Relativistic Magnetic Reconnection in Jets: Particle Acceleration and Radiation Production

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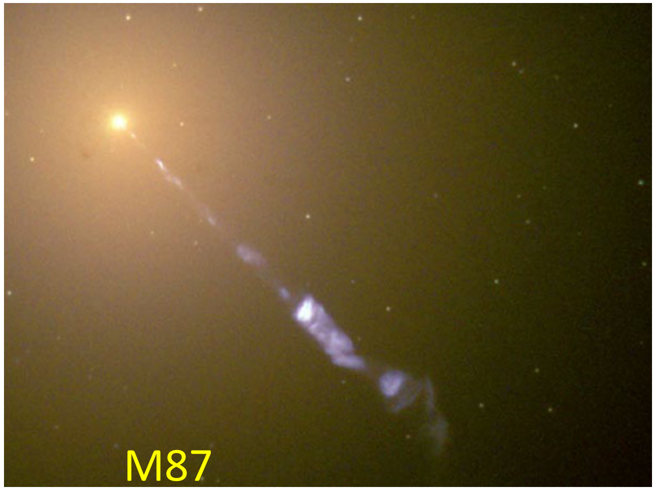
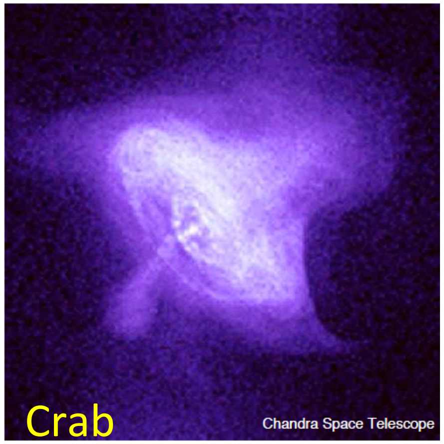
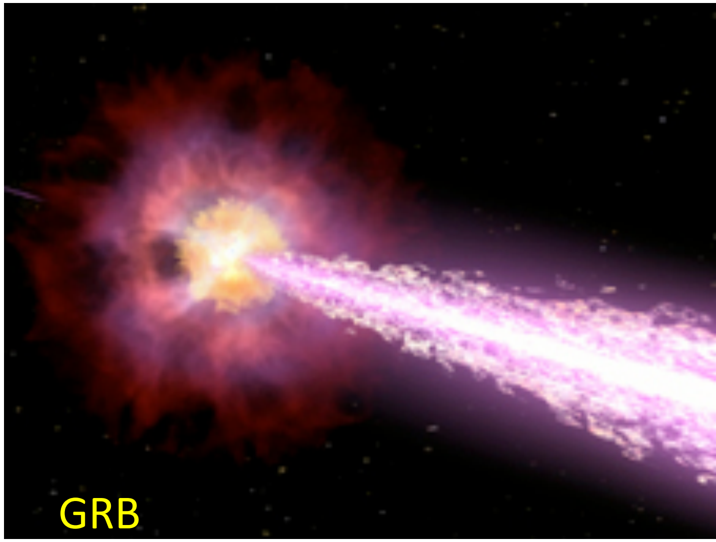
OUTLINE

- ***Introduction: role of reconnection in powering jet emission.***
- ***Particle Acceleration in Relativistic Reconnection:***
  - ***energy spectrum power-law and cutoff;***
  - ***angular anisotropy (kinetic beaming).***
- ***Summary***

Dissipation and emission in astrophysical flows







- Astrophysical jets shine.
- Often, radiative cooling time is << travel time from central source → in-situ dissipation and particle acceleration.
- Distributed emission along jets (we see them!) → *distributed energy dissipation Q(z)*=?

Similarity with Solar Wind

- Similar to the problem of *solar wind heating*:

$T_{sw}(r)$ drops off with distance much slower (~ $r^{-0.7}$ for 1-10 AU) than adiabatic expansion or electron thermal conduction would predict.

- Popular ideas to explain solar wind heating:
  - Gradual dissipation of turbulence caused by *perturbations advected from wind base* (corona);
  - Dissipation of turbulence powered by *in-situ instabilities* (KH between slow and fast wind);
  - Exotic processes: resonant charge exchange pick-up ions.

