Particle acceleration in magnetic reconnection

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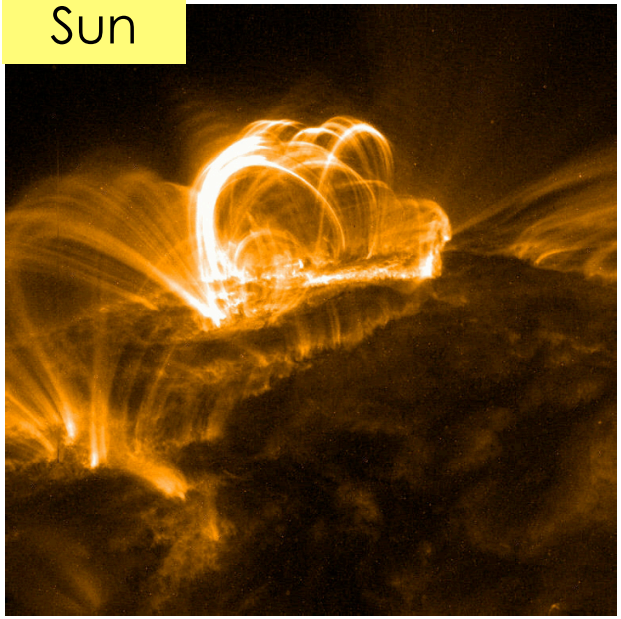
Outline

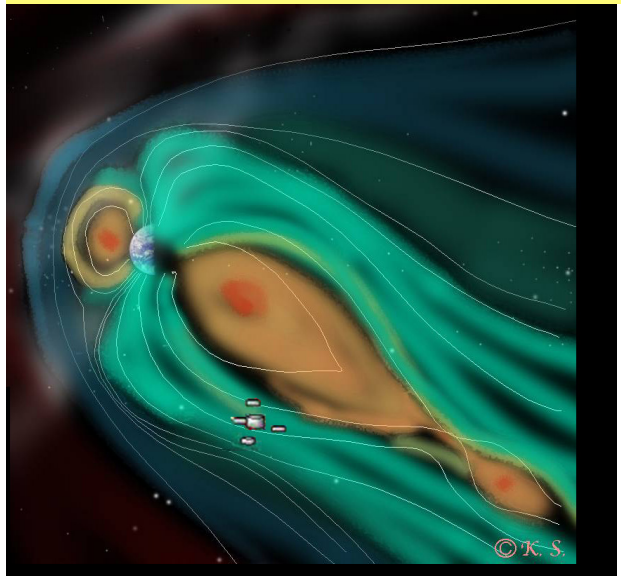
- 1. Acceleration mechanisms in nonrelativistic magnetic reconnection
  - Single X-line systems
  - Multi X-line systems
- 2. Particle acceleration in relativistic magnetic reconnection
  - Relativistic X-line acceleration
  - 3D problem
- 3. Summary

Magnetic reconnection (MRX)

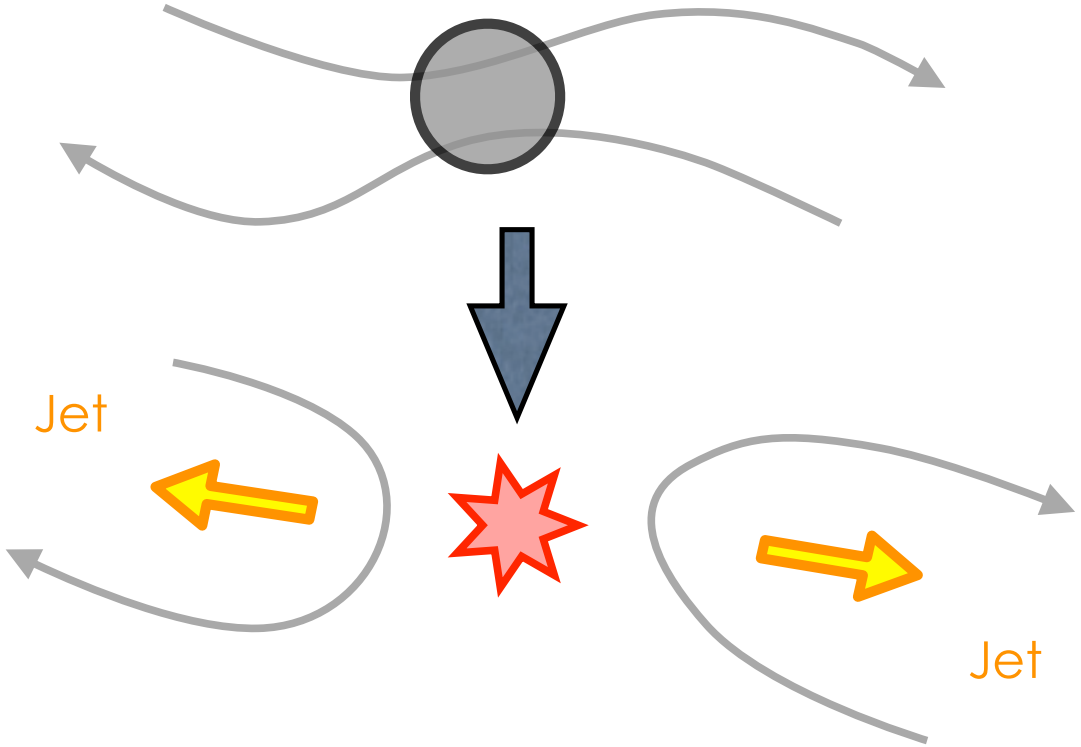
Sun



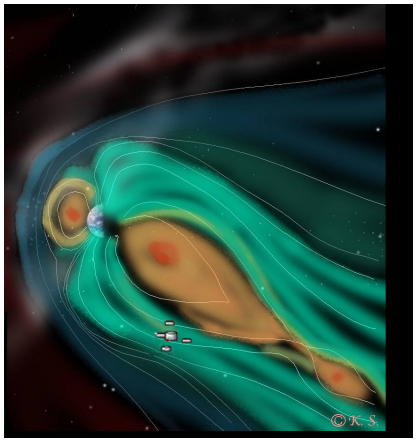
Earth's Magnetosphere



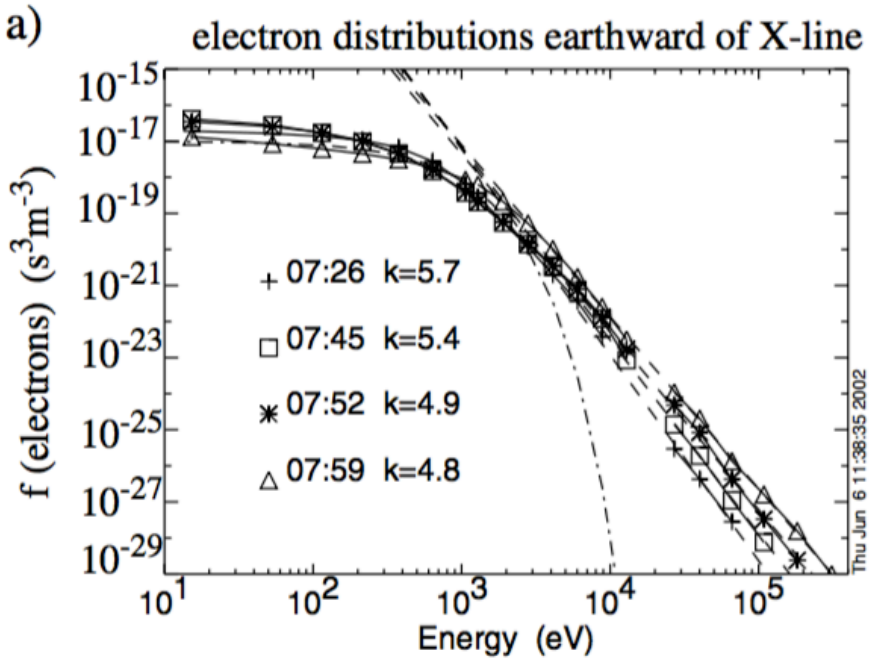
- Fundamental process in plasma systems
- Conversion from magnetic energy to plasma energy -- bulk flow energy, plasma heating, or nonthermal particle acceleration



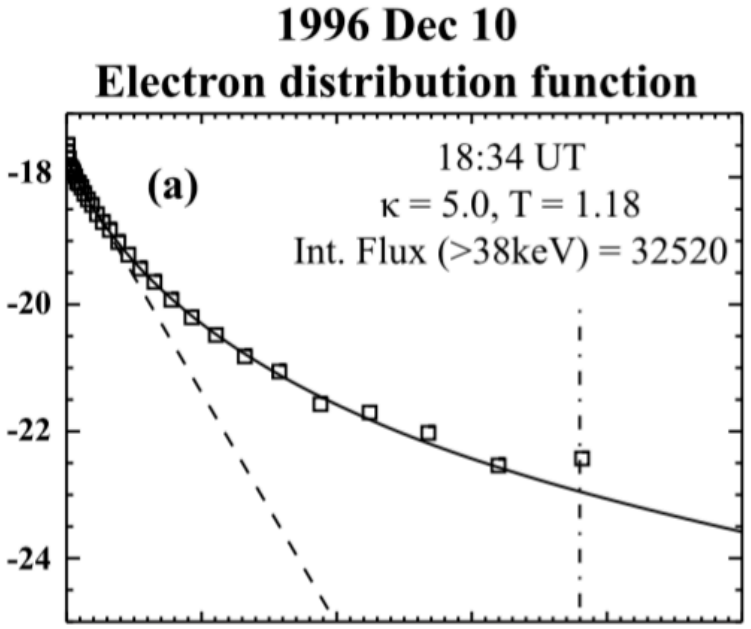
Observations in the Earth M'sphere



- Nonthermal electrons (and ions) during reconnection events
- Numerical modeling as well as ultrahigh-resolution observation (MMS mission since 2015/09) will help us to understand particle acceleration in MRX

