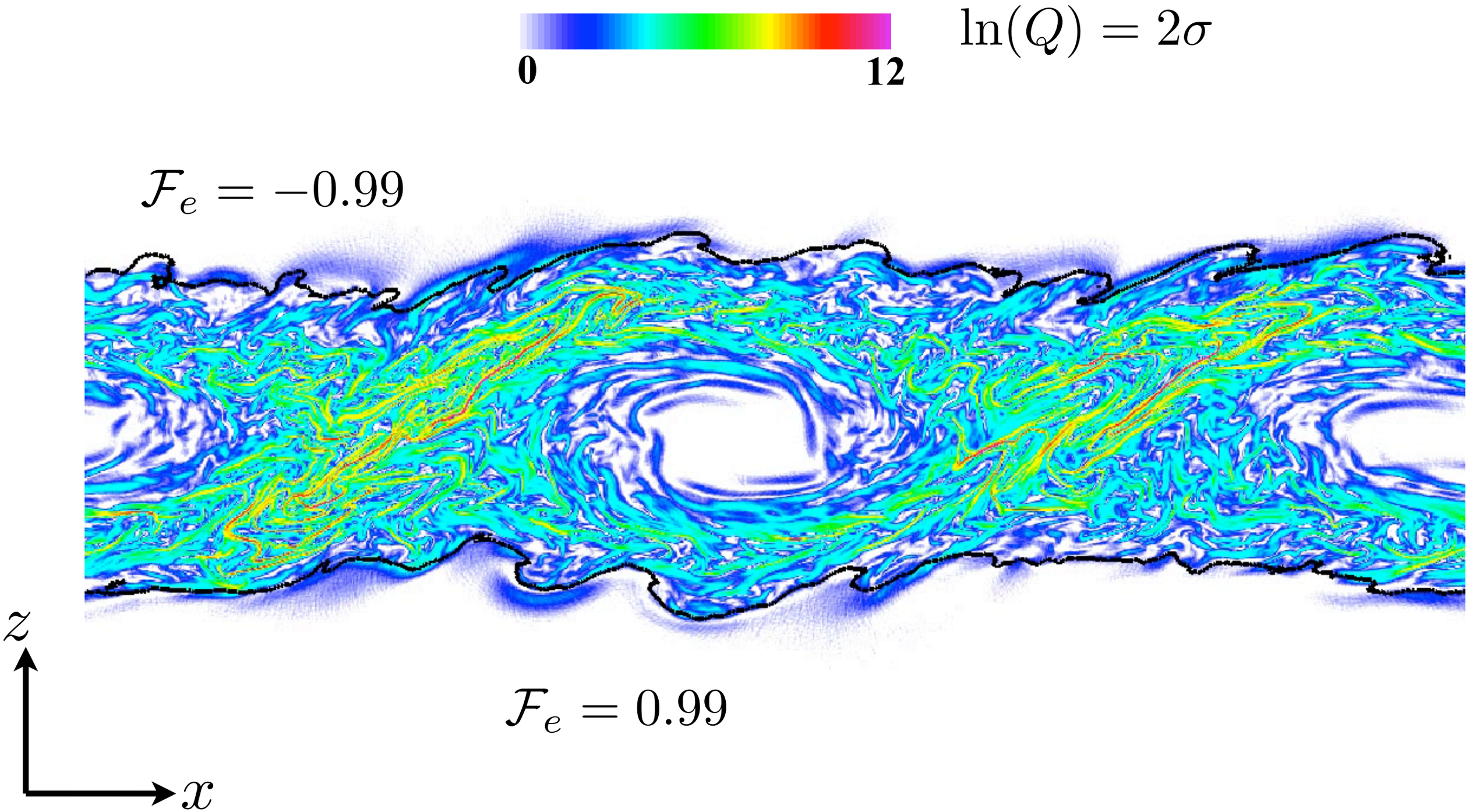


Time Evolution of Current Density



