Mechanisms for electron acceleration in reconnection and implications for exploring energetic particle production in macro-scale systems

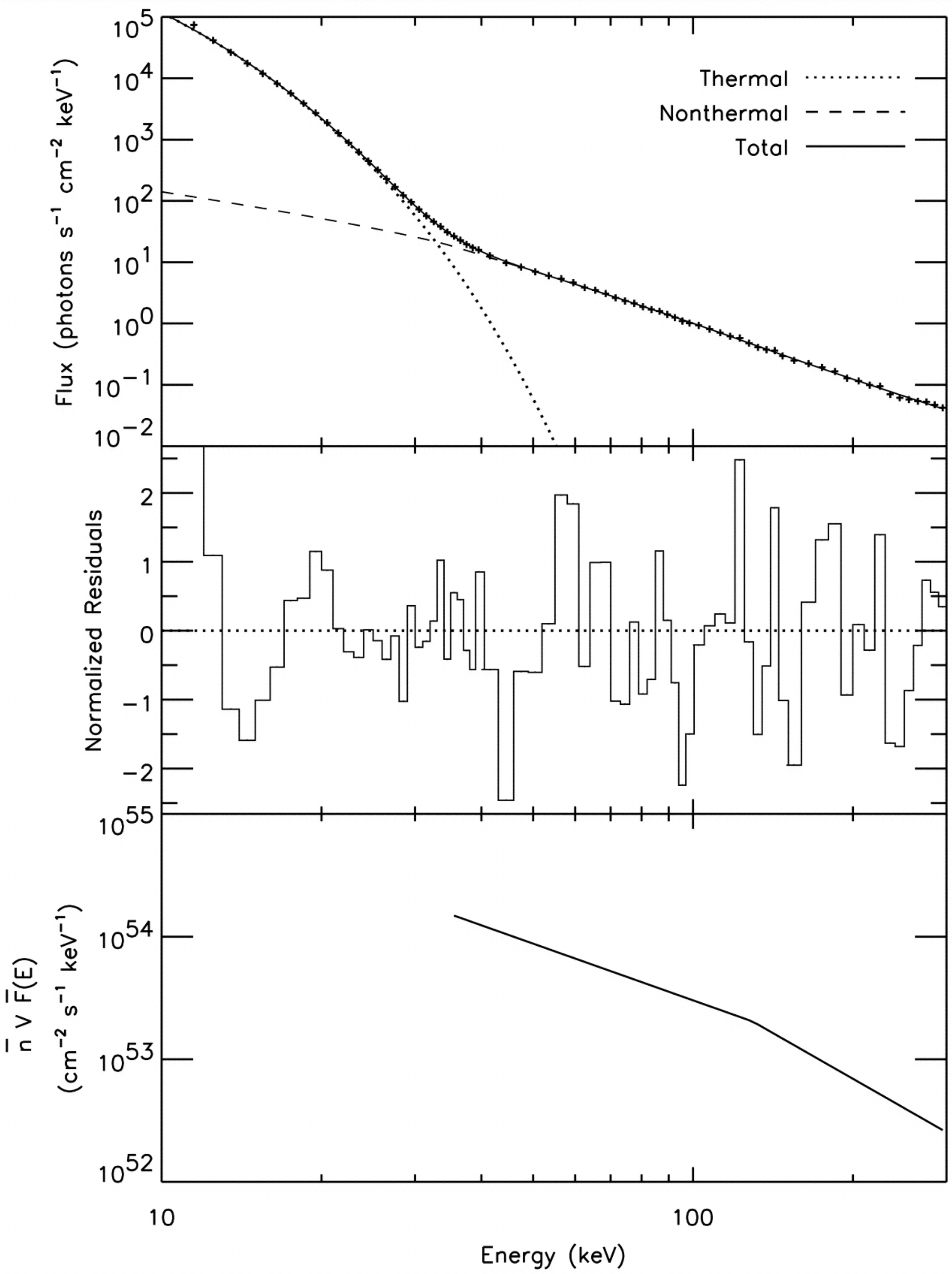
J. F. Drake University of Maryland
M. Swisdak University of Maryland
J. Dahlin GSFC

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)



The computational challenge: an enormous separation of scales most astrophysical systems

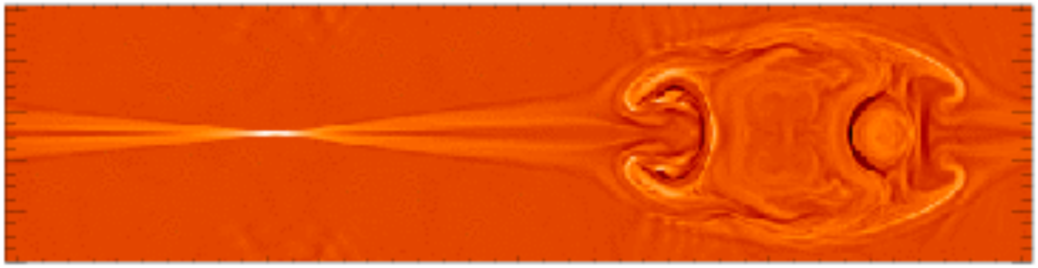
- The exploration of energetic particle production during reconnection requires a kinetic treatment
  - PIC simulations must resolve a range of kinetic scales
- Solar corona characteristic scale lengths (T ~ 100eV, n ~ 10^{10}/cm^3)
  - Debye length ~ 0.1cm
  - Electron skin depth ~ 5cm
  - Ion inertial length ~ 2.5m
  - Coronal x-ray emission region ~ 10^4km
- Separation of scales ~ 10^{10}
- PIC simulations of flares in the corona are hopeless, even using a PIC code embedded in an MHD model
- Need a new computational model for exploring reconnection-driven particle acceleration in macro-scale systems