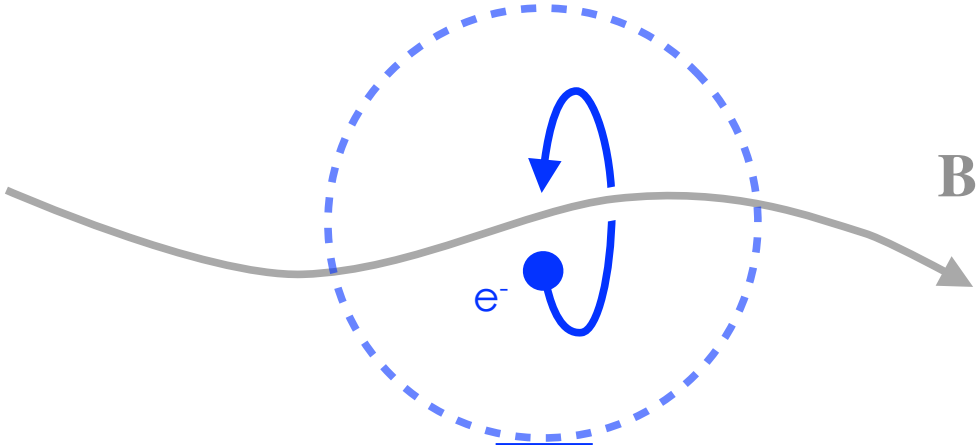


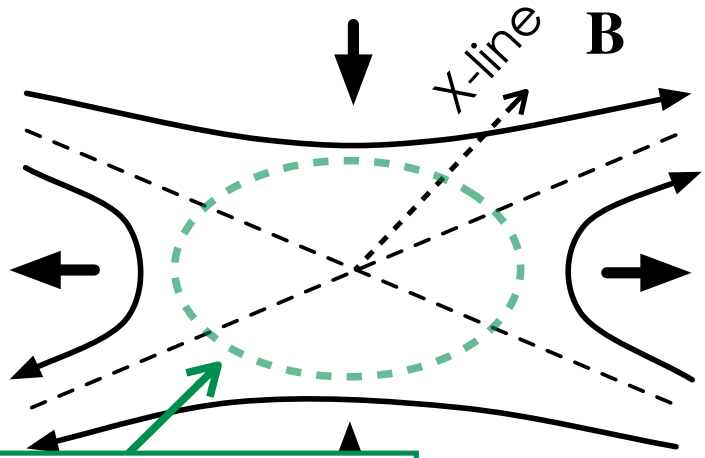
Oieroset+ 2002 PRL

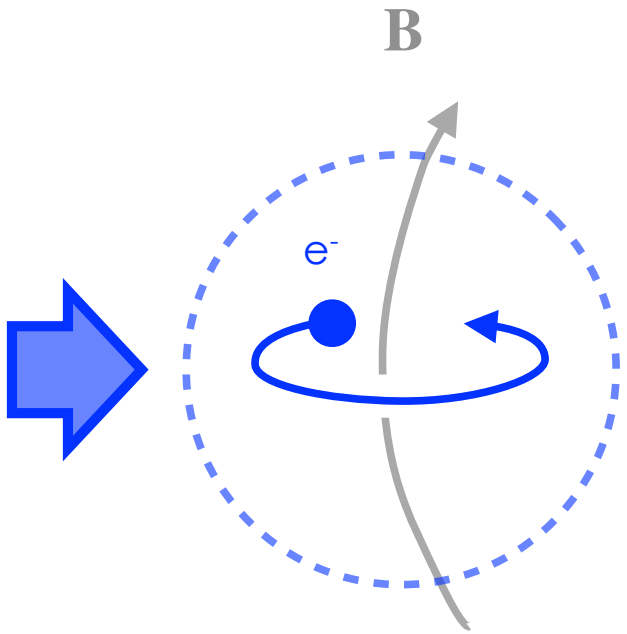


Imada+ 2011 JGR

Structure of the MRX site

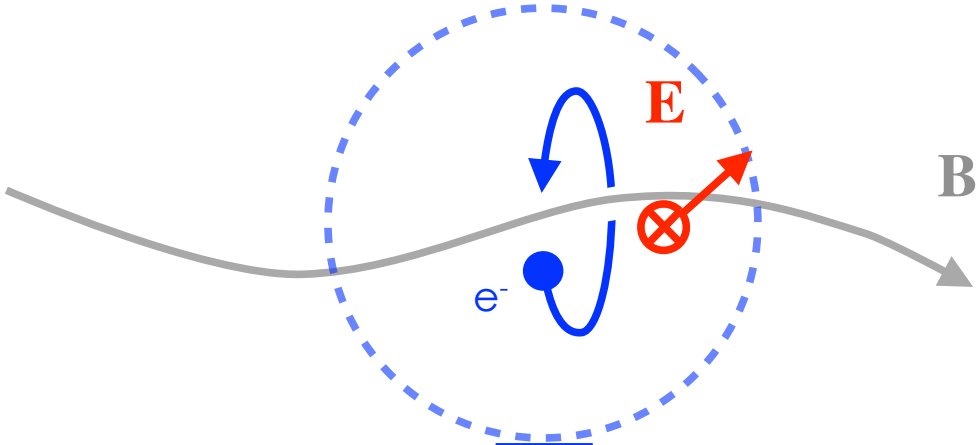


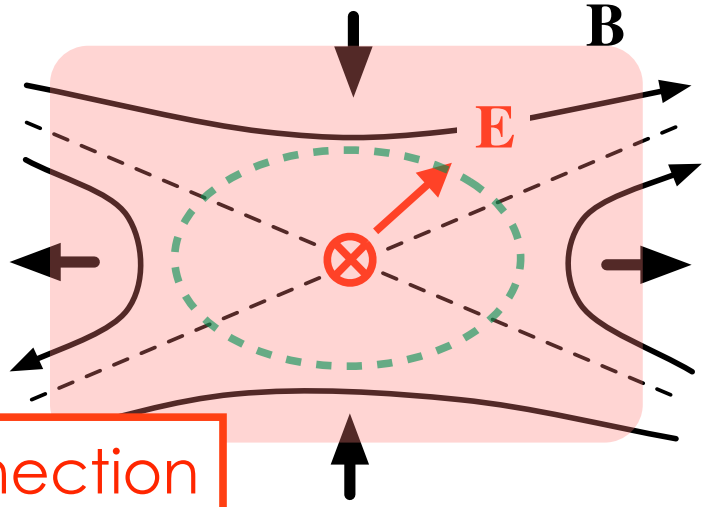


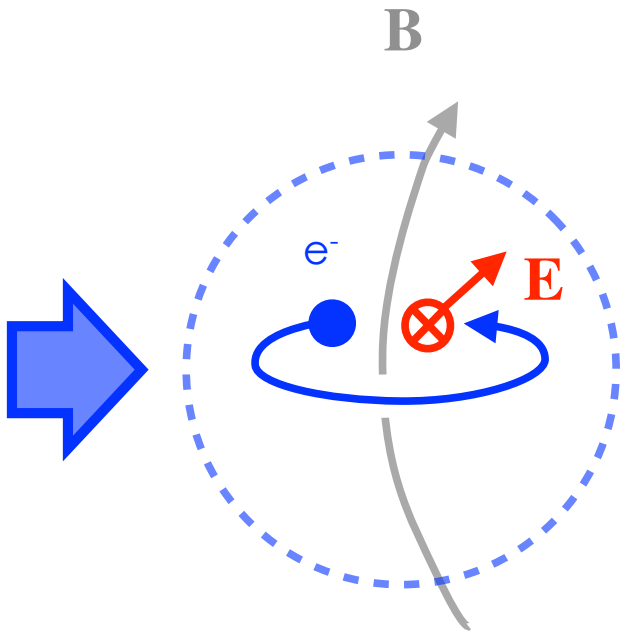


- Particles get unmagnetized
- Larmor radius > scale length

Structure of the MRX site



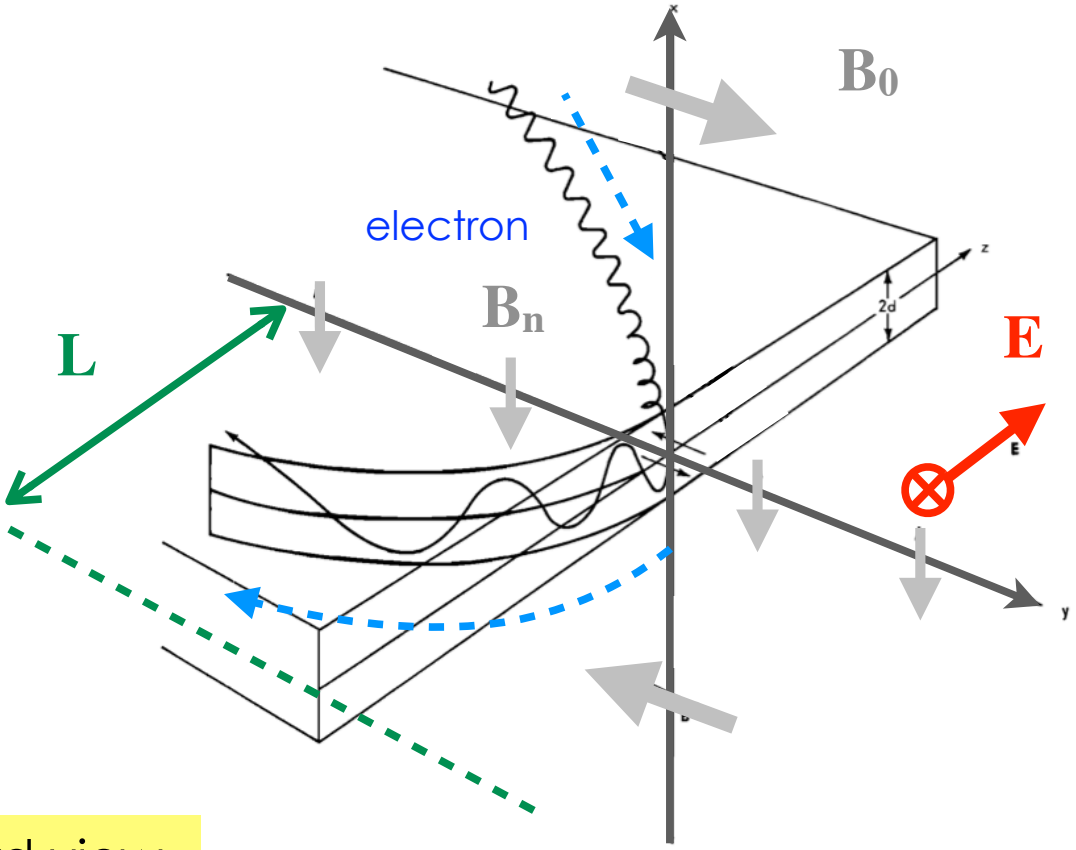




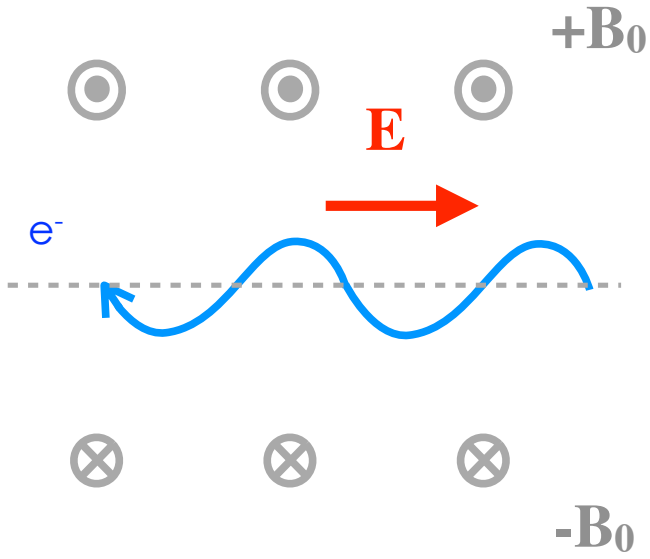
E (Reconnection electric field)

X-line acceleration

- Speiser motion (Speiser 1965)
  - Fast bounce motion between the field reversal ($\pm B_0$)
  - Slow gyration about the normal field (B_n)
- Energy gain ~e**EL**



