# Turbulent Reconnection in Collisionless Mesoscale Layers

William Daughton

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*Connecting Micro and Macro Scales: Acceleration, Reconnection and Dissipation in Astrophysical Plasmas*

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# Introduction

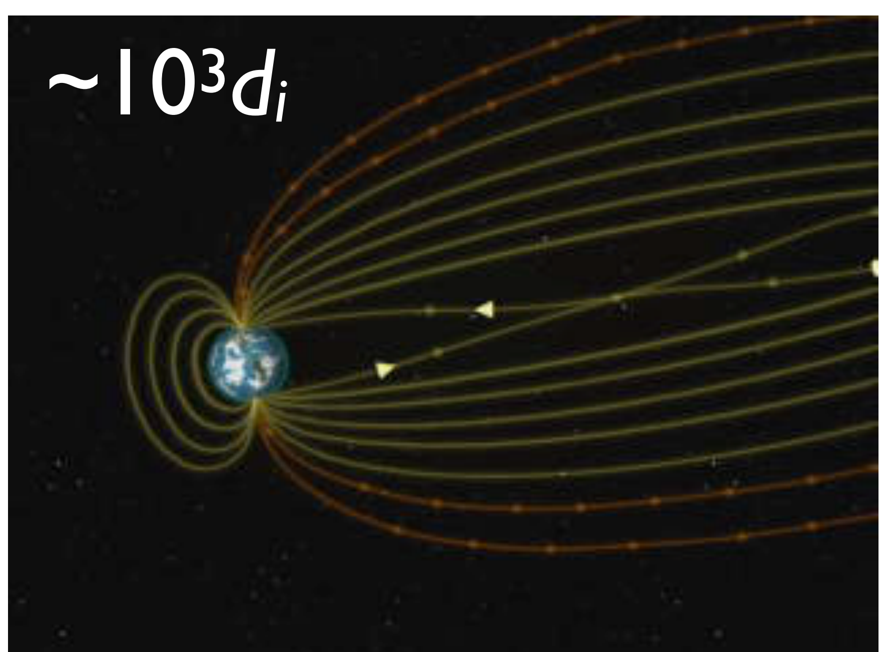
## Kinetic Regime

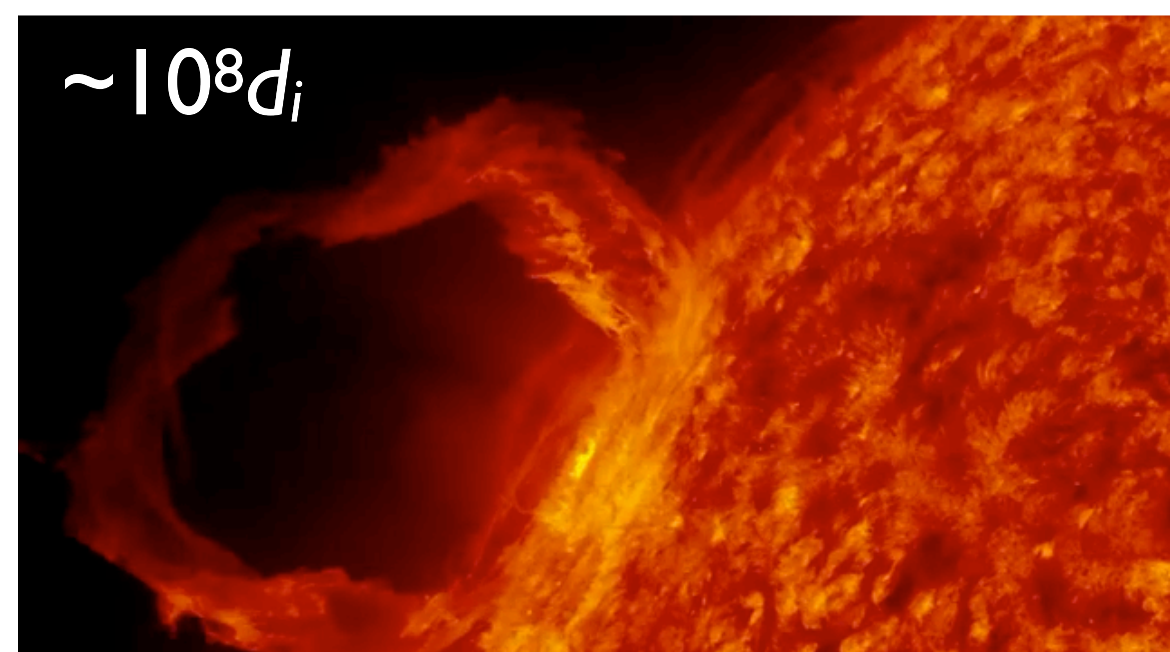
- Simulations + MMS + lab. exp.
- Validated - reaching maturity
- R~0.1 for thin sheets
- Coupling to MHD scales ?
- 3D turbulence ?

## MHD Regime

- Plasmoid instability - R~0.01
- Fractal structure to kinetic - R~0.1
- Runaway fields $E_r \gg E_D$
- Phase diagrams - 2D physics
- 3D turbulence ?

***Scale***

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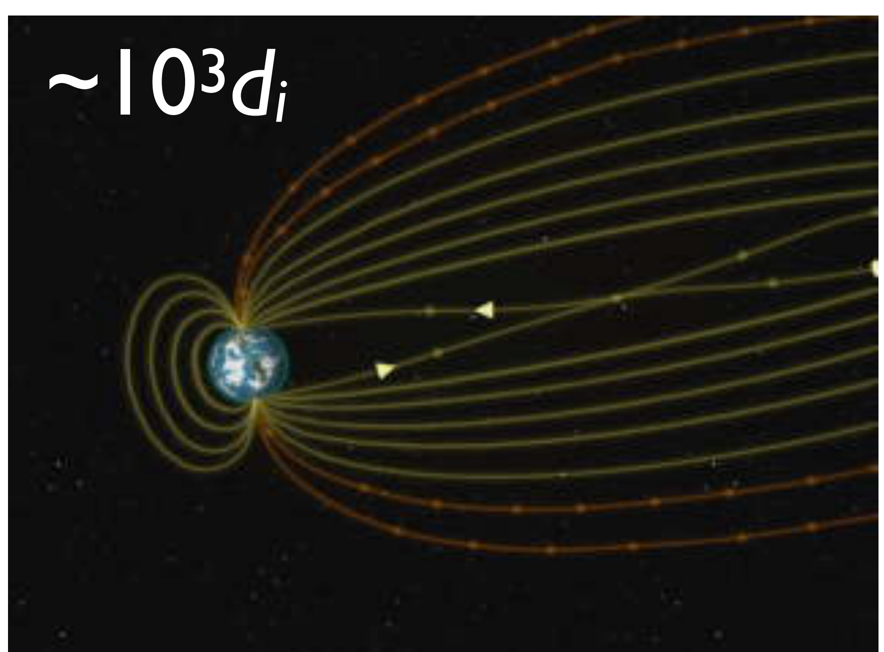
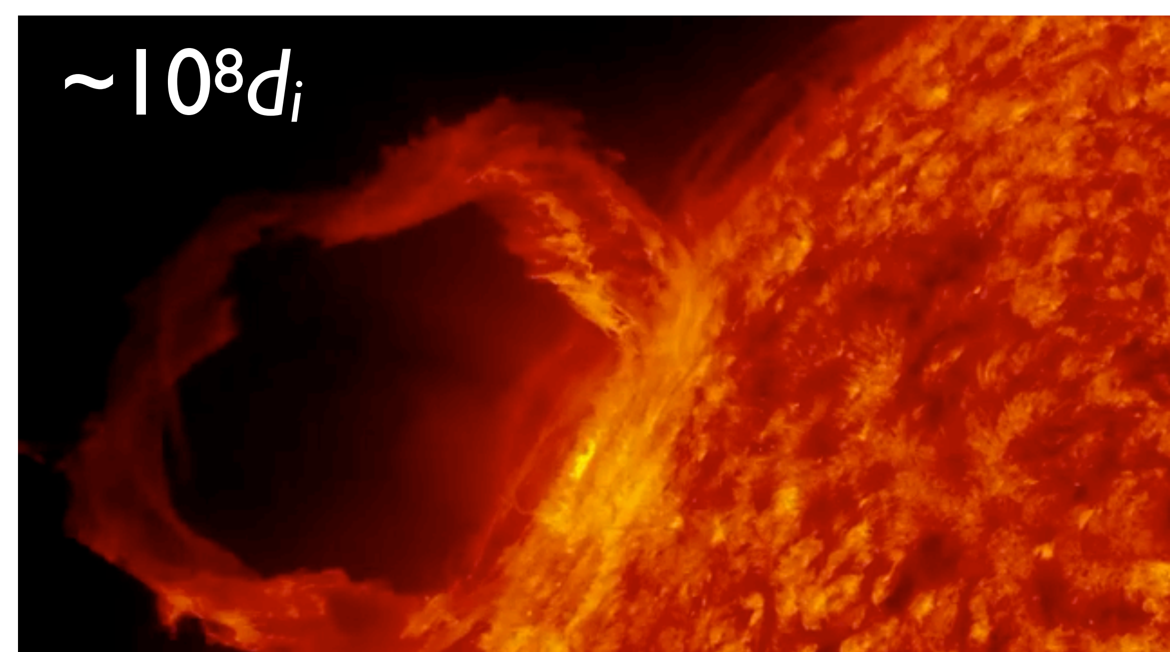
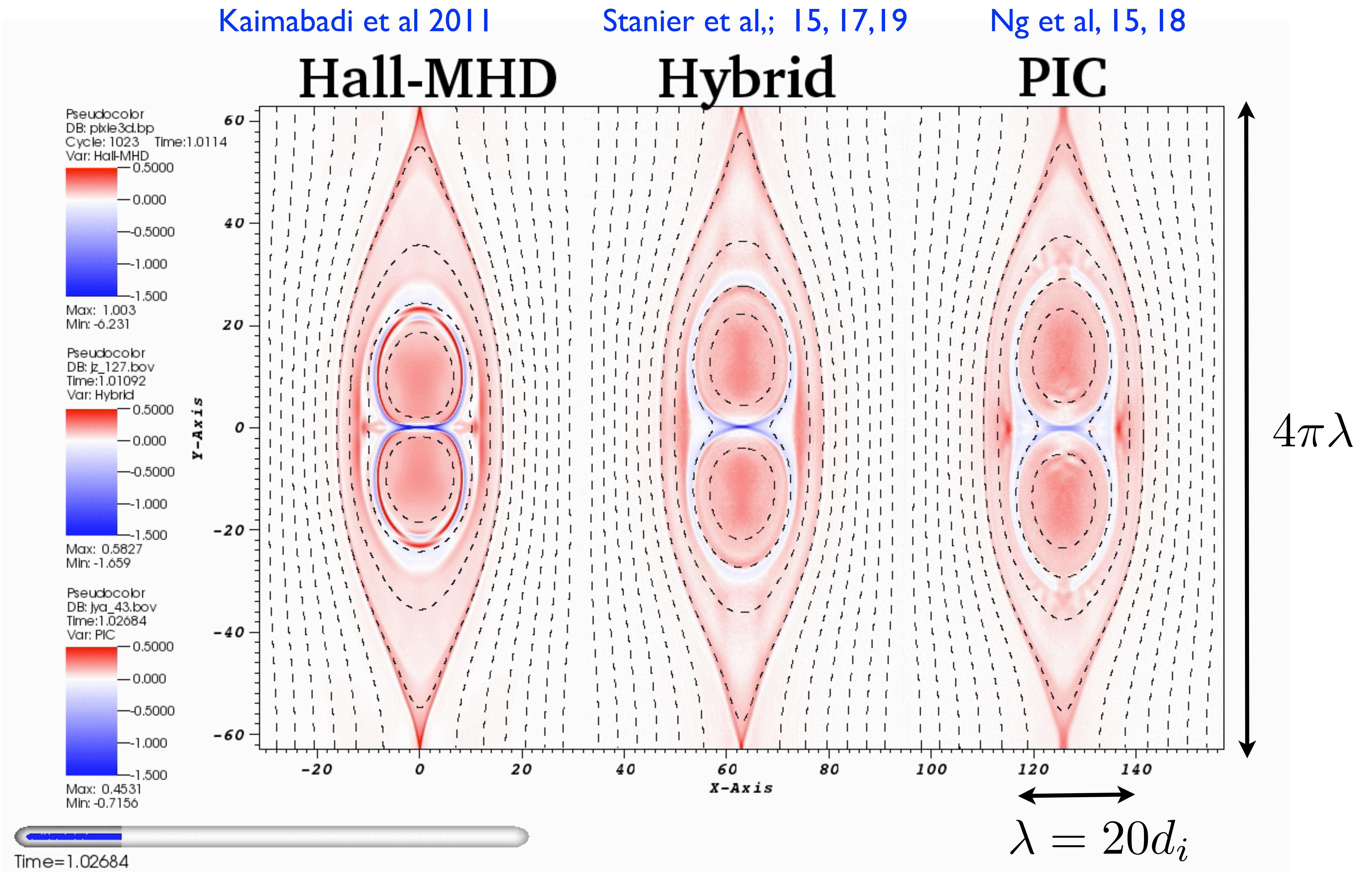


# Outline

- **Kinetic / MHD coupling in 2D reconnection**
- **Turbulent reconnection in thin layers** $\sim d_i$
- **Exploratory runs for mesoscale layers** $\sim (20 \rightarrow 35) d_i$

# Coupling between MHD & kinetic scales remains a difficult unsolved problem



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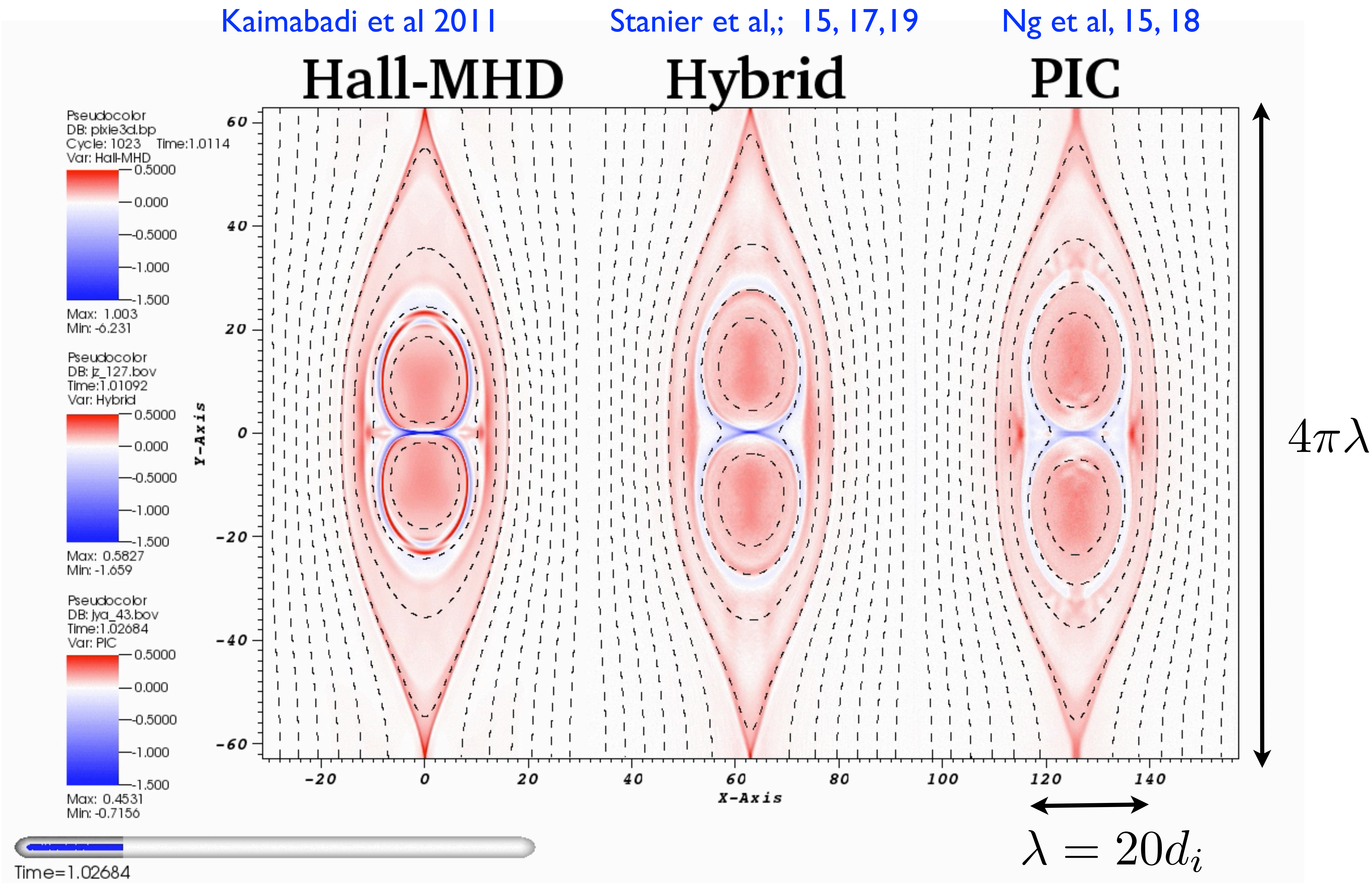
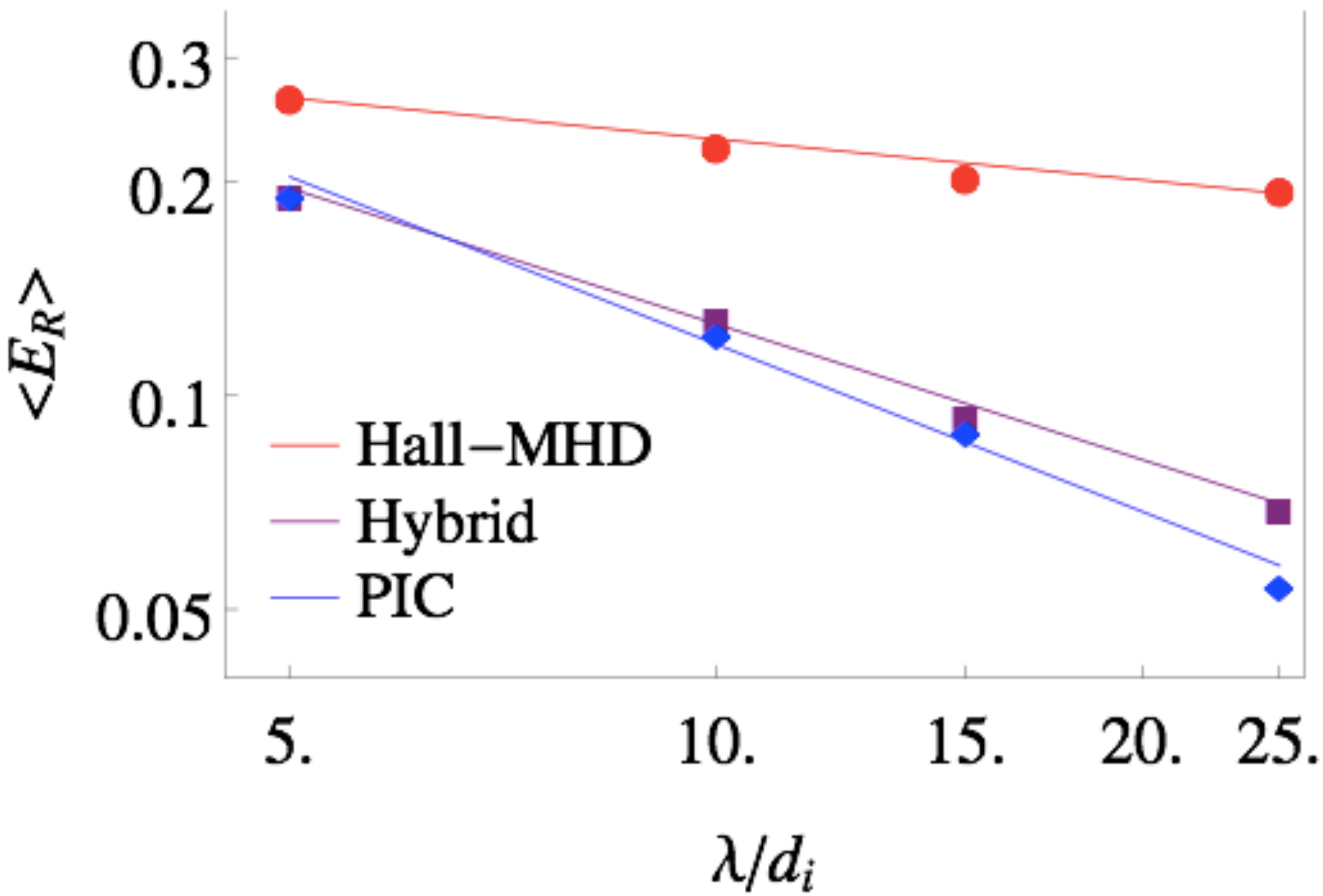
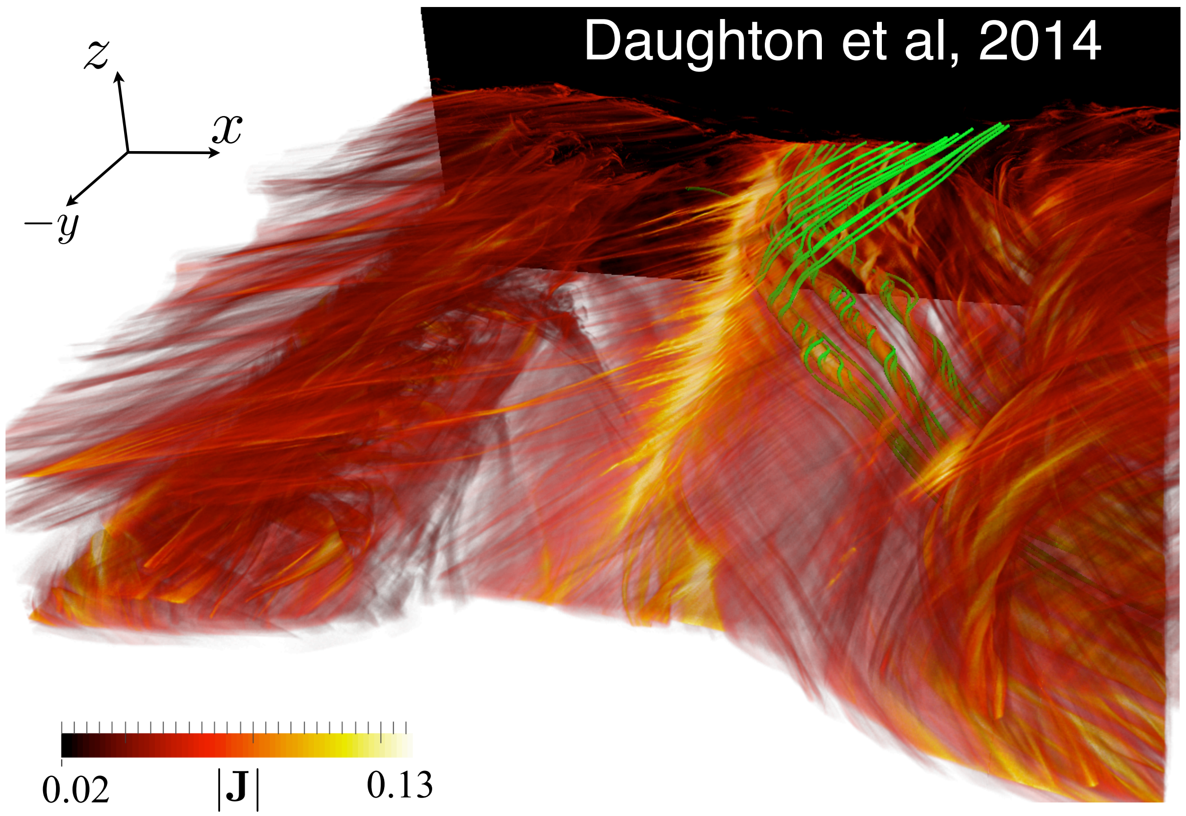


