Particle Acceleration from Relativistic Magnetic Reconnection in Highly Magnetized Plasmas

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Collaborators:
William Daughton, Yi-Hsin Liu (LANL)
Kirit Makwana (U Chicago)

Papers:

1) Guo, Li, Daughton, Liu, PRL, 2014 -- particle acceleration mechanism
2) Guo et al. ApJ, 2015 – parameter studies of high-sigma reconnection
3) Makwana et al. PoP, 2015 – cascade and current sheet statistics
4) Y. Liu et al. PRL, 2014, 2015 – Relativistic Reconnection rates
5) W. Liu et al. PoP, 2011 – particle acceleration in sigma ~ 1 pair plasmas
6) Bowers & Li, PRL, 2007 – 3D sheet pinch reconnection physics

Relativistic Jets in AGNs (1997)
Edit Michał Ostrowski et al.

Title: The Galactic Dynamo, the Helical Force Free Field and the Emissions of AGN

Authors: Colgate, S. A.; Li, H.

Affiliation: AA(T-6, MS B288,
B288, LANL, Los A

Publication: Relativistic Jets in A
p.170-179

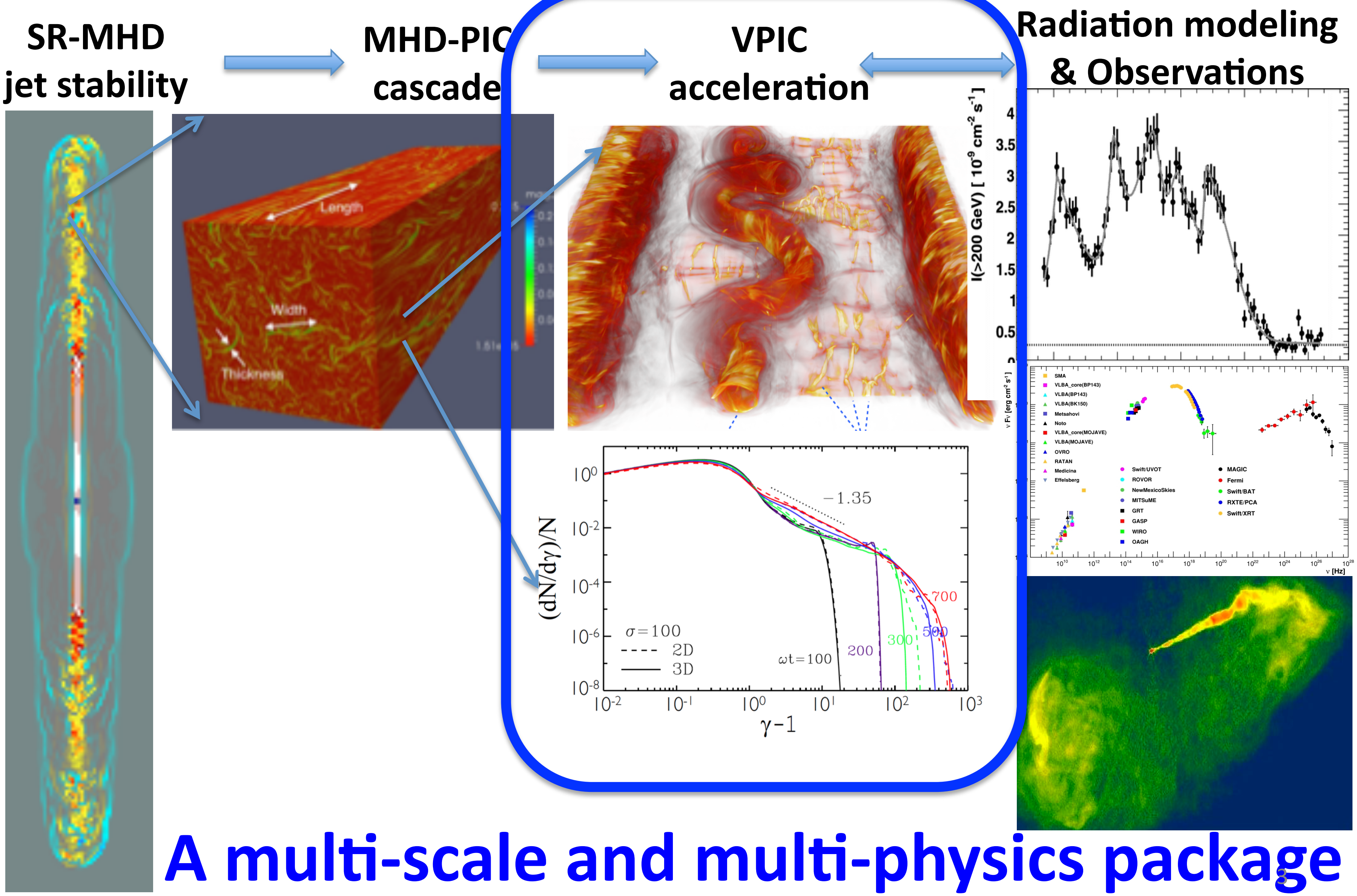
Publication Date: 00/1997

Origin: AUTHOR

Bibliographic Code: 1997rja..proc..170C

We present a theory relating the central gal
through an accretion disk. The associated A
result of the dynamo process. A unified the
with the collapse of damped Lyman-alpha c
central disk and black hole. An alpha-Ome
augmentation of the poloidal field from the toroidal field depends upon star disk collisions. The
winding number of the inner-most orbit of the disk is so large, S\sim 10^11$ that the total gain of the

From Fluid to Kinetics to Radiation to Observations



A multi-scale and multi-physics package

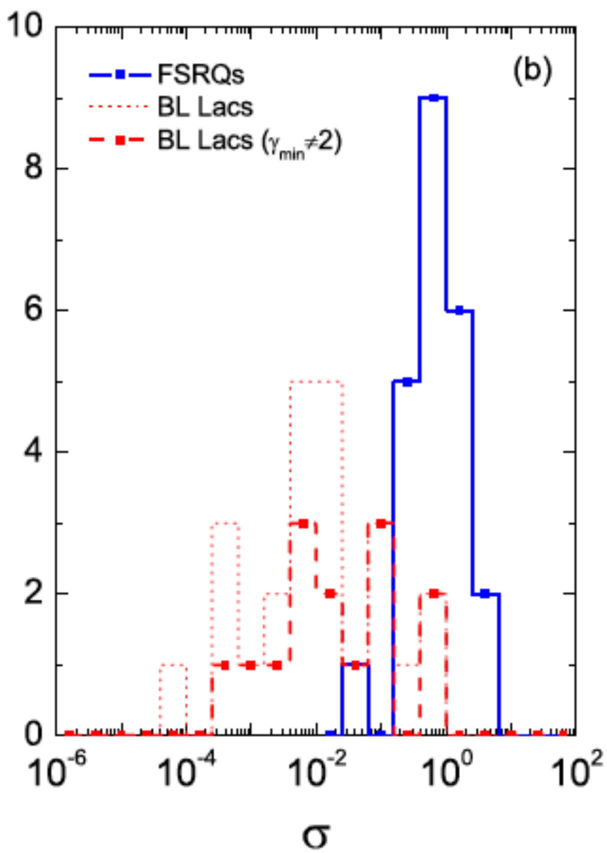
Outline

- Challenge: Coupling Macro-Micro Scales
- Hierarchical Current Sheet Model
- Single Sheet Studies: 2D+3D PIC Simulation Showing Particle Acceleration
- Particle Acceleration Mechanism
- Summary and Future Work

Blackman & Field (1994); Lyutikov & Uzdensky (2003); Lyubarsky (2005);
Zenitani et al. 2009; Liu et al. 2011; Hoshino 2012; Bessho & Bhattacharjee 2012;
Takamoto 2013; Sironi & Spitkovsky 2014; Guo et al. 2014; Melzani et al. 2014
+ many others …

Challenge – Uncertain Plasma Conditions

- $B \sim 1$ G, $\quad n_e \sim 10^{-2}$ cm^{-3}, $\quad \Omega_{ce}/\omega_{pe} \sim 200(B/n_{-2}^{1/2})$
- $\sigma = \dfrac{B^2}{4\pi n m_e c^2} = (\Omega_{ce}/\omega_{pe})^2 \sim 40000$



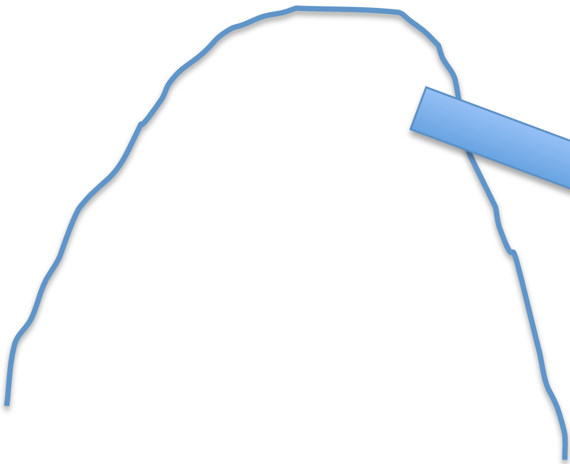
See their Poster
Jin Zhang et al. (2014)

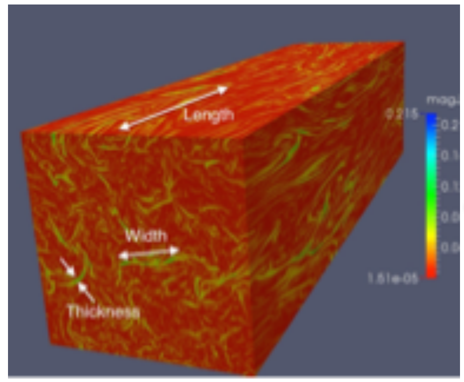
$$\sigma = \frac{P_B}{P_p + P_e + Pr}$$

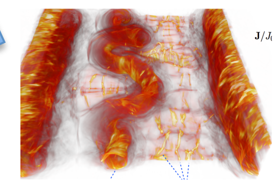
See their Poster
Xuhui Chen et al.
(2012, 2014)

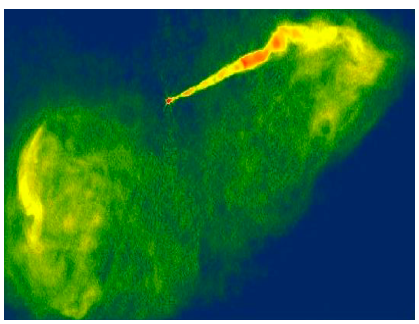
FSRQ PKS 0208-512

Challenge – Enormous Scale Separation









Kinetic simulations particle dynamics

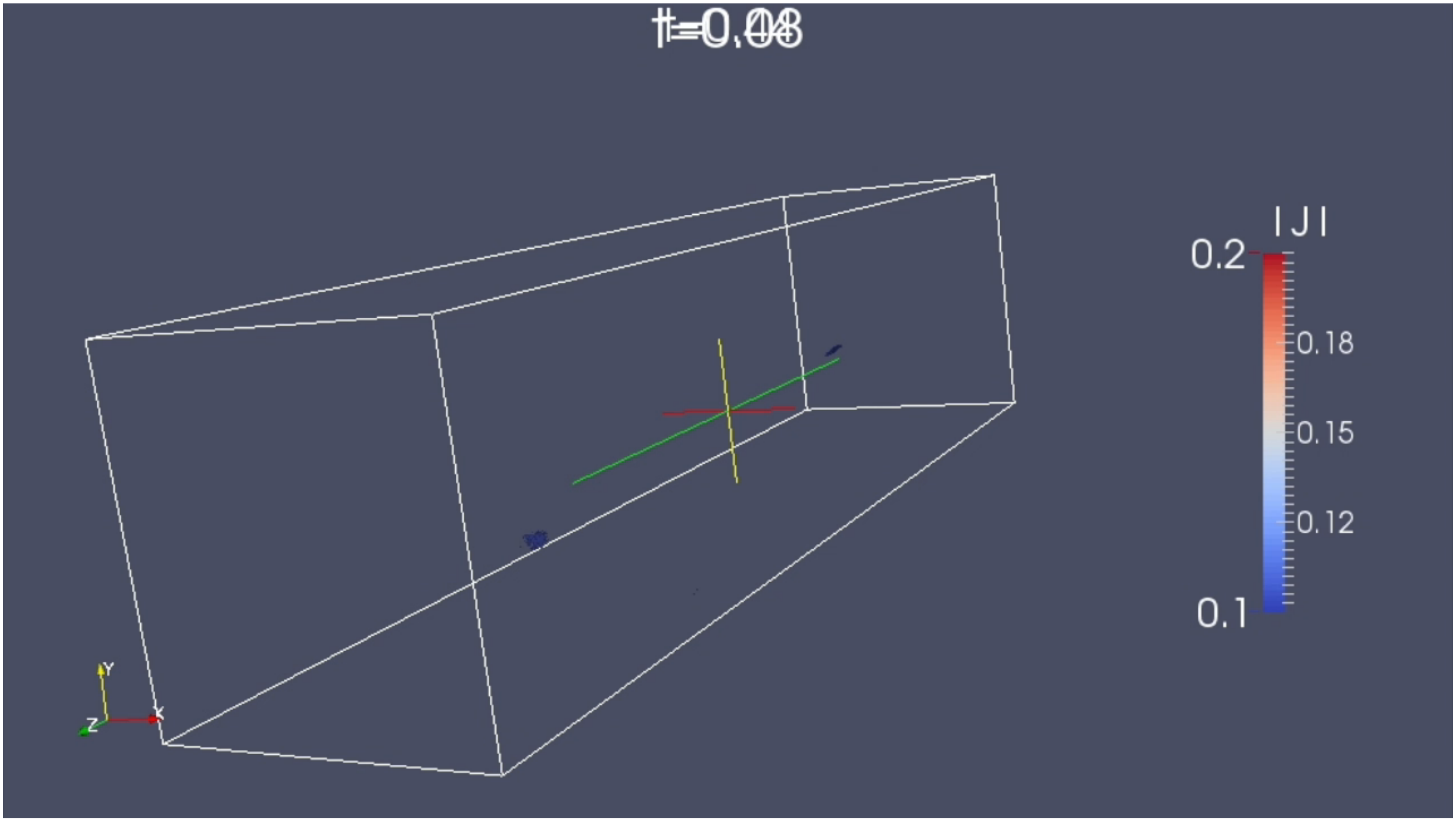
- emission: 10^{11} cm - pc
- jet: 100 kpc