- *(Are there useful lessons for understanding jets?)*

Paths to Dissipation

AVAILABLE FREE ENERGY

Bulk Kinetic

Magnetic (Poynting flux)

Magnetic reconnection

- longitudinal:

shocks

(e.g., termination shock, colliding shells)

STRUCTURE

current sheets*:*

- advected from central engine

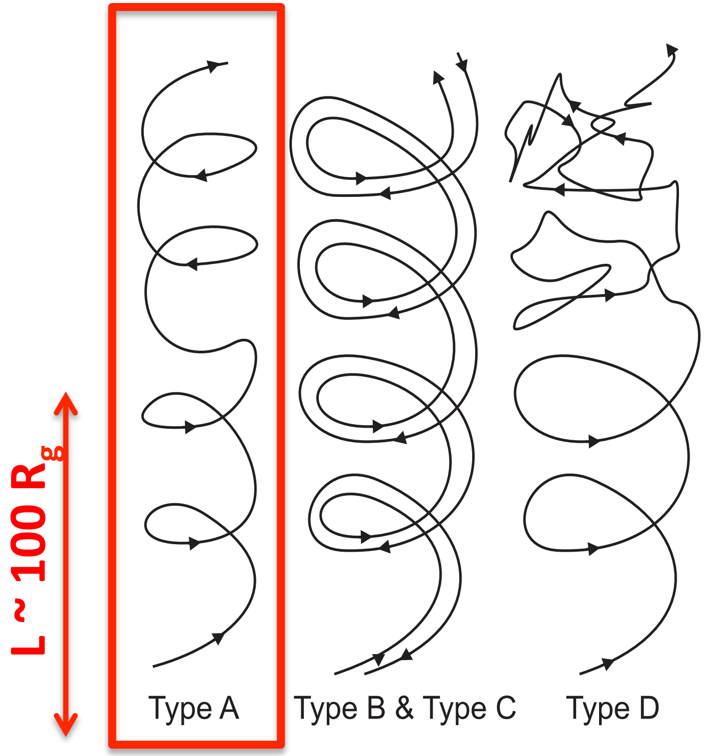
- developing spontaneously, (e.g., kink MHD instabilities)

- transverse:

shear (KH) instability → turbulence

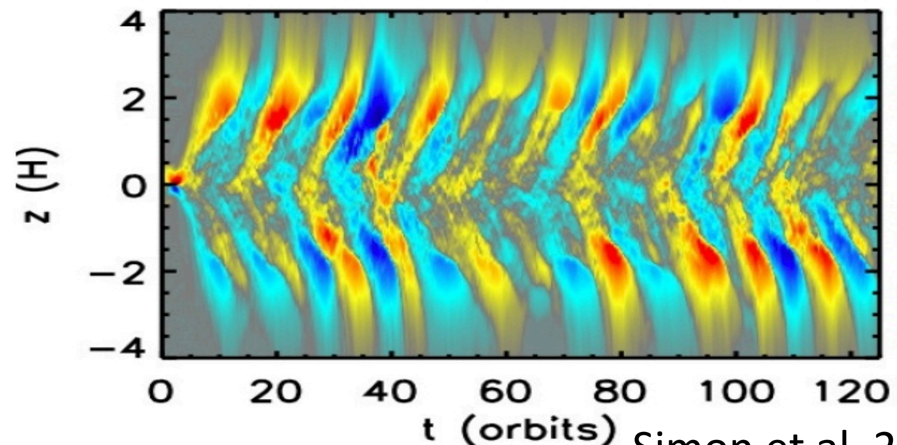
(e.g., boundary btw fast jet and slower wind)

Setting up reconnection in jets: field reversals by disk dynamo



McKinney & Uzdensky 2012

- Reconnection needs current-sheet formation which needs magnetic field reversal.