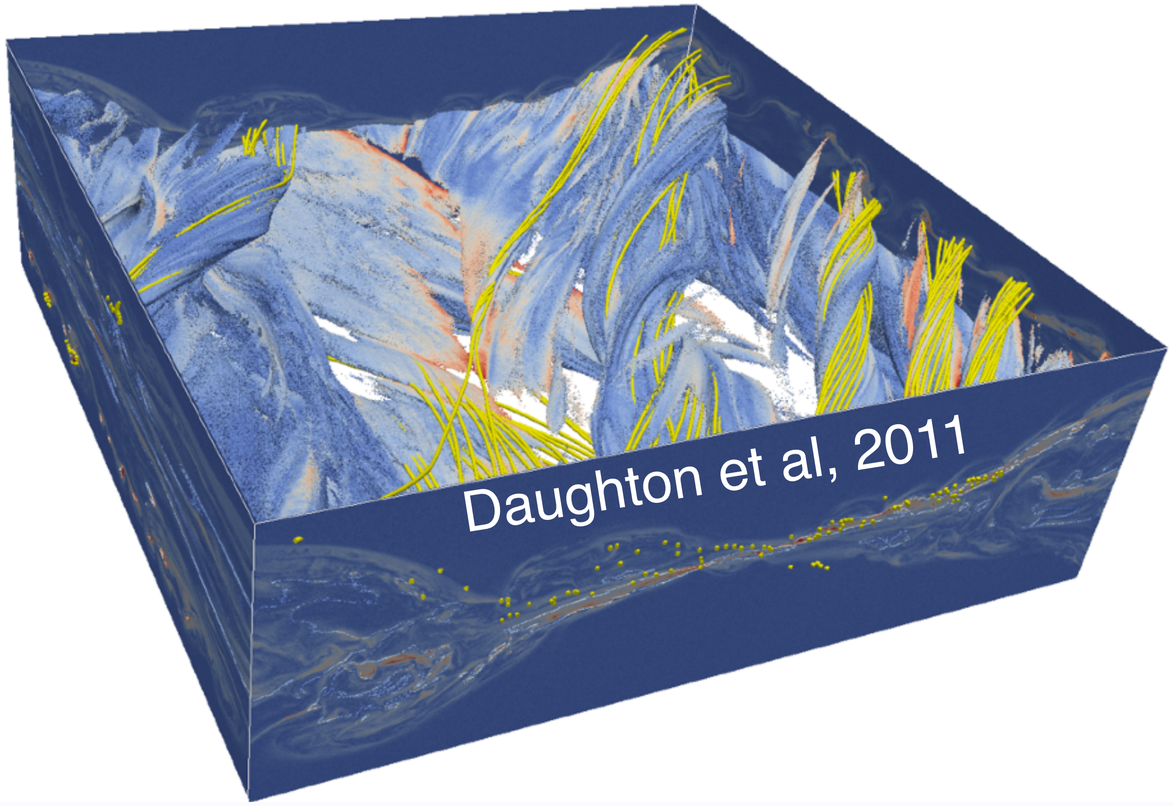
# For larger islands - average reconnection rate decreases more rapidly in kinetic than fluid

