Energy Evolution and Particle Energization in Different Turbulent Environments

Hui Li (李暉)
Los Alamos National Laboratory

Collaborators: Fan Guo, Xiaocan Li (LANL),
Li-Ping Yang (LANL/SWL)

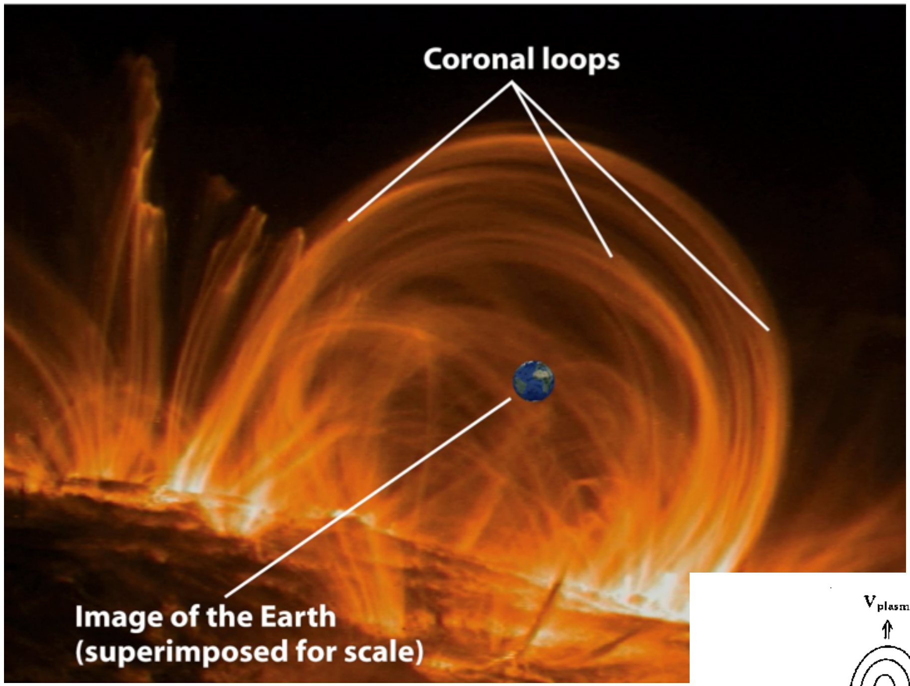
Outline:

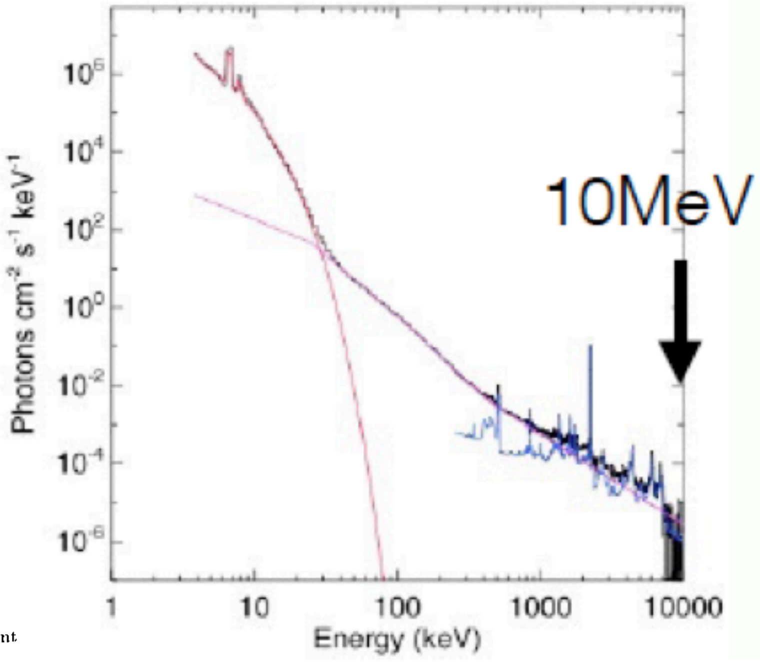
1. **Part 1: Observations**
2. **Part 2: PIC (VPIC) tool**
3. **Part 3: Some elementary ideas and approaches on turbulence and acceleration**
4. **Part 4: Turbulence vs. Reconnection: Different forms of initial free energy;**
5. **Part 5: Particle energization in systems with current sheets mediated by turbulence;**
6. **Part 6: Open issues on 3D reconnection + turbulence**

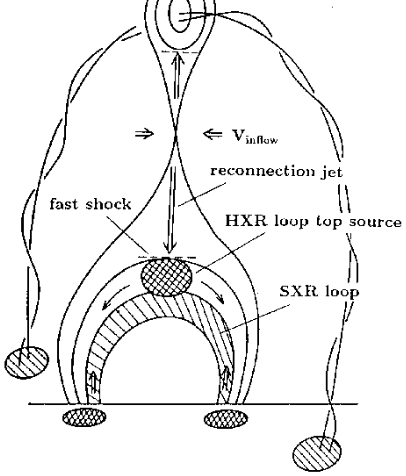
Part 1: Observations

- For systems with
  - large scale separation (some laboratory experiments, solar corona, accretion disks, jets/lobes, etc.)
  - magnetic field energy dominant
- it is often observed that these systems undergo bursty ”flares”, along with non-thermal particles, some of which can be quite extreme.

Corona on Solar Surface







Shibata model

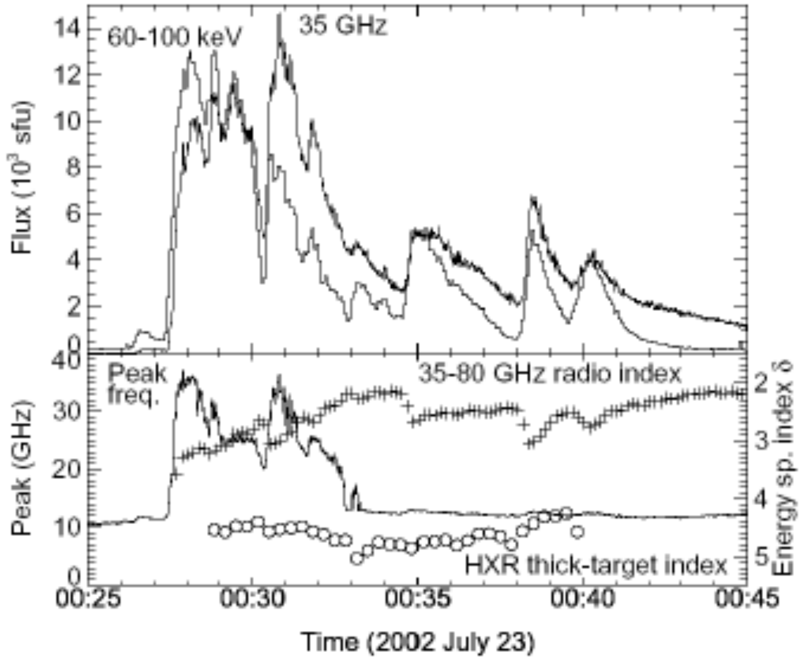
Solar corona:

$v_{driving} \ll v_A$

Unclear how turbulent

Impulsive flare timescales

- Hard x-ray and radio fluxes
  - 2002 July 23 X-class flare
  - Onset of 10's of seconds
  - Duration of 100's of seconds.



RHESSI and NoRH Data

(White et al., 2003)

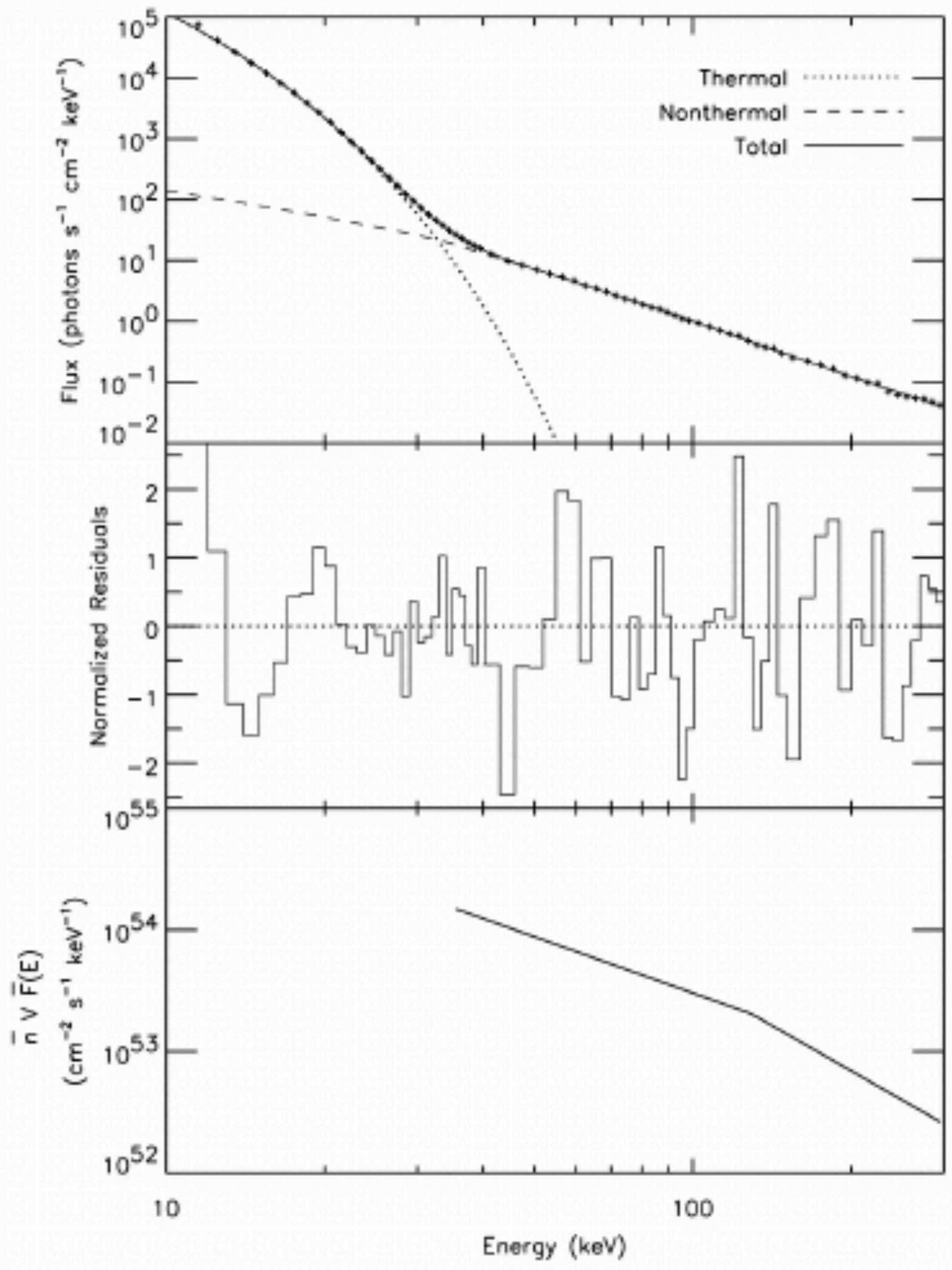
Slide from Drake et al.

RHESSI observations

- July 23 γ-ray flare (Holman, *et al*., 2003)
- Double power-law fit with spectral indices:

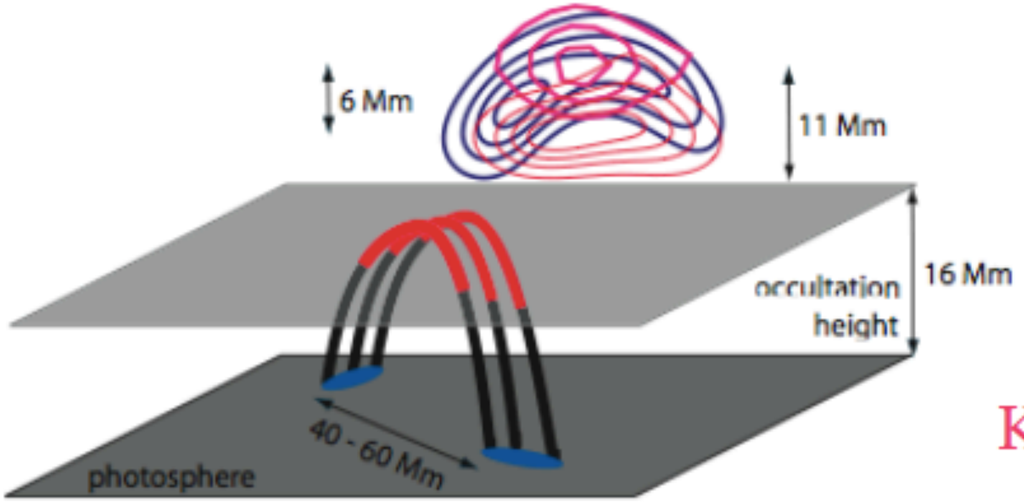
  1.5 (34-126 keV)

  2.5 (126-300 keV)



Slide from Drake et al.

RHESSI occulted flare observations



30-50keV

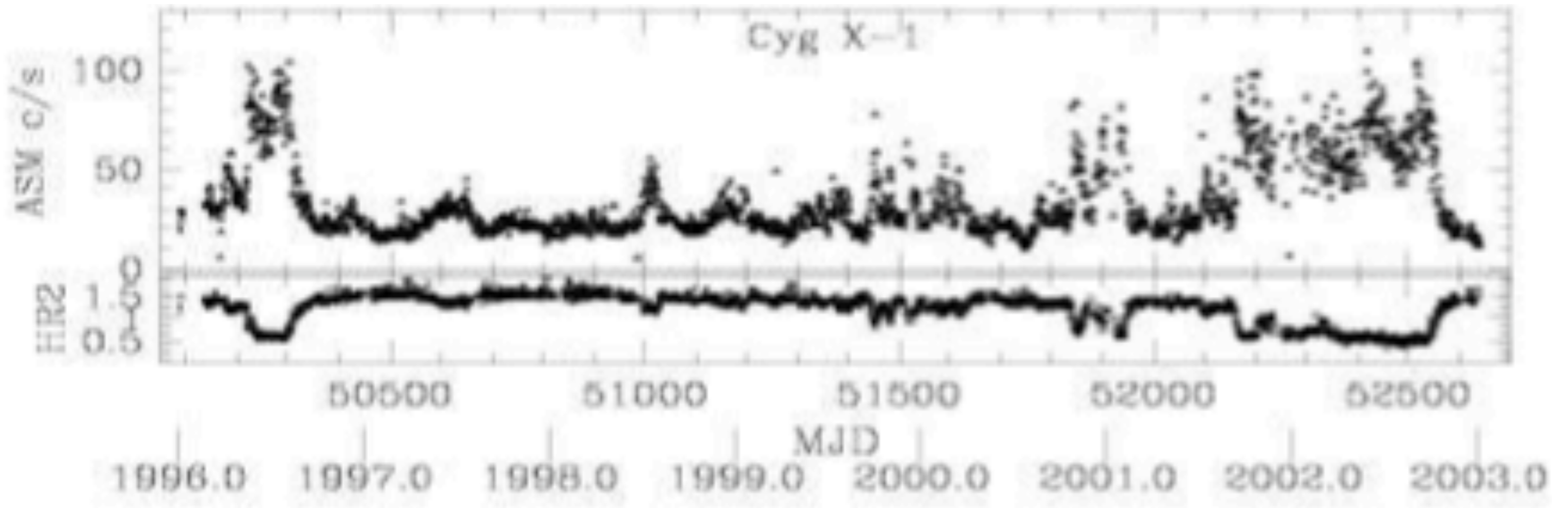
17GHz

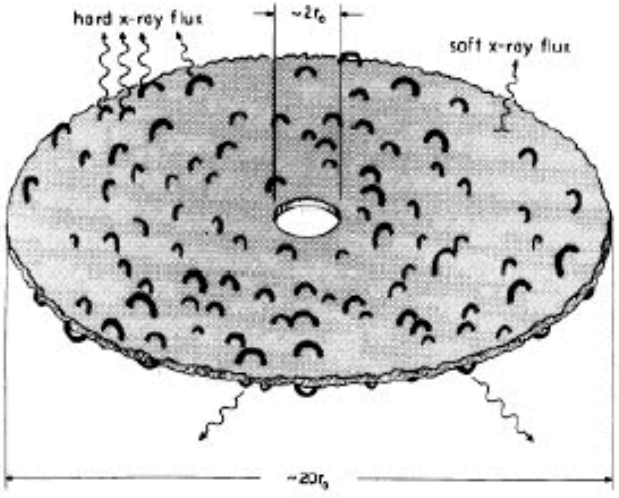
Krucker et al 2010

- Observations of a December 31, 2007, occulted flare
  - A large fraction of electrons in the flaring region are part of the energetic component (10keV to several MeV)
    - Not just a few resonant particles
  - The pressure of the energetic electrons approaches that of the magnetic field

Slide from Drake et al.

(Postulated) Corona on Accretion Disk





Accretion disk corona:

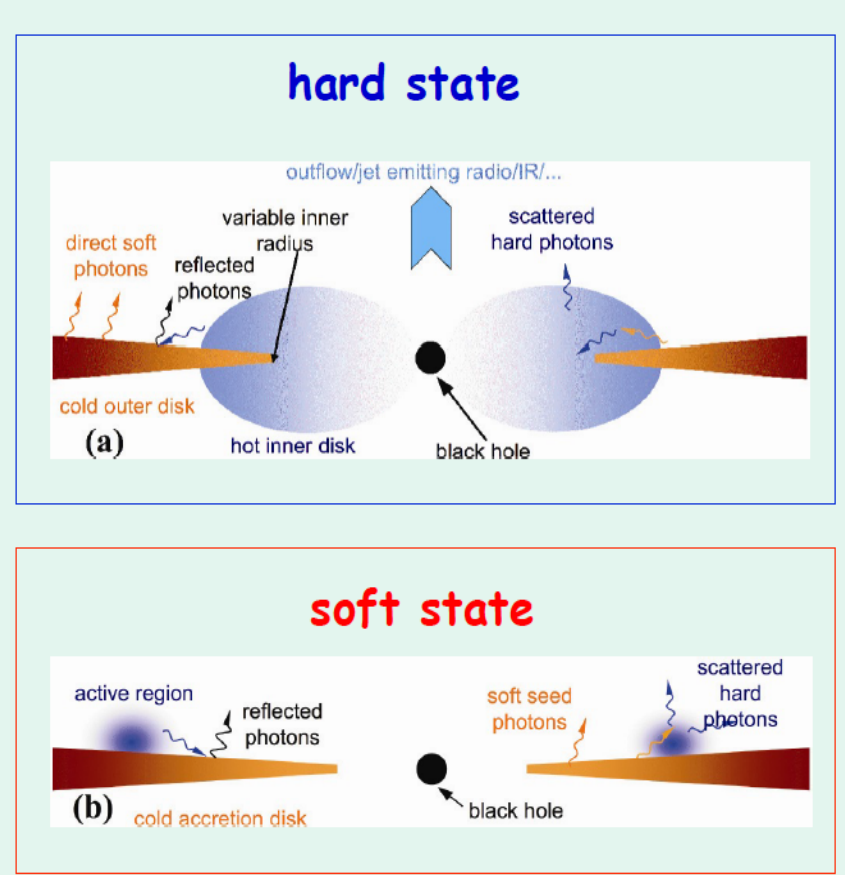
$v_{driving} \sim v_A$

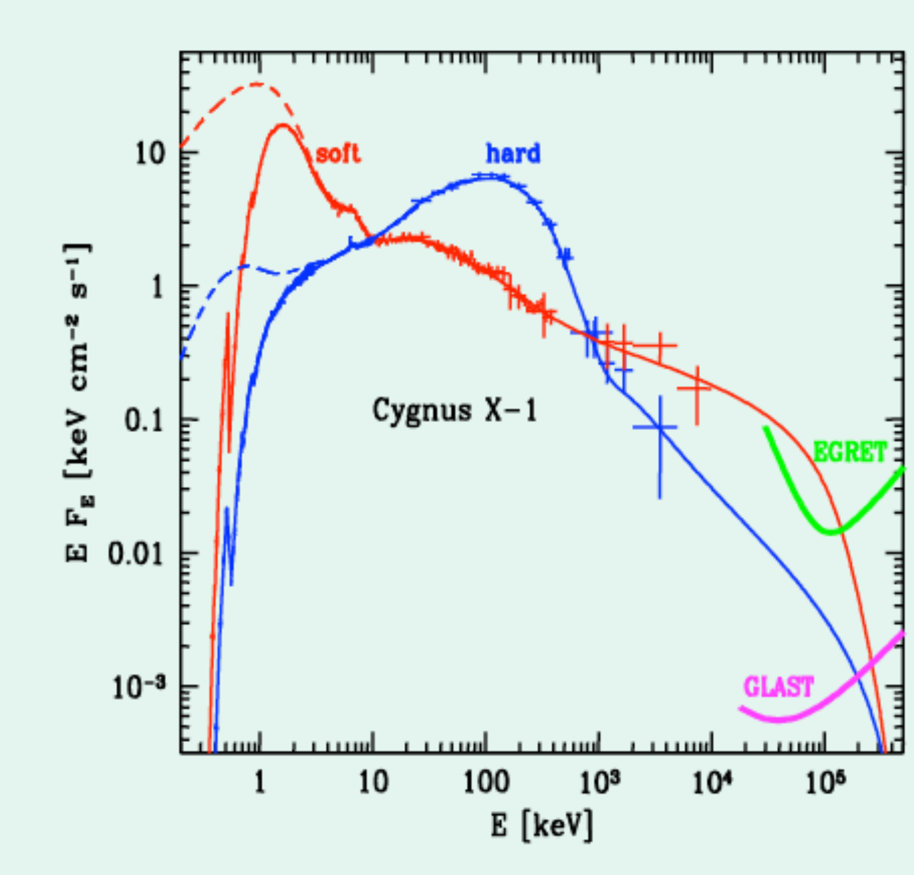
Disk corona: Likely highly turbulent

Galeev, Rosner, & Vaiana, ApJ, **489**, 865 (1979)

(Postulated) Corona on Black Hole Accretion Disks

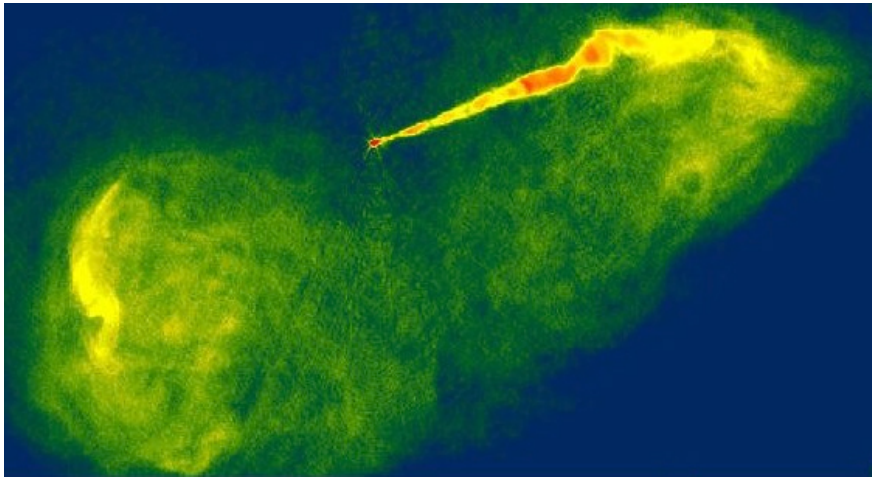
Zdziarski & Gierliski'04

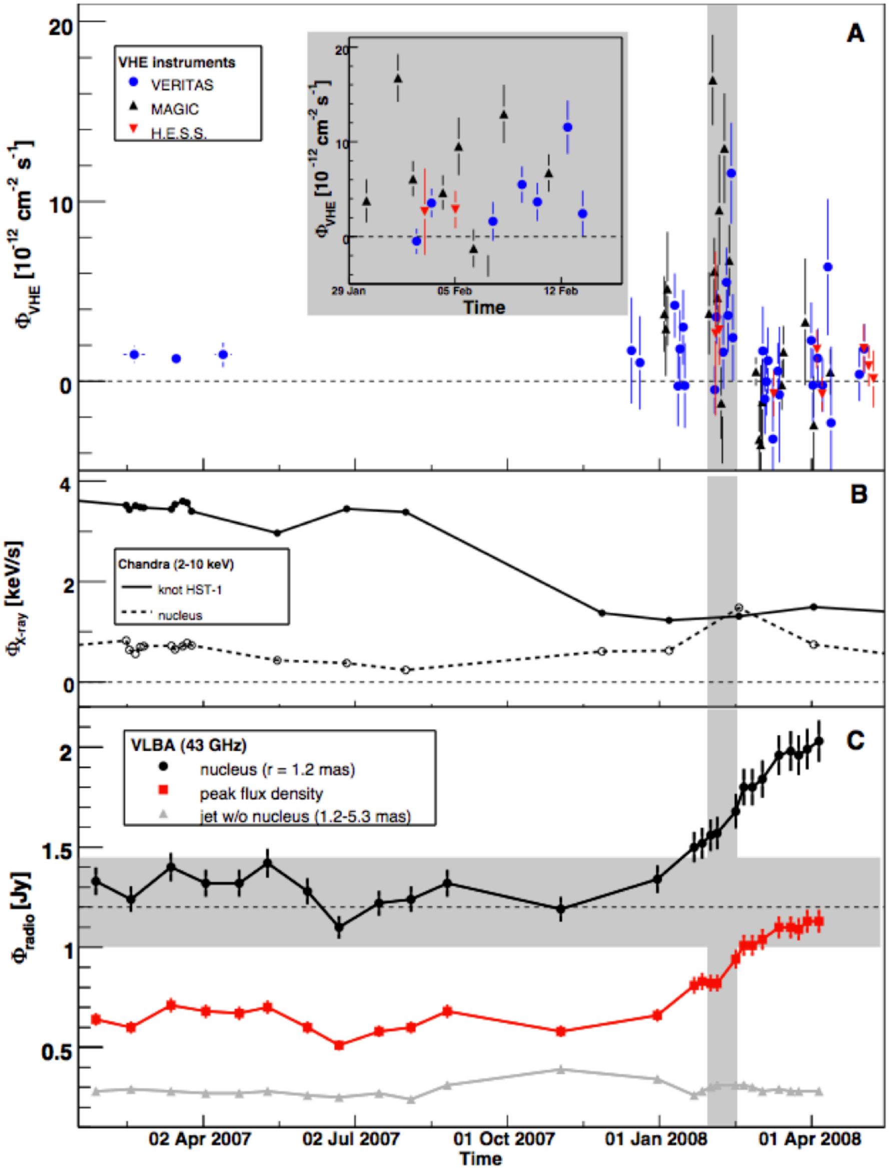




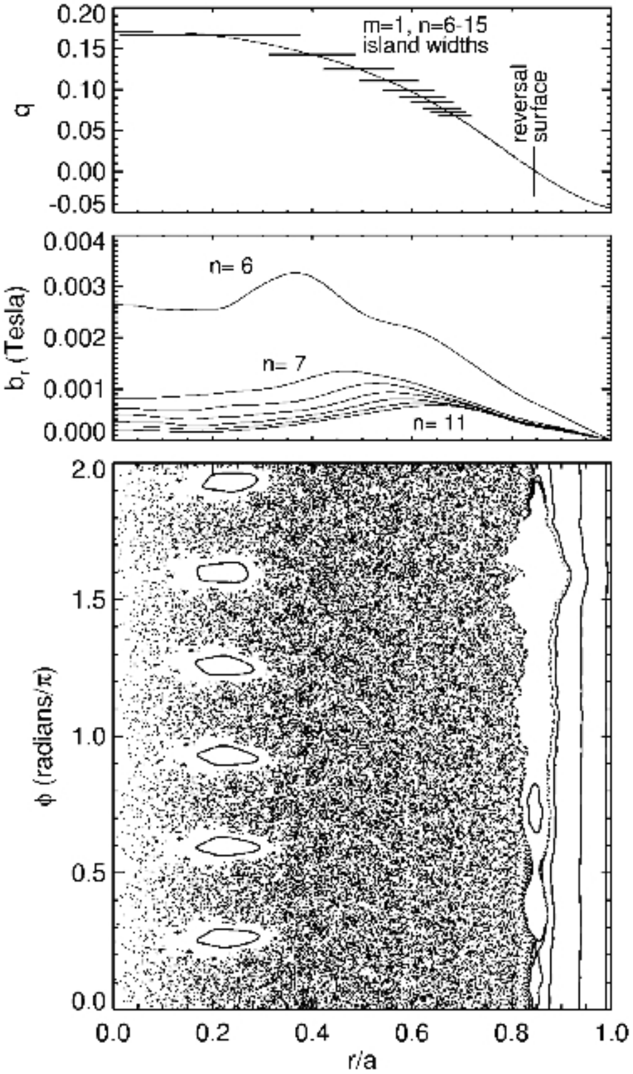
Extra-Galactic Jets/Lobes

M87

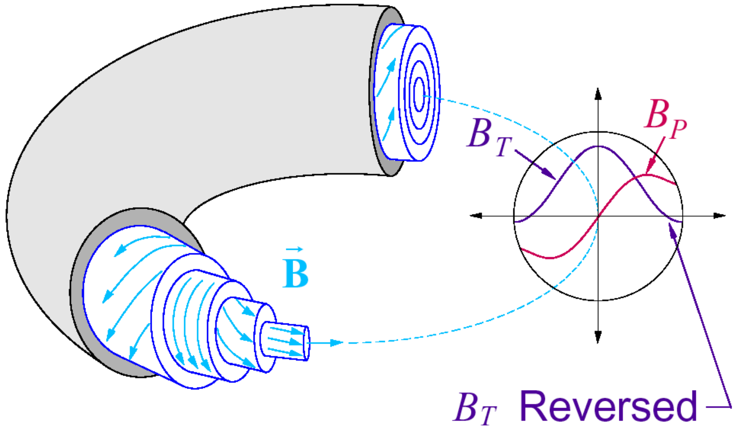


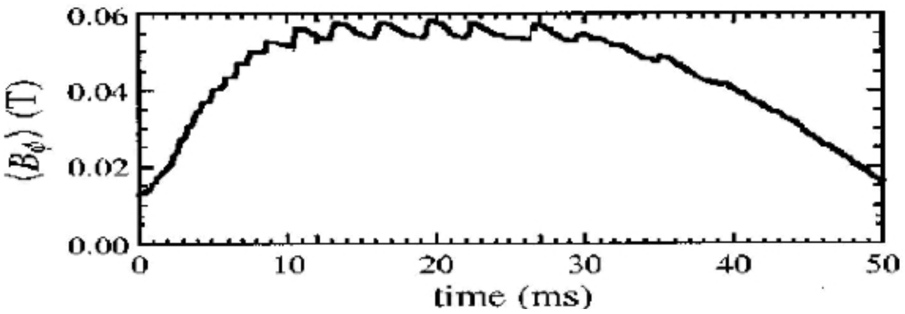


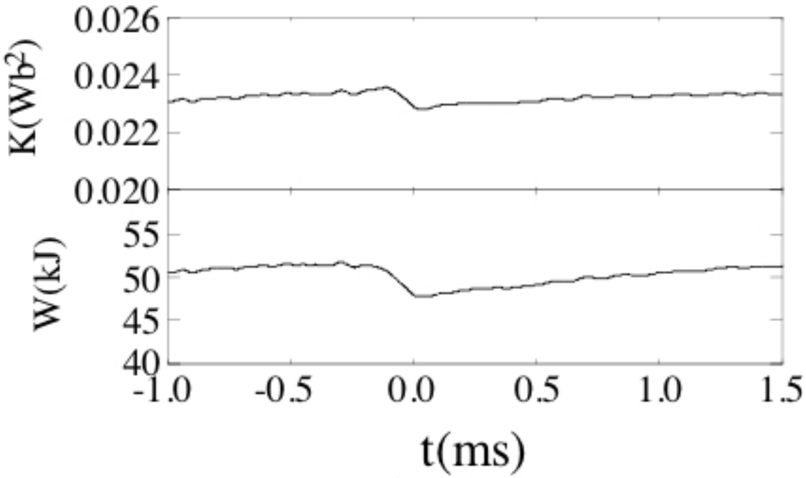
A Taste of Reality



Biewer et al. 2003
Reversed Field Pinch - MST Experiment



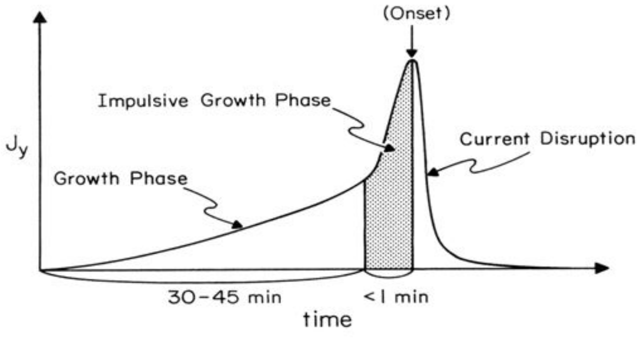




Ji et al. 1995

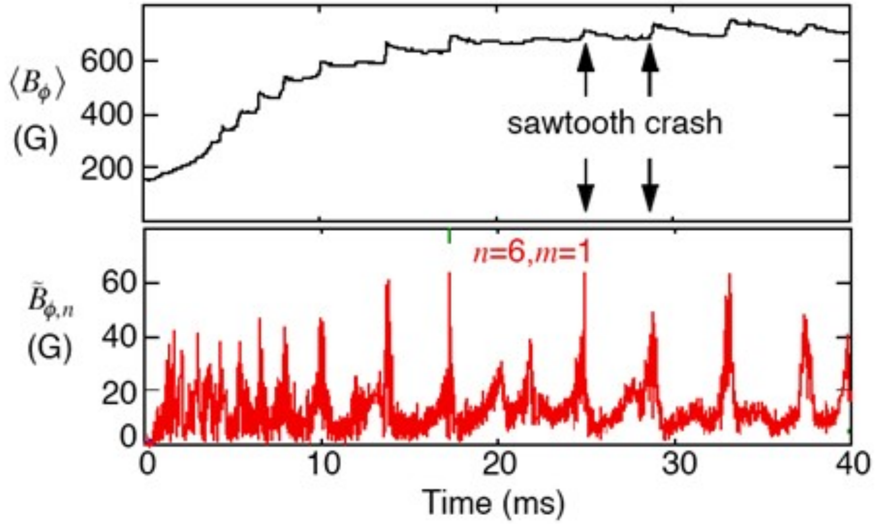
(Slow) Storage & (Fast) Release

Current Disruption in the Near-Earth Magnetotail



[Ohtani, Kokubun, and Russell 1992]

