Particle Energization in Different Turbulent Environments

Hui Li (李暉)

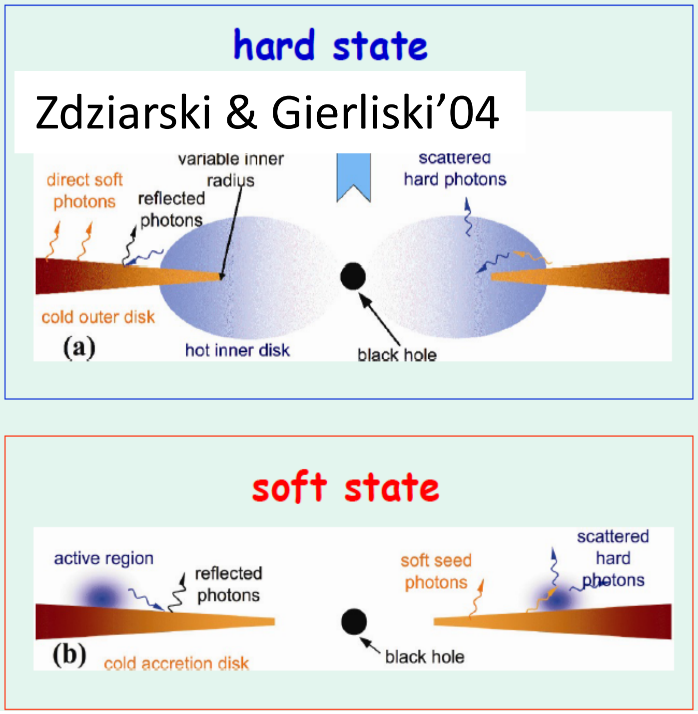
Xiaocan Li, Fan Guo (LANL)

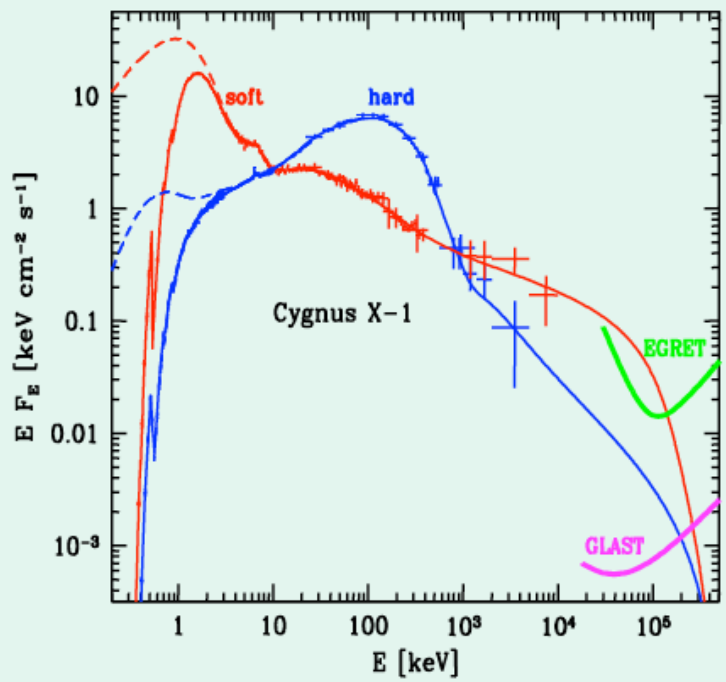
Outline:

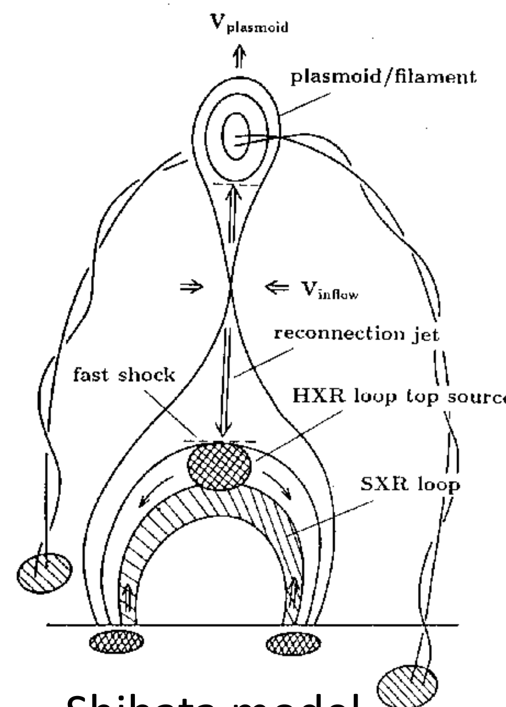
1. **Examples:** **Solar and Accretion Disk coronae are likely highly magnetized β <<1 (σ_e > 1);**
2. **Turbulence vs. Reconnection: Different forms of initial free energy;**
3. **Particle energization in systems with current sheets mediated by turbulence;**
4. **Open issues on 3D reconnection + turbulence.**

Various talks since 2015
Makawana+'15; 17

Examples: Corona on Solar Surface and Black Hole Accretion Disks







Shibata model

Accretion disk corona:

$v_{driving} \sim v_A$

Disk corona: Likely highly turbulent

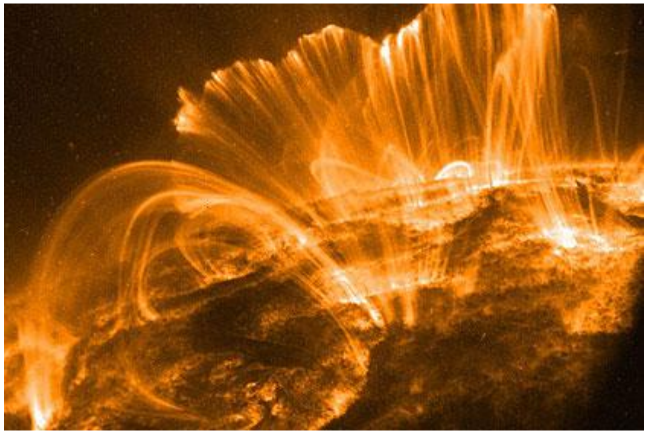
Solar corona:

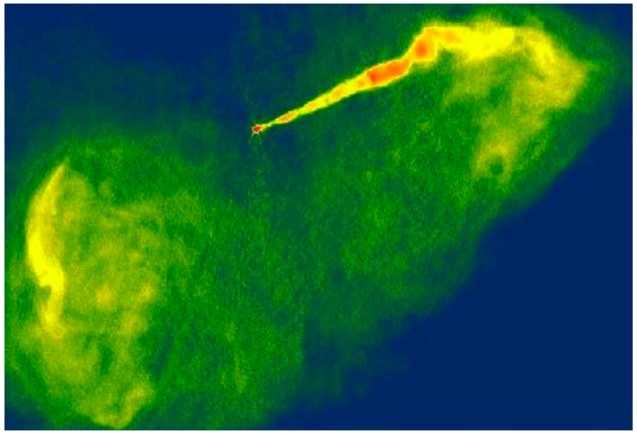
$v_{driving} << v_A$

Unclear how turbulent

For this talk, Several Key Issues

1. Different forms of free energy: turbulence, current sheets, and reconnection
2. Different forms of free energy can have very different particle energization processes
3. Reconnection is too easy and too fast (Turbulence can further speed up reconnection). Guide fields might delay the on-set of reconnection





We all want to use Magnetic (free) Energy

1. Likely Strongly magnetized (also low beta)

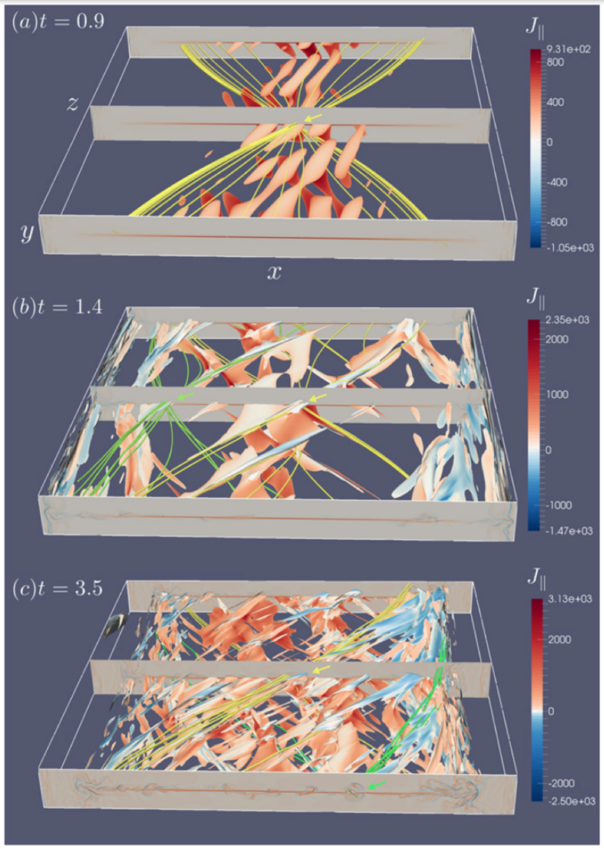
$$\sigma_e = \frac{B^2}{4\pi n_e m_e c^2} \quad \begin{aligned} &\approx 0.1 - 1 \quad \text{for SFs} \\ &\approx 0.5 - 5 \quad \text{for GBHs;} \\ &\approx 20 - 200 \quad \text{for AGNs} \end{aligned}$$

$$\beta_{th} \ll 1$$

2. Quasi-collisionless
3. Very high Rm (>>1) but could be low ion Re (unity)
4. Large scale separation: R >>> d_e and R_e
5. Mixture of thermal and non-thermal) plasmas

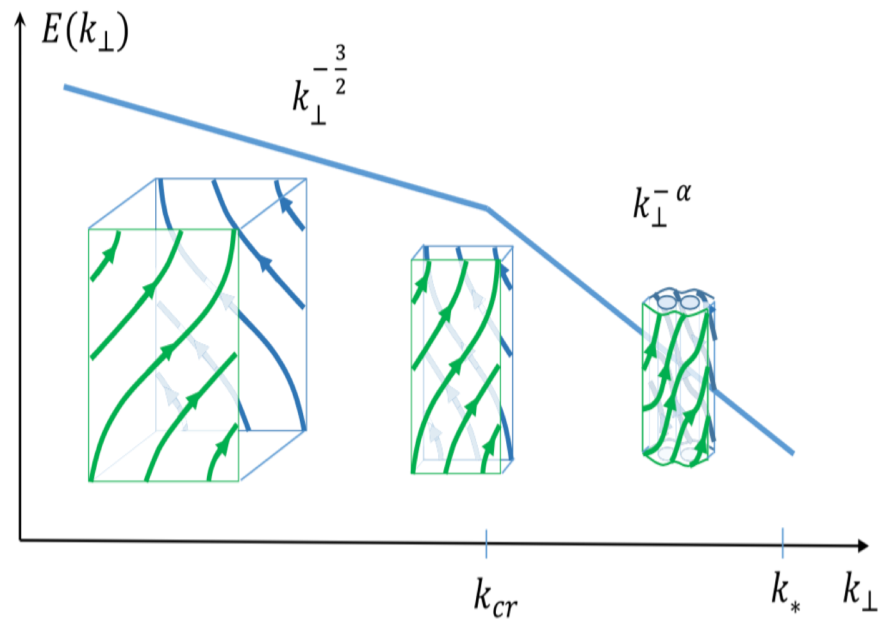
Turbulence & Reconnection: Two Different Forms of Free Energy