Bird view

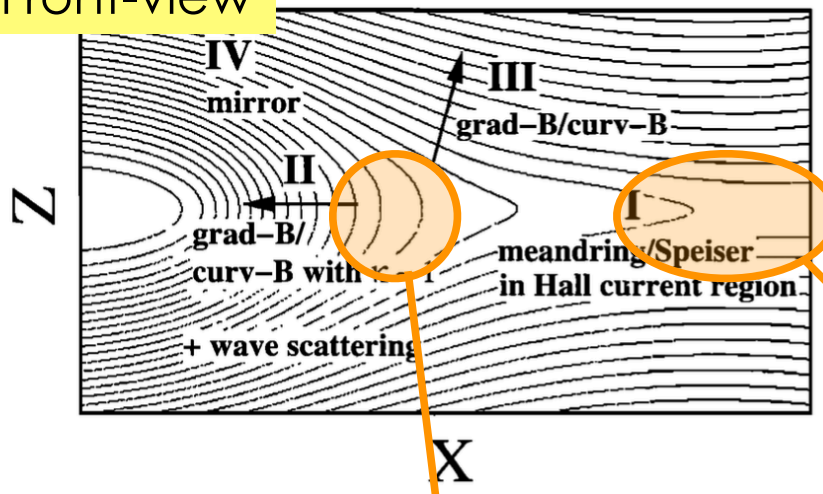


Side view

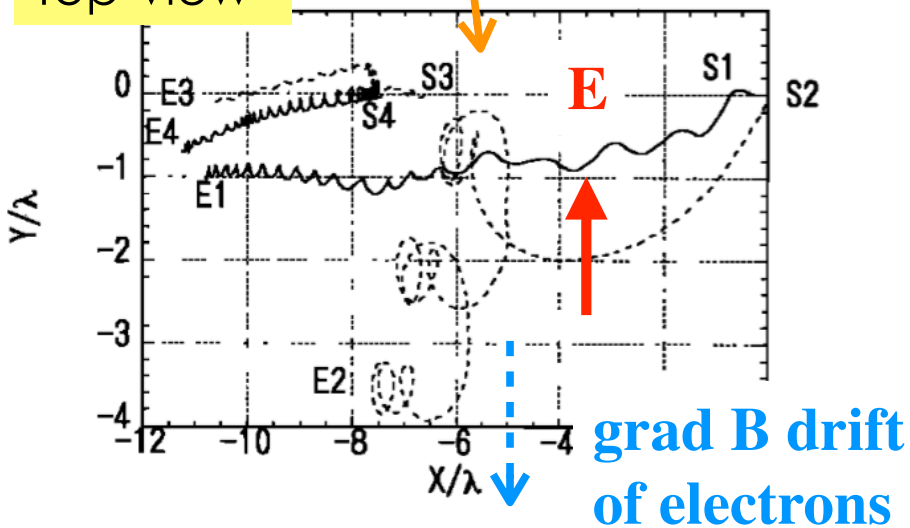
Speiser 1965 JGR

Electron acc. in particle-in-cell (PIC) simulations

Front-view

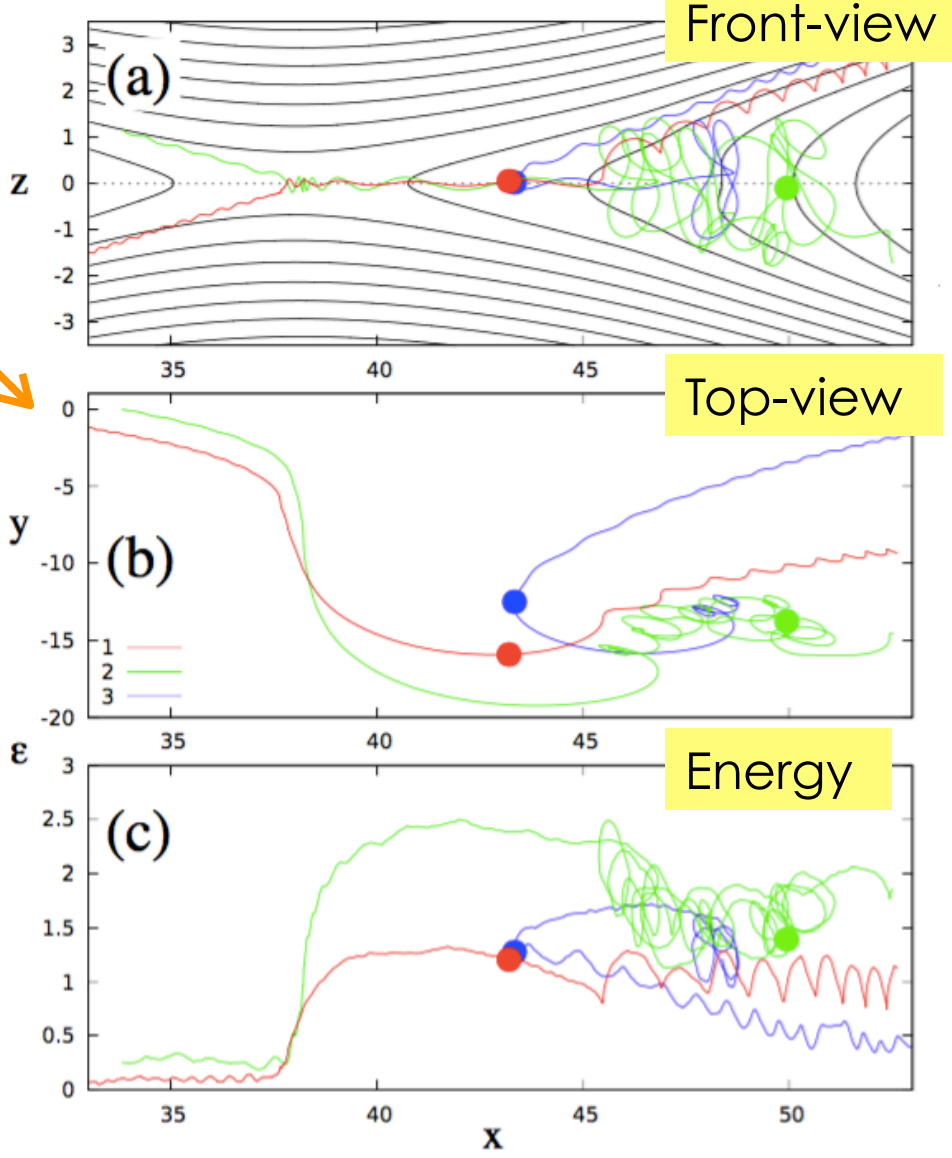


Top-view



grad B drift of electrons

Front-view

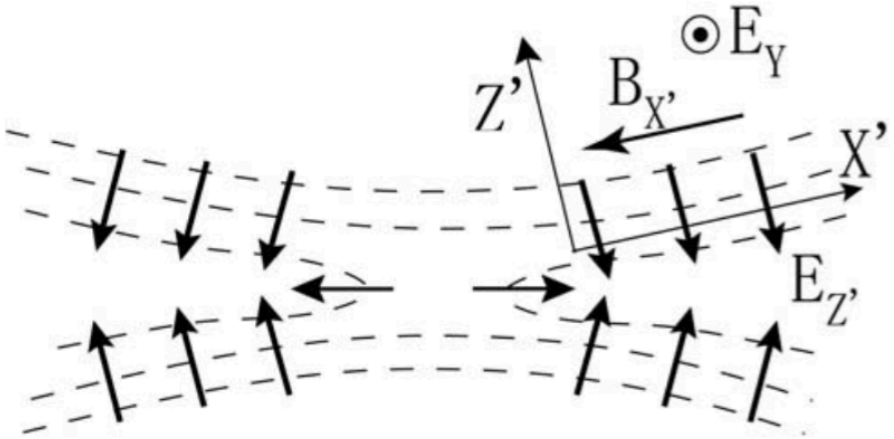


Top-view

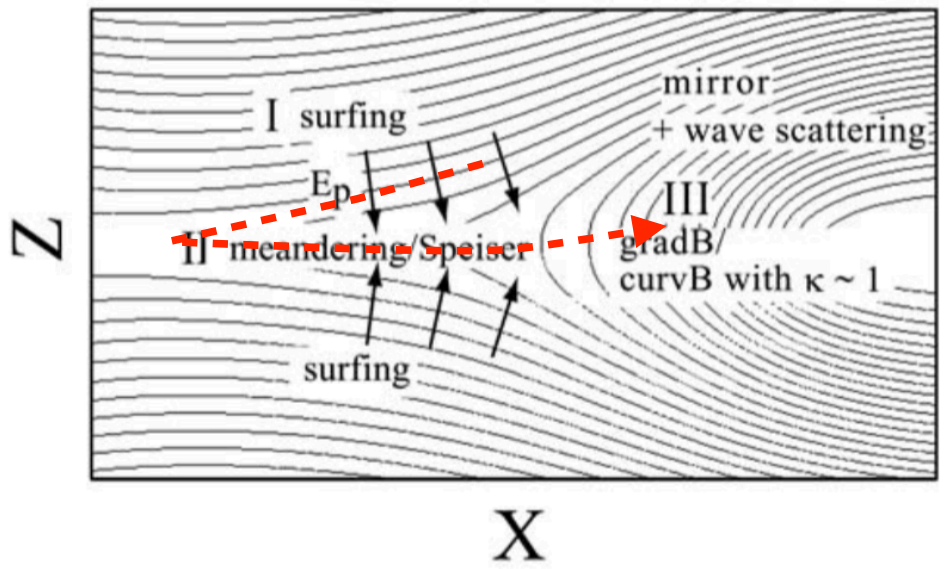
Energy

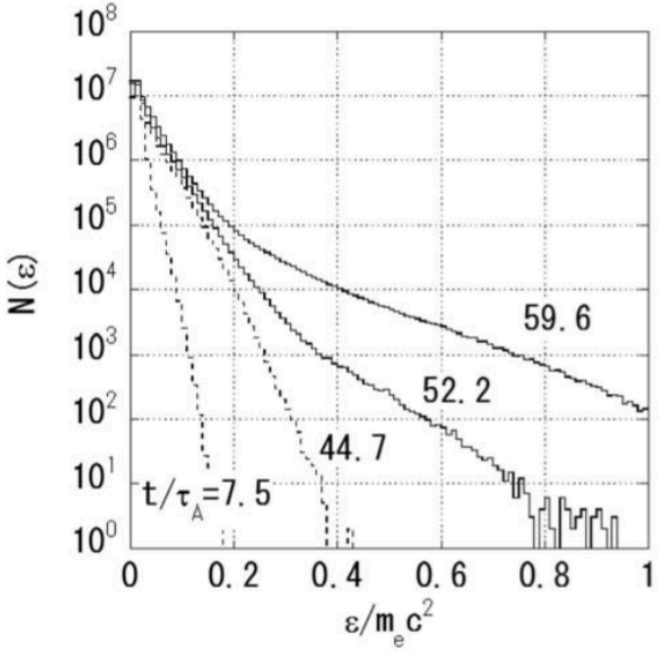
Hoshino 2001+ JGR

Multi-step electron acc. in PIC simulation



- Polarization electric field traps and accelerates electrons (Hoshino 2005, SZ+ 2016a)
- Upper limit: ~E_p/B
- Combination of three acc. mechanisms