Main Points

- Basic physics of non-relativistic reconnection
  - Heating and particle acceleration are dominated by parallel electric fields and Fermi reflection
  - Fermi reflection dominates the production of energetic particles
    - Not parallel electric fields
  - Particle acceleration is dominated by the dynamics of macro-scale magnetic islands
    - Can dump all kinetic scales
    - The classic picture of dissipation at small spatial scales is invalid
- Minimalist MHD/kinetic model for exploring energetic particles during reconnection in macro-systems
  - Order out all kinetic scales
  - An MHD backbone controls electric and magnetic fields
  - Include guiding center particles on the MHD grid
  - Include the feedback of particles on the MHD dynamics

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”

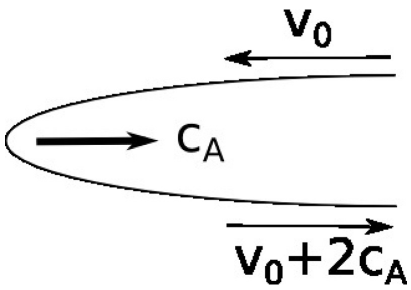
Basic mechanisms for particle energy gain during reconnection

- 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

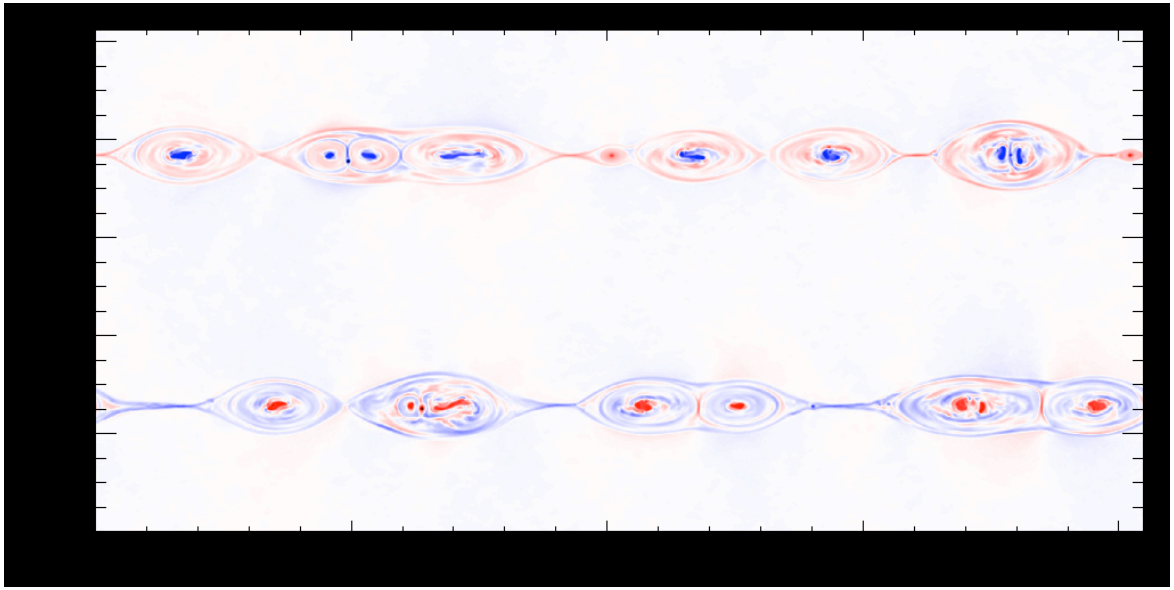
$$v_B = \frac{v_{\perp}^2}{2\Omega}\vec{b}\times\frac{\vec{\nabla}B}{B}$$

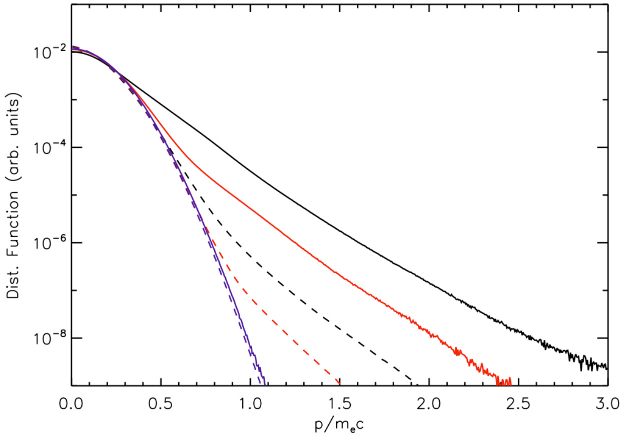
$$\mu = \frac{mv_{\perp}^2}{2B}$$

Electron heating during reconnection

- Carry out PIC simulations of electron-proton system with a range guide fields
- Focus here on 2D -- $819.2d_i \times 409.6d_i$
  - Compare all of the heating mechanisms
  - Dahlin et al ’14
- Do not see powerlaws in energetic particles
- Strong anisotropy – dominant acceleration parallel to the magnetic field

