Multi X-line magnetic reconnection and particle acceleration

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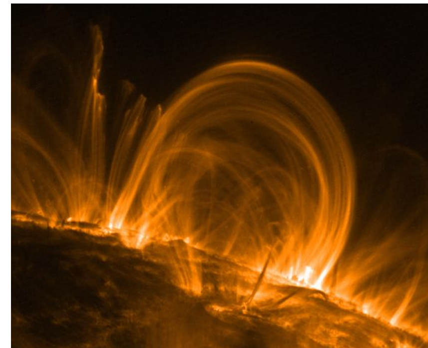
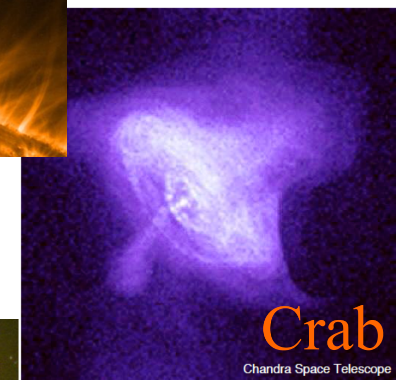
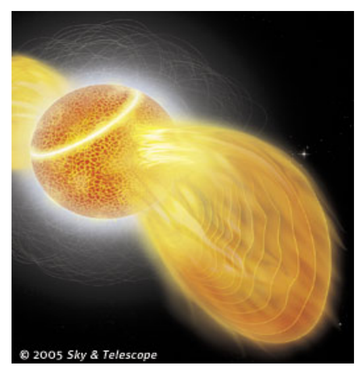
Astrophysical reconnection

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

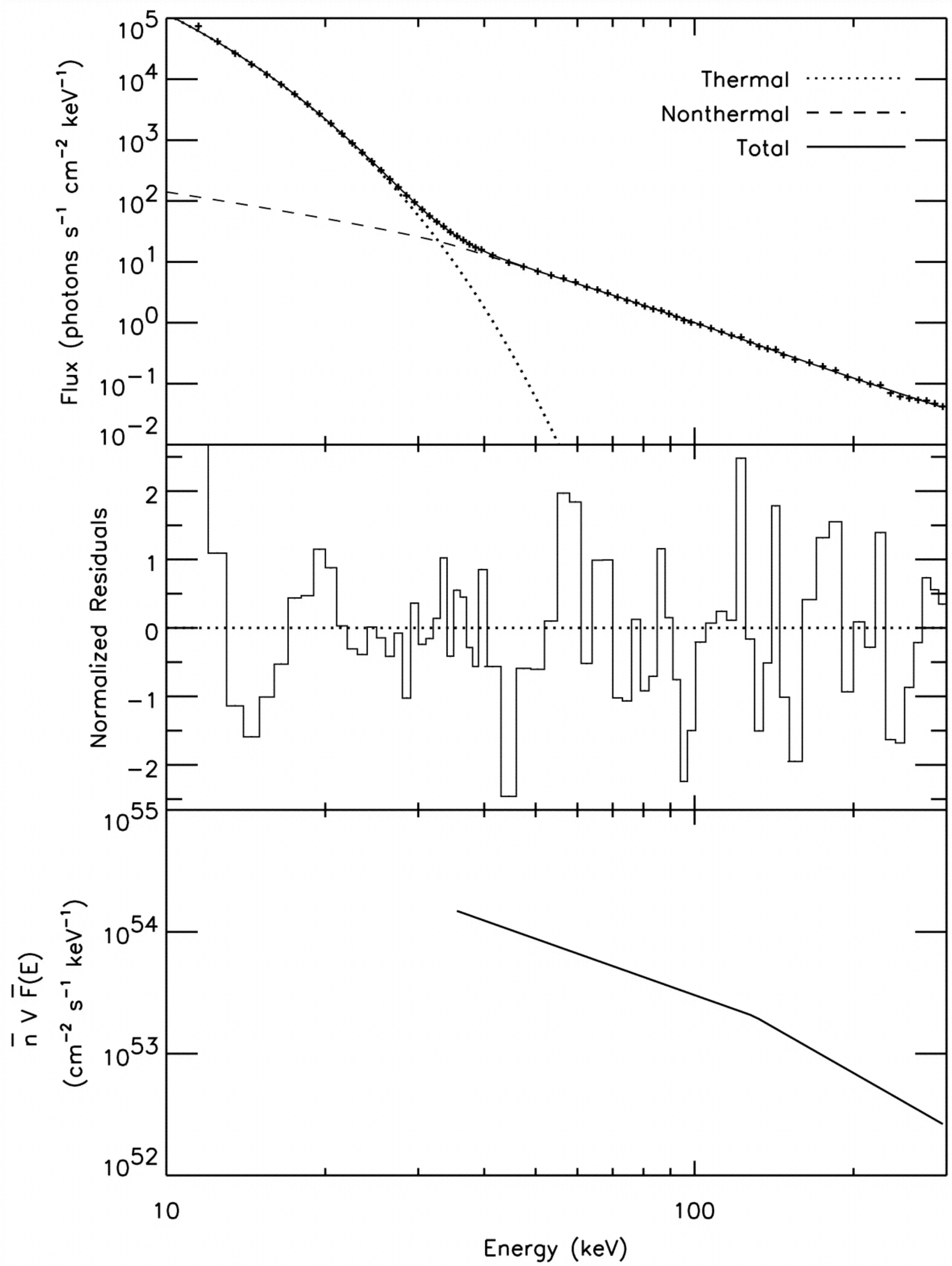




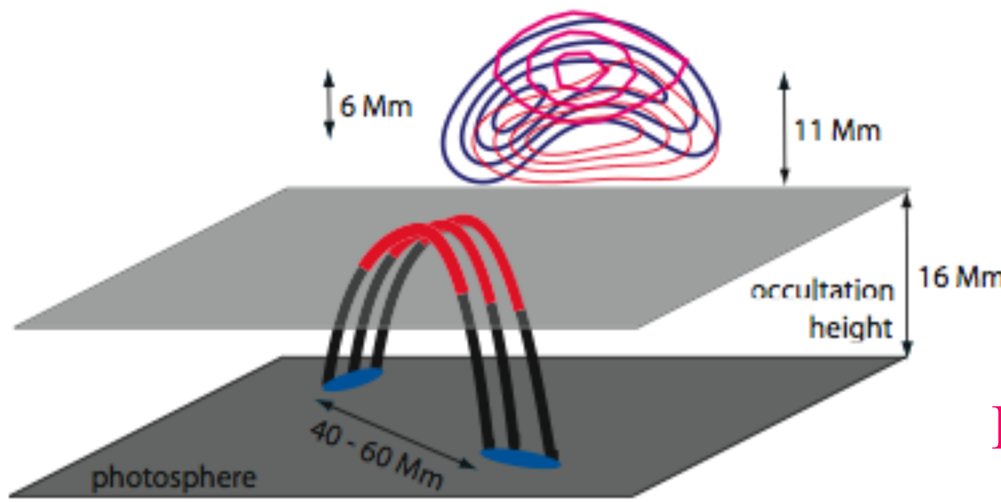


RHESSI observations

- 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



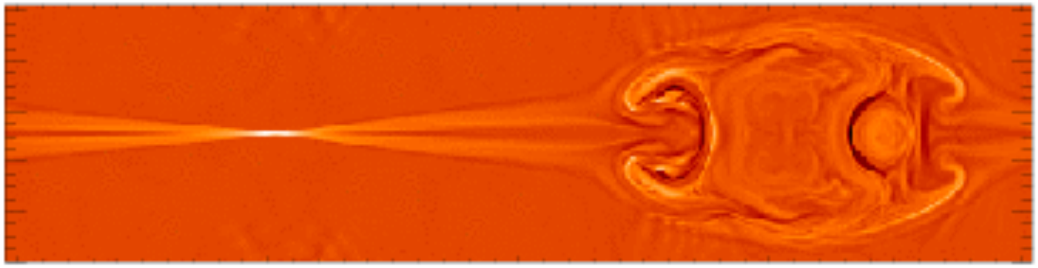
30-50keV

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!