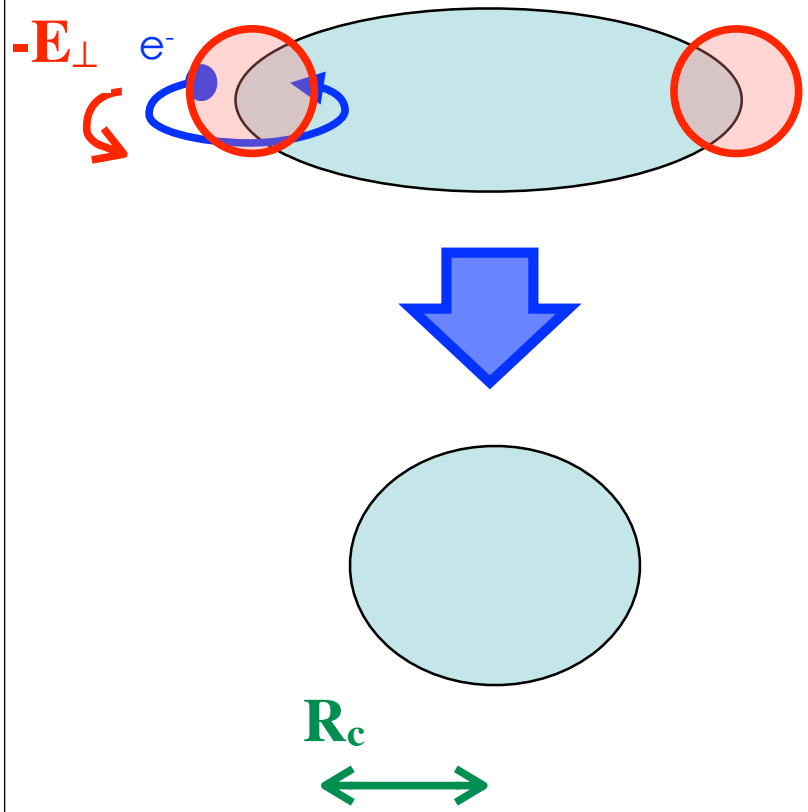


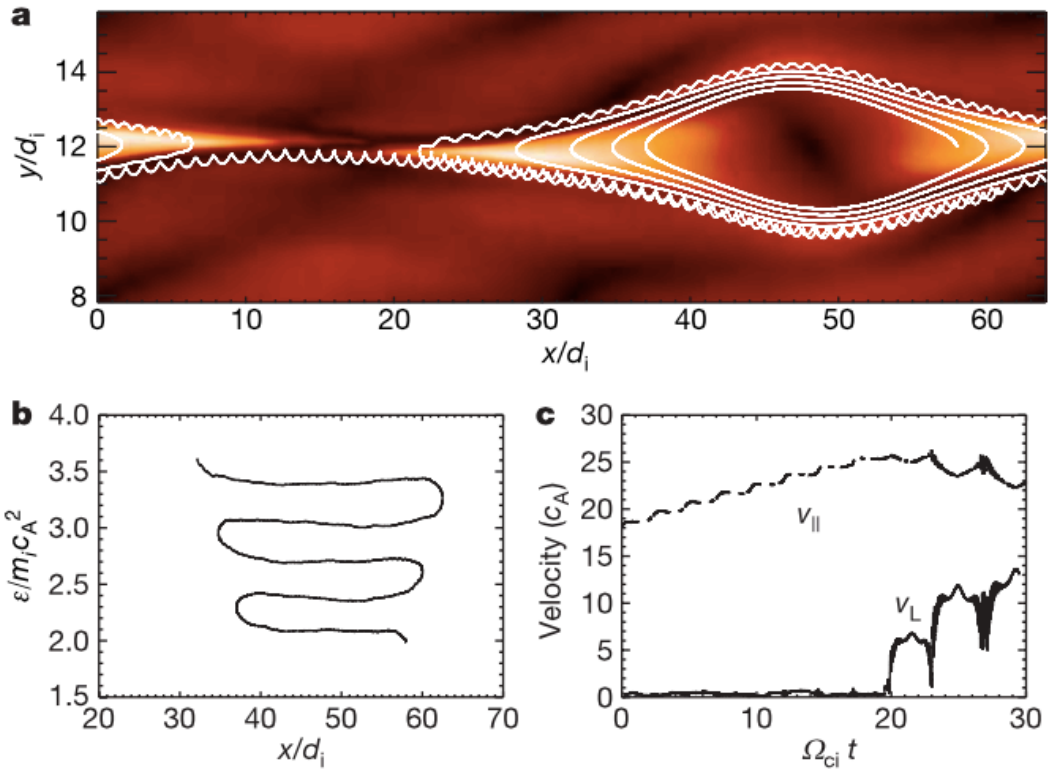


Hoshino 2005 JGR

Magnetic islands in multiple MRX system

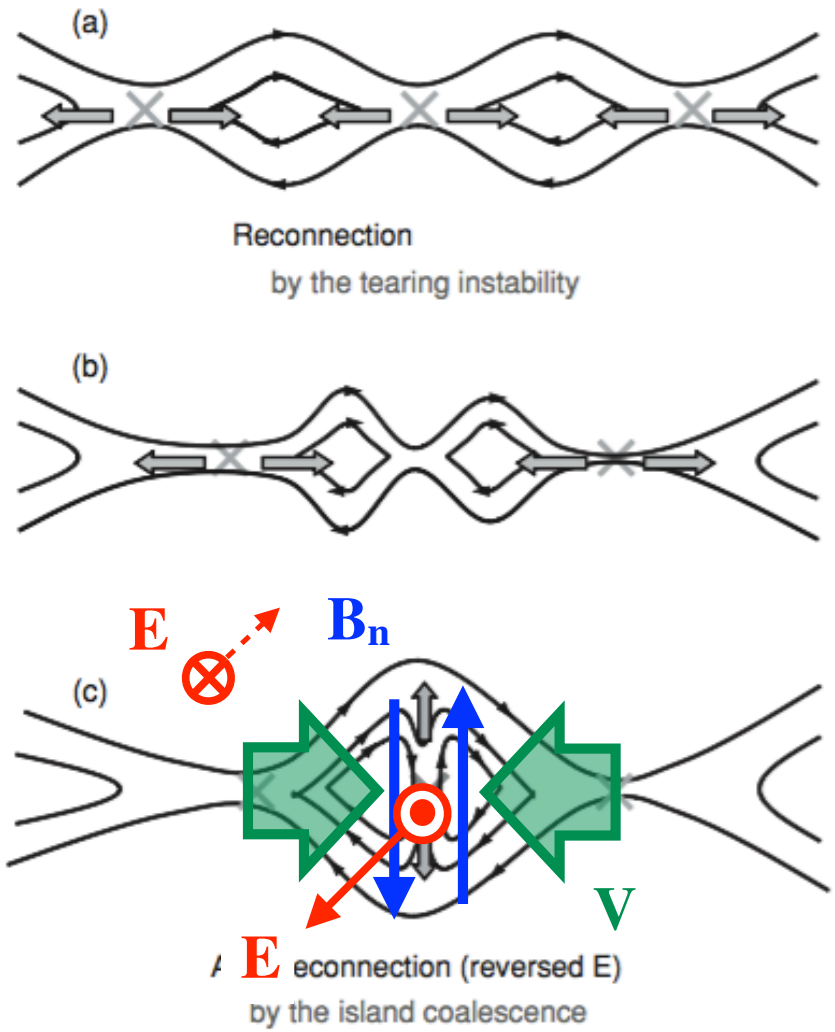
- Magnetic islands try to be round by the tension force
- Electrons spin up at the contracting edges
- Efficient in the nonrelativistic regime
- Maximum energy: ~curvature radius R_c





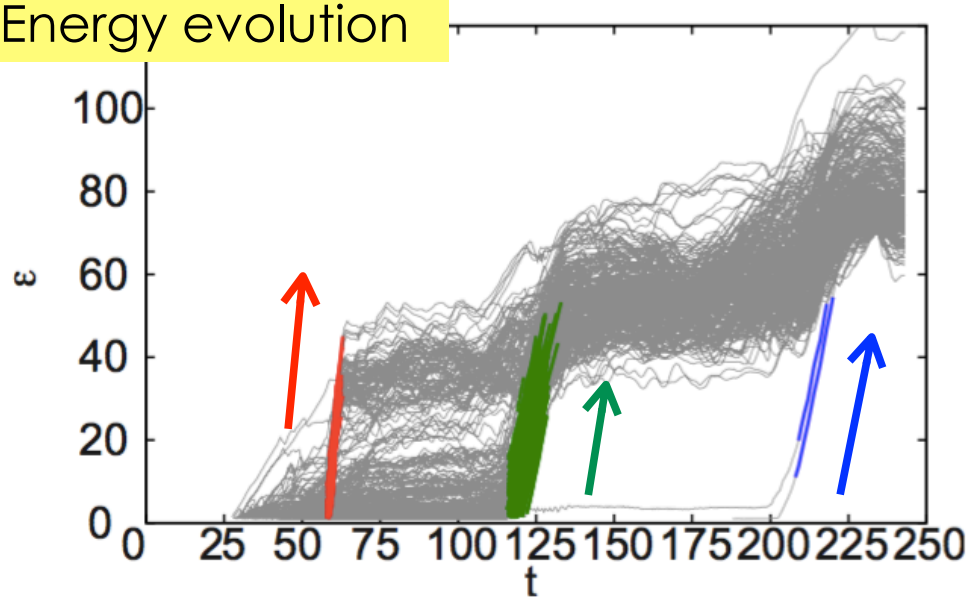
Drake+ 2006 Nature

Island merger acceleration



- Variant of X-line acceleration
- Accumulated magnetic field (B) and the islands' speed (V) lead to strong $E \sim VB_n$
- Powerful, but impulsive