Magnetic reconnection events where mean fields are generated are accompanied by increases in magnetic fluctuations



Summary #1: Magnetic (free) Energy

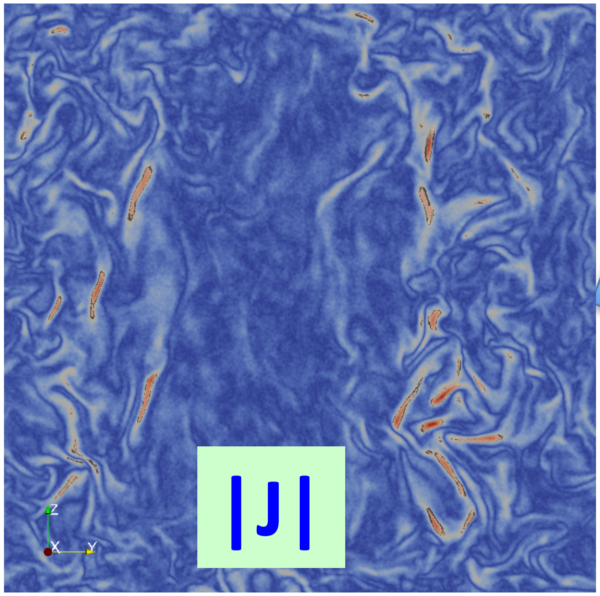
1. **Likely Strongly magnetized (also low thermal beta)**

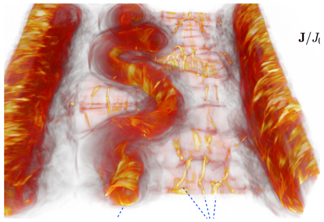
$$\sigma_e = \frac{B^2}{4\pi n_e m_e c^2} \quad \begin{array}{l} \approx 0.1 - 1 \quad \text{for SFs} \\ \approx 0.5 - 5 \quad \text{for GBHs;} \\ \approx 20 - 200 \quad \text{for AGNs} \end{array}$$

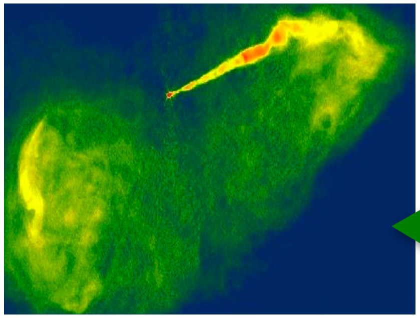
2. **Thermal beta** $\beta_{th} \ll 1$
3. **Quasi-collisionless**
4. **Very high Rm (>>1) but could be low ion Re (unity)**
5. **Mixture of thermal and non-thermal plasmas**

Summary #2: very large scale separation, implying that particle energization in turbulent environment

Free energy injection







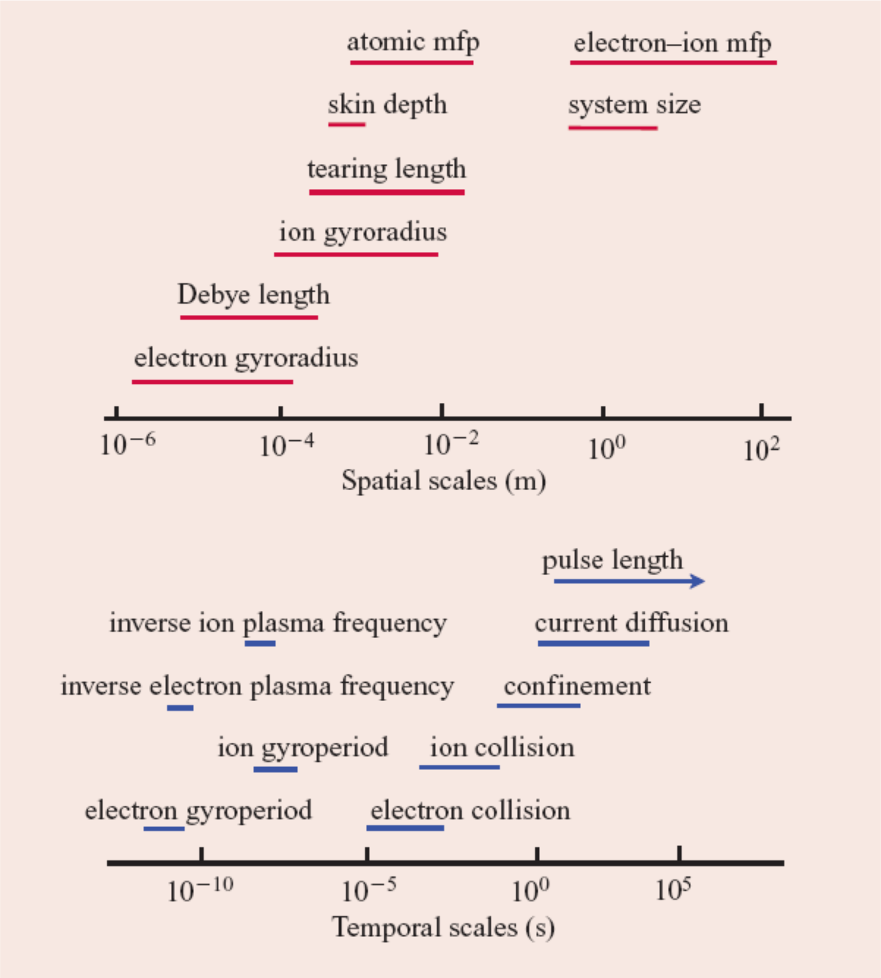
Kinetic simulations particle dynamics

- emission: 10^{11} cm - pc
- jet: 100 kpc

- $R_L \sim 2 \times 10^3 \gamma B$ cm
- $d_e \sim 5 \times 10^6 \gamma^{1/2} n_{-2}^{-1/2}$ cm

Wave-number

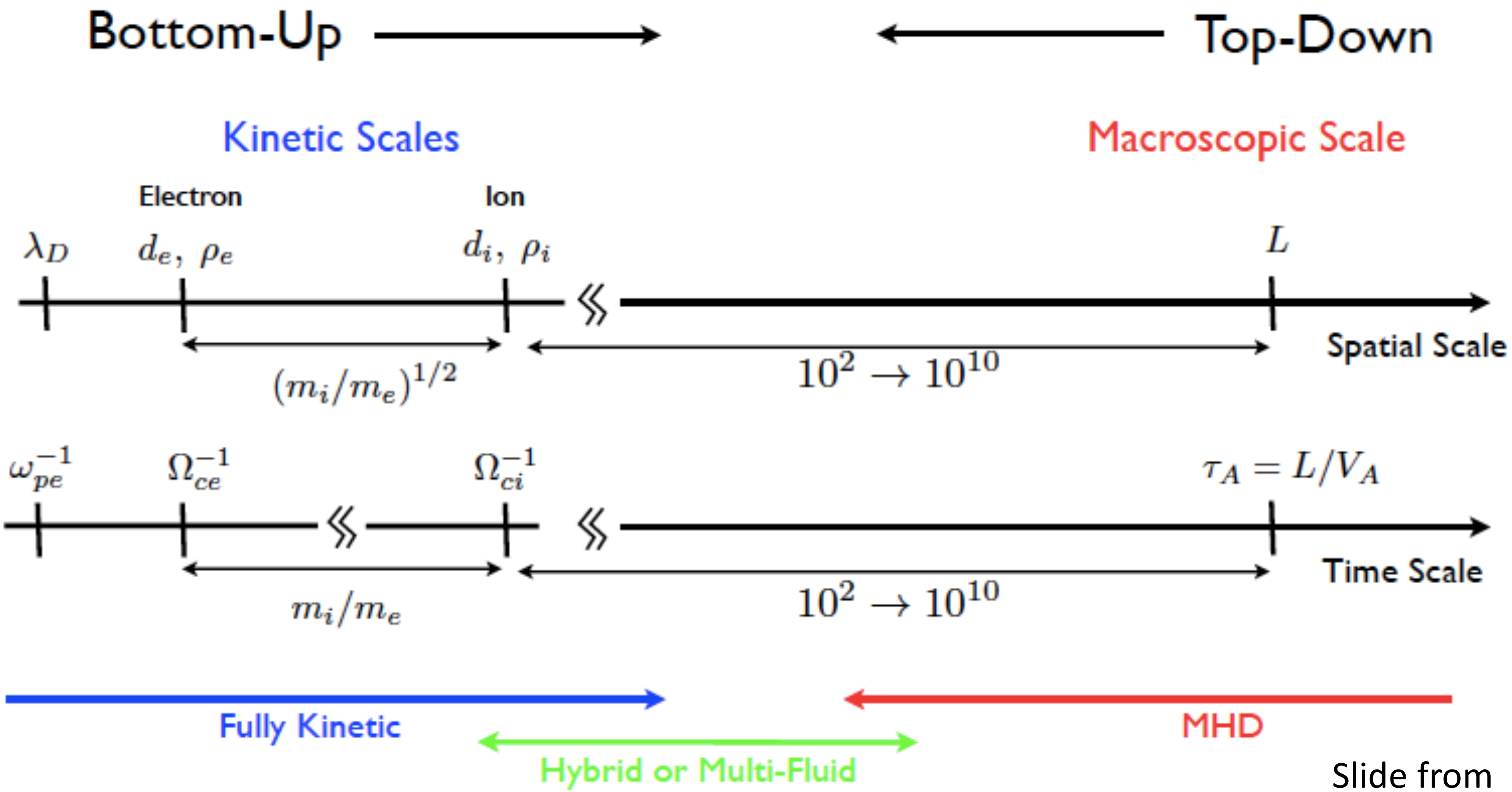
Spatio-Temporal Scales of Fusion Plasma



S.Either et al, IBM J. RES. & DEV. Vol. 52 2008

Slide from Prof. Kwon

Scale Separation is a Key Challenge



Bottom-Up →

← Top-Down

Kinetic Scales

Macroscopic Scale

Electron

Ion

λ_D $d_e,\ \rho_e$ $d_i,\ \rho_i$ L

Spatial Scale

$(m_i/m_e)^{1/2}$

$10^2 \rightarrow 10^{10}$

ω_{pe}^{-1} Ω_{ce}^{-1} Ω_{ci}^{-1} $\tau_A = L/V_A$

Time Scale

m_i/m_e

$10^2 \rightarrow 10^{10}$

Fully Kinetic

Hybrid or Multi-Fluid

MHD

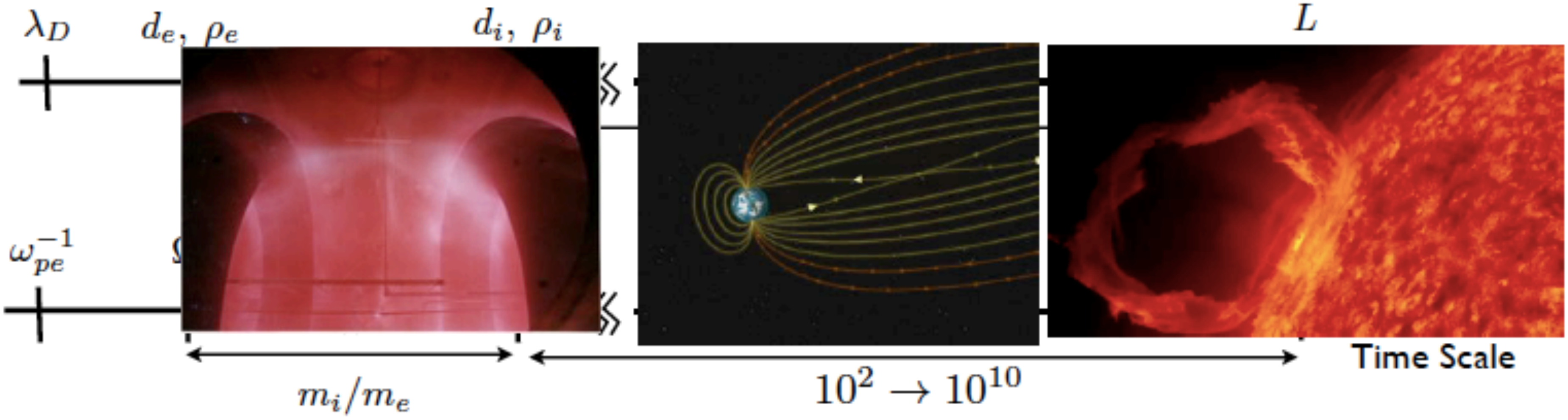
Slide from Daughton

Scale Separation is a Key Challenge

Bottom-Up → ← Top-Down

Kinetic Scales

Macroscopic Scale



Electron

Ion

λ_D

$d_e,\ \rho_e$

$d_i,\ \rho_i$

L

ω_{pe}^{-1}

Time Scale

m_i/m_e

$10^2 \rightarrow 10^{10}$

Fully Kinetic →

↔ Hybrid or Multi-Fluid

← MHD

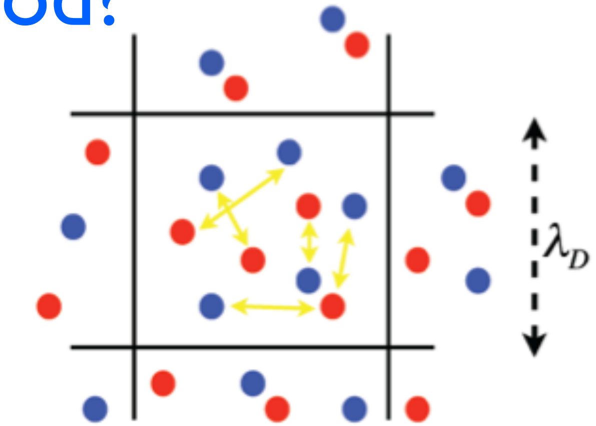
Slide from Daughton

Part 2: PIC (VPIC)

- Because we want to study particle acceleration, kinetic simulations provide the most direct approach in linking particle (kinetic) physics with their environment described by E & B fields.

What is PIC method?

- Solve Vlasov/Boltzmann equation in the simulation domain (particle-in-cell) and solve Maxwell equations on numerical grids



- Simulate a plasma system by following a number of macro-particles. Use particles to sample the phase space distribution, rather than solve the 6D equation.

- Calculating Lorentz force by interpolating E and B fields back to particle locations (Ignoring the inter-particle forces). Source terms like current density J and charge density q are calculated by depositing particle information on grids.

- Still computation-intensive compare to fluid method (usually >80% computing time is used for calculating particle motions.

Overview of the Fluid Description

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

Take velocity space moments of the kinetic equation:

$$\int \mathcal{A}\, d\mathbf{v} \;\longrightarrow\; \frac{\partial n_s}{\partial t} + \nabla \cdot (n_s \mathbf{U}_s) = 0 \;\longrightarrow\; \text{mass conservation}$$

$$\int \mathcal{A}\, m\mathbf{v}\, d\mathbf{v} \rightarrow n_s m_s \frac{d\mathbf{U}_s}{dt} + \nabla \cdot \mathbf{P}_s + q_s n_s \left(\mathbf{E} + \frac{\mathbf{U}_s \times \mathbf{B}}{c}\right) = m_s \int \mathbf{v} C_s d\mathbf{v} \rightarrow \text{momentum conservation}$$

$$\int \mathcal{A}\, \frac{mv^2}{2}\, d\mathbf{v} \rightarrow \text{energy conservation}$$

- Each fluid equation contains higher order moment
- Rigorous closure possible only in collisional plasmas
- In collisionless plasmas, fluid-like behavior requires $\rightarrow \rho \ll L$
- Can combine & simplify further into one-fluid MHD model
- MHD is an asymptotic theory - no intrinsic scales
- For reconnection - we are still debating what physics is needed

Slide from
Daughton

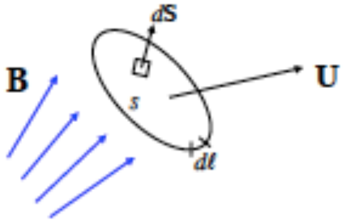
Slide from
Daughton

Kinetic simulations offer a rigorous treatment of some key issues in reconnection physics:

- How is the frozen-flux condition broken?
- Length & thickness of diffusion region
- Influence of kinetic-scale instabilities
- Generation & influence of pressure anisotropy
- Self-consistent treatment of particle acceleration
- Turbulence: either from driven cascade or self-generated?

Fully kinetic simulations permit rigorous treatment of non-ideal physics

Slide from Daughton



$$\frac{d\psi}{dt} = -c \oint \left(\mathbf{E} + \frac{\mathbf{U} \times \mathbf{B}}{c} \right) \cdot d\ell$$

Re-write first moment of electron kinetic equation:

$$e n_e \left(\mathbf{E} + \frac{\mathbf{U}_e \times \mathbf{B}}{c} \right) \;=\; m_e \int \mathbf{v} C_{ei}\, d\mathbf{v} - n_e m_e \frac{d\mathbf{U}_e}{dt} - \nabla \cdot \mathbf{P}_e$$

Collisions Inertia Anisotropy & Agyrotropy

Can fluctuations break frozen-in constraint?

$$\mathbf{E} = \langle \mathbf{E} \rangle + \delta \mathbf{E}$$

$$n_e = \langle n_e \rangle + \delta n_e$$

$$\langle \delta \mathbf{E} \rangle = \langle \delta n_e \rangle = 0$$

$$\langle n_e \mathbf{E} \rangle = \langle n_e \rangle \langle \mathbf{E} \rangle + \underset{\uparrow}{\langle \delta n_e \delta \mathbf{E} \rangle}$$

anomalous resistivity

Roytershteyn et al, 2012
Dorfman et al, 2012
Pritchett & Mozer, 2012
Yi-Hsi Liu et al, 2013
Torbert et al, 2016
Price et al, 2016

Fusion community

Reduced Problem Size

- Problem size for KSTAR plasma

Number of grids: $N_x \times N_y \times N_z \times N_{v_x} \times N_{v_y} \times N_{v_z}$

$\geq 256 \times 256 \times 256 \times 128 \times 128 \times 128 \sim 10^{13}$

Number of grids: $N_x \times N_y \times N_z \times N_{v_\parallel} \times N_\mu$

$\geq 256 \times 256 \times 256 \times 128 \times 16 \sim 10^{10}$

Electron-Ion mass ratio ~ 1:3600

➔ Time scale disparity ~ 100

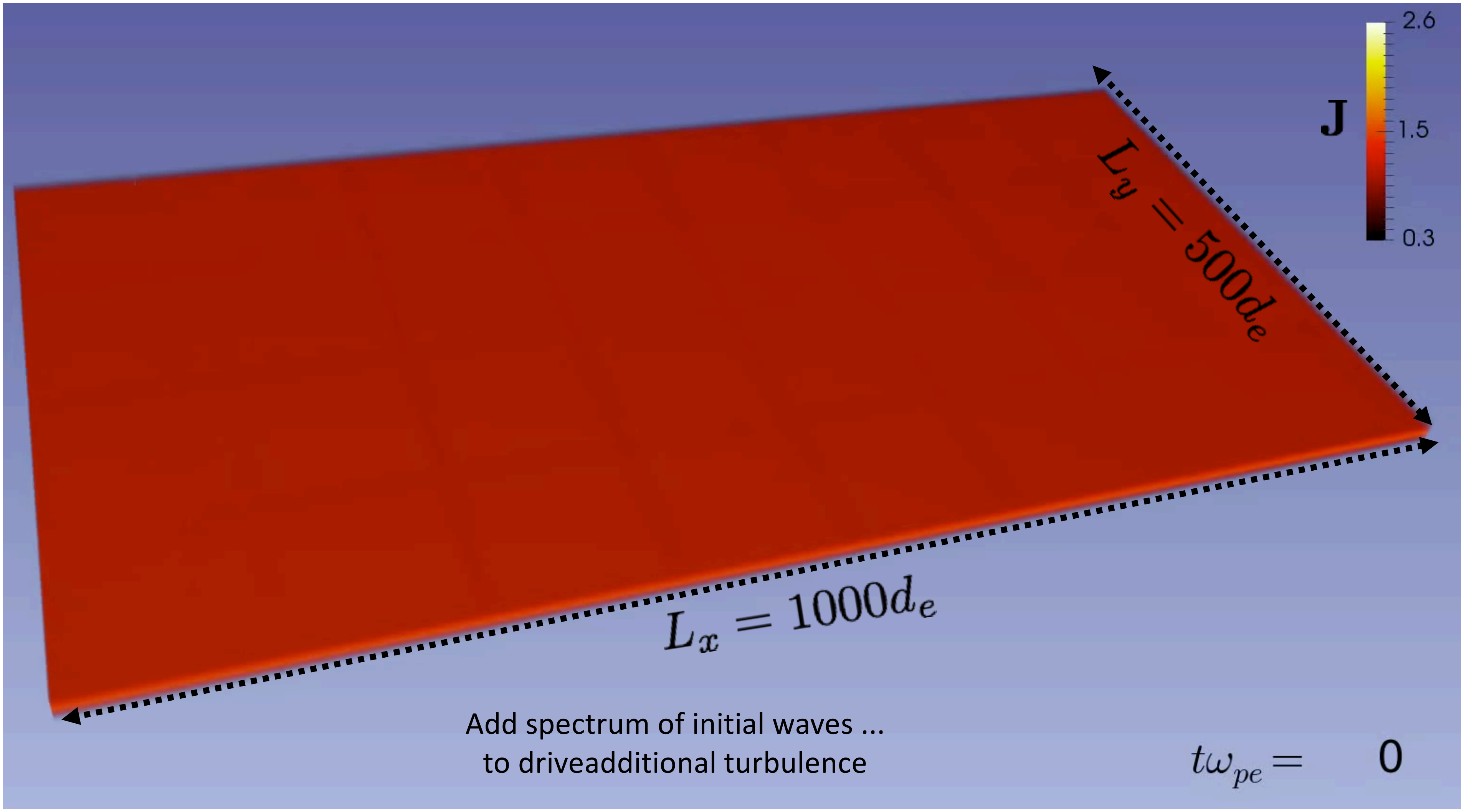
Fluid Model?

Slide from Prof. Kwon

Trinity runs

$4096 \times 2048 \times 2048$ cells

$\sim 5.2 \times 10^{12}$ particles track $\sim 10^{8}$ particles



Add spectrum of initial waves ...
to driveadditional turbulence

$\sigma = 100$ Electron-positron pairs **F. Guo + 2016**

Part 3: Some elementary ideas and approaches on turbulence and acceleration

In mid-90’s: Can Turbulence be considered as ”ensemble of waves”?

$$\frac{\partial N_e}{\partial t} = -\frac{\partial}{\partial E}\left\{\left[\left\langle\frac{dE}{dt}\right\rangle + \left(\frac{dE}{dt}\right)_{\rm loss}\right] N_e\right\} + \frac{1}{2}\frac{\partial^2}{\partial E^2}[(D+D_c)N_e] \qquad + \dot{Q}(\gamma)$$

$$\frac{\partial W_{\rm T}}{\partial t} = \frac{\partial}{\partial k}\left[k^2 D\,\frac{\partial}{\partial k}\left(k^{-2}W_{\rm T}\right)\right] - \gamma W_{\rm T} + Q_{\rm W}\,\delta(k-k_0)$$

turbulence

$$\frac{\partial n_{\rm ph}(\varepsilon)}{\partial t} = -n_{\rm ph}(\varepsilon)\int dE\, N_e(E)\, R(\varepsilon, E) +$$

photon

$$\int\!\!\int d\varepsilon'\, dE\, P(\varepsilon;\varepsilon', E)\, n_{\rm ph}(\varepsilon') N_e(E) + \dot{n}_{\rm ext}(\varepsilon) + \dot{n}_{\rm emis}(\varepsilon) - \dot{n}_{\rm abs}(\varepsilon) - \frac{n_{\rm ph}(\epsilon)}{t_{\rm esc}}\,.$$

Li et al. 1997; 1999: with stochastic particle acceleration;
Coppi 1999 + others: with relativistic particle injection;

Key: MHD turbulence leading to stochastic particle acceleration.

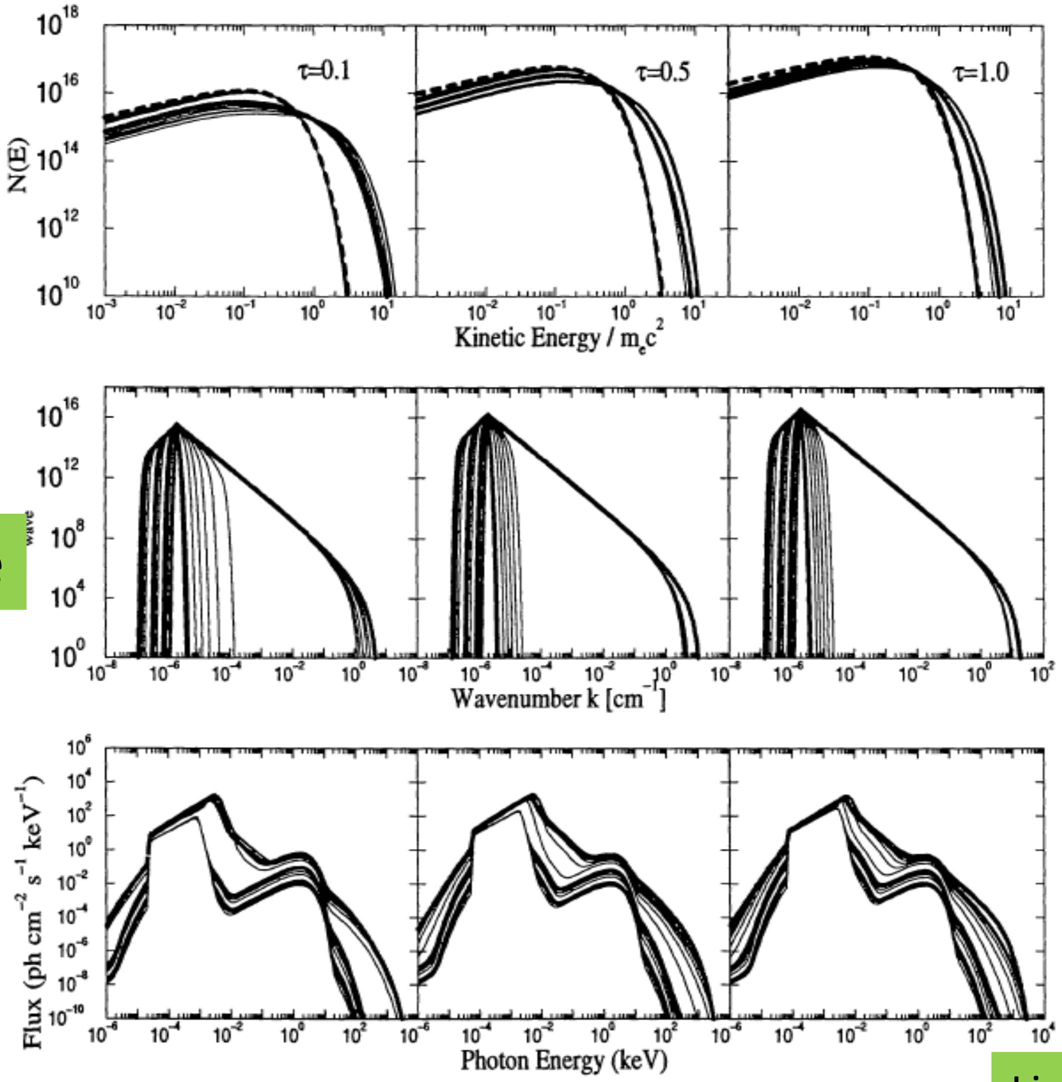
Modeling Hybrid Corona Plasmas

-- A long history

particle

turbulence

photon



Li et al. 1997, 1999

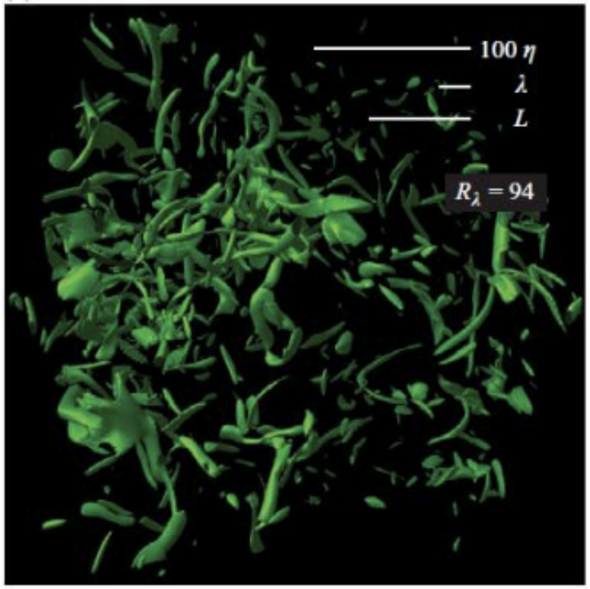
Since 80’s (in space community) and late 90’s (in astro community):

Magnetic structures are anisotropic in MHD turbulence (e.g., Cho, Vishniac, Lazarian, + many others)

Magnetic turbulence in numerical simulations

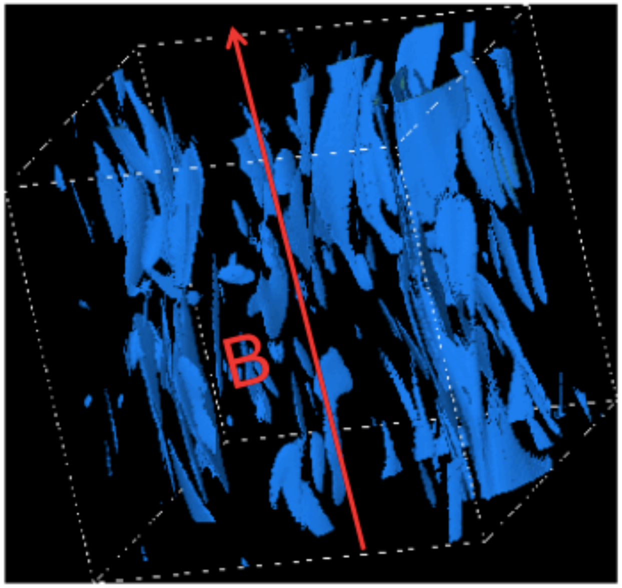
structures

Neutral fluid, B=0



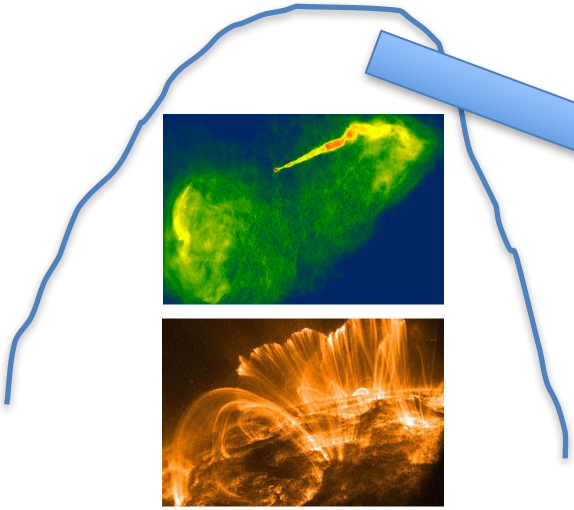
Filaments

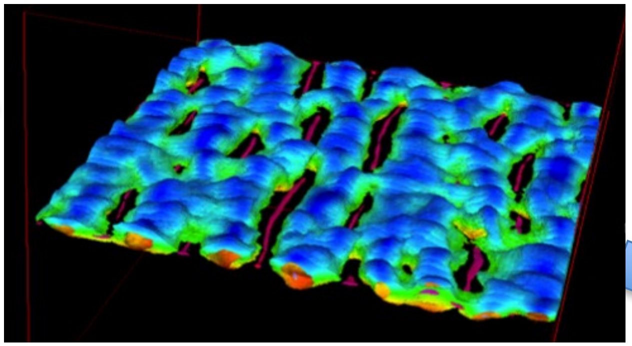
MHD, B $\neq$ 0



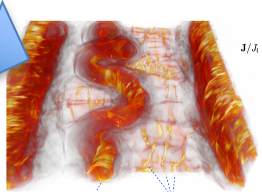
“Ribbons” stretched along B

Modern View:
Magnetic Dissipation in 3D Low-β Plasmas





$$\frac{\delta B}{B} \sim k^{-1/3}$$



Large Scale Energy Inputs: Turbulence, Instability, etc.

