Particle acceleration during 2D and 3D magnetic reconnection

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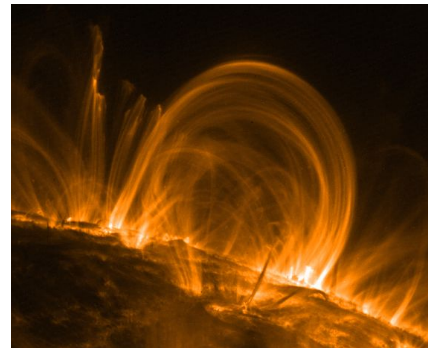
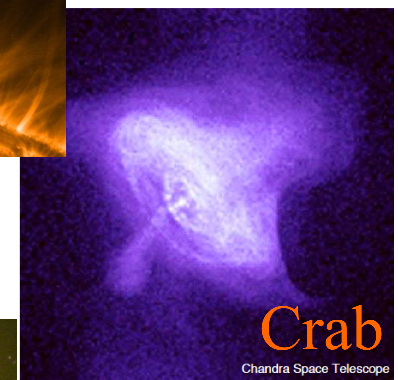
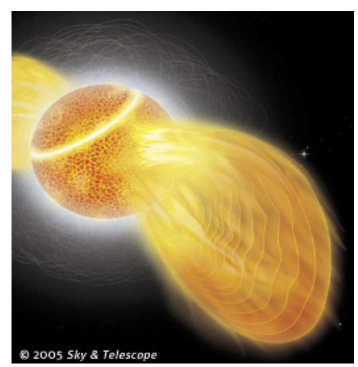
Astrophysical reconnection

- Solar and stellar flares
- Pulsar magnetospheres, winds, PWNe
- AGN (e.g., blazar) jets, radio-lobes
- Gamma-Ray Bursts (GRBs)
- Magnetar flares

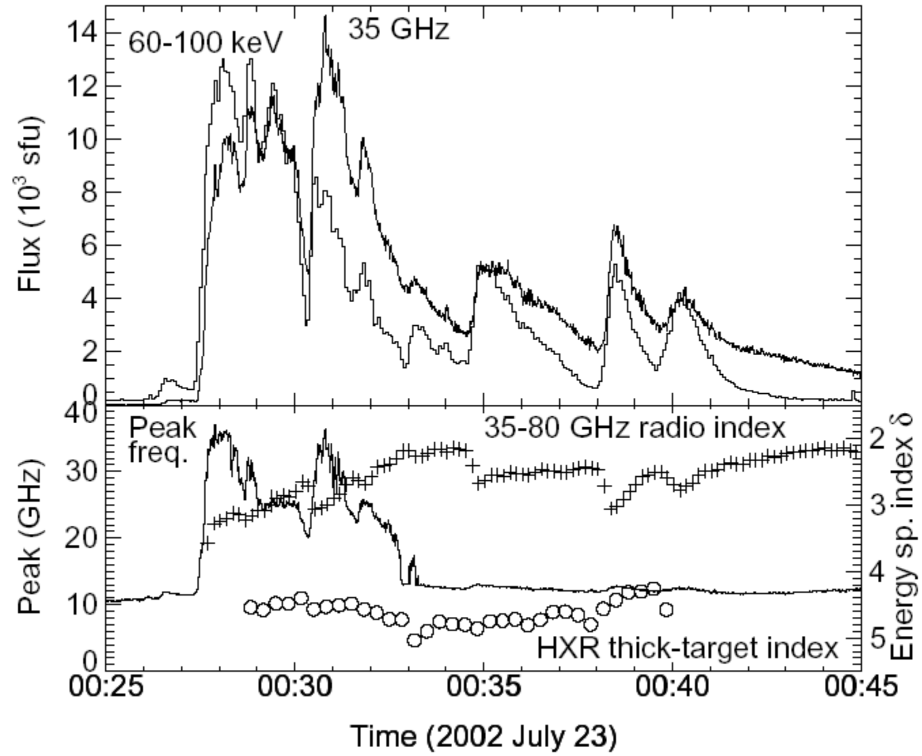






Impulsive flare timescales

- Hard x-ray and radio fluxes
  - 2002 July 23 X-class flare
  - Onset of 10's of seconds
  - Duration of 100's of seconds.

