Recent Progress and Future Outlook for Kinetic Simulations of Magnetic Reconnection

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NSF : Kraken

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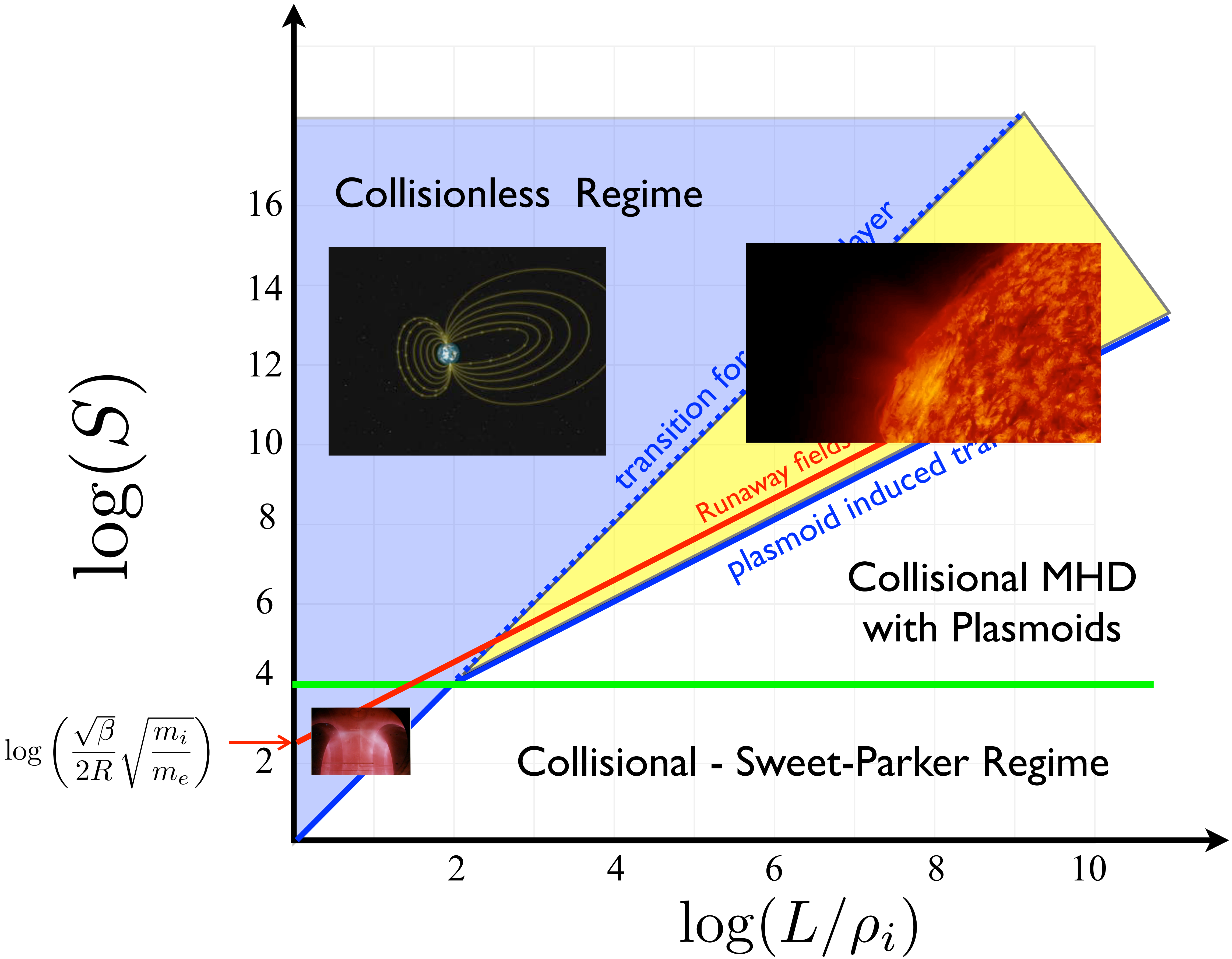
Wide range of applications to consider:

- Planetary magnetospheres $\longrightarrow$ magnetopause
  magnetotail
- Solar applications $\longrightarrow$ chromosphere, transition region, corona - flares, prominences, coronal mass ejections
- Solar wind
- Laboratory fusion machines
- Astrophysical problems

$\left.\begin{array}{l}\text{stellar flares}\\ \text{galactic magnetotails}\\ \text{accretion disks}\end{array}\right\}$ Hydrogen

$\left.\begin{array}{l}\text{pulsar winds}\\ \text{gamma-ray bursts}\\ \text{jets from AGN}\end{array}\right\}$ Electron-Positron

When do we need a kinetic description?



Kinetic Particle-in-cell Simulations

First-Principles Approach for all Regimes

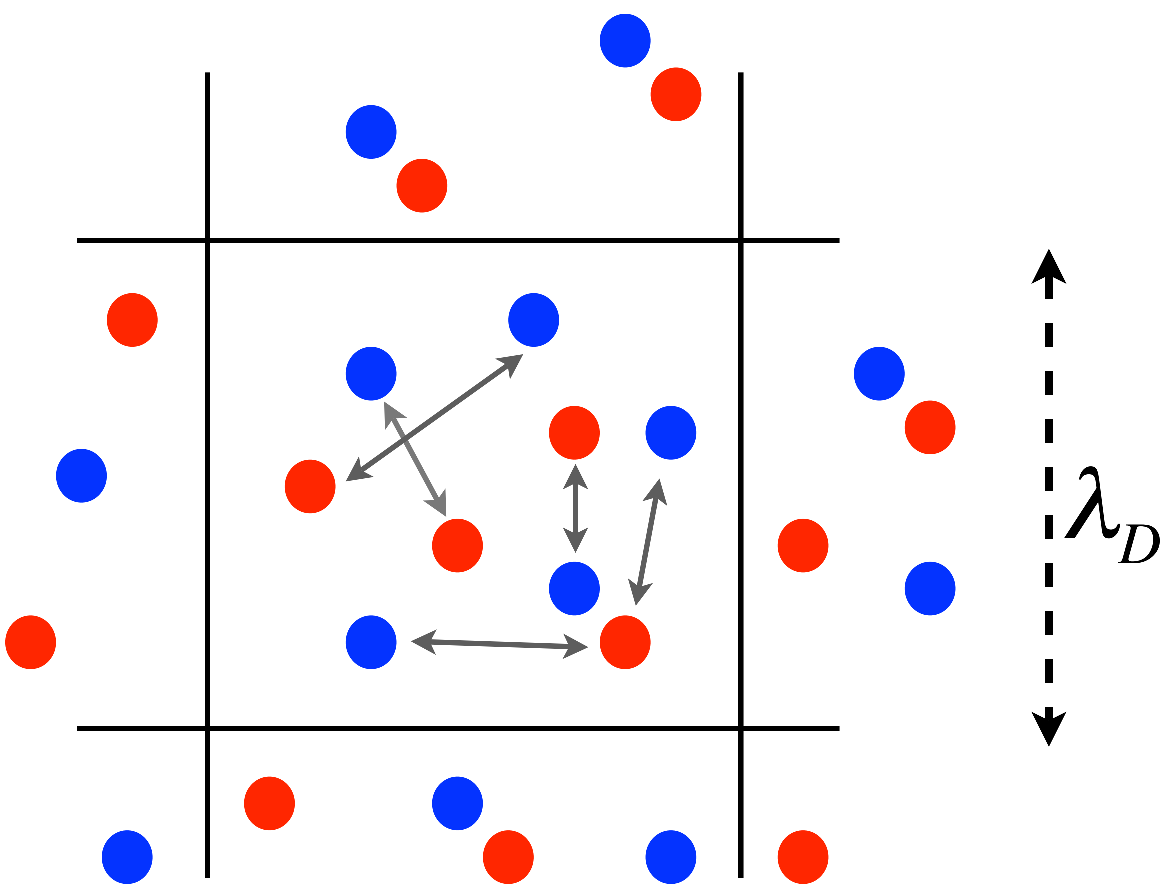
$$\frac{\partial f_s}{\partial t} + \mathbf{v} \cdot \frac{\partial f_s}{\partial \mathbf{x}} + \frac{q_s}{m_s}\left(\mathbf{E} + \frac{\mathbf{v} \times \mathbf{B}}{c}\right) \cdot \frac{\partial f_s}{\partial \mathbf{v}} = \sum_{s'} \mathcal{C}_{ss'}$$

Fokker-Planck
Collision Operator

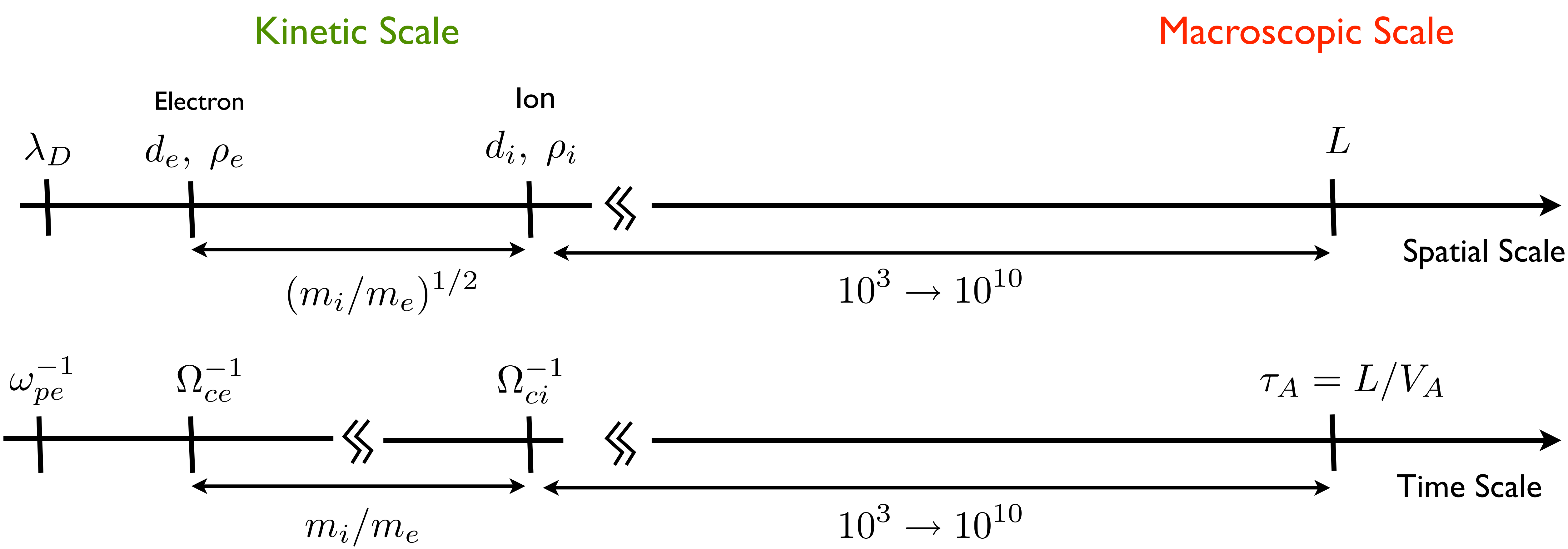
\+ Maxwell's Equations

Using particle-in-cell method:
VPIC code - Bower et al, 2008, 2009

1. Relativistic, full Maxwell treatment
2. Monte-Carlo Coulomb collisions
3. Optimized to exploit newest computers

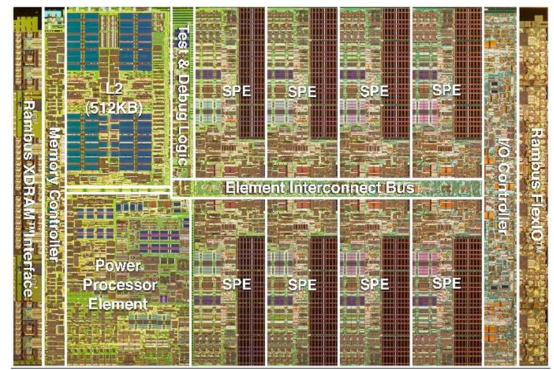


Difficult due to vast scale separation



Computational cost in 3D $\propto \left(\frac{m_i}{m_e}\right)^{5/2} \left(\frac{L}{d_i}\right)^4$

Peta-scale machines offers new opportunities, but also new challenges

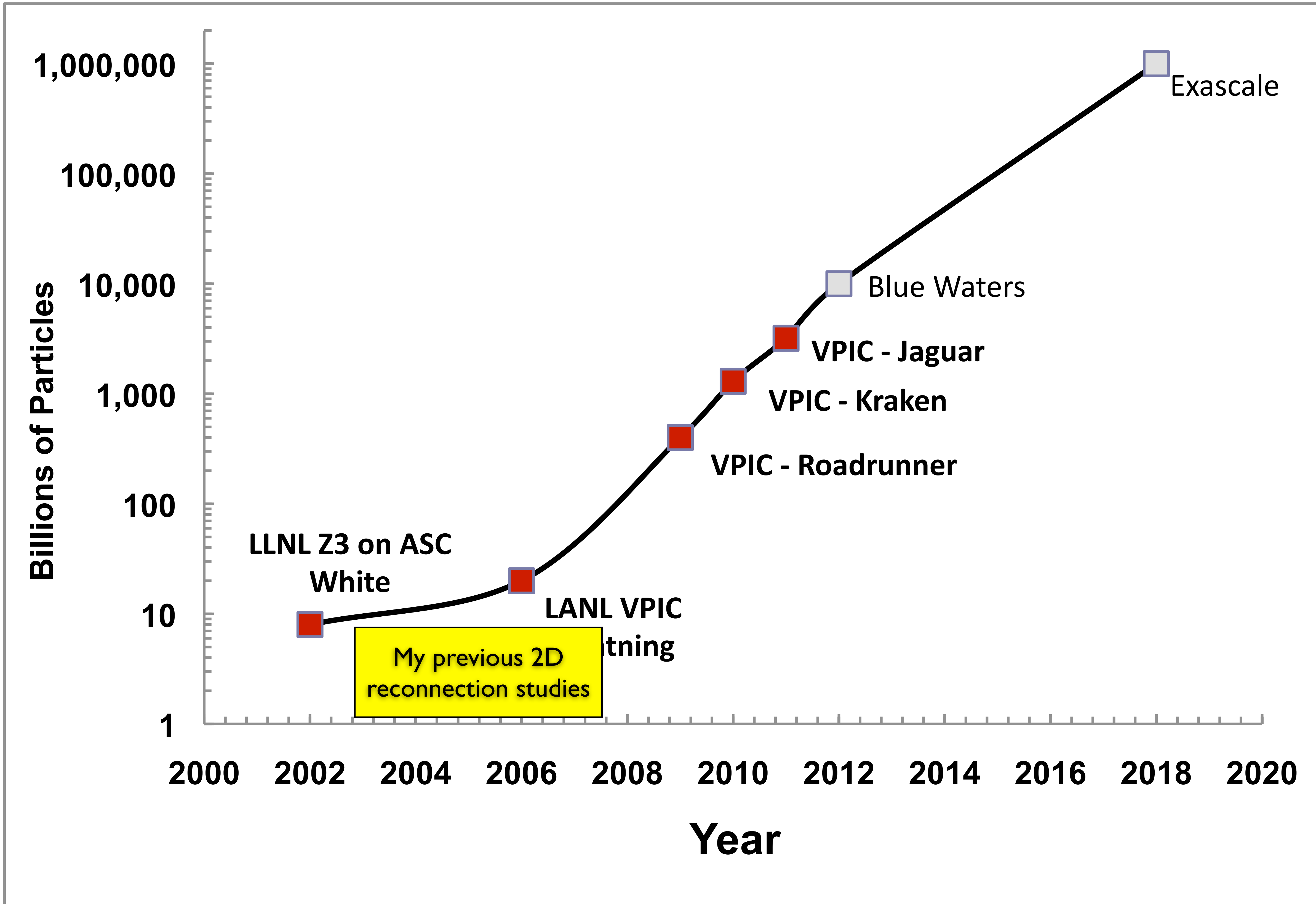


Roadrunner
Cell CBE Chip
~110,000 cores

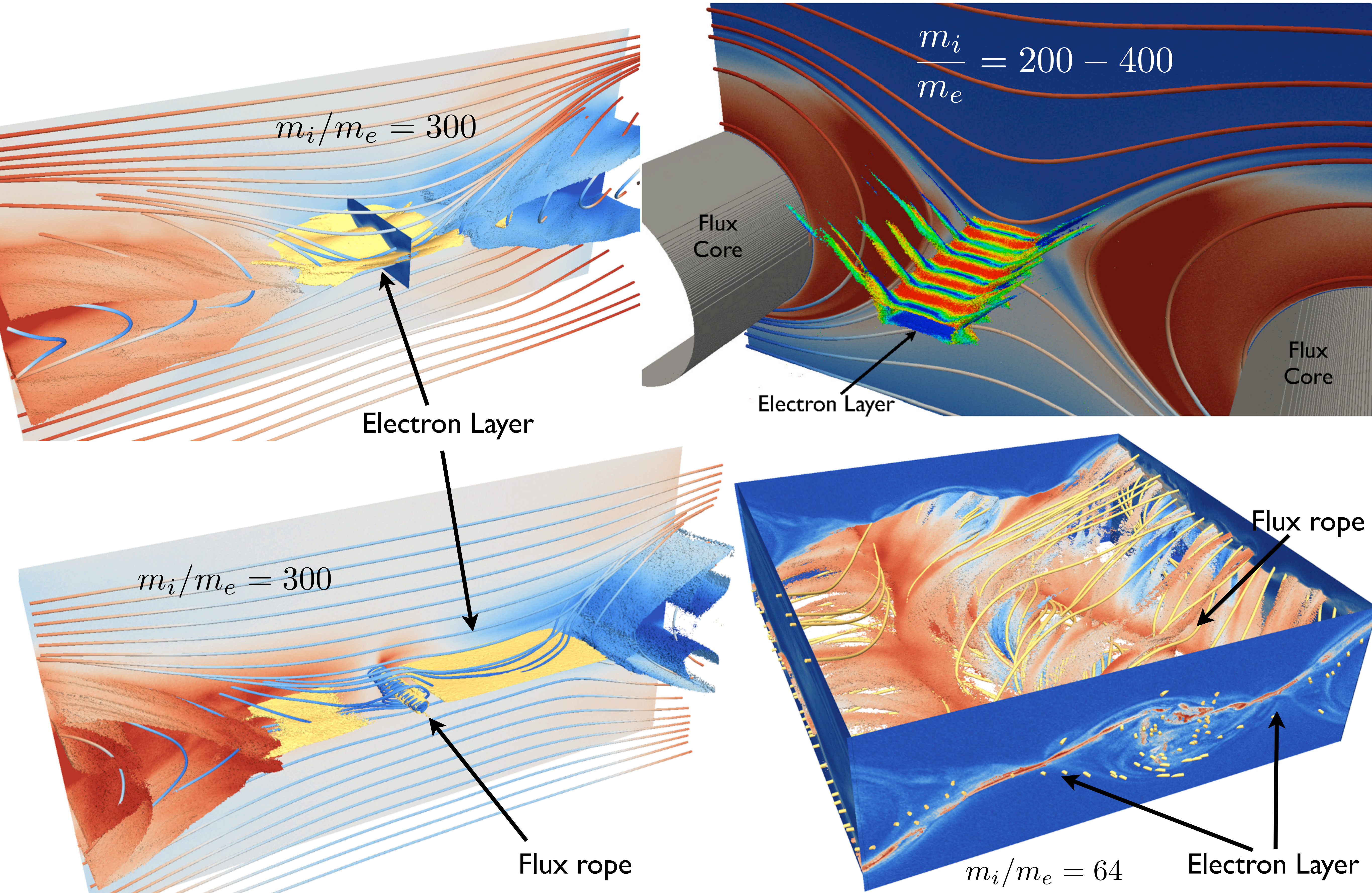
Kraken - NSF
Cray XT5
~100,000 cores

Jaguar - DOE
Cray XT5
~220,000 cores

These efforts are permitting an exponential increase in problem size



What 3D problems are we looking at?