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

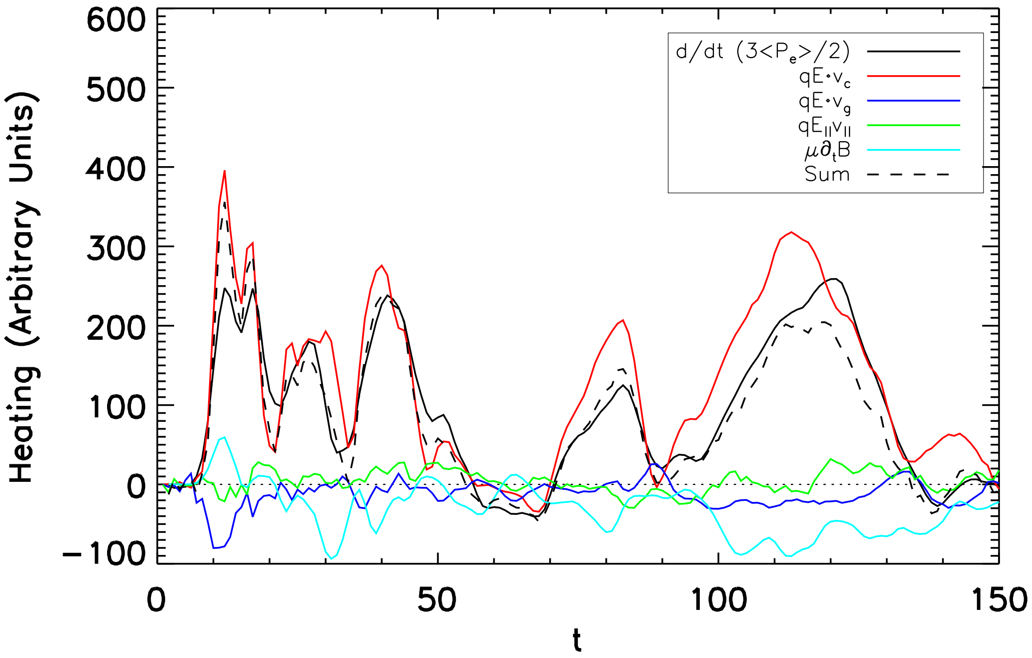




Electron heating mechanisms: weak guide field

- 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.

