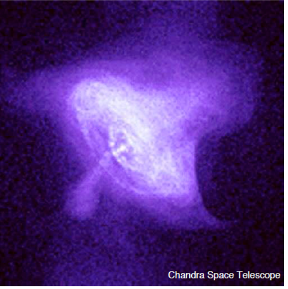
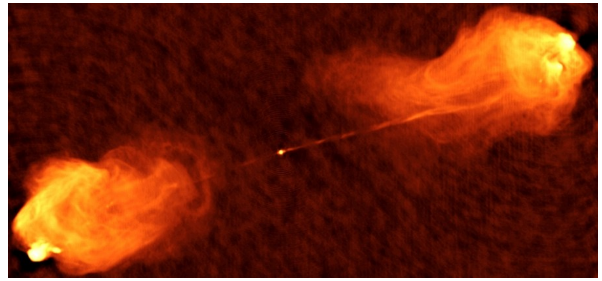
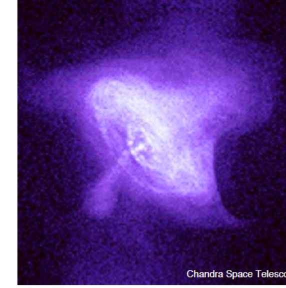






Relativistic Nonthermal Particle Acceleration in Magnetic Reconnection

Dmitri Uzdensky

(University of Colorado Boulder)

<u>Thanks to Univ. Colorado Theoretical Plasma Astrophysics Group</u>:

- Greg Werner
- Vladimir Zhdankin
- Mitch Begelman

(support by NSF, NASA, DOE)

3rd Purdue Workshop, May 8, 2018

OUTLINE:
Theory of NTPA In Magnetic Reconnection

- Physical Picture and Assumptions.
- Empirical (numerical) Knowledge Base.
- Key Ingredients of the Kinetic Equation:
  - Acceleration by reconnection electric field;
  - Magnetization by reconnected magnetic flux: (*power-law slope*)
  - Trapping in plasmoids: (*high-energy cutoff*)
- Effects of Guide magnetic Field
- Conclusions
- (Radiative Turbulence)

Physical Picture: Reconnection

- Plasmoid-dominated magnetic reconnection plasmoid chain, characterized by a plasmoid distribution function $F(w)$ and a cumulative distribution $N(w)$:

$$N(w) = \int_{w}^{w_{\max}} F(w')dw'$$

- Reconnection may or not be relativistic.
- Reconnection rate: $E_{rec} = \beta_{rec} B_0 = \varepsilon V_A B_0/c = \varepsilon \beta_A B_0$

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

  - "Hot" magnetization: $\boldsymbol{\sigma_h = B_0^2/(4\pi\, nh)}$; h = relativistic enthalpy per particle.

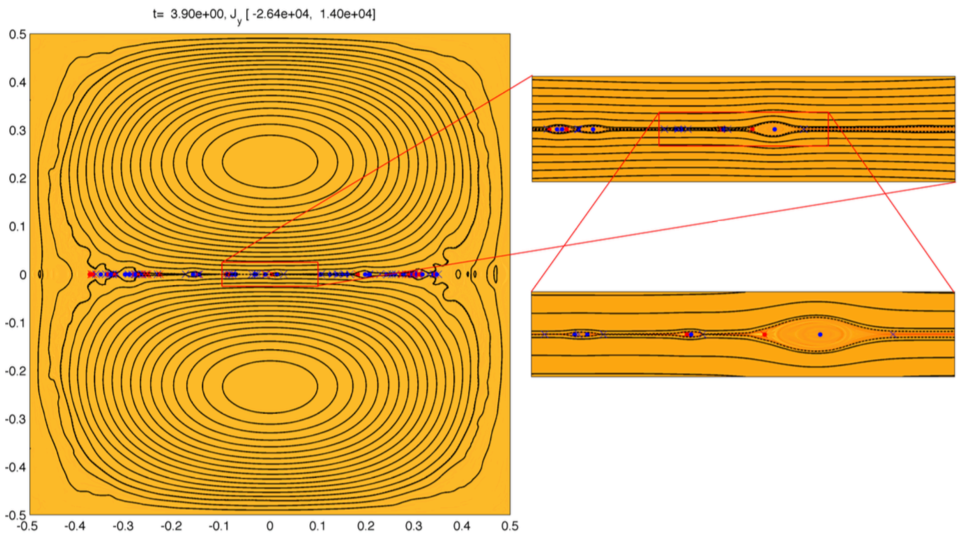
    rel. limit: $\boldsymbol{\sigma}_h \gg 1 \rightarrow V_A \sim c$

    non-rel. limit $\boldsymbol{\sigma}_h \ll 1 \rightarrow \beta_A = V_A/c \sim \boldsymbol{\sigma}_h^{1/2} \ll 1$.

