Flux Rope Formation from Magnetic and Velocity Shear

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Two Key Formation Mechanisms

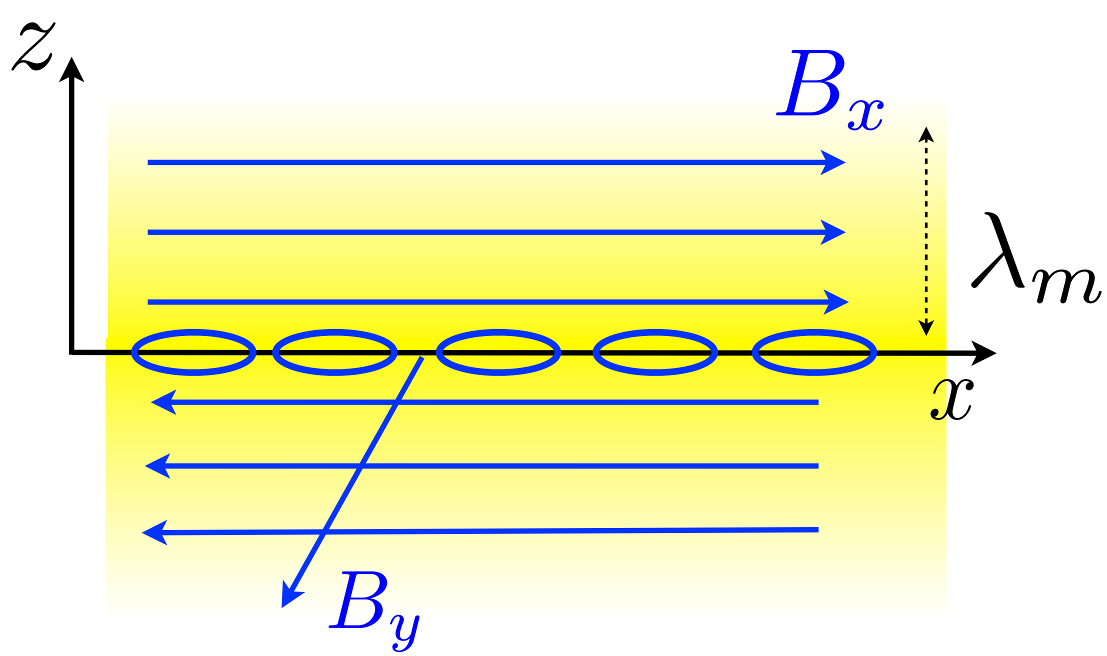
Magnetic Shear

Tearing

↔

Velocity Shear

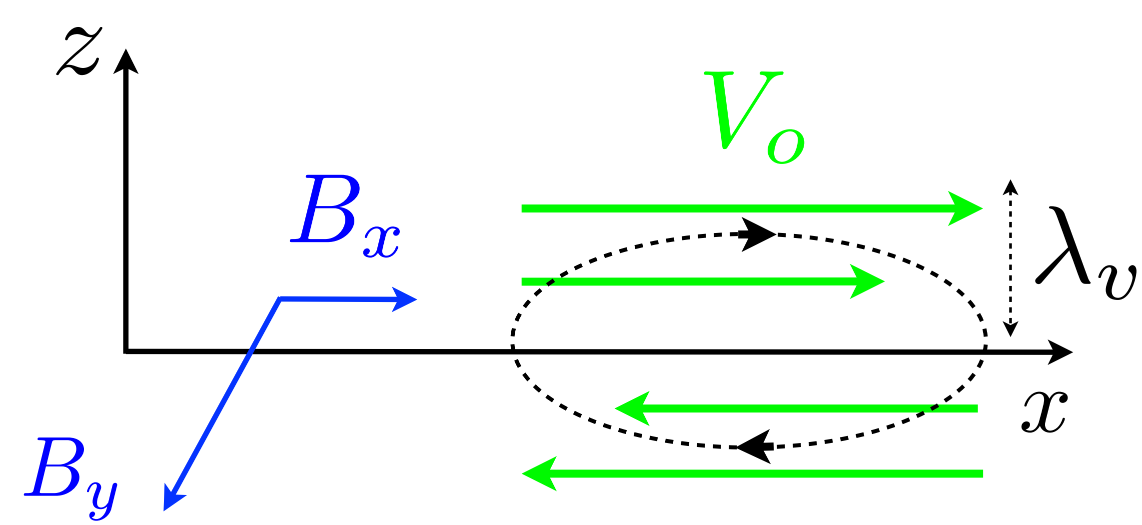
Kelvin-Helmholtz



$$k\lambda_m \sim 0.5$$

- Linear mechanism
- Ion or electron scale layers
- Threshold B_z
- Growth rate:

$$\frac{\gamma}{k v_{th_e}} \sim \frac{d_e^2 \Delta'}{2\sqrt{\pi} l_s}$$



$$k\lambda_v \sim 0.5 \rightarrow 1$$

- Inherently non-linear
- KH vortex + reconnection
- Ion or electron layers
- Threshold shear $V_o > V_{Ax}$
- Growth rate

$$\gamma \sim \frac{1}{10} \frac{V_o}{\lambda_v}$$

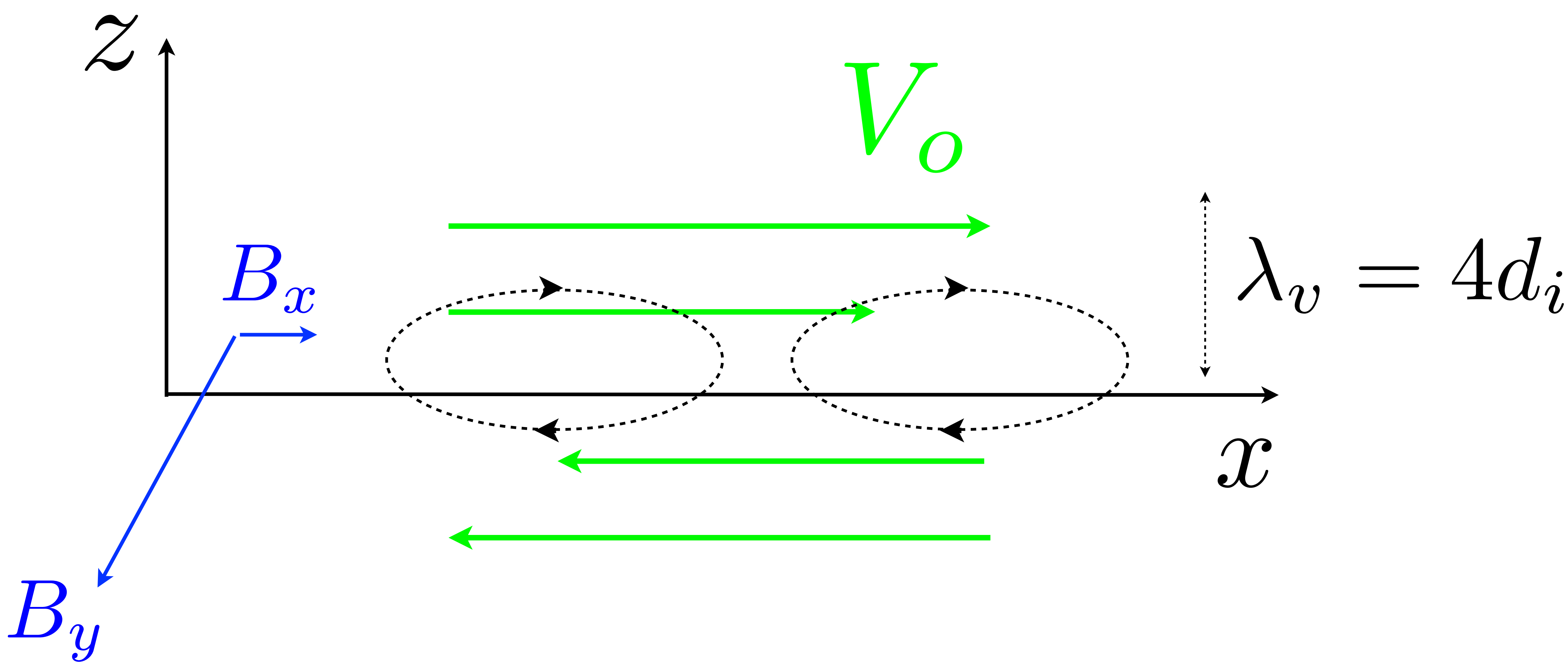
Highlight new papers that illustrate both mechanisms & their coupling