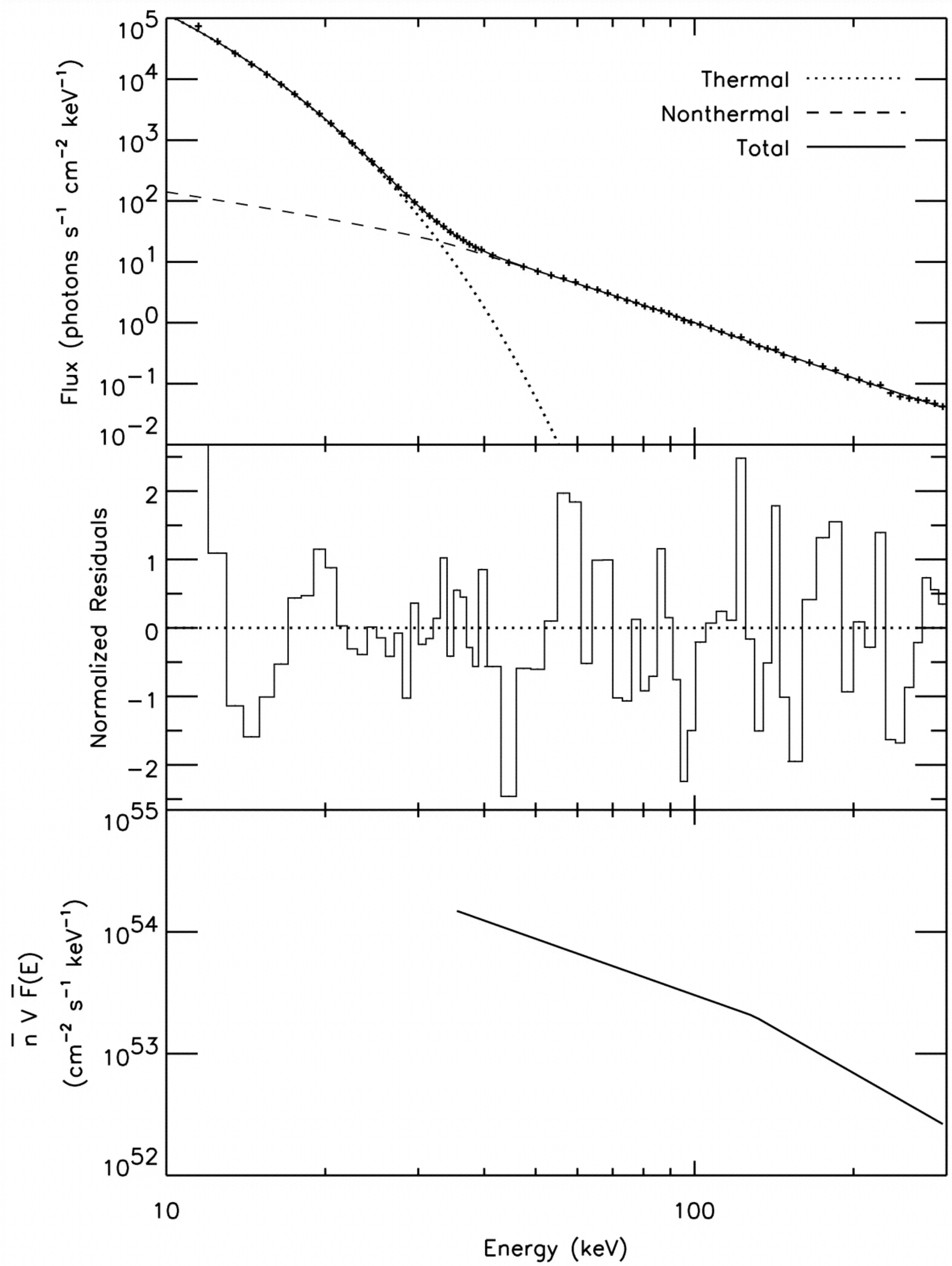


RHESSI and NoRH Data

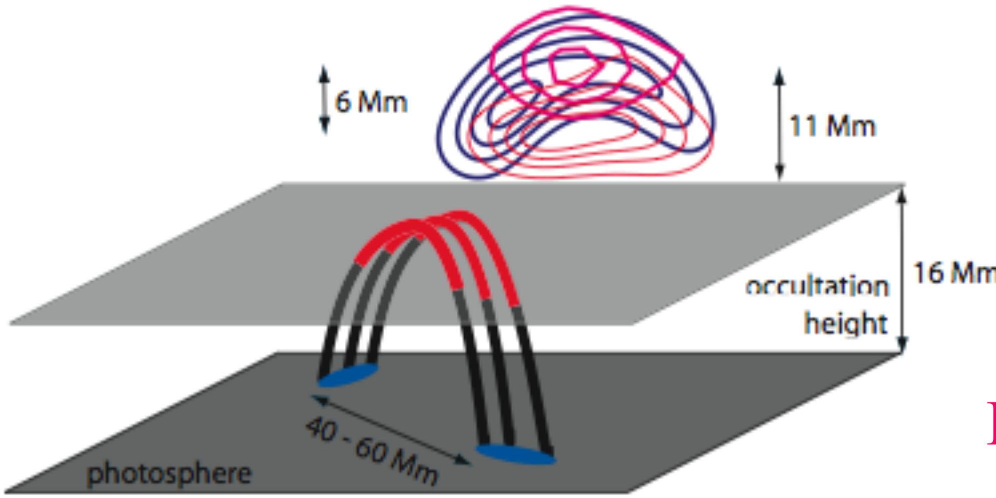
(White et al., 2003)

RHESSI observations

- July 23 γ-ray flare (Holman, *et al*., 2003)
- Double power-law fit with spectral indices:
  1.5 (34-126 keV)
  2.5 (126-300 keV)



RHESSI occulted flare observations



30-50keV

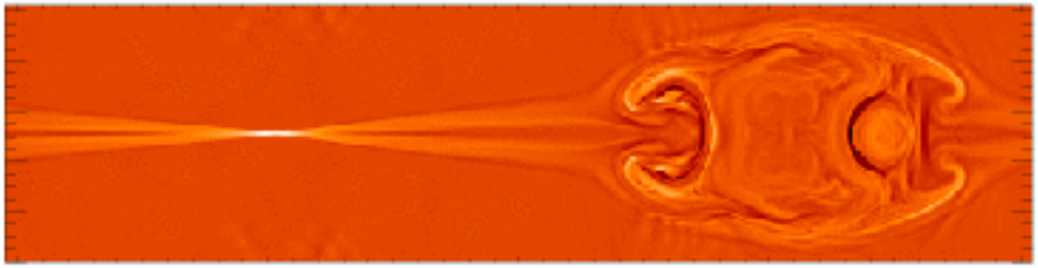
17GHz

Krucker et al 2010

- Observations of a December 31, 2007, occulted flare
  - A large fraction of electrons in the flaring region are part of the energetic component (10keV to several MeV)
  - The pressure of the energetic electrons approaches that of the magnetic field
  - Remarkable!

Energy release during reconnection

- The change in magnetic topology for reconnection takes place in the "diffusion" region
  - A very localized region around the x-line
  - This is not where significant magnetic energy is released



- Energy release primarily takes place downstream of the x-line where newly-reconnected field lines relax their tension
- Mechanisms for particle heating and energization can not be localized in the "diffusion region"

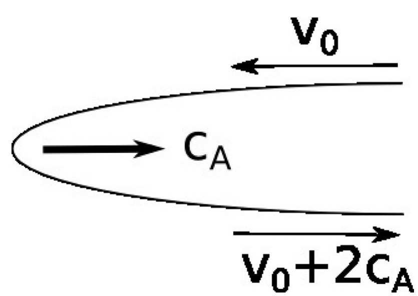
Basic mechanisms for particle energy gain during reconnection

- In the guiding center limit

$$\frac{d\varepsilon}{dt} = qv_{\parallel}E_{\parallel} + q\vec{v}_c \bullet \vec{E} + \mu\frac{\partial B}{\partial t} + q\vec{v}_B \bullet \vec{E}$$

- Curvature drift
  - Slingshot term (Fermi reflection) increases the parallel energy

$$v_c = \frac{v_{\parallel}^2}{\Omega}\vec{b} \times (\vec{b} \bullet \vec{\nabla}\vec{b})$$



- Grad B drift
  - Betatron acceleration increases perpendicular energy – μ conservation

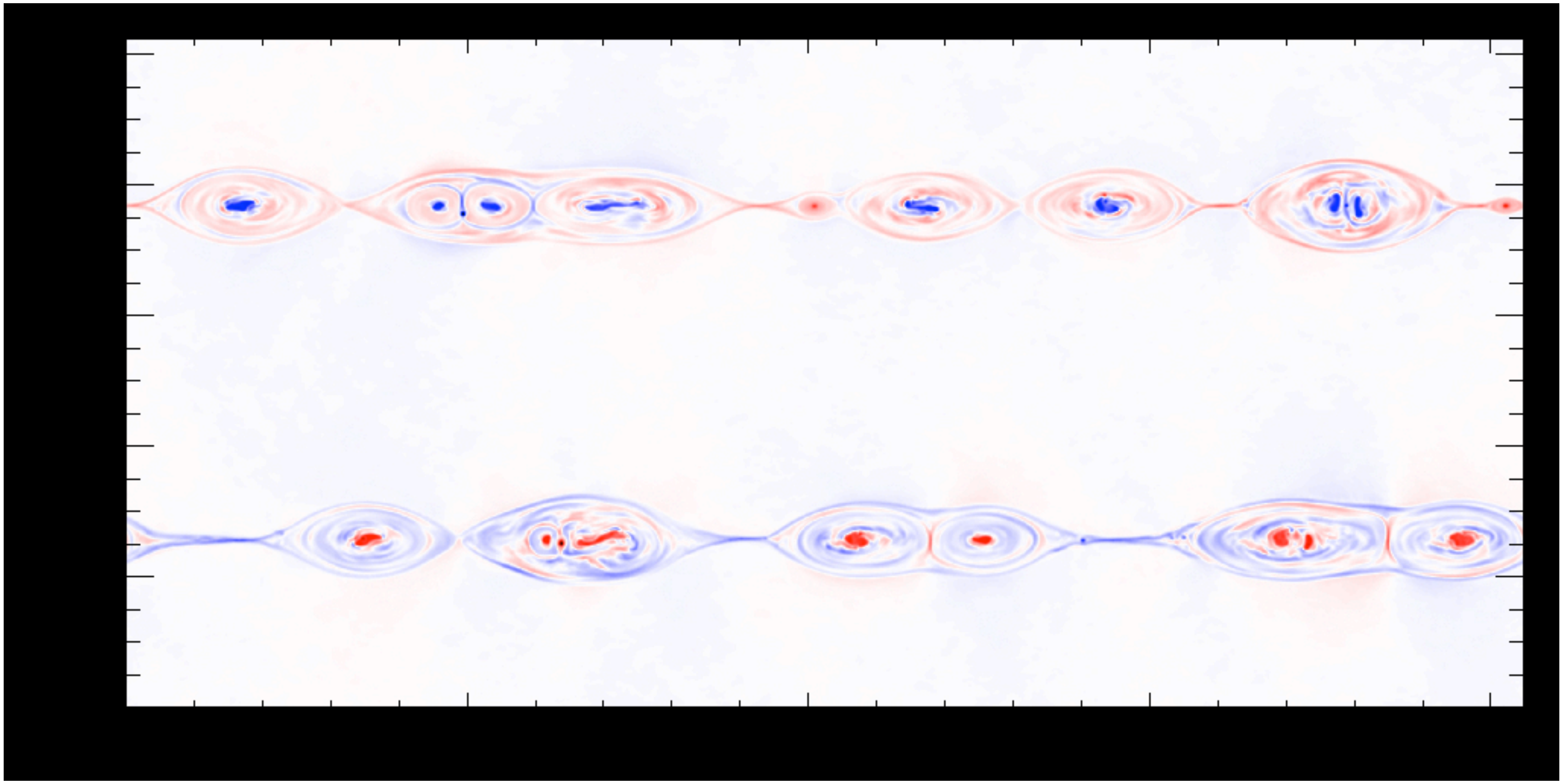
$$v_B = \frac{v_{\perp}^2}{2\Omega}\vec{b} \times \frac{\vec{\nabla}B}{B}$$