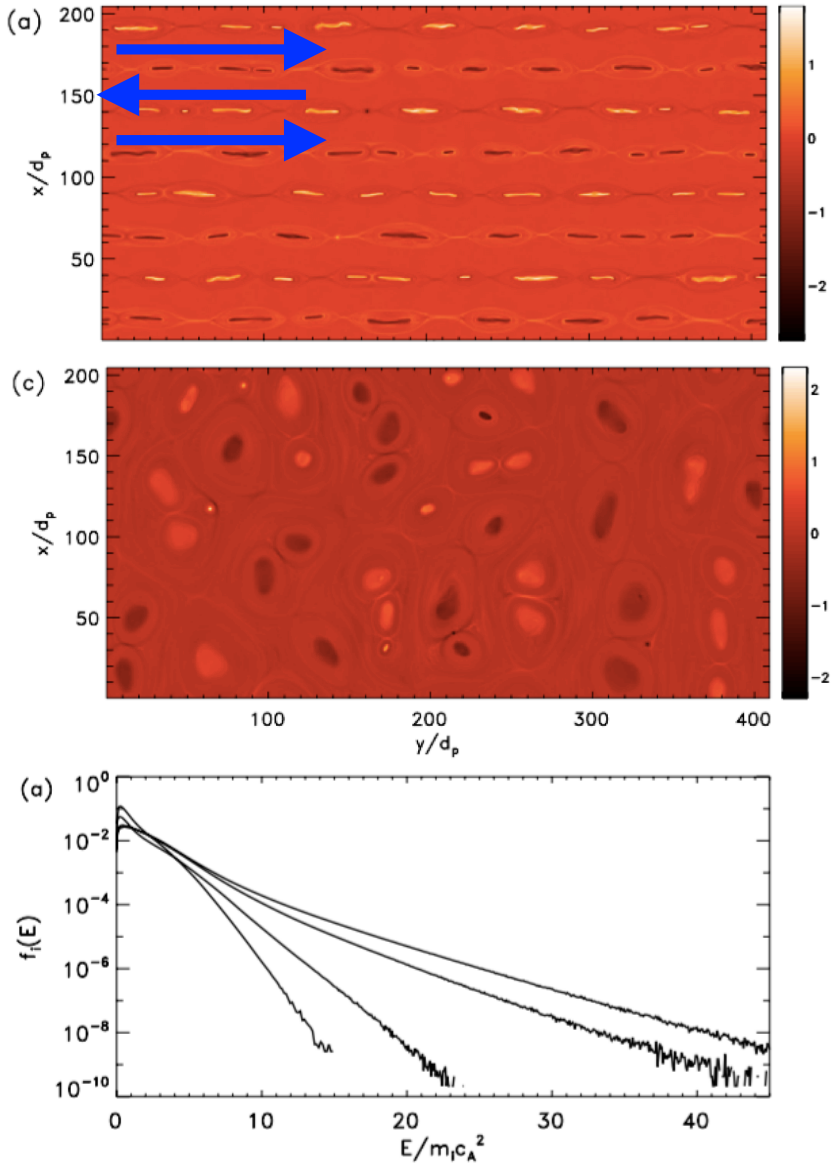
Energy evolution



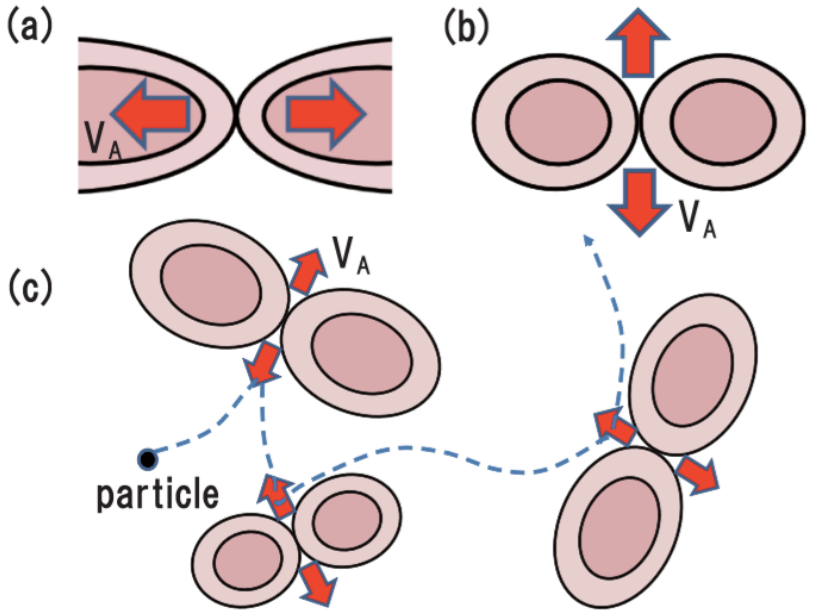
Oka+ 2010 ApJ

Tanaka+ 2010, 2011 PoP

MRX in multiple current-sheets systems



- Bath of magnetic bubbles
- Multiple reflections by contracting islands and/or reconnection jets
- First-order Fermi acc. claimed



Drake+ 2010 ApJ

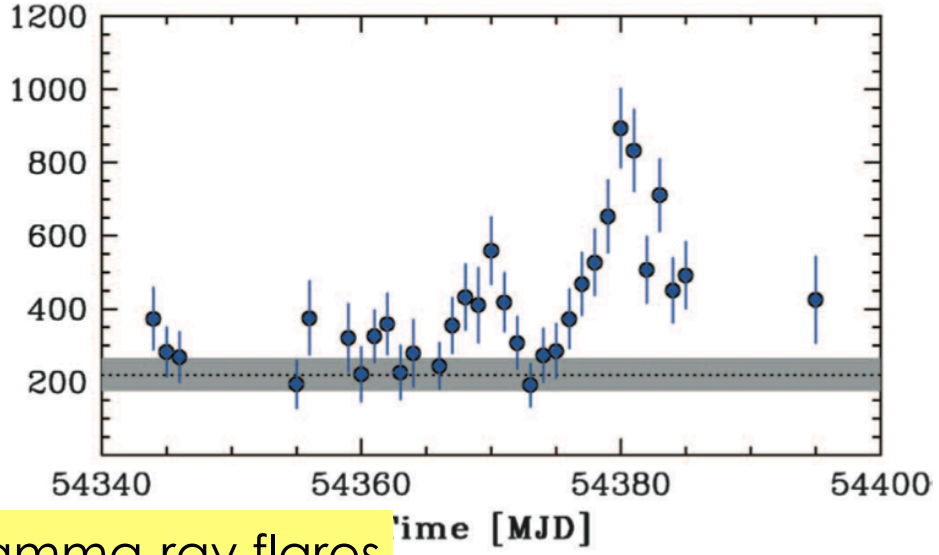
Hoshino 2012 PRL

Interim Summary

- Acceleration mechanisms in magnetic reconnection
  - X-line acceleration
  - Surfing acceleration (only for electrons)
  - Island contraction
  - Island merger
  - Statistical acceleration in multiple current sheet system
- Combination of these mechanisms lead to generation of nonthermal particles
- Most of theories remain phenomenological
  - Acc. efficiency
  - Physical/numerical parameter spaces

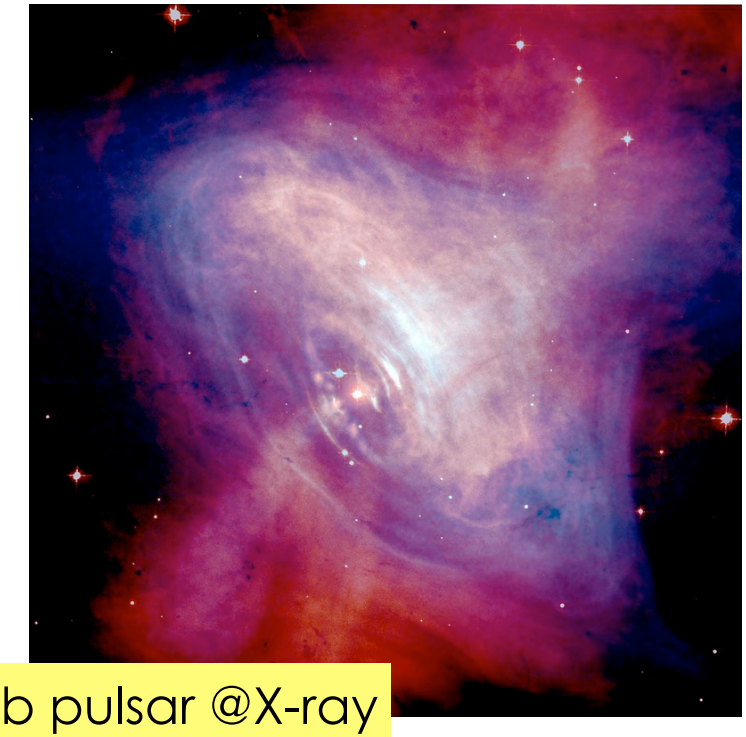
Magnetic reconnection in high-energy settings

- Relativistic magnetic reconnection is expected

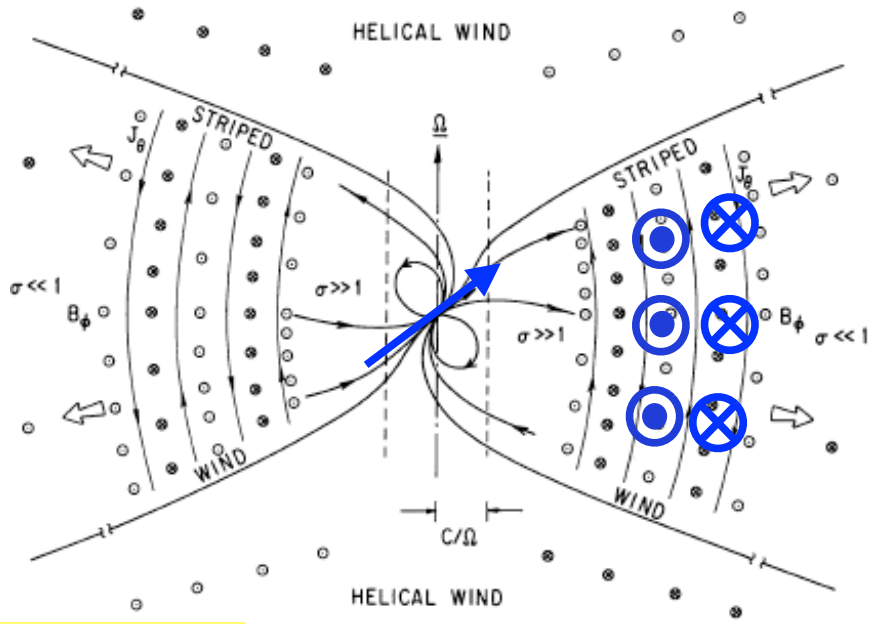


Gamma-ray flares

Tavani 2011 Science



Crab pulsar @X-ray



Striped wind

Coroniti 1990 ApJ

"Relativistic" reconnection?

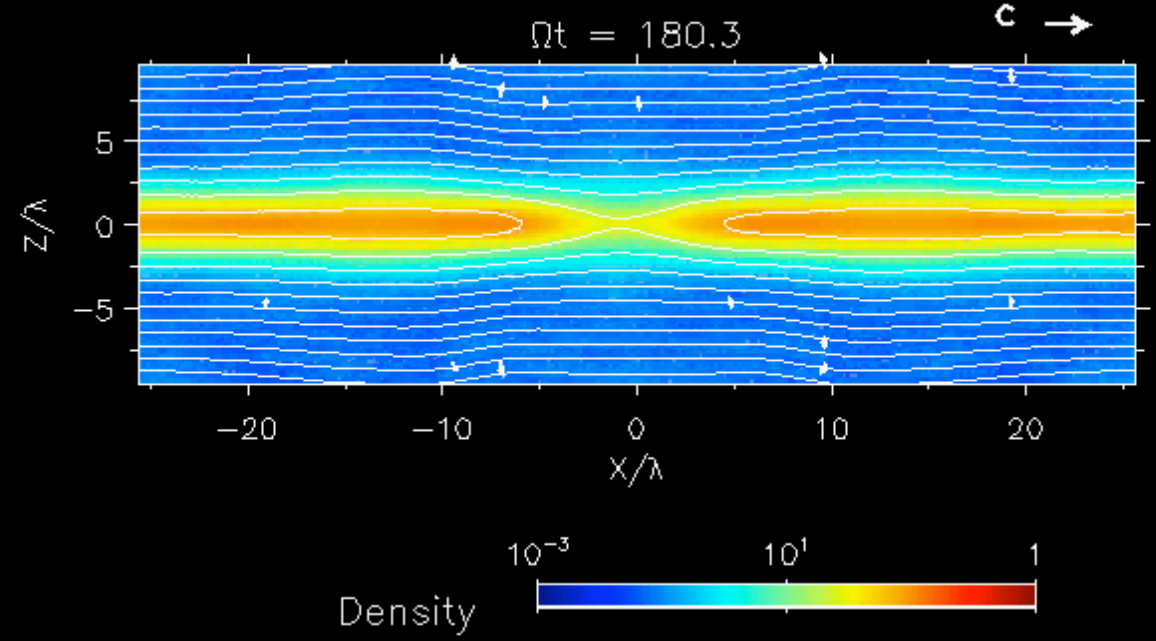
- Magnetization parameters
  - Poynting flux : plasma energy flux (Zenitani+ 2009)
  - Available magnetic energy per particle

