Dynamic of Current Sheets and Their Associated Particle Energization

Hui Li (李暉)

PIC studies:

Xiaocan Li, Fan Guo, Kirit Makwana, Bill Daughton

Makwana et al. Phys Plasmas 2015; X. Li et al. ApJL 2015;
X. Li et al. 2016 (in preparation)

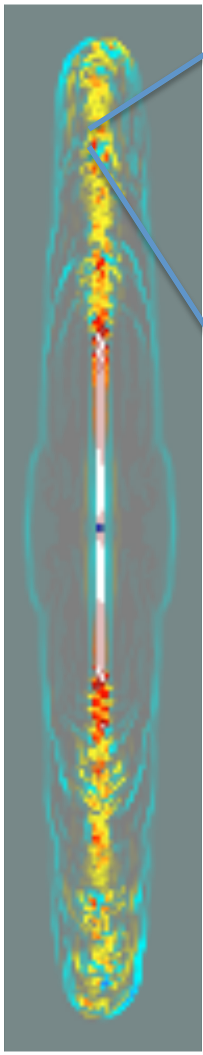
MHD studies:

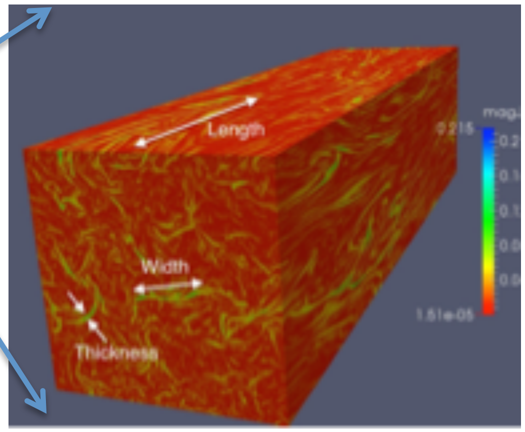
Andrey Beresnyak

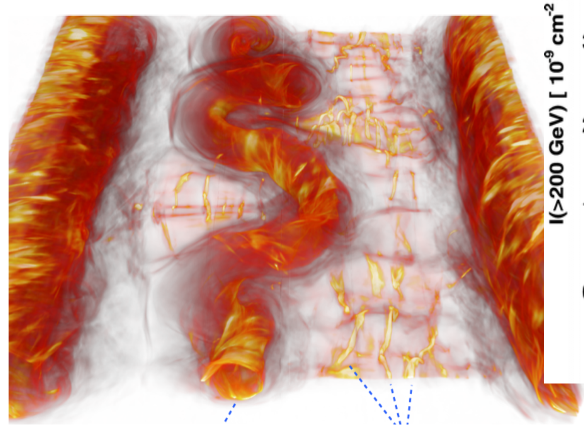
Beresnyak & Li, ApJL 2016; Beresnyak & Li 2013 (unpublished);

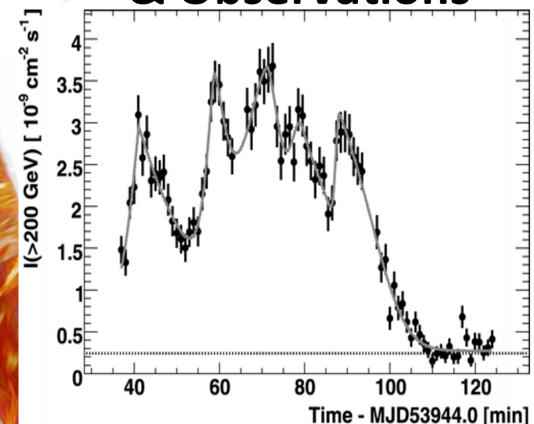
From Fluid to Kinetics to Radiation to Observations

SR-MHD jet stability → **MHD-PIC cascade** → **VPIC acceleration** ↔ **Radiation modeling & Observations**









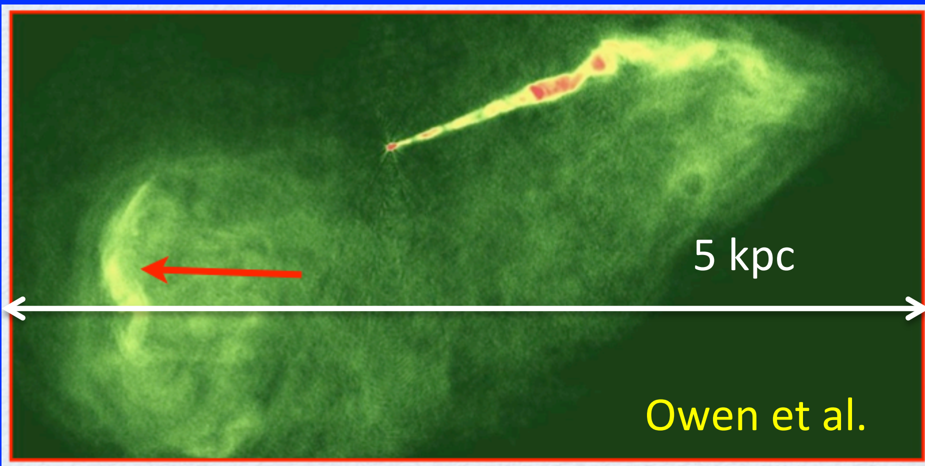
Please check out two posters

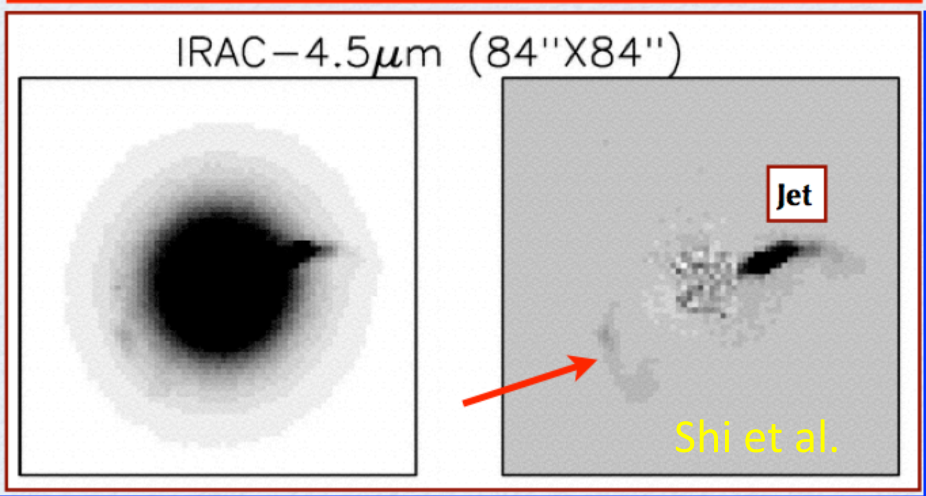
Interpret the polarization observations using collision-induced reconnection model
(Deng et al. 2016, ApJL)

MHD-based radiative modeling of polarization signatures of blazar emission

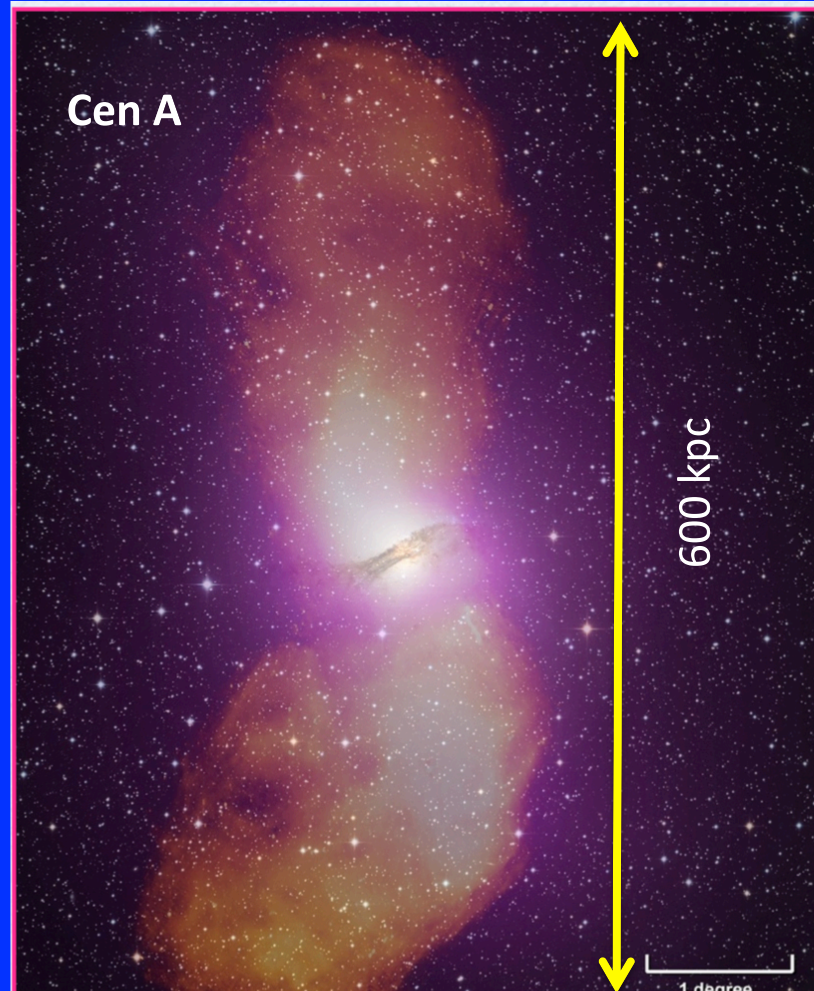
Haocheng Zhang[1,2], Hui Li[2], Wei Deng[2,3]

In-situ Acceleration and Volumetric





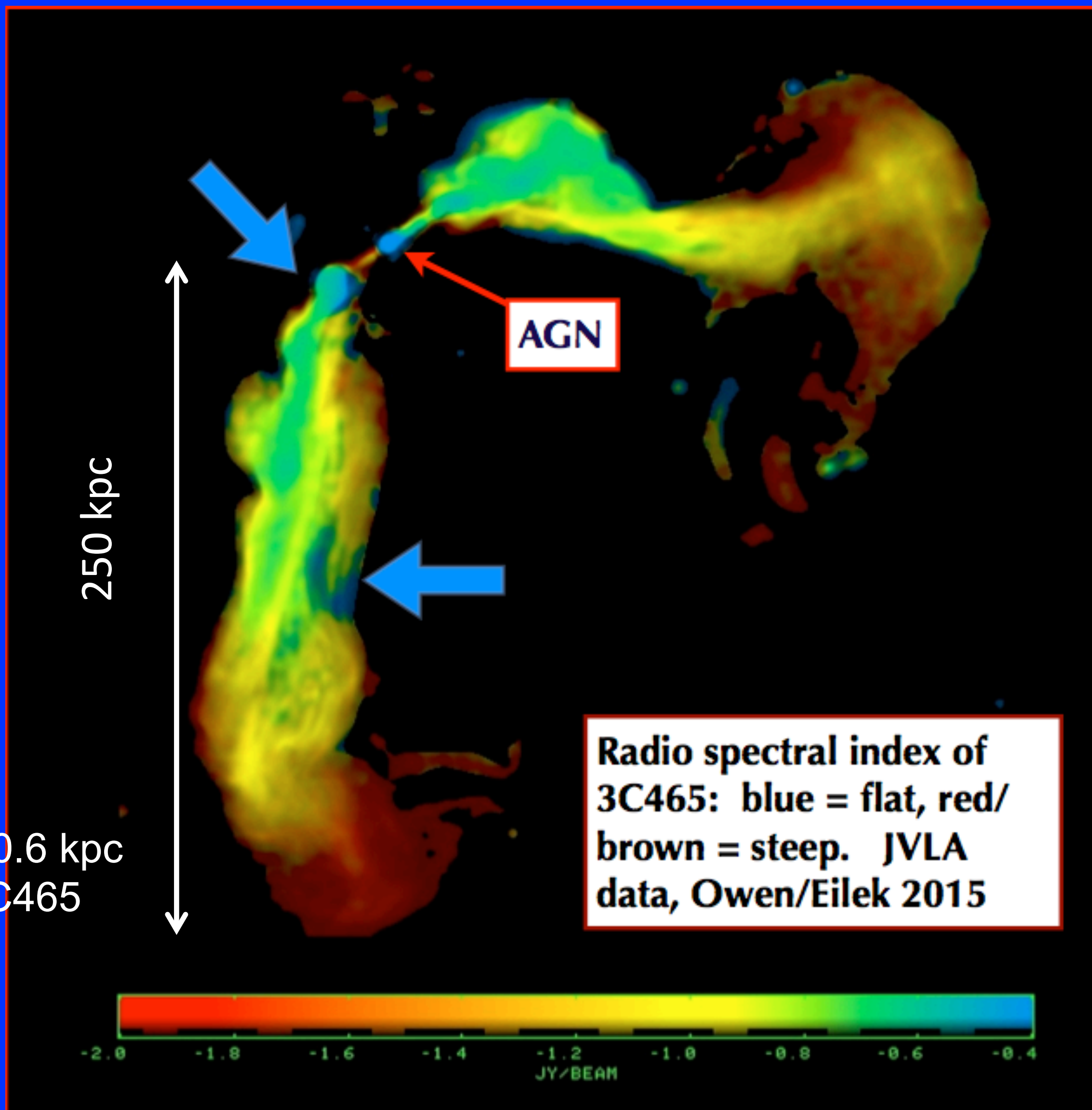
1” = 80 pc @ M87



Radio image of giant lobes (orange, Feian etal) overlaid on gamma ray and optical images.