$$\mu = \frac{mv_{\perp}^2}{2B}$$

Electron heating during reconnection

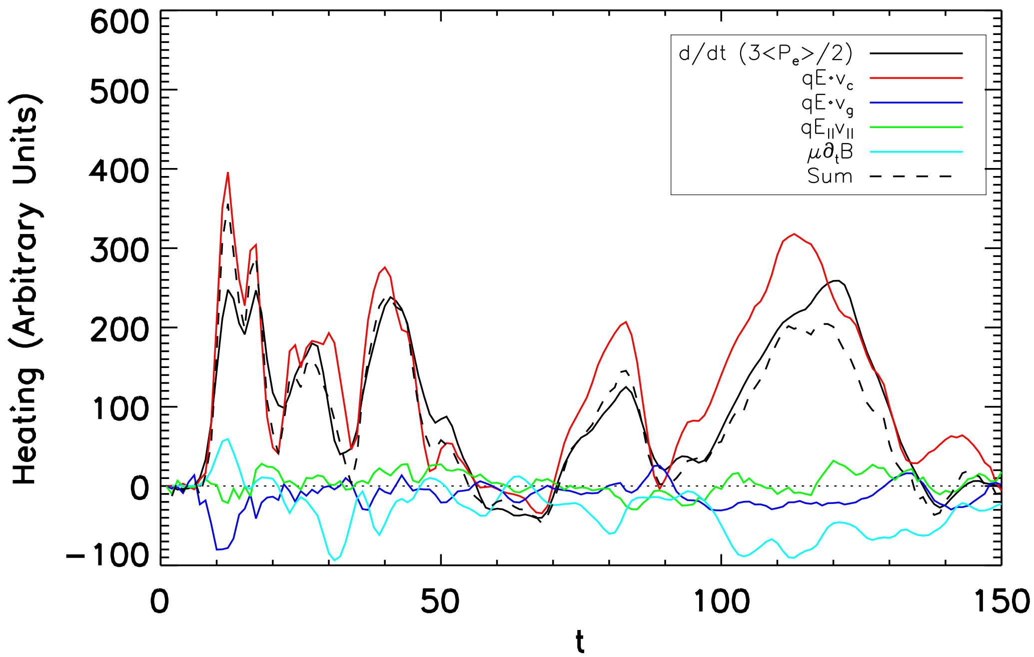
- Carry out 2-D PIC simulations of electron-proton system with a weak and strong guide fields (0.2 and 1.0 times the reconnection field)
  - $819.2d_i$ x $409.6d_i$
  - Compare all of the heating mechanisms
  - Dahlin et al '14

$$d_i = \frac{c}{\omega_{pi}}$$



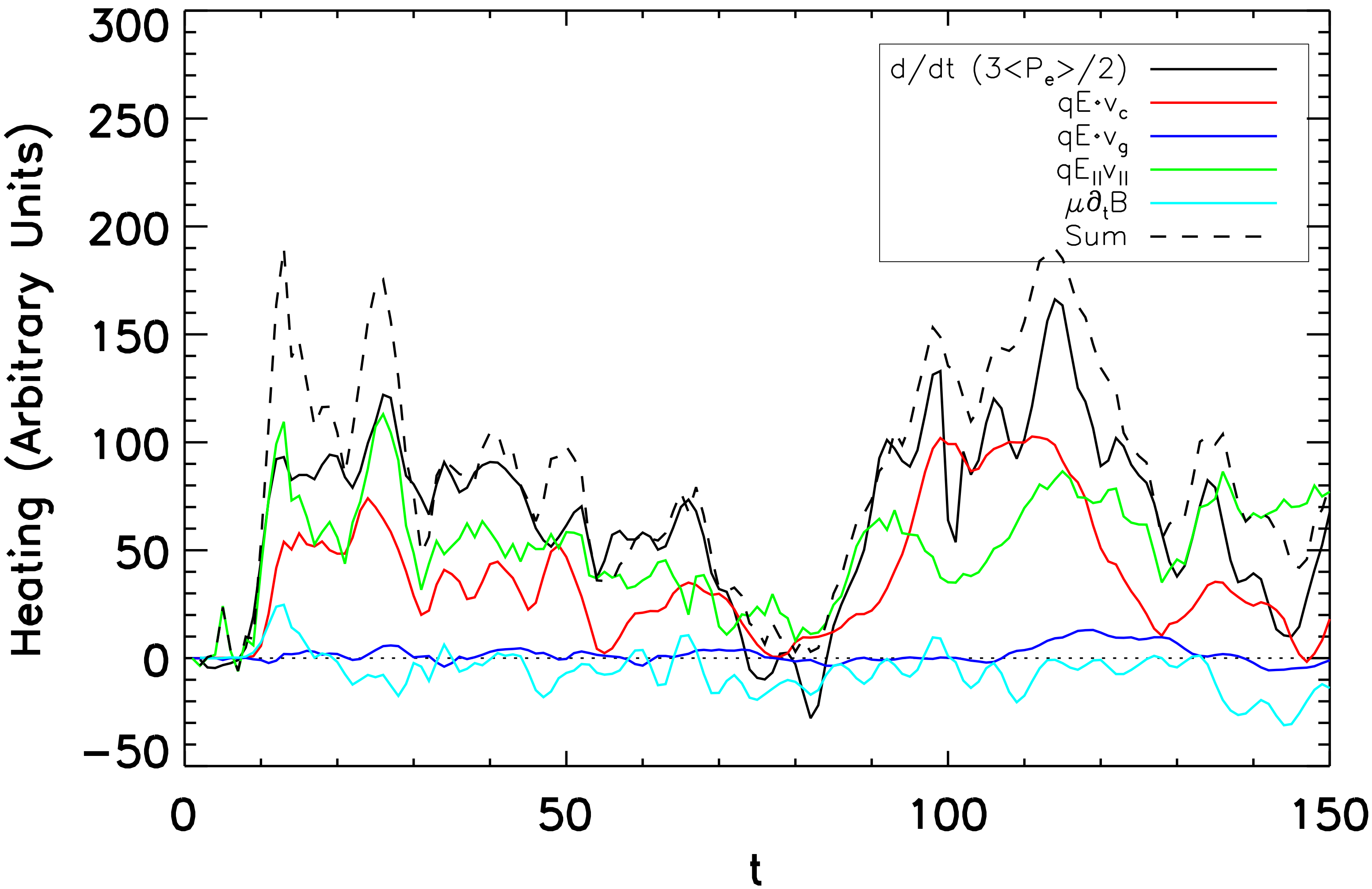
Electron heating mechanisms: weak guide field

- Slingshot term dominates (Fermi reflection)
- Parallel electric field term small – a surprise
- Grad B term is an energy sink
  - Electrons entering the exhaust where B is low lose energy because μ is conserved.



