Relativistic Nonthermal Particle Acceleration in Magnetic Reconnection

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INCITE

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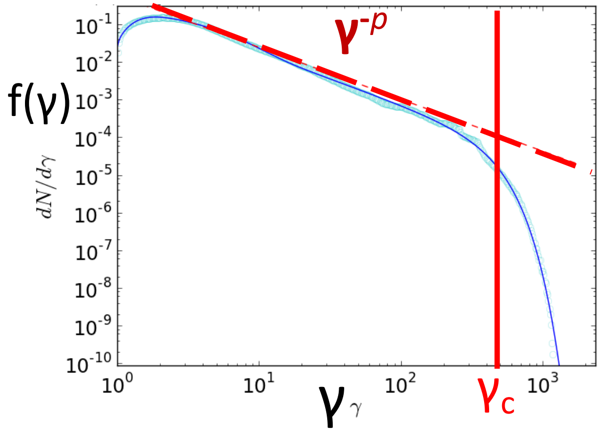
Nonthermal Particle Acceleration in Magnetic Reconnection

- **Goals:** Understand the physical mechanisms of nonthermal particle acceleration (***NTPA***) and characterize it quantitatively across a broad parameter space:

System parameters → → power-law index $\boldsymbol{p}$ and cutoff $\boldsymbol{\gamma_c}$

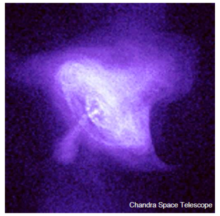


Provide a usable prescription for the astro and space communities for NTPA parameters (p, γ_c) but also reconnection rate, electron/ion heating ratio, etc.

- **Tools:** PIC sims (+ some analytical theory)

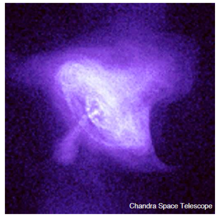
- Multi-dimensional **Parameter Space** (flavors of collisionless reconnection):

Dimensionality, L_z/L_x	2D or 3D
Plasma Composition	pair, electron-ion, mixed
Boundary Conditions	periodic, open, receding
Guide field, B_g/B_0	anti-parallel (B_g=0) or guide-field
Relativity (σ_h)	ultra-relativistic, semirelaltivistic, or non-relativistic
Extra Physics:	Radiation reaction, pair creation, etc.



OUTLINE:

Numerical (PIC) Studies of Nonthermal Particle Acceleration in Collisionless Relativistic Magnetic Reconnection



1. ***Ultra-relativistic pair plasma in 2D (with and without radiaction)***
2. ***Semirelativistic electron-ion plasma in 2D***
3. ***Ultra-relativistic pair plasma in 3D***
4. ***Trans-relativistic pair plasma in 3D***

Current Frontier!

Main goal: chart out the resulting observable particle acceleration and radiation parameters (spectral indices, cutoffs) as functions of system's input parameters: upstream magnetization σ, size L, guide magnetic field B_g.

Magnetization σ parameter

- Physical parameters of ambient/upstream background plasma:
  - Particle density n_b; Temperature $\theta_e = T/m_e c^2$,
  - Reconnecting magnetic field B_0; Guide magnetic field B_{gz}
- Important dimensionless parameter – (upstream) **magnetization σ**:
  - **"Cold" sigma: $\sigma = B_0^2/(4\pi\, n_b\, mc^2)$**

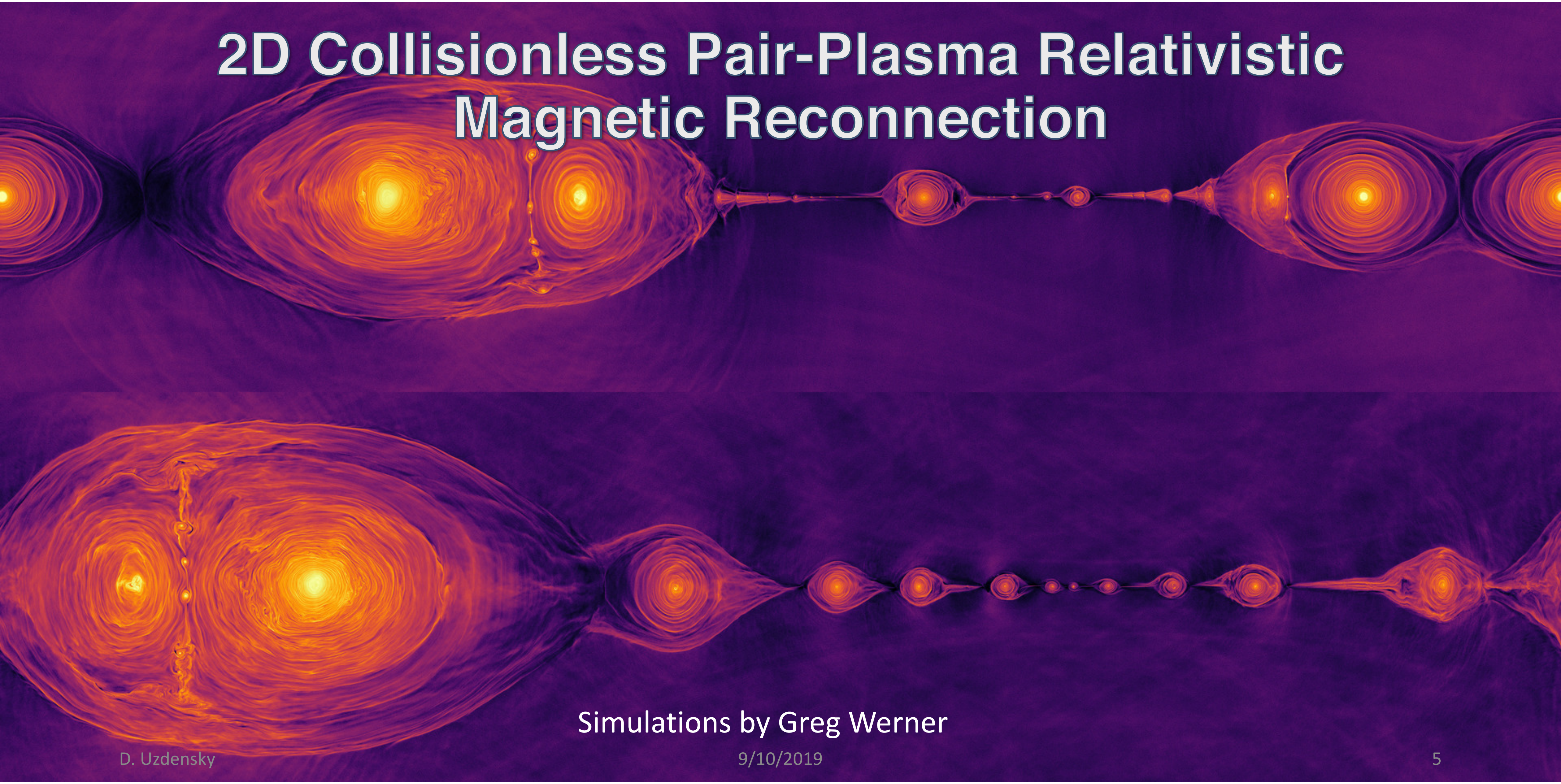
    (sets the scale for available magnetic energy per particle);
  - **"Hot" sigma: $\sigma_h = B_0^2/(4\pi\, h)$**,

    where $h = n_b \langle\gamma\rangle mc^2 + p_b$ = relativistic enthalpy density (including rest-mass) --- governs Alfven velocity and thus how relativistic plasma motions are.

    $$V_A = c\beta_A = c\frac{\sqrt{\sigma_h}}{\sqrt{1+\sigma_h}}$$
  - Relativistically-cold plasma ($T \ll m_e c^2$): $\sigma_h \approx \sigma$.
  - Ultrarelativistically-hot plasma ($T \gg m_e c^2$): $h \approx 4 n_b \theta_e\, mc^2 \rightarrow$

    $$\sigma_h \approx \sigma/4\theta_e = B_0^2/(16\pi\, n_b\, \theta_e\, mc^2) = 1/(2\beta)$$

2D Collisionless Pair-Plasma Relativistic Magnetic Reconnection



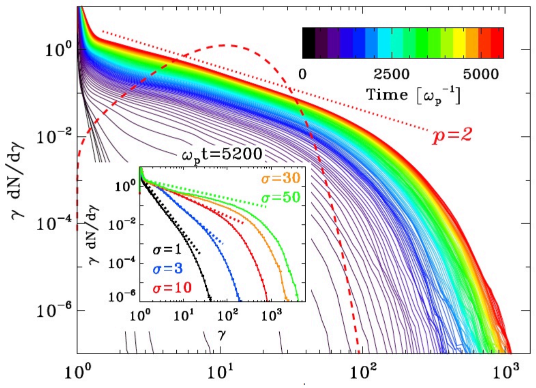
Simulations by Greg Werner

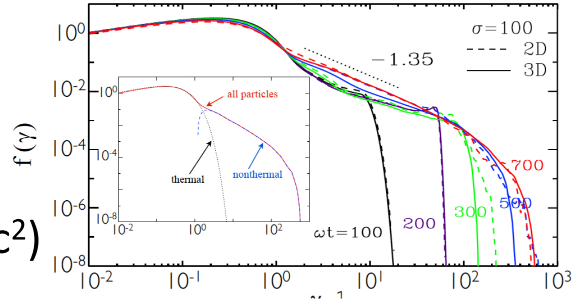
2D Relativistic Pair Reconnection: Nonthermal Particle Acceleration (2014-2019 view)

Important pioneering early work by *Zenitani & Hoshino (2001, 2005, 2007-2008)*, also by *Jaroschek+'04, Lyubarsky & Liverts '08, Bessho & Bhattacharjee'07-08, Liu+'11, Cerutti+'13-14, etc…*

Recent (~2014) 2D PIC studies: relativistic reconnection in pair plasmas drives robust nonthermal particle acceleration!

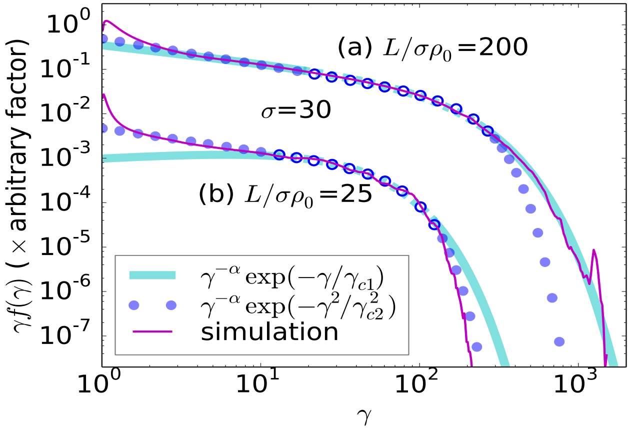
- Sironi et al. – Columbia/Princeton
- Guo et al. – Los Alamos
- Werner et al. – Colorado





(γ = ε/mc²)

γ f(γ)



How do power-law characteristics – power-law index α (aka *p*), high-energy cutoff γ_c – depend on system parameters?

Power-law index:

2D PIC studies with cold upstream plasma, so $\sigma_h \approx \sigma = B_0^2/(4\pi\, n_b\, mc^2)$

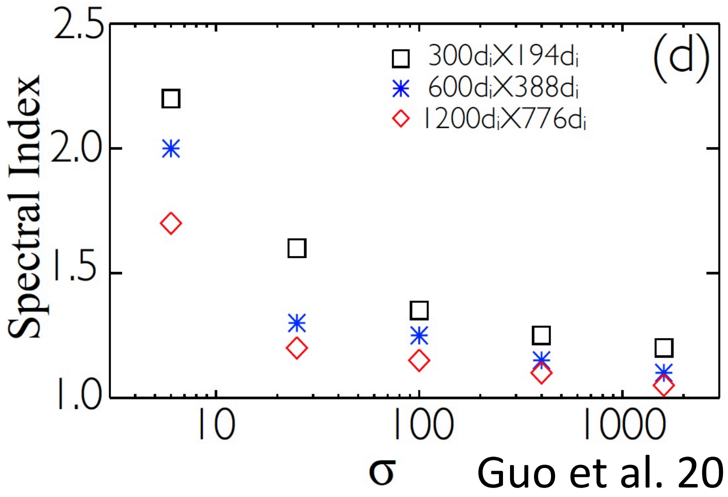
$\sigma = B_0^2/(4\pi\, nmc^2)$

$B_g = 0$

$f(\gamma) \sim \gamma^{-\alpha}$

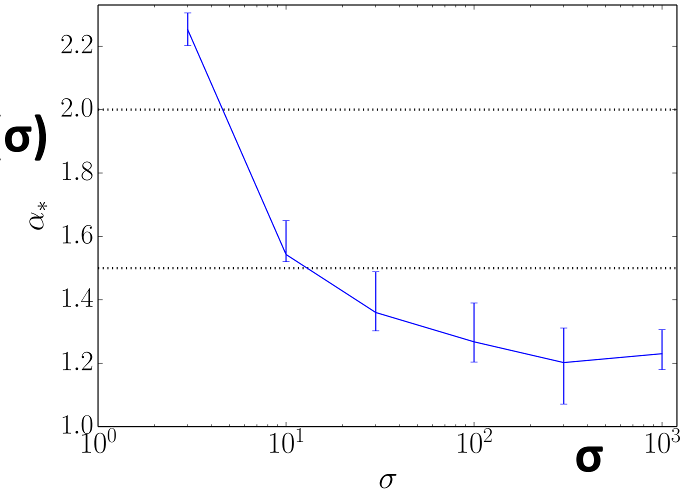
- $\alpha = \alpha(\sigma_h, L)$
- α converges to a finite value $\alpha_*(\sigma)$ as $L \rightarrow \infty$.
- $\alpha_*(\sigma)$ decreases with σ but approaches a finite asymptotic value **$\alpha \approx 1\text{-}1.2$** as $\sigma_h \rightarrow \infty$.