1. Pure velocity shear
2. Velocity & magnetic shear
3. Force-free current sheets

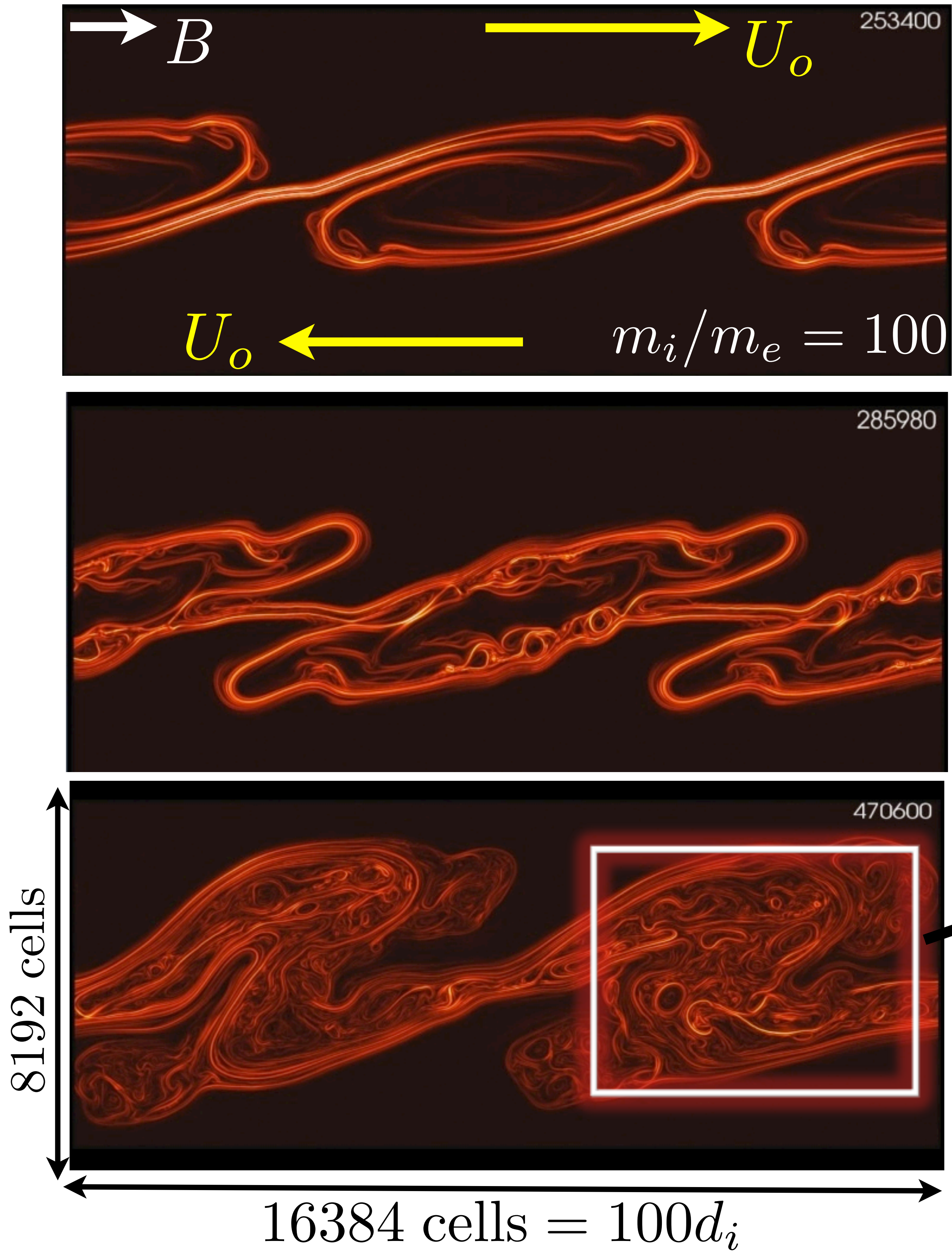
Pure Velocity Shear

Karimabadi, Roytershteyn, Wan et al, PoP, 2012

Wan, Mattheaus, Karimbadiet al, PRL, 2012

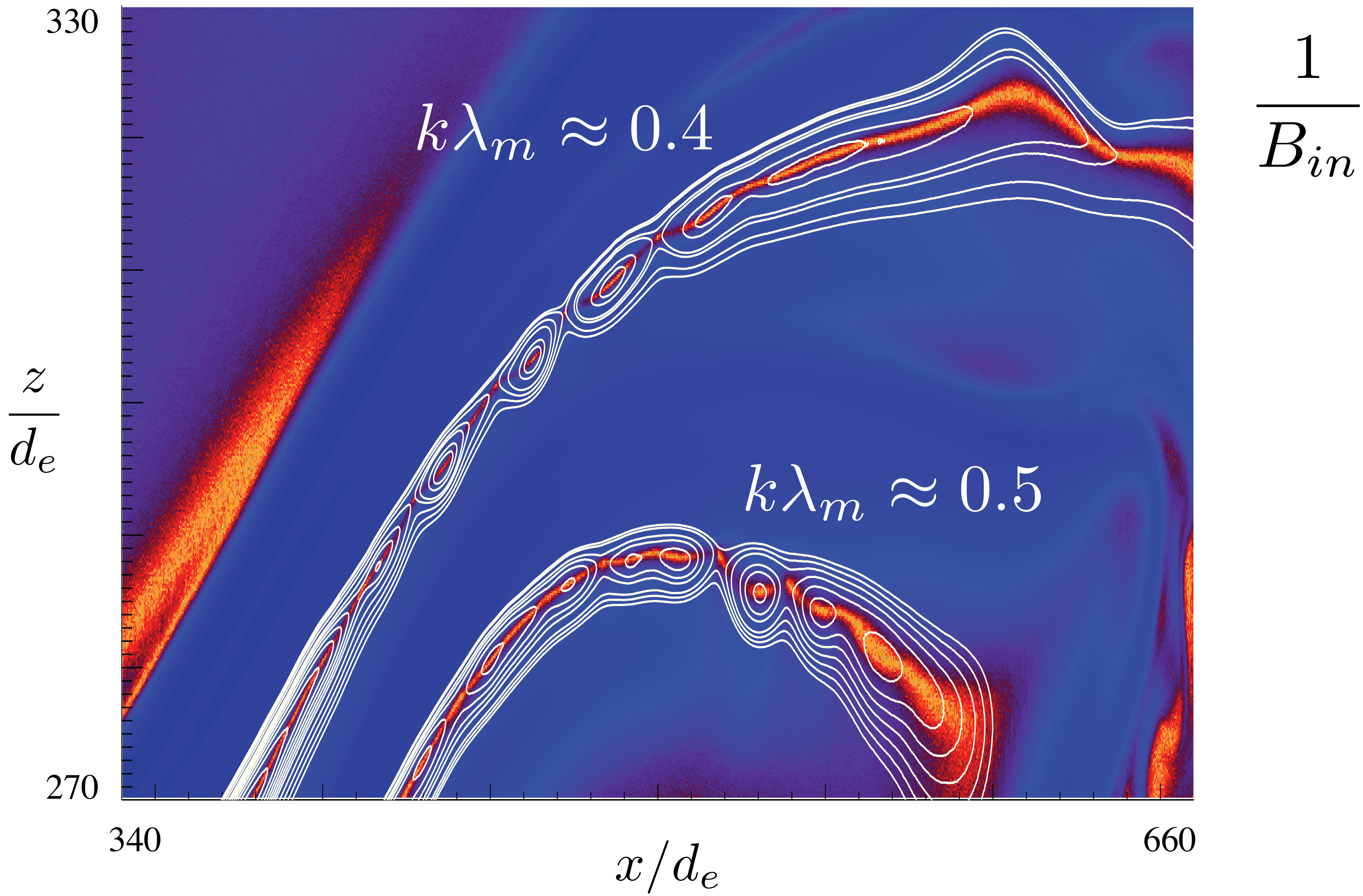


Fully kinetic 2D simulation of Kelvin-Helmoltz

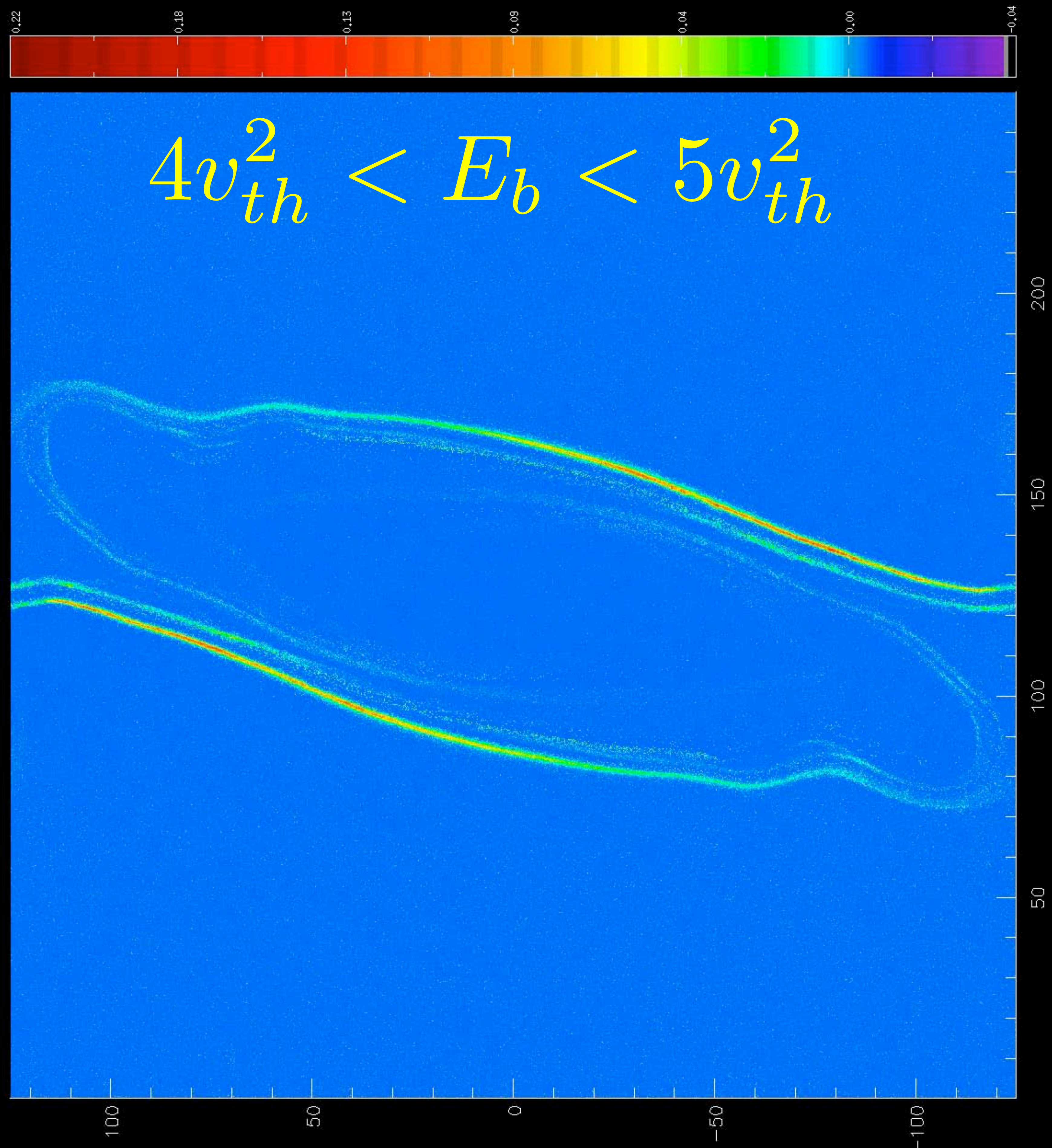


- Vortex scale $\sim 50 d_i$
- Kinetic scale layers
- Tearing + reconnection
- Power law spectra $E_B \propto k_\perp^{-8/3}$
- Electron heating dominant
- In-plane B is crucial

