Influence of Magnetic Shear and Profile Asymmetry on Reconnection at the Magnetopause

William Daughton

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Princeton University
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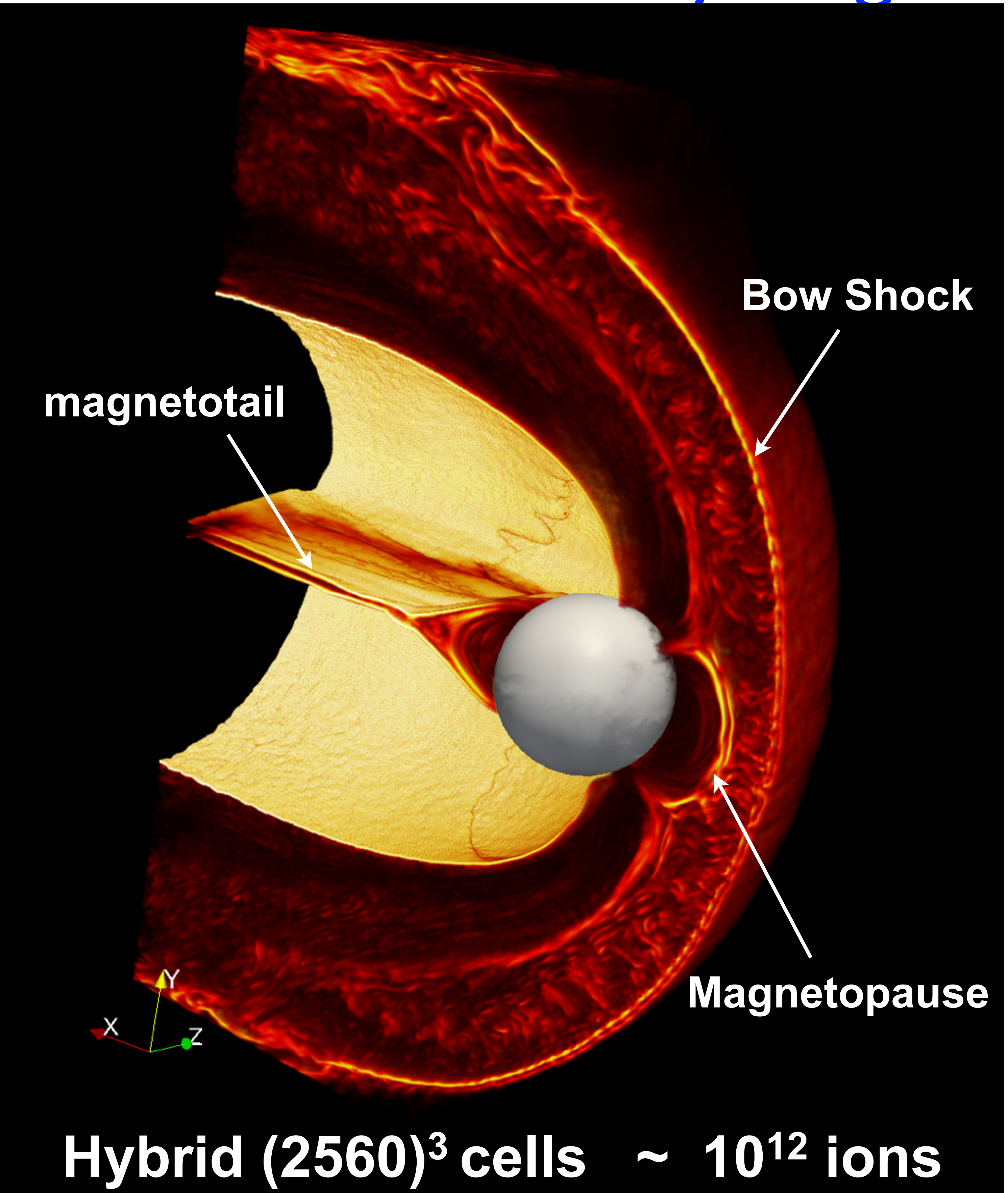
Los Alamos
NATIONAL LABORATORY
EST. 1943

Uusing a combination of hybrid & fully kinetic simulations to study magnetopause reconnection



Hybrid offers good description of:

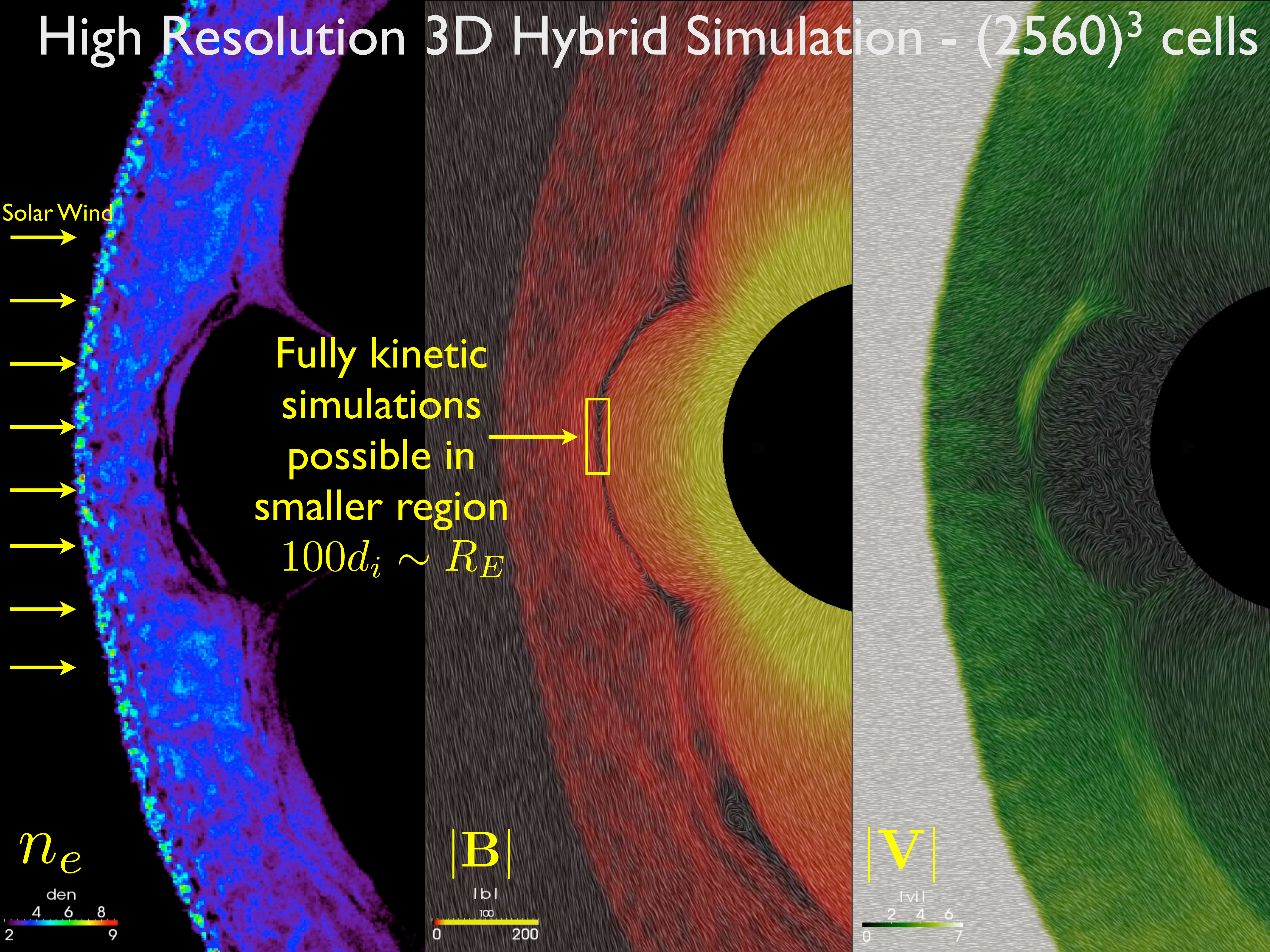
- Collisionless shocks
- Ion kinetic & FLR effects
- Ion temperature anisotropy
- Structure of ion-scale layer

Electrons are massless fluid - missing kinetic physics which is essential for magnetic reconnection

Influence of electron physics is the main science goal MMS mission

Will launch in 2014 and orbit will be optimum to study magnetopause during first 1.5 years

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



Formation & stability of electron layers are the major focus of our fully kinetic simulations