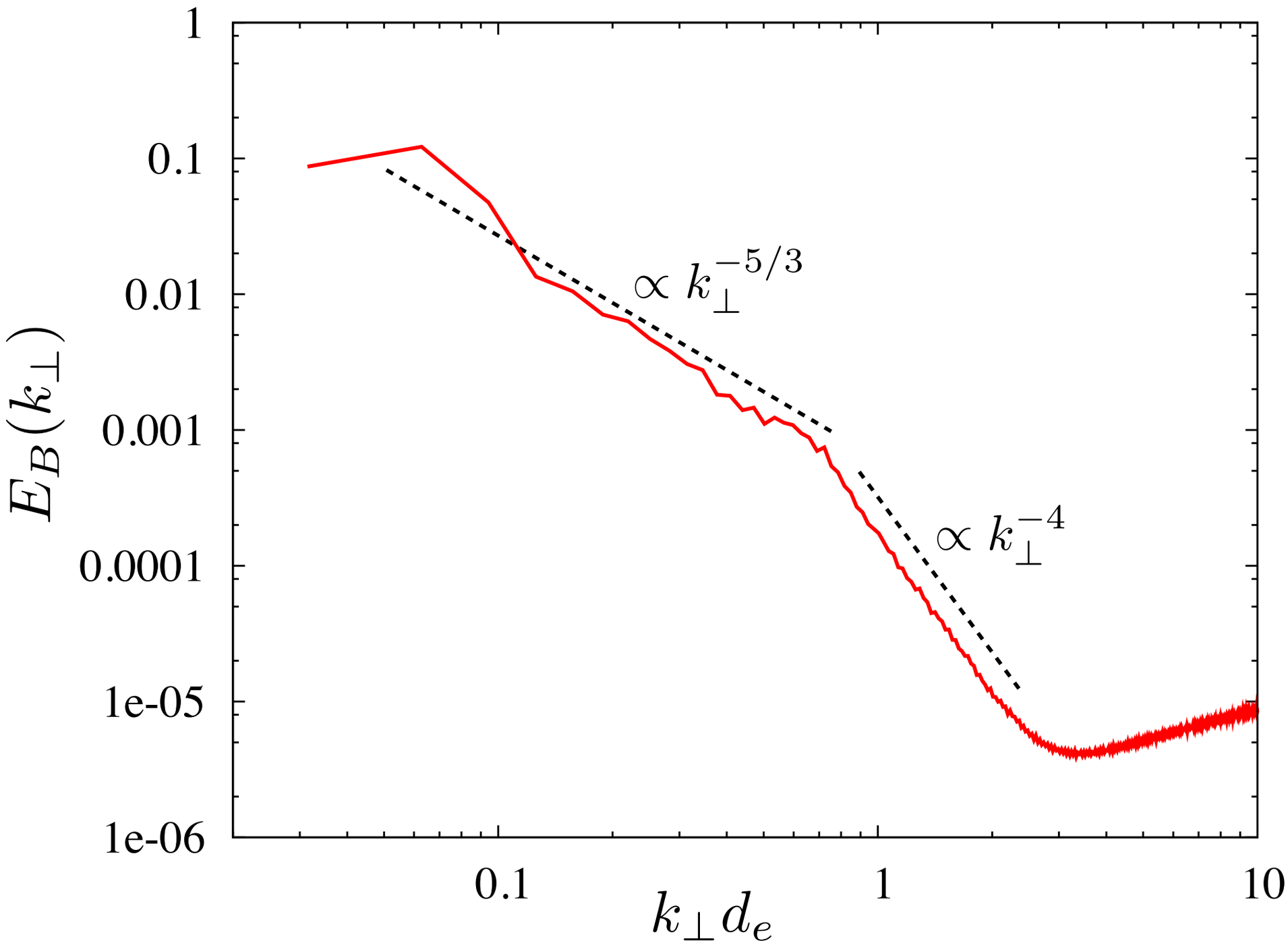
$$\mathcal{F}_e = \frac{n_{bot} - n_{top}}{n_{bot} + n_{top}}$$