Free Energy: CS shear B fields (CSs)



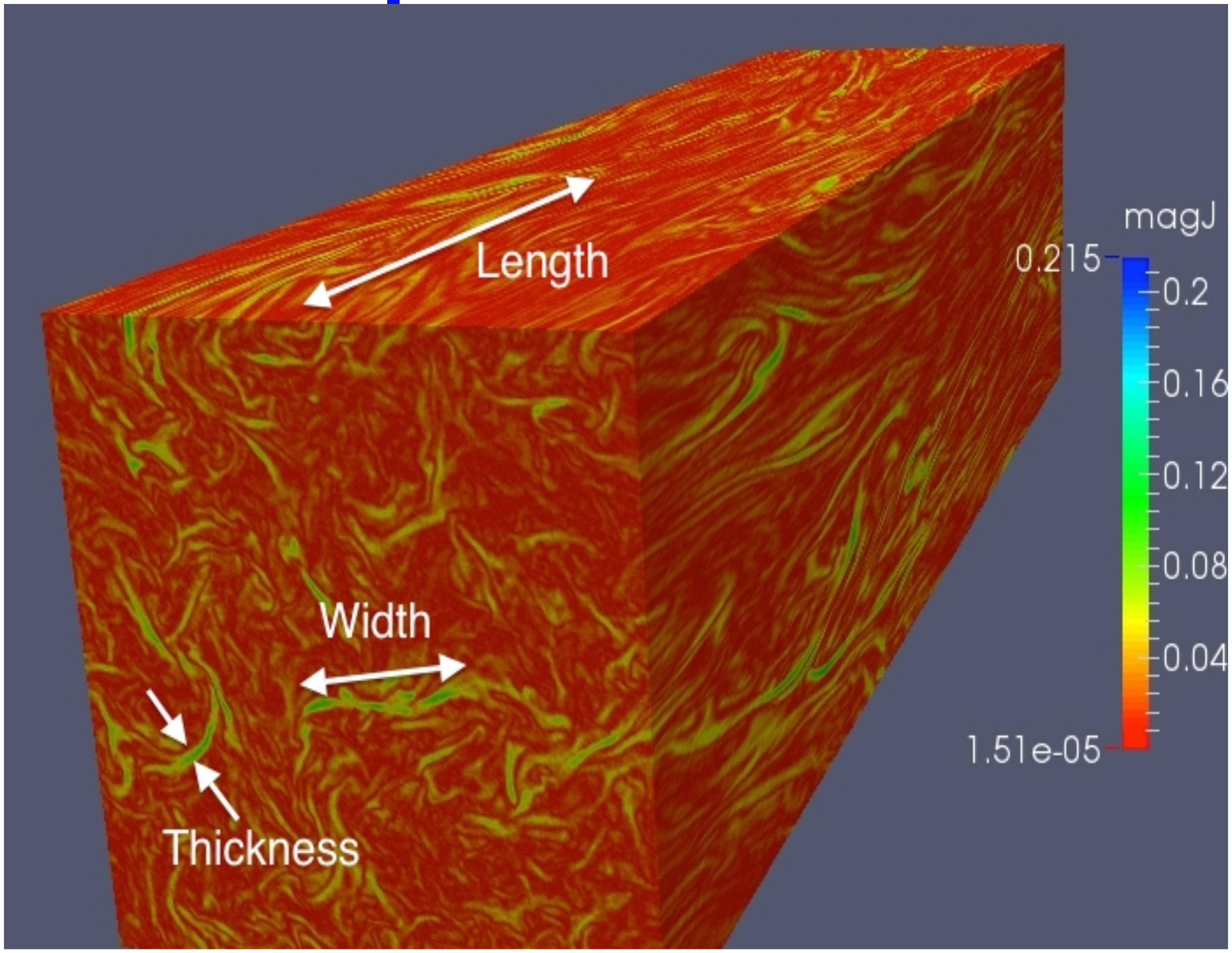
Drake et al
Huang & Bhattacharjee'16
Participants of this workshop

Free Energy: Turb injected turbulence



Uzdensky'15
Loureiro & Boldyrev '16,17
Zhdankin et al.
Participants of this workshop

Current Sheets (CSs) and Turbulence cannot separate from each other

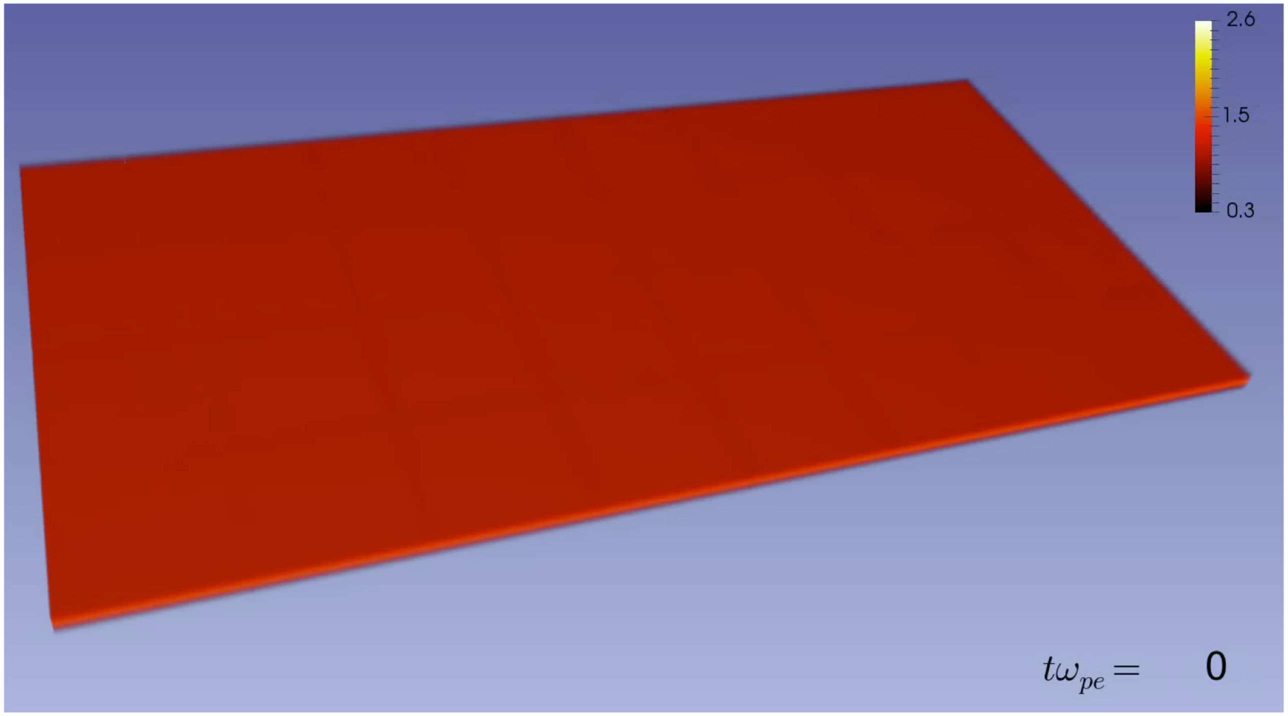


Makawana+'15; 17

VPIC sim

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

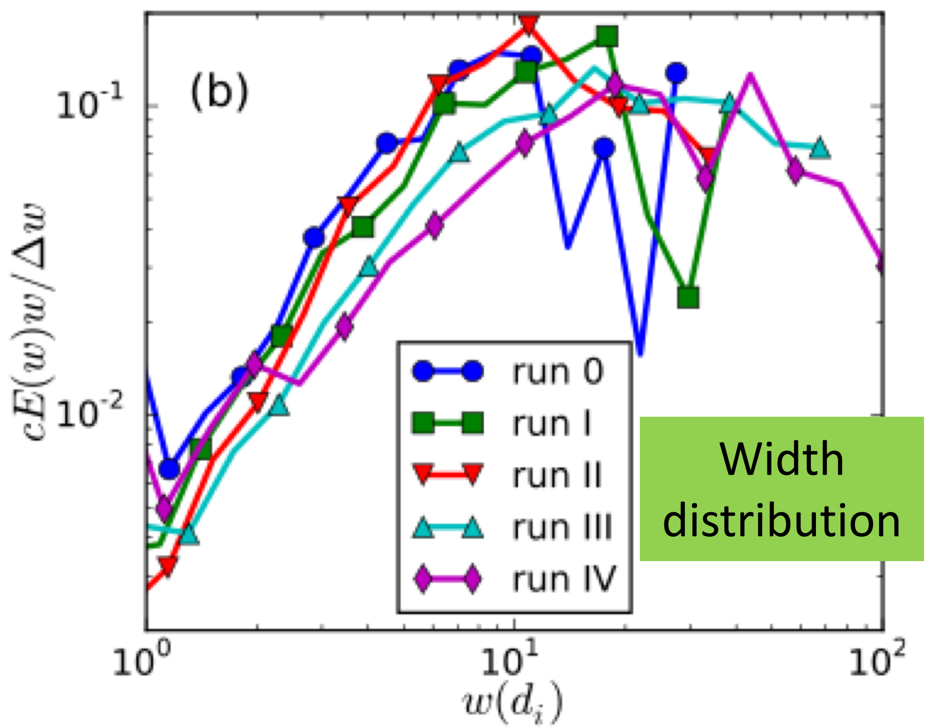
Issue #1: From turbulence cascade, do we ever get large aspect ratio current sheets in real physical systems?

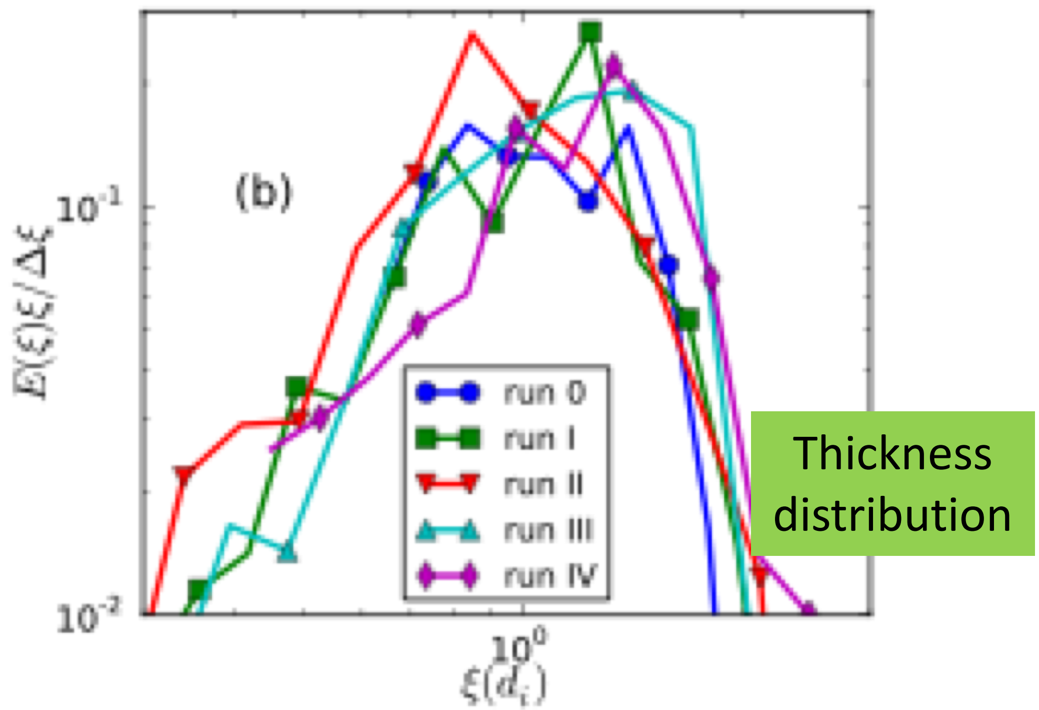


Guo et al.