- Magnetic islands ⟶ flux ropes in 3D

Daughton et al, Nature Physics ,2011

- Electron temperature anisotropy

Critical role in layer formation
Accurate fluid closure ⟶ Ohia et al, PRL,2012

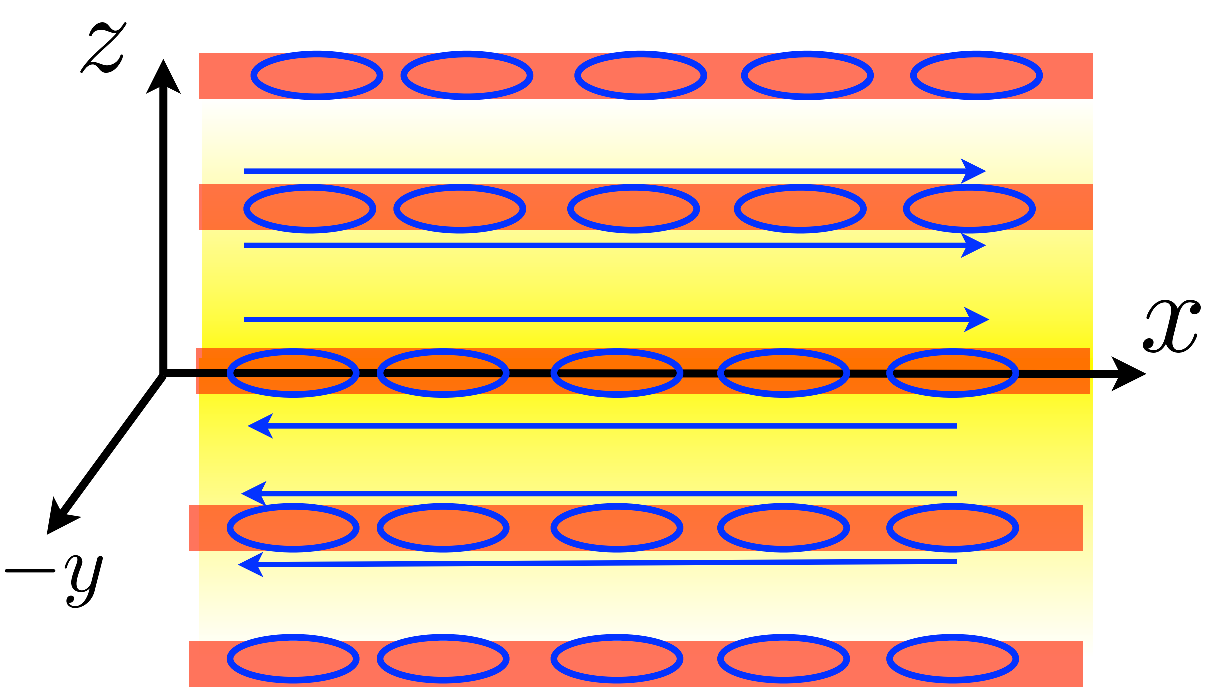
- Lower-hybrid drift instability

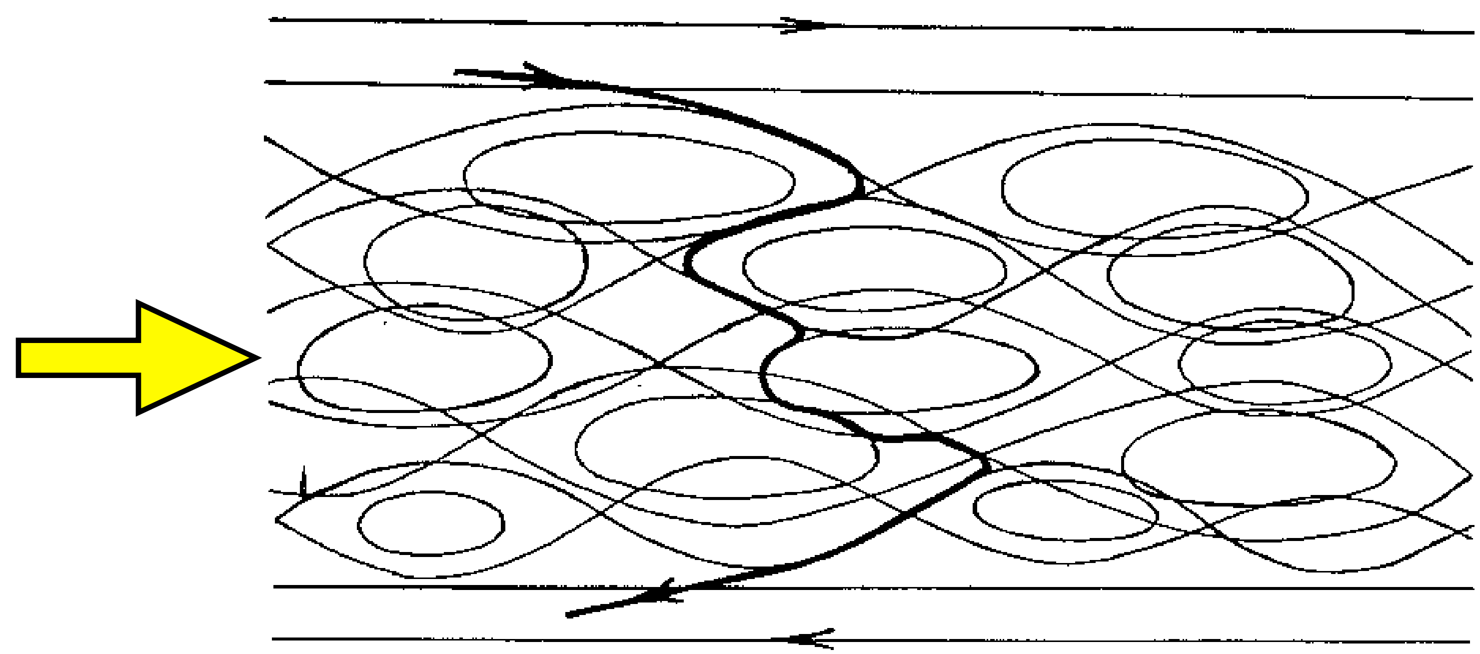
Anomalous dissipation ⟶ Roytershteyn et al, PRL, 2012
Can broaden layers and suppress secondary tearing

- Kelvin-Helmholtz driven vortices

Reconnecting shear-driven turbulence ⟶ Karimabadi et al, 2012
Combination of magnetic & velocity shear ⟶ Nakamura et al, 2012

Tearing → Flux Ropes → Turbulence?





Galeev, 1986

Does it really work this way?

Standard Harris Sheet $\longrightarrow$ $\mathbf{J} \times \mathbf{B} = \nabla P$

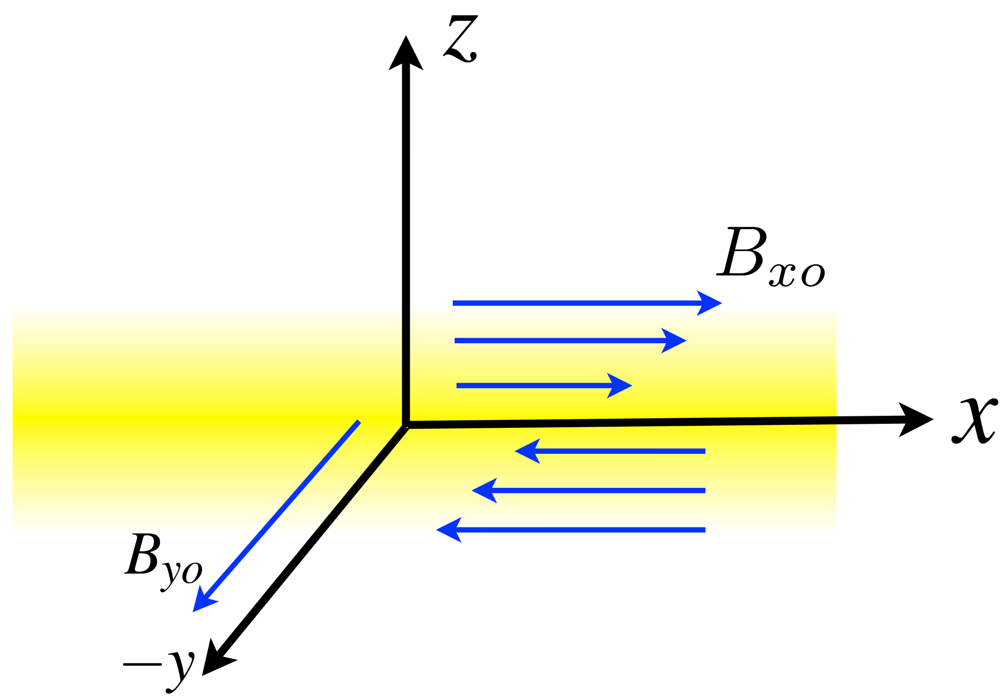
$m_i = m_e$ $\longrightarrow$ **Yes**

$m_i \gg m_e$ $\longrightarrow$ **No** $\longrightarrow$ However - similar picture arises from secondary instabilities

Force-Free Current Sheets $\longrightarrow$ $\mathbf{J} \times \mathbf{B} = 0$

Yes $\longrightarrow$ Works for arbitrary m_i/m_e $\longrightarrow$ Yi-Hsin Liu, poster

Range of parameters in 3D simulations



$$m_i/m_e = 100$$

Shear Angle $\phi = 146^\circ,\ 127^\circ,\ 90^\circ$

Symmetric - Open BC

$$\frac{B_{yo}}{B_{xo}} = 0.3, 0.5, 1.0$$

$L_x \times L_y \times L_z = 70d_i \times 70d_i \times 35d_i$

$2048 \times 2048 \times 1024$ cells

10^{12} particles

Asymmetric - Periodic BC

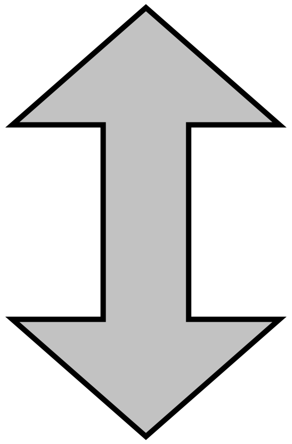
$$\frac{B_{yo}}{B_{xo}} = 0.3, 1 \qquad \frac{n_{bot}}{n_{top}} = 8$$