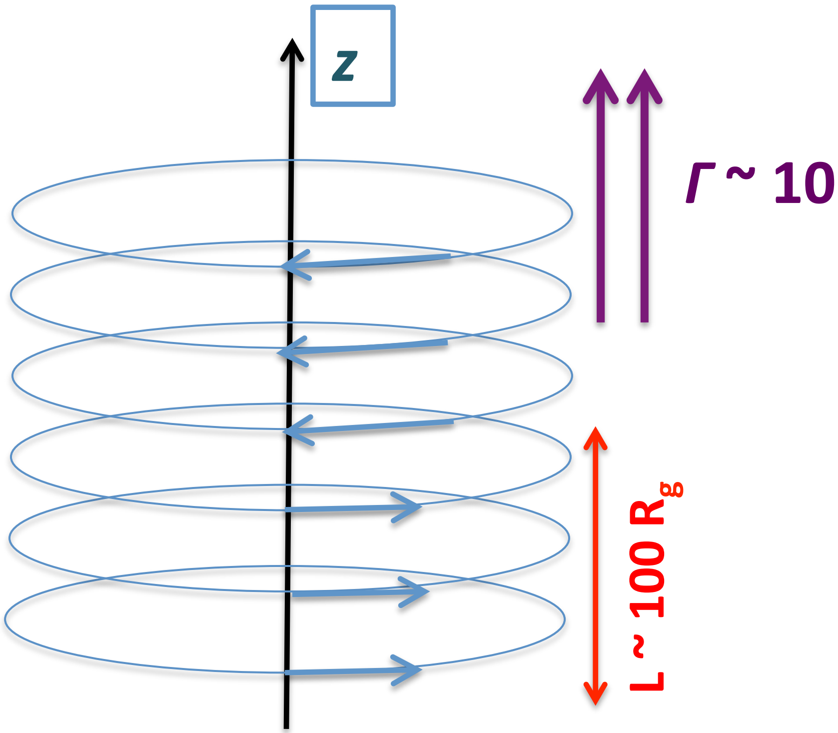
Simon et al. 2012

- Quasi-periodic Magnetic Field reversals due to accretion-disk dynamo cycle *(e.g., Davis et al 2010; O'Neall et al. 2011; Simon et al. 2012)*.
- Reversal Period t ~ 10 P ~ 100 R_g/c.

Similar to 11-year solar dynamo cycle.

Striped Wind Formation and Reconnection Distance

(c.f.: Lyubarsky, Giannios)



As jets propagates and expands:

$$R \sim \vartheta z \gg L = 10^2 R_g,$$

this turns into a striped wind.

How long does it take to reconnect/ dissipate the stripes?

- Length in co-moving frame:
  $L' = \Gamma L$
- Recn. time in comoving frame:
  $t'_{rec} \sim L'/v_{rec} \sim 10\, L'/c \sim 10\, \Gamma L/c$
- Reconnection time in lab frame:
  $t_{rec} \sim \Gamma t'_{rec} \sim 10\, \Gamma^2 L/c$

Dissipation zone length:

$Z_{rec} = c\, t_{rec} \sim 10\, \Gamma^2 L \sim 10^3\, \Gamma^2 R_g \sim 10^5\, R_g$

~ 1 parsec for $M_{BH} = 10^8\, M_O$

Observational Properties of High-Energy Emission in Jets:

- 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 (with a cut-off) in particle energy distribution that extends to energies ε_{max} >> <ε> (averaged released energy per particle). (e.g., $\langle\varepsilon\rangle \sim B^2/8\pi n \sim \sigma\, mc^2$ for reconnection).

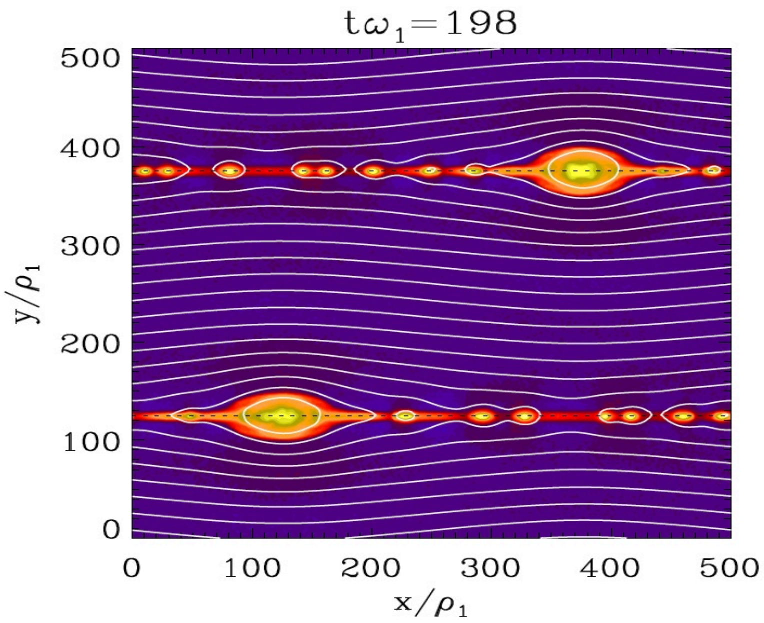
- Intense rapid gamma-ray flares →

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

Can reconnection explain these properties?