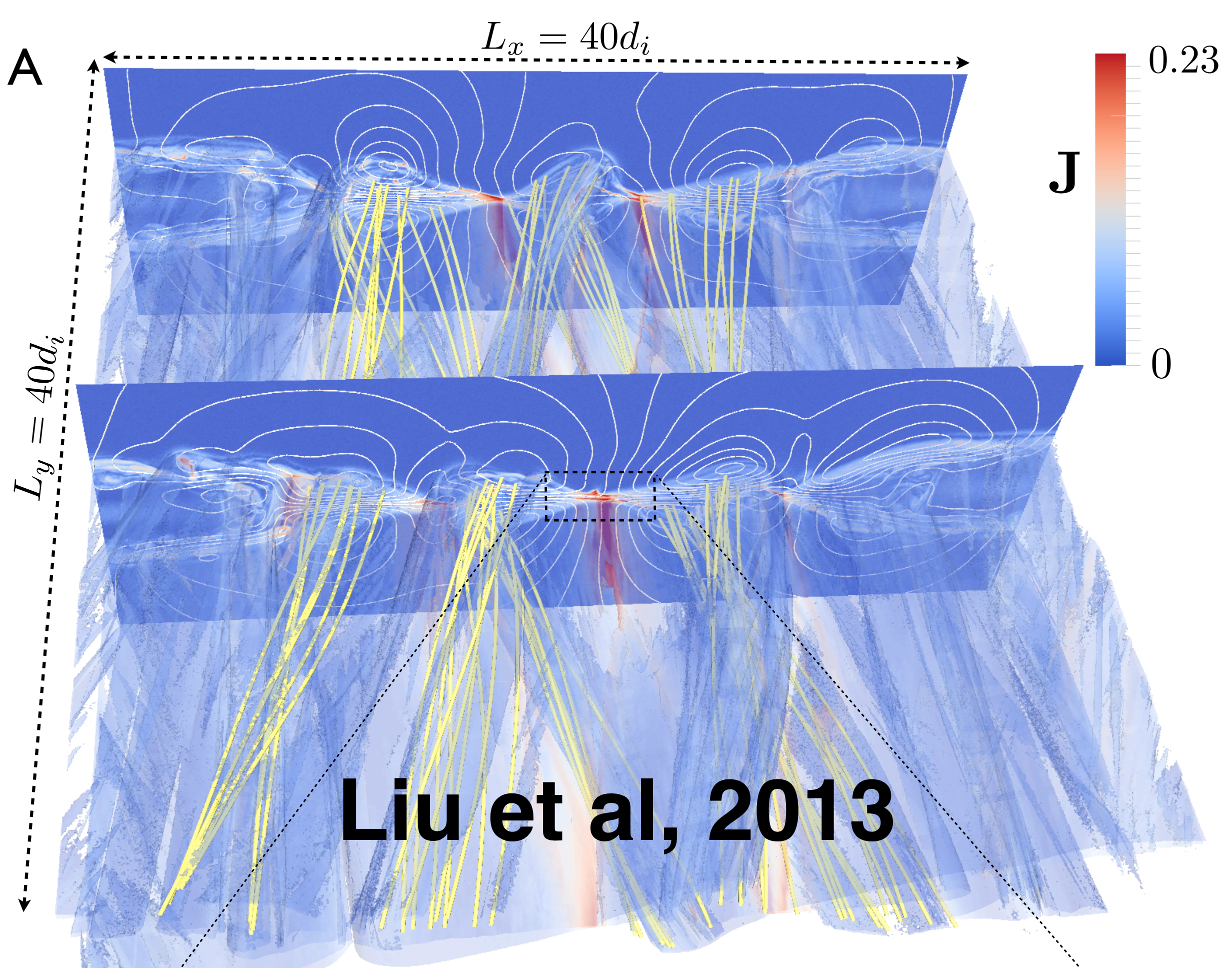


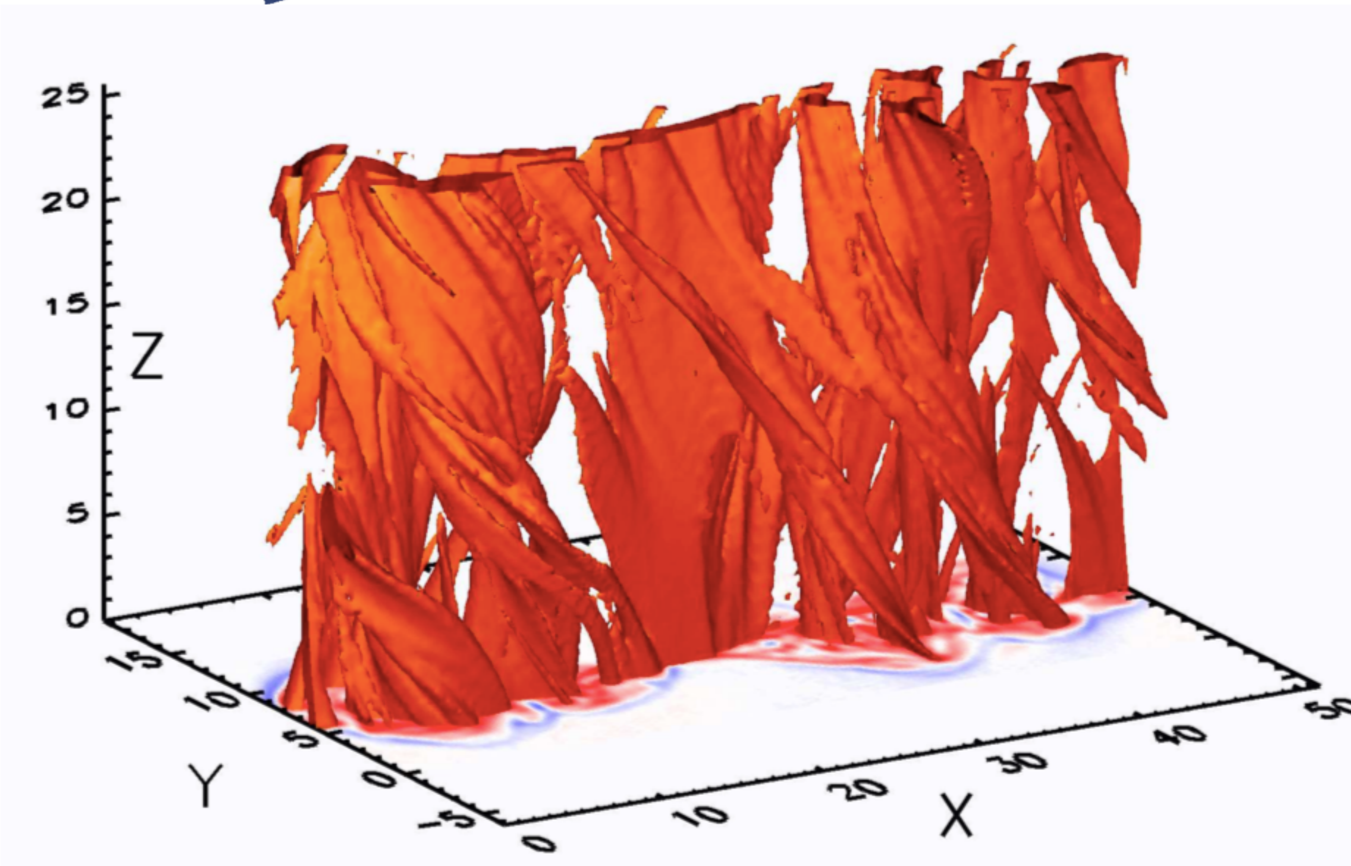

**Key Physics** ➜ Flux pileup + ion anisotropy, agyrotropy
Stainer et al, 15, 17

# 3D Turbulence in Kinetic Scale Layers



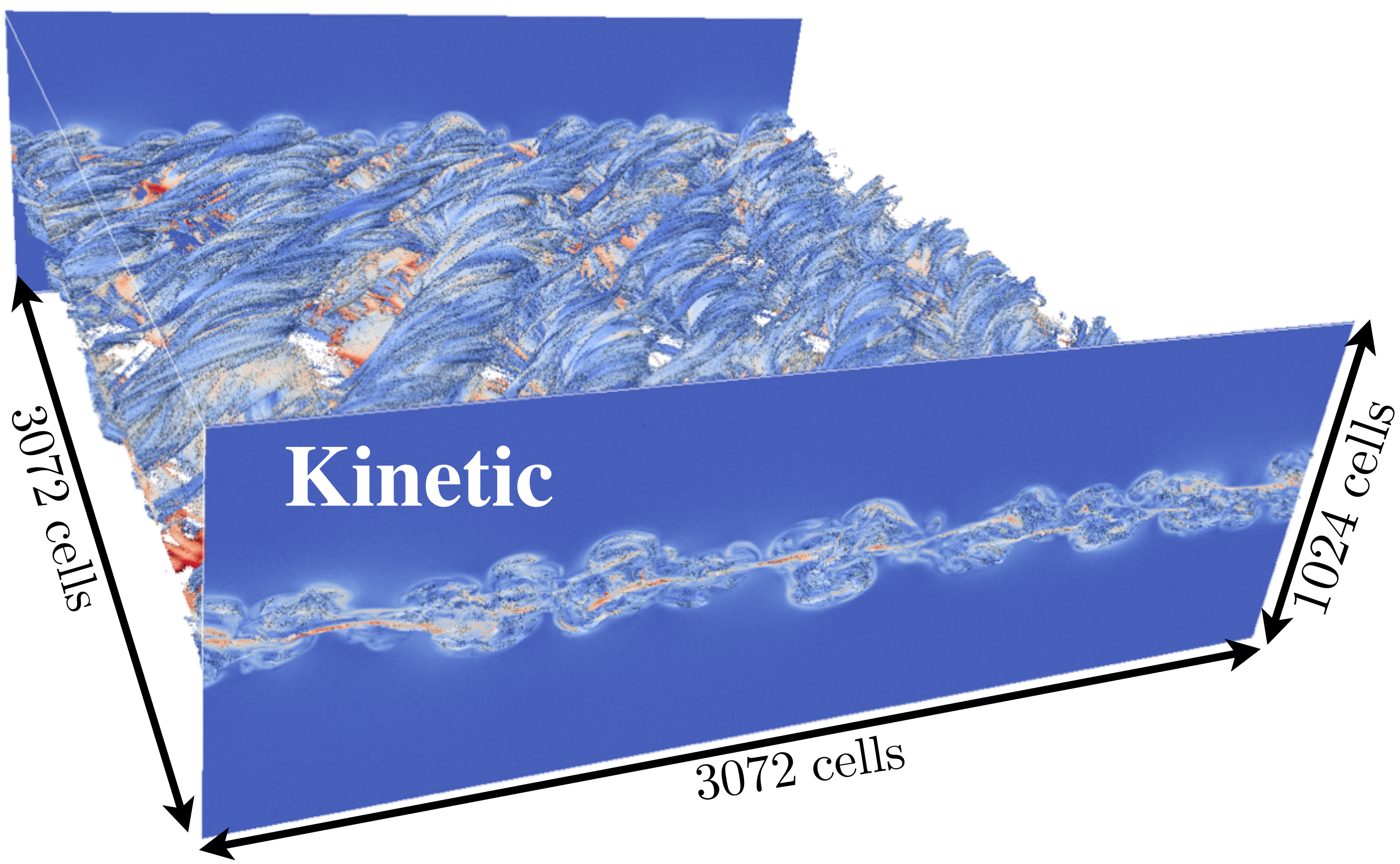



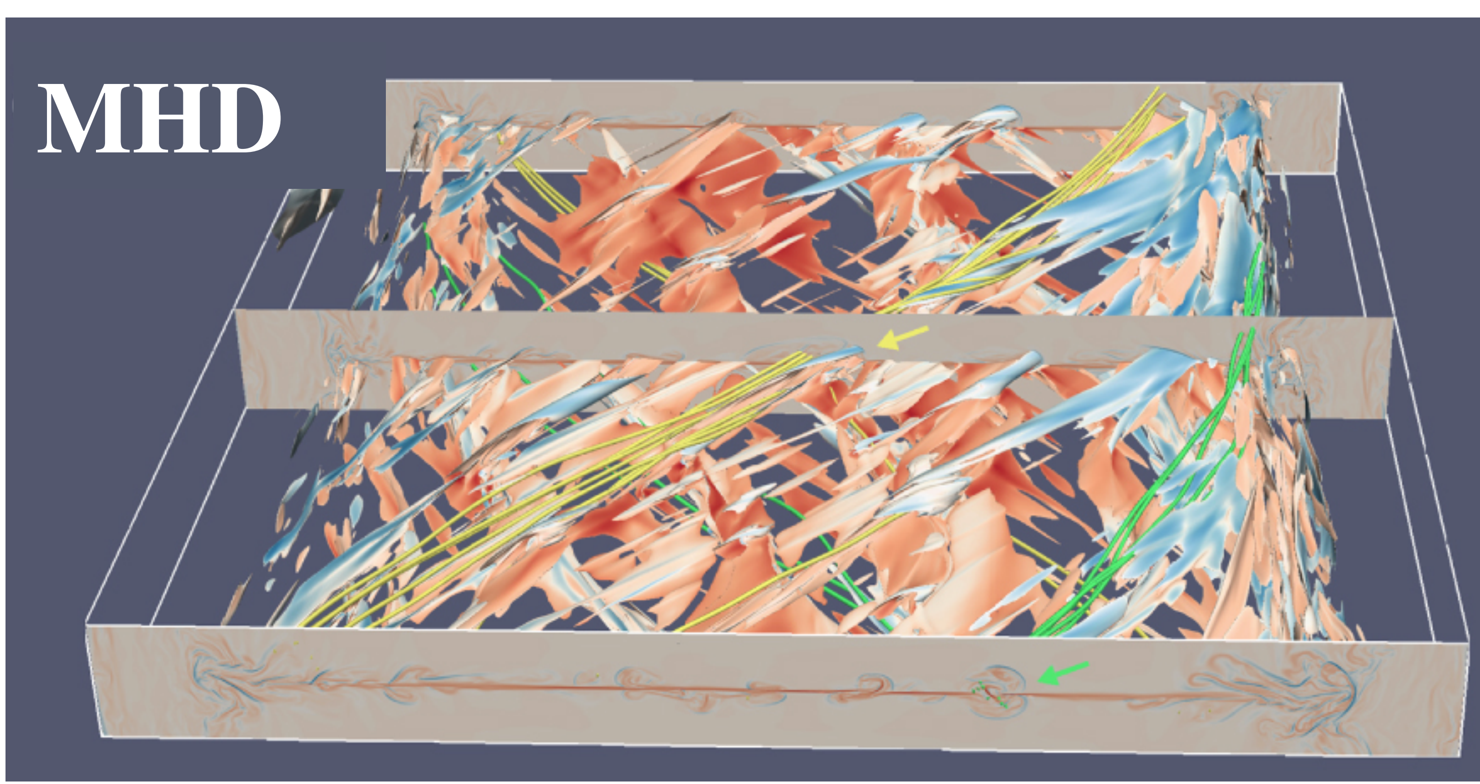



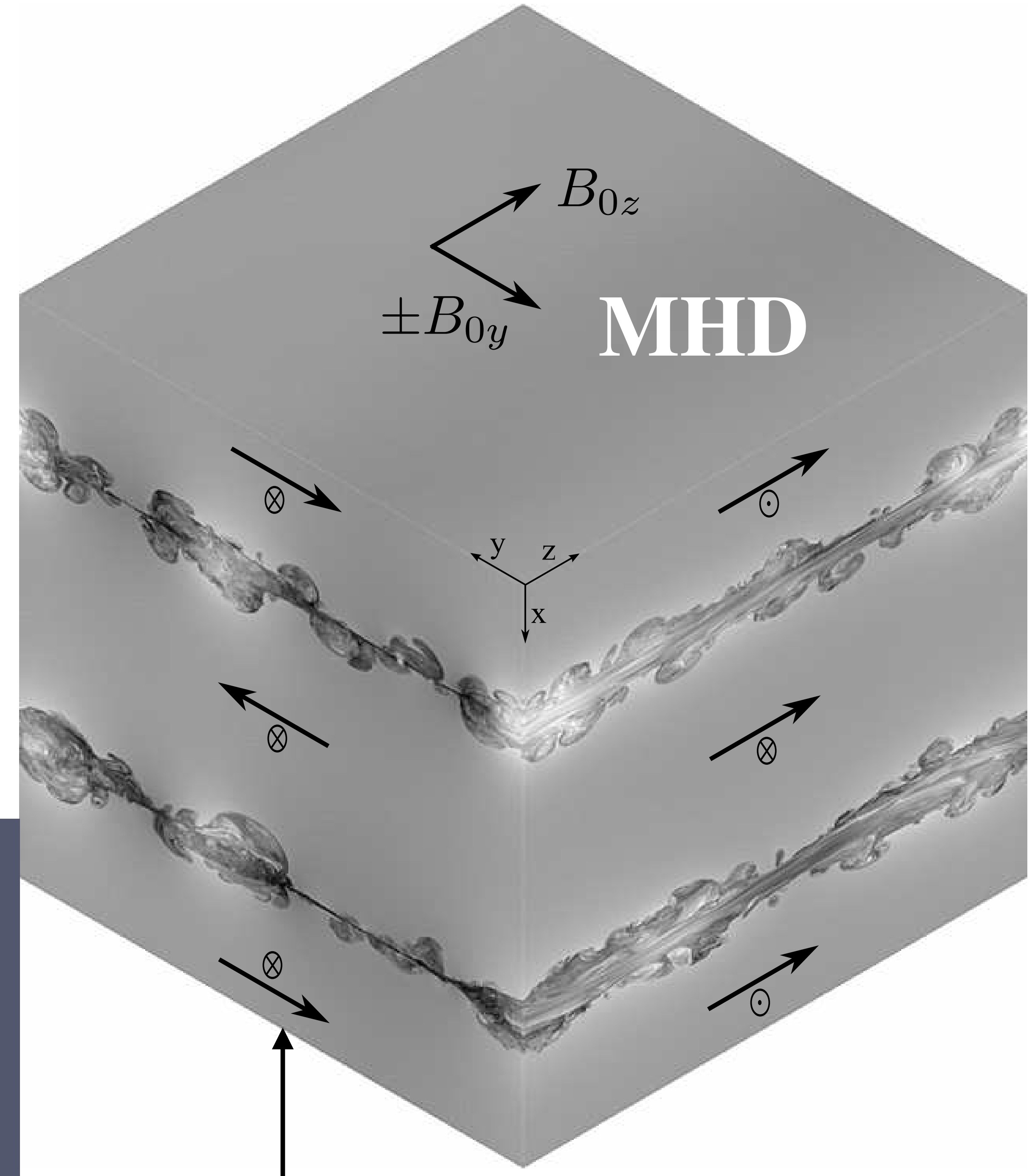




J. Dahlin et al, 2016

# Structure of 3D turbulence appears similar in both Kinetic and MHD simulations



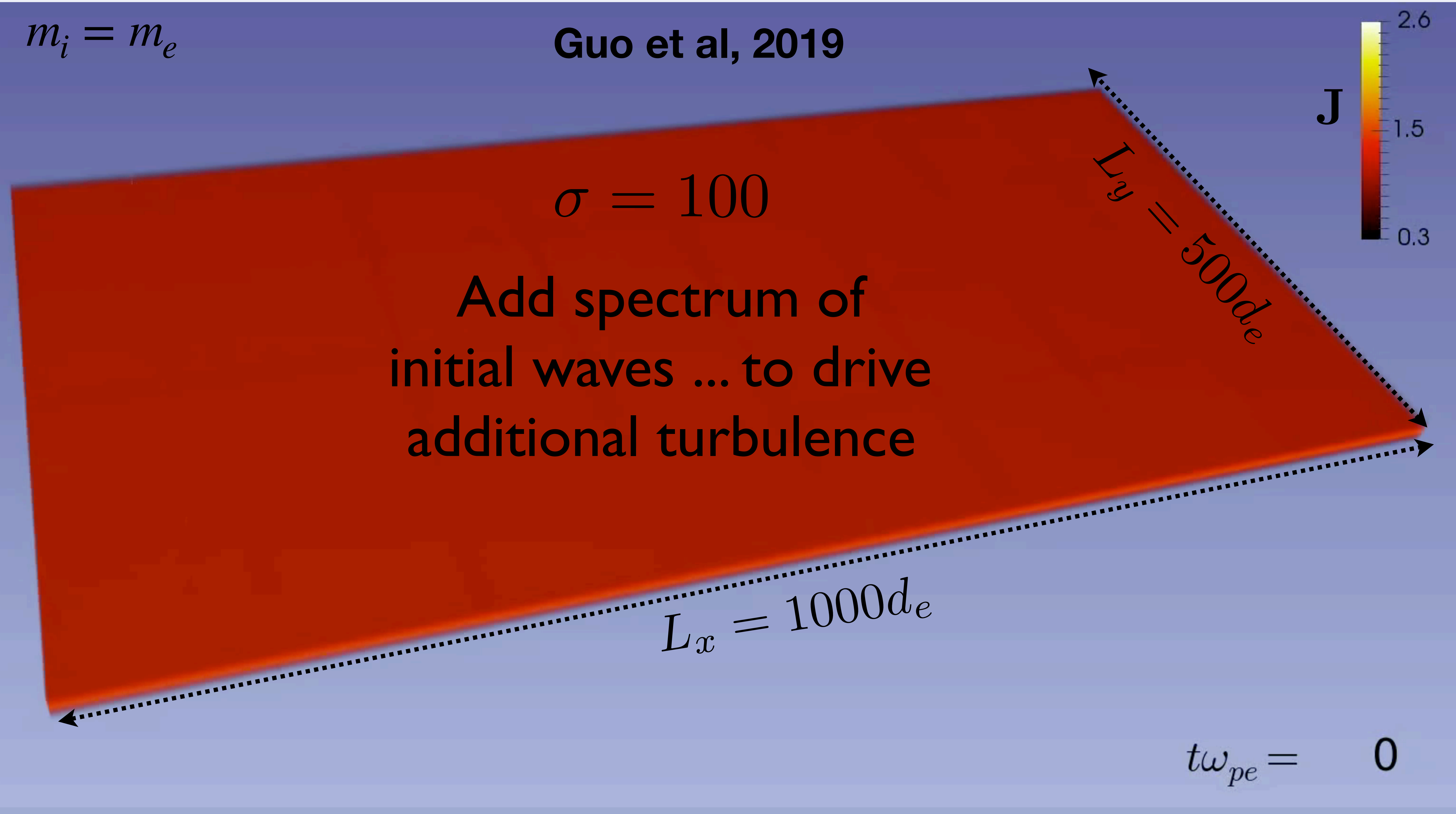




Beresnyak, 2014; 2018

Huang et al, 2015, 2017

# Relativistic pair plasmas permit largest domains which are highly turbulent




$4096 \times 2048 \times 2048$ cells $\sim 6 \times 10^{12}$ particles

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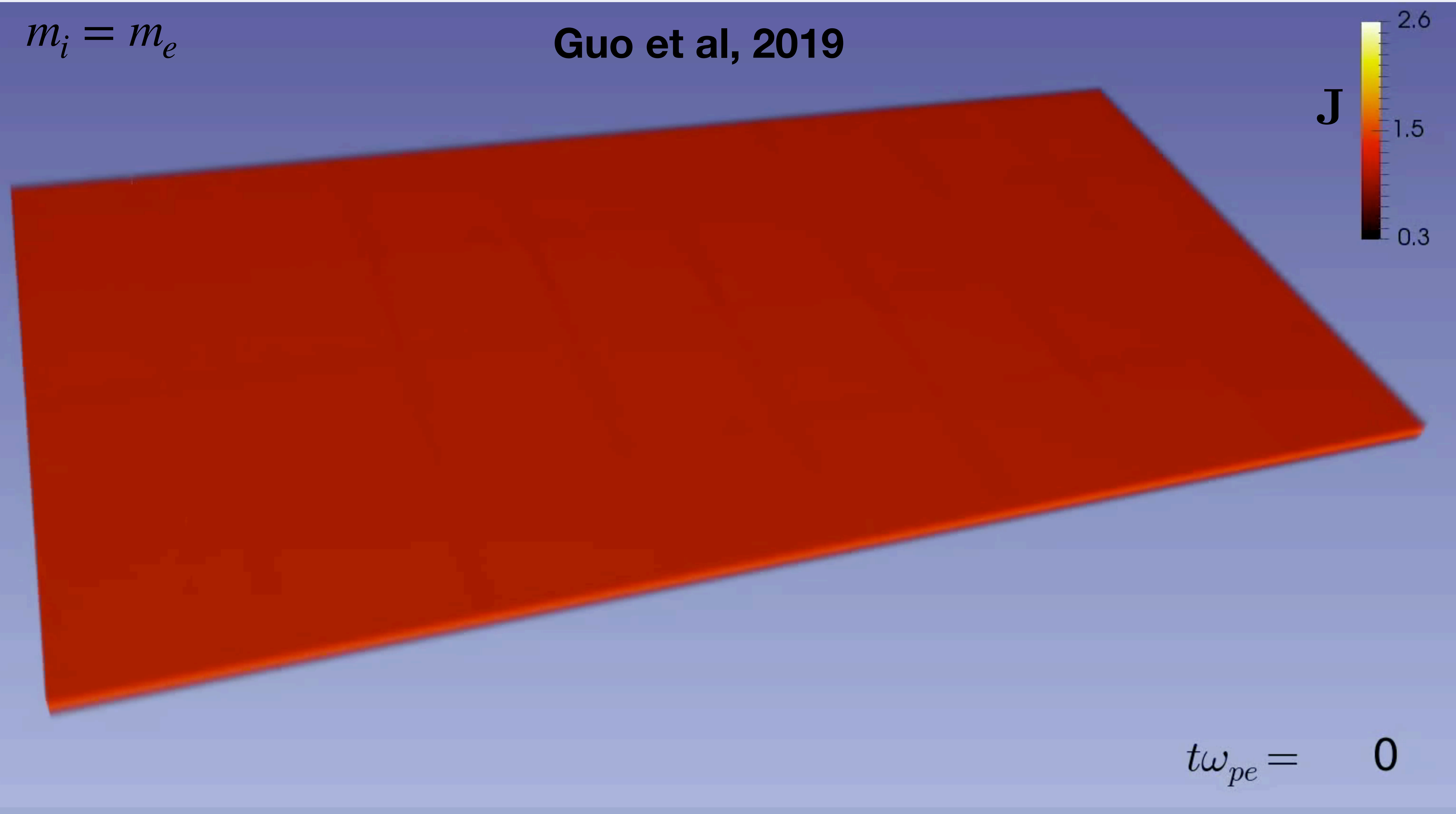


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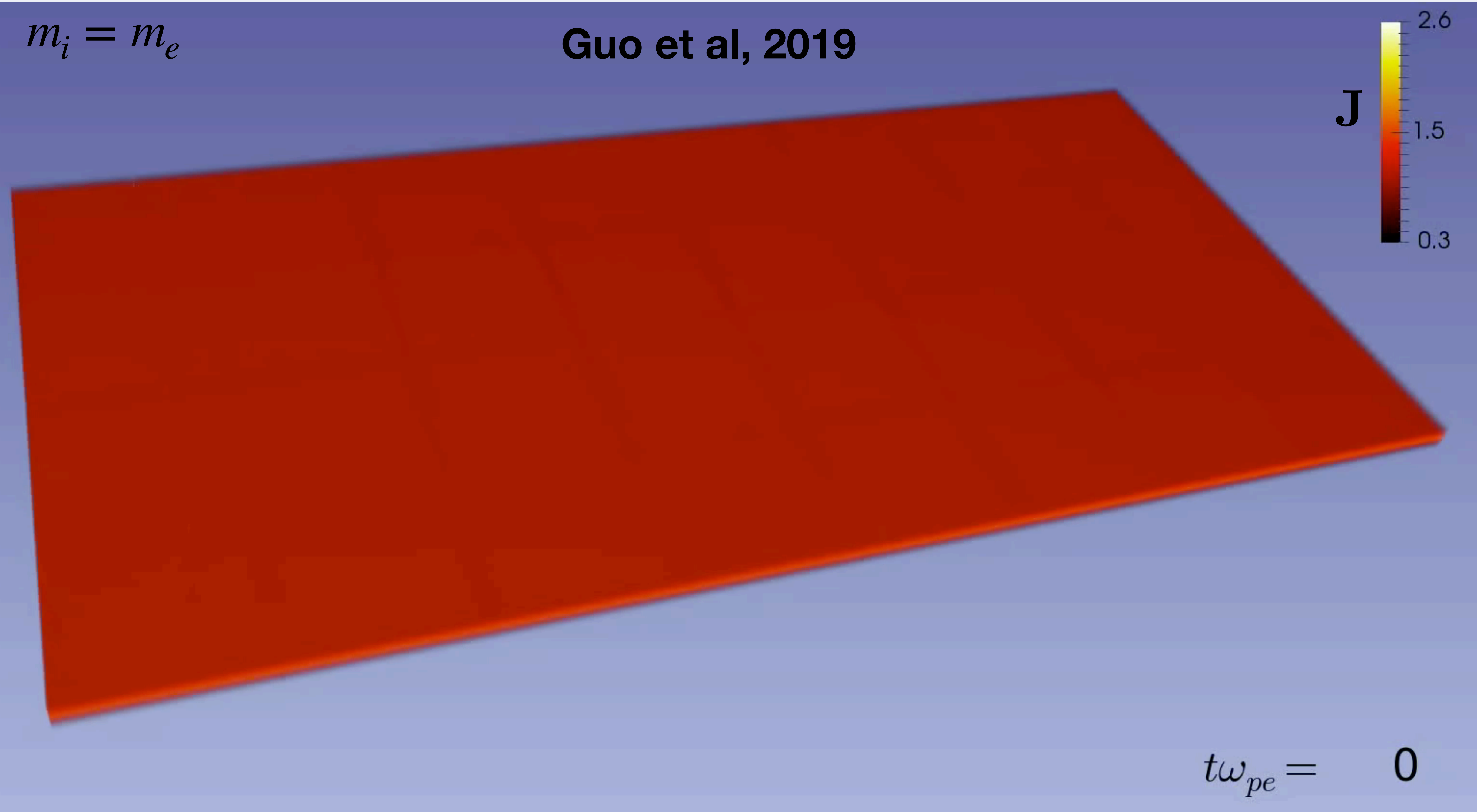


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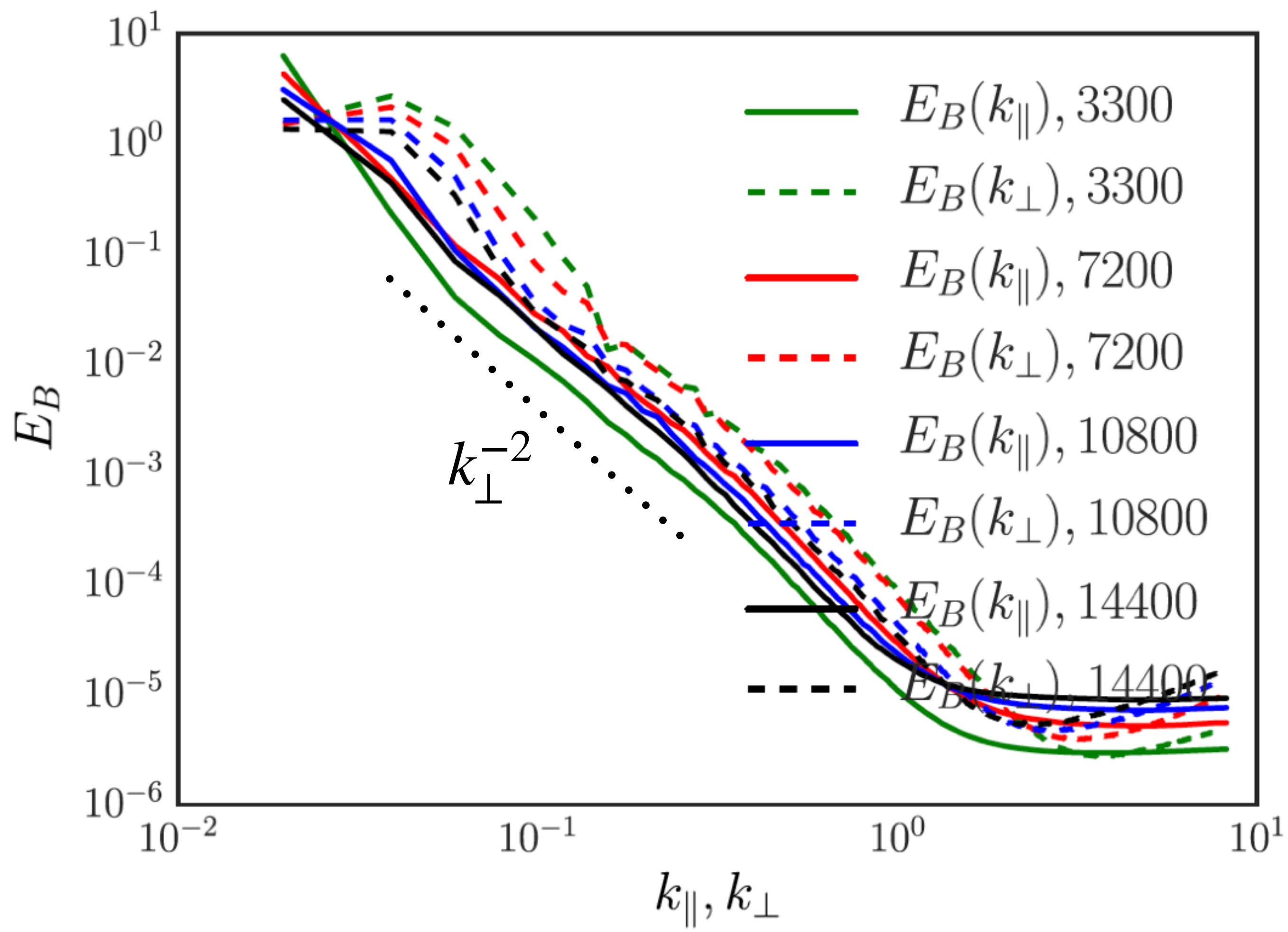
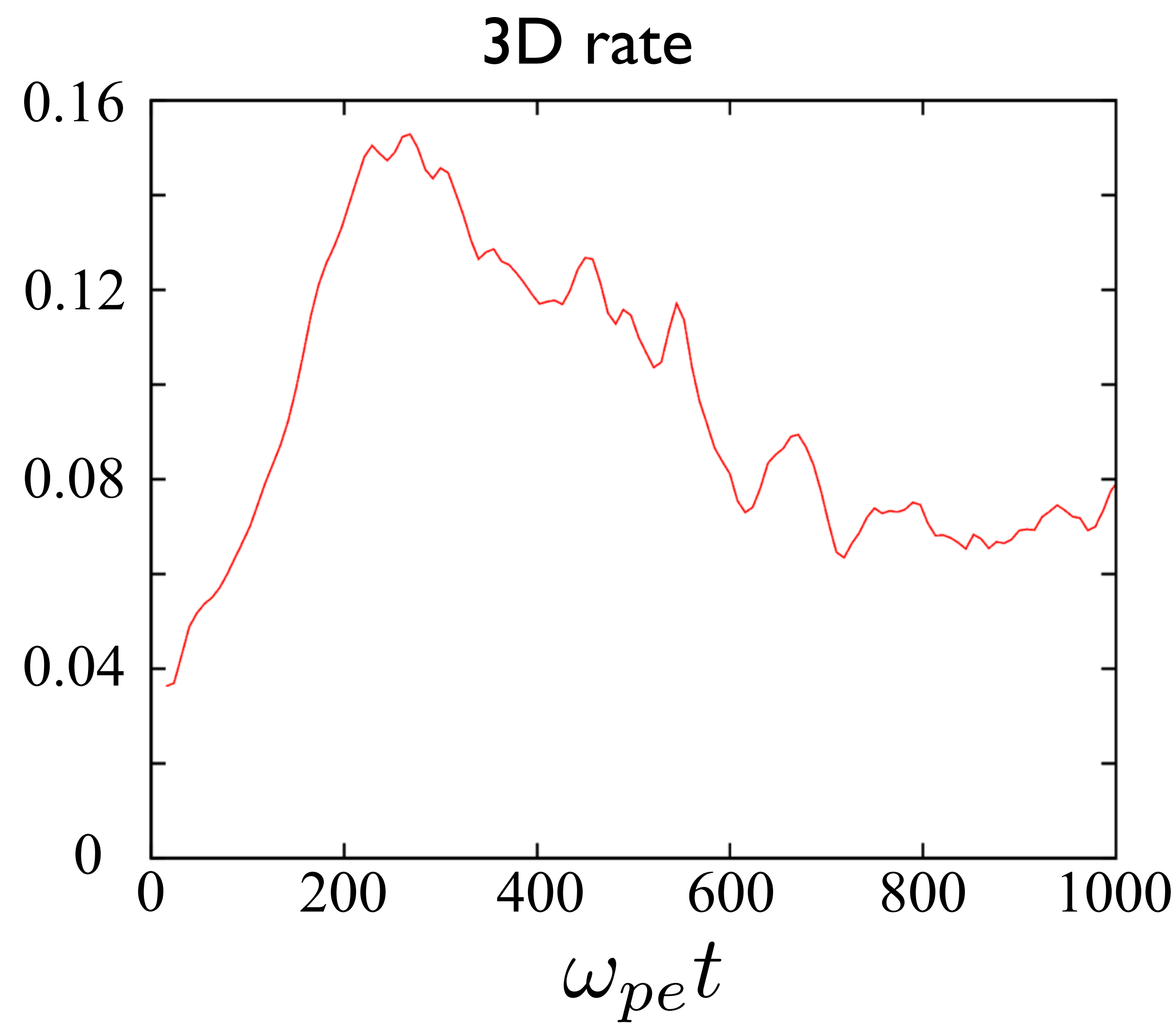
# Power law turbulence + Fast Reconnection Rate