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

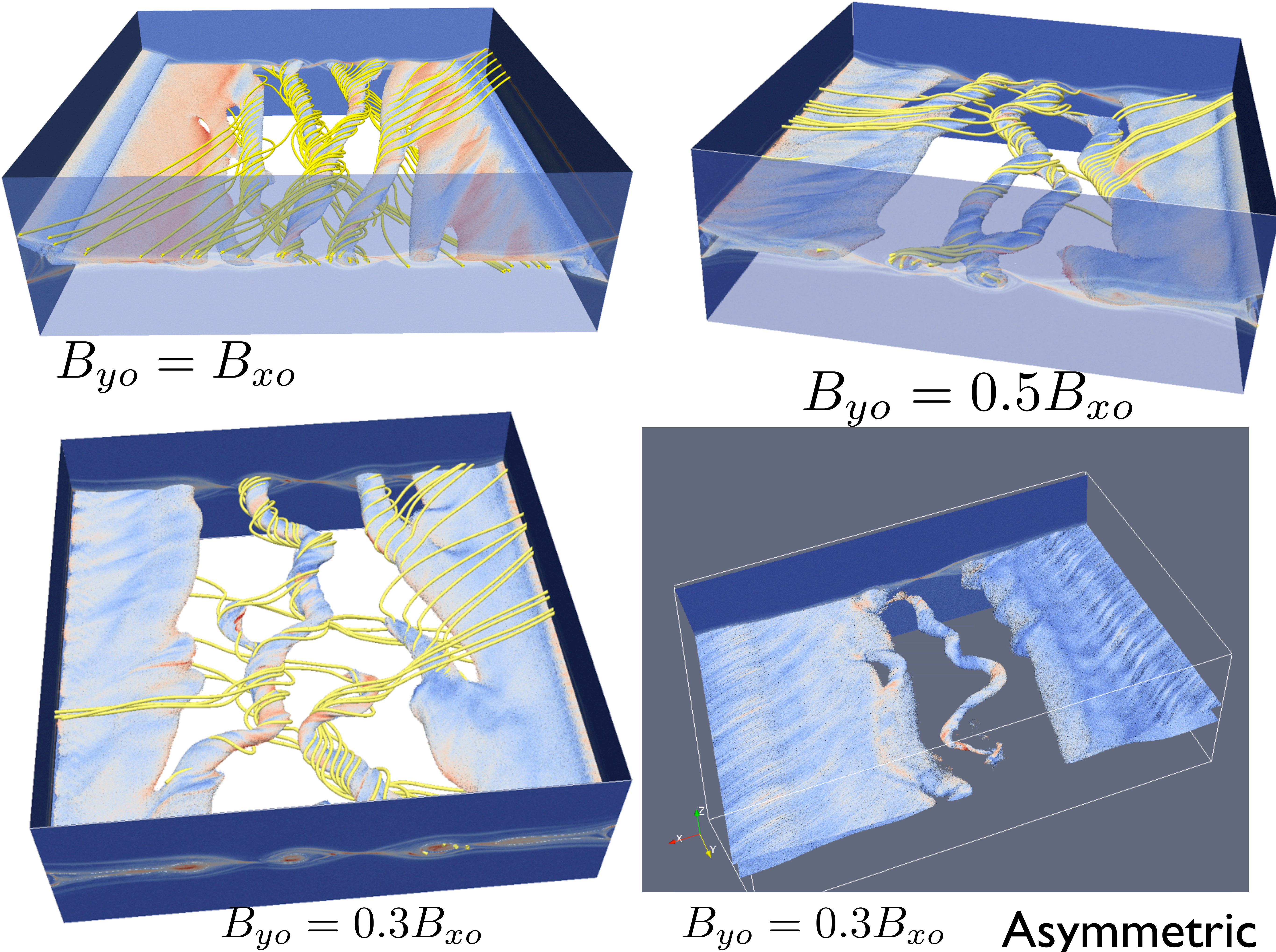
$3072 \times 3072 \times 1024$ cells

2×10^{12} particles

Primary Flux Ropes



Generated by tearing instability within ion-scale current layers

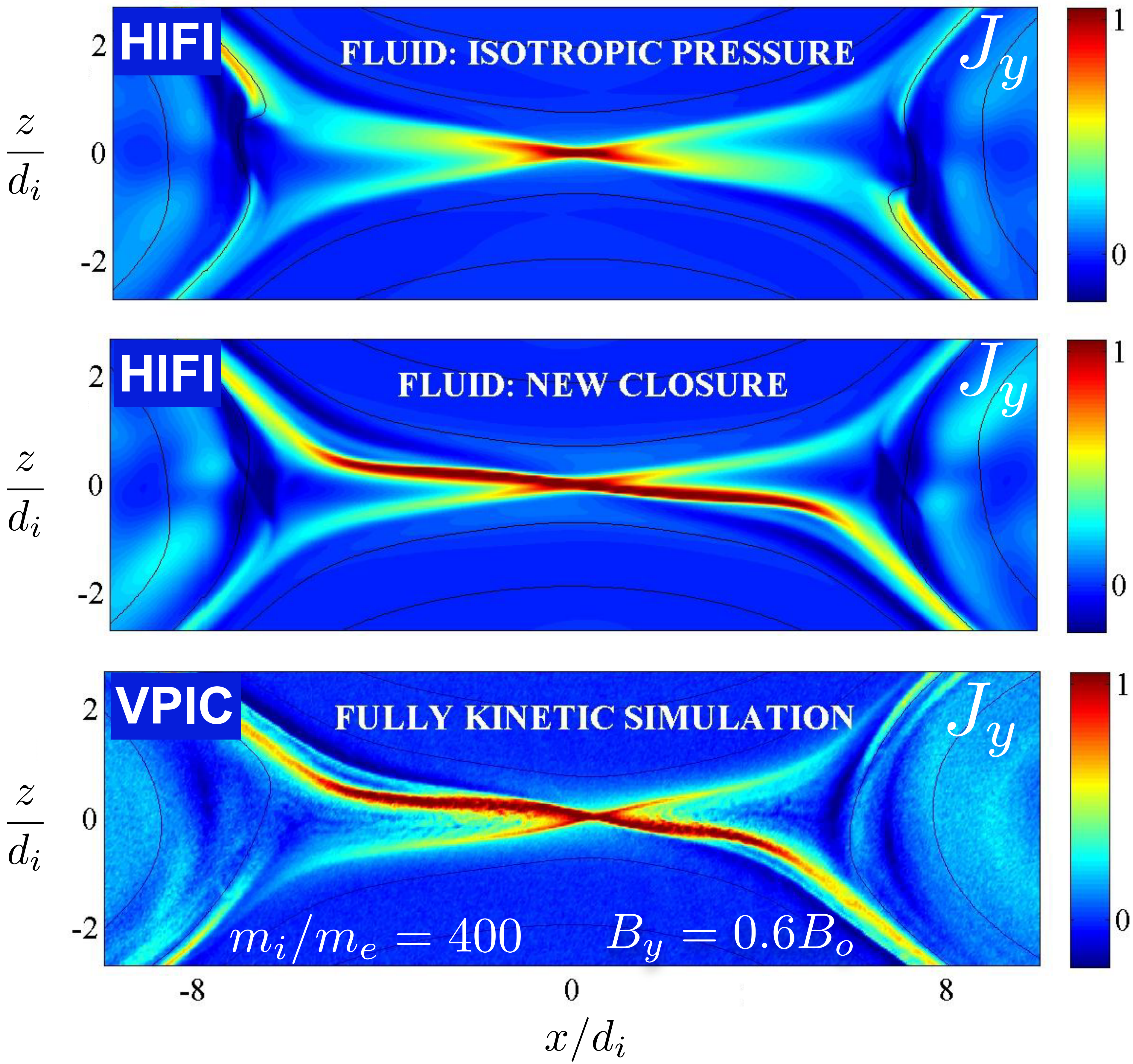

$B_{yo} = B_{xo}$
$B_{yo} = 0.5B_{xo}$
$B_{yo} = 0.3B_{xo}$
$B_{yo} = 0.3B_{xo}$
Asymmetric

After the onset, reconnection gives rise to extended electron-scale current sheets

Why are these so much longer in kinetic simulations than in two-fluid?

Do the results depend on $\dfrac{m_i}{m_e}$?