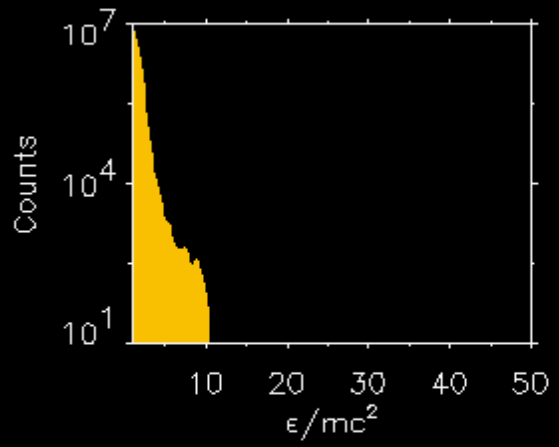
$$\sigma_m \equiv \frac{B_0^2}{4\pi\gamma^2 nmc^2} \qquad \sigma_\varepsilon \equiv \frac{B_0^2}{4\pi\gamma^2 w} \qquad \sigma_m \approx \sigma_\varepsilon$$

- Alfvén speed
  - c_A approaches c for higher σ
  - σ >> 1 for relativistic reconnection

$$V_{\rm jet} \approx c_A = c\sqrt{\frac{\sigma_\varepsilon}{1+\sigma_\varepsilon}}$$

Relativistic MRX = particle accelerator

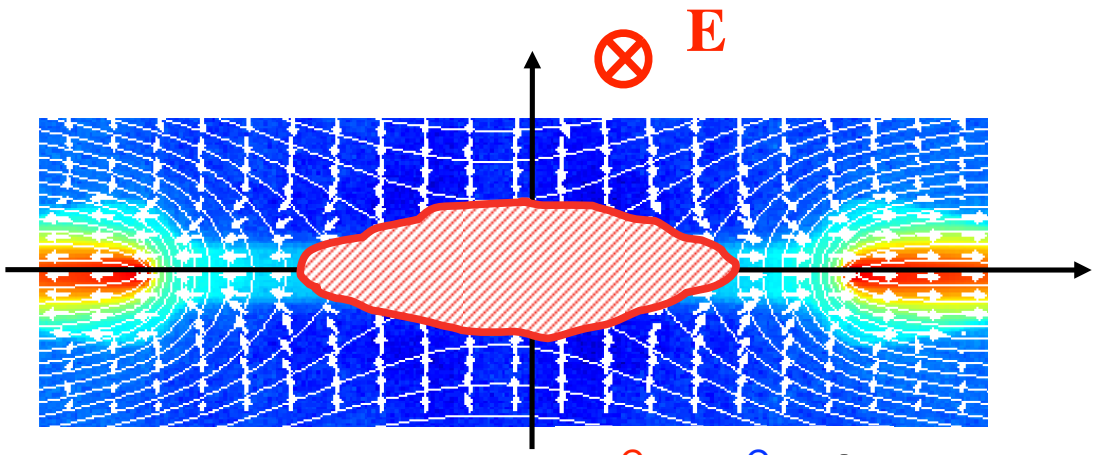




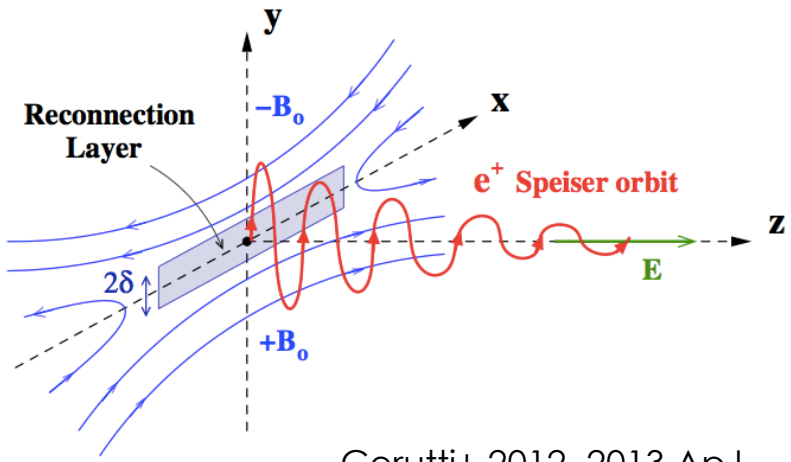
Zenitani & Hoshino 2001, 2007 ApJ

- Spectral index: -1 (acceleration site), -2.x (entire box)
- Online version: http://th.nao.ac.jp/MEMBER/zenitani/files/reconnection.mov

