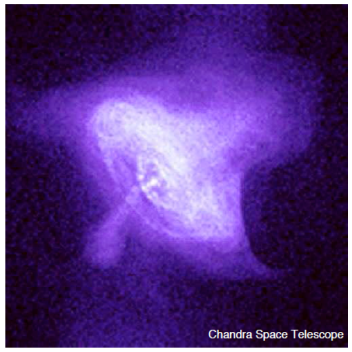
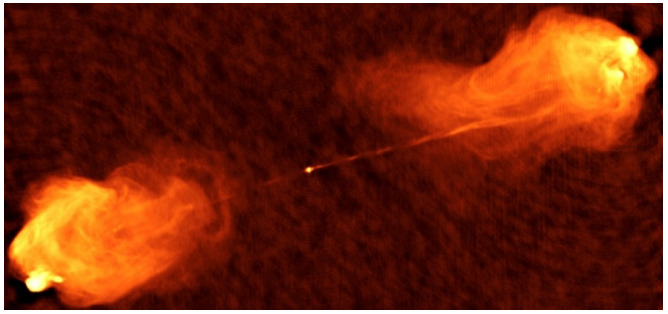
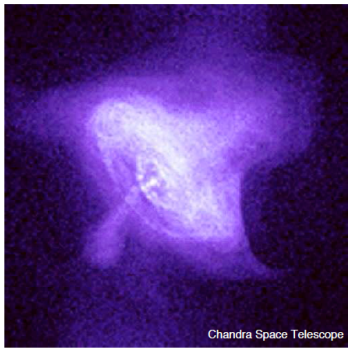






Nonthermal Particle Acceleration in Magnetic Reconnection and Turbulence in Collisionless Relativistic Plasmas

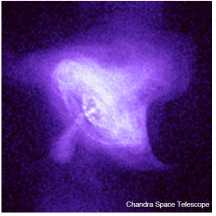
Dmitri Uzdensky

(University of Colorado Boulder and Institute for Advanced Study)

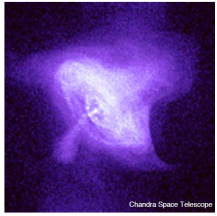
In collaboration with (Univ. Colorado):

- Greg Werner
- Vladimir Zhdankin
- Mitch Begelman

PPPL Heliophysics/Astroplasmas Seminar, June 12, 2017



OUTLINE



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

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

Our main goal: chart out 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

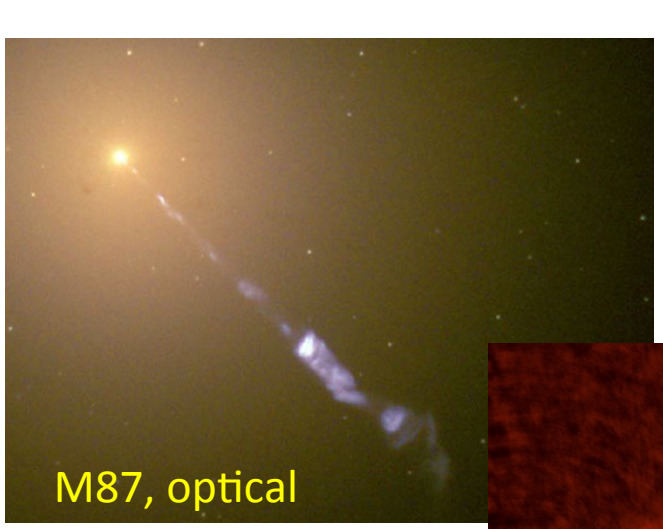
2D and 3D numerical kinetic studies of relativistic ***reconnection*** (lead by Greg **Werner**) and ***turbulence*** (lead by Vladimir **Zhdankin**) done with two relativistic Particle-in-Cell (PIC) codes:

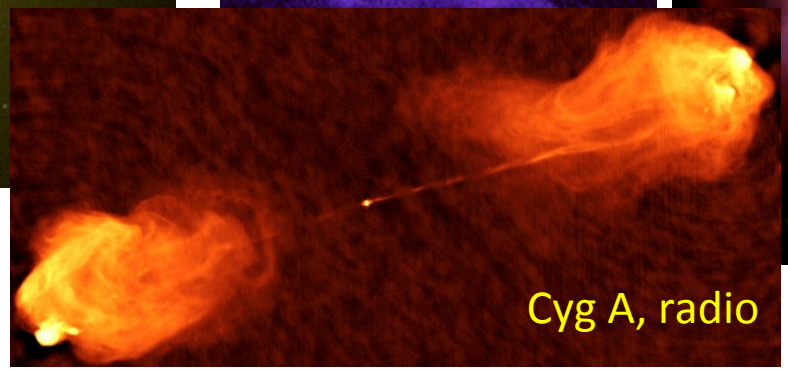
- **VORPAL/VSim** (non-radiative; radiation via post-processing);
- **ZELTRON** (**radiative PIC**):
- developed at Univ. Colorado by **Benoit Cerutti and Greg Werner**

(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

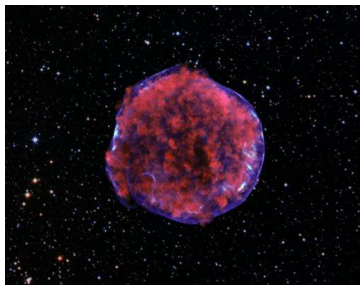
AVAILABLE FREE ENERGY

Bulk Kinetic

Magnetic (Poynting flux)

- longitudinal:

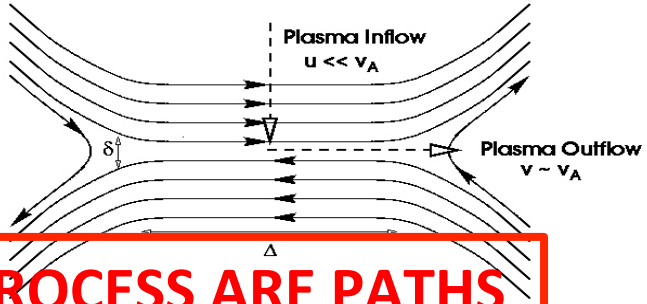
shocks



STRUCTURE

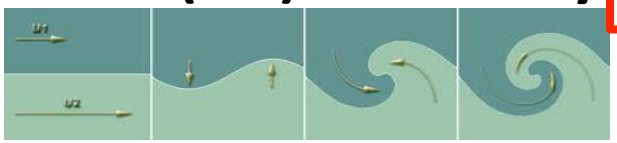
Magnetic reconnection

current sheets:



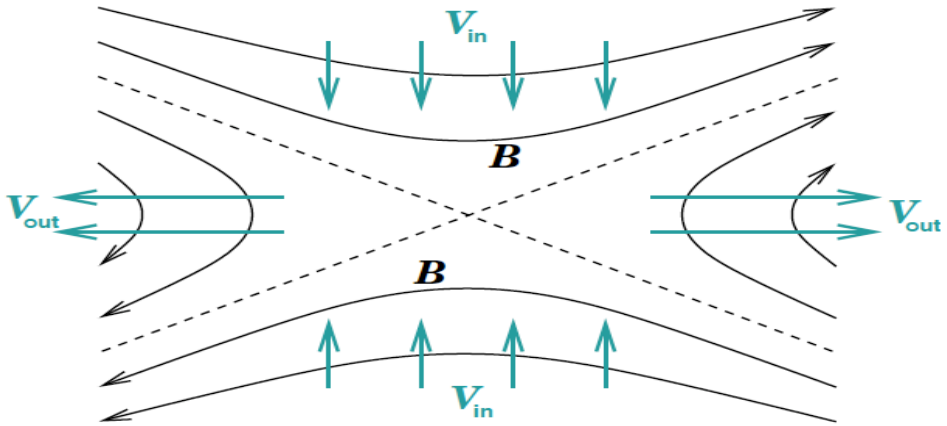
- transverse:

shear (KH) instability



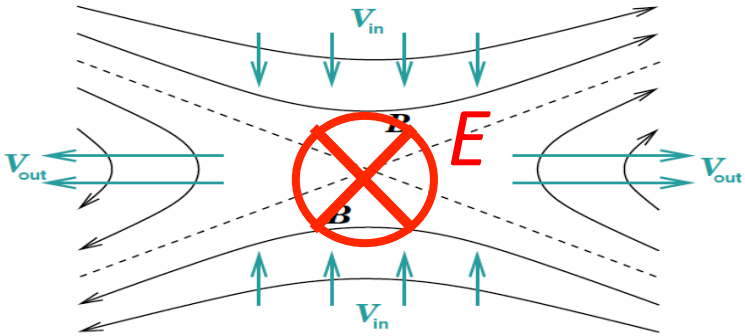
MANY OF THESE PROCESS ARE PATHS TO DEVELOPING TURBULENCE!!