Slides from J. Eilek

In-situ Acceleration: regions of (radio) Flat Spectra



1” = 0.6 kpc @ 3C465

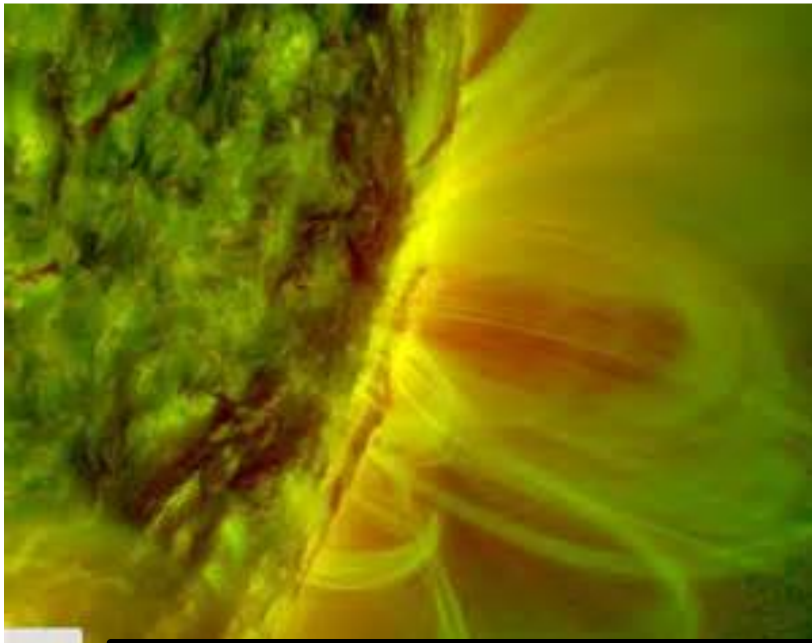
1) slope:

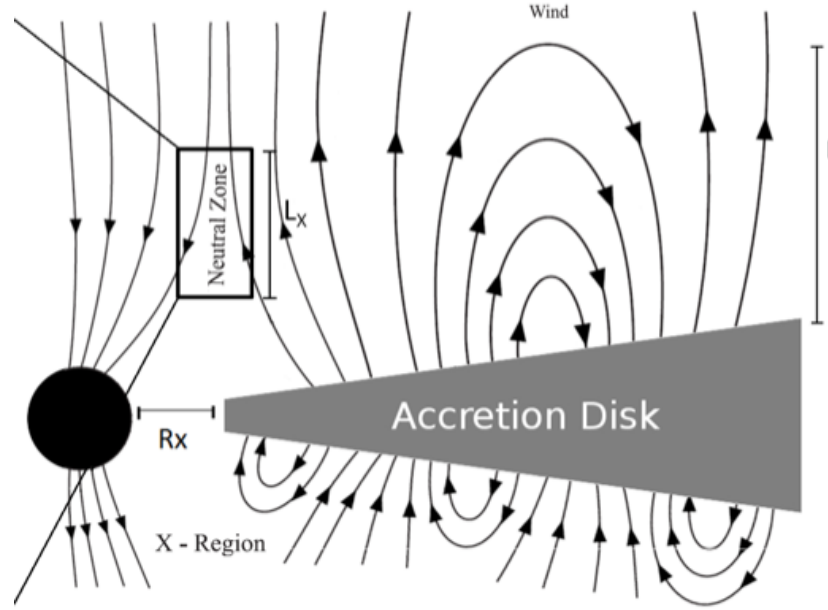
$$\alpha = \frac{\delta - 1}{2}$$

2) spatial: Need of in-situ acceleration

Both constrain acceleration processes.

Magnetically Dominated Corona



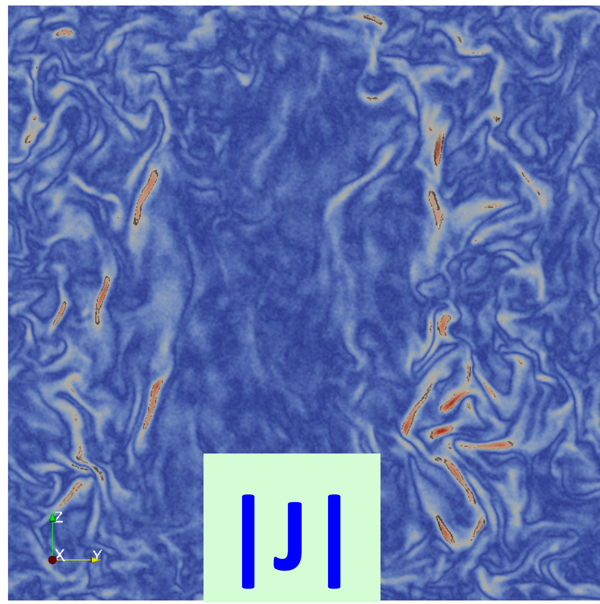


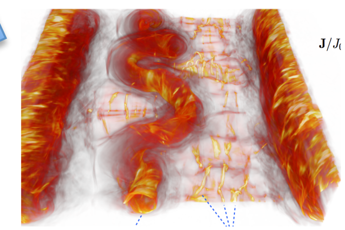
Brief Summary of Key features of jets, lobes, and coronae:

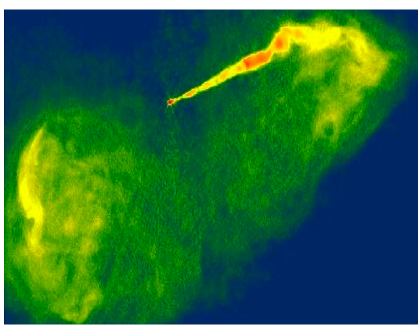
1) in-situ acceleration needed;
2) Volumetric;
3) Likely magnetically dominated.

Current Sheet Formation as "hand-shake" process

Free energy injection







Kinetic simulations particle dynamics

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

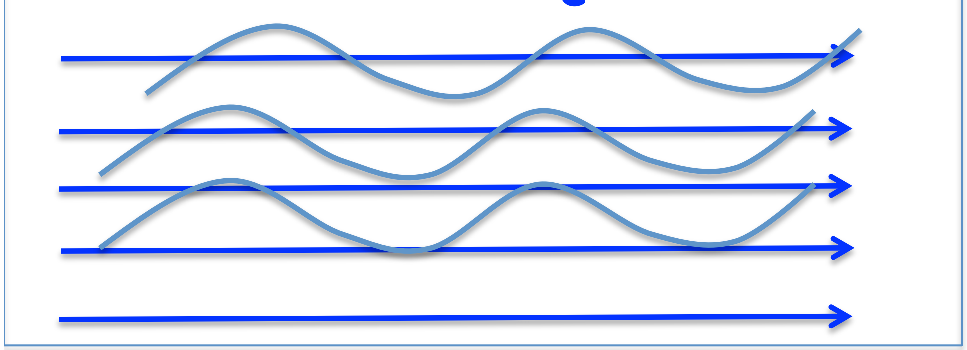
- $R_L \sim 2 \times 10^3 \gamma B$ cm
- $d_e \sim 5 \times 10^6 \gamma^{1/2} n_{-2}^{-1/2}$ cm

Wave-number

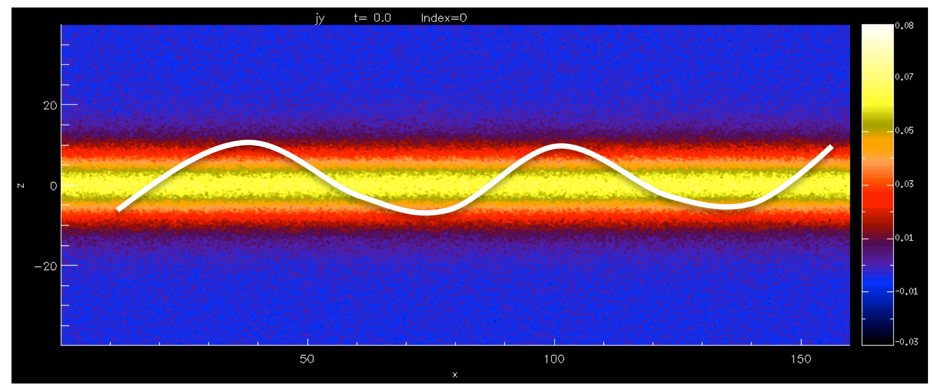
"Configuration Energy E_c"

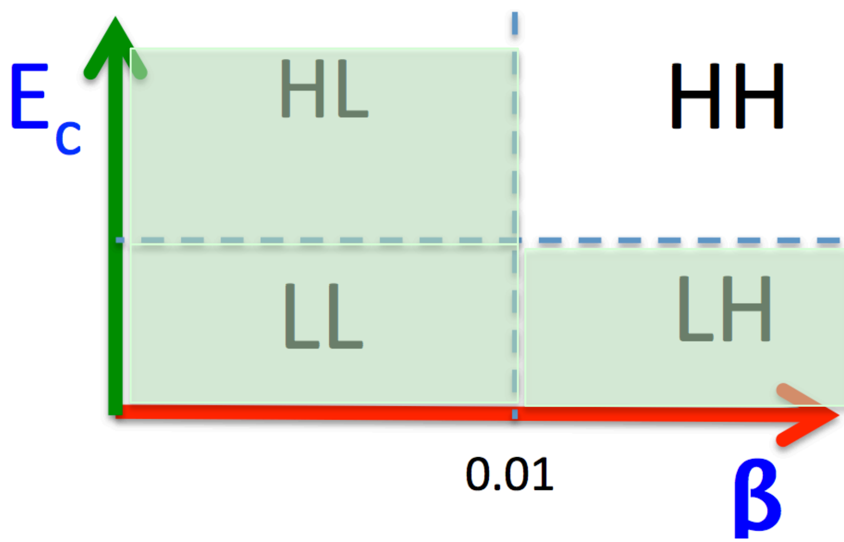
1) Uniform B + perturbation

Low E_c



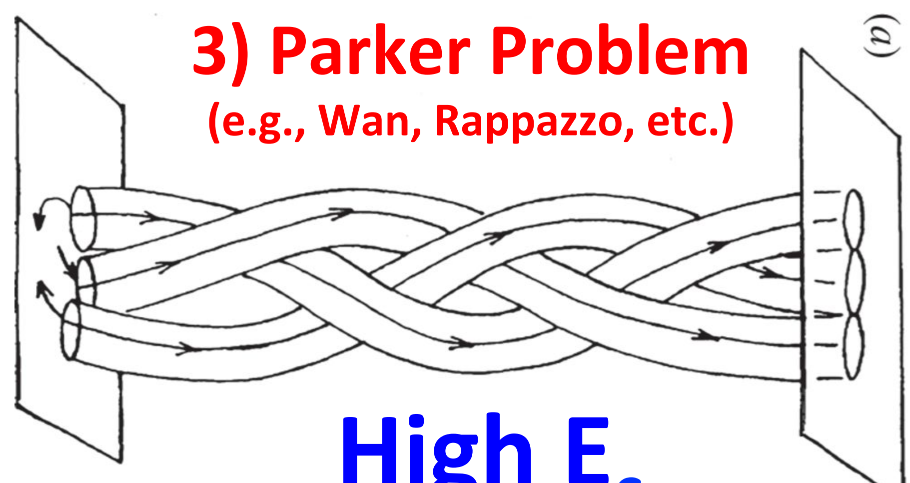
2) (thick) current sheet + perturbation





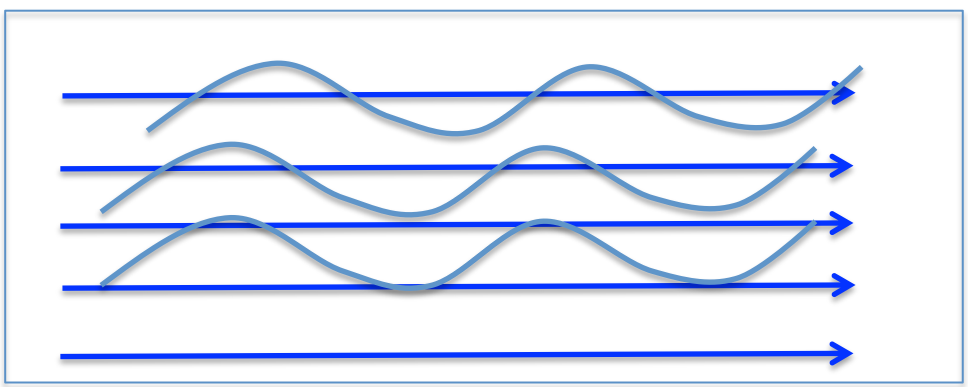
3) Parker Problem

(e.g., Wan, Rappazzo, etc.)



High E_c

"Experiment A": Forming Current Sheet Self-Consistently and Particle Energization



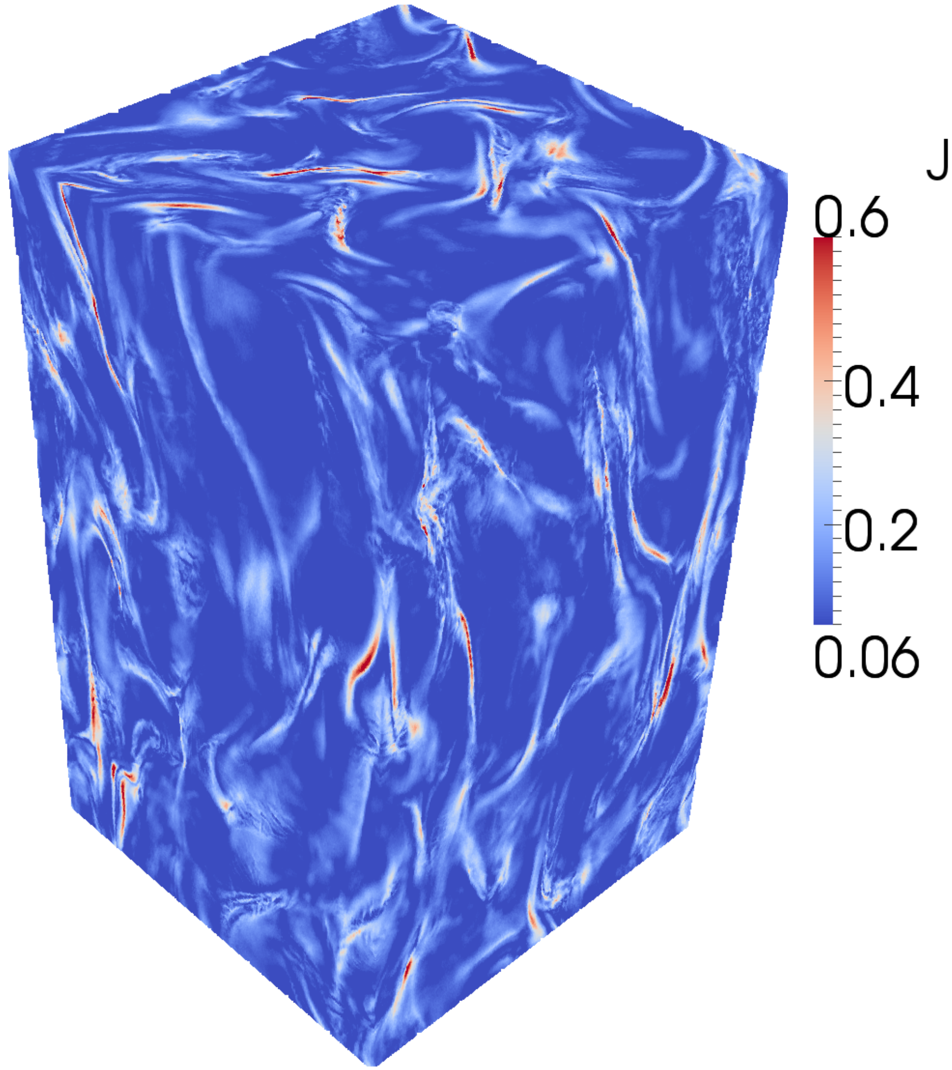
Low E_c

What Should We Expect?