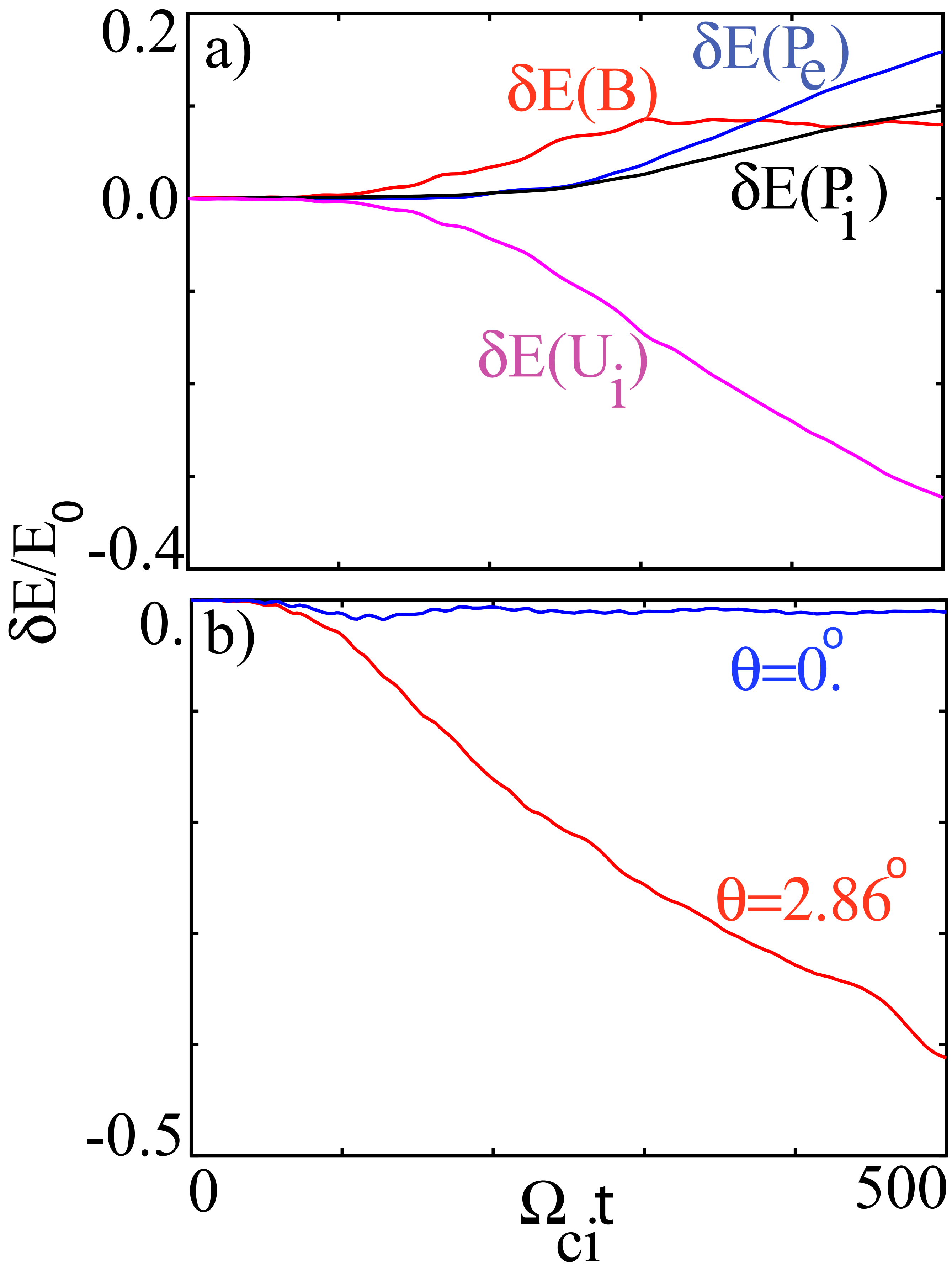
Tearing instability & reconnection is triggered in current sheets with in-plane B reversal



Electron Heating in Layers



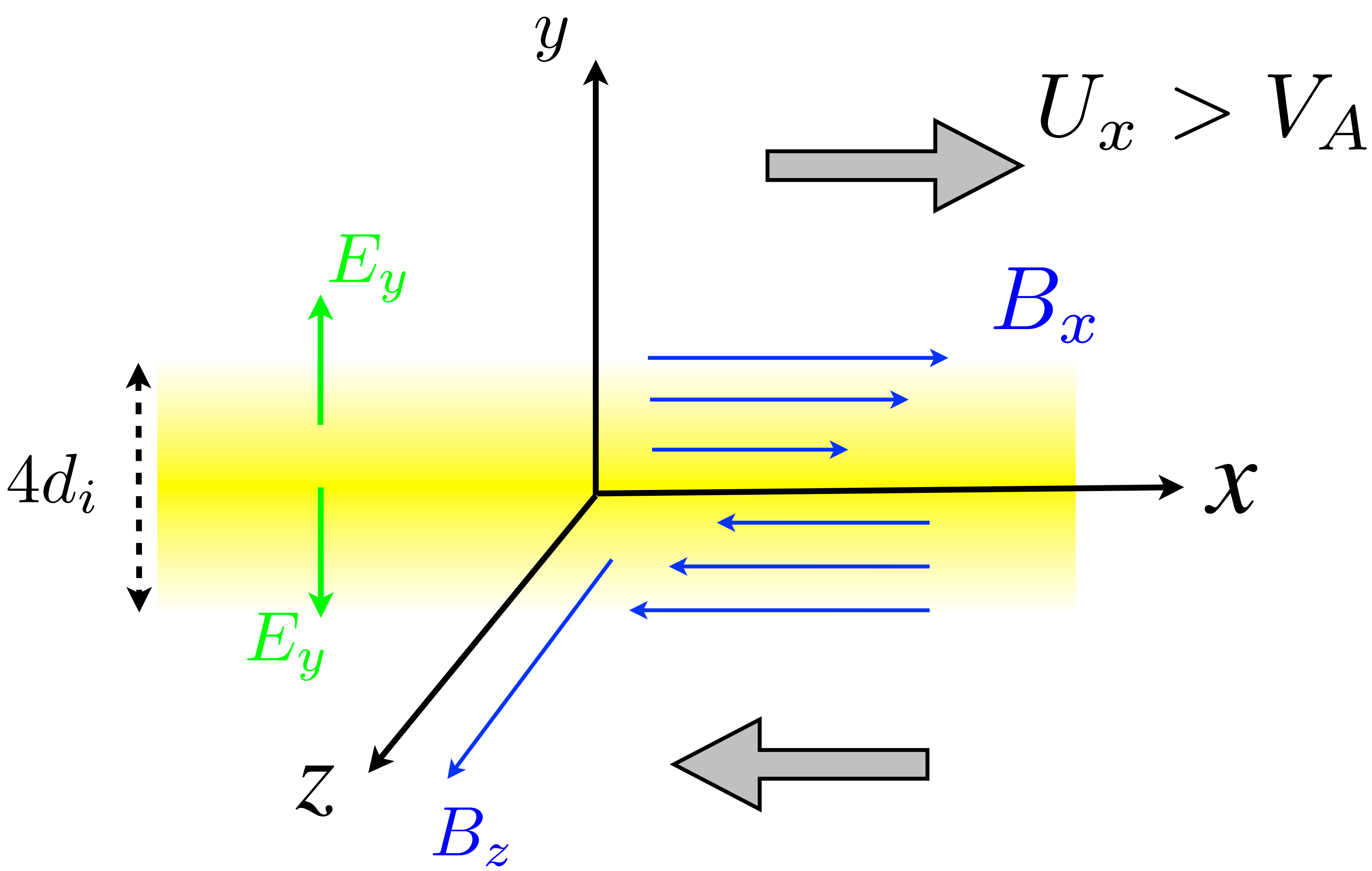
Electrons get majority of energy!



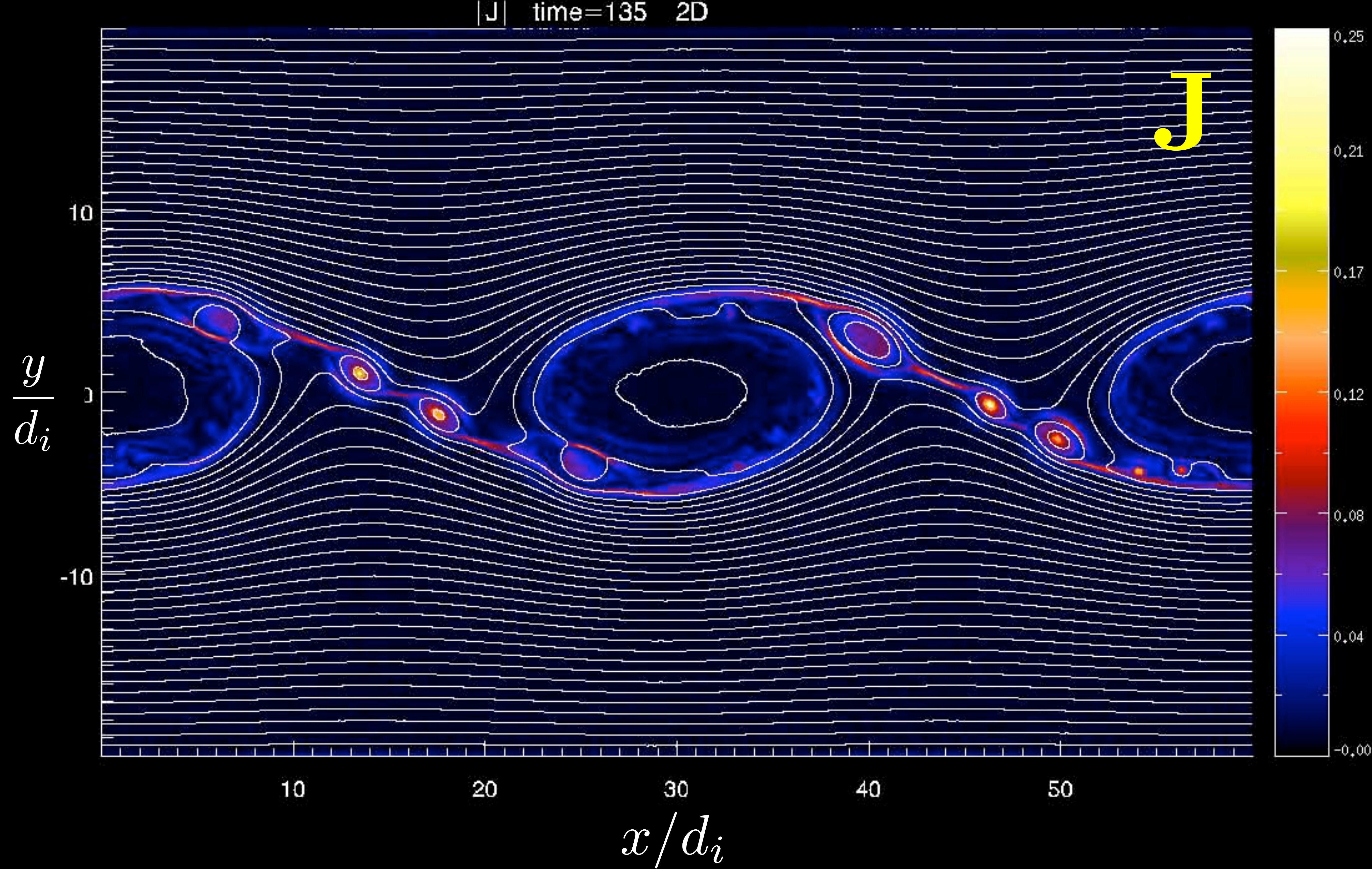
Weak in-plane field plays essential role!