(consistent with other studies: Zenitani & Hoshino, Lyubarsky & Liverts 2008, …)



Guo et al. 2014

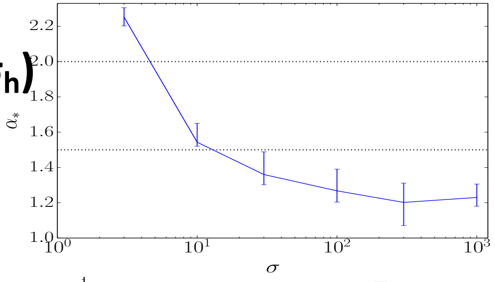
$\alpha_*(\sigma)$



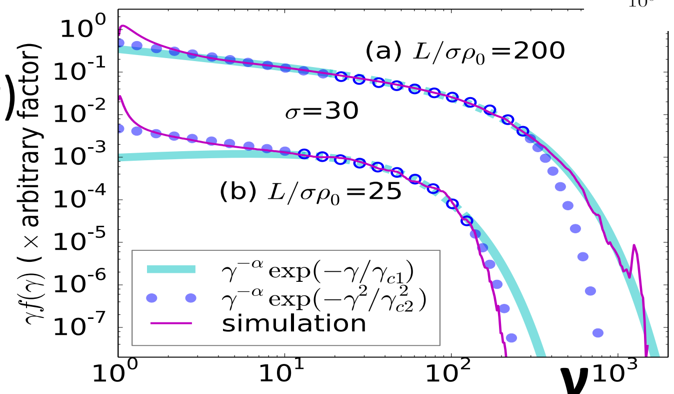
Werner et al. 2014-16

High-Energy Power-Law Cutoff

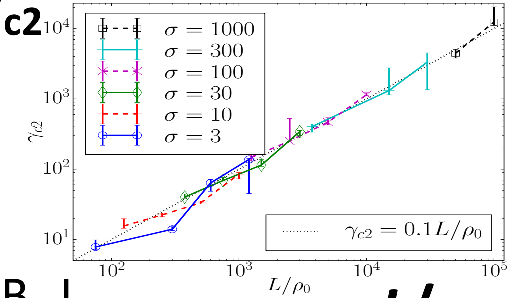
(Werner, Uzdensky, Cerutti, Nalewajko, Begelman 2016)



$$\boxed{f(\gamma) = \frac{dN}{d\gamma} \;\propto\; \gamma^{-\alpha} \exp\left(-\gamma/\gamma_{c1} - \gamma^2/\gamma_{c2}^2\right)}$$



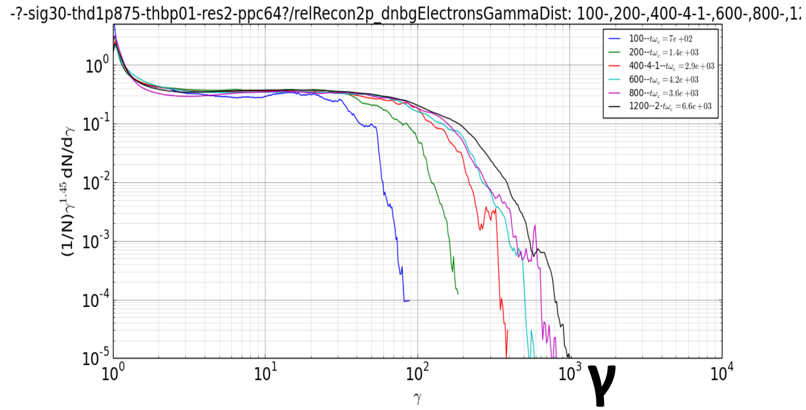
Two high-energy cutoffs:



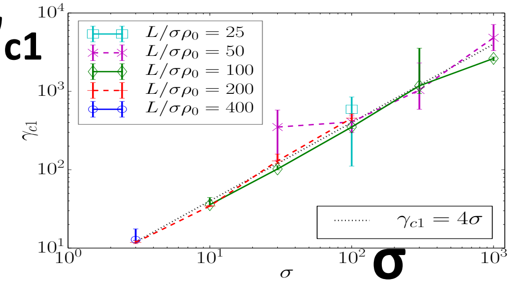
- exp $[-(\gamma/\gamma_{c2})^2]$; **$\gamma_{c2} \sim 0.1\, L/\rho_0$**
- independent of σ.

($\rho_0 = m_e c^2/e B_0$)

Total voltage drop: $\varepsilon_{max} \sim e\, E_{rec}\, L \sim 0.1\, e\, B_0\, L$
("extreme", or Hillas, acceleration)



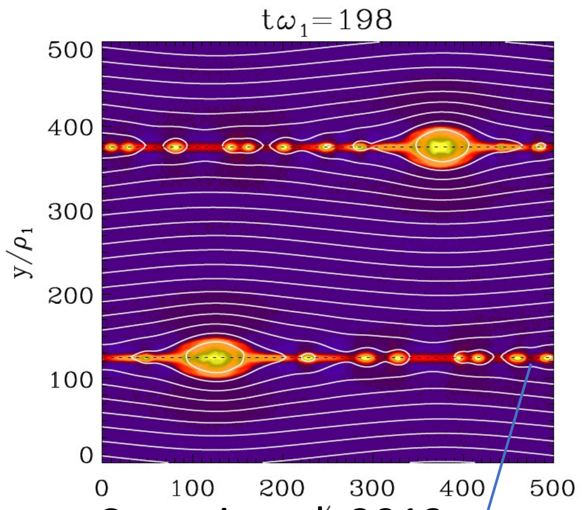
- exp $(-\gamma/\gamma_{c1})$; **$\gamma_{c1} \sim 4\sigma \sim 10 \langle\gamma\rangle$**
- independent of *L*;



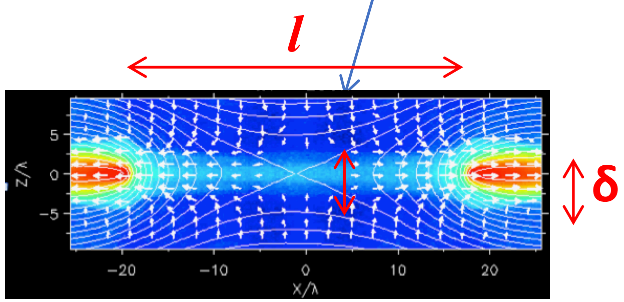
Large-system regime:
($\gamma_{c1} < \gamma_{c2}$):
$L/\rho_0 > 40\,\sigma$

Confirmed by Kagan et al.'18

Why is there a $\gamma_c \approx 4\sigma$ cutoff?



Cerutti et al. 2013



Zenitani & Hoshino 2001

$\rho_0 = m_e c^2/e B_0$

$\sigma = B_0^2/(4\pi\, nmc^2)$

(Werner et al. 2016)

- Cutoff comes from small laminar ***elementary inter-plasmoid layers*** at the bottom of the plasmoid hierarchy (marginally stable to tearing).
- Particles are accelerated in these layers but then become **trapped inside plasmoids**.

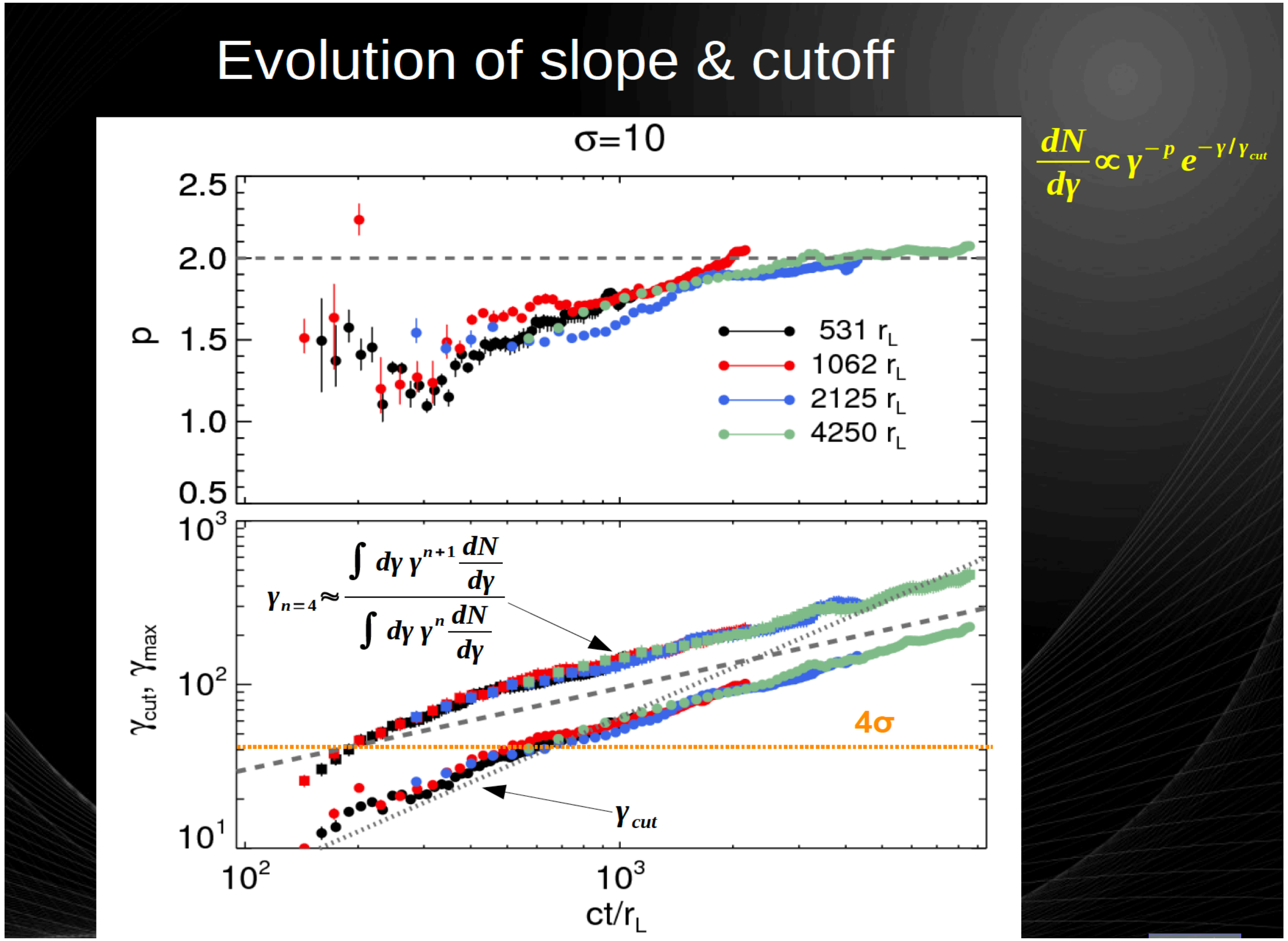
- Cutoff: $\boldsymbol{\gamma_c} = e E_{rec}\, l/m_e c^2 \approx 0.1\, e B_0\, l/m_e c^2 = \mathbf{0.1}\, \boldsymbol{l/\rho_0}$
- Layers are marginally stable to tearing → $\boldsymbol{l \sim 100\, \delta}$
- Layer thickness: $\boldsymbol{\delta} \simeq \rho(\langle\gamma\rangle) = \langle\gamma\rangle\, \rho_0 \simeq \boldsymbol{(\sigma/3)\, \rho_0}$.
- Thus, $\boldsymbol{l/\rho_0 \simeq 100\, \delta/\rho_0 \approx 30\, \sigma}$ => $\boldsymbol{\gamma_c \simeq 3\, \sigma}$.