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

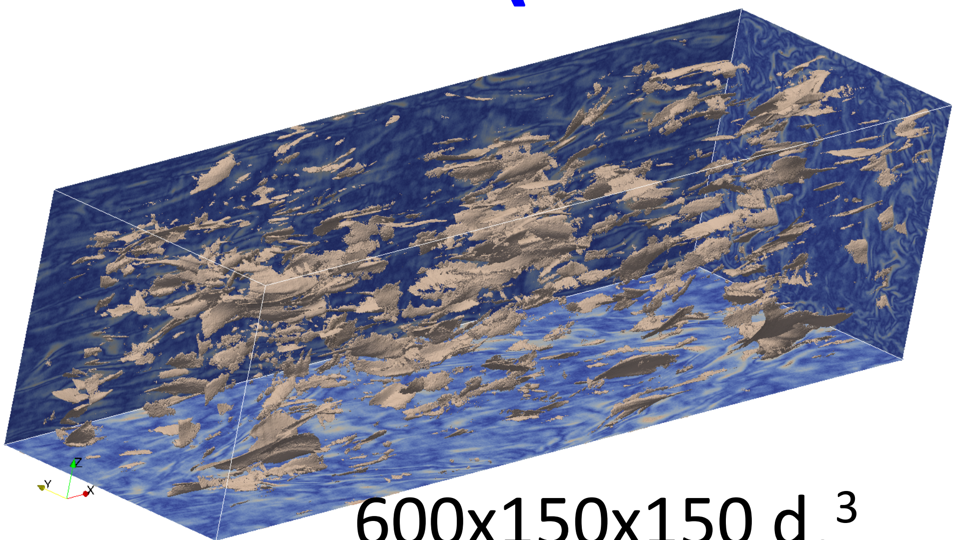
Wave-number

Hierarchical Current Sheet Model

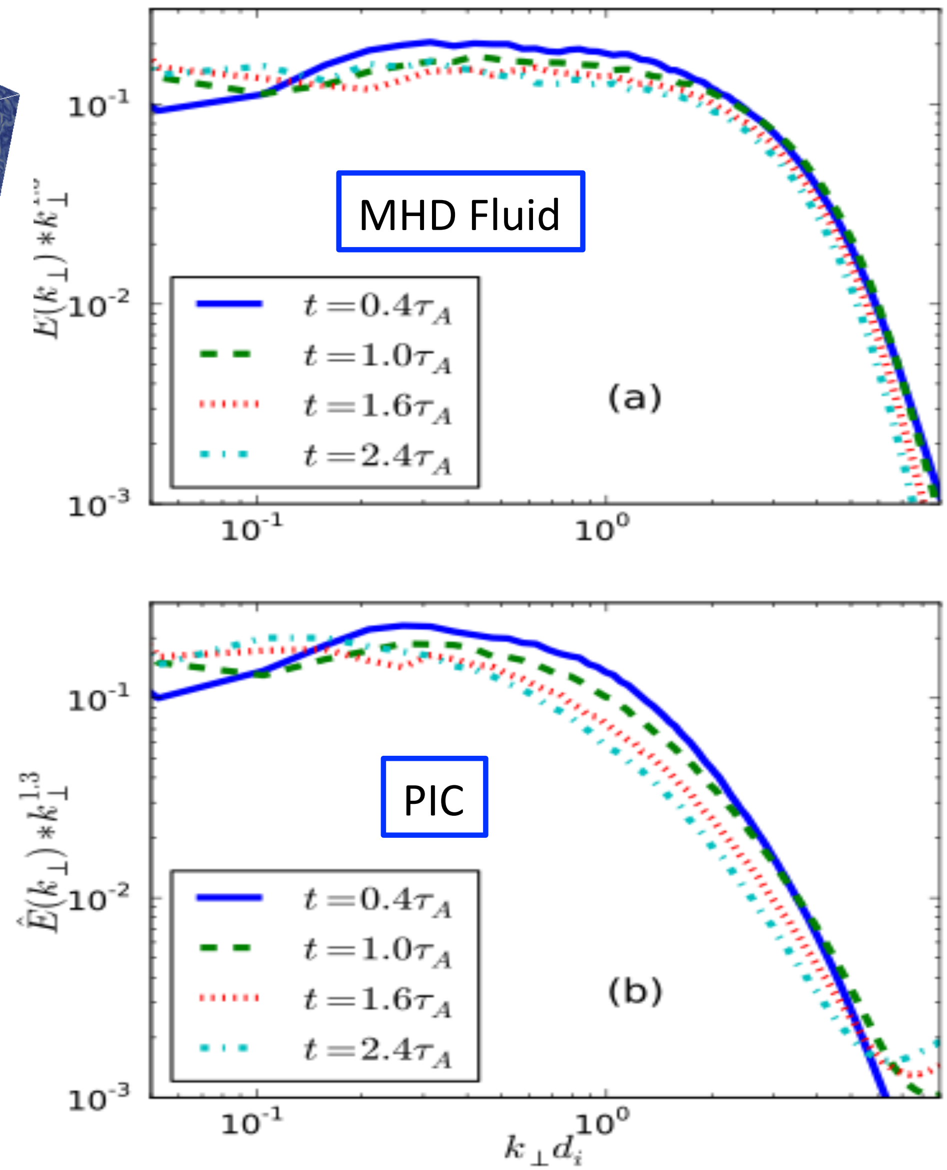
3D PIC Simulation 600x150x150 d_e^3 (Makwana et al. 2015)



Hierarchical Formation of Current Sheets (Sheet within Sheet)



600x150x150 d_e^3



Current sheet: 3D

Thickness: ~ d_e

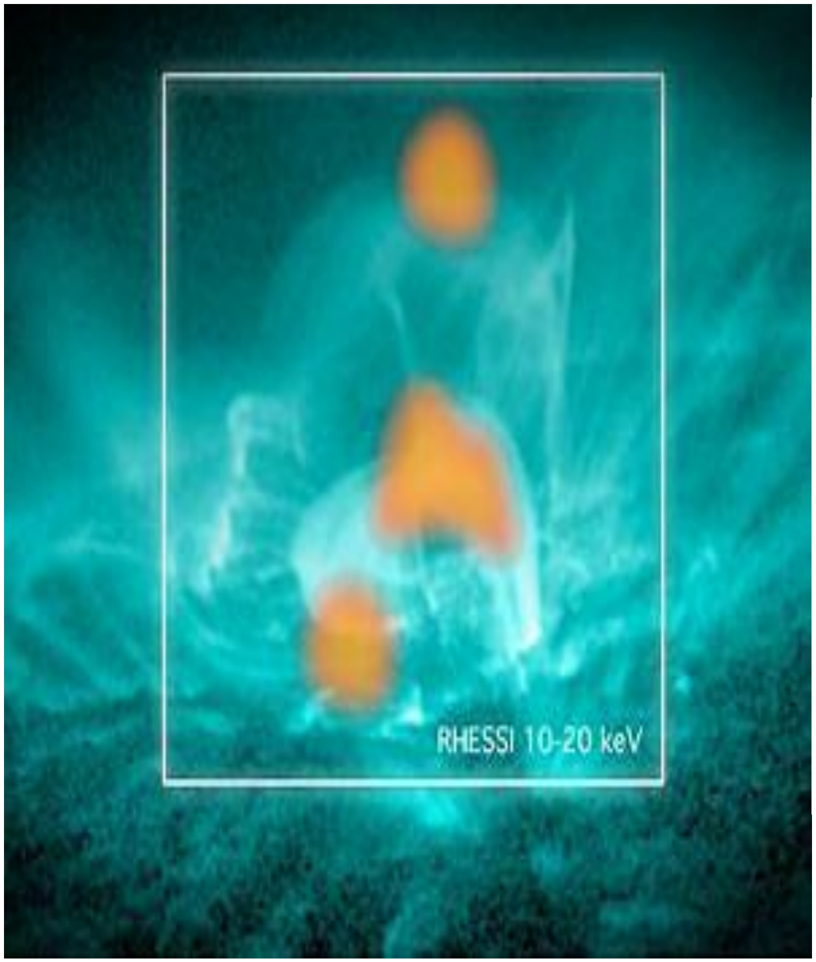
Width: ~ 10 d_e

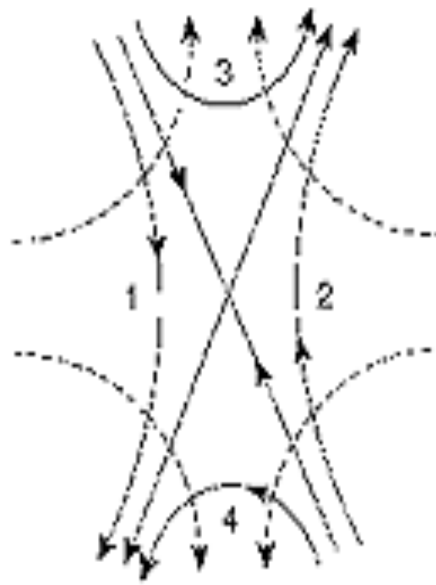
Length: ~ 100 d_e

Makwana et al. 2015

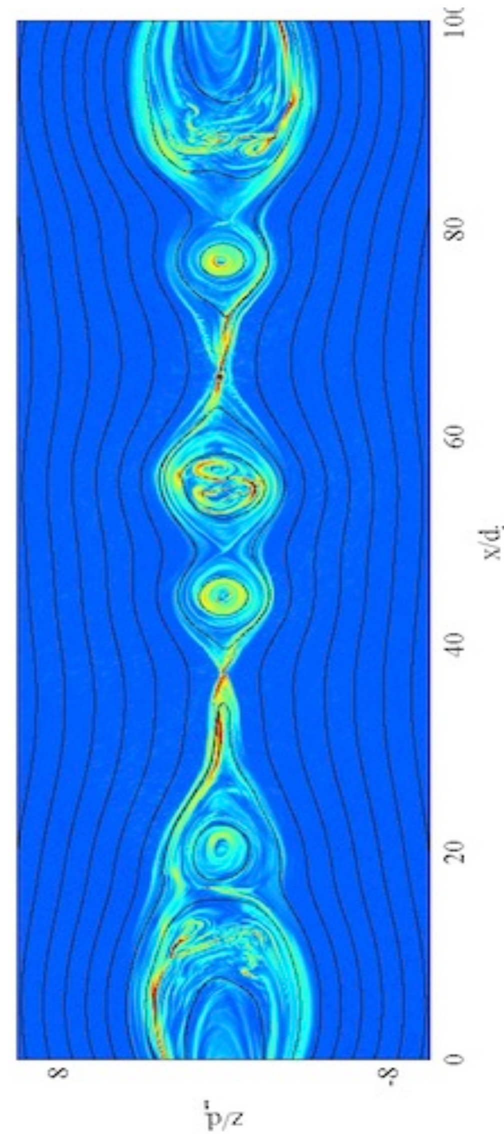
See also Zhdankin et al. 13,14

Reconnection as Energy Conversion and Particle Acceleration





Magnetic merging at an X-type neutral-line. Solid lines are magnetic field lines, dashed lines flow lines of the plasma.