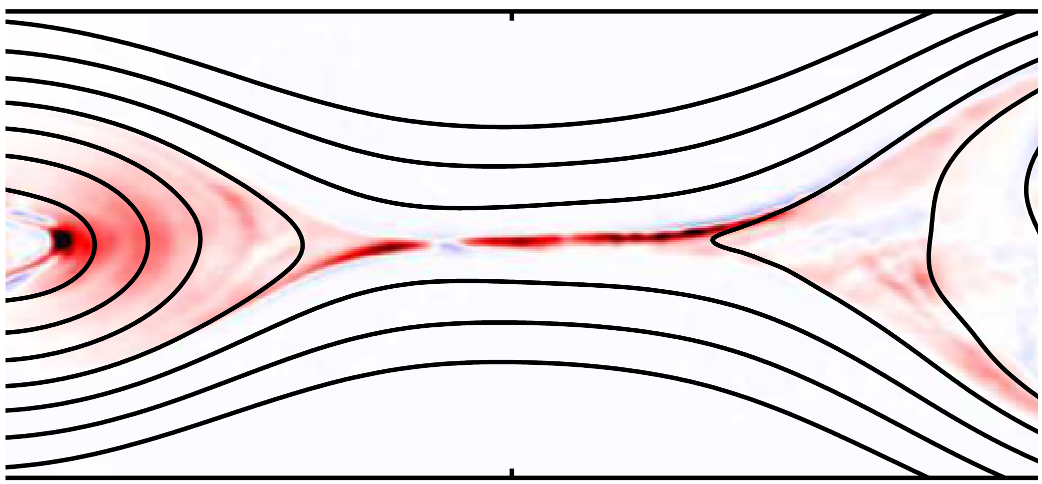
Electron heating mechanisms: strong guide field

- Fermi and parallel electric field term dominate
  - Longer current layers where $E_{\|} \neq 0$ with a guide field



Spatial distribution of heating rate from Fermi reflection

- Electron heating rate from Fermi reflection
  - Fills the entire exhaust
  - Not localized to narrow boundary layers



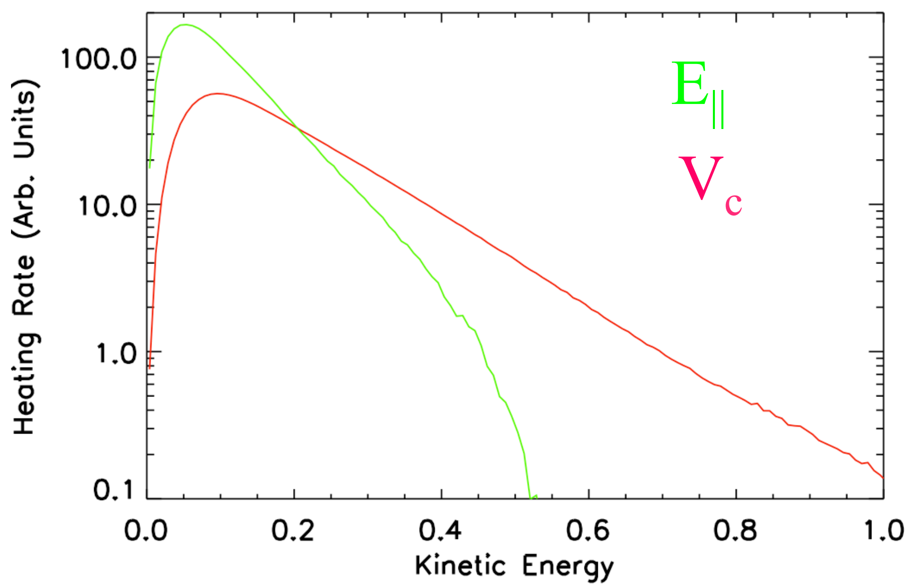
Acceleration mechanism for highest energy electrons

- Fermi reflection dominates energy gain for highest energy electrons

$$\frac{d\varepsilon}{dt} \sim q v_{\parallel} E_{\parallel} + q \vec{v}_c \bullet \vec{E}$$

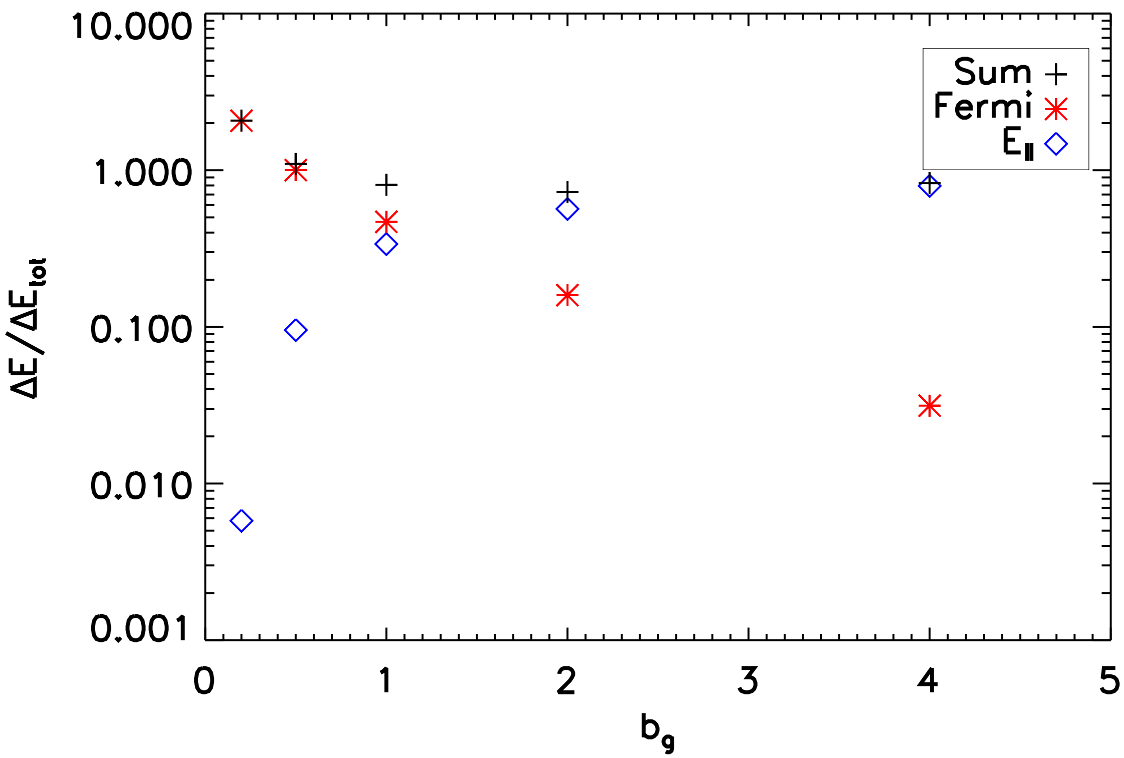
  - Where $v_c \sim v_{\parallel}^2$

- Recent simulations of pair and relativistic reconnection also see the dominance of Fermi reflection (Guo et al '14, Sironi and Spitkovsky '14)



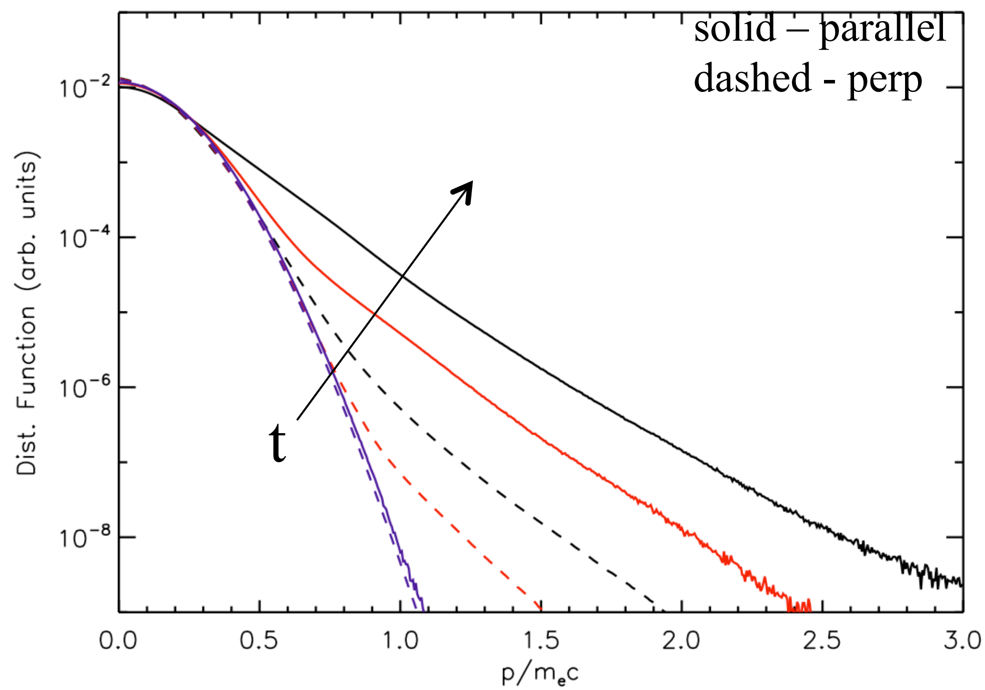
Transition to strong guide field reconnection