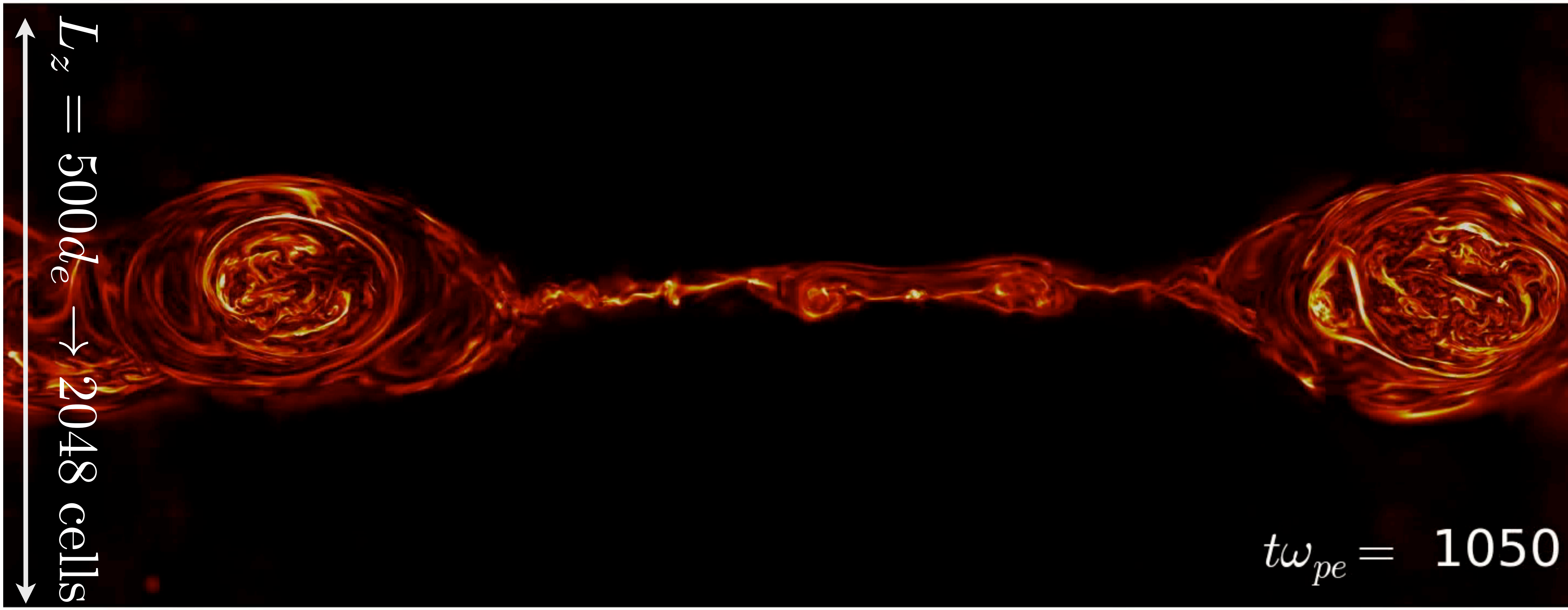




**Turbulence matters for particle acceleration - not for rate**

J. Dahlin et al, 2016

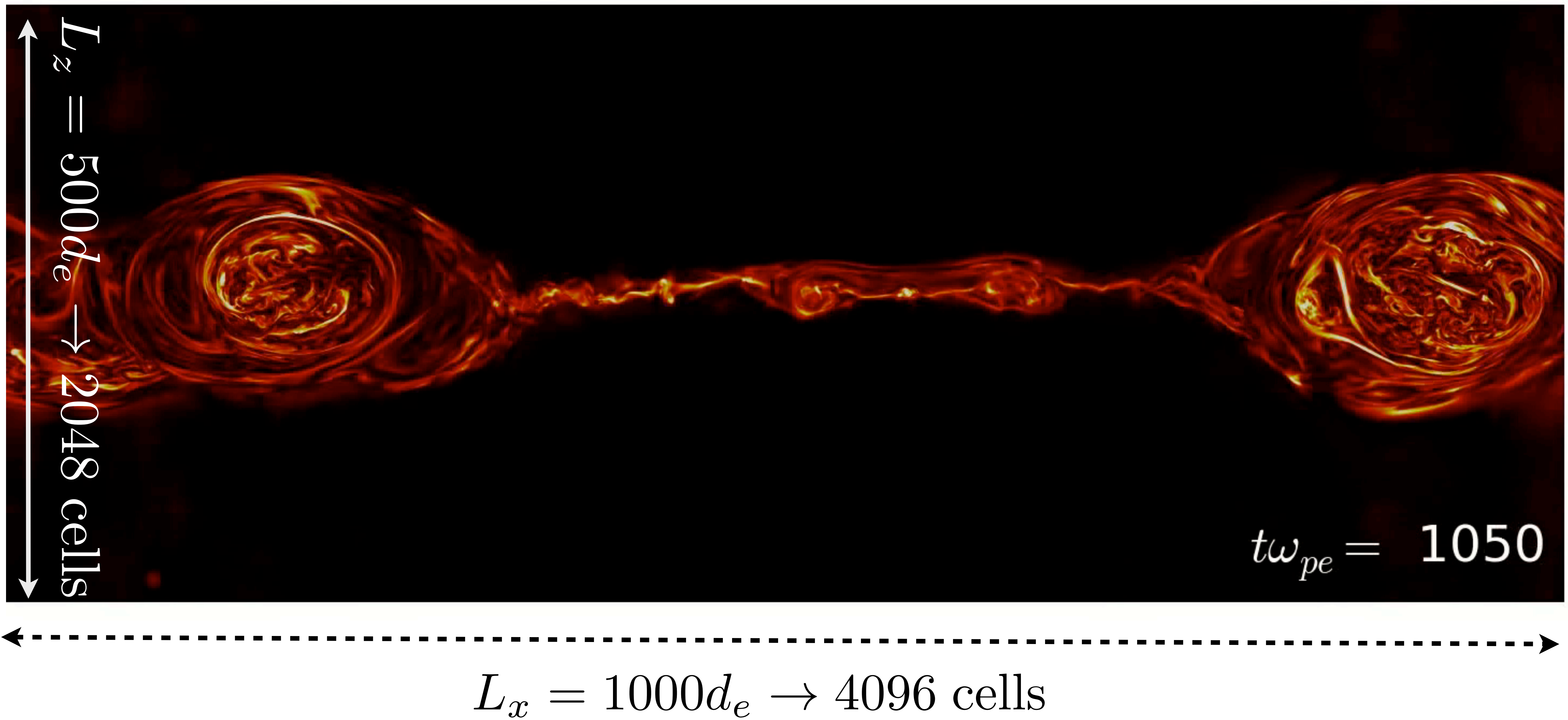
F. Guo et al - 14, 16, 19

# Despite complexity ... a slice of current density shows many of same features as 2D




$L_x = 1000d_e \rightarrow 4096$ cells

# Despite complexity ... a slice of current density shows many of same features as 2D



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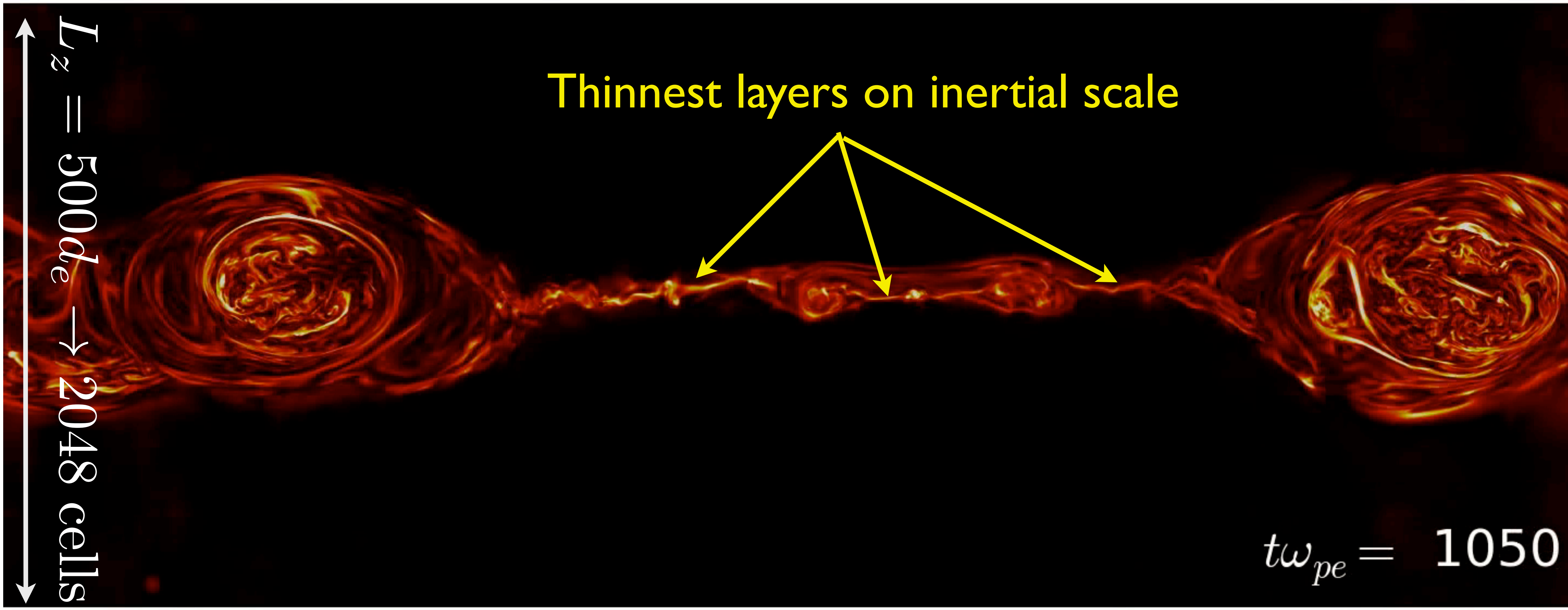



$L_x = 1000d_e \rightarrow 4096$ cells

**Global flux changes across inertial scale layer!**

# Does it really work this way in large systems?

Holman -2012

$B \sim 100$ G

$T \sim 100$ eV

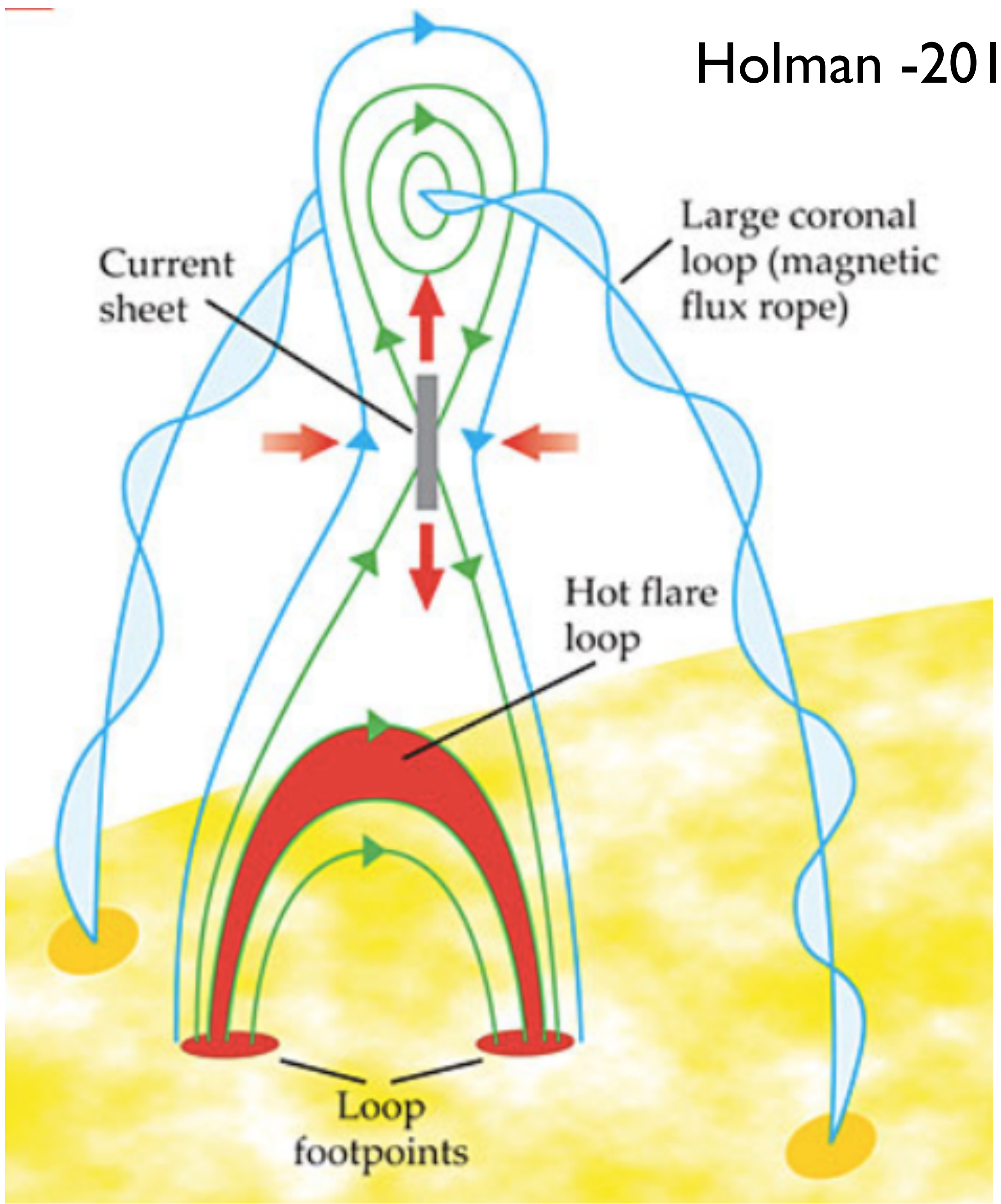
$n \sim 10^9$ cm$^{-3}$

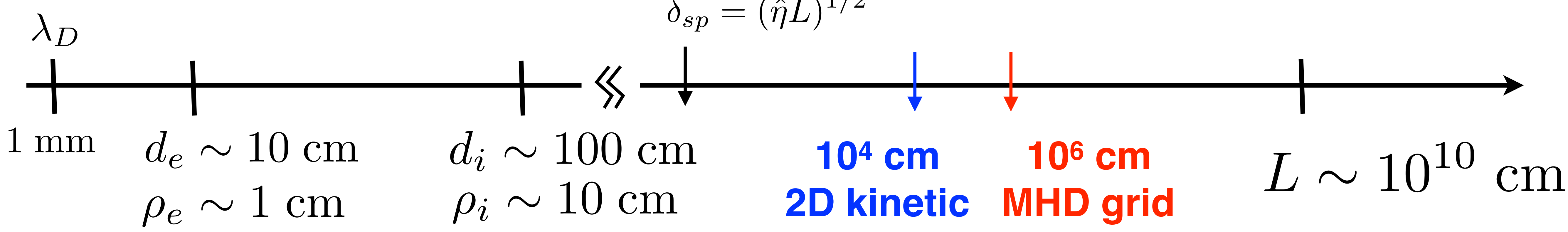
$\nu_{ei} \sim 10^2$ sec$^{-1}$

$\Omega_{ce} \sim 10^9$ sec$^{-1}$

$$\hat{\eta} = \frac{\nu_{ei}}{\Omega_{ce}} = 10^{-7}$$

$$S = \frac{\hat{d}_i}{\hat{\eta}} = 10^{15}$$

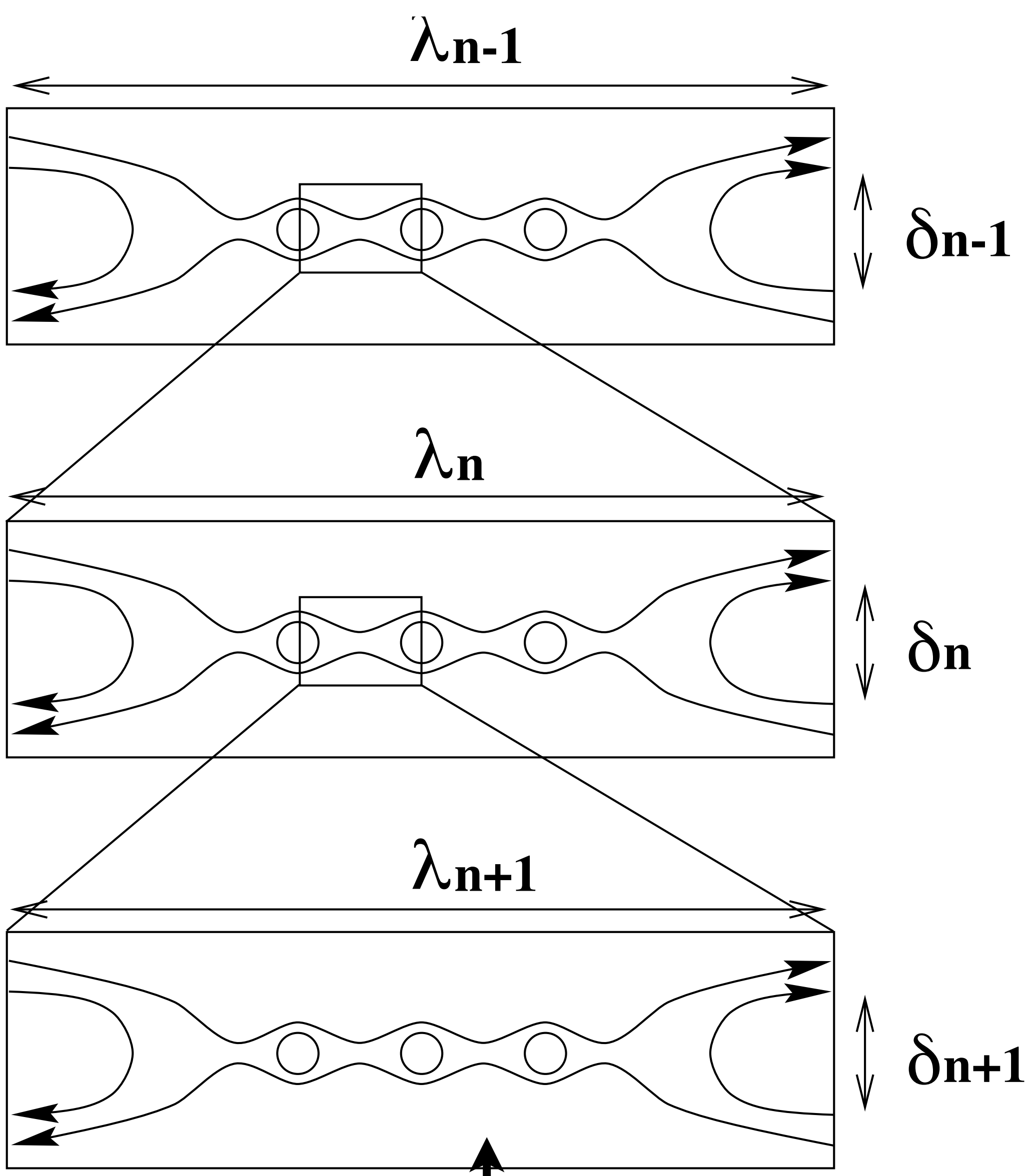


# Cartoons have been suggested

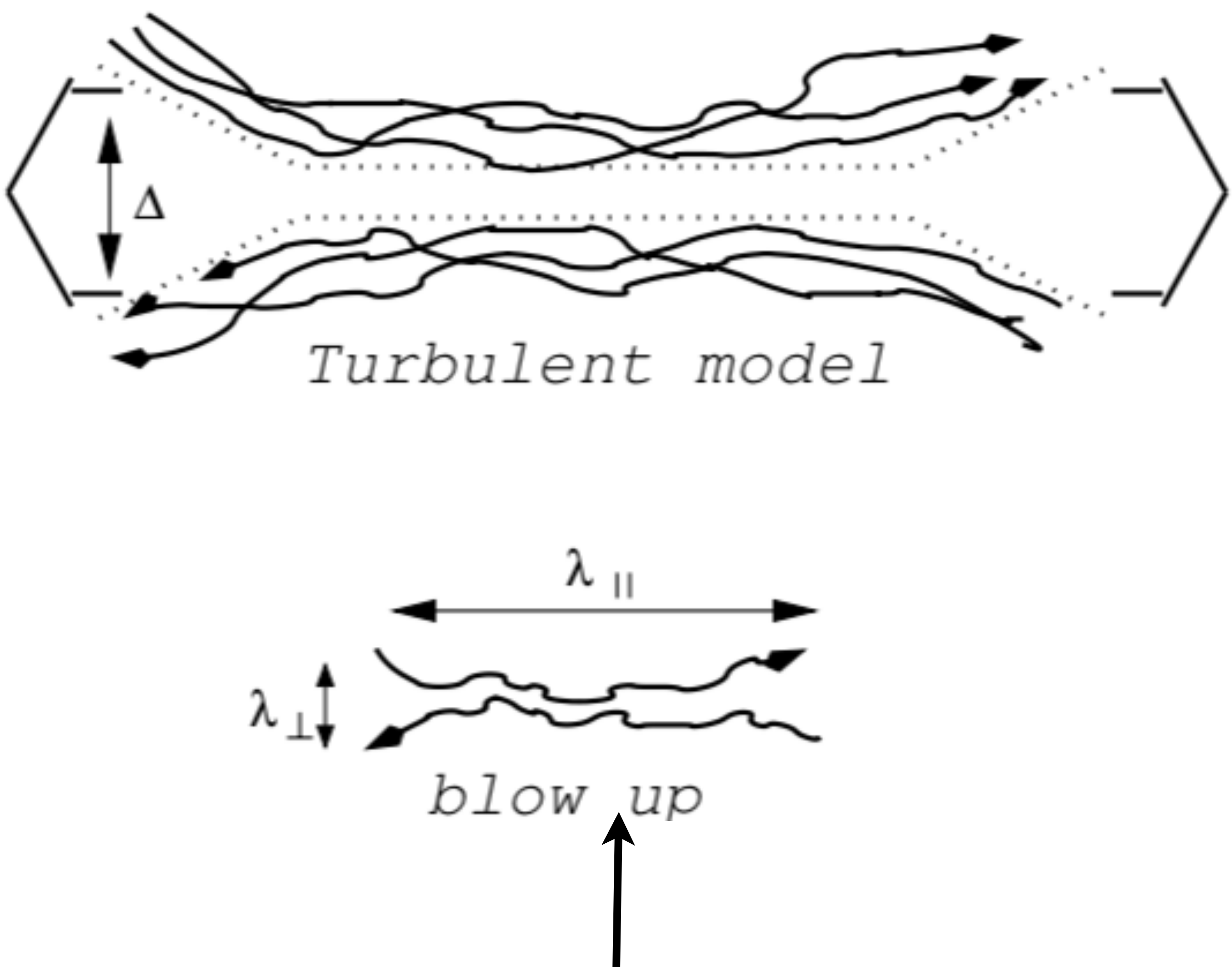
*self-similarity is a key ingredient*

**Shibata & Tanuma, 2001**



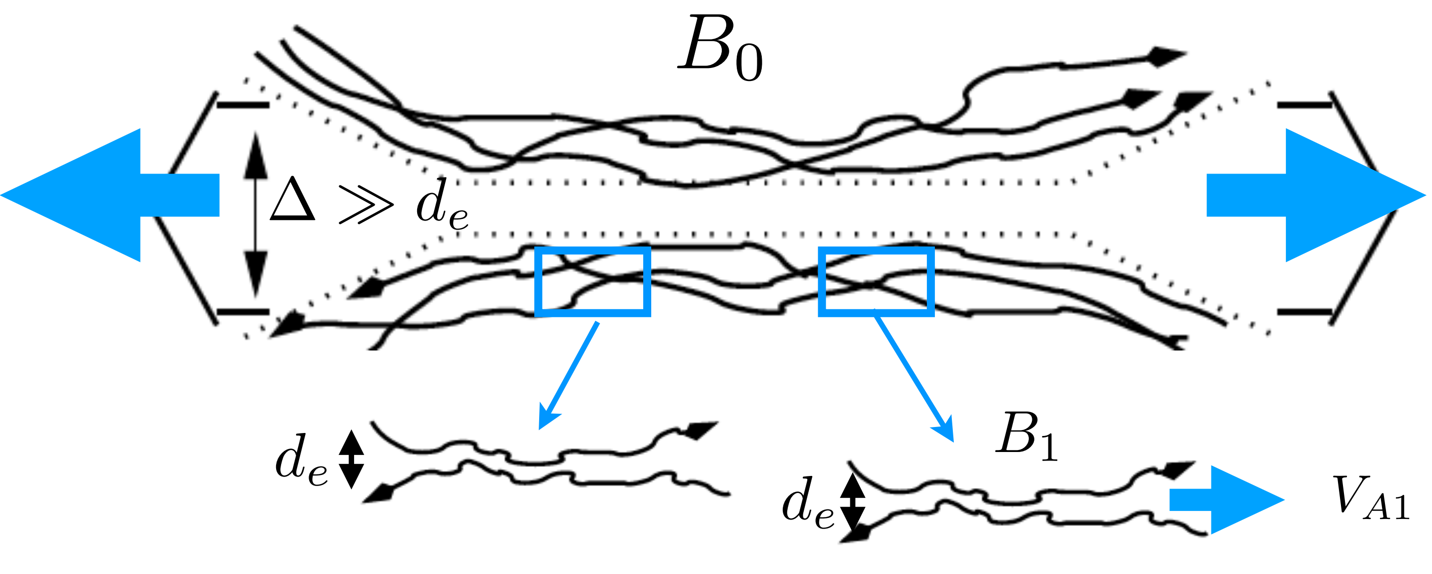

kinetic scales

**Lazarian & Vishniac, 1999**




kinetic scales?