Current sheets formation

Particle Dynamics

$$R_L = 2 \times 10^3 \gamma / B \text{ cm}$$

$$d_e = 5 \times 10^5 \gamma^{1/2} n^{-1/2} \text{ cm}$$

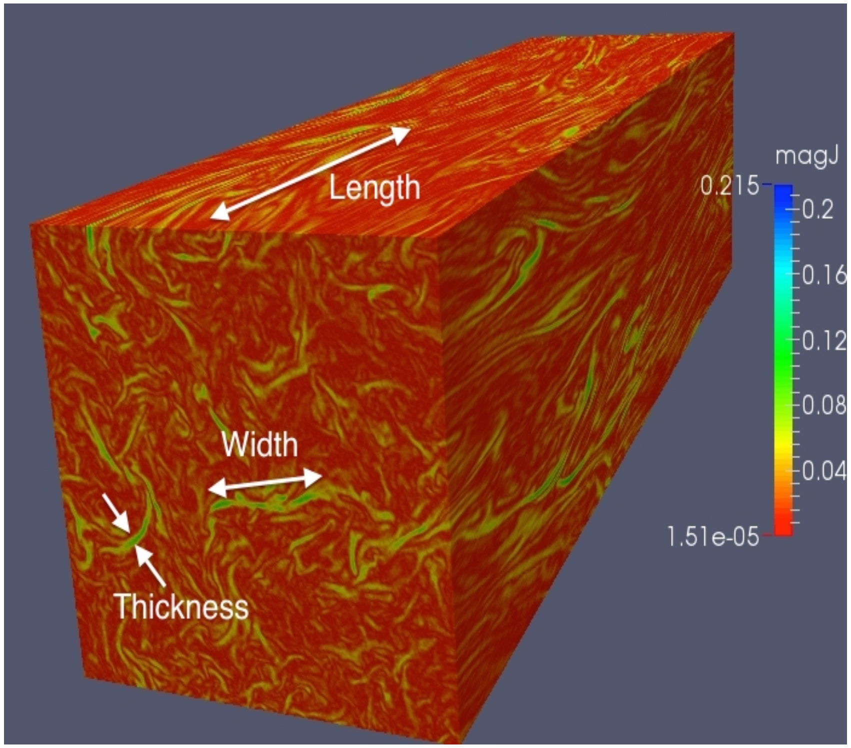
R

Wave-number = 1 / size

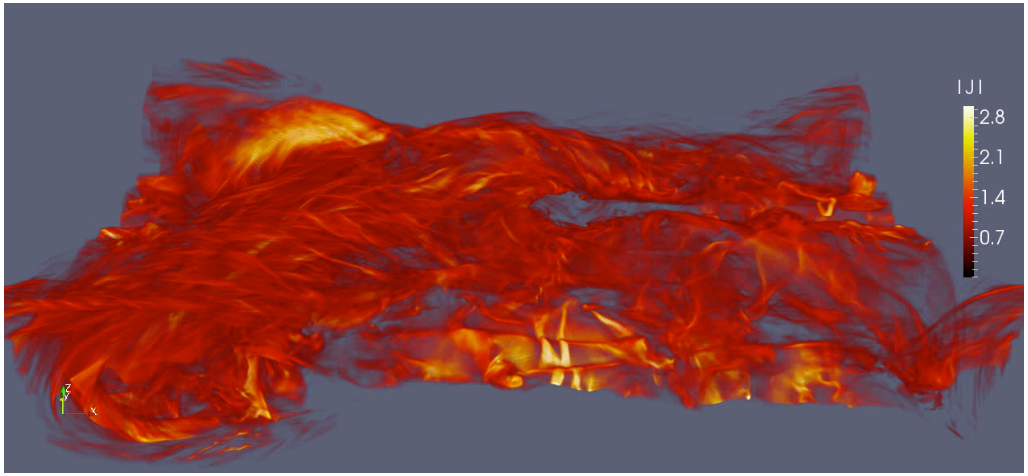
Turbulence, Current Sheets, Reconnection, First + Second Order Fermi Acceleration

VPIC: 3D Turbulence Cascade

VPIC: 3D Magnetic Reconnection



Makawana+'15; 17



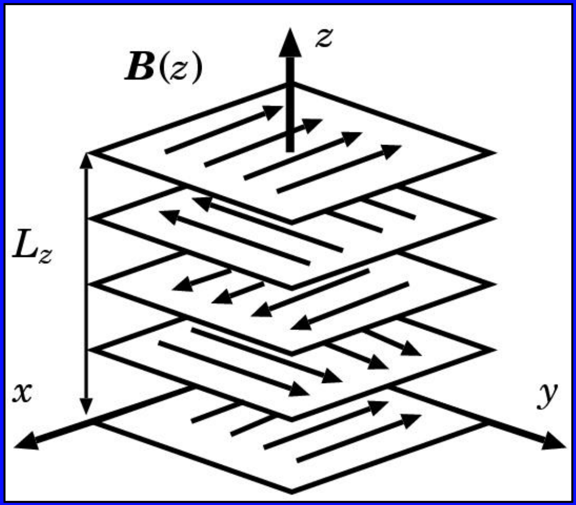
Guo+'17

An Early Effort:

3D FF Reconnection: Abundant current sheet formation and reconnection-driven turbulence

An idealized Problem

Sheet-Pinch:



$$B_x(z) = B_0 \cos \alpha z$$

$$B_y(z) = B_0 \sin \alpha z$$

$$B_z(z) = 0$$

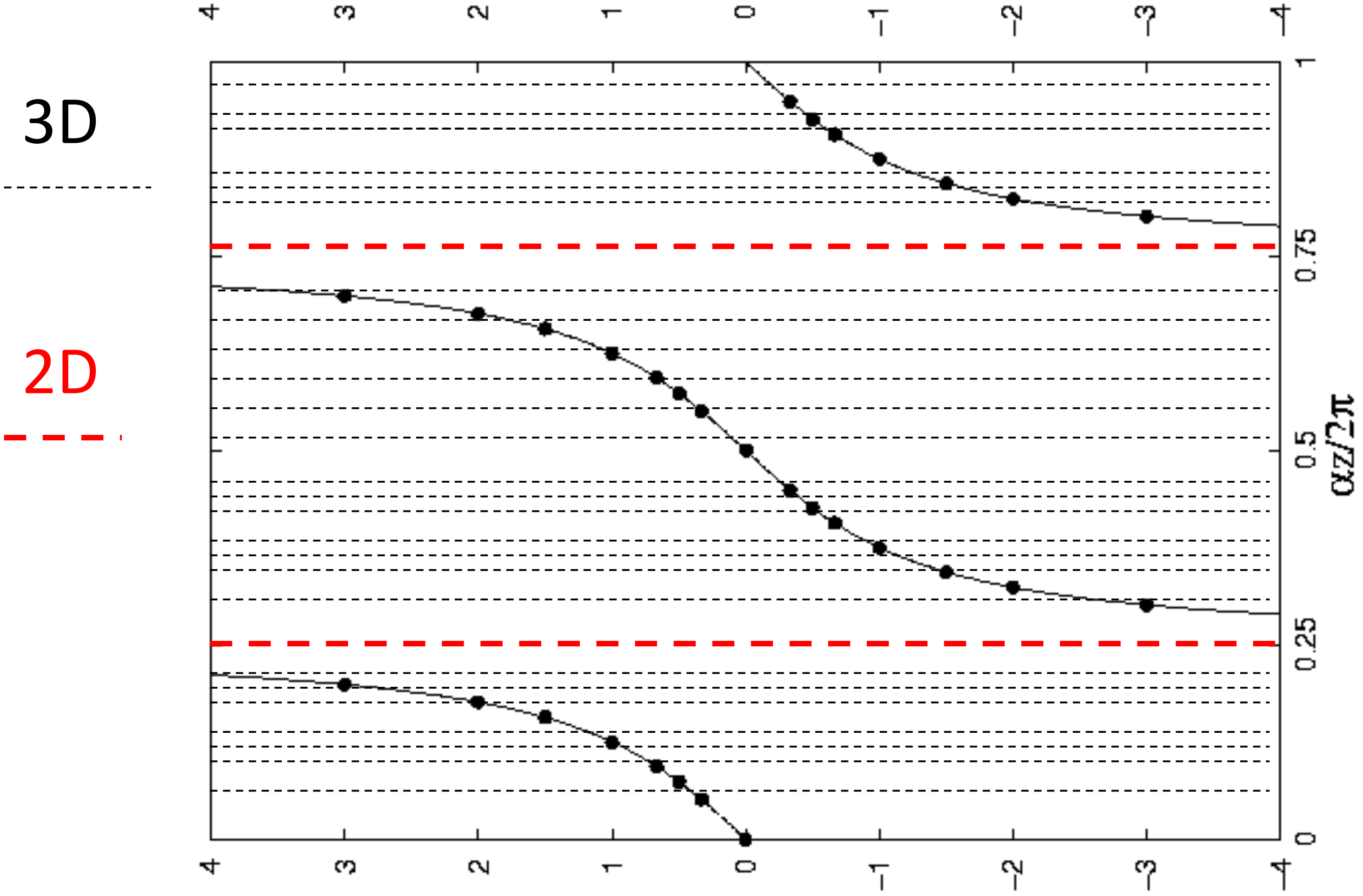
- MHD and kinetic equilibrium: Bobrova et al.'01
- Collisionless tearing unstable: Drake & Lee'77; Li et al.'03
- 2D simulations: Bobrova et al.'01; Nishimura et al.'03; Li et al.'03
- 3D simulations: Li & Bowers'03; Bowers & Li'06

- **Force-free;**
- **mi/me = 100;**
- **$\omega_{pe}/\Omega_{ce} = 1.93$**

Bowers & HL, PRL, 2007

Multiple Resonant Surfaces (q-profile)

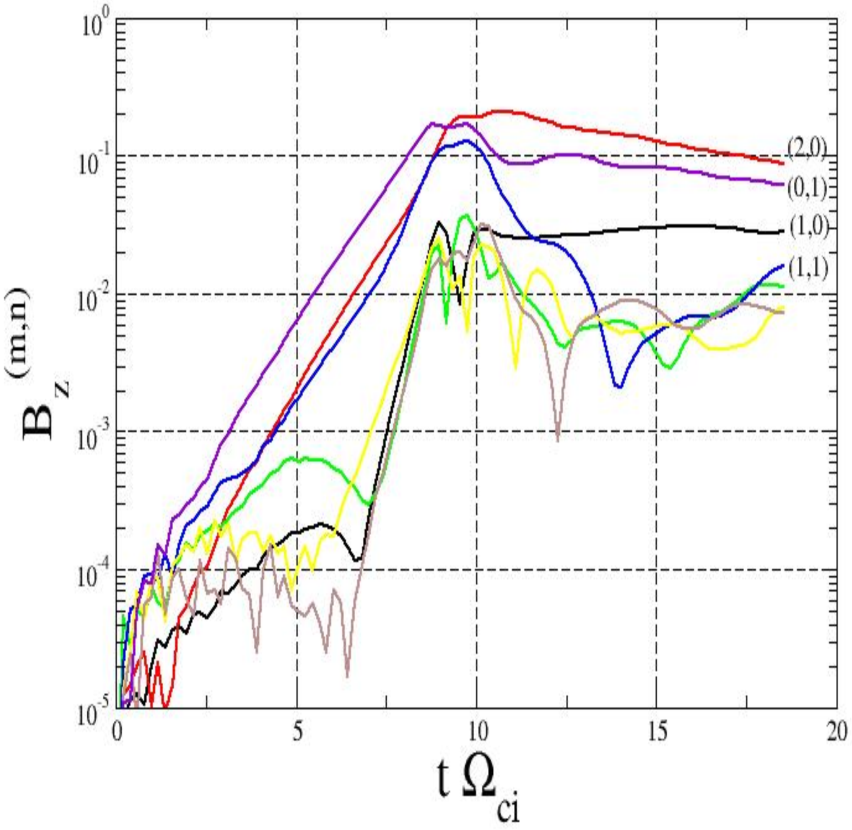
$q = B_y / B_x$

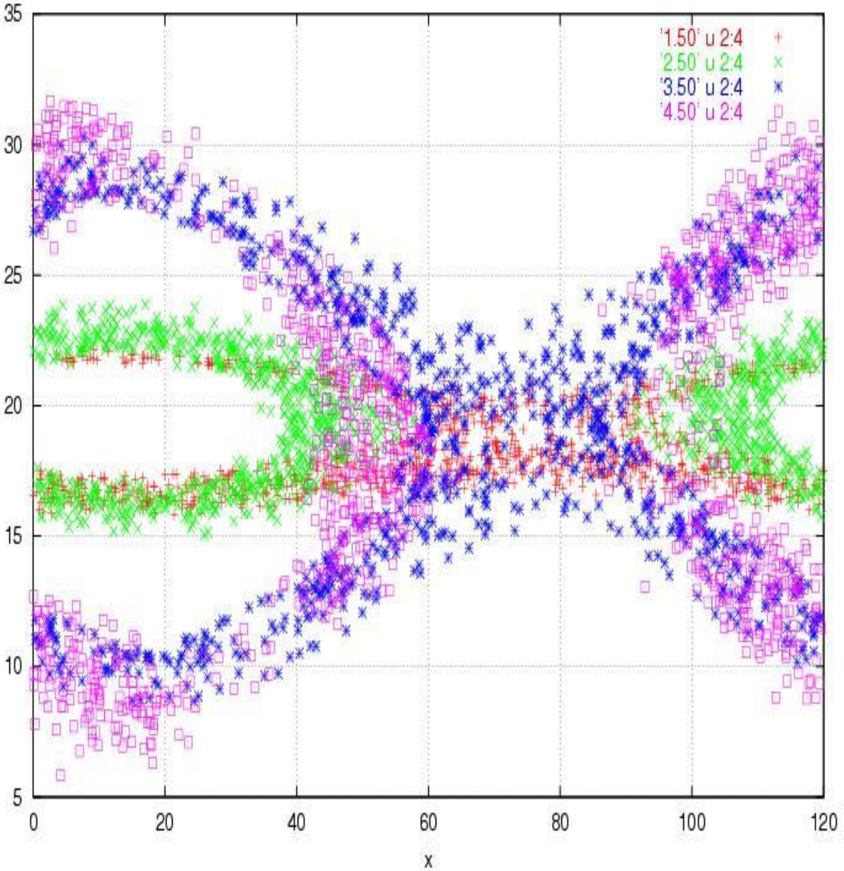


3D

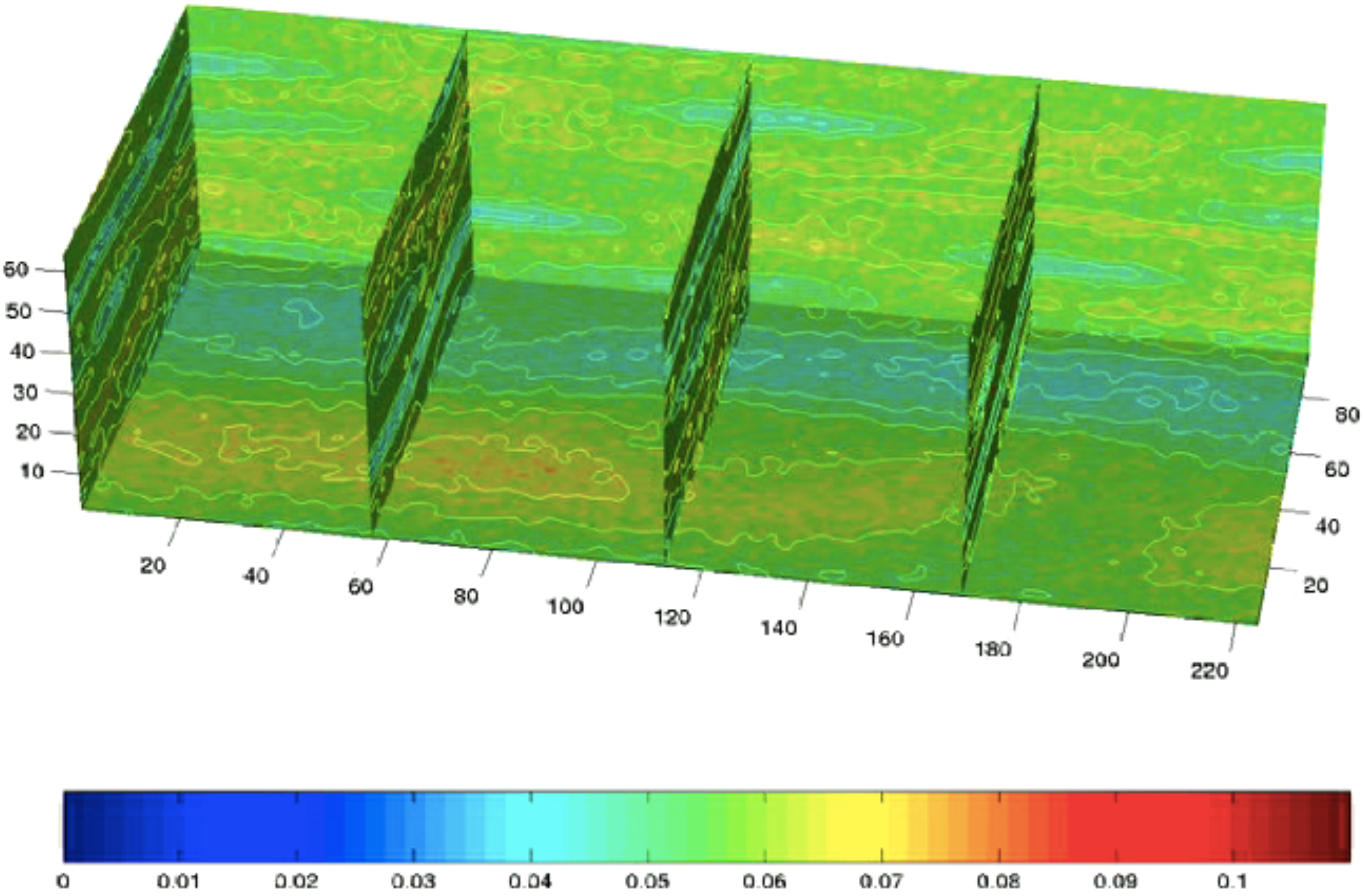
2D

Tearing Island Growth and Transition to Stochastic Field lines



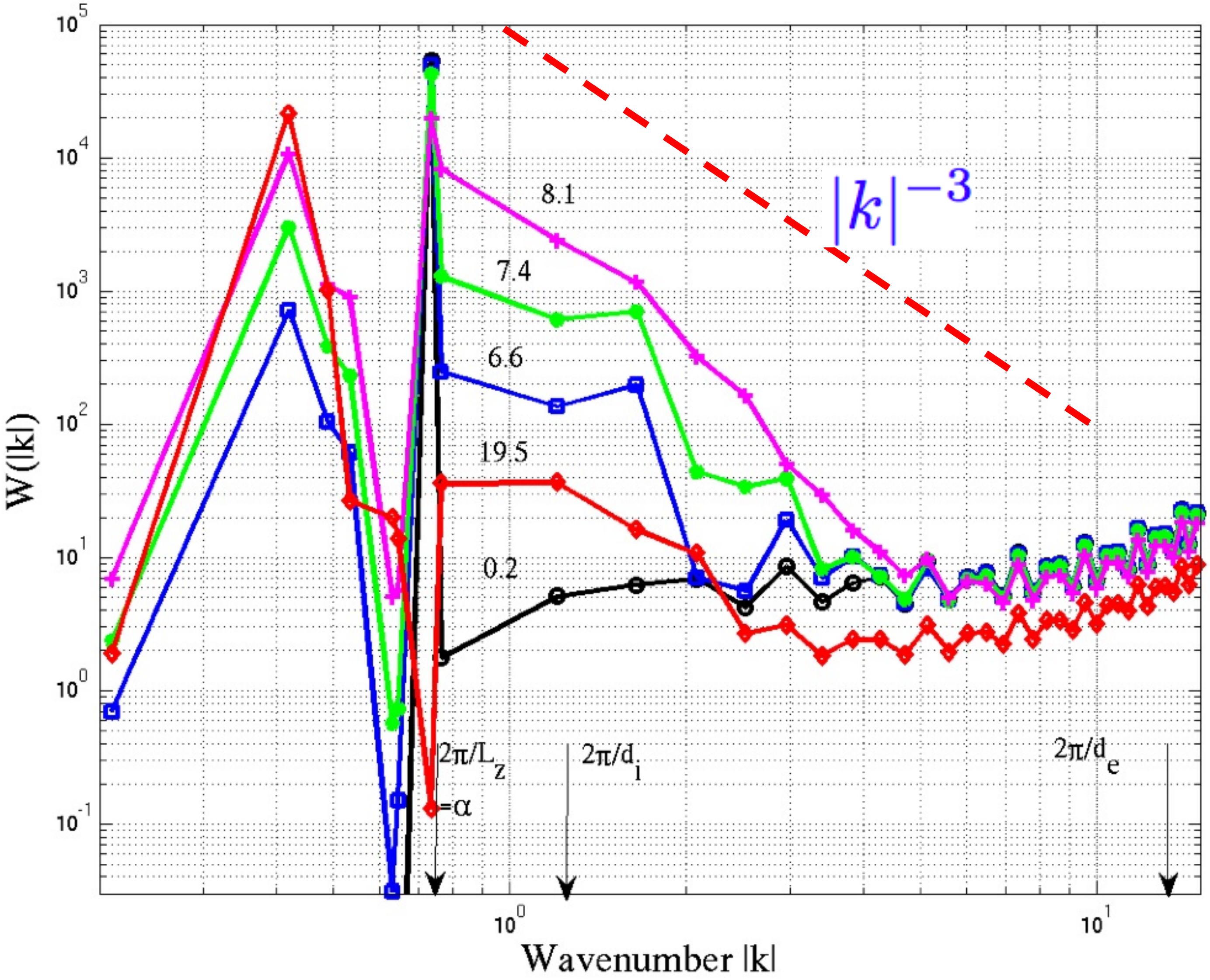


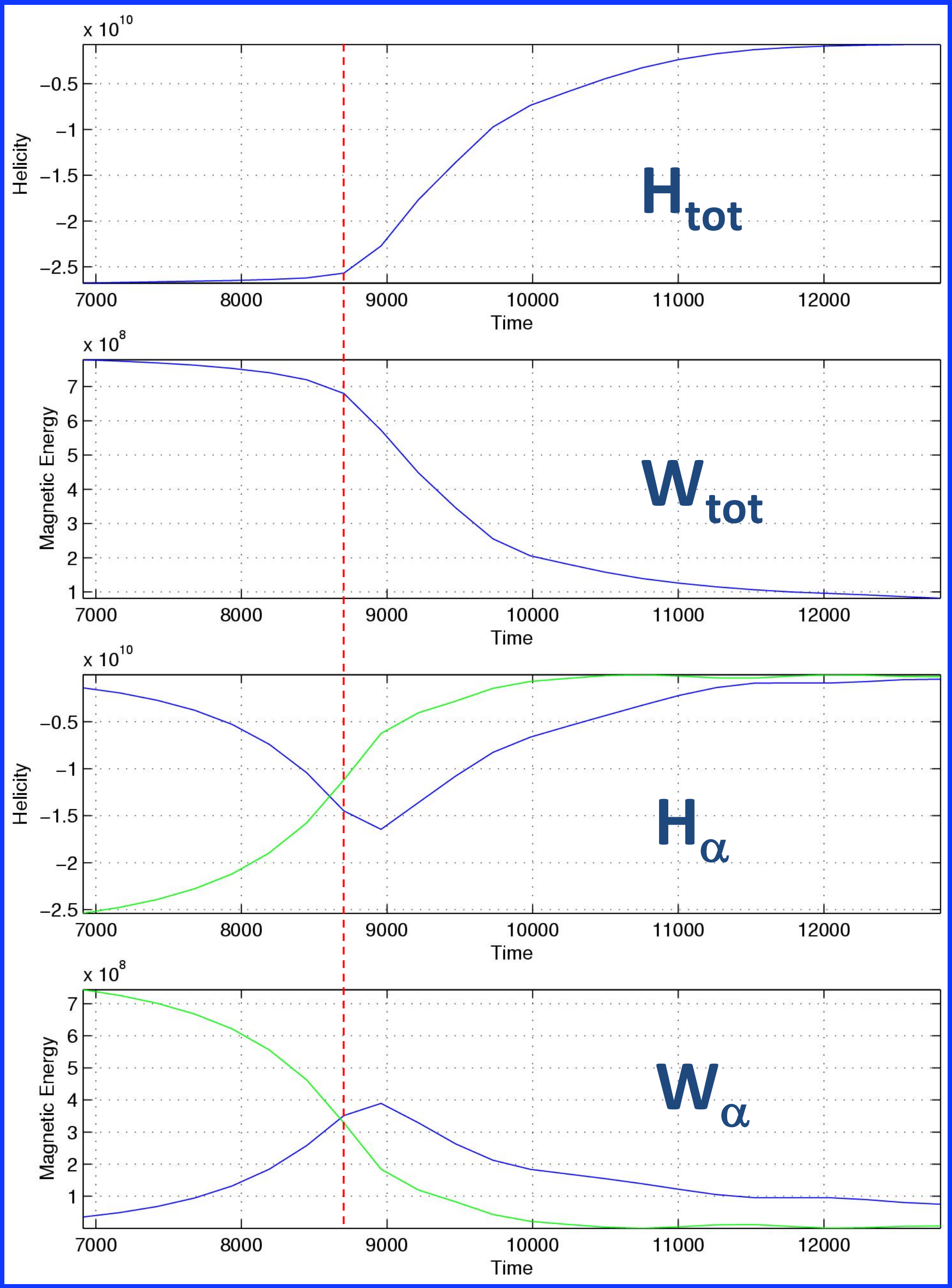
Global Current Sheets and Filamentation



Spectral Energy Transfer

$$\mathbf{E_B} = \int \mathbf{W}(|\mathbf{k}|)\mathbf{d}|\mathbf{k}|, \quad |\mathbf{k}| = \sqrt{\mathbf{k_x^2} + \mathbf{k_y^2} + \mathbf{k_z^2}}$$





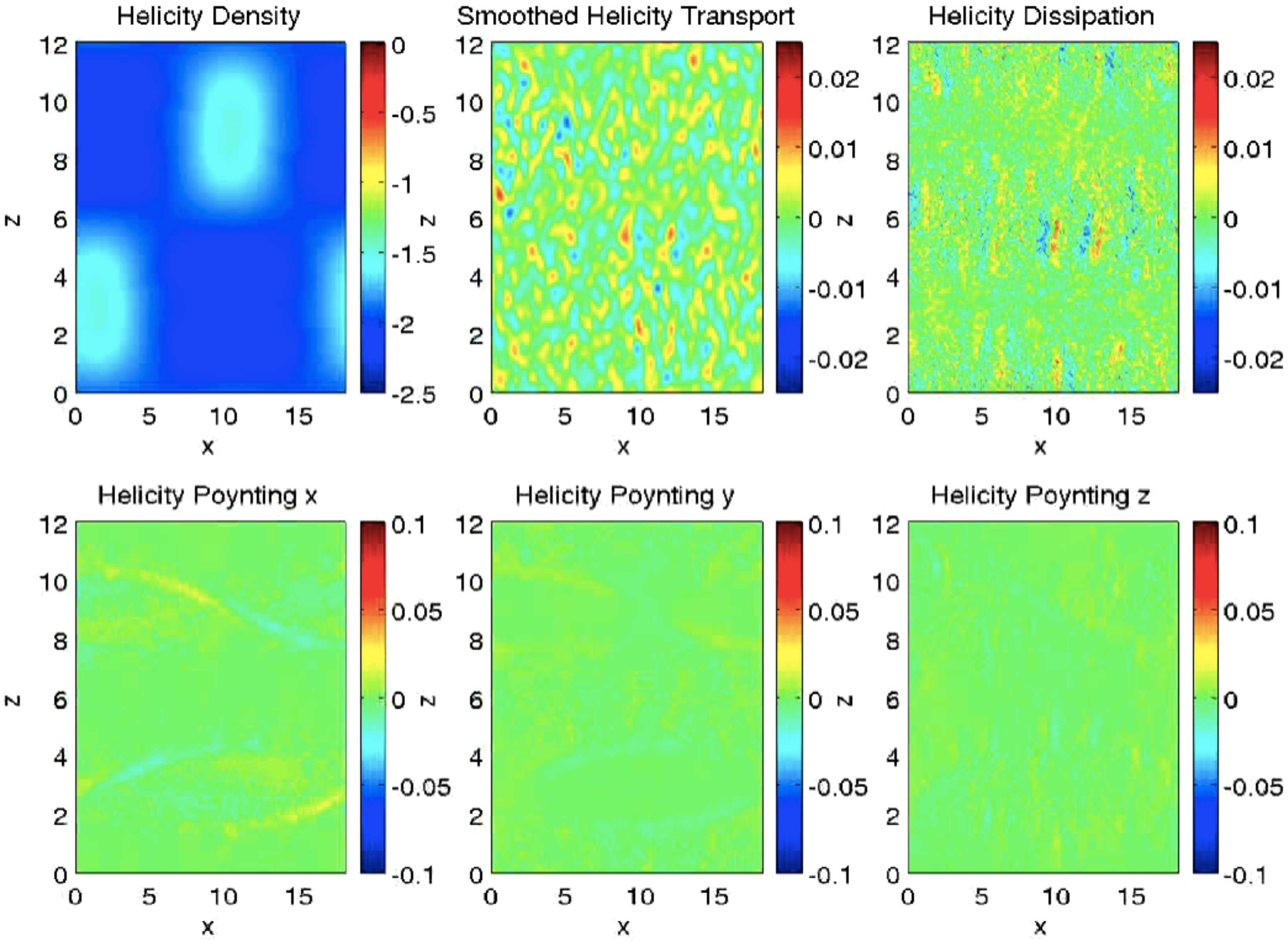
Helicity and Energy Evolution

Two Stage:

- Total H & W conserved but with significant spectral transfer, ideal MHD?
- Net H and W dissipation.

$$\int d^3x\,(A\bullet B) = \int d^3k\, H_k$$

$$H_k = \mathrm{Re}(A_k B_k^*)$$


Helicity Density
Smoothed Helicity Transport
Helicity Dissipation
Helicity Poynting x
Helicity Poynting y
Helicity Poynting z
z
x
0
2
4
6
8
10
12
0
5
10
15
-2.5
-2
-1.5
-1
-0.5
0
-0.02
-0.01
0
0.01
0.02
-0.1
-0.05
0
0.05
0.1

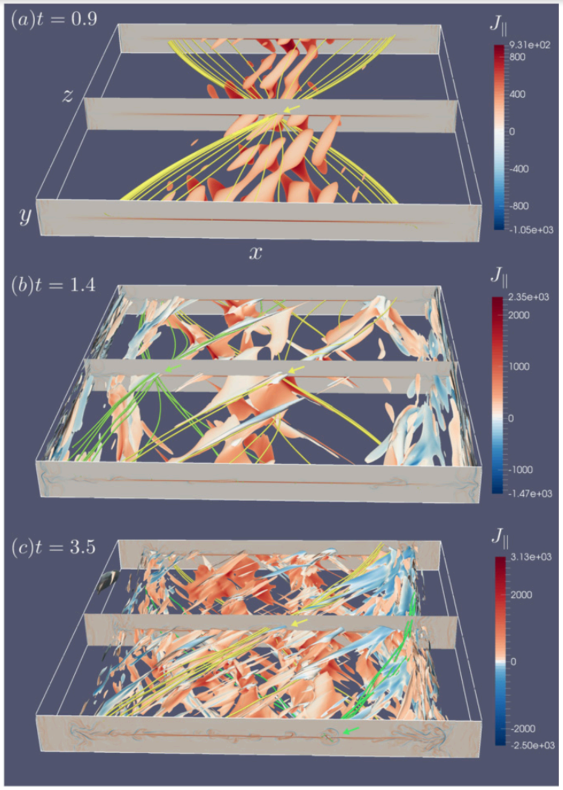
Part 4 & 5: Turbulence vs. Reconnection

Different forms of initial free energy and the associated Particle energization

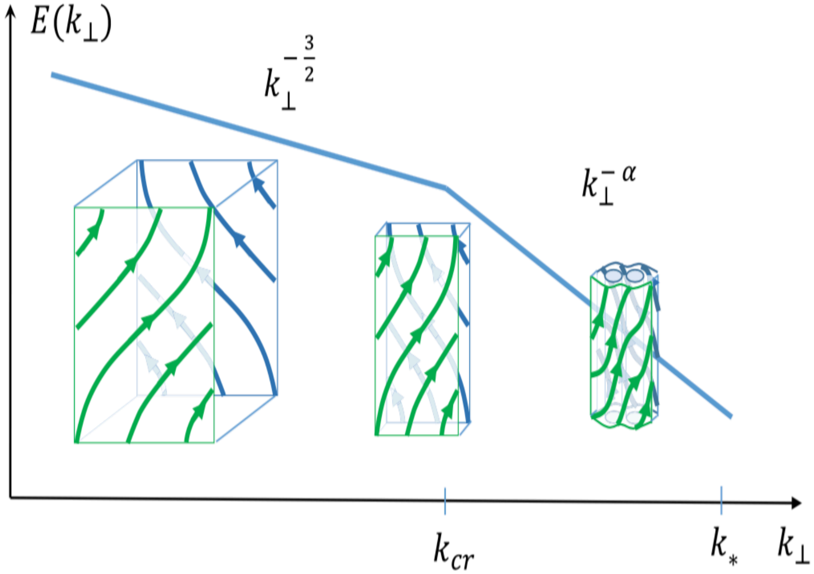
Turbulence & Reconnection: Two Different Forms of Free Energy

Free Energy: CS
shear B fields (CSs)

Free Energy: Turb
injected turbulence



Drake et al
Huang & Bhattacharjee’16
Many others



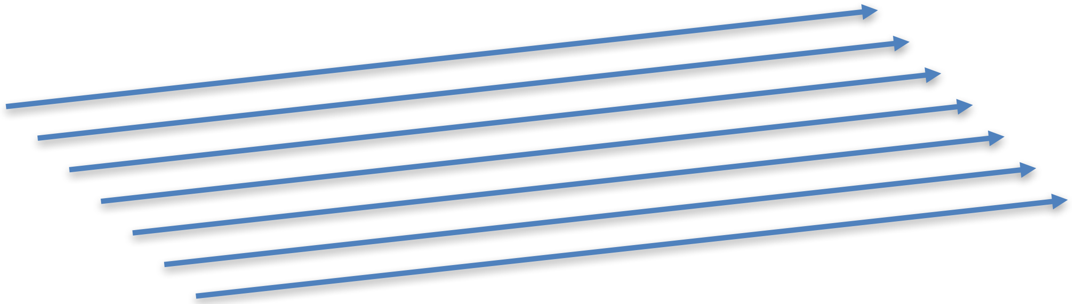
Beresnyak et al.
Boldyrev et al.
Uzdensky’15
Loureiro & Boldyrev ’16,17
Zhdankin et al.
Many others

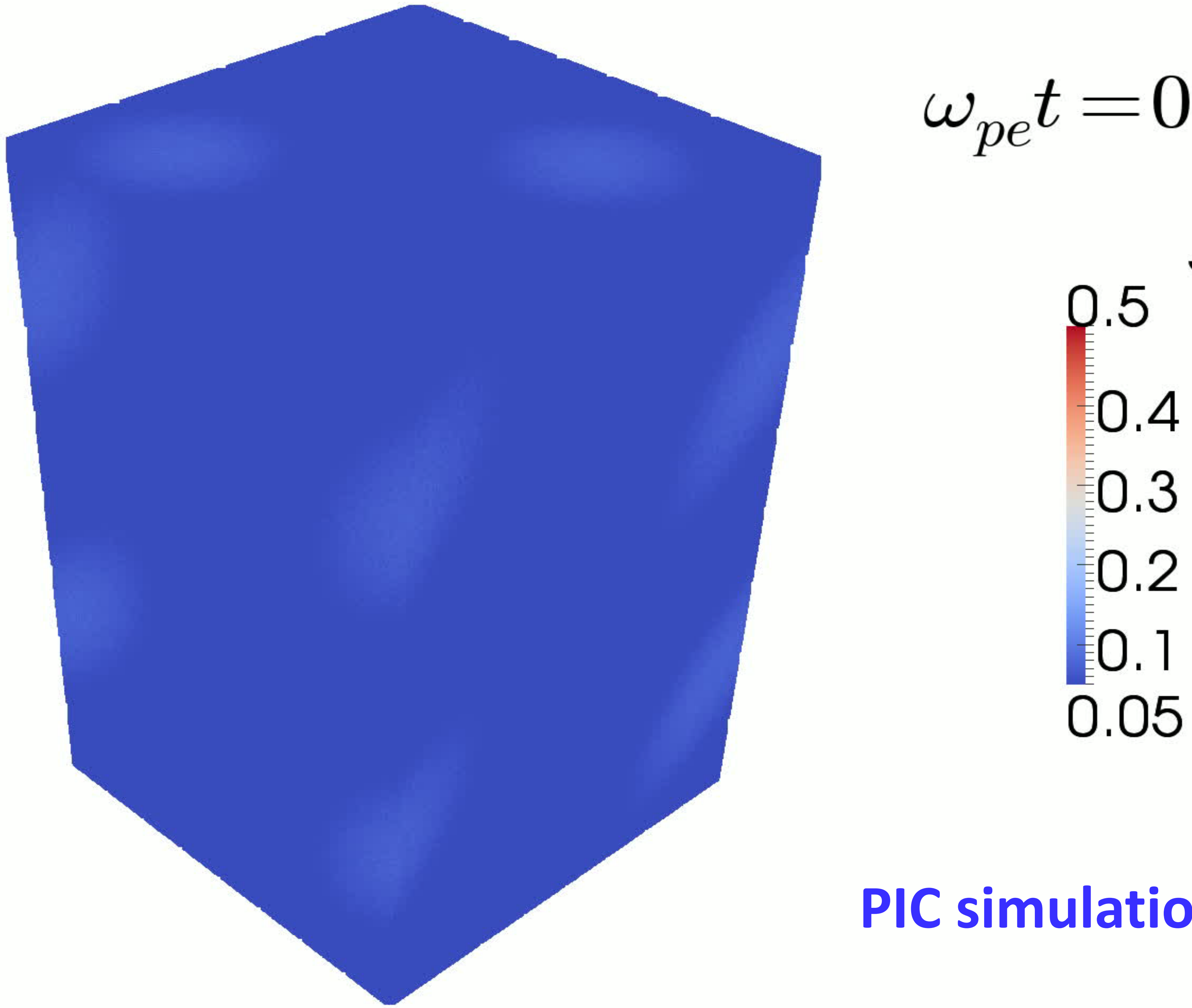
Three Cases:

- Case (A): uniform background B field + injected turbulence at large-scale
- Case (B): unstable magnetic shear (current sheets) without initial turbulence
- Case (C): unstable magnetic shear (current sheets) with initial turbulence

Free Energy (A):

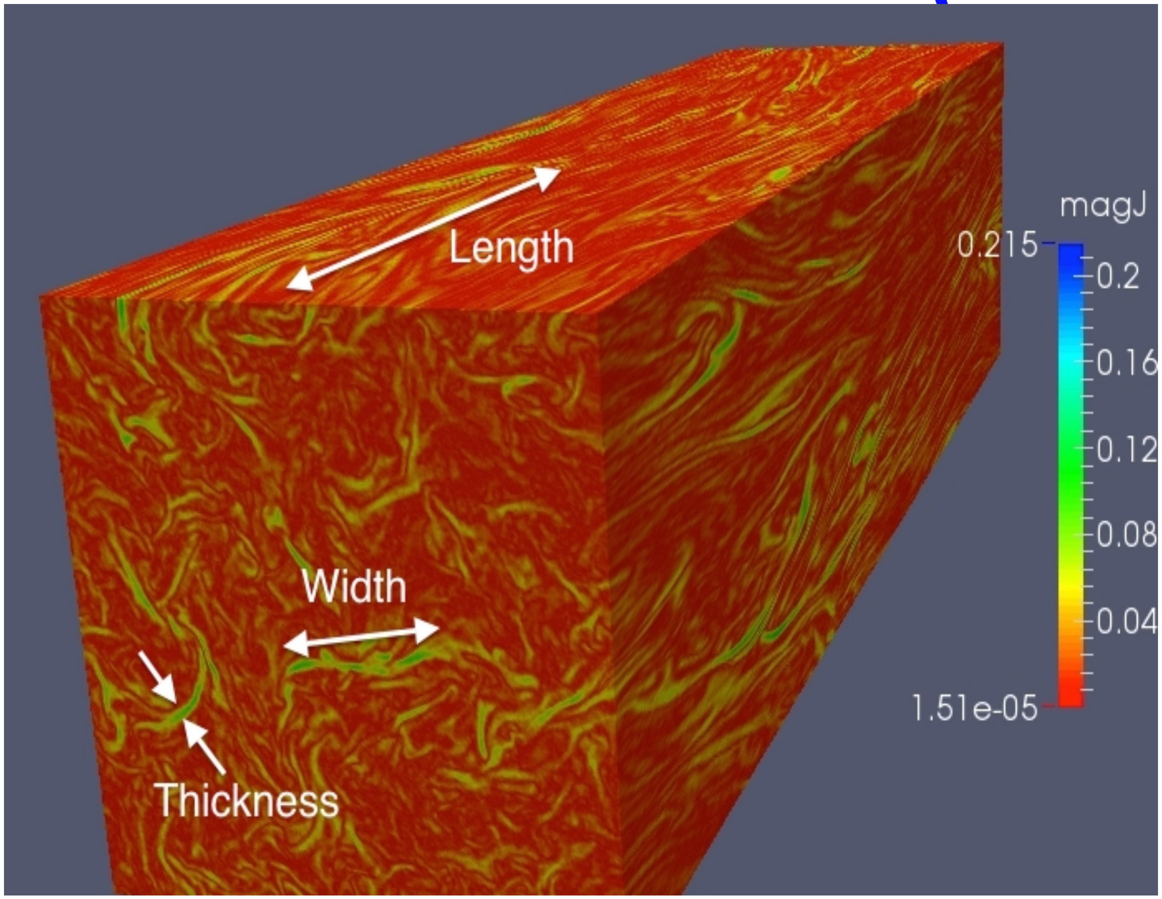
Externally Injected Turbulence with a mean B_0





PIC simulations

Spontaneously Formed Current Sheets associated with cascade (PIC sim.)

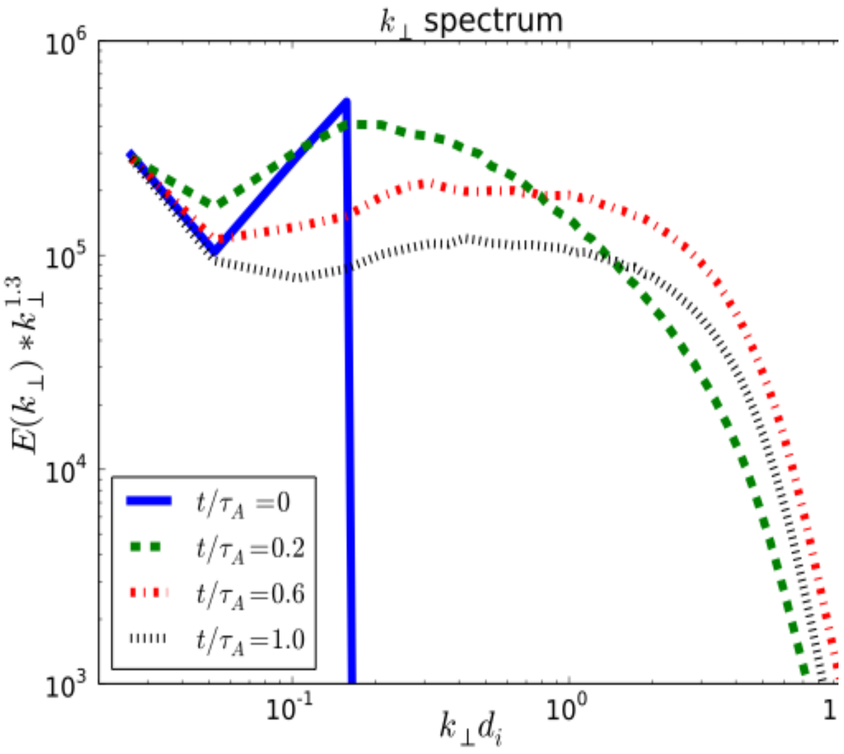


Makawana+'15; 17

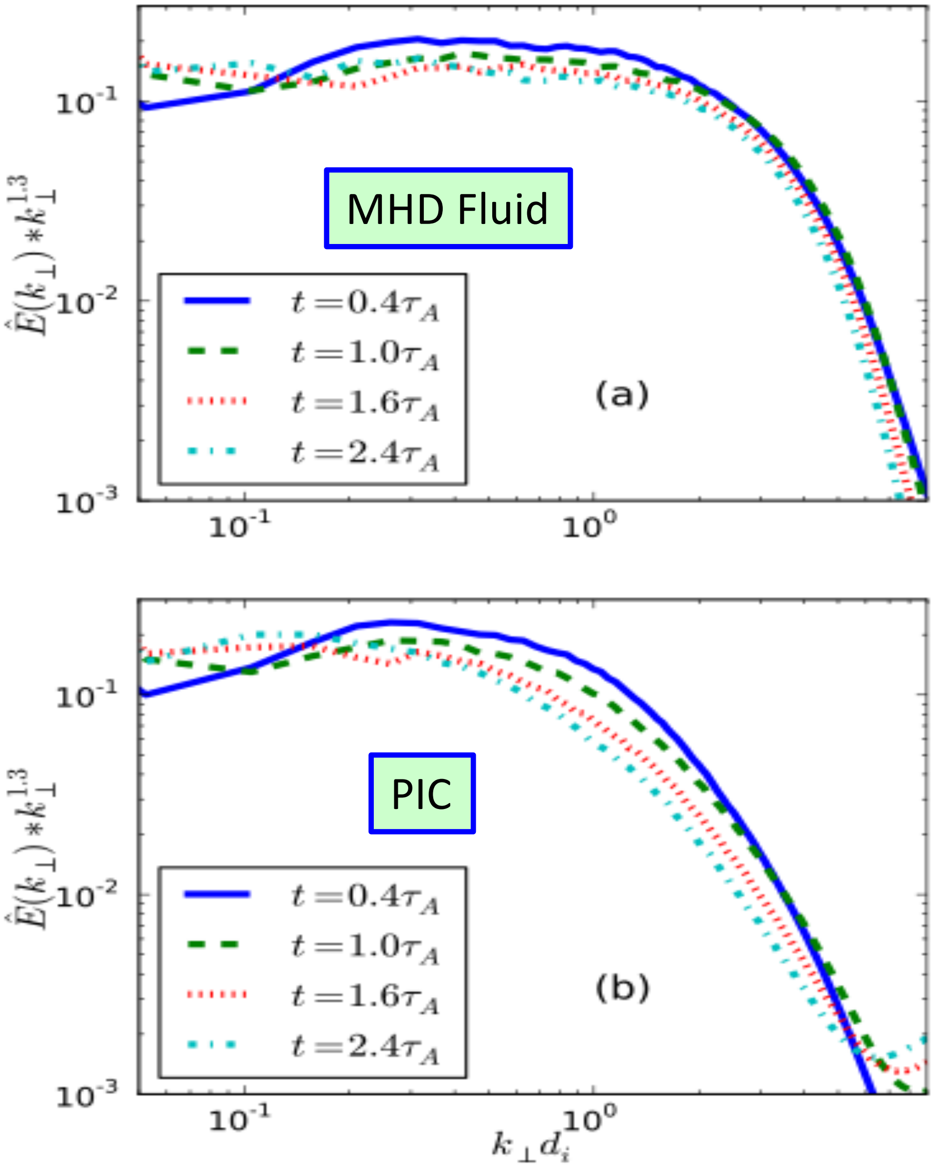
VPIC sim

Run	$L_x(d_i)$	$L_y(d_i)$	$L_z(d_i)$	$N_{x,y,z}$
IV	480	480	1920	1152

Evolution of energy spectrum

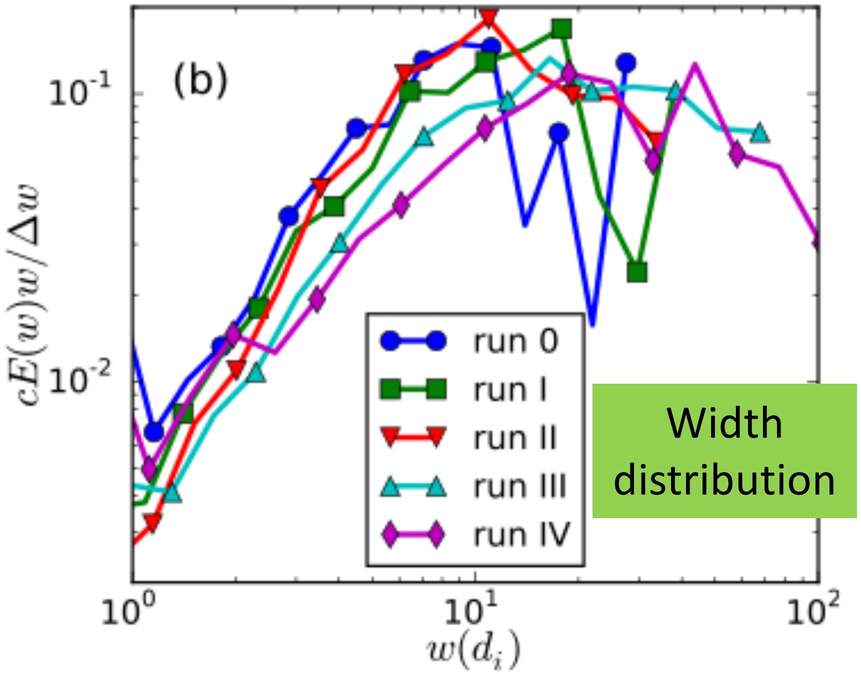


Spectrum fills up rapidly and decays

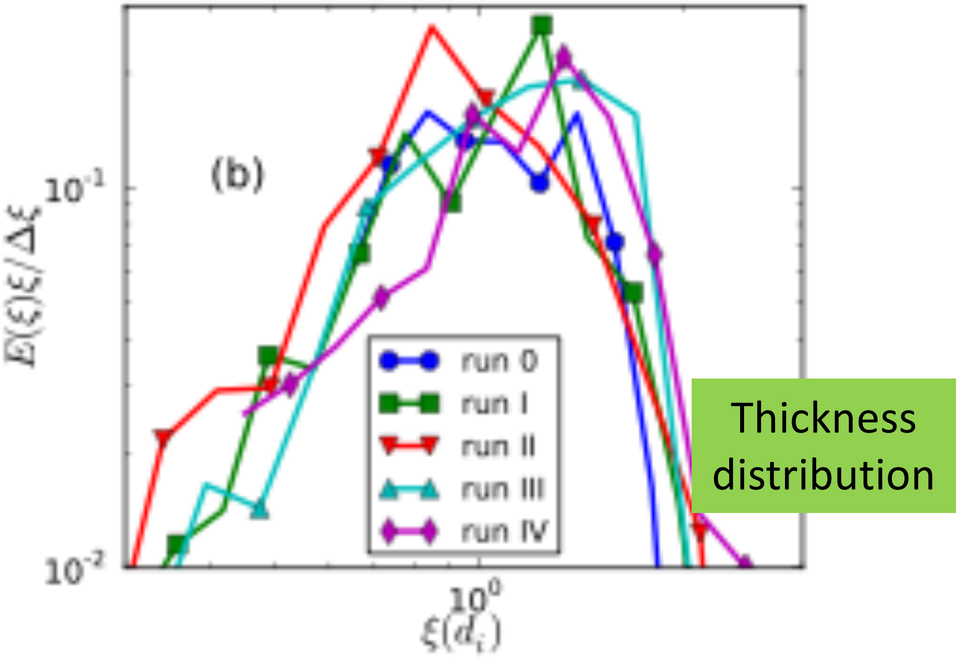


CSs from turbulent cascade could be "paper-like"

Makwana+ 2015



Width distribution



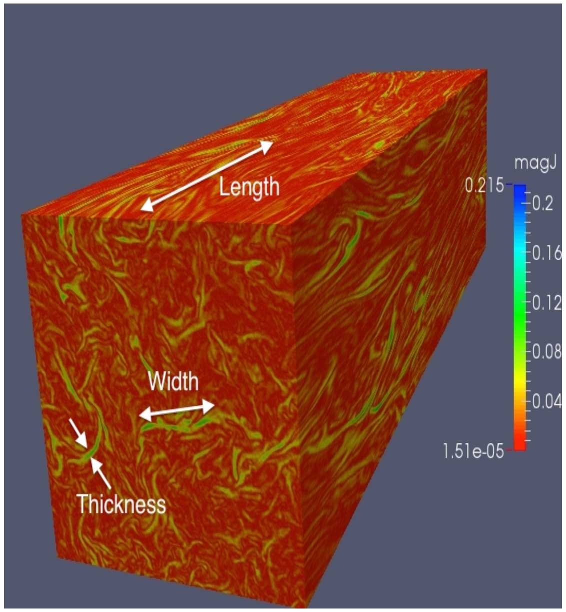
Thickness distribution

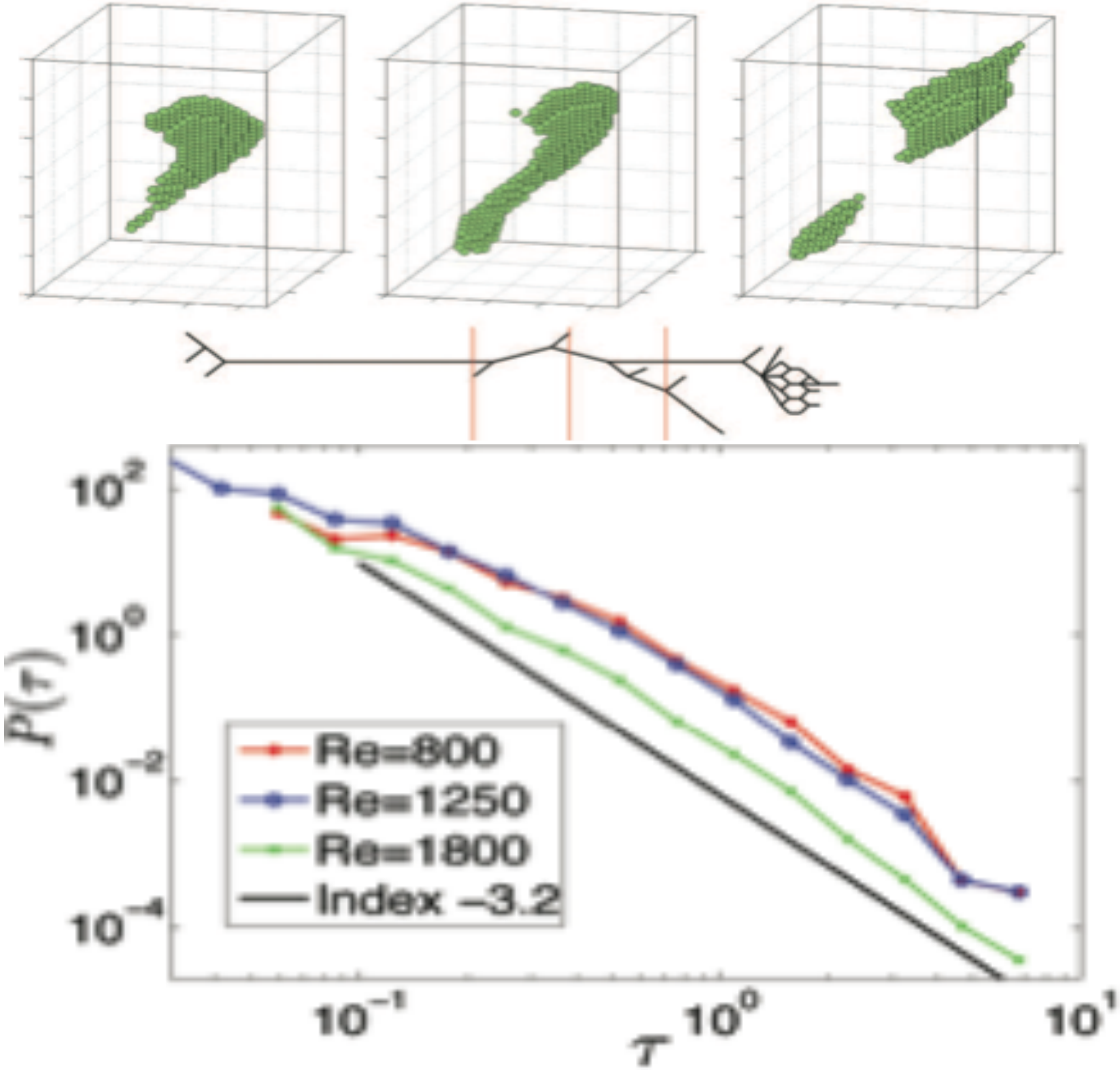
$$\text{width} \sim 10 d_i \qquad \text{thickness} \sim d_i$$

$$\text{Aspect Ratio} \sim 10$$

See also
Zhdankin et al. 2014, 2017

But: 1) Sheets have finite lifetimes

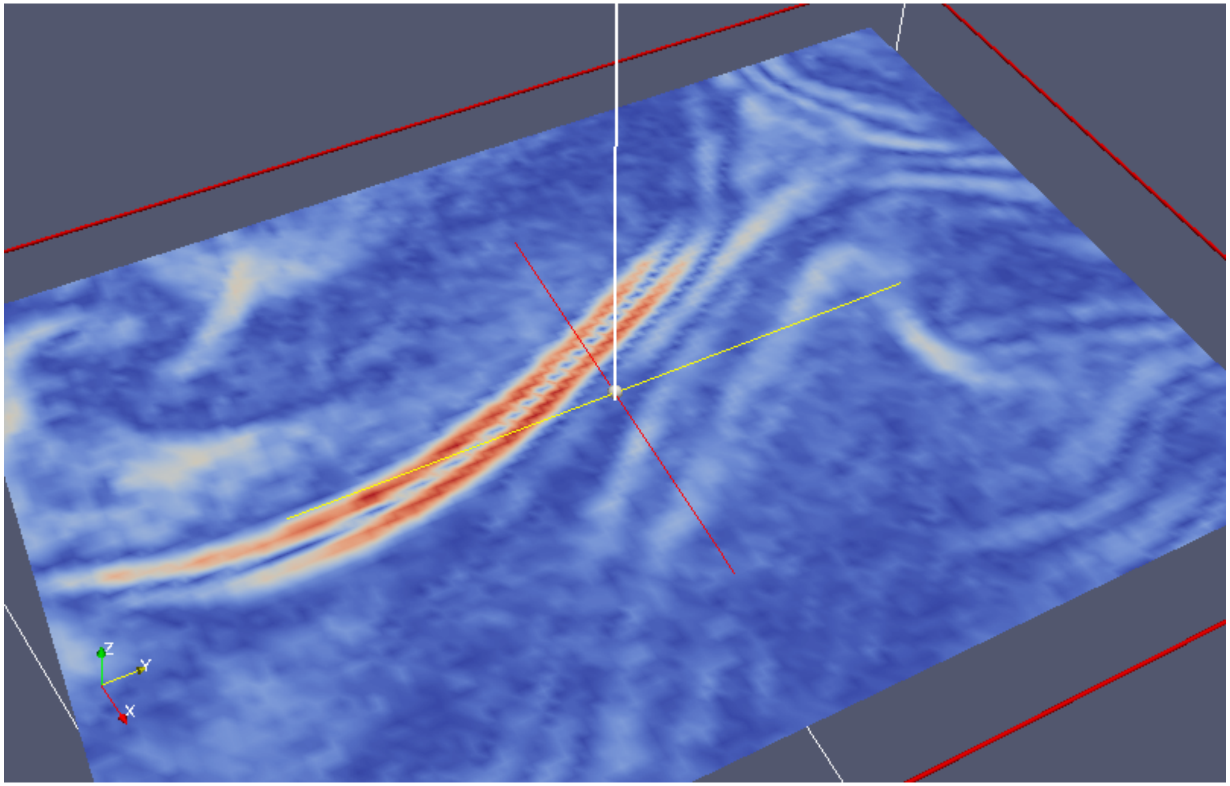




Zhdankin, et al., (2014, 2015)