Magnetic Reconnection

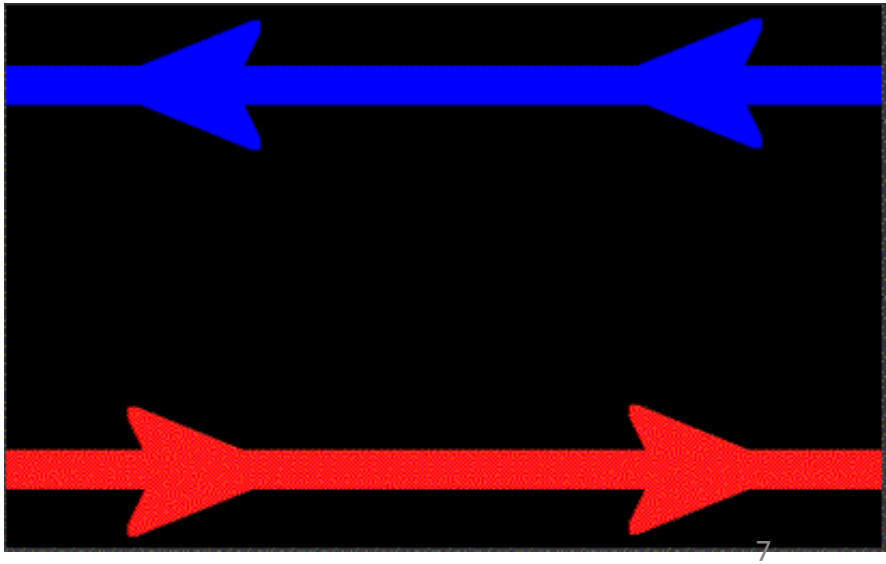


Introduction: Magnetic Reconnection

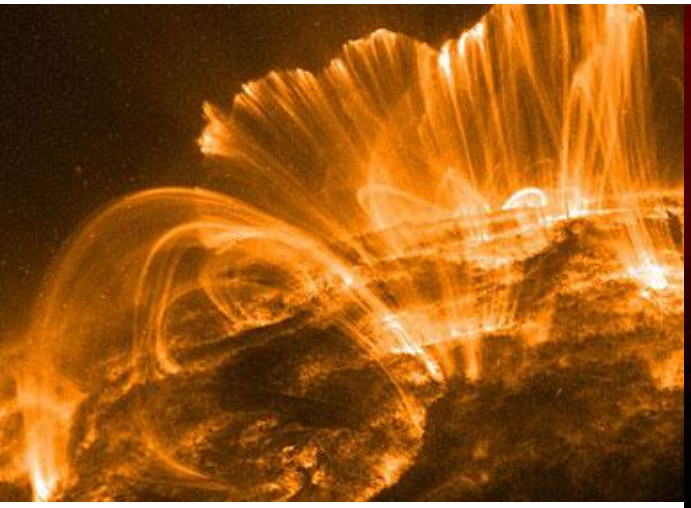
- **Magnetic reconnection** is a rapid rearrangement of magnetic field topology

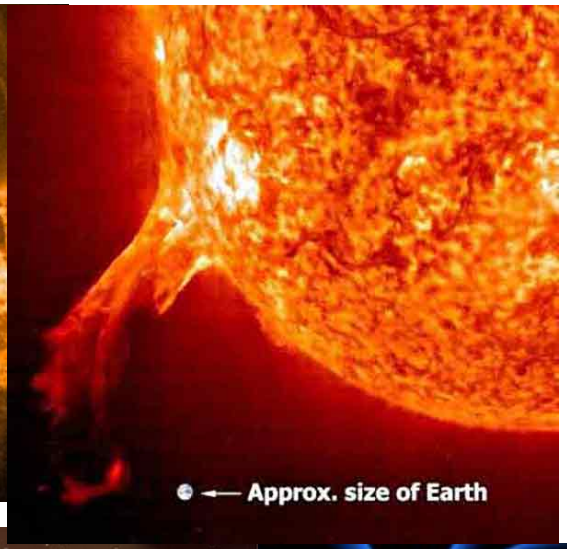


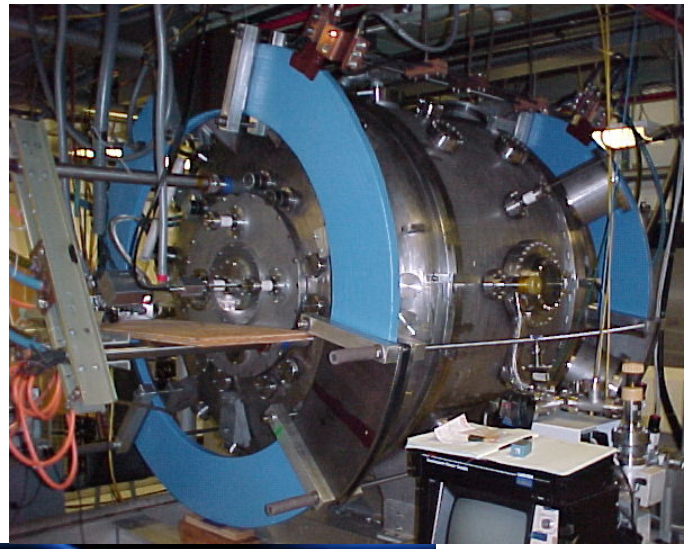
- Reconnection often results in violent release of magnetic energy and its conversion to:
  - electron and ion heating
  - bulk kinetic energy
  - non-thermal particle acceleration



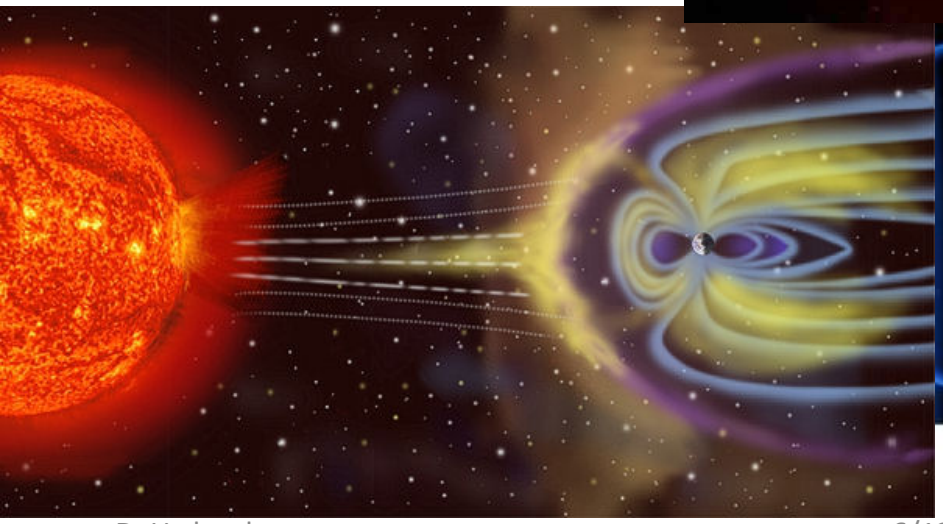
Traditional Magnetic Reconnection in the Solar System

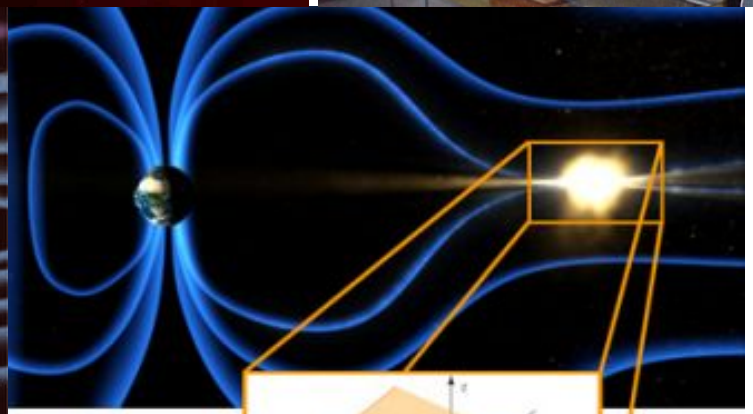






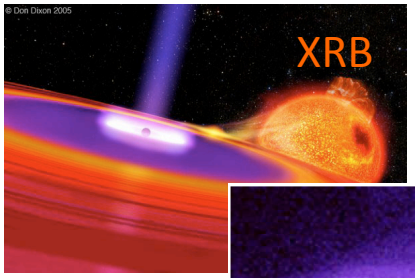
MRX

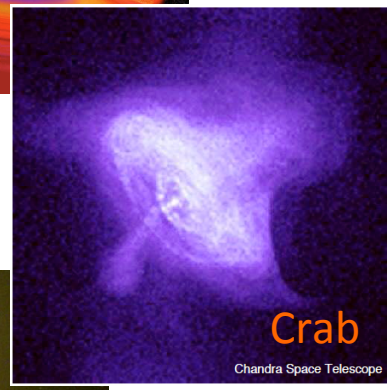


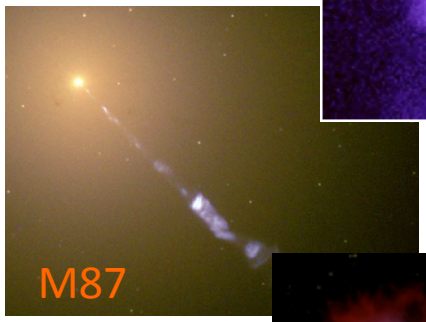


Reconnection in High-Energy Astrophysics

- 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







Observational Properties of Astrophysical High-Energy Emission:

❖ Often non-thermal: power-law spectra →

nonthermal particle acceleration

Particle Acceleration --- efficient production of high-energy nonthermal particles, yielding a high-energy power-law tail in particle energy distribution extending to energies $\varepsilon_{max} >> <\varepsilon>$ (averaged released energy per particle).