Anisotropic electron pressure plays crucial role



Ohia et al, 2012

Egedal et al, 2011

Le et al, 2009

HIFI code - S. Lukin

$$\Phi_{||} \gg T_e$$

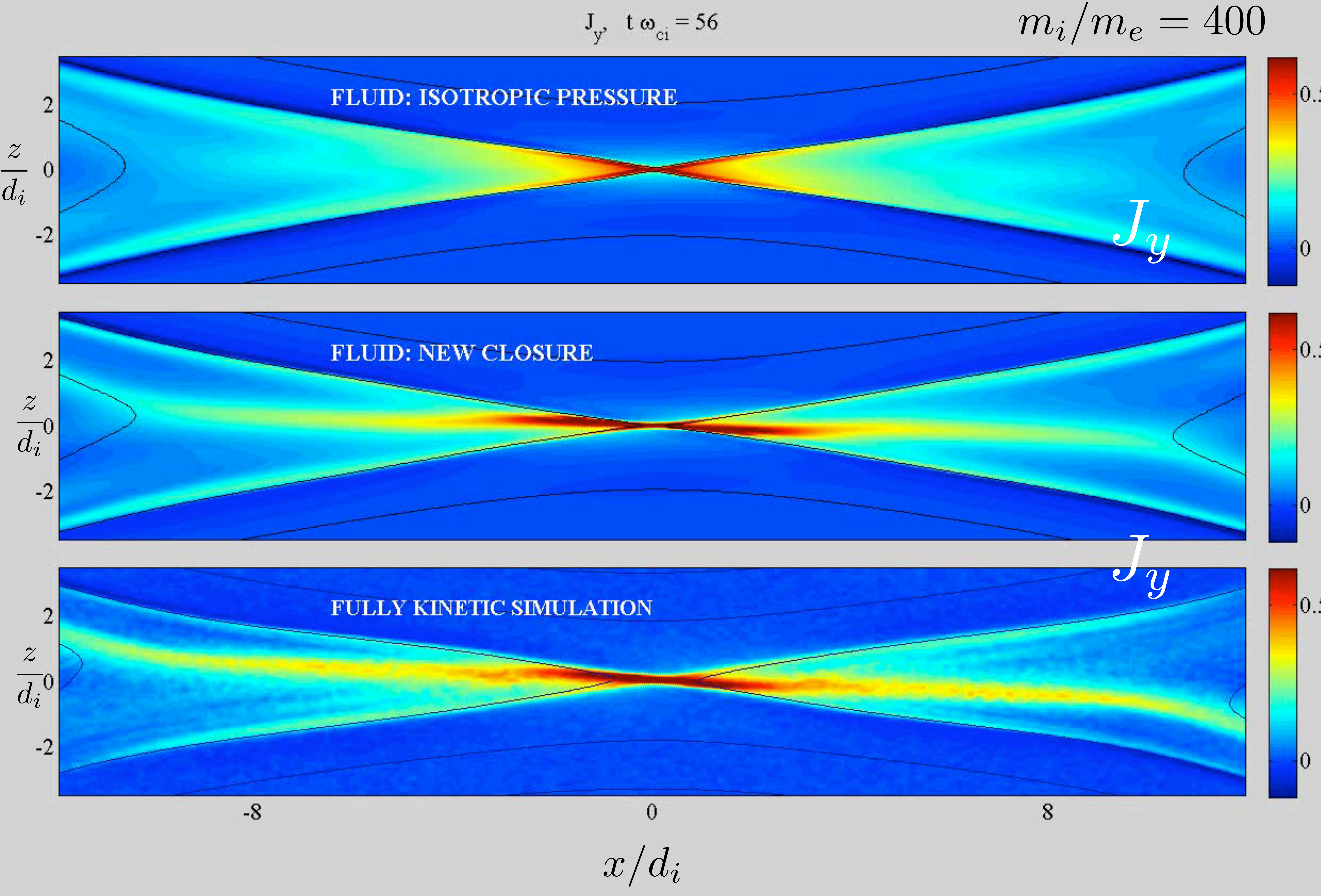
$$P_{e||} \propto \frac{n_e^3}{B^2}$$

$$P_{e\perp} \propto n_e B$$

Details influenced by guide field

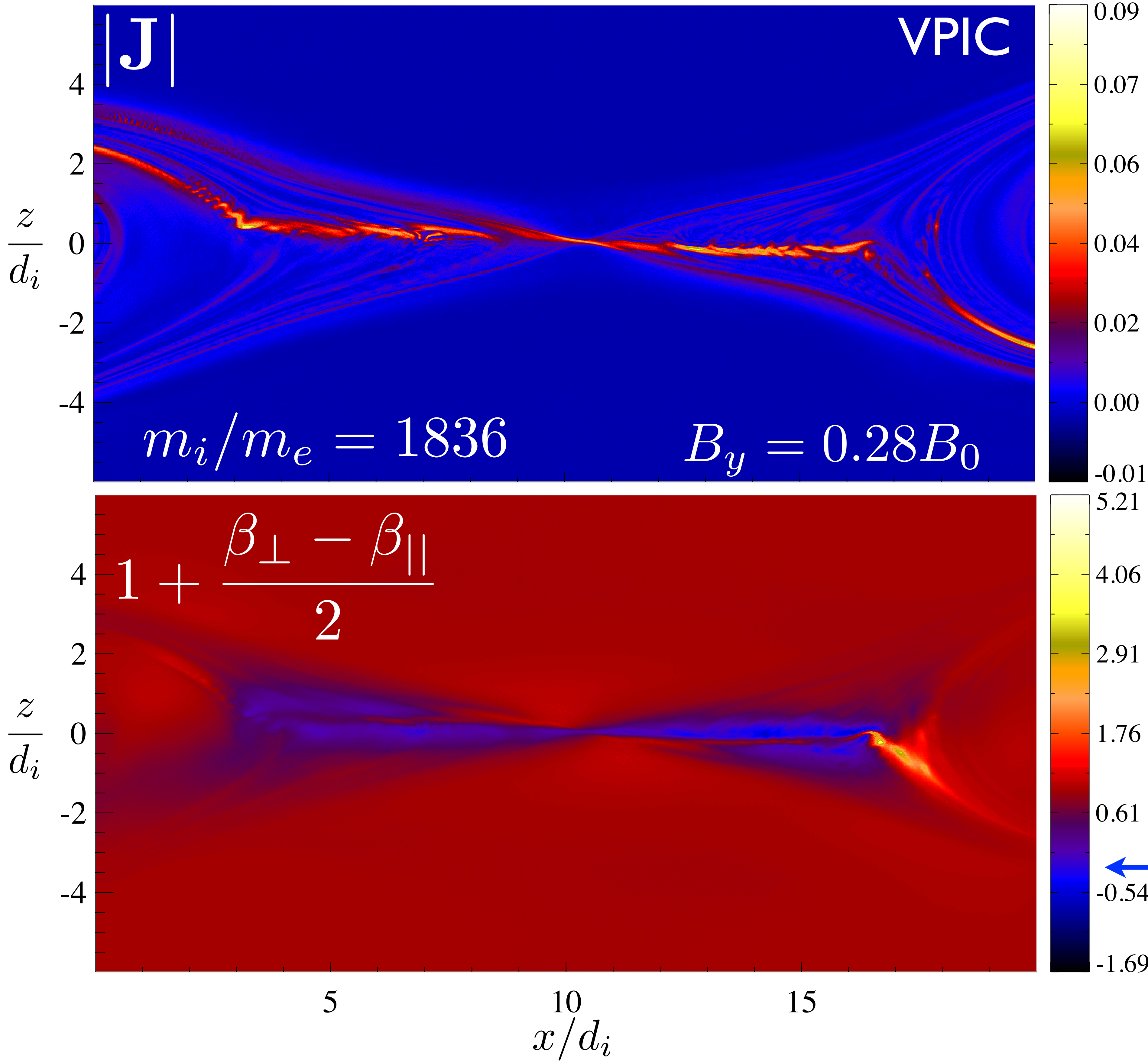
$B_y = 0.4 B_o$

$m_i/m_e = 400$



We are mapping out influence of mass ratio

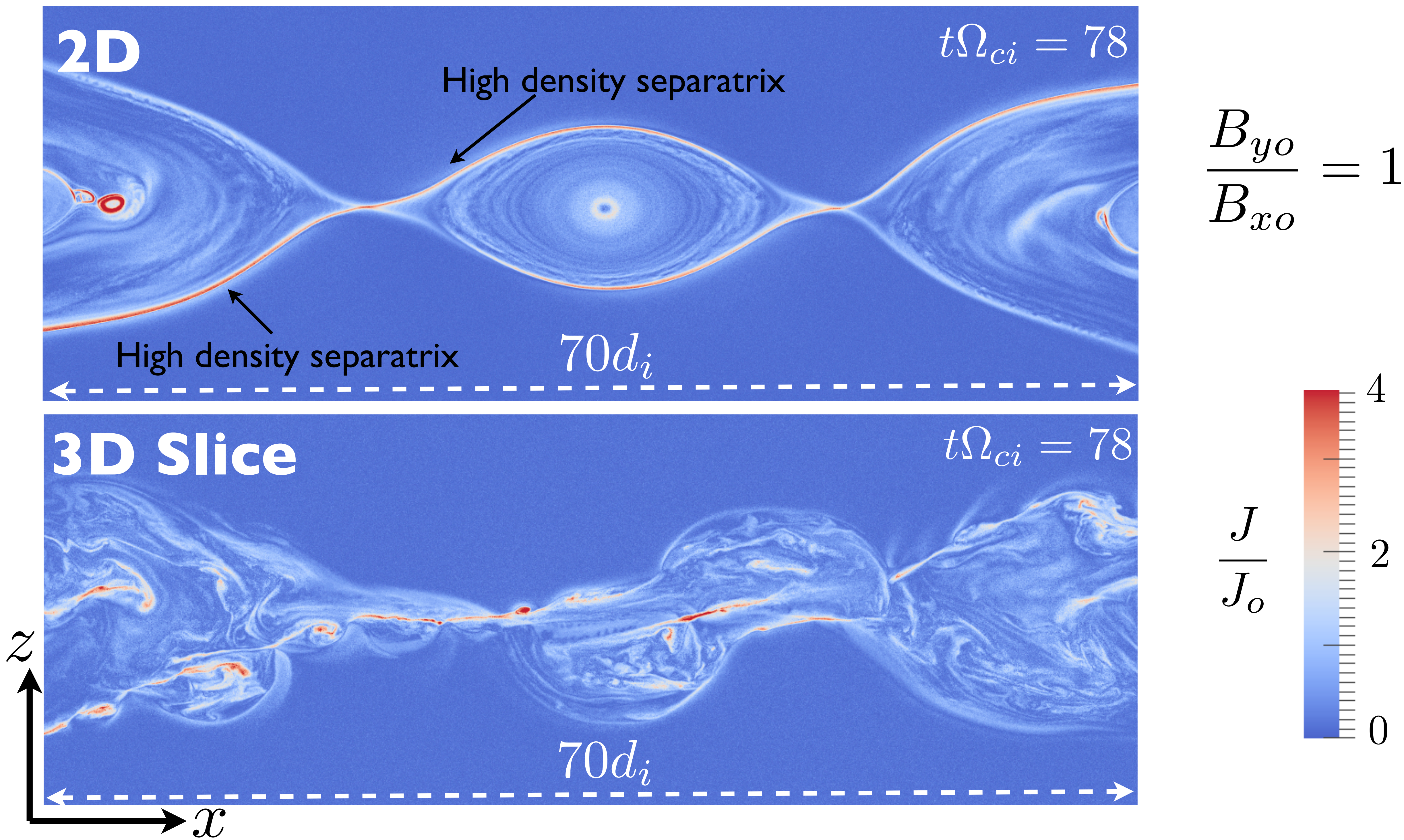
$$m_i/m_e = 100 \rightarrow 400 \rightarrow 1836$$



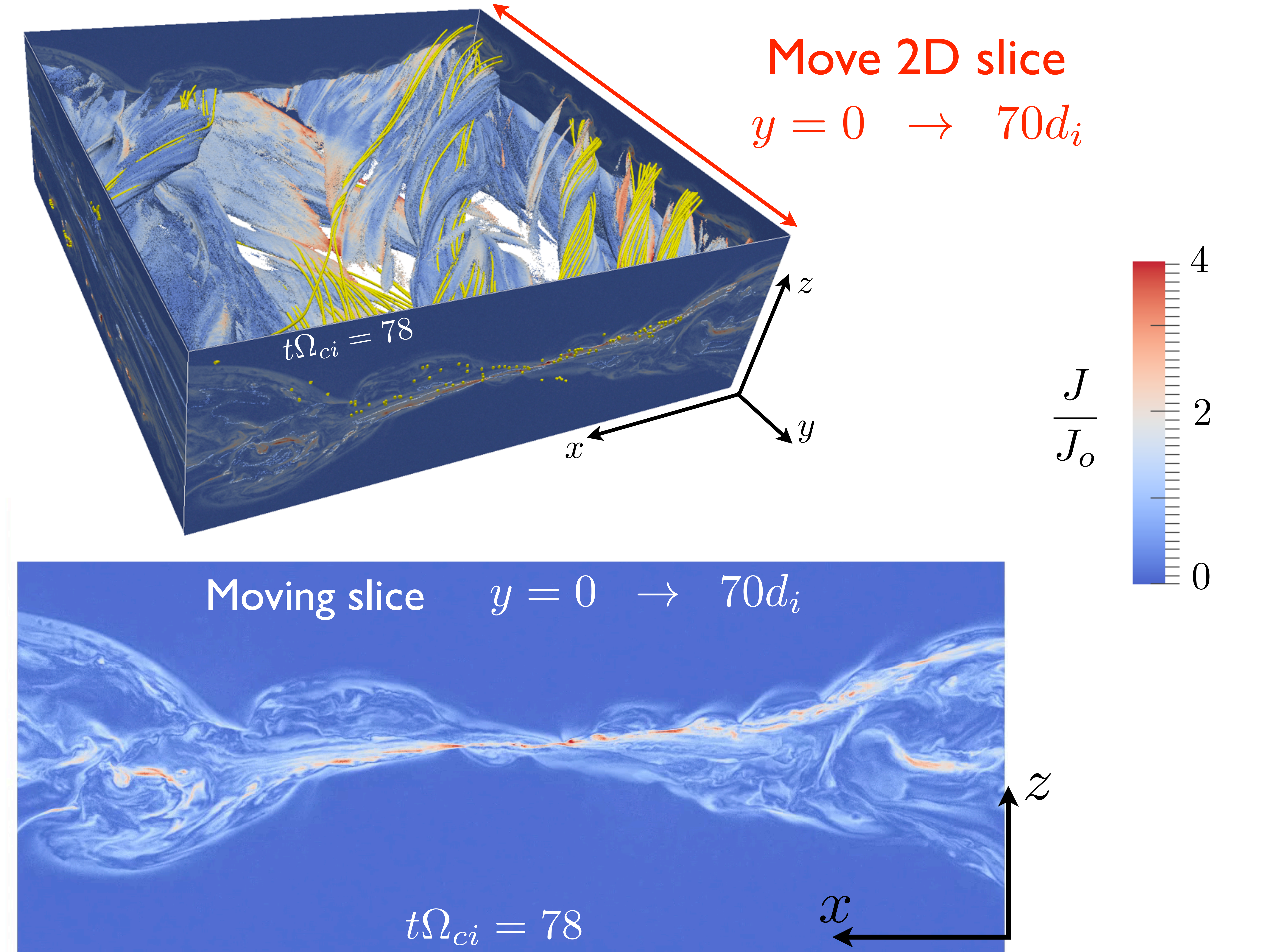
Le, Egedal
Daughton, 2012

Marginal
Firehose

Electron layers are unstable in 3D to secondary tearing instabilities



see Daughton et al, Nature Physics, 2011

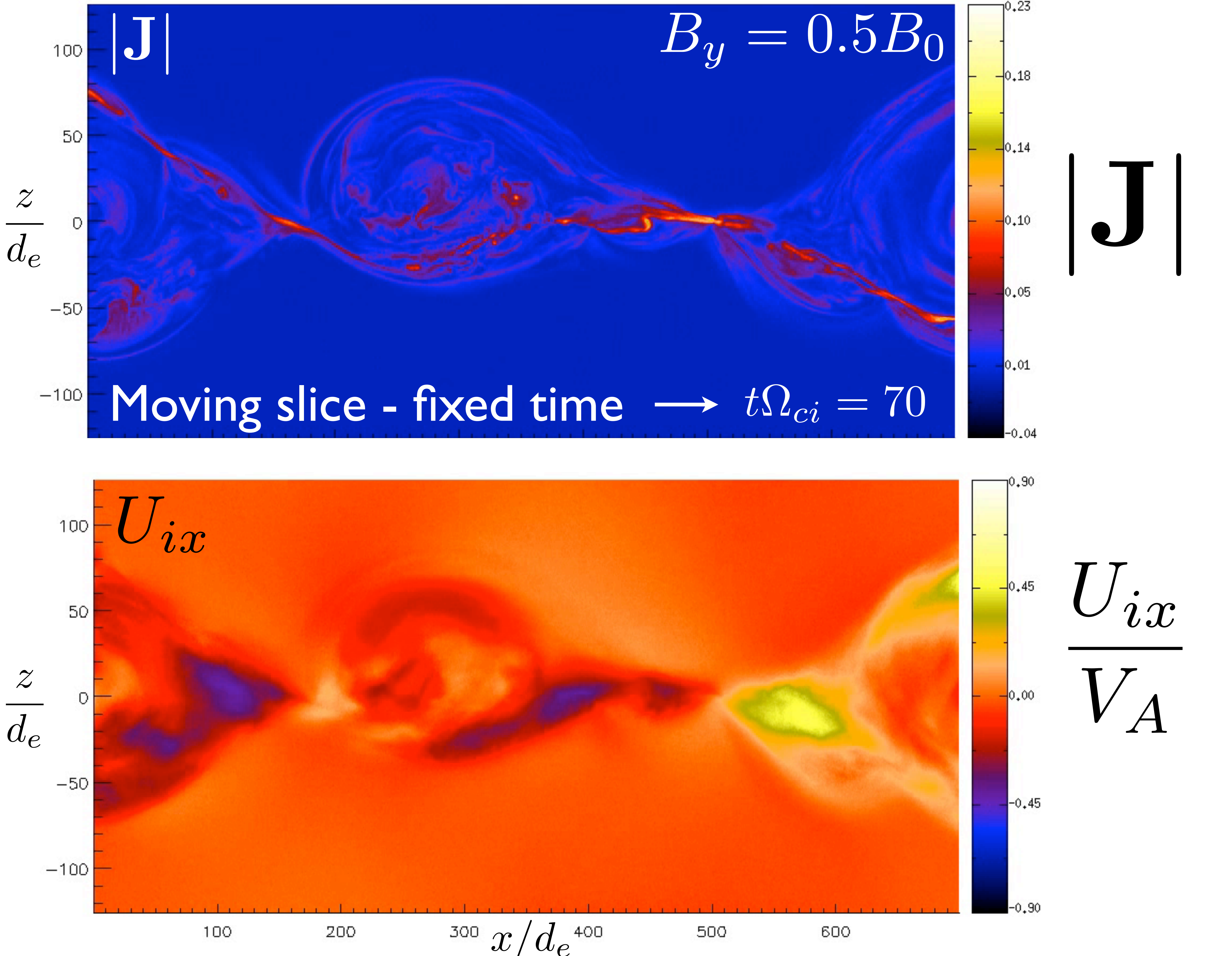


Move 2D slice
$y = 0 \rightarrow 70d_i$
$t\Omega_{ci} = 78$
z
x
y
$\frac{J}{J_o}$
4
2
0
Moving slice $y = 0 \rightarrow 70d_i$
$t\Omega_{ci} = 78$
z
x