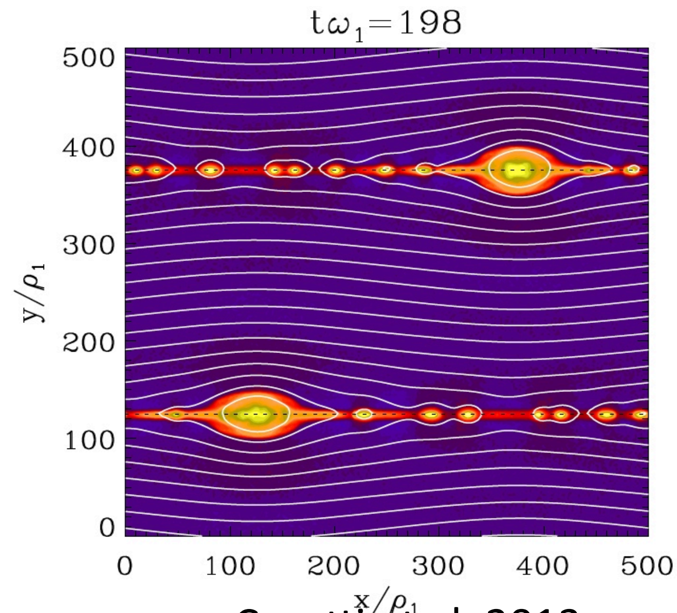
  - I will also use cold $\boldsymbol{\sigma = B_0^2/(4\pi\, n_b\, mc^2)}$

- But particles under consideration are ultra-relativistic.

Self-similar hierarchical plasmoid chain



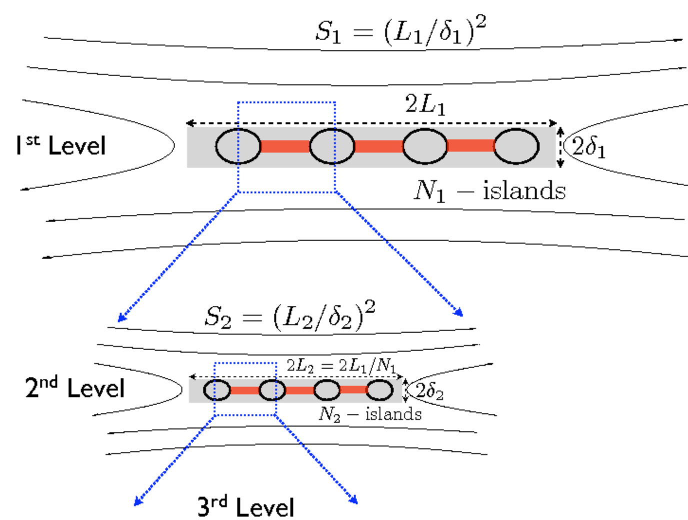
Bhattacharjee et al. 2009



Cerutti et al. 2013

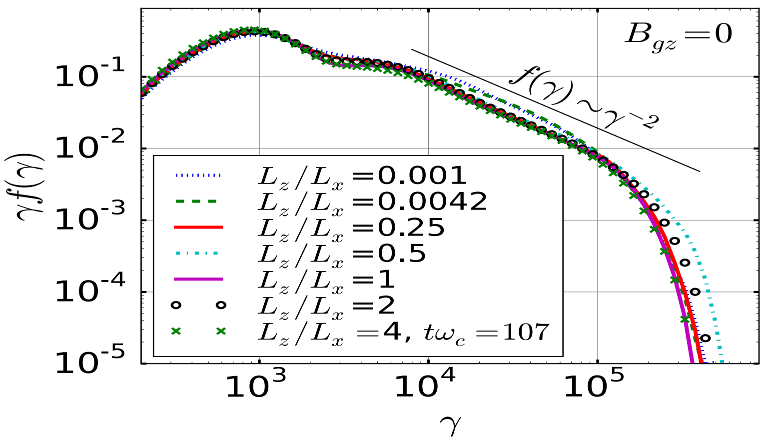
Two Phases of Reconnected Magnetic Field:

- of order $B_1 = \varepsilon B_0 = 0.1\ B_0$ in current sheets
- of order B_0 in plasmoids



Dimensionality

- Real world is 3D.
- However, recent PIC simulations of relativistic pair-plasma reconnection (Werner & Uzdensky 2017, also Sironi & Spitkovsky 2014, Guo et al. 2015) show that 2D and 3D give the same NTPA.



- (However, for non-relativistic electron-ion plasma reconnection, 2D and 3D NTPA may be different, see Dahlin et al. 2015-2017.)
- Thus here we will consider 2D reconnection.
- Direction perpendicular to current sheet: particles confined to the sheet by reconnecting magnetic field → consider only motion along the sheet.

Basic Picture

- While they are unmagnetized, energetic particles are accelerated by the main reconnection electric field E_{rec}.
- This steady acceleration proceeds until a particle is captured by the reconnected magnetic field.
- Reconnected magnetic field is bimodal:
  - ~ $B_1 \sim \varepsilon B_0 \sim 0.1 B_0$ in inter-plasmoid current layers;
  - ~ B_0 in circularized plasmoids [with size distribution F(w)]
- We will treat magnetization in B_1 and trapping in plasmoids separately.