❖ Intense rapid gamma-ray flares →

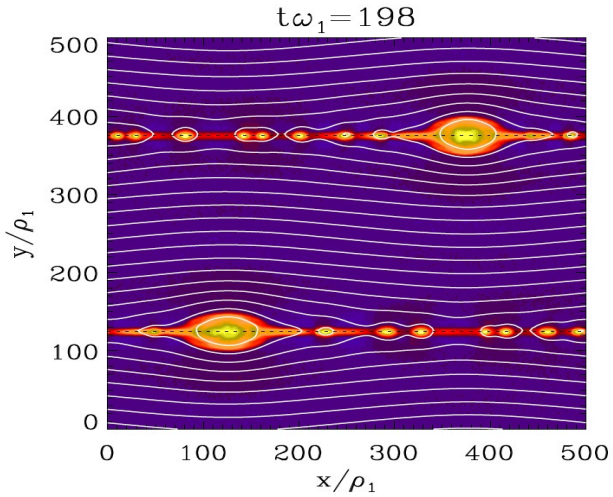
short time variability (e.g., 10-min TeV blazar flares).

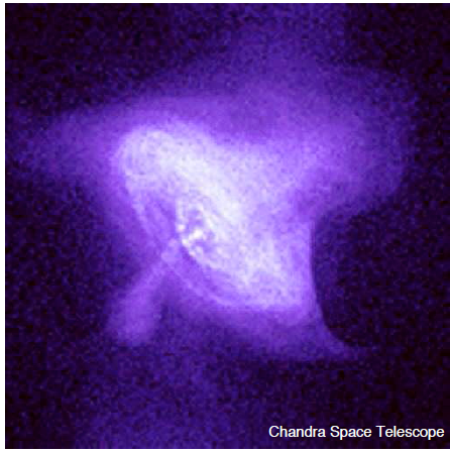
Can reconnection explain these properties?

(Yes)

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.* accepted (*2017)*

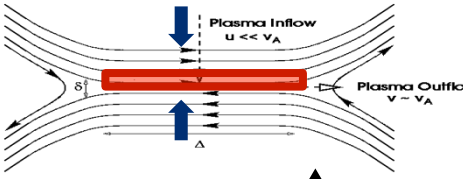
Collisionless Relativistic Pair Reconnection: General reconnection dynamics

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

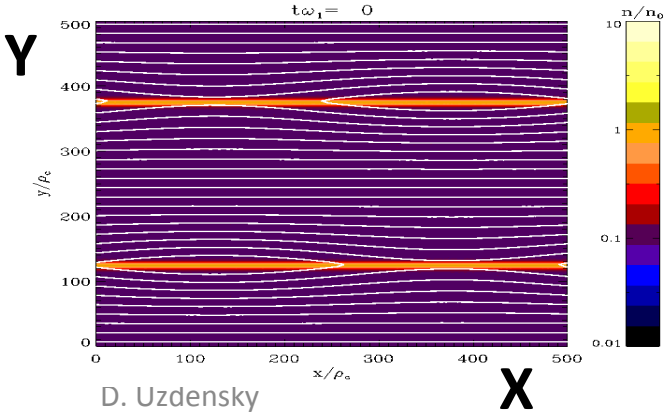
(*Zenitani & Hoshino '01, '05, '07, '08; Jaroschek + '04; Bessho & Bhattacharjee '07, '08, '12; Lyubarsky & Liverts '08; Jaroschek & Hoshino '09; Liu + '11; Sironi & Spitkovsky'14; Cerutti + 2012, 2013, 2014; Kagan + 2013, Guo + 2014, 2015; Melzani + 2014; Werner + 2014-2017, Sironi et al 2015-2016)*

Key Features:

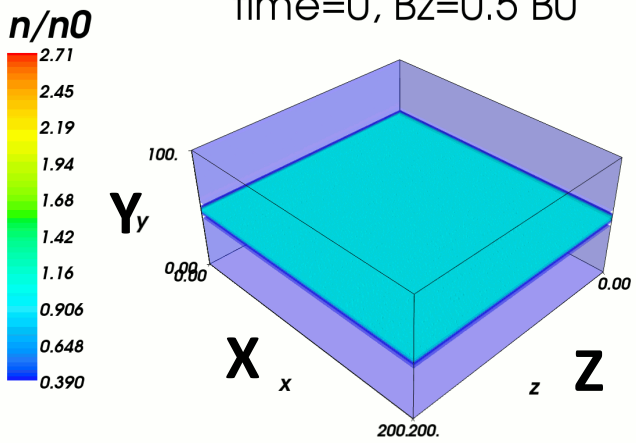
- Pair plasma reconnection is **fast:** v_{rec} ~ 0.1— 0.2 c
- Reconnecting current sheets in large systems (L > 50-100 ρ_L) are unstable to **secondary instabilities** (tearing and kink) and reconnection is highly dynamic.



tearing (2D)



kink (3D)



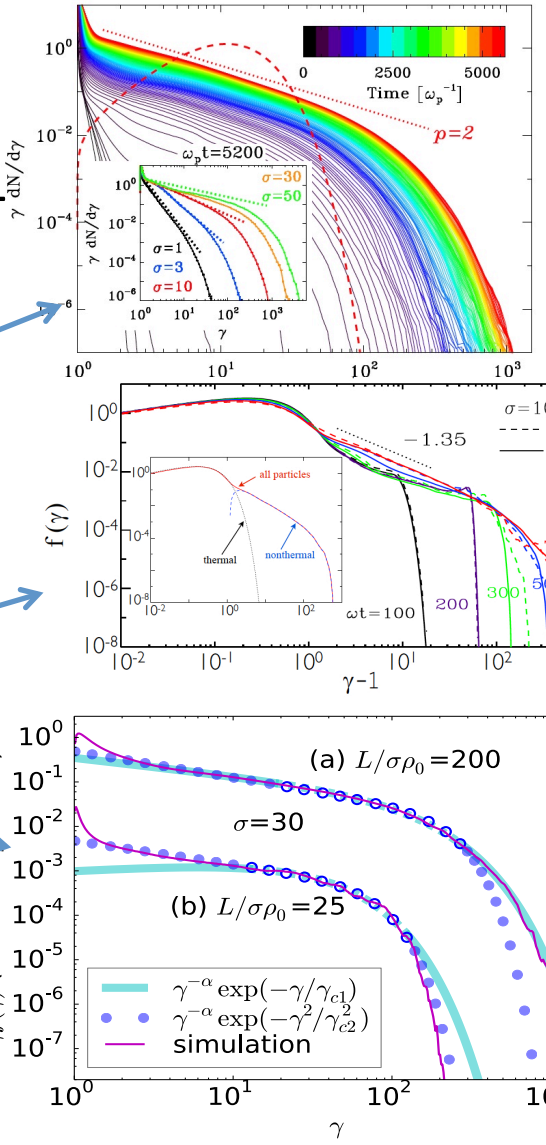
Collisionless Relativistic Pair Reconnection: Nonthermal Particle Acceleration (2014-2017 view)

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 et al. (2014-2016) – CfA, Columbia
- 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: $\sigma = B_0^2/(4\pi n_b mc^2)$

  (sets the scale for available magnetic energy per particle);
  - "Hot" sigma: $\sigma_h = B_0^2/(4\pi n_b h)$, 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 $\sigma_h \approx \sigma/4\theta_e = \sigma = B_0^2/(16\pi\, n_b\, \theta_e\, mc^2)$.

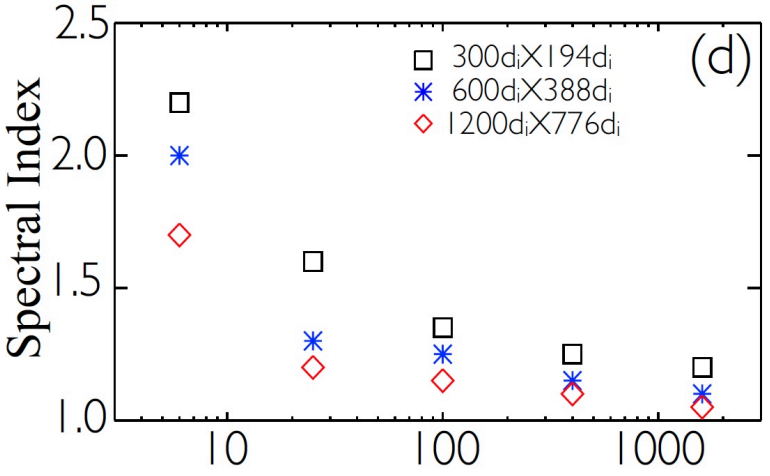
Power-law index

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

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

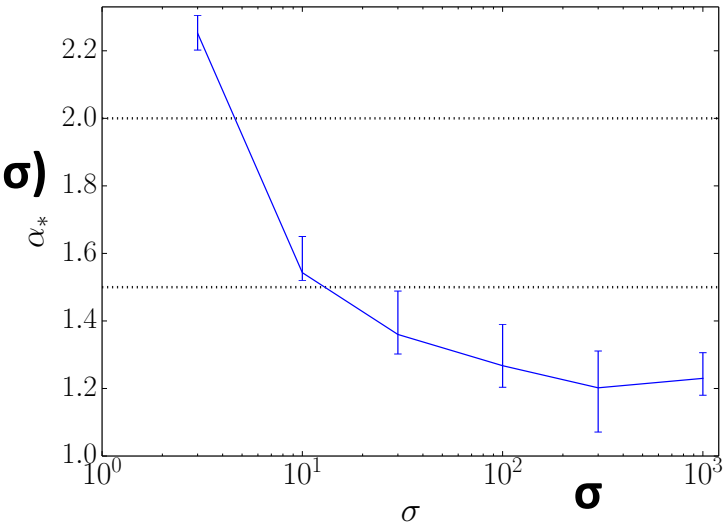
- $\alpha = \alpha(\sigma_h, L)$
- α depends on L for small L, but asymptotes to a finite value $\alpha_*(\sigma_h)$ as $L \rightarrow \infty$.
- $\alpha_*(\sigma)$ is > 2 for $\sigma_h \sim 1$ but decreases with σ_h and approaches a finite asymptotic value **$\alpha \approx 1\text{-}1.2$** as $\sigma_h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