CSs from turbulent cascade could be "paper-like"

Makwana+ 2015



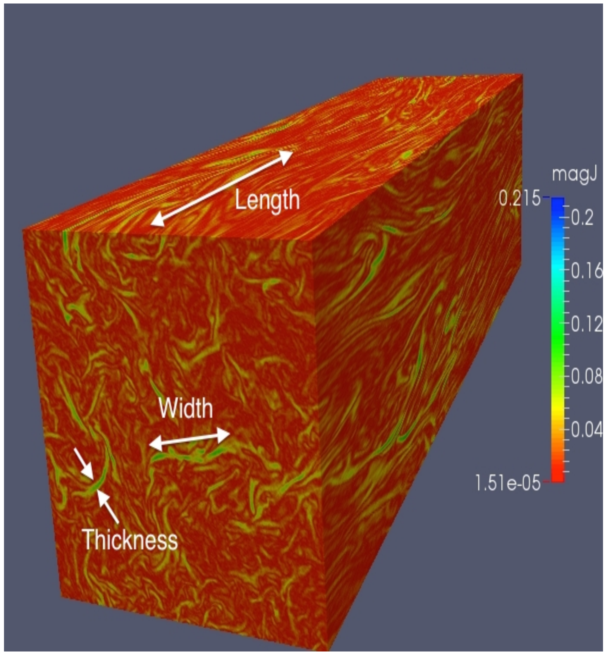


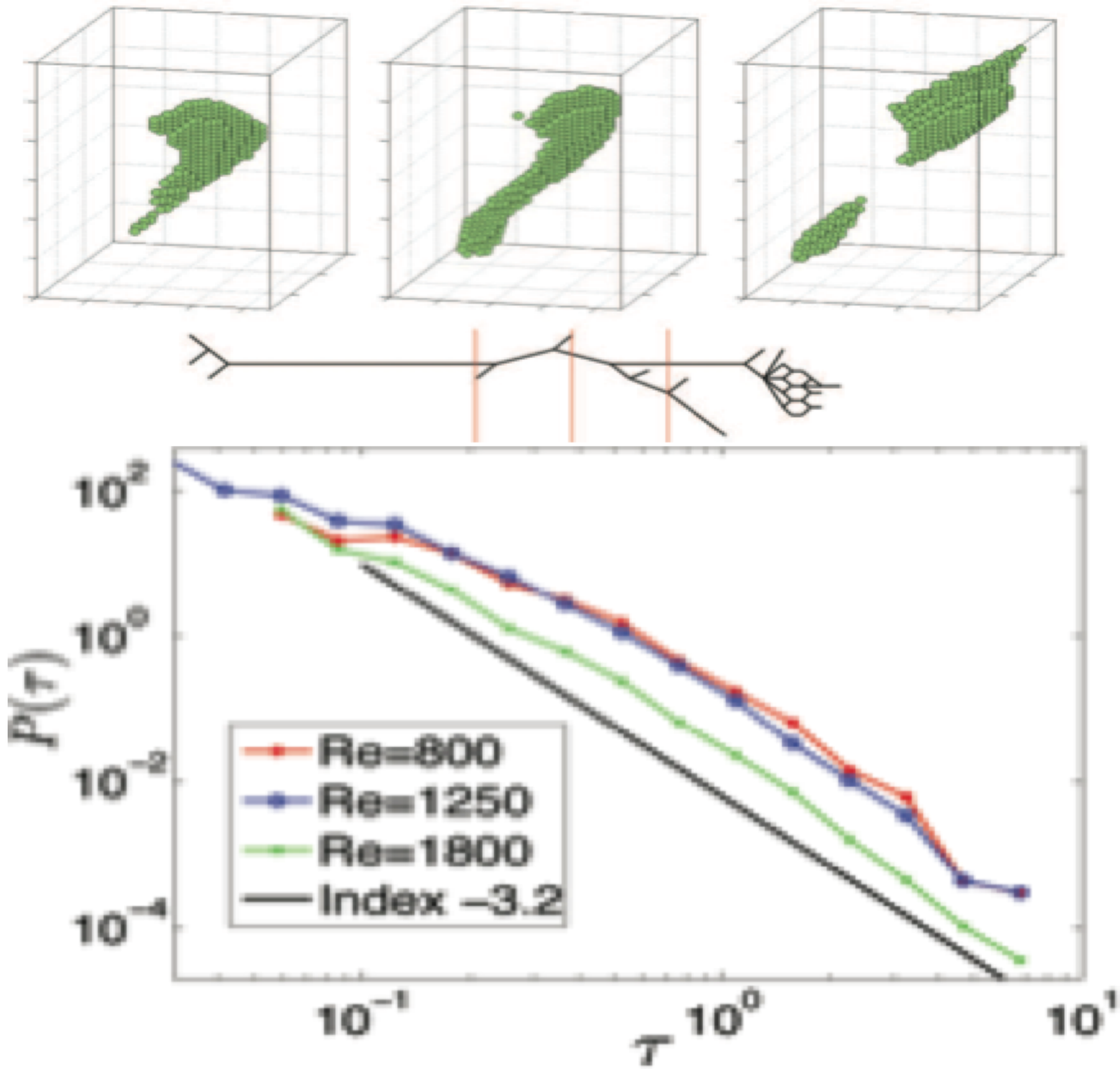
$$\text{width} \sim 10 d_i \qquad \text{thickness} \sim d_i$$

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

See also
Zhdankin et al. 2014, 2017

But: 1) Sheets have finite lifetimes

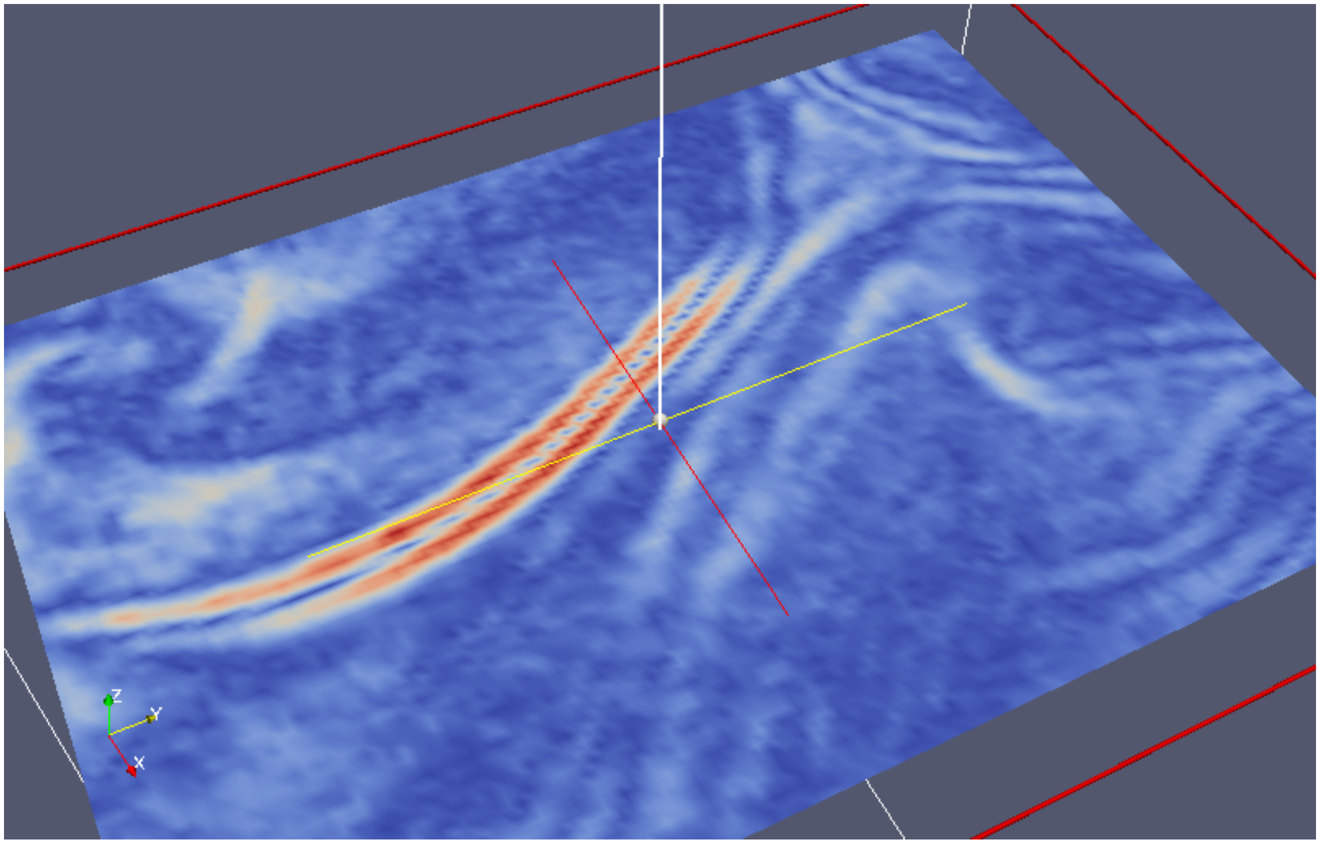




Zhdankin, et al., (2014, 2015)