# How might this work at mesoscale ?




$$V_{A0} = \frac{B_0}{\sqrt{4\pi n m_i}}$$

$$V_{A1} = \frac{B_1}{\sqrt{4\pi n m_i}}$$

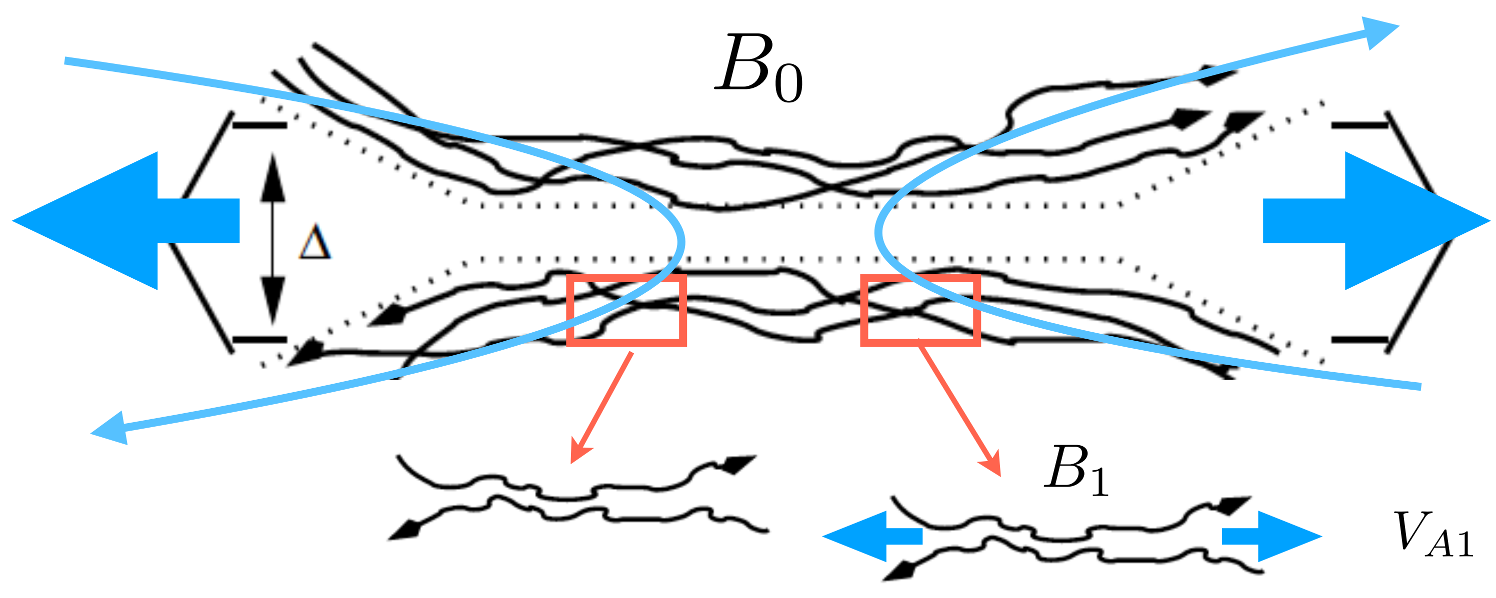
## Requirements

- Thick layer $\Delta \gg d_e$
- Alfvénic jet
- R ~ 0.01 - 0.1
- Break flux with known non-ideal physics
- No stirring allowed !

## My Assumptions:

1. Frozen flux is a strong constraint
2. Collisional terms valid for sub-Dreicer fields ⟶ $\frac{E_r}{E_D} \approx R \left(\frac{m_e}{m_i}\right)^{1/2} \frac{\Omega_{ce}}{\nu_{ei}}$
3. Weak evidence for anomalous resistivity
4. Frozen-flux is broken in $d_e$ - scale layers ⟶ $\propto (d_e/\Delta)^2$
5. Tearing growth increases rapidly ⟶ $\gamma \propto (d_e/\Delta)^3$
6. Reconnection remains fast for very strong guide field ⟶ **Liu et al, 2014** **TenBarge et al, 2013**
7. Dynamics generates new $d_e$ - scale layers

# Potential problems with cartoon




$$V_{A0} = \frac{B_0}{\sqrt{4\pi n m_i}}$$

$$V_{A1} = \frac{B_1}{\sqrt{4\pi n m_i}}$$

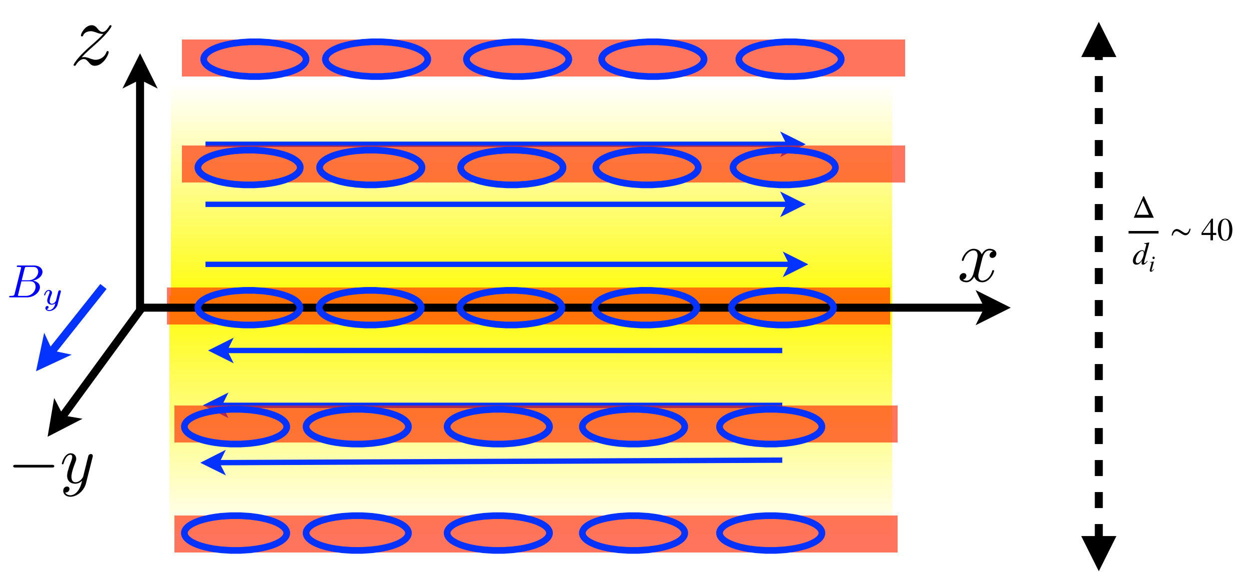
1. **Do kinetic outflows combine coherently?**
   (a) Destructive interference seems more likely
   (b) *Alfvenic outflow* vs *turbulent diffusion*

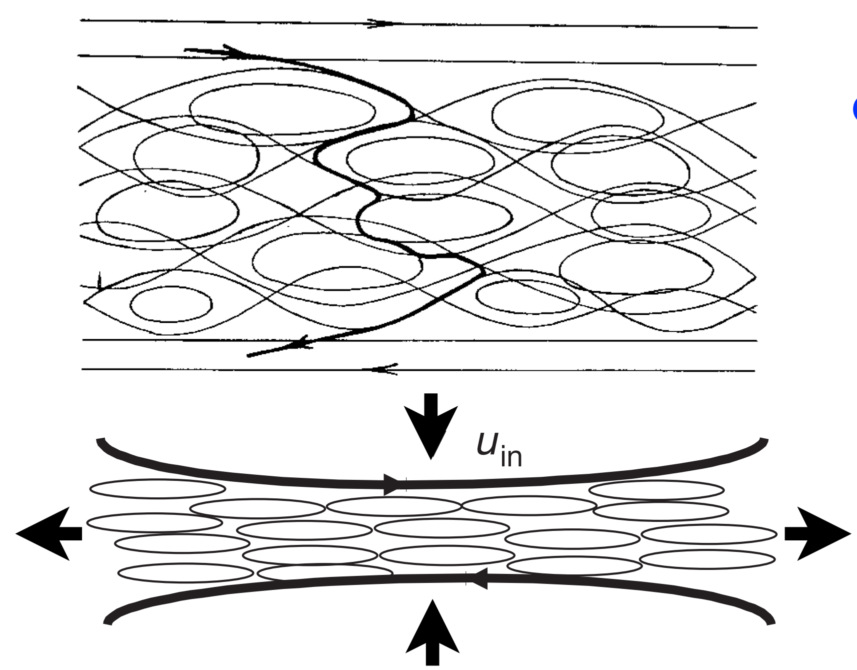
2. **Kinetic reconnection produces anisotropy** $\longrightarrow$ $T_{||} > T_{\perp}$
   (a) Degrades field line tension
   (b) May suppress outflow $\longrightarrow$ $\left(1 + \frac{p_\perp - p_{||}}{B^2/8\pi}\right)\frac{(\mathbf{B}\cdot\nabla)\mathbf{B}}{4\pi}$

3. **How to initialize this dynamics?**

# Might be possible for kinetic pair plasmas ?

- Cost scales as $(m_i/m_e)^{5/2} \quad \rightarrow \quad 1836^{5/2} \sim 1.4 \times 10^8$
- Kinetic dissipation + MHD scale dynamics
- Tearing growth rate is too weak in thick sheet $\quad \gamma \propto (d_e/\Delta)^3$




Galeev et al, 1986

Drake et al, 2006

- ***Can we kickstart dynamics into turbulent regime ?***
- No reason to believe initial current layer is smooth
- Natural systems have fluctuations and sub-layers

# Magnetotail current sheet is often fragmented with sub-scale structures



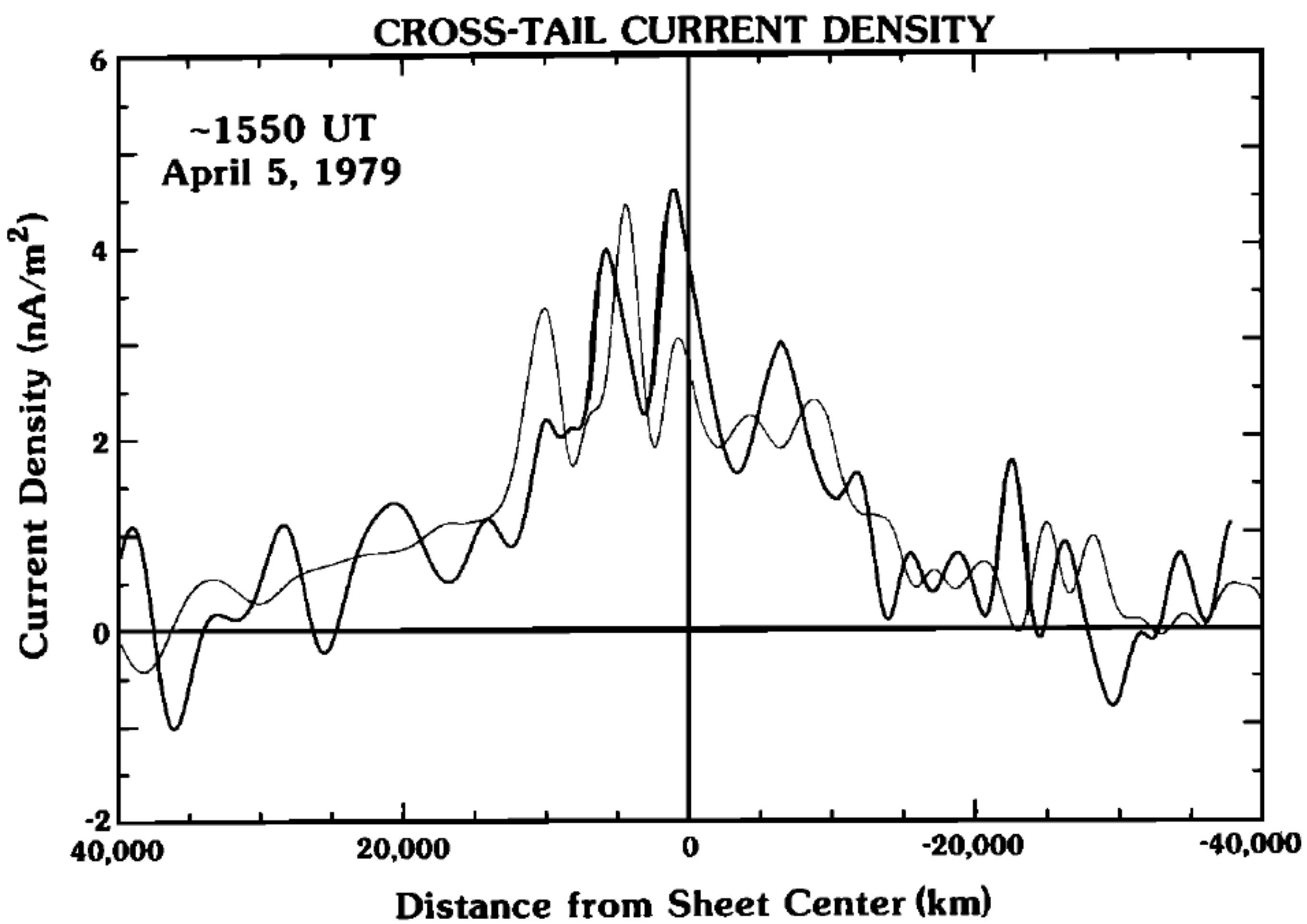



Fig. 6. Cross-tail current density distributions for ISEE 1 and 2 displayed as a function of distance from the current sheet midplane for the crossing at ~1550 UT at −17.6, −3.2, 0.2 $R_E$ GSM. The distributions show the sheet to consist of a central current density enhancement surrounded on either side by lower-density "shoulders." Further, the sheet is highly structured, the narrow density peaks being a fraction of an $R_E$ thick, and variable.

**Compression of thick sheets leads to formation of sub-scale structures - Birn & Schindler**

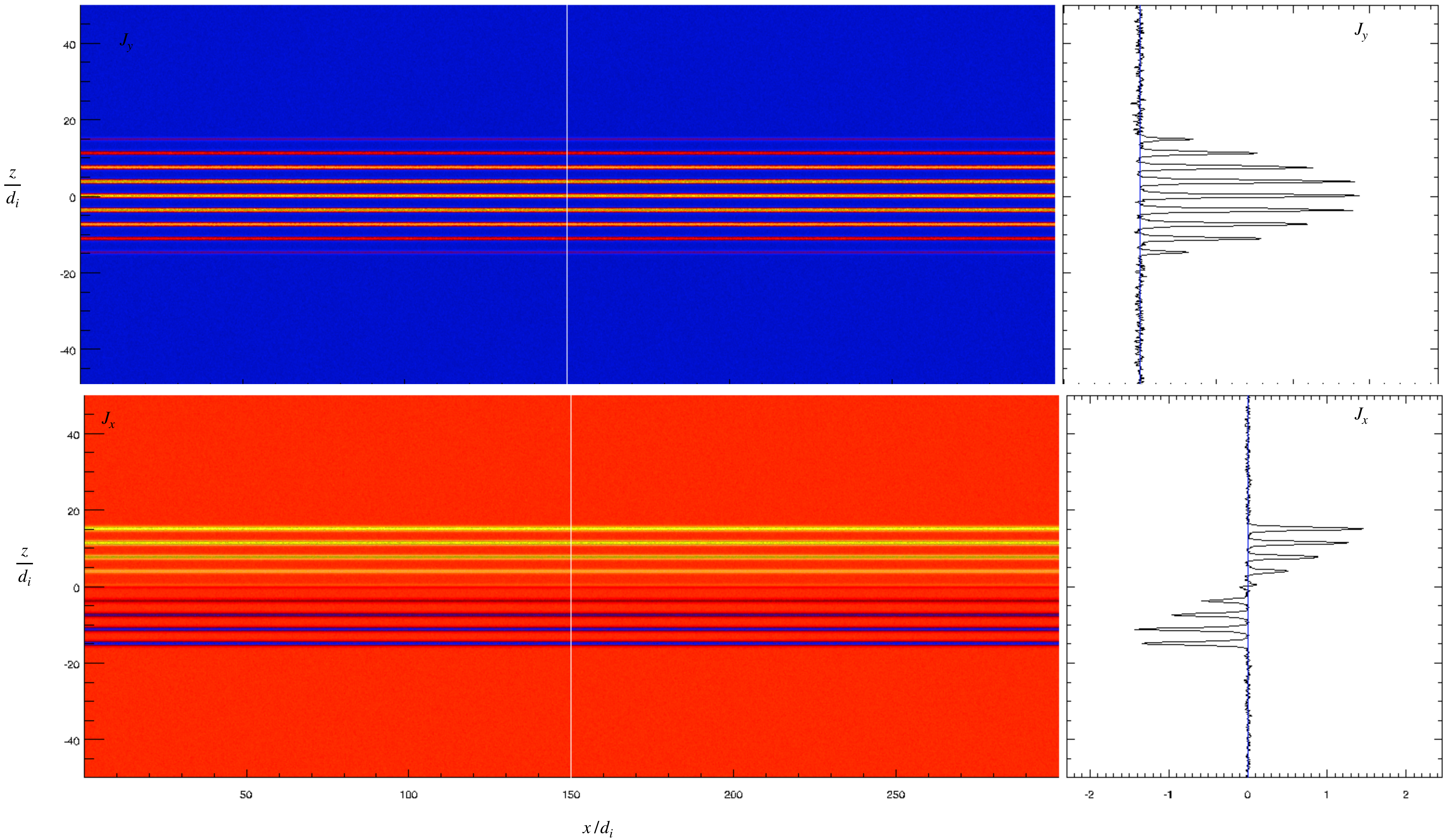
# Consider two initial setups

Thick layers $\longrightarrow$ $\Delta/d_e \approx 25-35$

1. Embedded kinetic scale sheets

2. Inject waves to drive turbulence

**Setup #1 -** Thick sheet with embedded kinetic sub-layers to kickstart reconnection dynamics




**Each sub-layer is a force-free sheet**

# Initialize sub-layers are force-free sheets

- Pick macroscopic thickness and rotation angle $\longrightarrow$ $L, \phi$
- Choose number & thickness of sublayers $\longrightarrow$ $N, \delta \rightarrow \theta = \phi/N$
- Load each sub-layer with analytic form

$$B_x'(z) = B_0 \tanh\left(\frac{z - z_j}{\delta}\right)$$

$$B_y'(z) = B_0 \left[b_g^2 + \text{sech}^2\left(\frac{z - z_j}{\delta}\right)\right]^{1/2} \qquad j = 1 \rightarrow N$$