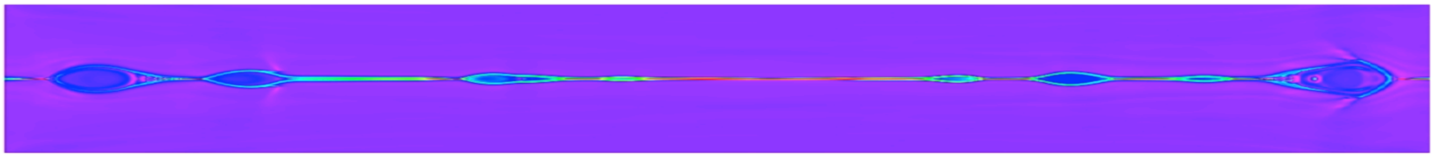
(Yes)

Relativistic Collisionless Magnetic Reconnection and Particle Acceleration



Modern view: nonsteady, plasmoid-dominated reconnection

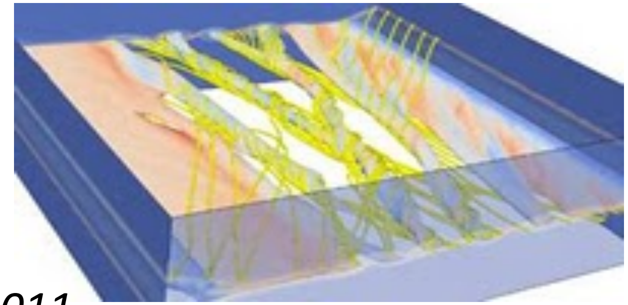
(Loureiro et al. 2007, 2009, 2012; Lapenta 2008; Samtaney et al. 2009; Daughton et al. 2009; 2011; Bhattacharjee 2009; Cassak et al. 2009, 2010; Uzdensky et al. 2010; Huang et al. 2010)



Loureiro et al. 2012

- Long current sheets (with $L/\delta > 100$) are tearing-unstable and break up into chains of plasmoids (flux ropes in 3D).
- Statistically steady-state self-similar plasmoid hierarchy *(Shibata & Tanuma'01)* develops with fast reconnection rate even in collisional plasma): $cE \approx 0.01\, B_0 V_A$.
- The hierarchy provides a route towards small scales and facilitates transition to collisionless reconnection (with $cE \approx 0.1\, B_0\, V_A$)

- **Collisionless reconnection in large systems is also plasmoid-dominated!**



Daughton et al. 2011

Collisionless Relativistic Pair Reconnection: General reconnection dynamics

Analytical work: *Larrabee et al. 2003, Lyubarsky et al., Kirk 2004, others…*

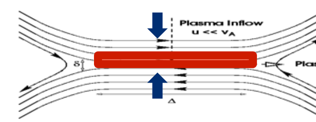
Tool of choice: PIC simulations

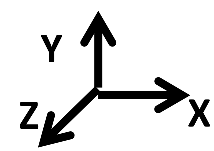
(*Zenitani & Hoshino '01, '05, '07, '08; Jaroschek + 2004; Bessho & Bhattacharjee '07, '08, '12; Lyubarsky & Liverts '08; Jaroschek & Hoshino '09; Liu + '11; Sironi & Spitkovsky '11, '14; Cerutti + 2012, 2013, 2014; Kagan + 2013, Guo + 2014; Melzani + 2014; Werner + 2014*)

Key Features:

- Pair reconnection is **fast:** v_{rec} ~ 0.1— 0.2 c --- even without Hall effect!
- Reconnection in **small** current layers (L~10 d_e) is mediated by off-diagonal components of **pressure tensor** (Bessho & Bhattacharjee 2007,08).
- In large systems (L > 50-100 ρ, d_e) fast reconnection