But: Sheet are

2) Dynamic; 3) not force-free

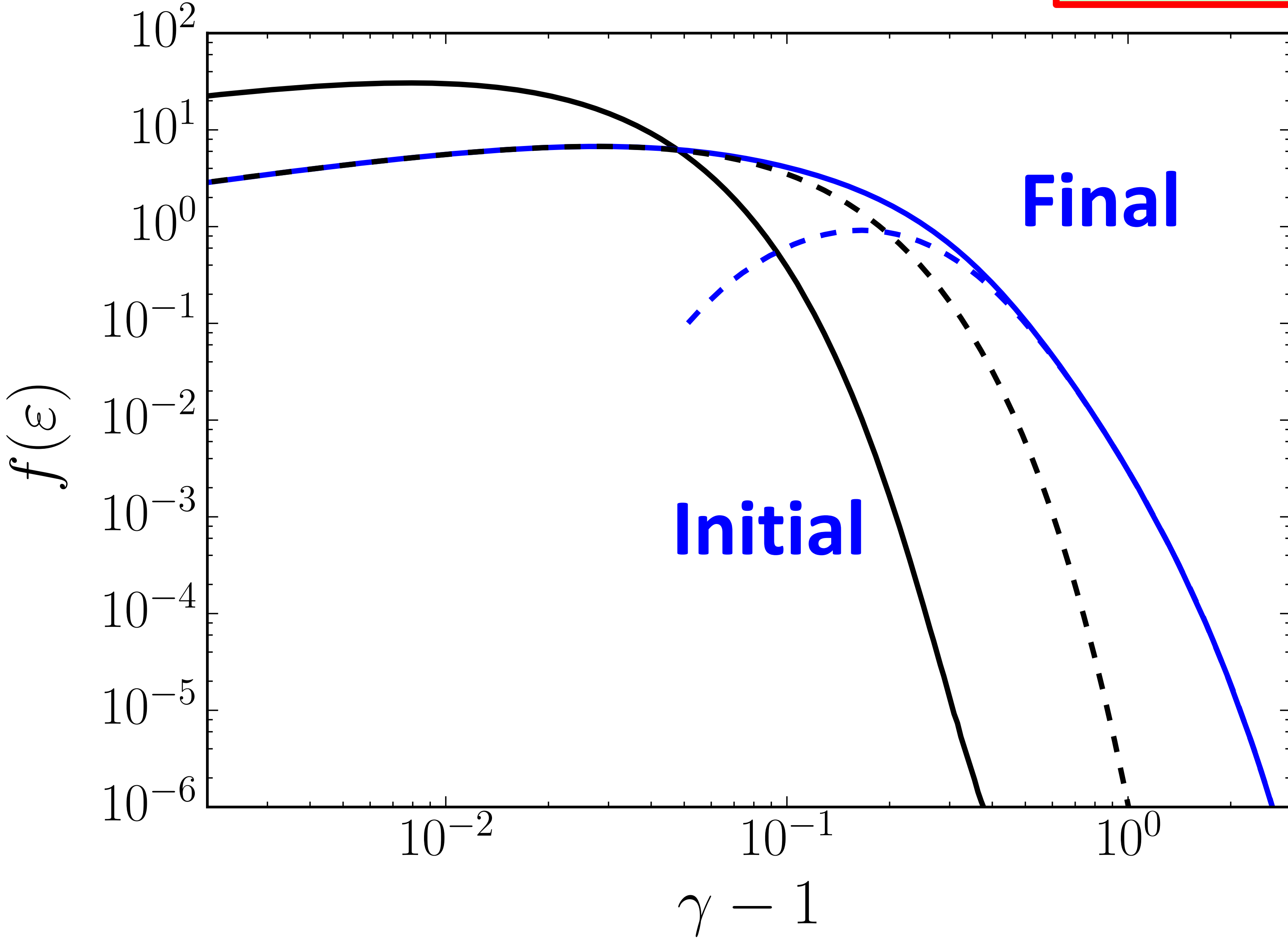


|JxB|
Non-force-free

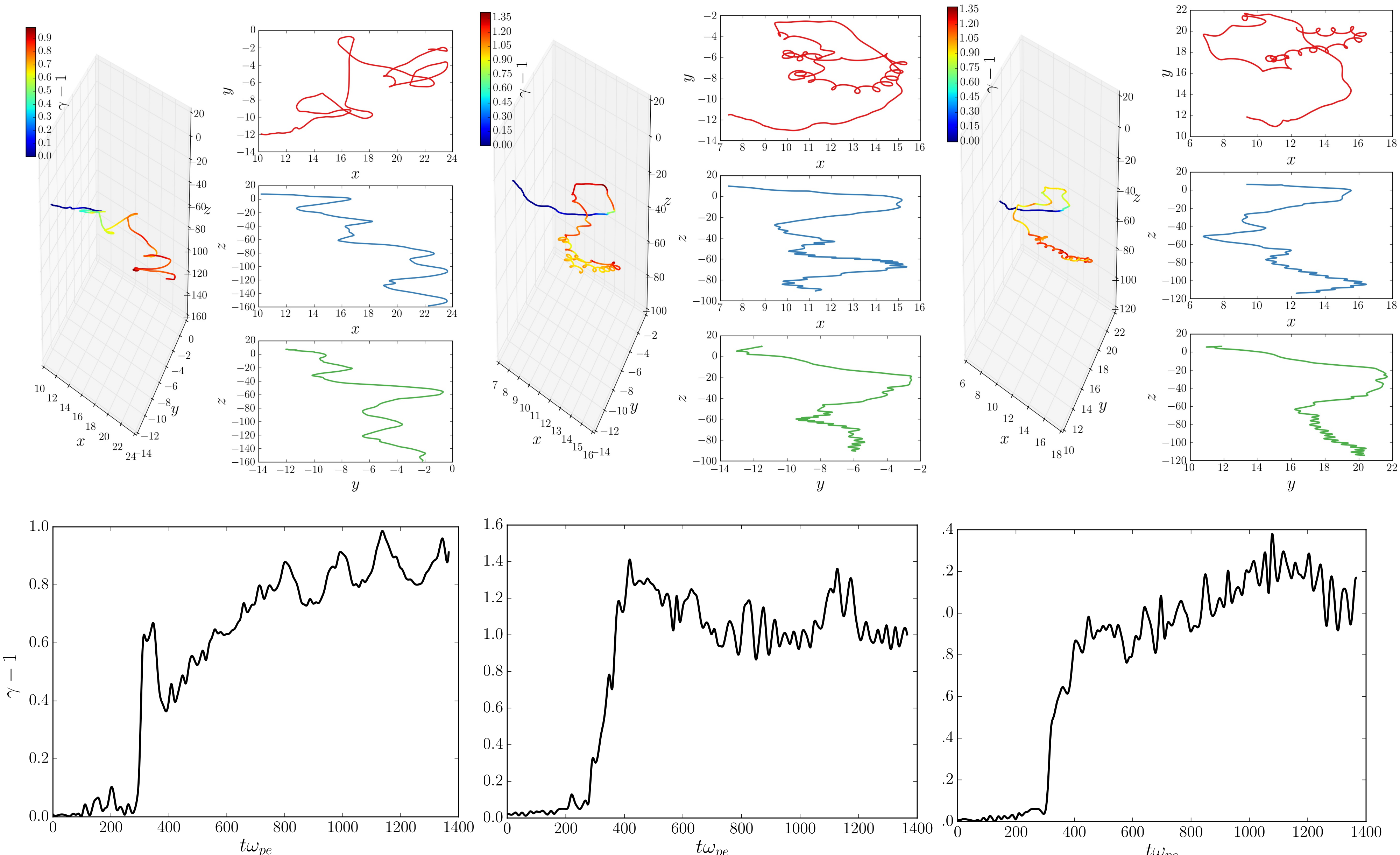
Makwana et al. 2015
See also Zhdankin et al. 13,14