Extended current sheets and secondary-islands are a common feature of large-scale 2D studies

$$\frac{m_i}{m_e} = 1 \rightarrow 1836$$

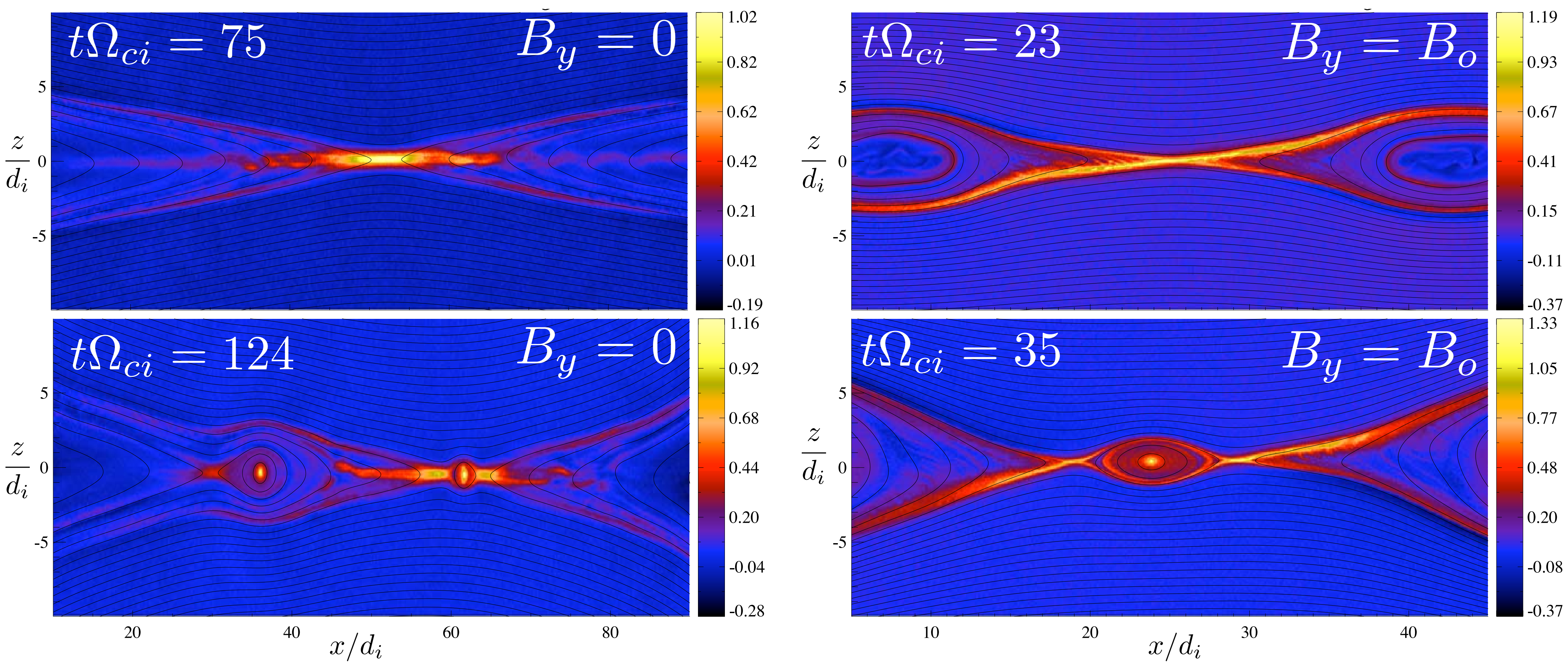
Strong and weak guide fields

Collisional $\Rightarrow$ Collisionless

Motivation for 3D Kinetic Treatment

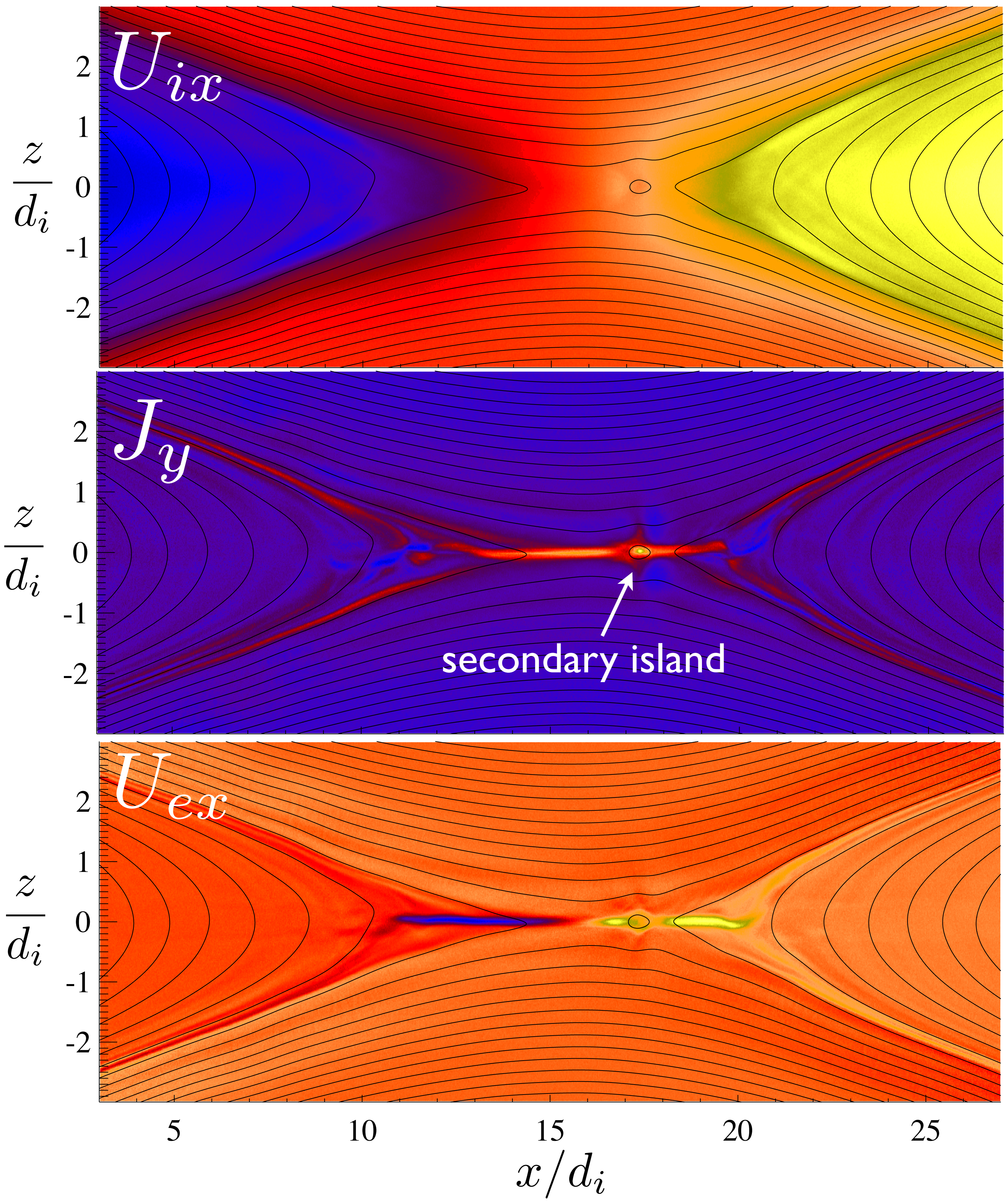
- Thin sheets are the preferred sites for the onset of reconnection

- Reconnection leads to the formation of new current sheets



- Secondary magnetic islands may play an important role in the reconnection rate, energy partition & particle acceleration

Results confirmed for hydrogen mass ratio



$$\frac{m_i}{m_e} = 1836$$

Recent VPIC run on Kraken

Open boundary conditions

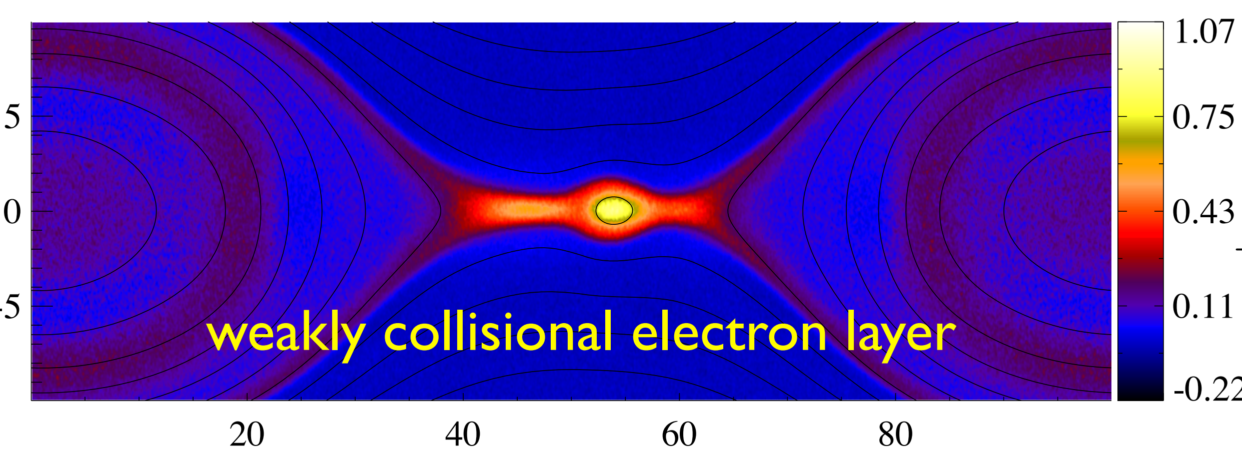
Fokker-Planck Treatment of Collisions

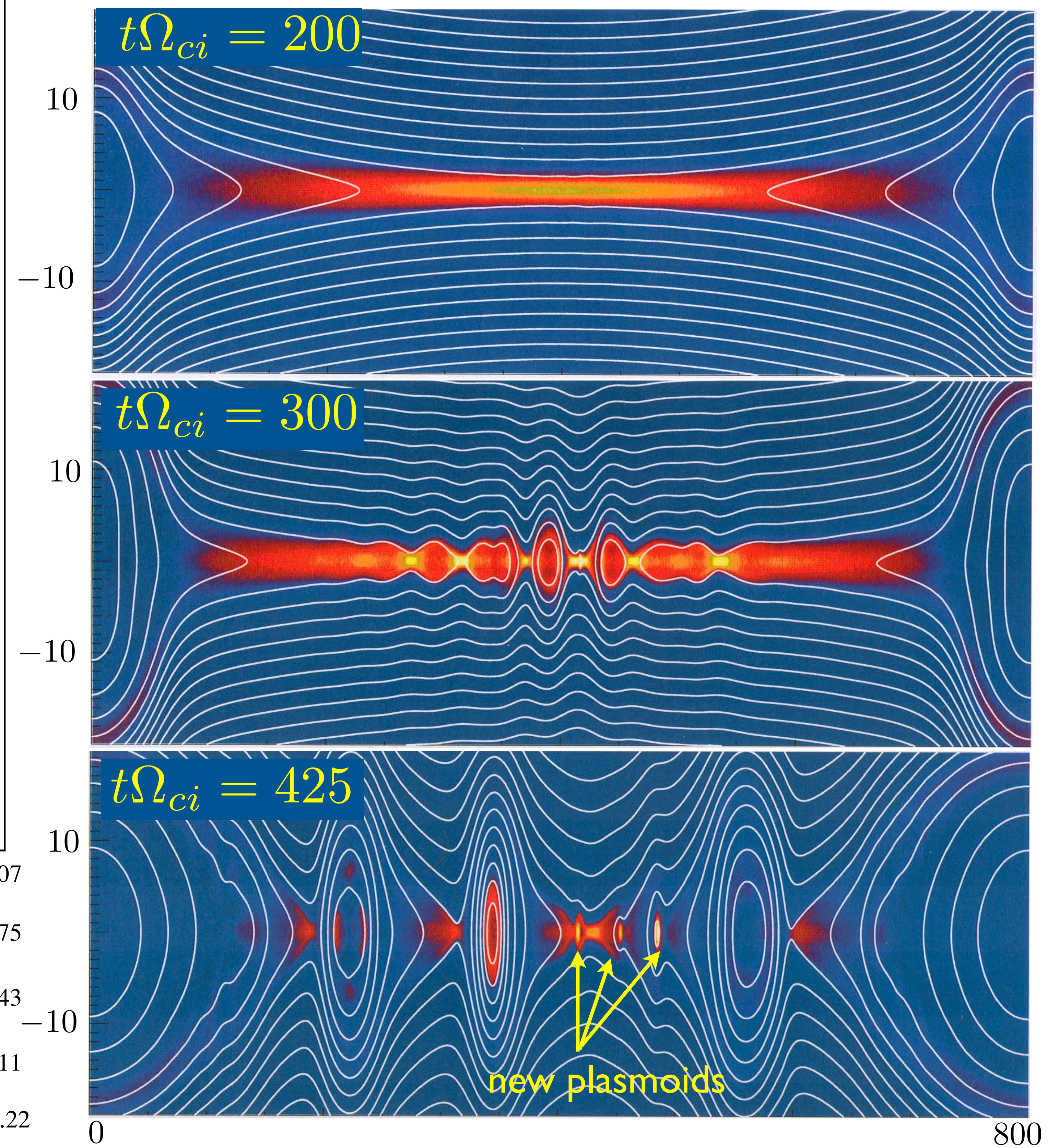
Daughton et al, PRL, 2009
Daughton et al, PoP, 2009

- Rigorous treatment of transition between fluid & kinetic regimes
- Benchmarks with Braginskii
- For S ~1000, transition from Sweet-Parker to kinetic observed

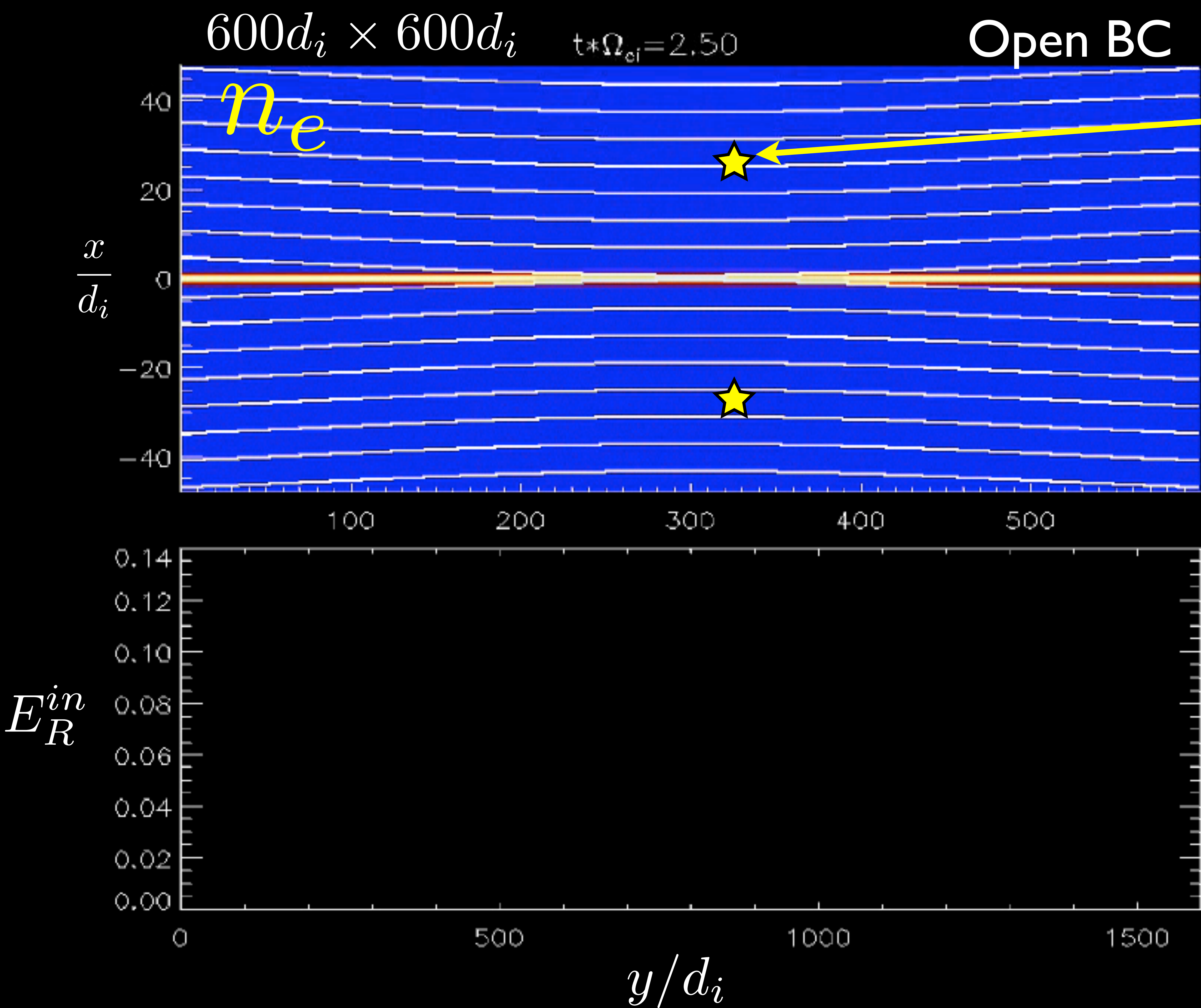
$\boxed{\delta_{sp} \approx d_i}$ → critical resistivity

- Simple estimate fails completely in large systems due to plasmoids
- New electron layers also unstable to plasmoids





Reconnection Rate Modulated with Plasmoid Formation



Open BC

Measure Reconnection Inflow

$\frac{m_i}{m_e} = 1$

Daughton & Karimabadi, PoP, 2007

How do these results extend to real 3D systems?

