A Magnetic Reconnection Mechanism for Ion Acceleration and Abundance Enhancement in Impulsive Flares

J. F. Drake

University of Maryland

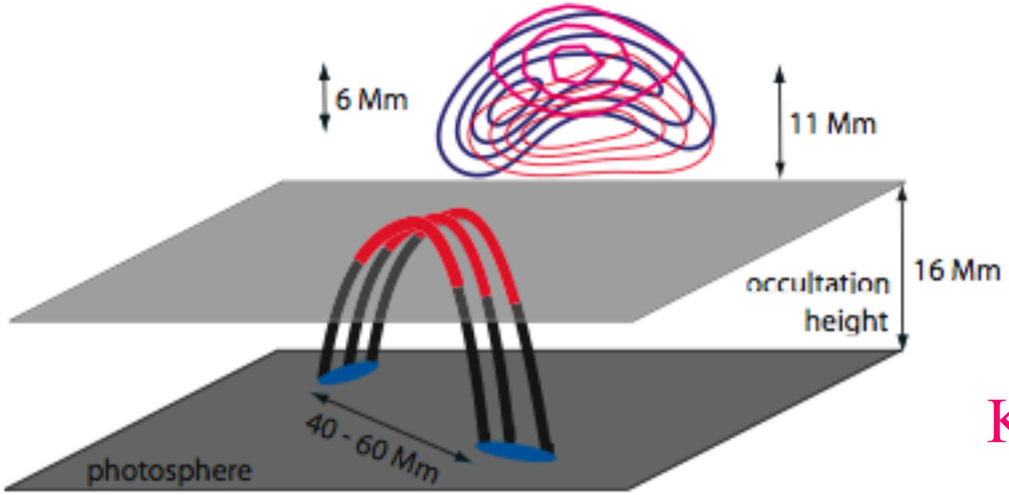
M. Swisdak University of Maryland
K. Knizhnik University of Maryland
S. P. Gary LANL

Energetic particle observations in impulsive flares

- Flare and coronal observations
  - In solar flares energetic electrons up to MeVs and ions up to GeVs have been measured
    - A significant fraction of the released magnetic energy appears in the form of energetic electrons and ions (Lin and Hudson '76, Emslie et al '05, Krucker et al '10)
    - A large number of electrons undergo acceleration – the "numbers problem"
    - Correlation between > 300keV energetic electrons and > 30 MeV ions (Shih et al 2008) ⇒ common acceleration mechanism
  - In impulsive flares see enhancements of high M/Q ions as well as ^{3}He(Mason '07)
  - In the extended corona $T_\perp > T_\parallel$ (Kohl '97)
    - Minority ion temperature more than mass proportional

$$T_i / T_p \geq m_i / m_p$$

RHESSI occulted flare observations



30-50keV

17GHz

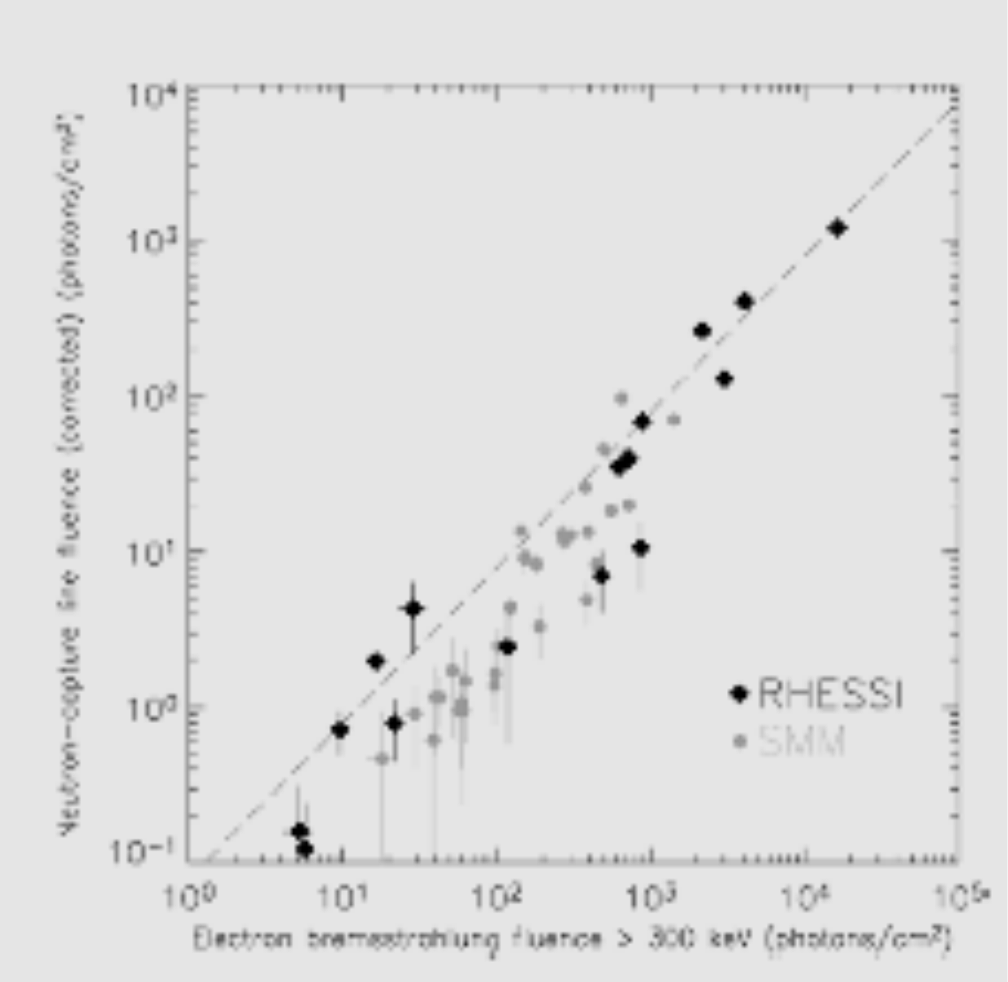
Krucker et al 2010

- Observations of a December 31, 2007, occulted flare
  - All 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
  - Conversion of magnetic energy to energetic particles is very efficient
  - Remarkable!

Energetic electron and ion correlation

- > 300keV x-ray fluence (electrons) correlated with 2.23 MeV neutron capture line (> 30 MeV protons)
- Acceleration mechanisms of electrons and protons linked?