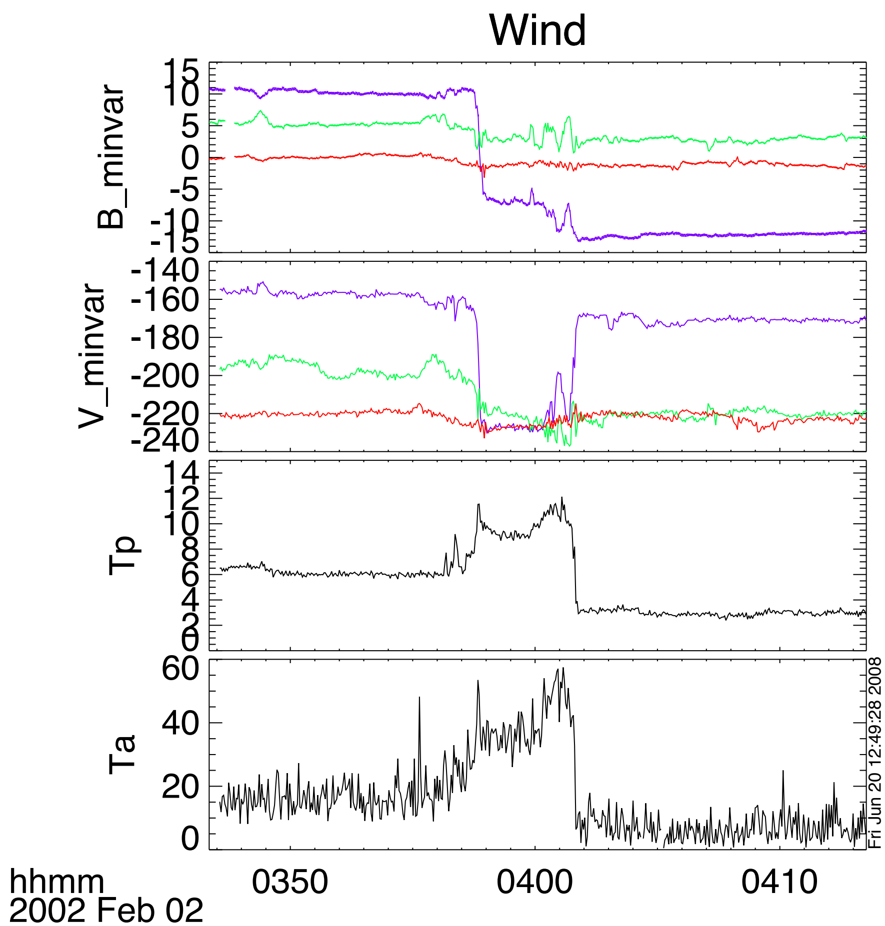
The importance of the reconnection outflow



- Most of the magnetic energy release during reconnection takes place downstream of the x-line where newly reconnected field line relax their tension
  - Not around the x-line
- Magnetotail observations suggest that the ions carry most of the released magnetic energy (Eastwood et al 2013)
  - Bulk Alfvenic flow
  - Ion heating – enthalpy flux

Ion energy gain during reconnection

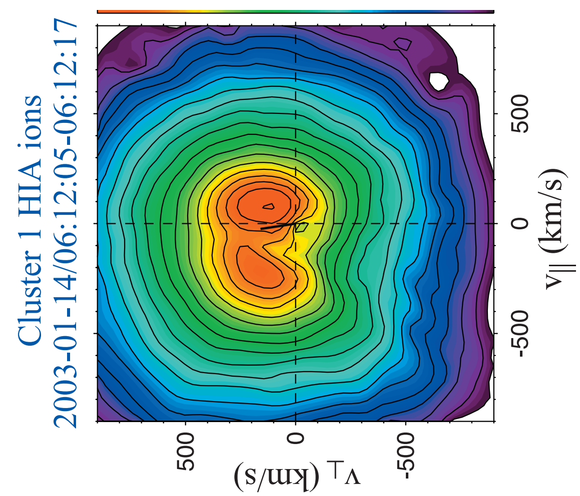
- Wind spacecraft observations in the solar wind (Phan et al 2006)
- What is the mechanism for ion heating?



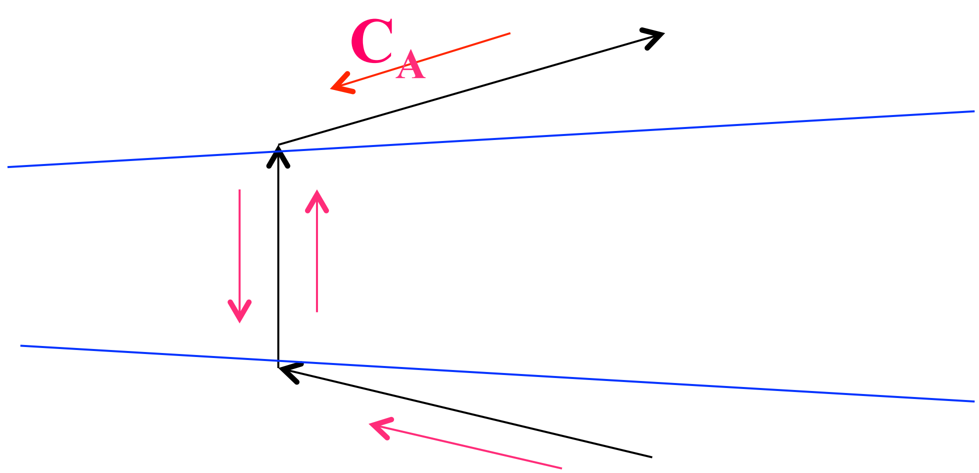
Counter-streaming ions within reconnection exhausts

- In the exhaust outflow frame
- Counter-streaming ions are measured throughout the magnetosphere(Hoshino et al '98, Gosling et al '05, Phan et al '07)
- Basically a Fermi reflection mechanism
  - curvature drift along the reconnection electric field

Phan et al '07



$$\Delta T_{||} \sim m_i c_A^2$$



Basic mechanisms for electron energy gain during reconnection

- Electron heating and acceleration less well understood
- In the guiding center limit