Particle Energy Gain is modest

$\beta_e = 0.02$



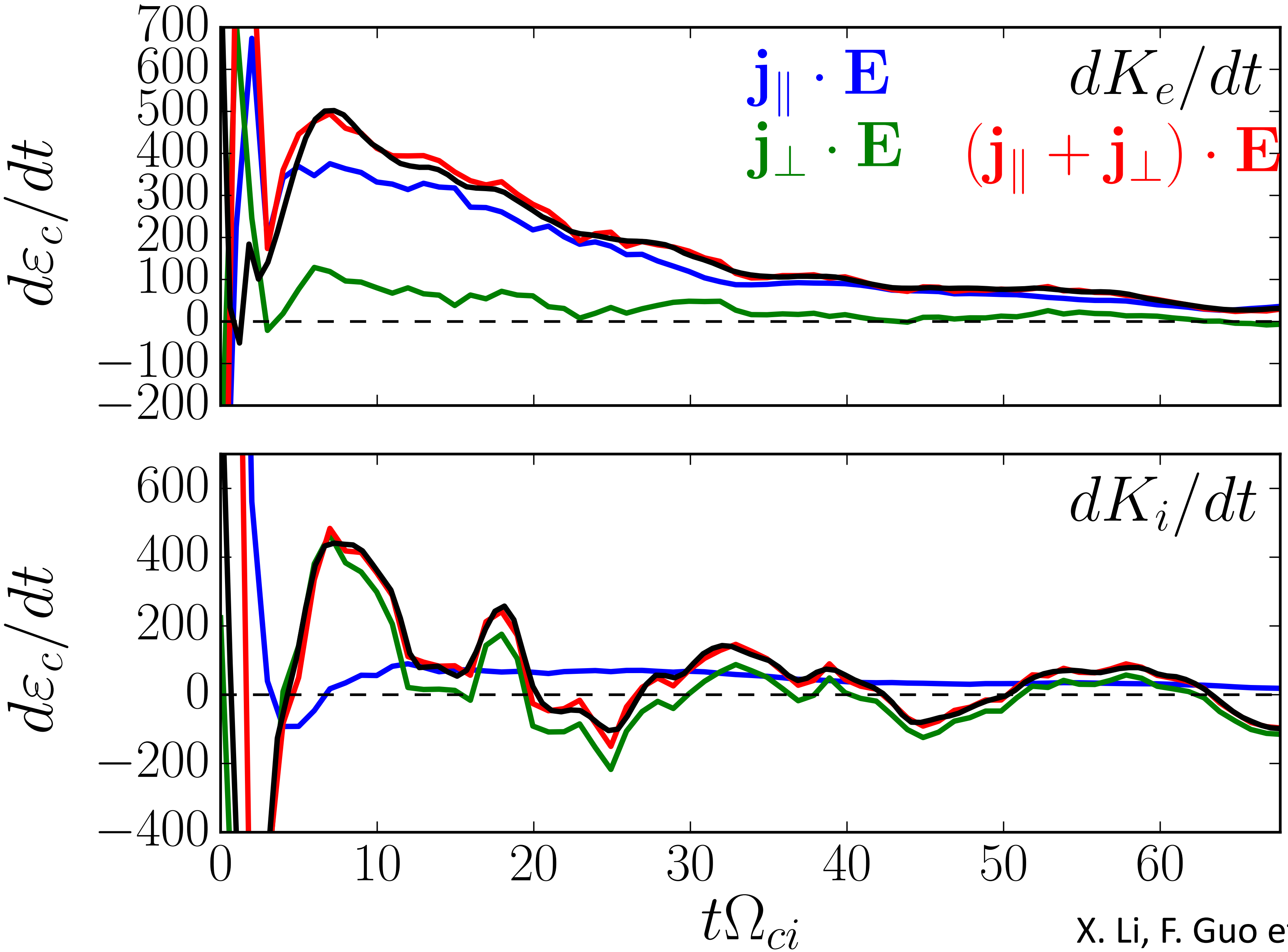
Sample Particle Trajectories



X. Li, F. Guo et al. 2016

E_parallel Dominant

$\beta_e = 0.02$



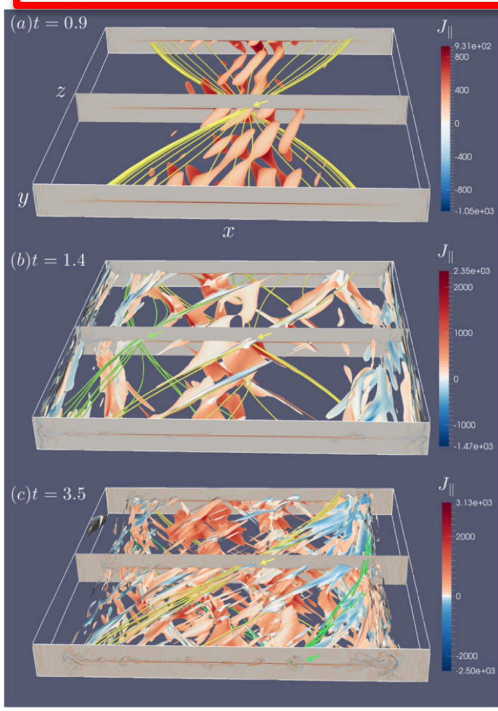
X. Li, F. Guo et al. 2016

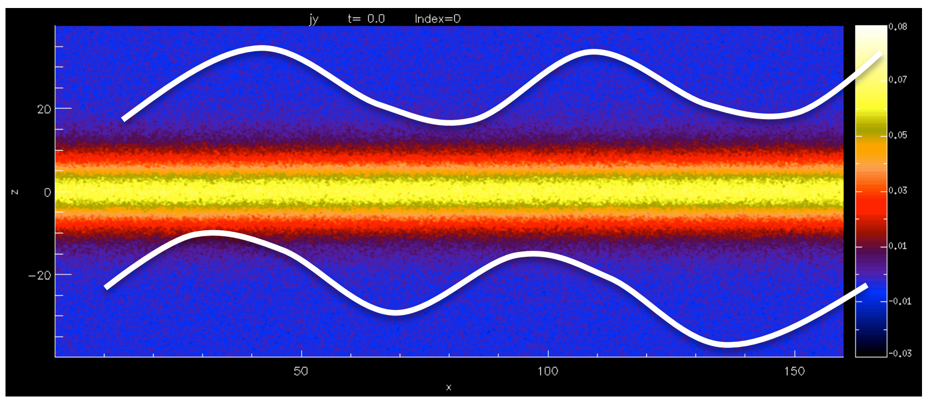
Issue #2: Interaction of turbulence with Pre-existing Thick Current Sheets

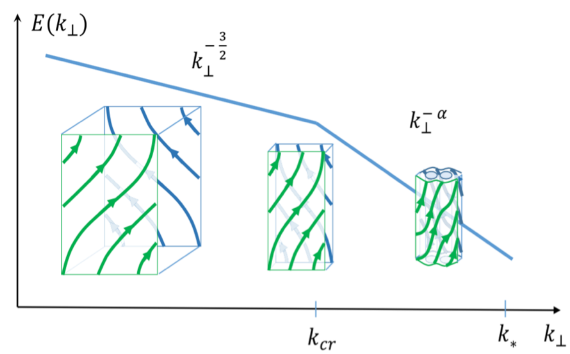
Free Energy: CS
shear B fields (CSs)

Free Energy: CS + Turb
shear B fields (CSs) with injected turbulence

Free Energy: Turb
injected turbulence







Thick Sheets:

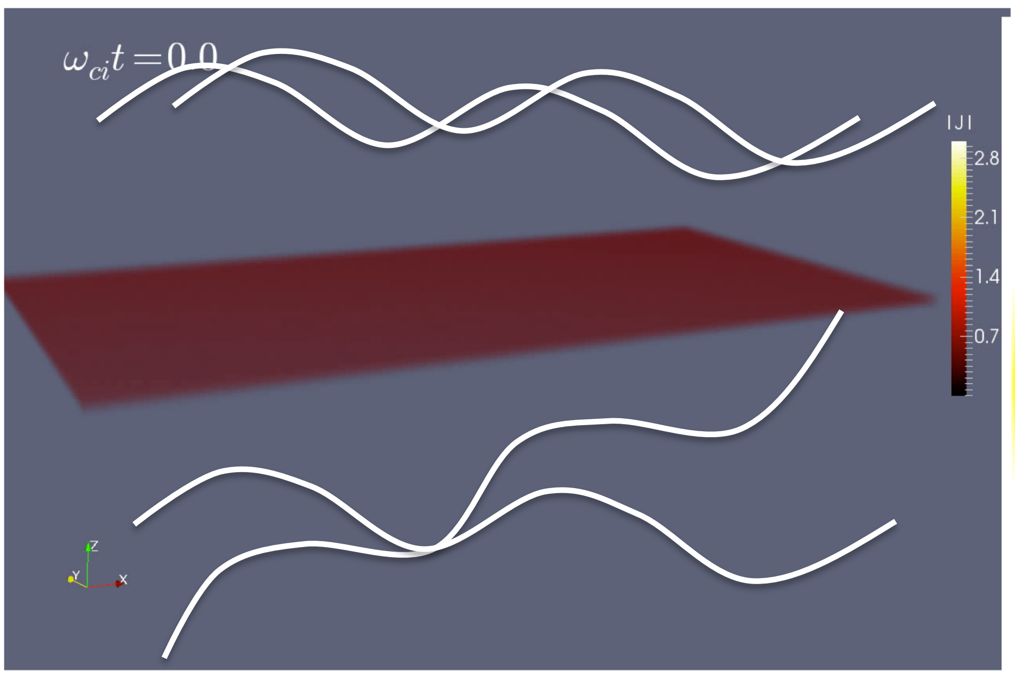
1) **Collisionless tearing is very slow**
2) **Turbulence injection scale > thickness**

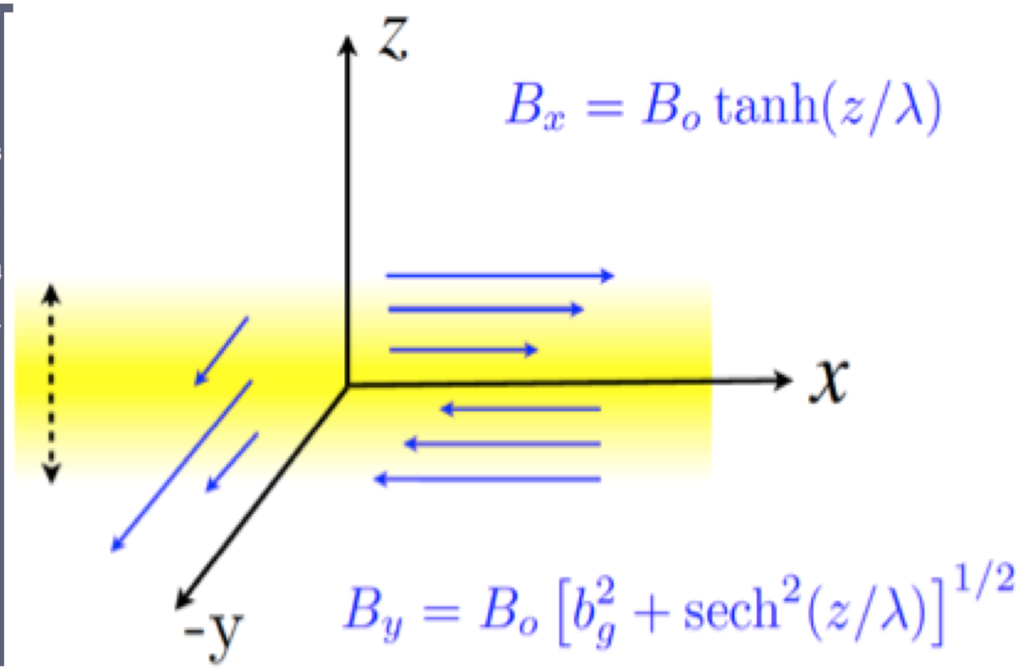
Inject Turbulence w initial CS

can be destabilized quickly by turbulence

(no guide field)

- Force-free Harris (no B_g);
- 3D: 640x320x320 de
- Cells: 1650x840x800; 100 ppc;
- Initial thickness: 18 de;
- mi/me=25; σ_e = 25; σ_i = 1;
- Initial perturbation: dB/B=0.1 with 10 modes.
- Total: ~ 5 Alfven time





Parameters

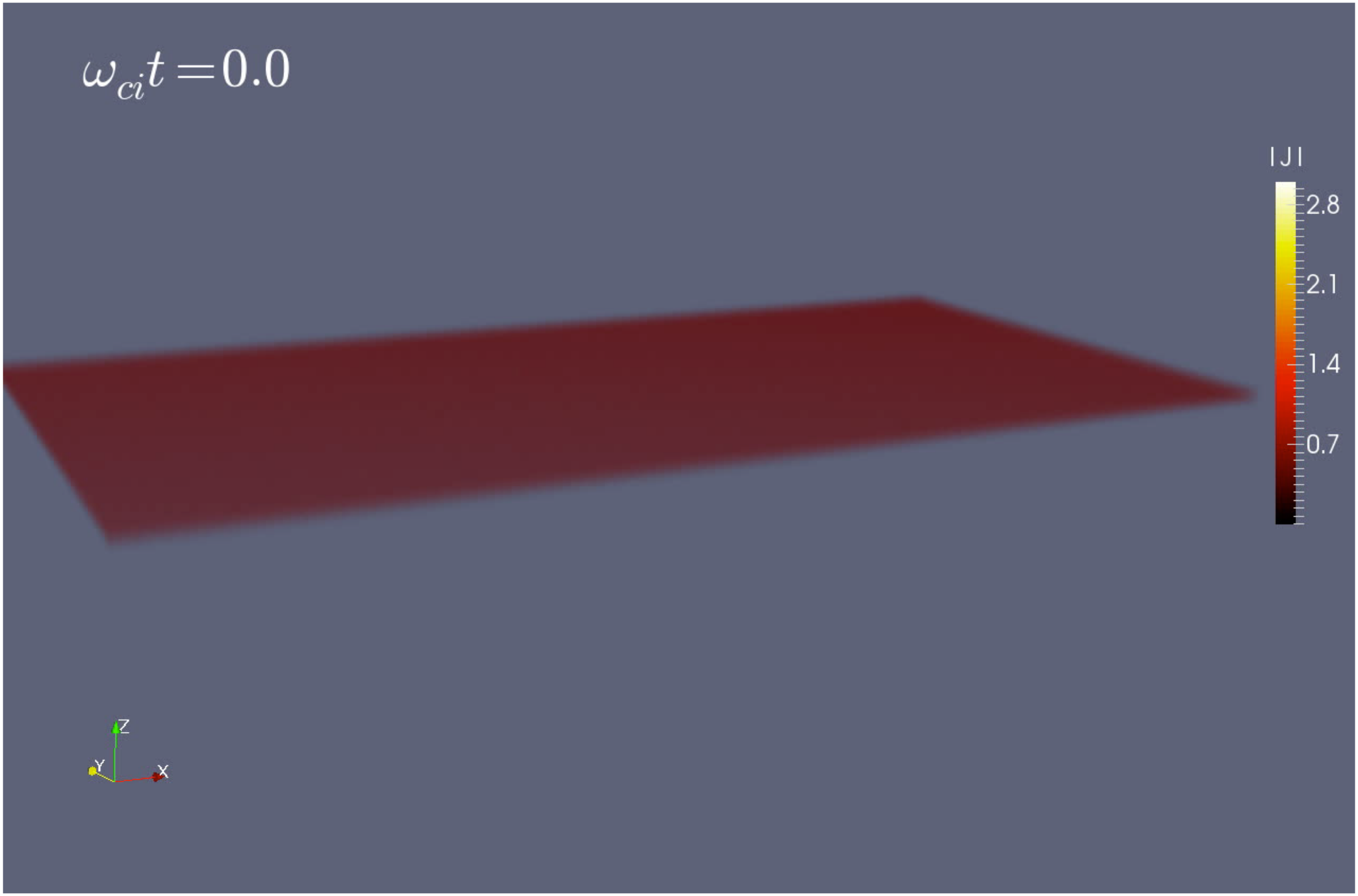
	Case A:	**Case B:**
m_i/m_e:	25	25
Box(d_e^3):	320	120
	320	120
	640	200
$\Delta B / B_0$:	0.316	0.316
Ω_{ce}/ω_{pe}:	**5**	**1**
β_e :	**~0.02**	**~0.02**
Guide fld:	**no**	**yes**
Init width:	**18 d_e**	**self-form**