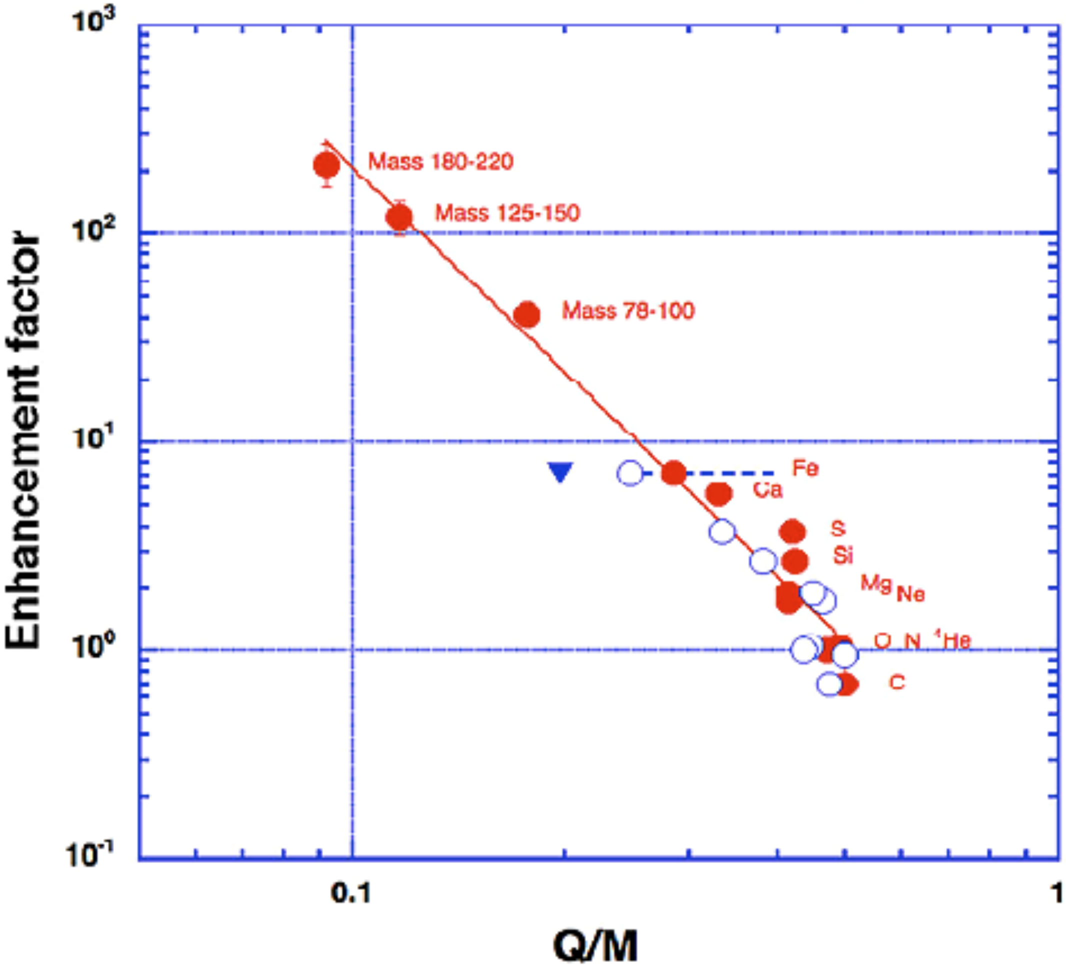
Shih et al 2008



Impulsive flare energetic ion abundance enhancement

- During impulsive flares see heavy ion abundances enhanced over coronal values
- Enhancement linked to Q/M

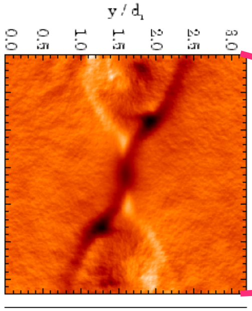
$$\propto \left(\frac{Q}{M}\right)^{-3.26}$$



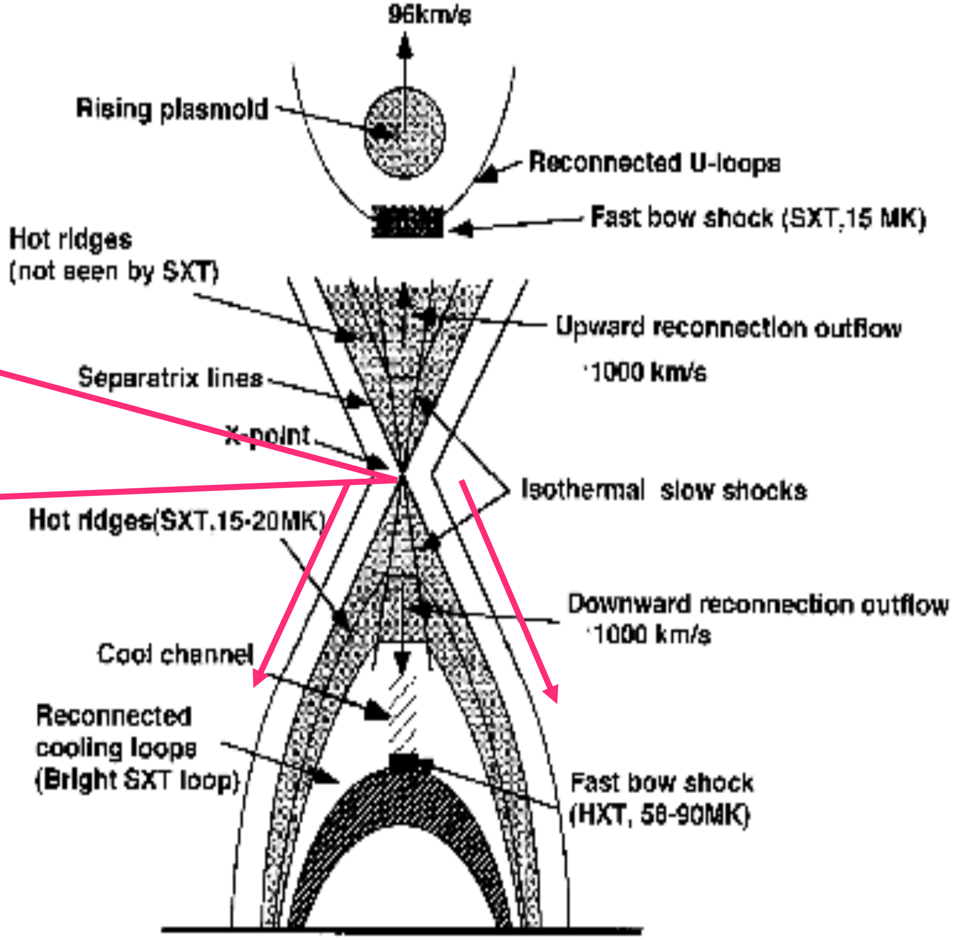
Mason, 2007

Single x-line model: the sun

- Can parallel electric fields in a single x-line produce the large number of electrons seen in flares?
  - Around 10^{37} electrons/s
  - Downflow currents in a single x-line would be enormous
    - Producing 10^{9}G fields for L ~ 10^{4}km
  - Parallel electric fields are shorted out except around the x-line



- Magnetic energy is not released at the x-line but downstream as the reconnected fields relax their stress
  - The x-line is not where energy is released
  - The x-line region has negligible volume
- Can’t explain the large number of energetic electrons



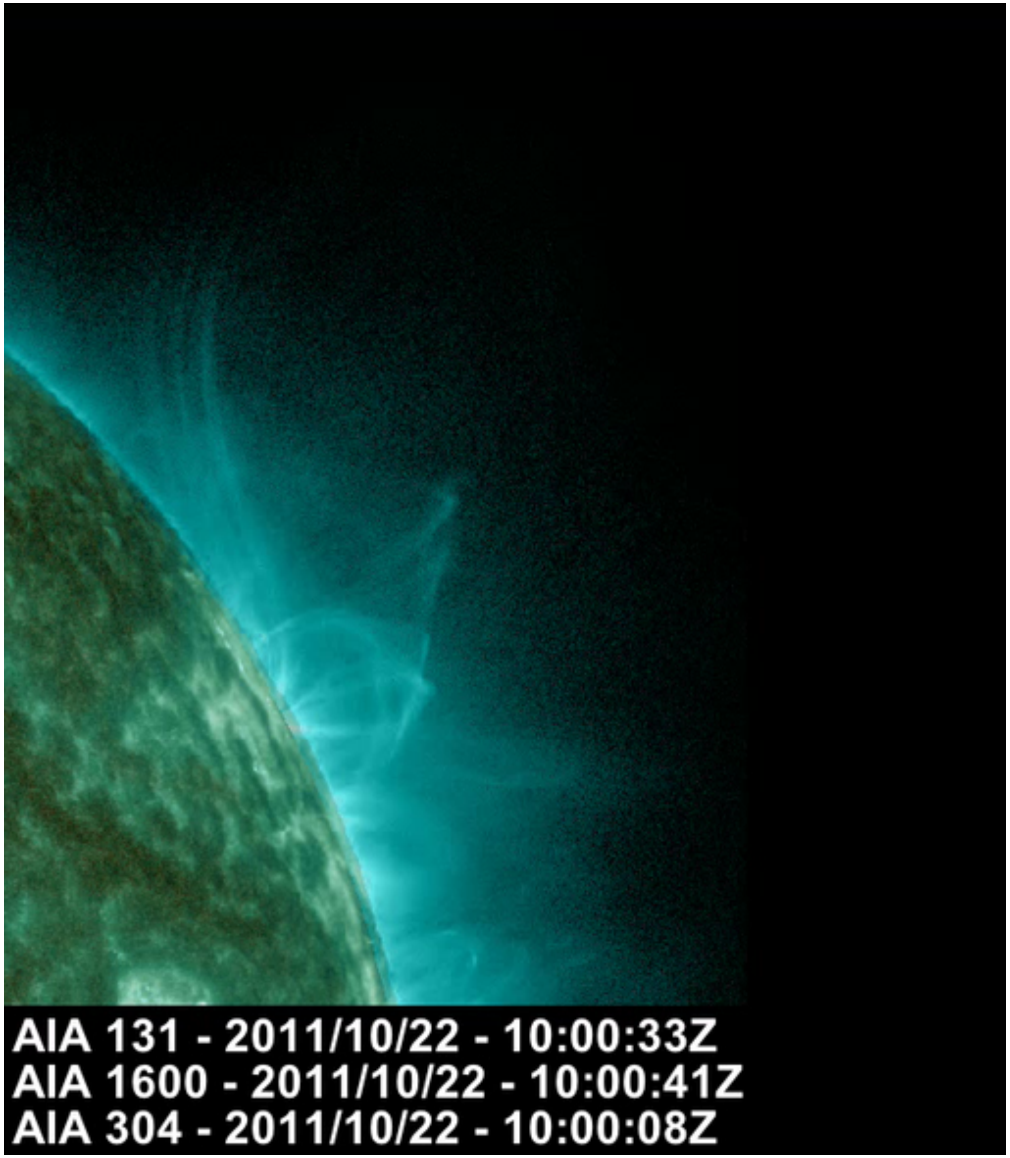
Tsuneda 1997

Must abandon single x-line model!