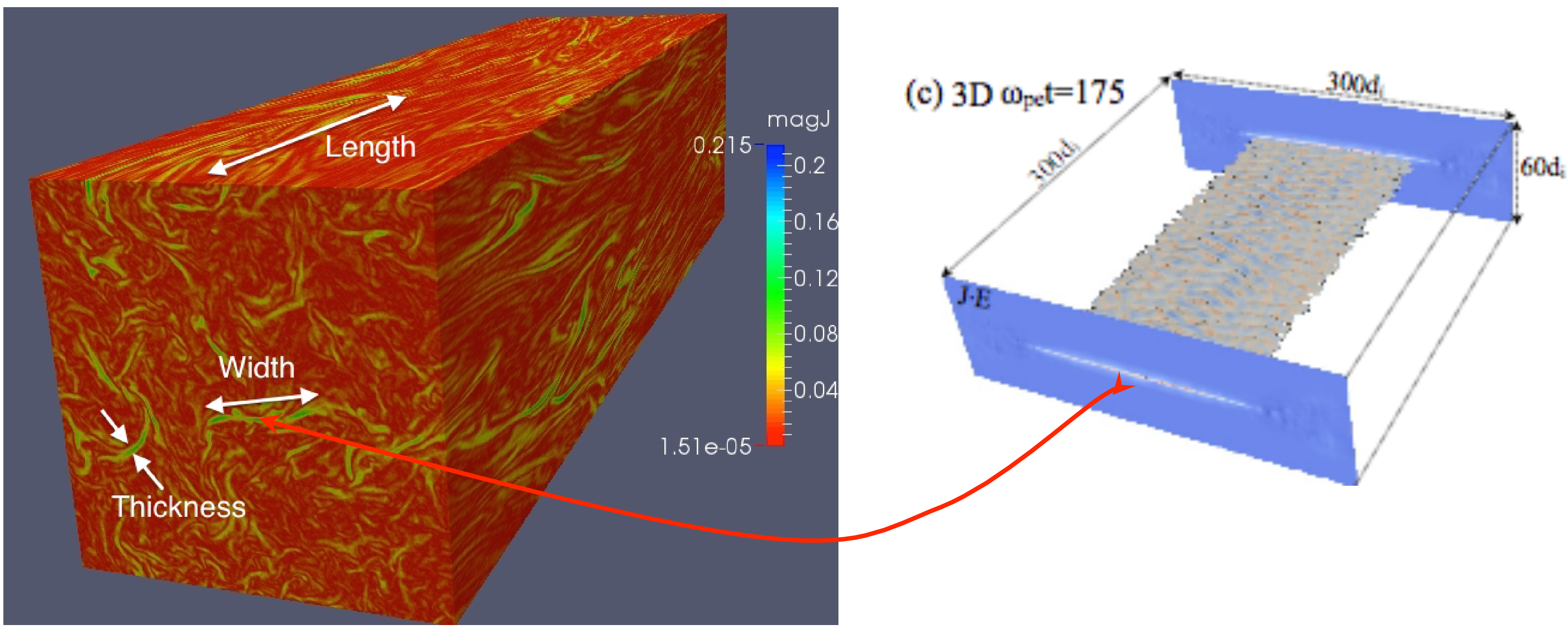


Solar

Single Sheet Studies:

2D+3D PIC Simulation

Showing Particle Acceleration



Initial Setup & Parameters

Pair plasmas

$$kT_i = kT_e \sim 0.3 m_e c^2$$

$$2D : \sigma = 1 \rightarrow 1600$$

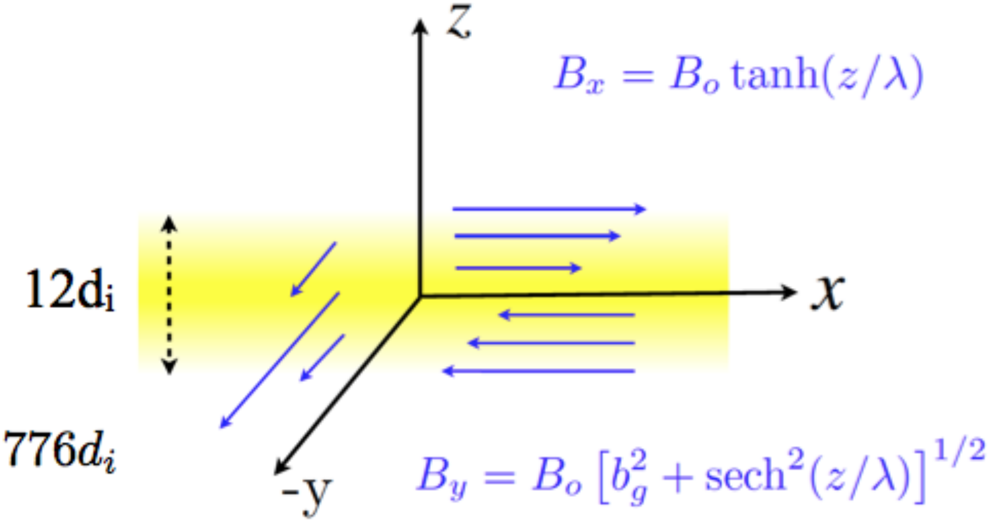
$$L_x \times L_z = 300 d_i \times 194 d_i \rightarrow 1200 d_i \times 776 d_i$$

$$3D : \sigma = 100$$

$$L_x \times L_z \times L_y = 300 d_i \times 194 d_i \times 300 d_i$$

Results converge for
>100 particles per cell

Force-free current sheet

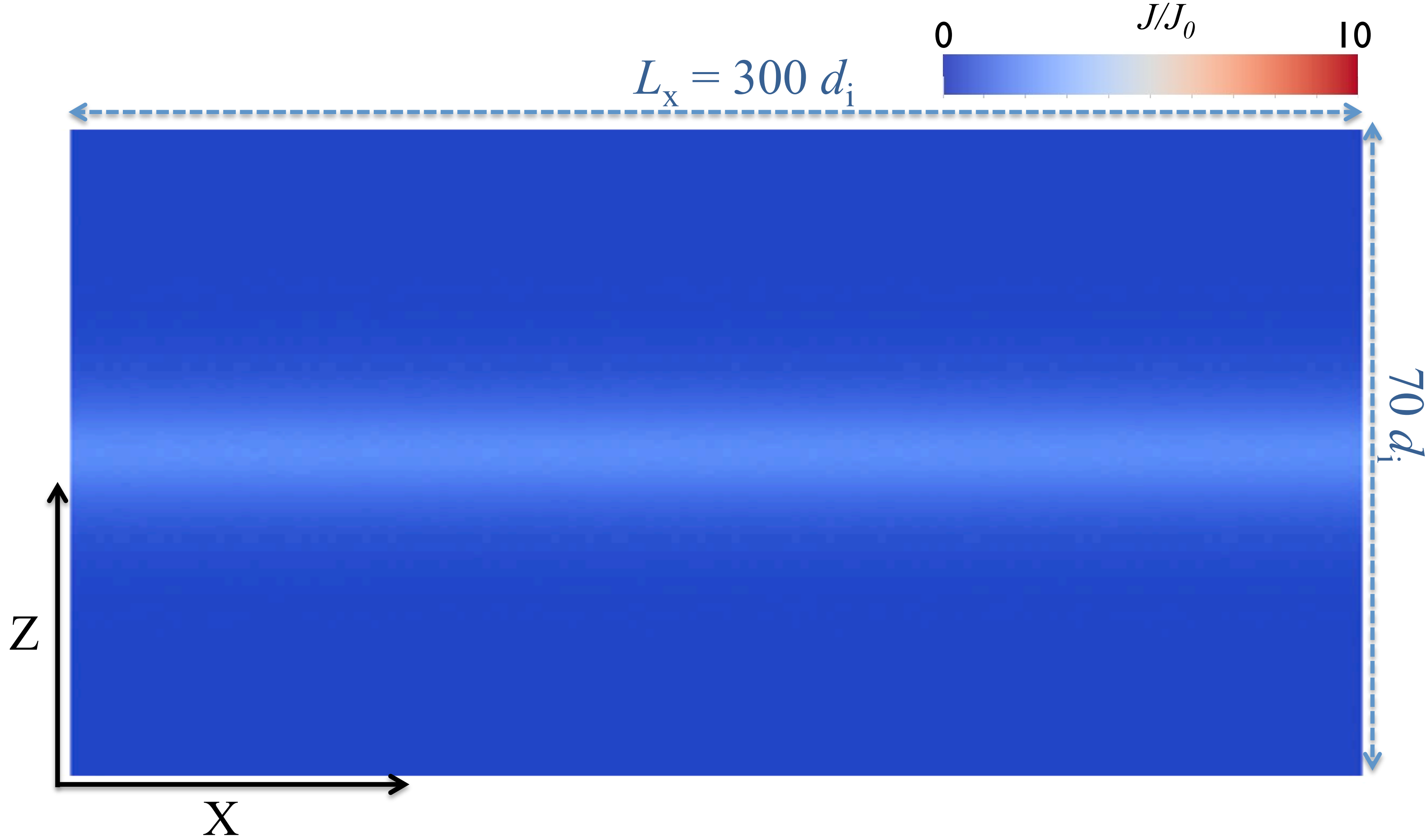


Boundaries for fields: x - periodic
z - conducting
y - periodic (3D)
Boundaries for particles: x - periodic
z - reflection
y - periodic (3D)
No guide field: bg = 0
Initial perturbation (GEM challenge)

Run	σ	system size	λ	p	γ_{max}	$E_{kin}\%$	$(J \cdot E)_\perp\%$
2D-1	6	300×194	$6d_i$	2.2	45	23%	83%
2D-2	6	600×388	$6d_i$	2.0	56	32%	92%
2D-3	6	1200×776	$6d_i$	1.7	79	34%	93%
2D-4	25	300×194	$6d_i$	1.6	195	28%	85%
2D-5	25	600×388	$6d_i$	1.3	339	37%	90%
2D-6	25	1200×776	$6d_i$	1.2	617	42%	90%
2D-7	100	300×194	$6d_i$	1.35	650	29%	73%
3D-7	100	$300 \times 194 \times 300$	$6d_i$	1.35	617	28%	71%
2D-8	100	600×388	$6d_i$	1.25	1148	40%	78%
2D-9	100	1200×776	$6d_i$	1.15	1862	45%	94%
2D-10	400	300×194	$12d_i$	1.25	1514	20%	54%
2D-11	400	600×388	$12d_i$	1.15	3715	31%	75%
2D-12	400	1200×776	$12d_i$	1.1	5495	36%	86%
2D-13	1600	300×194	$24d_i$	1.2	2812	13%	45%
2D-14	1600	600×388	$24d_i$	1.1	7913	21%	53%
2D-15	1600	1200×776	$24d_i$	1.05	11220	30%	66%