Magnetic & Velocity Shear

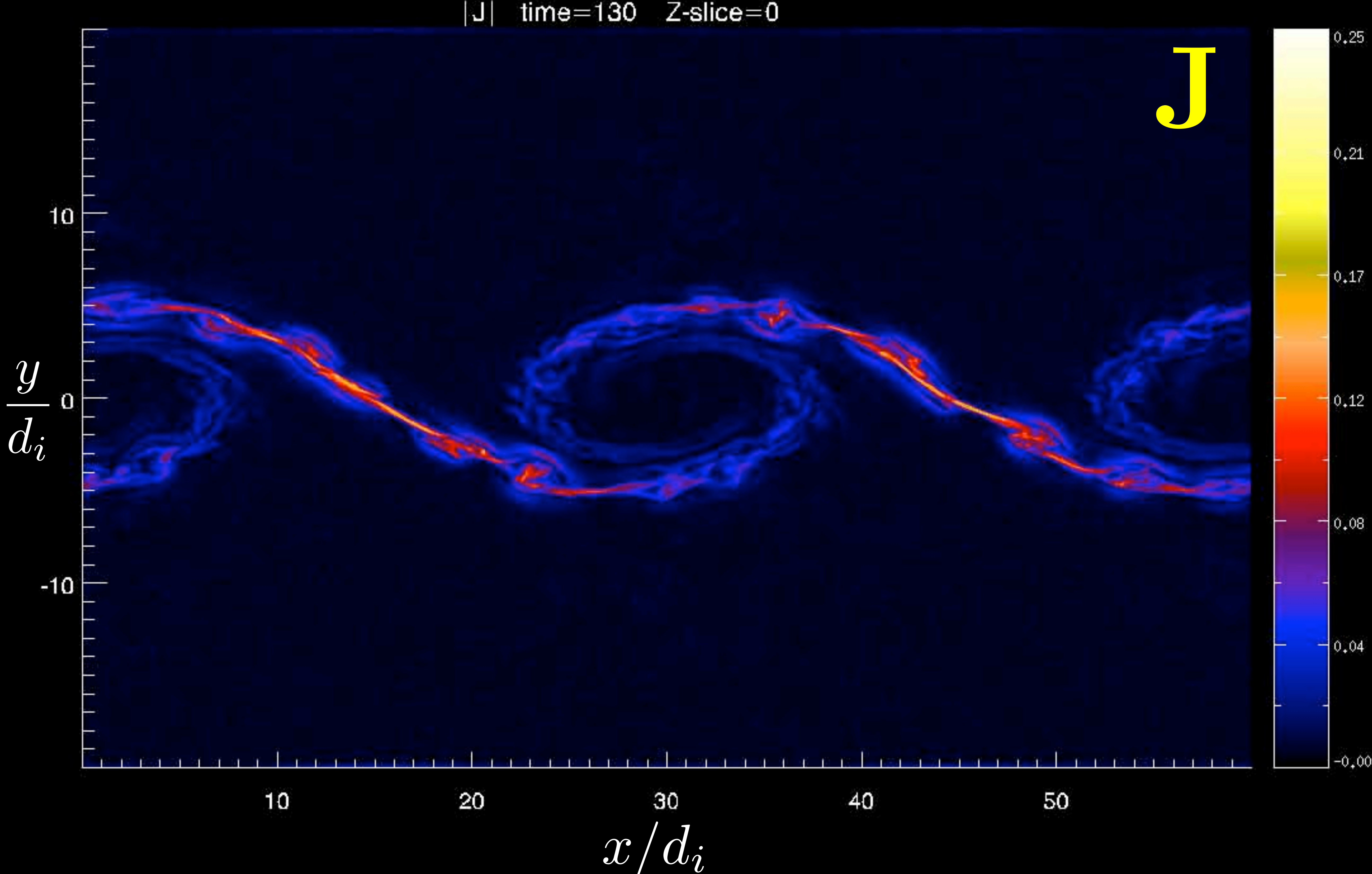
Nakamura, Daughton, Karimabadi, JGR, 2012

