Magnetic Reconnection: dynamics and particle acceleration

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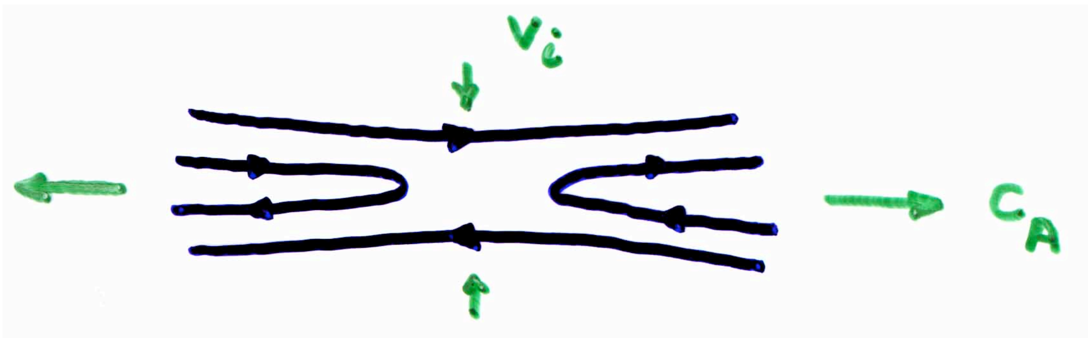
Magnetic Energy Dissipation in the Universe

- The conversion of magnetic energy to heat and high speed flows underlies many important phenomena in nature
  - solar and stellar flares
  - Energy releases from magnetars
  - magnetospheric substorms
  - disruptions in laboratory fusion experiments
- More generally understanding how magnetic energy is dissipated is essential to model the generation and dissipation of magnetic field energy in astrophysical systems
  - accretion disks
  - stellar dynamos
  - supernova shocks

Basic questions

- Known systems are characterized by a slow buildup of magnetic energy and fast release
  - Mechanism for fast release?
  - Why does reconnection occur as an explosion?
- Why does so much energy go into electrons?
  - Up to the range of MeV in the magnetosphere and solar flares
  - A significant fraction of the released magnetic energy in flares goes into electrons. Why?
- Energetic ions
  - Up to the GeV range in flares
  - Why is energy proportional to mass in solar energetic particle events?
- Recent observations suggest that in flares electrons and ions have a common mechanism for acceleration.
- Can reconnection compete with shocks as the source of energetic cosmic rays in the universe?

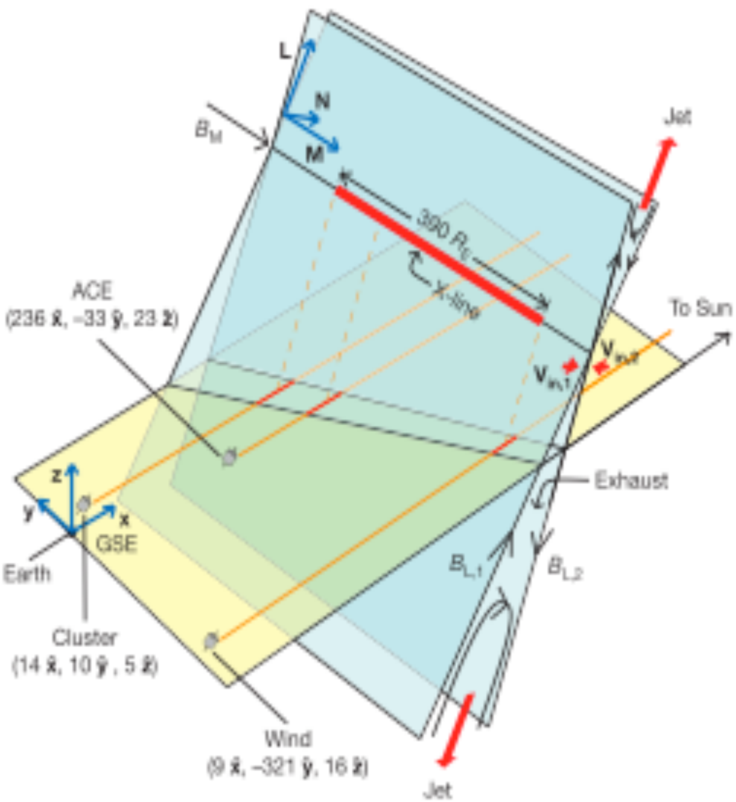
Magnetic Reconnection

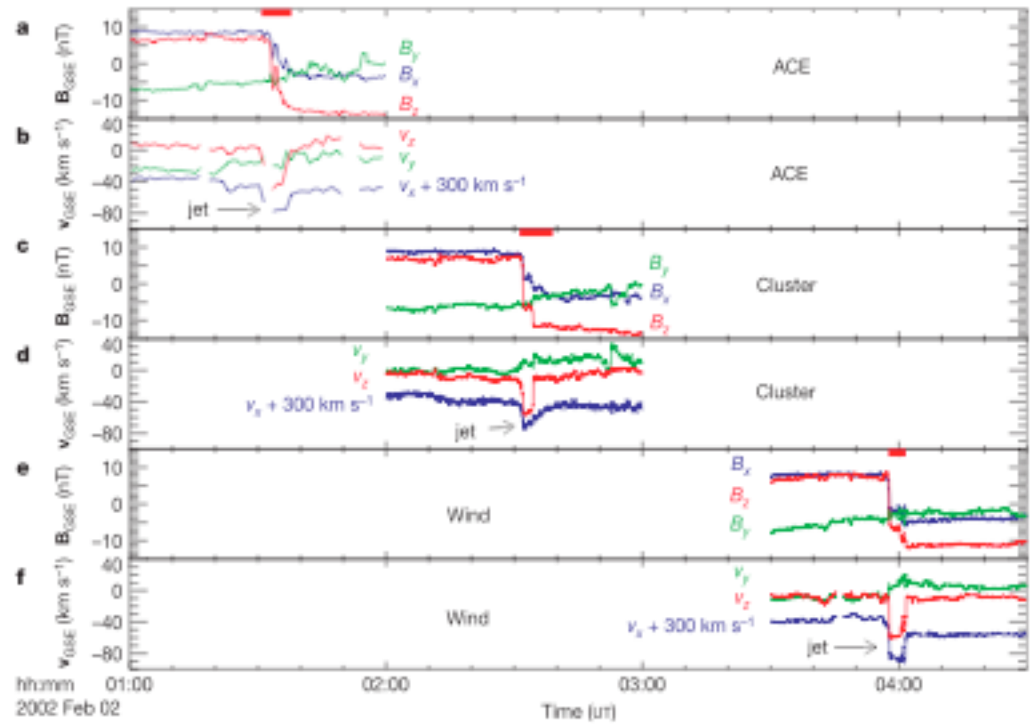


- Reconnection is driven by the relaxation in tension in newly reconnected field lines
  - Pressure drop near near the x-line pulls in upstream plasma
  - Magnetic reconnection is self-driven
- Dissipation required to break field lines
- Key issue is how newly reconnected field lines at very small scales expand and release their tension

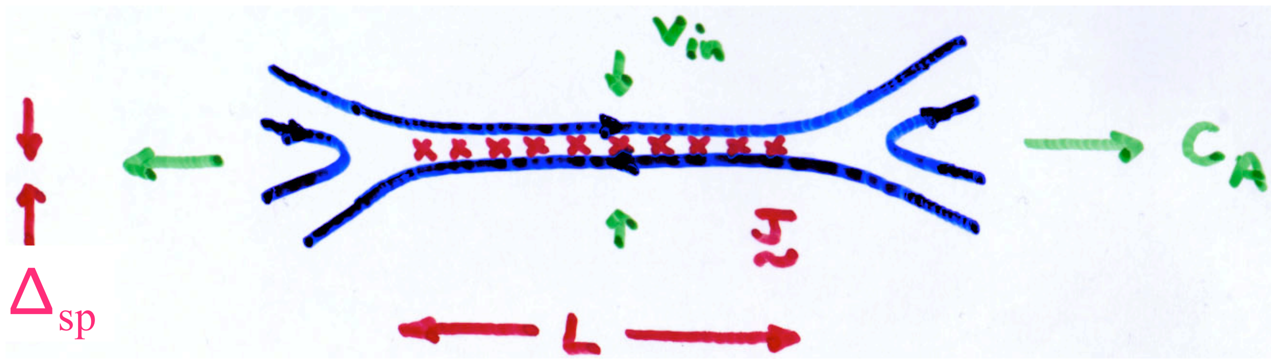
Large solar wind reconnection events

- Solar wind reconnection events are providing an important in-situ source of data for understanding reconnection
  - 390 R_E reconnectionn encounter (Phan et al 2006)