- Secondary magnetic islands → Flux ropes
- More freedom to form islands in 3D
- Can interact in complex ways not possible in 2D
- Stochastic magnetic fields?
- Influence of pre-existing turbulence upstream?
- Potential influence on nearly every aspect of the problem - basic cartoon, dissipation rate, etc
- Real need for theory - primary & secondary islands

Focus in detail on one problem:

Island Formation
in Guide Field Reconnection

Theory

$$\frac{m_i}{m_e} = 1 \rightarrow 1836$$

Simulations

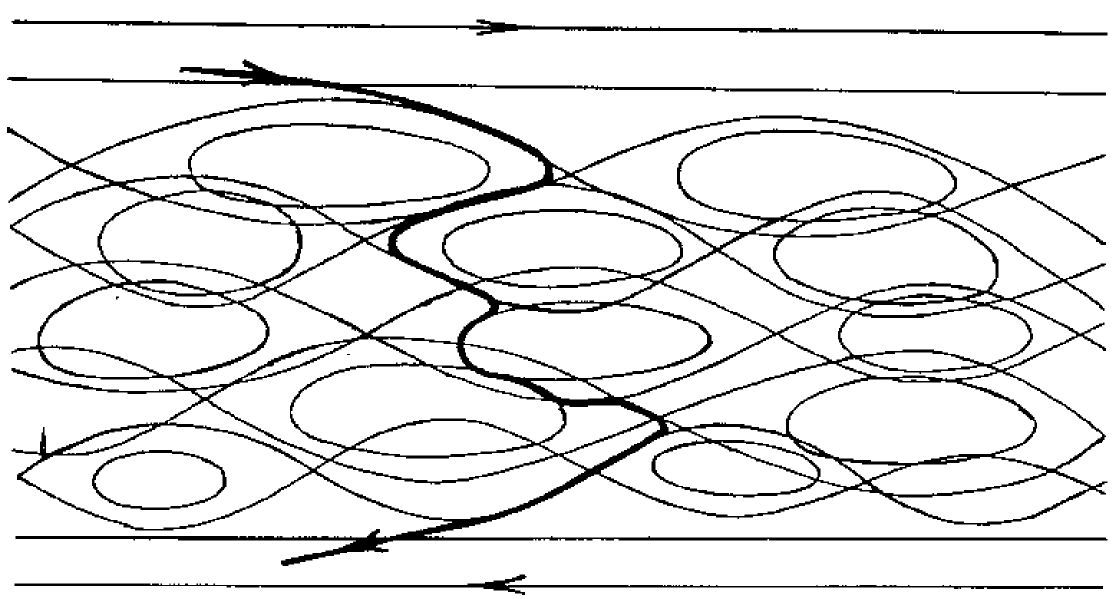
$$\frac{m_i}{m_e} = 1 \rightarrow 64$$

Island formation is more complicated in 3D

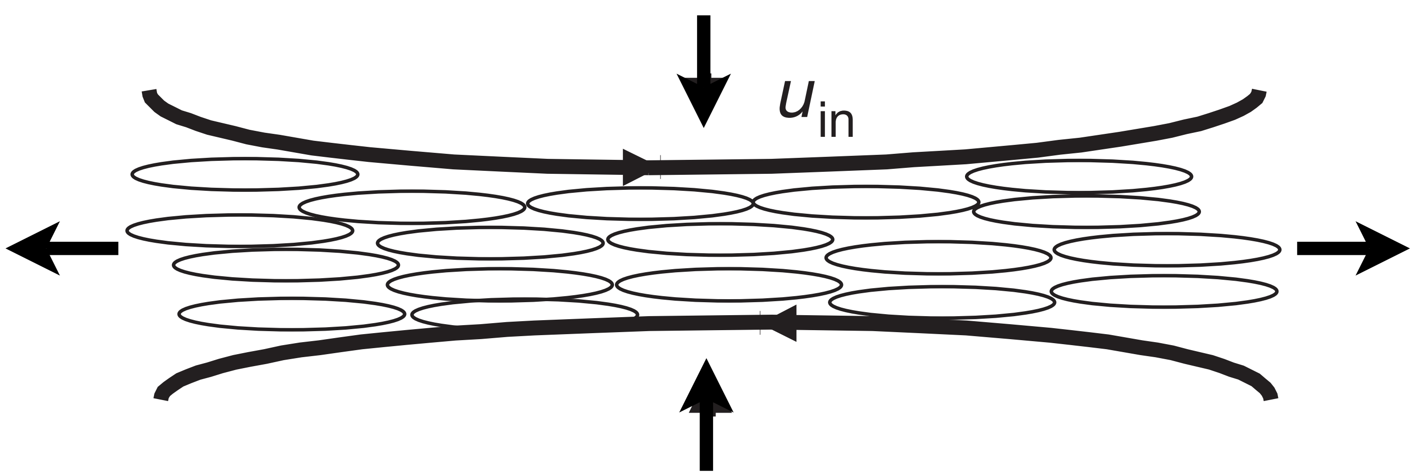
Drift Tearing - Coppi et al, 1979, Basu & Coppi, 1981, Catto 1974, Bussac et al, 1978, Drake et al, 1983

Magnetopause - Galeev, Kuznetsova, Zeleny, 1986, Gladd, 1990, Daughton et al, 2005

Volume filling islands - Drake et al, Nature, 2006



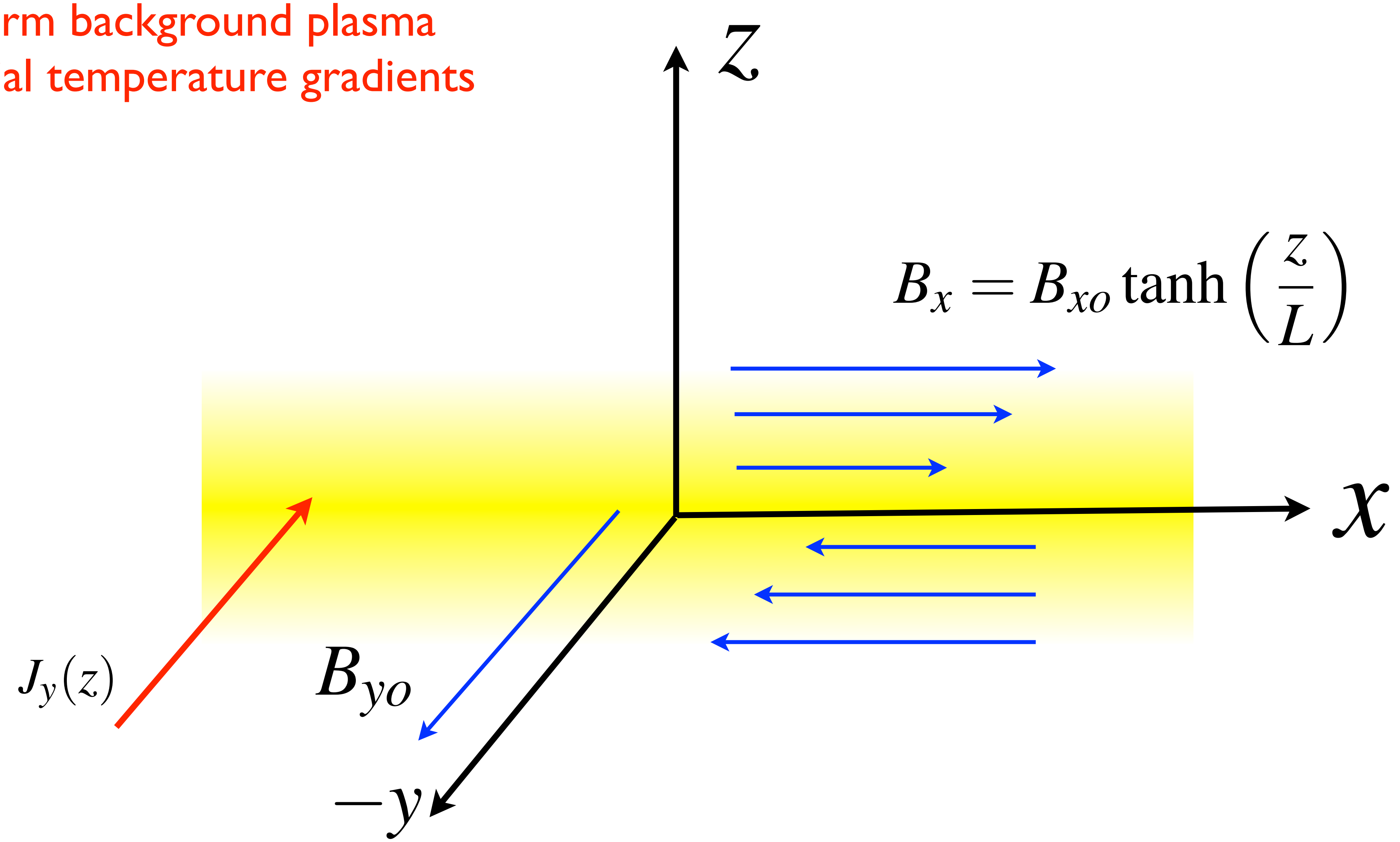
Galeev et al, 1986



Drake et al, 2006

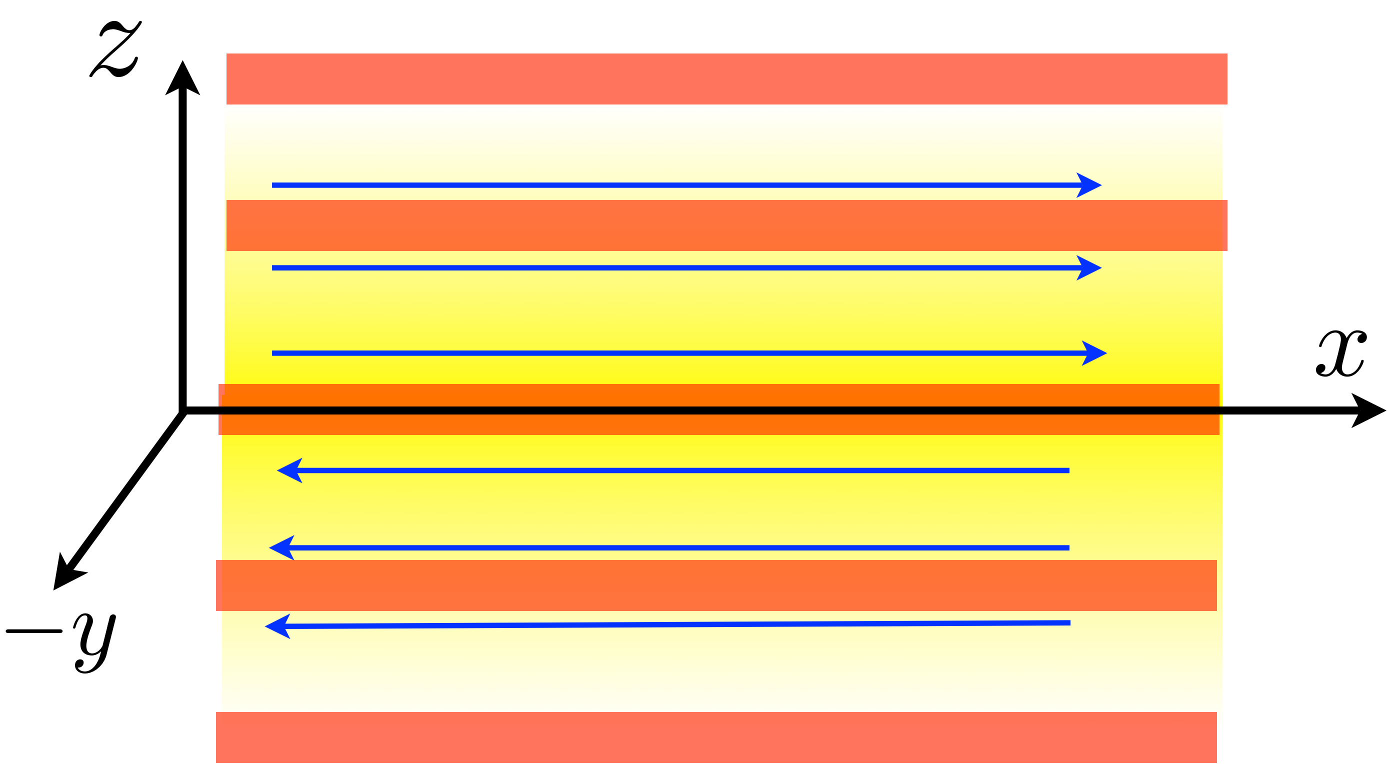
Harris Sheet Geometry with a Guide Field

Uniform background plasma
No initial temperature gradients



Consider: 1. Electron-positron plasma
2. Hydrogen plasma

Tearing Modes are Localized about Resonant Surfaces



Outer Region $E_{\|} = 0$

Singular Layer $E_{\|} \neq 0$

Outer Region $E_{\|} = 0$

General Perturbation

$$\hat{\mathbf{E}} = -\nabla\phi - \frac{1}{c}\frac{\partial \hat{\mathbf{A}}}{\partial t}$$

$$\hat{\mathbf{A}} = \tilde{\mathbf{A}}(z) \exp\left[-i\omega t + ik_x x + ik_y y\right]$$

$$\hat{\phi} = \tilde{\phi}(z) \exp\left[-i\omega t + ik_x x + ik_y y\right]$$

Electrostatic part "shorts out" response - except when

$$\mathbf{k} \cdot \mathbf{B} = 0$$

$$\hat{E}_{\|} = \mathbf{b} \cdot \hat{\mathbf{E}} = -i\cancel{k_{\|}}\hat{\phi} + i\frac{\omega}{c}\mathbf{b} \cdot \hat{\mathbf{A}}$$