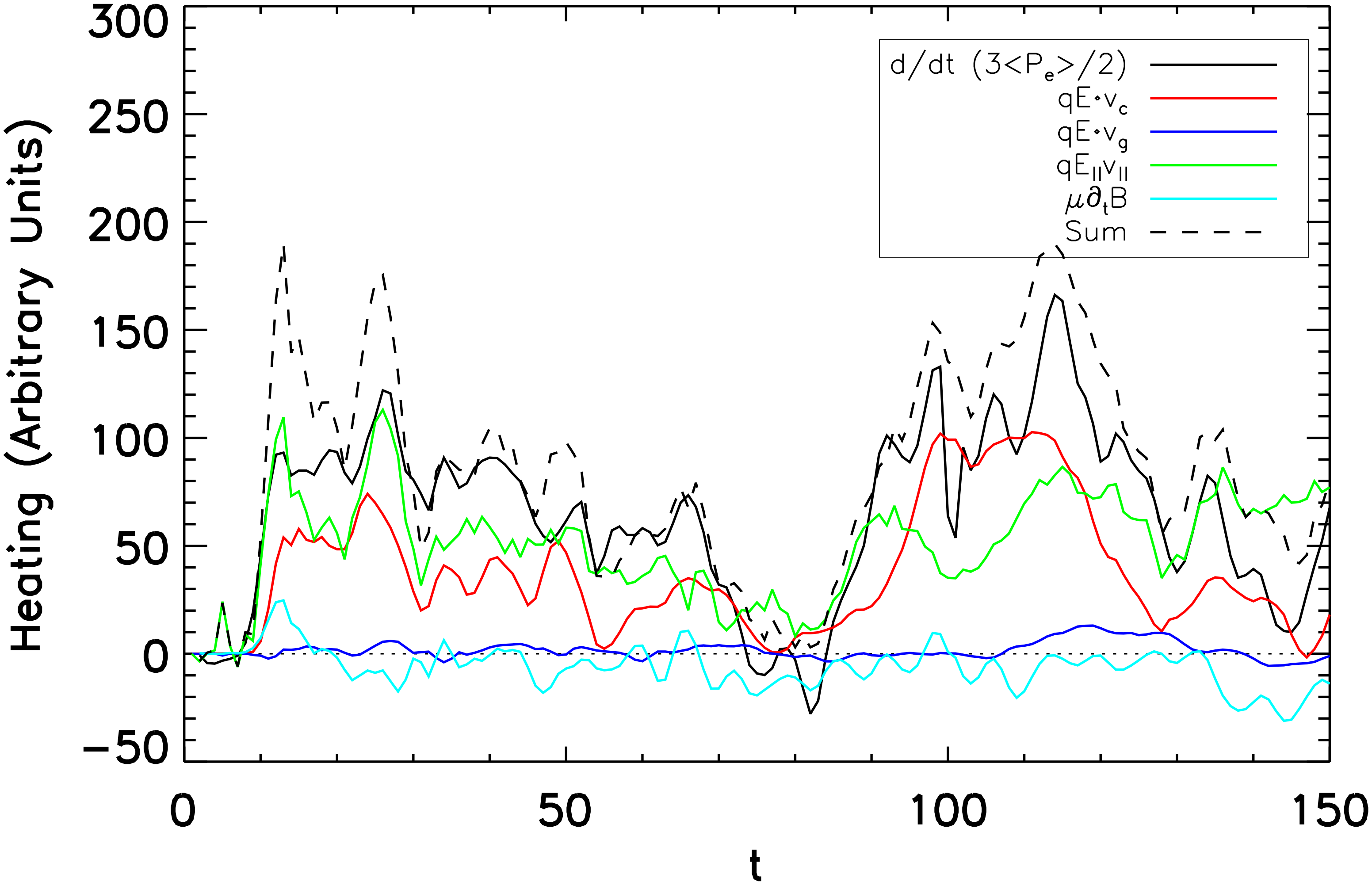
$B_g=0.2B_r$



Electron heating mechanisms: strong guide field

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

B_g=1.0B_r



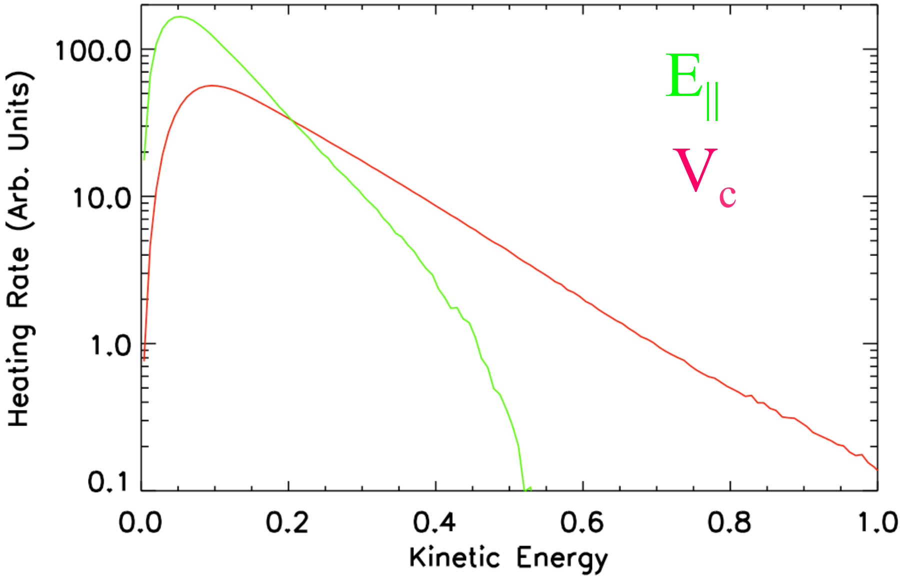
Acceleration mechanism for highest energy electrons