Resistive MHD Description



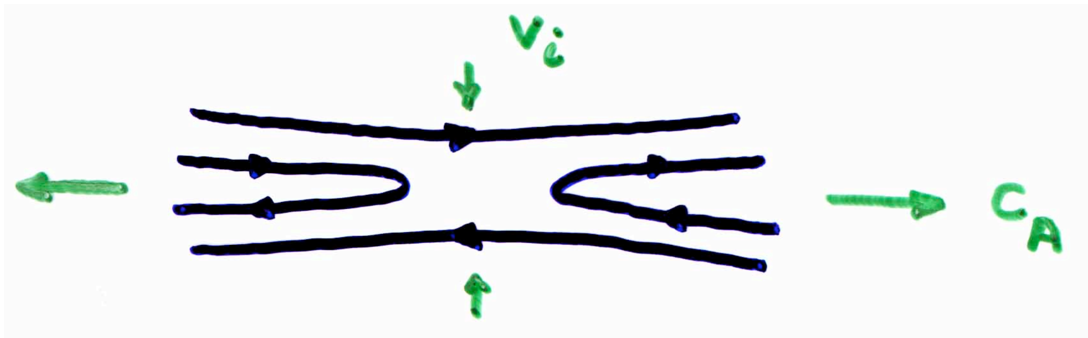
- Formation of macroscopic Sweet-Parker layer

$$\mathbf{V \sim (\Delta_{sp} /L)\, C_A \sim (\tau_A/\tau_r)^{1/2}\, C_A \ll C_A}$$

•Slow reconnection ⇒ not consistent with observations
•sensitive to resistivity
•macroscopic nozzle

- Petschek-like open outflow configuration does not appear in resistive MHD models with constant resistivity (Biskamp ‘86)

Hall Reconnection



- MHD model breaks down in the dissipation region at small spatial scales where electron and ion motion decouple
  - At scales below the ion inertial scale length $d_i = c/\omega_{pi}$
- Key is to understand how newly reconnected field lines expand at very small spatial scales where MHD no longer valid
  - The outflow from the x-line is driven by whistler and kinetic Alfven waves ⇒ dispersive waves
  - fast reconnection even for very large systems
- Key signatures of Hall reconnection have been measured by magnetospheric satellites and laboratory experiments

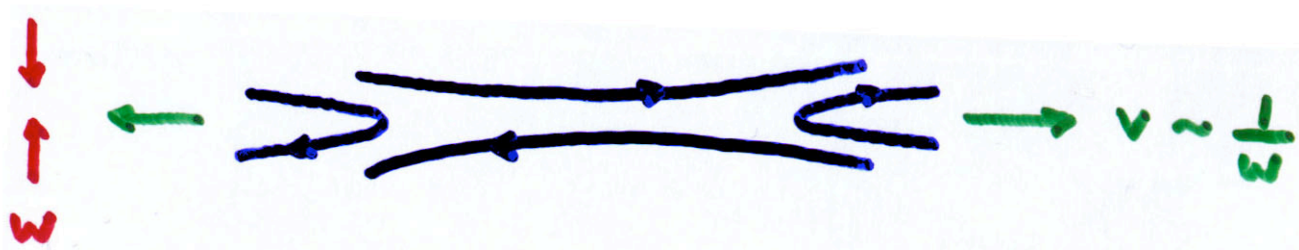
Why is wave dispersion important for the reconnection rate?

- Quadratic dispersion character

  $\omega \sim k^2$

  $v_p \sim k$

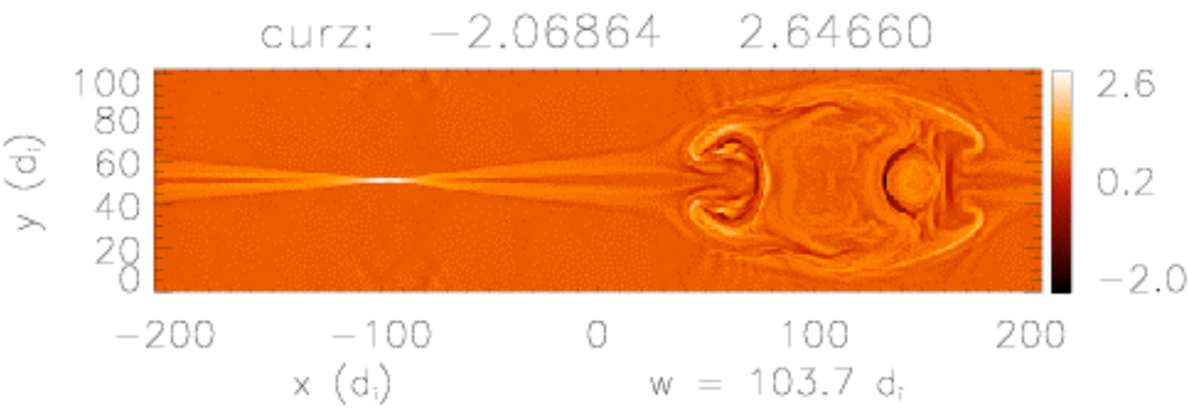
  - smaller scales have higher velocities
  - weaker dissipation leads to higher outflow speeds



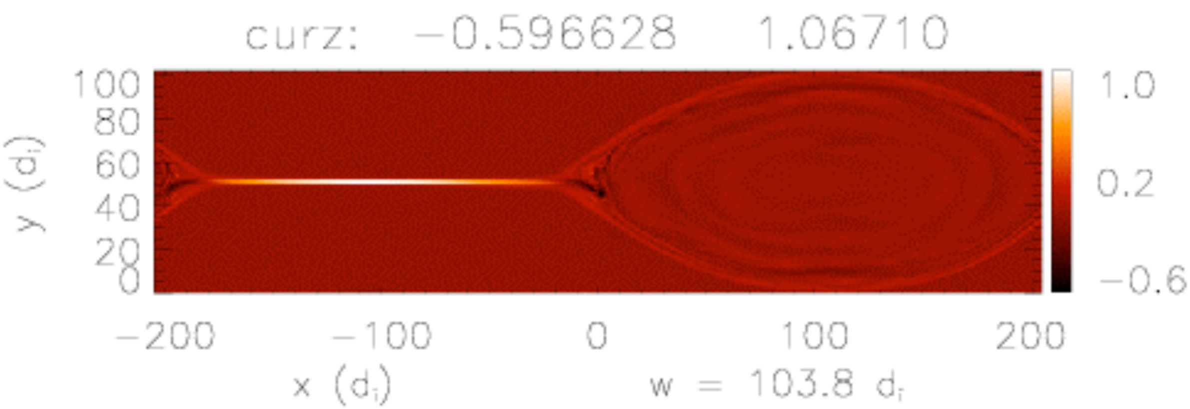
  - flux from x-line ~ vw
    - » Flux insensitive to dissipation
    - » Reconnection rate insensitive to dissipation