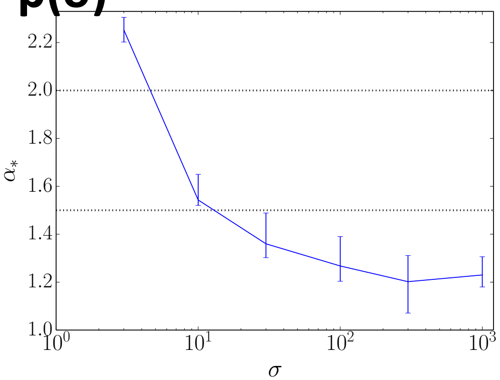
Empirical Numerical Properties of Reconnection-driven relativistic NTPA

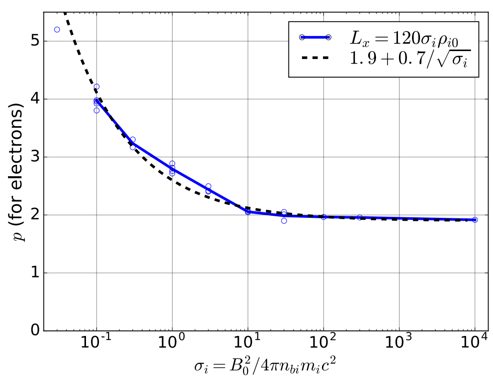
Power-law index *p*

- *p* scales with $\boldsymbol{\sigma}_h$ as

$$p \sim C_1 + C_2 / \boldsymbol{\sigma}_h^{1/2}$$

p(σ)



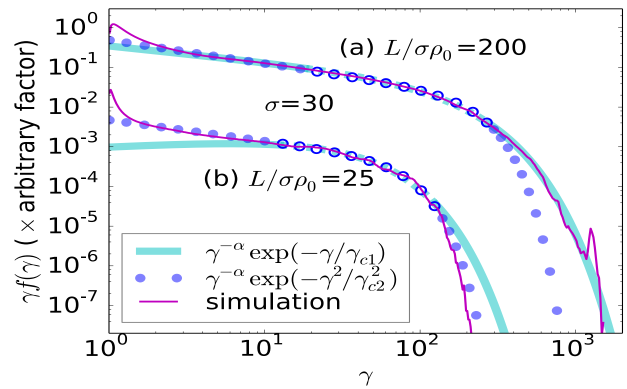


pair plasma:
Werner et al. 2016

electron-ion plasma:
Werner et al. 2018

High-energy cutoff

(Werner et al. 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}); **$\gamma_{c1} \sim 4\sigma$,**

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

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

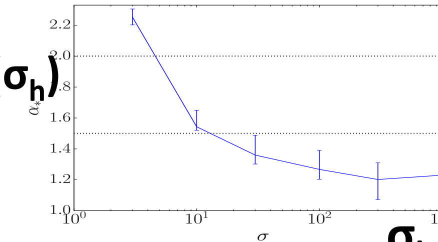
(guide magnetic field suppresses NTPA, see below)

High-Energy Power-Law Cutoff

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

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

$\alpha_*(\sigma_h)$



σ_h

Two high-energy cutoffs:

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

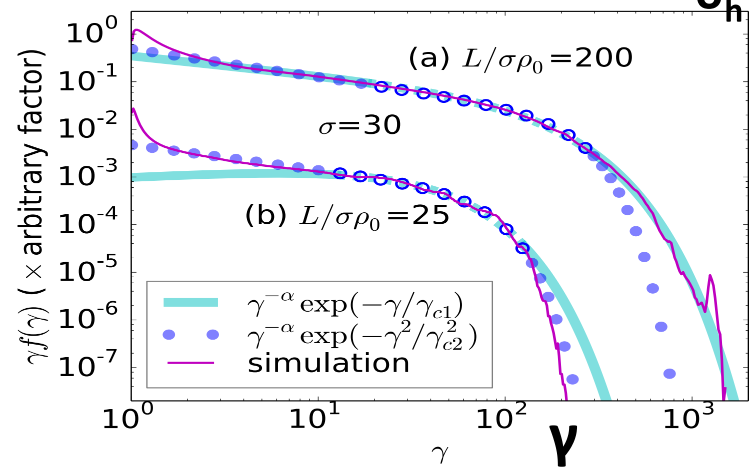
- independent of L;

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

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

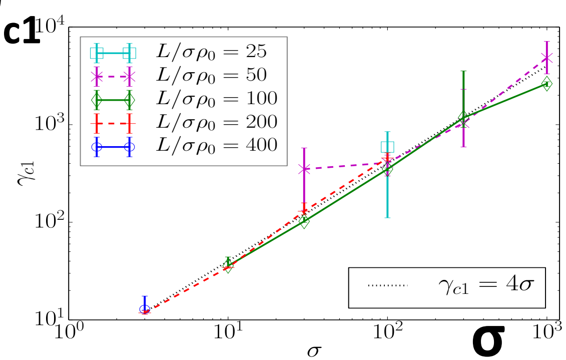
- independent of σ.