Guo et al. 2015

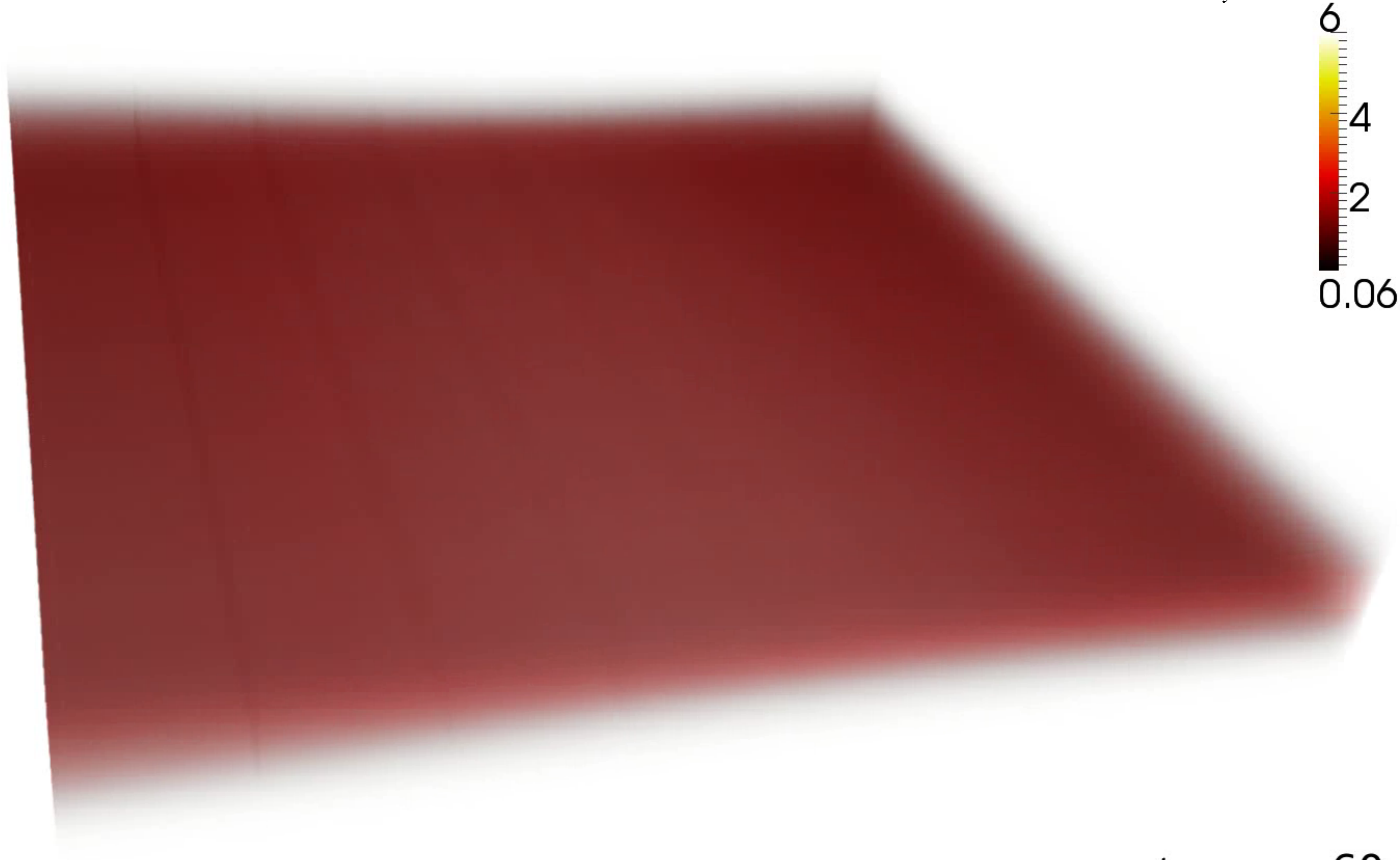
Time evolution of current density in 2D (σ = 100)



~ 1.4×10^{12} particles, **|J|** $\sigma = 100$

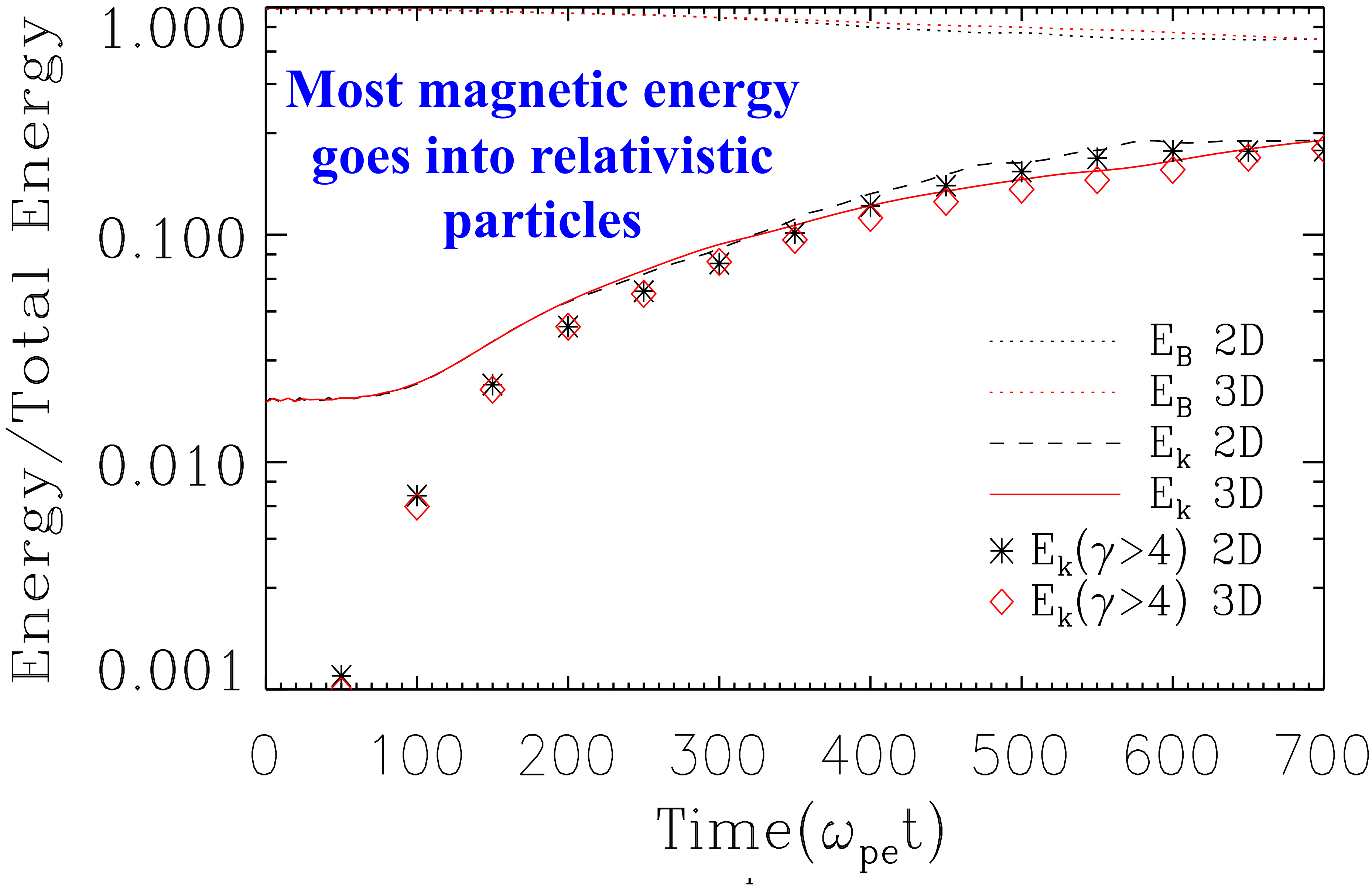
$L_x = 300 d_i, L_z = 192 d_i, L_y = 300 d_i$

$N_x = 2048, N_z = 2048, N_y = 2048$

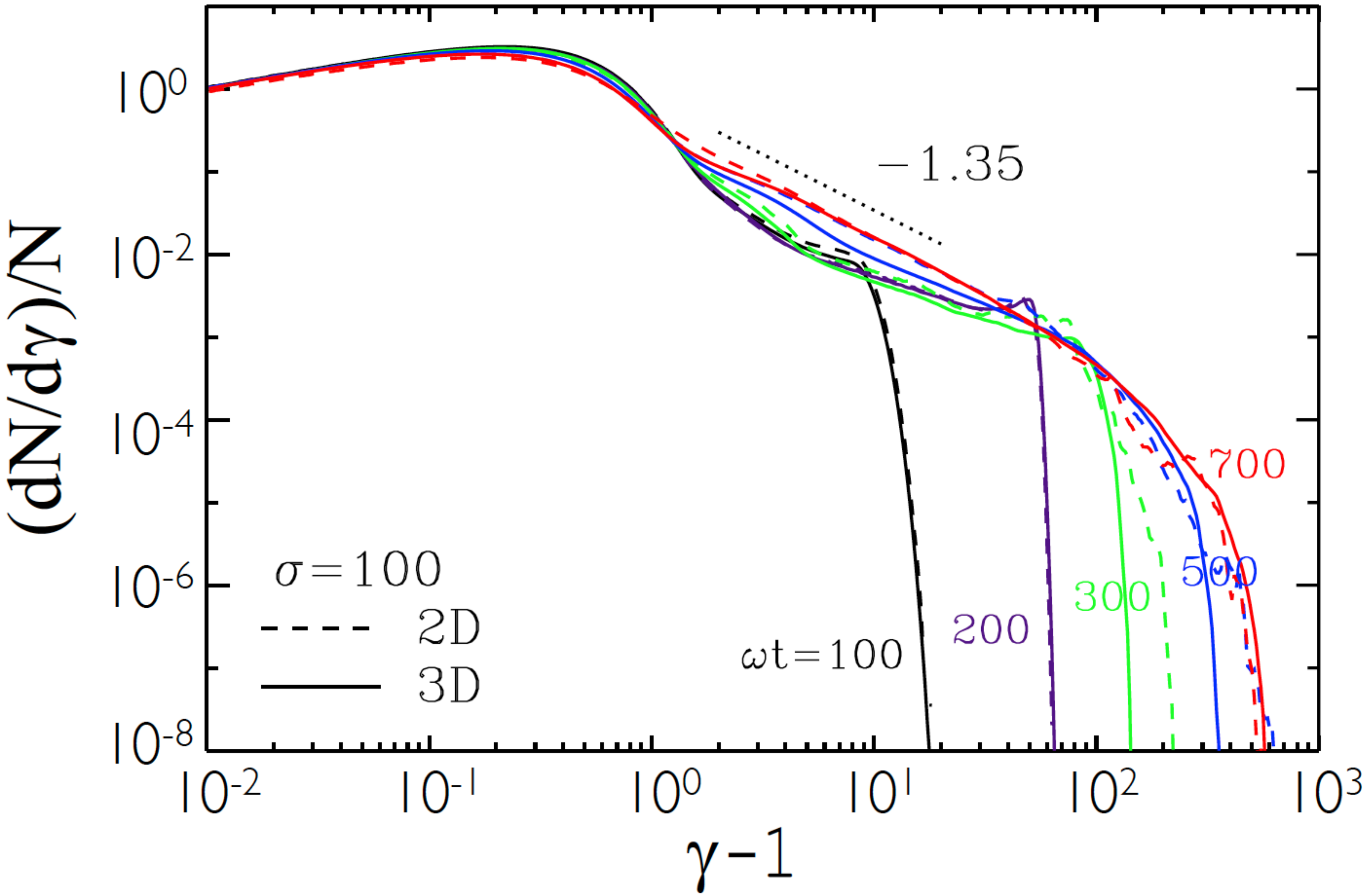


$t\omega_{pe} =$ 60

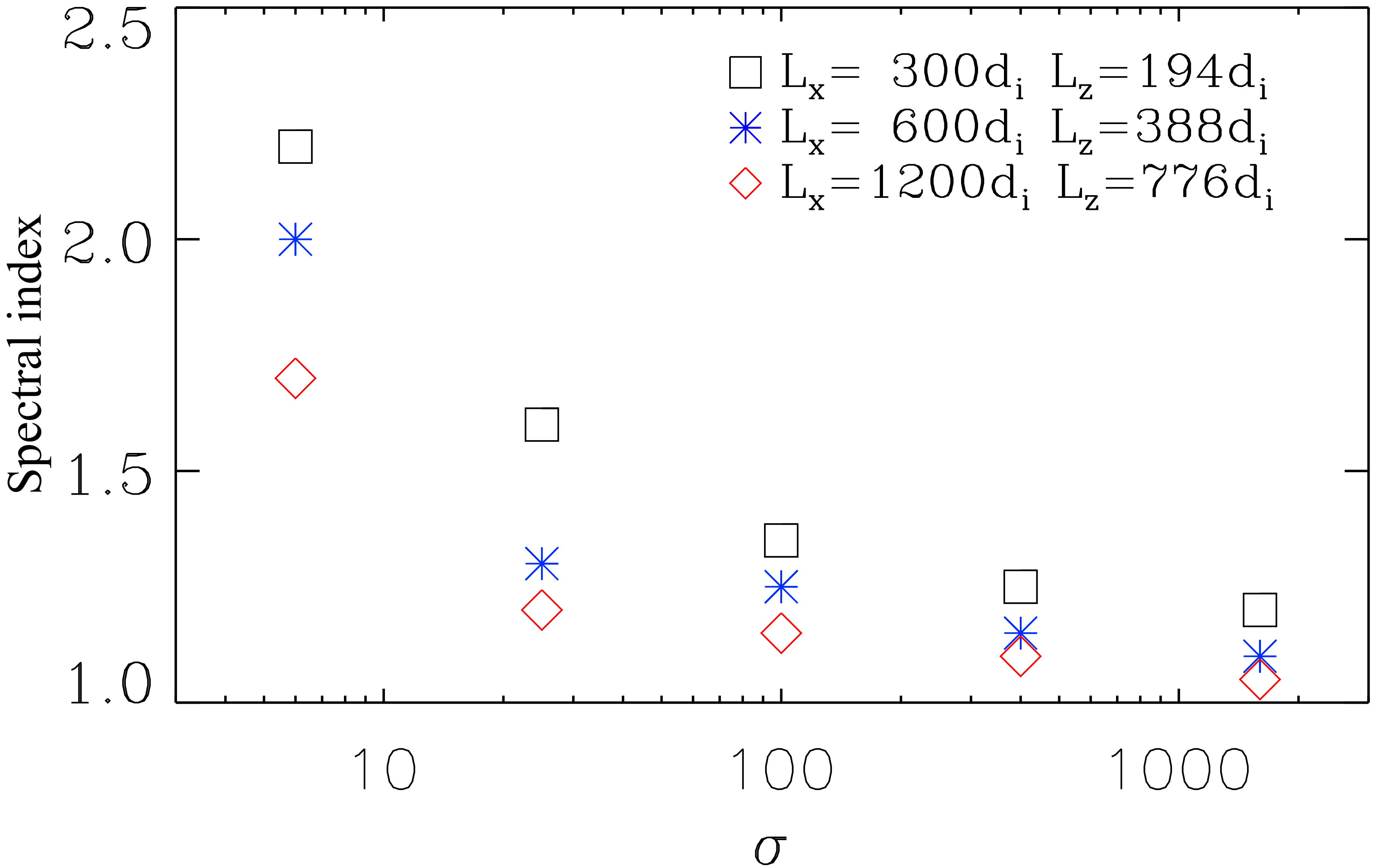
Energy Evolution (σ= 100)