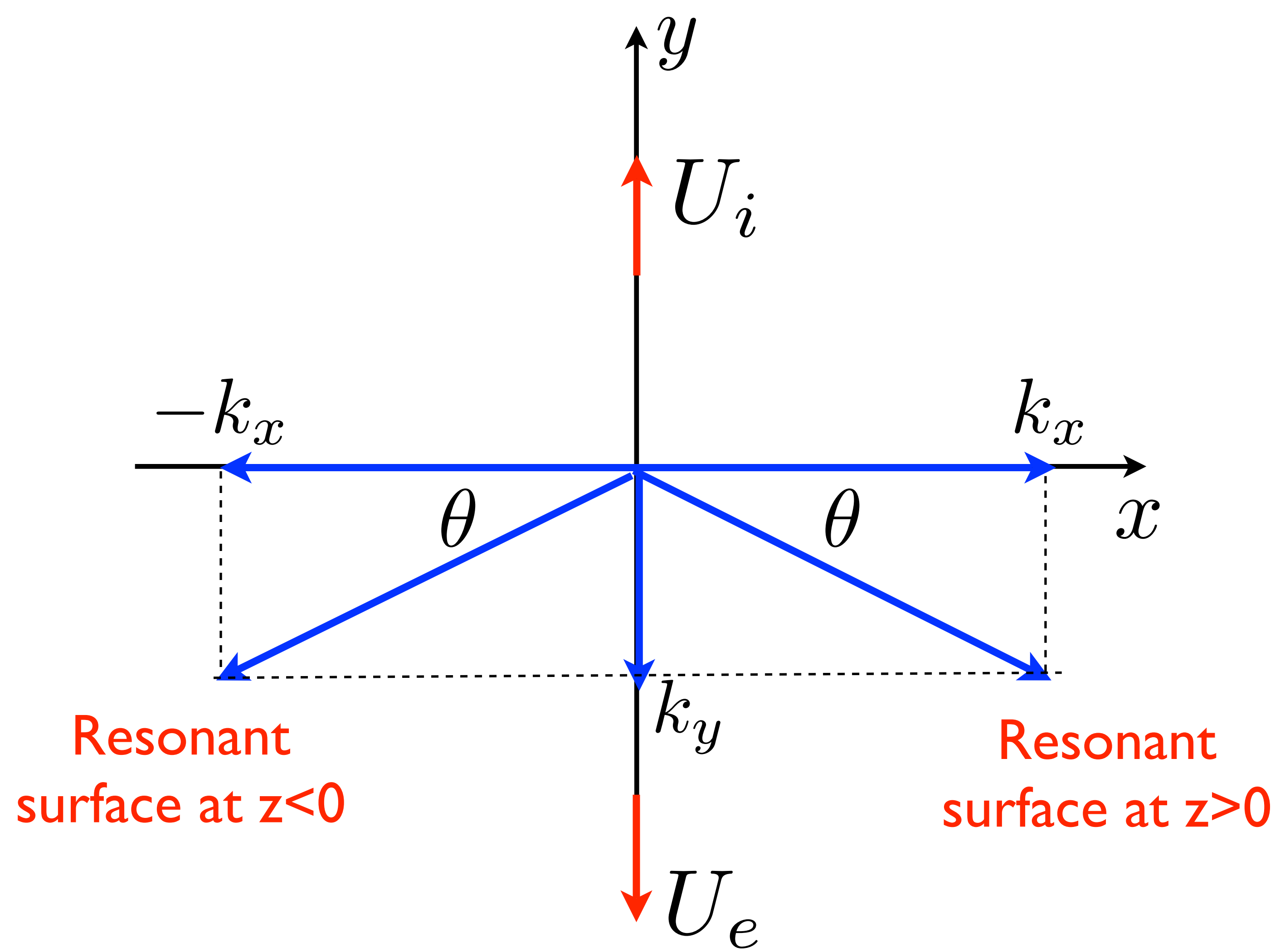
0

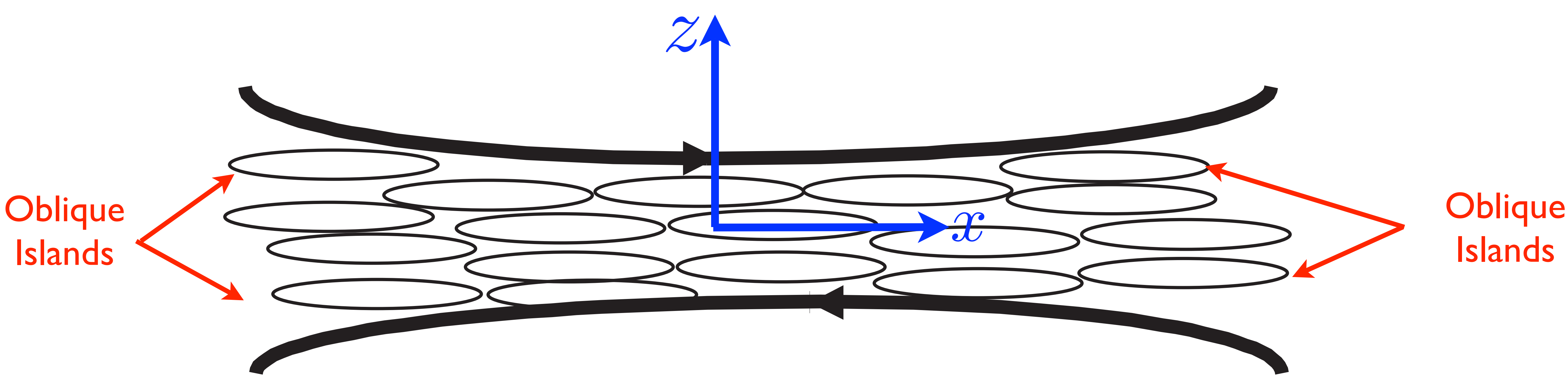
Resonant surface

Resonant Surfaces for Harris Sheet Geometry

$$\mathbf{k}\cdot\mathbf{B} = 0$$

$$\boxed{\frac{z_s}{L} = -\tanh^{-1}\left(\frac{k_y B_{yo}}{k_x B_{xo}}\right) \approx -\frac{k_y B_{yo}}{k_x B_{xo}}}$$





Kinetic Theory is Tricky in Thin Layers $\longrightarrow L \leq \rho_i$

Use formally exact technique $\longrightarrow$ Daughton, PoP, 2003

Method of Characteristics $\longrightarrow$

$$\tilde{f}_s = -\frac{q_s f_{os}}{T_s}\left[\tilde{\phi} - \frac{U_s}{c}\tilde{A}_y + i\left(\omega - k_y U_s\right)\tilde{S}\right]$$

Orbit Integral

$$\tilde{\rho} = \sum_s q_s \int \tilde{f}_s \, d\mathbf{v}$$

$$\tilde{\mathbf{J}} = \sum_s q_s \int \mathbf{v}\tilde{f}_s \, d\mathbf{v}$$

$$\frac{d^2\tilde{\phi}}{dz^2} - \left(k_x^2 + k_y^2 - \frac{\omega^2}{c^2}\right)\tilde{\phi} = -4\pi\,\tilde{\rho}$$

$$\frac{d^2\tilde{\mathbf{A}}}{dz^2} - \left(k_x^2 + k_y^2 - \frac{\omega^2}{c^2}\right)\tilde{\mathbf{A}} = -\frac{4\pi}{c}\tilde{\mathbf{J}}$$

Numerically solve integro-differential eigenvalue problem

We also developed new asymptotic theory

Serious issues with previous theories

1. Incorrect outer layer equation
2. Which means Δ' is not right
3. Oblique modes sensitive to matching

Tendency to drives modes oblique

$$\Delta' \approx \frac{2}{L}\left(\frac{1}{kL} - kL\right)\left[1 + \frac{\tanh^2(z_s/L)}{2}\left(1 + \frac{1}{1-kL}\right)\right]$$

$$\frac{\gamma}{\Omega_{ci}} = \frac{1}{\sqrt{\pi}\mathcal{F}}\left(\frac{\rho_i}{L}\right)^3\left(\frac{m_e T_e}{m_i T_i}\right)^{1/2}\left(1 + \frac{T_e}{T_i}\right)\left[1 - (kL)^2\right]\frac{B_{xo}}{B_{yo}}\,\mathcal{G}$$

$$\mathcal{G} = \left[1 - \sin^2(\theta)\left(1 - \left(\frac{B_{yo}}{B_{xo}}\right)^2 \frac{1 - kL/2}{1 - kL}\right)\right]\frac{1}{1 + \hat{n}_b \cosh^2(z_s/L)}$$

Conditions to Drive Oblique Modes

Range of allowable angles is limited $\longrightarrow$ $\theta < \tan^{-1}(B_{xo}/B_{yo})$

Fastest growing modes are oblique when

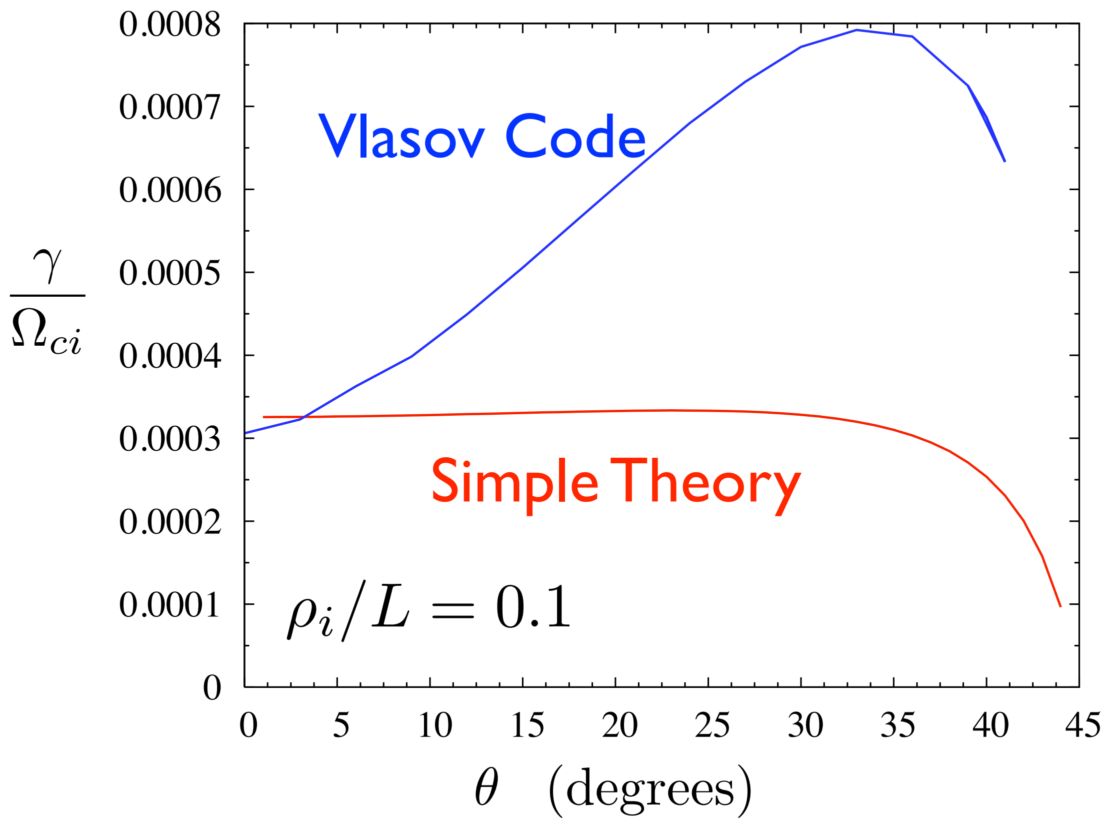
$$\boxed{\frac{B_{yo}}{B_{xo}} > \left(\frac{1-kL}{1-kL/2}\right)^{1/2}}$$

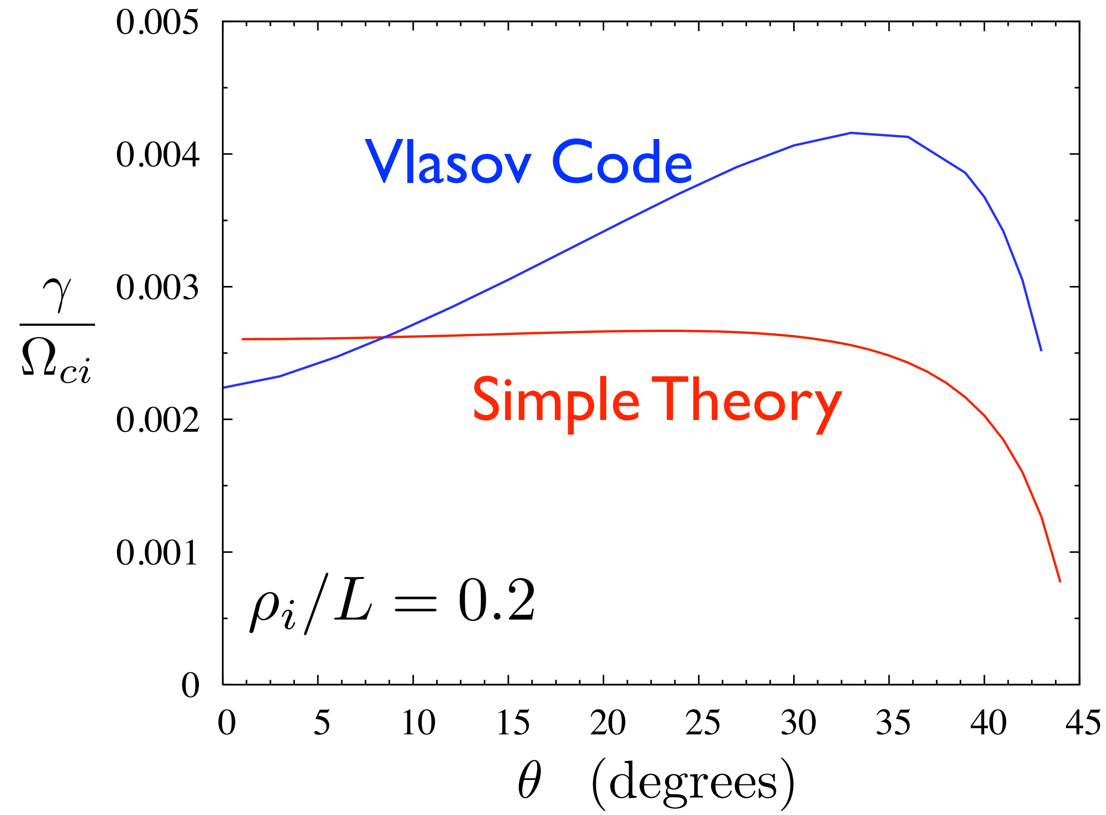
For long wavelength $kL \ll 1$ this is simply $B_{yo} > B_{xo}$

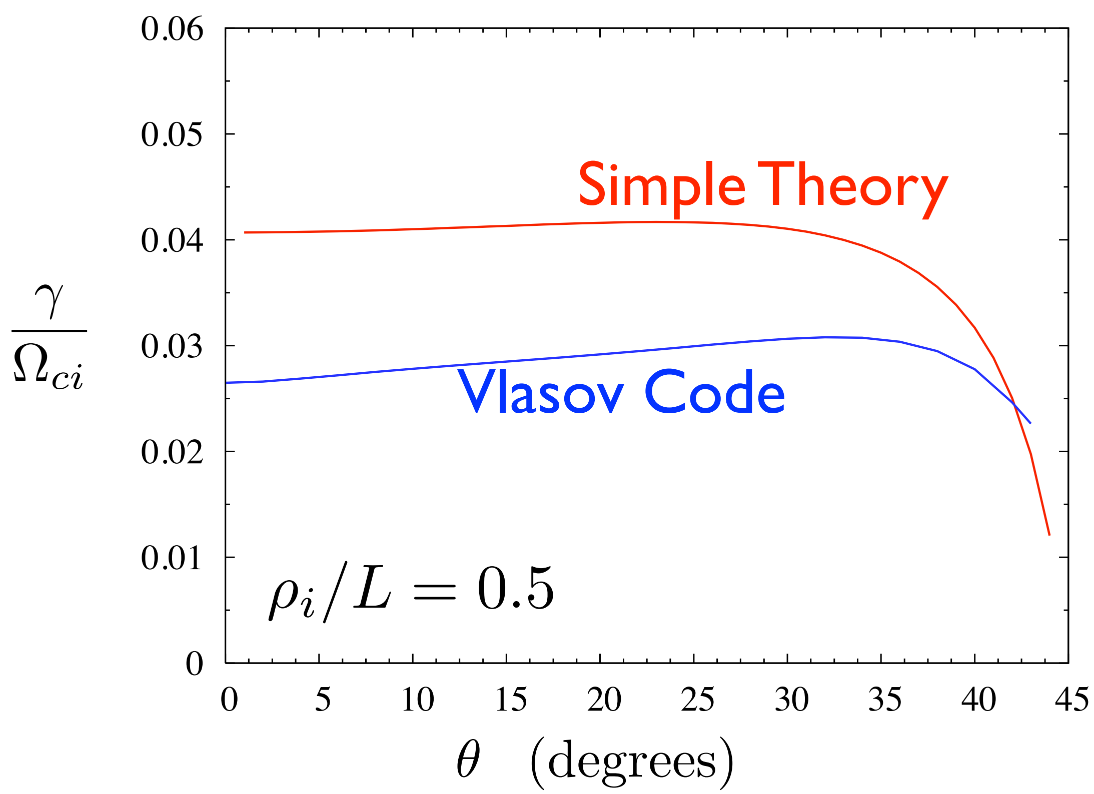
How well does asymptotic theory compare with exact linear Vlasov approach ?