SDO/AIA flare observations

- Super Arcade Downflows (SADs) are interpreted as signatures of magnetic islands from an overlying reconnection site (Sheeley et al 2004)
- Such SAD events are now considered typical and not anomalies.
- Must abandon the classical single x-line picture!!

Savage et al 2012

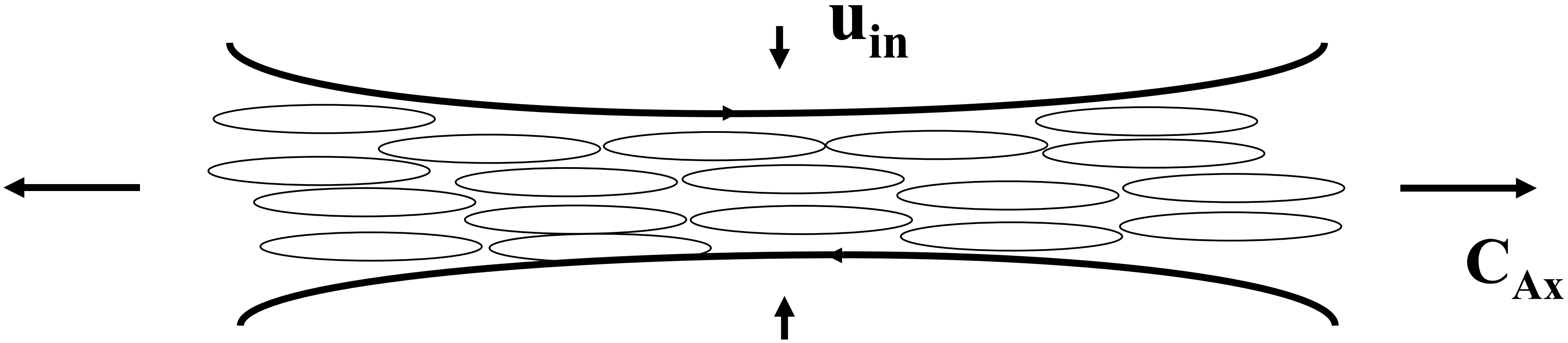


A multi-island acceleration model

- A single x-line line model can not explain the high fraction of energy going into the very energetic electrons and ions in flares
  - Must abandon the classical single x-line picture!!
- Current layers spawn multiple magnetic islands in reconnection with a guide field (Drake et al '06, Onofri et al '06, Daughton et al '11)

⇒ islands have a huge range of scales

⇒ SADs in flares



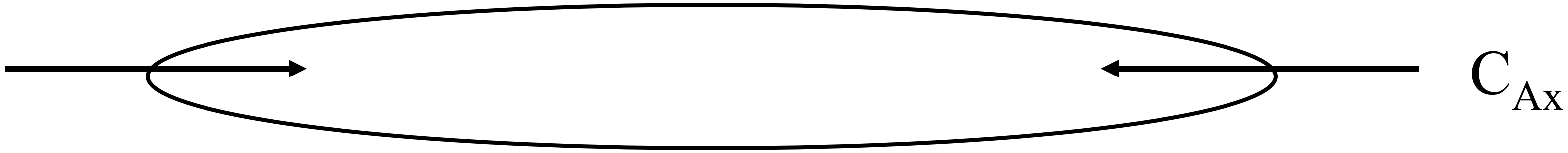
Particle acceleration in multi-island reconnection

- How are electrons and ions accelerated in a multi-island environment?
  - Fermi reflection in contracting magnetic islands (Kliem 94, Drake et al 2006, Drake et al 2010)

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

  - Rate of energy gain independent of particle mass

⇒ linkage between particle energy gain and magnetic energy release



Two-stage mechanism for ion heating in flares

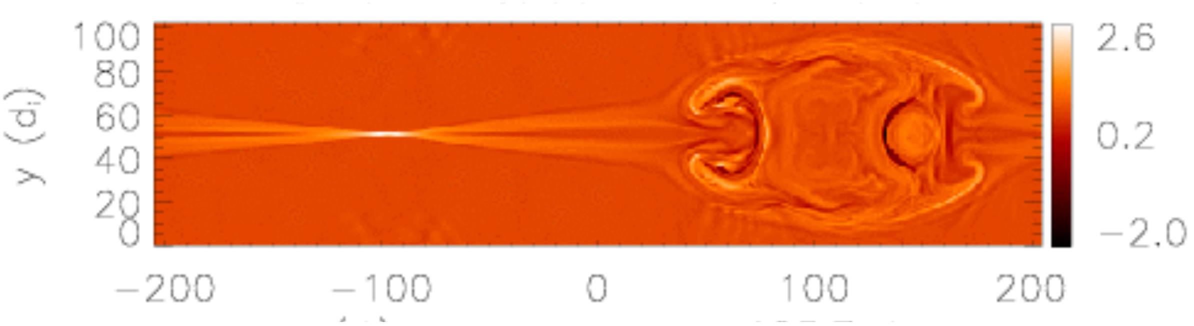
- Electrons are directly accelerated through the contracting island mechanism even in the low β corona.
- In low β conditions ions are too slow to bounce
  - Need a seed ion heating mechanism
- Stage 1: pickup of ions on entry into reconnection exhausts
  - Ions gain an effective thermal velocity comparable to the exhaust velocity

$$\Rightarrow \beta_x \sim 8\pi nT/B_x{}^2 \sim 1$$

  - Dominantly perpendicular heating in the guide field case
- Stage 2: Fermi reflection in contracting and merging magnetic islands

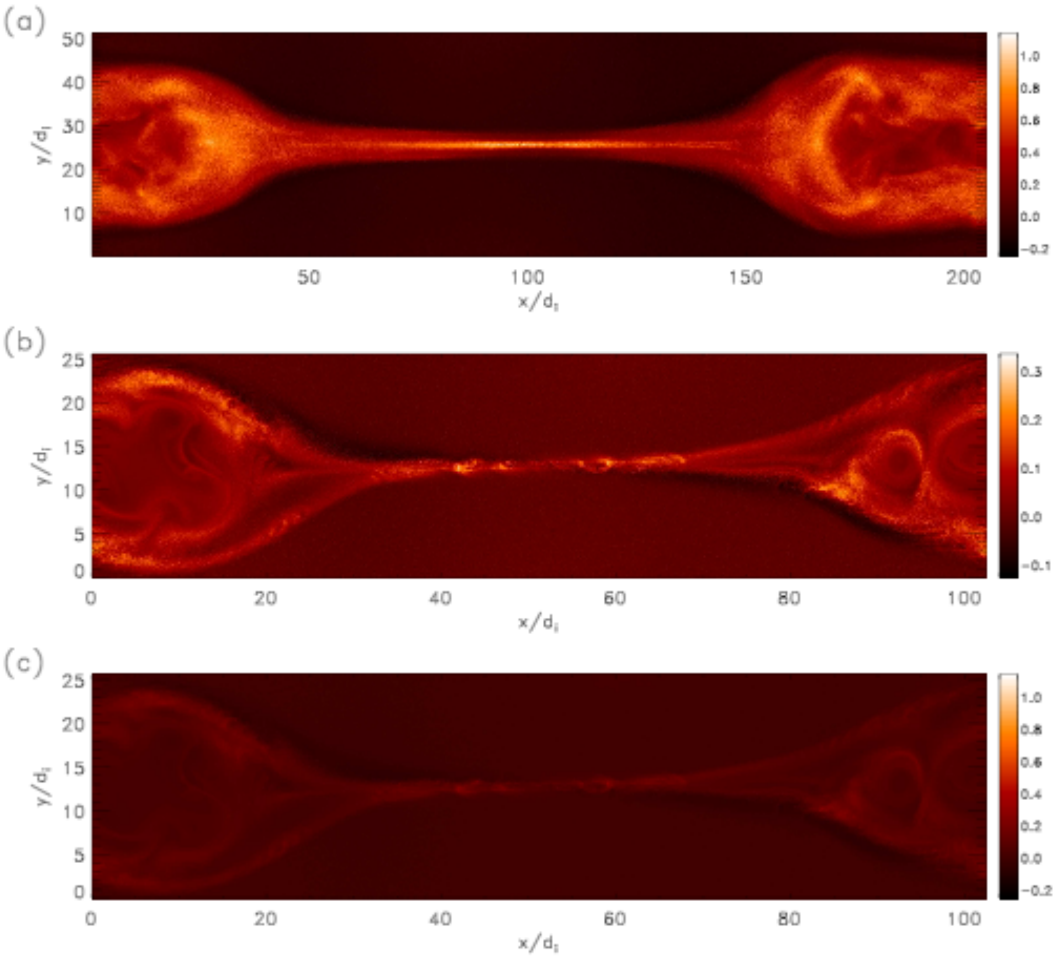
Seeding super-Alfvenic ions through pickup in reconnection exhausts

