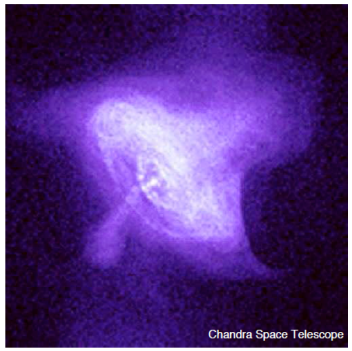
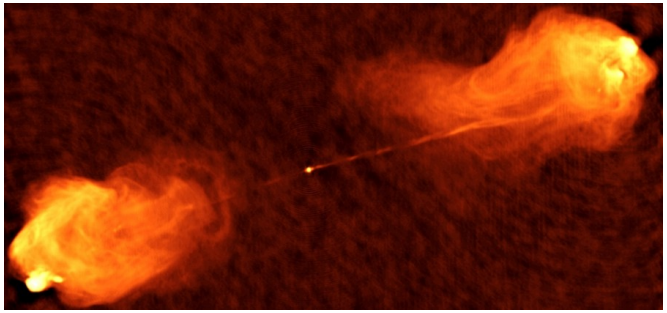
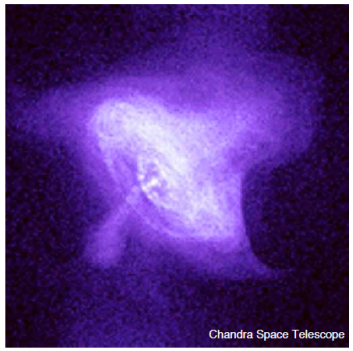






Nonthermal Particle Acceleration in Magnetic Reconnection in Collisionless Relativistic Plasmas

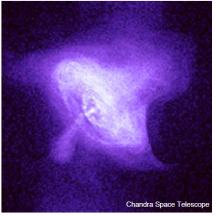
Dmitri Uzdensky

(University of Colorado Boulder)

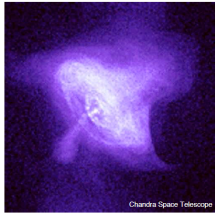
In collaboration with (aka work actually done by) (all Univ. Colorado):

- **Greg Werner**
- Vladimir Zhdankin
- Mitch Begelman

Vienna, WPI, July 27, 2017



OUTLINE



Numerical (PIC) Studies of Nonthermal Particle Acceleration in Kinetic Relativistic Plasma Processes:

- ***magnetic reconnection:***
  - ***pair plasma (2D and 3D)***
  - ***electron-ion plasma (2D)***
- ***kinetic turbulence:***
  - ***pair plasma (3D)***

Our 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.

(This talk will focus on non-radiative simulation results)

Overview of our group's recent (2014-2017) Particle-in-Cell (PIC) Kinetic Simulations Studies of Relativistic Magnetic Reconnection and Turbulence

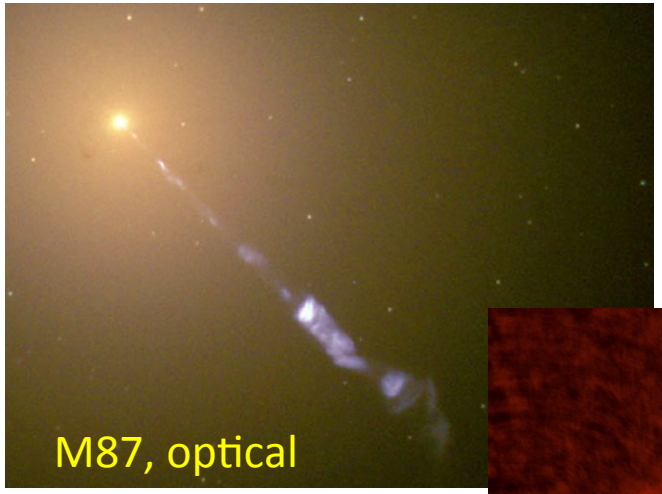
2D and 3D numerical kinetic studies of relativistic ***reconnection*** (lead by Greg **Werner**) and ***turbulence*** (lead by Vladimir **Zhdankin**) done with two relativistic Particle-in-Cell (PIC) codes:

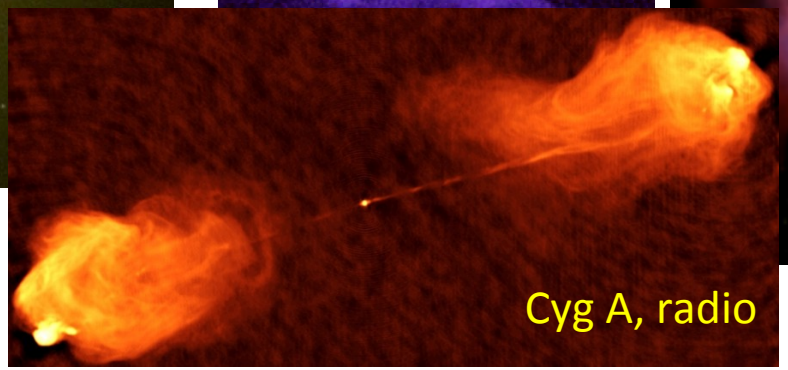
- **VORPAL/VSim** (non-radiative; radiation via post-processing);
- **ZELTRON** (**radiative PIC**):
- developed at Univ. Colorado by **Benoit Cerutti and Greg Werner**

(with additional development by K. Nalewajko and V. Zhdankin);

- includes synchrotron and inverse-Compton **radiation reaction force**;
- self-consistently computes produced radiation spectra, light-curves, etc.;
- used by us in previous years (Cerutti et al. 2013-2014) to study relativistic pair-plasma reconnection with synchrotron cooling for Crab γ-ray flares.
- publicly available.

Dissipation and emission in astrophysical plasmas





- Many astrophysical flows shine.
- Often, radiative cooling time is << travel time from central source → *in-situ dissipation and particle acceleration!*
- Popular nonthermal acceleration collisionless processes: **magnetic reconnection**, shocks, and **turbulence**.

Dissipation Mechanisms

AVAILABLE FREE ENERGY

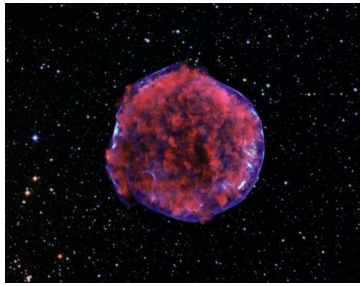
Bulk Kinetic

Magnetic (Poynting flux)

Magnetic reconnection

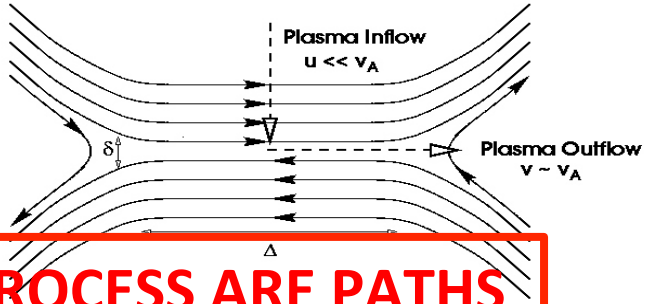
- longitudinal:

shocks



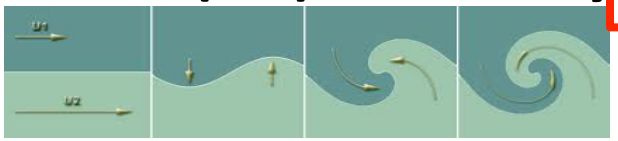
STRUCTURE

current sheets:



- transverse:

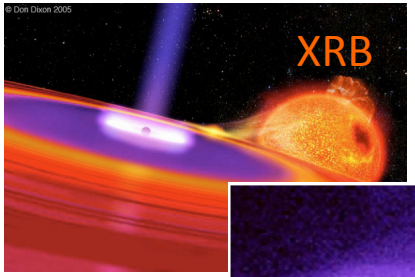
shear (KH) instability

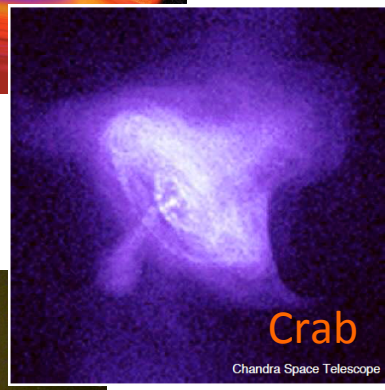


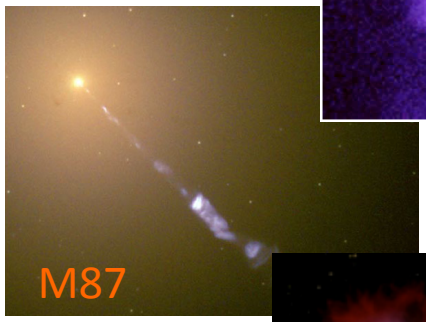
MANY OF THESE PROCESS ARE PATHS TO DEVELOPING TURBULENCE!!