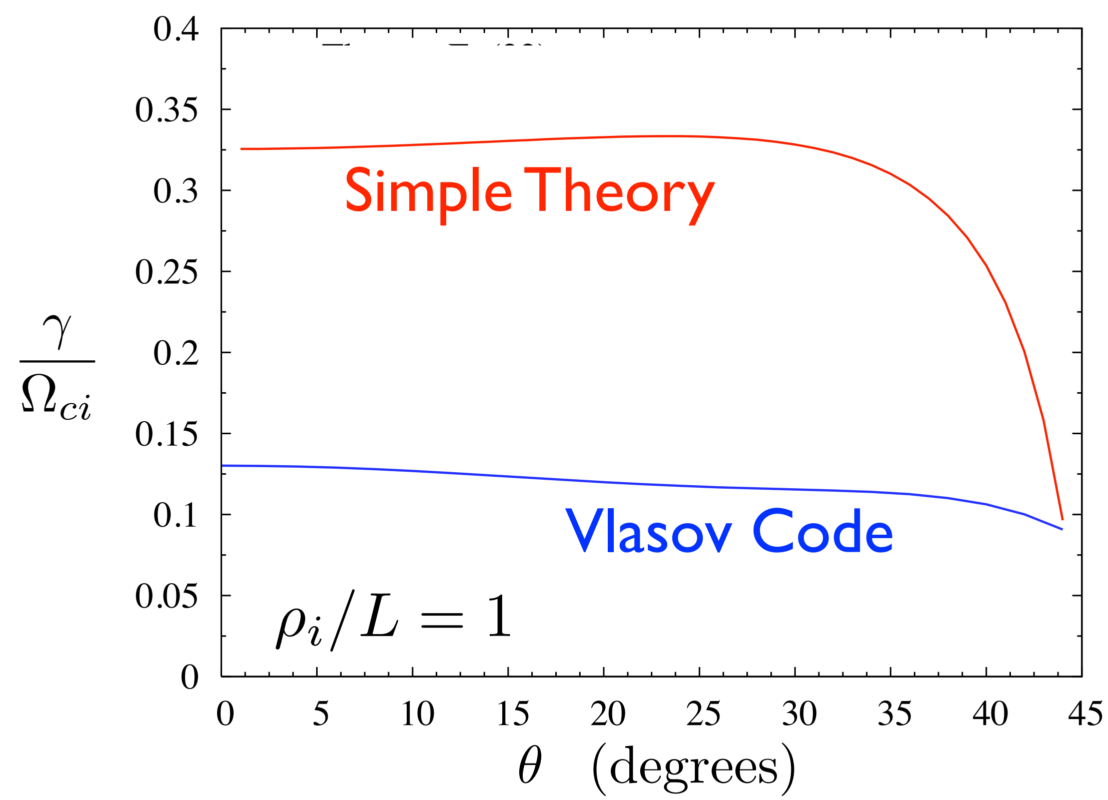
Example comparisons for pair limit

$$m_i = m_e$$
$$B_{yo} = B_{xo}$$
$$n_b/n_o = 0.3$$

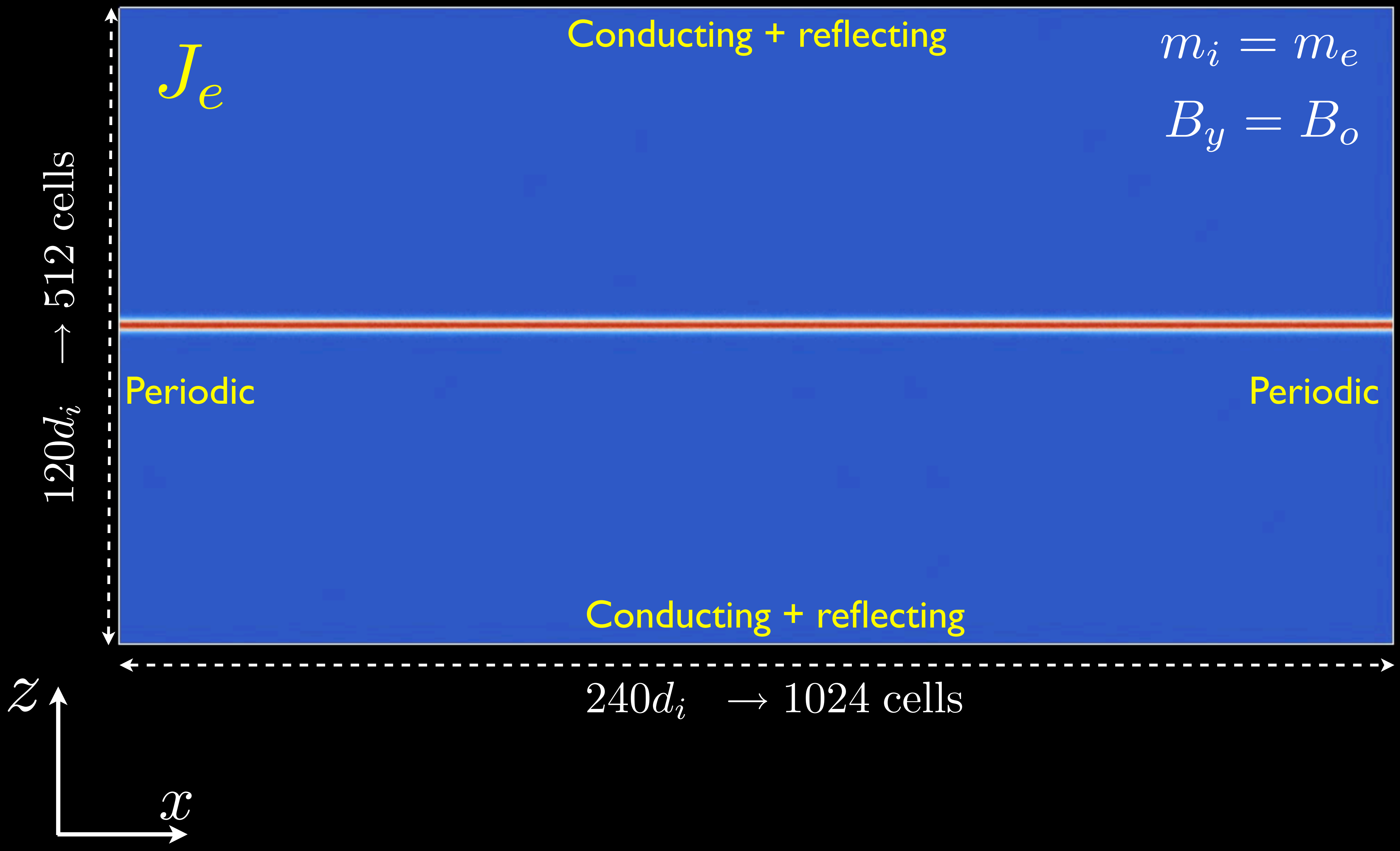


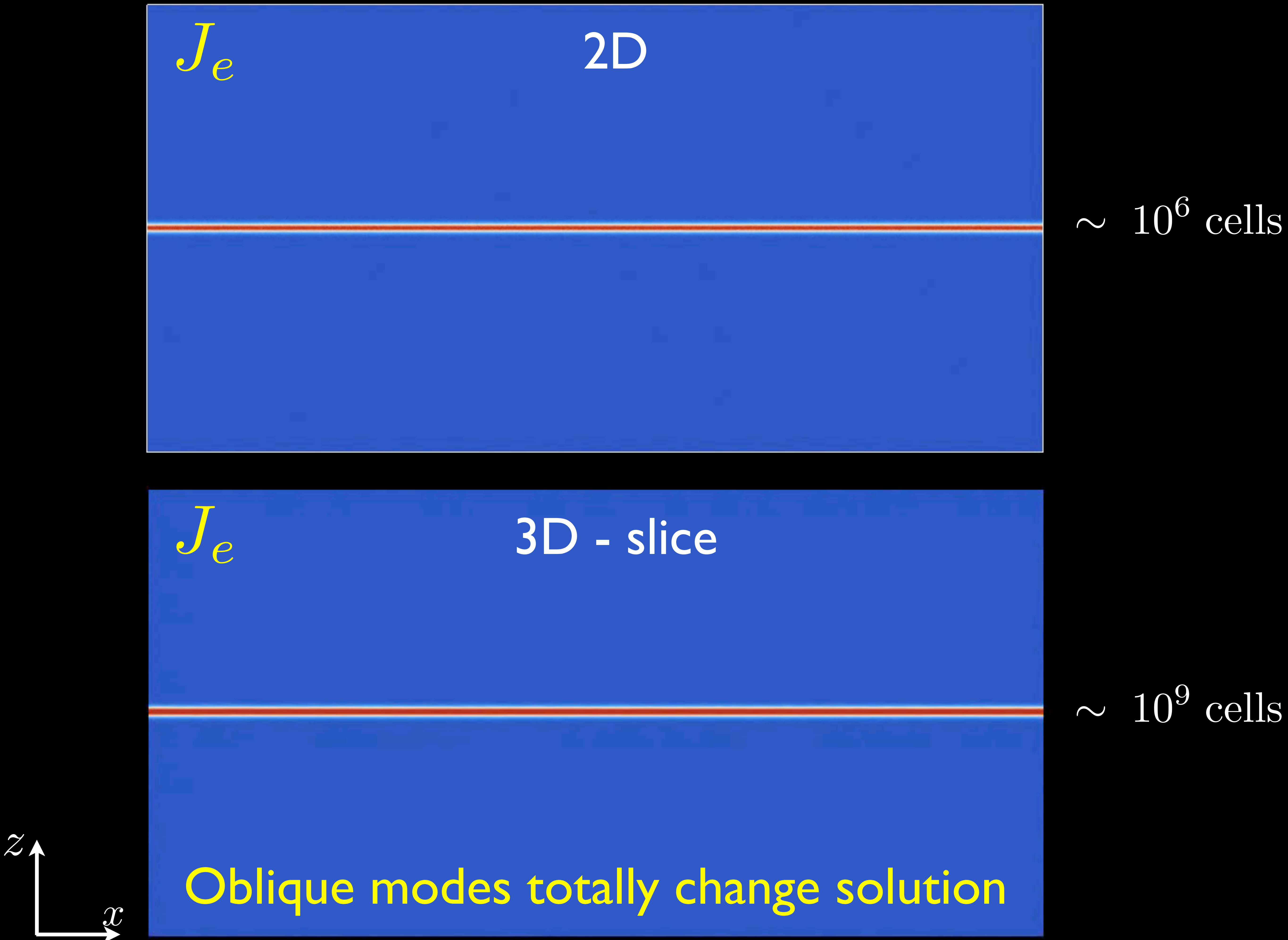






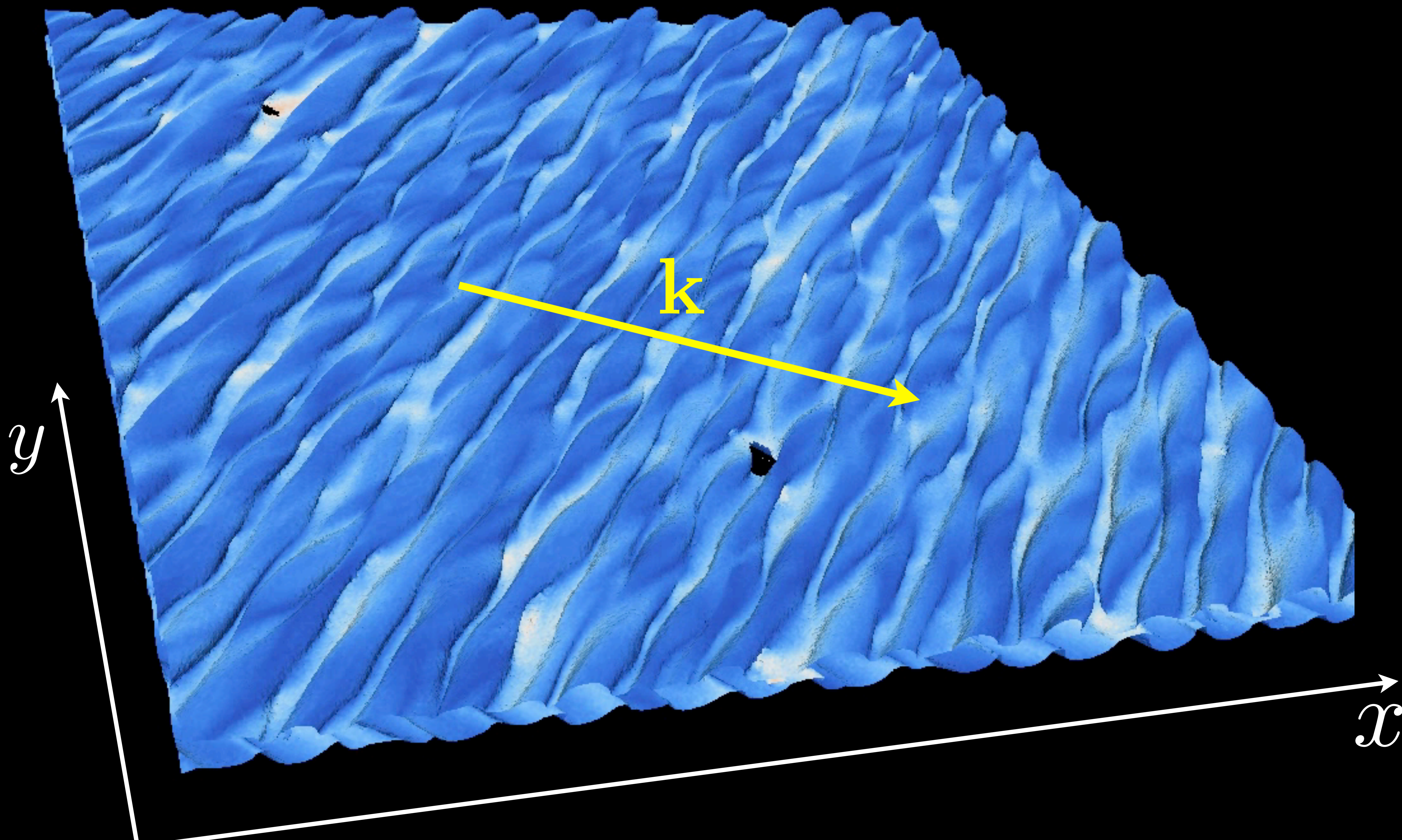
2D Simulations Only Permit Resonant Surface at z=0





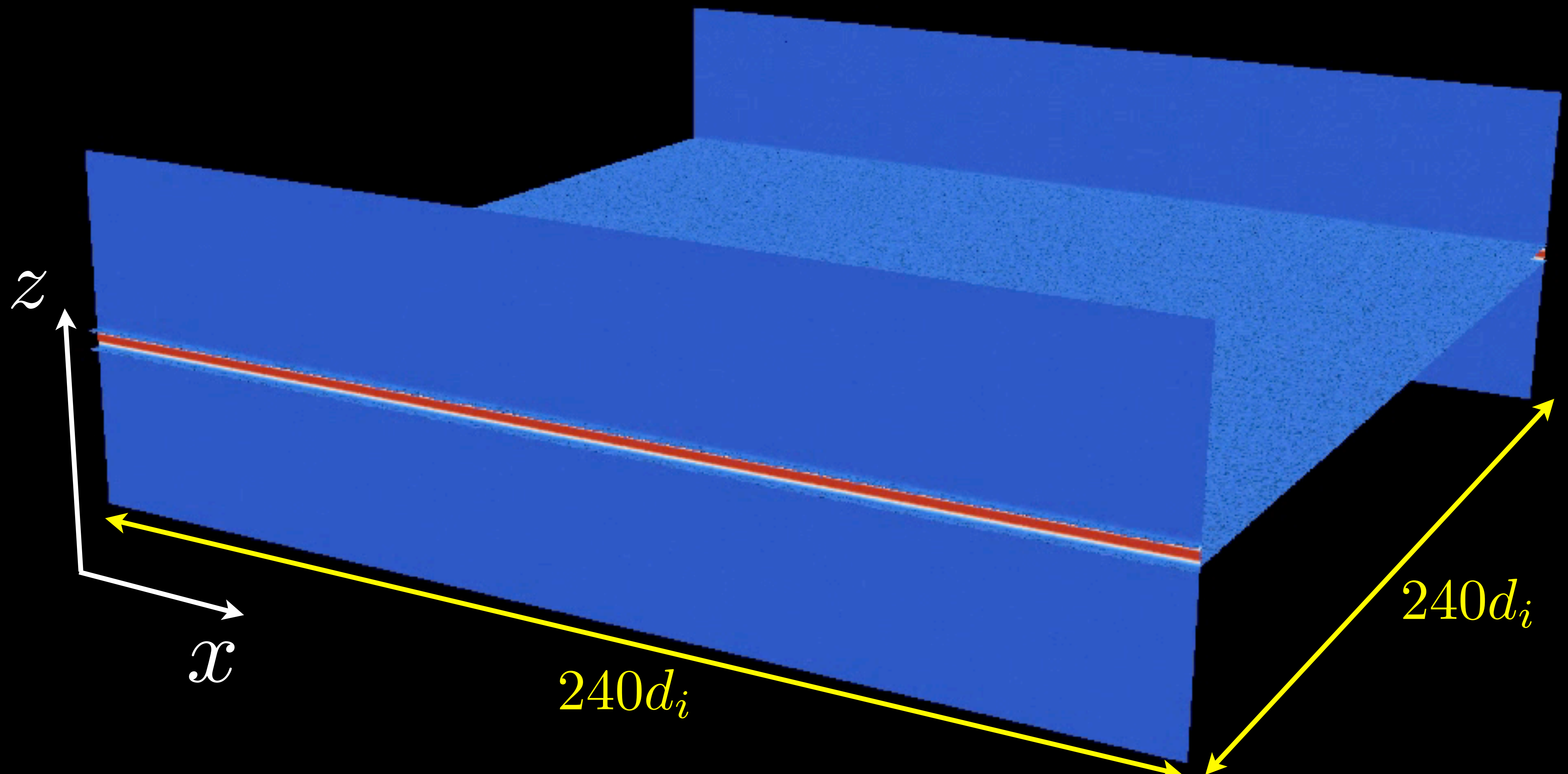
J_e
2D
$\sim\ 10^6$ cells
J_e
3D - slice
$\sim\ 10^9$ cells
Oblique modes totally change solution
z
x