- Ion heating is dominated by large-scale reconnection exhausts rather than the localized region around the x-line
- Ions moving from upstream cross a narrow boundary layer into the Alfvenic reconnection exhaust
- The ion can then act like a classic "pick-up" particle, where it gains an effective thermal velocity equal to the Alfvenic outflow $T_i \sim m_i c_{Ax}^2$
  - during guide field reconnection there is a threshold for pickup behavior and heating is mostly in $T_\perp$



Ion temperature in reconnection outflows: anti-parallel versus guide field

- Comparison of PIC simulations with and without a guide field
- Temperature increments of protons
  - Little proton heating with strong guide field
  - Protons are adiabatic
  - Why?

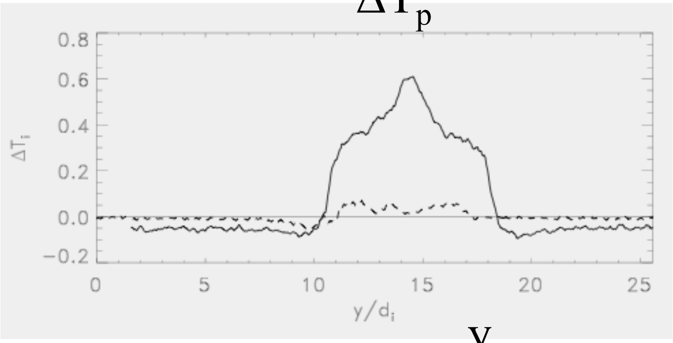


B_{z0}=0

B_{z0}=2

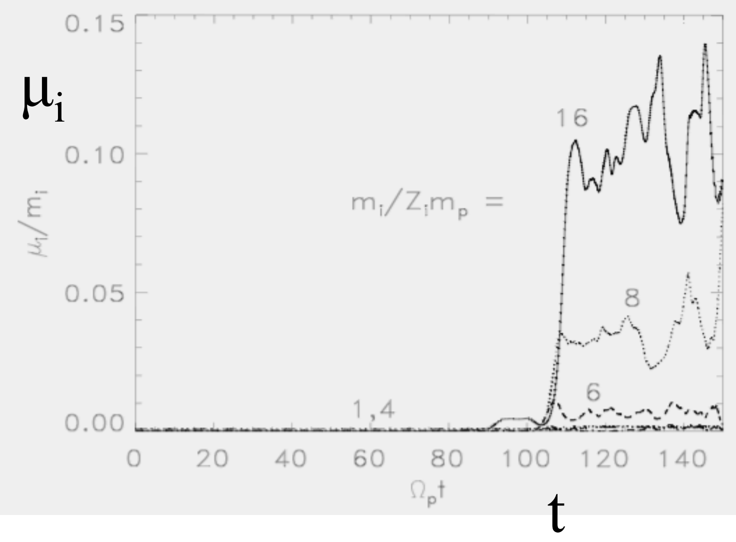
B_{z0}=2

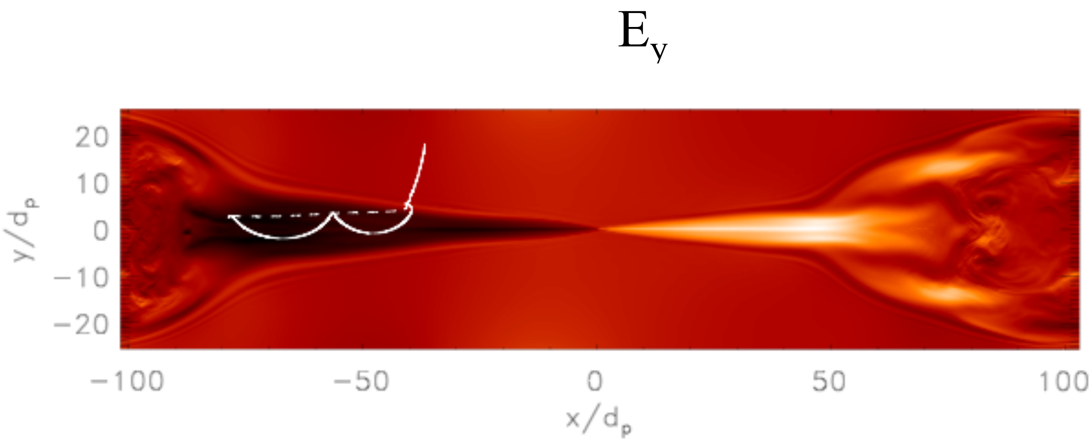
ΔT_p



y

Pickup threshold: guide field





$B_{z0} = 5.0$

- Protons and alpha particles remain adiabatic (μ is conserved)
- Only particles that behave like pickup particles gain significant energy ➔ threshold for pickup behavior

$$\frac{v_{iy}}{\Delta} \approx \frac{0.1 c_{Apx}}{\rho_{sp}} > \Omega_i \Rightarrow \frac{m_i}{Z_i m_p} > \sqrt{\beta_{px}}$$