- Carried out a scaling study with guide field to determine electron acceleration mechanisms



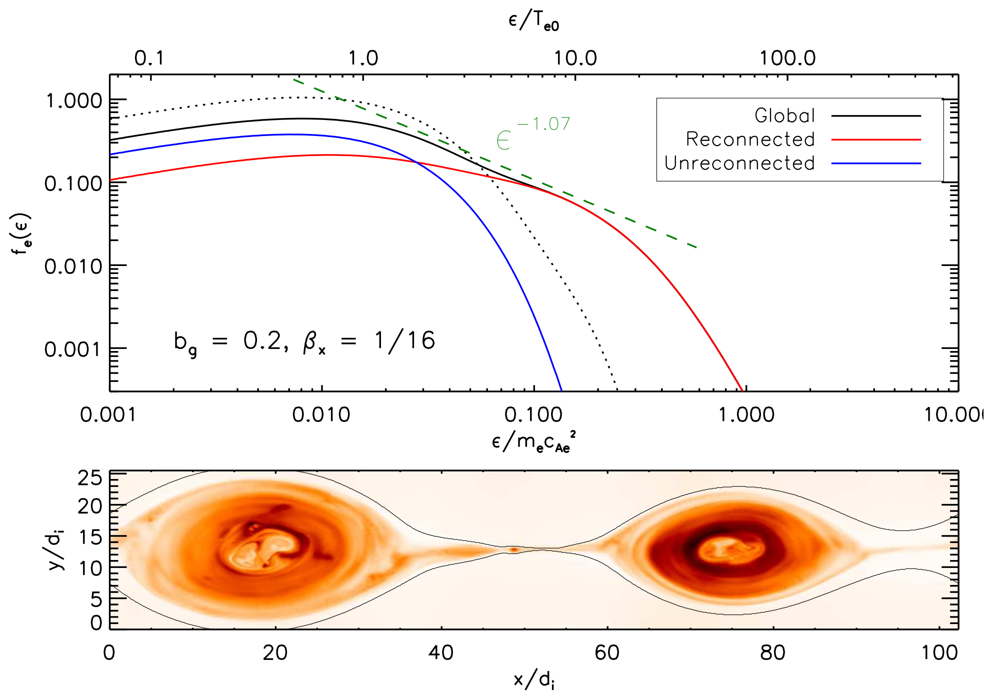
Electron spectral anisotropy

- The dominant acceleration mechanisms accelerate electrons parallel to the local magnetic field – Fermi slingshot and $E_{||}$
  - Extreme anisotropy in the spectrum of energetic electrons
  - More than a factor of 10^2
  - What limits the anisotropy?
  - Do not see powerlaw distributions



What about powerlaws in low beta systems?

- It has been suggested that powerlaws are produced in reconnection in electron-ion systems with low initial beta (Li et al 2015)
  - The powerlaw is a consequence of superimposing high energy particles within the magnetic island with the upstream distribution
  - There does not appear to be a local powerlaw

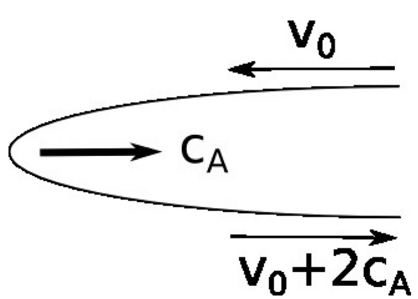


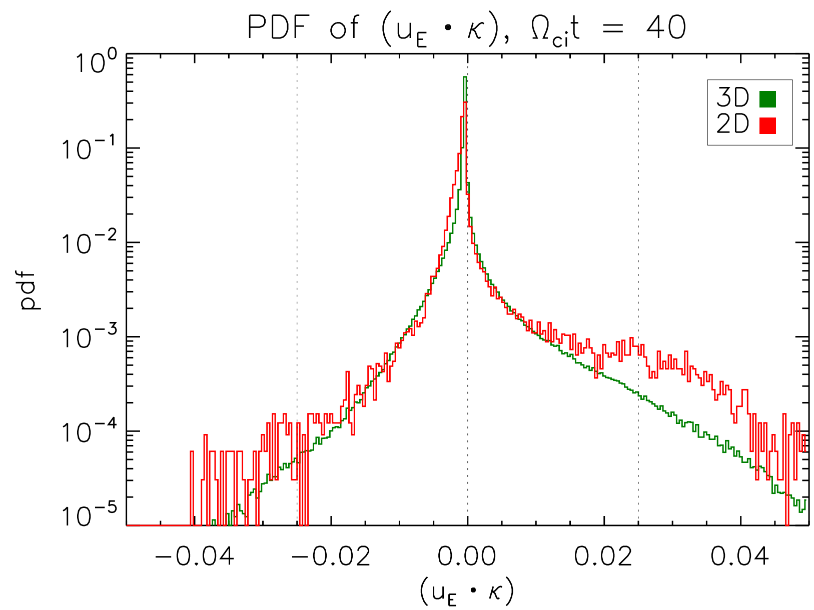
A measure of particle acceleration efficiency

- A measure of the rate of energy release and particle acceleration is the parameter

$$\vec{\kappa} \bullet \vec{V}_{ExB} = (\vec{b} \bullet \vec{\nabla}\vec{b}) \bullet \frac{c\vec{E} \times \vec{B}}{B^2}$$

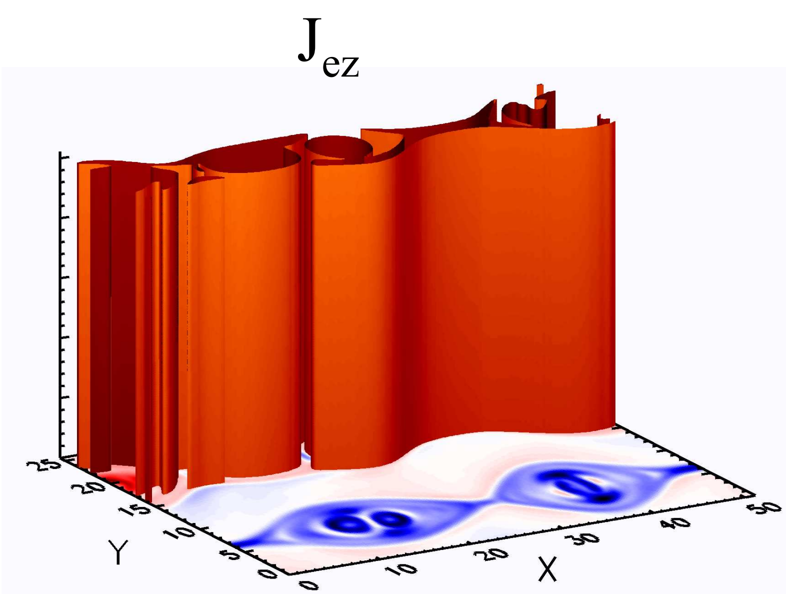
  – Dominantly positive and a reconnecting system and negative in a dynamo systems
  – The dominance of positive values establishes that particle acceleration is a first order Fermi mechanism