But: Sheet are

2) Dynamic; 3) not force-free



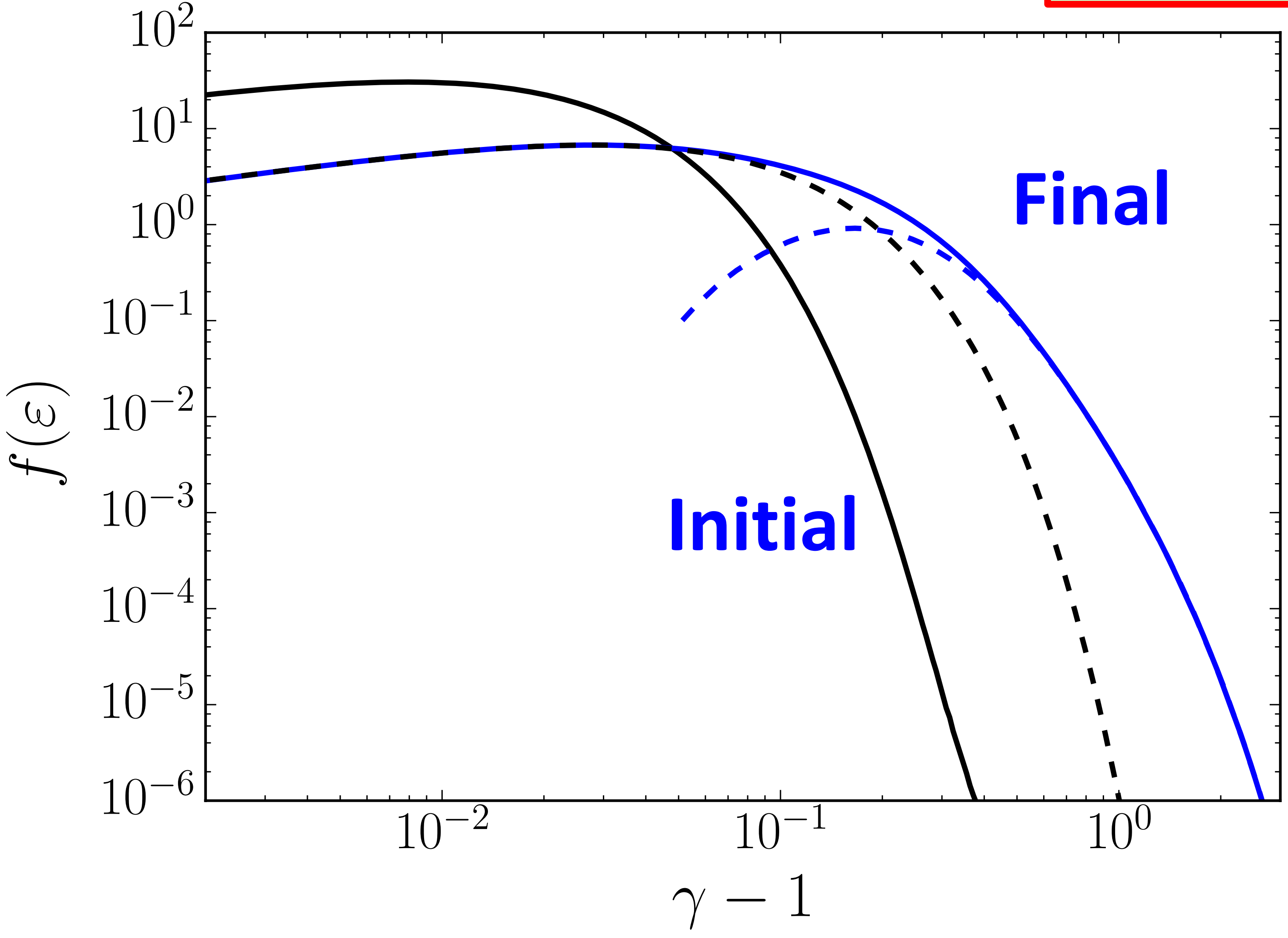
|JxB|

Non-force-free

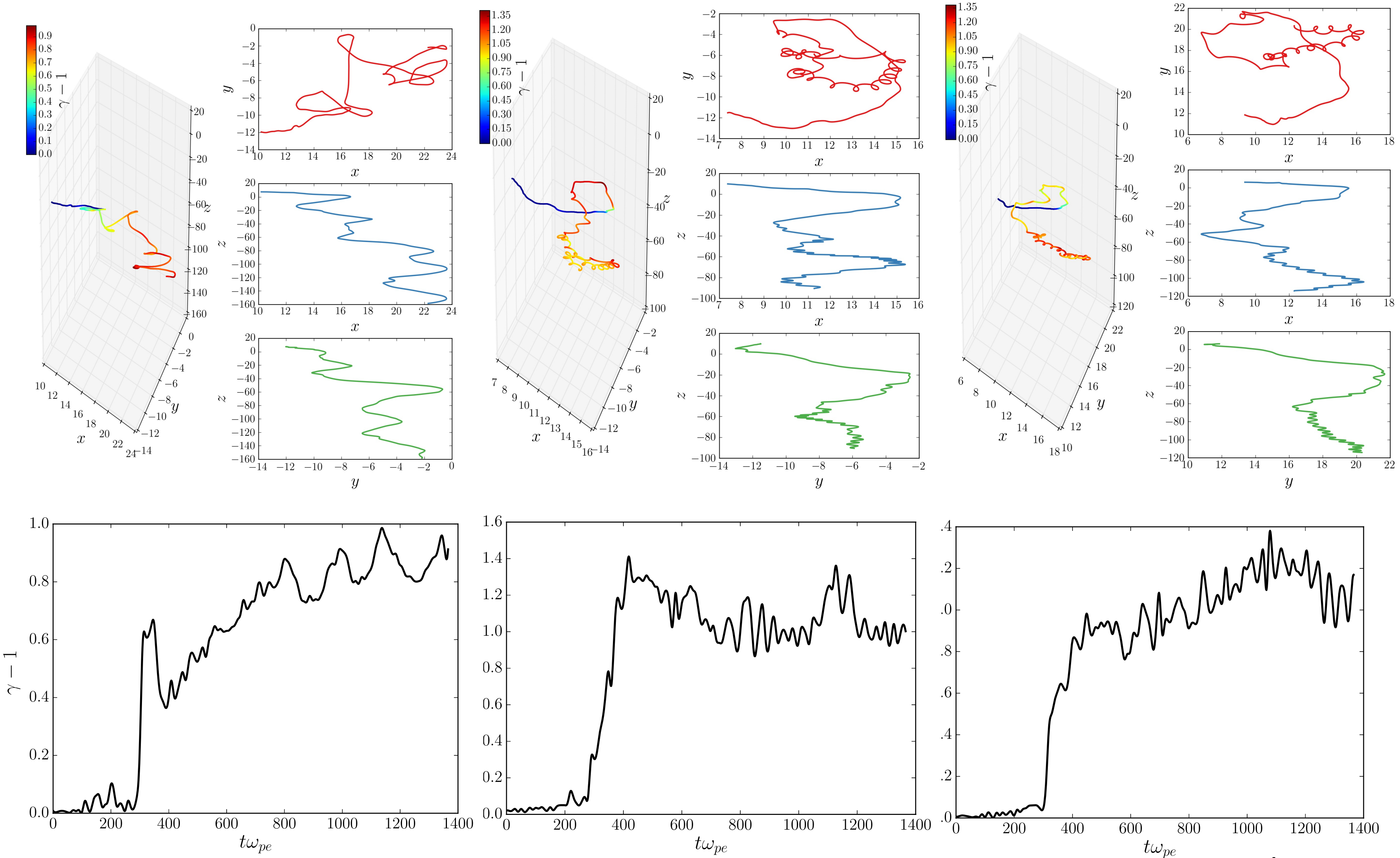
Makwana et al. 2015
See also Zhdankin et al. 13,14

Particle Energy Gain is modest

$\beta_e = 0.02$



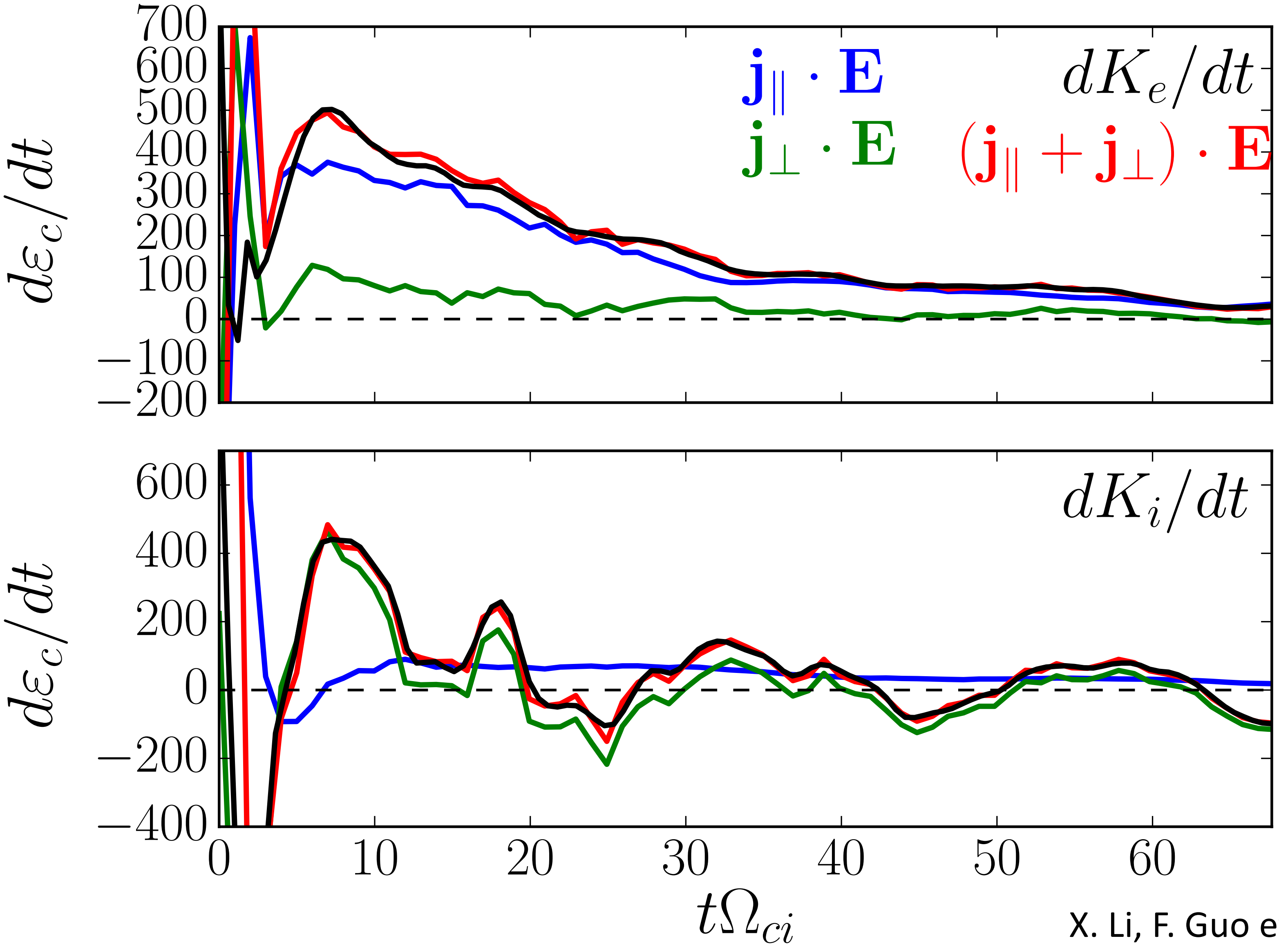
Sample Particle Trajectories



X. Li, F. Guo et al. 2016

E_parallel Dominant

$\beta_e = 0.02$



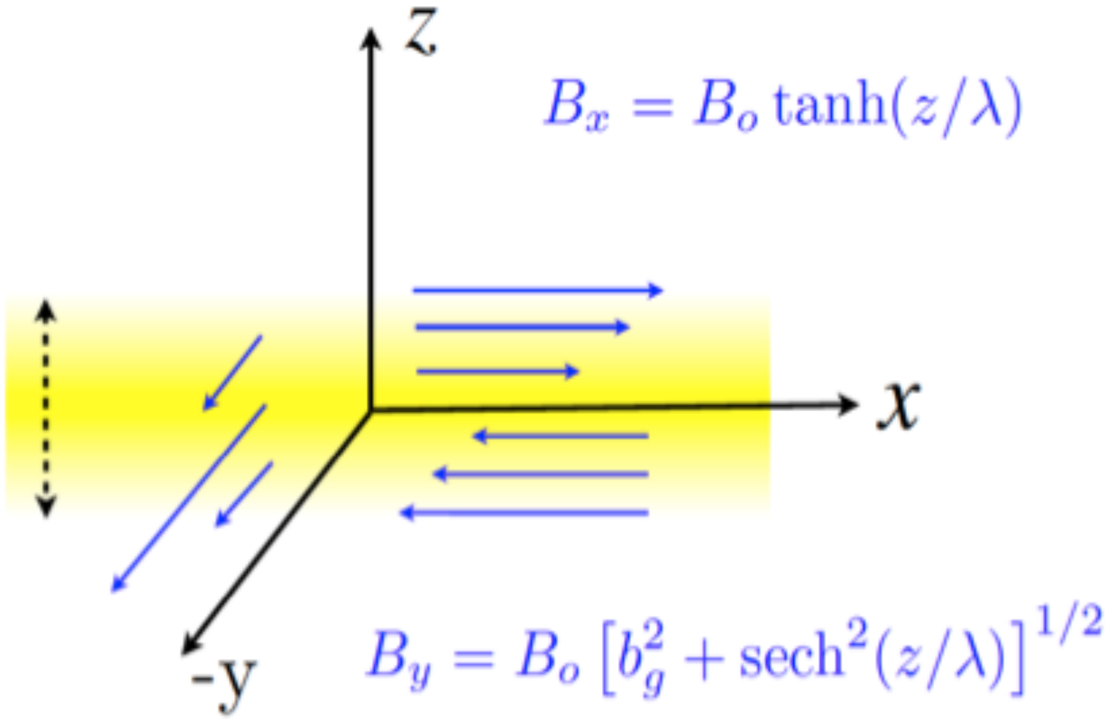
X. Li, F. Guo et al. 2016

Case A: Brief Summary

- With free energy as injected turbulence, the cascade process forms “transit” current sheets;
- These sheets have strong guide fields, live within one Alfven time and unstable;
- Particle energization is mostly via E_parallel at these sheets, though second order energization is possible (needs much longer time).

Free Energy (B):

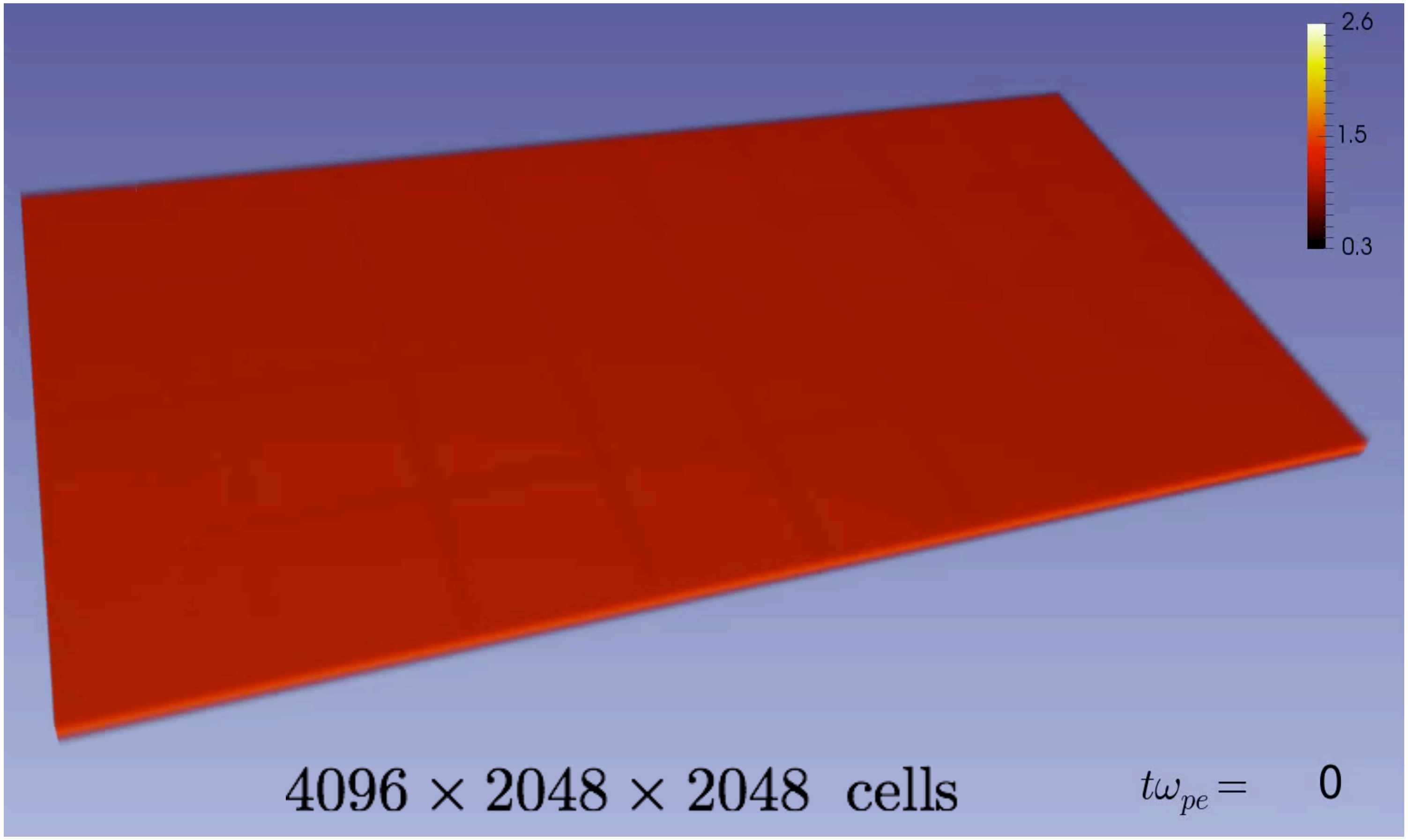
magnetic shear associated with current sheets



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

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

Driven by 3D global reconnection, release of significant fraction of magnetic energy and produce "turbulence"

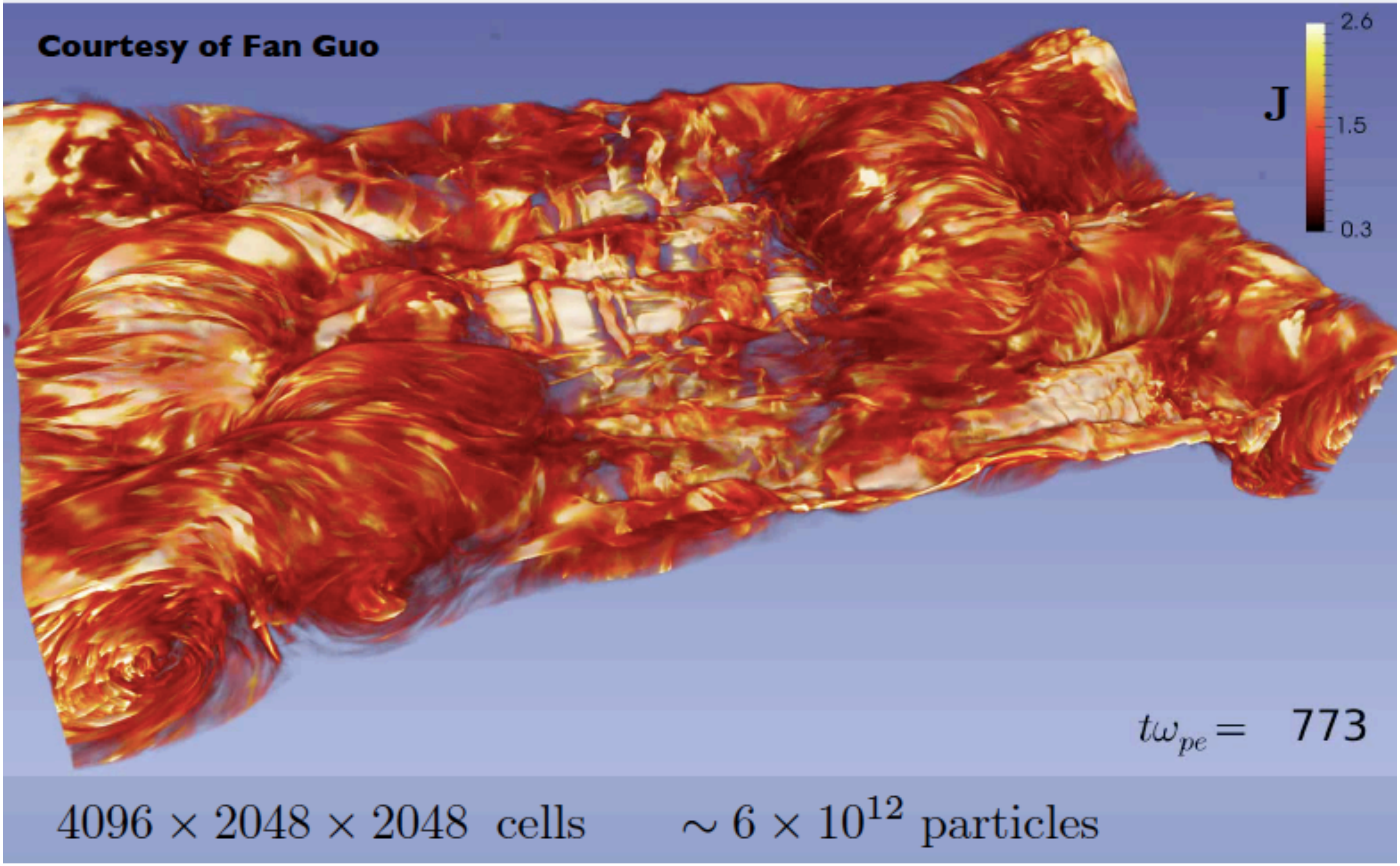


$\sim 5.2 \times 10^{12}$ particles track $\sim 10^{8}$ particles

Guo et al. 18

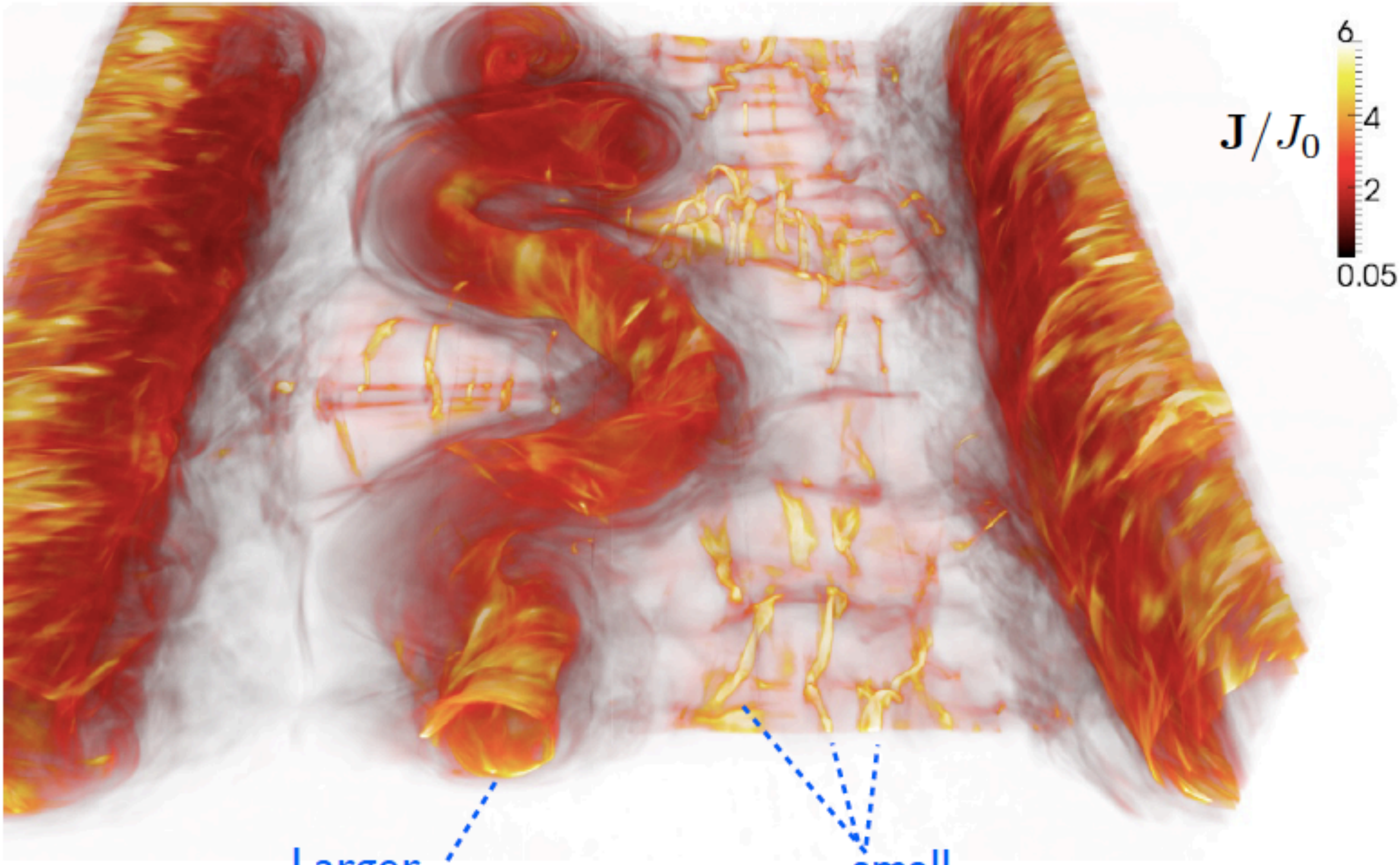
Trinity machine is permitting even larger runs!

VPIC is now open source - https://github.com/losalamos/vpic.git
Visualization & analysis tools included in ParaView



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

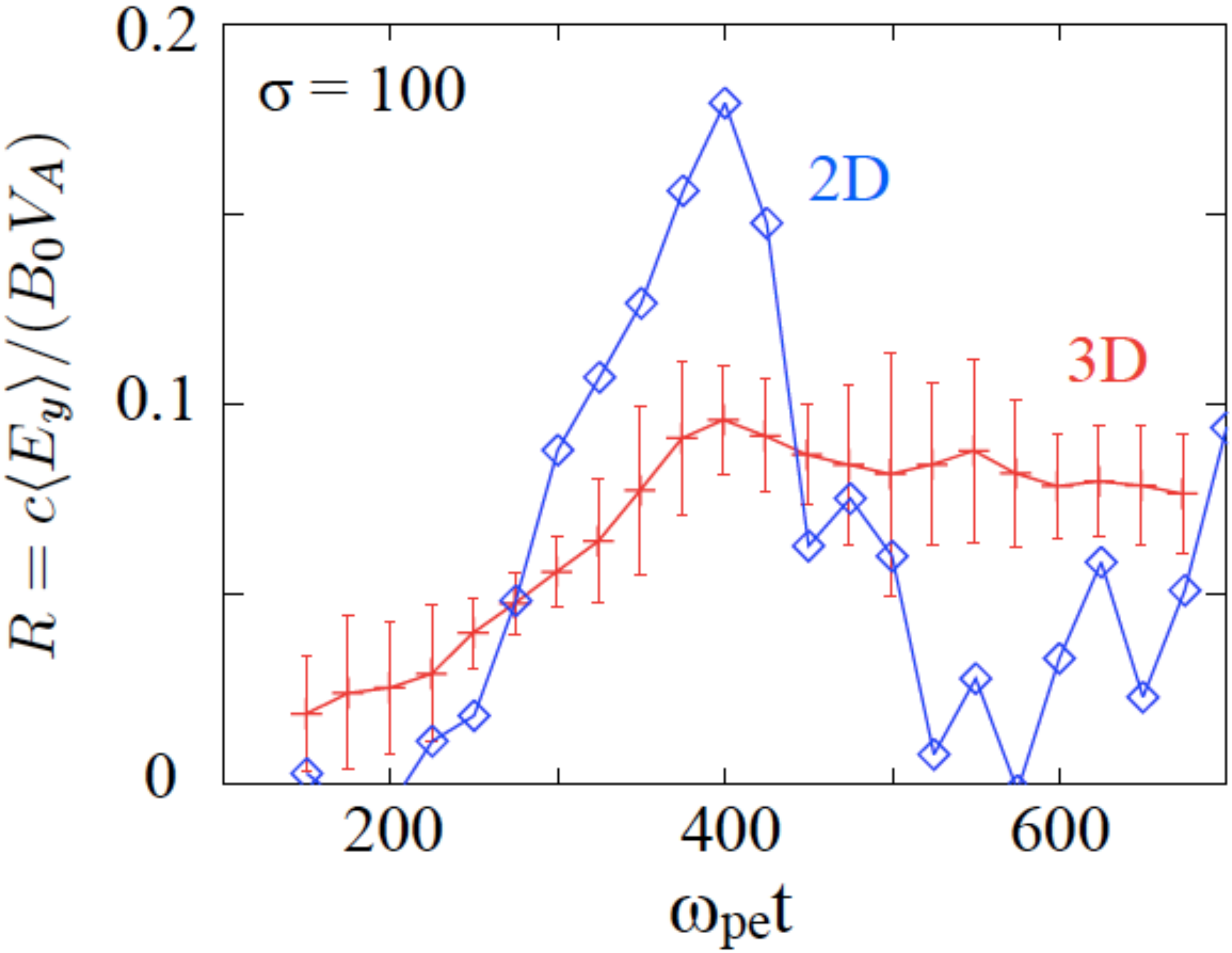
Interacting Flux Ropes are Kink Unstable



Larger
flux rope

small
flux ropes

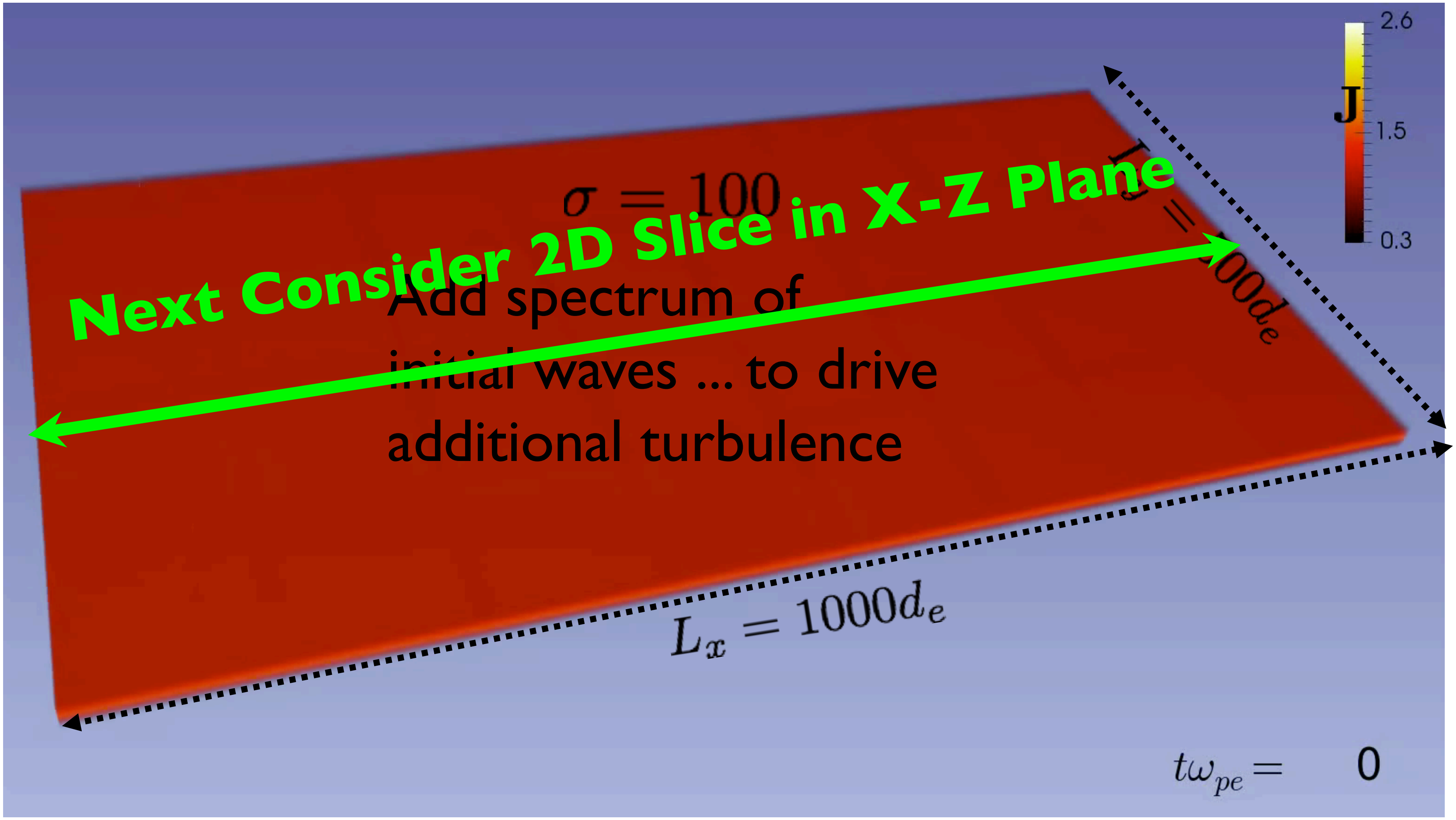
Only modest difference in 2D vs 3D Reconnection Rate



~50% reduction in peak rate
- similar to non-relativistic pair plasma

Trinity machine is permitting even larger runs!