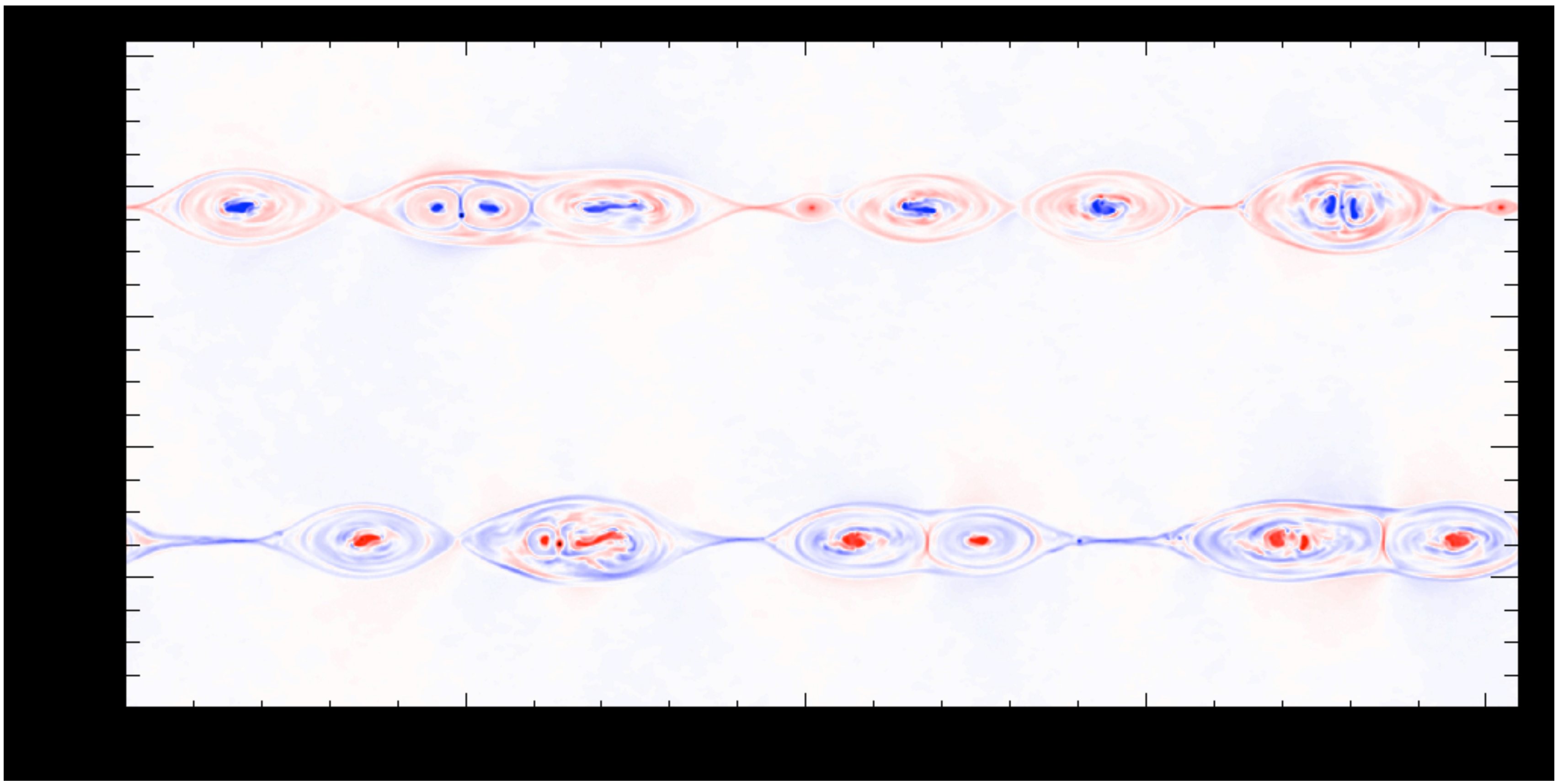
$$\frac{d\varepsilon}{dt} = \frac{\mu}{\gamma}\frac{\partial B}{\partial t} + qv_{\parallel}E_{\parallel} + q\vec{v}_c \bullet \vec{E} + q\vec{v}_B \bullet \vec{E}$$

- Curvature drift $$v_c = \frac{\gamma v_{\parallel}^2}{\Omega}\vec{b} \times (\vec{b} \bullet \vec{\nabla}\vec{b})$$
  – Slingshot term (Fermi acceleration) increases the parallel energy
- Grad B drift $$v_B = \frac{\gamma v_{\perp}^2}{2\Omega}\vec{b} \times \frac{\vec{\nabla}B}{B}$$
  – Betatron acceleration increases (or decreases) perpendicular energy
- Magnetic moment

$$\mu = \frac{m\gamma^2 v_{\perp}^2}{2B}$$

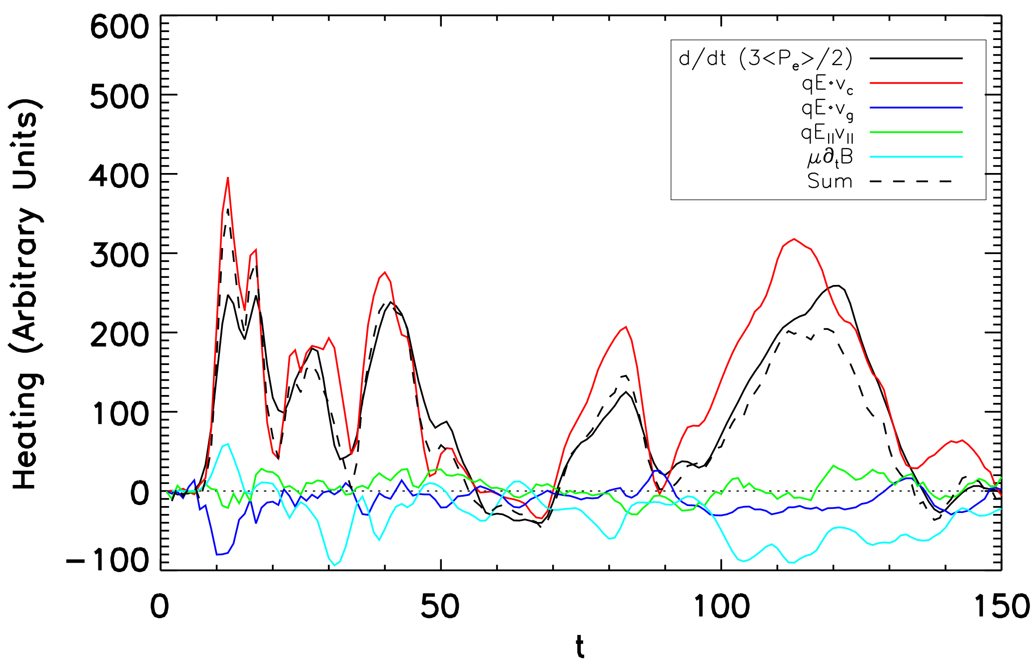
Electron heating during reconnection

- 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 $409.6d_i$
  - Mass-ratio m_i/m_e=25
  - Compare all of the heating mechanisms