Particle Energy Distribution



Spectral index for all runs



Particle Acceleration Mechanism

Diagnosing the Acceleration Mechanism

Evaluate exact expression for energy gain of all particles:

$$m_j c^2 \frac{d\gamma}{dt} = q_j \mathbf{v} \cdot \mathbf{E} = q_j v_{\|} E_{\|} + q_j \mathbf{v}_{\perp} \cdot \mathbf{E}_{\perp}$$

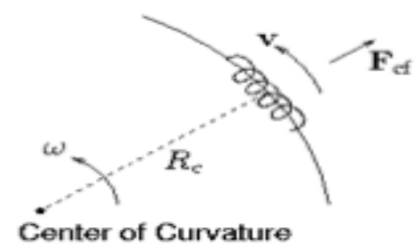
Also evaluate energy gain from guiding center approximation

$$m_j c^2 (\Delta\gamma)_{gc} = q_j \int (\mathbf{v}_{curv} + \mathbf{v}_{\nabla B}) \cdot \mathbf{E}\, dt$$

similar to J Dahlin et al, 2014

Dominant acceleration term is from the curvature drift

$$\mathbf{v}_{curv} = \frac{\gamma v_{\|}^2}{\Omega_{ce}} \left[\mathbf{b} \times (\mathbf{b} \cdot \nabla)\, \mathbf{b}\right]$$



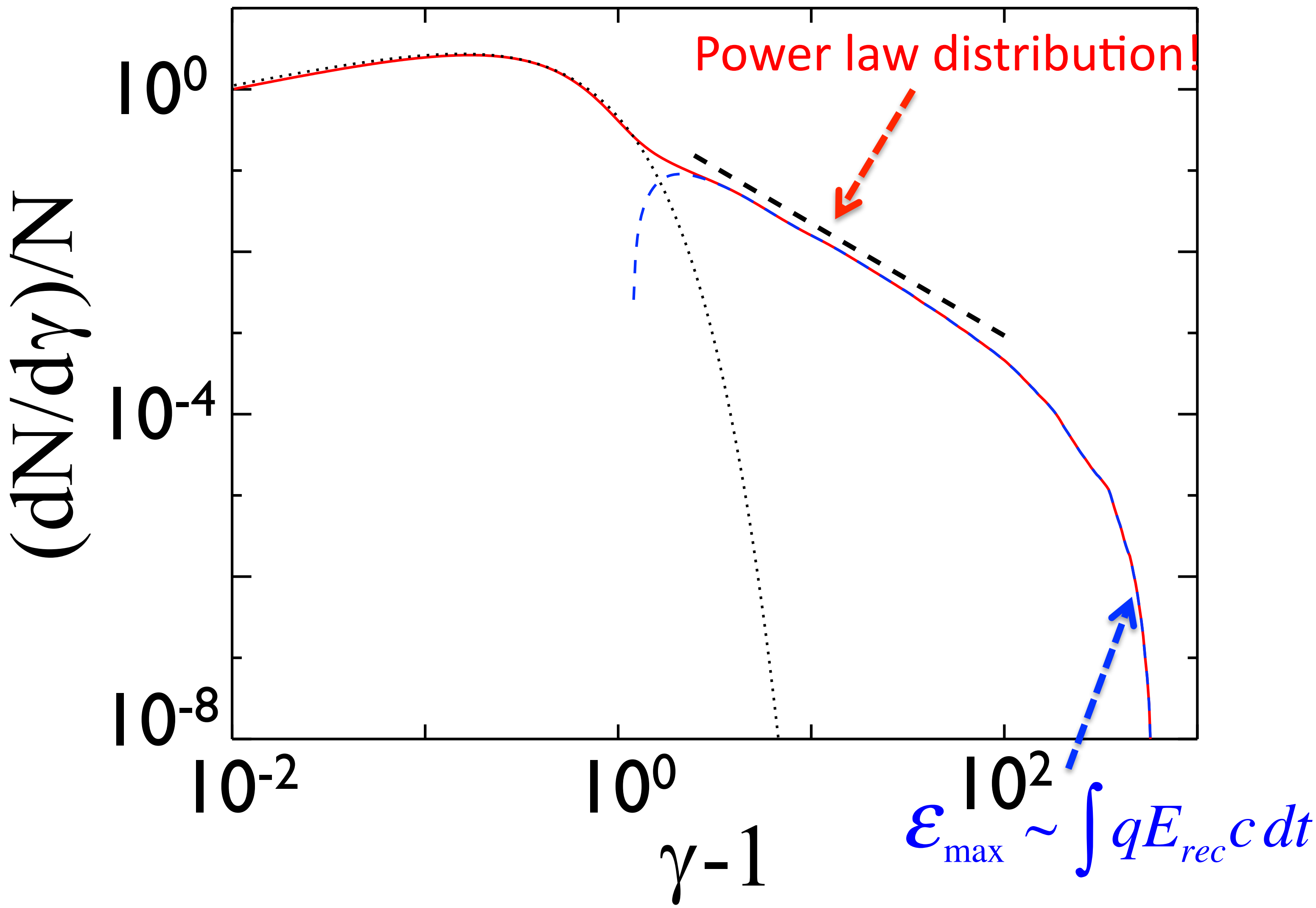
Two Stages

1) **Direct E_parallel acceleration at X-line**

2) **Further acceleration within island (first-order Fermi)**

Two Stages

1) Direct E_parallel acceleration at X-line
2) Further acceleration within island (first-order Fermi)



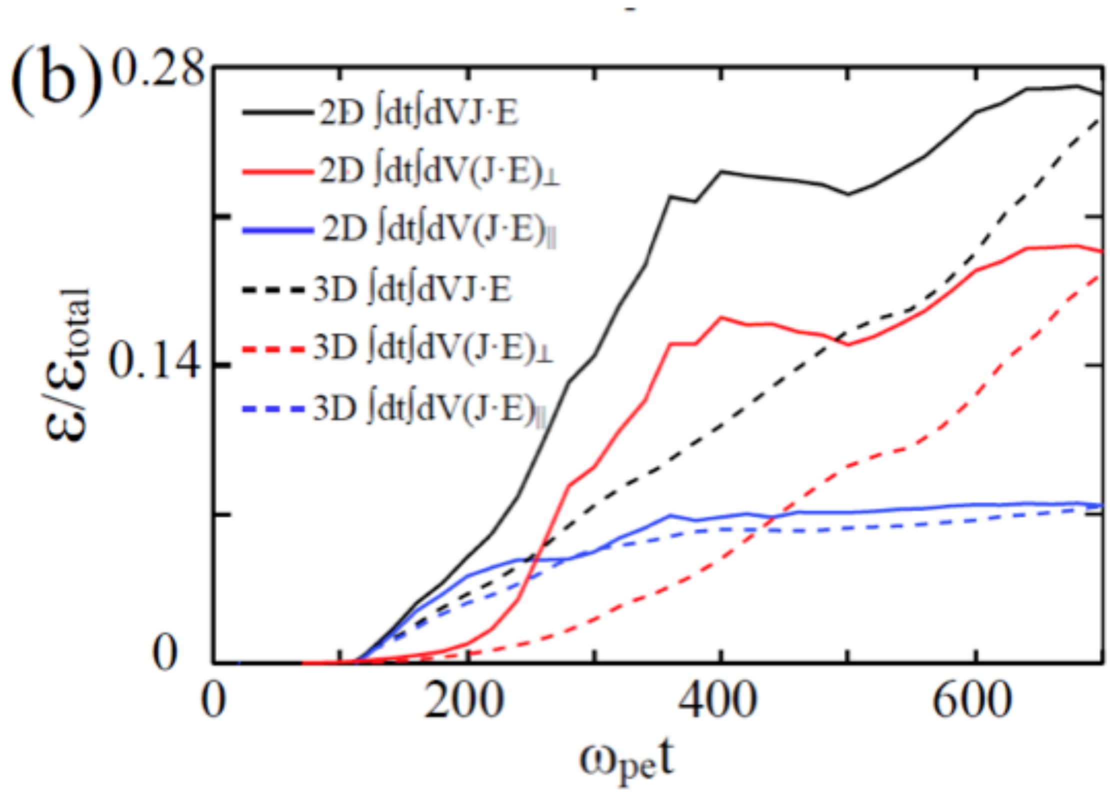
1) Global Consideration

$$J_{||} \cdot E_{||}$$

Important for initial thin sheet

$$J_{\perp} \cdot E_{\perp}$$

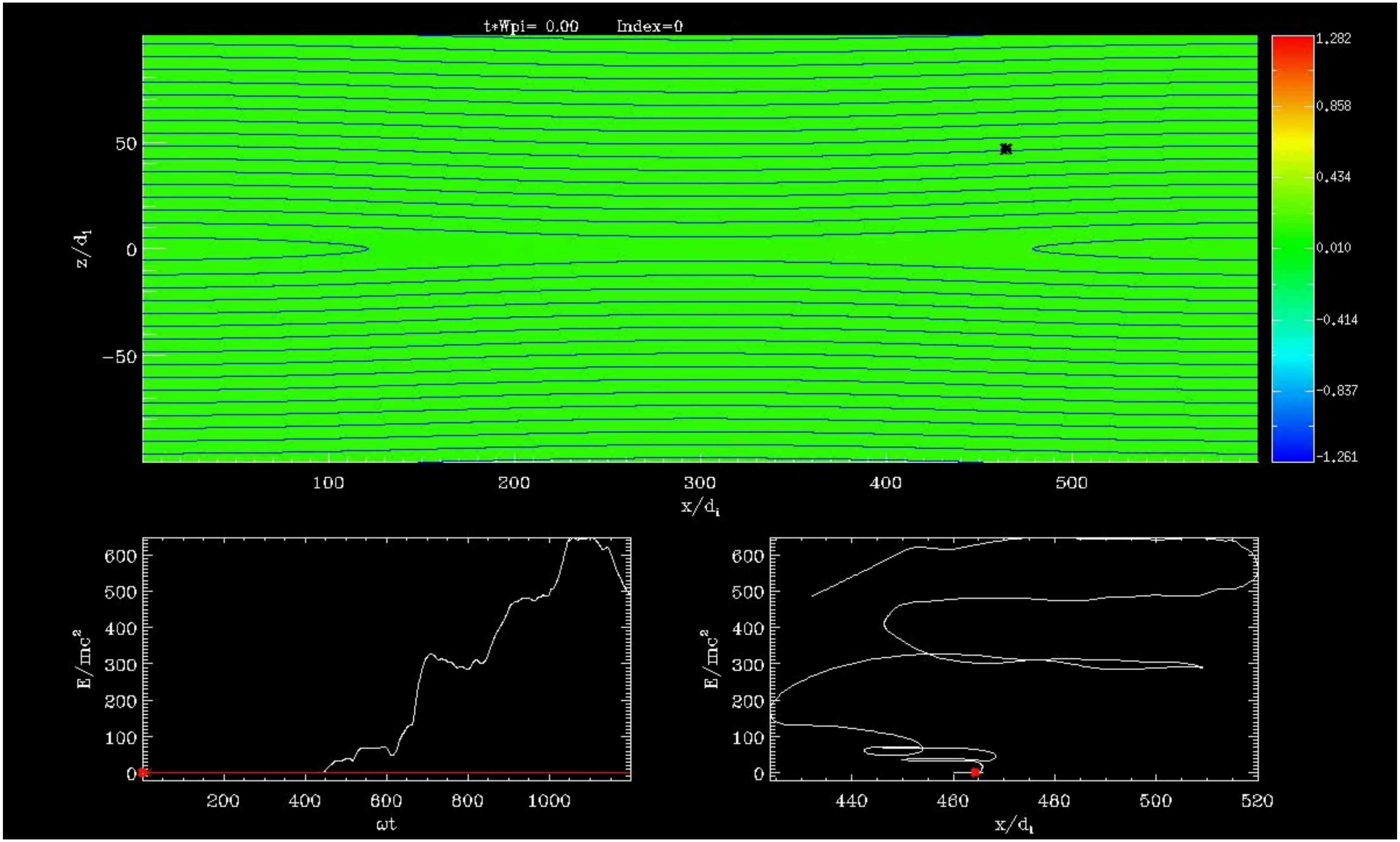
Dominant term for islands/flux ropes system