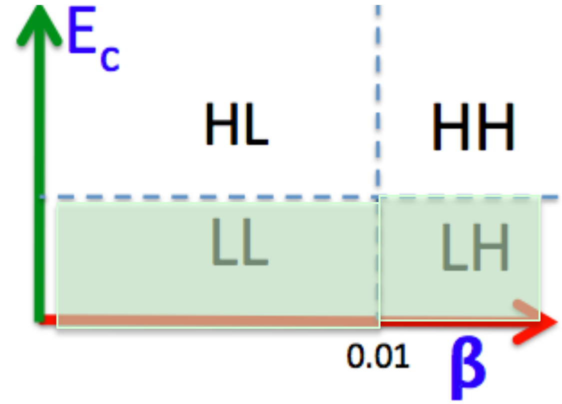
Magnetic:
1) Cascade
2) Field Line diffusion
3) Current sheet formation

How about particles?
1) Stochastic energization

Q:
Will it produce non-thermal particles?

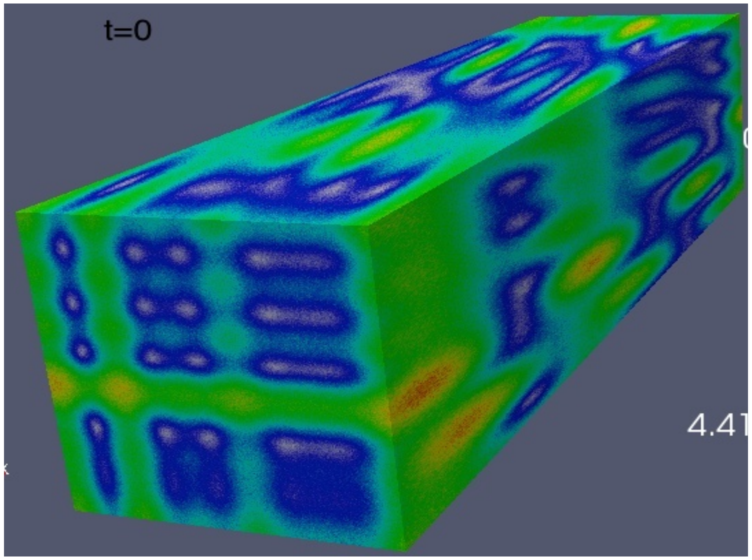


PIC Simulations Set-up



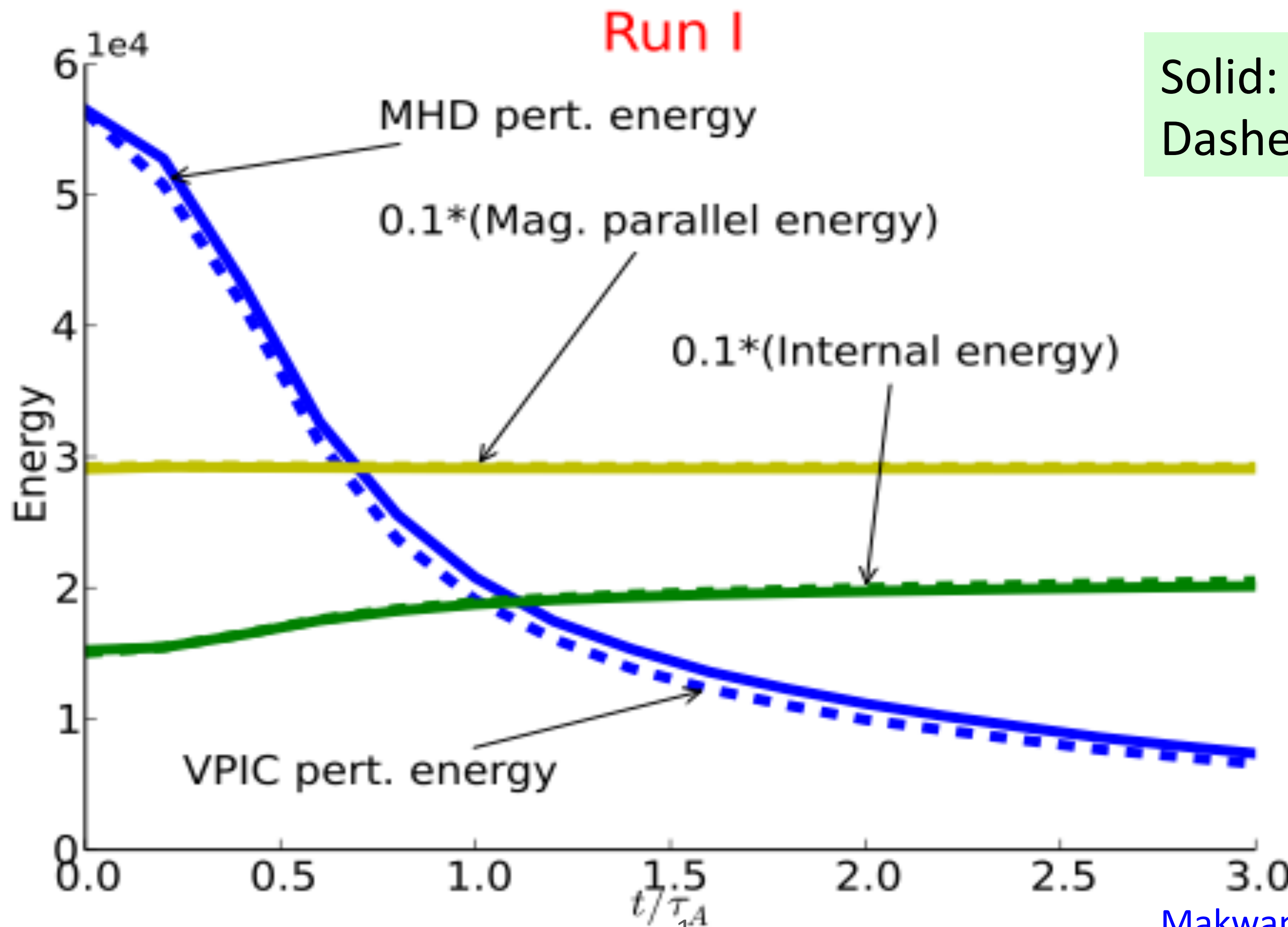
Uniform B_0 + 3D perturbations:

	LL run	LH run
m_i/m_e:	25	1
Box(d_e^3):	120	150
	120	150
	200	600
v_{the}/c:	0.1	0.08
$\Delta B / B_0$:	0.316	0.316
ω_{pe}/Ω_{ce}:	**1**	**3.6**
β_e :	**0.02**	**0.33**