Reconnection in High-Energy Astrophysics

- Accreting black holes in XRBs and AGN
- Pulsar magnetospheres, winds, PWNe
- AGN (e.g., blazar) jets, radio-lobes
- Gamma-Ray Bursts (GRBs)
- Magnetar (SGR) flares

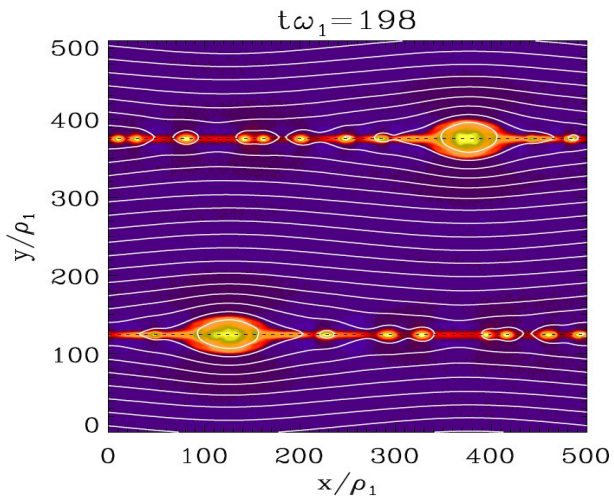


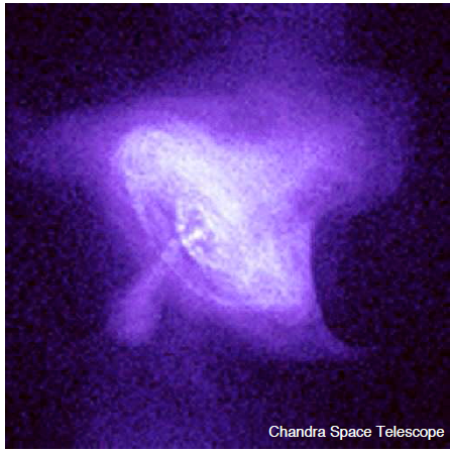




Relativistic Collisionless Magnetic Reconnection and Nonthermal Particle Acceleration:

1. Pair (e^+e^-) Plasmas





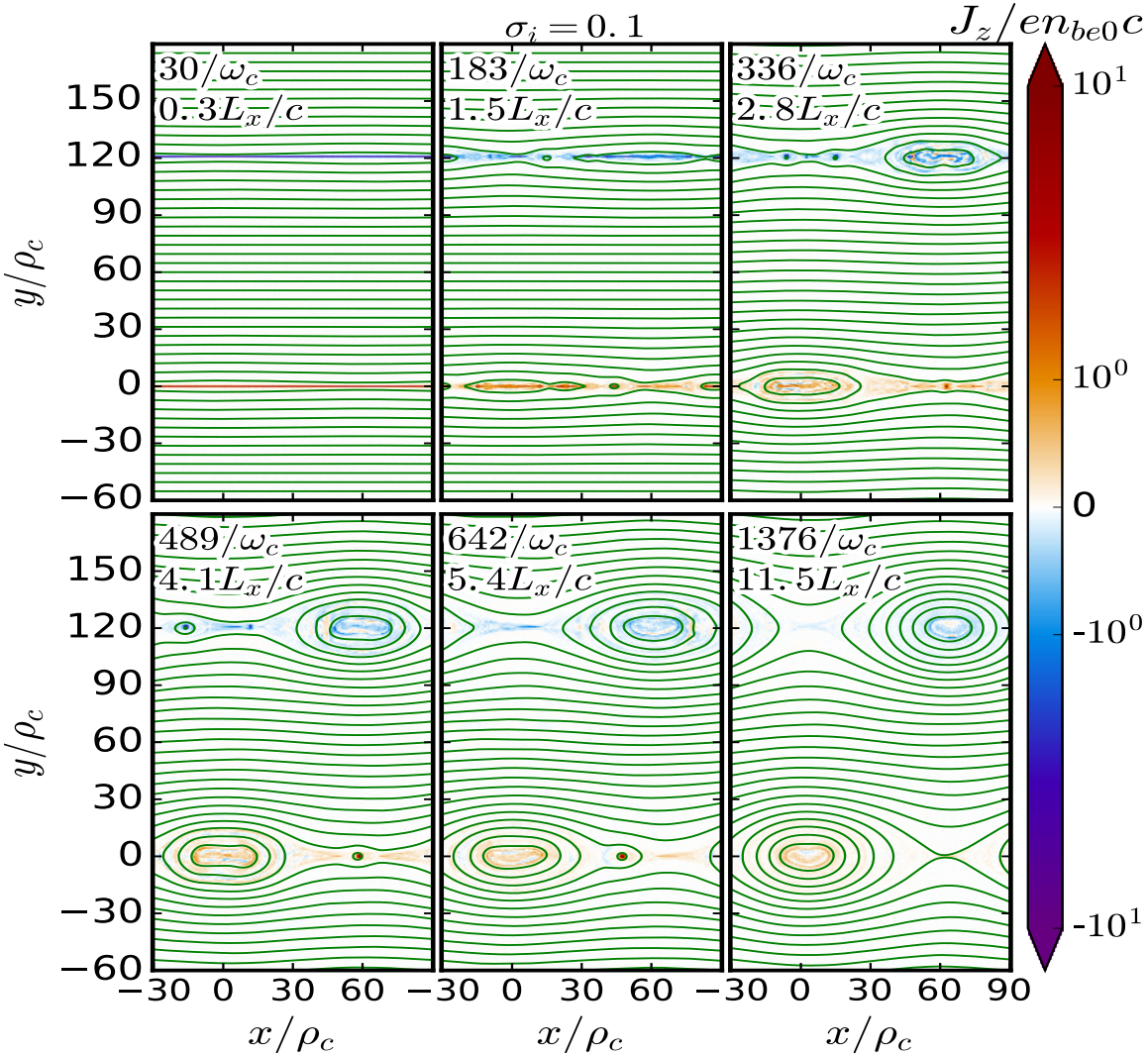
Why pair plasmas?

1) actually exist in Nature, astrophysically relevant: pulsar magnetospheres, pulsar wind nebulae (PWN);
2) conceptually and technically simpler.

2D: *Werner et al.:* arXiv:1409.8262*; ApJ Lett.* 816, L8, *2016*

3D: *Werner & Uzdensky:* arXiv:1705.05507*; ApJ Lett.* (*2017)*

Evolution of magnetic field and current density in our 2D double-periodic PIC reconnection simulations



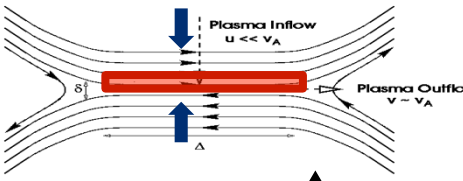
Collisionless Relativistic Pair Reconnection: General reconnection dynamics

Tool of choice: **Particle-in-Cell (PIC) kinetic simulations**

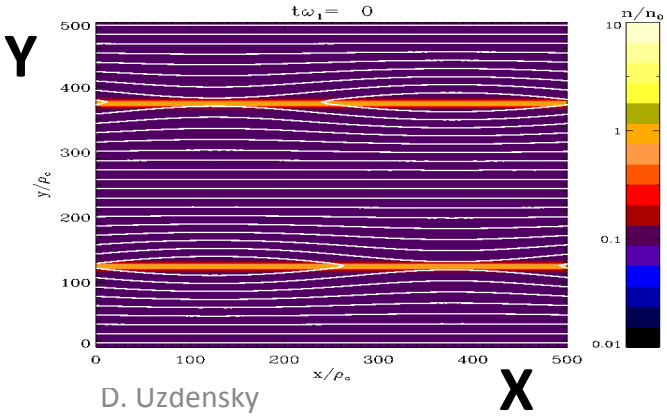
(*Zenitani & Hoshino '01, '05, '07, '08; Jaroschek + '04; Bessho & Bhattacharjee '07, '08, '12; Lyubarsky & Liverts '08; Jaroschek & Hoshino '09; Liu + '11; Sironi & Spitkovsky'14; Cerutti + 2012, 2013, 2014; Kagan + 2013, Guo + 2014, 2015; Melzani + 2014; Werner + 2014-2017, Sironi et al 2015-2016)*

Key Features:

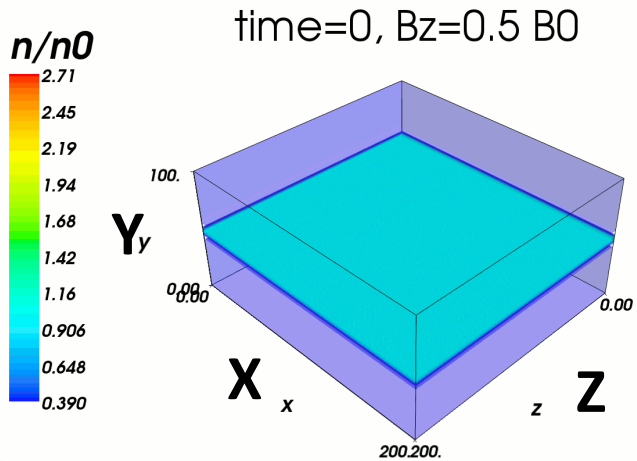
- Pair plasma reconnection is **fast:** $v_{rec} \sim 0.1 — 0.2\ c$
- Reconnecting current sheets in large systems ($L > 50\text{-}100\ \rho_L$) are unstable to **secondary instabilities** (tearing and kink) and reconnection is highly dynamic.



tearing (2D)



kink (3D)

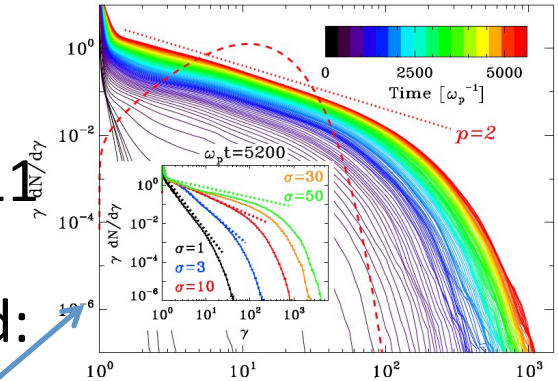


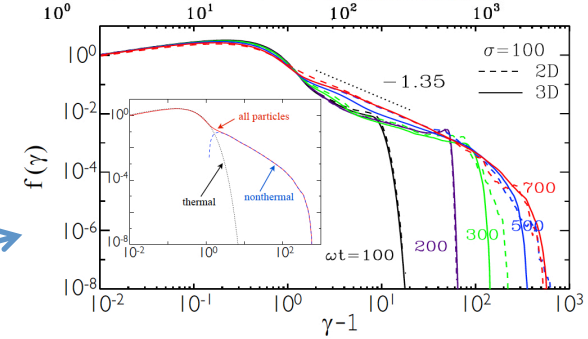
Collisionless Relativistic Pair Reconnection: Nonthermal Particle Acceleration (2014-2017 view)

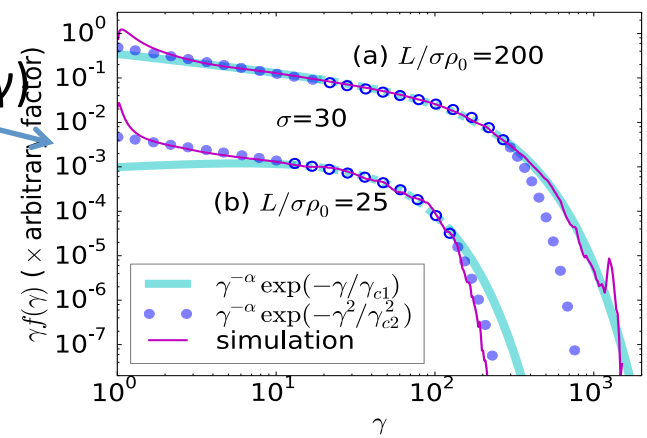
Important pioneering early work by Zenitani & Hoshino (2001, 2005, 2007-2008), also by Jaroschek'04, Lyubarsky & Liverts '08, Liu etal.'11

Recent 2D PIC studies by several groups showed: relativistic reconnection in pair plasmas indeed leads to nonthermal particle acceleration!

- Sironi & Spitkovsky et al. (2014-2016)
- Guo et al. (2014-2015) – Los Alamos
- Werner et al. (2014-2016) – Colorado







How do the power-law characteristics – power-law index α, high-energy cutoff γ_c – depend on system parameters?

The magnetzation 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 -- **magnetization σ**:
  - "Cold" sigma: $\boldsymbol{\sigma = B_0^2/(4\pi\, n_b\, mc^2)}$

  (sets the scale for available magnetic energy per particle);
  - "Hot" sigma: $\boldsymbol{\sigma_h = B_0^2/(4\pi\, n_b\, h)}$, where h is average relativistic enthalpy per particle including rest-mass: $h = mc^2 \langle\gamma\rangle + p/n$.
  - for relativistically-cold plasma ($T \ll m_e c^2$): $\sigma_h \approx \sigma$.
  - for ultra-relativistically-hot plasma ($T \gg m_e c^2$): $h \approx 4\,\theta_e\, mc^2$ and $\sigma_h \approx \sigma/4\theta_e = \sigma = B_0^2/(16\pi\, n_b\, \theta_e\, mc^2)$.

Power-law index

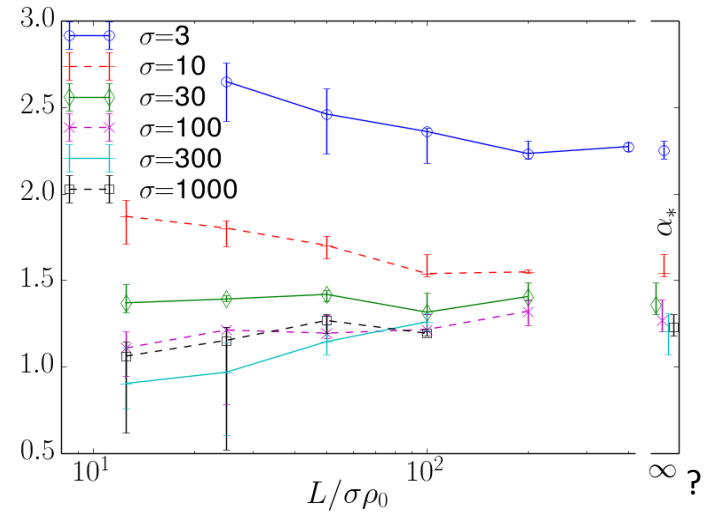
2D PIC studies with cold upstream plasma, so $\sigma_h \approx \sigma = B_0^2/(4\pi\, n_b\, mc^2)$

$$f(\gamma) \sim \gamma^{-\alpha} \qquad (\gamma = \varepsilon/mc^2)$$

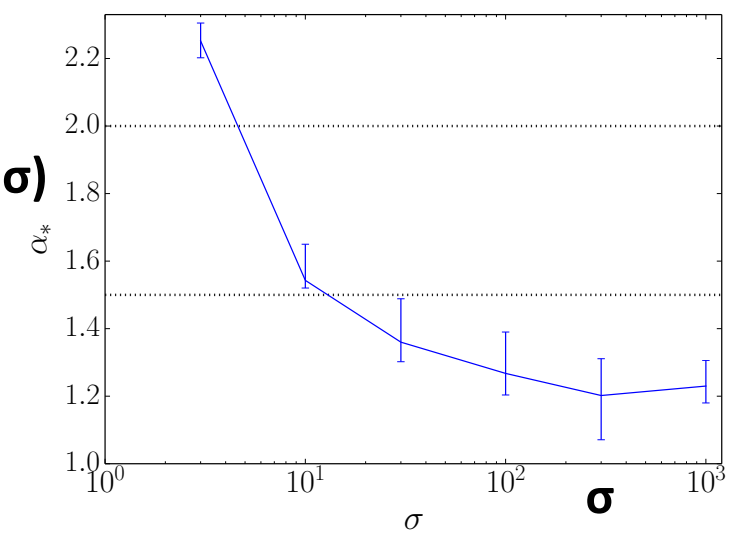
- $\alpha = \alpha(\sigma_h, L)$
- α depends on L for small L, but asymptotes to a finite value $\alpha_*(\sigma_h)$ as $L \rightarrow \infty$.
- $\alpha_*(\sigma_h)$ is > 2 for $\sigma_h \sim 1$ but decreases with σ_h and approaches a finite asymptotic value **$\alpha \approx$ 1-1.2** as $\sigma_h \rightarrow \infty$.