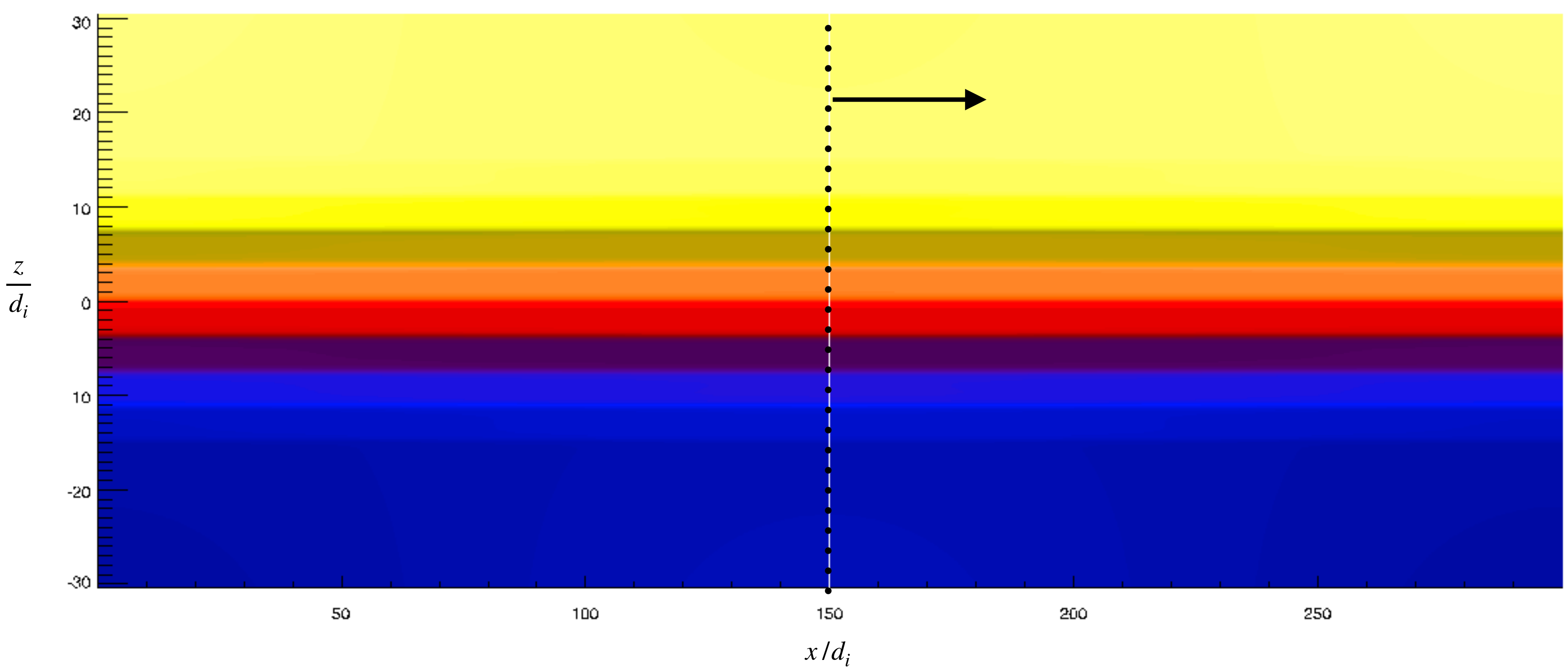
$$b_g = \left(\frac{1 + cos(\theta)}{1 - cos(\theta)}\right)^{1/2}$$

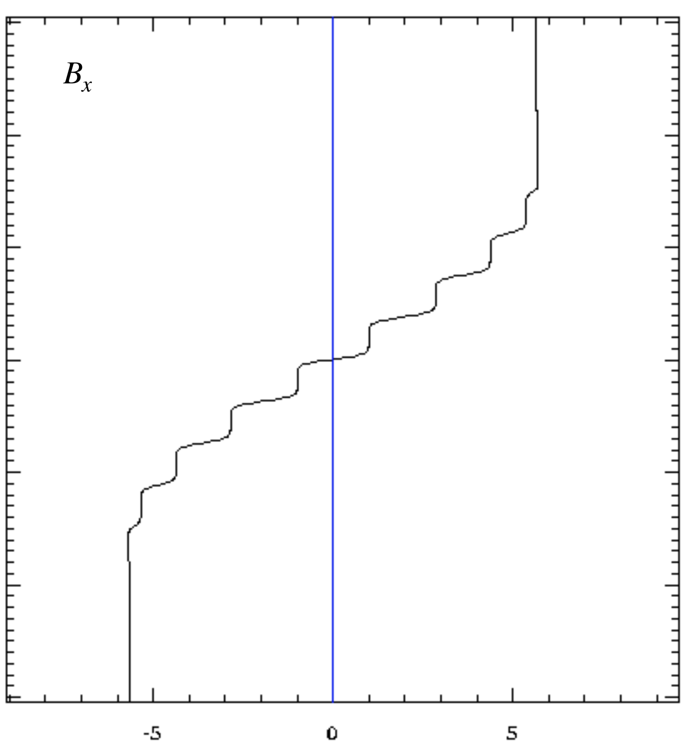
$$\frac{\gamma}{kv_{th_e}} \sim \frac{d_e^2 \Delta'}{2\sqrt{\pi} l_s}$$ Liu et al, 13

Reconnection remains fast for strong guide field

Liu et al, 13,14

TenBarge et al, 14

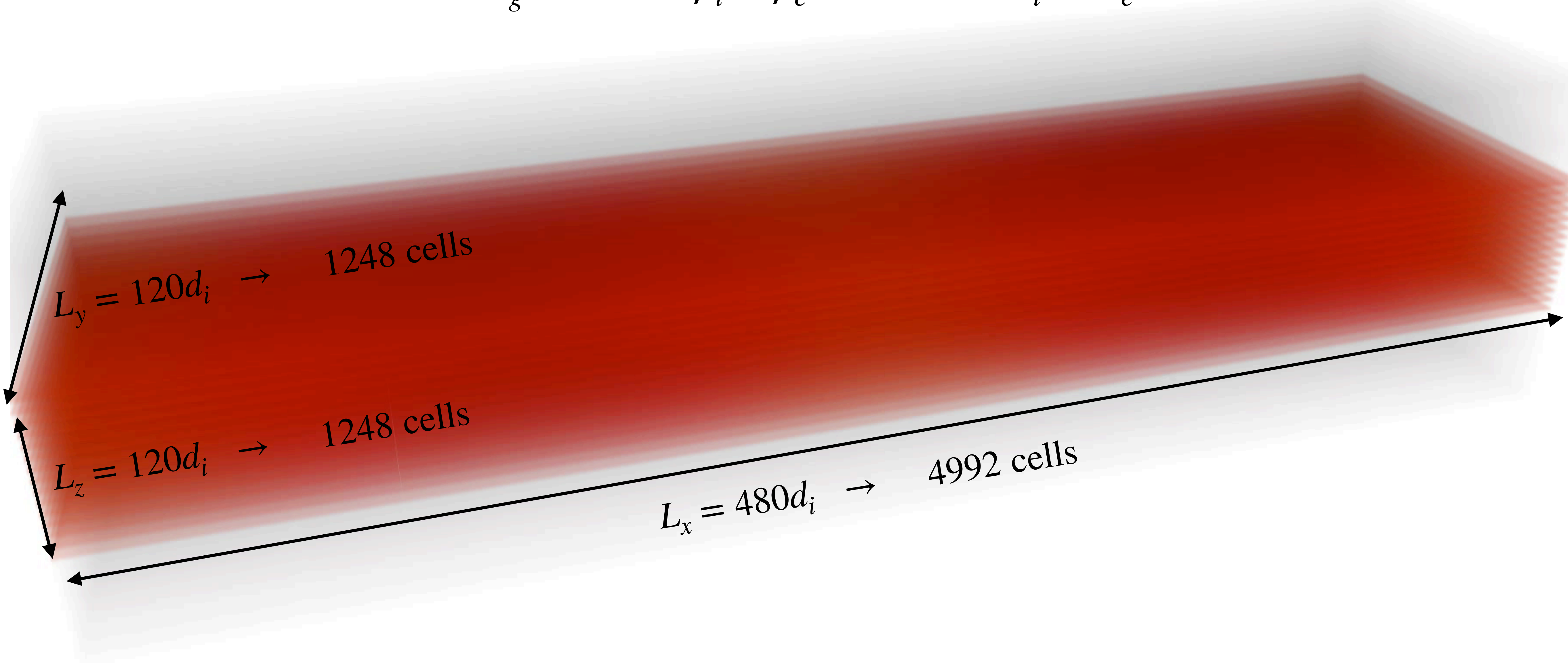


# Example #1

$\phi = 180^\circ \qquad N = 15 \qquad \theta = 12^\circ \qquad \Delta = 24d_i \qquad \delta = 0.5d_i$

$b_g = 9.5 \qquad \beta_i = \beta_e = 10^{-2} \qquad m_i = m_e$



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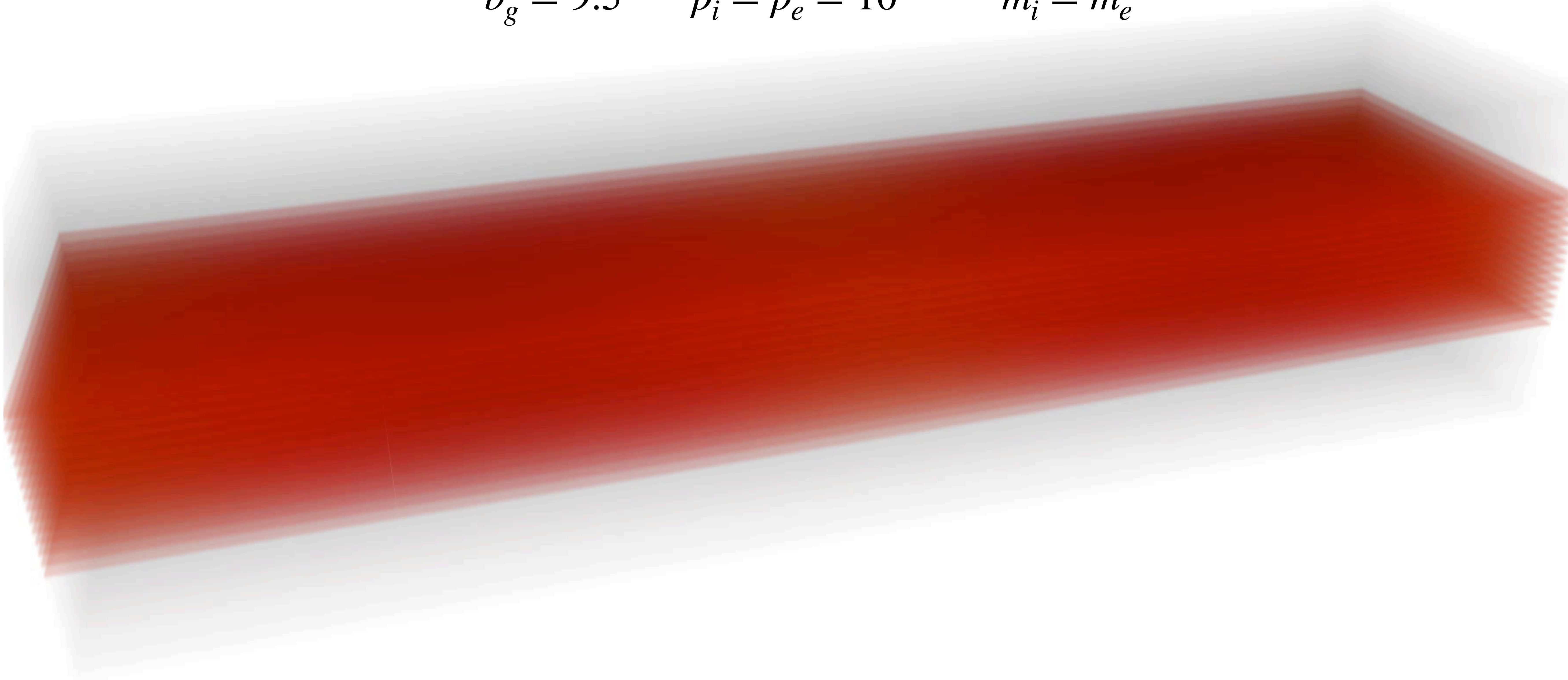

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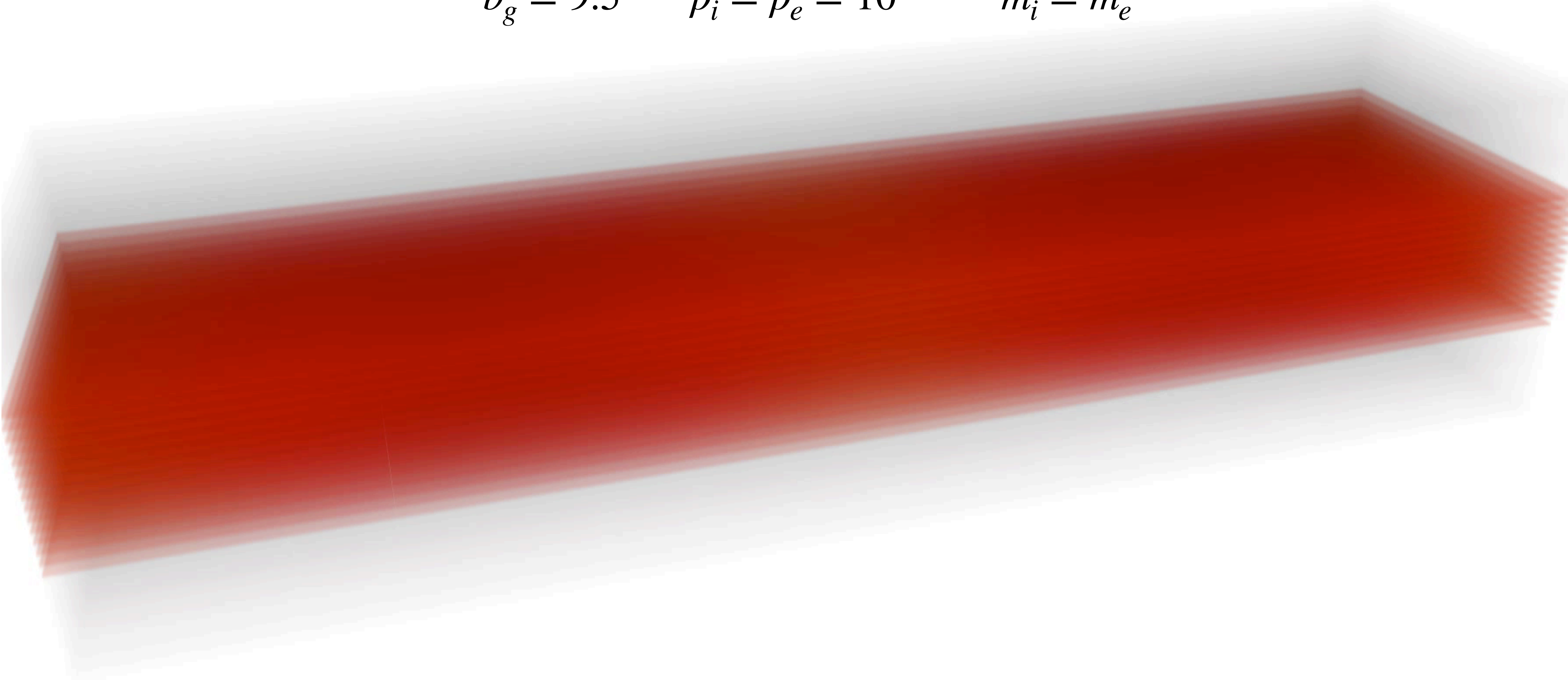
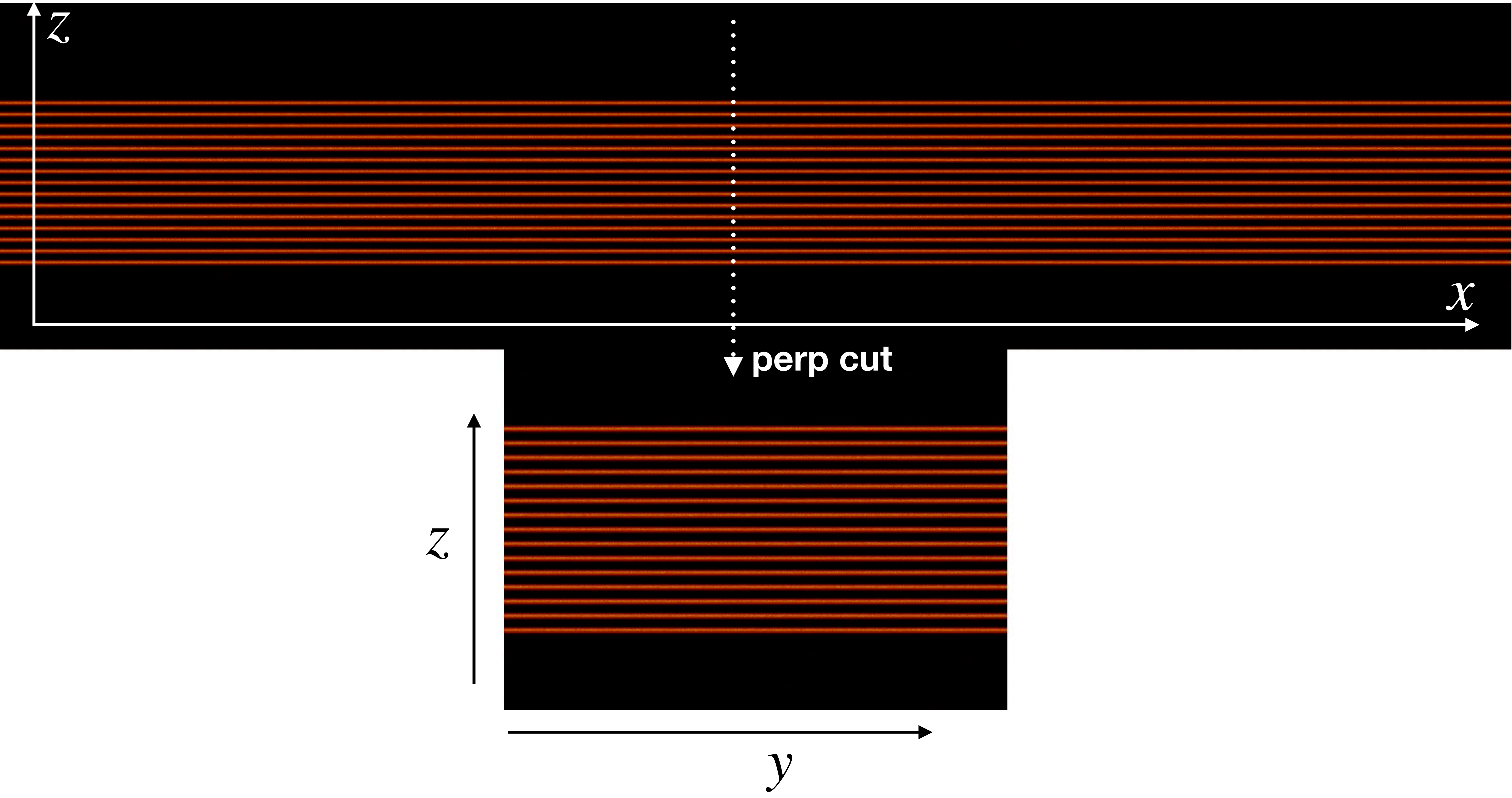


**Collapses back to same dynamics ➜ Guo et al, 2014, 2016, 2019**

# Example #1 X-Z and Y-Z Slices



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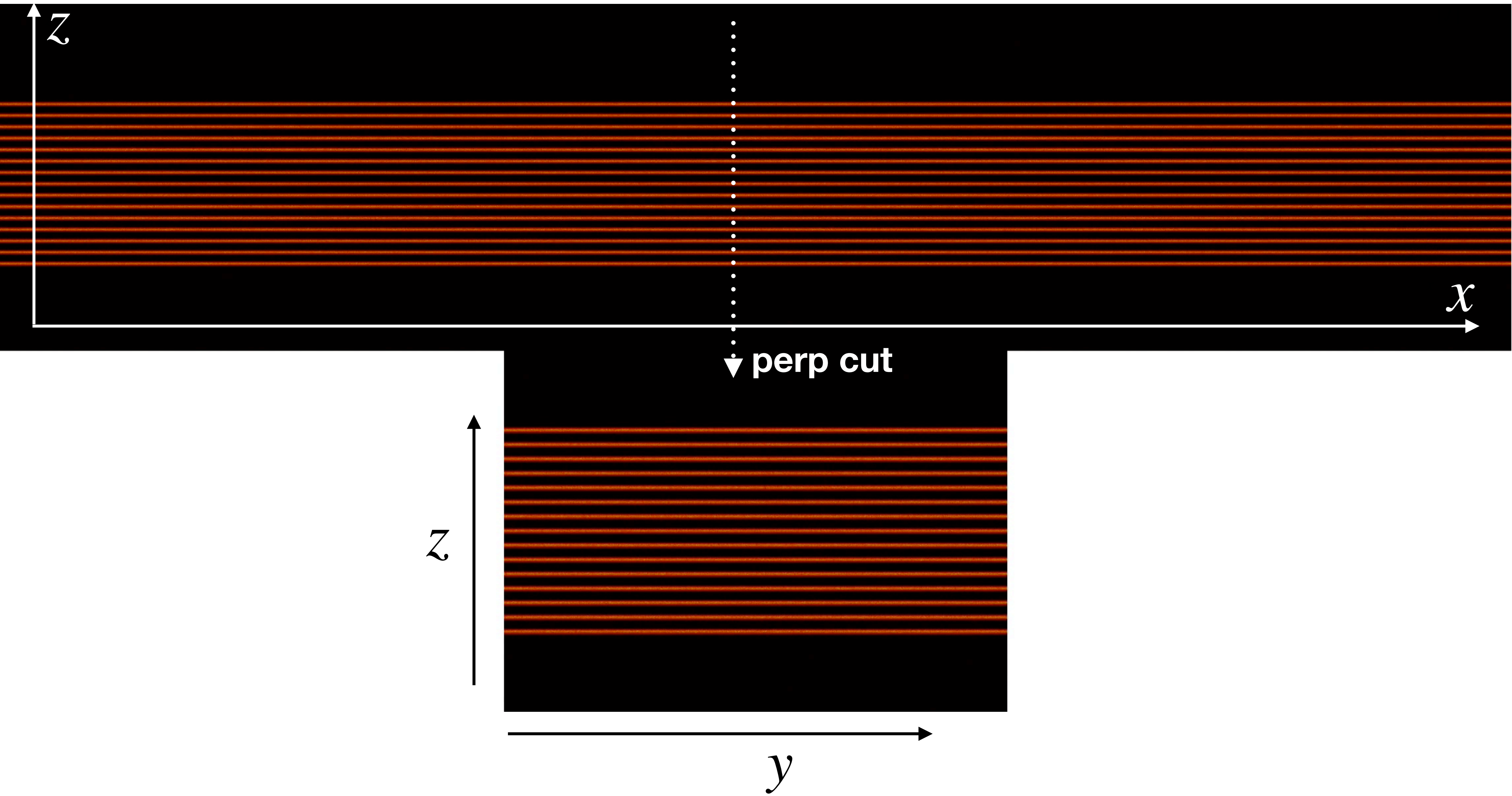
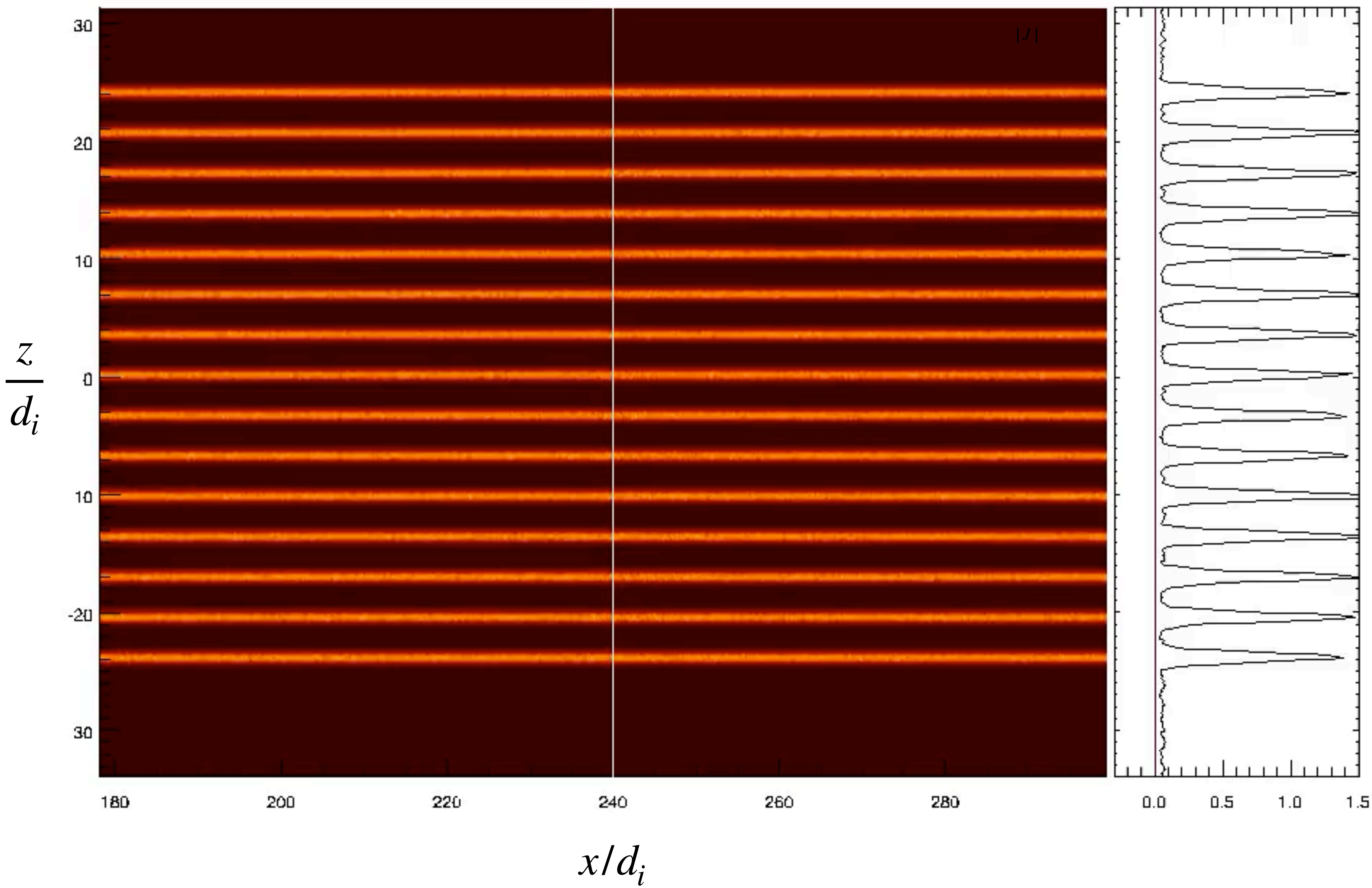