Hall versus MHD reconnection

Hall



MHD

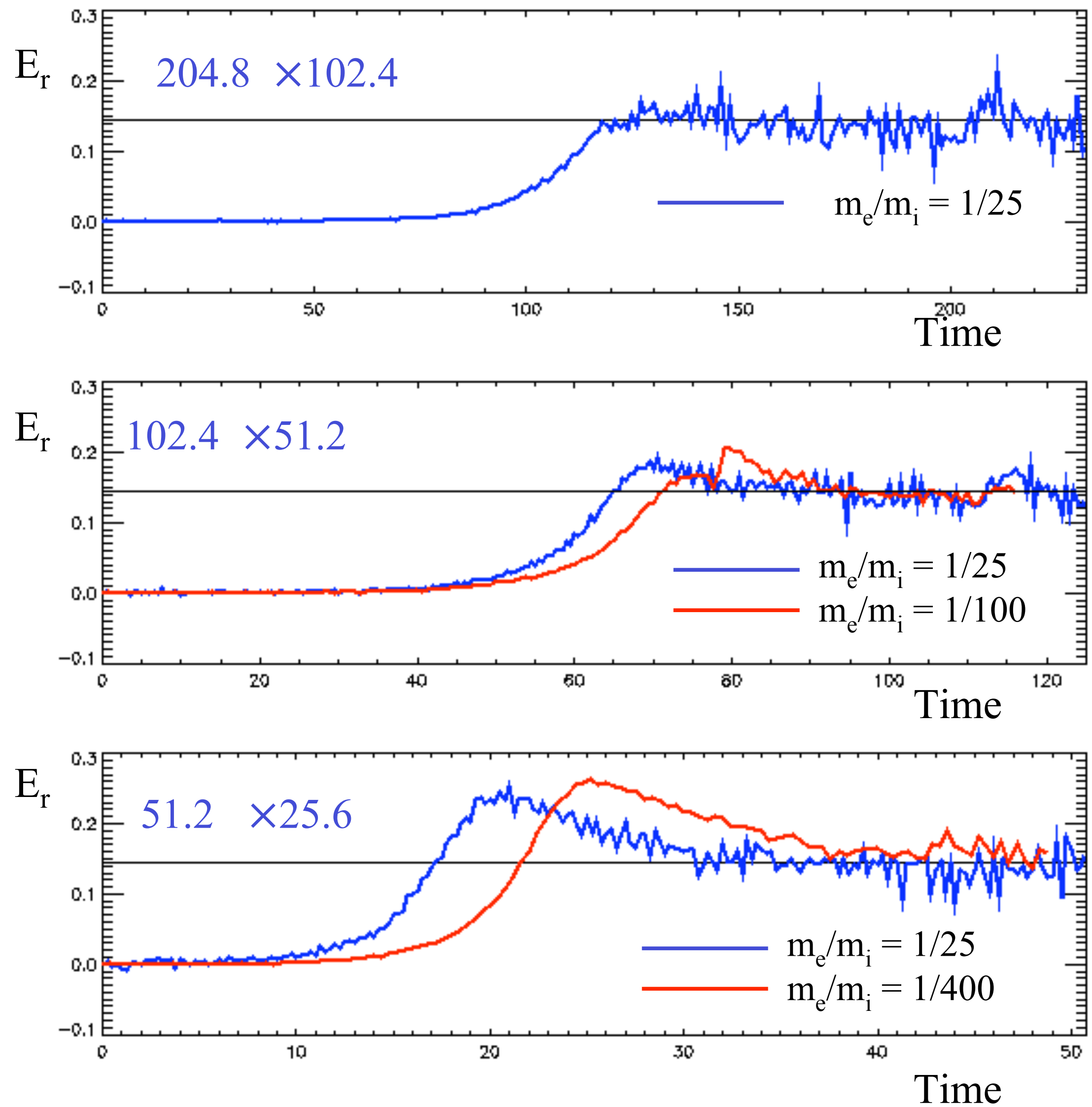


– MHD model produces rates of energy release too slow to explain observations -- macroscopic nozzle *a la* Sweet-Parker

– Hall model produces fast reconnection as suggested by Petschek

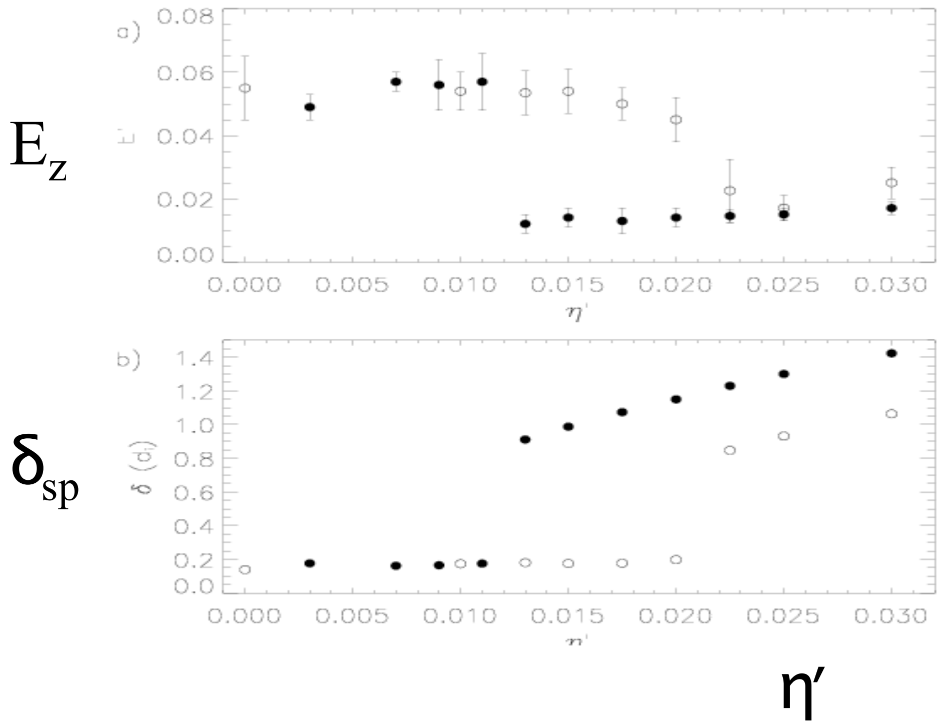
Reconnection Rates

- PIC simulation results from large periodic domains (Shay et al 2007)
- Asymptotic reconnection rate $E_r \approx 0.14$
  - Independent of domain size
  - Independent of electron mass
- Periodic versus open boundary simulations
  - Averaged reconnection rates in agreement
  - Modulation from secondary islands



Why is reconnection explosive?

- Slow Sweet-Parker reconnection and fast Hall reconnection are valid solutions for the same parameters

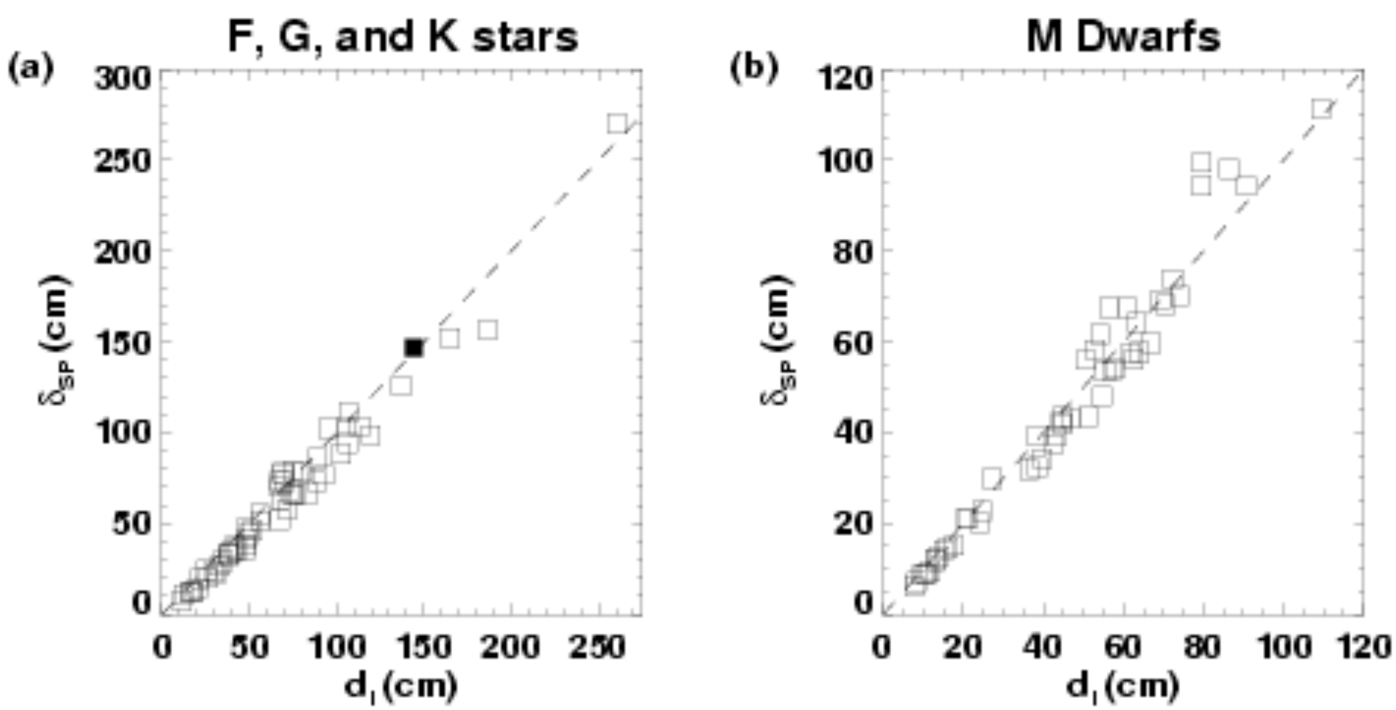


Cassak et al 2005

- Sweet-Parker solution does not exist below a critical resistivity
  - ⇒ Where $\delta_{sp} < d_i$ (e.g., Aydemir 92, Wang and Bhattaharjee 95)
  - ⇒ η' and δ_{sp} decrease with time as reconnection proceeds $\eta' \sim B_{up}^{-1}$
  - ⇒ For the solar corona the critical temperature is around 100 eV and the reconnection rate will jump a factor of 10^5

Hall reconnection and stellar coronae

- Powerlaw distributions of flare energy release suggest that coronae evolve into an organized critical state
  - What controls this critical state?
  - Data suggests that at flare onset coronae lie at the boundary between Sweet-Parker and Hall reconnection
    - Flares increase the density until $\delta_{sp} \sim d_i$ where flares self-stabilize (Uzdensky 2007)
    - Similar behavior in accretion disc coronae (Goodman and Uzdensky 2008)