(consistent with studies by Sironi & Spitkovsky 2014, Zenitani & Hoshino, Lyubarsky & Liverts 2008)

α(L)



$\alpha_*(\sigma)$

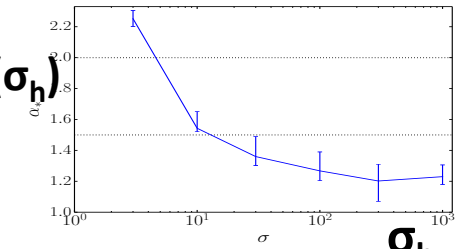


Werner et al. 2014-2016

High-Energy Power-Law Cutoff

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

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



Two high-energy cutoffs:

- exp (- γ/γ_{c1}); $\gamma_{c1} \sim 4\sigma$,

  $\gamma_{c1} \sim 10 \langle\varepsilon\rangle$

- independent of *L*;

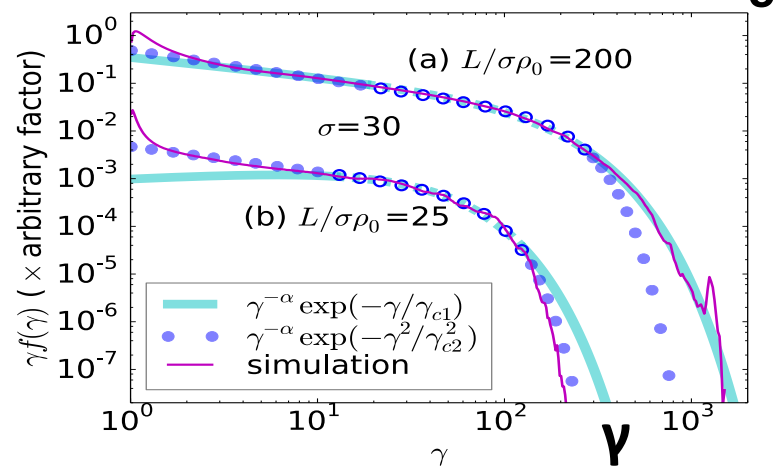
- exp [-(γ/γ_{c2})^2]; $\gamma_{c2} \sim 0.1\, L/\rho_0$

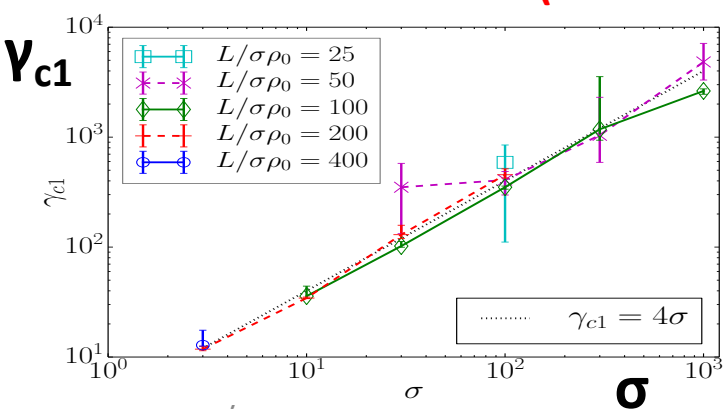
  available voltage drop

  $\varepsilon_{max} \sim e\, E_{rec}\, L \sim 0.1\, e\, B_0\, L$

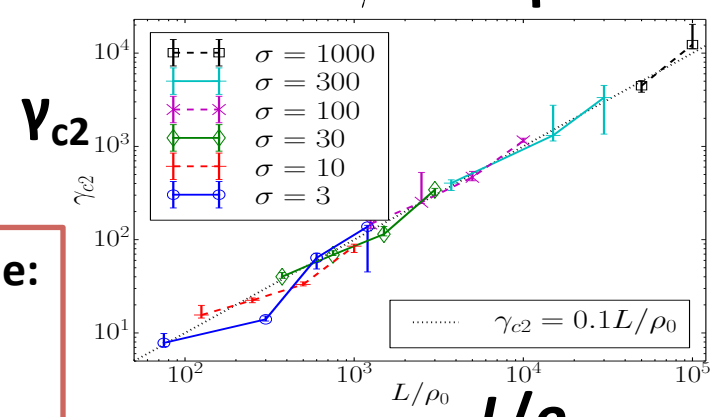
  ("extreme acceleration")

- independent of σ.





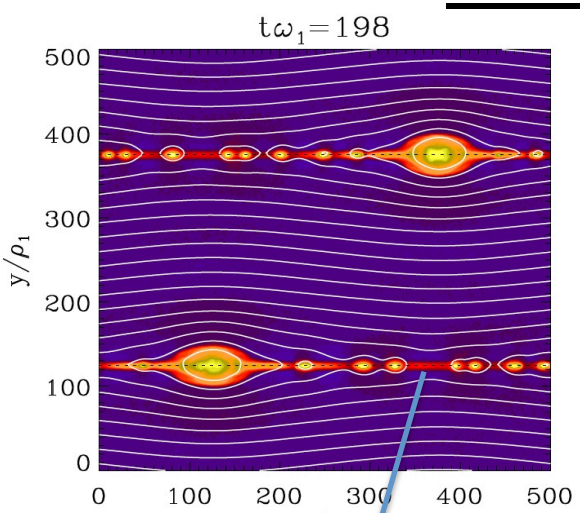
(ρ_0=$m_e c^2/e B_0$)



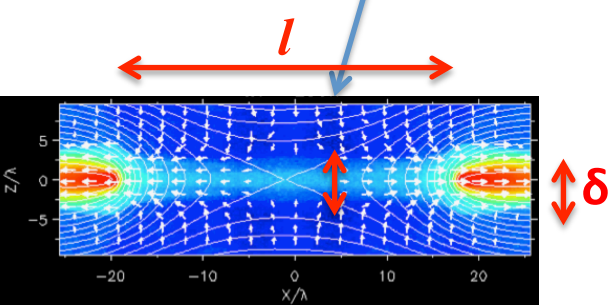
Large-system regime:
($\gamma_{c1} < \gamma_{c2}$):

L/ρ_0 > 40 σ

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



Cerutti et al. 2013



Zenitani & Hoshino 2001

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

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

- Cutoff comes from small laminar ***elementary inter-plasmoid layers*** at the bottom of the plasmoid hierarchy (marginally stable to plasmoid instability).
- Modest-energy particles are accelerated in these layers but then become trapped inside plasmoids.
- Rel. particle acceleration in a laminar single-X-point elementary layer:

resulting energy spectrum is well approximated by the expression proposed by Larrabee et al. (2003):

$$\frac{dn}{d\gamma} \propto \frac{1}{\gamma} \exp\left(-\frac{\gamma}{\gamma_0}\right). \qquad (10)$$

(Larrabee et al. '03; Lyubarsky & Liverts '08)

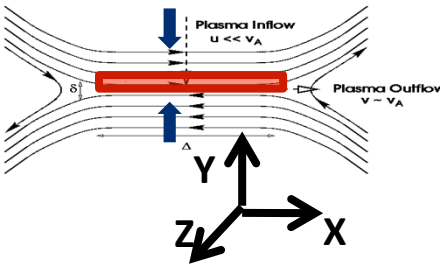
- Cutoff: $\boldsymbol{\gamma_0} = e\, E_{rec}\, l\, /m_e c^2 \approx 0.1\, e\, B_0\, l\, /m_e c^2 = \mathbf{0.1}\, \boldsymbol{l\, /\rho_0}$.
- Layers are marginally stable to tearing → $\boldsymbol{l \sim 100\, \delta}$.
- Layer thickness: $\boldsymbol{\delta} \approx \rho\, (\langle\gamma\rangle) = \langle\gamma\rangle\, \rho_0 \approx \boldsymbol{(\sigma/3)\, \rho_0}$.
- Thus, $\boldsymbol{l\, /\rho_0 \approx 100\, \delta/\rho_0 \approx 30\, \sigma}$ => $\boldsymbol{\gamma_0 = 3\, \sigma}$.

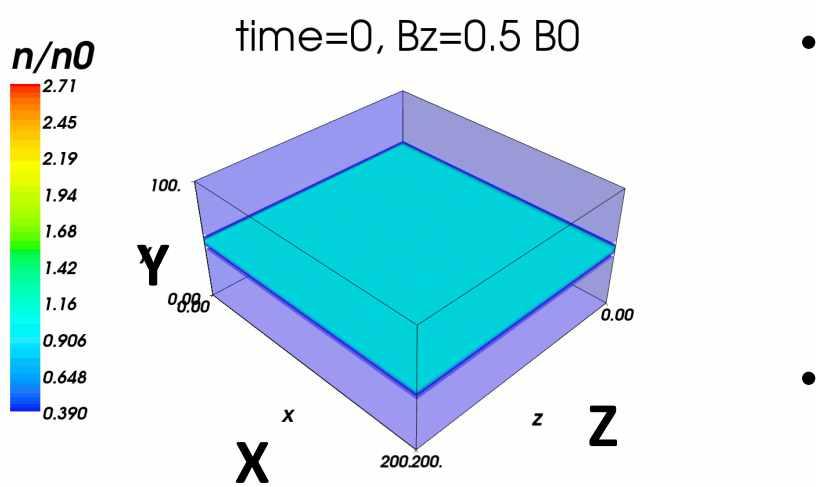
Relativistic Pair Plasma Reconnection in 3D

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

Should we be concerned?

- Reason for concern: ***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.





- **Zenitani & Hoshino**'s (2007-2008) 3D PIC simulations: nonlinear development of **RDKI** without strong guide field leads to efficient heating but ***suppresses nonthermal particle acceleration.***
- More recent work (e.g., Sironi & Spitkovsky '14, Guo et al.'15): particles are still accelerated efficiently on longer timescales.