# Close-up of Central Region



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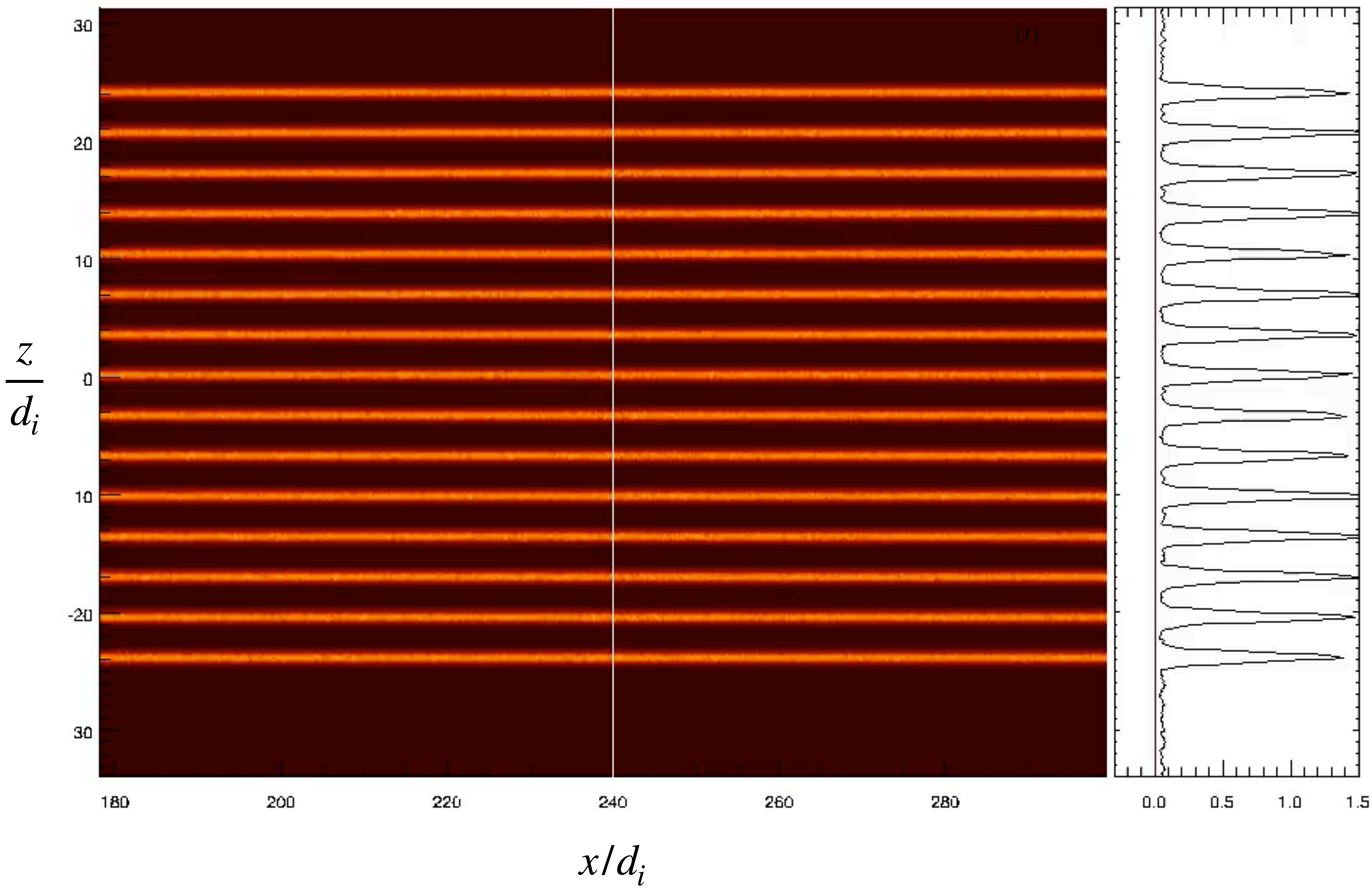
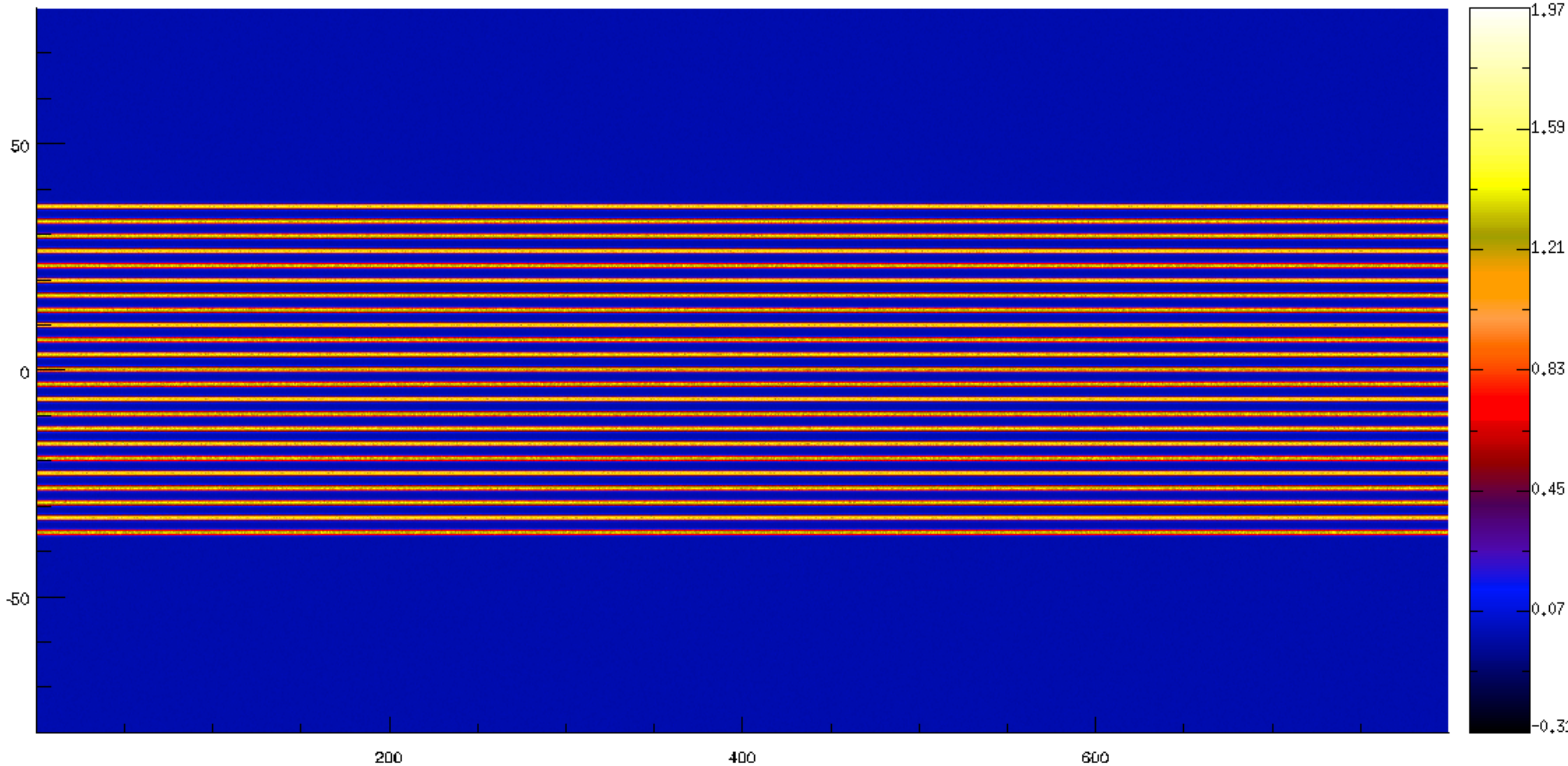


# Example #2 - Larger run with thicker layer

$\phi = 180^\circ \qquad N = 23 \qquad \theta = 7.8^\circ \qquad \Delta = 36d_i \qquad \delta = 0.5d_i$

$b_g = 14.6 \qquad \beta = 10^{-2} \qquad m_i = m_e \qquad T_i = T_e$

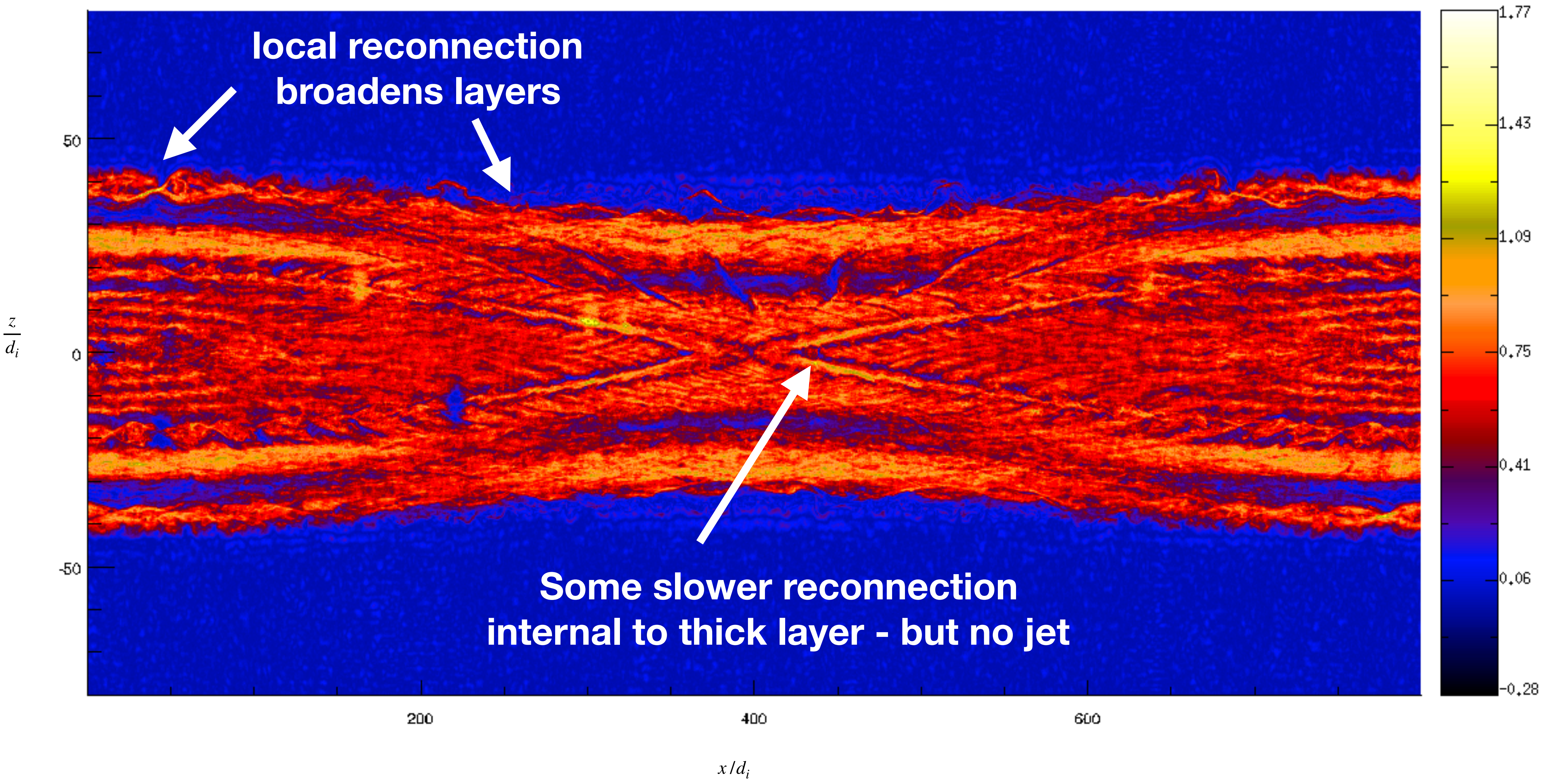
$800d_i \times 160d_i \times 160d_i \rightarrow 6144 \times 1280 \times 1280$




$\frac{z}{d_i}$

$x/d_i$

# Turbulent layer - but no onset of large-scale reconnection



# **Setup #2 -** Thick sheet with spectrum of initial waves

$$B_x(z) = B_0 \tanh\left(\frac{z}{\Delta}\right)$$

**Thick Force-Free Layer**

$$\Delta = 20 d_i$$

$$B_y(z) = B_0 \left[ b_g^2 + \operatorname{sech}^2\left(\frac{z}{\Delta}\right) \right]^{1/2}$$

**+ Wave perturbations, modes 2-6**

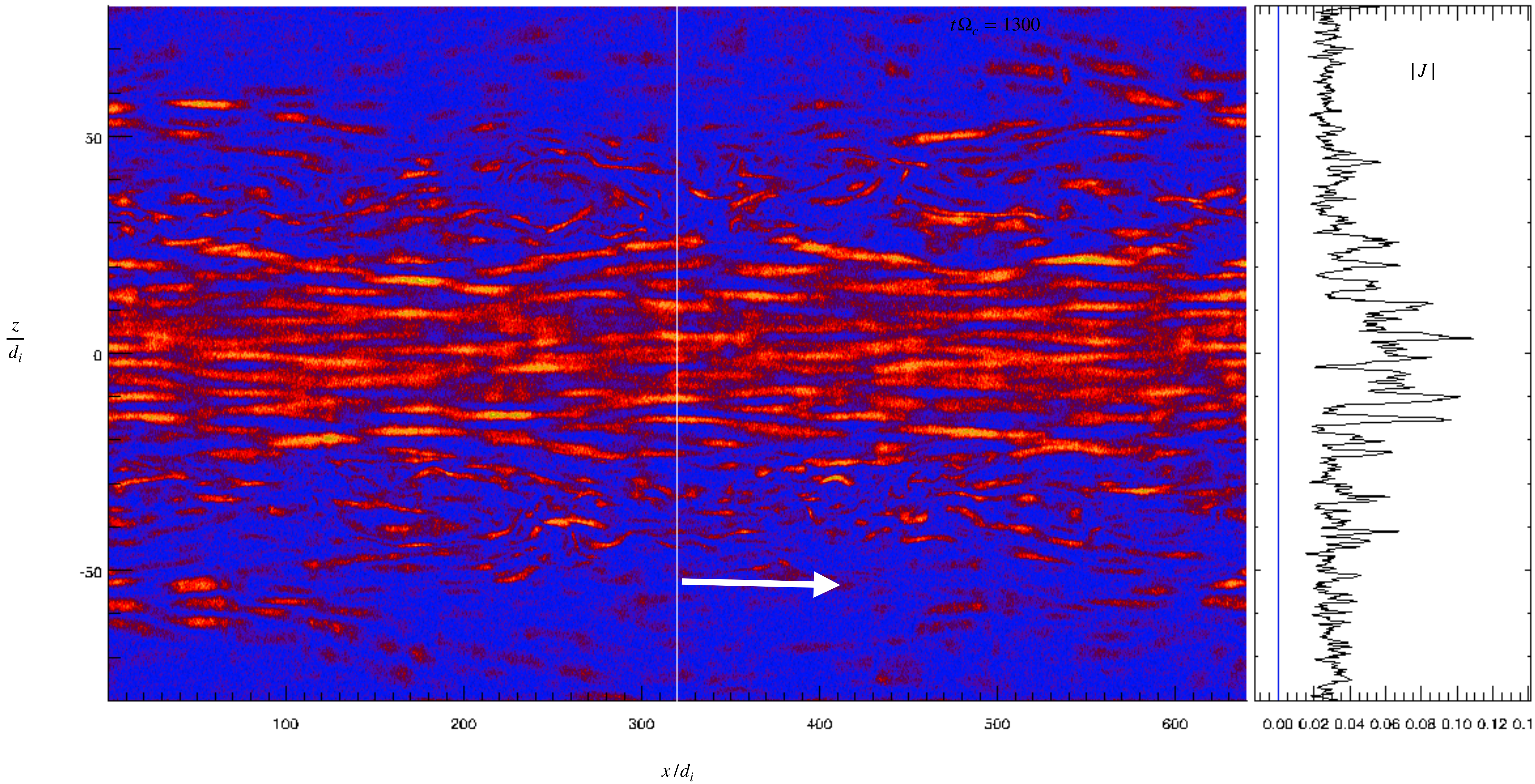
$$+ \delta B_x \cos\left(\frac{2\pi x}{L_x}\right) \sin\left(\frac{\pi z}{L_z}\right)$$

**M=1 to drive reconnection in center of box**

$$+ \delta B_z \sin\left(\frac{2\pi x}{L_x}\right) \cos\left(\frac{\pi z}{L_z}\right)$$

# Interaction of initial waves produces many embedded kinetic scale current sheets

$b_g = 0 \quad \beta_i = \beta_e = 0.1 \quad m_i = m_e \quad \Delta = 20d_i \quad |\delta B|/B \sim 0.1$