VPIC is now open source - https://github.com/losalamos/vpic.git
Visualization & analysis tools included in ParaView

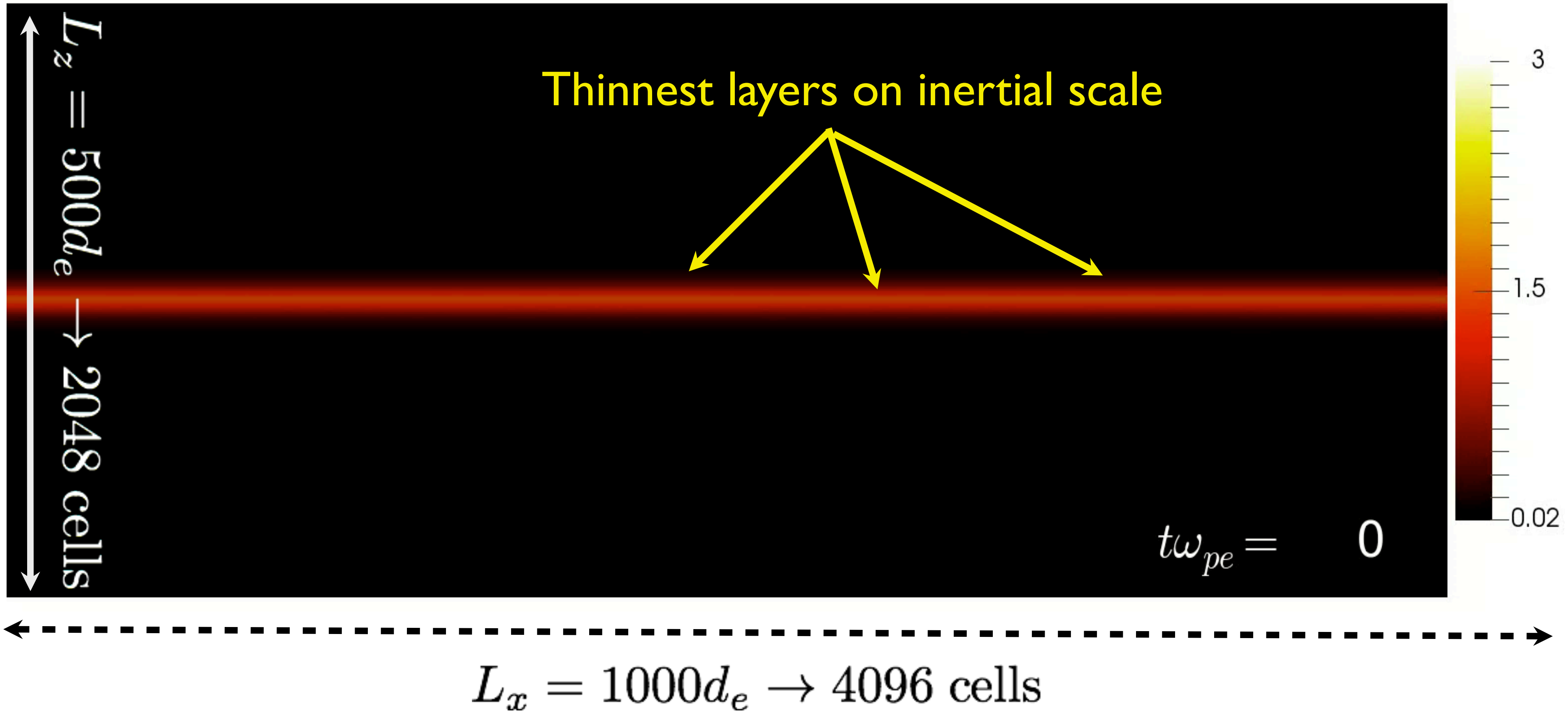


Next Consider 2D Slice in X-Z Plane

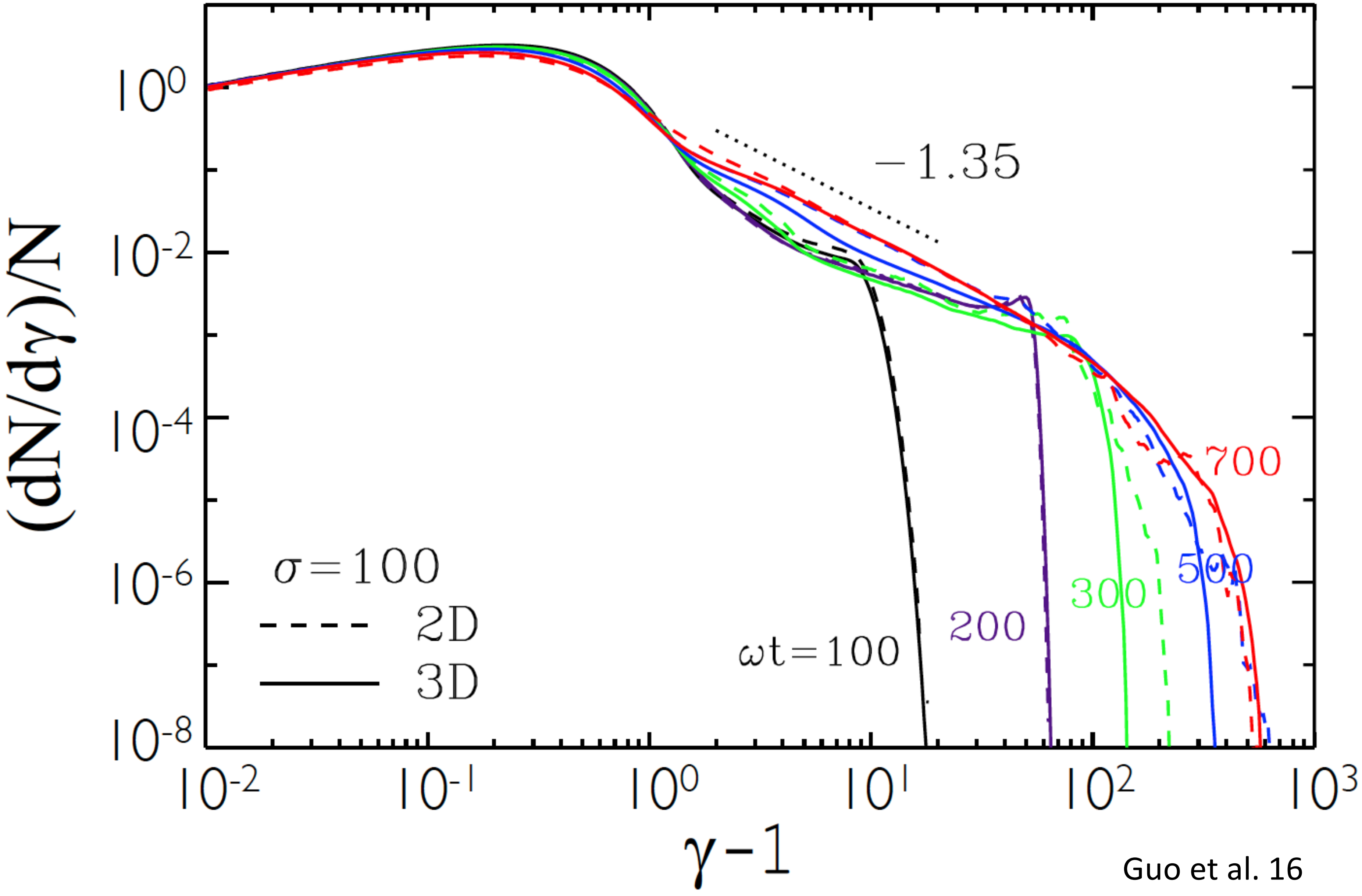
Add spectrum of initial waves ... to drive additional turbulence

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

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


Thinnest layers on inertial scale

Particle Energy Distribution

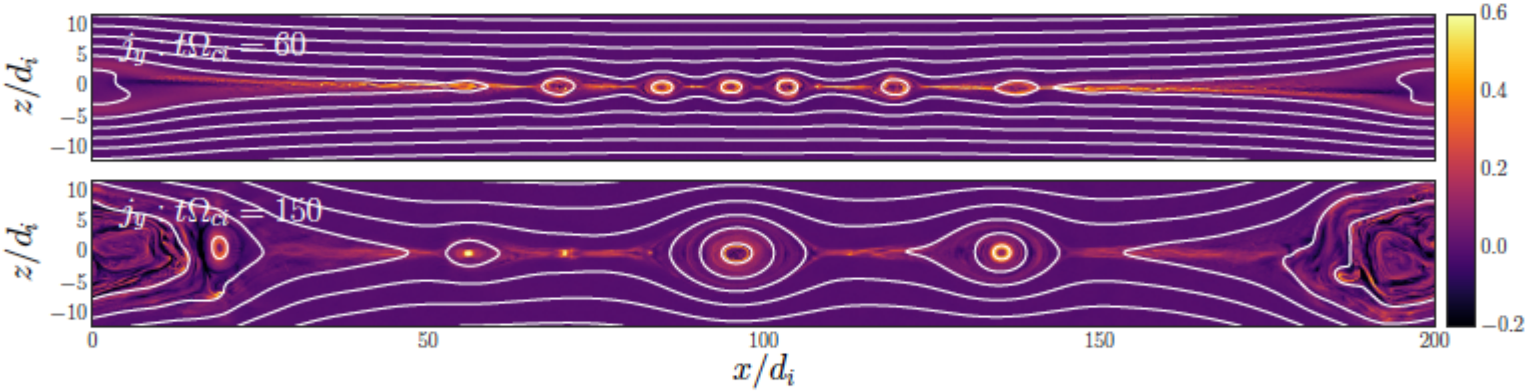


Guo et al. 16

Kinetic simulations of magnetic reconnection with different β and guide field

- β_e: 0.02 (solar corona), 0.08 (solar wind), 0.32 (solar wind)
- Guide field B_g/B_0: $0, 0.2, 0.5, 1.0$.

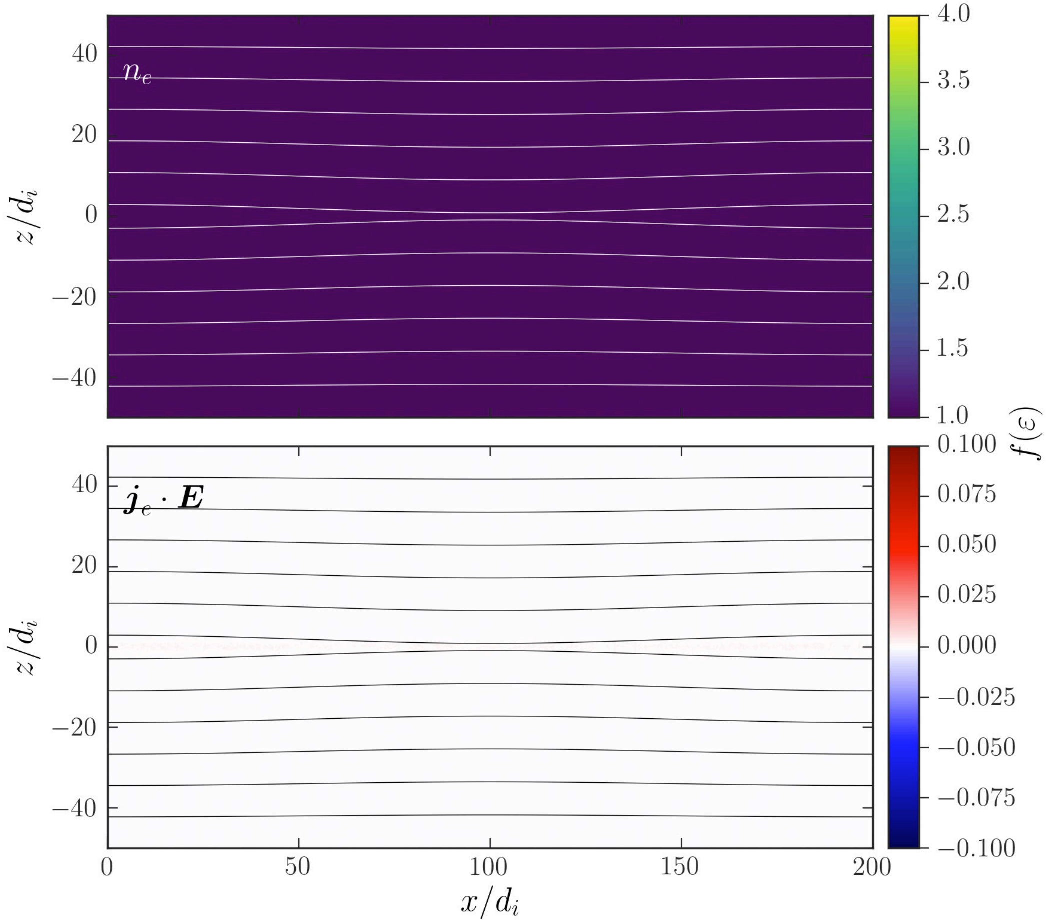
$B_g = 0$



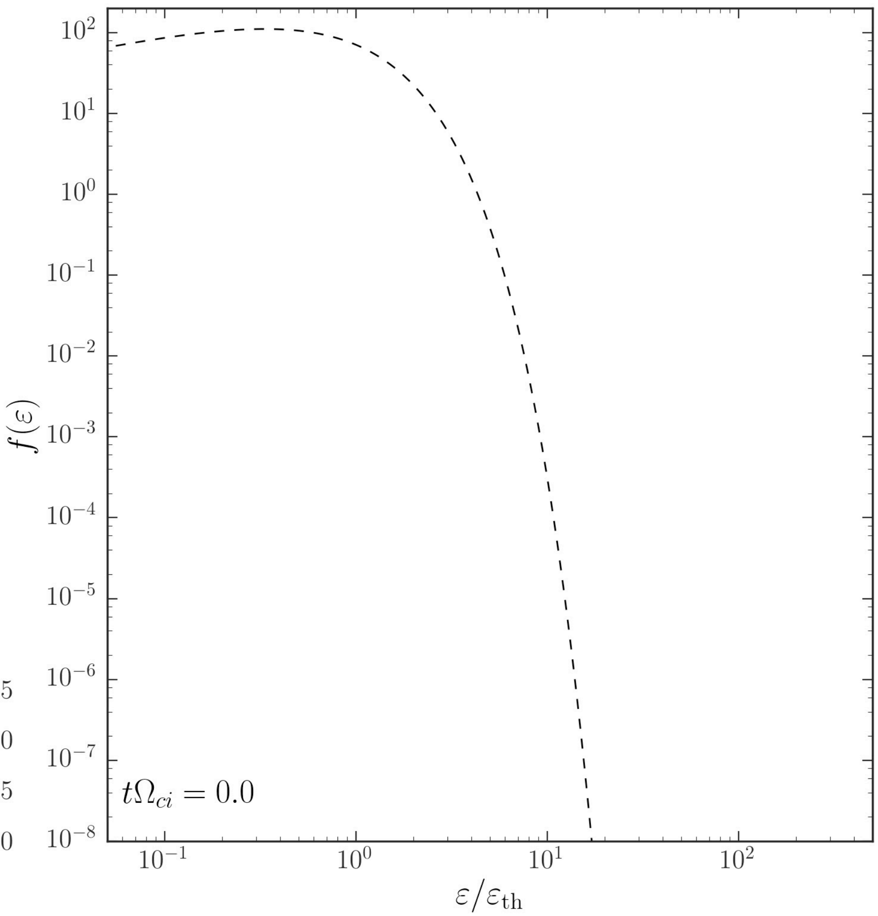
VPIC simulation, $m_i/m_e = 25$, $\beta_e = 0.02$, $200d_i \times 100d_i$

X. Li et al. 2015; 2017; 2018

Ele. Density

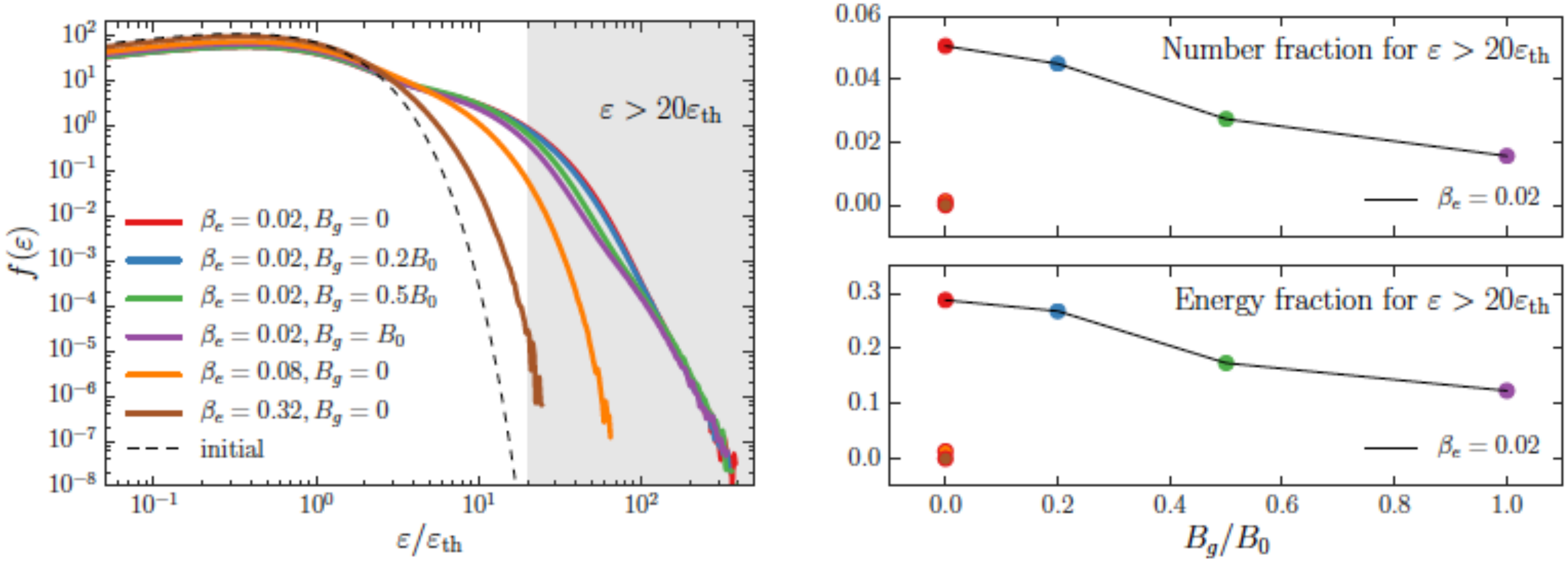


Local electron
Exchange Rate



Evolution of
Electron Distribution

Plasma β and guide field affect particle energization



- High-energy tails are more prominent in low-β simulations
- Less high-energy particles when there is a guide field

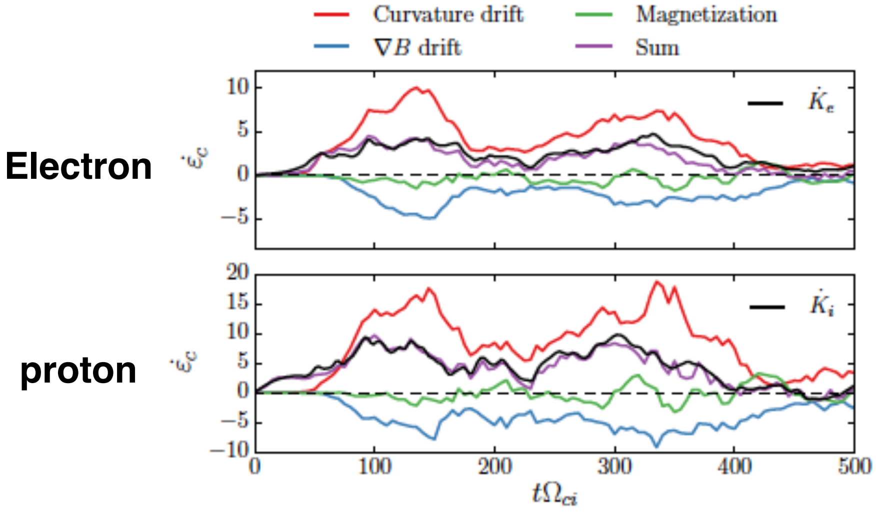
The major acceleration is due to particle curvature drift

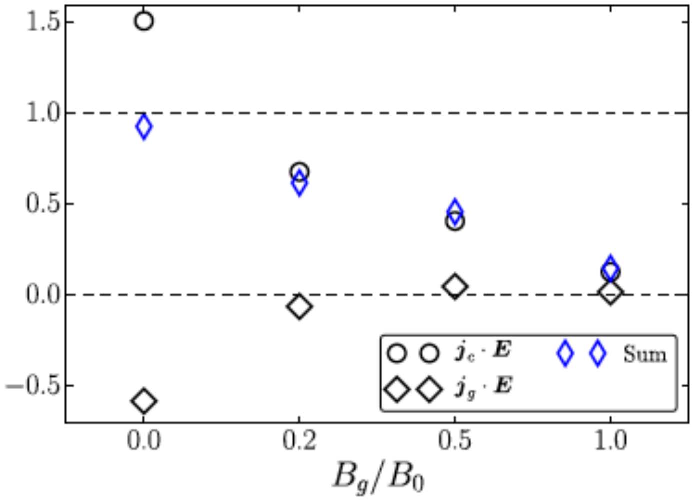
In the guiding-center approximation,

Volumetric Analysis

$$\boldsymbol{j}_{s\perp} \approx p_{s\parallel}\frac{\boldsymbol{B}\times(\boldsymbol{B}\cdot\nabla)\boldsymbol{B}}{B^4} + p_{s\perp}\frac{\boldsymbol{B}\times\nabla B}{B^3} - \left[\nabla\times\frac{p_{s\perp}\boldsymbol{B}}{B^2}\right]_\perp + \cdots$$

Curvature drift **Gradient drift** **Magnetization drift**





$\beta_e = 0.02, B_g = 0.$ Good agreement with the total particle energization.

Dahlin 2014, Guo 14, 15
X. Li 2015, 2017

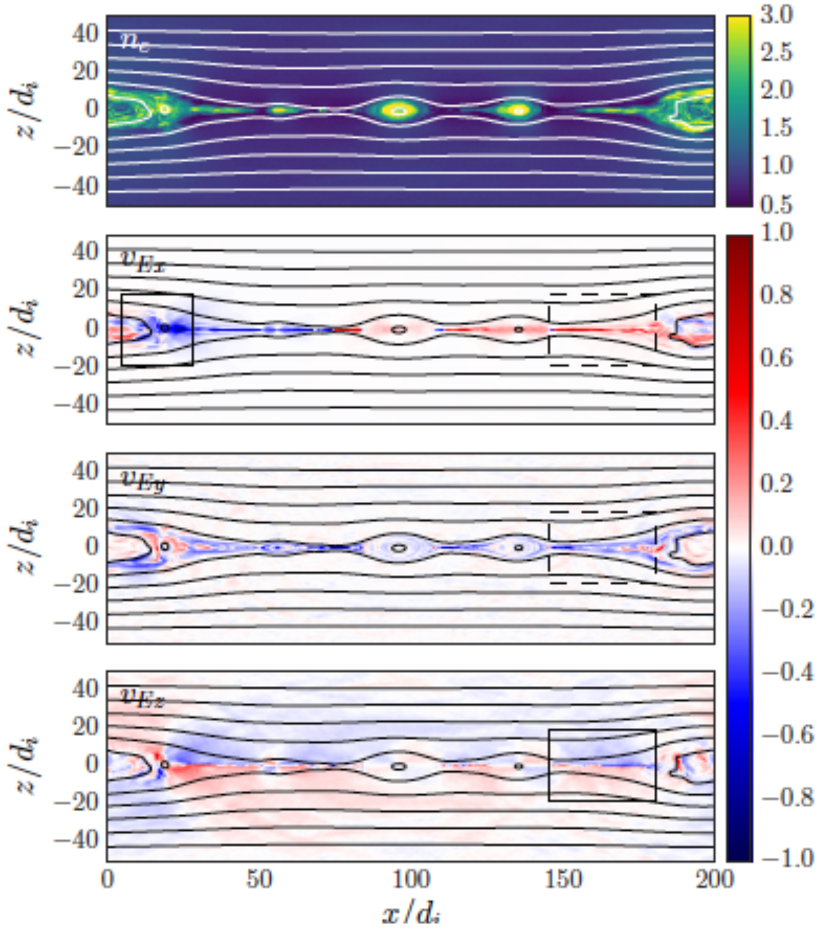
Drift energization processes are included in compression and shear effects

Treating proton+electron as fluid elements

The energization $\boldsymbol{j}_{s\perp} \cdot \boldsymbol{E}_{\perp} = -\boldsymbol{j}_{s\perp} \cdot (\boldsymbol{v}_E \times \boldsymbol{B})$, which is

$$\nabla \cdot (p_{s\perp} \boldsymbol{v}_E) - p_s \nabla \cdot \boldsymbol{v}_E - (p_{s\|} - p_{s\perp}) b_i b_j \sigma_{ij} + n_s m_s (d\boldsymbol{u}_s/dt) \cdot \boldsymbol{v}_E$$

(see also le Roux et al. 15).



ele. density

(ExB)drift_x

(ExB)drift_y

(ExB)drift_z

Compression + Shear

Shear

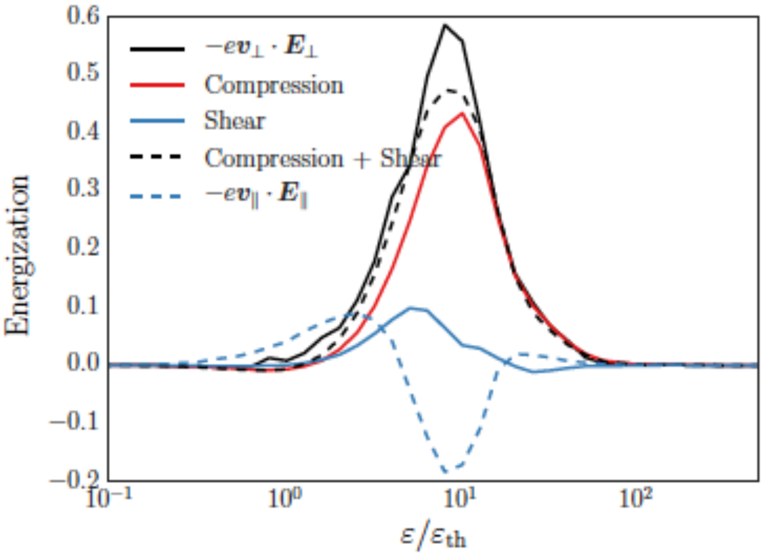
Compression

X. Li et al. 2018

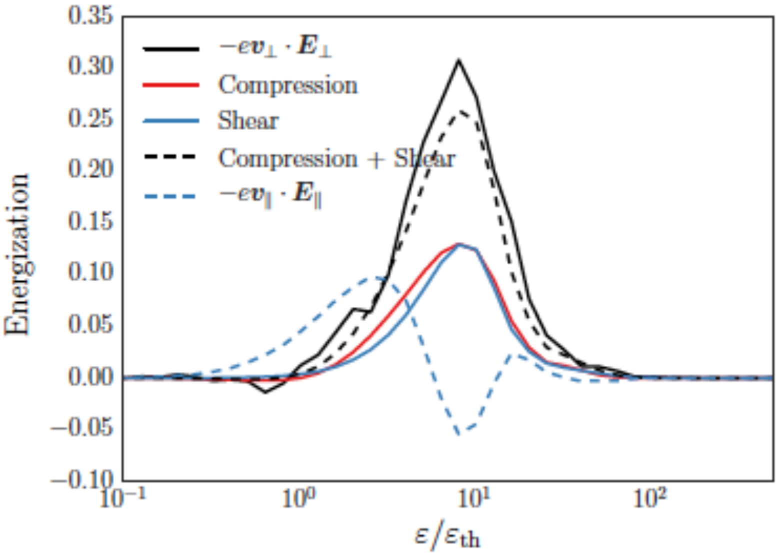
Compression and shear effects dominate high-energy particle energization

Use individual particles to evaluate these terms

$-p_s \nabla \cdot \boldsymbol{v}_E - (p_{s\|} - p_{s\perp}) b_i b_j \sigma_{ij}$ can be evaluated for single particles (see also le Roux et al. 15).



$\beta_e = 0.02,\ B_g = 0$



$\beta_e = 0.02,\ B_g = 0.5B_0$

What do we learn from kinetic simulations?

- Particles can be accelerated to a few hundreds of their initial thermal energy when plasma β is low (solar corona).
- When the guide field is not strong ($B_g \leq 0.5B_0$),
    - The plasma energization is mostly through particle drift motions when guide field is not strong
    - High-energy particle acceleration is due to compression and shear

Parker's transport equation includes the compression acceleration

Thinking more global set-up, using MHD reconnection fields (flows and B fields - compressible effects)

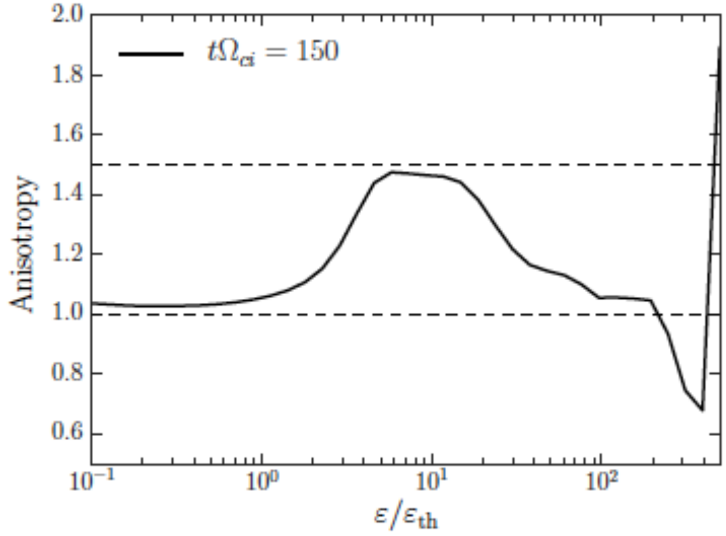
Parker's transport equation

$$\frac{\partial f}{\partial t} + (\boldsymbol{U} + \boldsymbol{V}_d) \cdot \nabla f - \frac{1}{3}\nabla \cdot \boldsymbol{U} \frac{\partial f}{\partial \ln p} = \nabla \cdot (\boldsymbol{\kappa} \nabla f) + Q,$$

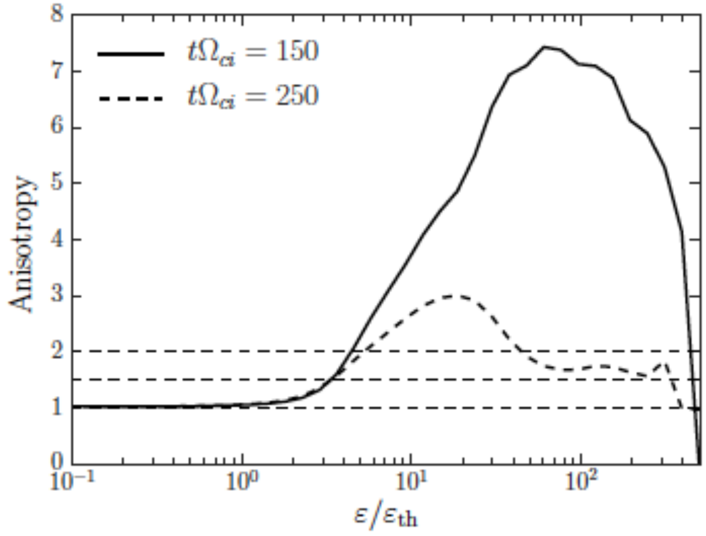
- f is assumed to be isotropic
- PIC simulations show anisotropic particle distribution, but how anisotropic is high-energy particle distribution?