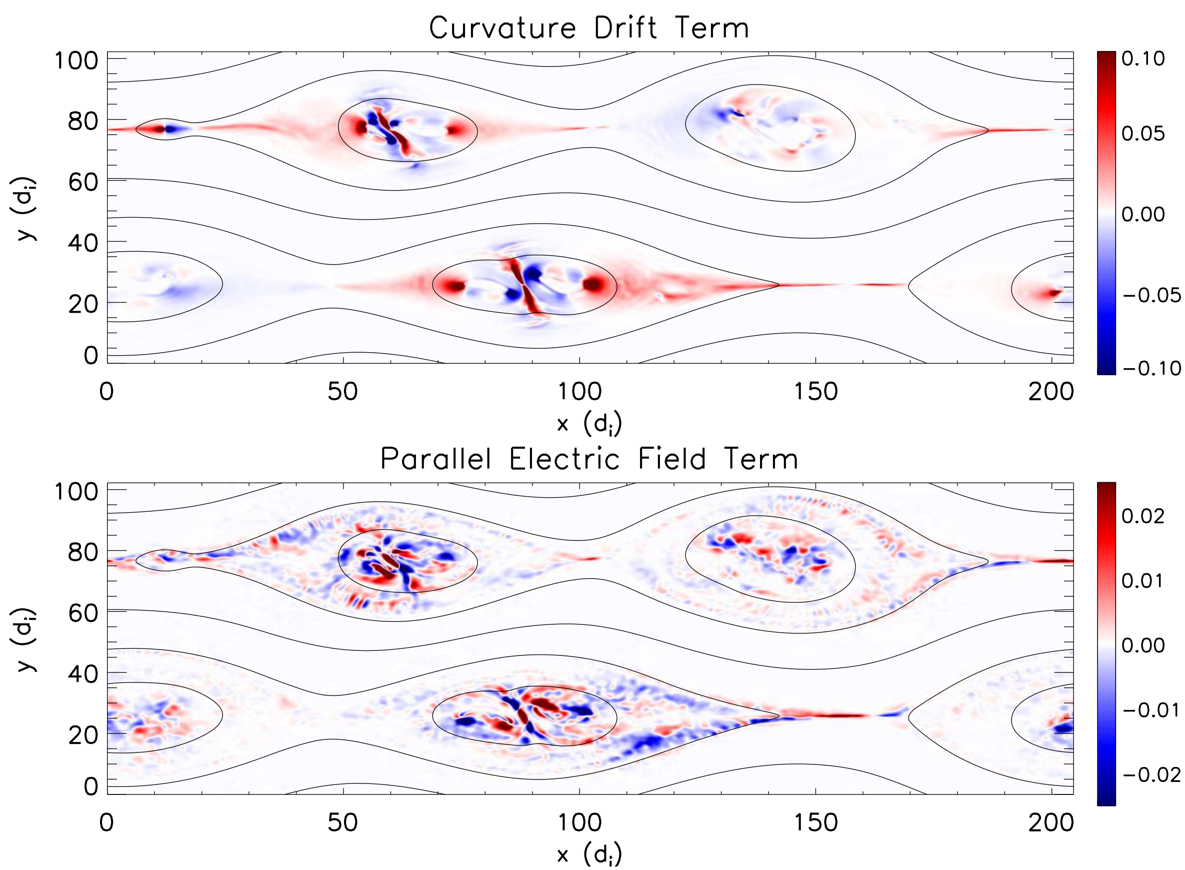
Electron heating mechanisms: weak guide field

- 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.



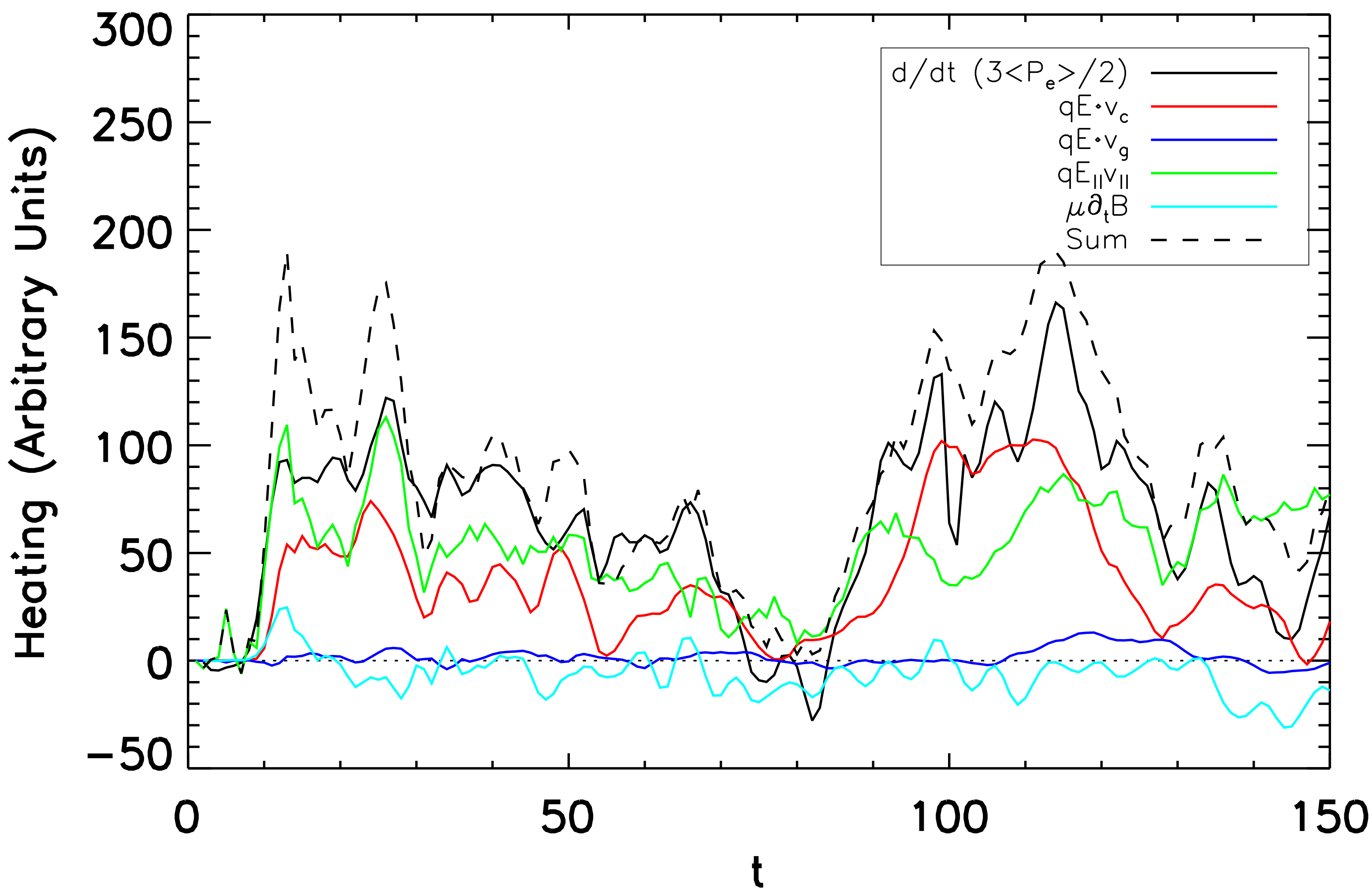
Spatial distribution of heating: weak guide field