For large systems,
>80% of energy is converted through

$$E = -V \times B / c$$

2) A representative trajectory (color: V_x)



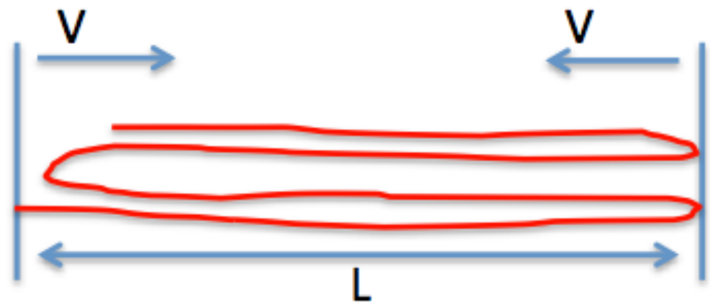
3) 1st order Fermi mechanism

- Acceleration by "collision" in between moving magnetic clouds (Fermi 1949)

$$\Delta\gamma = \left(\Gamma^2(1 + \frac{2Vv_x}{c^2} + \frac{V^2}{c^2}) - 1\right)\gamma$$

$$\Delta t = L_{is}/v_x$$

$$\alpha = \Delta\gamma/(\gamma\Delta t)$$

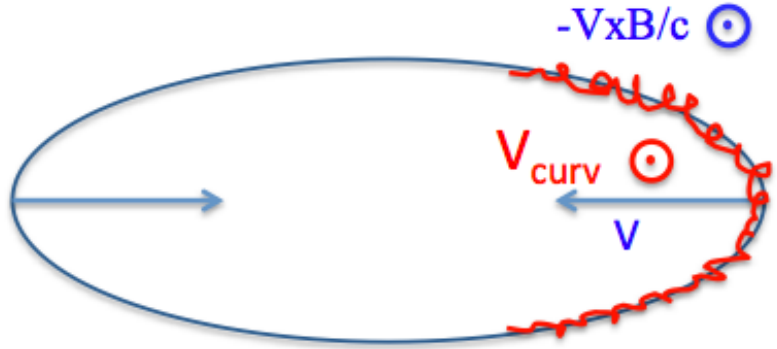


$$\mathbf{v}_{curv} = \frac{\gamma v_{\parallel}^2}{\Omega_{ce}} \left[\mathbf{b} \times (\mathbf{b} \cdot \nabla)\,\mathbf{b}\right]$$

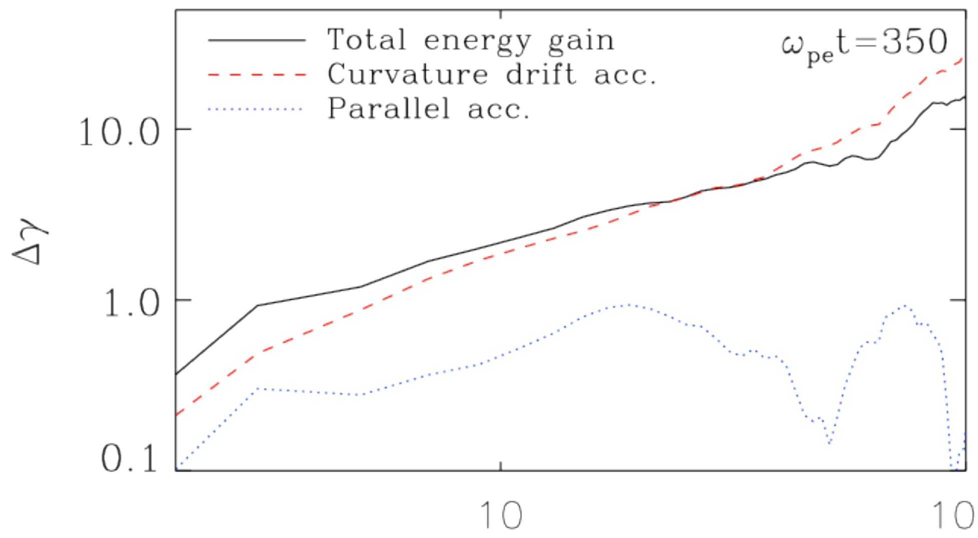
- In large-scale simulations, the dominant electric field for energy release

$$E = -V \times B/c$$

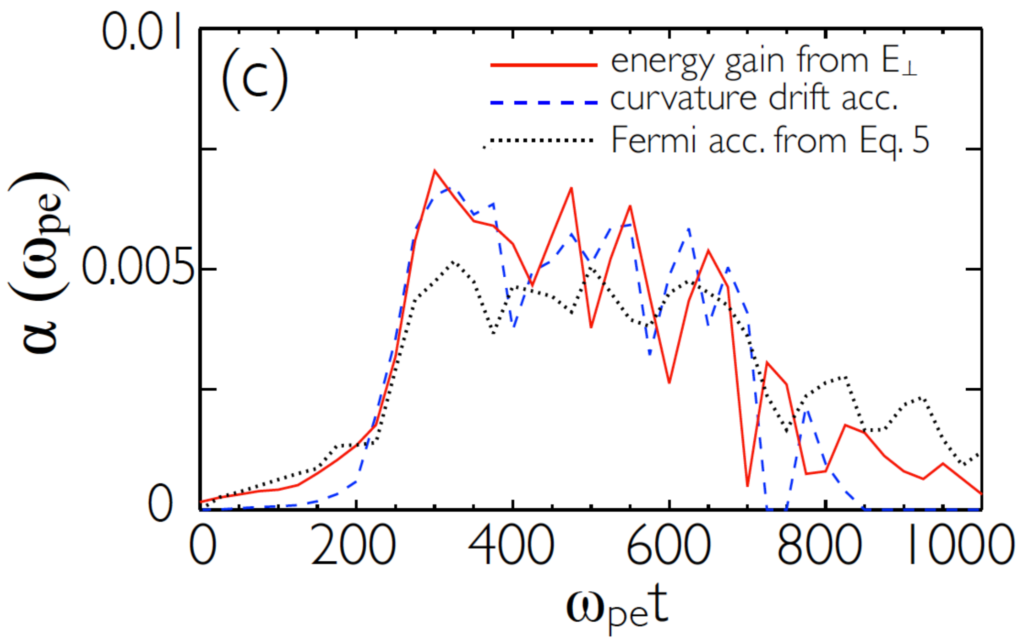
- In reconnection region, the Fermi process is accomplished by curvature drift motion in plasmoids along the motional electric field.



Type-B Fermi process (Fermi 1949)
Drake et al. 2006, 2010; Birn et al. 2012
Guo et al. 2014



The acceleration is dominated by energy gain through curvature drift motion



Fermi acceleration formula agrees with the acceleration by curvature drift motion.

$$\Delta\gamma = \left(\Gamma^2(1 + \frac{2Vv_x}{c^2} + \frac{V^2}{c^2}) - 1\right)\gamma$$

$$\Delta t = L_x/v_x$$

$$\alpha = \Delta\gamma/(\gamma\Delta t)$$

Power law solution (Fermi 1949)

$$\frac{\partial f}{\partial t} + \frac{\partial}{\partial \varepsilon}(\frac{\partial \varepsilon}{\partial t} f) = -\frac{f}{\tau_{esc}}$$

$$\varepsilon = m_e c^2 (\gamma - 1)/T$$

$$\alpha = \frac{1}{\varepsilon}\frac{\partial \varepsilon}{\partial t}$$

Power law solution (Fermi 1949)

$$\frac{\partial f}{\partial t} + \frac{\partial}{\partial \varepsilon}\left(\frac{\partial \varepsilon}{\partial t} f\right) = -\frac{f}{\tau_{esc}}$$

$$\varepsilon = m_e c^2(\gamma - 1)/T$$

$$\alpha = \frac{1}{\varepsilon}\frac{\partial \varepsilon}{\partial t}$$

$$f \propto \varepsilon^{-(1+\frac{1}{\alpha \tau_{esc}})}$$

Consider evolution of f in a closed system

$$\frac{\partial f}{\partial t} + \frac{\partial}{\partial \varepsilon}\left(\frac{\partial \varepsilon}{\partial t} f\right) = 0$$

$$\varepsilon = m_e c^2(\gamma - 1)/T$$

$$\alpha = \frac{1}{\varepsilon}\frac{\partial \varepsilon}{\partial t}$$

$$f_0 = \frac{2}{\sqrt{\pi}}\sqrt{\varepsilon}\exp(-\varepsilon)$$

Consider evolution of f in a closed system

$$\frac{\partial f}{\partial t} + \frac{\partial}{\partial \varepsilon}\left(\frac{\partial \varepsilon}{\partial t} f\right) = 0$$

$$\varepsilon = m_e c^2 (\gamma - 1)/T$$

$$\alpha = \frac{1}{\varepsilon}\frac{\partial \varepsilon}{\partial t}$$

$$f_0 = \frac{2}{\sqrt{\pi}}\sqrt{\varepsilon}\exp(-\varepsilon)$$

$$\downarrow$$

$$\frac{df}{dt} + \alpha f = 0$$

Consider evolution of f in a closed system

$$\frac{\partial f}{\partial t} + \frac{\partial}{\partial \varepsilon}\left(\frac{\partial \varepsilon}{\partial t} f\right) = 0$$

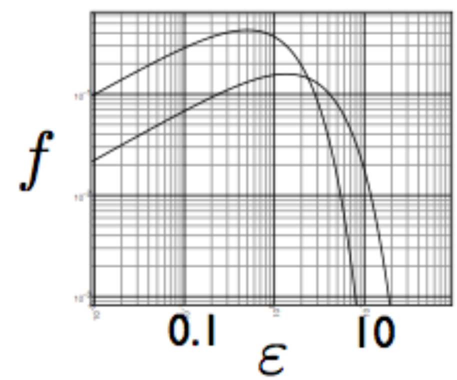
$$\varepsilon = m_e c^2(\gamma - 1)/T$$

$$\alpha = \frac{1}{\varepsilon}\frac{\partial \varepsilon}{\partial t}$$

$$f_0 = \frac{2}{\sqrt{\pi}}\sqrt{\varepsilon}\exp(-\varepsilon)$$

$$\frac{df}{dt} + \alpha f = 0$$

$$f = \frac{2}{\sqrt{\pi}}\sqrt{\varepsilon}e^{-3\alpha t/2}\exp(-\varepsilon e^{-\alpha t})$$



The distribution is heated up $T \longrightarrow Te^{\alpha t}$

Consider escape

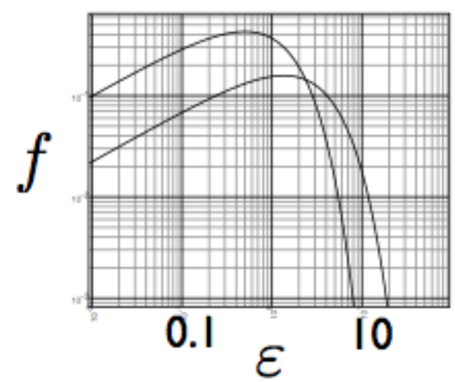
$$\frac{\partial f}{\partial t} + \frac{\partial}{\partial \varepsilon}\left(\frac{\partial \varepsilon}{\partial t} f\right) = -\frac{f}{\tau_{esc}}$$

$$\varepsilon = m_e c^2(\gamma - 1)/T$$

$$\alpha = \frac{1}{\varepsilon}\frac{\partial \varepsilon}{\partial t}$$

$$f_0 = \frac{2}{\sqrt{\pi}}\sqrt{\varepsilon}\exp(-\varepsilon)$$

$$\frac{df}{dt} + \left(\alpha + \frac{1}{\tau_{esc}}\right) f = 0$$

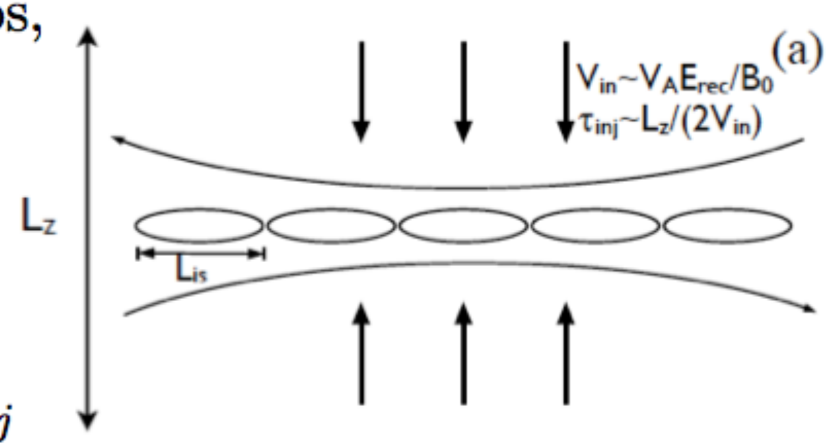


The distribution is heated up.
No power-laws

Escape does not give a power law.