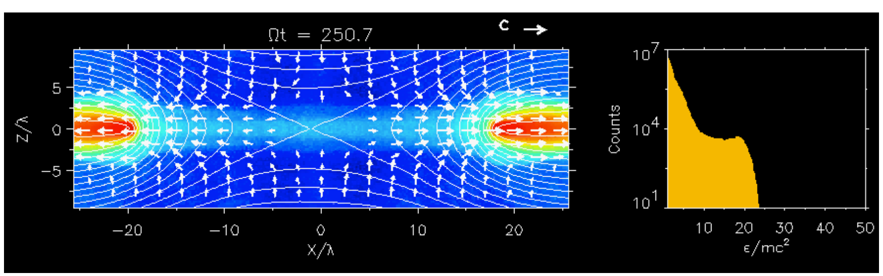
is mediated by **secondary instabilities** (tearing and RDKI)





tearing

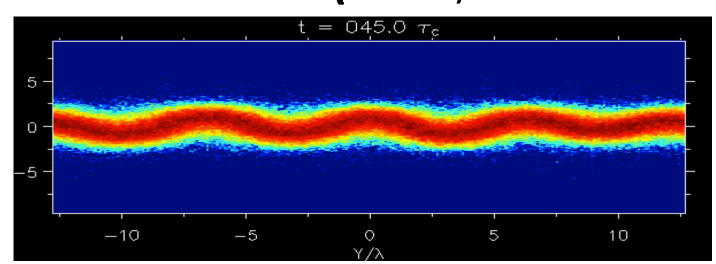
Y



X

rel. drift kink (RDKI)

Y



Z

Nonthermal Particle Acceleration in Collisionless Relativistic Reconnection (2014-2015 view)

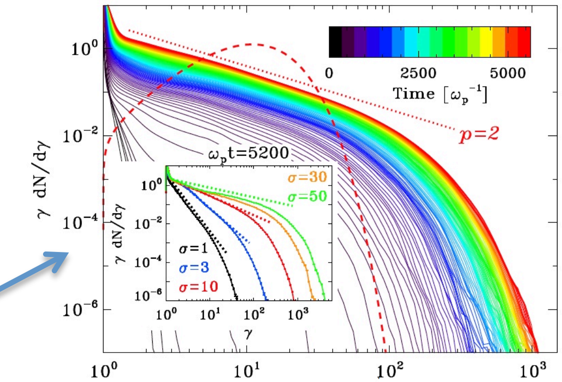
- Particle acceleration requires ***kinetic*** theory.
- Tool of choice in numerical studies: ***particle-in-cell (PIC)*** code.

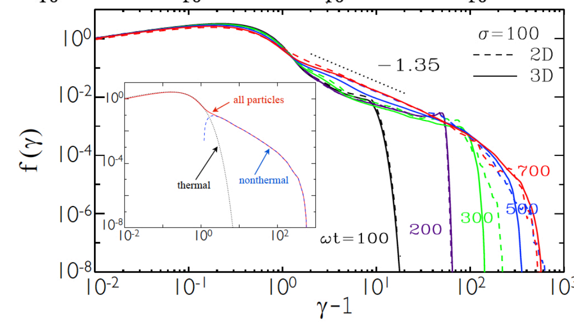
Recent PIC studies by several groups showed: reconnection does lead to significant particle acceleration!

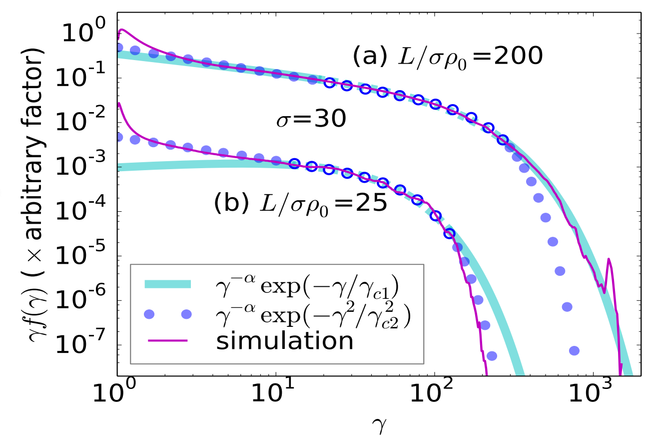
- Sironi & Spitkovsky (2014)
- Guo et al. (2014)-LANL
- Werner et al. (2014)-Colorado