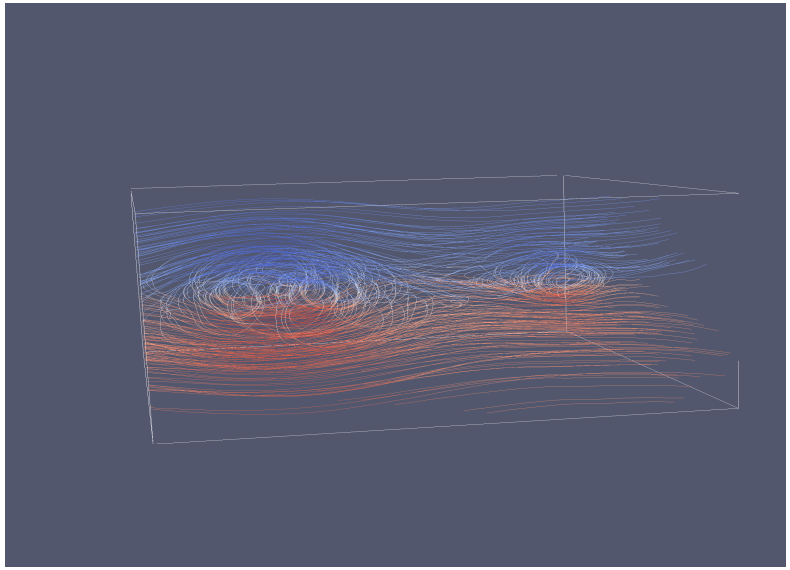
Relativistic Pair Plasma Reconnection in 3D

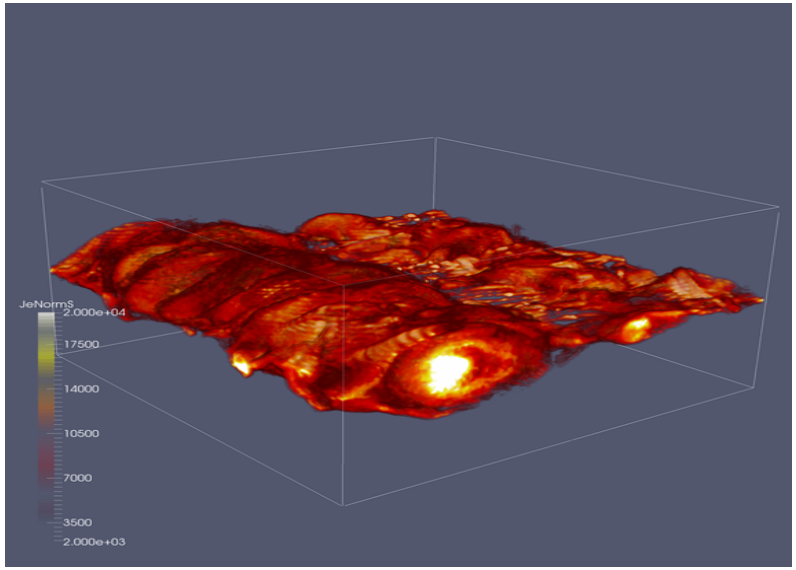
(Werner & Uzdensky ApJ Lett., 2017)

We have recently completed a thorough 2D/3D comparison for ultra-relativistic pair reconnection, for varying:

- layer's aspect ratio L_z/L_x – proxy for 3D;
- guide magnetic field (B_{gz}/B_0).

[keeping fixed upstream temperature $T_b >> m_e c^2$ and magnetization: $\sigma_{hot} = B_0^2/(4\pi\, n\, \theta_e mc^2) = 25$]



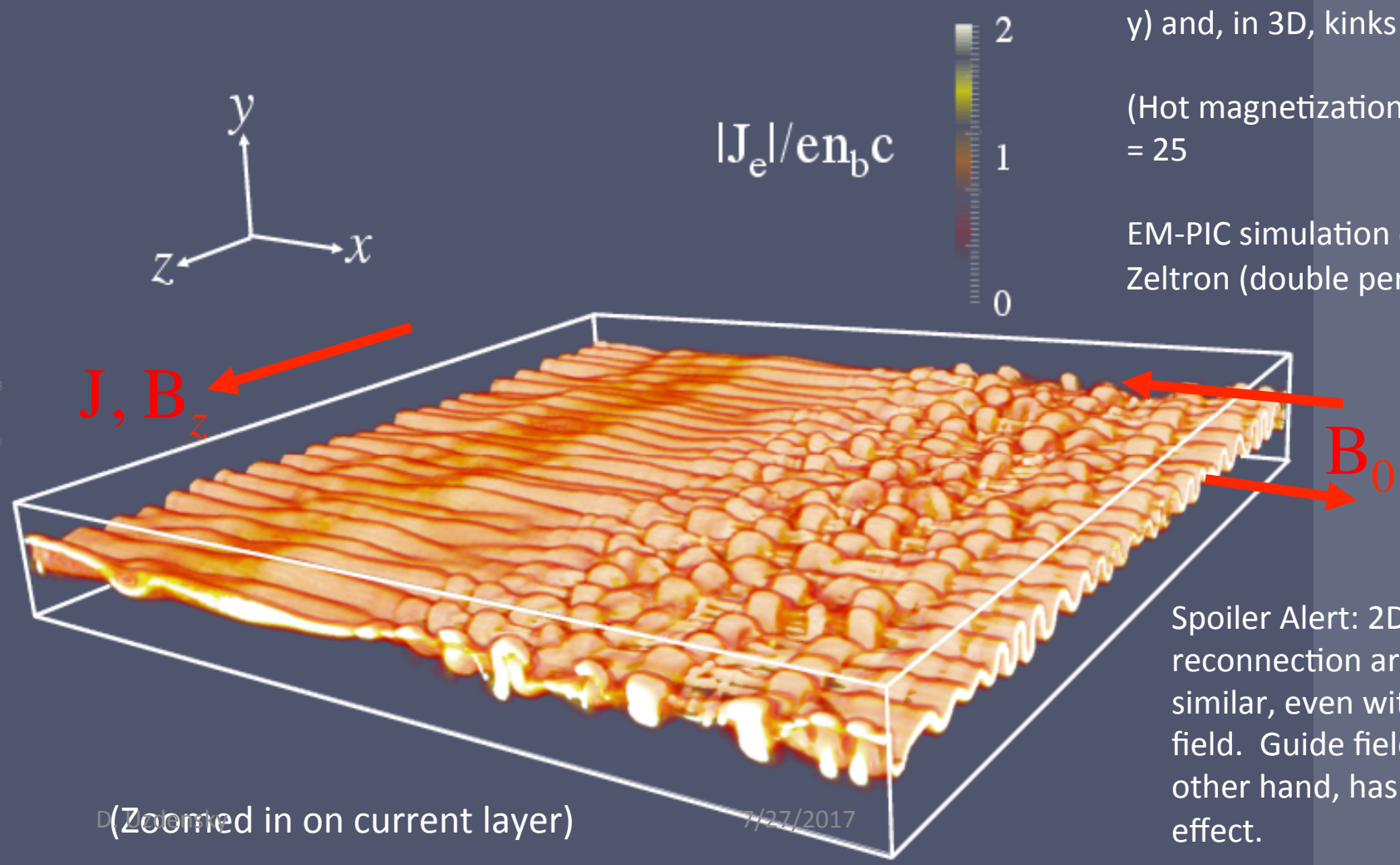


Relativistic Pair Reconnection: 2D vs. 3D vs. guide field B_{gz}

Starting from a Harris configuration, with a small magnetic field perturbation (uniform in z), the initial current layer rapidly tears (in x-y) and, in 3D, kinks (in y-z).

(Hot magnetization) sigma_hot = 25

EM-PIC simulation code: Zeltron (double periodic box)