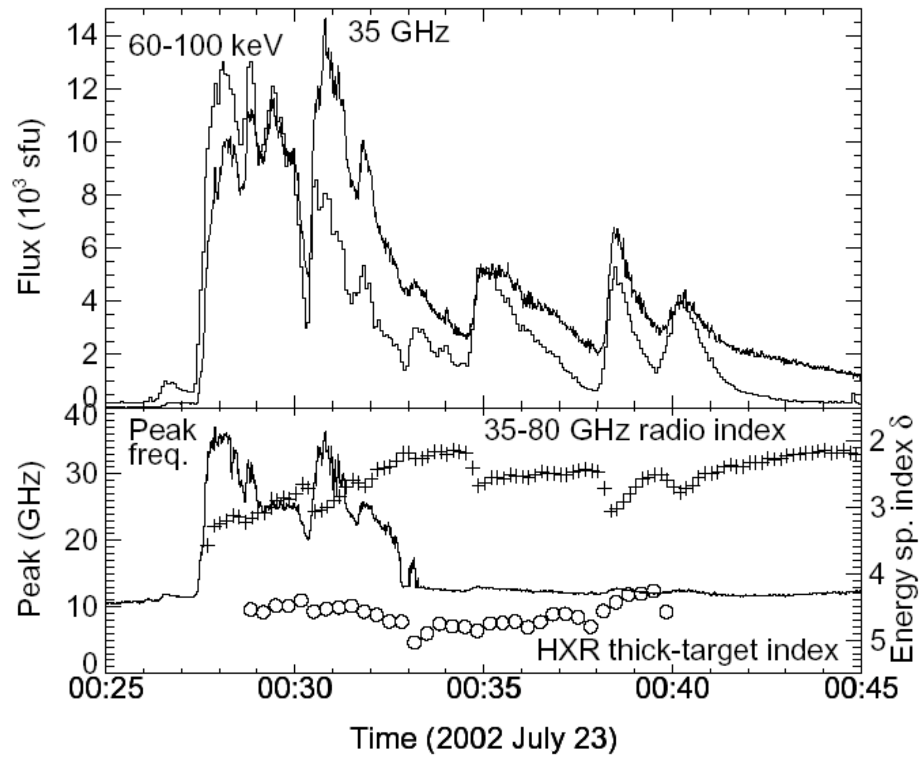
Cassak et al., 2007

Energetic electron and ion production during reconnection in the heliosphere

- In solar flares energetic electrons up to MeVs and ions up to GeVs have been measured
  - Up to 50% of the released magnetic energy appears in the form of energetic electrons (Lin and Hudson, 1971)
    - Why is the electron energy linked to the energy release?
    - powerlaw distributions above ~ 20 keV
    - Large numbers of energetic electrons
  - Correlation between energetic electrons and ions in impulsive flares possibly indicating a common heating mechanism
  - Enhancement of energetic high M/Q ions compared with ambient coronal values
- Observations of electron heating during magnetotail reconnection
  - Powerlaw distributions (Oieroset et al 2002)
  - Energetic electrons fill magnetic islands (Chen et al 2007)
- Heated ions in solar wind reconnection events (Gosling et al, 2005; Phan et al 2006)
  - Energy proportional to mass

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

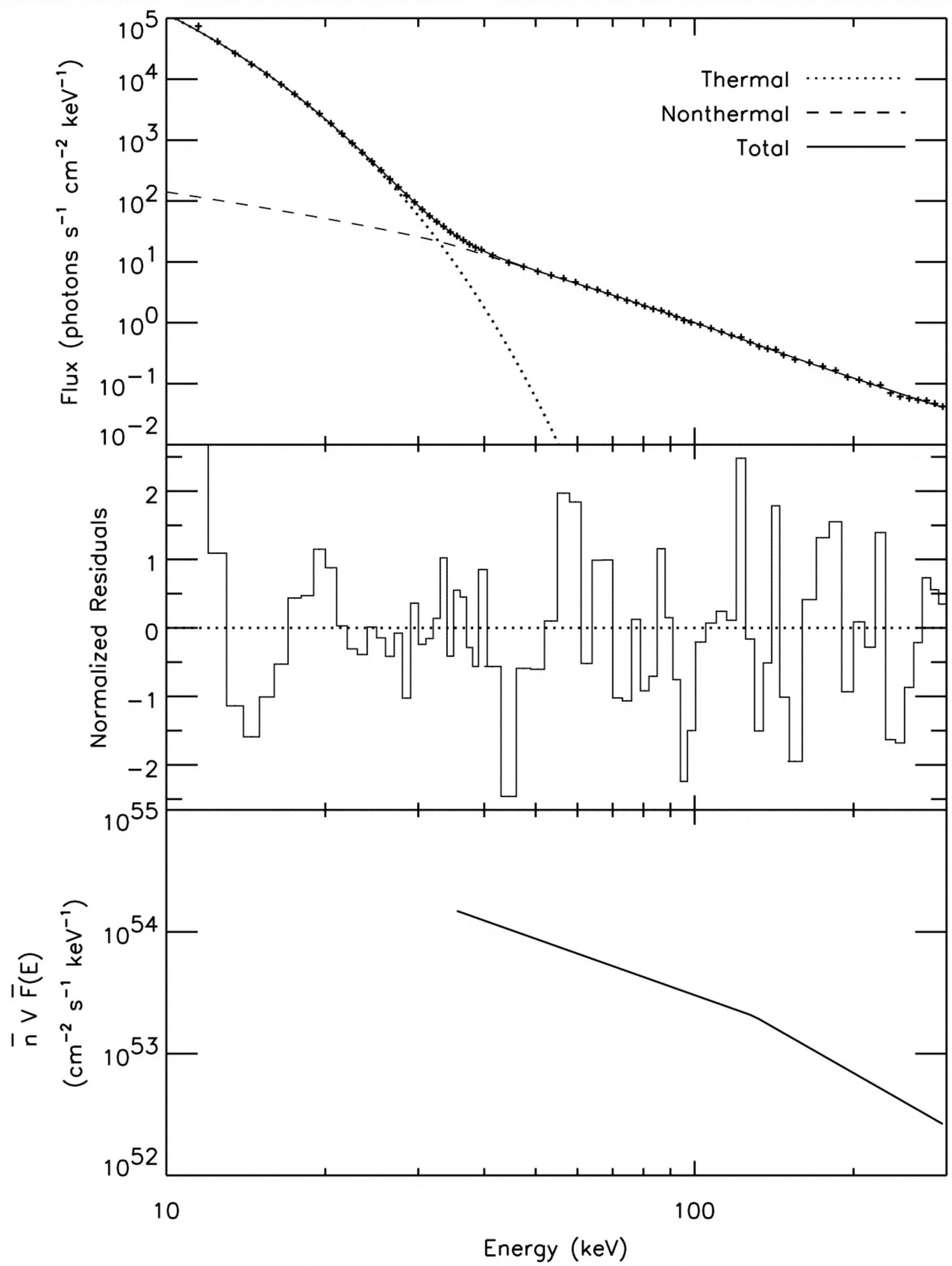
(White et al., 2003)

RHESSI observations

- July 23 γ-ray flare
- Holman, *et al.*, 2003
- Double power-law fit of electron flux with spectral indices:

  1.5 (34-126 keV)