- Mostly perpendicular heating

$$\Delta T_\perp = \frac{1}{2} m_i c_{Ax}^2 \qquad \Delta T_\parallel = 0$$

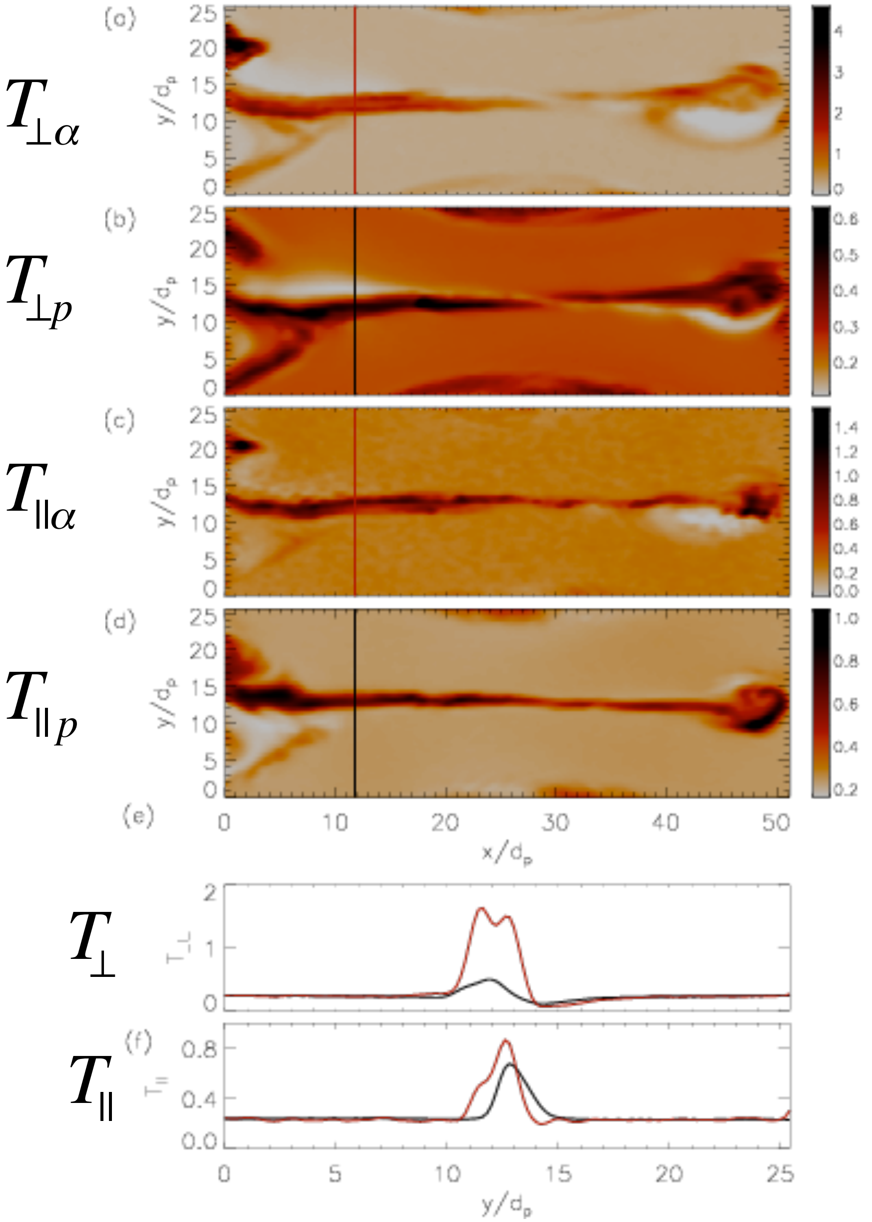
Reconnection with multiple ion species

- PIC simulations with a guide field 2.0 times the reconnecting field
  - Protons in the adiabatic regime
  - Include 1% fully stripped alpha particles
    - In the pickup regime

Alpha and proton heating

- Strong enhancement of $T_{\perp\alpha}$

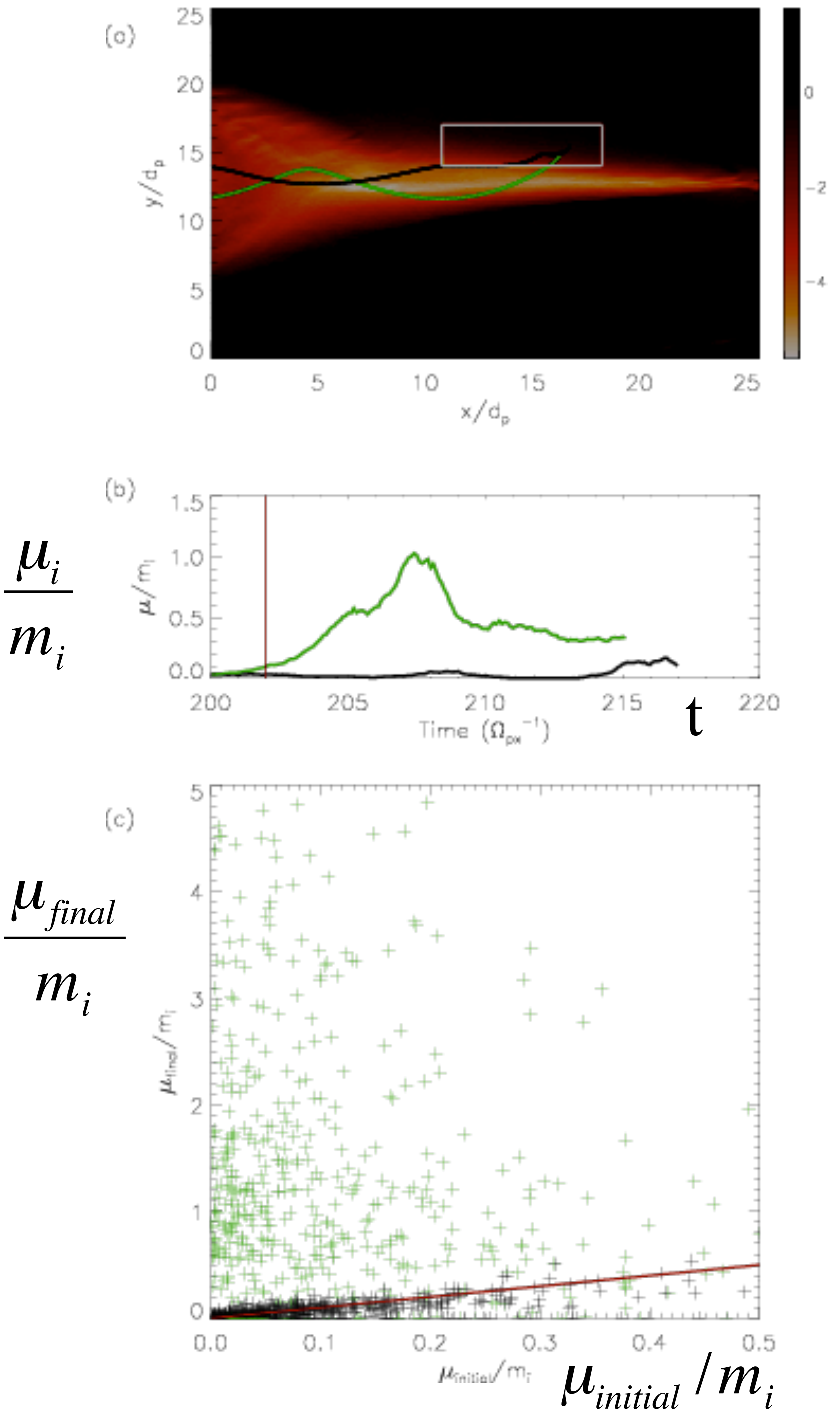
  $T_{\perp\alpha} >> T_{\parallel\alpha}$
  - Very different from anti-parallel reconnection
- Strong alpha heating compared to that of protons
  - Consistent with predictions



Pickup behavior of alphas

- Alpha trajectories are consistent with pickup behavior
- Strong increase in alpha magnetic moment μ_α
- No significant change in μ_p

Knizhnik et al ‘11



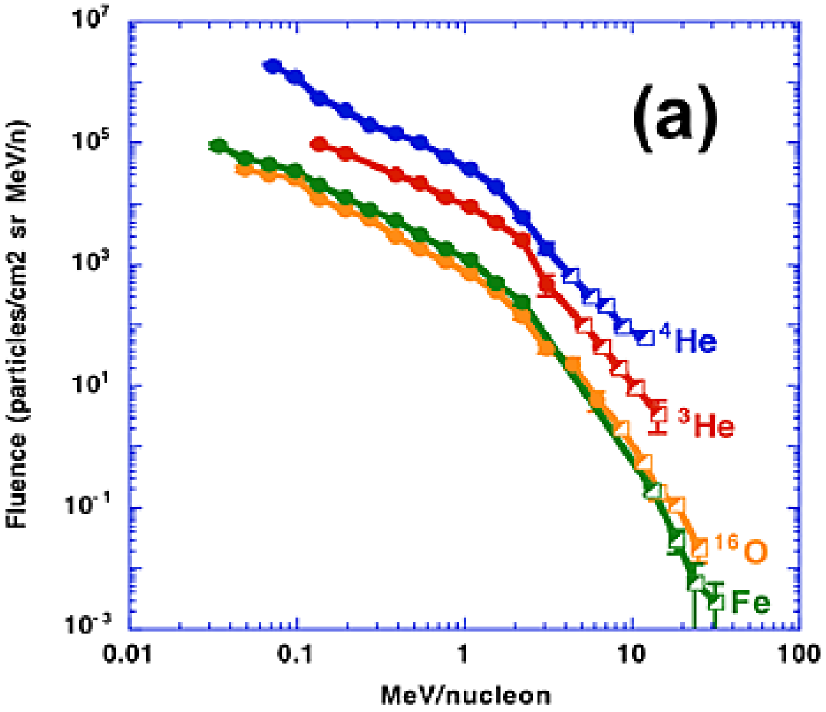
Reconnection exhaust heating

- For typical coronal parameters (B ~ 50G, n ~ 10^9), temperature increments ~ 25keV/nucleon
  - Typical of thermal component in flare heating
- Ion heating scenario
  - In a typically wide current sheet the reconnection magnetic field B_{0x} is very small ⇒ $\beta_{px} \sim 8\pi n T_p/B_{0x}^2 \gg 1$
    - Adiabatic behavior for all ions
  - As reconnection proceeds B_{0x} increases and β_{px} decreases and ions with progressively smaller $m_i/Z_i m_p$ behave like pickup particles and gain energy $$\frac{m_i}{Z_i m_p} > \sqrt{\beta_{px}}$$
  - Mostly perpendicular heating
- Heavy trace ions gain energy first
- Consistent with coronal observations with $T_{perp} > T_{||}$ and abundance enhancements in impulsive flares?