Further particle acceleration is possible, e.g., in:

- 2nd-stage reconnection in plasmoid mergers (but this occurs with lower σ and smaller *L*).
- slow adiabatic compression inside plasmoids (Petropolou & Sironi ’18)

High-Energy Power-Law Cutoff

Petropoulou & Sironi 2018



Cutoff γ_c in large systems:

- first rises quickly to $\gamma_c \sim 4\sigma$;
- then slows down to $\gamma_c \sim t^{1/2}$, probably due to gradual compression of plasmoid cores + conservation of magnetic moment.
- Still remains below "extreme acceleration".

Radiative Magnetic Recoonnection with ICy Cooling

(Werner, Philippov, & Uzdensky 2019)

2D radiative-PIC sims of rel. reconnection with external inverse-Compton (ICy) radiaction.
Relevant to accreting BH coronae. (σ_h=100, B_{gz}=B_0/4)

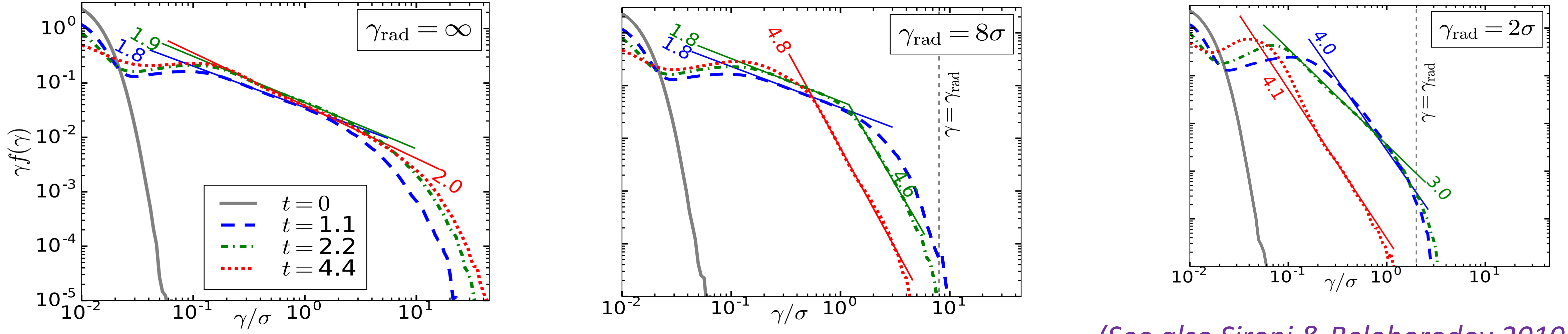
Weak cooling (large γ_{rad}/σ): usual hard power law

Strong cooling (small γ_{rad}/σ): variable steep power law

Intermediate (medium γ_{rad}/σ): both power laws

Inverse-Compton radiaction limit:
(Uzdensky'16)

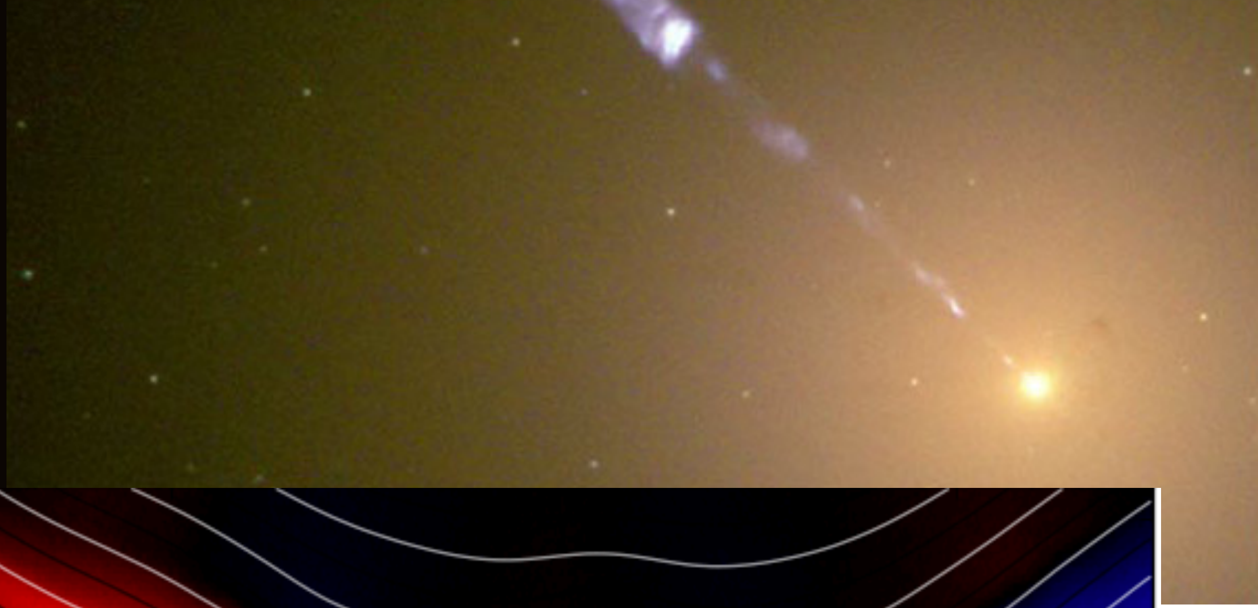
$$\gamma_{\rm rad}^{\rm IC} = \left[\frac{3}{4}\,\frac{eE}{\sigma_T U_{\rm rad}}\right]^{1/2}$$

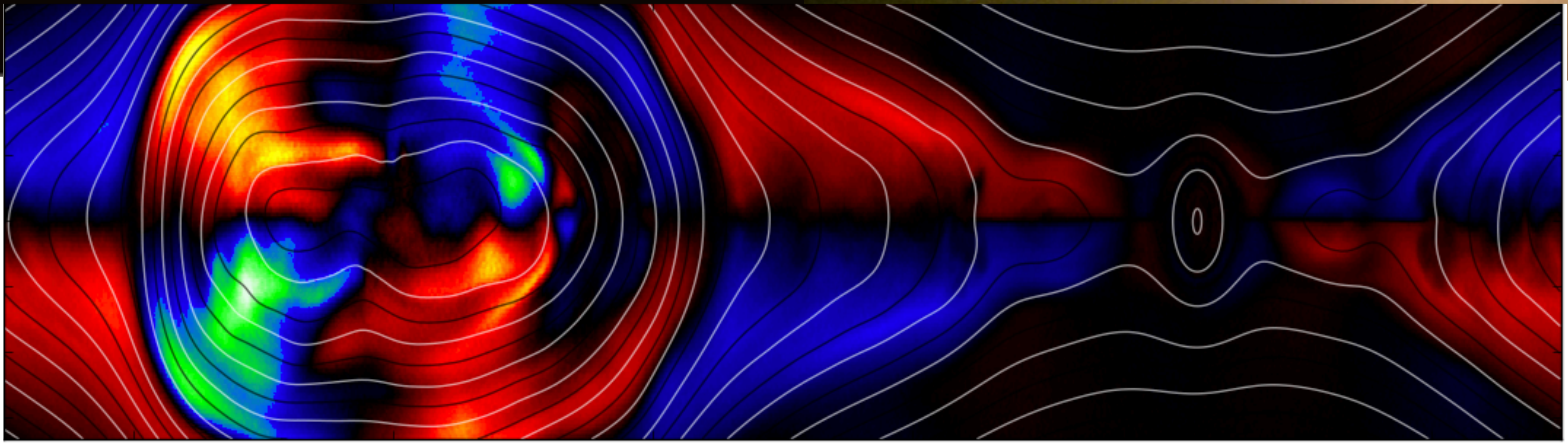


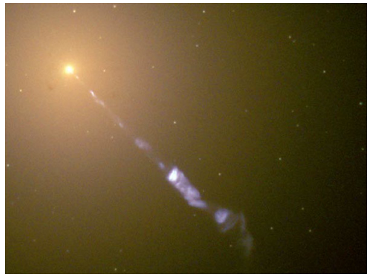
(See also Sironi & Beloborodov 2019)

Also: radiative QED-PIC relativistic reconnection with pair creation
(Schoeffler et al. 2019, Hakobyan et al. 2019)

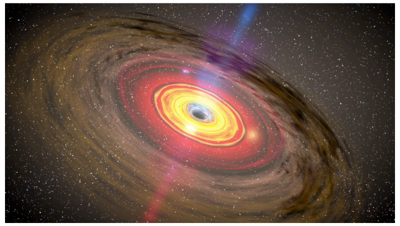
Semi-Relativistic and Relativistic Reconnection in Electron-Ion Plasmas



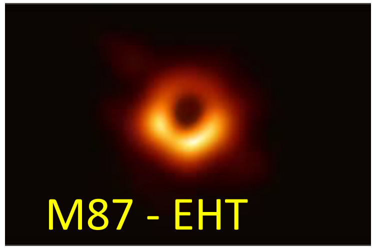




Semi-Relativistic and Relativistic Reconnection in Electron-Ion Plasmas



Werner et al. (arXiv:1612.04493) – MNRAS 473, 4840 (2018)



[Black hole accretion flows, accretion disk coronae, jets]

- PIC studies of ***electron-ion*** relativistic reconnection began only recently

(Werner et al. 2013-2018, Melzani et al. '14, Guo et al. '15, Sironi et al. '15-18).

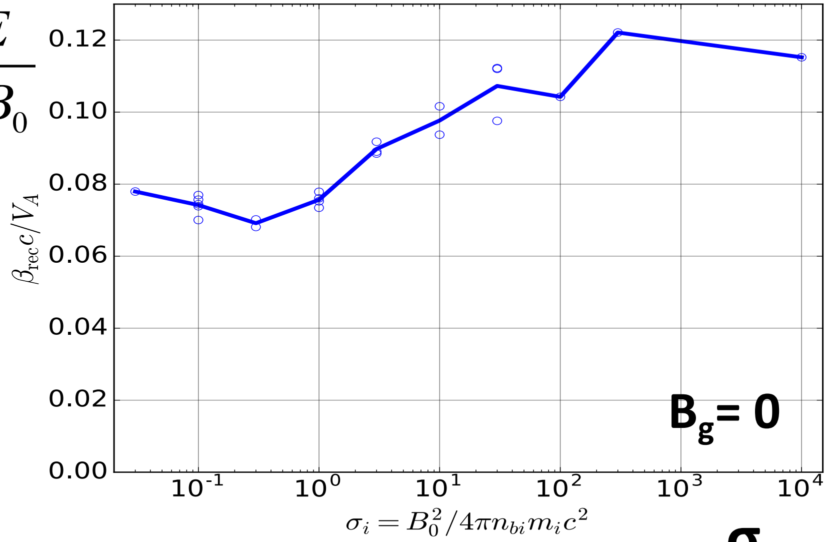
- When both electrons and ions are *ultra-relativistic*, they behave the same → *reconnection is similar to pair-plasma* case.
- ***Semi-relativistic regime***: ultra-relativistic electrons but non-relativistic ions.

Relativistic *e-i* reconnection: Key Results I: Energetics

Werner et al. MNRAS 2018 (arXiv:1612.04493)

Reconnection rate: $v_{in}/c = E/B_0$

$$\frac{cE}{V_A B_0}$$

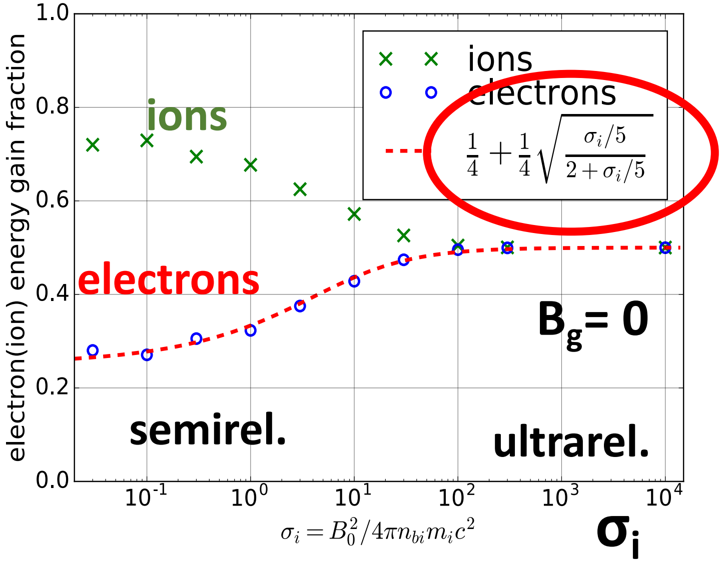


σ_i

$$V_A = c\frac{B_0}{\sqrt{4\pi n_i m_i c^2 + B_0^2}} = c\frac{\sqrt{\sigma_i}}{\sqrt{1+\sigma_i}}$$

Reconnection rate normalized to V_A is the usual 0.1.