- The distribution of Fermi and $E_{||}$ heating



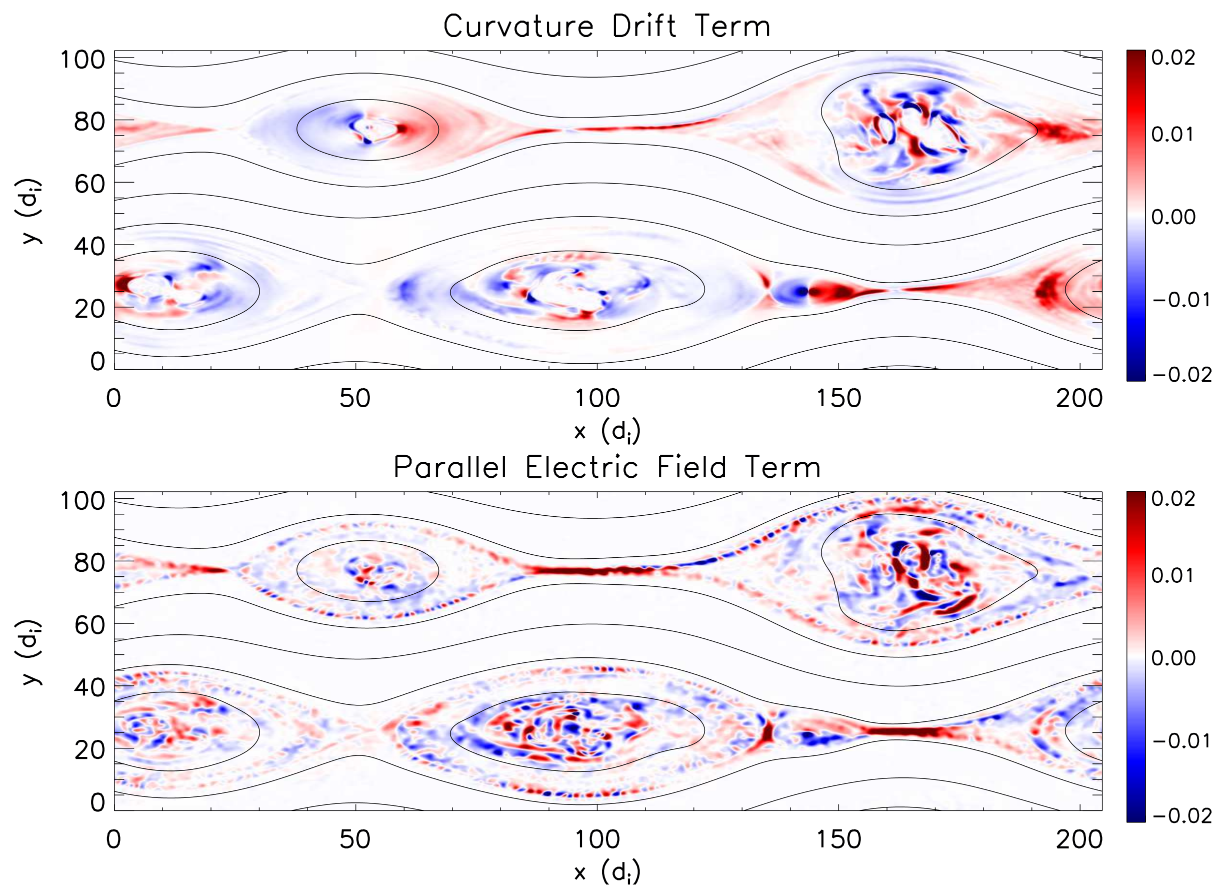
Electron heating mechanisms: strong guide field

- Fermi and parallel electric field term dominate



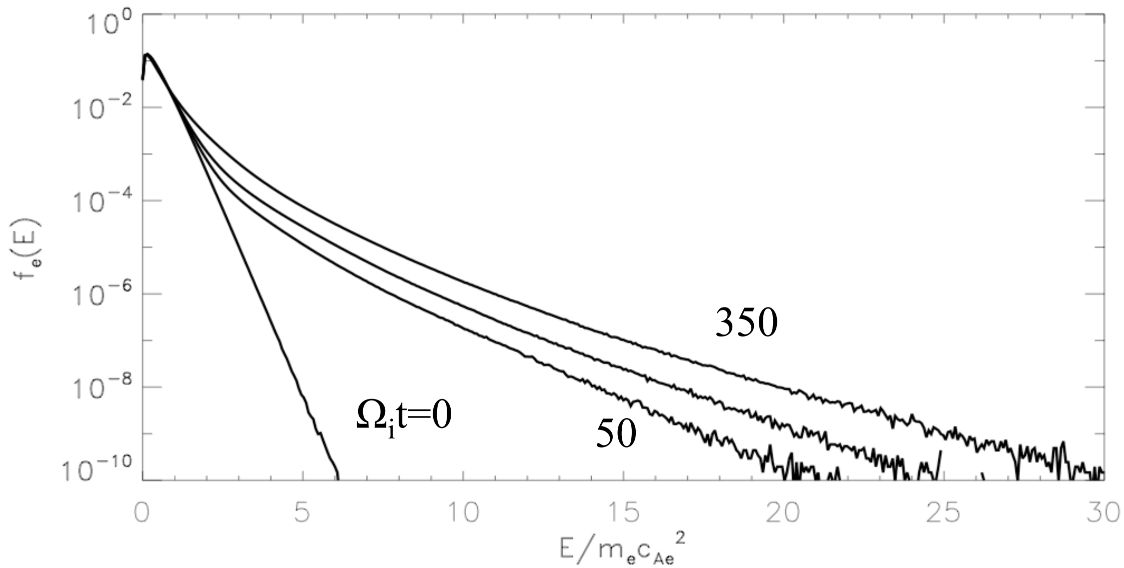
Spatial distribution of heating: strong guide field

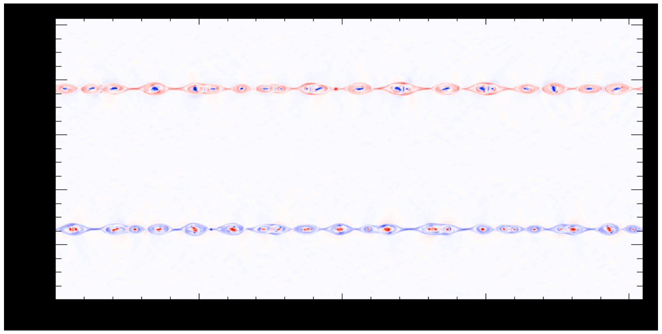
- The distribution of Fermi and $E_{||}$ heating
- Longer current layers and electron holes (Buneman)
  - Not much heating from electron holes