Field-Line Exponentiation & Mixing Boundary

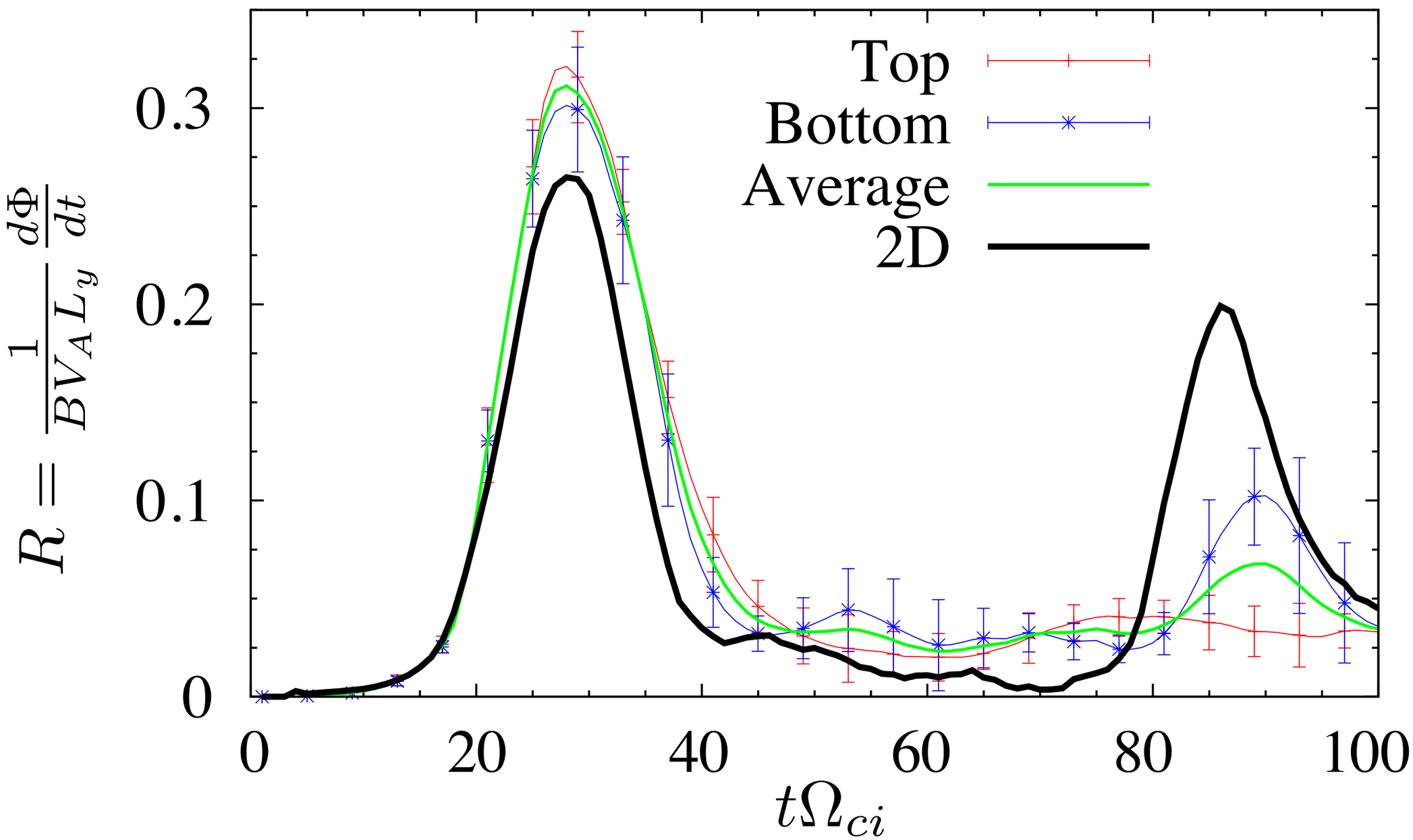


$$\mathcal{F}_e = \frac{n_{bot} - n_{top}}{n_{bot} + n_{top}}$$

Energy Spectrum of Magnetic Field



Time Evolution of 3D Reconnection Rate



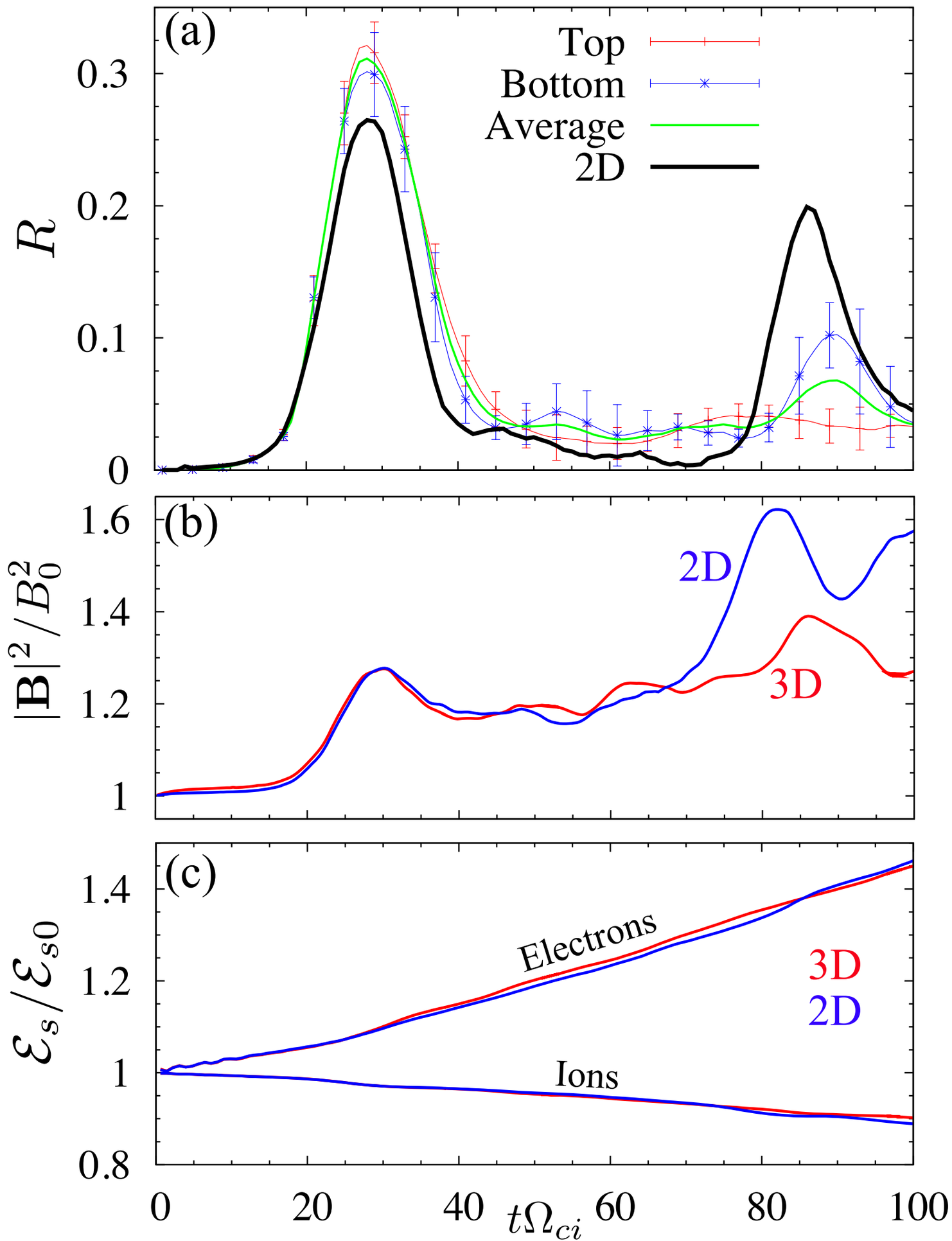
Reconnection Rate

↓

Magnetic Energy

↓

Kinetic Energy



Summary

- Magnetic reconnection can generate turbulence in large systems through tearing and flow driven instabilities

- Turbulence is highly anisotropic and is dominated by coherent structures - flux ropes, current sheets, vortices

- Clear power-laws in the range $\propto k_\perp^{-5/3} \rightarrow k_\perp^{-8/3}$

- Mixing of particles across the layer can be used to infer topology, and rapidly compute reconnection rate:
  - Clear qualitative and quantitative changes in 3D rate
  - However - energy conversion rates remain very similar
  - *Turbulent mixing* vs *turbulent reconnection* ?
  - Implications for larger systems ?

- Range of observational signatures that can be tested with current and upcoming spacecraft missions such as MMS