Somewhat later $\longrightarrow$ $t\Omega_{ci} = 150$



Oblique modes begin to dominate at later times

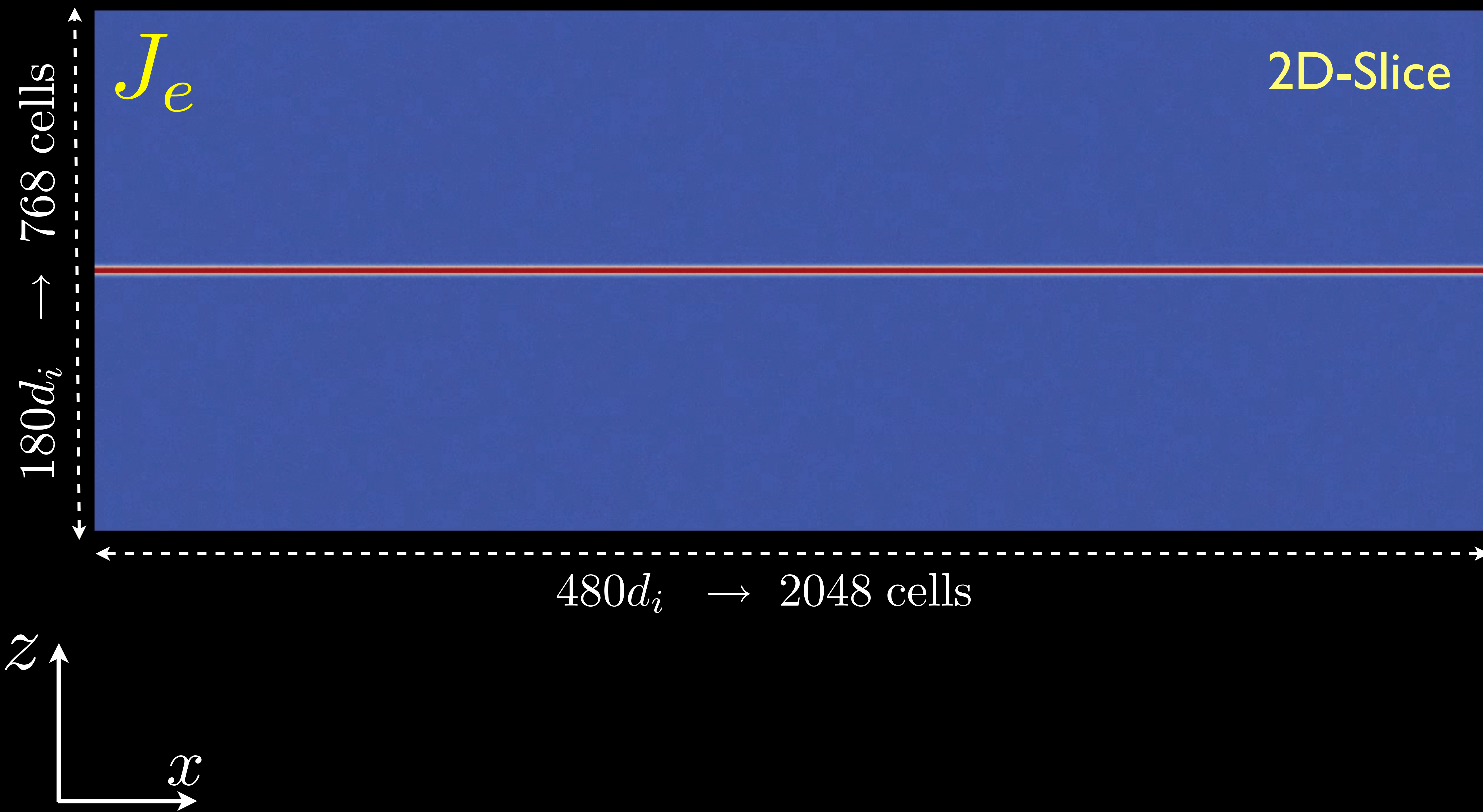
3D Evolution on Roadrunner



0.5 billion cells ~200 billion particles

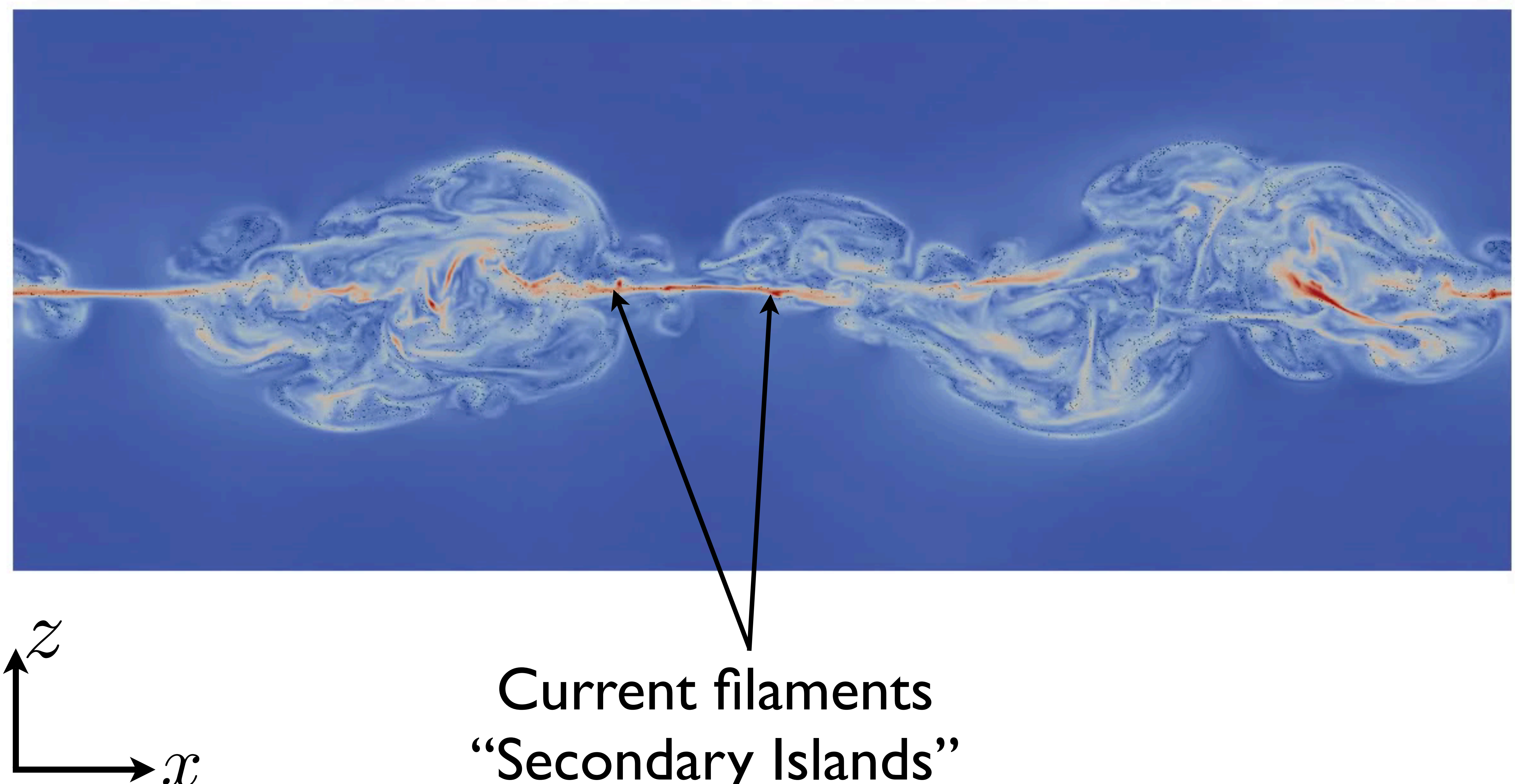
New Run on Kraken - Scaling Study

$\sim 3.3 \times 10^9$cells $\quad \sim 1.3 \times 10^{12}$ particles

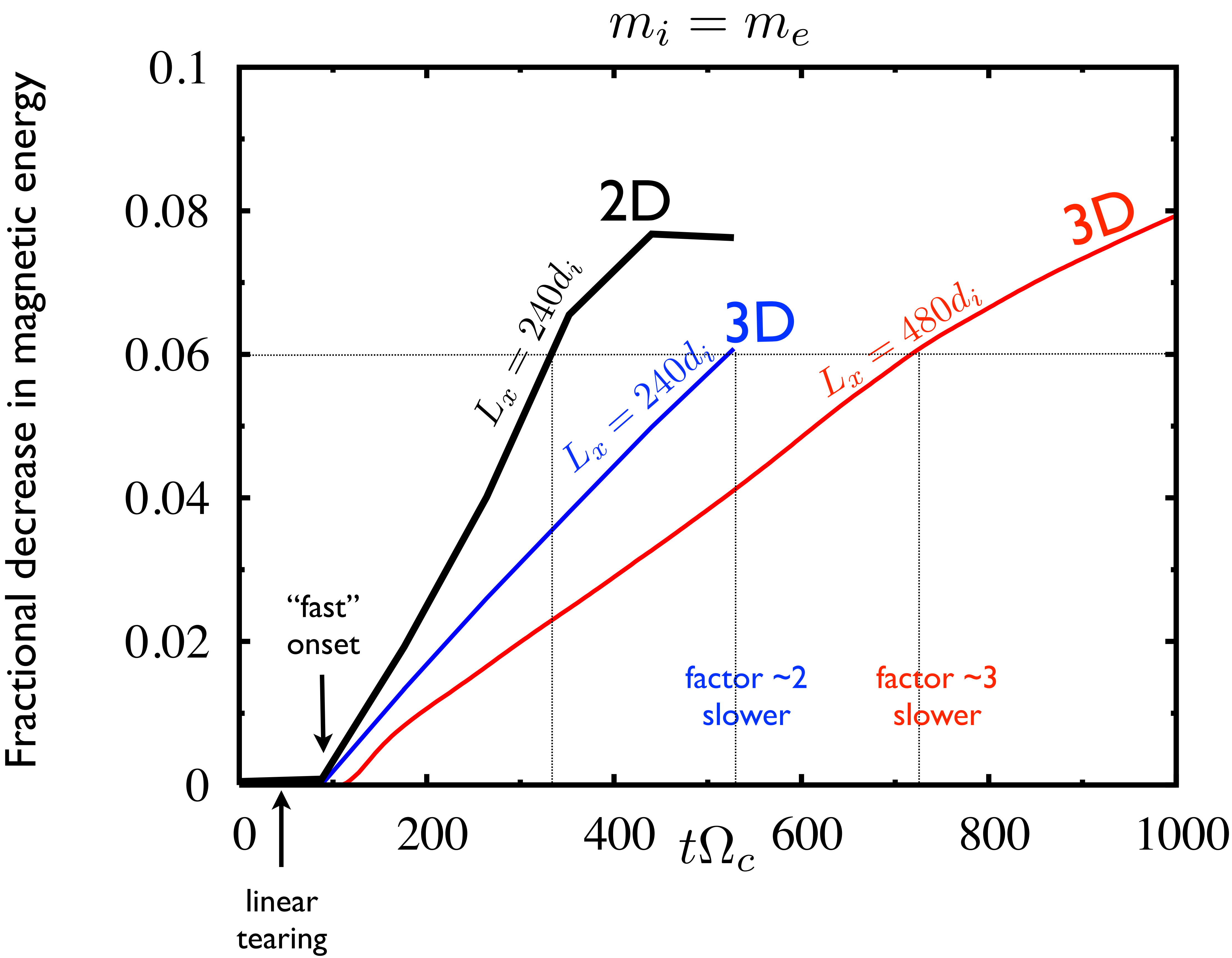


3D Structure from Kraken Run

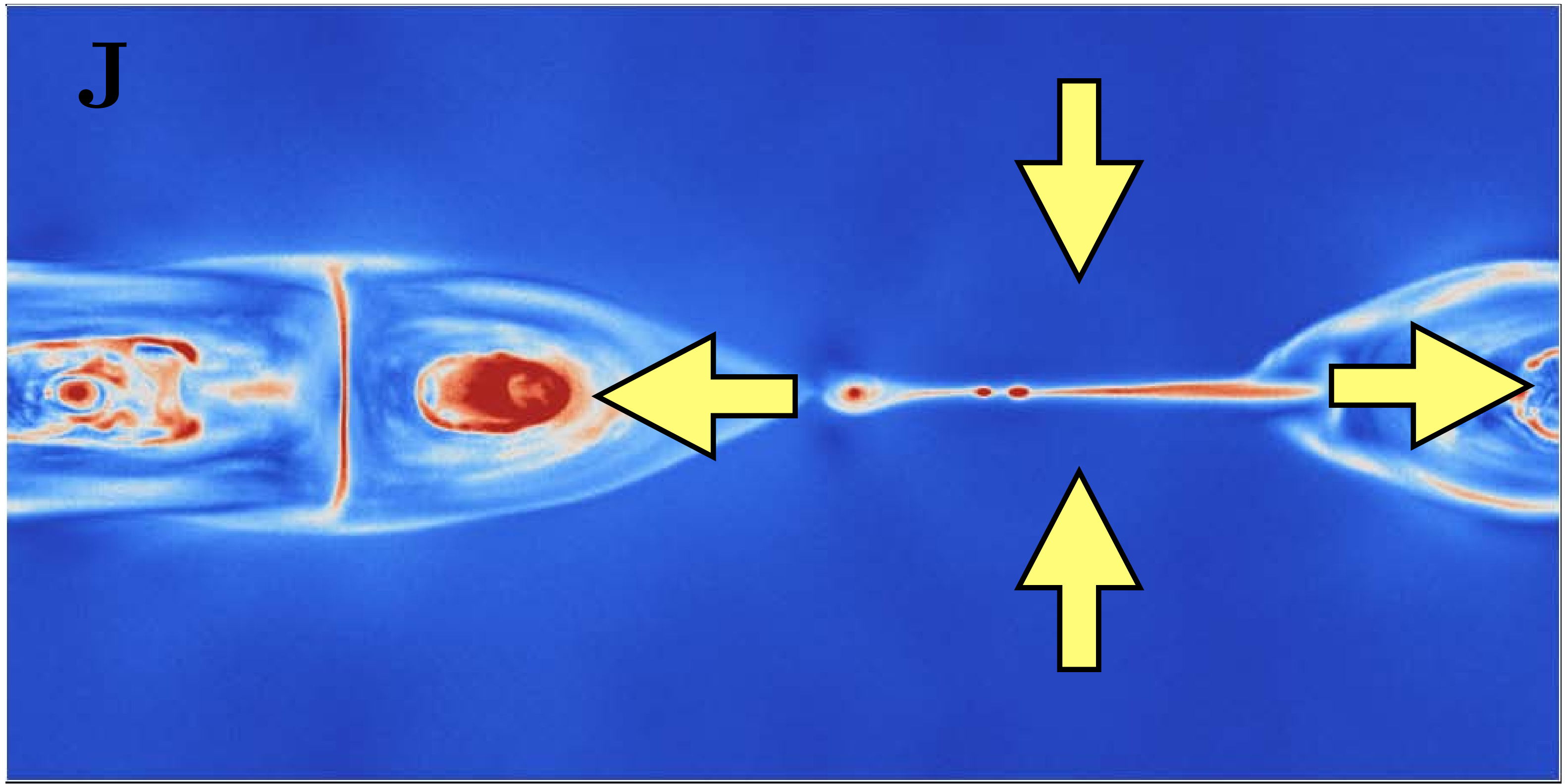
$$\sim 3.3 \times 10^9 \text{cells} \qquad \sim 1.3 \times 10^{12} \quad \text{particles}$$



3D Complexity slows energy dissipation!