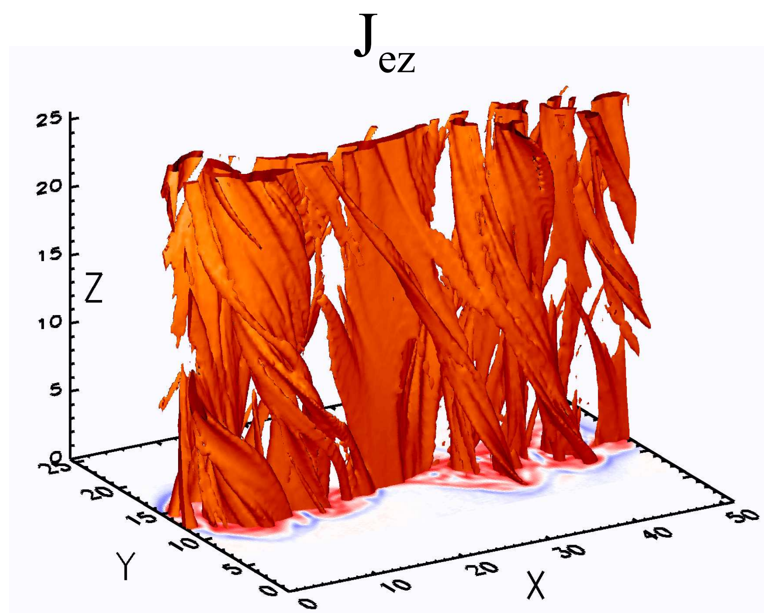




Particle acceleration in 3D reconnection

- In a 3D system with a guide field magnetic reconnection becomes highly turbulent
  - No magnetic islands
  - Chaotic field line wandering and associated particle motion
- What about particle acceleration?

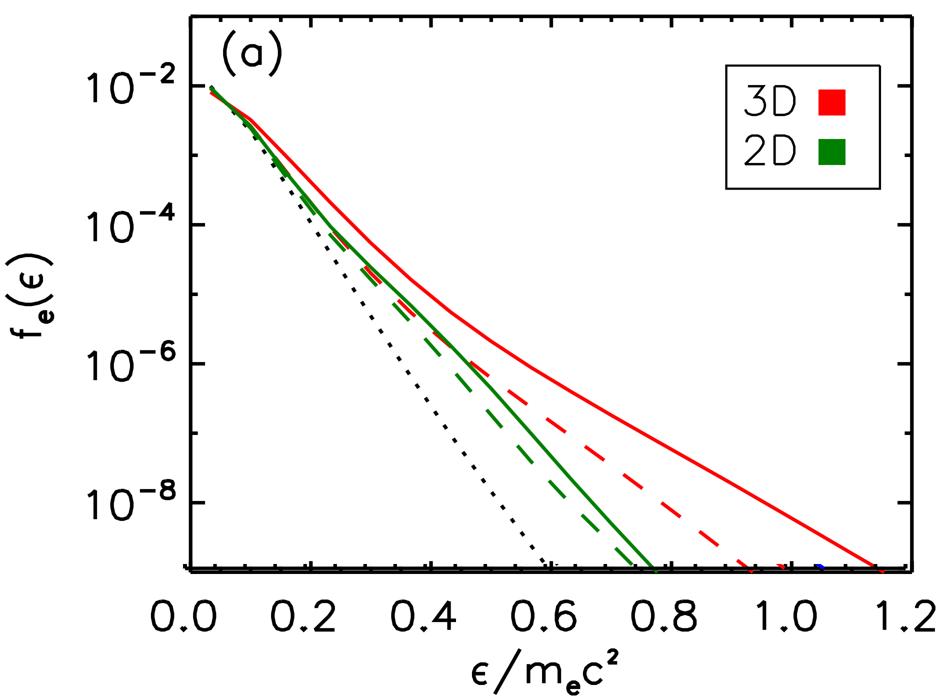




Dahlin et al ’15

Energetic electron spectra in 3D reconnection

- The rate of energetic electron production is greatly enhanced in 3D
  - The number of energetic electrons increases by more than an order of magnitude
  - The rate of electron energy gain continues robustly at late time with no evidence for saturation as in the 2D model. Why?



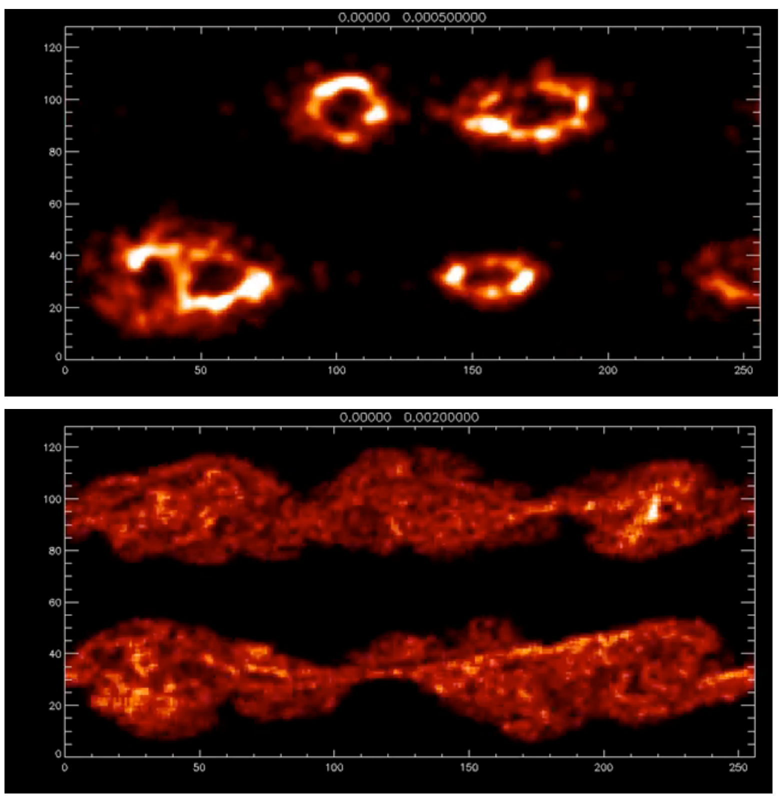
Impact of 3-D dynamics on particle acceleration

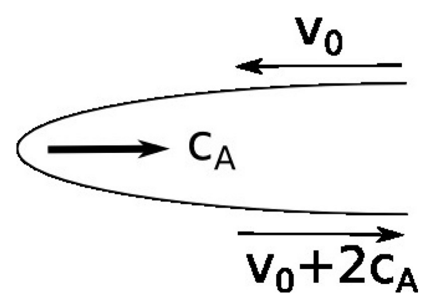
- In 3-D field lines can wander so particles are not trapped within islands
- Electrons gain energy anywhere in the reconnecting volume where magnetic field lines are locally relaxing their tension