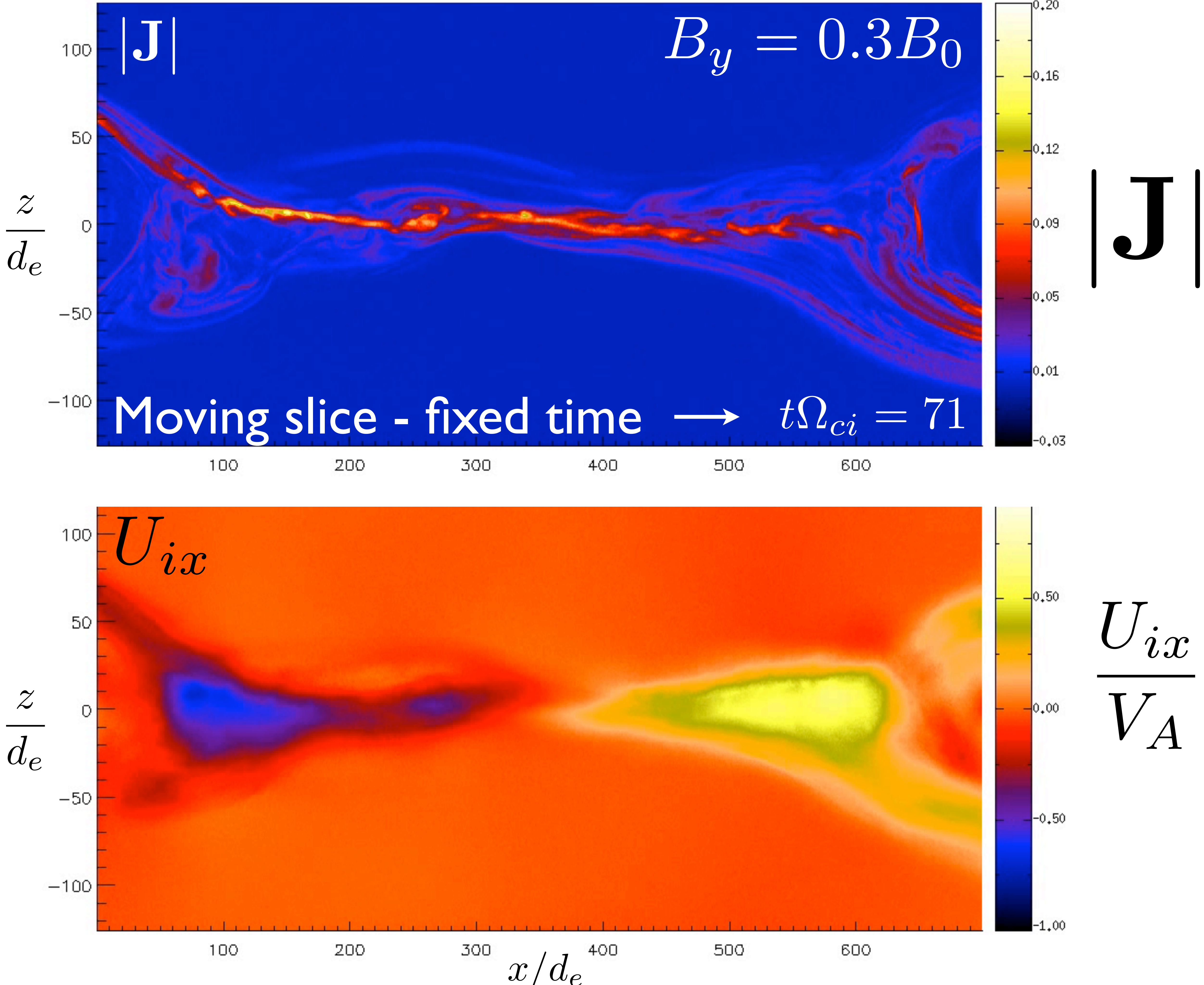
What happens for weaker guide fields?

- Electron layers are spatially located inside outflow, rather than directly along separatrices
- Electron layers near marginal firehose
- More secondary flux ropes, but smaller in size

Note: In all cases, ion flow structure is much simpler $\longrightarrow$ easy to identify reconnection jets

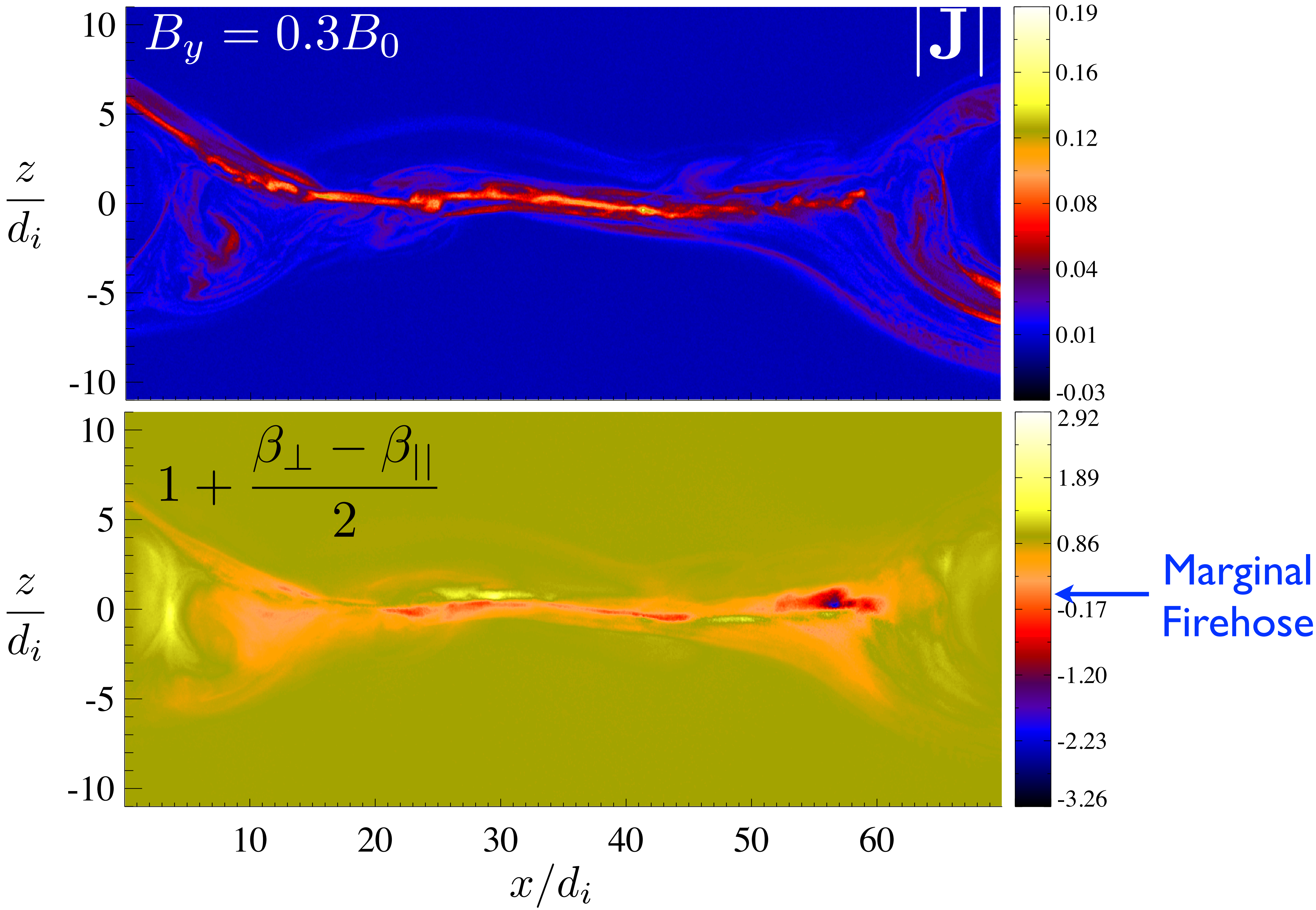


$|\mathbf{J}|$
$B_y = 0.5B_0$
Moving slice - fixed time $\longrightarrow$ $t\Omega_{ci} = 70$
$\frac{z}{d_e}$
100
50
0
−50
−100
0.23
0.18
0.14
0.10
0.05
0.01
−0.04
$|\mathbf{J}|$
U_{ix}
$\frac{z}{d_e}$
0.90
0.45
0.00
−0.45
−0.90
$\frac{U_{ix}}{V_A}$
100
200
300
x/d_e
400
500
600

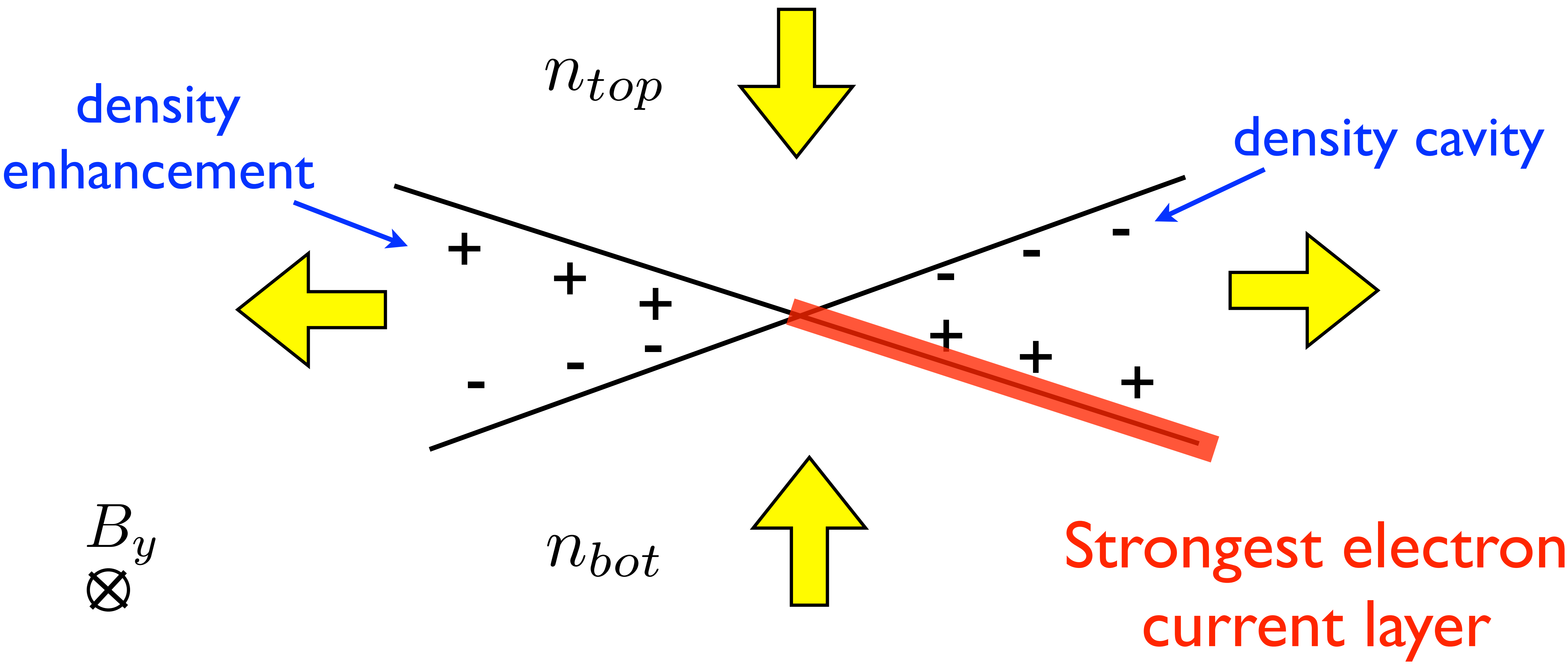


|J|
$B_y = 0.3B_0$
Moving slice - fixed time ⟶ $t\Omega_{ci} = 71$
U_{ix}
$\frac{z}{d_e}$
x/d_e
$|\mathbf{J}|$
$\frac{U_{ix}}{V_A}$