Makwana+ 2015
X. Li et al. 2016

Energy Evolution



Solid: MHD
Dashed: PIC

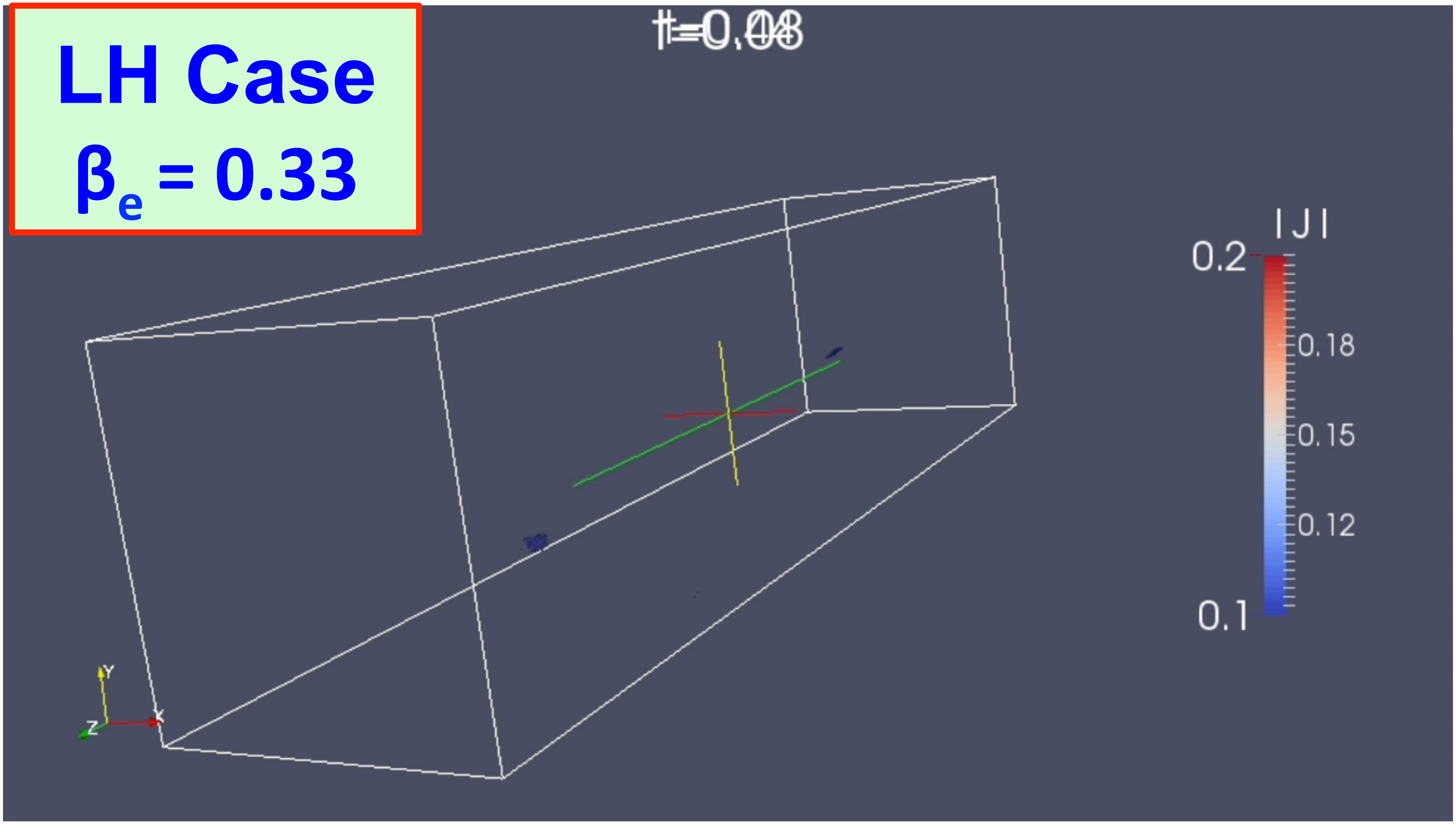
Makwana+ 2015

Hierarchical Current Sheet Structures

3D PIC Simulation 600x150x150 d_e^3

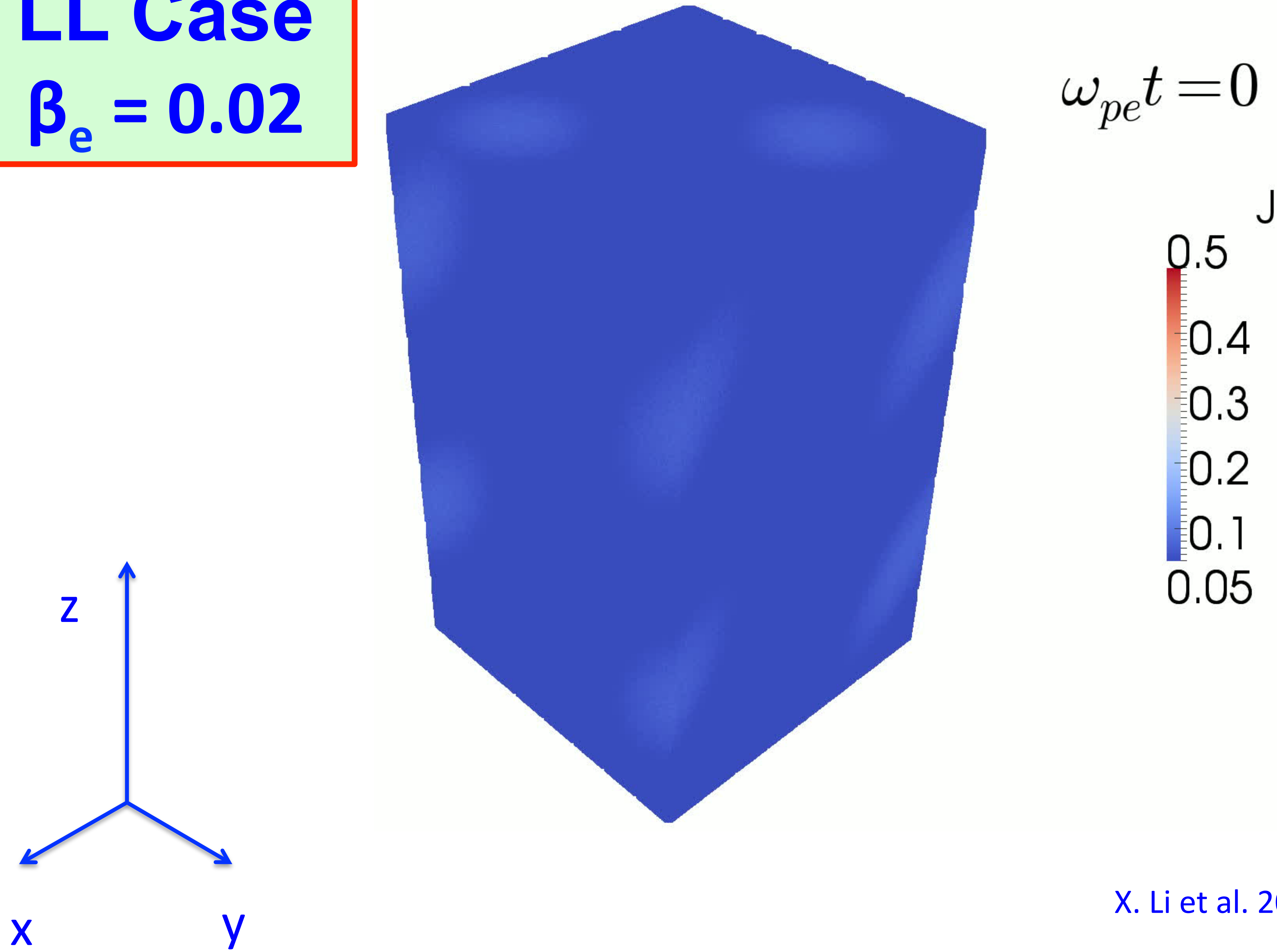
LH Case

$\beta_e = 0.33$



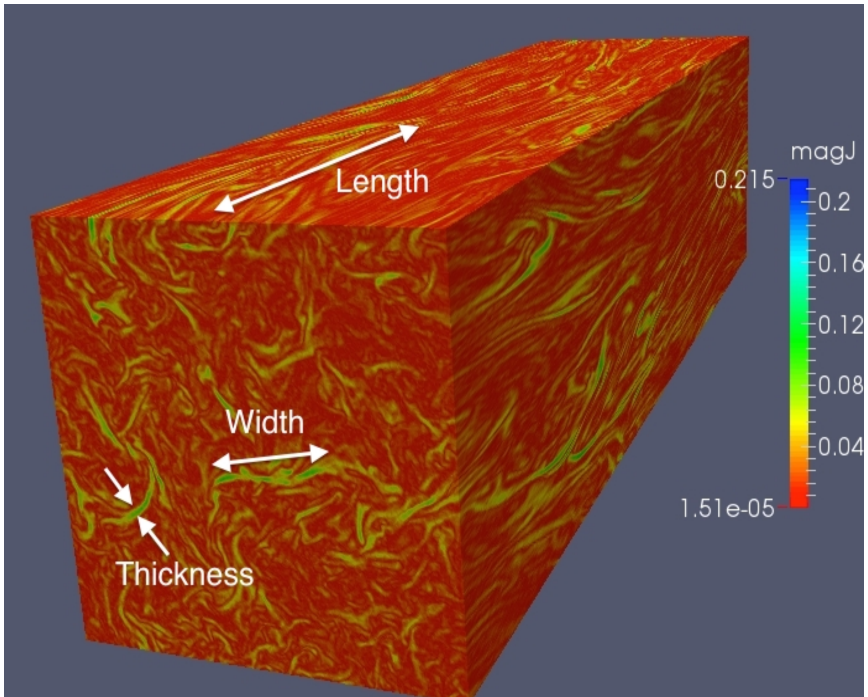
Makwana+ 2015

LL Case
β_e = 0.02



X. Li et al. 2016

Sheet Properties:
1) 3D Structures; 2) Dynamic; 3) not focr-free

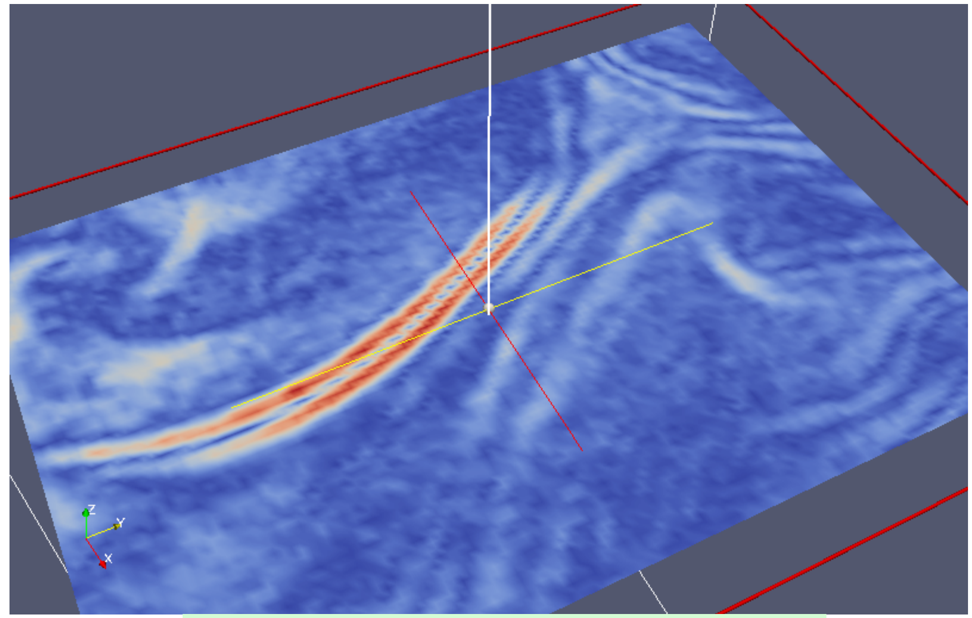


Current sheet: 3D

Thickness: ~ d_e

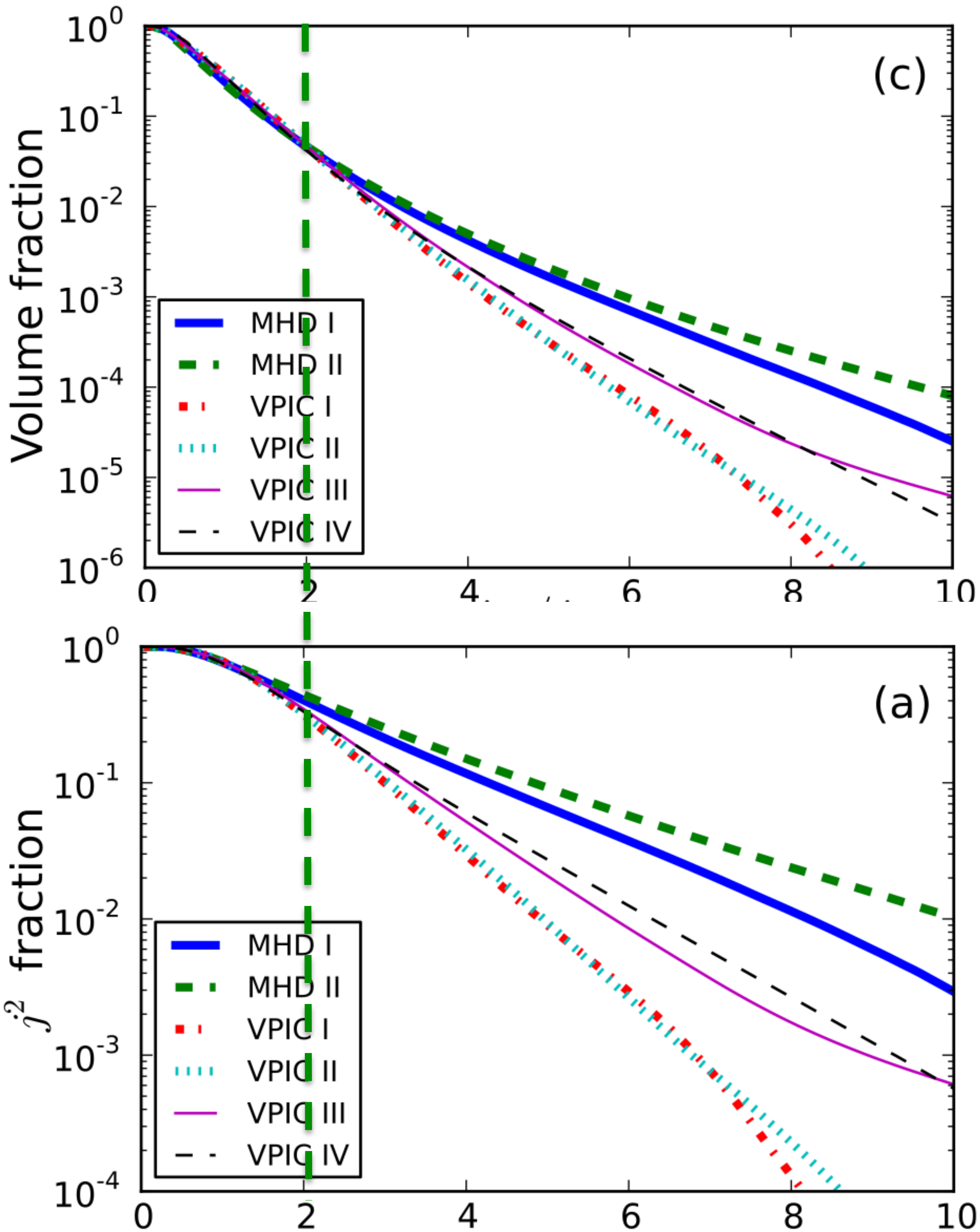
Width: ~ 10 d_e

Length: ~ 100 d_e



|JxB|
Non-force-free

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



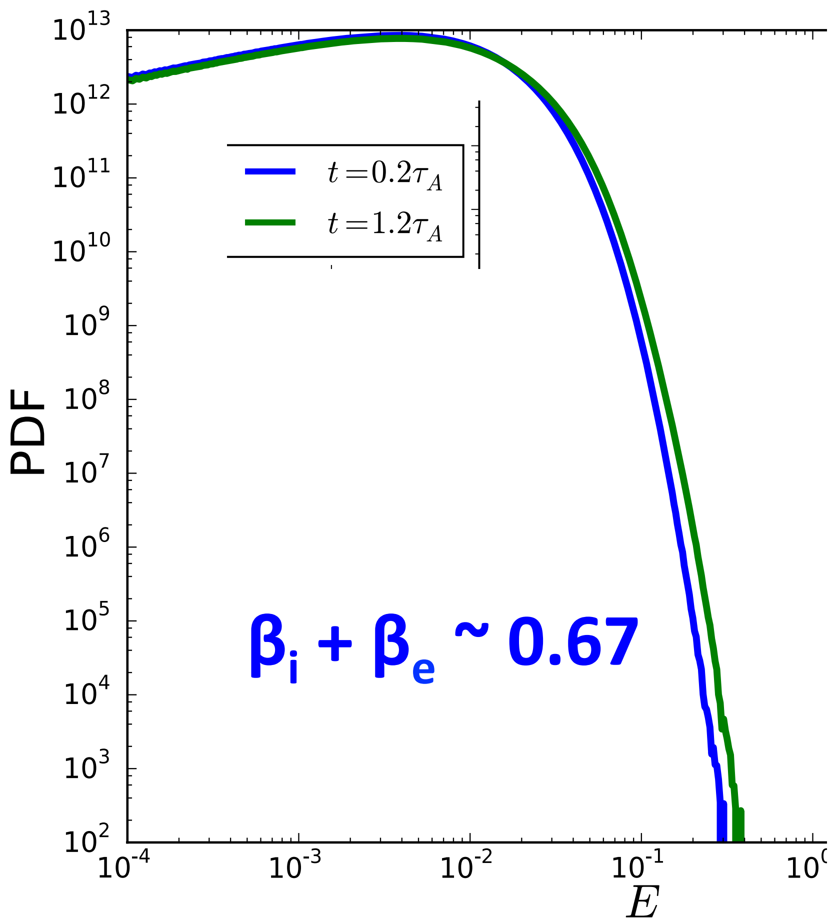
Properties: 4) Significant fraction of dissipation in current sheets