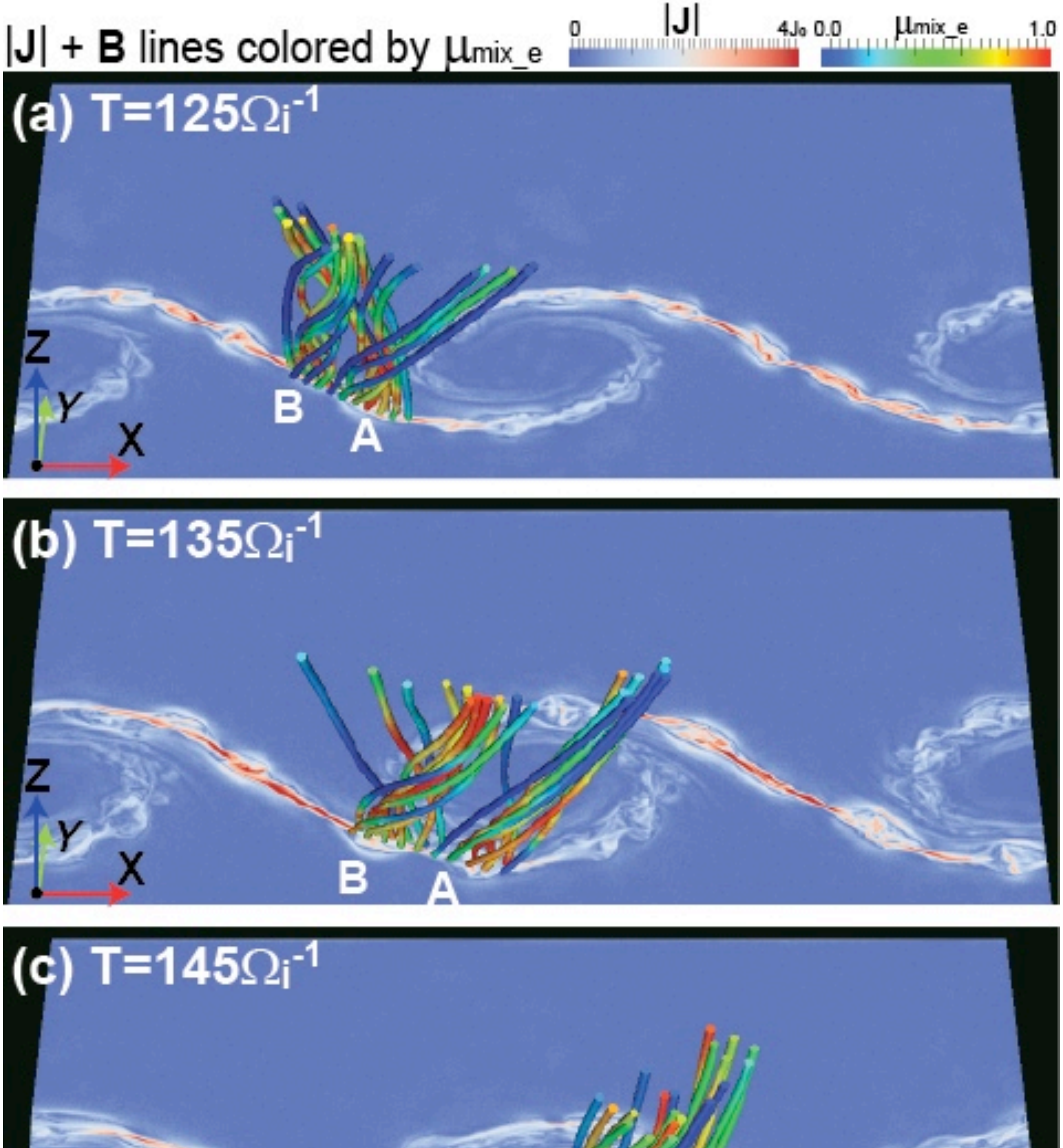


Two-Dimensional Evolution



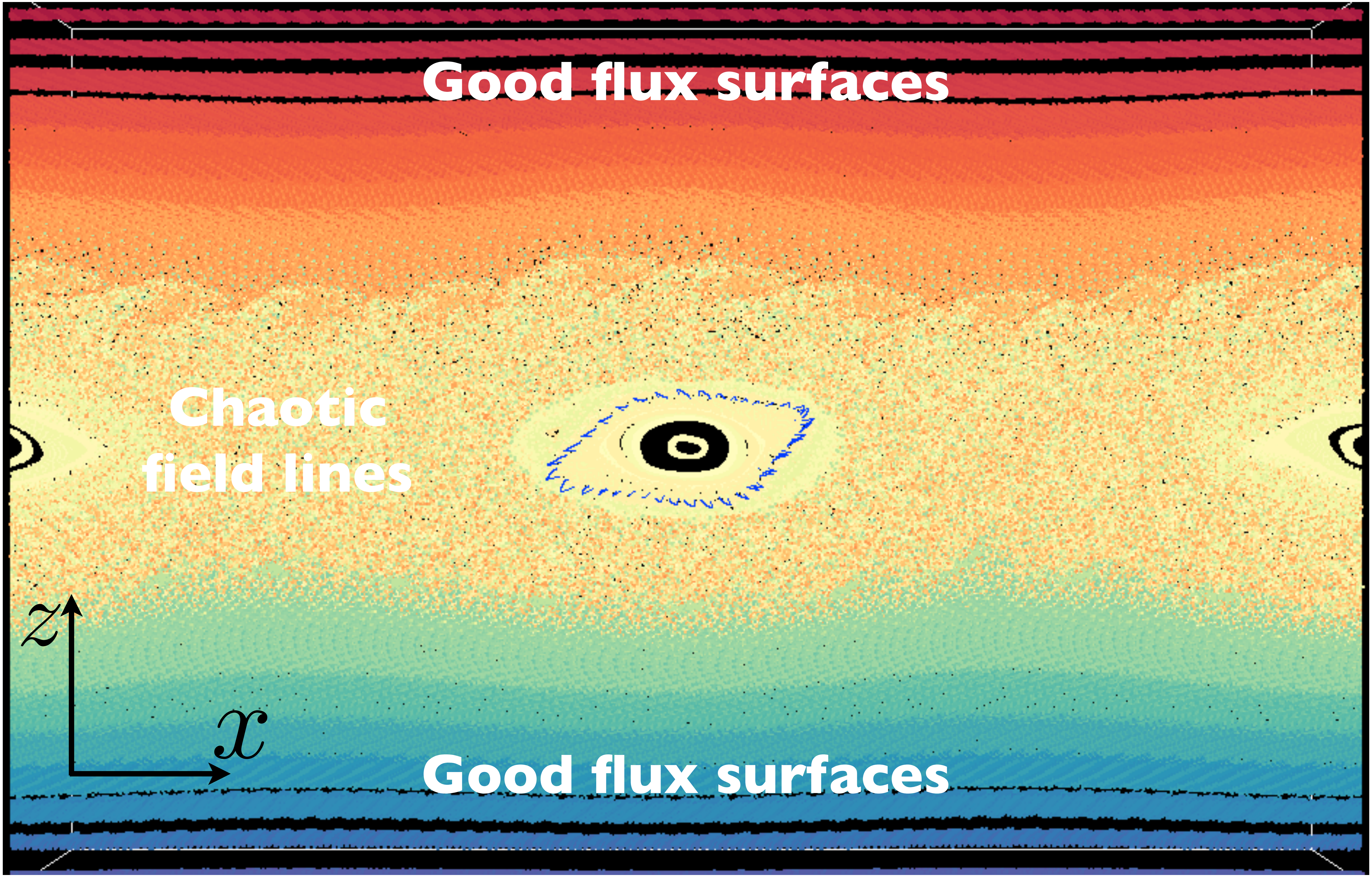
Three-Dimensional Evolution



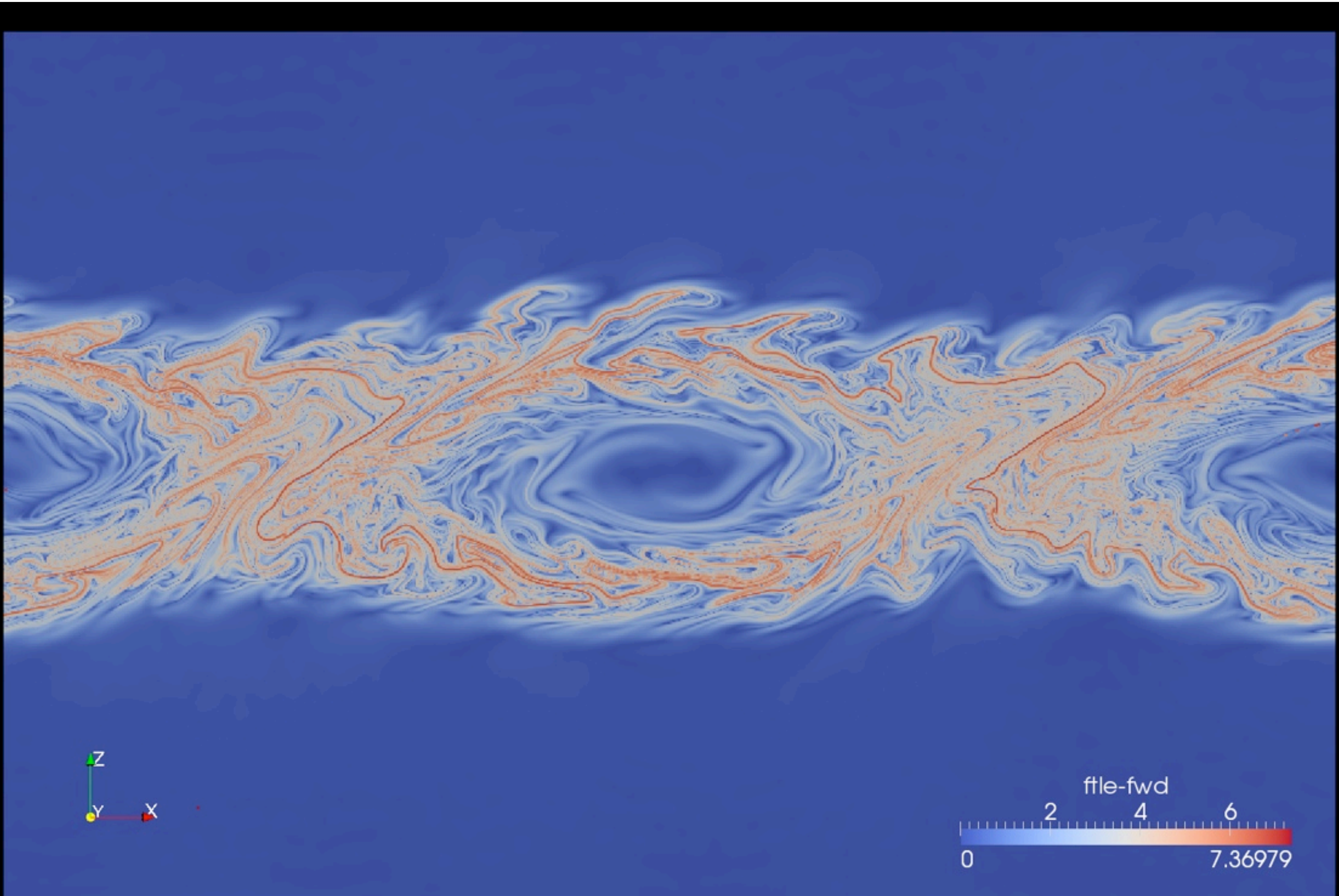


|J| + B lines colored by μmix_e
|J|
0
4J0
μmix_e
0.0
1.0
(a) T=125Ωi-1
Z
Y
X
B
A
(b) T=135Ωi-1
Z
Y
X
B
A
(c) T=145Ωi-1