Energy partitioning btw electrons and ions



σ_i

In semirelativistic $B_g = 0$ case ions gain 3 times more energy than electrons.

Later extended to include β-dependence by Rowan et al…

Relativistic *e-i* reconnection: Key Results II: NTPA

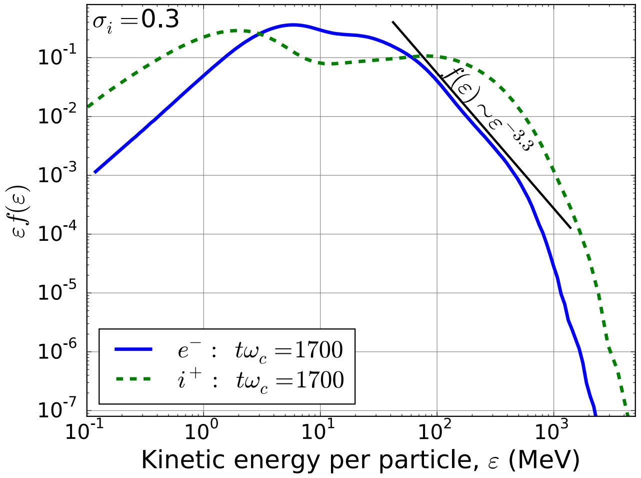
Werner et al. MNRAS 2018 (arXiv:1612.04493)

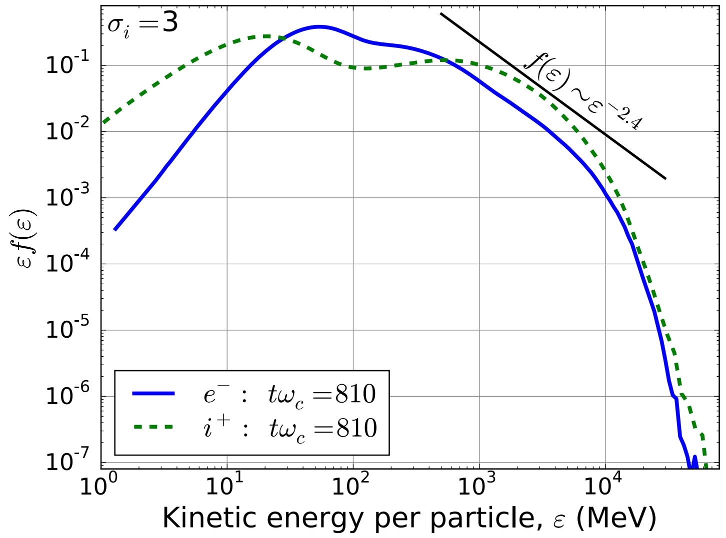
$B_g = 0$

Nonthermal Particle Acceleration:

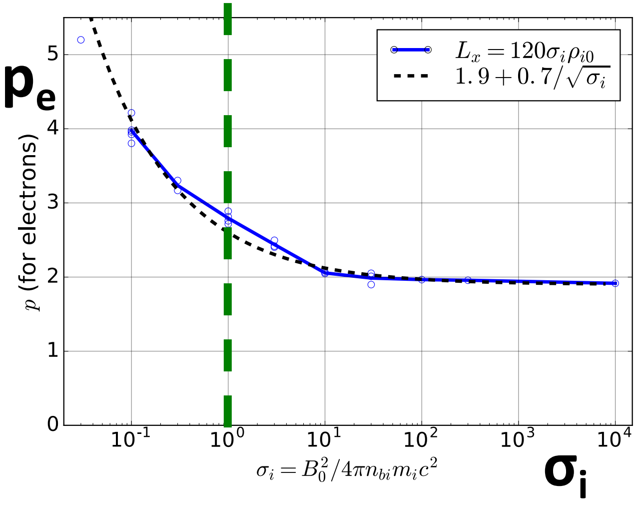
- electrons:

- ions ?





Electron power-law index *p* and cutoff γ_c:

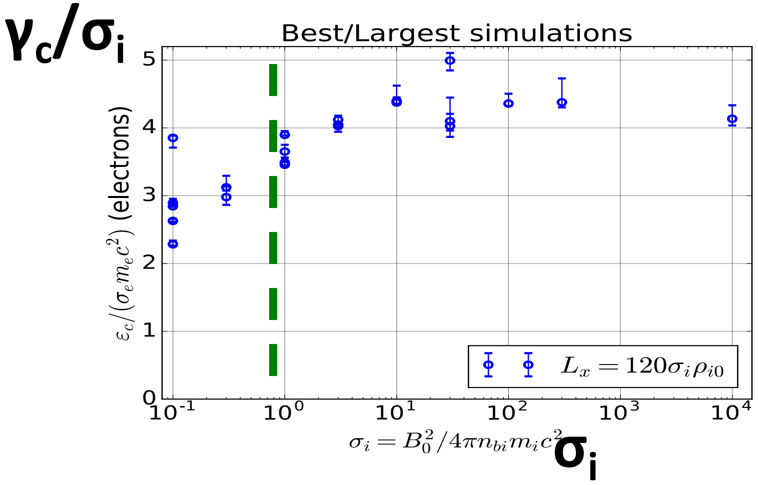


$$\boxed{p_e = 1.9 + 0.7\,\sigma_h^{-1/2}}$$

Werner et al. 2016-2018

Concrete simple prescription that can be used for BH coronae spectral modelling.

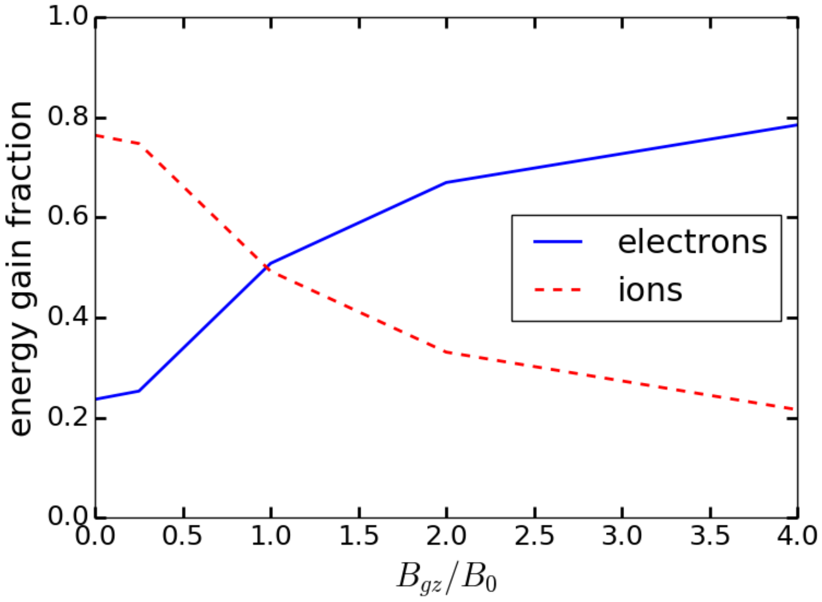
Later extended to include β-dependence by Ball et al'18



Guide Field Effects on Semirelativistic Electro-Ion Reconnection

σ_i = 0.1

Electron-ion energy partition vs. guide field

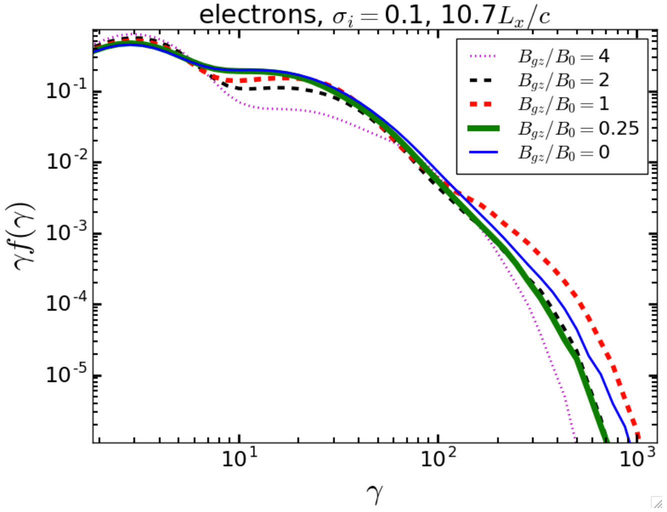


Electron energy fraction rises with B_g.

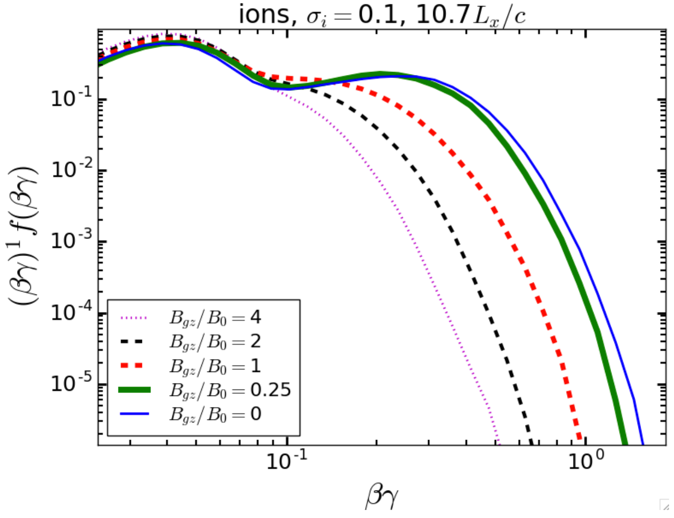
(see also Rowan et al.'19)

Particle spectra

electrons



ions



Electron spectra show modest change until $B_{gz}/B_0>2$. But dependence is not monotonic: $B_{gz}=B_0$ shows stronger acceleration than smaller or larger B_{gz}.

Ion energization is suppressed by B_g.

(see also Dahlin et al for non-relativistic reconnection)

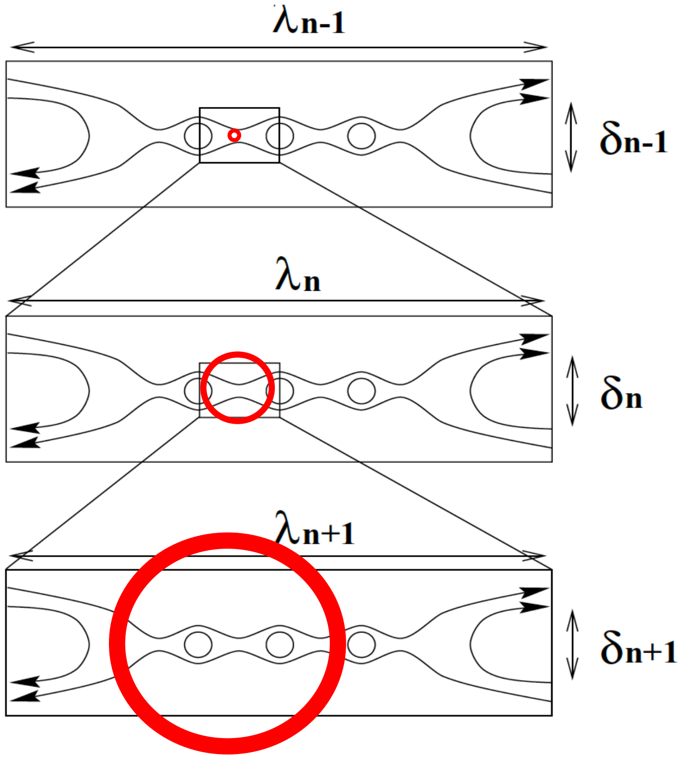
Can we understand the $p_e = 1.9 + 0.7\sigma_h^{-1/2}$ scaling ?

2D self-similar hierarchical plasmoid chain

Large system, plasmoid-mediated reconnection: hierarchical plasmoid chain.