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



Guo et al. 2014

$\alpha_*(\sigma)$

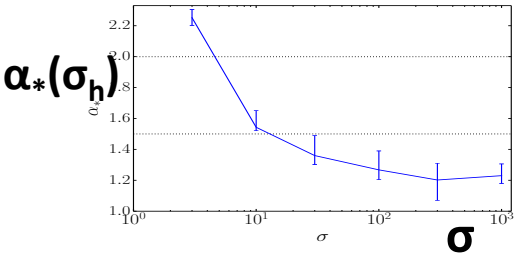


Werner et al. 2014-2016

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*;

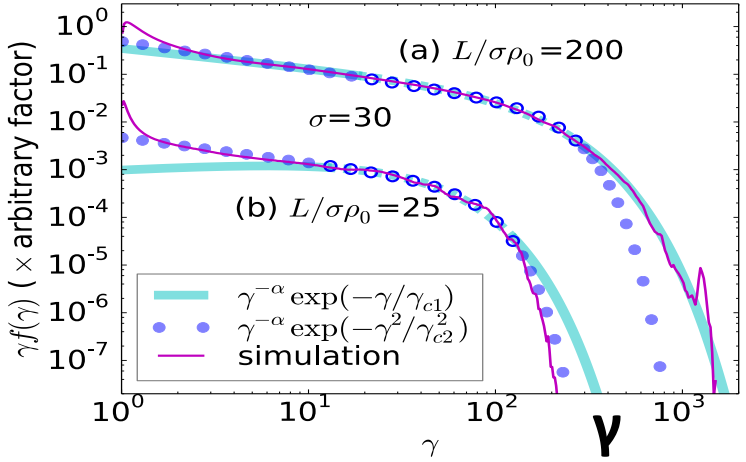
- exp [-(γ/γ_{c2})^2]; $\gamma_{c2} \sim 0.1\, L/\rho_0$

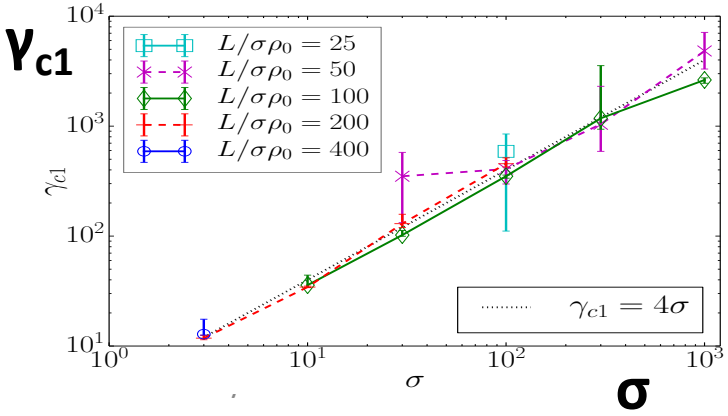
  - independent of σ.

available voltage drop

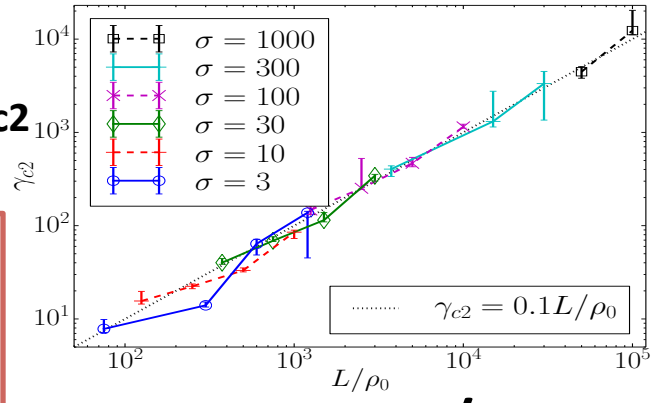
$\varepsilon_{max} \sim e\, E_{rec}\, L \sim 0.1\, e\, B_0\, L$

("extreme acceleration")





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

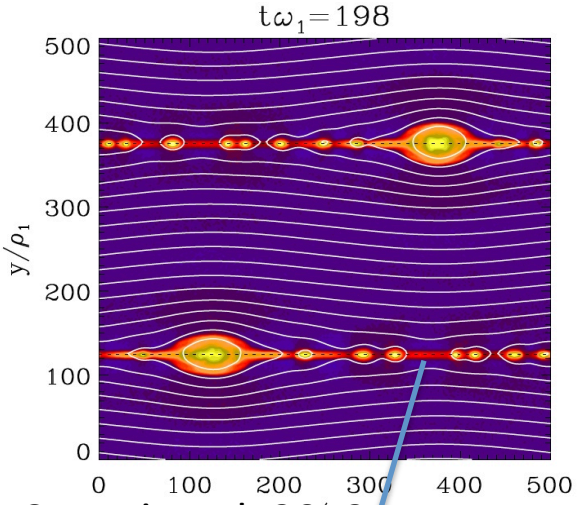


Large-system regime:

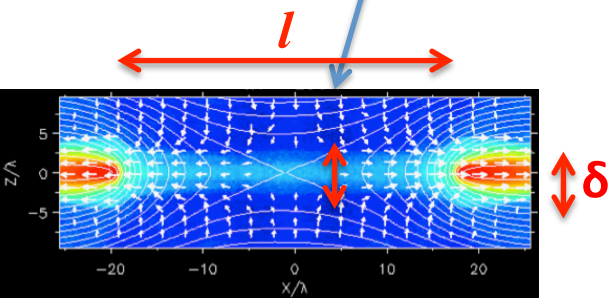
($\gamma_{c1} < \gamma_{c2}$):

$L/\rho_0 > 40\,\sigma$

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)

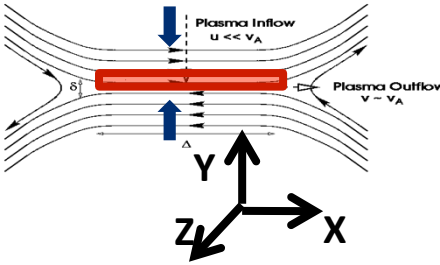
- Cutoff: $\boldsymbol{\gamma_0} = e\, E_{rec}\, l\, /m_e c^2 \approx 0.1\, e\, B_0\, l\, /m_e c^2 = \mathbf{0.1}\, l\, /\rho_0$.
- Layers are marginally stable to tearing → $l \sim 100\, \delta$.
- Layer thickness: $\delta \approx \rho\,(\langle\gamma\rangle) = \langle\gamma\rangle\, \rho_0 \approx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

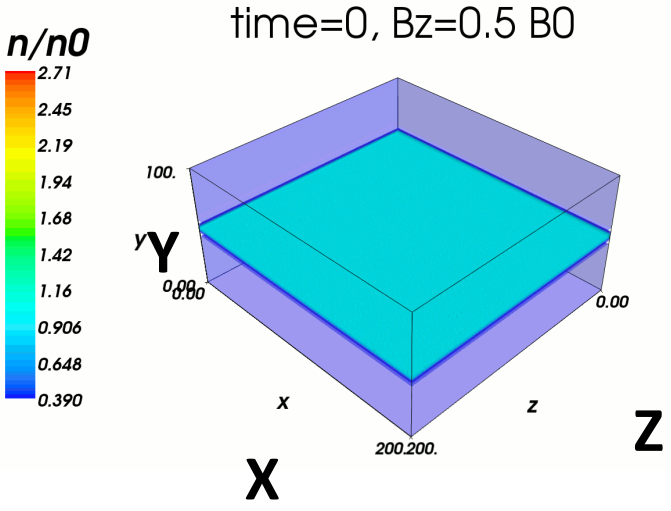
Relativistic Pair Plasma Reconnection in 3D

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

Should we be concerned?

- Reason for concerned: ***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 times.

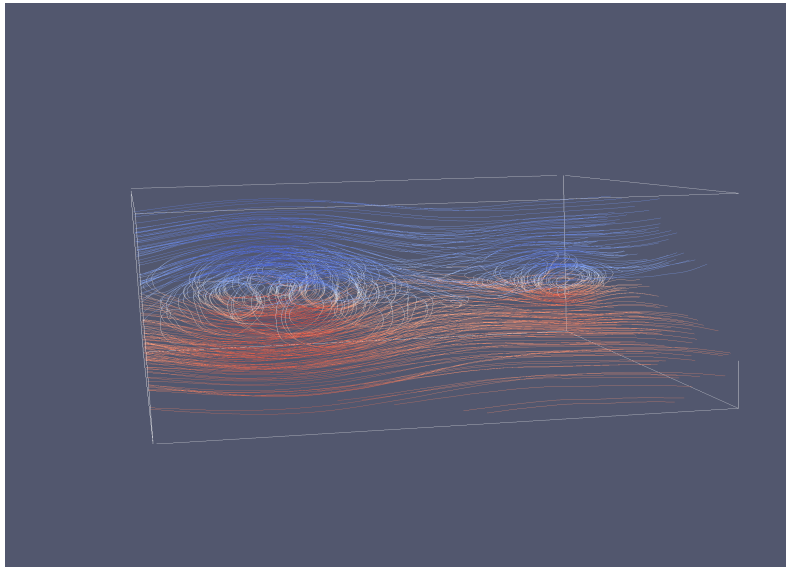
Relativistic Pair Plasma Reconnection in 3D