Reconnection drives electron layers towards marginal firehose condition

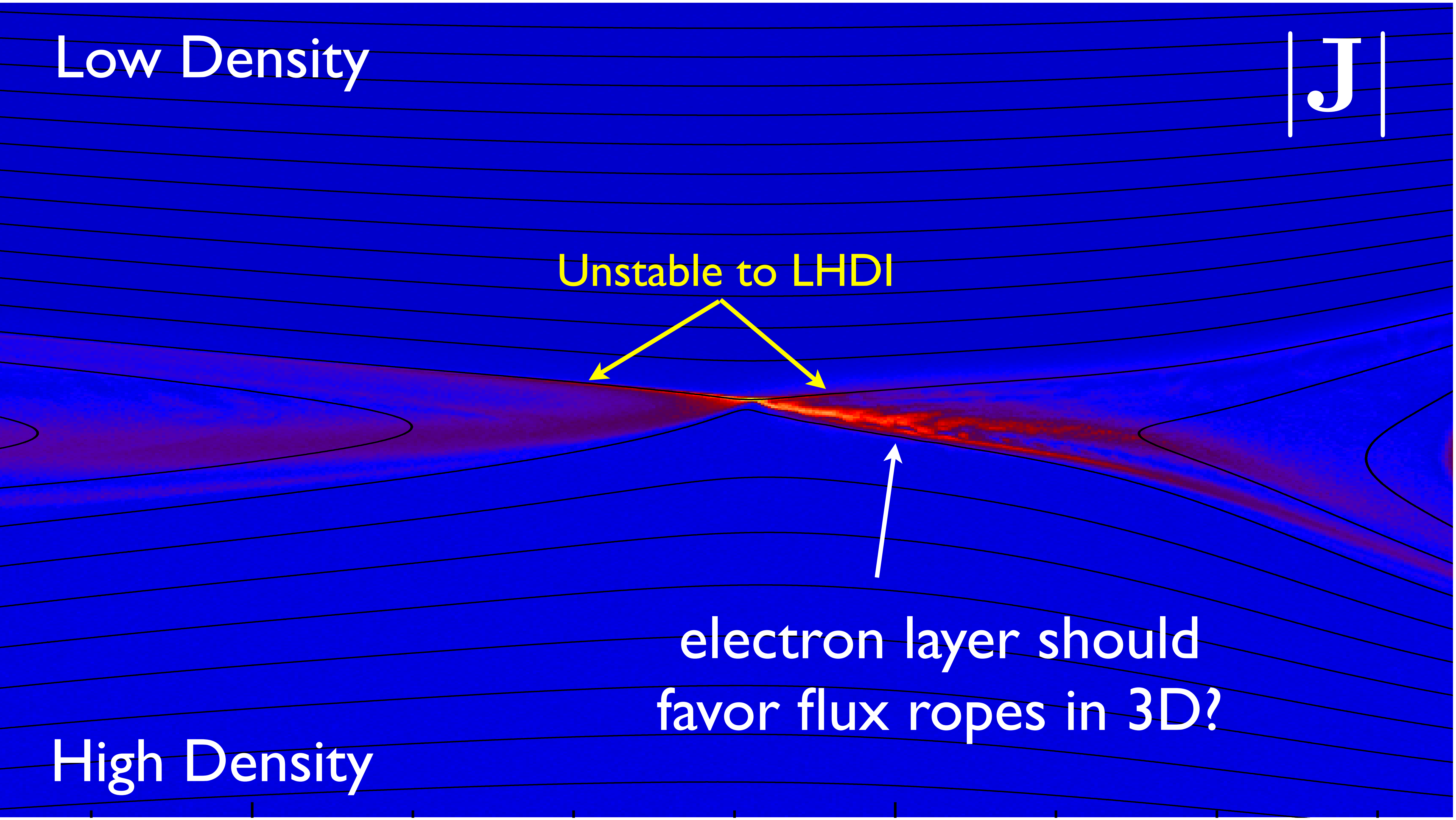


Influence of Density Asymmetry



Asymmetric Layer $\longrightarrow$ $n_{bot} > n_{top}$

Influence of Density Asymmetry

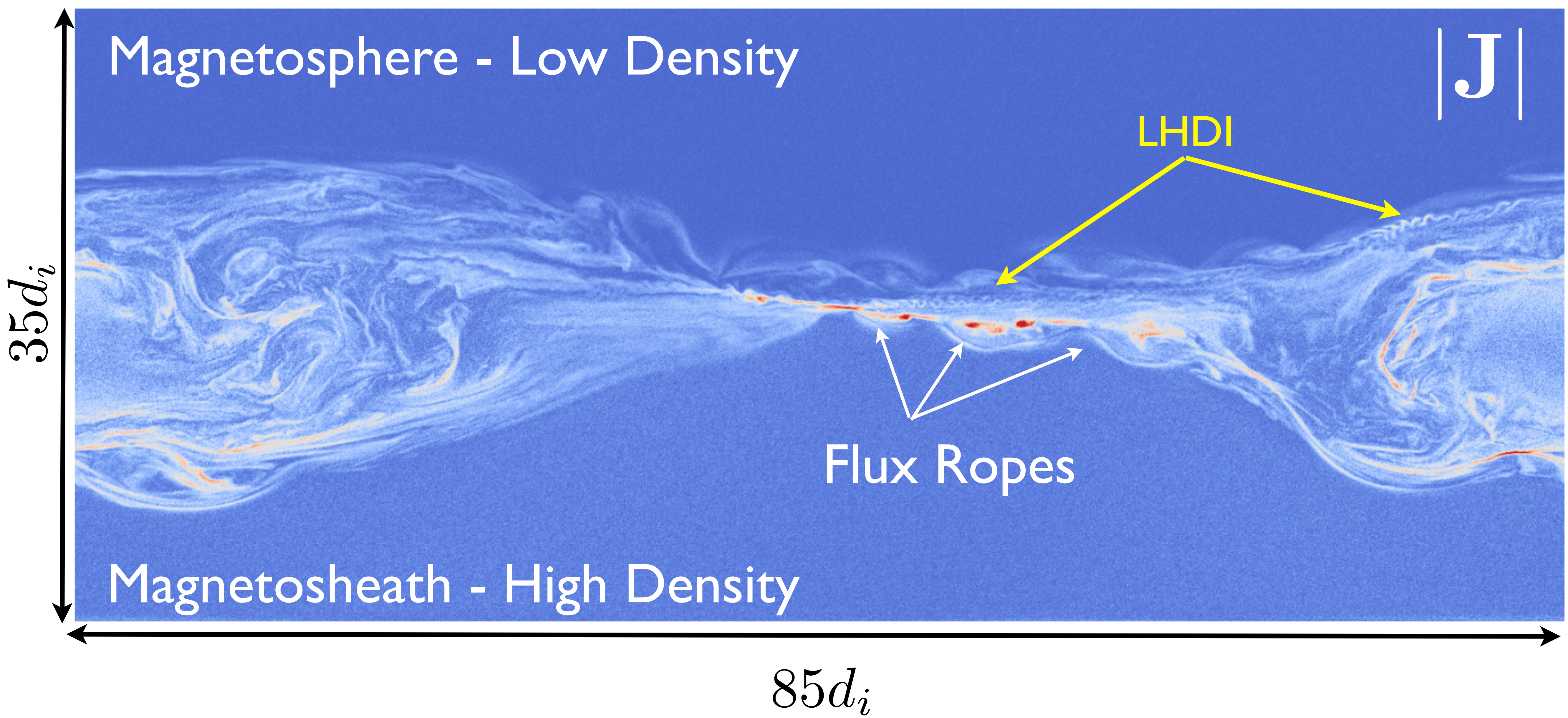


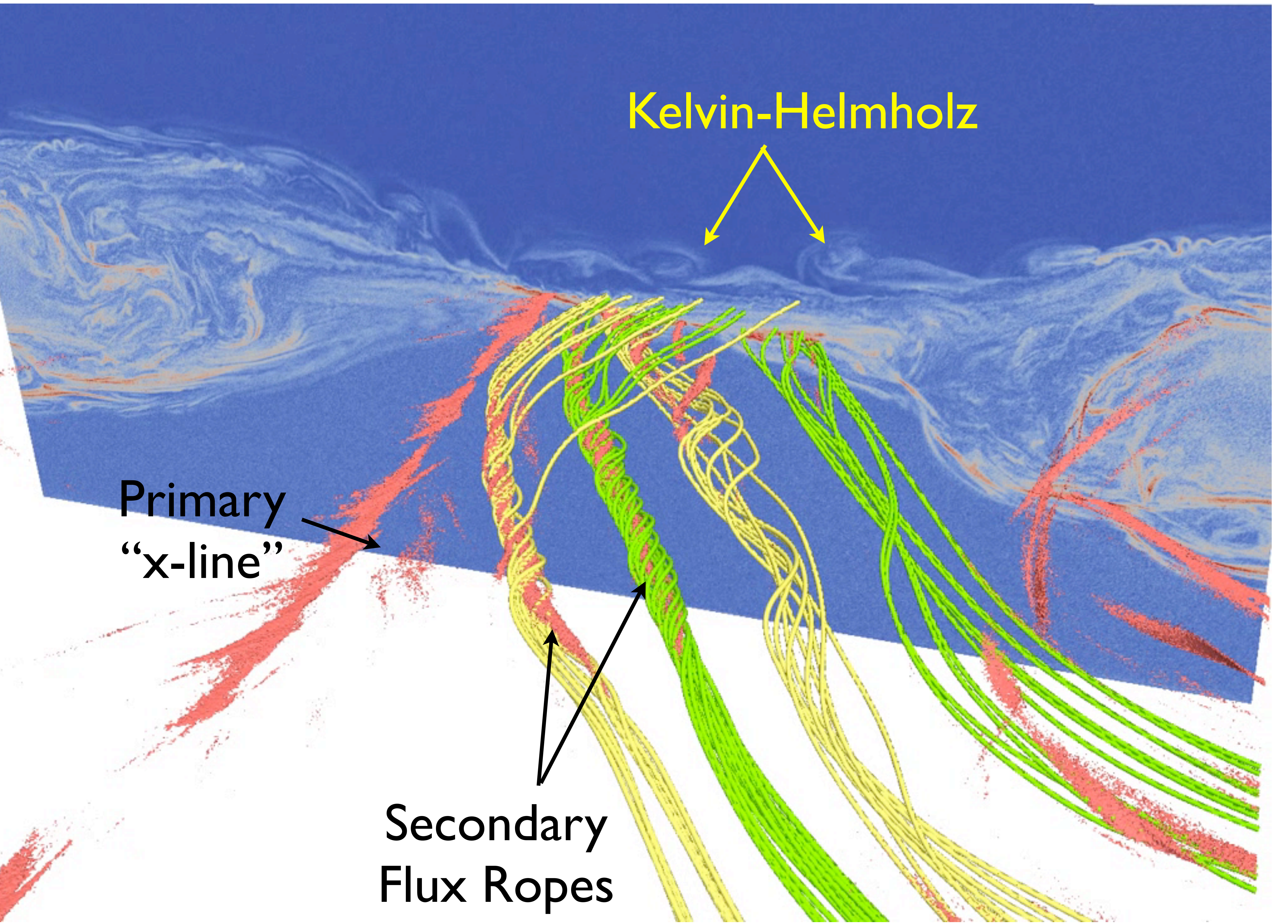
Asymmetric Layer $\longrightarrow$ $n_{bot} > n_{top}$

Influence of Density Asymmetry?