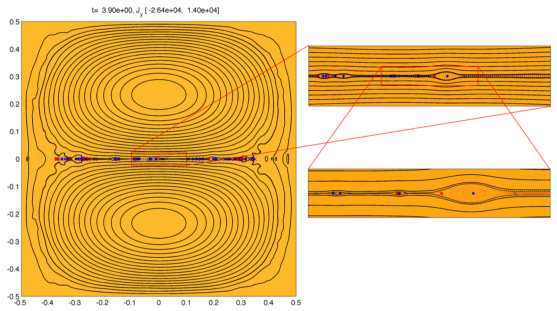
(Shibata & Tanuma '01, Bhattacharjee et al. 2009, Uzdensky et al. 2010, Loureiro et al. 2012)

Shibata & Tanuma 2001



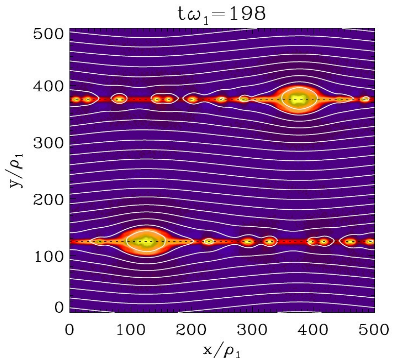
Larmor circle of a given particle

This picture applies to various plasma regimes:



Resistive MHD:

e.g., Bhattacharjee et al. '09 Loureiro et al. '12, etc.



Relativistic collisionless pair plasma (PIC):

e.g., Cerutti et al. '13, Sironi & Spitkovsky'14, Guo et al. '14, Werner '16-17, Sironi et al. '16

Self-similar chain: looks the same on each scale!

Basic Picture *Uzdensky, in prep. (2019)*

- Focus on *energetic relativistic* particles:

Energy $\varepsilon=\gamma\, m_e c^2$ with $\gamma \gg \langle\gamma\rangle$;

Typical Larmor radius: $\boldsymbol{\rho}_L = \gamma\, m_e c^2/eB_0 = \gamma\, \rho_0$ **($\rho_0 = m_e c^2/e\, B_0$)**

$\gamma \gg \langle\gamma\rangle \rightarrow \boldsymbol{\rho}_L(\gamma) > \boldsymbol{\delta}$ (but still $\ll L$)

- Such particles are ***blind*** to EM structures (e.g., small plasmoids) of size w << $\boldsymbol{\rho}_L(\gamma)$.

- Primary acceleration of unmagnetized particles by main reconnection electric field $E_{rec} \simeq \varepsilon V_A B_0/c = \varepsilon\, \beta_A B_0$ (ε~0.1).

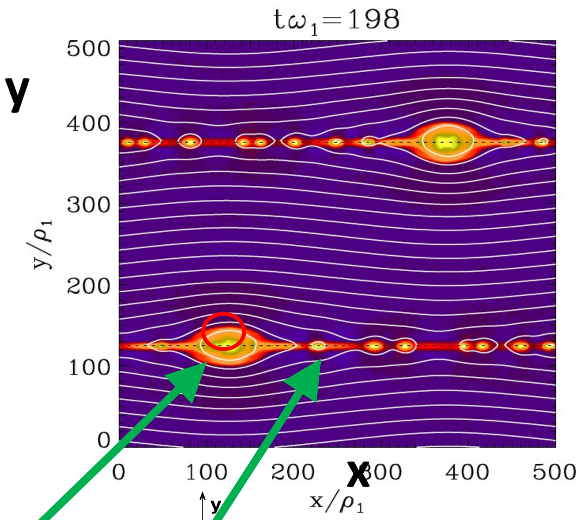
- This rapid regular acceleration stops when particle gets magnetized by ***reconnected*** magnetic field B_y.

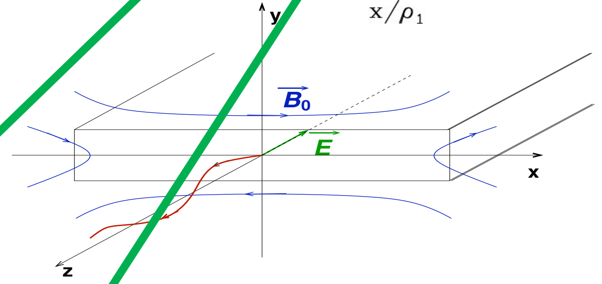
- ***On any scale***, B_y is ***bimodal***:

  $B_y \sim B_1 \sim \varepsilon\, B_0 \sim 0.1\, B_0$ in inter-plasmoid current layers;

  $B_y \sim B_0$ in circularized plasmoids.

We will treat magnetization in B_1 and trapping in plasmoids separately.





Kinetic Equation

Uzdensky, in prep. (2019)

$$\partial_t f(\gamma,t) = -\partial_\gamma(\dot\gamma_{\rm acc} f) - \frac{f(\gamma)}{\tau_{\rm magn}(\gamma)} - \frac{f(\gamma)}{\tau_{\rm tr}(\gamma)}$$

3 Main Ingredients:

- Acceleration by reconnection electric field:
  $\dot\gamma_{\rm acc} = eE_{\rm rec}c/m_e c^2 = \epsilon\beta_A\Omega_0$ -- independent of γ !
- Magnetization by reconnected B_1-field (→ power-law).
- Trapping by large [$w > \rho_L(\gamma)$] plasmoids (→ cutoff):
  controlled by plasmoid distribution.

$$V_A = c\beta_A = c\frac{\sqrt{\sigma_h}}{\sqrt{1+\sigma_h}}$$

- Relativistic limit: $\boldsymbol{\sigma}_h \gg 1$ → $V_A \simeq c$
- Non-rel. limit: $\boldsymbol{\sigma}_h \ll 1$ →

$\beta_A = V_A/c \simeq \boldsymbol{\sigma}_h^{1/2} \ll 1.$

Thus, reconnection may or may not be relativistic, but particles are relativistic.

Steady-State Kinetic Equation:

- Since $\dot\gamma_{\rm acc} = eE_{\rm rec}c/m_e c^2 = \epsilon\beta_A\Omega_0$ is independent of γ:

$$\dot\gamma_{\rm acc}\frac{{\rm d}f}{{\rm d}\gamma} = -\frac{f(\gamma)}{\tau(\gamma)}$$

- Integrate: $$f(\gamma) = C\,\exp\left(-\frac{1}{\dot\gamma_{\rm acc}}\int\frac{{\rm d}\gamma}{\tau(\gamma)}\right)$$

where τ is escape time from acceleration zone: $$\frac{1}{\tau(\gamma)} = \frac{1}{\tau_{\rm magn}(\gamma)} + \frac{1}{\tau_{\rm trap}(\gamma)}$$

Magnetization by Reconnected Field

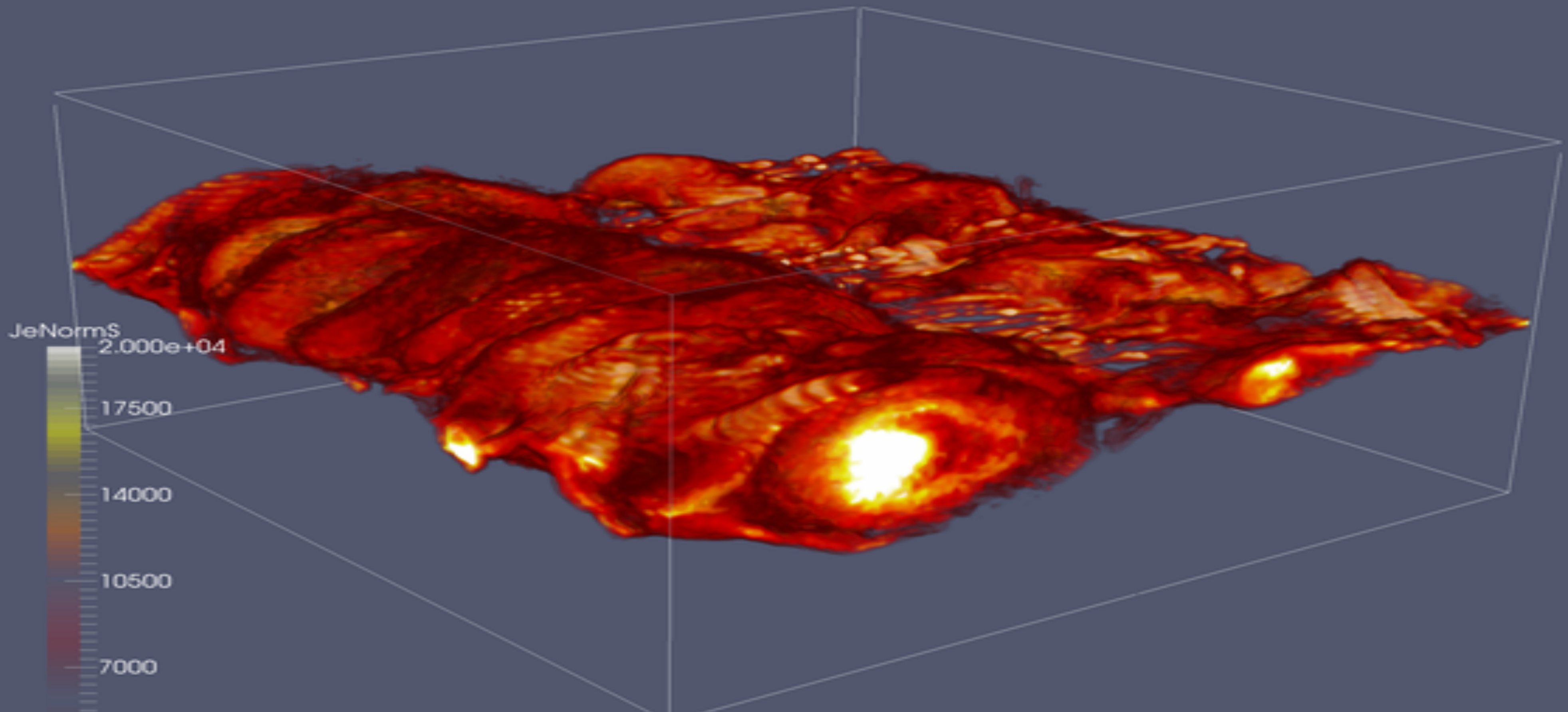
- Energetic particle passes right through small plasmoids.
- Distance a particle travels before it is magnetized by $B_1 = \varepsilon B_0$:

  $l_{mag}(\gamma) \sim \rho_L(\gamma, B_1) = (B_0/B_1)\, \rho_L\, (\gamma, B_0) = \varepsilon^{-1}\, \rho_0\, \gamma$
- Magnetization time-scale: $\tau_{\rm mag}(\gamma) \sim \ell_{\rm mag}/c \sim \epsilon^{-1}\gamma\Omega_0^{-1}$
- $\boldsymbol{\tau}_{mag} \sim \gamma \Rightarrow$ balance of magnetization and acceleration by E_{rec}: $\dot{\gamma}_{\rm acc} = eE_{\rm rec}c/m_e c^2 = \epsilon\beta_A\Omega_0$

gives a power-law solution: $f(\gamma) \sim \gamma^{-p}$

- **power-law index:** $$\boxed{p = p(\sigma_h) \sim \frac{1}{\beta_A} = \sqrt{\frac{1+\sigma_h}{\sigma_h}}}$$
  - ultra-rel. ($\sigma_h \gg 1$): $p \longrightarrow \text{const} \simeq 1$ (cf. Zenitani & Hoshino 2001)
  - non-rel. case ($\sigma_h \ll 1$): $p \sim \sigma_h^{-1/2}$ (c.f., Werner et al. 2018)

3D Pair-Plasma Reconnection



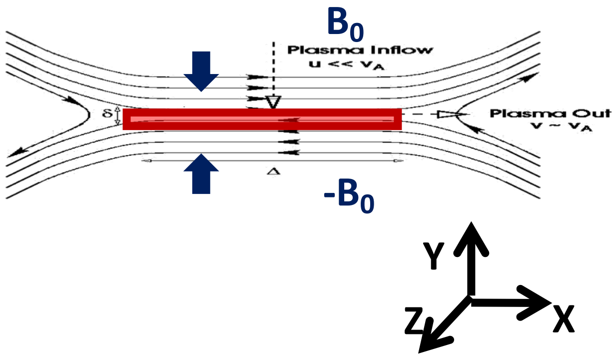
1) Ultra-relativistic (Werner & Uzdensky 2017)

2) Trans-relativistic (Werner & Uzdensky 2019, in prep)

Relativistic Pair Plasma Reconnection in 3D

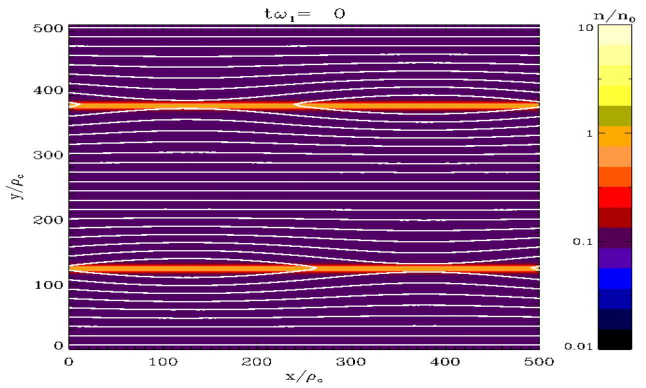
- Most PIC reconnection sims are 2D, but real world is **3D**.