- Fermi reflection dominates energy gain for highest energy electrons

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

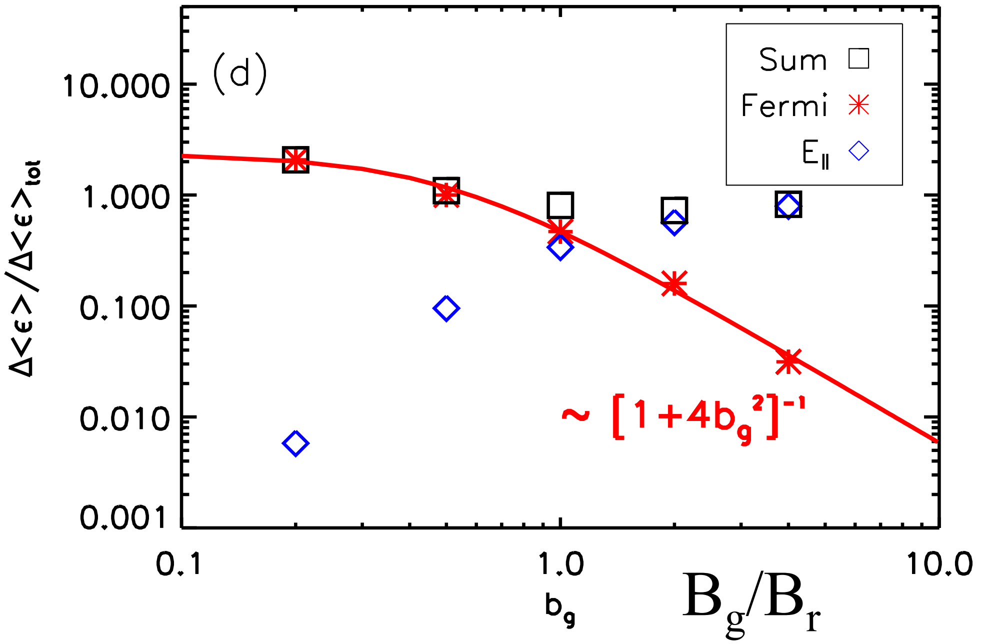
  - Where $v_c \sim v_{\|}^2$

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



Electron heating: dependence on the guide field

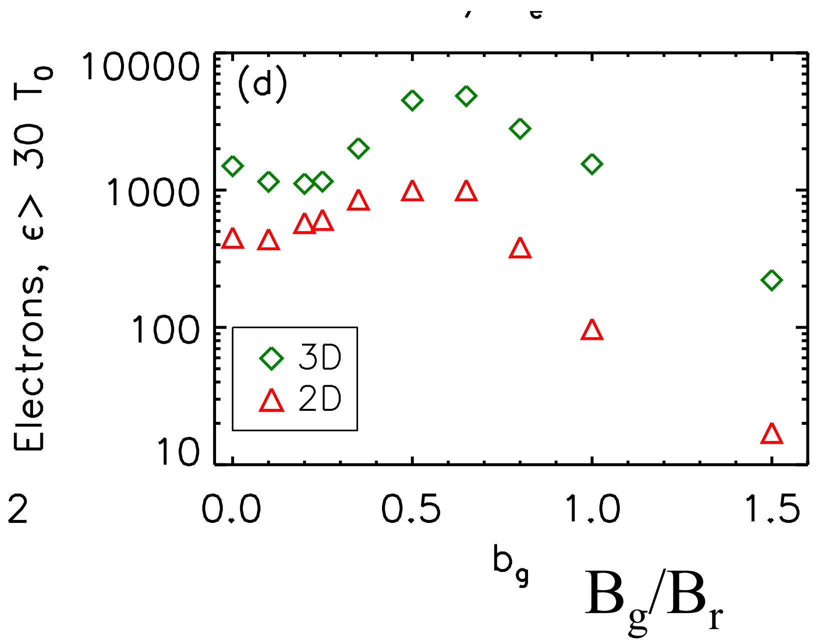
- Fermi reflection dominates for weak guide field
- $E_{||}$ dominates for strong guide field
  - Consistent with gyro-kinetic ordering



Dahlin et al ‘16

Production of energetic electrons: versus guide field

- Compare the production of energetic electrons versus the strength of guide field
  - Weak to modest guide field Fermi dominates
  - Large guide field $E_{\|}$ dominates
- Virtually no energetic particles produced in strong guide field reconnection
- Parallel electric fields are not the driver of the most energetic electrons

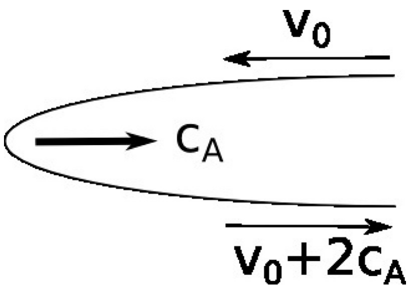


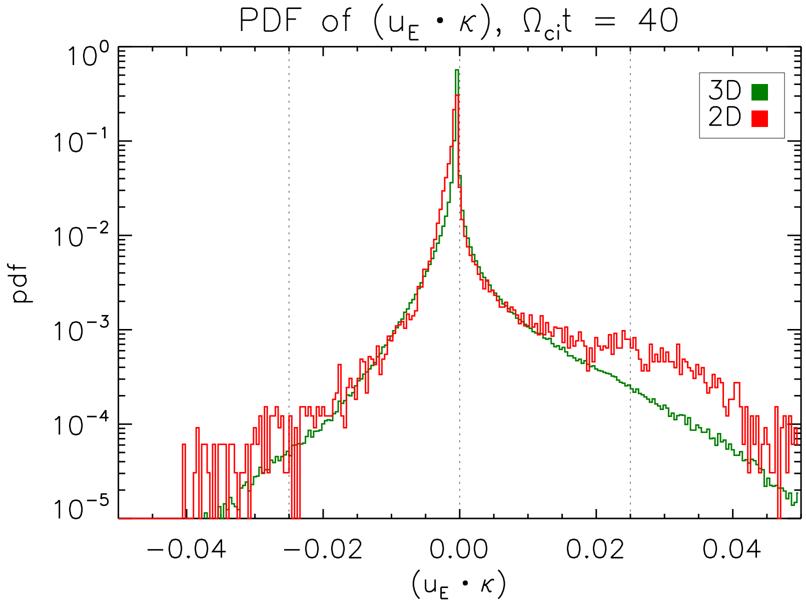
A measure of particle acceleration efficiency

- A measure of the rate of energy release and particle acceleration during reconnection 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 in a reconnecting system and negative in a dynamo systems
  - The dominance of positive values in a reconnecting systems establishes that particle acceleration is a first order Fermi mechanism





Spatial scales of energy dissipation in reconnection

- The canonical picture in MHD turbulence is that energy cascades to small spatial scales, where dissipation takes place
  - What about during reconnection in collisionless plasma?

- Parallel electric field $\dot{\varepsilon}_{\parallel} = J_{\parallel} E_{\parallel}$
  - Linked to the electron skin depth c/ω_{pe}

- Fermi reflection $\dot{\varepsilon}_{c} = \vec{J}_{c} \bullet \vec{E}$
  - Not linked to any kinetic scale

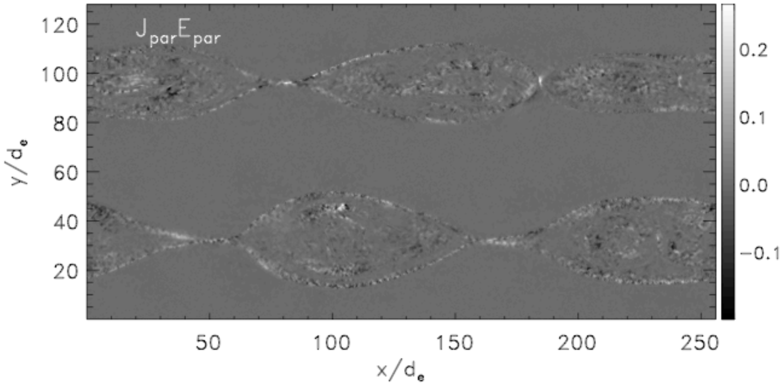
$$\vec{J}_{c} = -ne\vec{v}_{c} = -ne\frac{v_{\parallel}^{2}}{\Omega}\vec{b} \times (\vec{b} \bullet \vec{\nabla}\vec{b})$$