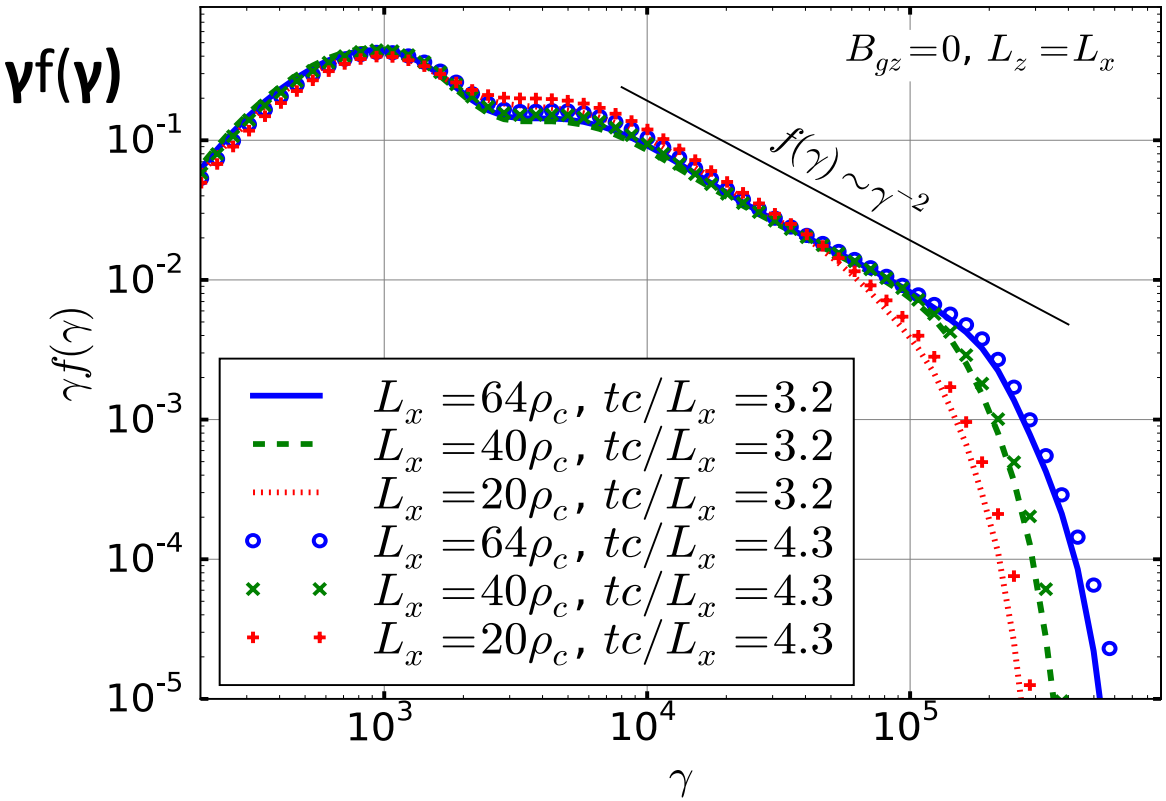
(Zoomed in on current layer)

Spoiler Alert: 2D and 3D reconnection are very similar, even without guide field. Guide field, on the other hand, has a large effect.

Relativistic Pair Plasma Reconnection in 3D

(Werner & Uzdensky 2017)

Particle spectra for different L_x: box-size dependence



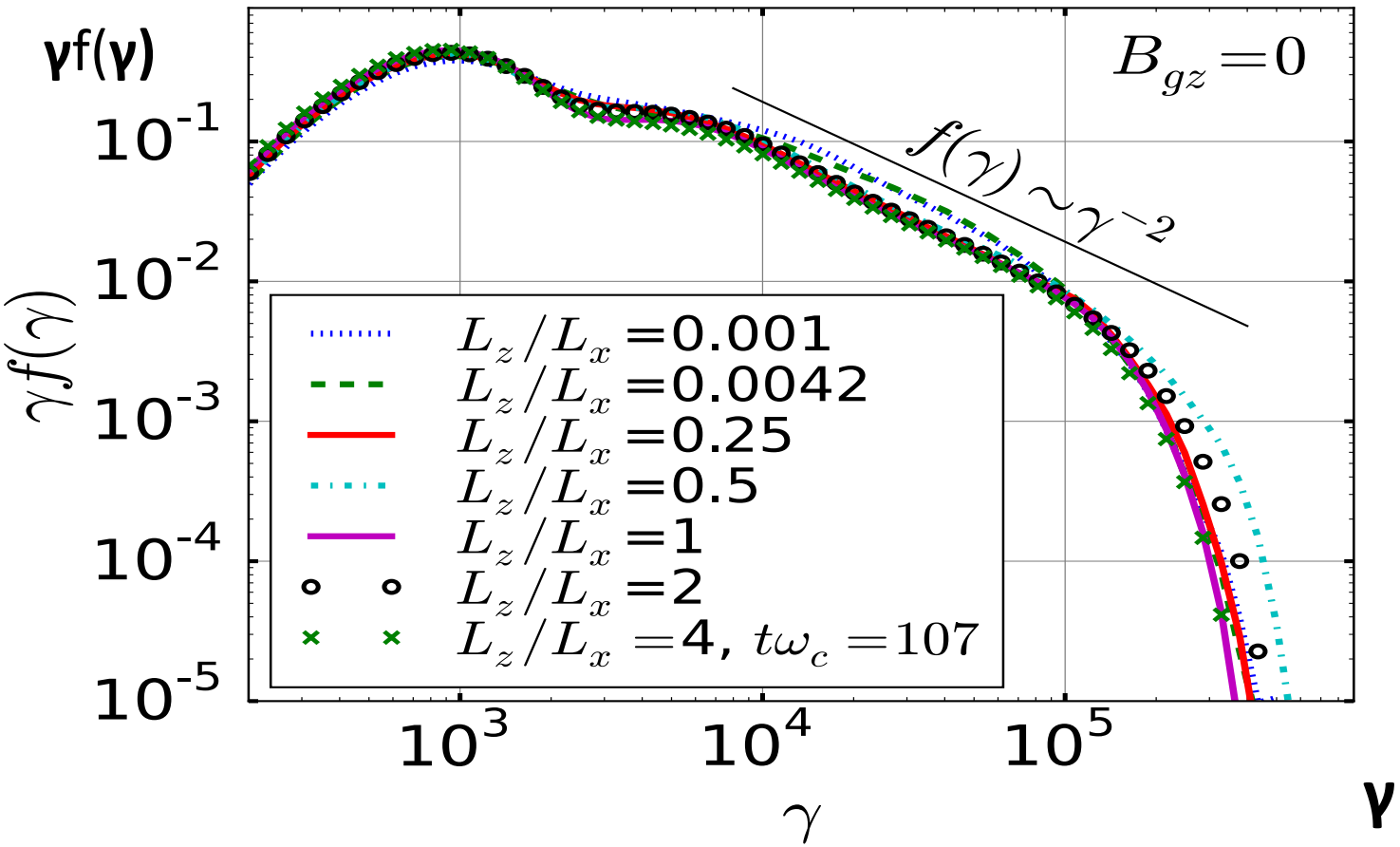
$B_z = 0$

$L_z/L_x = 1$

Conclusion: power-law index converges with L_x

Relativistic Pair Plasma Reconnection in 3D

Particle spectra for different L_z/L_x: no guide field

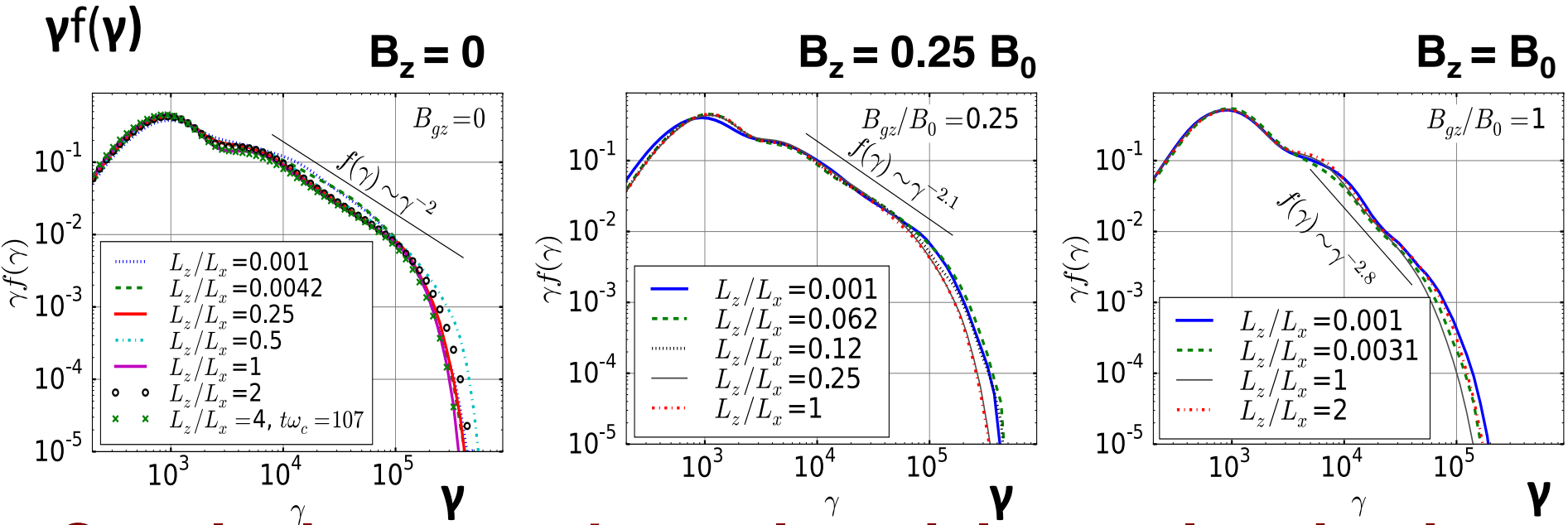


$B_z = 0$

Conclusion: 2D and 3D are fairly similar!

Relativistic Pair Plasma Reconnection in 3D

Does this conclusion depend on guide field?