$85d_i \times 85d_i \times 35d_i$ $\quad \frac{B_y}{B_o} = 1$ $\quad \frac{n_{bot}}{n_{top}} = 8$

10 billion cells
2 trillion particles





Kelvin-Helmholz
Primary
"x-line"
Secondary
Flux Ropes

Kelvin-Helmholtz offers another mechanism to create flux ropes, current sheets, & turbulence

Coherent Structures, Intermittent Turbulence and Dissipation in High-Temperature Plasmas

H. Karimabadi[1], V. Roytershteyn[1], M. Wan [2], W. H. Matthaeus[2], W. Daughton[3], P. Wu[2], M. Shay[2], B. Loring[4], J. Borovsky[5], E. Leonardis[6], S. Chapman[6], & T. K. M. Nakamura[3]

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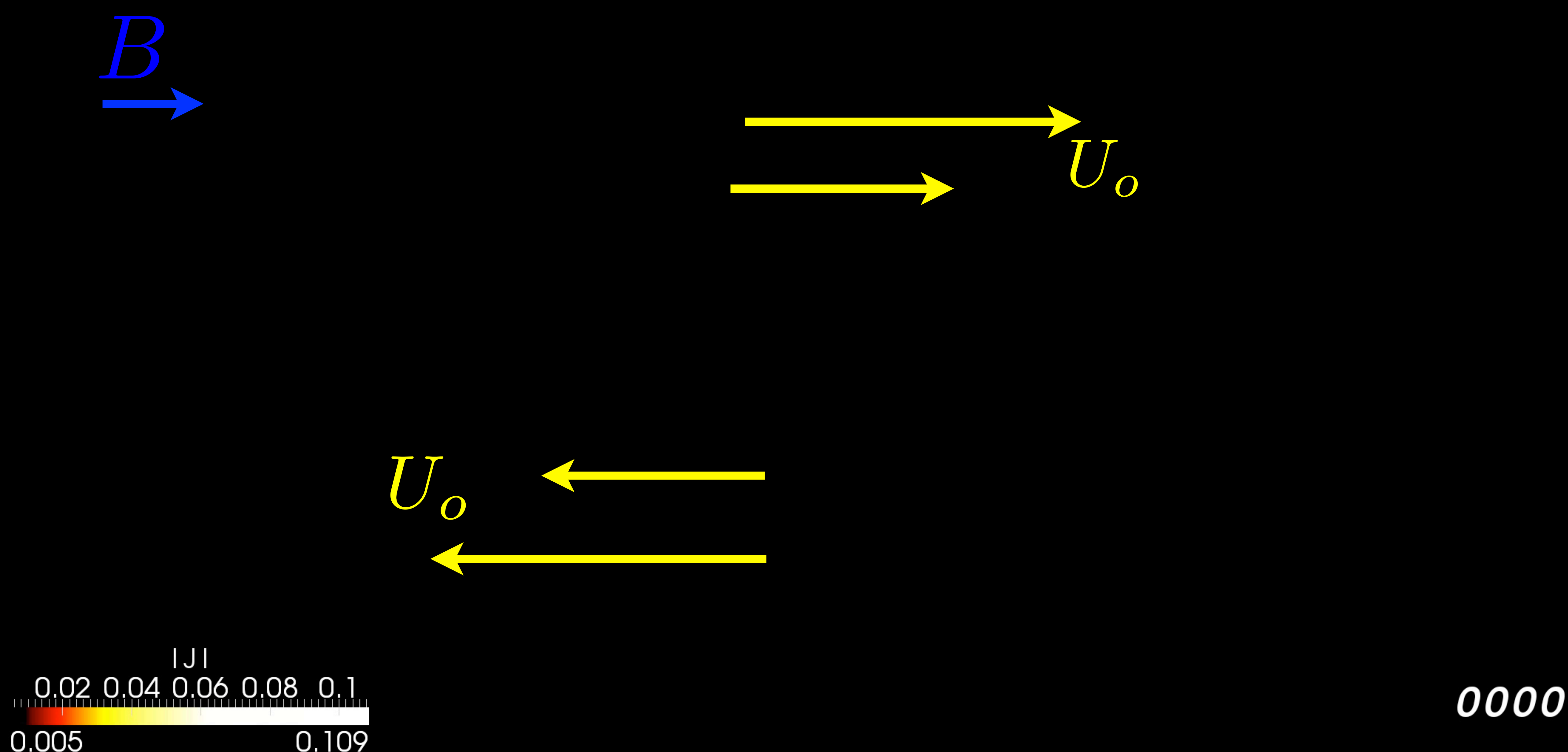
MHD scale vortices generate current sheets, flux ropes, reconnection & turbulence