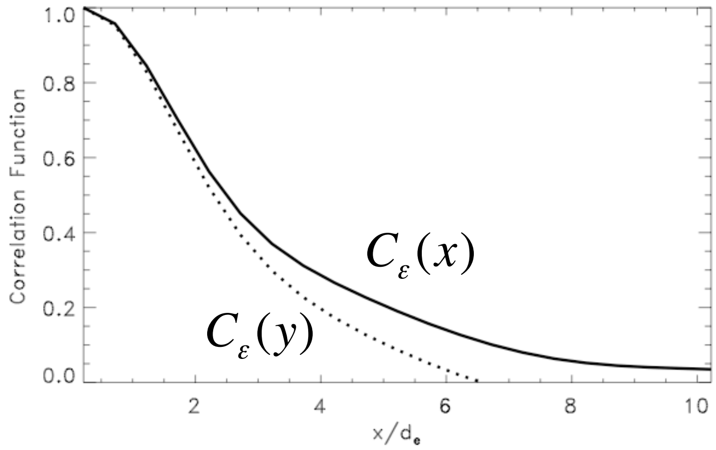
Correlation scales of electron dissipation

- Calculate the correlation function of electron dissipation from reconnection simulations

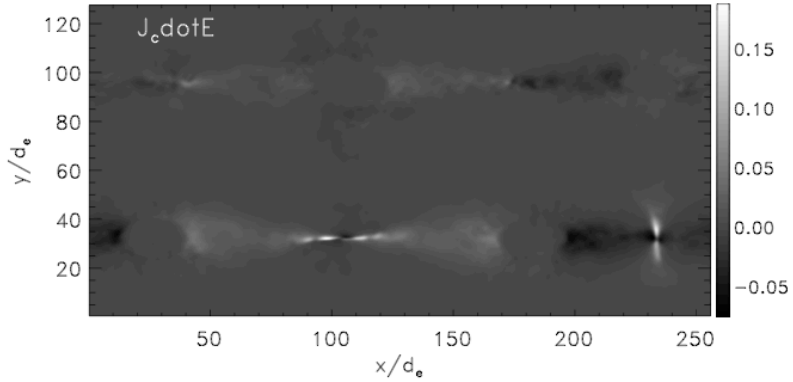
$$C_\varepsilon(\vec{r}) = < \dot{\varepsilon}(\vec{x}+\vec{r})\dot{\varepsilon}(\vec{x}) >$$