1) Case A:
Pre-existing CS
+ 3D perturbations

2) Case B:
Uniform B_0
+ 3D perturbations

Makwana+ '15,17
X. Li et al. 2016

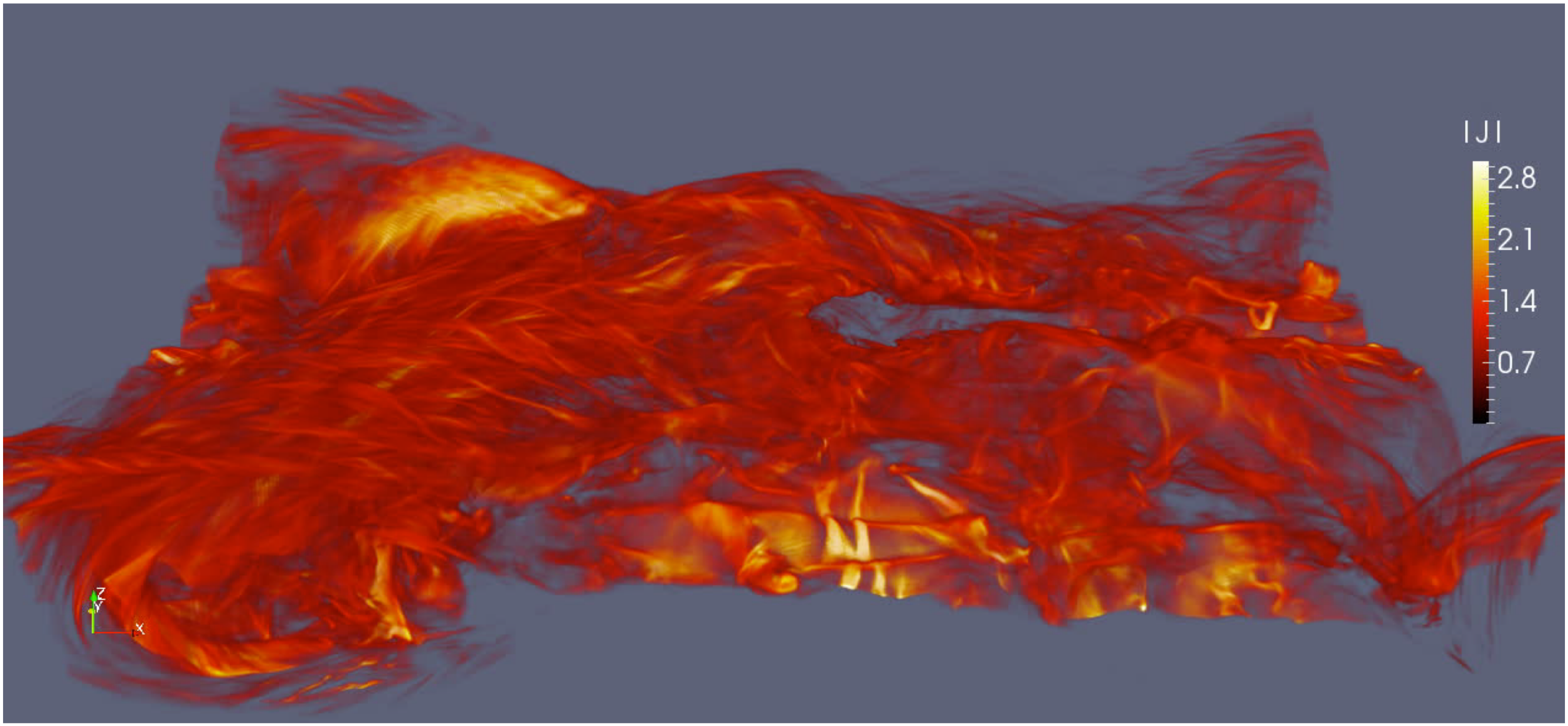
3D Collisionless Reconnection (using VPIC)



Guo et al. '18

Strong 3D Nature of CS:

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



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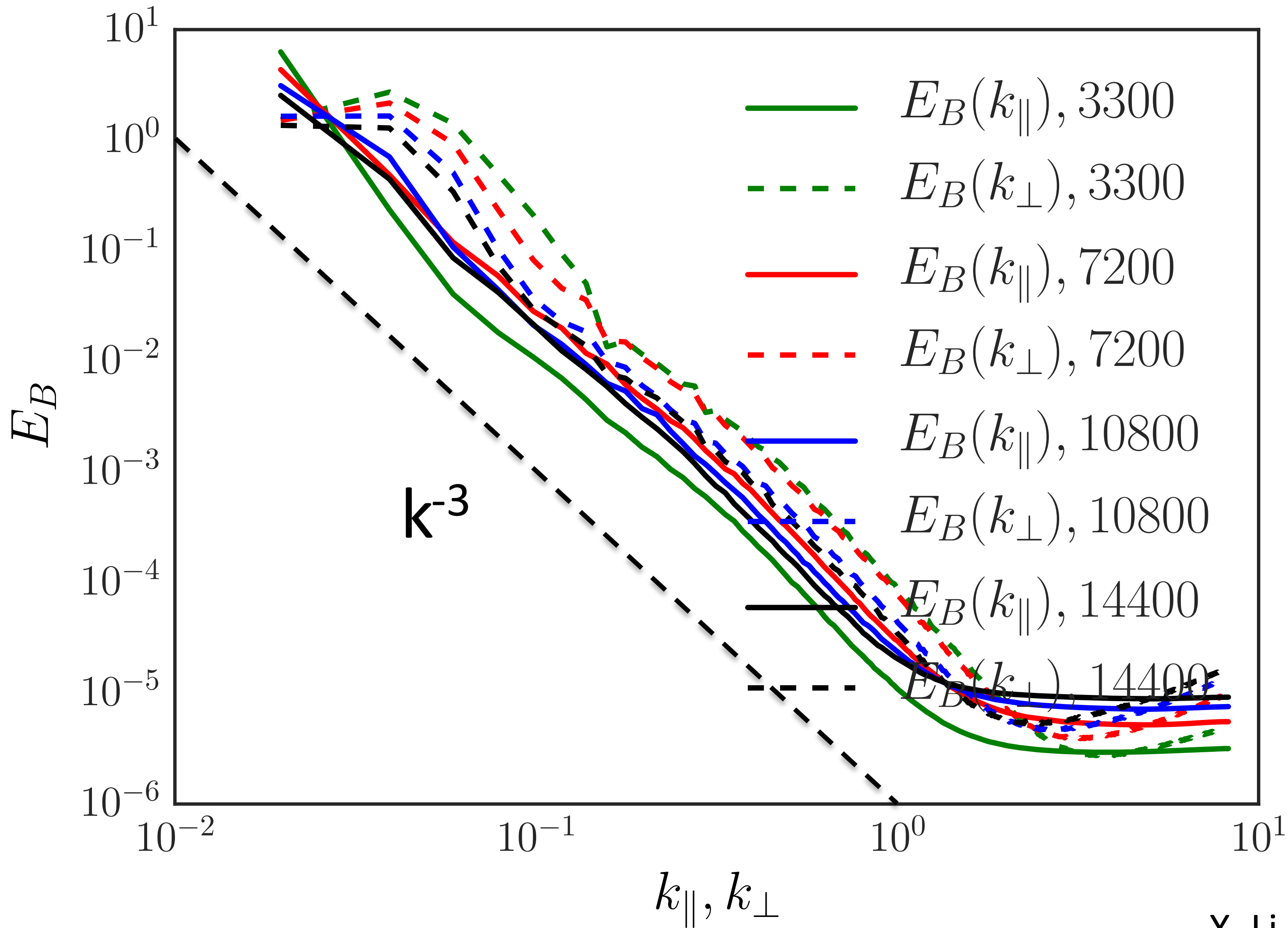
Magnetic turbulence spectra are essentially isotropic



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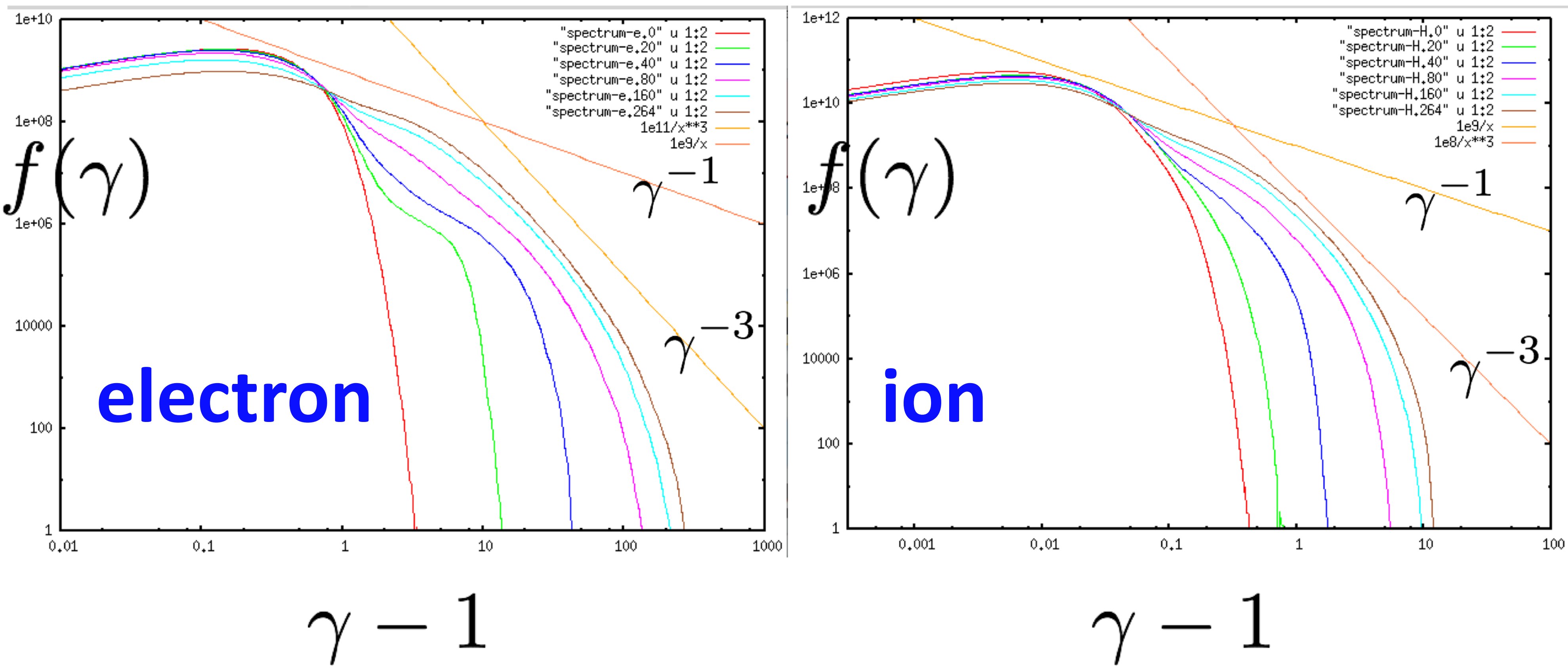
Both Electrons and Ions are Efficiently Accelerated by Reconnection



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.