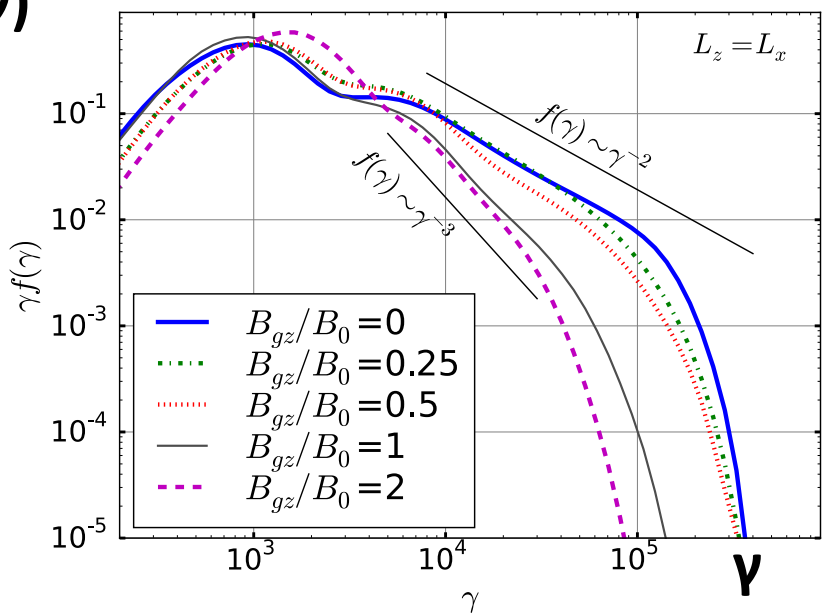
Conclusion: **nonthermal particle acceleration in relativistic pair-plasma reconnection is similar in 2D and 3D for any given guide field.**

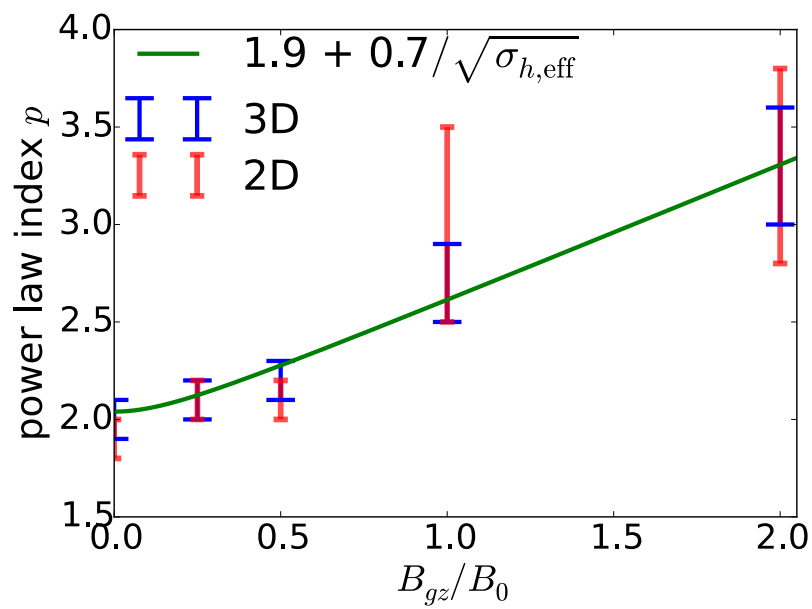
Implication: 2D simulations are sufficient, adequate for studies of NTPA in relativistic pair reconnection.

Relativistic Pair Plasma Reconnection in 3D

Particle spectra for different B_z/B_0: $L_z/L_x = 1$

$\gamma^2 f(\gamma)$



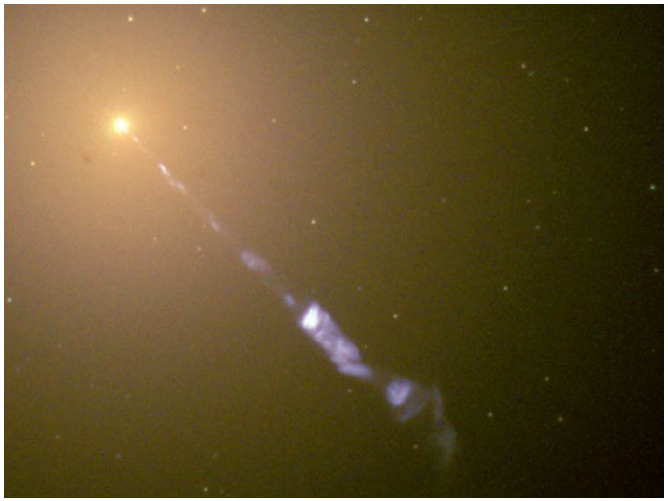


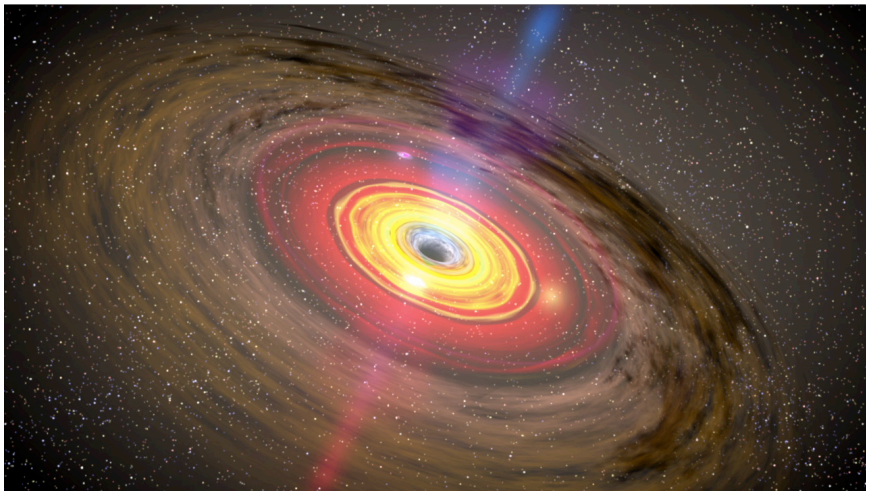
<u>Conclusion:</u> particle acceleration is negatively affected by strong guide field.

Proposal: Enthalpy of the guide magnetic field, $B_{gz}^2/4\pi$, modifies the effective hot sigma: $\boldsymbol{\sigma_{h,eff} = B_0^2/(B_{gz}^2 + 4\pi\, nh)}$

Relativistic Collisionless Magnetic Reconnection and Nonthermal Particle Acceleration:

2. Semi-Relativistic and Relativistic Reconnection in Electron-Ion Plasmas





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

Werner et al. (arXiv:1612.04493)

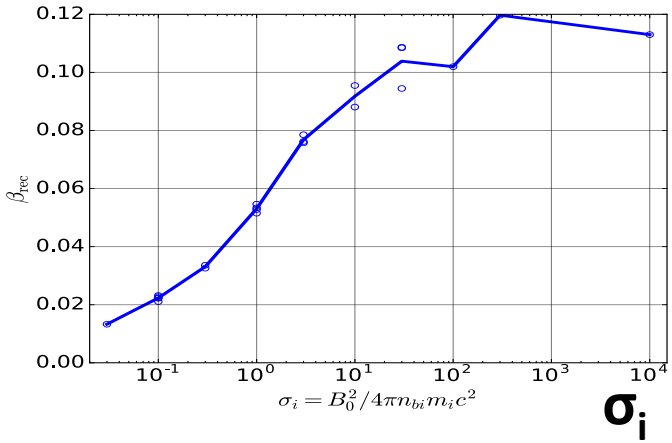
Electron-Ion Reconnection in Semi-relativistic and ultra-relativistic regimes

- PIC studies of ***electron-ion*** rel. reconnection have just begun *(Werner et al. 2013, 2015, Melzani et al. '14, Guo et al. '15, Sironi et al. '15)*.
- When both electrons and ions are ***ultra-relativistic***, they behave the same → ***reconnection is similar to pair-plasma*** case.
- ***Semi-relativistic reconnection regime***: ultra-relativistic electrons but non-relativistic ions – relevant to many astro systems (BH ADC).
- We conducted a ***systematic 2D PIC study*** (no guide field, real mass ratio m_i/m_e=1836) of reconnection in *ei* plasmas in semi- and trans-relativistic regimes (Werner et al. 2016b).
- **Main question:** how do key reconnection characteristics – rec. rate, energy partitioning, particle acceleration – change as one *transitions from semi-relativistic ($\sigma_i << 1$) to full-relativistic regime ($\sigma_i >> 1$)* ?