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



γ

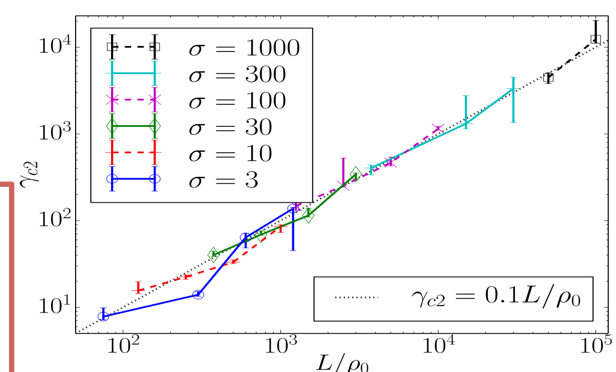
γ_{c1}



σ

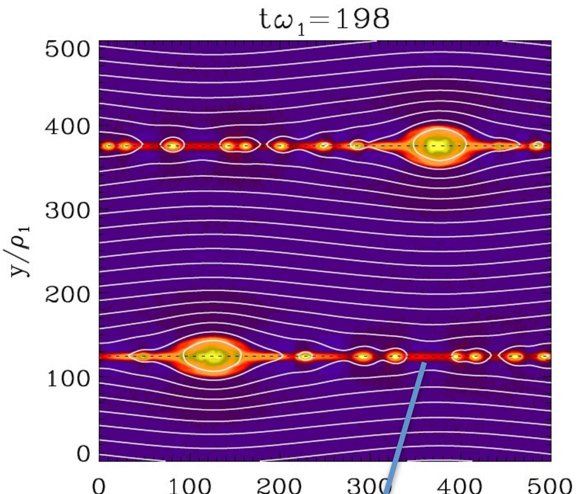
($\rho_0 = m_e c^2 / e B_0$) γ_{c2}

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

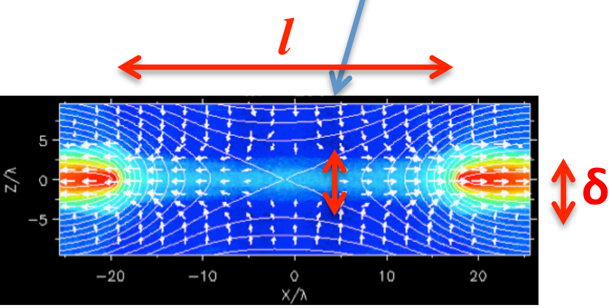


L/ρ_0

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 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: $\boldsymbol{\delta} \approx \rho(\langle\gamma\rangle) = \langle\gamma\rangle \rho_0 \approx \boldsymbol{(\sigma/3)\, \rho_0}$.
- Thus, $\boldsymbol{l/\rho_0 \approx 100\, \delta/\rho_0 \approx 30\, \sigma}$ **=>** $\boldsymbol{\gamma_0 = 3\, \sigma}$.

Further particle acceleration is possible, e.g., in plasmoid mergers, but this 2nd-stage reconnection acceleration occurs with lower sigma and smaller *L*.

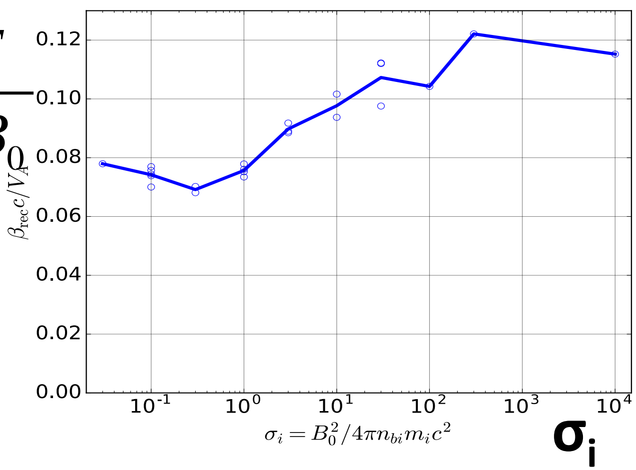
Relativistic *e-i* reconnection: Key PIC Sims Results I

Werner et al., MNRAS 2018; arXiv:1612.04493

Systematic 2D PIC study:
(no guide field, m_i/m_e=1836)