Should we be concerned?

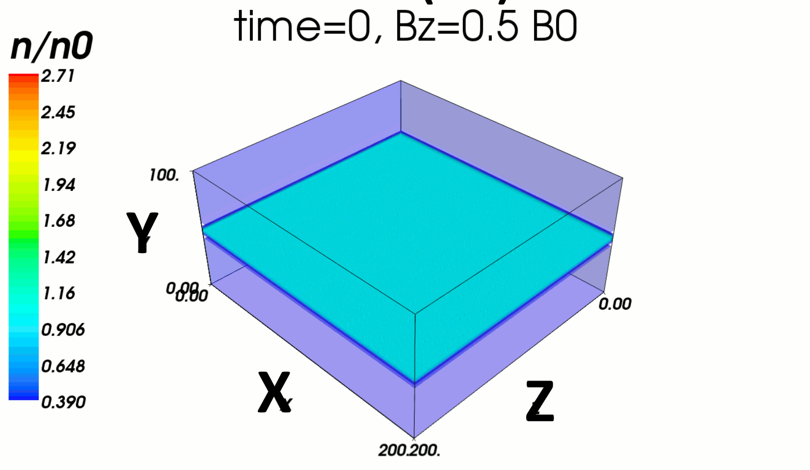


- Reason for concern (Zenitani & Hoshino, 2007-2008):
  Relativistic Drift-Kink Instability (RDKI):
  - develops rapidly along the layer in ignorable *z*-direction, absent in 2D;
  - corrugates the layer and dramatically changes its structure;
  - suppressed by a strong guide magnetic field B_z.

tearing (2D)



kink (3D)



Reconnecting current sheets in large systems (L > 50-100 ρ_L) are unstable to **secondary instabilities** (tearing and kink); reconnection is highly dynamic.

3D Ultra-Relativistic Pair Plasma Reconnection

(Werner & Uzdensky ApJ Lett., 2017)

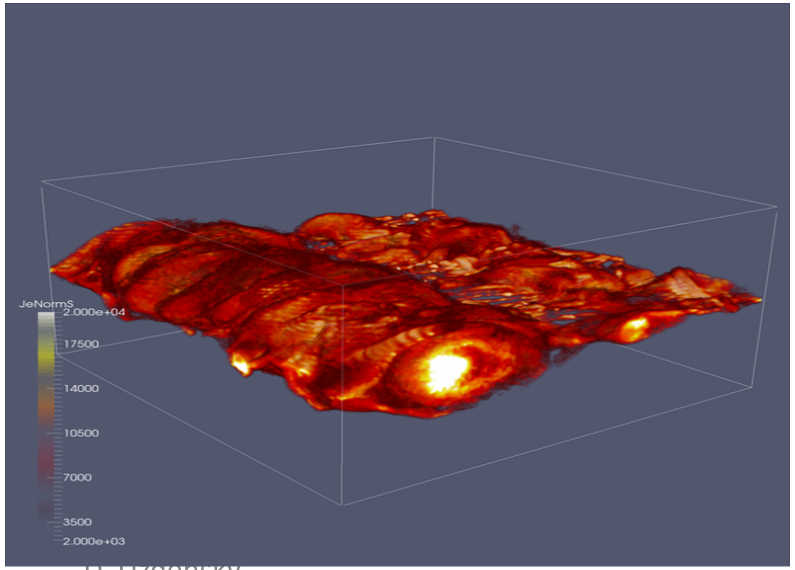
Direct 2D/3D comparison for **ultra-relativistic** pair reconnection, varying:

- Layer's aspect ratio L_z/L_x – proxy for 3D;
- Guide magnetic field B_{gz}/B_0.

$T_b >> m_e c^2$

$\sigma_h = B_0^2/(4\pi\, n\, \theta_e mc^2) = 25$

Modest size: L_x up to 64 $\sigma\rho_0$.

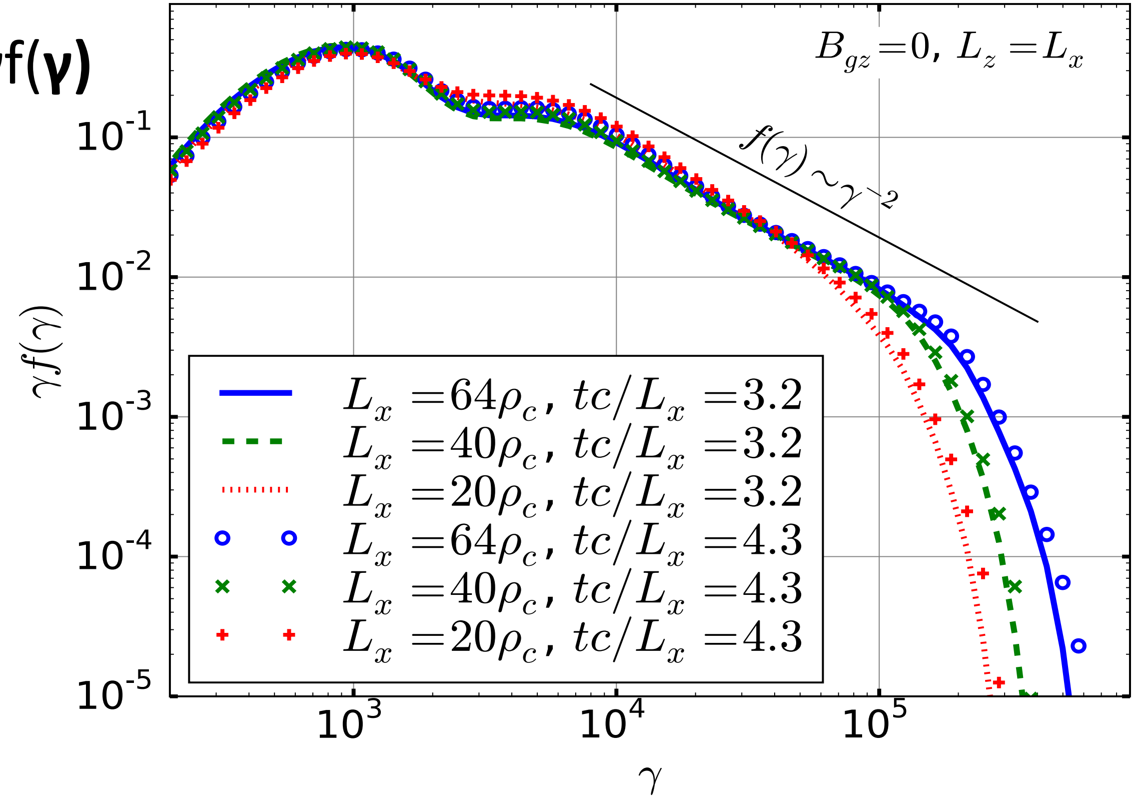


Ultra-Relativistic Pair Plasma Reconnection in 3D

(Werner & Uzdensky 2017)

Particle spectra for different L_x: box-size dependence

γf(γ)



$B_z = 0$

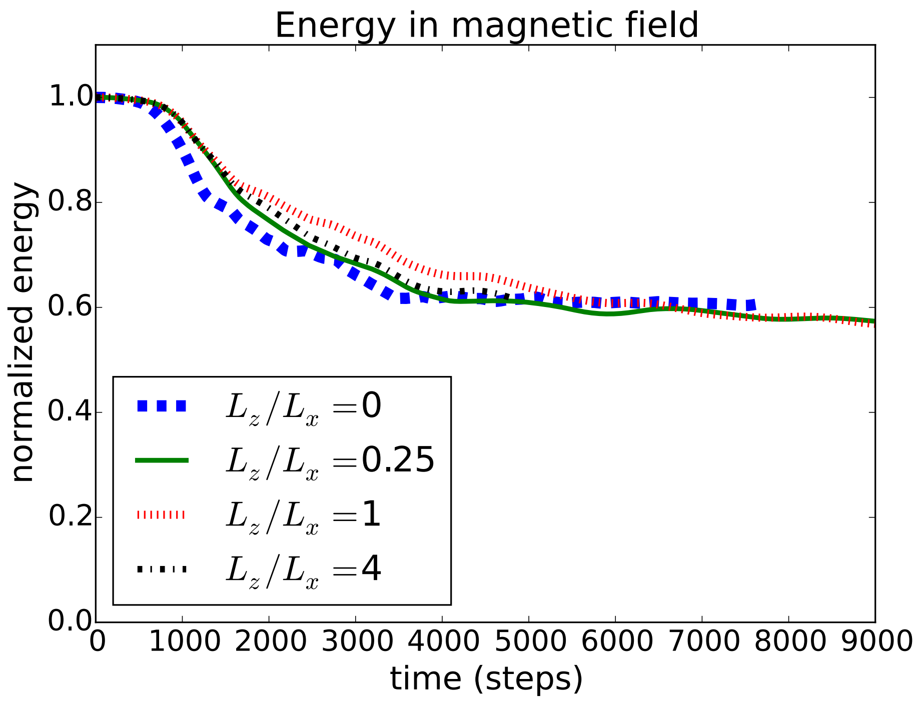
$L_z/L_x = 1$

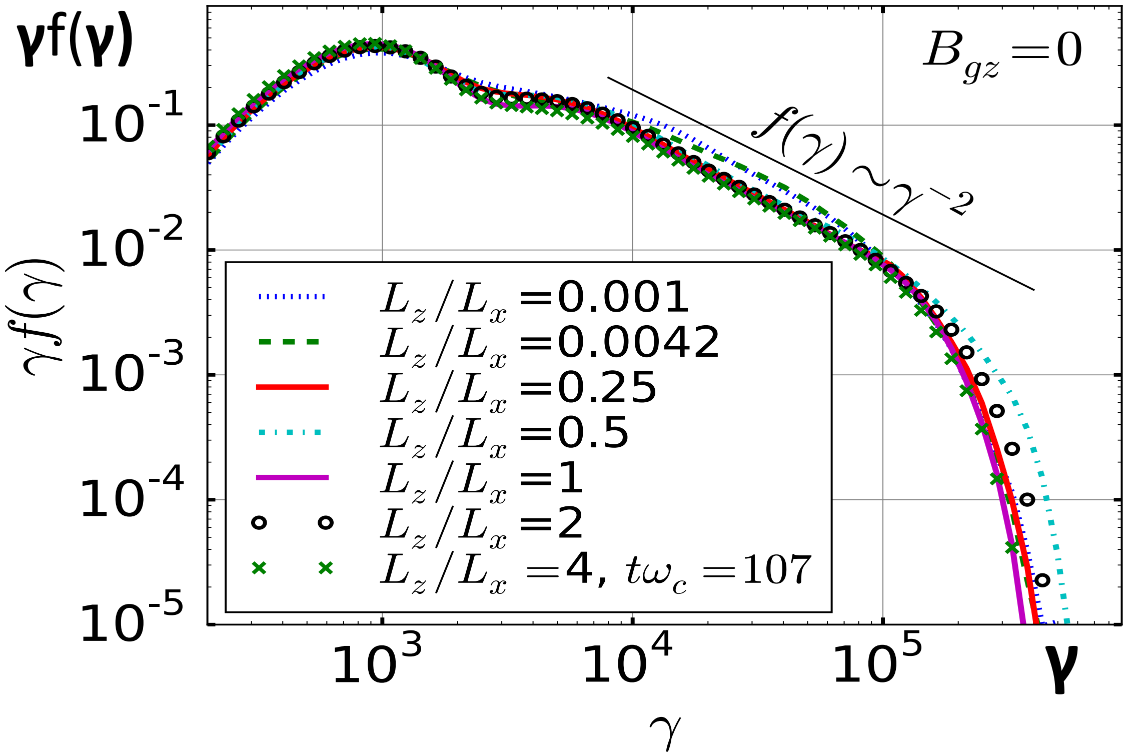
Conclusion: **Power-law index converges with L_x**