pair plasma

➢ Melzani et al. (2014): **electron-ion plasma**





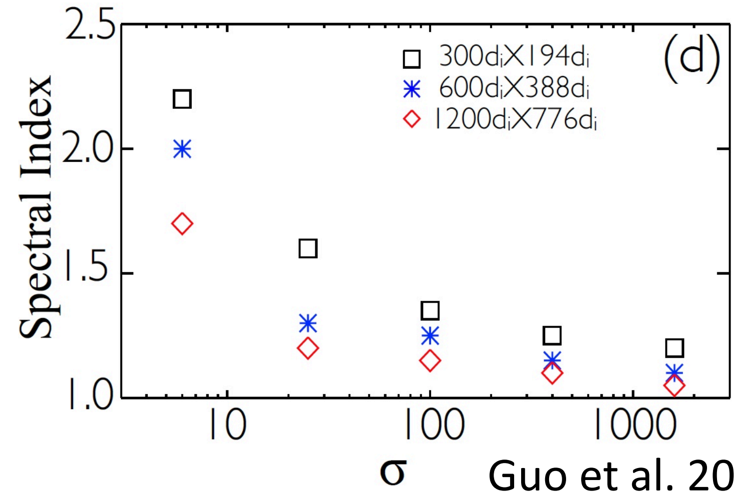


Power-law index:

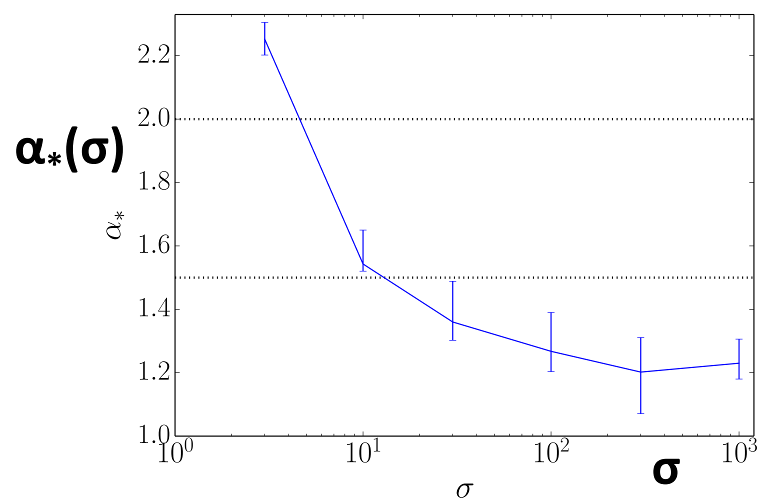
$f(\gamma) \sim \gamma^{-\alpha}$

- $\alpha = \alpha(\sigma, L)$
- α can be > 2 for $\sigma \sim 1$; decreases with L but asymptotes to a finite value $\alpha_*(\sigma)$ as $L \rightarrow \infty$
- $\alpha_*(\sigma)$ decreases with σ but approaches a finite asymptotic value **$\alpha \approx 1\text{-}1.2$**.

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



Guo et al. 2014



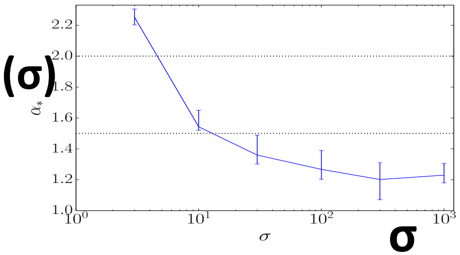
Werner et al. 2014

High-Energy Power Law Cutoff

(*Werner, Uzdensky, Cerutti, Nalewajko, Begelman 2014*)

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

$\alpha_*(\sigma)$



σ

Two high-energy cutoffs:

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

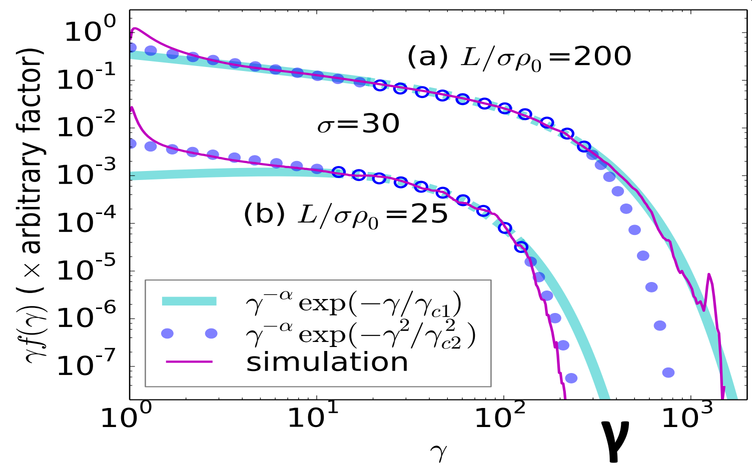
- independent of *L*;