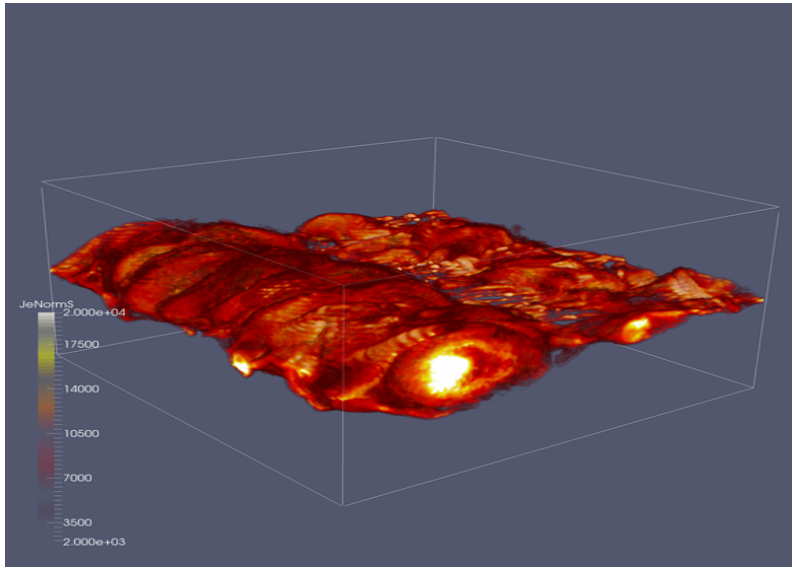
(Werner & Uzdensky ApJ Lett., 2017)

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: $\sigma_{hot} = B_0^2/(4\pi\, n\, \theta_e mc^2) = 25$]

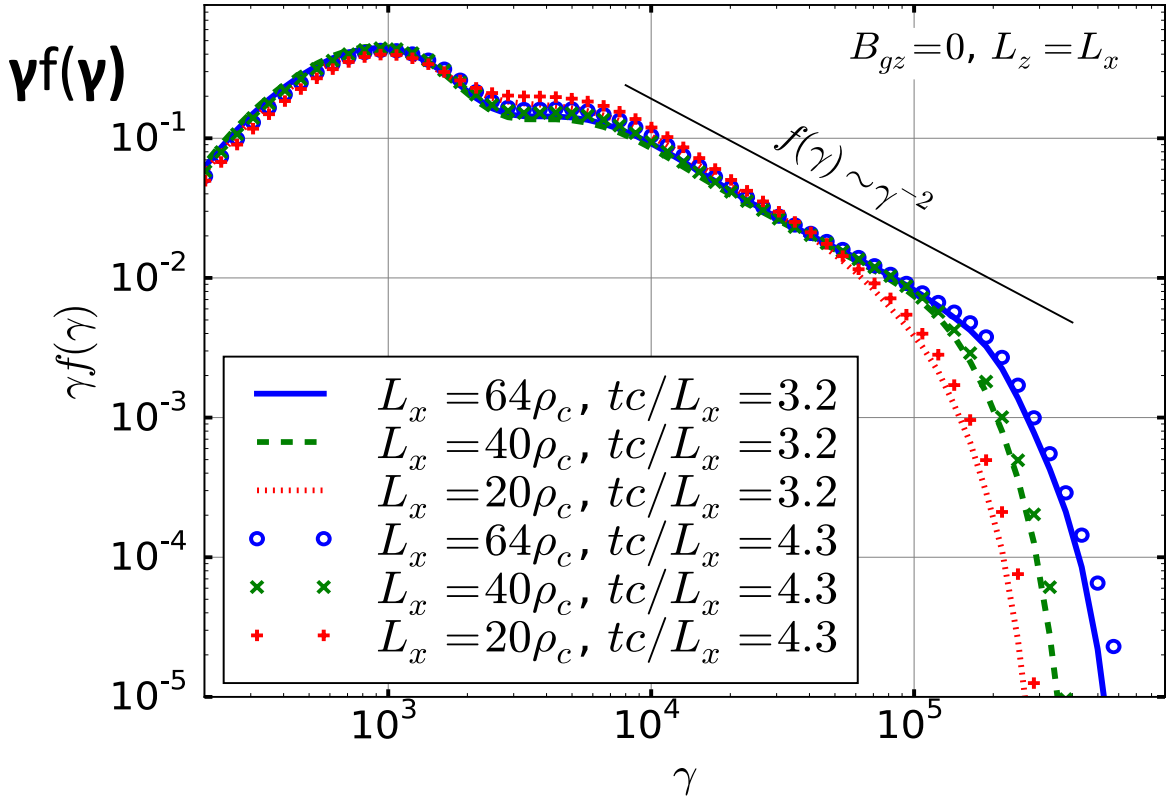




Relativistic Pair Plasma Reconnection in 3D

(Werner & Uzdensky 2017)