Electrons with $\gamma > 1.5$

2D

3D

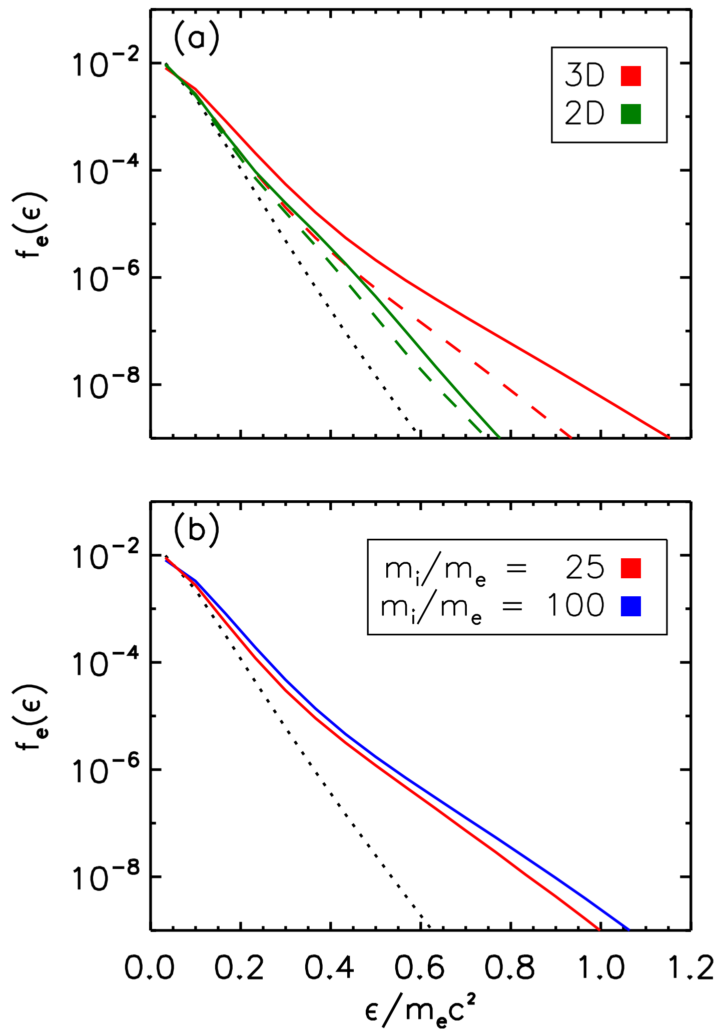




Dahlin et al ’15

Electron spectra in 2D versus 3D

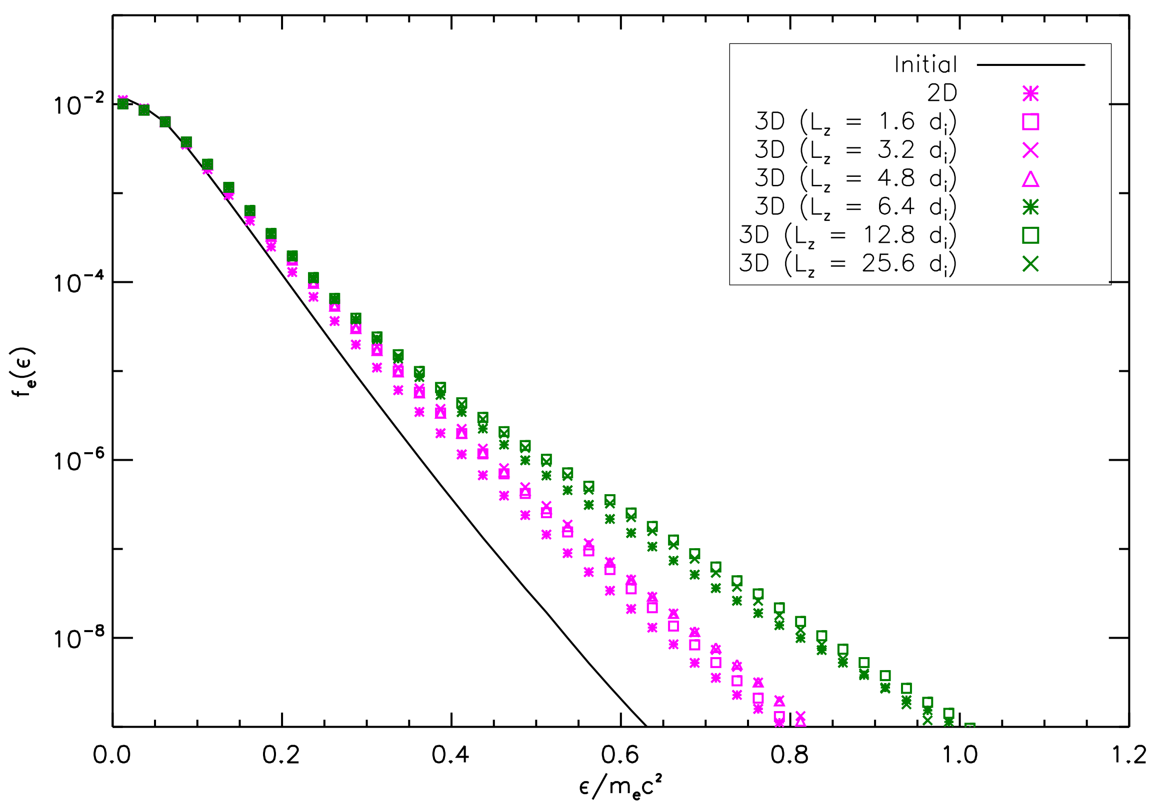
- 3D simulation with domain size $102.4d_i x 51.2d_i x 25.6d_i$
- The number of energetic electrons increases by an order of magnitude
  - High velocity electrons continue to sample energy release sites rather than being trapped in islands
- Ion heating reduced in 3D
- No difference between particle acceleration 2D and 3D in pair simulations
  - Particle and exhaust velocities are comparable



Dahlin et al '15

Transition from 2D to 3D reconnection

- Carried out simulations with varying lengths in the out-of-plane direction
  - Sharp transition from 2D to 3D for length in out-of-plane direction above a critical value



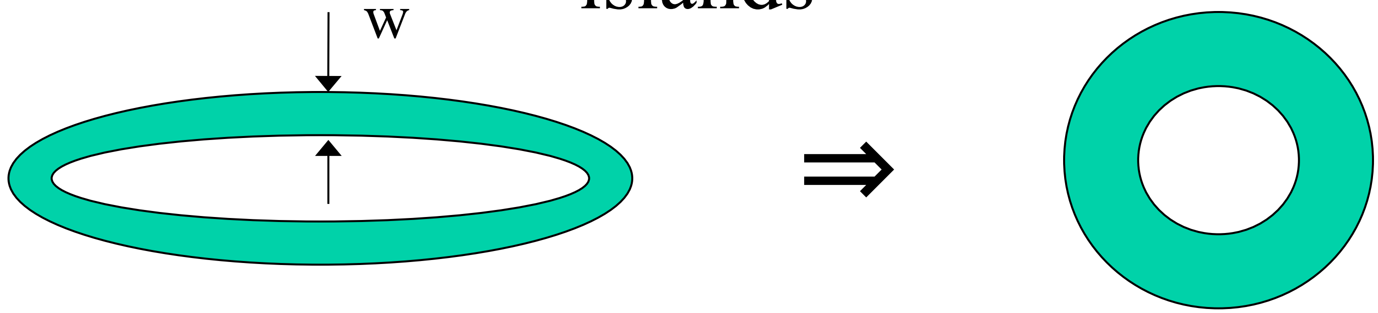
An upper limit on energy gain during reconnection

- Magnetic reconnection dominantly increases the parallel energy of particles, depending on the degree of magnetization
  - Traditional limits in which particle energy gain is balanced by synchrotron loss yield upper limits on photons of around 160MeV
  - Photon energies above this are seen in the Crab flares
  - Spectral anisotropy can change these limits
- An true upper limit on energy comes from a balance between the energy gain due to the magnetic slingshot ($\sim \gamma/R$) and the particle radiation due to its motion along the curved field line ($\sim \gamma^4/R^2$)

$$\gamma < \left(R / R_c\right)^{1/3}$$

  - Where $R_c = e^2 / mc^2$ is the classical electron radius and R is the field line radius of curvature.
  - For the Crab flares this limit yields electron energies of 10^{15}eV

Fermi acceleration in contracting and merging islands



- Area of the island Lw is preserved

  ⇒ nearly incompressible dynamics

- Magnetic field line length L decreases
- Parker's transport equation

$$\frac{\partial F}{\partial t} + \nabla \bullet uF - \nabla \bullet \kappa \bullet \nabla F - \frac{1}{3}(\nabla \bullet u)\frac{\partial}{\partial p} pF = 0$$