^{3}He abundance enhancement

- Abundance enhancements of ^{3}He range from 10^{3} – 10^{4}
  - Does not follow the typical M/Q trend of other ions
  - Spectra can differ significantly from other ions, especially for small flares
- Electron beam-driven ion cyclotron waves have been proposed as the heating mechanism for ^{3}He (Fisk '73, Temerin and Roth '96)
  - Volume of space with strong electron beams is limited because of constraints on the integrated current

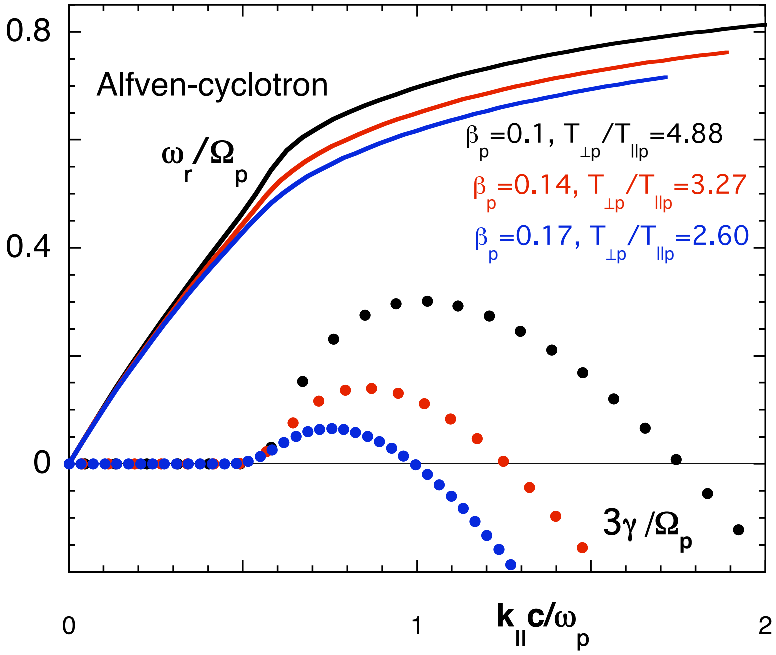
ACE ULEIS/SIS



Mason et al '02

Temperature anisotropy driven AIC waves

- The large ratio of $T_\perp/T_\parallel$ in reconnection exhausts can drive Alfven ion-cyclotron waves
  - Large volume of plasma with significant available free energy
- Are exploring this mechanism with PIC simulation with trace numbers of ^{3}He in a dominantly proton background with anisotropy

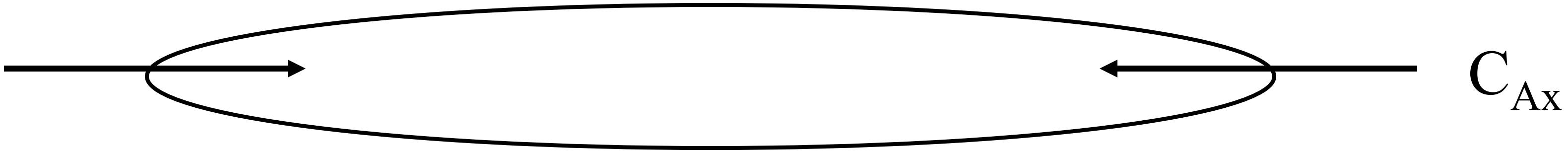


Gary et al ‘93

Particle acceleration in multi-island reconnection

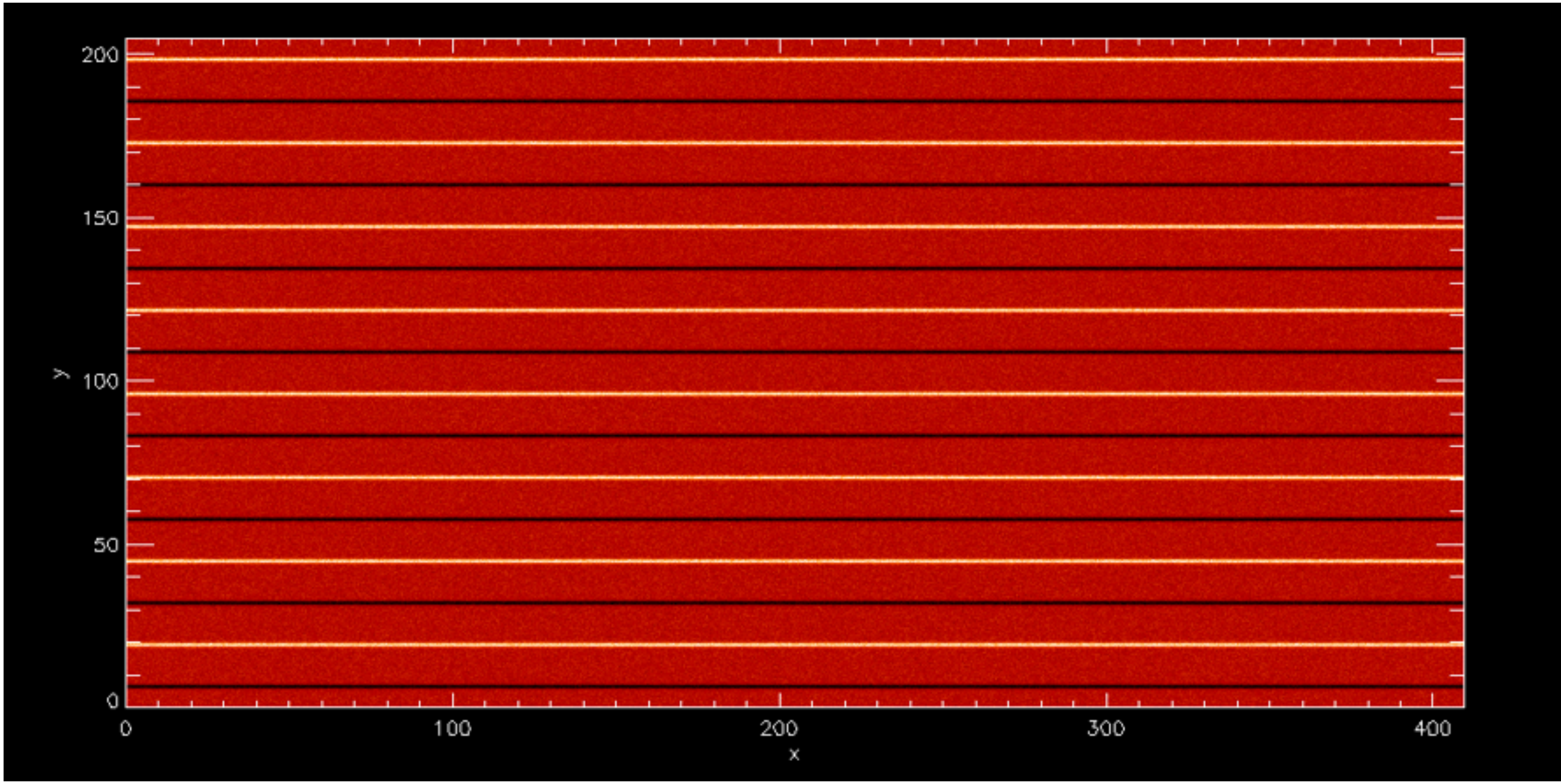
- Electrons and super-Alfvenic ions are accelerated to high energy in a multi-island environment
  - Fermi reflection in contracting magnetic islands (Kliem 94, Drake et al 2006, Drake et al 2010)
  - Dominantly parallel heating