Particle spectra for different L_x: box-size dependence



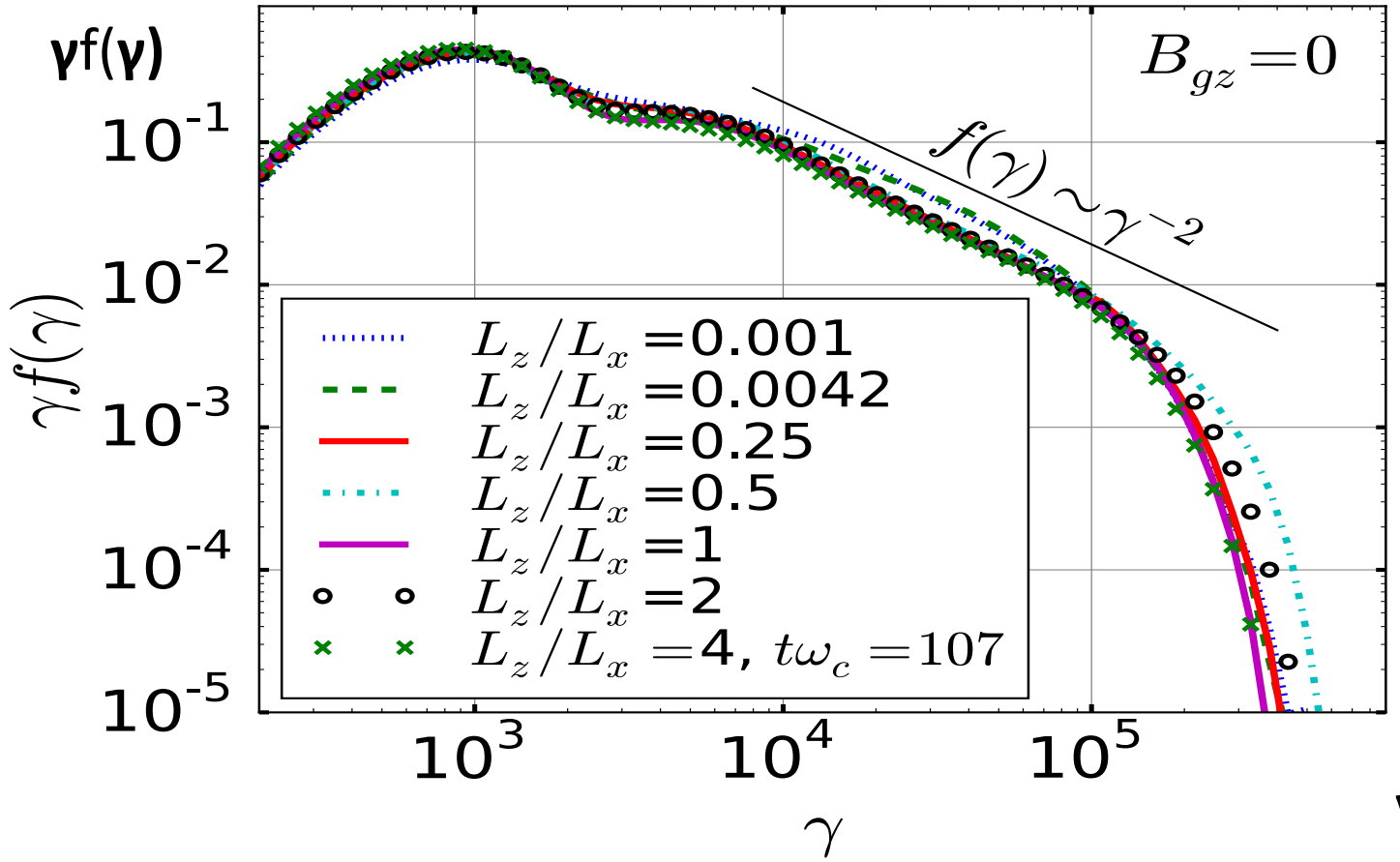
$B_z = 0$

$L_z/L_x = 1$

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

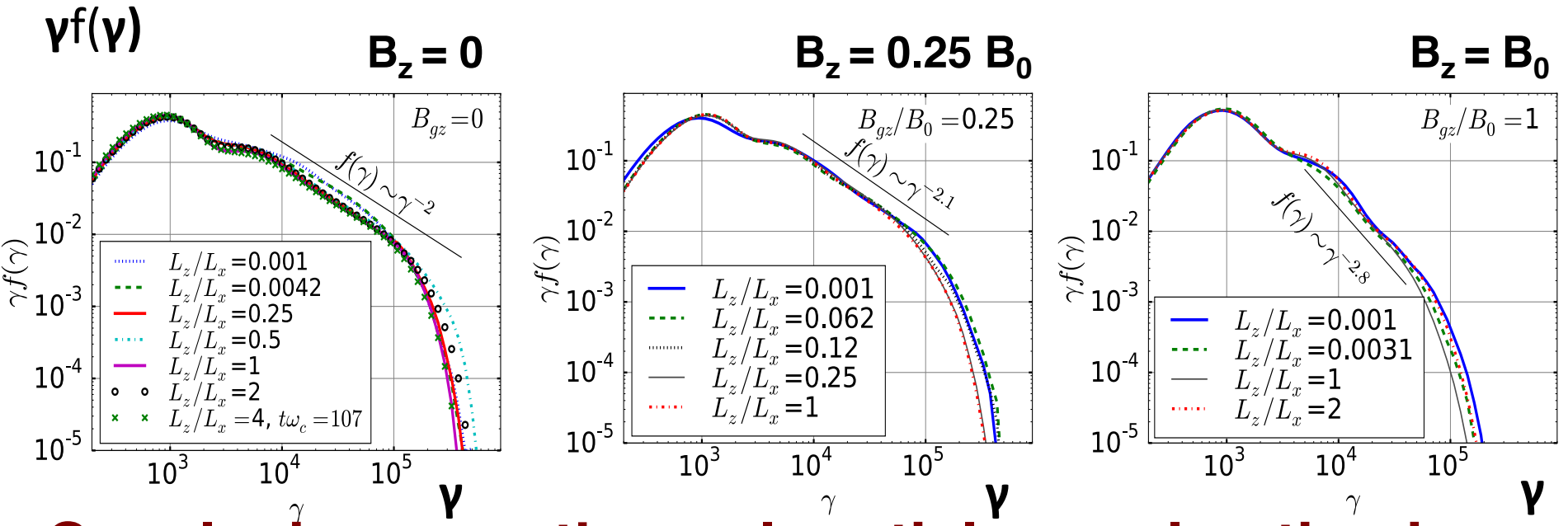


$B_z = 0$

Conclusion: 2D and 3D are fairly similar!

Relativistic Pair Plasma Reconnection in 3D

Does this conclusion depend on guide field?



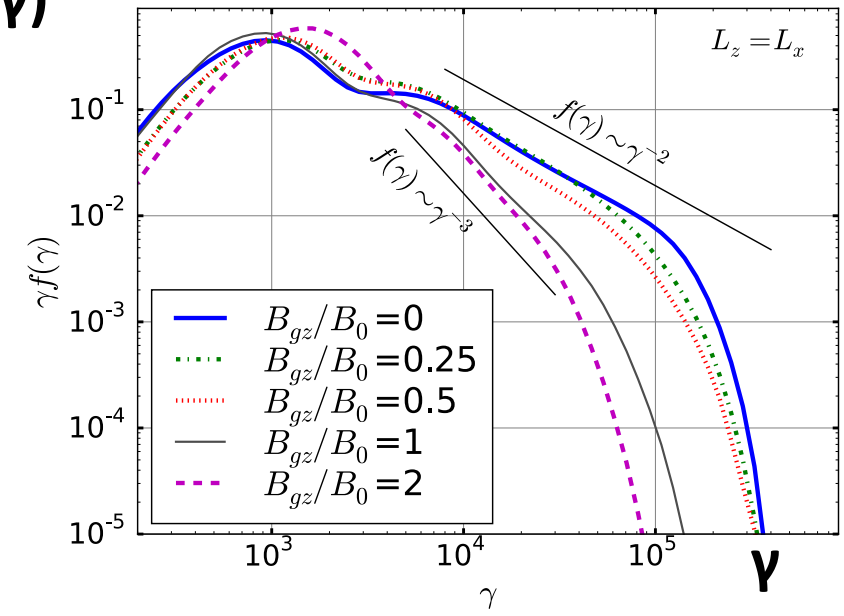
Conclusion: **nonthermal particle acceleration in relativistic pair-plasma reconnection is similar in 2D and 3D for any given guide field.**

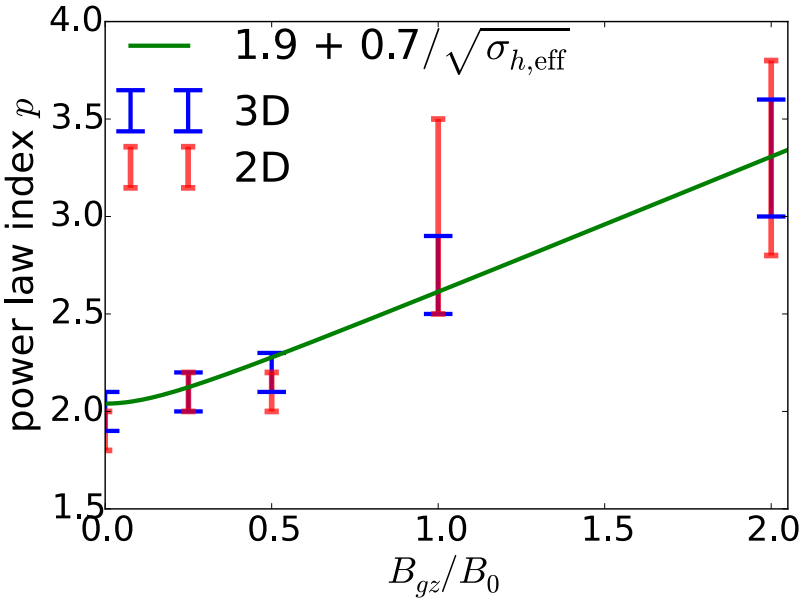
Implication: 2D simulations are sufficient, adequate for studies of NTPA in relativistic pair reconnection.

Relativistic Pair Plasma Reconnection in 3D

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

$\gamma^2 f(\gamma)$



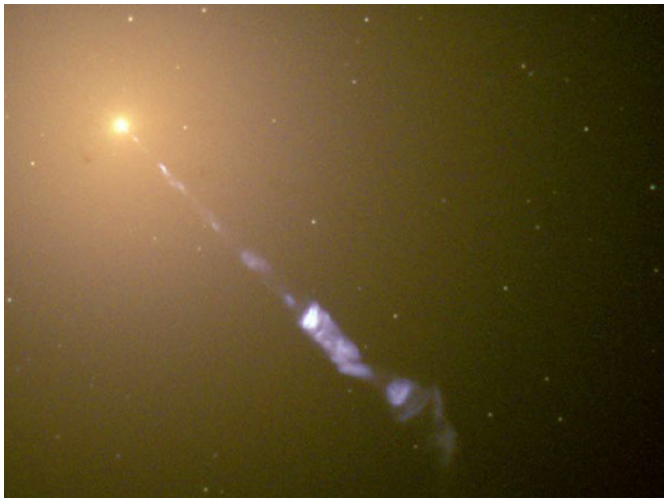


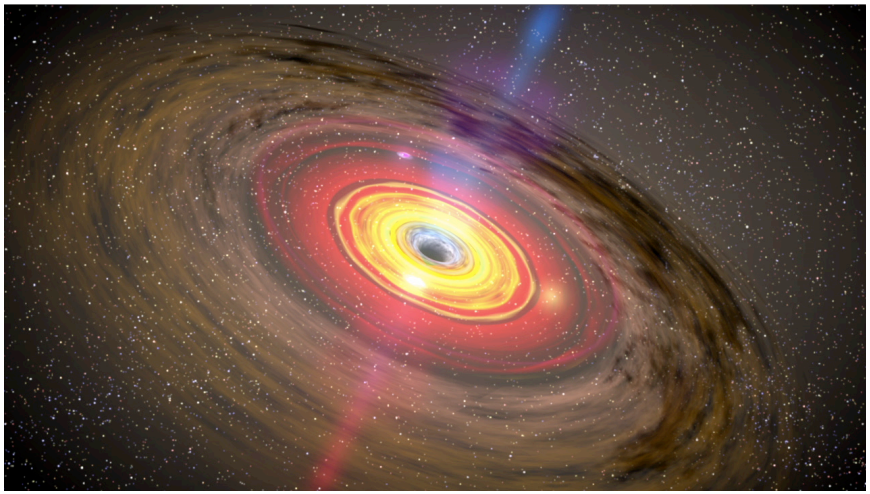
Conclusion: particle acceleration is negatively affected by strong guide field.