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

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

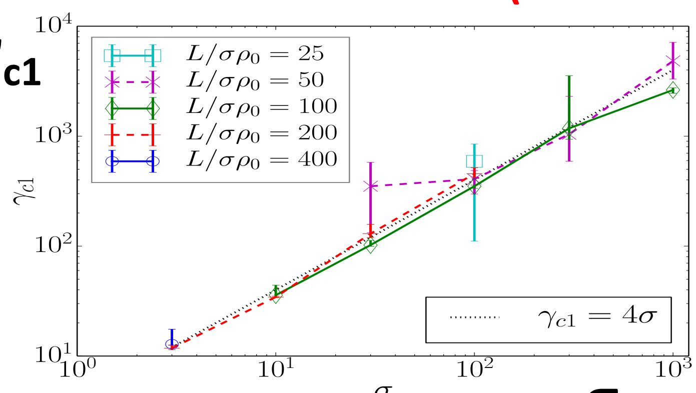
- independent of σ.

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



γ

γ_{c1}



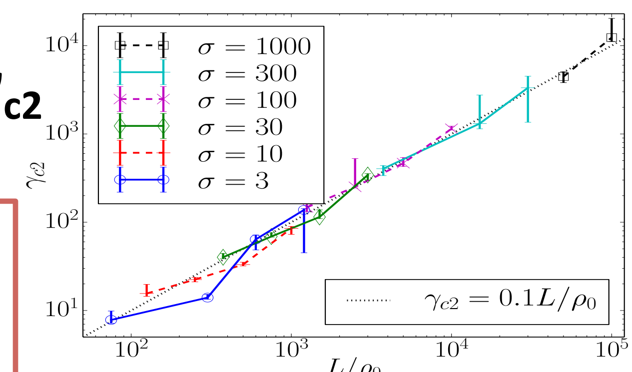
σ

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

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

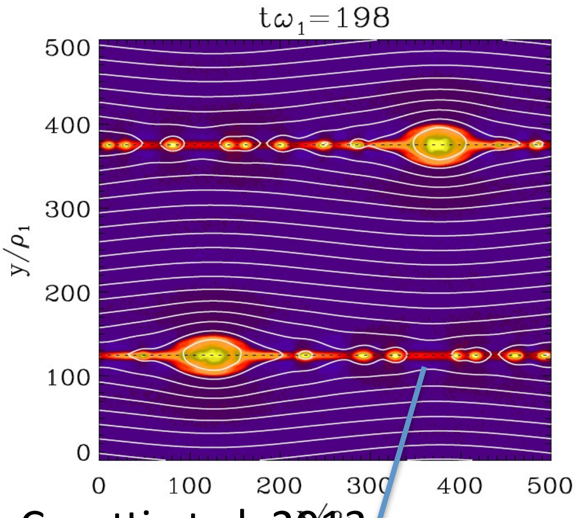
$L/\rho_0 > 40\,\sigma$

γ_{c2}

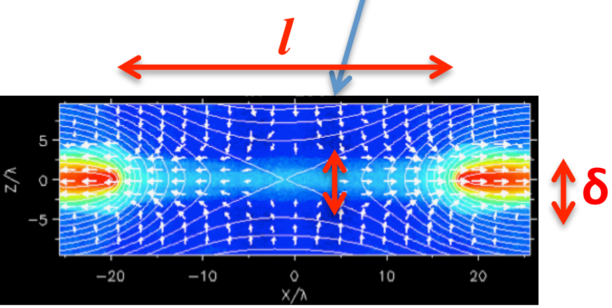


L/ρ_0

Why is there a ≈ 4σ cutoff?



Cerutti et al. 2013



Zenitani & Hoshino 2001

Pre-accelerated higher-energy particles with ρ > w are not trapped in small islands and may be accelerated further.