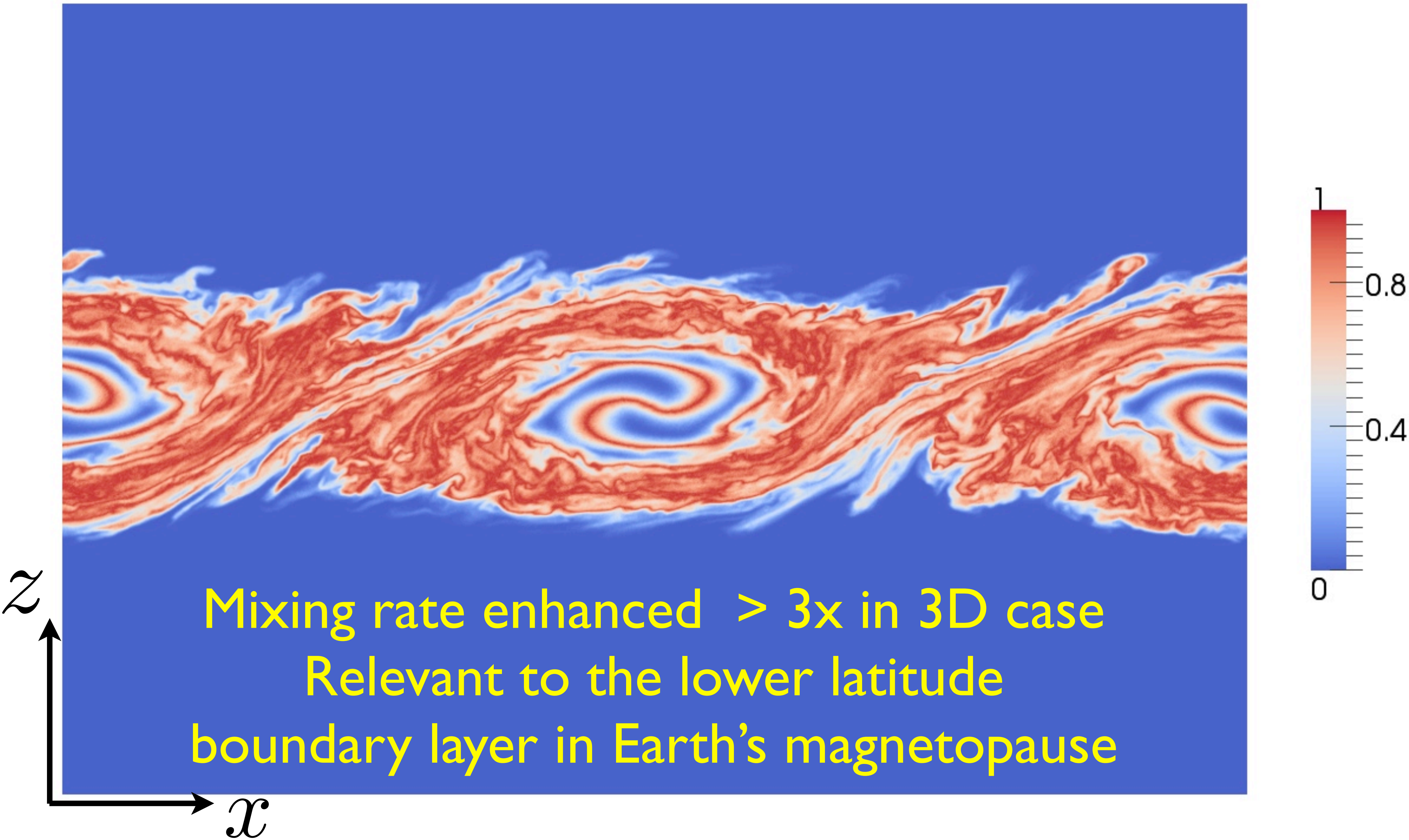
Poincaré Recurrence Map



Finite Time Lyapunov Exponent = FTLE

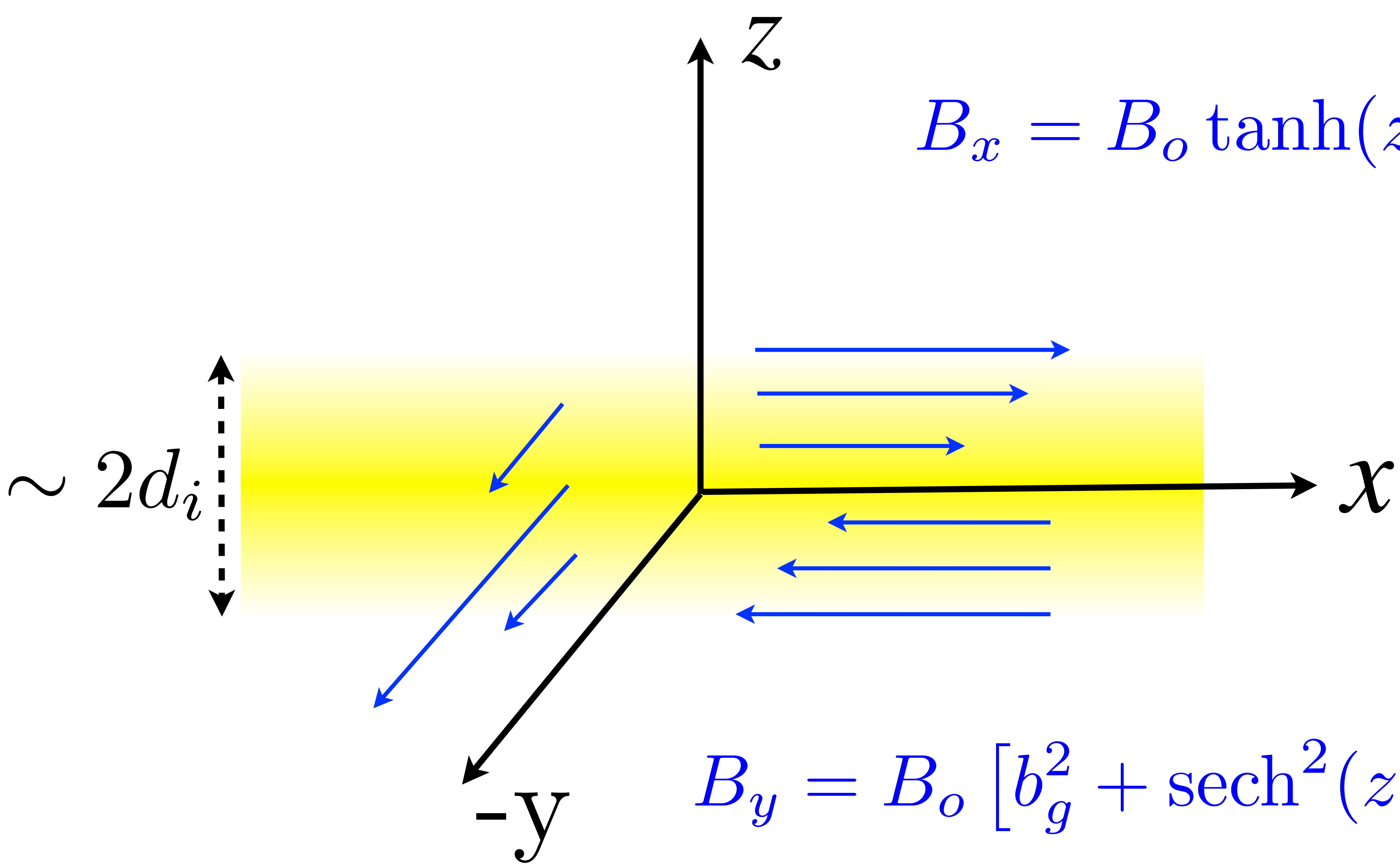


Mixing rate is enhanced due to 3D magnetic field structure



Pure Magnetic Shear: Force-free Current Sheet

Yi-Hsin Liu, Daughton, Karimabadi, 2012

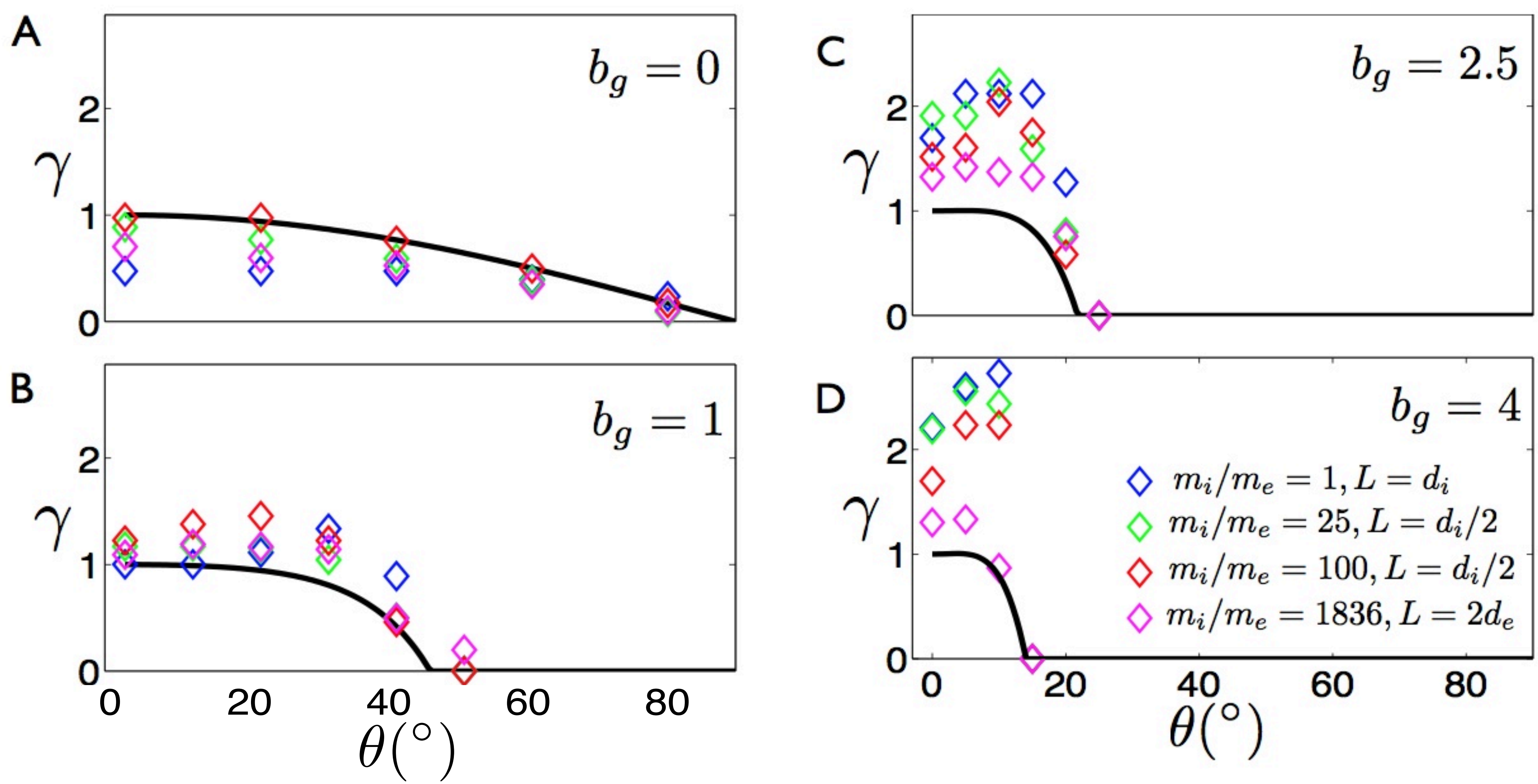


$$B_x = B_o \tanh(z/\lambda)$$