50% j^2 (Ohmic) dissipation in 5% volume

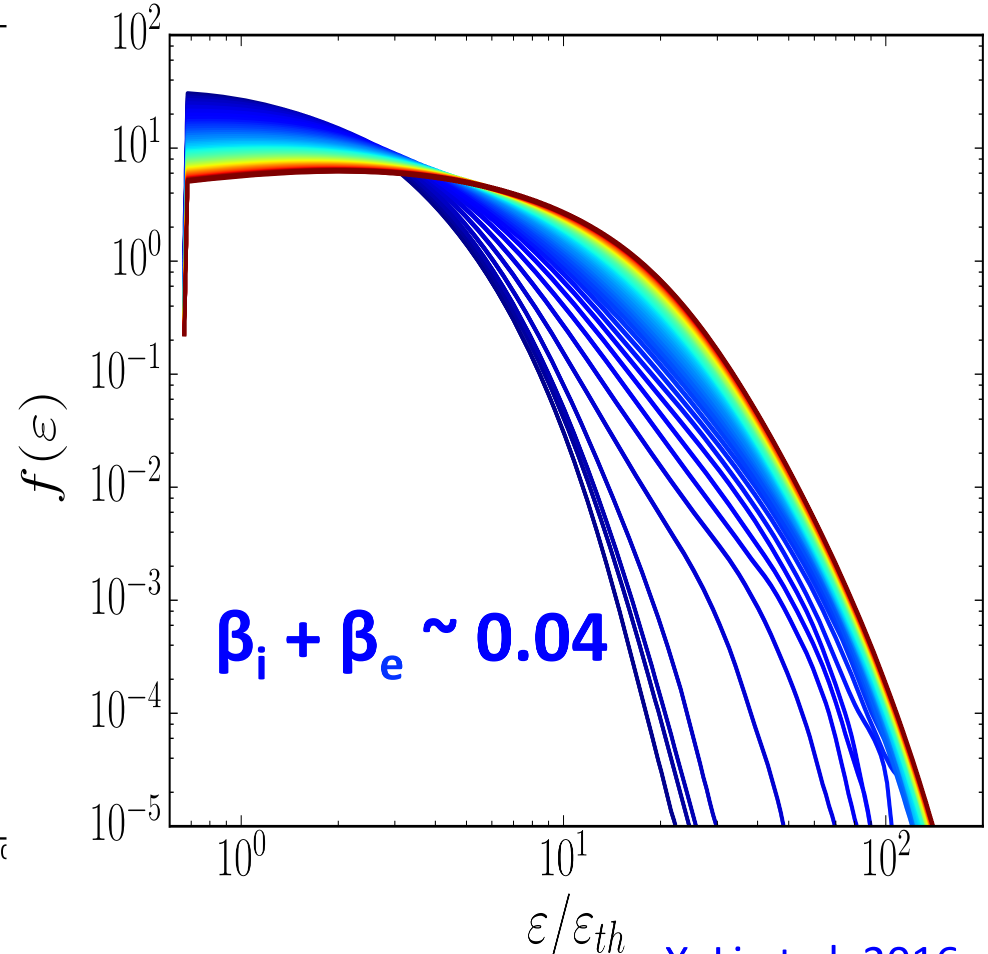
Makwana+ 2015

LH Case
$\beta_e = 0.33$

LL Case
$\beta_e = 0.02$



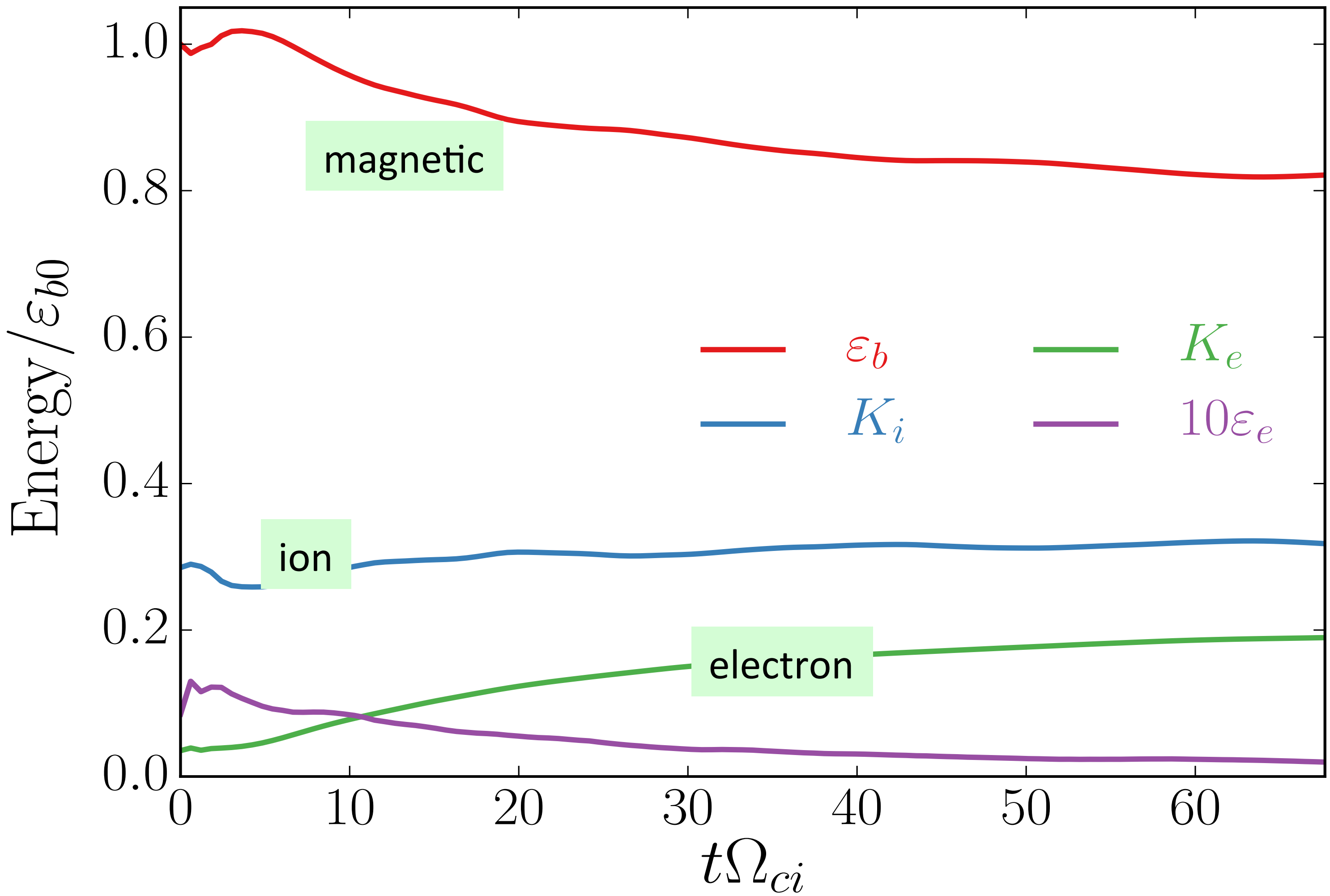
Makwana+ 2015



X. Li et al. 2016

Significant Electron Acceleration

LL Case
$\beta_e = 0.02$



X. Li et al. 2016

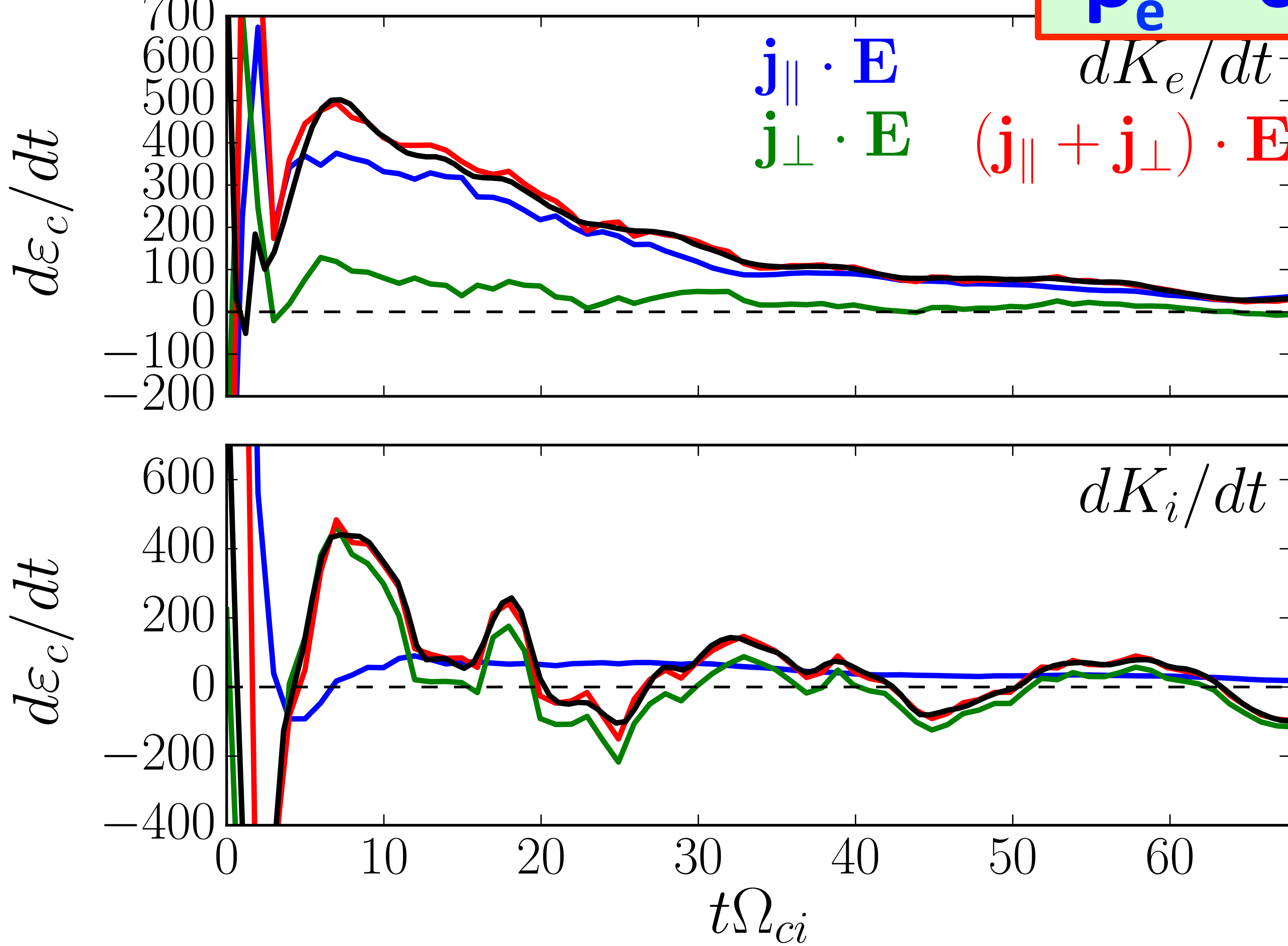
Relative strong correlation between |J| and |J.E|