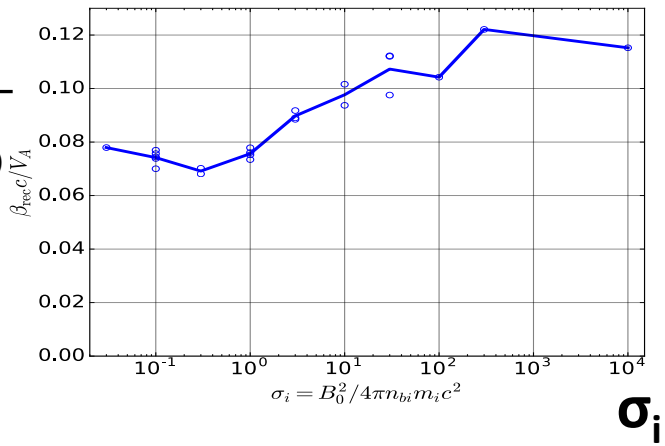
Relativistic *e-i* reconnection: Key PIC Sims Results I

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

$$\frac{E}{B_0}$$

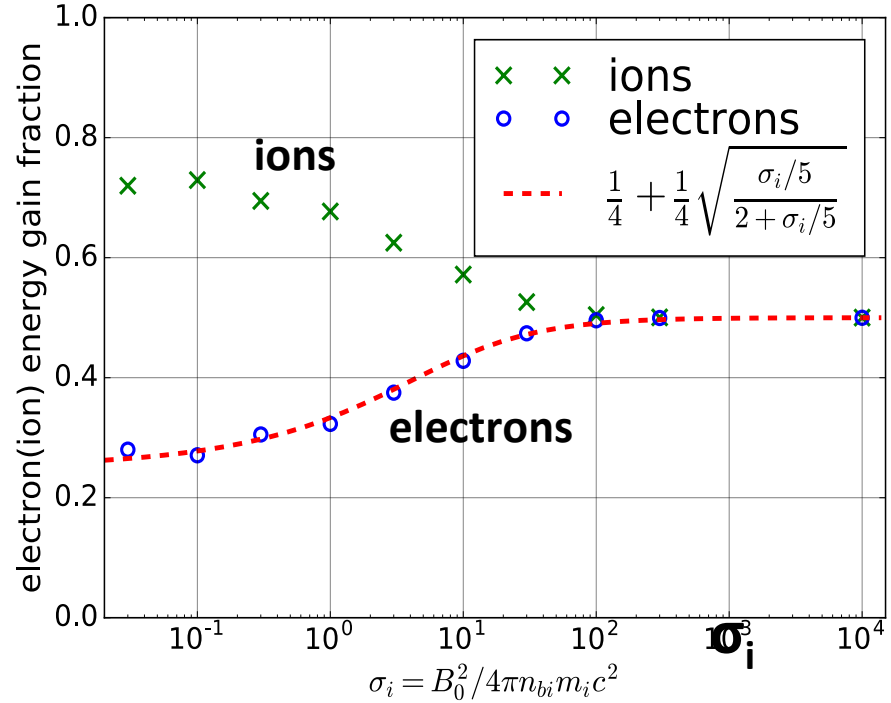


$$\frac{cE}{V_A B_0}$$



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

Energy partitioning between electrons and ions



In semi-relativistic case ions gain 3 times more energy than electrons.

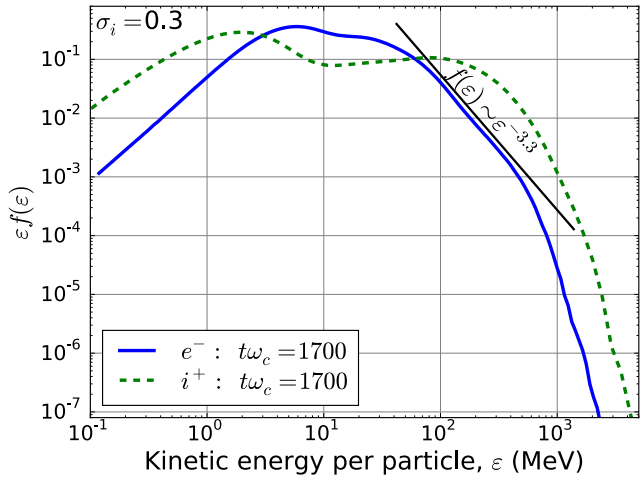
Werner et al. 2016

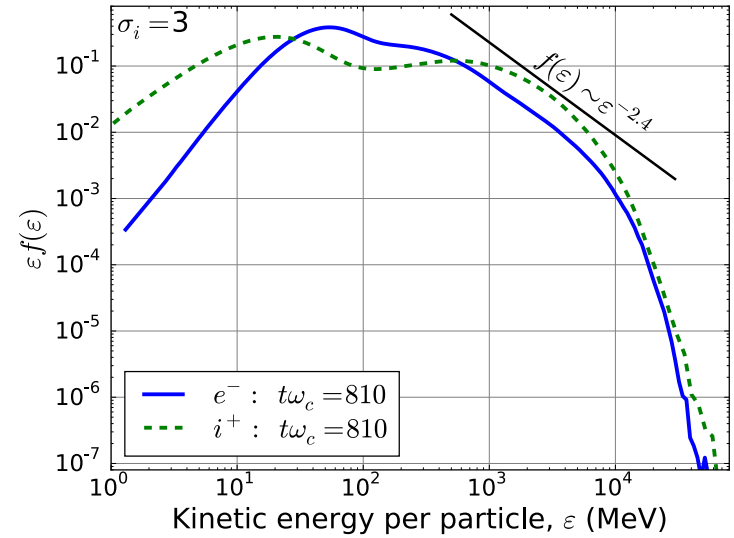
Relativistic *e-i* reconnection: Key PIC Sims Results II

Particle Acceleration:

- electrons: ✔

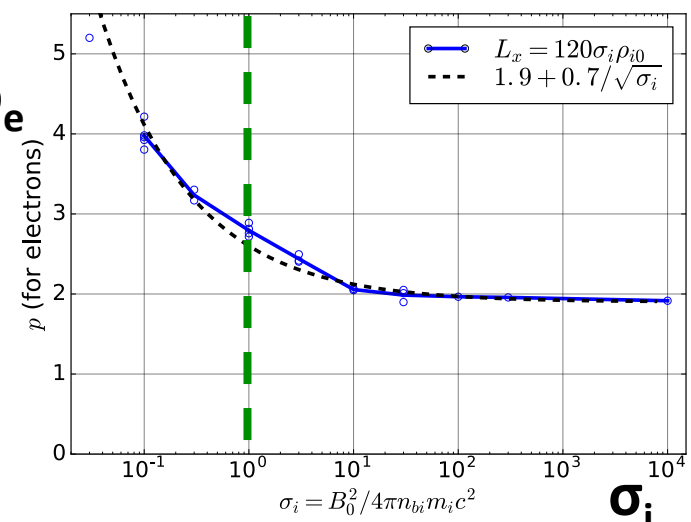
- ions ?





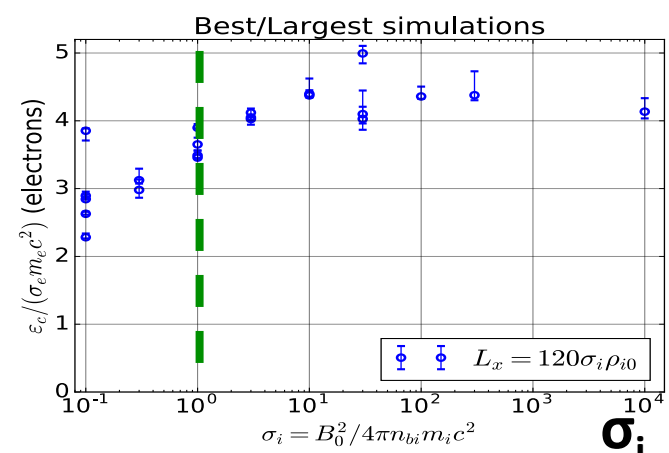
Electron power-law index *p* and cutoff γ_c:

p_e



σ_i

γ_c/σ_i



σ_i

Werner et al. 2016

SUMMARY

- **Relativistic reconnection** in ***pair*** plasmas produces robust **nonthermal particle spectra** in both **2D and 3D** with a power-law index **α** that:
  - becomes independent of L as $L \rightarrow \infty$.
  - decreases with magnetization σ: $\boldsymbol{\alpha \rightarrow 1}$ as $\sigma \rightarrow \infty$.
  - increases with B_{gz}: $\boldsymbol{\alpha \approx C_1 + C_2 (\sigma_{h,eff})^{-1/2}}$, $\boldsymbol{\sigma_{h,eff} = B_0^2/(B_{gz}^2 + 4\pi h)}$
- **Semi-Relativistic** (ultra-rel. electrons, non-rel. ions) and relativistic reconnection in ***electron-ion*** plasma (2D; B_g=0):
  - *electron energy fraction* grows from ~ ¼ to ½ as $\boldsymbol{\sigma_i}$ increases.
  - power-law *electron* spectra, with index $\alpha \sim C_1 + C_2/\boldsymbol{\sigma_i^{1/2}}$
  - nonthermal *ion* acceleration is not clear.