$$B_y = B_o \left[b_g^2 + \text{sech}^2(z/\lambda)\right]^{1/2}$$

$b_g = 0 \rightarrow 4$

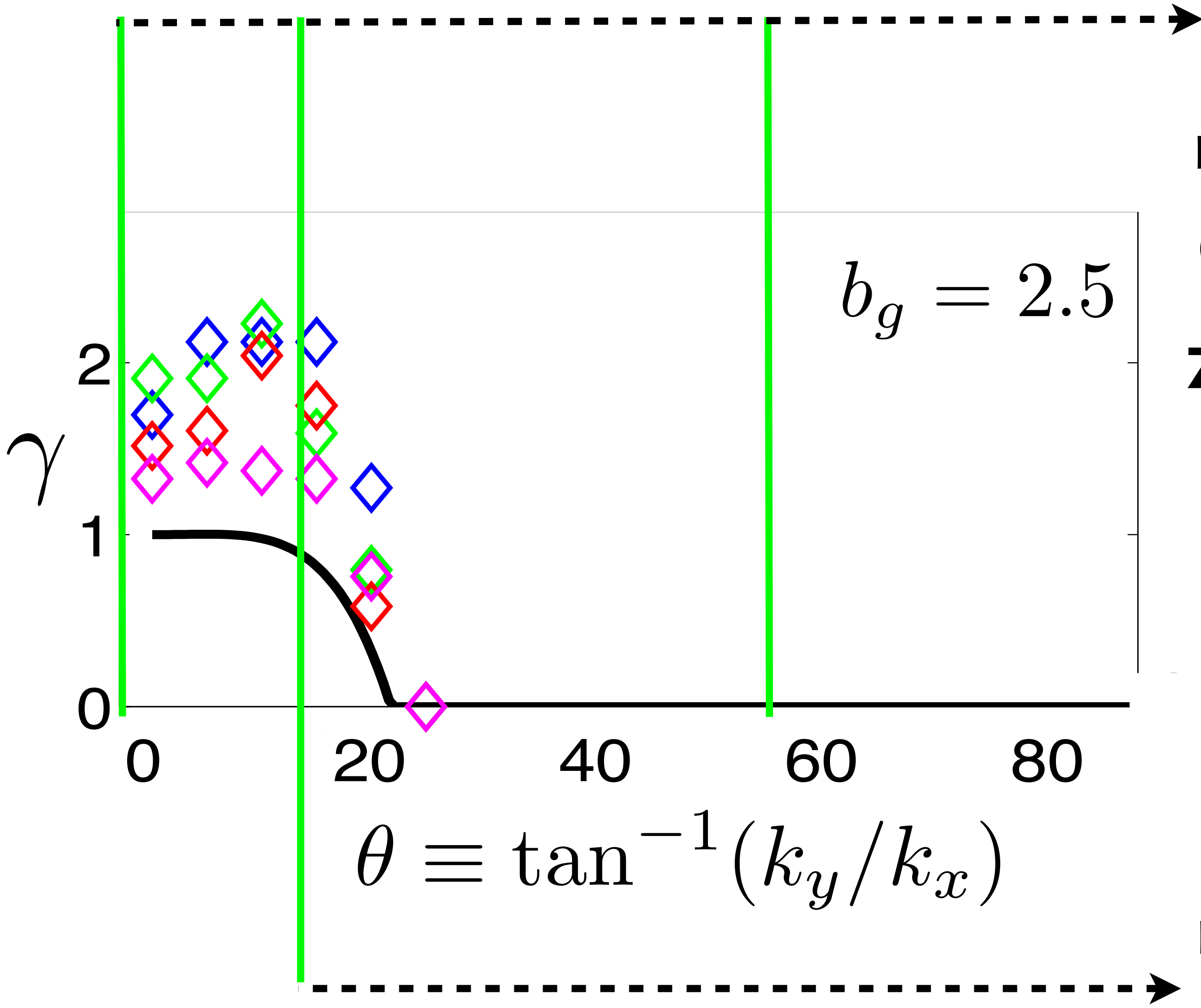
Oblique Tearing Growth Rates

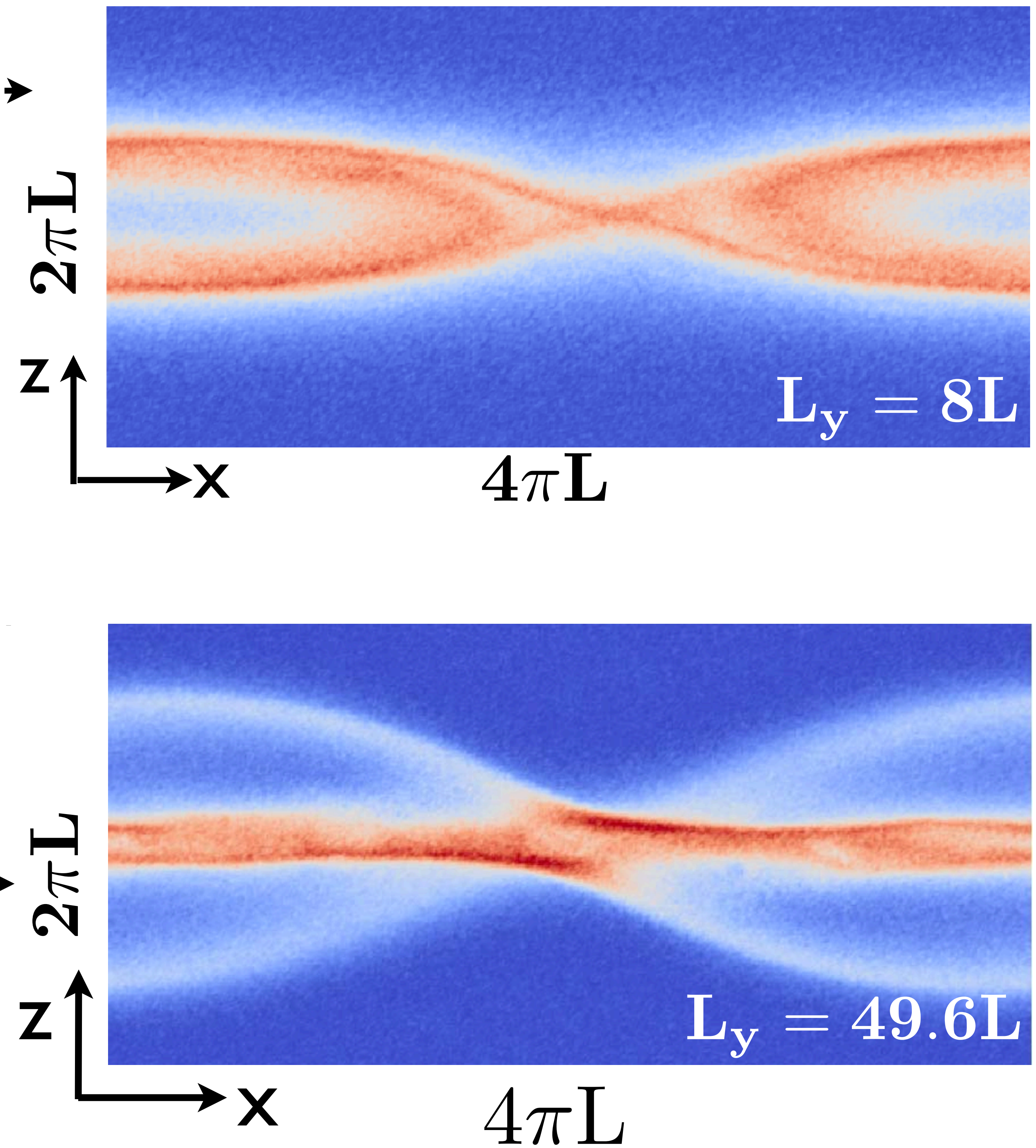


- Oblique tearing modes are unstable over a wide range of angles
- The most unstable tearing mode becomes oblique when $b_g \gtrsim 1$

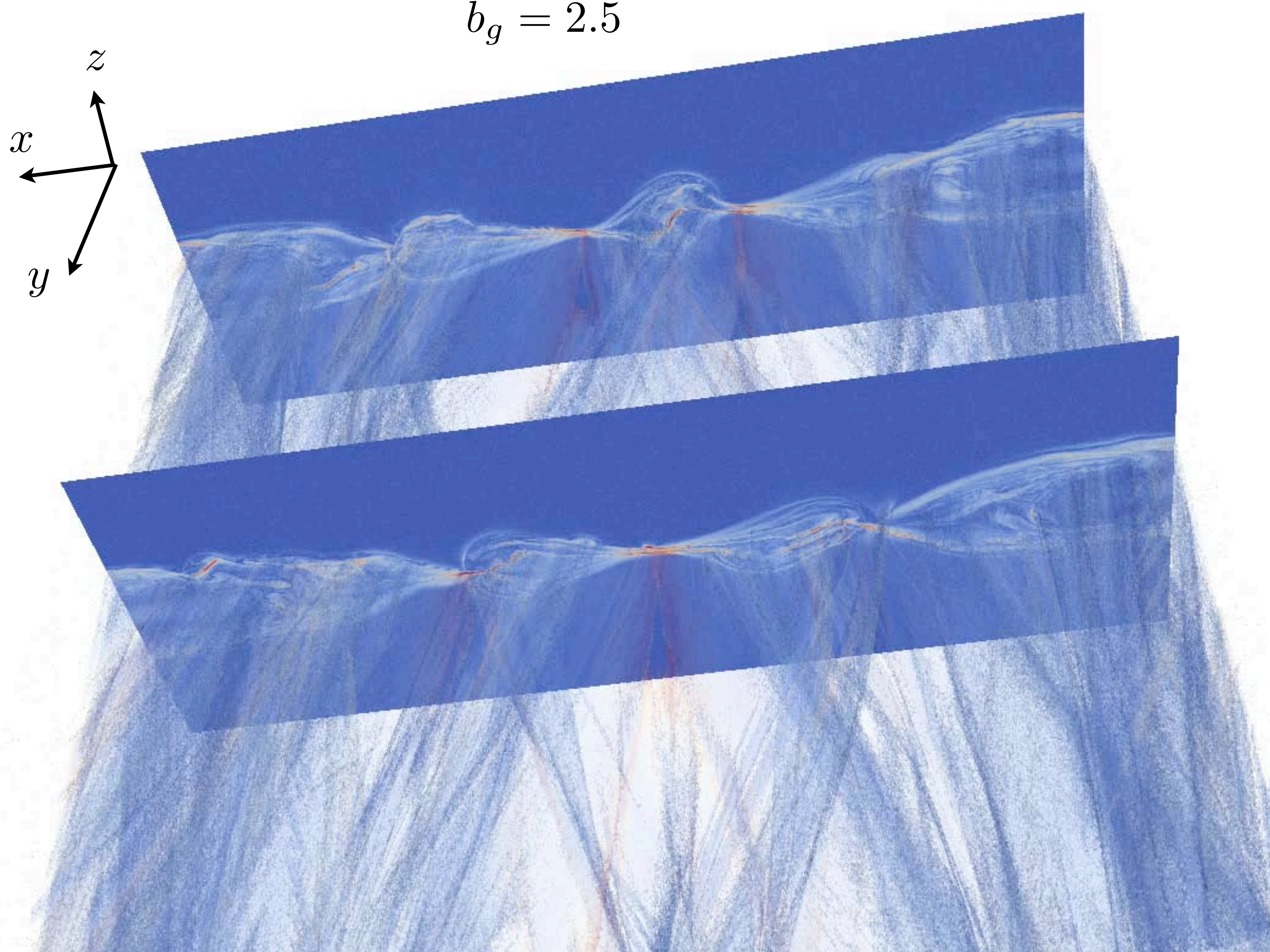
Oblique tearing is the dominant instability