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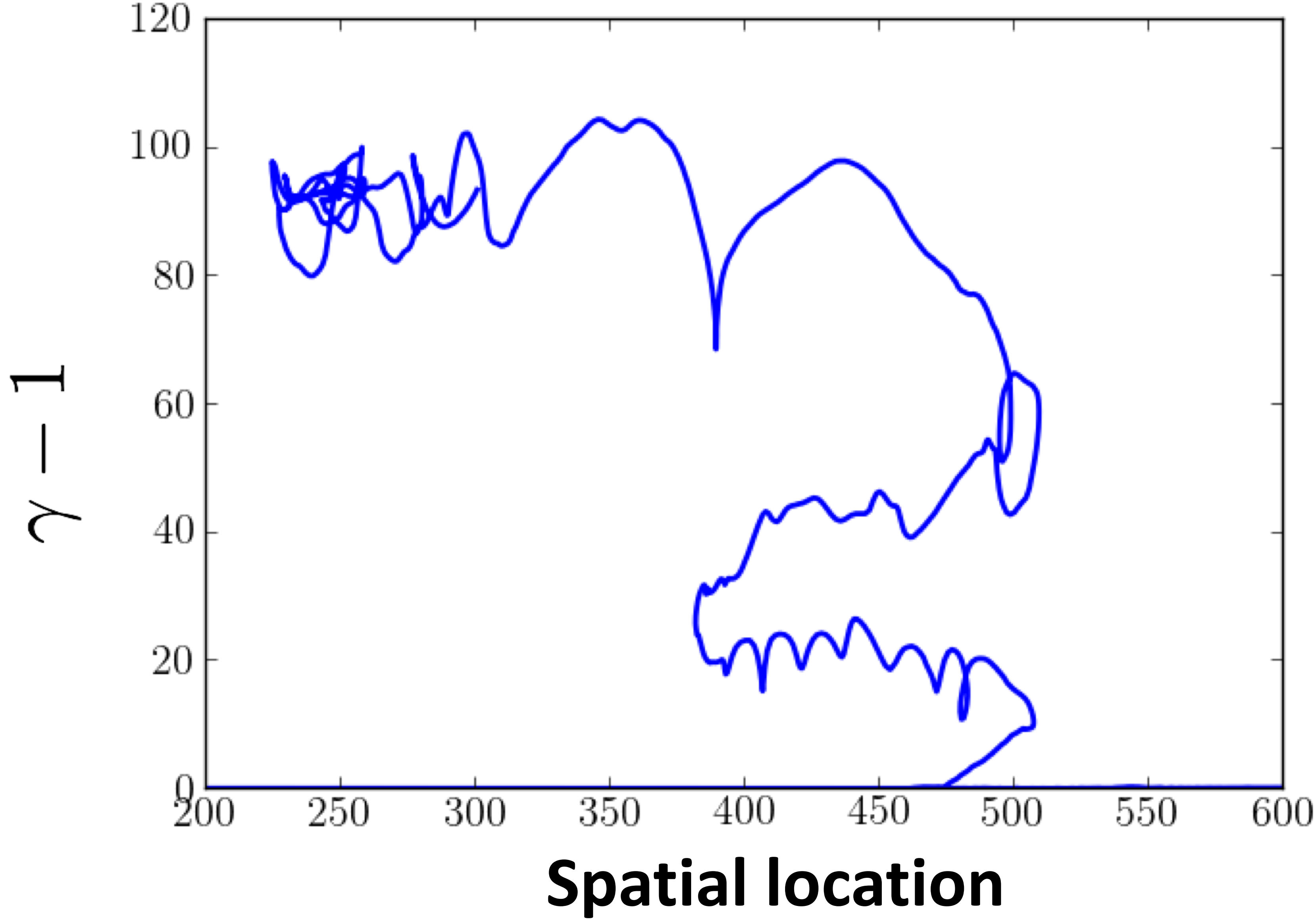
Electron Energization consistent with Fermi-like mechanism



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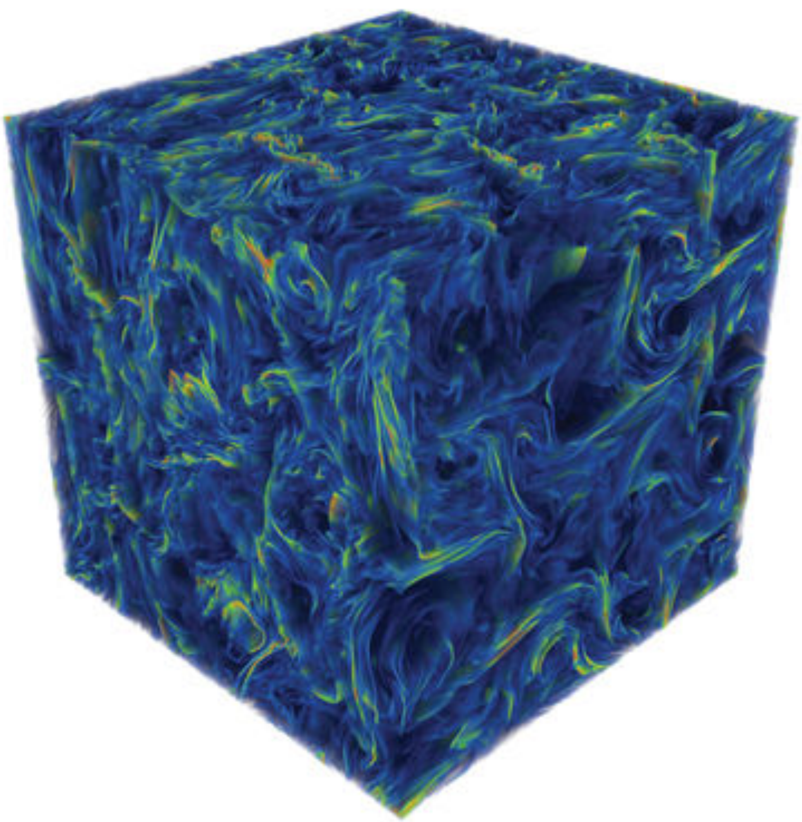
Issue #3: Efficiency of Particle Energization

Turbulence (from Reconnection)
is far more efficient than
Turbulence from injection-cascade

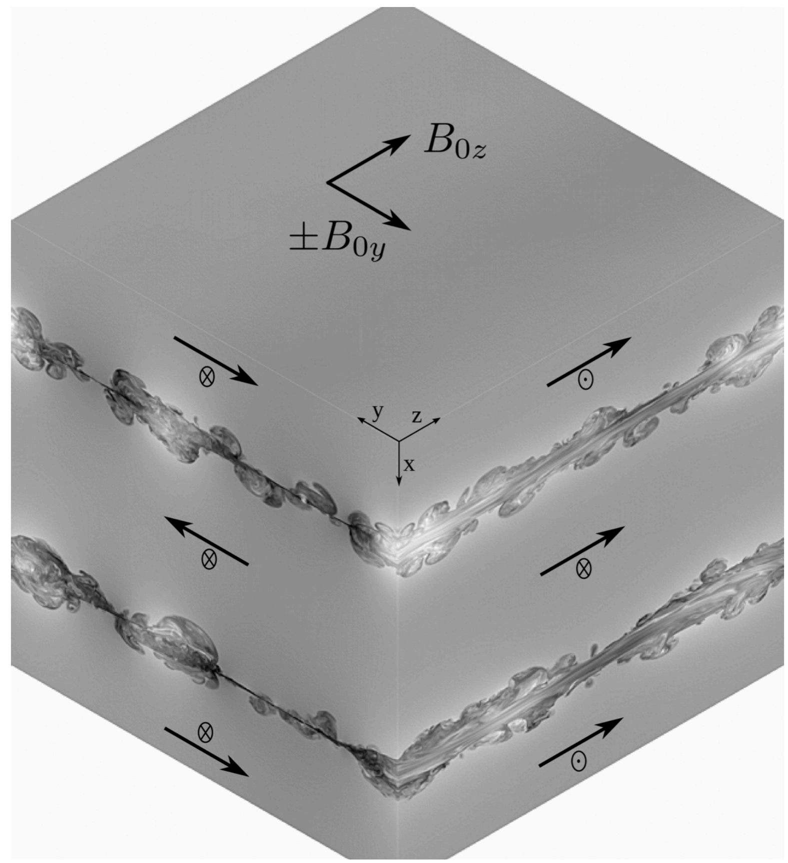
FIRST-ORDER PARTICLE ACCELERATION IN MAGNETICALLY DRIVEN FLOWS

ANDREY BERESNYAK[1] AND HUI LI[2]
[1] Naval Research Laboratory, Washington, DC 20375, USA
[2] Los Alamos National Laboratory, Los Alamos, NM 87545, USA
Received 2015 December 11; accepted 2016 January 17; published 2016 March 2

Turbulence from Large Scale Driving



Turbulence from Global Reconnection



Linking Global Energy Conversion with Particle Energy Gain

Fluid energy conversion:

V<->B energy transfer $\mathcal{T} = \mathbf{u}\cdot[\mathbf{j}\times\mathbf{B}]/c =$

$$-(\mathbf{u}\cdot\nabla)B^2/8\pi + \mathbf{u}\cdot(\mathbf{B}\cdot\nabla)\mathbf{B}/4\pi$$

$$\frac{1}{4\pi}\mathbf{u}\cdot(\mathbf{B}\cdot\nabla)\mathbf{B} = \boxed{\underbrace{\frac{1}{4\pi}(\mathbf{u}\cdot\mathbf{B})(\mathbf{b}\cdot\nabla)B}_{\mathcal{X}} +} \boxed{\underbrace{\frac{B}{4\pi}\mathbf{u}\cdot(\mathbf{B}\cdot\nabla)\mathbf{b}}_{\mathcal{D}}}$$