LL Case
β_e = 0.02

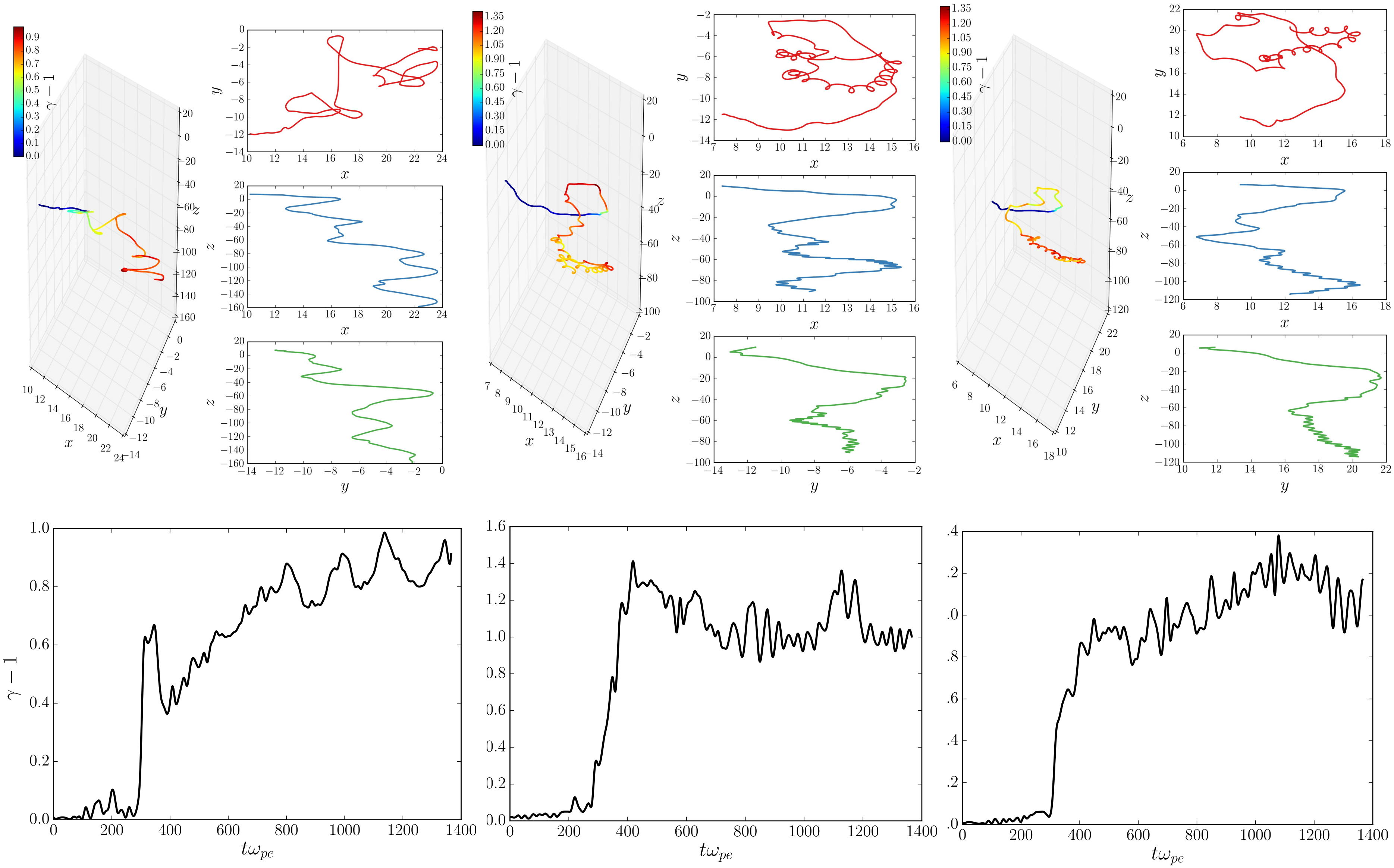
X. Li, F. Guo et al. 2016

E_parallel Dominant

LL Case
β_e = 0.02

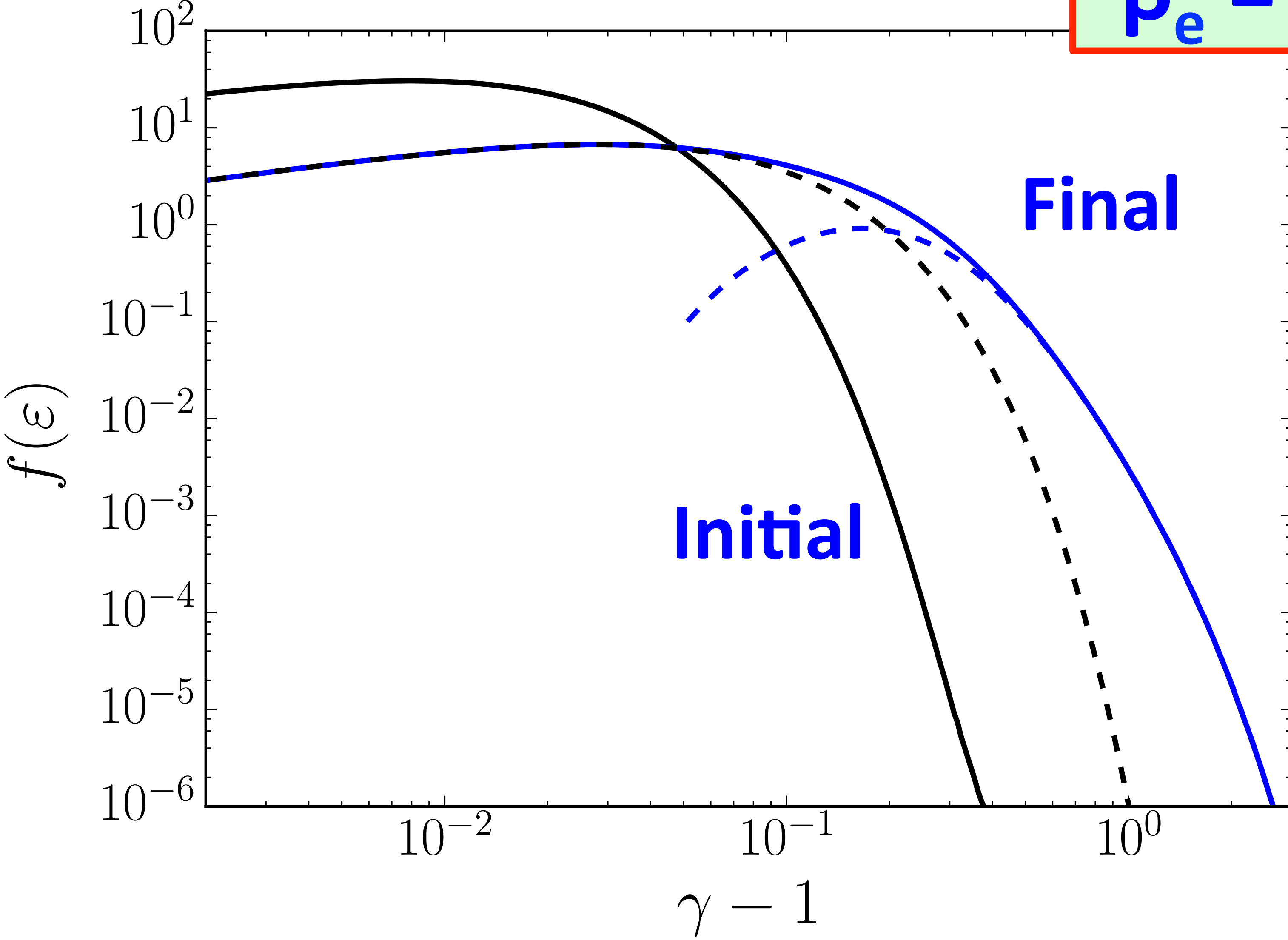


Sample Particle Trajectories



Particle Energy Distribution

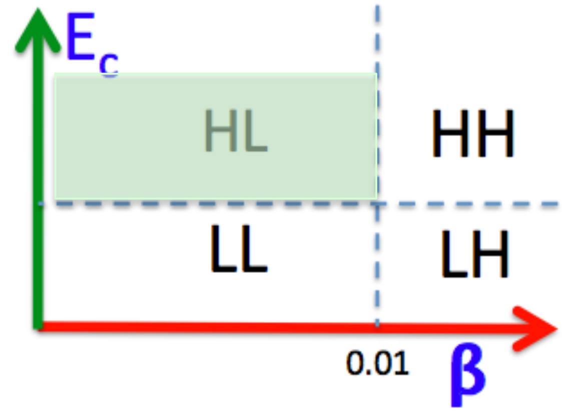
LL Case
$\beta_e = 0.02$

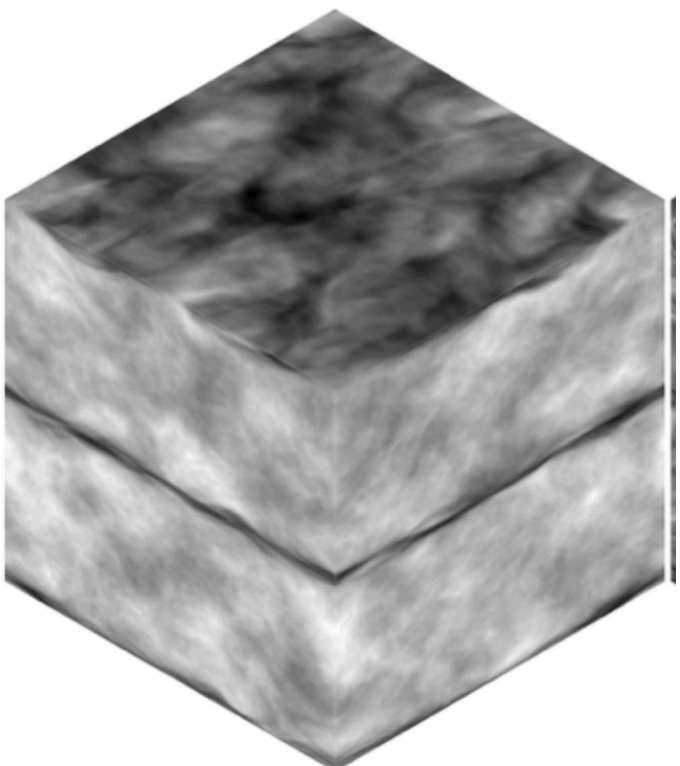


Brief Summary on "Expt A":

1) Significant particle energization can occur in low-beta (< 0.02) plasmas;
2) E_parallel associated with (transient) current sheet reconnection seems to be the main acceleration (similar to strong guide field reconnection?)
3) More work needed to differentiate the relative role of reconnection acceleration and 2^{nd} order Fermi.

"Experiment B":
Thick Current Sheet and Particle Energization in MHD

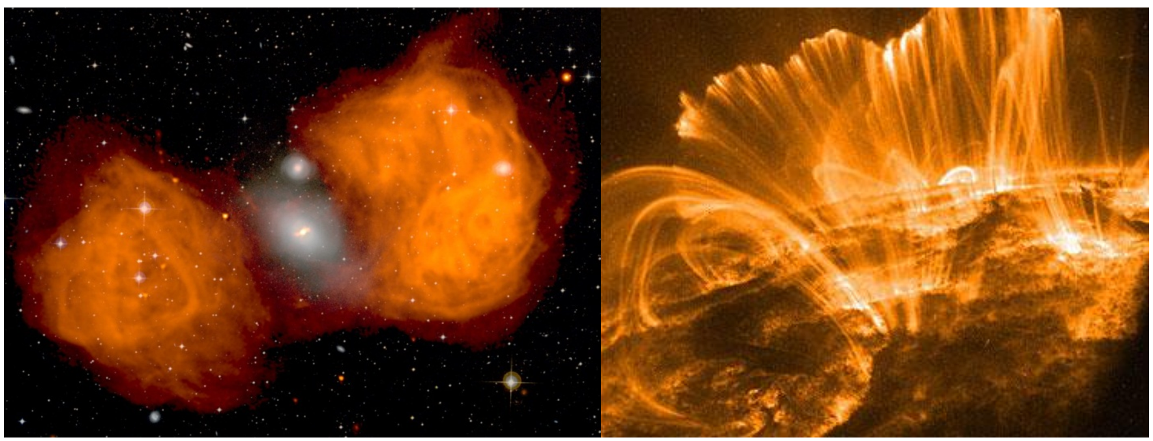




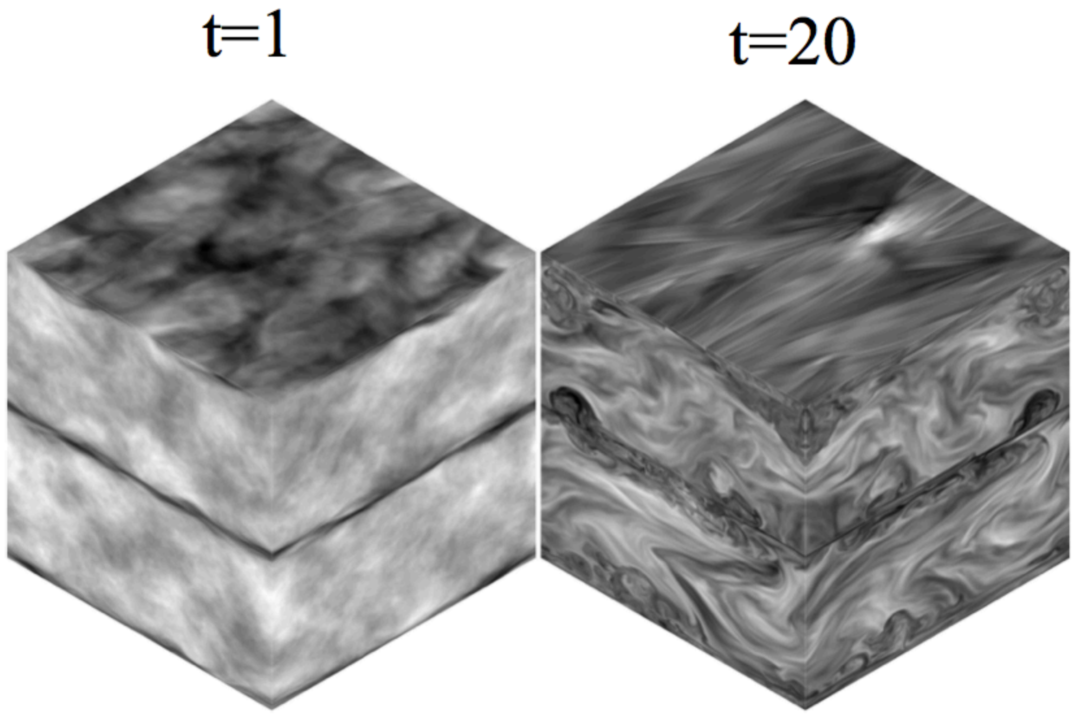
High Ec

Thick Sheets:

1) tearing is unimportant
2) Thickness > LV99 sheet
3) Turbulence injection scale > thickness



What Should We Expect?

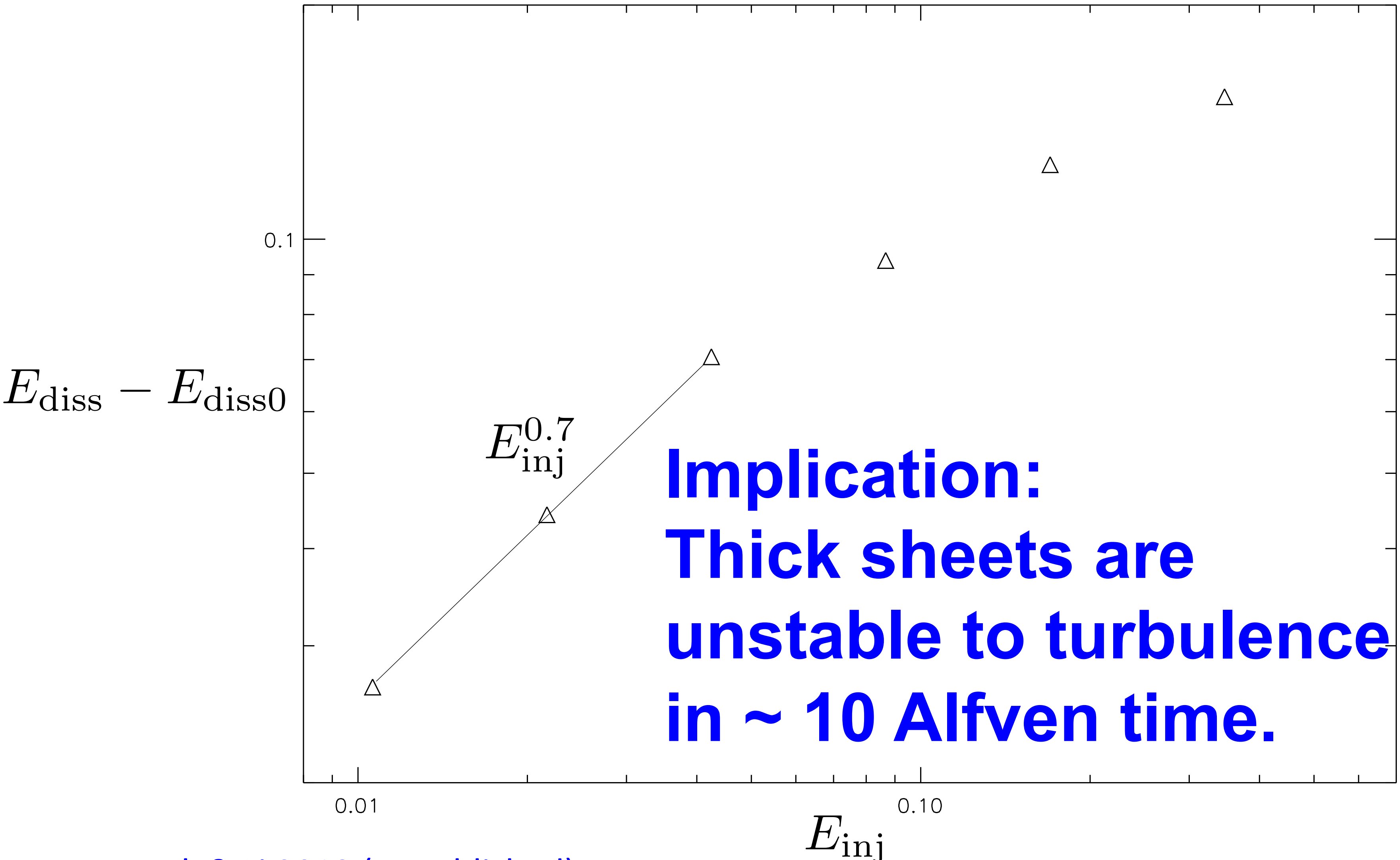


Using the same turbulence injection, comparing the case with and without a current sheet,

Q:
will we get a different amount of energy dissipation?

Beresnyak & Li 2013 (unpublished)

More Dissipation with (thick) Current Sheet

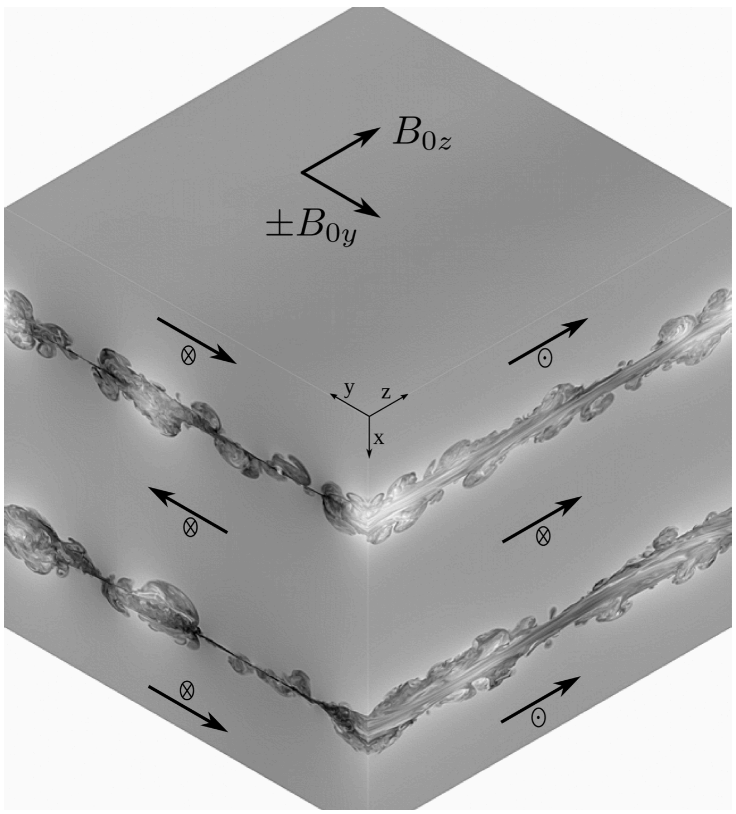


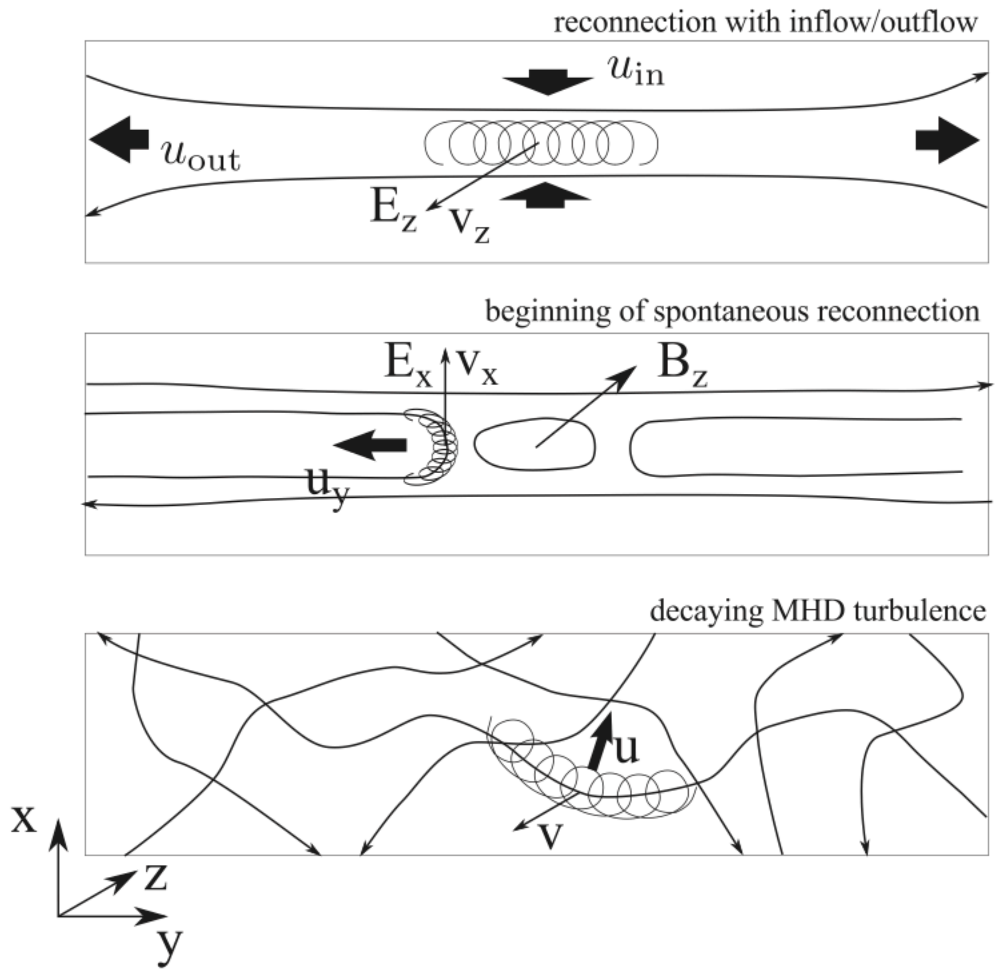
Implication:
Thick sheets are unstable to turbulence in ~ 10 Alfven time.