provided that we avoid Buneman instability $U_e < 1.5 V_{the}$

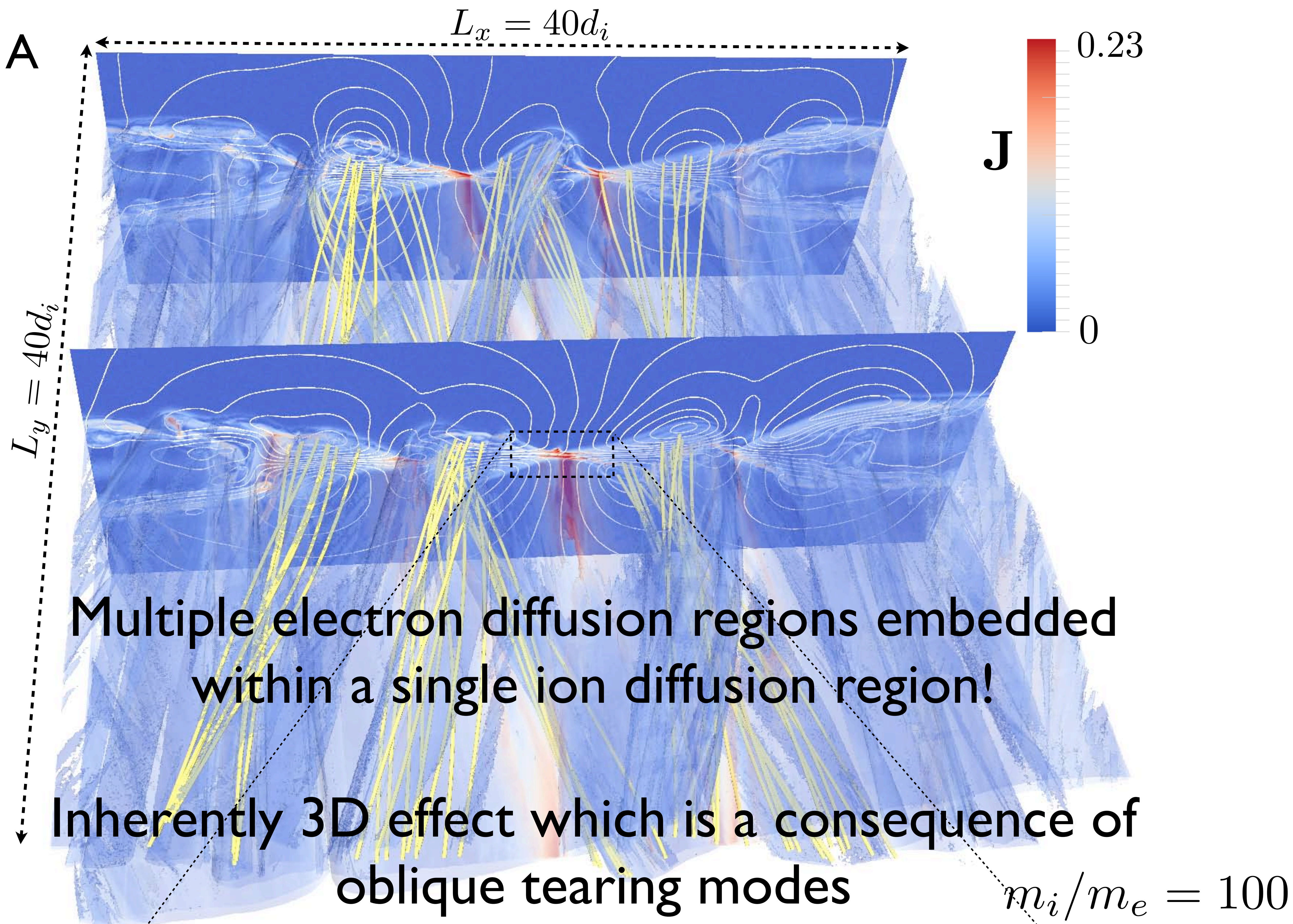




$$\Delta' > 0 \;\rightarrow\; \theta < \tan^{-1}(1/b_g)$$


$b_g = 2.5$
z
x
y

Oblique Flux Ropes Dominate



Multiple electron diffusion regions embedded within a single ion diffusion region!

Inherently 3D effect which is a consequence of oblique tearing modes

Generalized Ohms Law

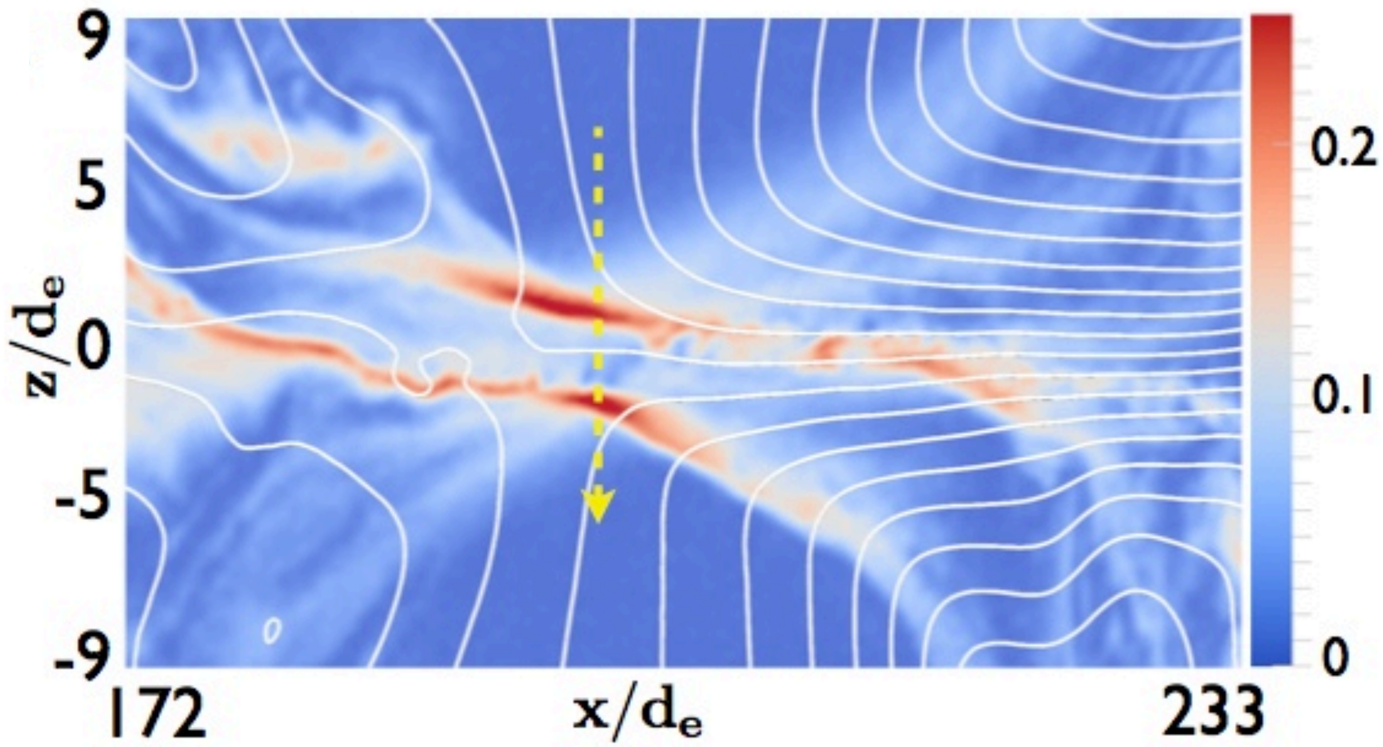
$b_g = 4$

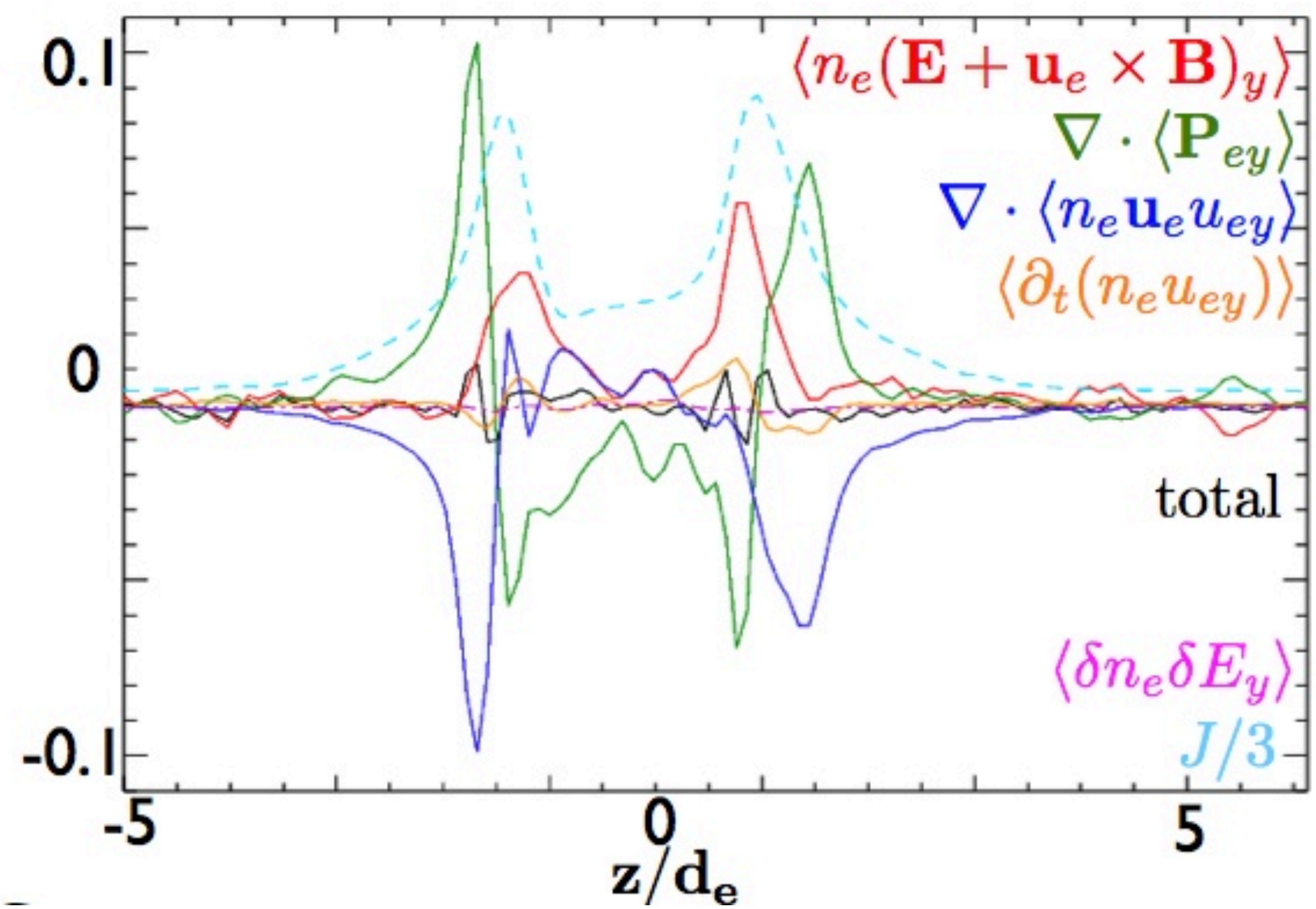
$n_e(\mathbf{E} + \mathbf{u}_e \times \mathbf{B}/c)$

= $-\nabla \cdot \mathbf{P}_e$

$-m_e \nabla \cdot (n_e \mathbf{u_e u_e})$

$-m_e \frac{\partial}{\partial t}(n_e \mathbf{u_e})$





$\nabla \cdot \mathbf{P}_e$ is dominant

non-ideal term

Summary

- Ion-scale boundary layers often include some combination of magnetic and velocity shear

- Large-scale magnetic shear will naturally drive reconnection and these flows may in turn drive Kelvin-Helmoltz

- Alfvenic velocity shear leads to KH vortices which generates current sheets & drives reconnection

- In real 3D applications, both of these mechanisms leads to flux ropes, turbulence and heating within these structures

- Spectra in all simulations feature power law in fluctuations with break at kinetic scales

- Influence on particle mixing across boundary layers