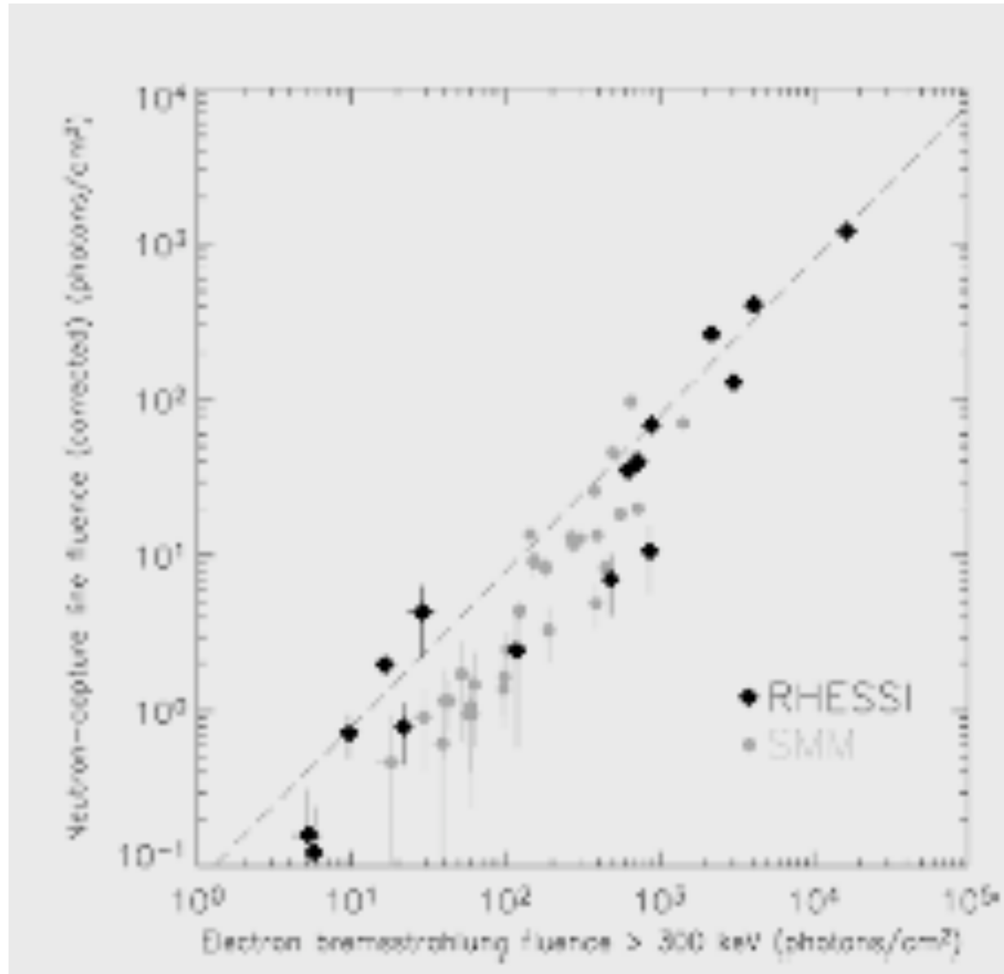
  2.5 (126-300 keV)



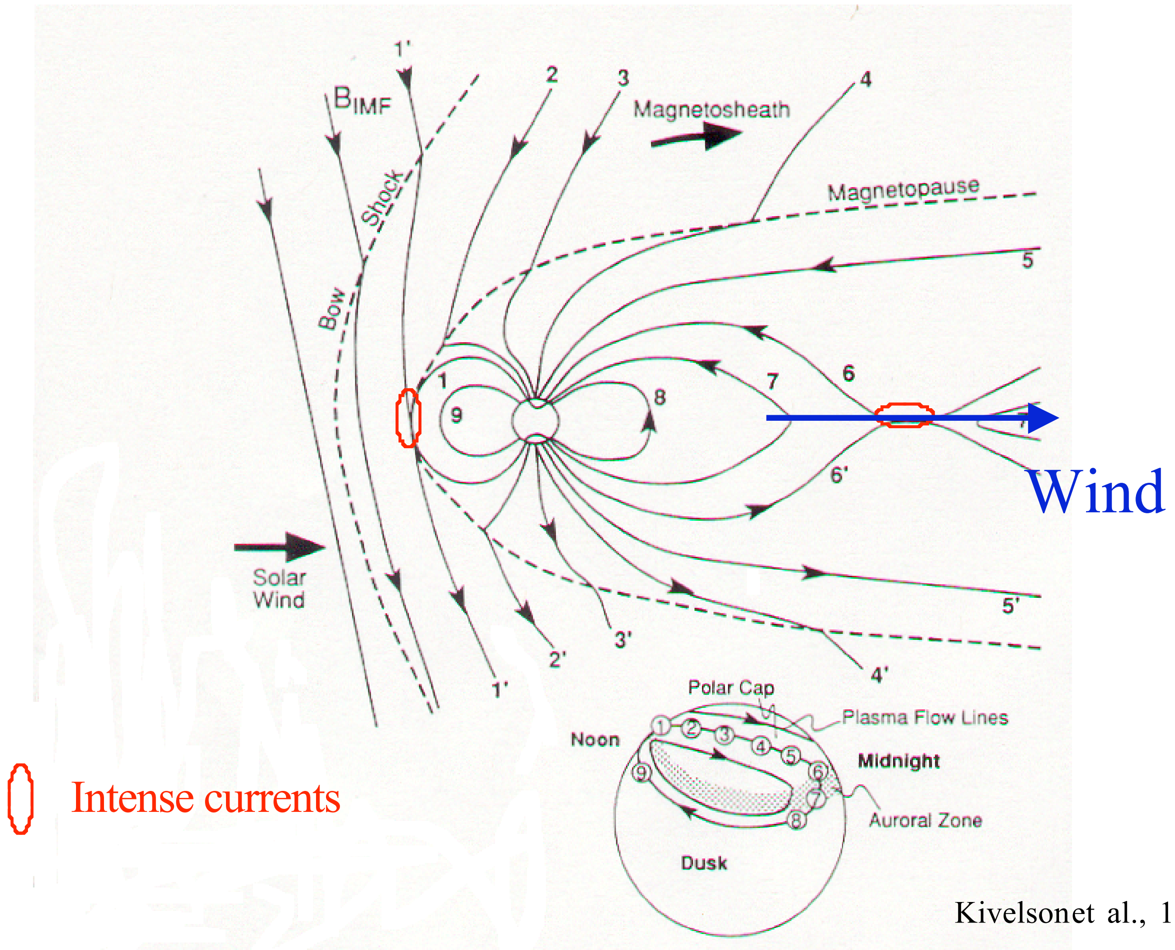
Energetic electron and ion correlation

- > 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



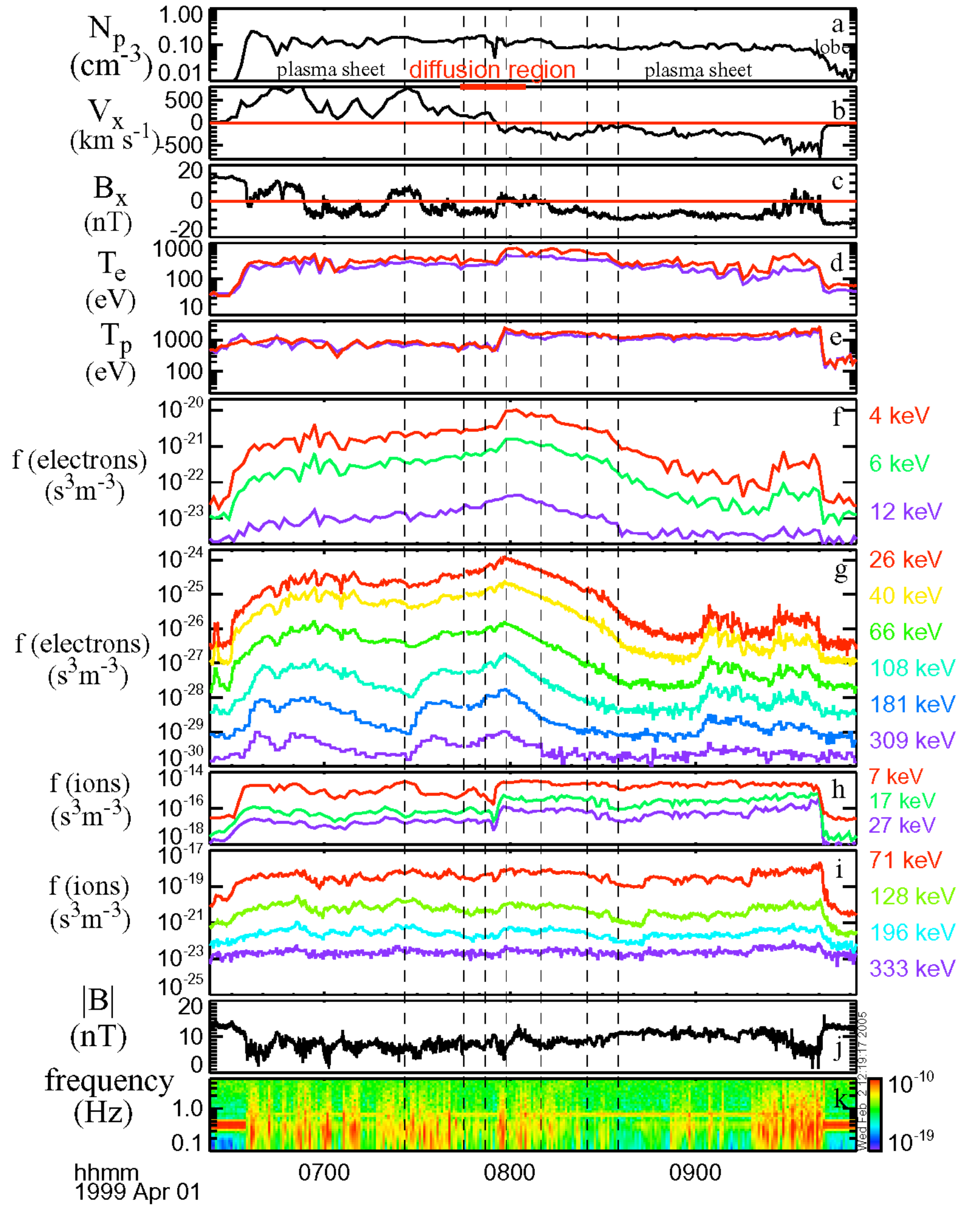
Wind spacecraft trajectory through the Earth's magnetosphere