Electron energy spectra

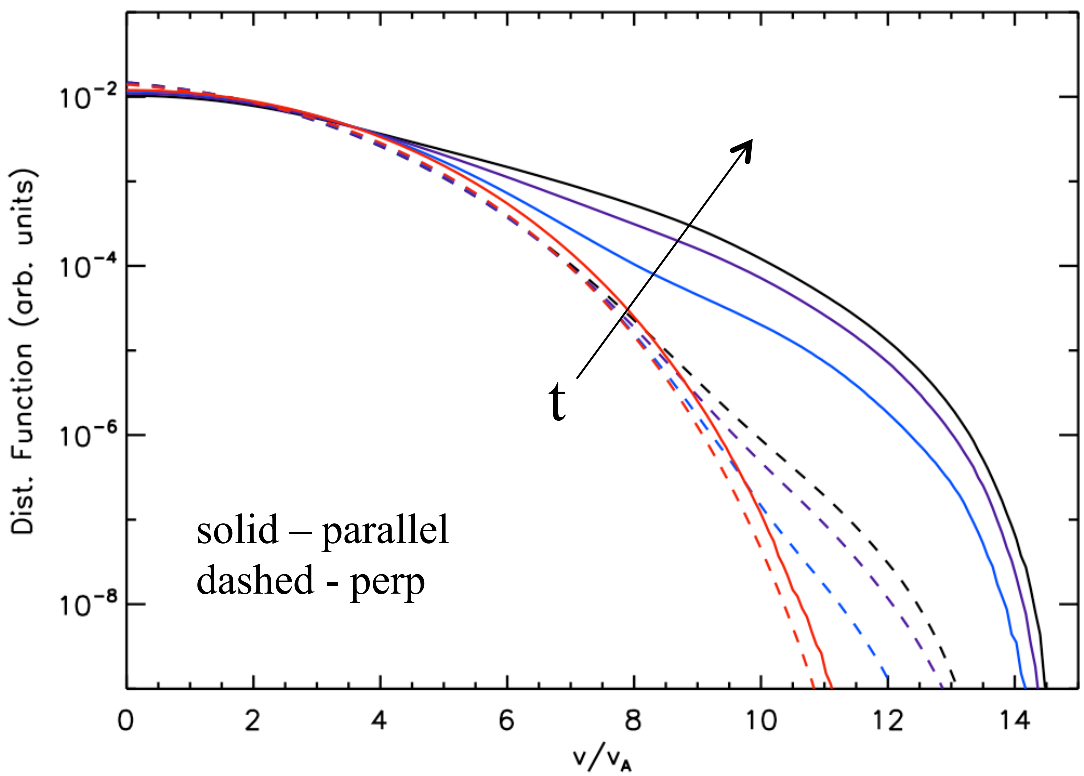
- Electron energy spectrum from guide field unity simulation
- Most rapid electron energy gain early in time when many small islands develop and merge
- No powerlaws – no loss mechanism in periodic system





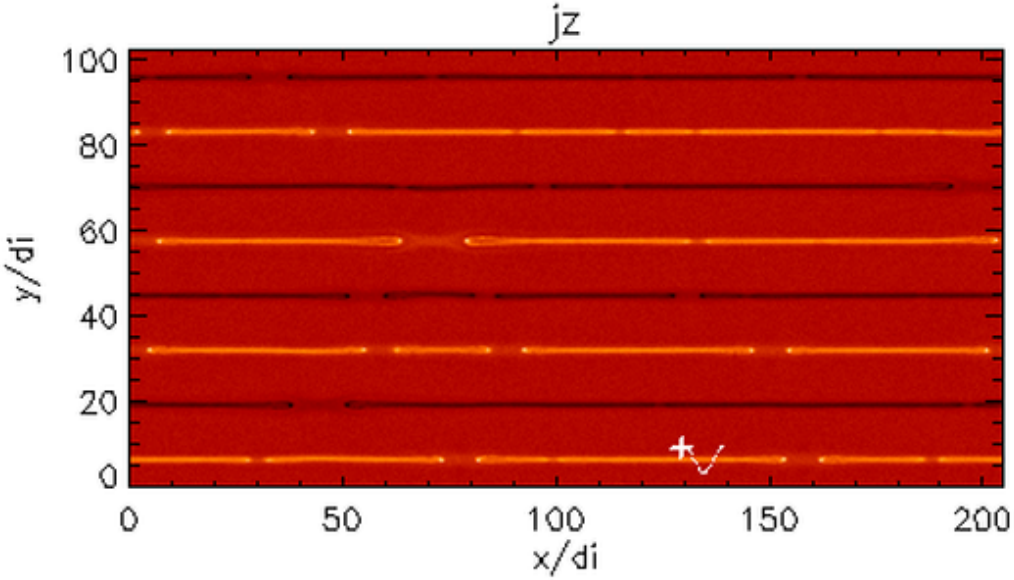
Electron spectral anisotropy

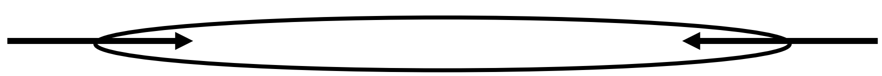
- The dominant acceleration mechanisms accelerate electrons parallel to the local magnetic field – Fermi slingshot and $E_{||}$
  - Extreme anisotropy in the spectrum of energetic electrons
  - More than a factor of 10^3
  - What limits the anisotropy?



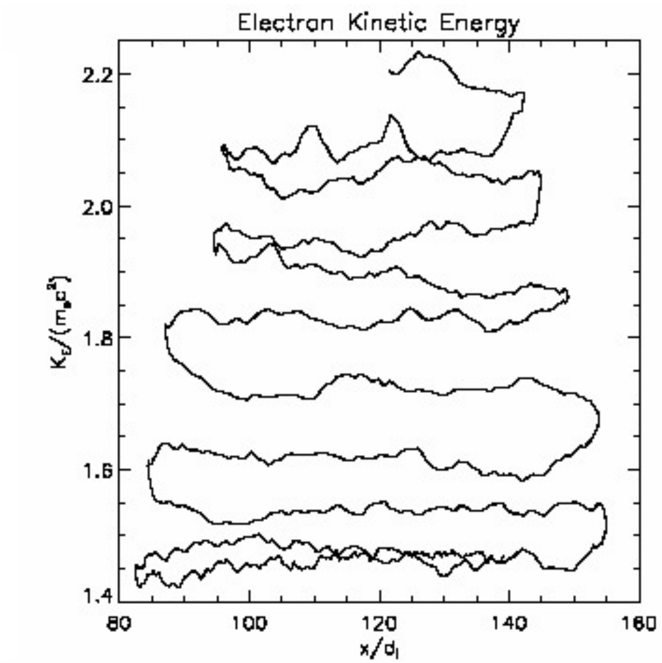
Fermi acceleration

- How do the most energetic particles gain energy?
  - Reflection from the ends of contracting islands
  - Increase of parallel energy and pressure





C_{Ax}



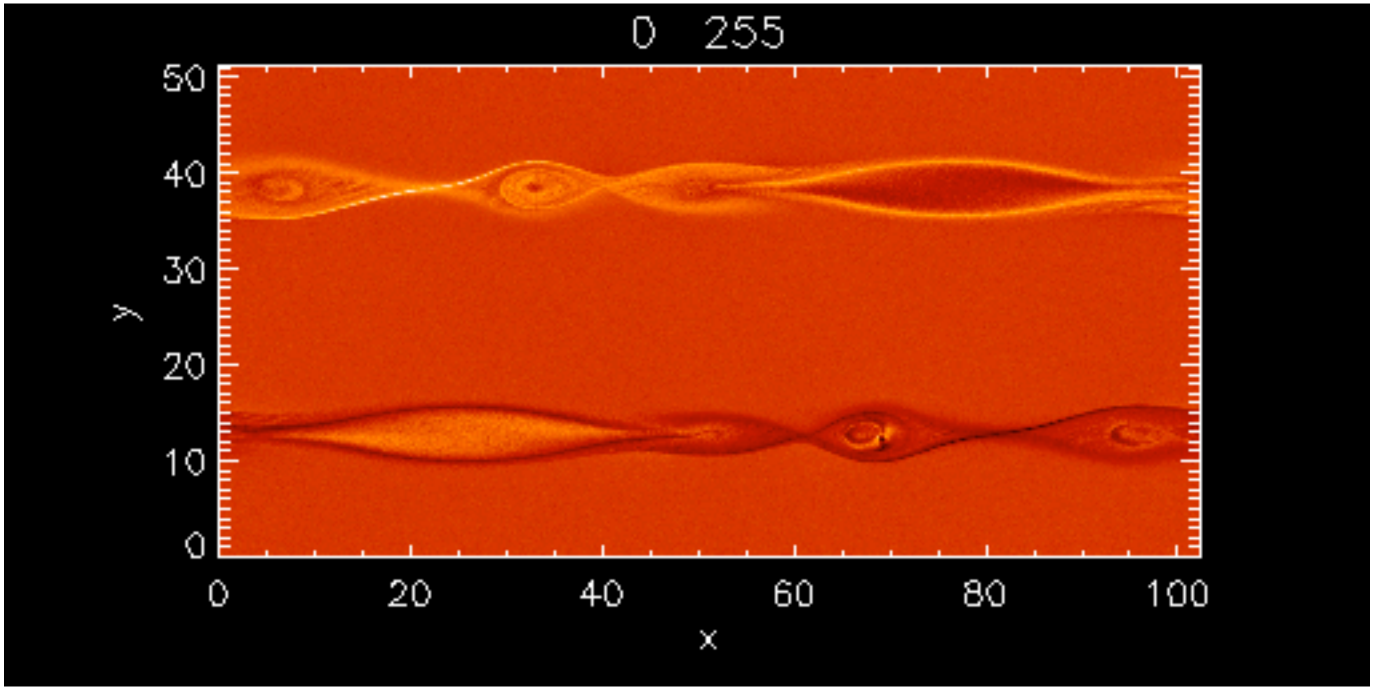
$$\frac{d\varepsilon_{\parallel}}{dt} \sim 2\varepsilon_{\parallel} \frac{c_A}{L_x}$$