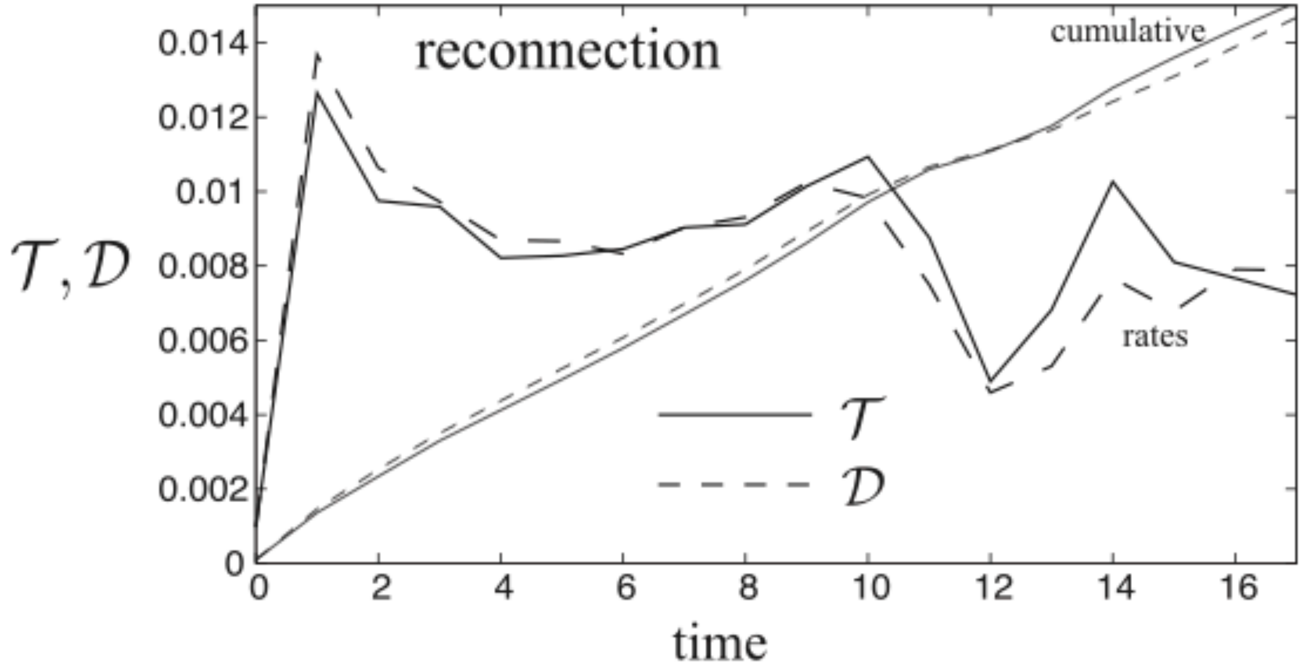
Particle energy via curvature drift:

$$d\mathcal{E}/dt = -2(\mathcal{E}_{\|}/B)[\mathbf{u}\times\mathbf{B}]\cdot[\mathbf{b}\times(\mathbf{b}\cdot\nabla)\mathbf{b}] = \boxed{\mathcal{E}_{\|}\frac{8\pi}{B^2}\mathcal{D}}$$

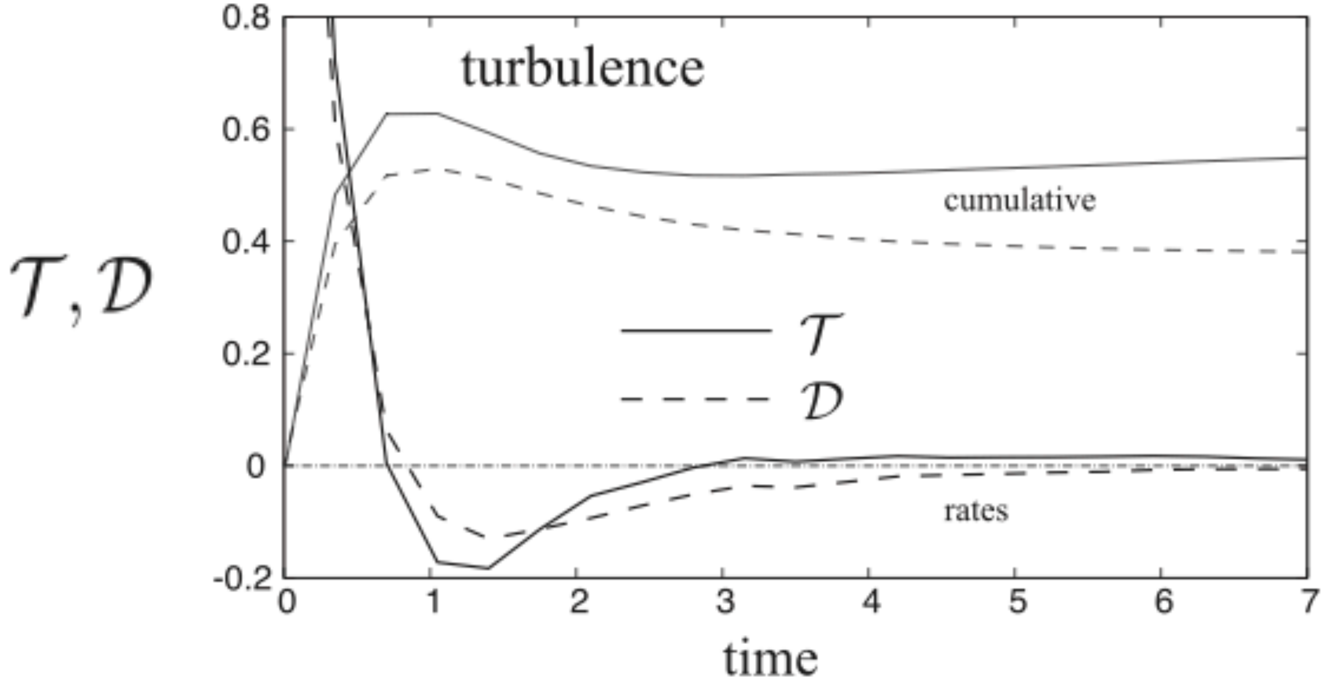
$$\mathcal{D} = \frac{B}{4\pi}\mathbf{u}\cdot(\mathbf{B}\cdot\nabla)\mathbf{b}$$

Drake's Talk

Turbulence from Reconnection is much more efficient in energizing particles



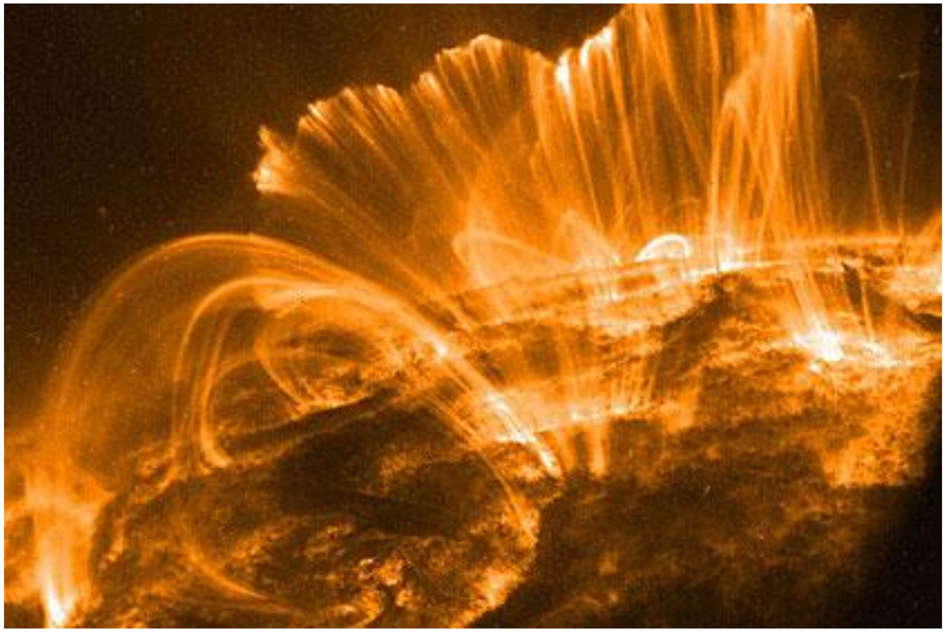
$\mathcal{T}$: Energy transfer from magnetic to flow



$\mathcal{D}$: Energy gain by particles via curvature drift

Beresnyak & Li, ApJL 2016

Issue #4: Could we Delay the On-set of reconnection?



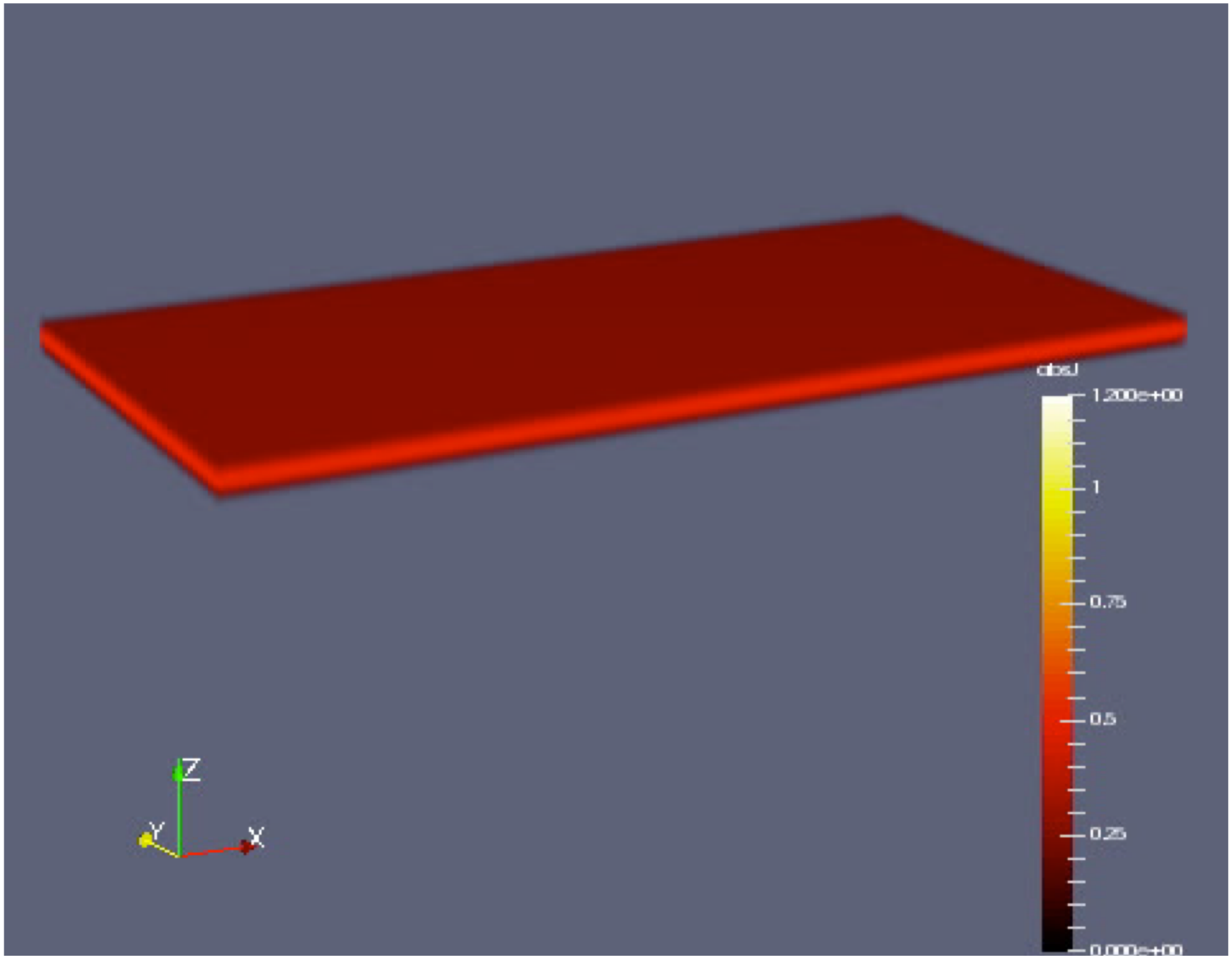
Strong Guide Fields Slows down the Disruption of 3D CS

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

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) Problems:
   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.