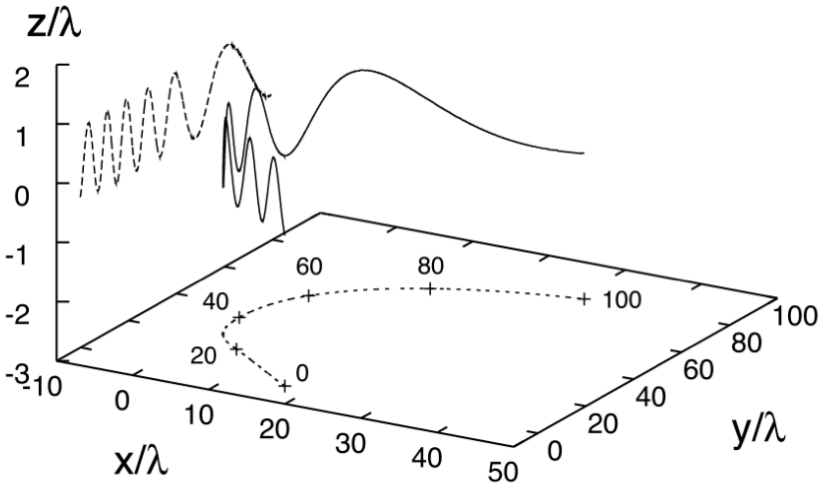
Relativistic X-line acceleration



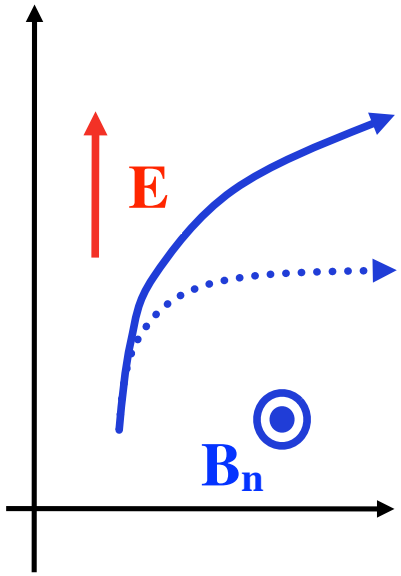
$E^2 - B^2 > 0$



Cerutti+ 2012, 2013 ApJ



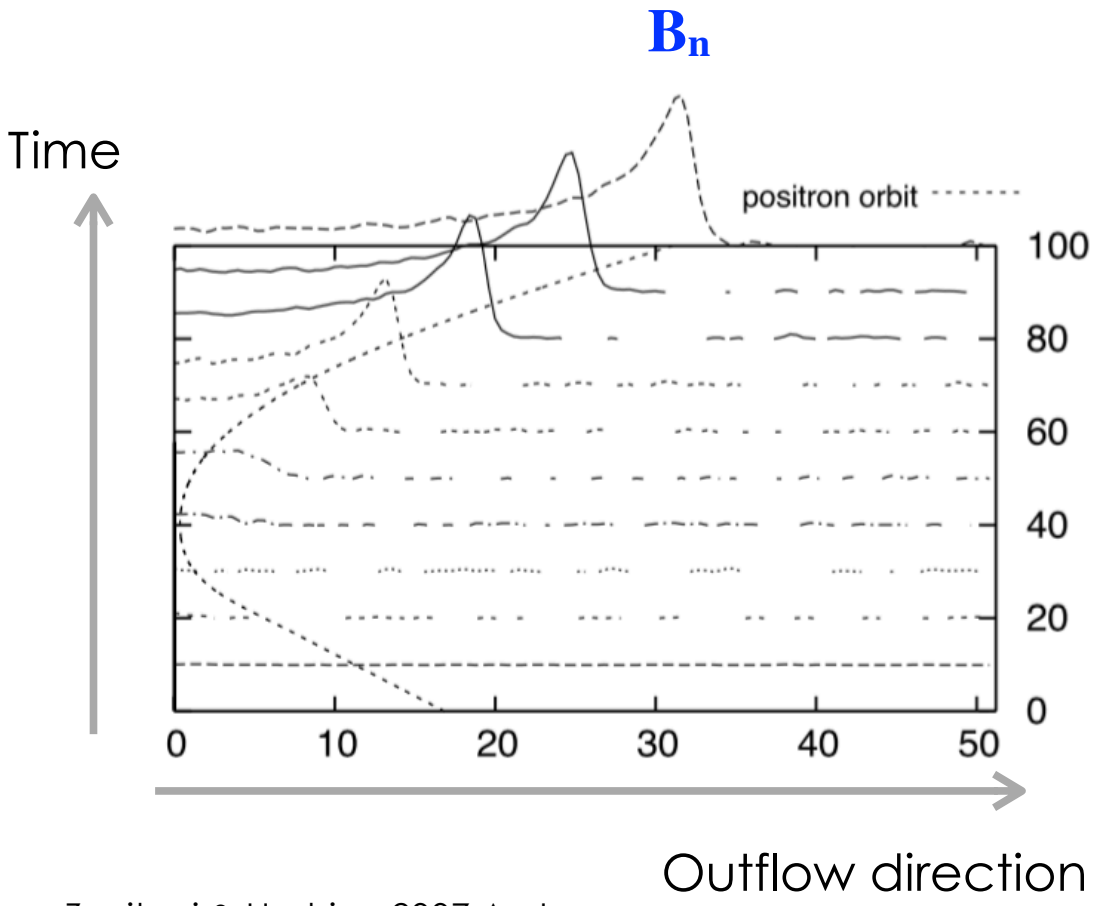
SZ & Hoshino 2007 ApJ



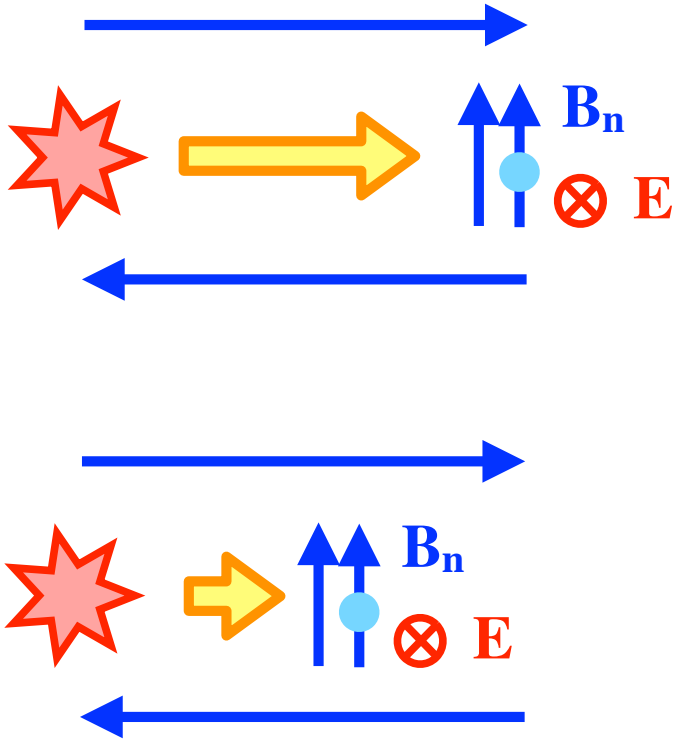
Top view

$$m_0\gamma = \frac{m_0}{\sqrt{1-(vc)^2}}$$

Resonant acc. at the jet front

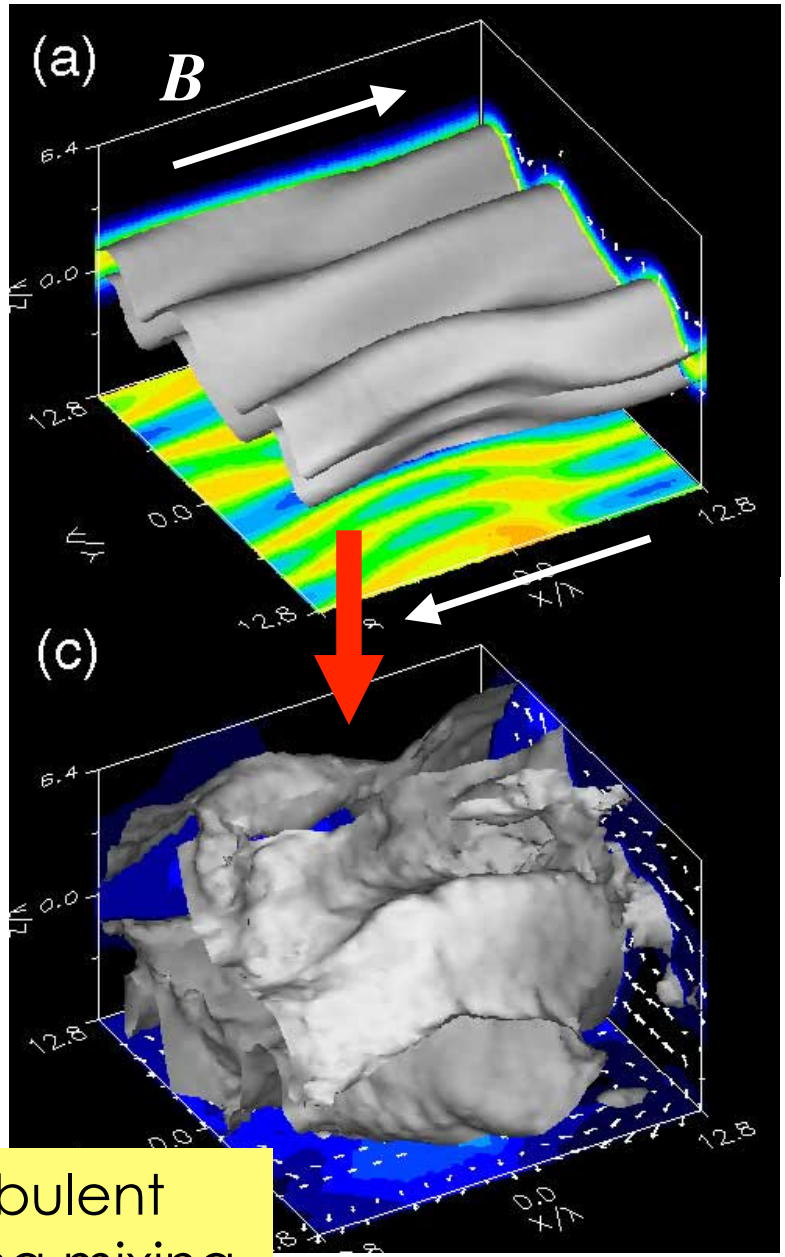


Zenitani & Hoshino 2007 ApJ



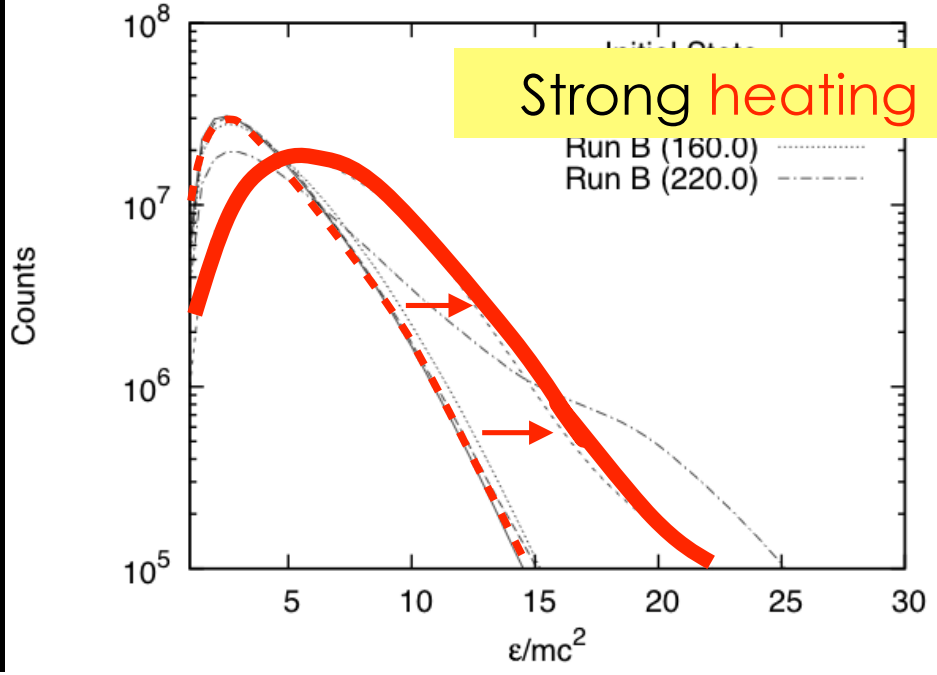
- Reconnection sweeps the magnetic field at the jet front
- Lucky energetic particles surf with the magnetic front

3D problem: the kink instability



Turbulent
Plasma mixing

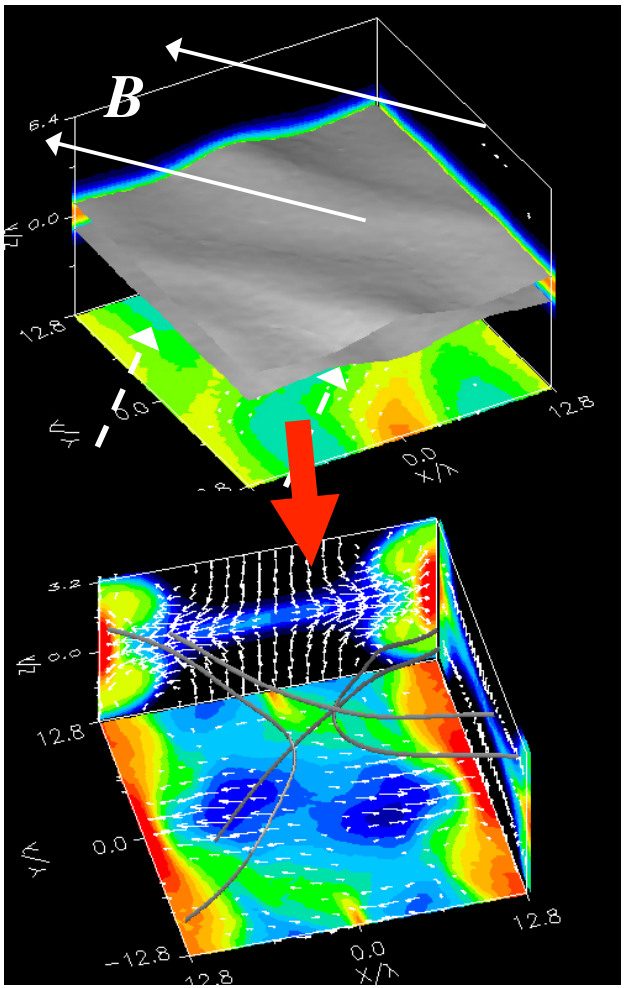
- Kink mode corrugates the current sheet in 3D
- This mode grows faster than the reconnection (tearing) mode

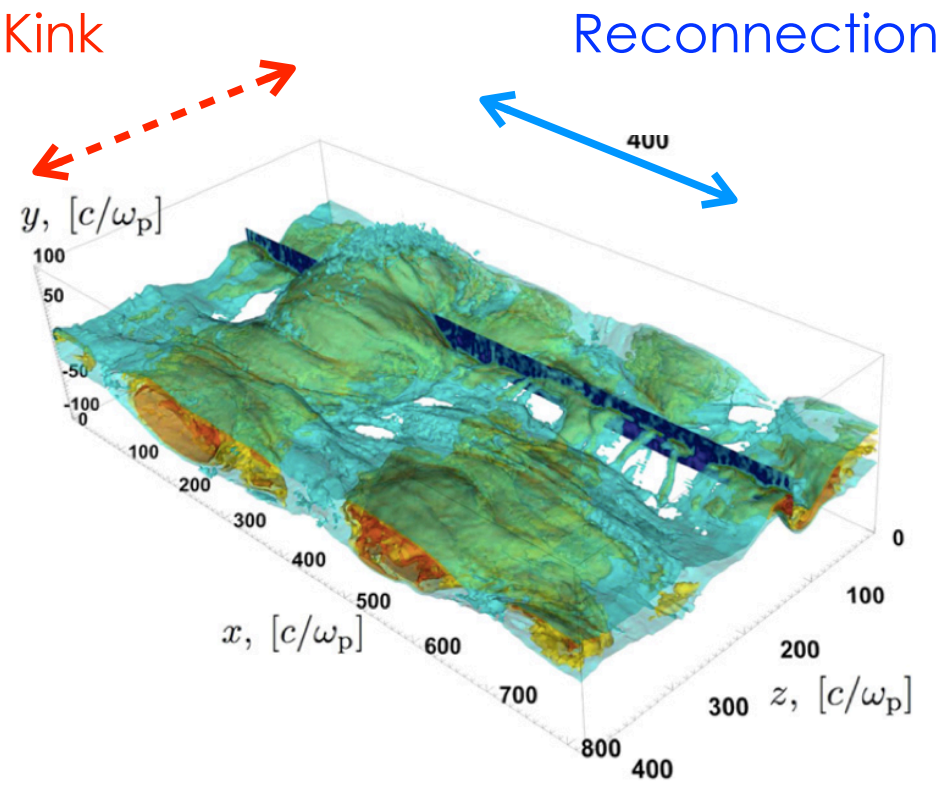


Zenitani & Hoshino 2005 PRL

3D onset problem

- MRX does occur in a twisted geometry
- MRX may dominate after the kink mode saturates