# Without driving term - no large-scale onset

# Waves + Drive Perturbation ➜ Reconnection

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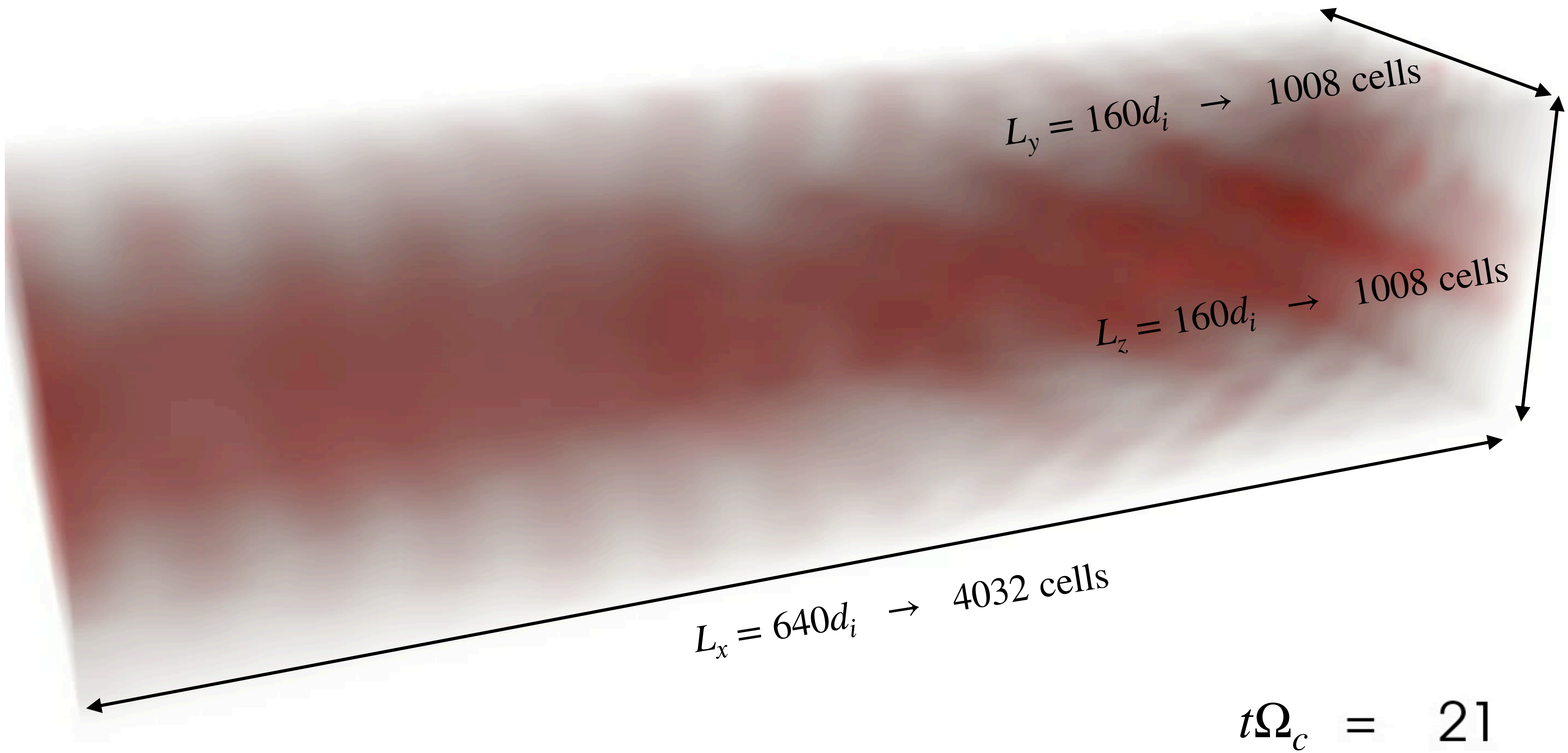

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$t\Omega_c = 21$

# Waves + Drive Perturbation ➜ Reconnection

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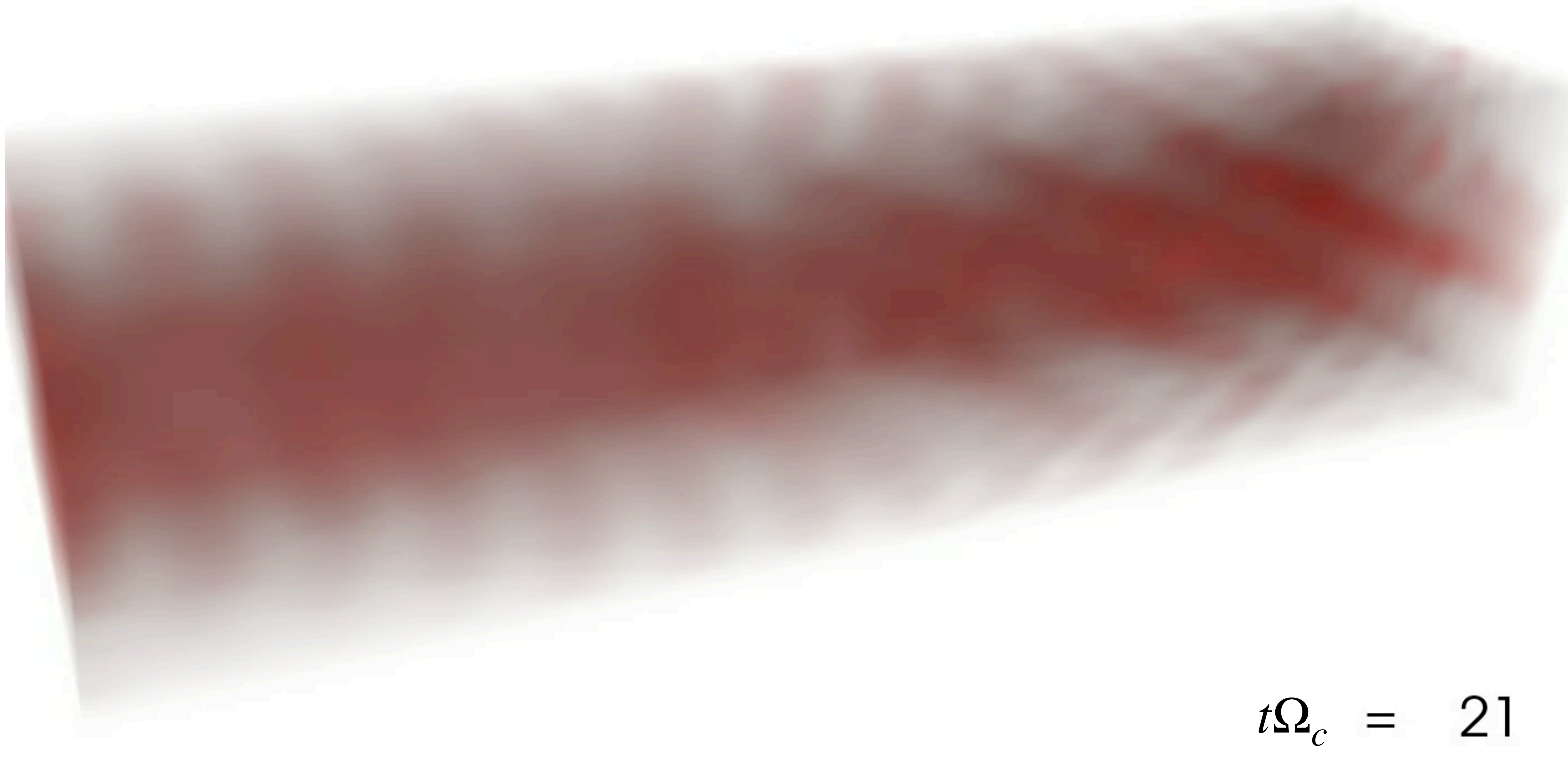
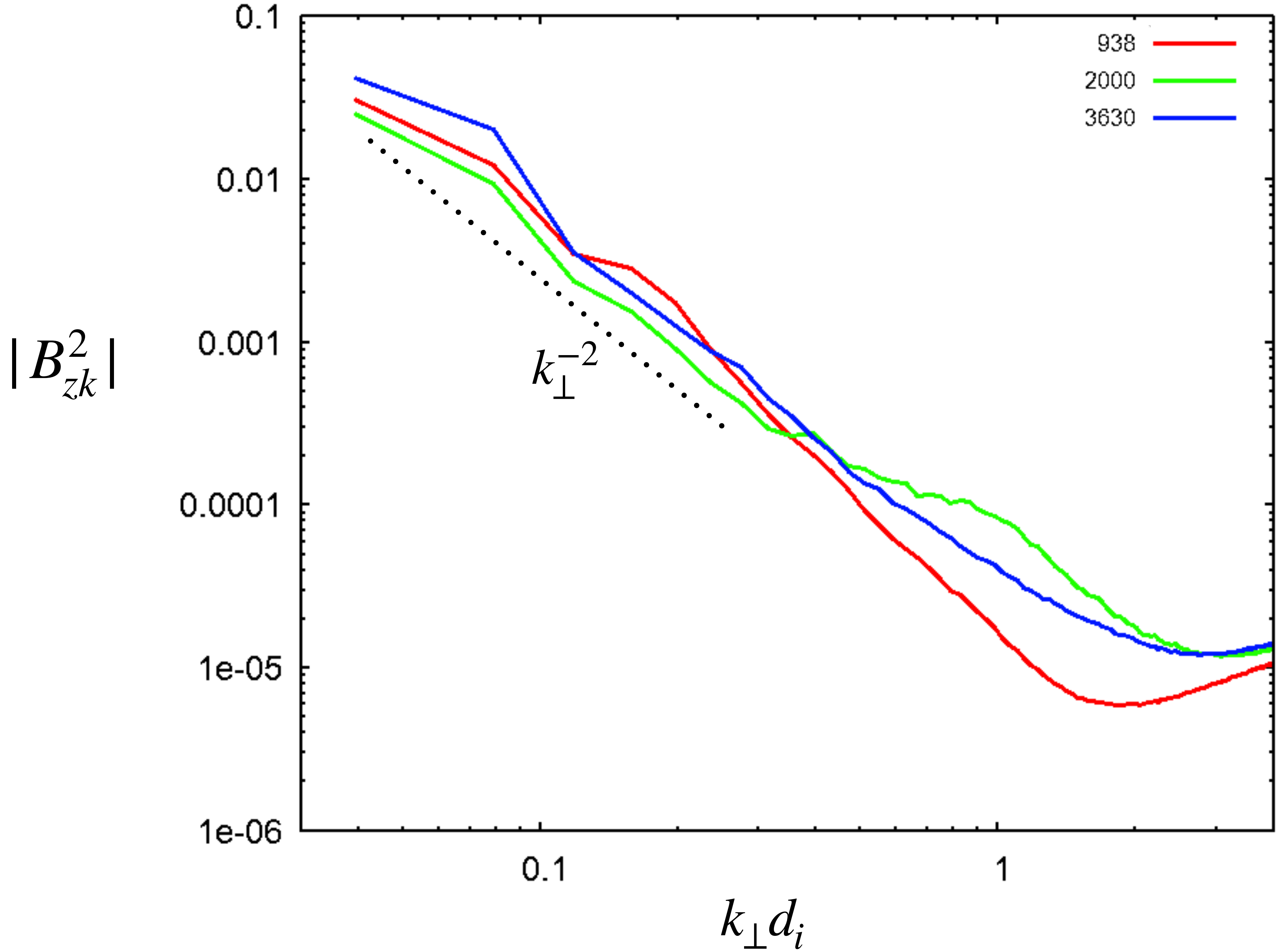
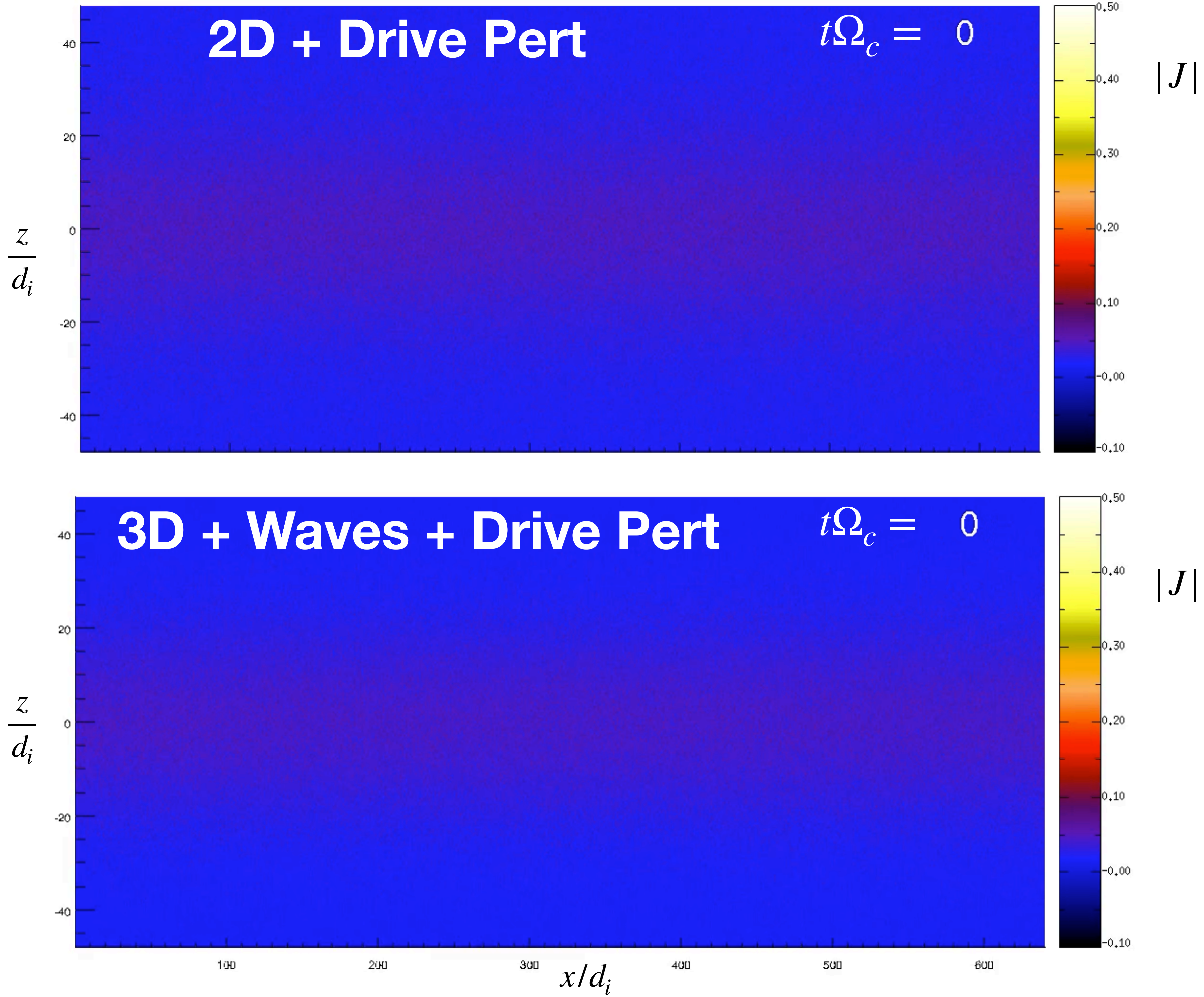
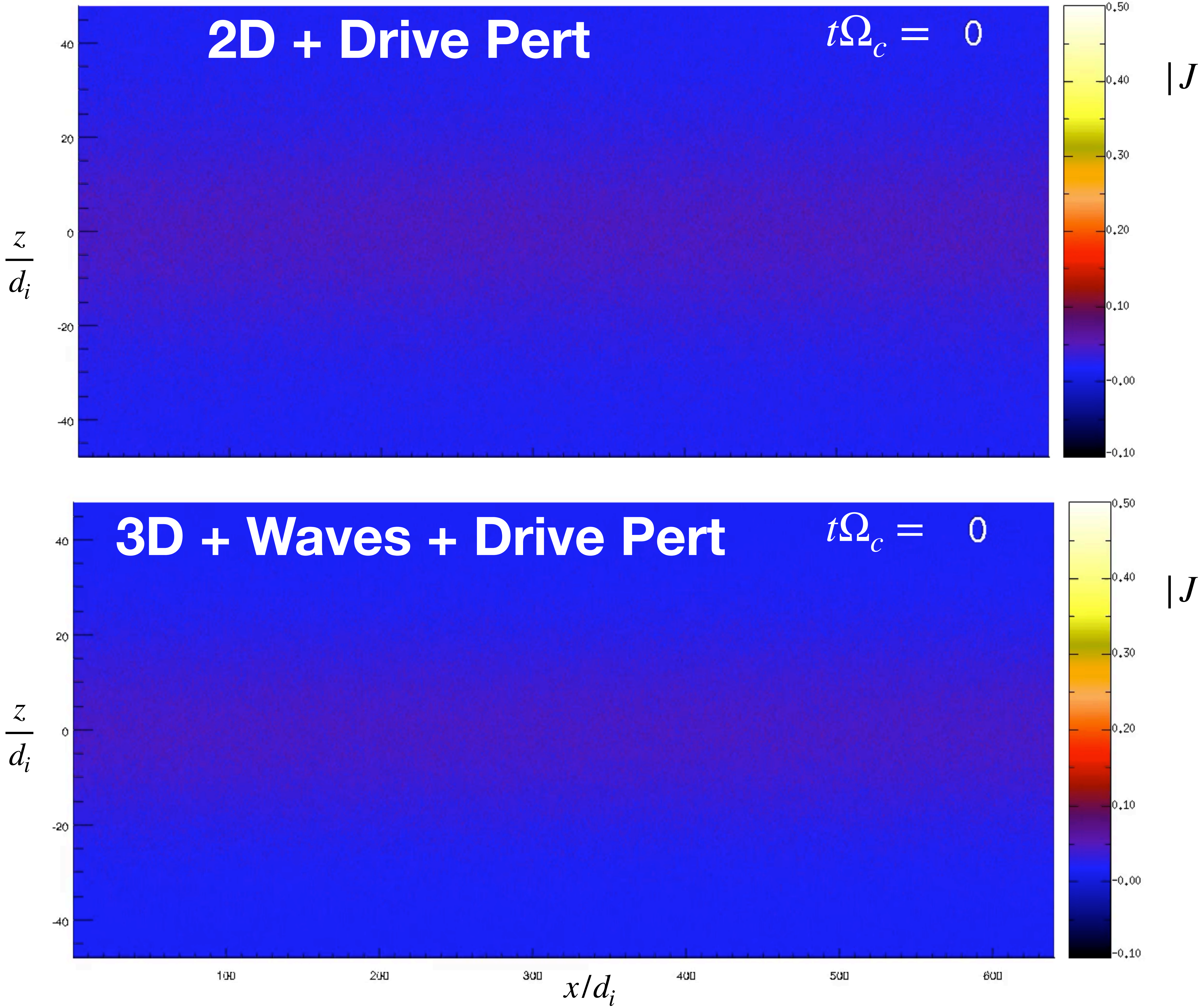


# Spectrum of Magnetic Fluctuations




2D + Drive Pert
$t\Omega_c = 0$
$|J|$
3D + Waves + Drive Pert
$t\Omega_c = 0$
$|J|$
$\frac{z}{d_i}$
$x/d_i$
40
20
0
-20
-40
100
200
300
400
500
600
0.50
0.40
0.30
0.20
0.10
-0.00
-0.10



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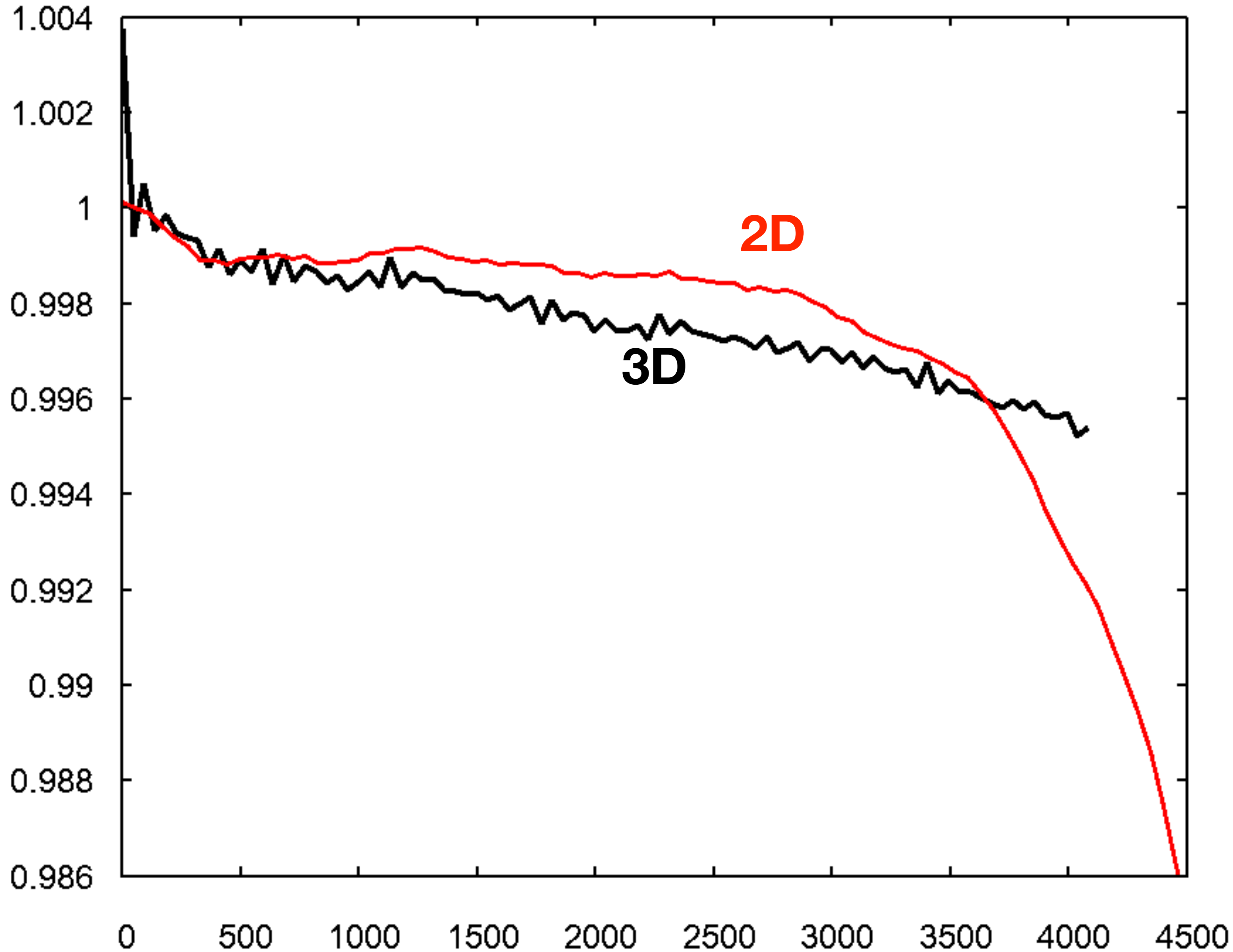
$x/d_i$

# Rate of energy conversion may be slower with 3D turbulence

$$\frac{\langle B^2(t)\rangle}{\langle B^2(t=0)\rangle}$$




$t\Omega_c$

# Summary

- Reconnection is likely turbulent in very large systems, but details remains unclear - *even at the cartoon level*
- *E*xtended kinetic sheets are not realistic initial condition
- Reconnection within *mesoscale* layers may offer new insights
- May be feasible to study with kinetic pair plasmas:
  - ***Embedded kinetic sub-layers*** ➜ strong turbulence in layer
    - *Fast reconnection associated with kinetic collapse*
    - *Alternate outcome is slow turbulent diffusion*
  - ***Initial spectrum of waves*** ➜ naturally drives kinetic sheets
    - F*aster reconnection also associated with kinetic collapse*
    - Turbulence appears to reduce reconnection rate
    - Some evidence of broader *turbulent diffusion region*
    - *Not clear this can be sustained - perhaps collapse inevitable?*