Anisotropy is weak for high-energy particles in kinetic simulations

$\sum \boldsymbol{v}_\parallel \cdot \boldsymbol{p}_\parallel / \sum 0.5\boldsymbol{v}_\perp \cdot \boldsymbol{p}_\perp$, where we sum over all electrons in an energy bin.



$\beta_e = 0.02$, $B_g = 0$



$\beta_e = 0.02$, $B_g = 0.5B_0$

- Anisotropy level decreases as the simulations evolve.
- Self-generated turbulence in 3D reconnection could scatter particles to get more isotropic energetic particle distribution.

Solving Parker's transport equation + MHD

The Fokker-Planck form of Parker's transport equation

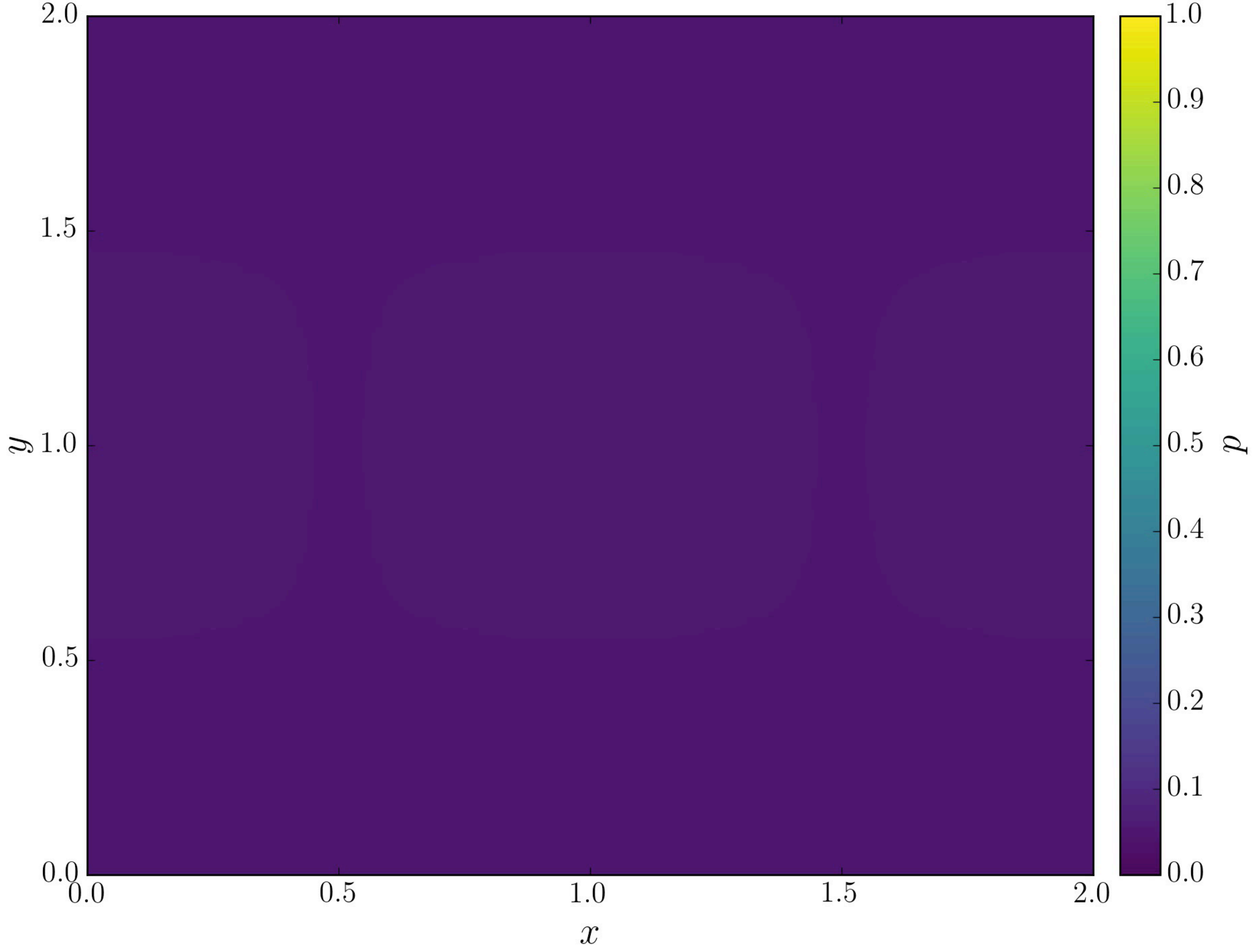
$$\frac{\partial F}{\partial t} = -\nabla \cdot [(\nabla \cdot \boldsymbol{\kappa} + \boldsymbol{U})F] + \frac{\partial}{\partial p}\left[\frac{p}{3}\nabla \cdot \boldsymbol{U} F\right] + \nabla^2(\boldsymbol{\kappa} F)$$

is equivalent to a system of stochastic differential equations (SDEs) of Ito type. We solve the SDEs using stochastic integration with MHD fields as background. MHD simulations:

- High-order Godunov code, Athena.
- Lundquist number $S = Lv_A/\eta = 10^5$
- $\beta = 0.1$
- 2×2 box with a grid size 8192×4096
- Guide field $B_g = 0.0, 0.2, 0.5, 1.0$

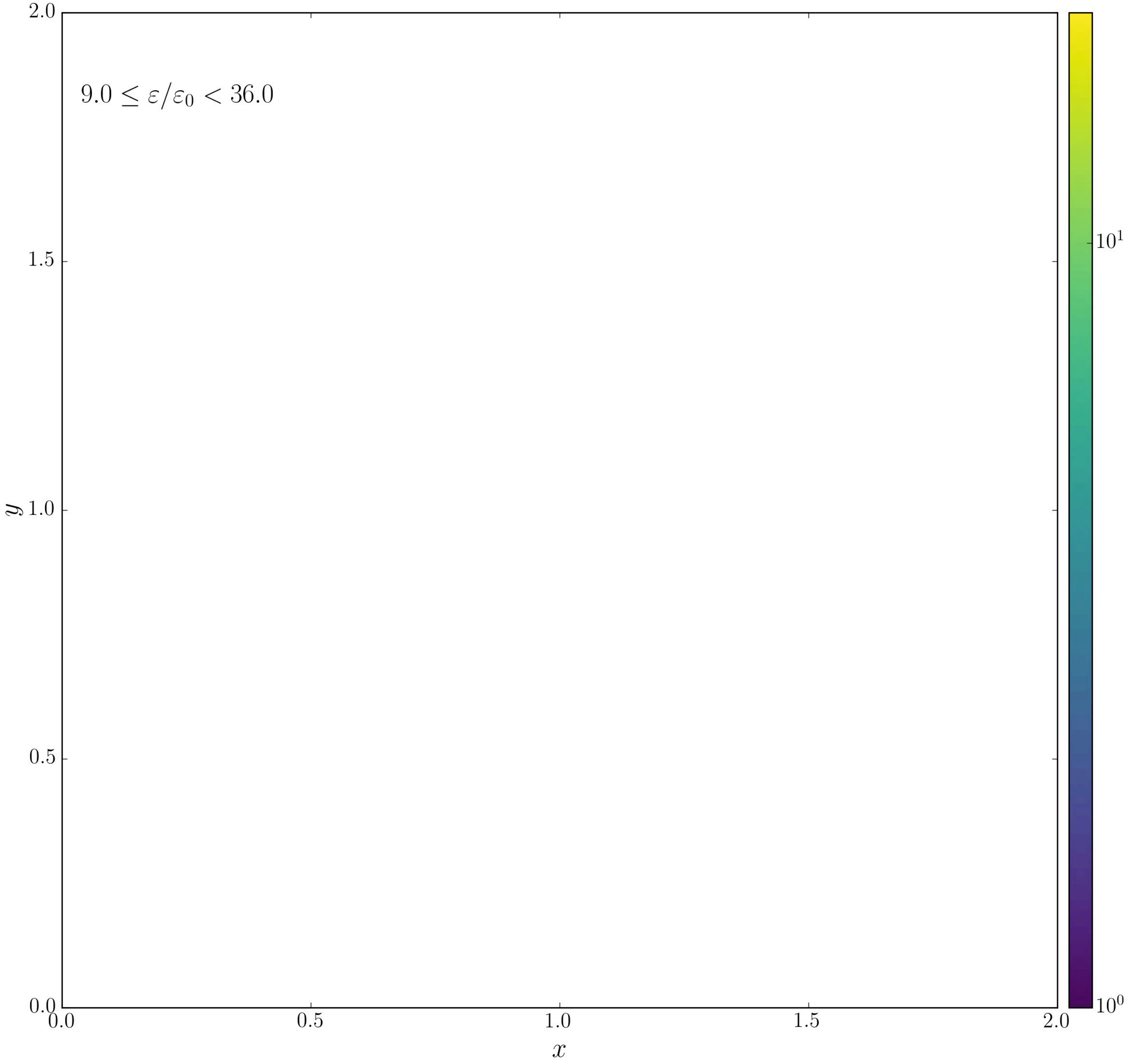
Normalization: $L_0 = 10$ Mm, $v_A = 1000$ km/s. $\kappa_0 = L_0 v_A$.
$B_0 = 50$ G. (Not the whole flare!)

Pressure



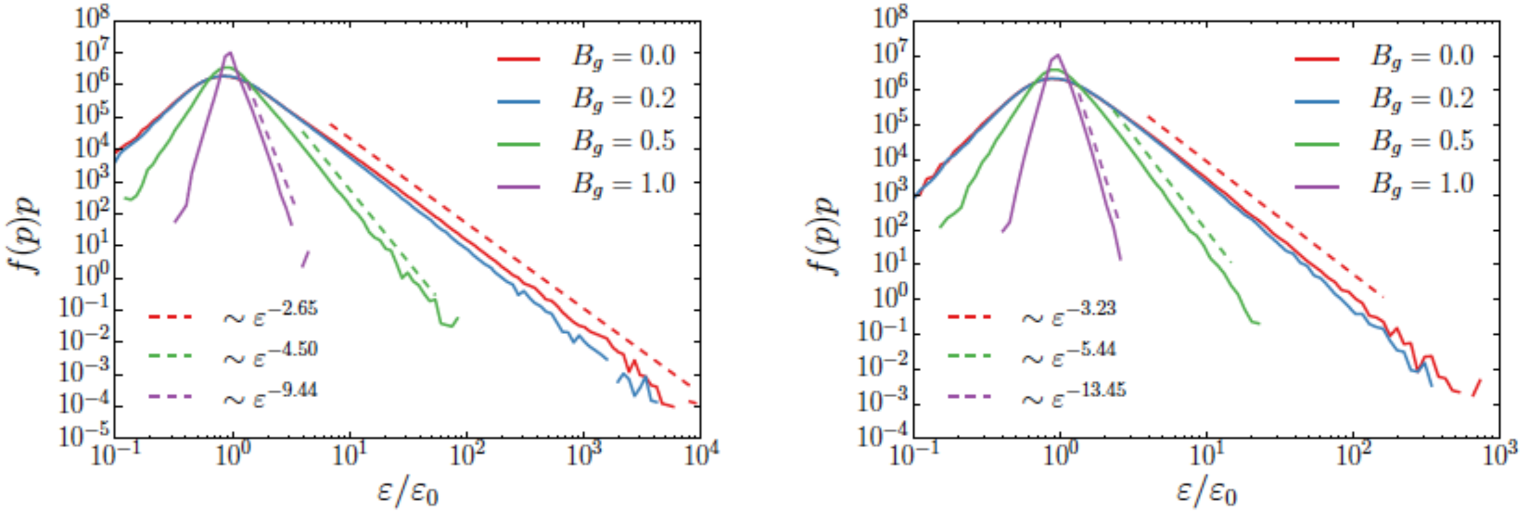
Energetic particles

$9 < E/E_0 < 36$



Power-law energy distributions (constant $\kappa_\parallel$ and $\kappa_\perp$)

$L_c \approx L_0/30$ for reconnection drive-turbulence (Huang et al. 2016).



- Proton: $\varepsilon_0 = 10$ keV
- $\kappa_\parallel = \kappa_\perp = 0.003\kappa_0$

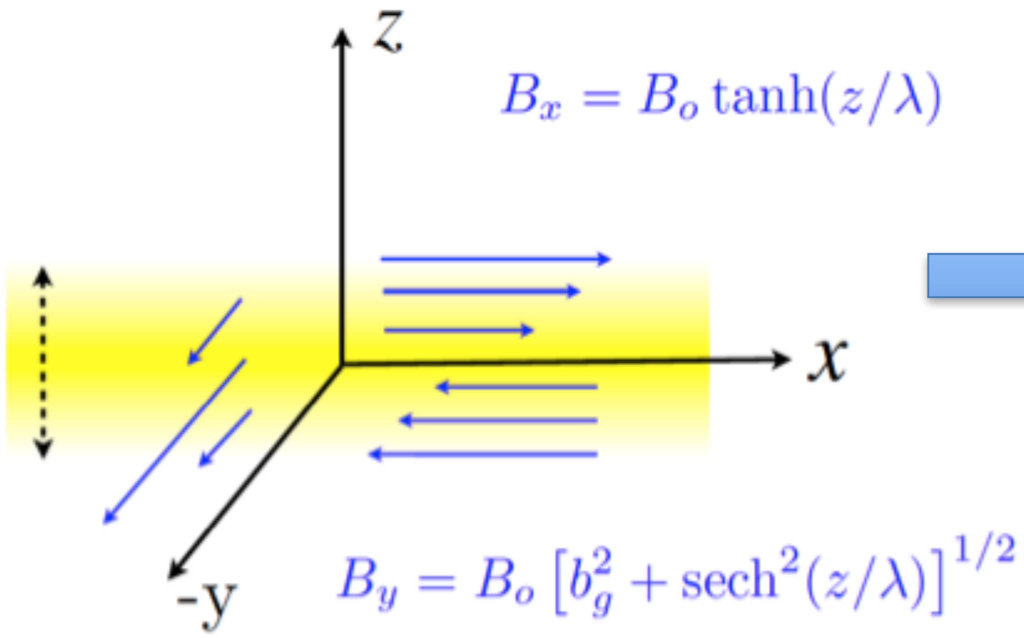
- Electron: $\varepsilon_0 = 1$ keV
- $\kappa_\parallel = \kappa_\perp = 0.008\kappa_0$

Case B: Brief Summary

- With free energy as the initial (unstable) current sheets without initial turbulence, these sheets reconnect and produce self-generated turbulence;
- Particle energization is via both E_parallel and curvature drifts (first order Fermi). More energy conversion occurs in the outflow region and islands.
- Guide field reduces efficiency of particle energization.
- The role of self-generated turbulence is unclear.

Free Energy (C):

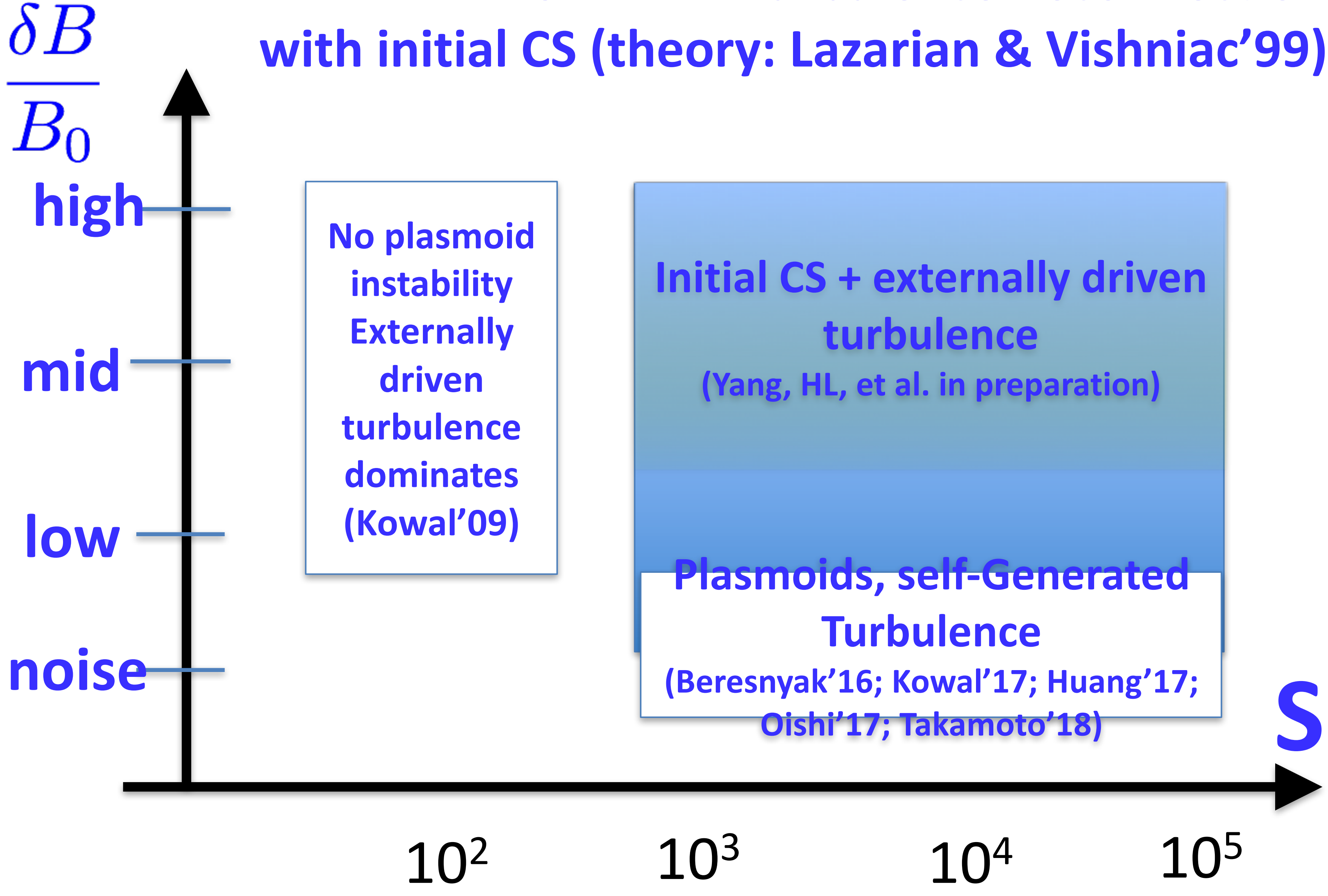
Combining CS magnetic shear with externally driven turbulence



+

Driven Turbulence

3D MHD Turbulence Reconnection with initial CS (theory: Lazarian & Vishniac'99)



No plasmoid instability
Externally driven turbulence dominates
(Kowal'09)

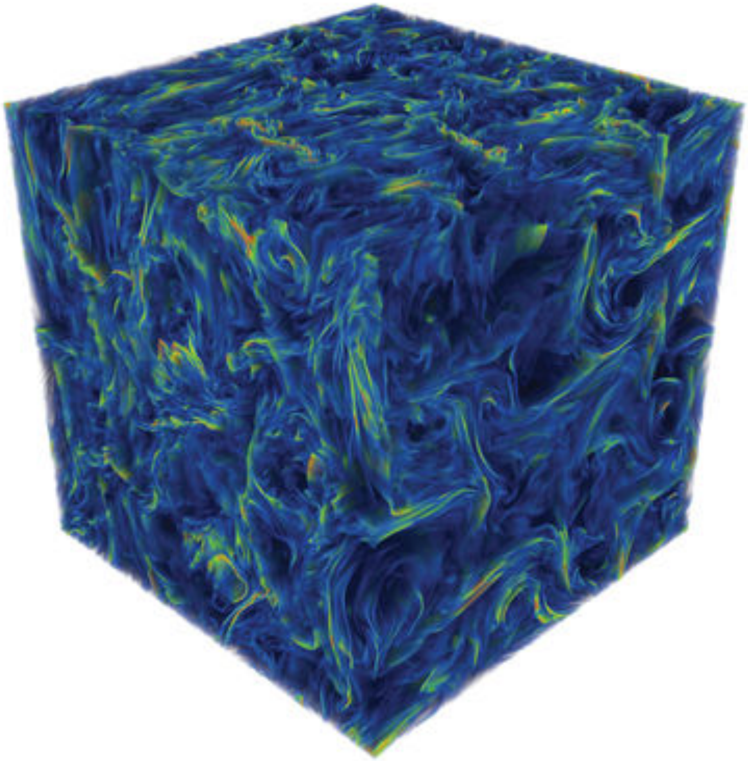
Initial CS + externally driven turbulence
(Yang, HL, et al. in preparation)

Plasmoids, self-Generated Turbulence
(Beresnyak'16; Kowal'17; Huang'17; Oishi'17; Takamoto'18)

Yang, HL, et al. 18, in preparation

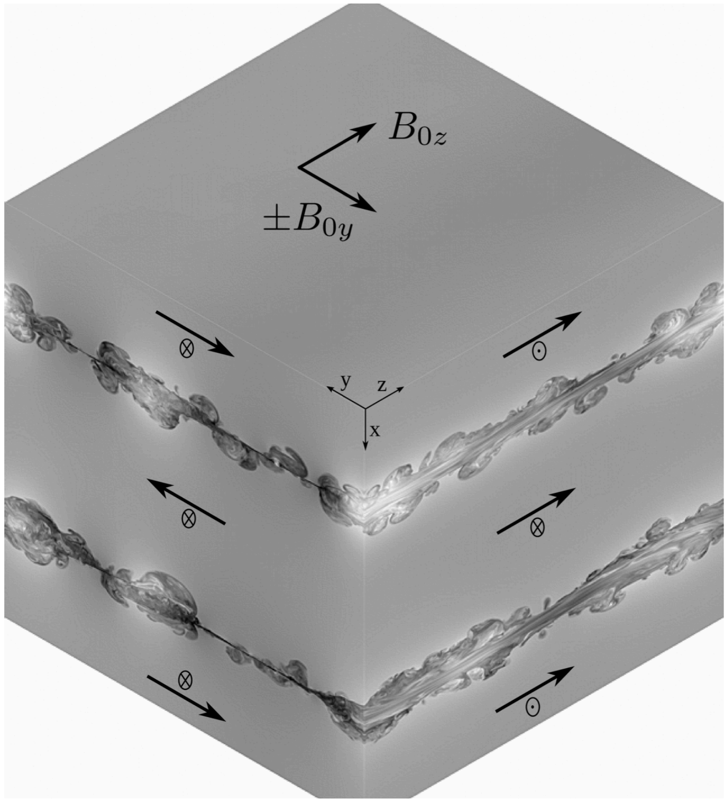
Combining these two …

Turbulence from Large Scale Driving



Aluie, Eyink, et al.

Turbulence from Global Reconnection



Beresnyak’16

3D PIC studies of combining driven turbulence with pre-existing large-scale current sheet

Parameters

	Case A:	**Case B:**
m_i/m_e:	25	25
Box(d_e^3):	320	120
	320	120
	640	200
$\Delta B / B_0$:	0.316	0.316
Ω_{ce}/ω_{pe}:	**5**	**1**
β_e :	**~0.02**	**~0.02**
Guide fld:	**no**	**yes**
Init width:	**18 d_e**	**self-form**

1) Case A:

Pre-existing CS

+ 3D perturbations

2) Case B:

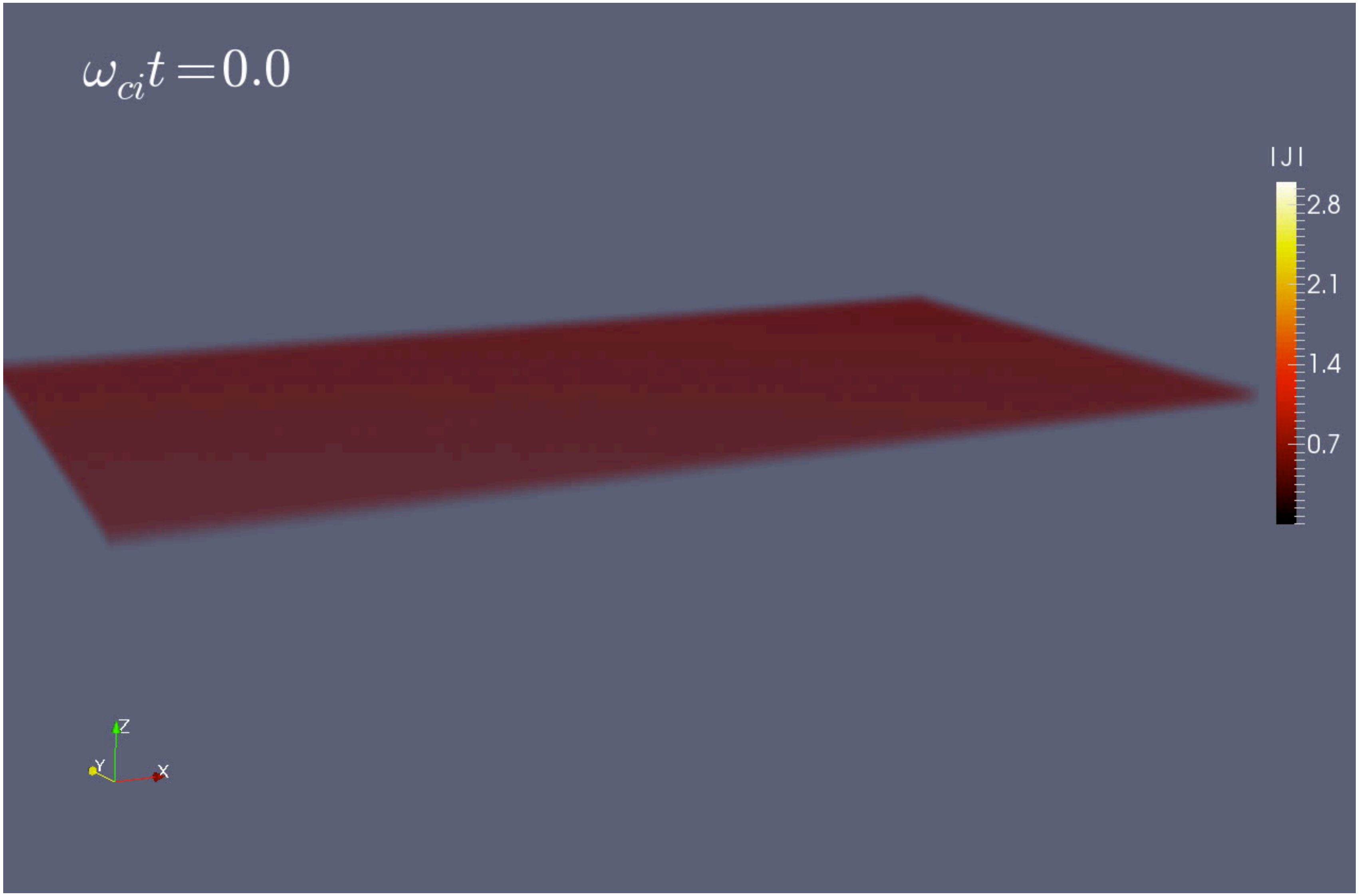
Uniform B_0

+ 3D perturbations

Makwana+ '15,17

X. Li et al. 2016

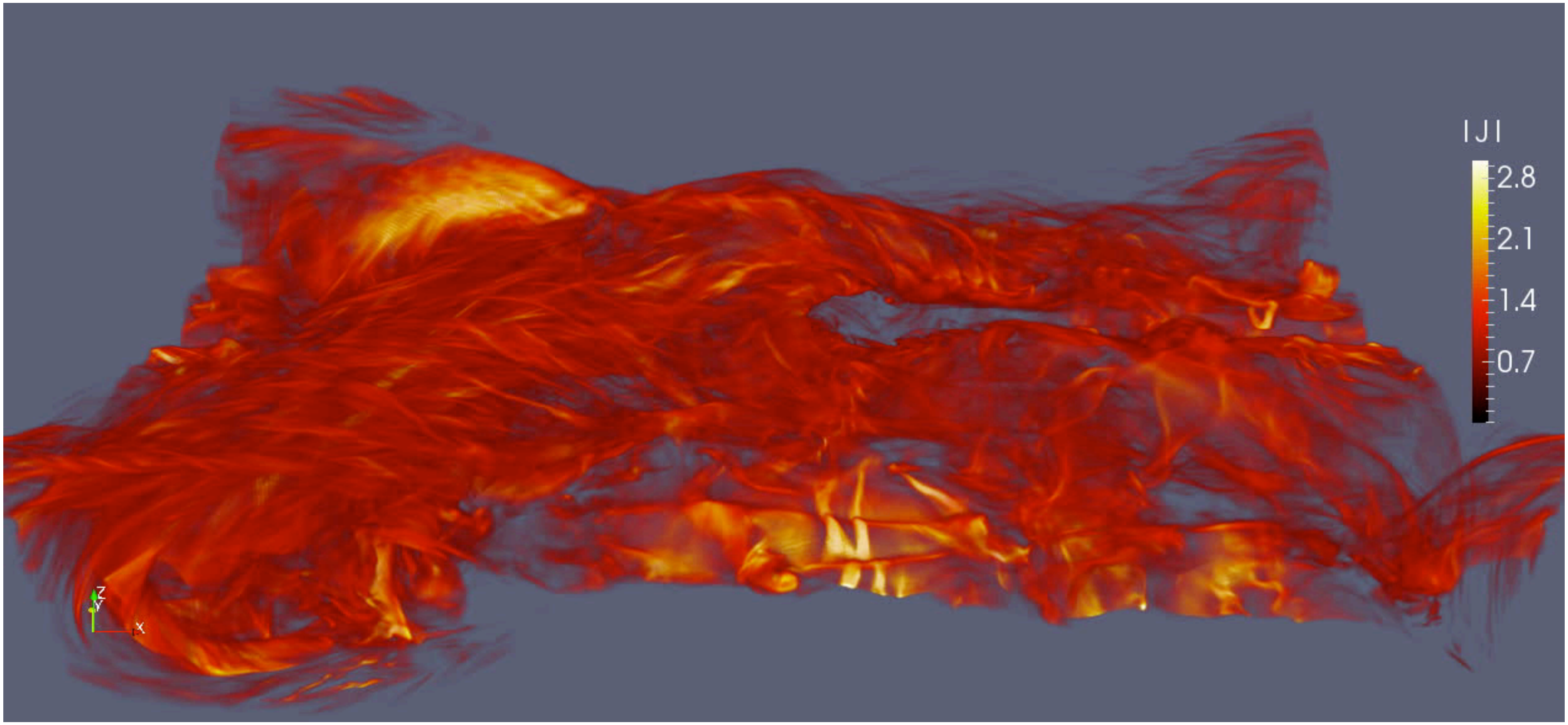
3D Collisionless Reconnection (using VPIC)



Guo et al. '18

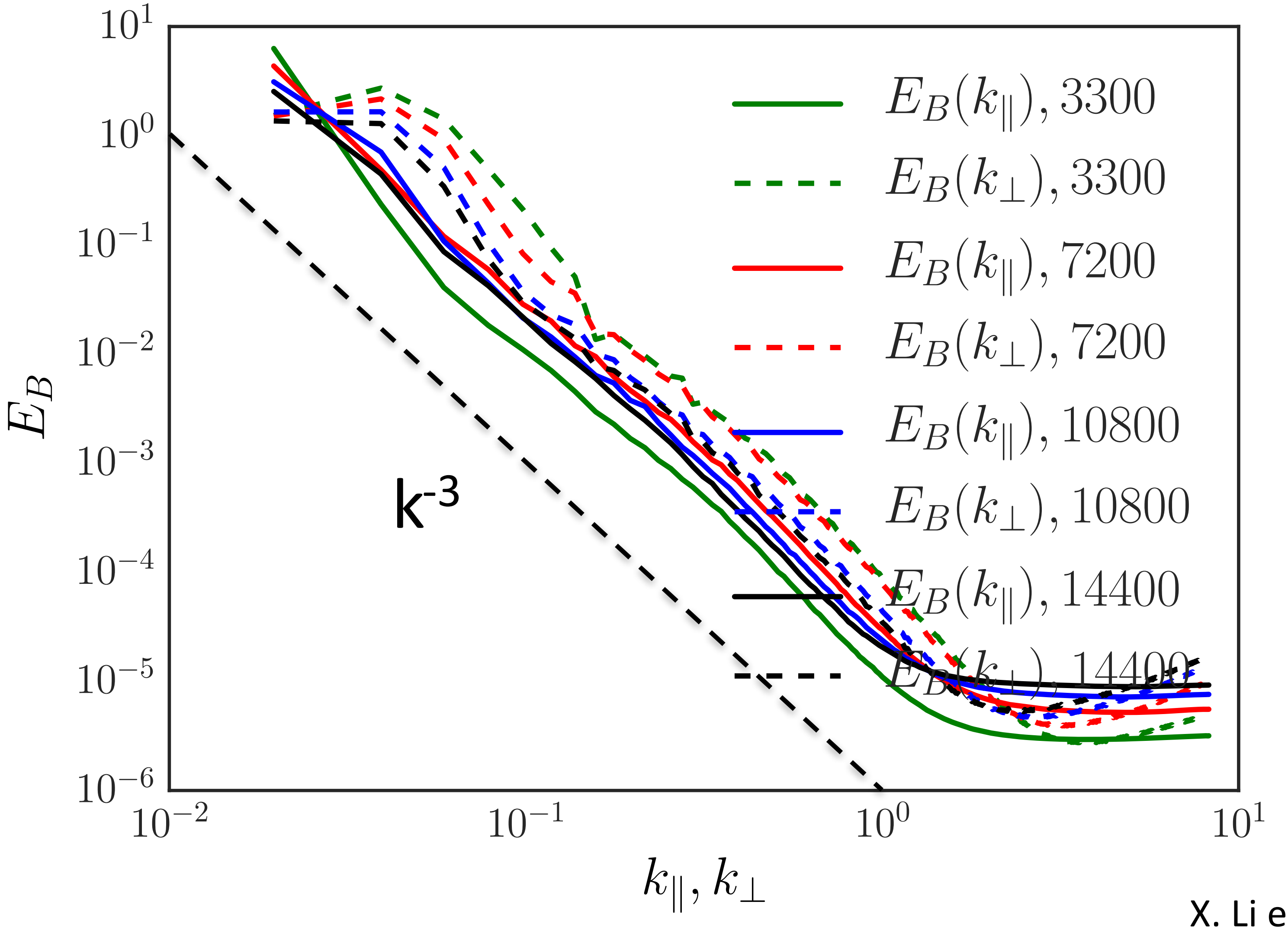
Strong 3D Nature of CS:

Secondary instabilities (Kink, KH ?) might dominate over the Plasmoid Instability?