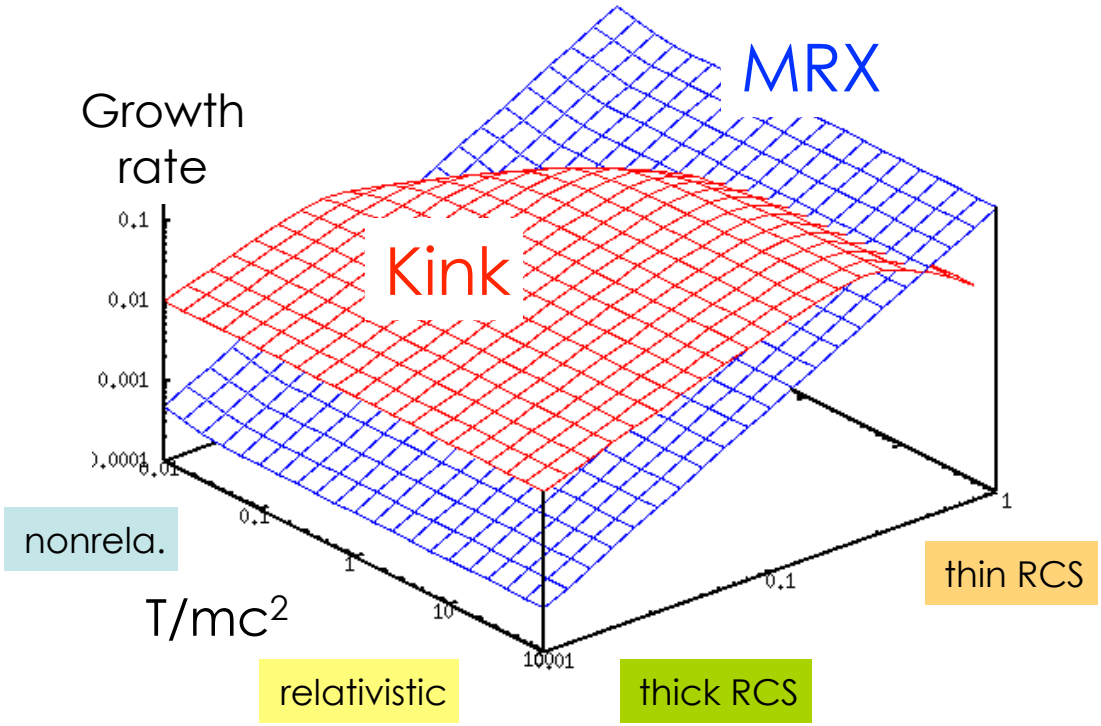


Zenitani & Hoshino 2005 PRL

Sironi & Spitkovsky 2014 ApJ

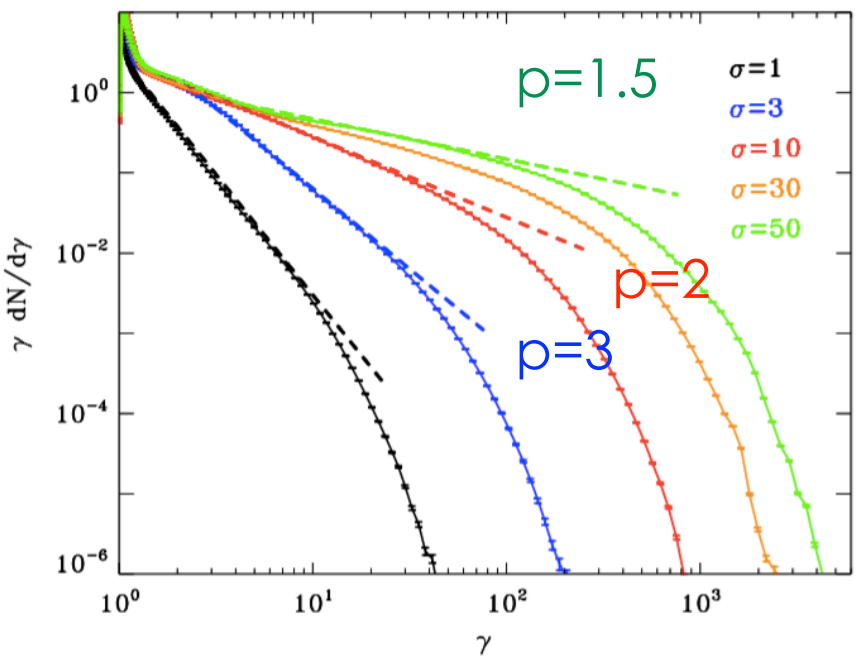
Current status of 3D onset problem

- Possibilities
  - Magnetic twist: guide-field (Zenitani & Hoshino 2005, Cerutti+ 2014)
  - Parameter window for MRX (Liu+ 2011)
  - Sufficiently large system (Sironi & Spitkovsky 2014)
  - Different models (Kagan+ 2013. Guo+ 2014)
- Some concerns
  - Sufficient # of particles?
  - Particle loading (Zenitani 2015)
  - Vlasov theory needed

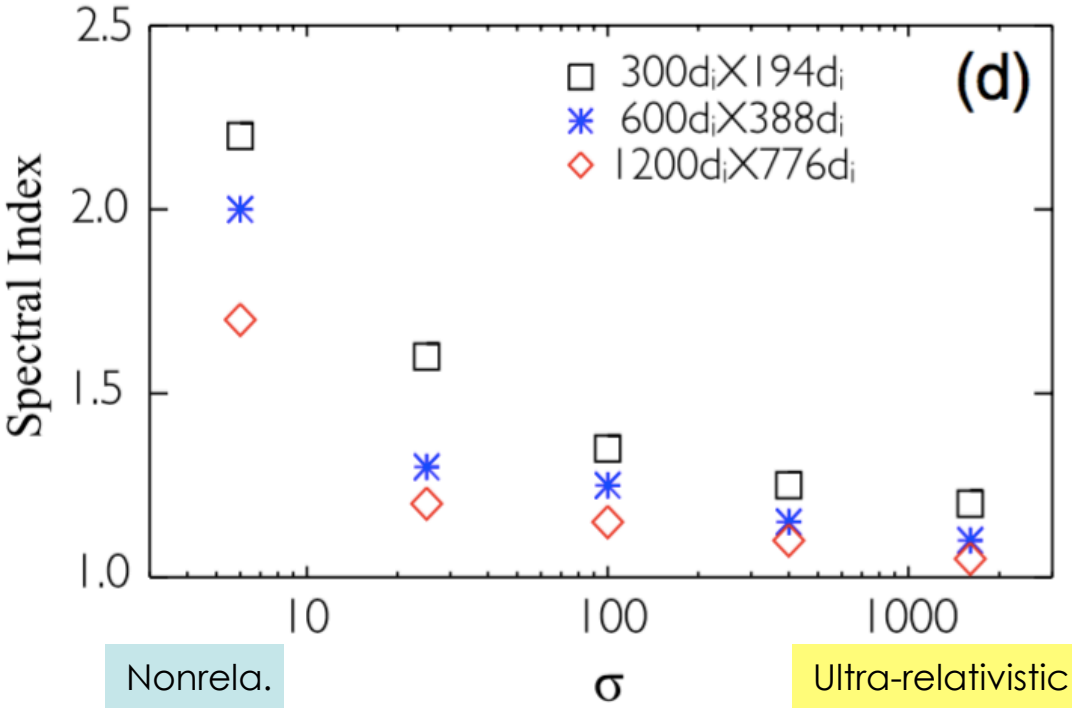


Zenitani & Hoshino 2007 ApJ

Harder spectra in higher-σ regimes



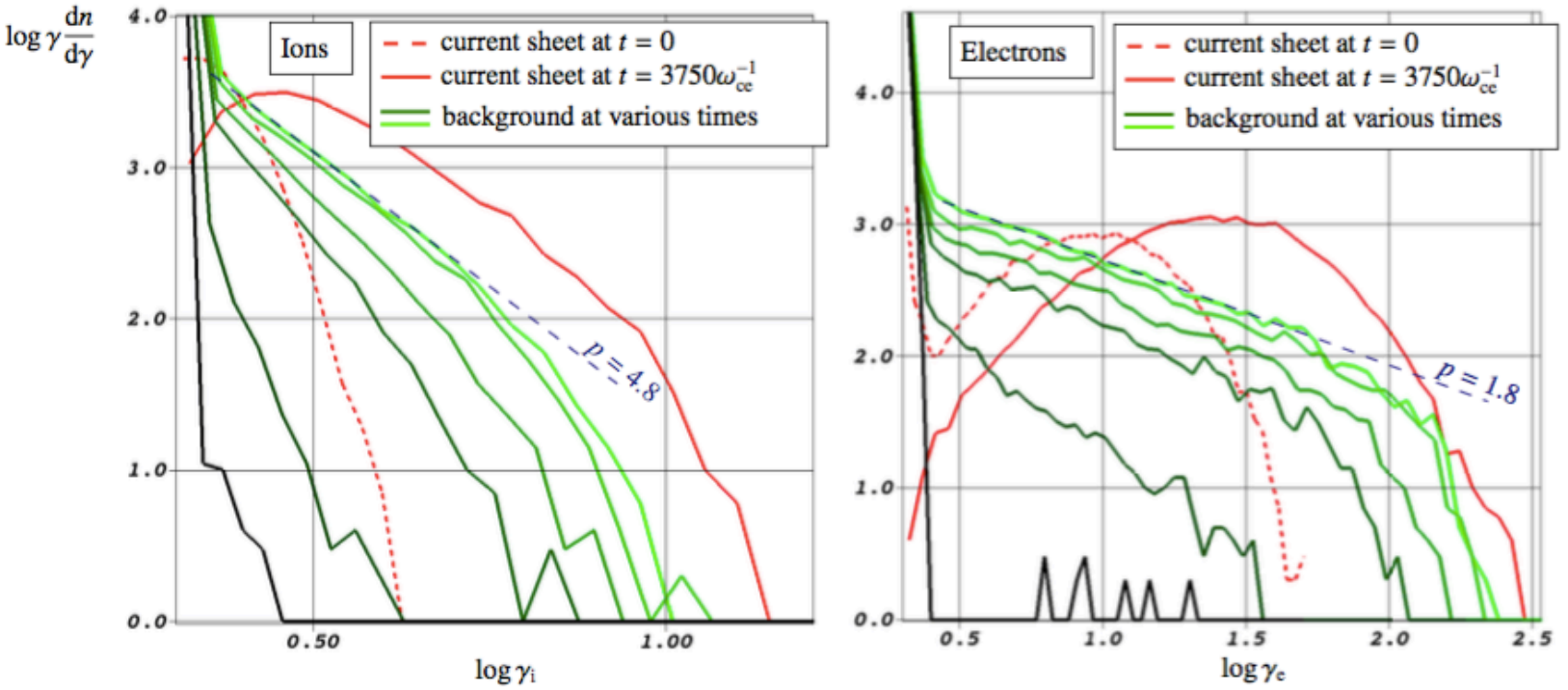
Kagan+ 2015 SSR



Guo+ 2014 PRL

- Once it occurs, relativistic MRX is an efficient accelerator
- Harder spectral index for higher-σ (Guo+ 2014, Sironi & Spitkovsky 2014)
- Similar indexes in 2D and 3D
- Which acc. mechanisms are working? (Nalewajko+ 2015)

Relativistic MRX in an ion-electron plasma



Melzani+ 2014 A&A

- Ions do accelerate. Heating or nonthermal acceleration?
- More acceleration in multiple current-sheet systems?
- More research needed

Summary

- Acceleration mechanisms in magnetic reconnection
  - X-line acceleration
  - Surfing acceleration (only for electrons)
  - Island contraction
  - Island merger
  - Stochastic acceleration in multiple current sheet system
- Relativistic magnetic reconnection
  - Relativistic X-line acceleration
  - 3D trigger problem needs to be better understood
  - Harder spectra for higher magnetization
  - Ions do accelerate
  - Which acc. mechanisms are working?

Magnetic reconnection is a favorable particle accelerator.
Stay tuned for upcoming researches!