Schoeffler et al 2011

Multi-island particle acceleration

- How does a multi-island environment develop?
- What is the size distribution of magnetic islands? (Fermo '10, Uzdensky '10)
- How does a bath of growing and merging islands accelerate particles?
  - Need a generalized Parker transport equation to describe reconnection driven particle acceleration
- How do energetic particles feed back on island growth?
  - firehose
- What is the upper limit on electron acceleration in a multi-island system?
  - Gyro-synchrotron radiation is significantly reduced in a system with extreme anisotropy – guide field case

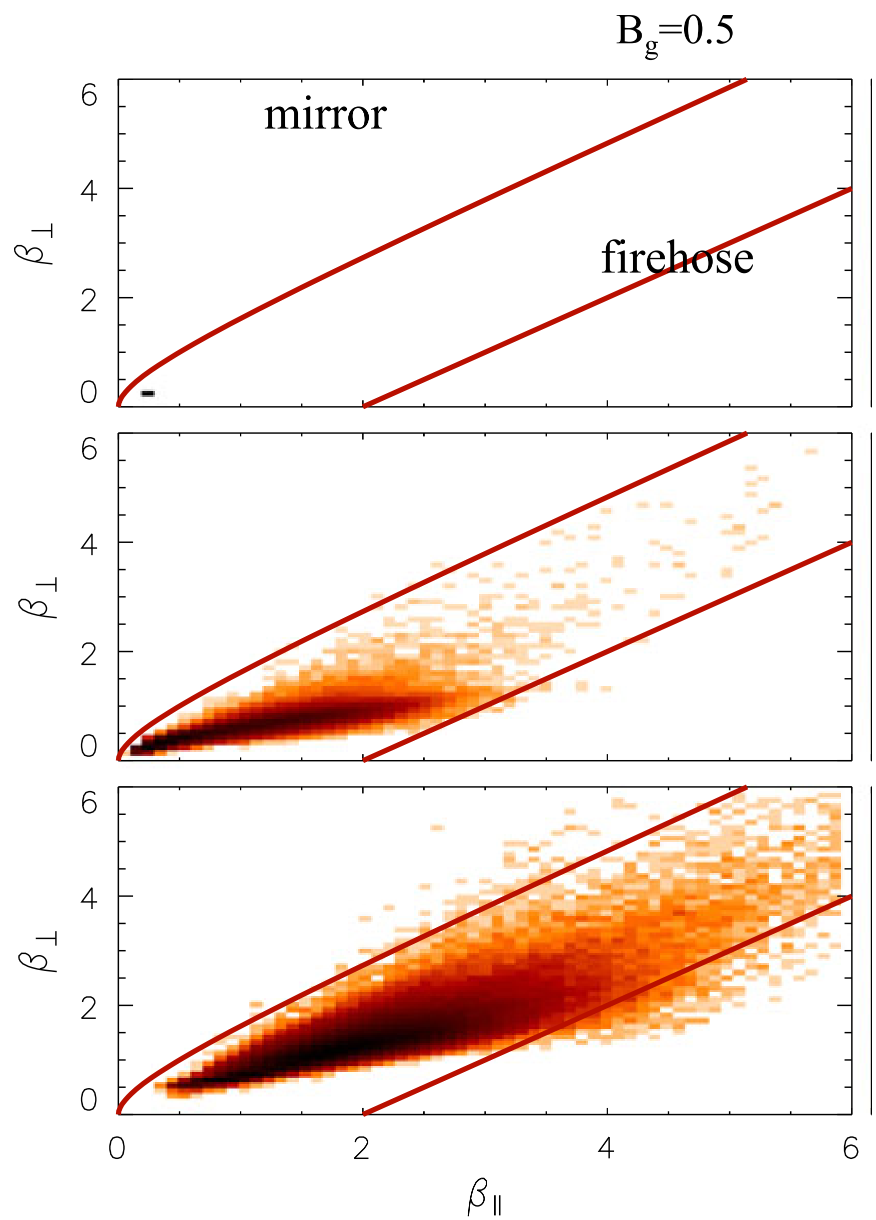
Multi-island reconnection with a guide field



- Narrow current layers spawn multiple magnetic islands in reconnection with a guide field (Drake et al 2006; Daughton et al 2011, Fermo et al 2012)
- Multi-island reconnection is generic

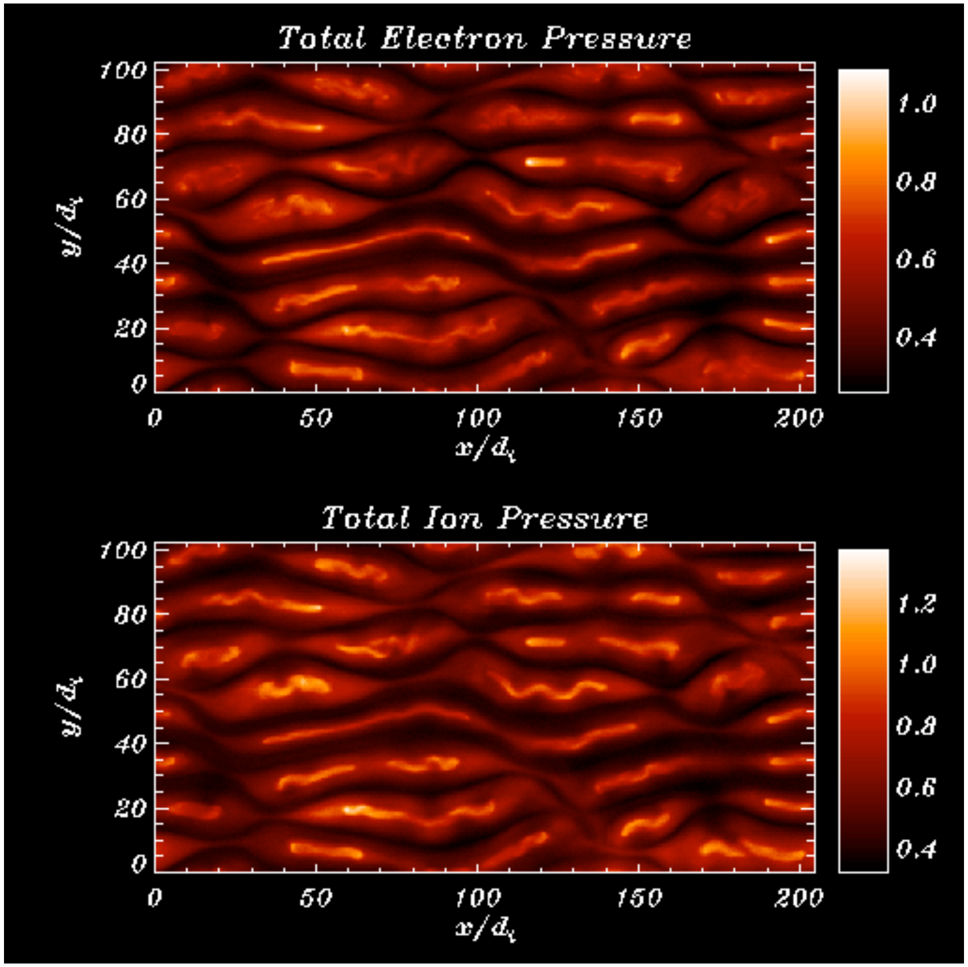
Development firehose limits reconnection