- Cuttoff comes from small laminar elementary inter-plasmoid current 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 even small plasmoids; they experience no further acceleration.
- 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):
>
> $$\frac{dn}{d\gamma} \propto \frac{1}{\gamma} \exp\left(-\frac{\gamma}{\gamma_0}\right). \qquad (10)$$

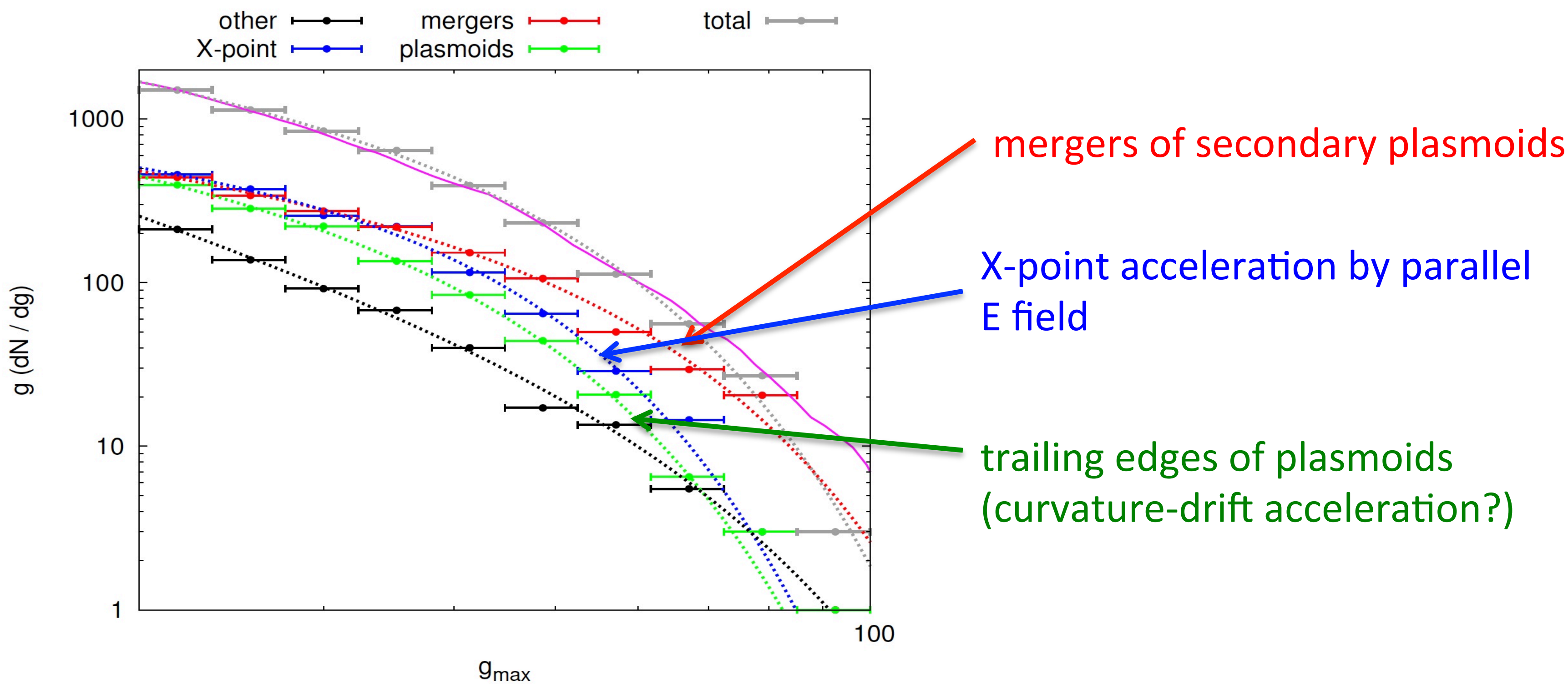
(Lyubarsky & Liverts 2008)

- 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, $\boldsymbol{l\,/\rho_0 \approx 100\,\delta/\rho_0 \approx 30\,\sigma}$ => $\boldsymbol{\gamma_0 = 3\,\sigma}$.

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

Sites of Particle Acceleration in Reconnection

(Nalewajko et al. 2015, in prep.)



SUMMARY

- **Magnetic Reconnection** is a viable, attractive mechanism for magnetic energy dissipation, particle acceleration, and radiation in relativistic astrophysical jets.
- Large-scale **magnetic field reversals** (~ every 10 orbits) due to accretion disk dynamo cycle provide a natural mechanism for setting up a **striped wind in the jet** and energy dissipation by reconnection at ~ 1-parsec scales in blazars.
- **Particle acceleration** in relativistic pair reconnection:

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

where **$\alpha \rightarrow 1.2$** as $L, \sigma \rightarrow \infty$,

and **$\gamma_{c1} \sim 4\sigma$**, **$\gamma_{c2} \sim 0.1\, L/\rho_0$**.