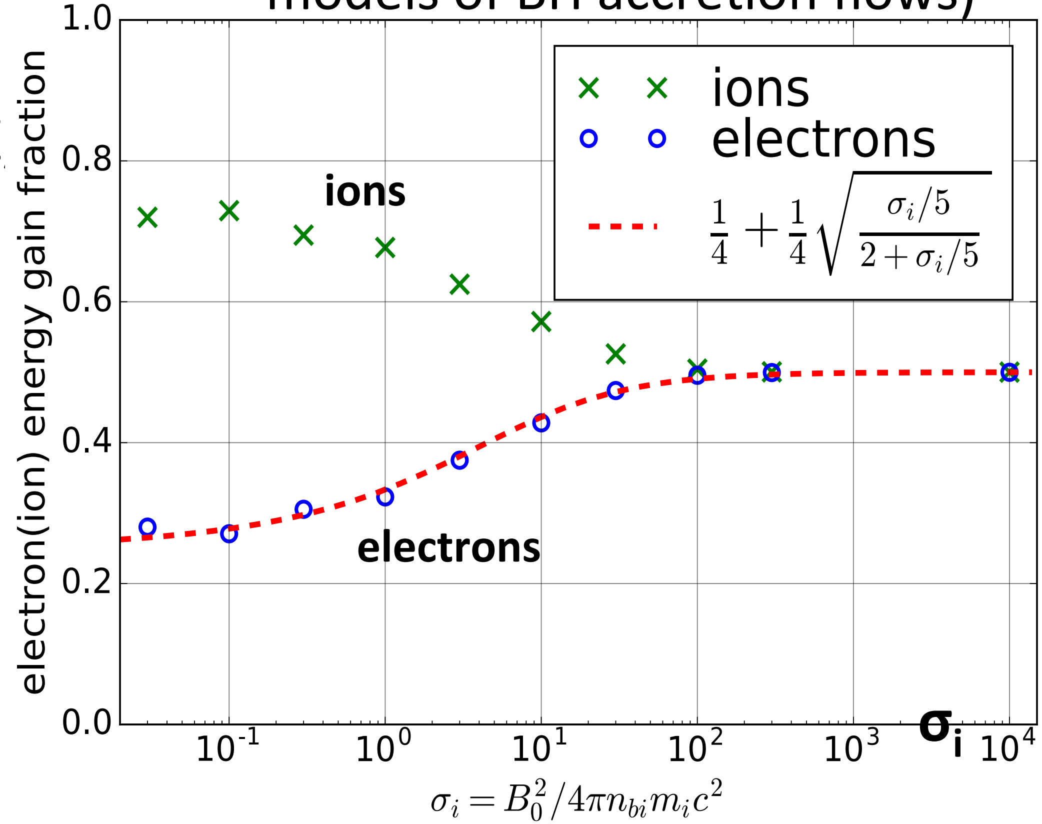
Reconnection rate: $v_{in}/c = E$

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



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

Energy partitioning between electrons and ions
(useful prescription for GRMHD models of BH accretion flows)



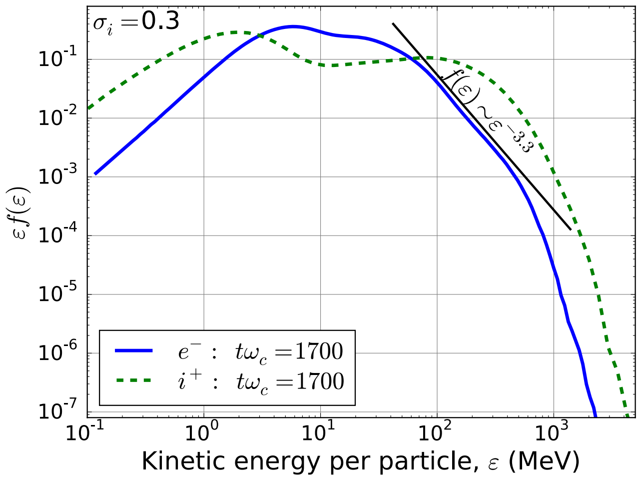
In semi-relativistic case ions gain 3 times more energy than electrons.

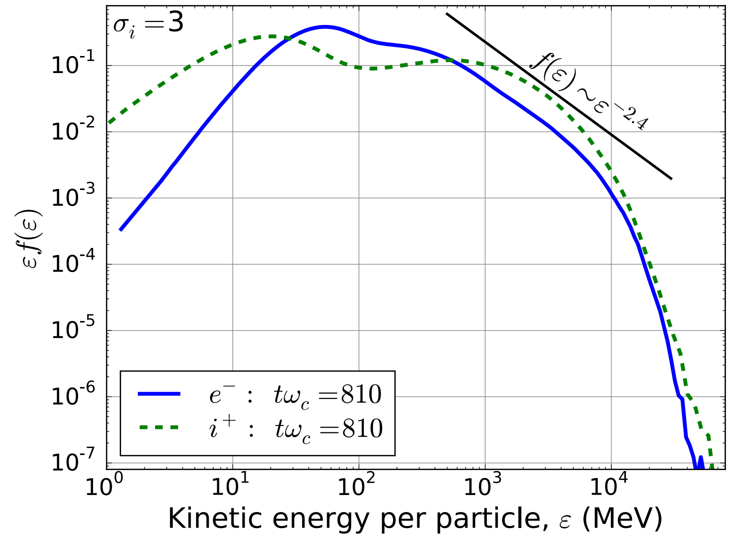
Relativistic *e-i* reconnection: Key PIC Sims Results II