Consider injection

Split injected distribution into N groups, and release jth group into acceleration region at $t = j\Delta t$ $\qquad \Delta t = \tau_{inj}/N$



Particle distribution injected at $t = t_j$

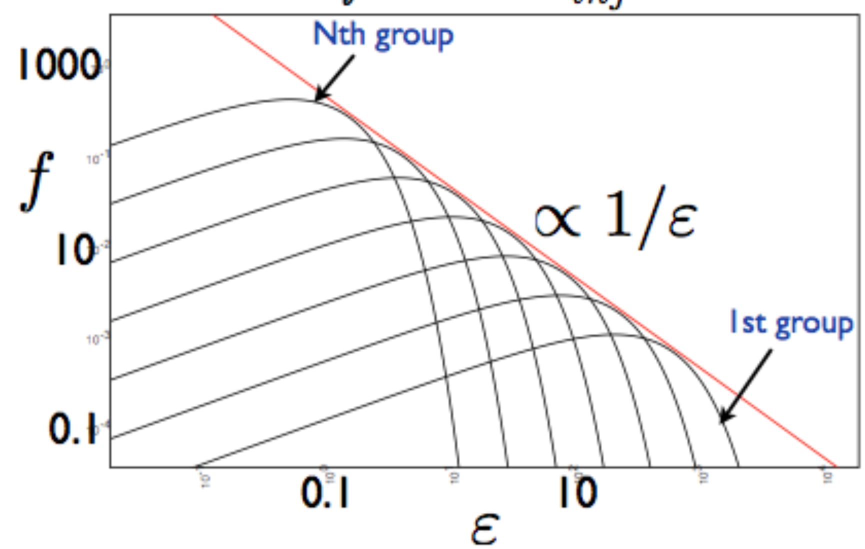
$$f = \frac{2}{\sqrt{\pi}}\sqrt{\varepsilon}e^{-3\alpha(t-t_j)/2}\exp(-\varepsilon e^{-\alpha(t-t_j)})$$

Total distribution f at $t = \tau_{inj}$

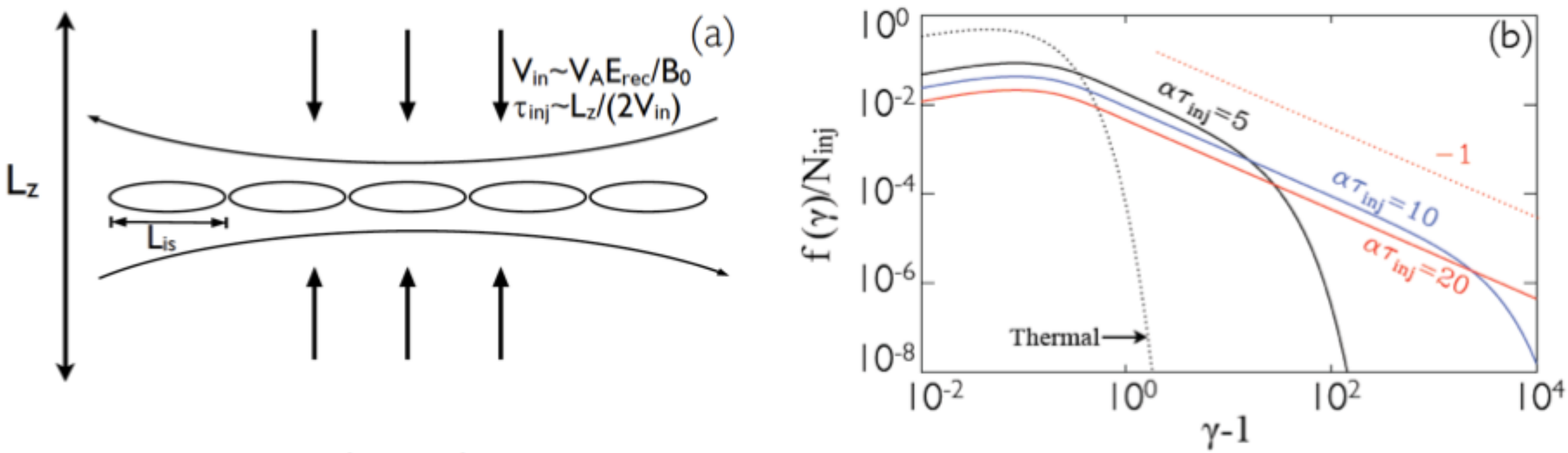
$$f(\varepsilon, t) \sim \frac{2N_{inj}}{\sqrt{\pi}\tau_{inj}}\int_0^{\tau_{inj}}\sqrt{\varepsilon}e^{-3\alpha t/2}\exp(-\varepsilon e^{-\alpha t})dt$$

$$\propto 1/\varepsilon$$

f at $t = \tau_{inj}$



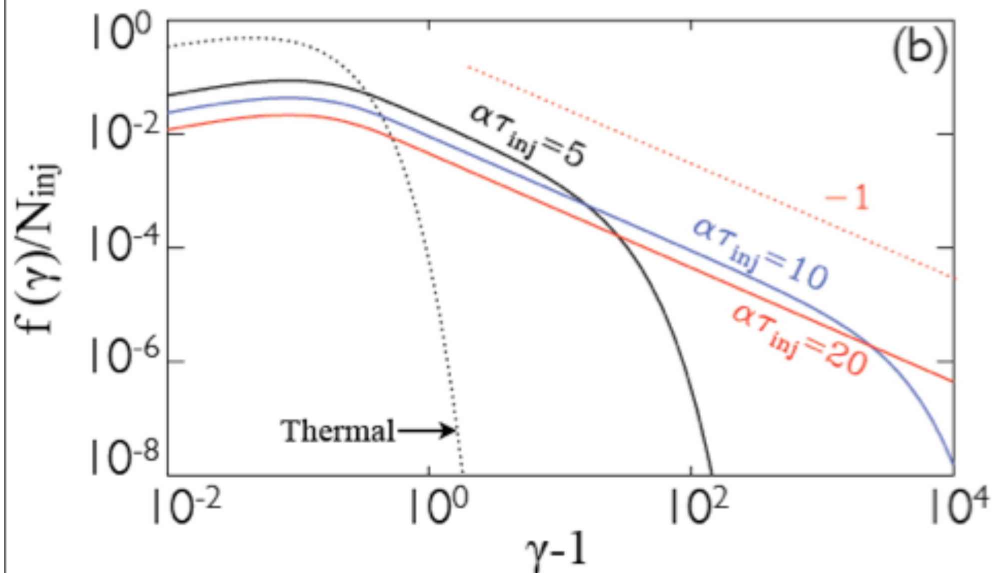
Time-dependent injection is the key factor:



$$\frac{\partial f}{\partial t} + \frac{\partial}{\partial \varepsilon}\left(\frac{\partial \varepsilon}{\partial t} f\right) = \frac{f_{inj}}{\tau_{inj}} - \frac{f}{\tau_{esc}} \qquad \alpha = \frac{1}{\varepsilon}\frac{\partial \varepsilon}{\partial t} \quad \beta \equiv (\alpha\tau_{esc})^{-1}$$

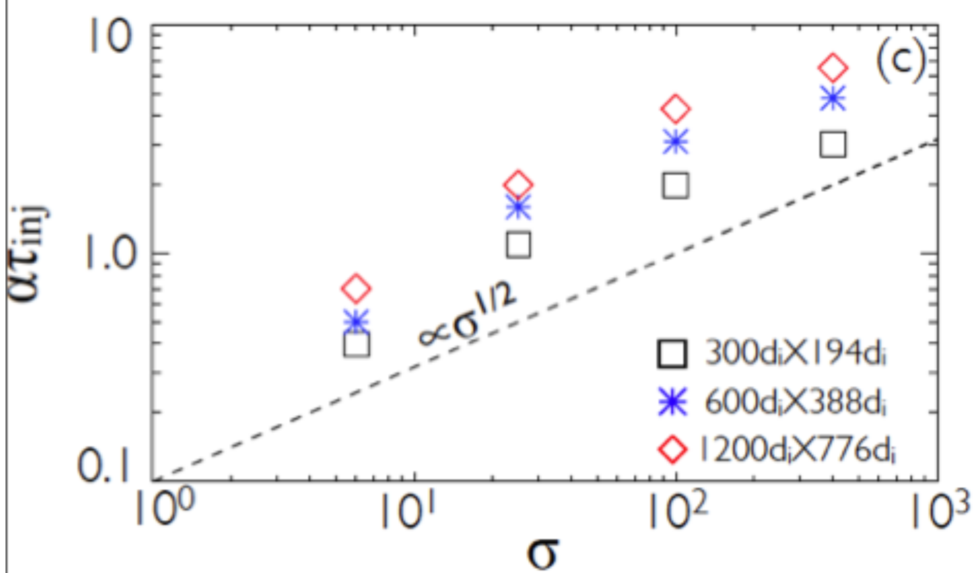
$$\begin{aligned} f(\varepsilon, t) &= \frac{2N_0}{\sqrt{\pi}}\sqrt{\varepsilon}e^{-(3/2+\beta)\alpha t}\exp(-\varepsilon e^{-\alpha t}) \\ &+ \frac{2N_{inj}}{\sqrt{\pi}(\alpha\tau_{inj})\varepsilon^{1+\beta}}\left[\Gamma_{(3/2+\beta)}(\varepsilon e^{-\alpha t}) - \Gamma_{(3/2+\beta)}(\varepsilon)\right], \end{aligned}$$