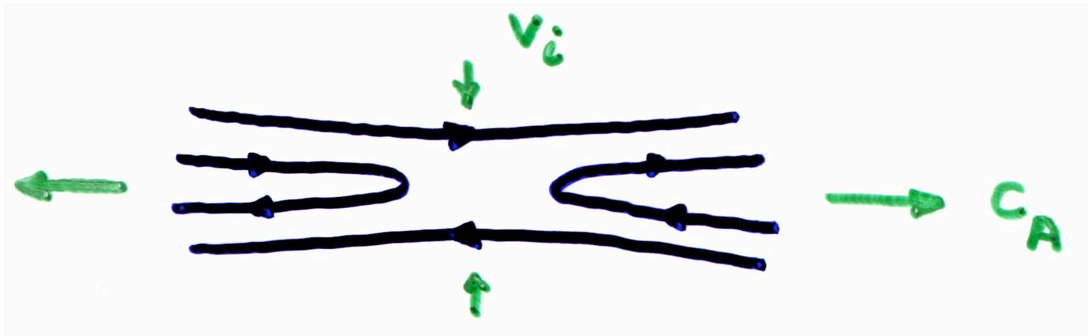
Kivelsonet al., 1995

Wind magnetotail observations

- Wind spacecraft observations revealed that energetic electrons peak in the diffusion region (Oieroset, et al., 2002)
  - Energies measured up to 300kev
  - Power law distributions of energetic electrons



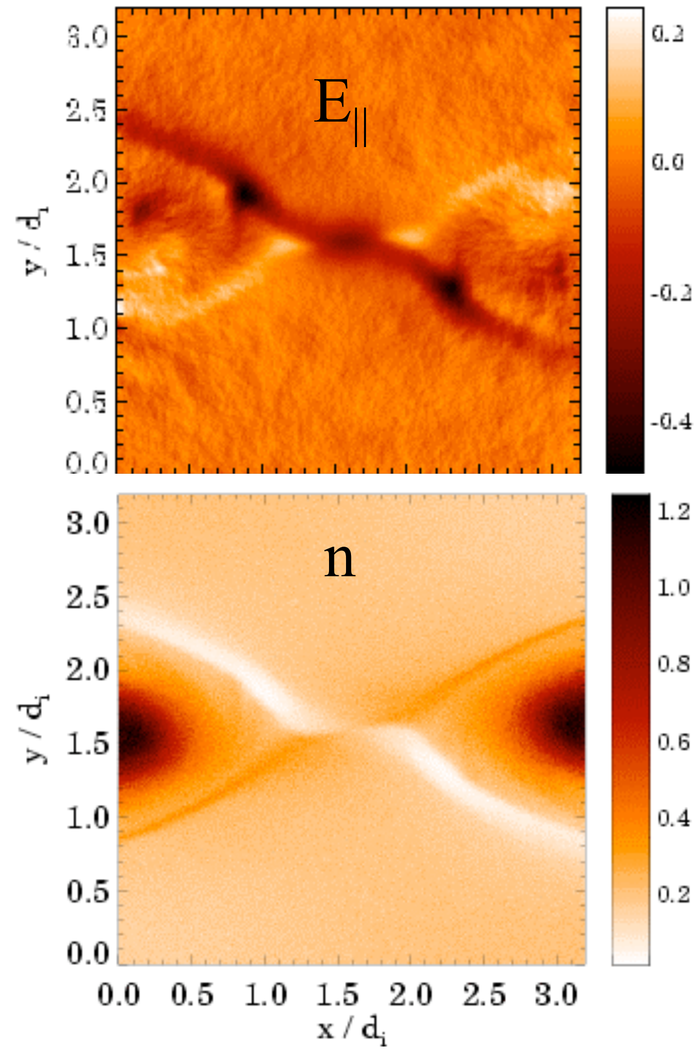
Single x-line model



- Can the parallel electric fields produced during reconnection explain the large number of energetic electrons?

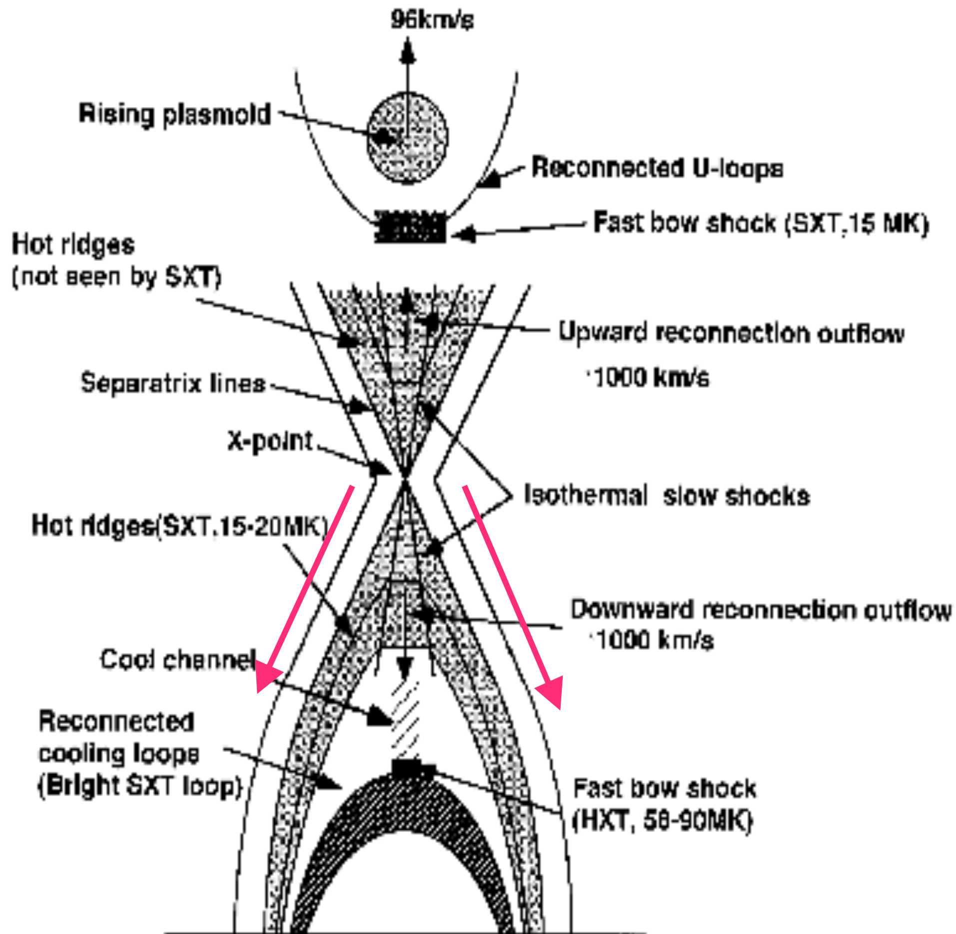
Structure of the parallel electric field

- Parallel electric fields remain strongly localized along the magnetic separatrix close to the x-line
  - Electrons in a high temperature plasma short out the parallel electric field
  - Beware of models with macroscale parallel electric fields!!
  - Too localized to be energetically important
- PIC simulations overemphasize the importance of parallel electric fields since simulation domains are too small.
  - Beware of believing your own simulations



Single x-line model: the sun

- Can parallel electric fields 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^{9}cm
  - Parallel electric fields are shorted out except near the x-line
    - kinetic modeling
- Magnetic energy is not released at the x-line but downstream as the reconnected fields relax their stress
  - The x-line dynamics breaks fieldlines but is not where energy is released
  - X-line has negligible volume on the physical scale of the region where energy is released in the corona
- Can't explain the large number of energetic electrons