- The Fermi mechanism drives the system towards the firehose threshold even in a system with very low initial β
- At the firehose threshold magnetic fields have no tension
  - No reconnection drive



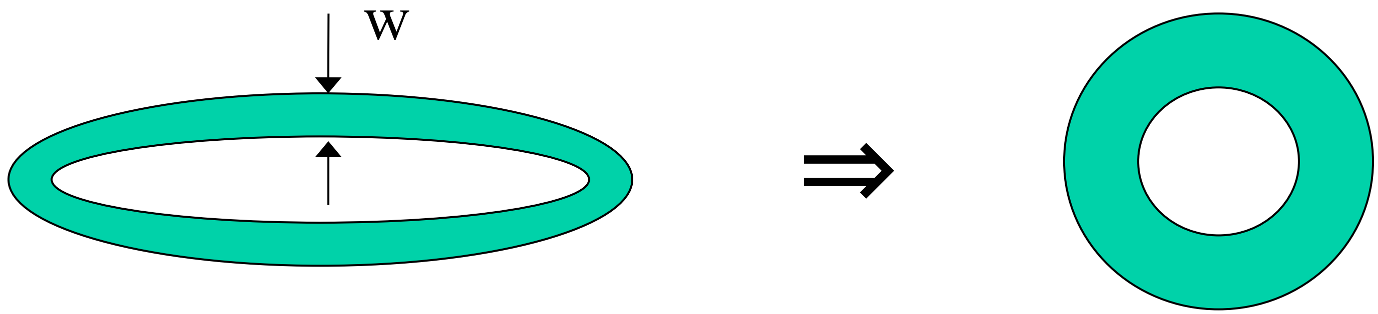
Firehose instability during island contraction

- Fermi reflection within islands increases $p_{||}$ and leads to firehose



Schoeffler et al 2011

Fermi acceleration in contracting 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

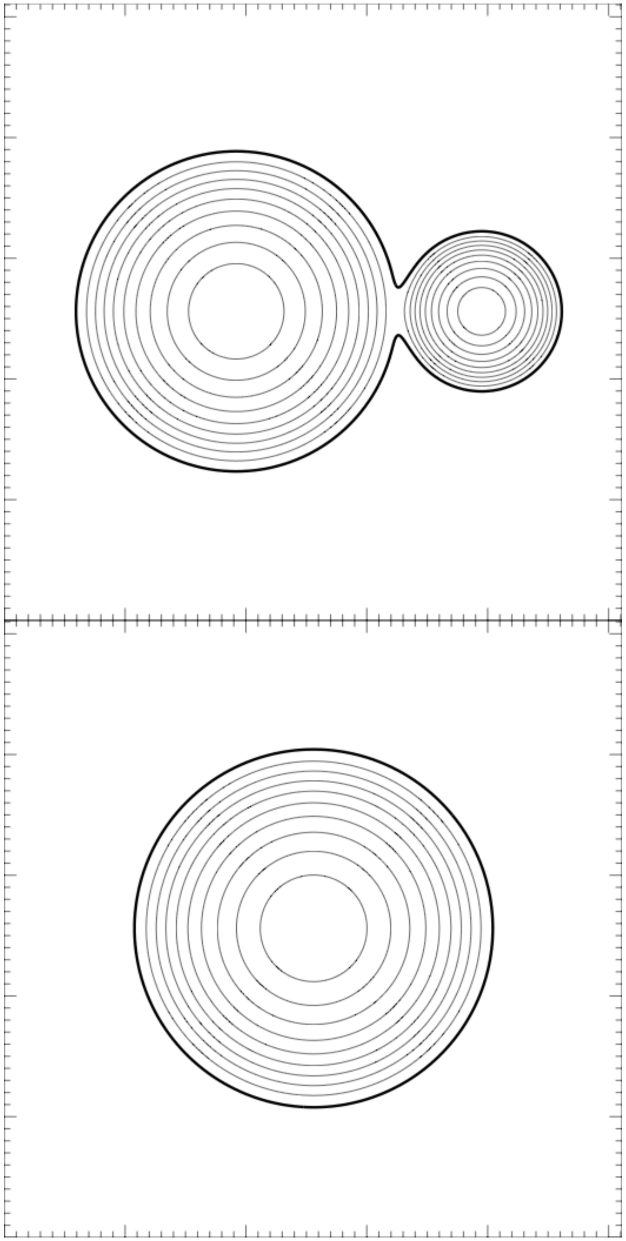
Energy gain in merging islands

- 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

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

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

  - 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
  - Drake et al 2013

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

merging drive

pitch-angle scattering

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

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

Energetic particle distributions

- Solutions in the strong drive limit – balance between drive and loss
  - Characteristic times
    - Heating time based on characteristic island size w: $\tau_{heat} = w/c_A$
    - Loss time based on characteristic system size L: $\tau_{loss} \sim L/c_A$
  - Typically heating time short compared with loss time (w << L)
  - Require feedback from the high pressure (firehose)
- 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 $$j \sim E^{-2}$$

An upper limit on energy gain during reconnection

- Magnetic reconnection dominantly increases the parallel energy of particles, depending on the degree of magnetization
  - Traditional synchrotron emission may not limit particle energy gain
- An 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 ($\sim \gamma^4$)

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

  - Where $R_c = e^2 / mc^2$ is the classical electron radius and R is the field line radius of curvature.

Conclusions

- The magnetic curvature and associated Fermi reflection is the dominant driver of electron acceleration during reconnection of anti-parallel fields
- Both Fermi and parallel electric fields dominant drivers of electron acceleration during guide field reconnection
- Significant acceleration requires electron interaction with multiple islands
- Energetic particles exhibit extreme anisotropy for reconnection with a guide field
  - What mechanism limits this anisotropy?

Conclusions (cont.)

- A transport equation describing particle heating and acceleration in a bath of merging magnetic islands generalizes the Parker transport equation to include anisotropy
  - Powerlaw solutions controlled by feed back from the pressure anisotropy
  - Can be used to explore particle acceleration in large-scale systems