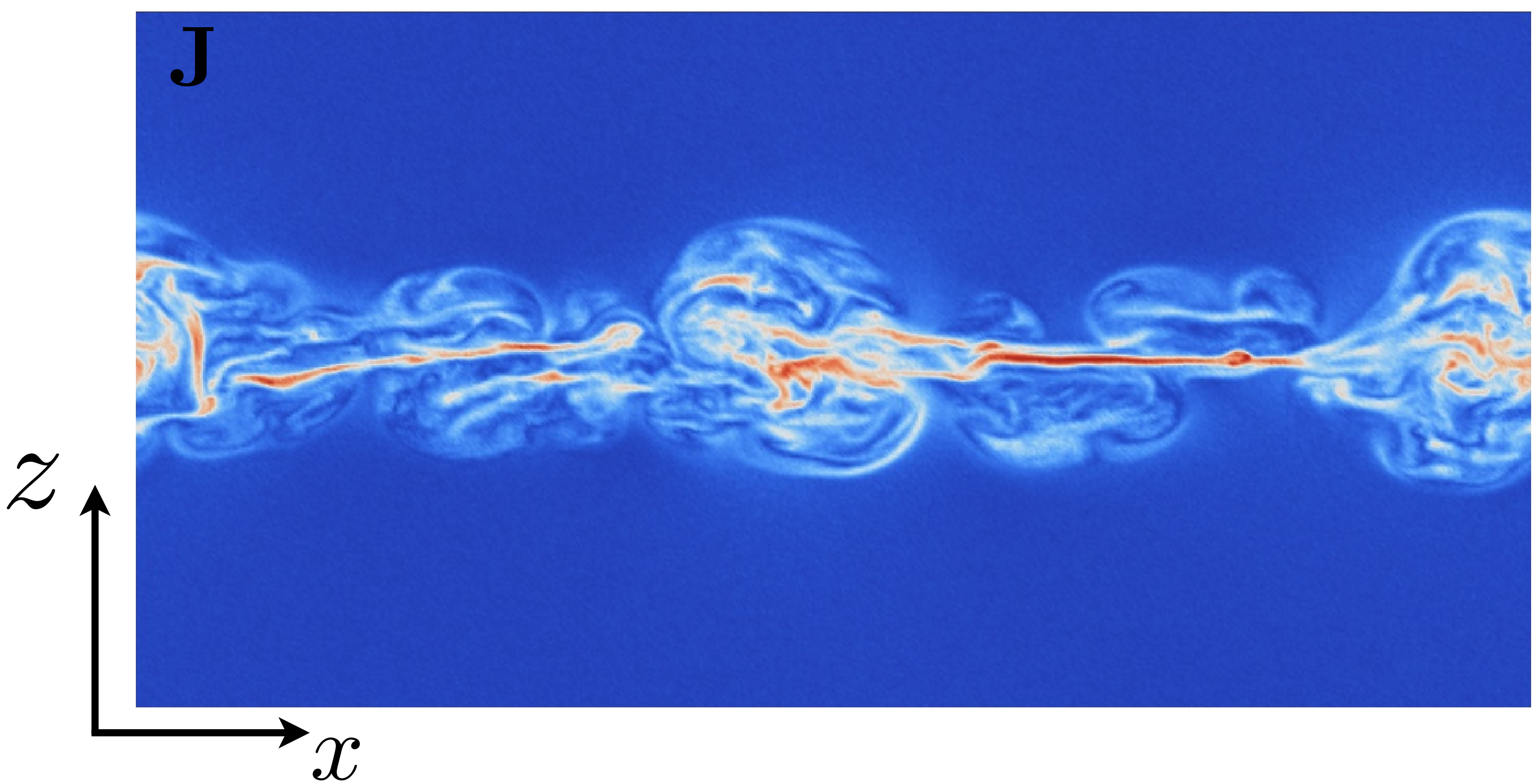


Coherent flow pattern from 2D is disrupted



2D

$\sim 10^6$ cells



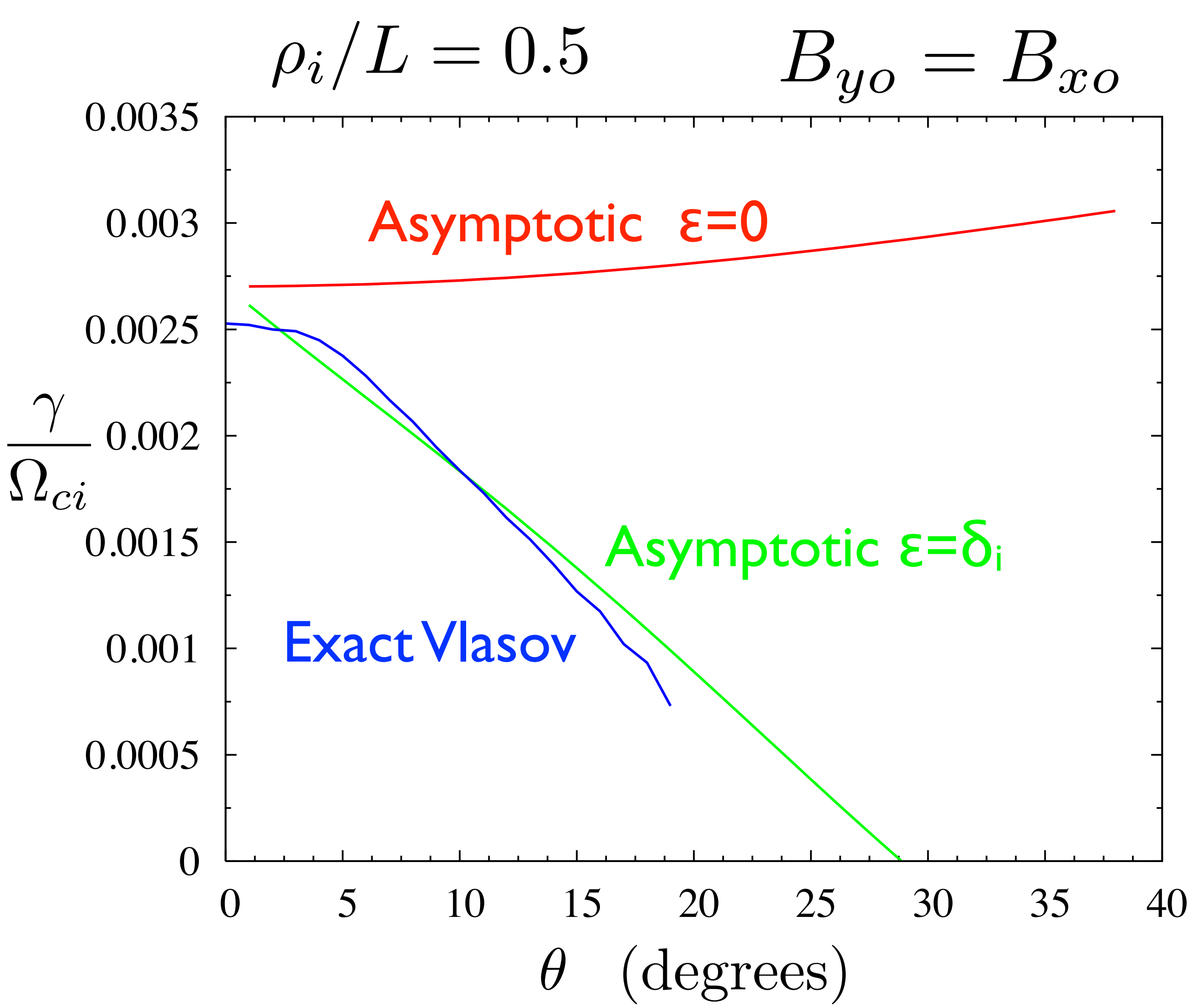
3D cut

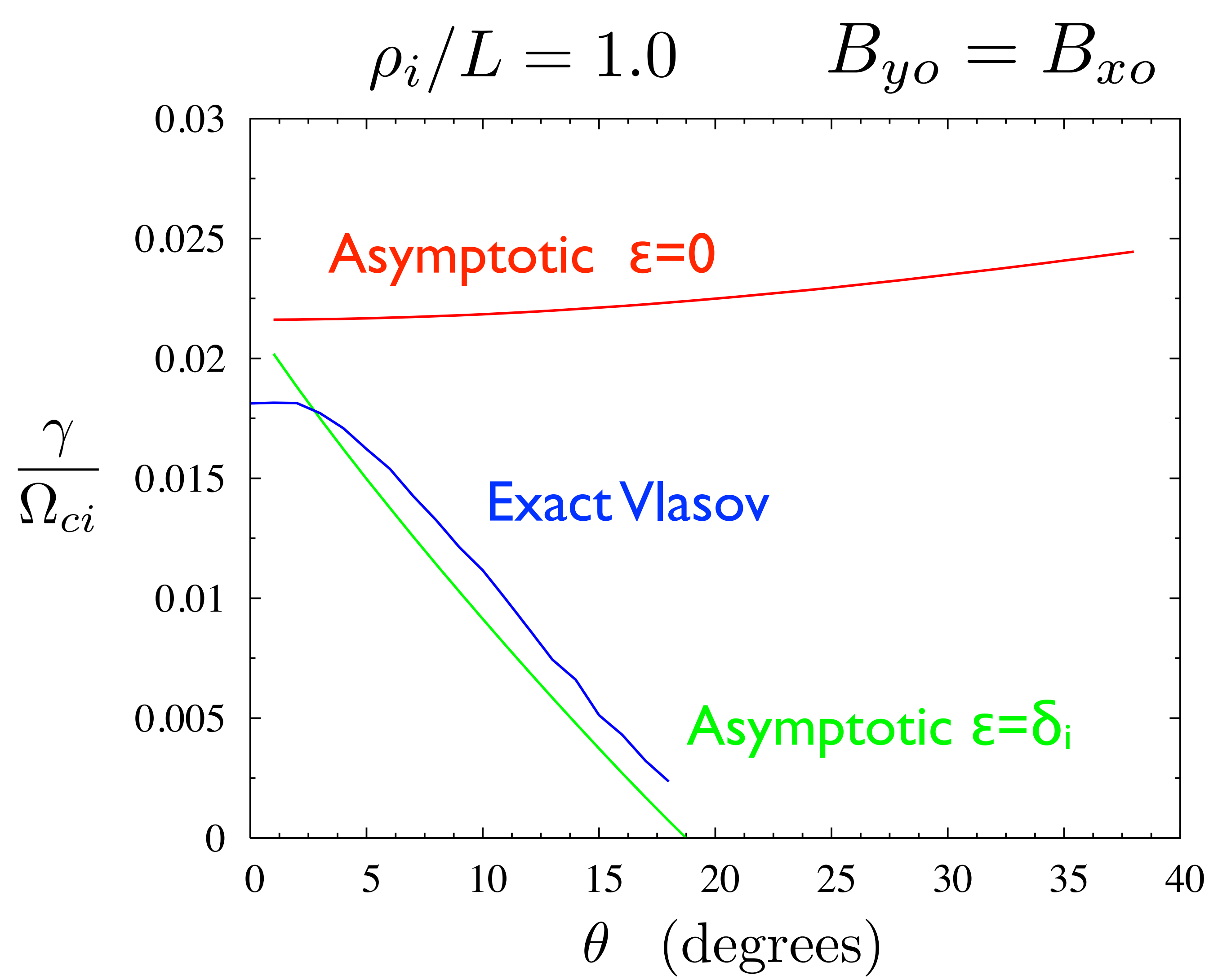
$\sim 10^9$ cells

Does this work the same way for hydrogen plasmas?

For hydrogen - location of matching between inner and outer regions is important

$$\Delta' \equiv \lim_{\epsilon \to 0} \left[\frac{1}{\tilde{A}_{\parallel}(z_s)} \left(\left.\frac{d\tilde{A}_{\parallel}}{dz}\right|_{z_s+\epsilon} - \left.\frac{d\tilde{A}_{\parallel}}{dz}\right|_{z_s-\epsilon} \right) \right] \qquad \delta_j = \frac{\omega l_s}{k V_{th_j}}$$

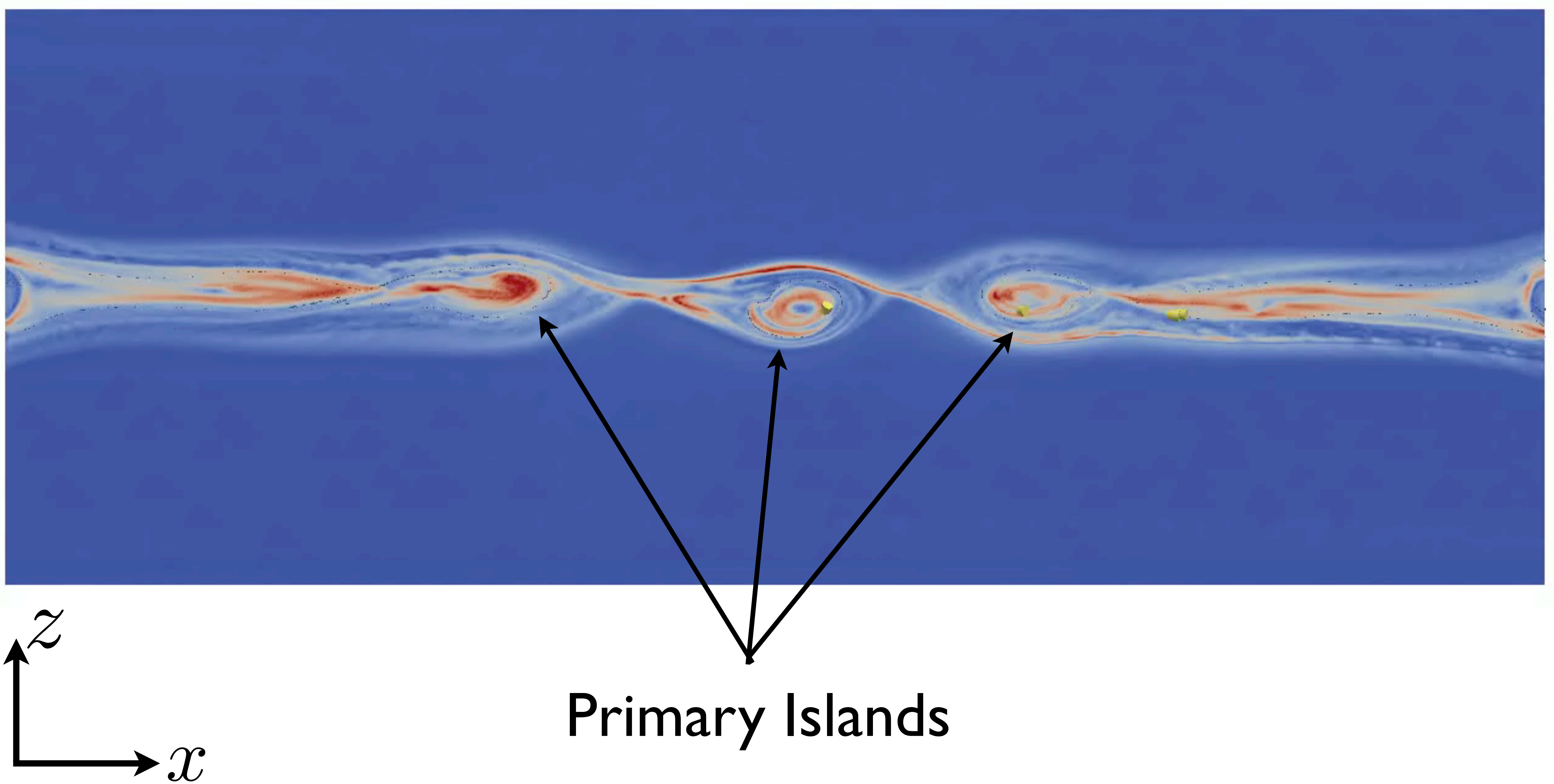




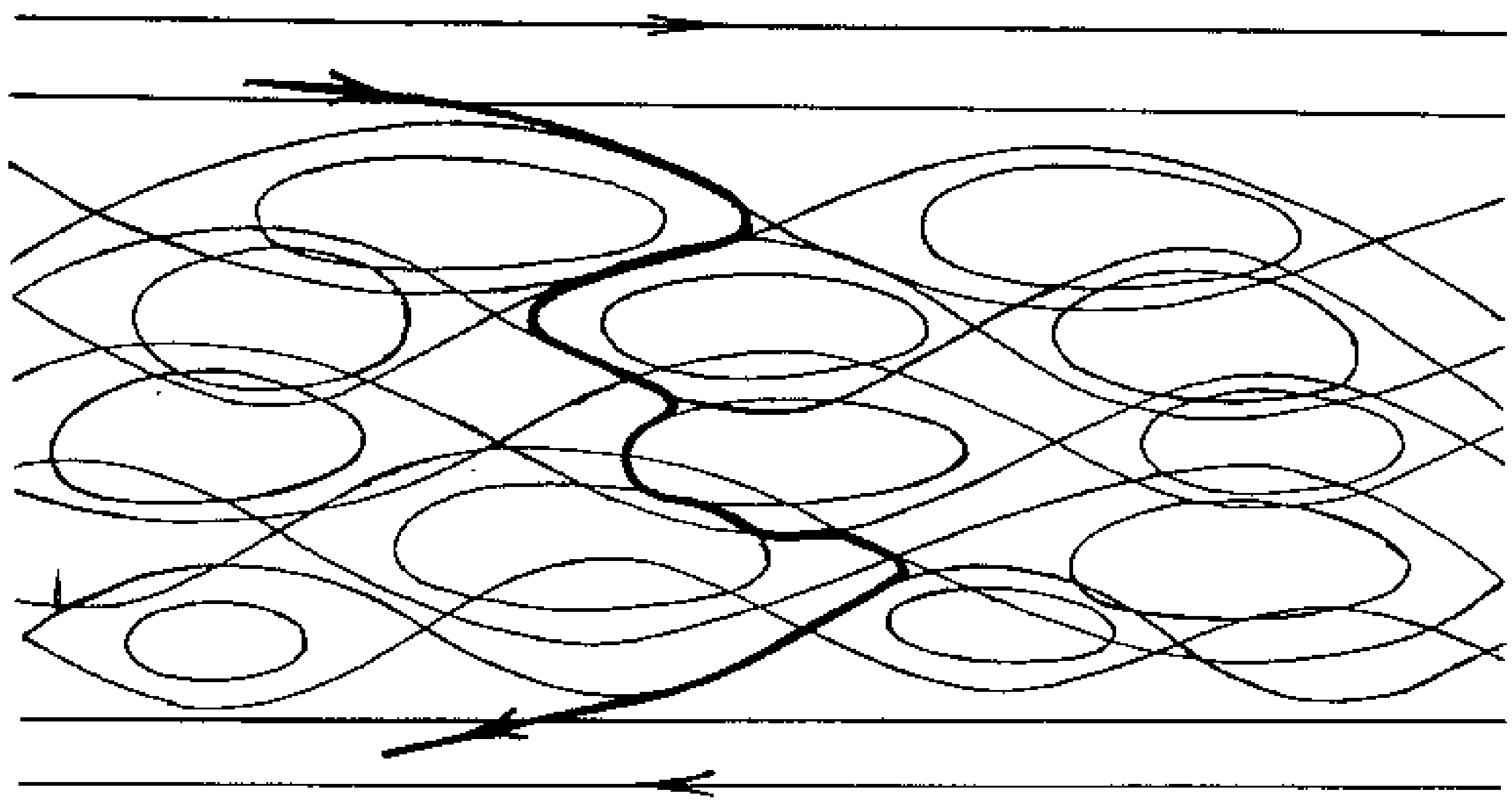
Early Structure at High Mass Ratio

$\sim 3.3 \times 10^9$cells $\quad \sim 1.1 \times 10^{12}$ particles

$$m_i/m_e = 64$$



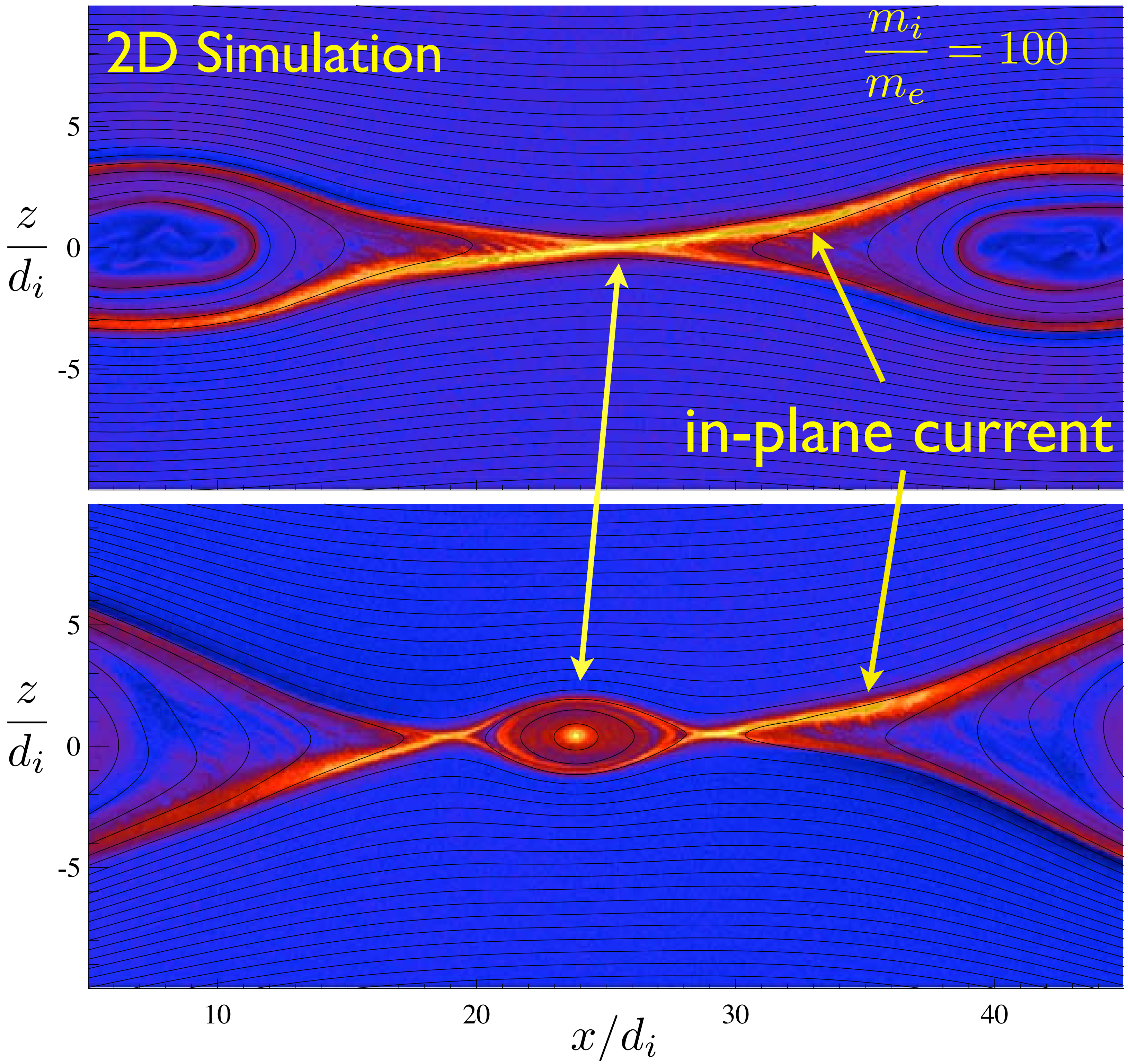
Dynamics does NOT result in this picture based on the initial tearing modes



Galeev et al, 1986

What about secondary instabilities?