Particle Acceleration:

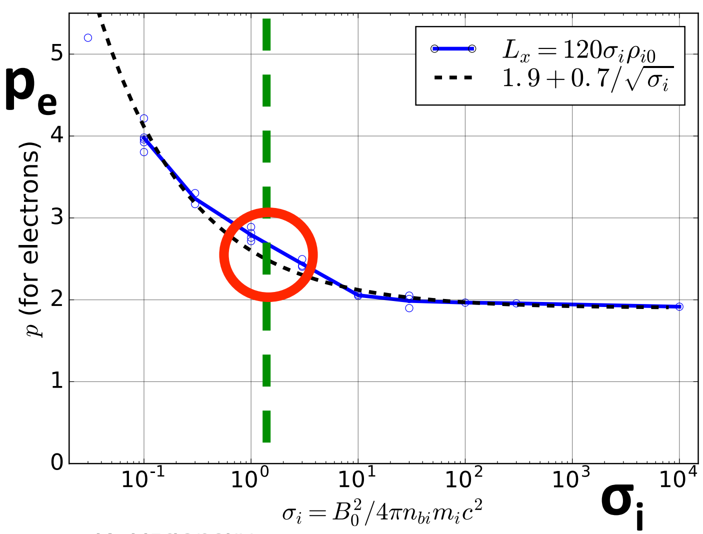
- electrons: ✔

- ions ?

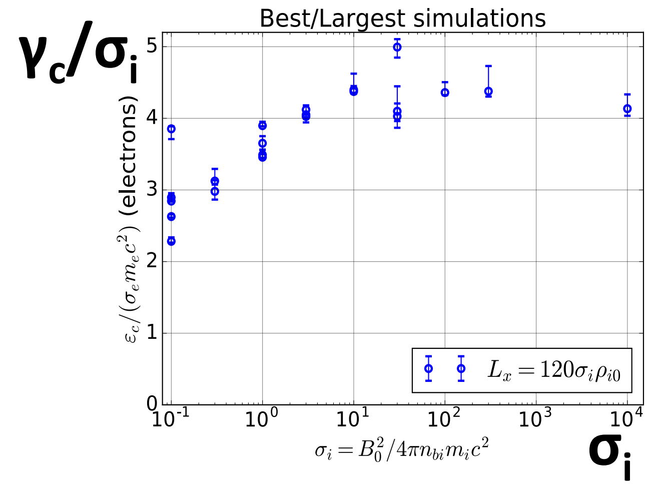




Electron power-law index *p* and cutoff γ_c:



Observed blazar p_e~2-3 imply $\boldsymbol{\sigma_i}$~1, consistent with expectations from MHD jet models.



Werner et al. 2018

Kinetic Equation

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

Key Ingredients:

- Acceleration by main 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-field (--> power-law):

$$\tau_{\rm mag}(\gamma) \sim \ell_{\rm mag}/c \sim \epsilon^{-1} \gamma \Omega_0^{-1}$$

- Trapping by large [w > $\rho_L(\gamma)$] plasmoids (→ cutoff):

  τ_{tr} controlled by plasmoid distribution function (below)

Steady State Kinetic Equation

- Since $\dot{\gamma}_{acc}$ is independent of γ, we get

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

- Solution:

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

where $$\frac{1}{\tau(\gamma)} = \frac{1}{\tau_{\rm magn}(\gamma)} + \frac{1}{\tau_{\rm trap}(\gamma)}$$

Magnetization by Reconnected Field and NTPA power law

- Energetic particle passes right through small plasmoids.
- Distance a particle travels before being magnetized

  $l_{mag}(\gamma) \sim \rho_L (\gamma, B_1) = (B_0/B_1)\, \rho_L (\gamma, B_0) = \varepsilon^{-1} \rho_0\, \gamma$
- magnetization time-scale $\tau_{\rm mag}(\gamma) \sim \ell_{\rm mag}/c \sim \epsilon^{-1}\gamma\Omega_0^{-1}$

- Balance magnetization with acceleration in kinetic eqn:
- power-law solution $f(\gamma) \sim \gamma^{-p}$
- power-law index: $p = p(\sigma_h) \sim \frac{1}{\beta_A} = \sqrt{\frac{1+\sigma_h}{\sigma_h}}$
  - ultra-rel (σ_h>>1): p → const (cf. Zenitani & Hoshino 2001)
  - non-rel. case (σ_h>>1): $p \sim \sigma_h^{-1/2}$ (c.f., Werner et al. 2018)

Plasmoid Chain I: single power-law

- Energetic particles can be trapped in *large* plasmoids when $w = w(\gamma) = \rho_L(\gamma) = \rho_0\,\gamma$ **($\rho_0 = m_e c^2/e B_0$)**
- **High-energy cutoff** is controlled by plasmoid distribution function $F(w) = -\,dN/dw$.
- $\tau_{tr} = \lambda_{pl}(w)/c$

where $\lambda_{pl}(w)$ is separation between plasmoids of size w:

- $\lambda_{pl}(w) = L/N(w)$
- Thus $\tau_{tr} = L/c\,N(w)$

Single-Power-law plasmoid chain

- Consider for illustration: $F(w) \sim w^{-\alpha}$ for $w < w_{max}$
- Cumulative distribution: $N(w) \sim (w/w_{max})^{1-\alpha}$

[where $N(w_{max}) = 1$]

$$\tau_{\rm trap}^{-1}(\gamma) \sim \frac{c}{L} N[w(\gamma)] \sim \frac{c}{L} \left(\frac{\gamma}{\gamma_{\rm max}}\right)^{1-\alpha} , \quad \alpha \neq 1$$

where $\gamma_{max} = w_{max}/\rho_0$

- Special case $\alpha = 2$: $\tau_{trap} \sim \gamma$ (same as for magnetization - later)
- Trapping rate overtakes magnetization at

$$\gamma_c = \gamma_{\rm max} \left(\frac{w_{\rm max}}{\epsilon L}\right)^{\frac{1}{\alpha-2}} .$$

- For $w_{max} \sim \varepsilon L$: $\gamma_c \sim \gamma_{max}$

Establishing Cutoff

- Balancing acceleration against trapping in plasmoids:

$$f(\gamma) \sim \exp\left[-\frac{w_{\max}}{\epsilon\beta_A L(2-\alpha)}\left(\frac{\gamma}{\gamma_{\max}}\right)^{2-\alpha}\right]$$

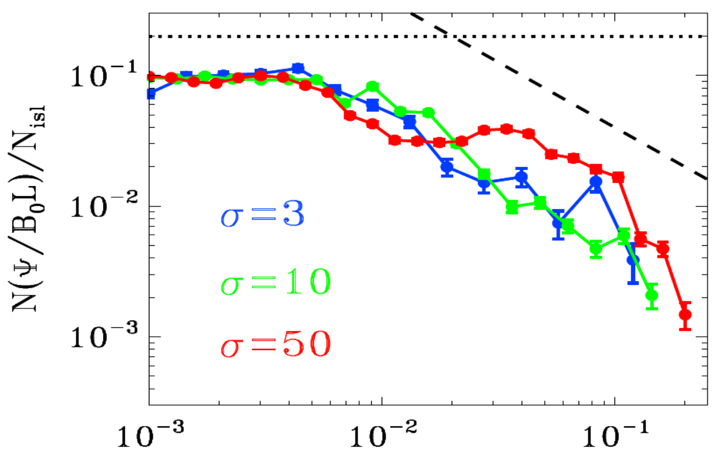
- Special case $\alpha \sim 1$ (ignoring log-corrections)

$$f(\gamma) \sim \exp\left[-\frac{\rho_0}{L}\frac{1}{\beta_A\epsilon}\gamma\right] = \exp(-\gamma/\gamma_{c1})$$

- where $\gamma_{c1} \equiv \beta_A\epsilon\frac{L}{\rho_0} \simeq \beta_A\frac{w_{\max}}{\rho_0}$ (can be $< \gamma_{max}$, if $\beta_A < 1$)
- Special case $\alpha=2$: no cutoff but another power-law: $p \simeq \frac{1}{\epsilon\beta_A}\frac{w_{\max}}{L}$
  - For $w_{max} \sim \varepsilon L$: $p \sim \beta_A^{-1}$ (~same as without plasmoids)
  - Combined with magnetization: → steeper (by x2) power law.

Plasmoid Chain II: Realistic double-power-law

- Real simulations show double-power-law plasmoid distributions (Loureiro et al. 2012, Huang et al. 2013, Sironi et al. 2016, Petropoulou et al. 2018)



$$F \sim w^{-\alpha_1} \quad , w < w_c$$

$$F \sim w^{-\alpha_2} \quad , w_c < w < w_{\max}$$

$$N(w < w_c) = N_c \left(\frac{w}{w_c}\right)^{1-\alpha_1}$$

$$N(w > w_c) = \left(\frac{w}{w_{\max}}\right)^{1-\alpha_2}$$

$$\gamma_{\rm cutoff} = \gamma_c \left(\frac{w_c}{\epsilon\lambda_c}\right)^{\frac{1}{\alpha_1 - 2}} \sim \gamma_c = w_c/\rho_0$$

Most likely: $\alpha_1 \approx 1$, $\alpha_2 \approx 2$

For $\alpha_1 \approx 1$: $\gamma_{\rm cutoff} = \gamma_c \left(\frac{\epsilon\lambda_c}{w_c}\right) \sim \gamma_c$

Important Question:

What controls w_c?

If $\alpha_2 \approx 2$: possible 2nd (steeper) power law above spectral break at γ_c

Important Question:

What controls w_c?