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

Relativistic Collisionless Magnetic Reconnection and Nonthermal Particle Acceleration:

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





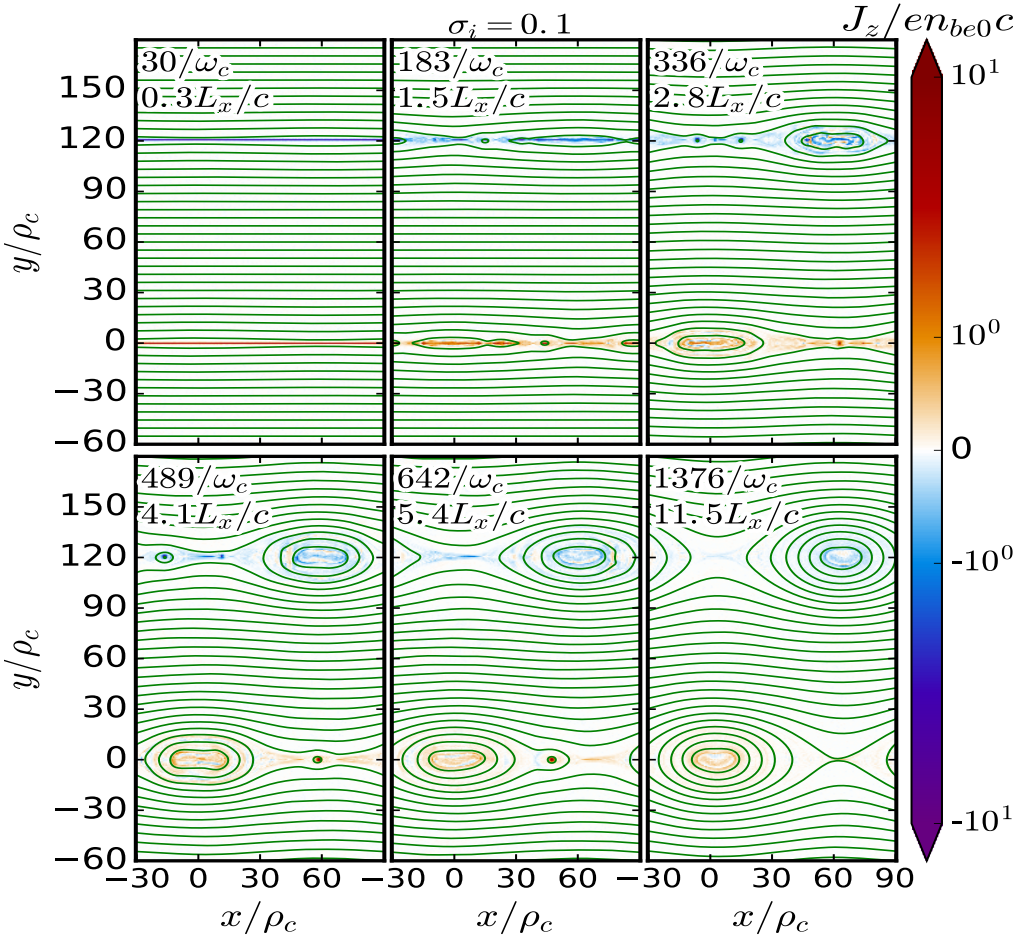
[Black hole accretion flows, accretion disk coronae, jets]

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 ($\sigma_i >> 1$)* ?

Electron-Ion Reconnection in 2D Semi-relativistic and Ultra-relativistic Regimes

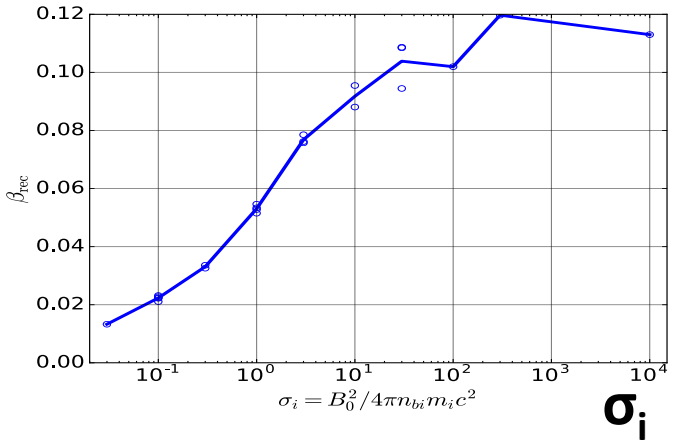


Evolution of magnetic field lines and current density in 2D electron-ion reconnection with σ_i=0.1.

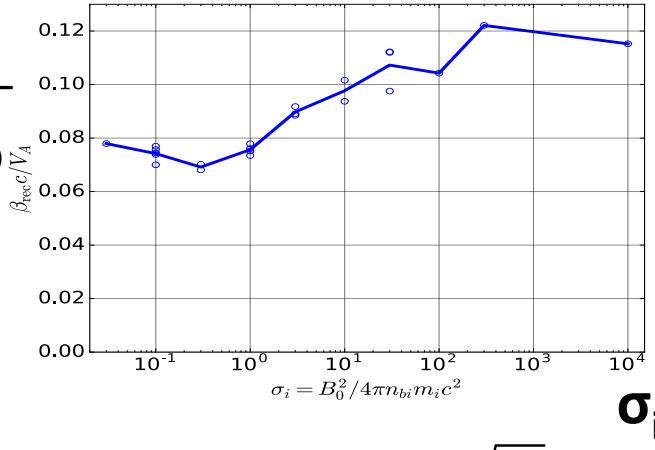
Relativistic *e-i* reconnection: Key PIC Sims Results I

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

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

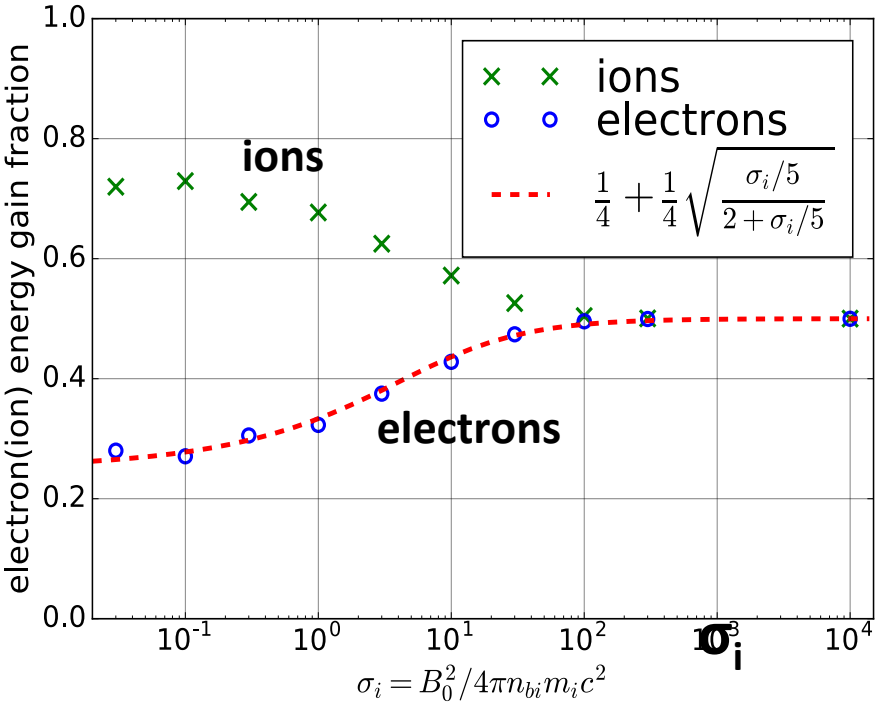


$$\frac{cE}{V_A B_0}$$



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

Energy partitioning between electrons and ions



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

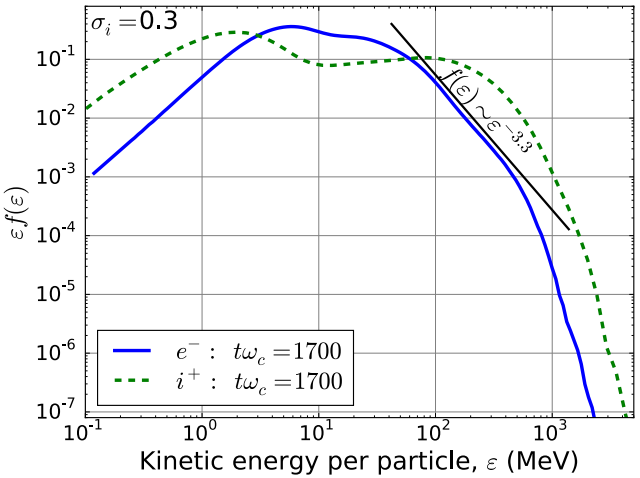
Werner et al. 2016

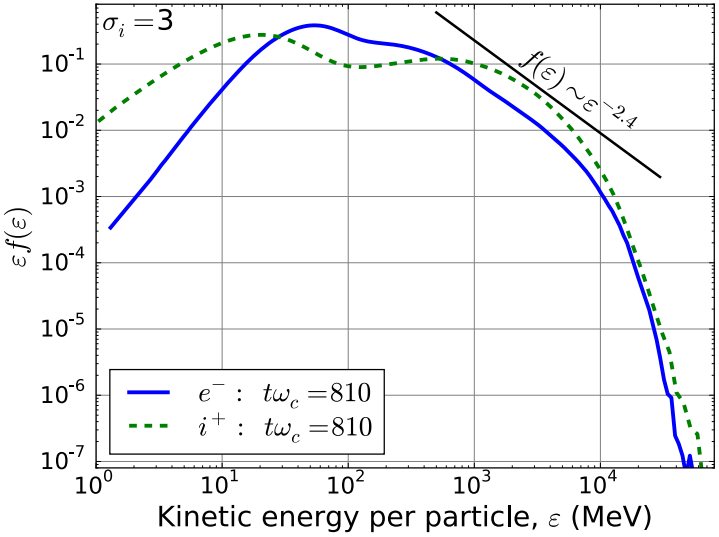
Relativistic *e-i* reconnection: Key PIC Sims Results II

Particle Acceleration:

- electrons: ✔

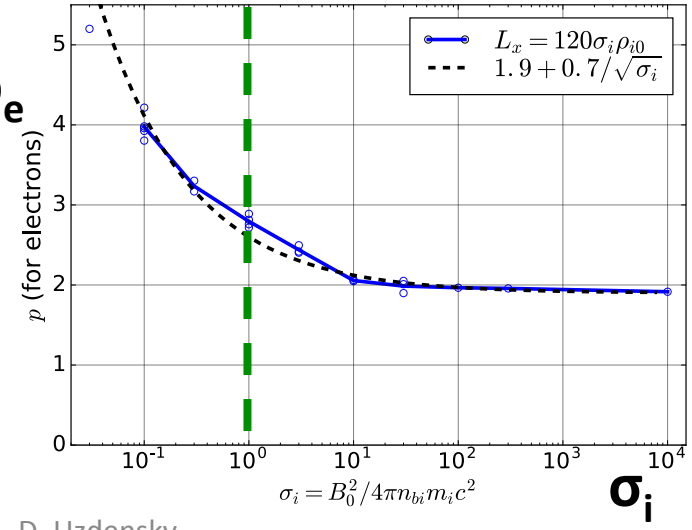
- ions ?