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



Particle acceleration during multi-island reconnection

- 2-D simulation in a multi-current layer system
  - Force-free with low initial β
  - Guide field equal to the reconnecting field



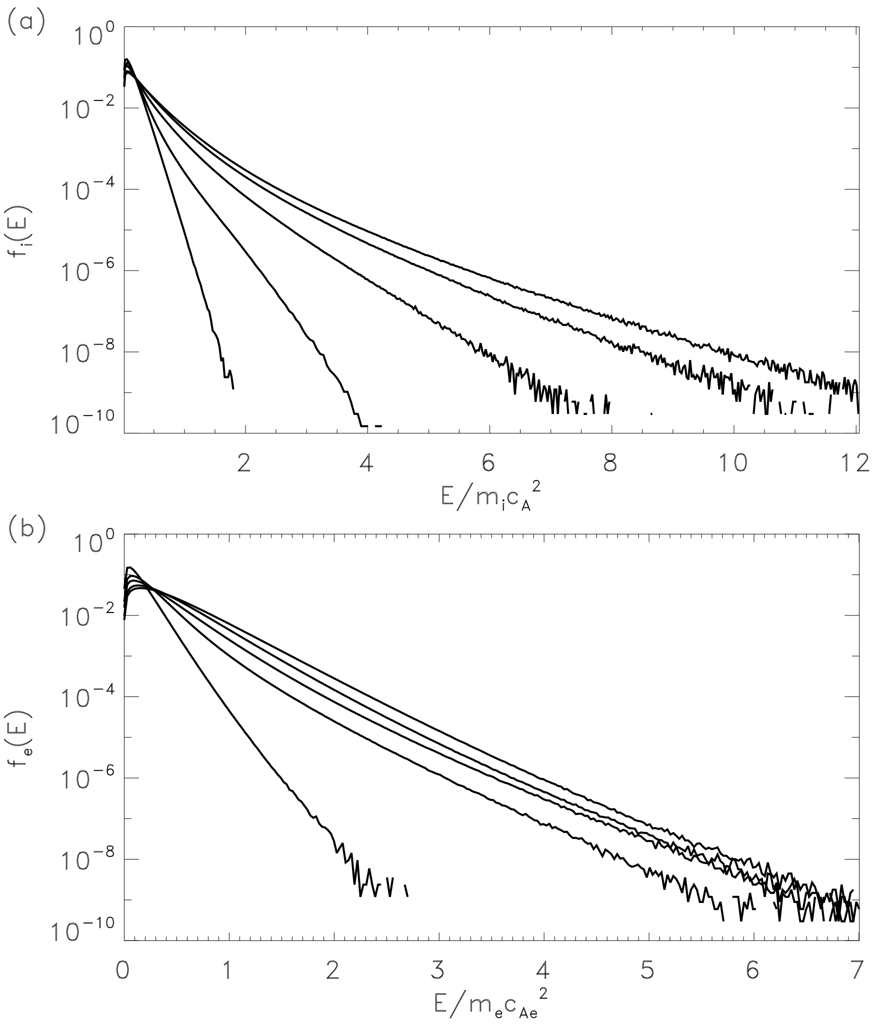
Electron and ion energy spectra

- Both ions and electrons gain energy
  - Electrons gain energy early and saturate. Why?
  - Ions gain energy later
- The rate of energy gain of particles increases with energy

⇒ consistent with first order Fermi

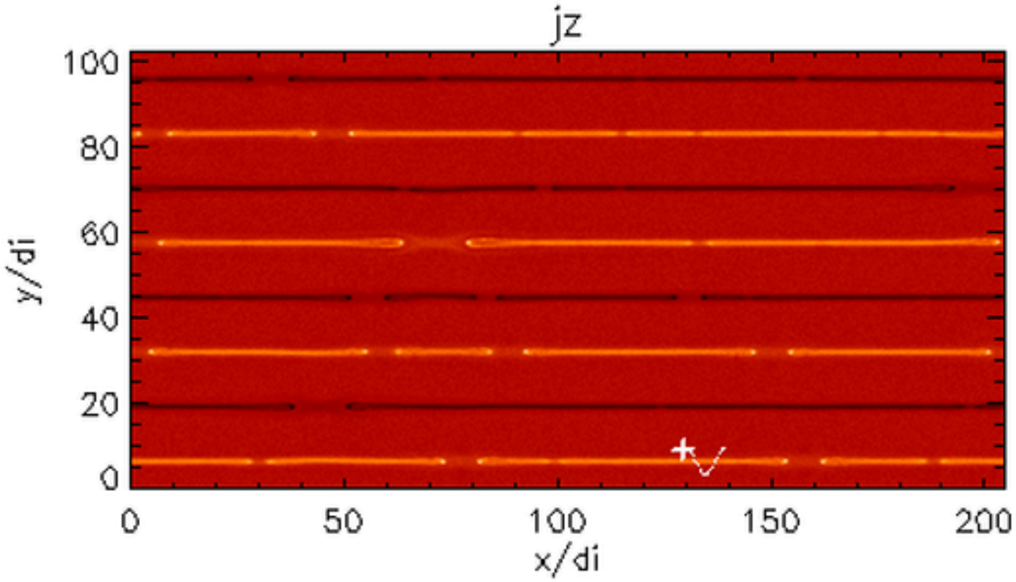
$$\frac{d\varepsilon}{dt} \propto \varepsilon$$

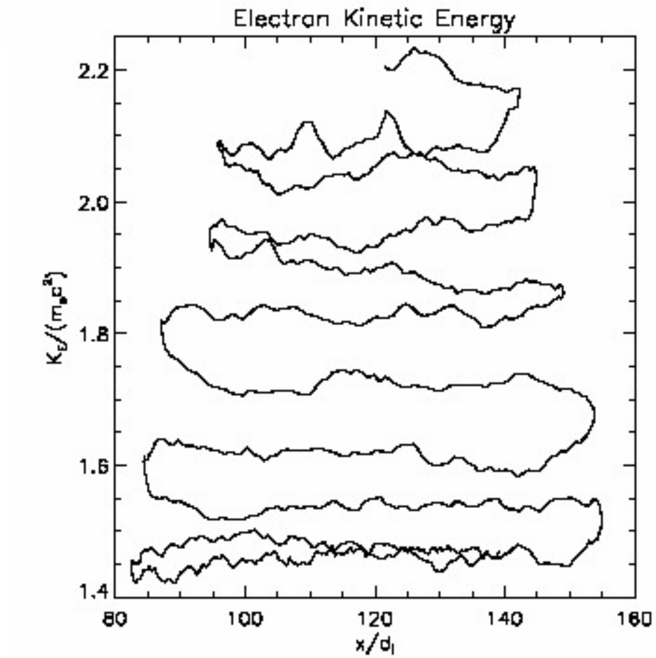
⇒ the simulation data is not a powerlaw since a log-linear plot



Fermi acceleration

- How do the most energetic particles gain energy?
  - Reflection from the ends of contracting islands
  - Increase of parallel energy and pressure $p_{\|}$