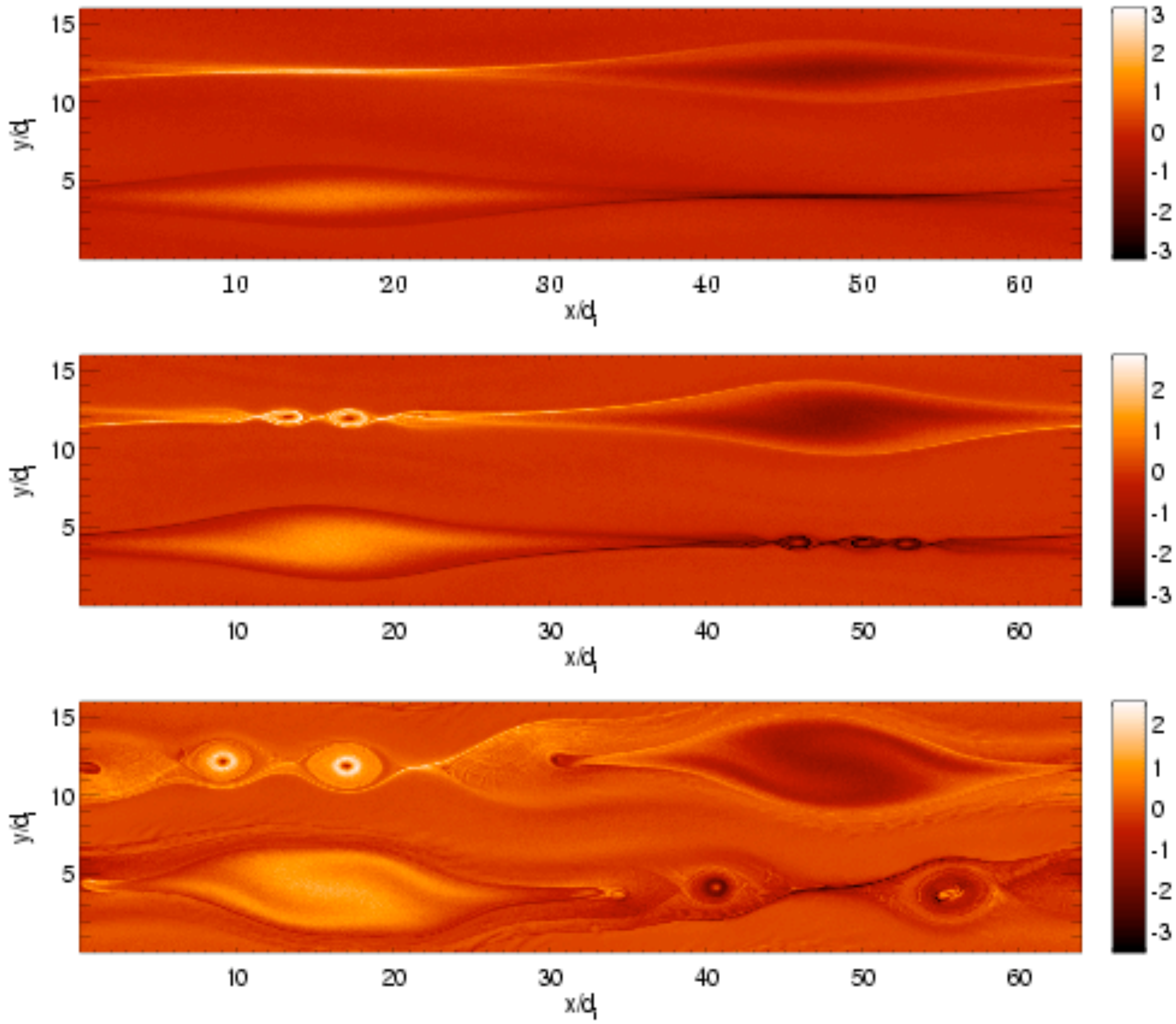


⇒Must abandon single x-line model

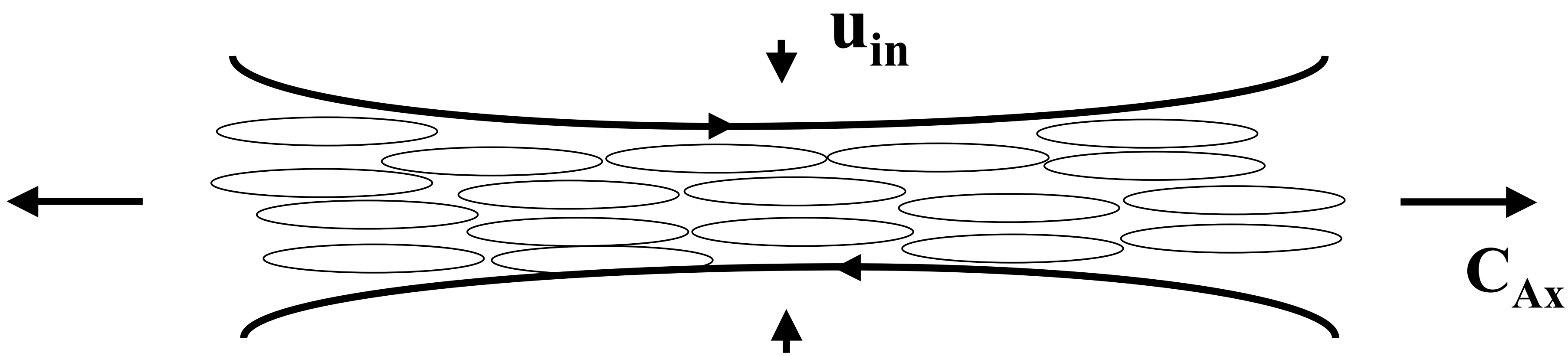
Tsuneda 1997

A multi-island acceleration model

- Narrow current layers spawn multiple magnetic islands in guide field reconnection
- Secondary islands seen in observations
  - In the magnetosphere
  - Downflow blobs in the corona
- In 3-D magnetic islands will be volume filling



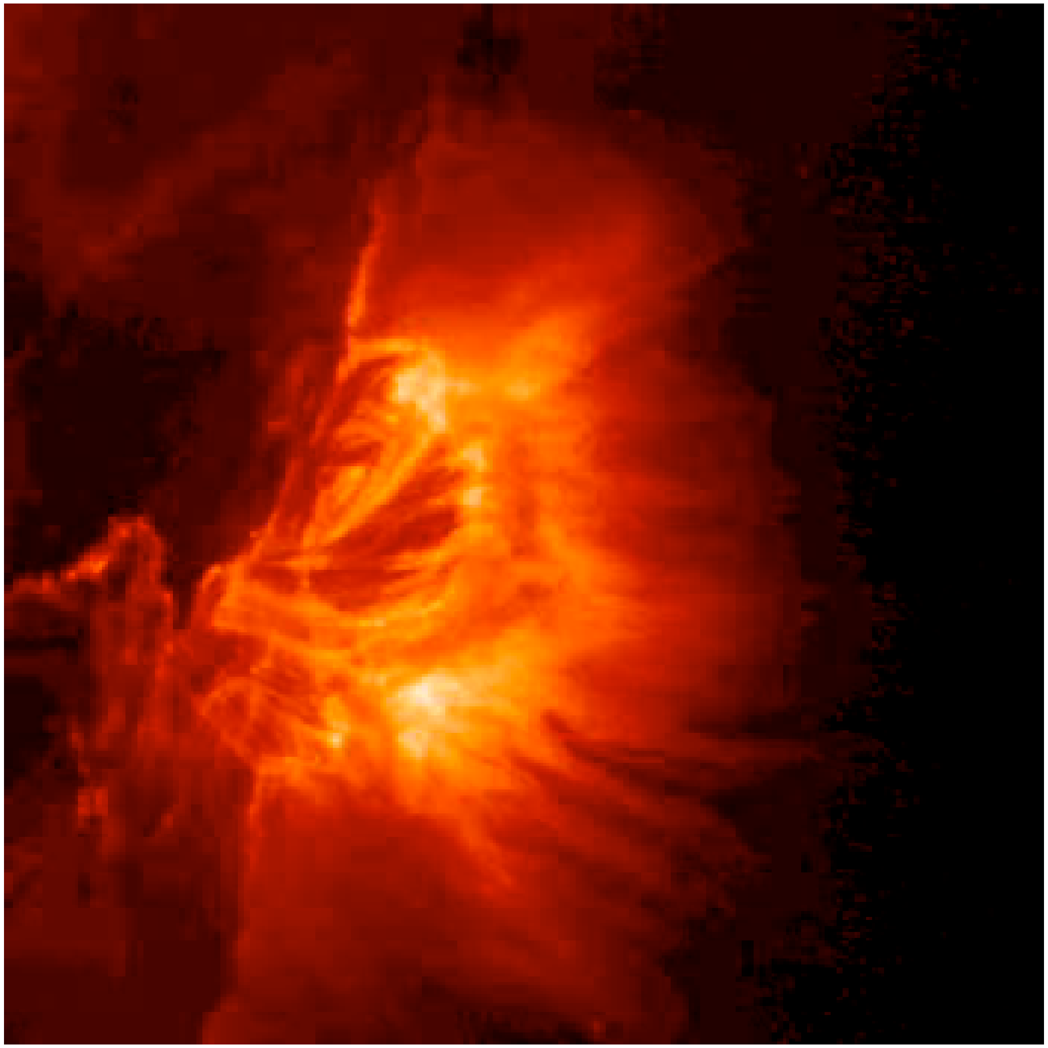
Multi-island reconnection



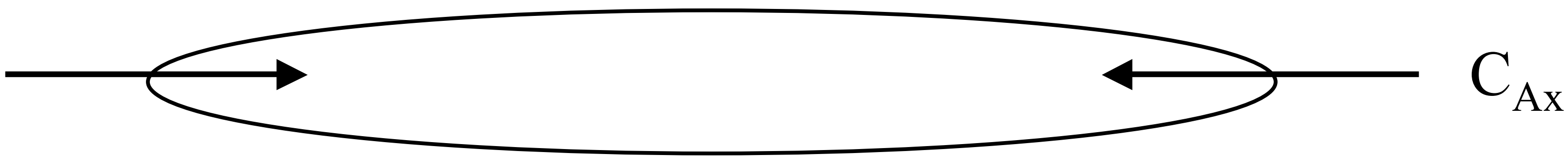
- Consider a reconnection region with multiple islands in 3-D with a stochastic magnetic field
- How are electrons and ions accelerated in a multi-island environment?