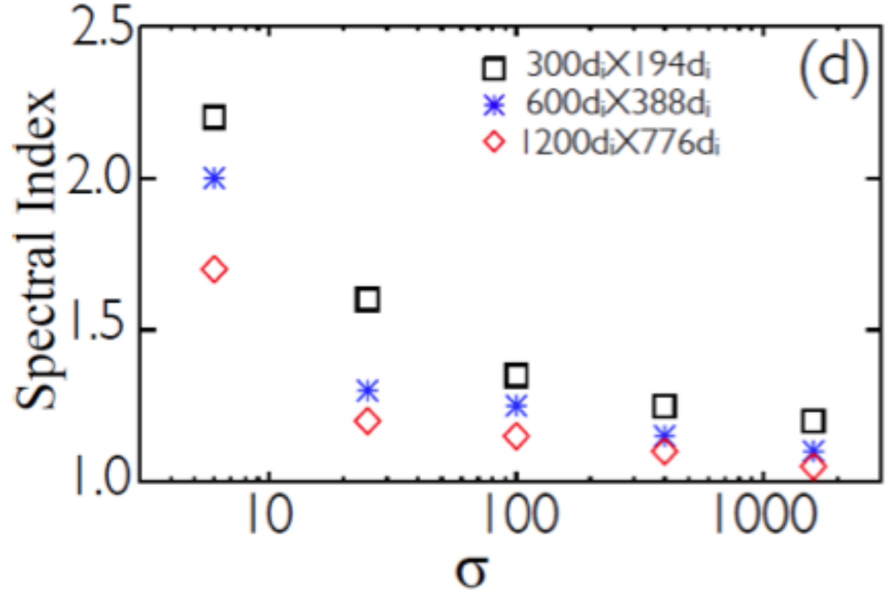
Power-law formation condition



$$\alpha \tau_{inj} > 1$$

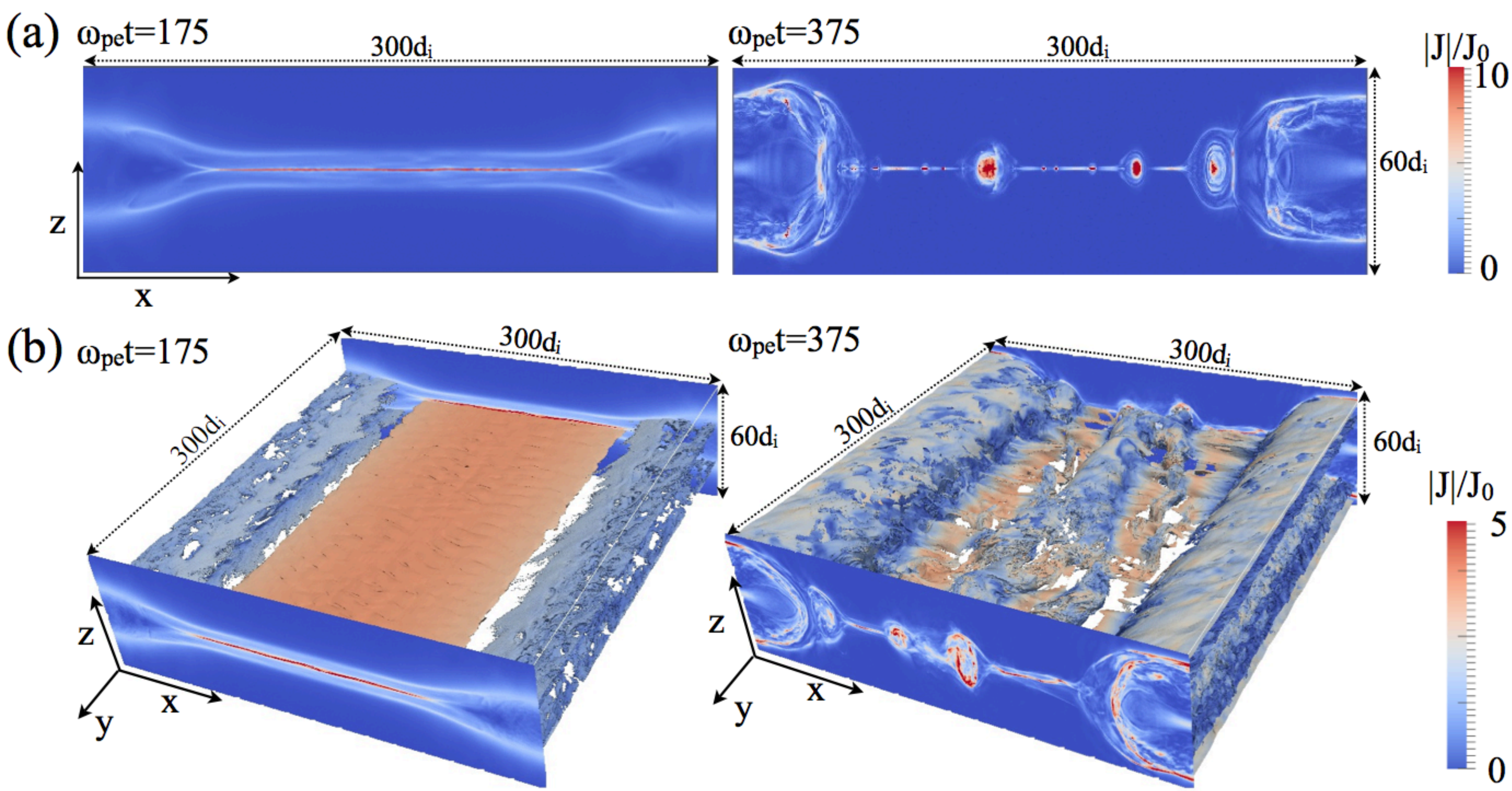
This can easily be satisfied in relativistic reconnection, even in kinetic scales.





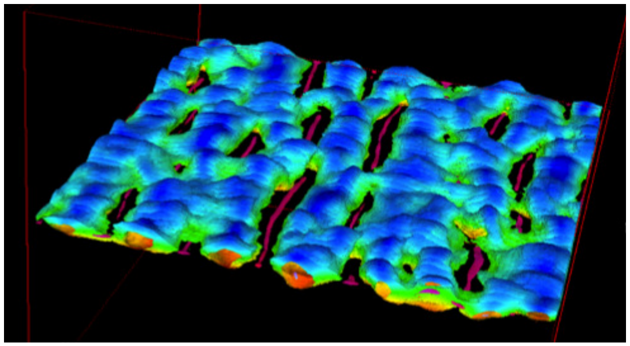
Some Open Questions

1) current distributions in 2D and 3D



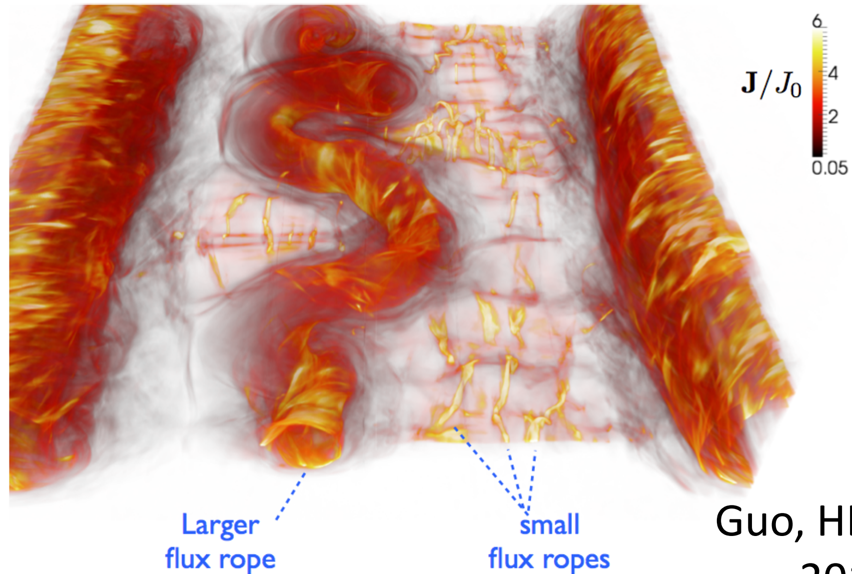
2) 3D Important

1) 3D Kink



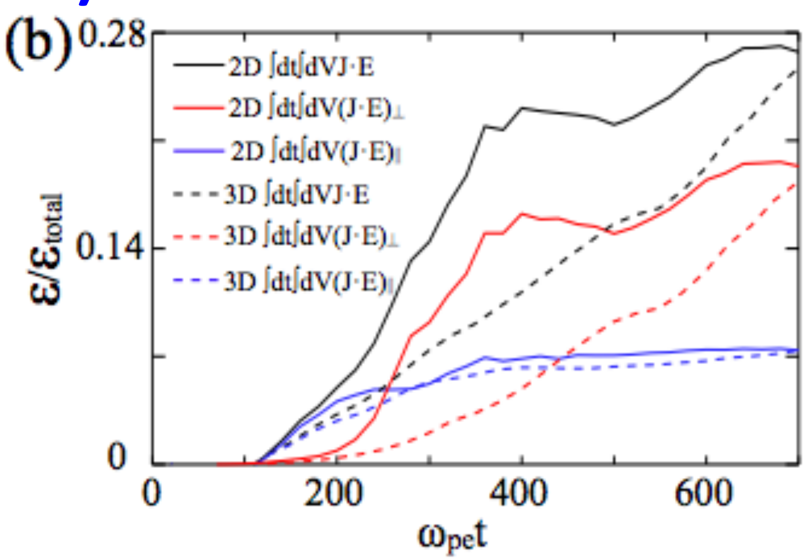
Liu, HL, et al. 2011

Interacting Flux Ropes are Kink Unstable



Guo, HL, et al. 2014

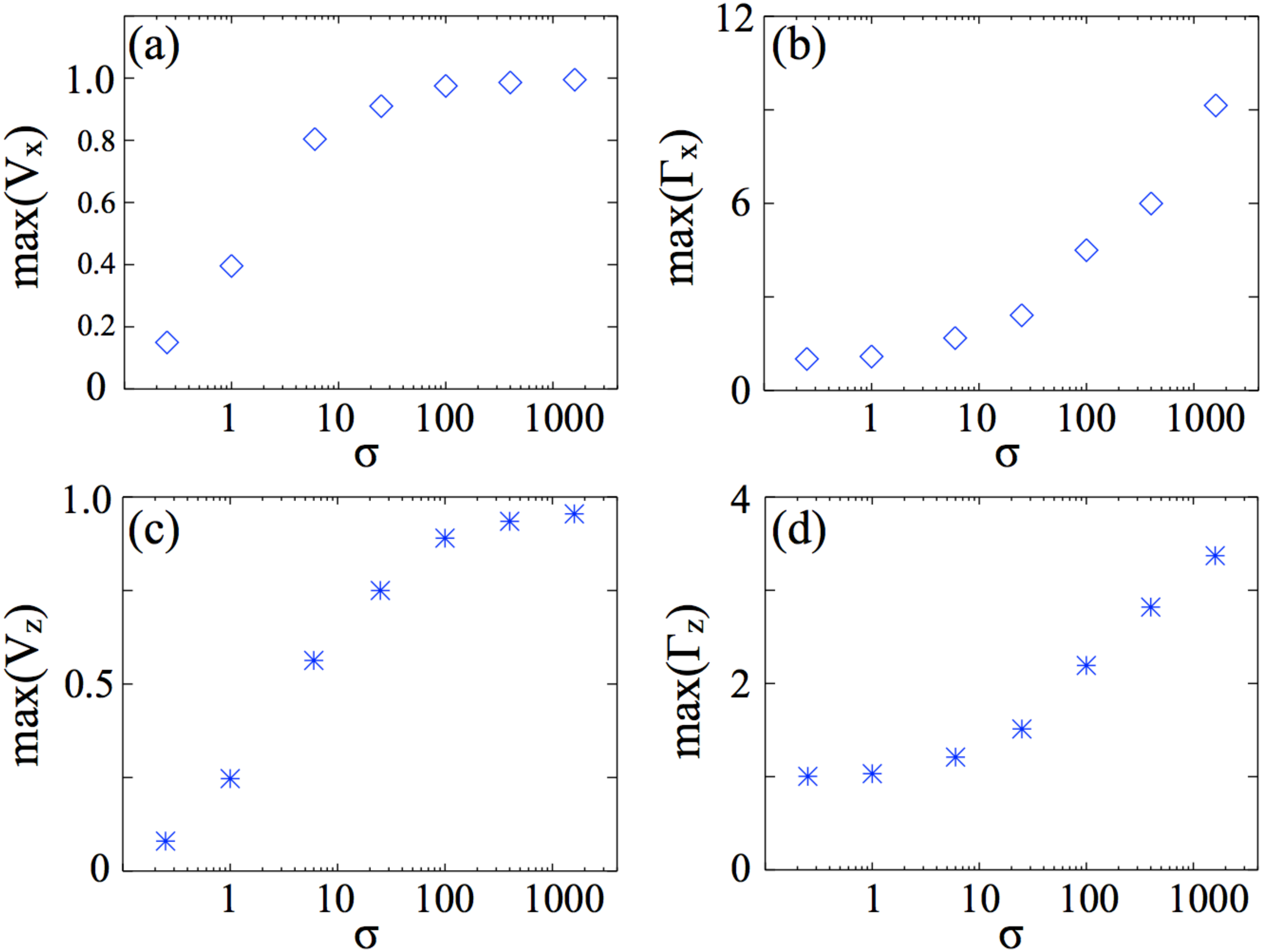
2) Particle acceleration



Energy dissipation rate (esp. in perp direction) is quite different in 2D and 3D

Guo et al. 2015

3) Outflows



(a)
max(V_x)
1.0
0.8
0.6
0.4
0.2
0
1
10
100
1000
σ
(b)
max(Γ_x)
12
6
0
1
10
100
1000
σ
(c)
max(V_z)
1.0
0.5
0
1
10
100
1000
σ
(d)
max(Γ_z)
4
2
0
1
10
100
1000
σ

Key results

- Fast reconnection and strong particle acceleration during magnetic reconnection in high-σ regime.
- Enhanced reconnection rate in relativistic regime.
- Efficient energy conversion and particle acceleration (nonthermal dominant)
- Two stage acceleration: direction acceleration and first-order Fermi acceleration via curvature drift.
- Formation of power laws: requires both Fermi acceleration and continuous inflow. Power-law formation condition: $\alpha\tau_{inj}>1$.

Apply to high-energy astrophysics:

- Efficient energy conversion and strong particle acceleration (power the system in high-energy wavelengths)
- Hard power laws (close to "-1") in high-σ regime
- Fast power-law formation (fast variability)
- Relativistic inflow/outflow.

Coupling between macro- and micro-scales will be essential