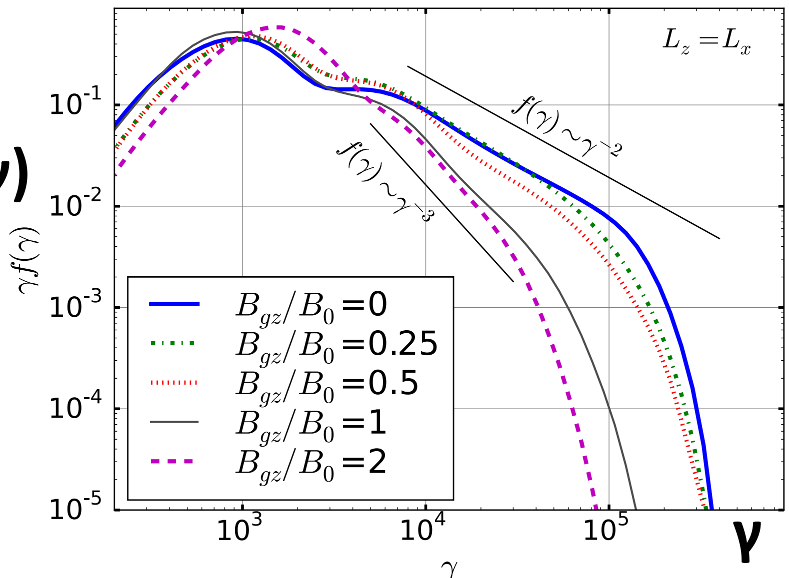
- Consider large-system regime: $L \gg \delta \sim \langle\rho\rangle \sim \sigma\, \rho_0$
- The plasmoid distribution break size w_c may be anywhere between microscopic $\sim \sigma\, \rho_0$ and macroscopic $\sim L$.
- If $w_c \sim \sigma\, \rho_0$, then $\gamma_c \sim \sigma$, e.g., $\gamma_c \approx 4\sigma$ (Werner et al. 2016)
- If $w_c \sim L$, then $\gamma_c \sim L/\rho_0$ -- "extreme" (Hillas) acceleration limit.

Effect of Guide Magnetic Field

(Werner & Uzdensky 2017 ApJL)

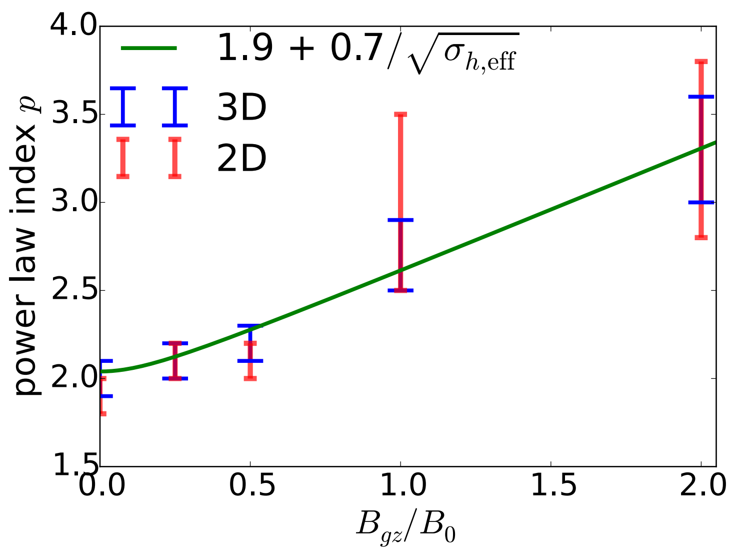
Particle spectra for different B_z/B_0:

$\gamma^2 f(\gamma)$



γ

$L_z/L_x = 1$



Particle acceleration is negatively affected by strong guide field.

<u>*Explanation:*</u> Guide field's ***inertia***: Guide-field needs to be advected out of the layer with the plasma, so guide field's inertia contributes $B_{gz}^2/4\pi$ to the enthalpy in the denominator of σ_h:

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

-- reduces in-plane V_A, hence recn. outflow speed, hence E_{rec}

Conclusions

Relativistic Nonthermal Particle Acceleration (NTPA) in reconnection is an interplay of:

– steady acceleration by reconnection electric field;

checked by "escape" from acceleration zone:

- (1) magnetization by general reconnected magnetic field $B_1 \sim 0.1\, B_0 \rightarrow$ power-law index

$$p \sim (E_{rec}/B_1)^{-1} \sim 1/\,\beta_A \sim [1+\sigma_h)/\sigma_h]^{1/2}$$

- (2) capture/trapping by plasmoids with $w \sim \rho_L(\gamma) = \gamma\, \rho_0$. $\rightarrow$ high-energy cutoff.
- Cutoff depends on plasmoid-distribution function, e.g., for α=1 it is simple exponential with $\gamma_c = w_{max}/\rho_0$.
- Realistic double-power-law F(w): cutoff at break size w_c and
- possible steeper power law (if $\alpha_2 \approx 2$) above w_c

• Guide field's inertia $B_{gz}^2/4\pi$ adds to enthalpy, reduces effective $\boldsymbol{\sigma_h}$