  - Only compression drives energy gain. Why?
  - Parker equation assumes strong scattering ⇒ isotropic plasma

- Retaining anisotropy is critical for reconnection

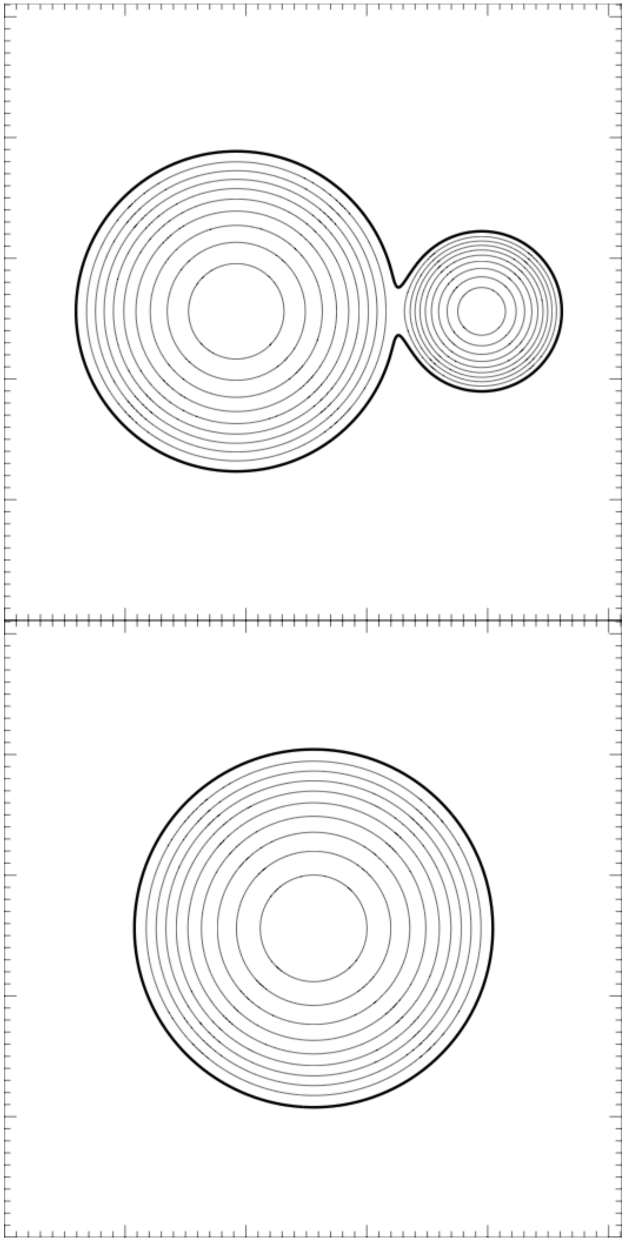
Energy gain in a bath of merging islands

- Total area preserved
- Magnetic flux of largest island is preserved
- Particle conservation laws
  - Magnetic moment $\mu = p_\perp^2 / 2mB$
  - Parallel action $p_{||} L$
    - Field line shortening drives energy gain

$$\frac{dp_{||}^2}{dt} \sim 2\frac{0.1c_A}{r_1 + r_2} p_{||}^2 \qquad \Uparrow$$

$$\frac{dp_\perp^2}{dt} \sim -\frac{0.1c_A}{r_1 + r_2} p_\perp^2 \qquad \Downarrow$$

  - No energy gain when isotropic



Particle acceleration in a multi-island reconnecting system

- Average over the merging of a bath of magnetic islands
- Kinetic equation for $f(p_{\parallel}, p_{\perp})$ with $\zeta = p_{\parallel}/p$
  - Equi-dimensional equation – no intrinsic scale
  - powerlaw solutions
  - The drive term without the loss term describes our simulations very well
  - We can calculate energy gain in reconnecting systems

$$\frac{\partial f}{\partial t} + \vec{u} \bullet \vec{\nabla} f - \vec{\nabla} \bullet \vec{\vec{D}} \bullet \vec{\nabla} f + R\left(\frac{\partial}{\partial p_{\parallel}} p_{\parallel} - \frac{1}{2p_{\perp}} \frac{\partial}{\partial p_{\perp}} p_{\perp}^2\right) f - \gamma \frac{\partial}{\partial \zeta}\left(1 - \zeta^2\right) \frac{\partial}{\partial \zeta} f = 0$$

merging drive

pitch-angle scattering

$$R \sim 0.1 \left\langle \frac{\alpha^{1/2} c_A}{r} \right\rangle \equiv \frac{1}{\tau_h}$$

$$\alpha = 1 - \frac{1}{2}\beta_{\parallel} + \frac{1}{2}\beta_{\perp}$$

Drake et al 2013

Energetic particle distributions

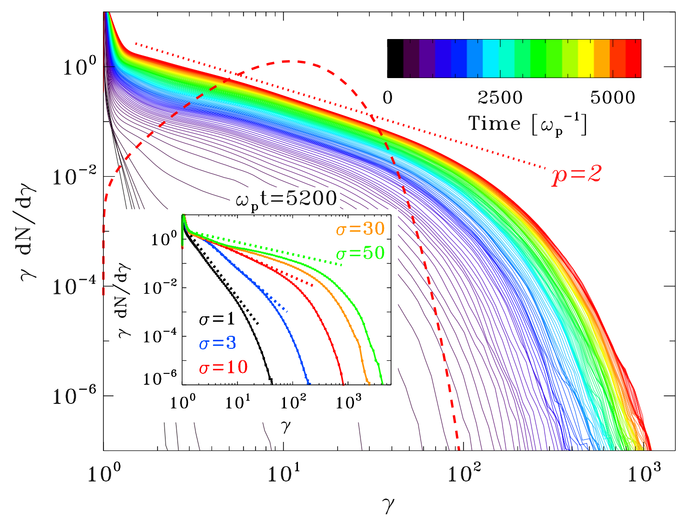
- Solutions in the strong drive limit – balance between drive and loss
  - Typically heating time short compared with loss time
- Pressure of energetic particles rises until it is comparable to the remaining magnetic energy
  - Equipartitian
  - Powerlaw solutions for the particle flux
    - Non-relativistic $$j \sim p^2 f(p) \sim p^{-3} \sim E^{-1.5}$$
    - Relativistic $$j \sim E^{-2}$$
- These distributions are the upper limits so that the energy integrals do not diverge
  - Harder spectra must have a limited range in energy

Powerlawspectra from reconnection

- Under what conditions do we expect powerlaws during reconnection?
  - With electron-proton reconnection in non-relativistic regime in periodic systems do not see powerlaws
    - Need loss mechanism to balance source to obtain powerlaws?
- Powerlaws develop in magnetically dominated plasmas. Why?

$$\sigma = B^2 / 4\pi n(m_i + m_e)c^2 >> 1$$

  - Powerlaws with indices p < 2 must have limited range in energy so the total integrated energy remains finite
    - Does a limited range powerlaw with index p < 2 make sense?



Sironi & Spitkovsky '14

Main Points

- Solar observations suggest that magnetic energy conversion into energetic electrons is extraordinarily efficient
- Fermi reflection and $E_{||}$ are the main drivers of electron acceleration during reconnection
  - Strong anisotropy of the energetic particle spectrum. What limits this anisotropy?
- Multi-x-line reconnection is required to produce the energetic component of the spectrum
  - Powerlaw spectra require a loss mechanism (electron-proton)
  - Powerlaw spectra seen in simulations in relativistic reconnection
    - Results with spectral indices harder than 2 require further scrutiny

Main Points

- The efficiency of energetic electron production in 3D increases dramatically compared with 2D
  - Electrons can wander throughout the reconnecting domain to access sites of magnetic energy release
  - No longer trapped within relaxed (contracted) magnetic islands as in 2D
- How are electrons confined within finite size regions where magnetic energy is being dissipated?
  - Their transit time is much shorter than their energy gain time
  - What controls the loss time of energetic particles in reconnection?