Ultra-Relativistic Pair Plasma Reconnection in 3D

Particle spectra for different L_z/L_x: no guide field

$B_z = 0$

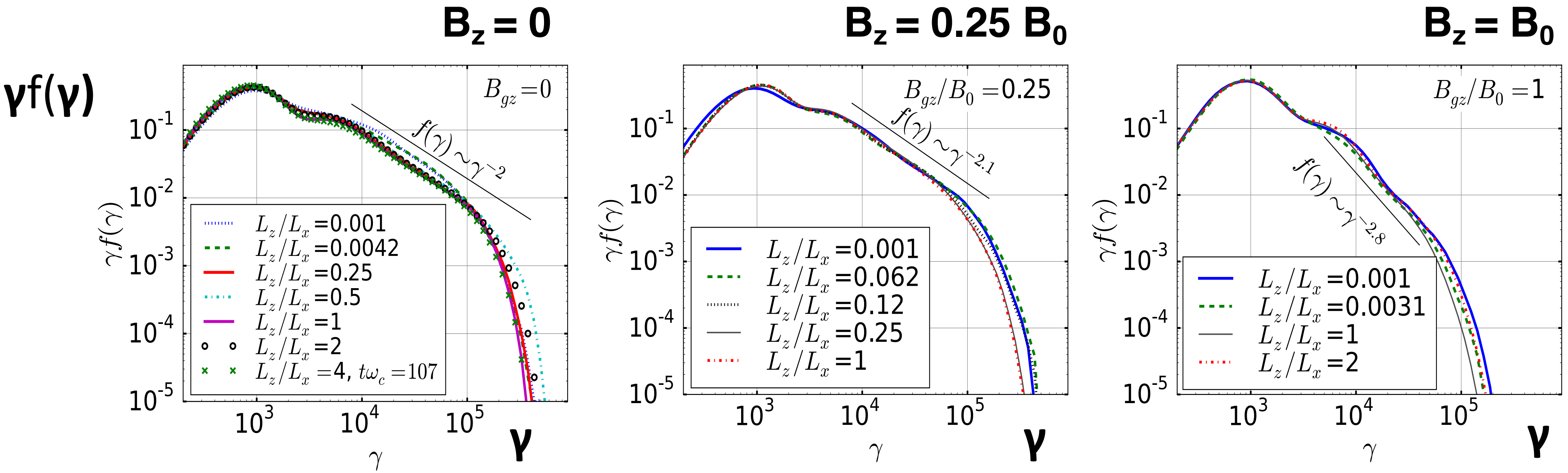




Conclusion: **Energetics and NTPA in 2D and 3D are similar in ultra-relativistic pair reconnection.**

Ultra-Relativistic Pair Plasma Reconnection in 3D

Does this conclusion depend on guide field?

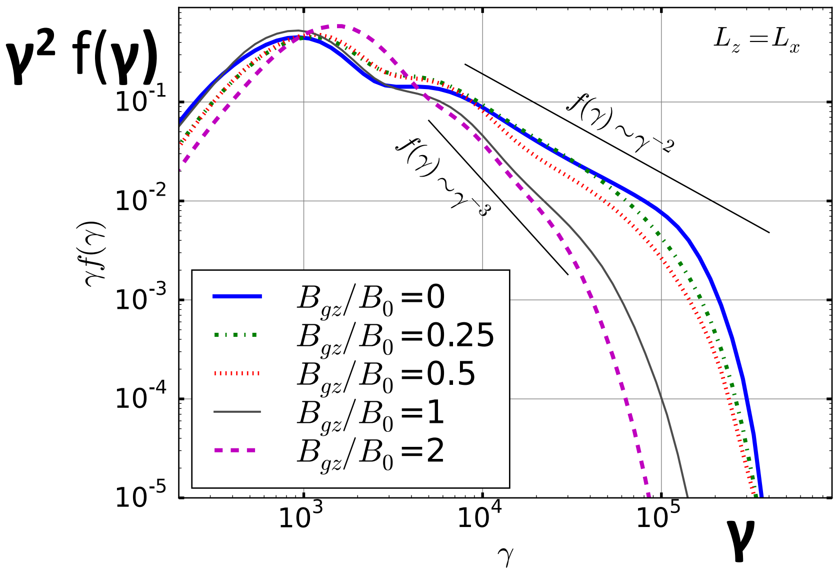


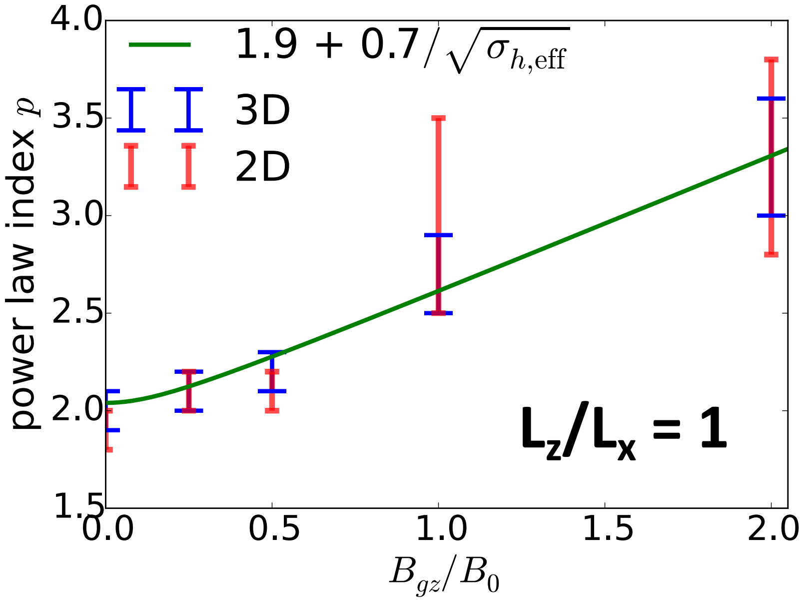
Conclusion: **Nonthermal particle acceleration in relativistic pair-plasma reconnection is similar in 2D and 3D for any given guide field.**

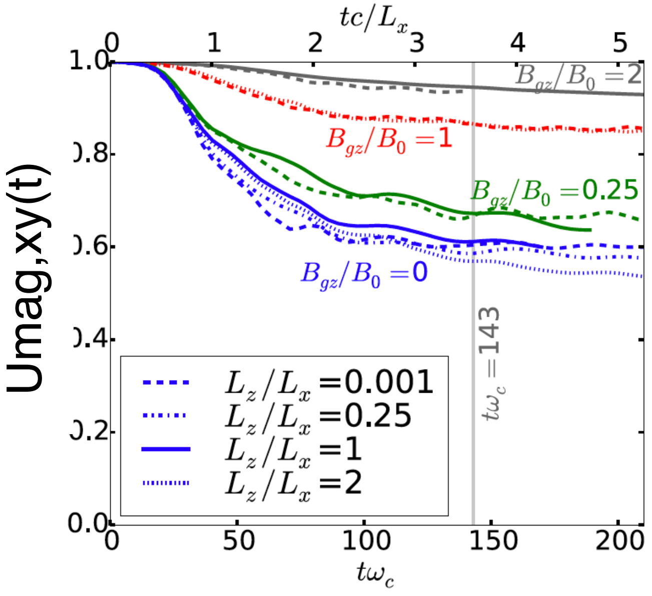
Implication: 2D simulations are sufficient, adequate for studies of NTPA in relativistic pair reconnection. (?)

Ultra-Relativistic Pair Plasma Reconnection in 3D

Particle spectra for varying B_{gz}/B_0:







<u>Conclusion:</u> Strong guide field B_{gz} slows down reconnection, reduces dissipated energy budget, inhibits NTPA, resists compression.

<u>Proposal:</u> Guide magnetic field's enthalpy, $B_{gz}^2/4\pi$, modifies appropriate σ_h:

$$\sigma_{h,\mathrm{eff}} = B_0^2/(B_{gz}^2 + 4\pi\, h)$$

3D Reconnection in Transrelativistic Pair Plasma

(Werner & Uzdensky 2019, in prep.)

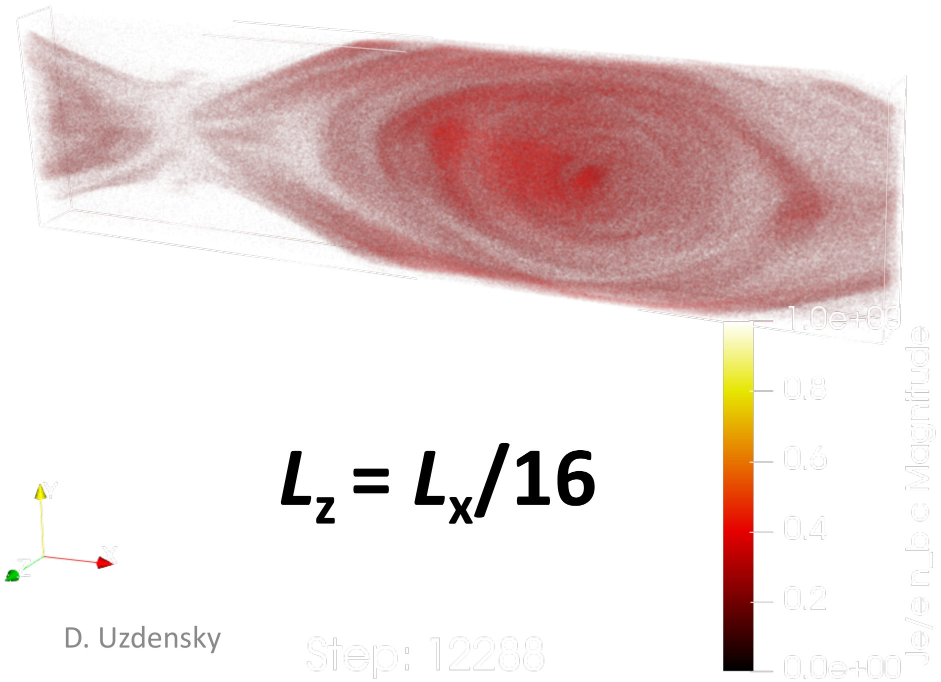
- $\sigma = B^2/(4\pi\,(2n_e)\,m_e\,c^2) = 10^4$
- $\sigma_h = \sigma/(2\,\theta_b)$
- $B_{gz} = 0$ (unless otherwise noted)

$\sigma_h = 1$

WORK IN PROGRESS!!

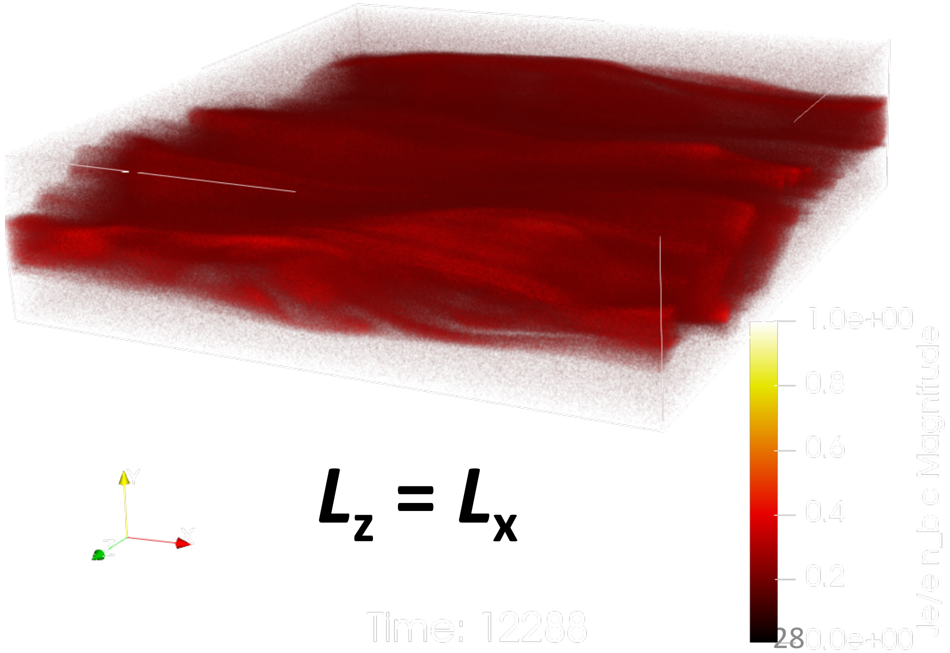
Motivation: easiest case, allows exploring most fundamental aspects for largest system sizes!