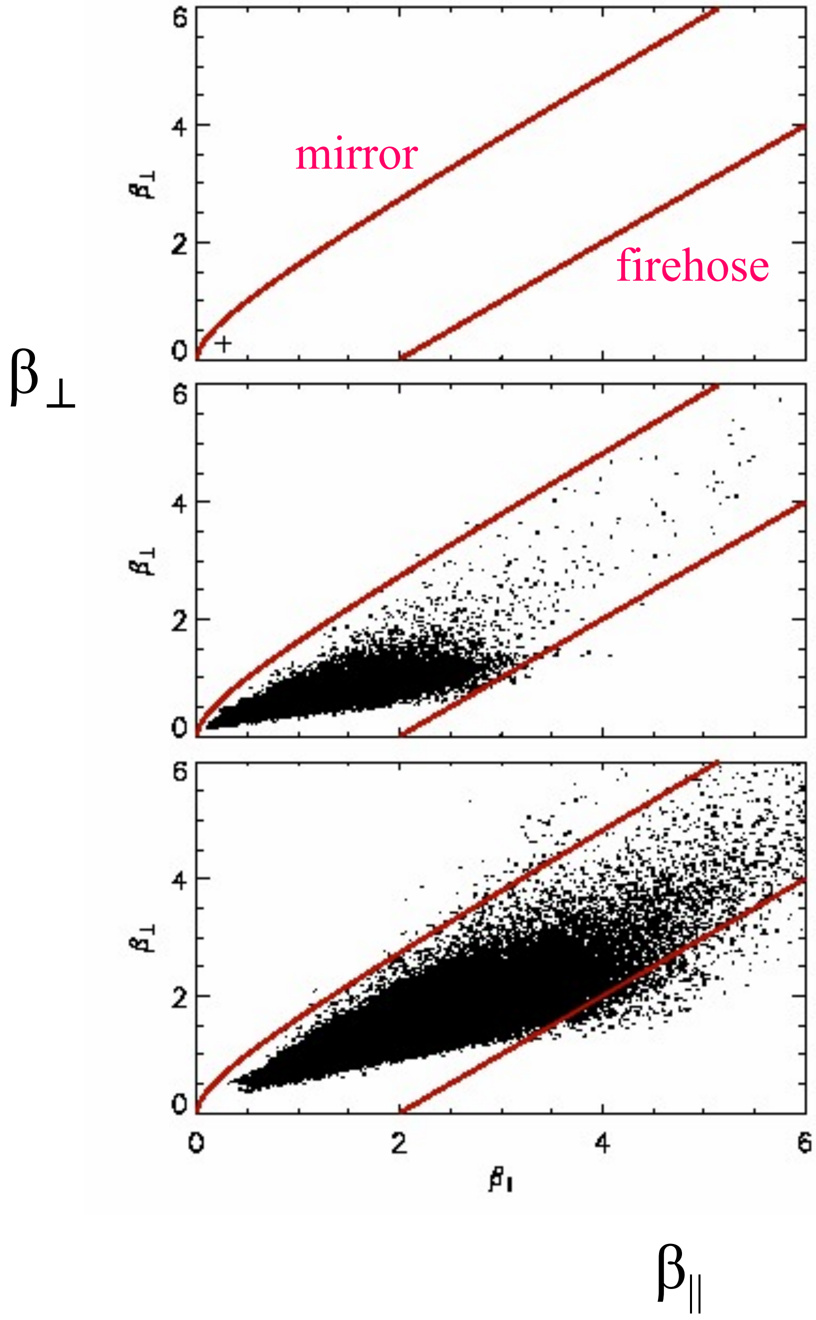
C_{Ax}

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

Schoeffler et al 2011

Mirror and firehose conditions: guide field

- Low initial β, guide field unity simulation
  - Each point corresponds to a grid point in the simulation
- At late time the islands bump against the firehose condition
- The energetic particles approach β ~ 1 even for low initial β
- Consistent with over-the-limb flare observations (Krucker et al 2010)



Energetic particle distributions

- Write down model equations for particle acceleration in contracting islands with feedback from the high pressure and convective loss
  - Powerlaw solutions for the omnidirectional energy flux

$$F(v) \sim \varepsilon^{-\gamma}$$

  - Spectral index given by

$$\gamma = 1.5 + \frac{\beta_0}{2}$$

  - Universal spectral index of 1.5 in low β systems

Conclusions

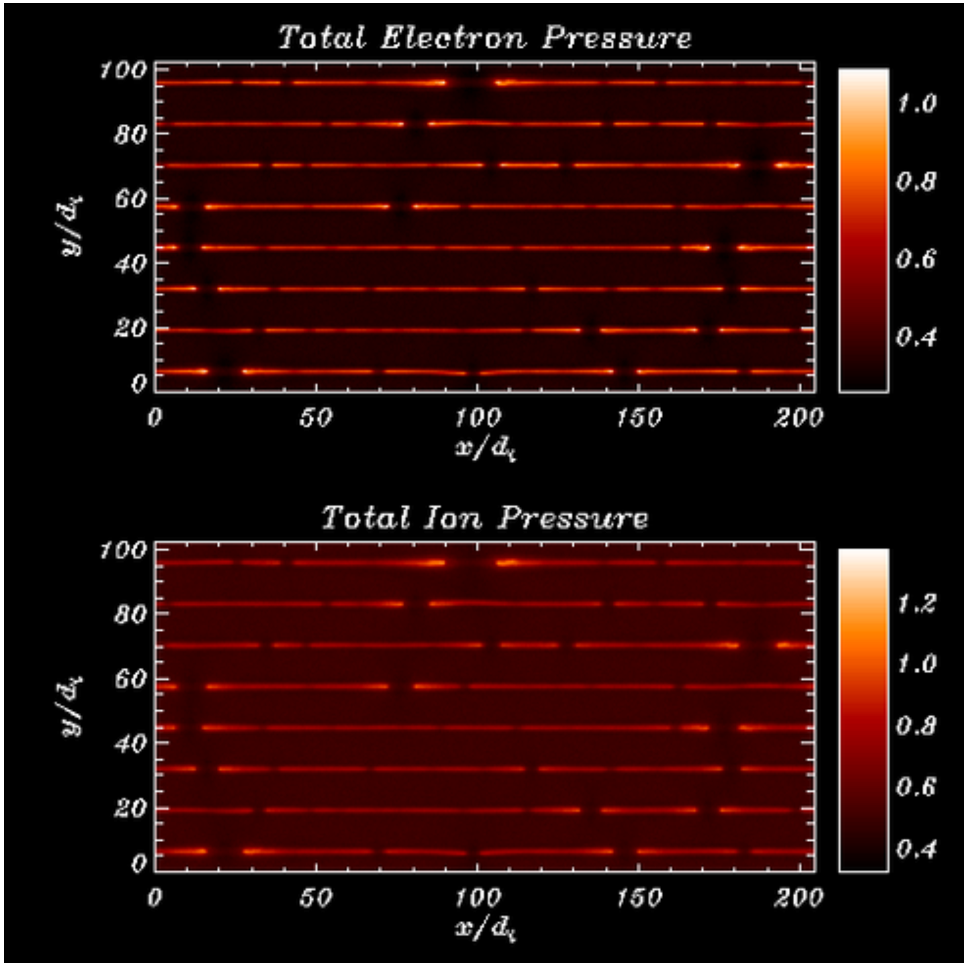
- Reconnection dominates reconnection in the solar wind close to the sun and in the corona where β is low.
- Ion interaction with the reconnection exhaust seeds them to super-Alfvenic velocities.
  - Ions act as pickup particles as they enter reconnection exhausts gain most energy
    - M/Q threshold for pickup behavior in guide field reconnection
    - Gain a thermal velocity given by the Alfven speed
    - Most of temperature increase is in $T_\perp$
- M/Q threshold for pickup behavior is a possible explanation of impulsive flare heavy ion abundance enhancements
- Alfven ion-cyclotron waves driven by $T_\perp > T_\parallel$ in reconnection exhausts preferentially heat ^{3}He and may be the source of abundance enhancements of ^{3}He

Conclusions (cont.)

- High energy particle production during magnetic reconnection requires the interaction with many magnetic islands
  - Not a single x-line
  - 1st order Fermi acceleration in contracting islands accelerates both ions and electrons
  - Island contraction is limited by the marginal firehose condition
  - Spectral indices of energetic particles take the form of powerlaws with spectral indices controlled by the firehose condition

Firehose instability during island contraction

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



Schoeffler et al 2011

1-D Model equations

- Rate of energy gain: first order Fermi

$$\dot{v} = \frac{dv}{dt} = \frac{1}{\tau_h}\left(1 - \frac{4\pi p}{B^2}\right)^{1/2} v \qquad \tau_h = \left\langle \frac{c_A}{L_w} \right\rangle^{-1}$$

Reduction of contraction rate due to firehose condition

- Model equation for the omnidirectional distribution function

  $F(v,t) = 4\pi v^2 f\,(v,t)$

$$\frac{\partial F}{\partial t} + \frac{\partial}{\partial v}\dot{v}F = -\frac{1}{\tau_L}\left[F - F_0(v)\right] \qquad \tau_L = \left\langle \frac{c_A}{L} \right\rangle^{-1}$$

- Above the source energy this is an equidimensional equation

  ⇒ powerlaw solutions