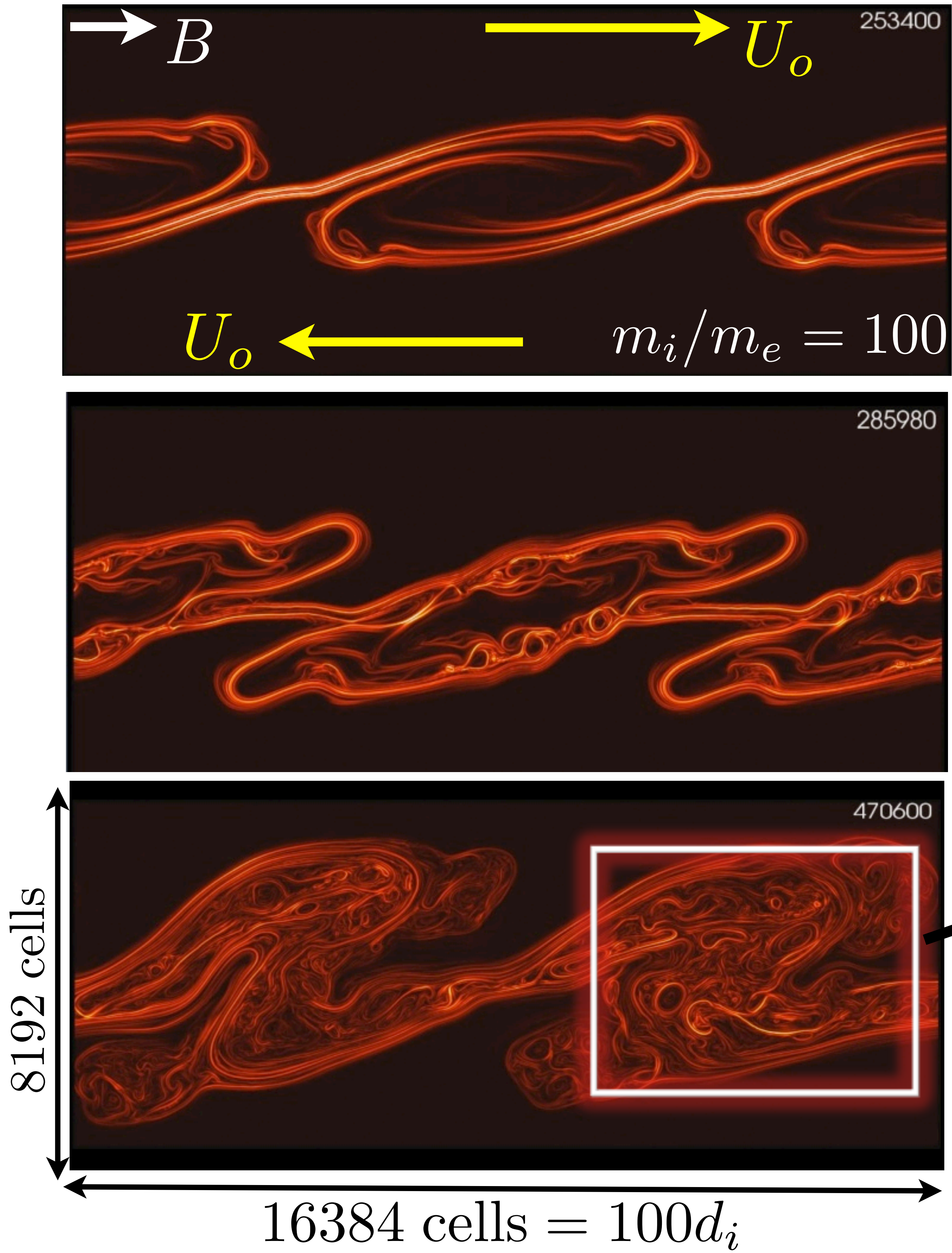


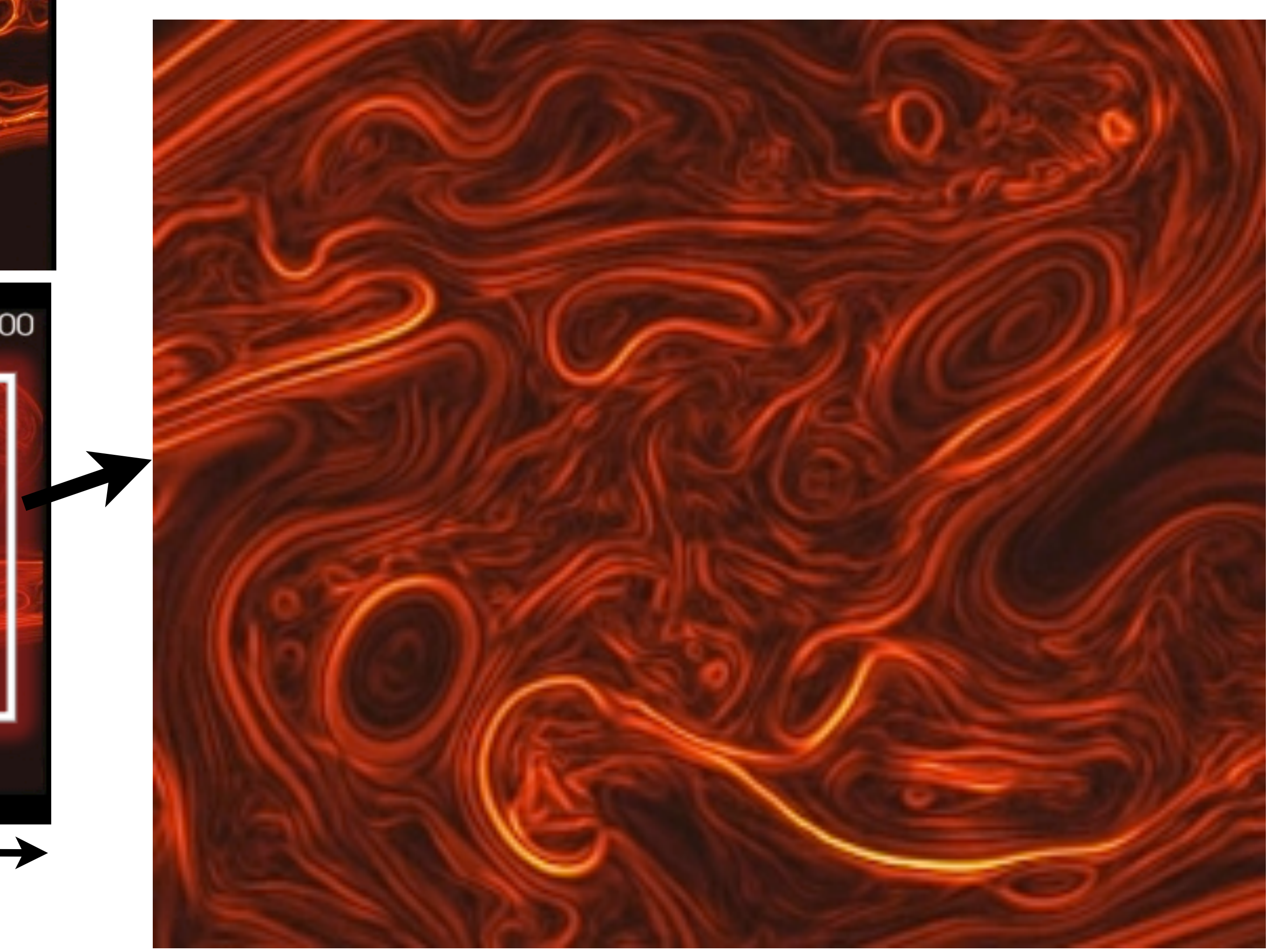
$U_o > V_A \quad \rightarrow \quad KH$

$m_i/m_e = 100$

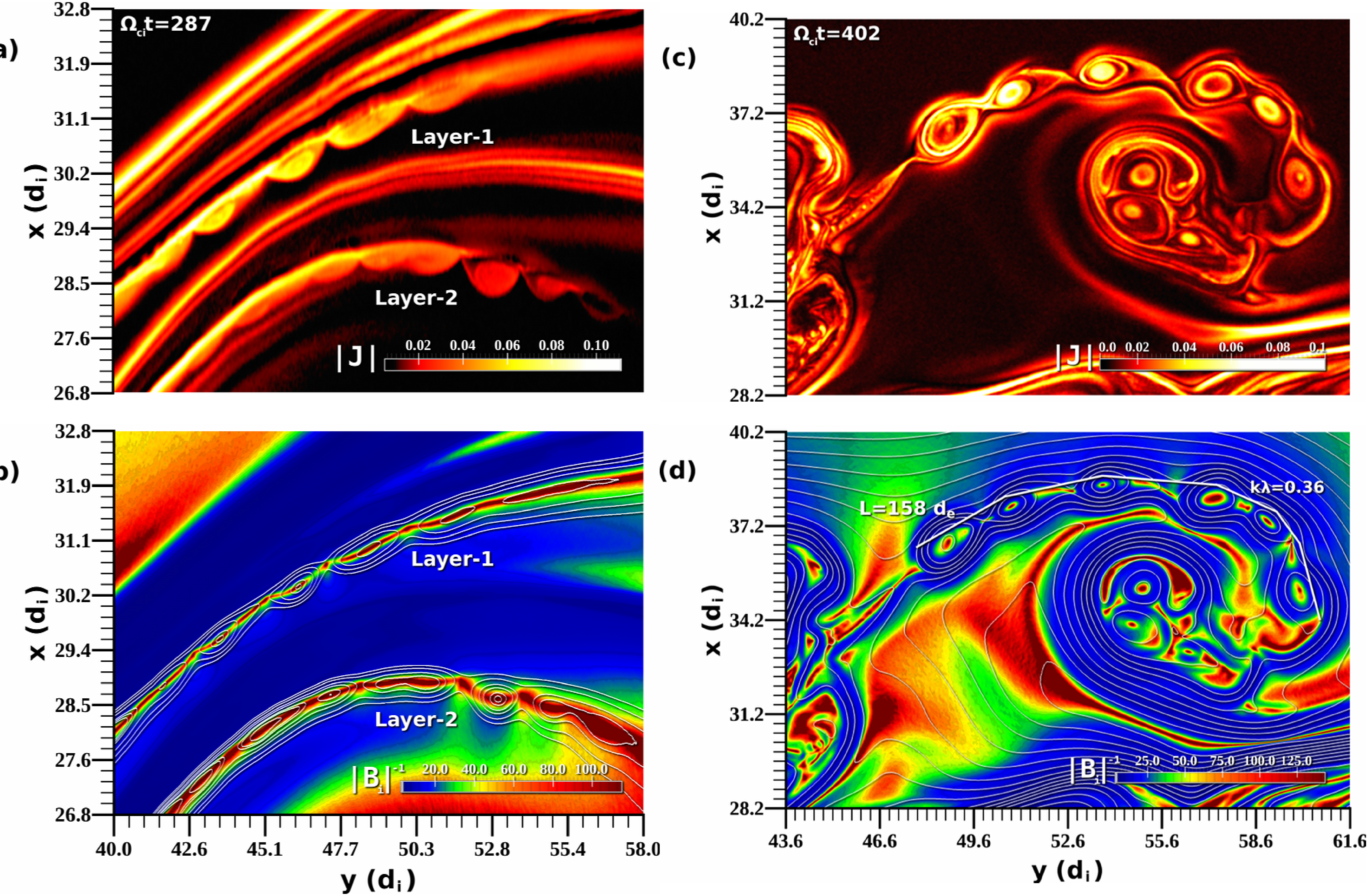
Fully kinetic 2D simulation of Kelvin-Helmoltz

- Vortex scale $\sim 50 d_i$
- Kinetic scale layers
- Secondary tearing & KH
- Power law spectra
- Electron heating dominant!

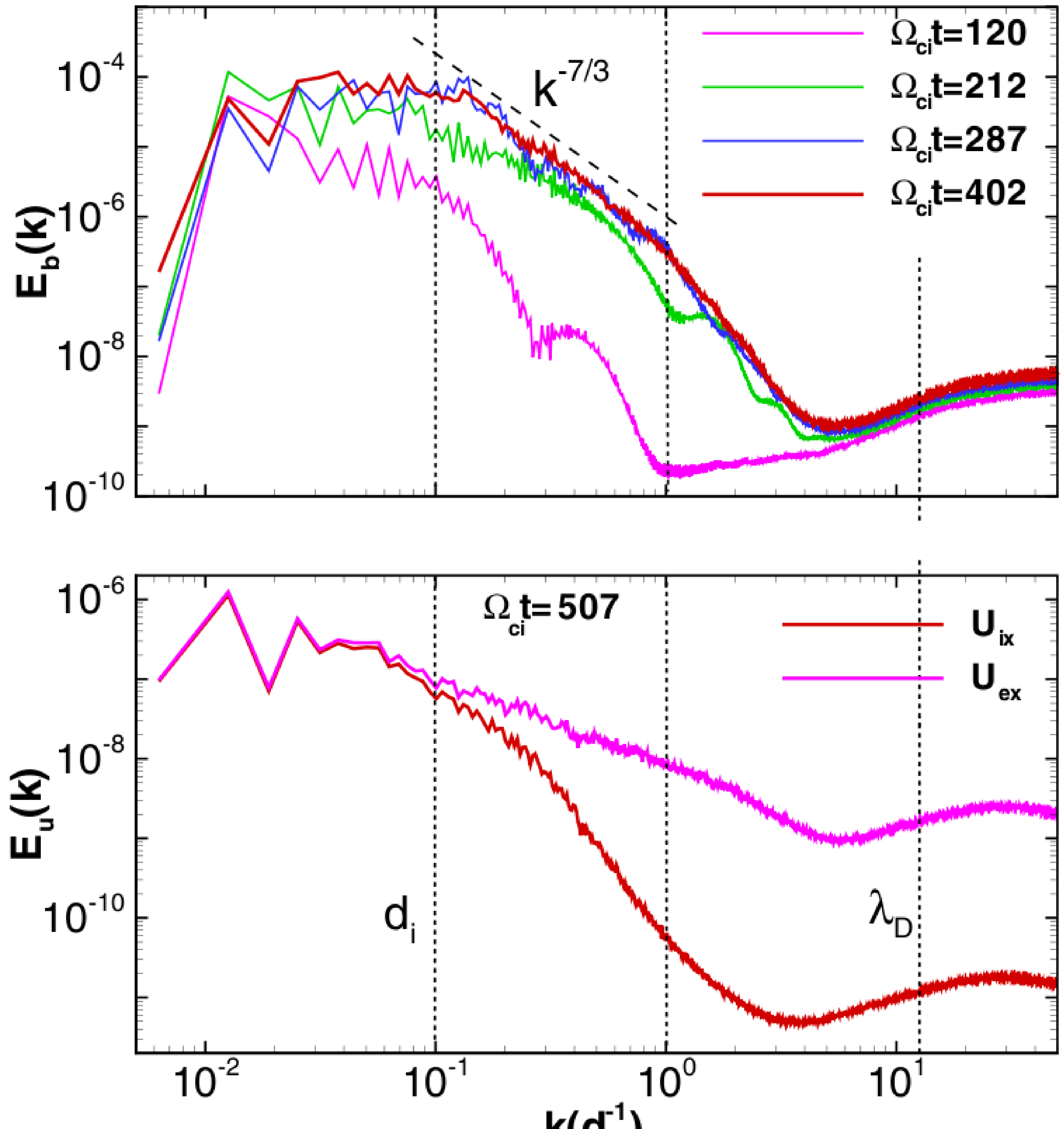




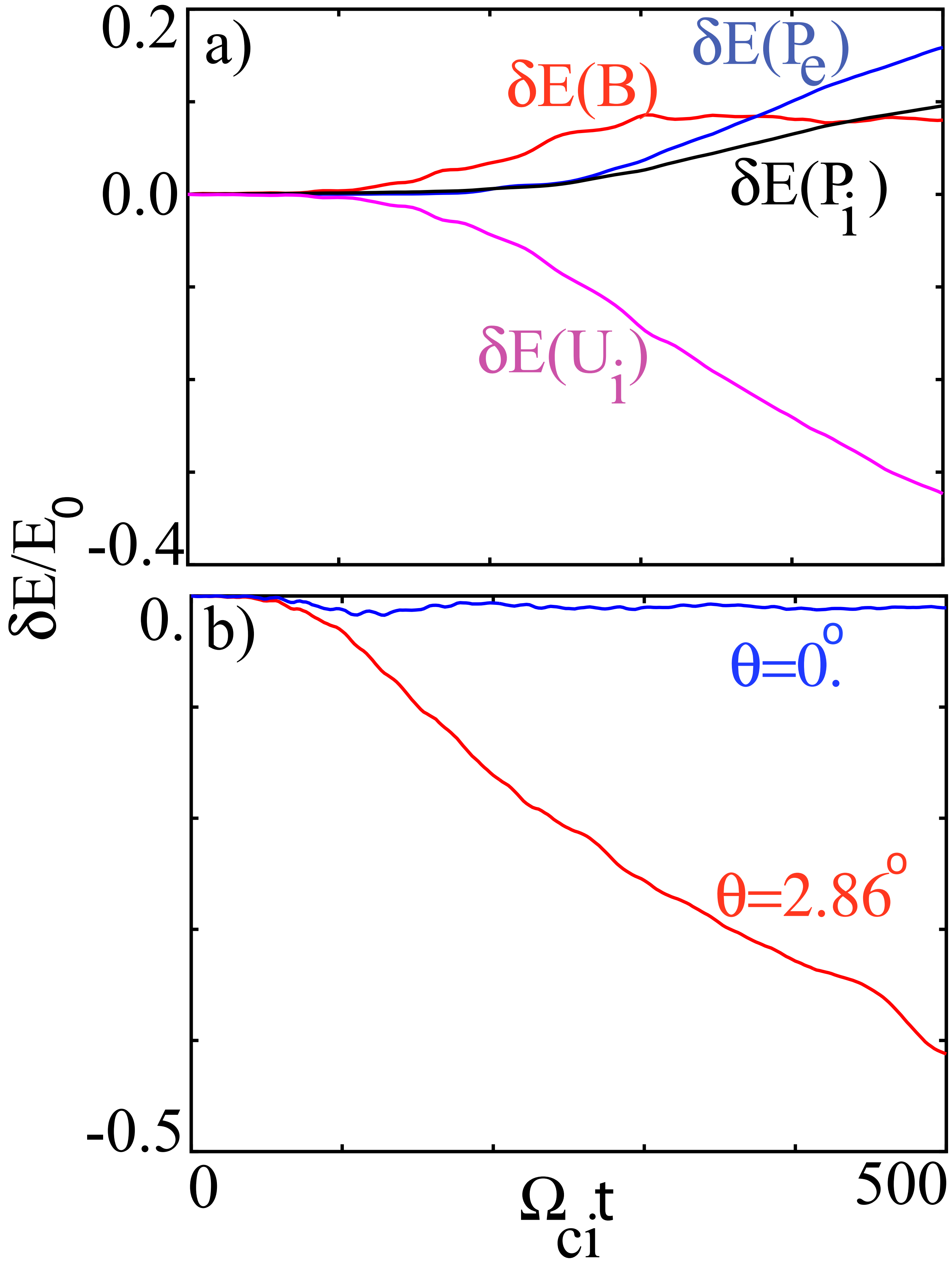
Secondary Tearing Instabilities



Turbulent Energy Spectra



Electrons get majority of energy!



Weak in-plane field plays essential role!

Summary

- Electron scale current layers are a key feature in magnetic reconnection at the magnetopause
- Layers are unstable to tearing-type instabilities which create 3D flux ropes
- May naturally drive turbulence for certain regimes
- Details depend on guide field and profile asymmetry
  - Temperature anisotropy is crucial for weak guide fields
  - LHDI can rapidly broader layers in low-β regions
- Velocity shear offers another mechanism to generate flux ropes, current sheets and turbulence