(Quasi-) 2D



$L_z = L_x/16$

3D



$L_z = L_x$

Moderate σ_h=1: nearly 2D vs. 3D

(Werner & Uzdensky 2019, in prep.)

Electron current density

(Quasi-) 2D $L_z = L_x/16$

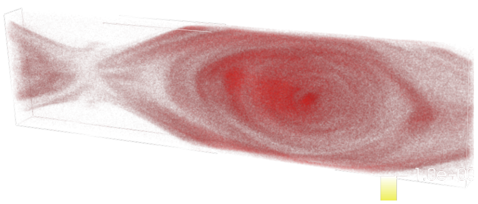
3D $L_z = L_x$

2D/3D: energetics evolution during main reconnection phase

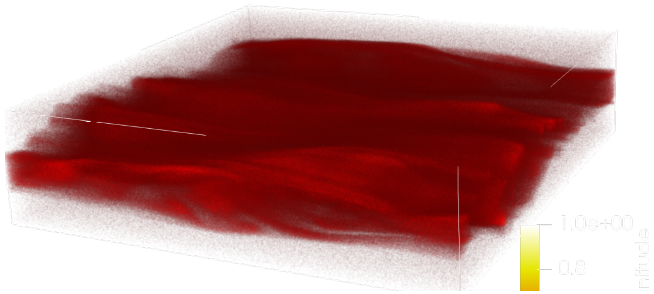
$B_z = 0$

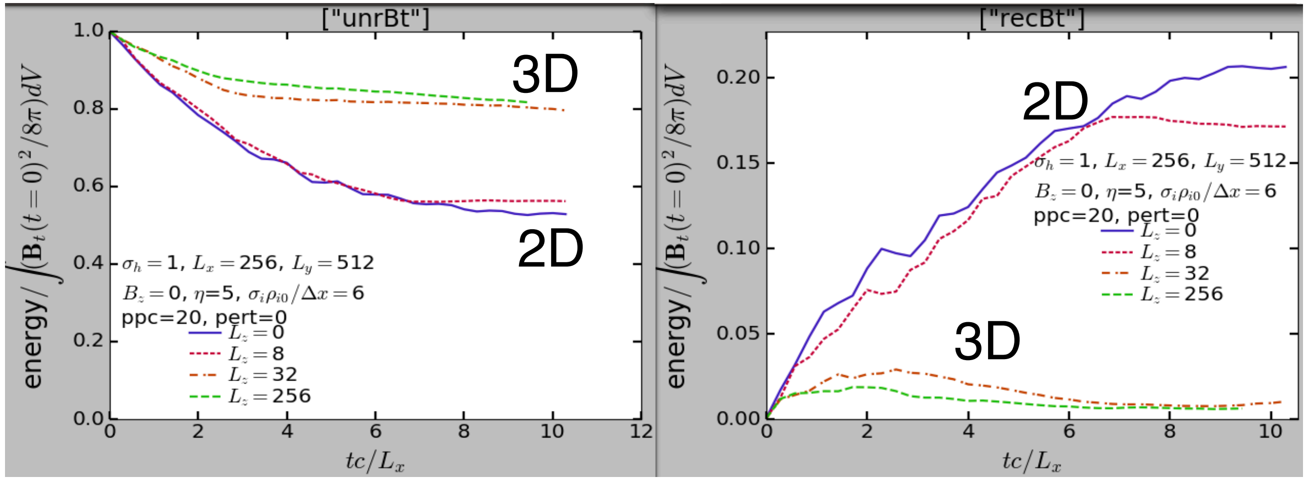
σ_h=1

(Quasi-) 2D



3D



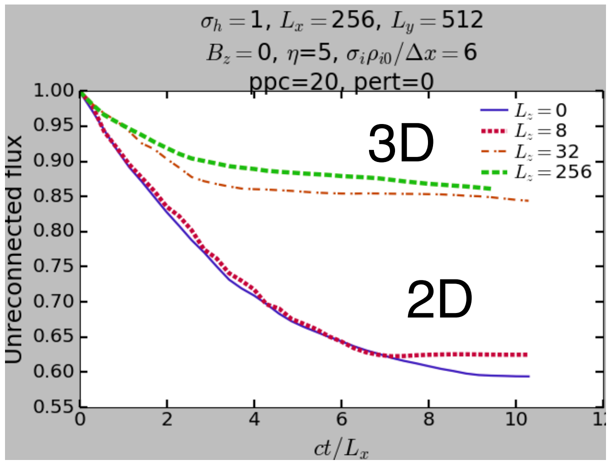


"unrBt" is transverse (Bx-By) magnetic energy in unreconnected region.
"recBt" is total transverse magnetic energy minus "unrBt"

Key findings: main reconnection phase:

- Reconnection layer morphology and energy dissipation are very different in 2D and 3D.
- Reconnection is slower in 3D;
- 2D: substantial magnetic energy remains in reconnected regions (in plasmoids);
- 3D: reconnected regions are much less magnetized! Almost all upstream energy goes to plasma.

Unreconnected magnetic flux



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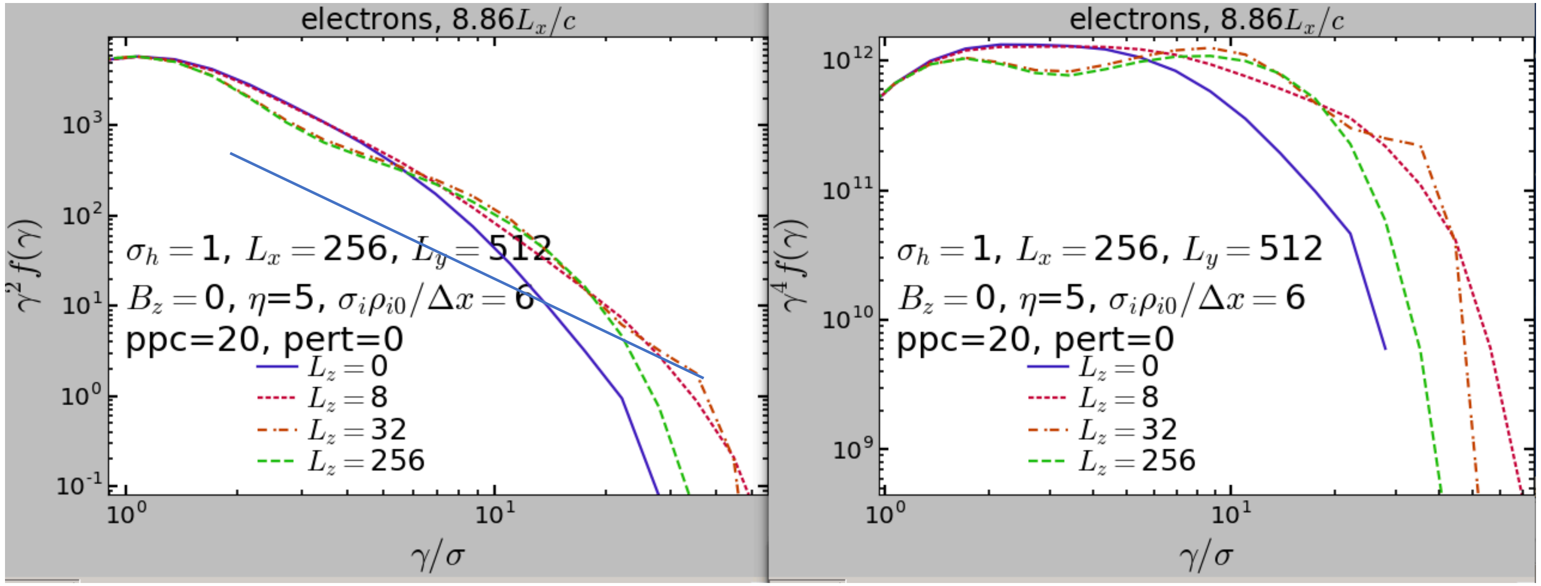
2D/3D: NTPA during main reconnection phase

$B_z = 0$
σ_h=1

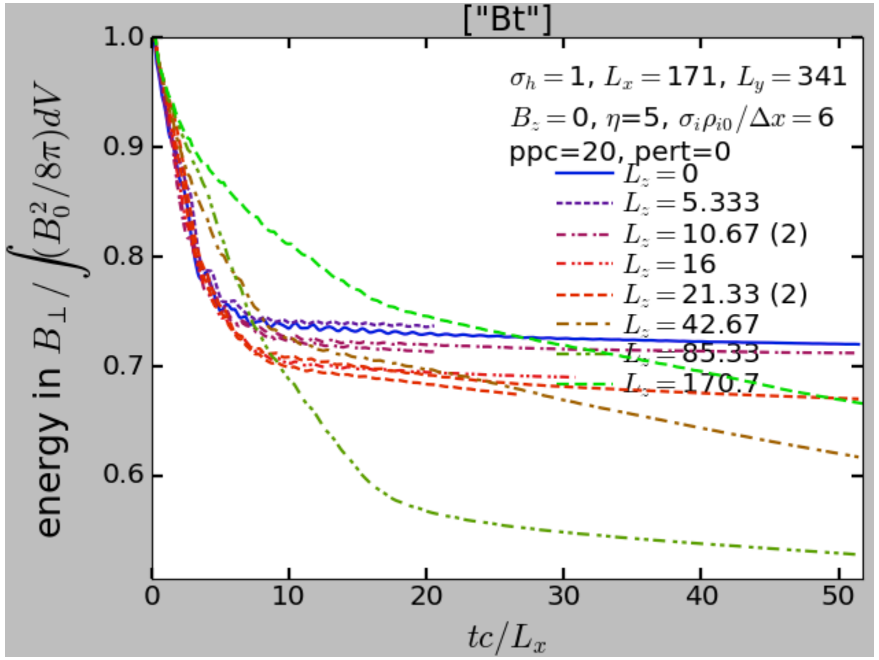
L_x= 512 σ ρ_0

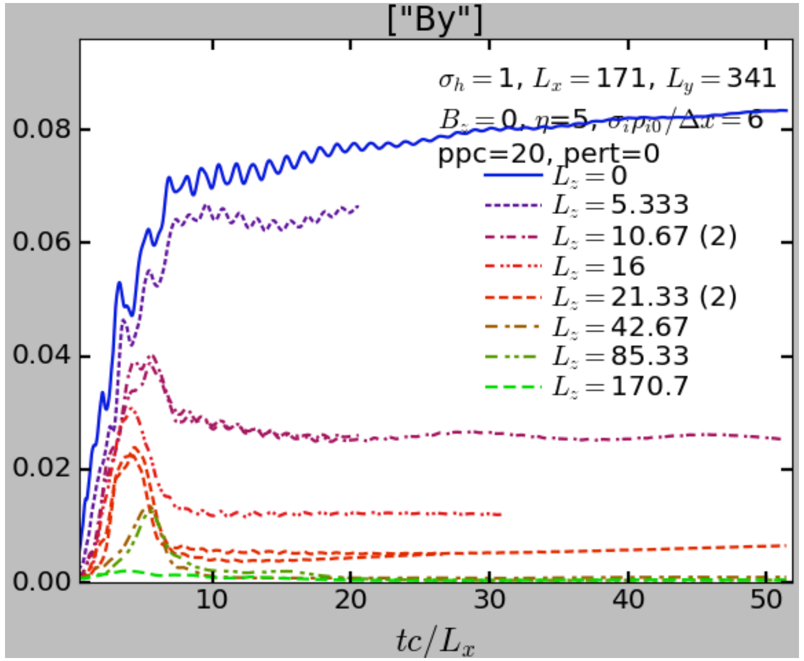
Particle spectra for different L_z/L_x:



- **Nonthermal spectra in trans-relativistic (σ_h=1) pair-plasma reconnection similar in 2D and 3D**
- **NTPA is somewhat enhanced in 3D due to escape of particles from reconnected regions (plasmoids) enabling further acceleration.** *(c.f., Dahlin et al., Guo, Li et al., for non-rel. case)*

3D Long-Term Evolution (50 Lx/c):
Energy vs time vs Lz





B_y represents magnetic energy (reconnected flux) trapped in plasmoids.

SUMMARY

- Relativistic magnetic reconnection is a ***powerful particle accelerator***!
- Reconnection-driven NTPA is ***amenable to PIC simulation*** studies.
- Significant and rapid ***progress on 2D relativistic reconnection*** in recent years, across a wide range of regimes.
- Reconnection in ***3D is the current frontier***: more challenging numerically and difficult to analyze, but progress is now being made.