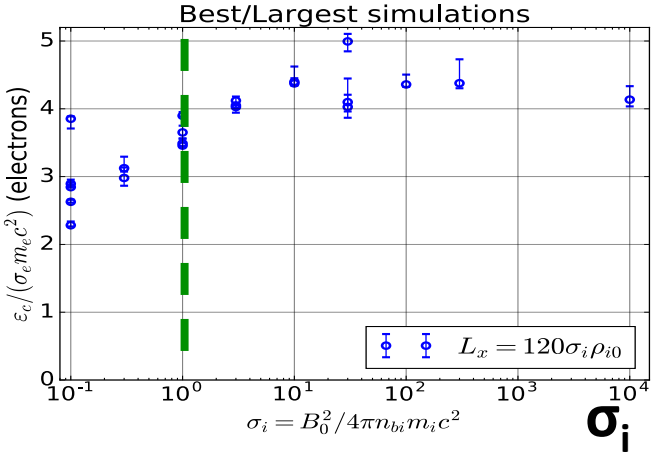


Electron power-law index *p* and cutoff γ_c:

p_e



γ_c/σ_i



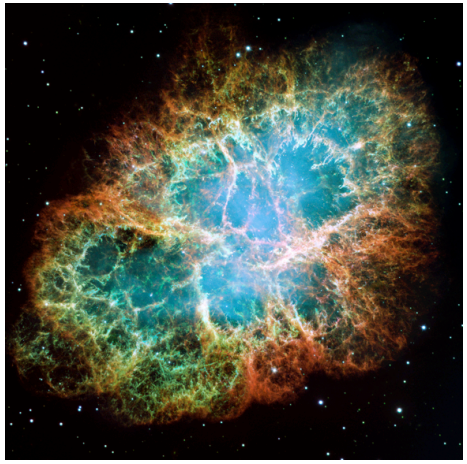
Werner et al. 2016

Kinetic Turbulence in Collisionless Relativistic Plasma

Zhdankin et al. *PRL **118**, 055103 (2017)*

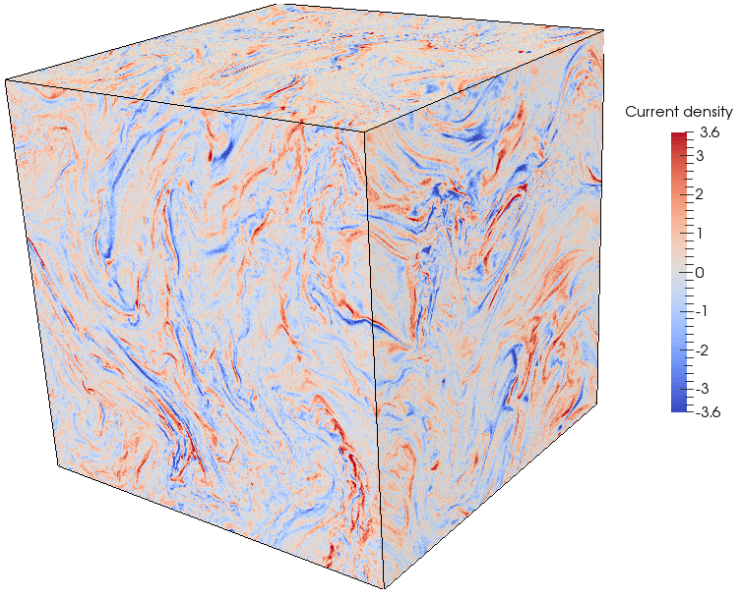
Kinetic simulations of turbulence in relativistic pair plasmas

*V. Zhdankin, G. Werner, D. Uzdensky, M. Begelman (PRL **118**, 055103 2017)*



Crab Nebula (M1): turbulent, magnetized hot, dilute, relativistic pair plasma

3D Particle-in-Cell (PIC) simulations of driven collisionless magnetized turbulence in relativistically-hot pair plasma



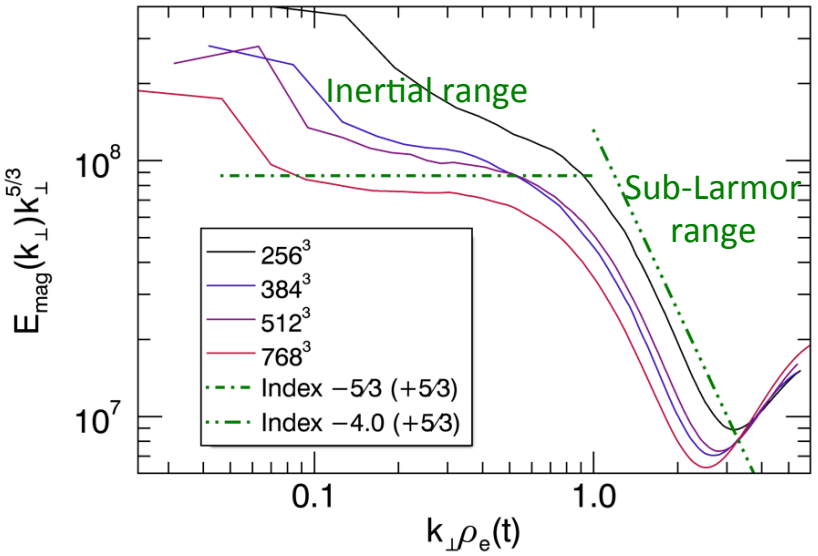
Key Questions:

- What are the statistical properties of turbulence: **power spectra** in inertial (MHD) range (***l* > *ρ*)** and sub-Larmor (kinetic) range (***l* < *ρ*)** ?
- **Is turbulence a viable mechanism for nonthermal particle acceleration?**

Kinetic simulations of turbulence in relativistic pair plasmas: Key Findings

*V. Zhdankin, G. Werner, D. Uzdensky, M. Begelman (PRL **118**, 055103 2017)*

Turbulent magnetic energy spectrum



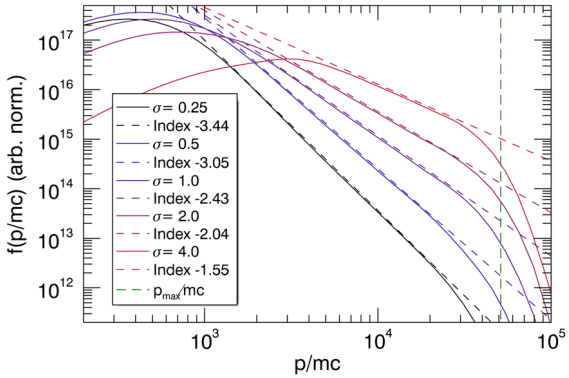
Two dimensionless parameters:

- ratio of system size to Larmor radius: ***L/ρ₀***

(up to ~700)

- initial magnetization: **$\sigma = B_{rms}^2/(4\pi\, n\, \gamma\, mc^2)$**

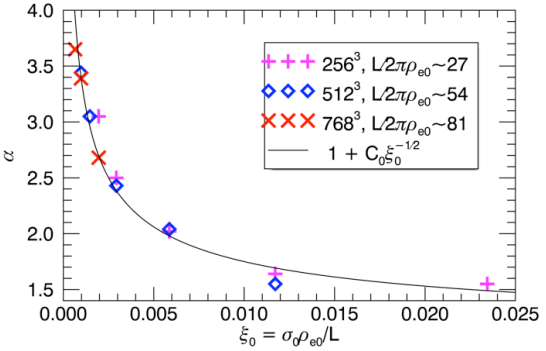
- Non-thermal power-law energy distribution



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

$$E \approx pc$$

- Hardens with increasing magnetization σ
- Steepens with increasing system size L/ρ_e



- Empirical fit:

$$\alpha \sim 1 + C_0(\sigma\rho_e/L)^{-1/2}$$

$$C_0 \approx 0.075$$

SUMMARY

- **PIC simulations** give us a great tool to explore astrophysically-relevant kinetic relativistic plasma processes --- reconnection, turbulence, shocks --- from first principles.
- **Relativistic reconnection** in ***pair*** plasmas produces robust **nonthermal particle spectra** in both **2D and 3D** with power-law index decreasing with magnetization sigma **$\alpha \rightarrow 1$** as L, $\sigma \rightarrow \infty$.
- **Semi-Relativistic** (ultra-rel. electrons, non-rel. ions) and relativistic reconnection in ***electron-ion*** plasma:
  - *electron energy fraction* grows from ~ ¼ to ½ as $\boldsymbol{\sigma_i}$ increases.
  - power-law *electron* spectra, with index ~ $C_1 + C_2/\boldsymbol{\sigma_i^{1/2}}$
  - nonthermal *ion* acceleration is not clear.
- **Kinetic turbulence** in relativistic plasmas:
  - MHD inertial (5/3) and steeper kinetic sub-inertial (~4) energy spectra
  - robust nonthermal particle acceleration with index $\alpha \sim 1 + C_0(\sigma\rho_e/L)^{-1/2}$
- **Radiative Plasma Astrophysics** as a new frontier!