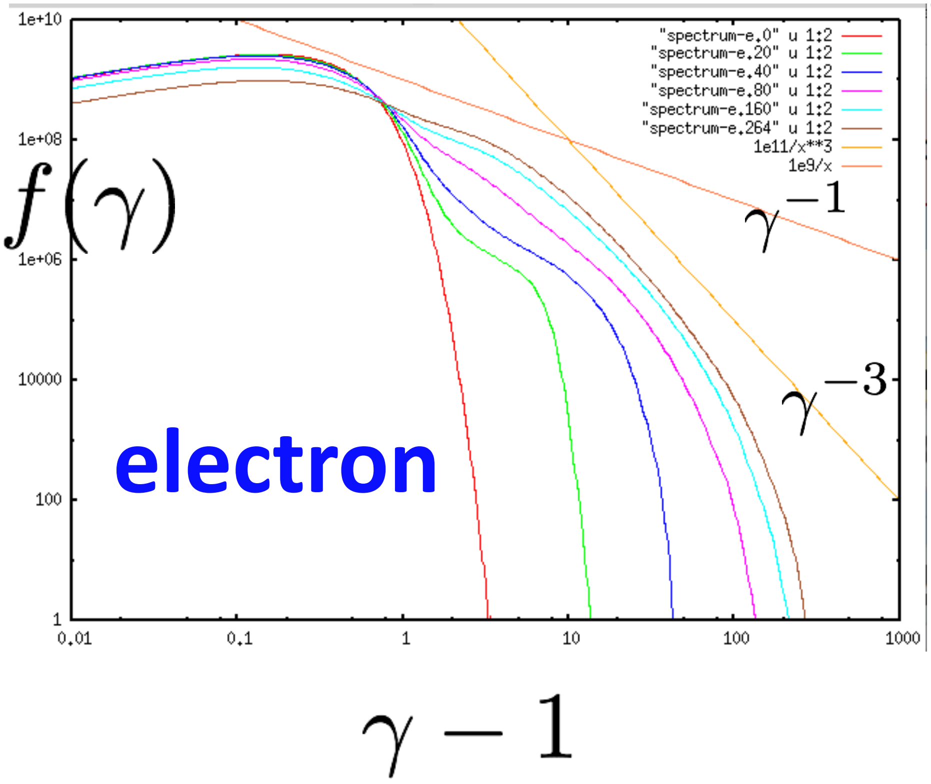
Guo et al. ‘18

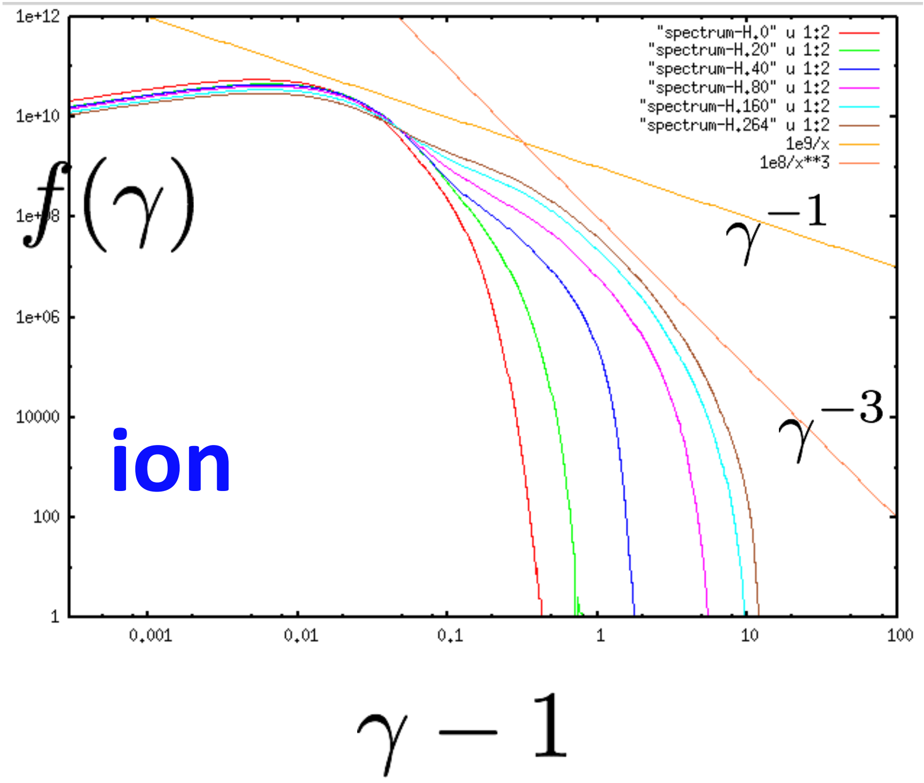
Magnetic turbulence spectra are essentially isotropic



X. Li et al. '18

Both Electrons and Ions are Efficiently Accelerated by Reconnection

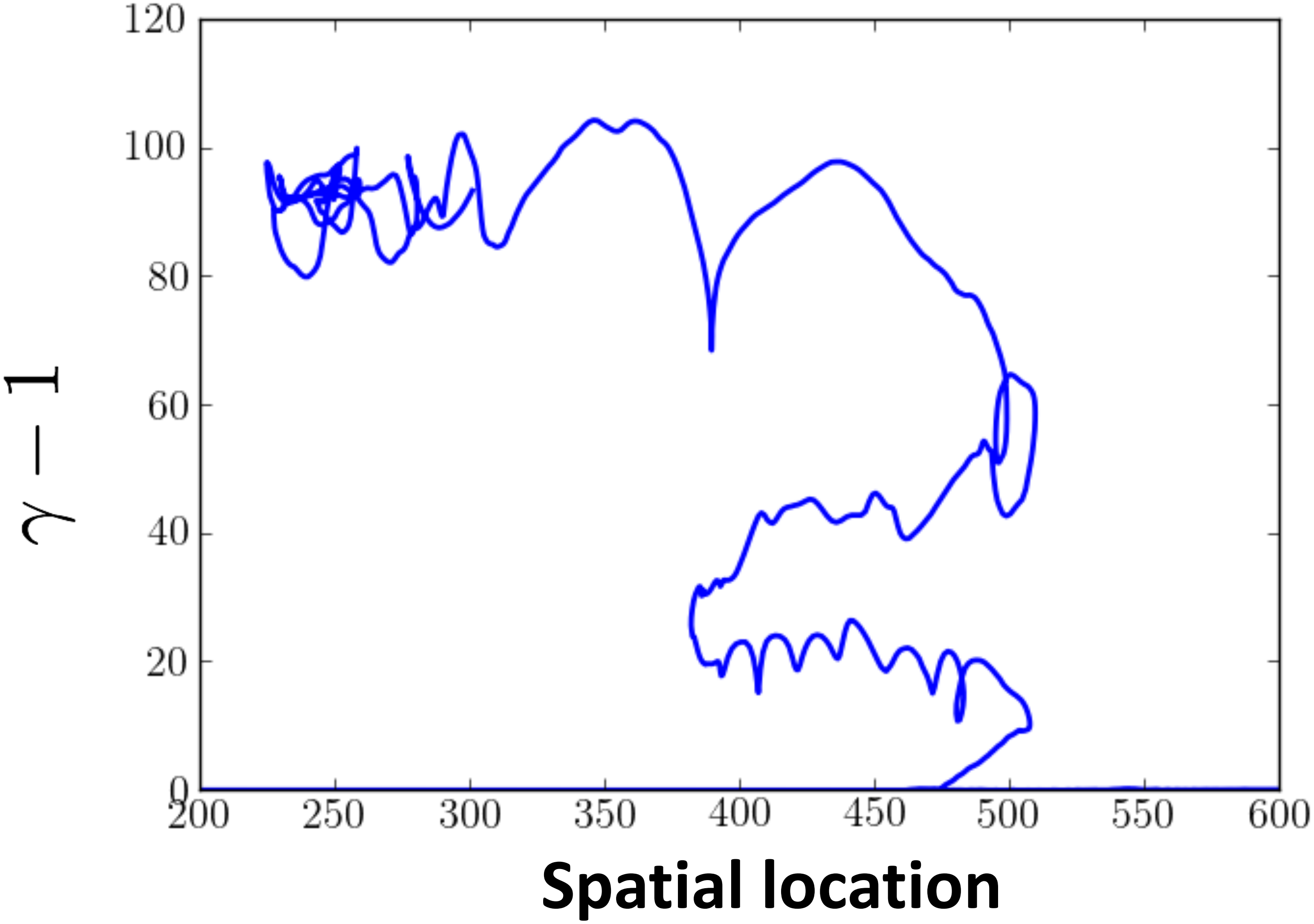




Large aspect ratio sheets are unstable on dynamic timescale and dissipates its magnetic energy mostly to non-thermal particles in the high σ_e limit.

X. Li et al. '18

Electron Energization consistent with Fermi-like mechanism



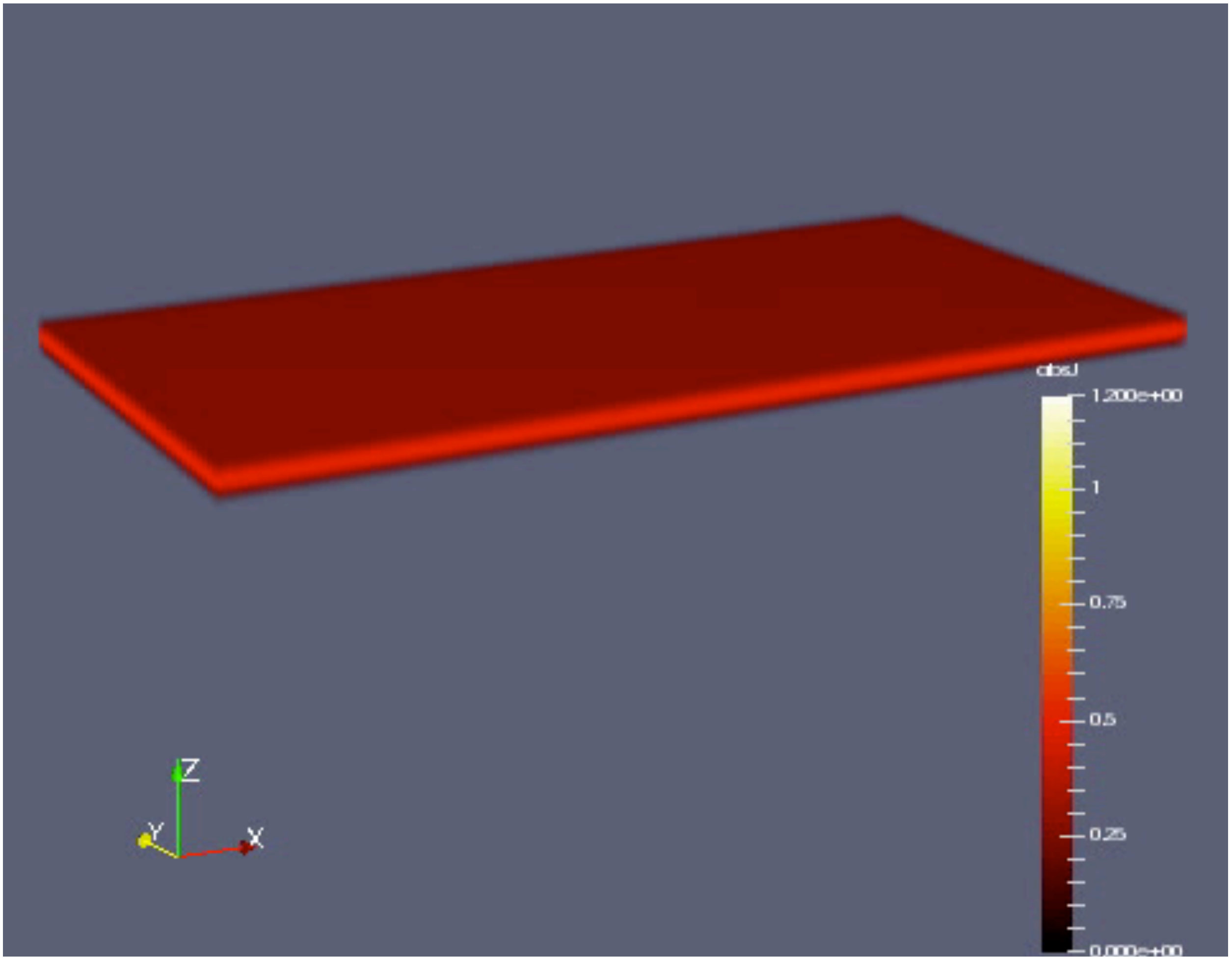
X. Li et al. ‘18

Strong Guide Fields Slows down the Disruption of 3D CS

Current sheets from turbulence typically have STRONG guide fields

- Force-free Harris
- **$B_g = 3$**
- 3D: 128x64x64 di
- Cells: 1650x840x800; 100 ppc;
- Initial thickness: 3.6 di;
- mi/me=25; $\sigma_e = 25$; $\sigma_i = 1$;
- Initial perturbation:
  dB/B=0.1 with 10 modes.
- **Total: ~ 5 Alfven time**

Guide Field Slows Down the On-set of Collisionless Reconnection

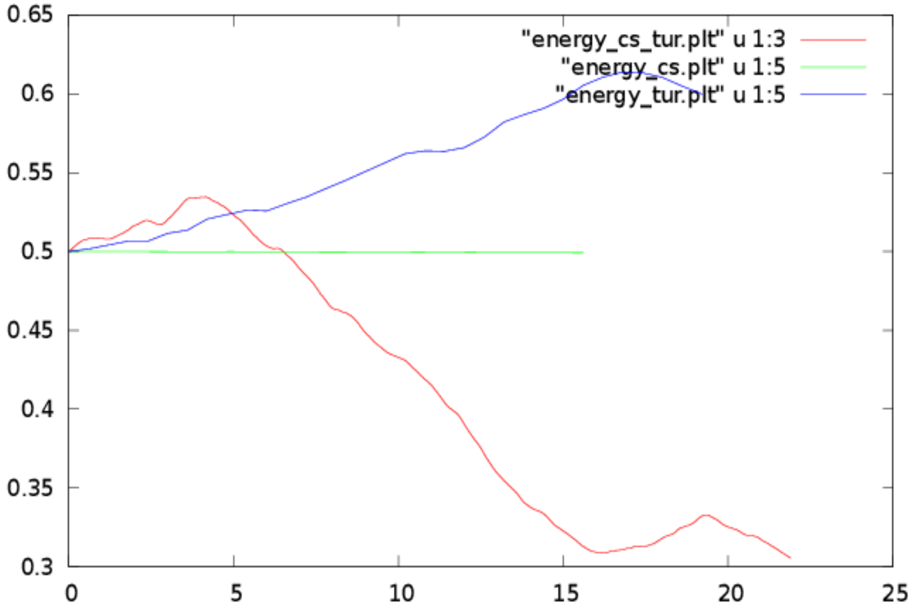


Liu et al., PRL, 2013

Guo et al. ‘18

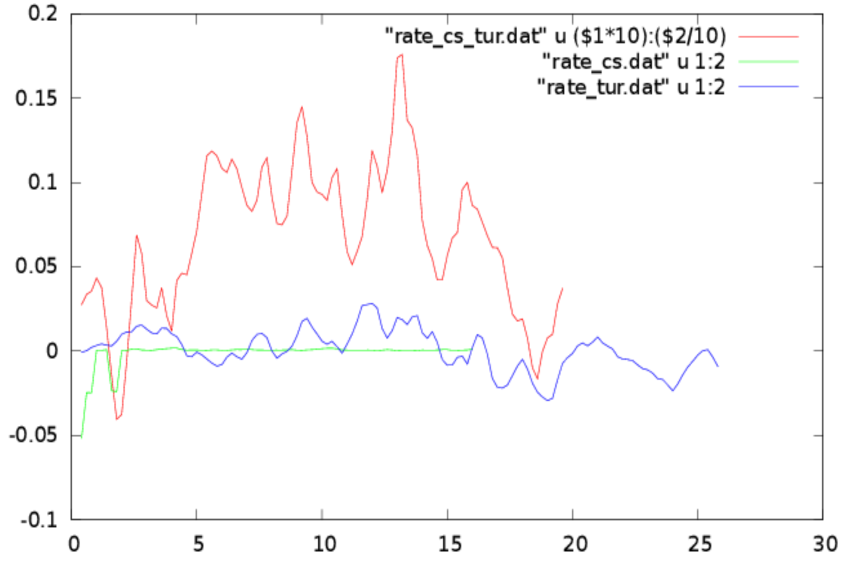
3D MHD studies of combining driven turbulence with pre-existing large-scale current sheet

Energy_B^2/2



time

reconnection rate

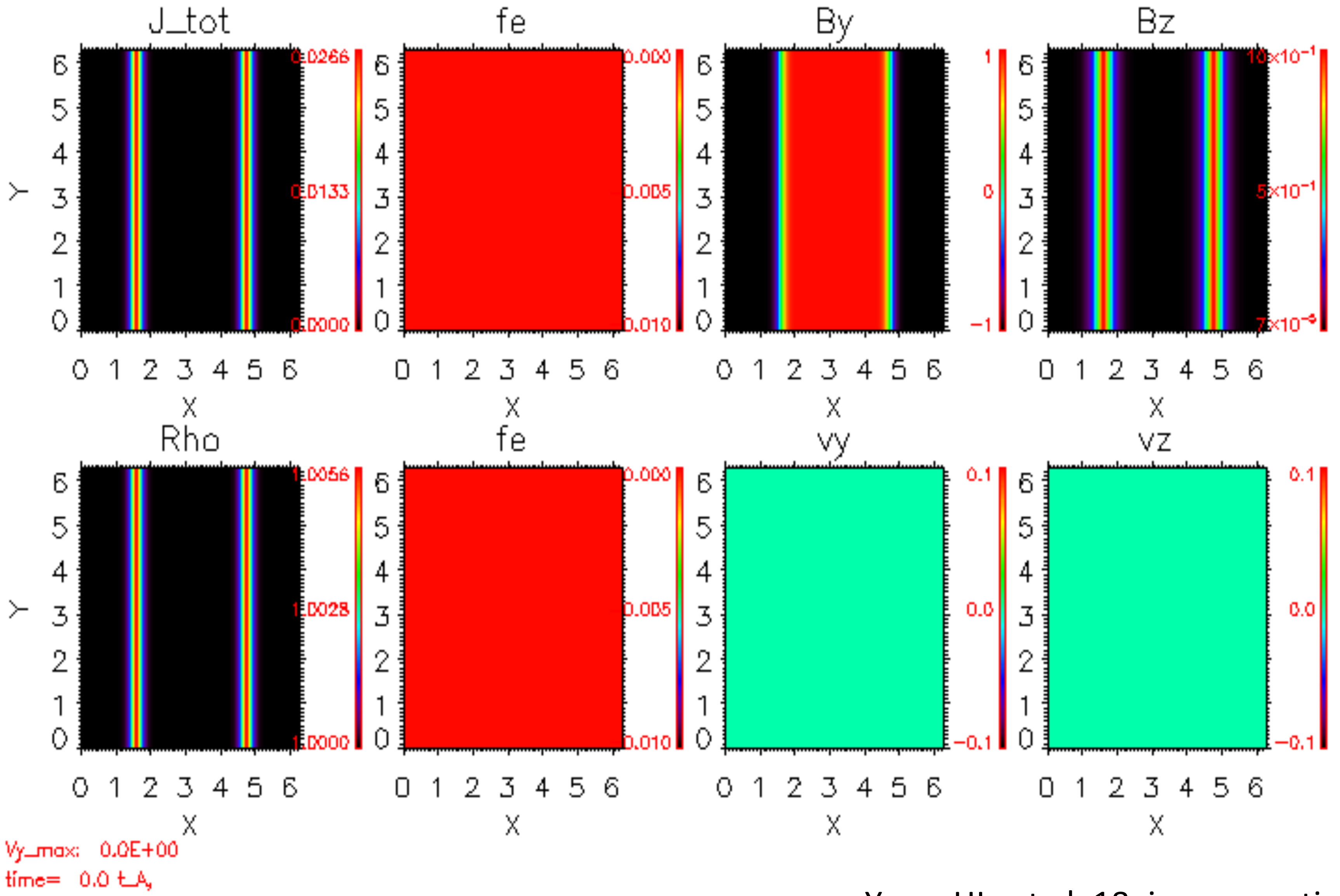


time

3 cases: cs_tur denotes both cs and turbulence (red);
cs denotes cs only (green);
tur denotes only turbulence with uniform field (blue);
Reconnection rate is computed according to the tracer.

Yang, HL, et al. 18, in preparation

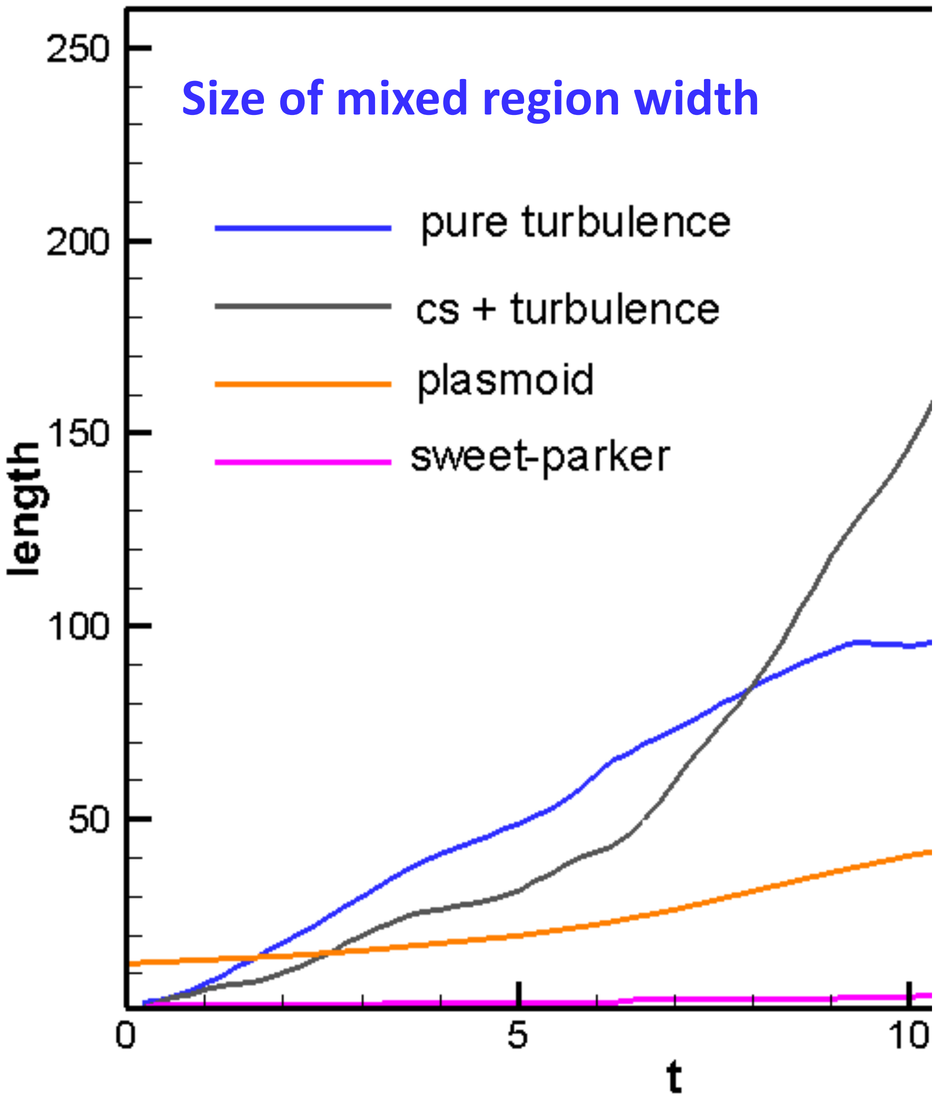
CS + external turbulence, guide field Bz = 0

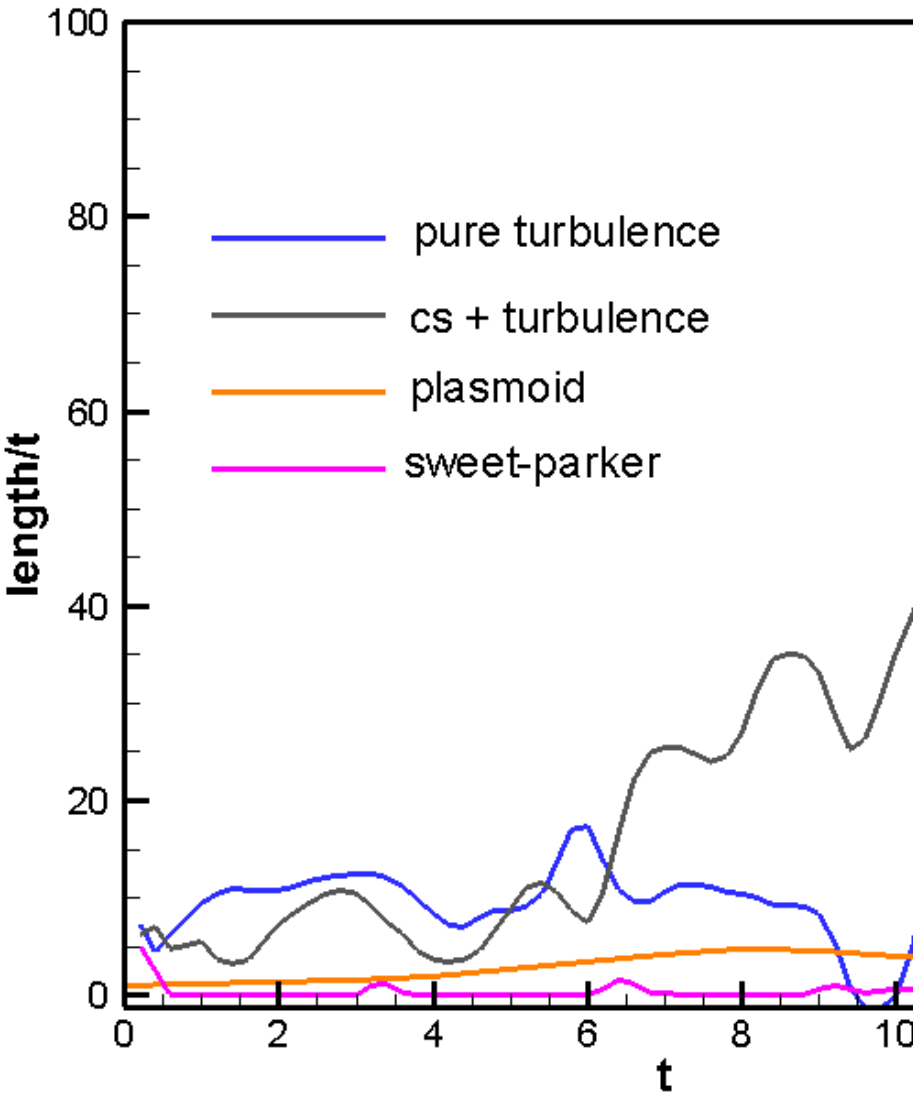


fe denotes diffusion of the traced plasma.

Yang, HL, et al. 18, in preparation

Diffusion of Field Lines





Yang, HL, et al. 18, in preparation

Case C: Brief Summary

- With free energy as the initial (unstable) current sheets with initial turbulence, these sheets evolve much faster (turbulent reconnection);
- Guide field can slow down the onset of reconnection;
- Particle energization is via both E_parallel and curvature drifts (first order Fermi). More energy conversion occurs in the outflow region and islands.
- The role of self-generated turbulence is unclear.

Summary:

1) Free energy: helical vs. non-helical ?
    1) Injected turbulence + cascade produces Transient current sheets, but such sheets can energize particles (via E_parallel), though not as efficient.
    2) Injected turbulence, however, can destabilize pre-existing thick and large-scale current sheets. Particles are energized mostly via Fermi-like process (curvature drift).
2) Implications:
    1) Turbulence threatens the life-time of pre-existing current sheets, limiting the energy storage process. Probably not a problem for accretion disk corona, but potentially serious for solar corona.
    2) Current sheets with guide field can survive a lot longer, even with turbulent perturbations. Implications for solar flare loops.