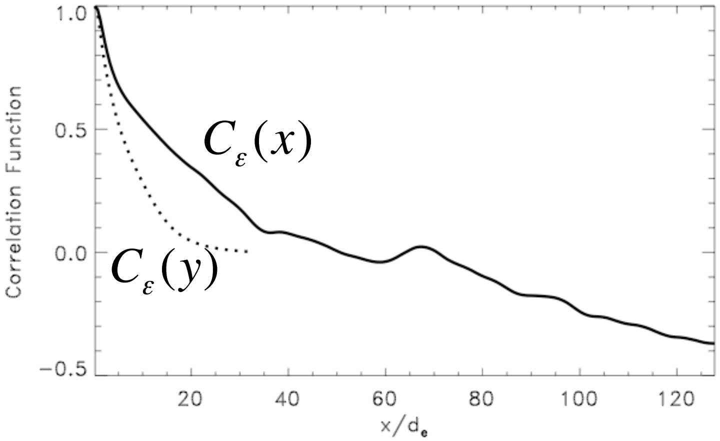
$$\dot{\varepsilon}_{||}$$





$$\dot{\varepsilon}_c$$

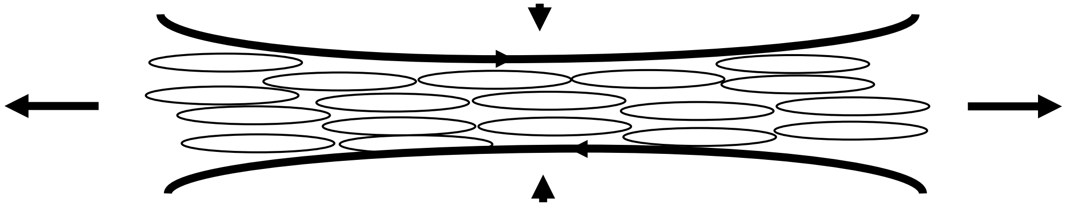


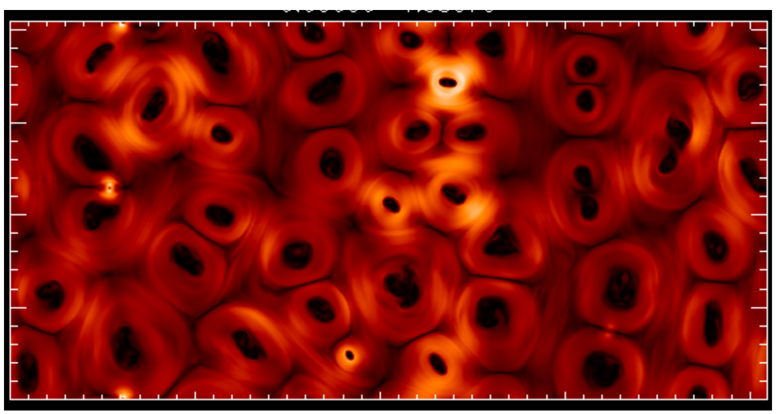


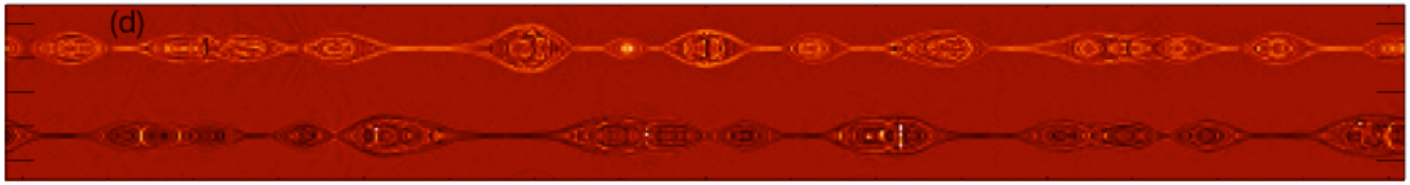
Particle acceleration in multi-island reconnection

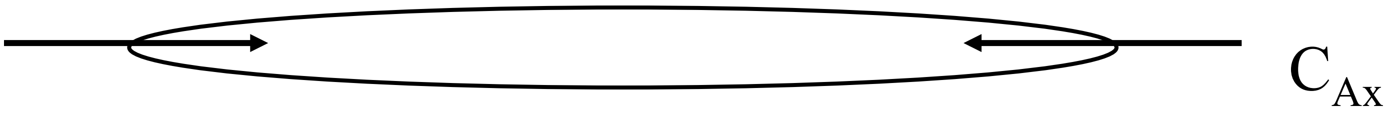
- Single x-line reconnection can not explain the most energetic particles seen in solar flares
  - Energy gain limited to around 10keV
- Greater energy gain in contracting and merging magnetic islands

Tajima and Shibata '97
Drake et al '06
Oka et al '10

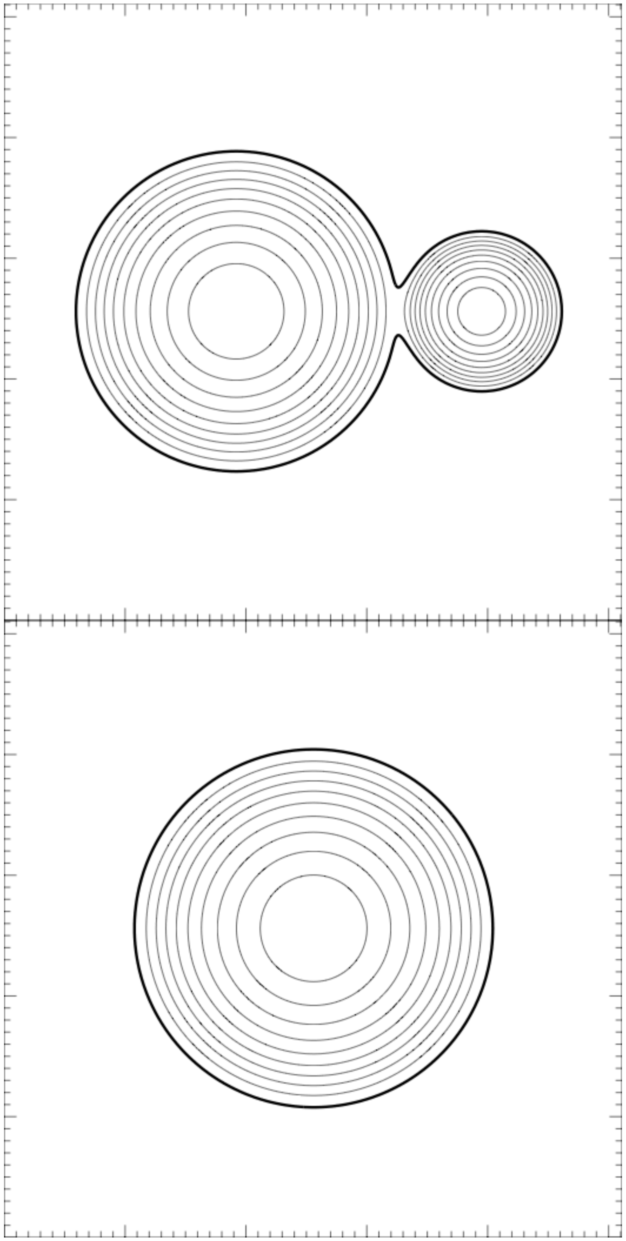








Energy gain in a bath of merging islands



- Total area preserved during merger
- Magnetic flux of largest island is preserved
- Merging islands shorten field lines
- Parallel action is conserved $p_{||} L$
  - L goes down during merger so $P_{||}$ goes up
  - Not valid for relativistic reconnection
- The merger of two equal sized islands doubles the parallel energy of particles within the islands