Beresnyak & Li 2013 (unpublished)

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





Beresnyak arXiv:1301.7424

Linking Global Energy Conversion with Particle Energy Gain

Fluid energy conversion:

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

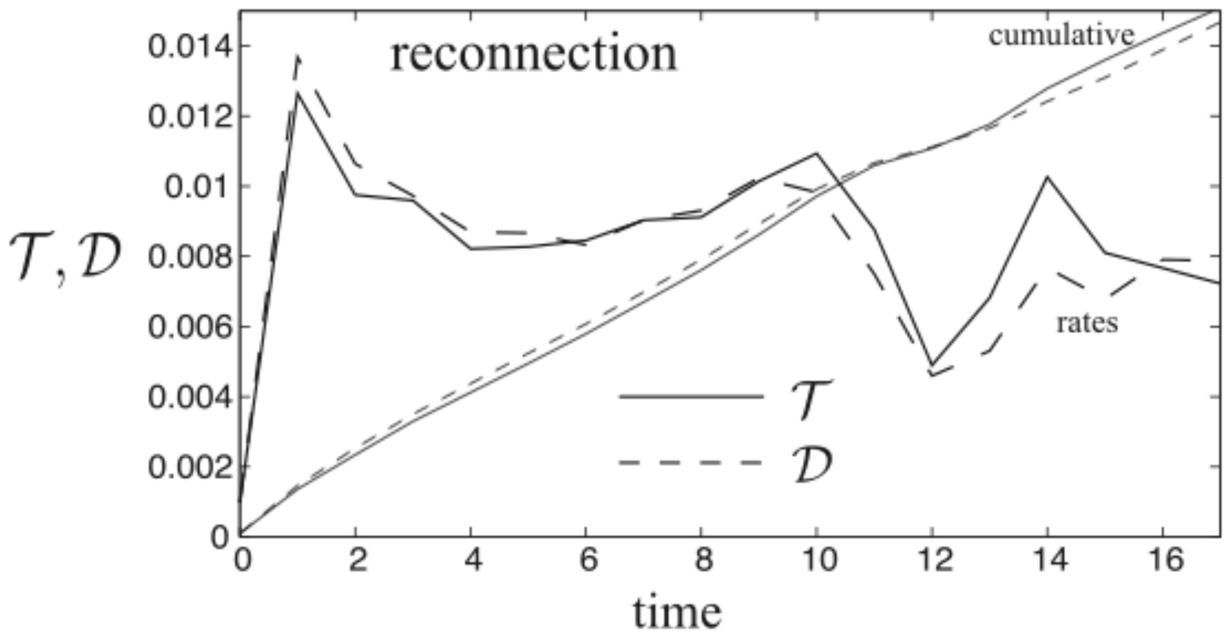
$$-(\mathbf{u} \cdot \nabla)B^2/8\pi + \mathbf{u} \cdot (\mathbf{B} \cdot \nabla)\mathbf{B}/4\pi$$

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

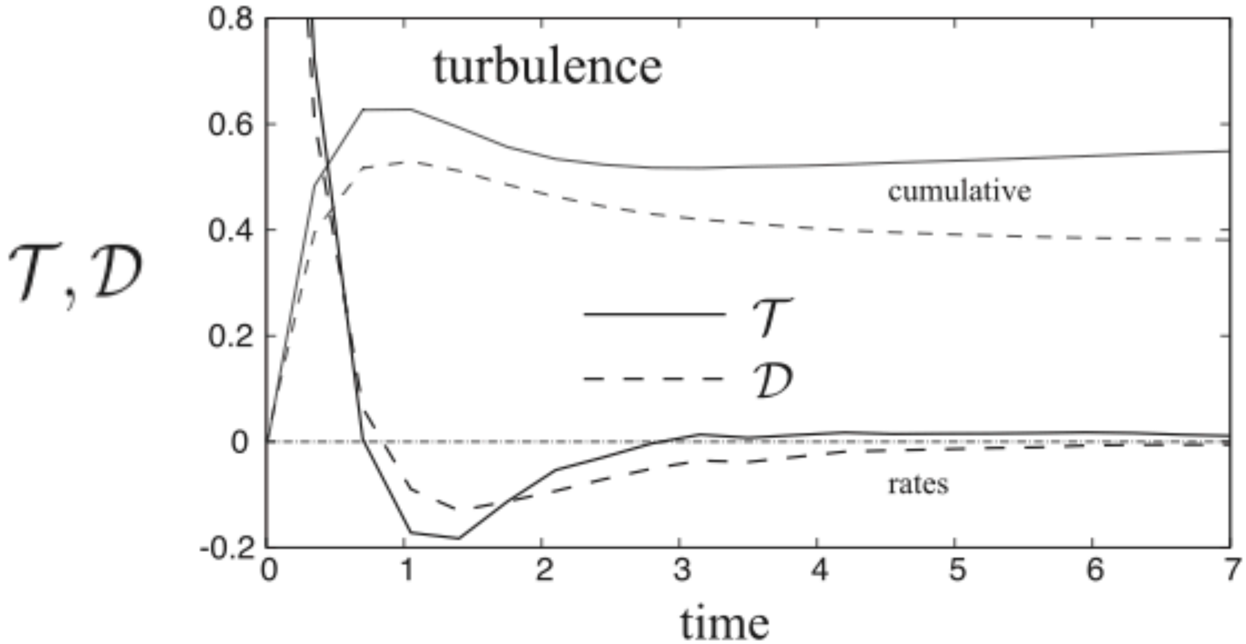
Particle energy via curvature drift:

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

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



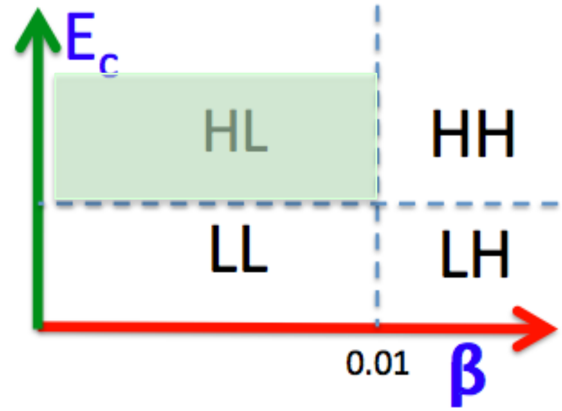
$\mathcal{T}$: Energy transfer from magnetic to flow

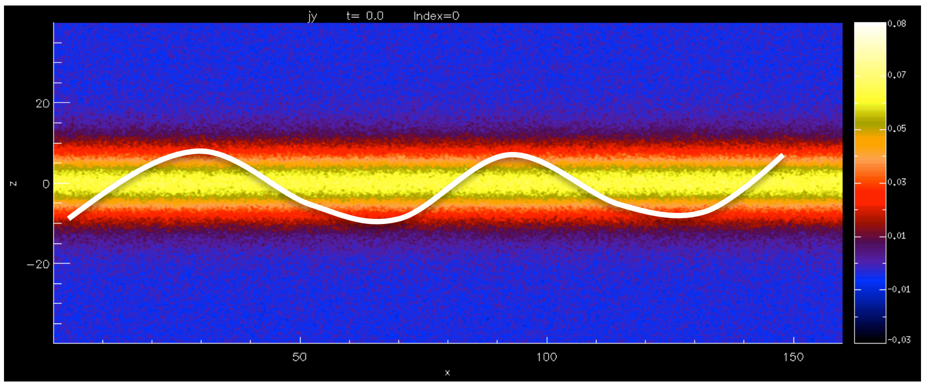


, $\mathcal{D}$: Energy gain by particles via curvature drift

Beresnyak & Li, ApJL 2016

"Experiment C": Thick Current Sheet and Particle Energization in PIC

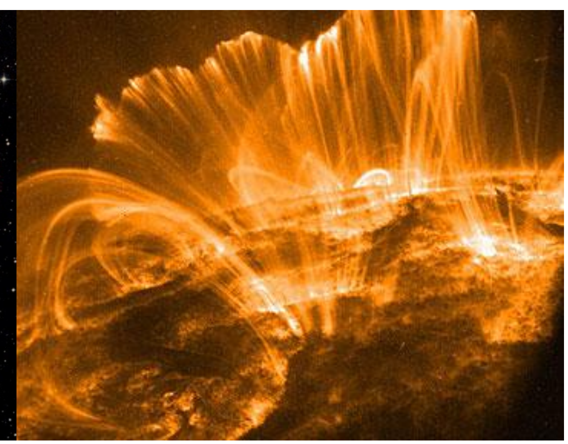




Thick Sheets:

1) Collisionless tearing is unimportant
2) Turbulence injection scale > thickness

High Ec



Initial PIC Simulation Set-up

Force-free Harris Current Sheet + 3D perturbations:

$$L_x \times L_y \times L_z = 200d_i \times 100d_i \times 100d_i$$

$$N_x \times N_y \times N_z = 768 \times 384 \times 384$$

$$m_i/m_e = 1 \quad \omega_{pe}/\omega_{ce} = 1.0$$

$$v_{the} = 0.1c \quad T_i = T_e$$

$$\beta_i = \beta_e = 0.02$$

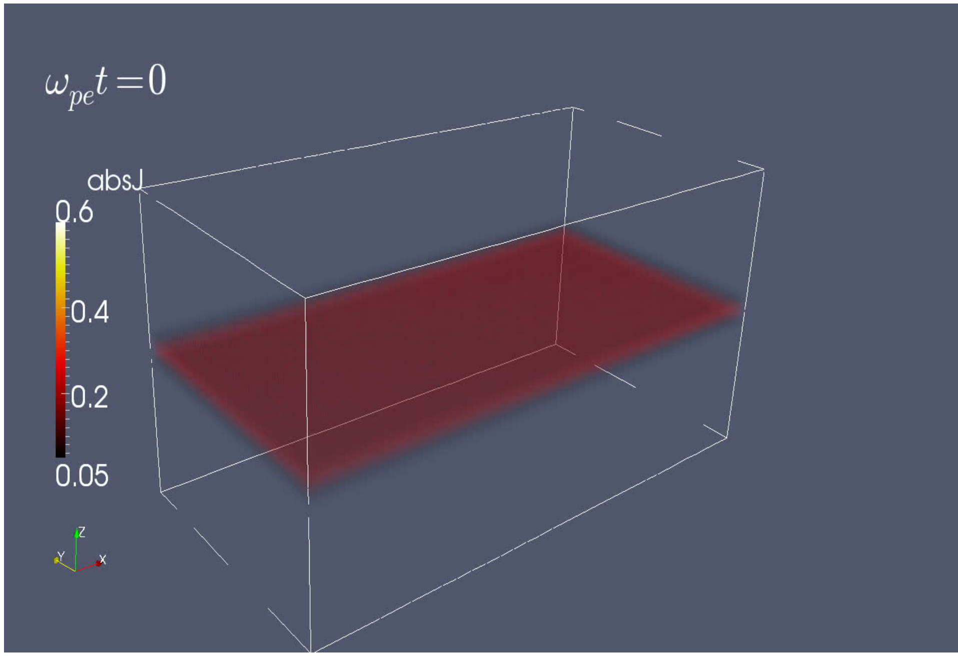
$$\delta B = 0.03 - 0.1 B_0$$

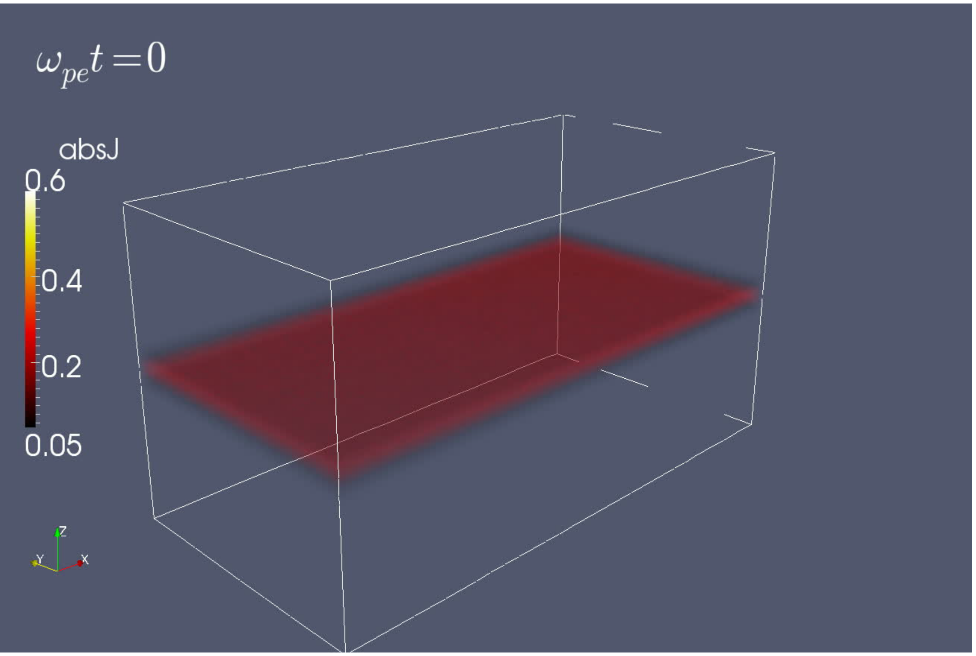
$$\boxed{\lambda = 5d_i}$$

Guo+ 2015

|J|: 3D

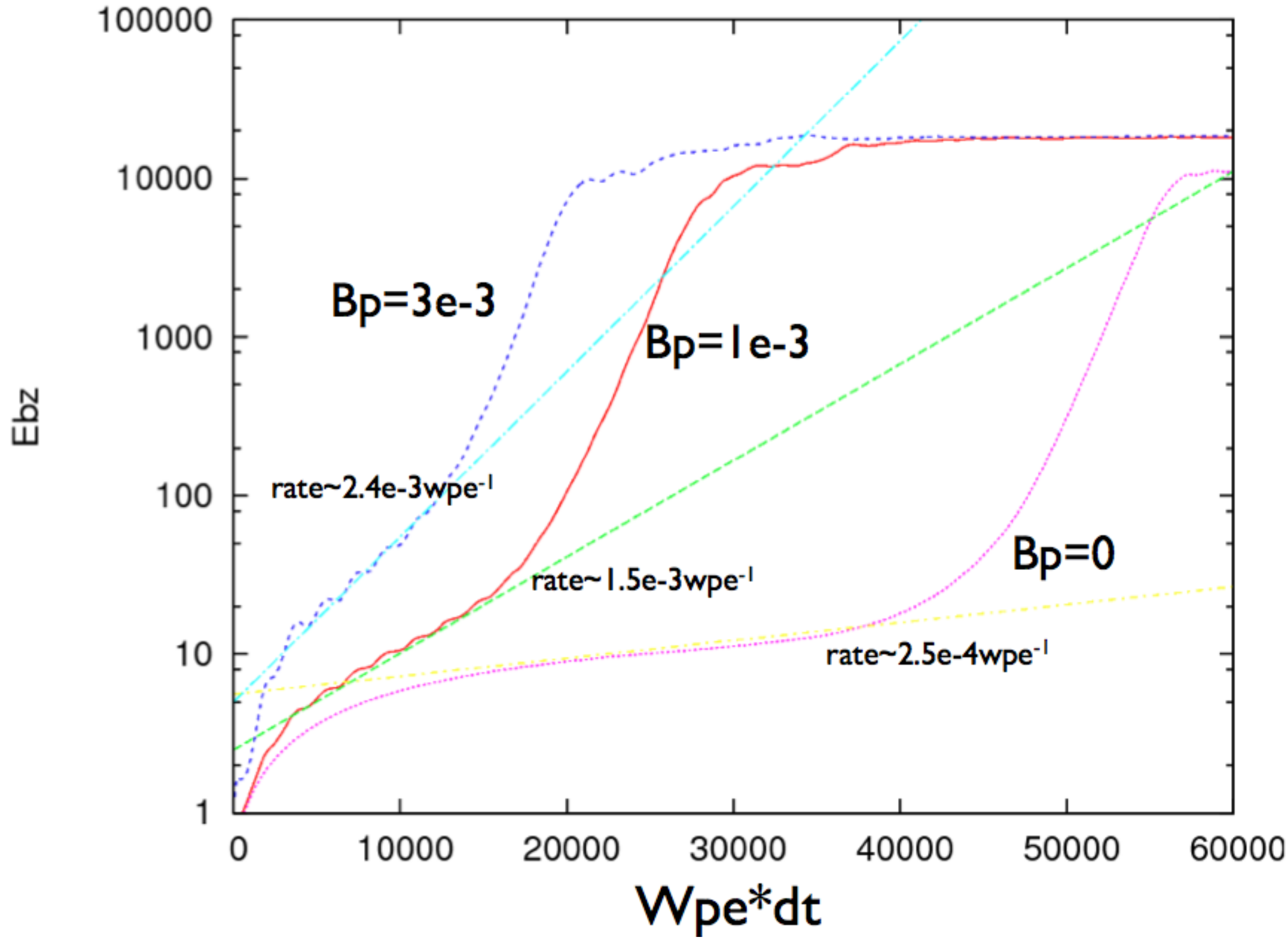
dB/B_0 = 0.03 (pairs) **dB/B_0 = 0.1 (pairs)**





Guo+ 2015, unpublished

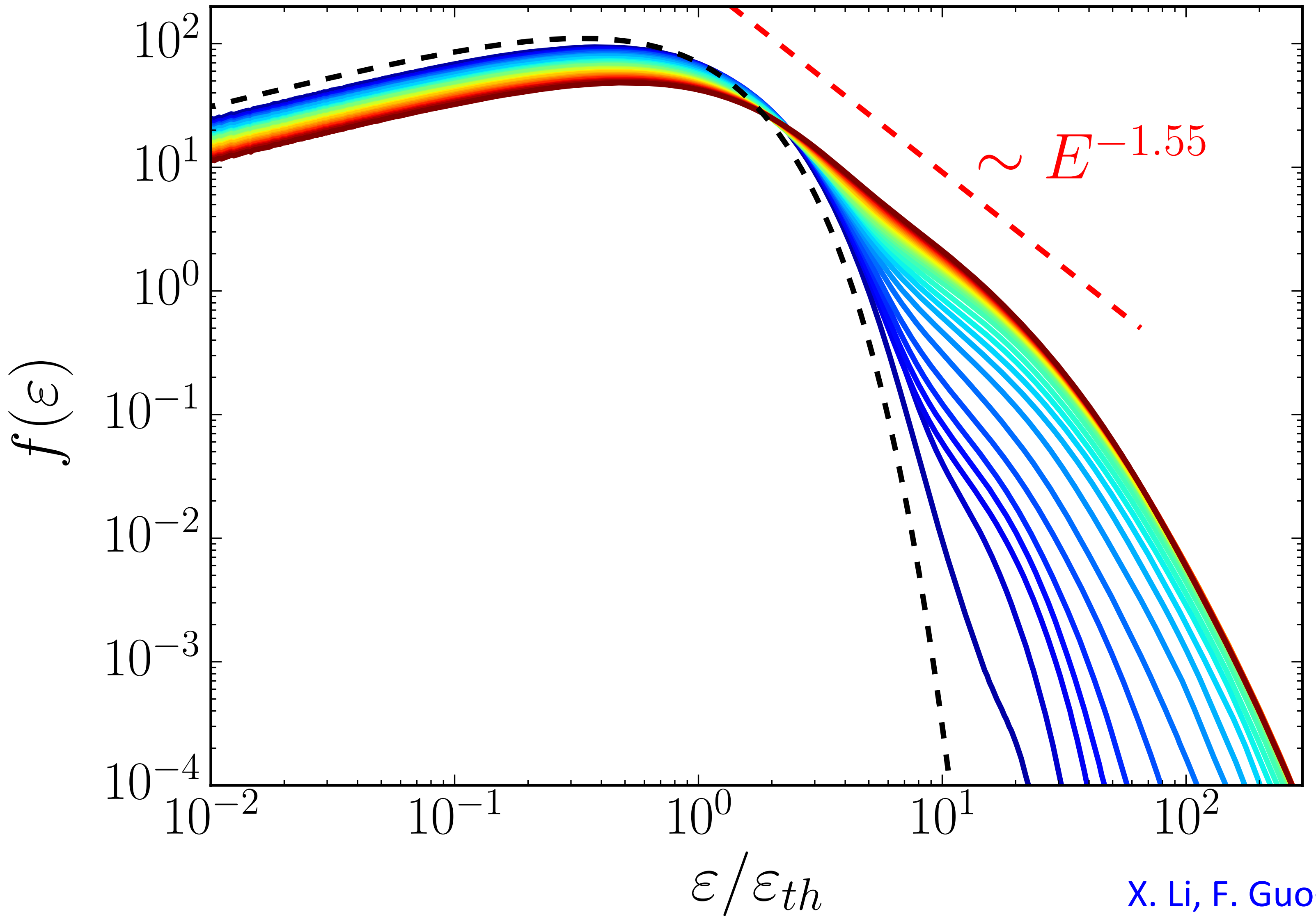
Higher Perturbation Enhances Growth of Tearing



$\Delta = 5\ d_i$

Guo+ 2015

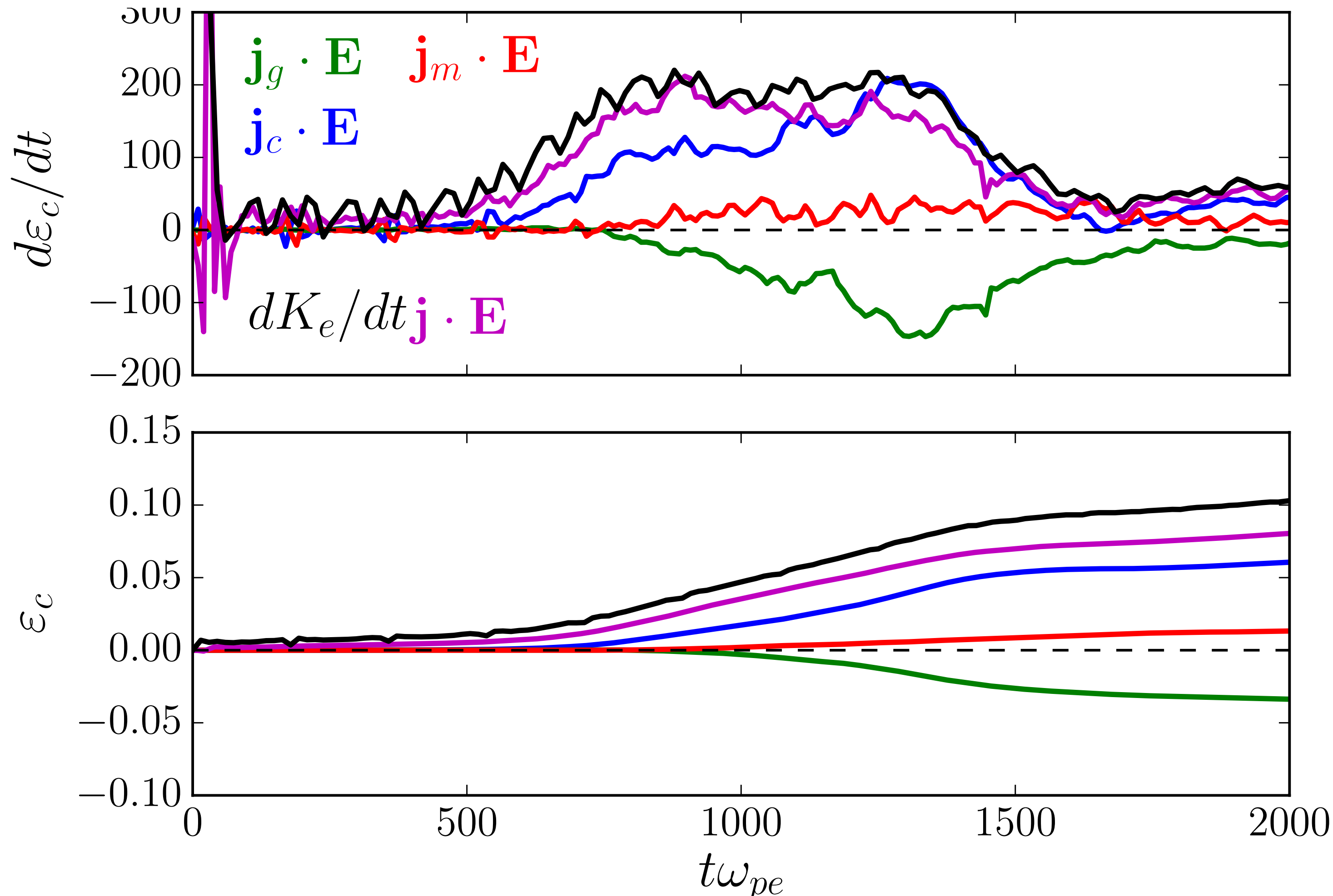
Particle Distribution (dB/B_0 = 0.1, pairs)



X. Li, F. Guo+ 2015

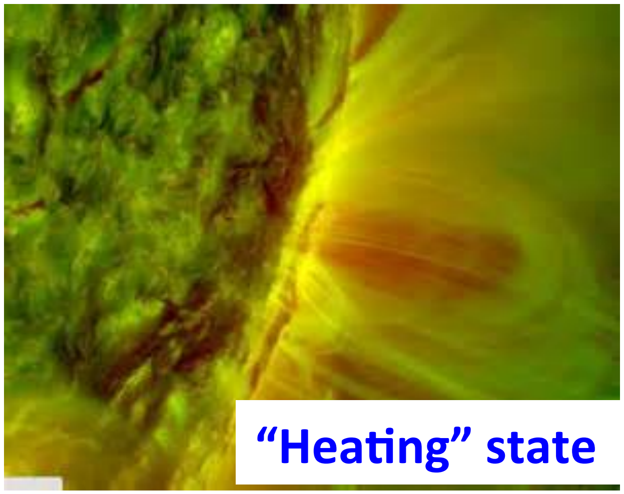
Curvature Drift Term Important

$$\mathbf{j}_\perp = P_\parallel \frac{\mathbf{B}\times(\mathbf{B}\cdot\nabla)\mathbf{B}}{B^4} + P_\perp\left(\frac{\mathbf{B}}{B^3}\right)\times\nabla B - \left[\nabla\times\frac{P_\perp\mathbf{B}}{B^2}\right]_\perp + \rho\frac{\mathbf{E}\times\mathbf{B}}{B^2} + \rho_m\frac{d\mathbf{u}_E}{dt}\times\frac{\mathbf{B}}{B^2}$$

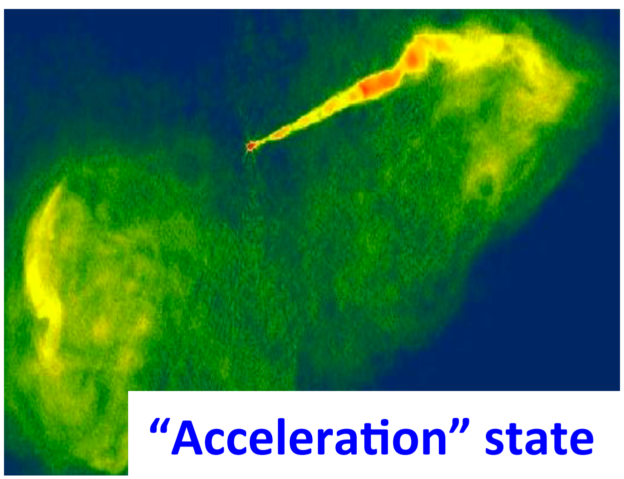


X. Li, F. Guo+ 2015

Summary



“Heating” state



“Acceleration” state

- Depending on the “configuration energy”, the formation, shape, and lifetime of current sheets can vary; this gives different particle energization processes.
- Heating state: when current sheets are relatively transient, we can get significant heating;
- Acceleration state: when current sheets are large and long-lived, it is possible to produce highly non-thermal particles via both 1st order Fermi and E_parallel;
- Much more work is needed to build up this picture.