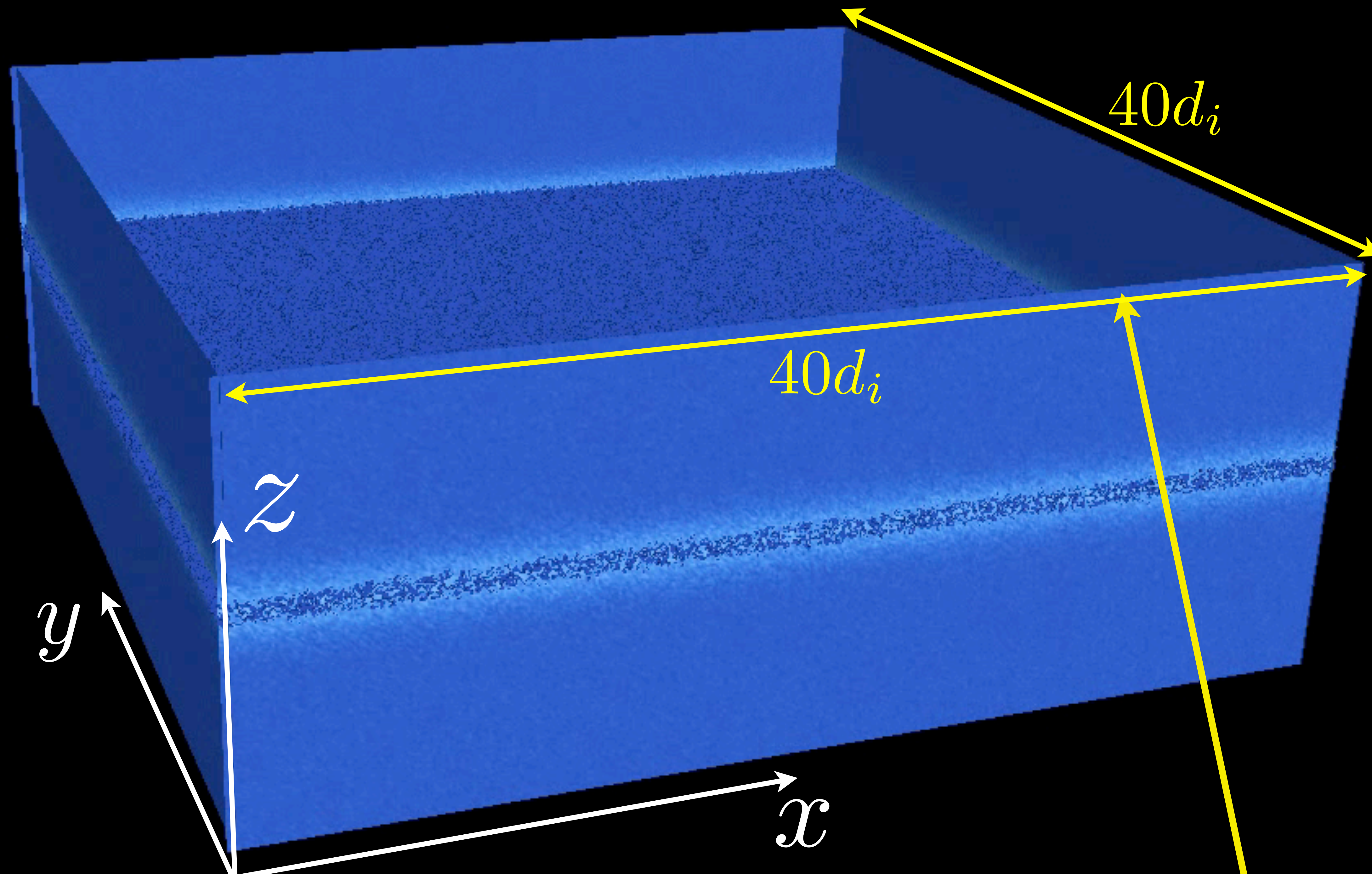
Electron layers that form along separatrices are also unstable to secondary islands



Secondary islands along separatrix needs finite k_y

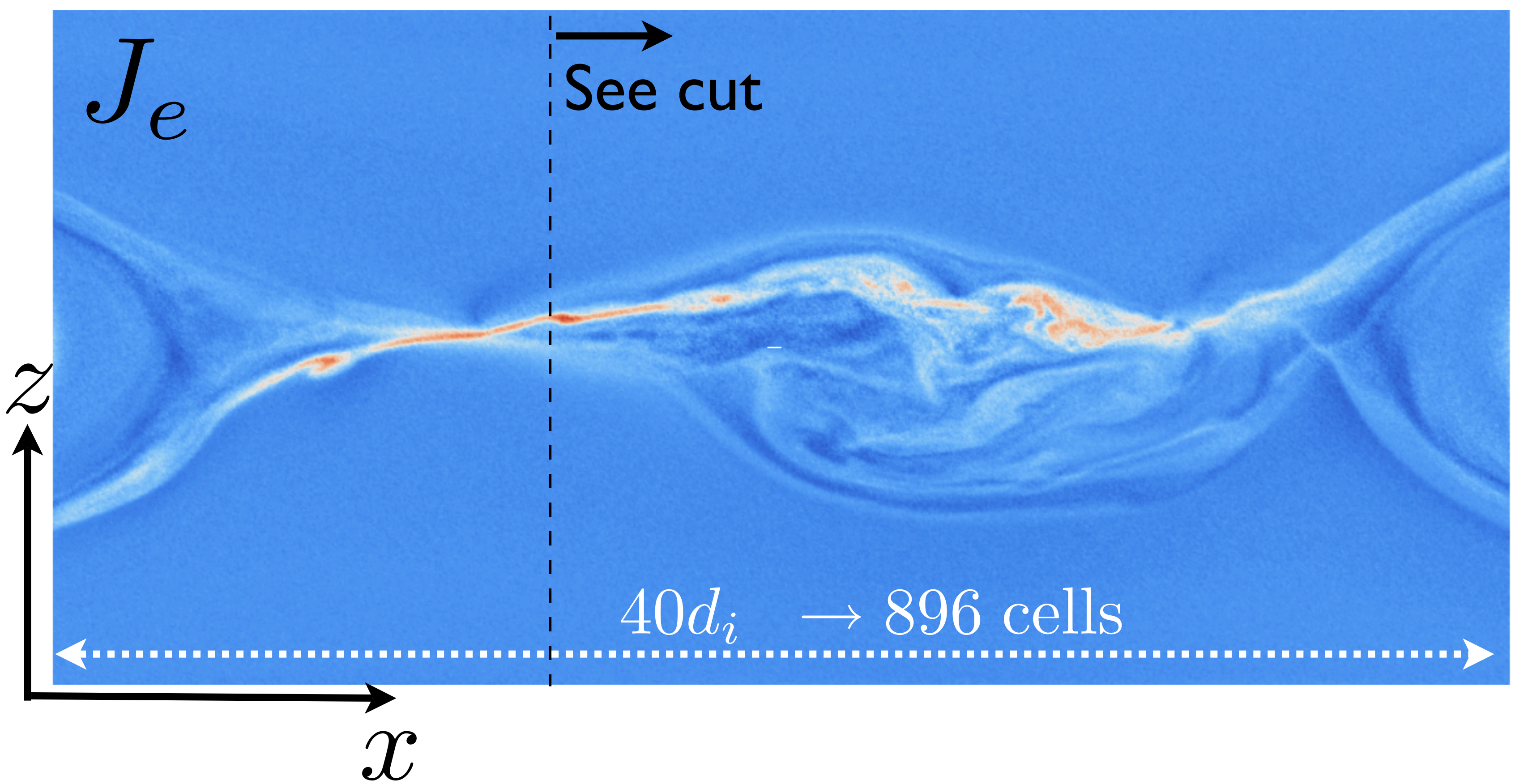
Can't occur in 2D

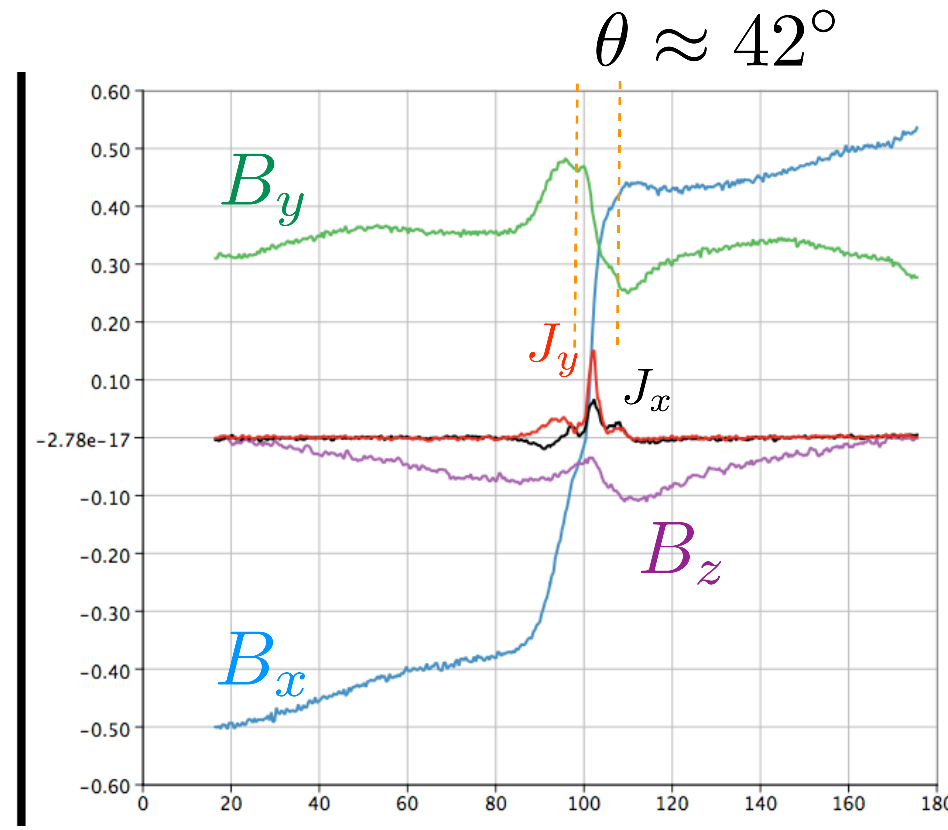
Time Evolution of Current Structures $m_i/m_e = 64$



Secondary magnetic islands form oblique flux ropes

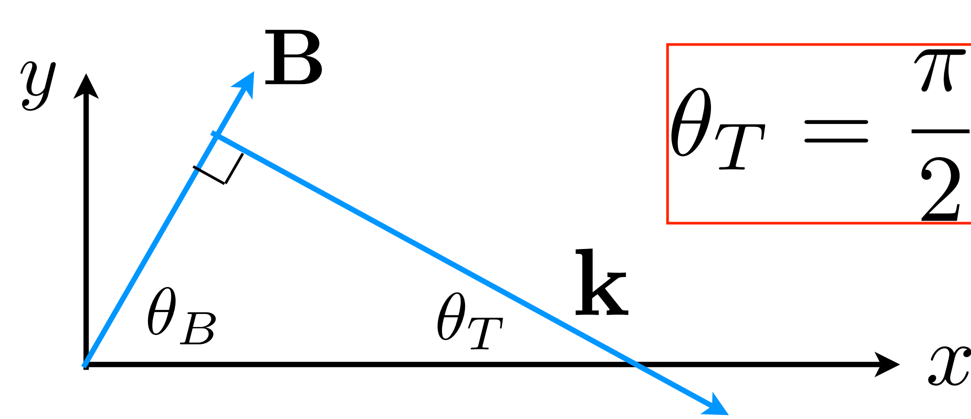
Electron current layers along separatrices produce strong magnetic shear





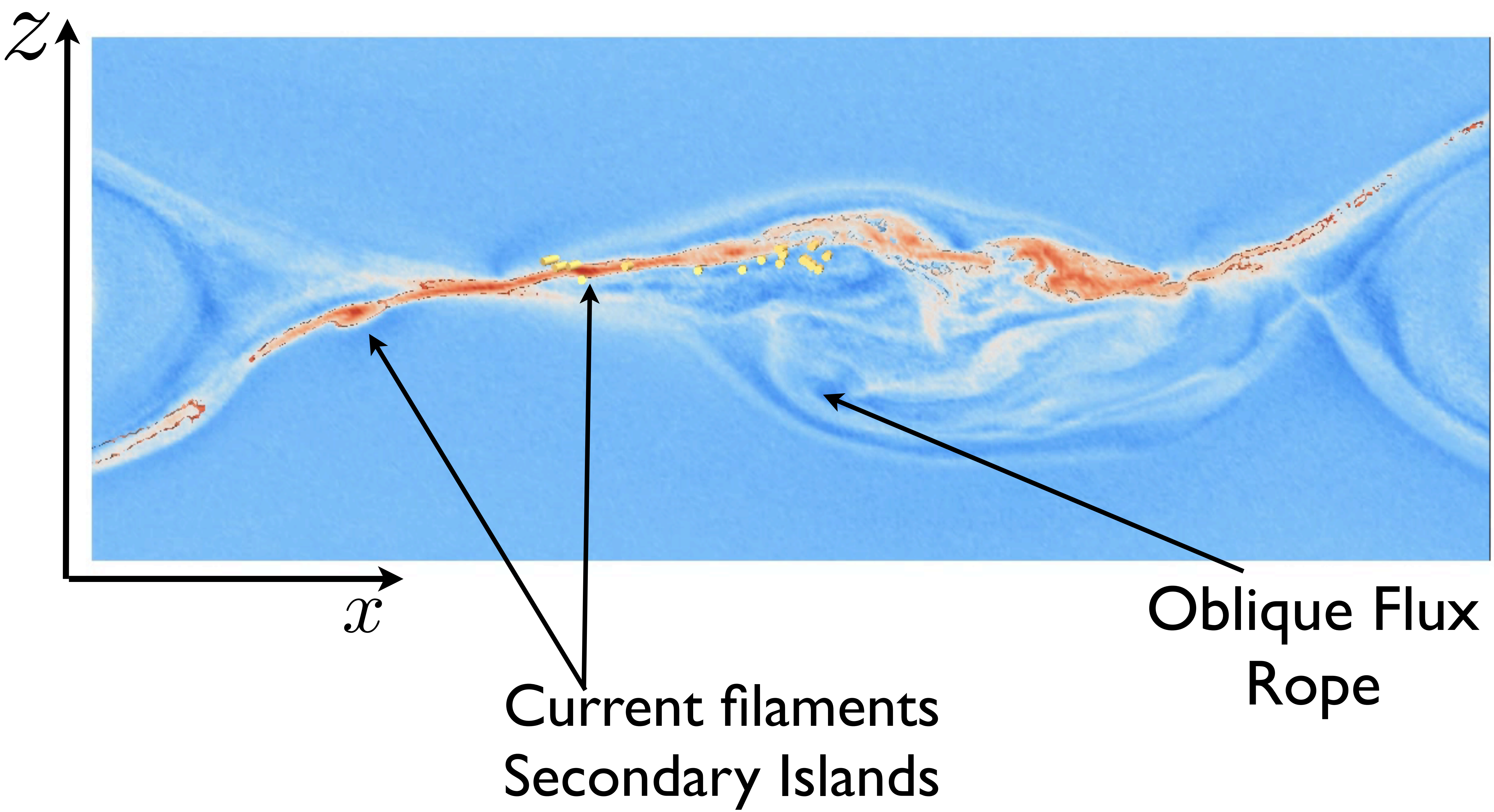
Near peak current $\theta_J = \tan^{-1}\left(\frac{J_y}{J_x}\right) \approx 66^\circ$ $\theta_B = \tan^{-1}\left(\frac{B_y}{B_x}\right) \approx 60^\circ$

$\mathbf{k} \cdot \mathbf{B} = 0 \longrightarrow$



$$\boxed{\theta_T = \frac{\pi}{2} - \theta_B \approx 30^\circ}$$

Secondary magnetic islands along separatrices form oblique flux ropes in 3D

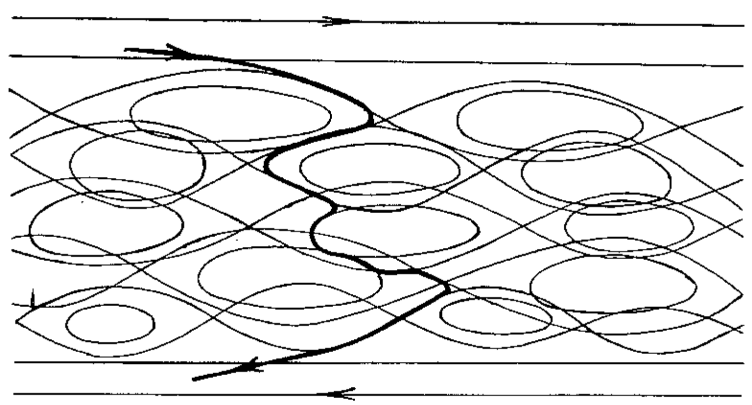


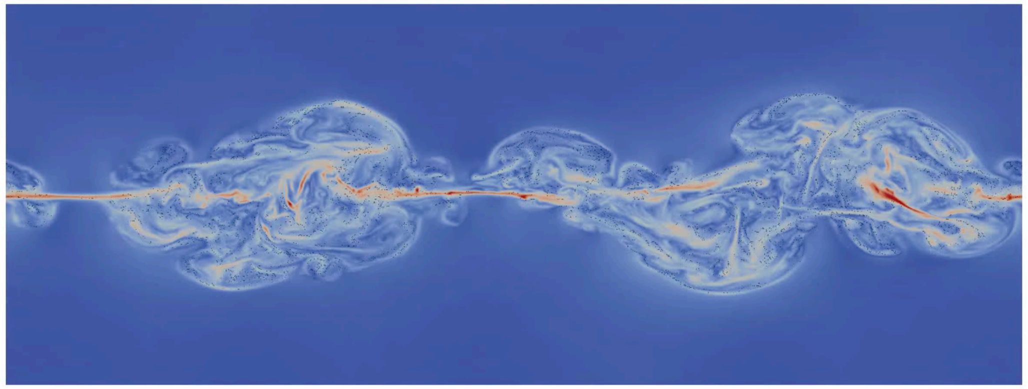
Summary & Future Outlook

- Petascale computing is allowing kinetic studies ~(100-1000)x larger than previous state-of-the-art efforts

- Real potential for breakthrough progress - but computing will never be a substitute for thinking - still desperately need theory, laboratory experiments, space observations, etc

- We can move beyond simple cartoons





- New asymptotic theory offers simple predictions of when to expect this complex evolution - need similar theory for secondary islands

Summary & Future Outlook

- For guide field regimes, reconnection be inherently 3D, which may have far reaching implications for:
    - Dissipation rate
    - Generation of stochastic magnetic fields
    - Structure of exhaust
    - Transport and acceleration of particles
- Studies of reconnection in large 3D systems will be increasingly interconnected with turbulence
- Influence of *pre-existing* upstream turbulence may be huge issue!
- Finally - we can also now start to think about 2D global kinetic modeling of many more kinds of problems