Drake et al '13, Montag et al '17

MeV electrons in a coronal hard x-ray source

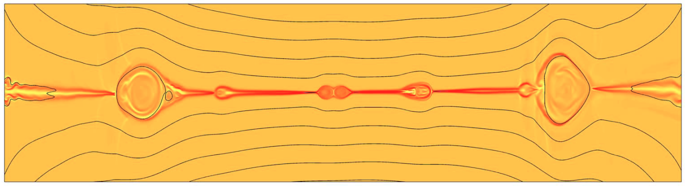
- How to get MeV electrons in the corona?
  - A two-step process – heating in single x-line reconnection following by island merging
- First step: single x-line reconnection splits released energy between electrons, ions and bulk flow
  - $\beta_e \sim 1/4$
  - For B ~ 50G, with n ~ 10^9cm^{-3}, obtain $T_{hot} \sim 15$keV
- Second step: island mergers
  - Each merger doubles the electron energy – field line shortening
  - How many island mergers takes 10keV electrons to 1MeV?

$$15keV \times 2^N = 1MeV \Rightarrow N = 6$$

  - Take typical island of size W ~ 10^3km
  - Two island merging time $t_{merge} \sim (W/2)/0.1c_A \sim 1.5s$
  - 1MeV electrons in $t_{1MeV} \sim 6t_{merge} = 9s$

Modeling reconnection-driven particle acceleration in macro-scale systems

- Eliminate all kinetic scales
  - Kinetic scales are needed to accurately describe parallel electric fields
  - They don't control the production of the most energetic particles
  - Particle production controlled by the dynamics of macro-islands
- Multi-island reconnection in MHD models produces fast reconnection (Bhattacharjee+ '09, Cassak+ '09, Huang+ '10)



- Test particle modeling in MHD fields (Onofri+ '06, Kowal+ '11, Guidoni+ '16)
  - Energy in energetic particles can run away
  - Need feedback of particles on MHD fields, e.g., firehose condition (Drake+ '13)

A self-consistent MHD/guiding-center kinetic model

- A model with an MHD backbone and with macro-particles evolved in parallel using the guiding center equations
  - All kinetic scales ordered out
  - Energetic component evolved in the MHD fields
  - Energetic particle feedback on the MHD fluid through the pressure driven currents of the energetic component
  - Total energy of the MHD system plus the energetic component is conserved
  - Not appropriate for shock acceleration where particle scattering is essential
- Similar models
  - Park et al ’92, gyrokinetic description – no Fermi contributions
  - Bai et al ’15, full kinetic description for shocks

Basic equations

- MHD momentum equation with MHD pressure P and the energetic particle current $\mathbf{J}_h$

$$m_i n \frac{d}{dt}\vec{v} = \frac{1}{c}\vec{J} \times \vec{B} - \vec{\nabla} P - \frac{1}{c}\vec{J}_h \times \vec{B}$$

- Order out the Hall terms $\vec{E} = -\frac{1}{c}\vec{v} \times \vec{B}$

- Particles – guiding center equations

$$\frac{d}{dt} p_{\parallel e} = \frac{c}{B} p_{\parallel e} \vec{b} \times \vec{\kappa} \bullet \vec{E} - \frac{\mu_e}{\gamma_e} \vec{b} \bullet \vec{\nabla} B$$

$$\mu = \frac{p_{\perp e}^2}{2 m_e B} = const.$$

Basic Equations (cont.)

- Particle Moments

$$\vec{\vec{P}}_h = P_{\parallel h}\vec{b}\vec{b} + P_{\perp h}(\vec{\vec{I}} - \vec{b}\vec{b}) \qquad \vec{\nabla}\bullet\vec{\vec{P}}_h = \frac{1}{c}\vec{J}_h \times \vec{B}$$

$$\vec{J}_h = \frac{c}{B}\left(P_{\parallel h}\vec{b}\times\vec{\kappa} + P_{\perp h}\vec{b}\times\vec{\nabla}\ln(B)\right) - c\vec{\nabla}\times(\frac{P_{\perp h}}{B}\vec{b})$$

curvature drift grad B drift magnetization current

- Energy Conservation

$$\frac{d}{dt}W_{MHD} = -\int d\vec{x}\vec{J}_h \bullet E = -\frac{d}{dt}W_h$$

$$\frac{d}{dt}W_h = \int d\vec{x}\left(P_{\parallel h}\vec{V}_E\bullet\vec{\kappa} + P_{\perp h}\vec{V}_E\bullet\vec{\nabla}\ln B + \frac{P_{\perp h}}{B}\frac{\partial}{\partial t}B\right)$$

$$\vec{V}_E = \frac{c}{B^2}\vec{E}\times\vec{B}$$

Main Points

- Solar observations suggest that magnetic energy conversion into energetic electrons is extraordinarily efficient
- Fermi reflection the dominant driver of energetic electron production during reconnection
  - $E_{||}$ is not the main driver of the energetic component
  - Fermi reflection is dominated by the dynamics of island formation and merger
- Energetic particle production can be modeled without including the kinetic boundary layers necessary for describing $E_{||}$
- A new hybrid model with an MHD backbone and but with macro-particles evolved in parallel using guiding center equations is being developed
  - The particles self-consistently feed back on the MHD fluid through their perpendicular currents
  - The total fluid plus energetic particle energy is conserved

Main Points (cont.)

- The particle-in-cell code *p3d* is being modified to advance the new hybrid equations
  - *p3d* is already set up to evolve the MHD equations
  - The coupling of the MHD equations to the particle stepping algorithm is now undergoing development
- Stay tuned for test results of the new model