TRACE observations of downflow blobs

- Data from the April 21, 2002, X flare
- Interpreted as patchy reconnection from overlying reconnection site



A Fermi acceleration mechanism inside contracting islands

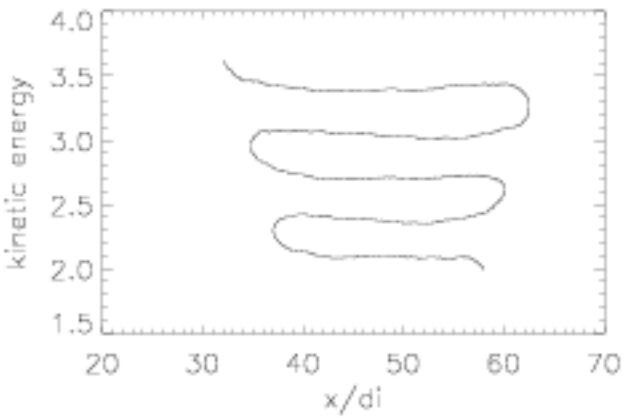


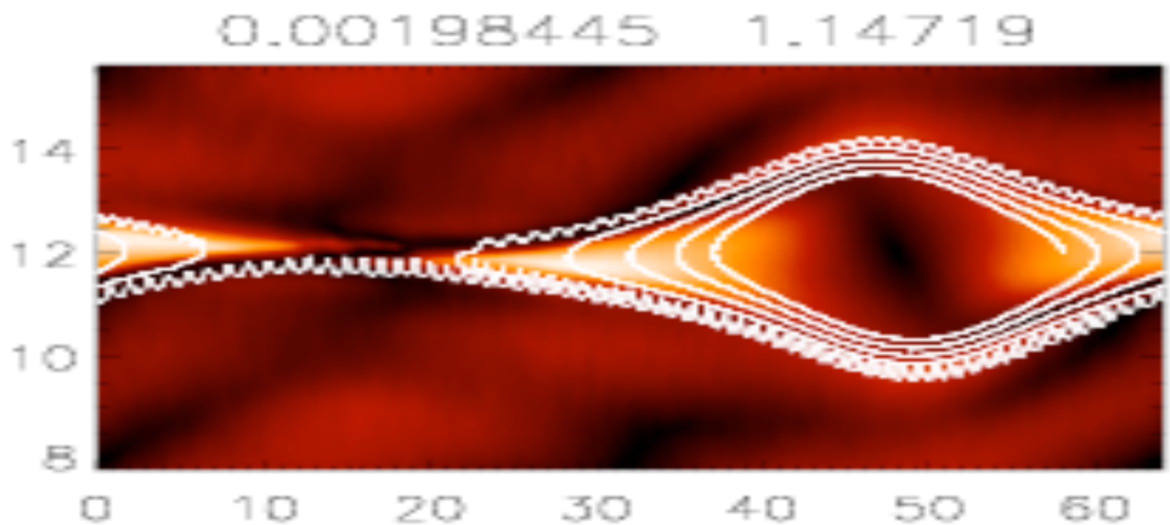
- Energy is released from newly reconnected field lines through contraction of the magnetic island
- Reflection of electrons from inflowing ends of islands yields an efficient acceleration mechanism for electrons even when the parallel electric field is zero (Kliem, 1994, Drake, et al., 2006)

$$\frac{d\varepsilon}{dt} = 2\varepsilon G \frac{C_{Ax}}{L_x} \qquad G(B_x, B_z) = \frac{B_x^2}{B^2}$$

- Energy gain independent of mass
  - Thermal ions are not fast enough to undergo multiple reflections
  - Need seed mechanism to generate super-Alfvenic ions

Electron Dynamics in simulation fields



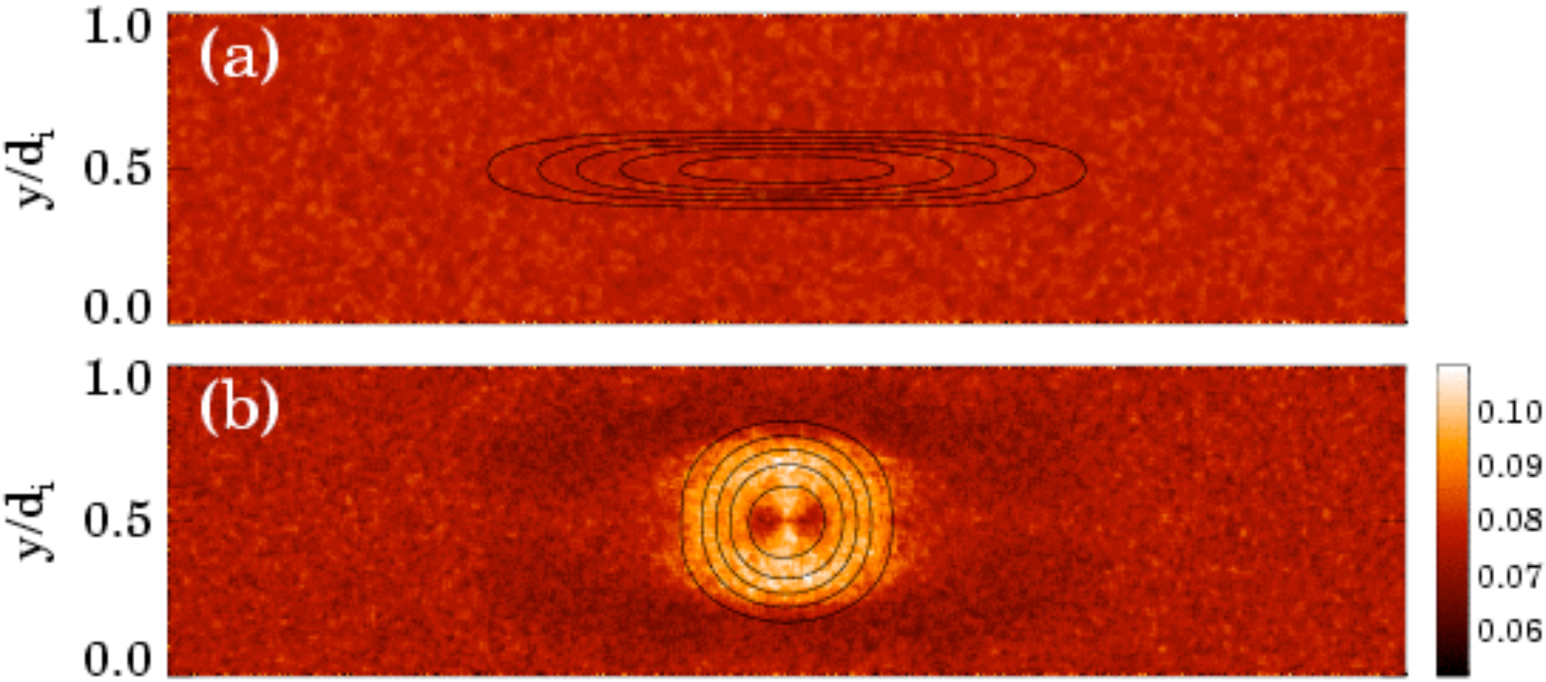


- Electrons follow field lines and drift outwards due to E×B drift
  - Eventually exit the magnetic island
- Gain energy during each reflection from contracting island
  - Increase in the parallel velocity

PIC Simulations of island contraction

- Separating electron heating due to the Fermi mechanism from heating due to $E_{||}$ during reconnection is challenging
  - Study the contraction of an isolated, flattened flux bundle (m_i/m_e=1836)
  - $E_{||}$=0

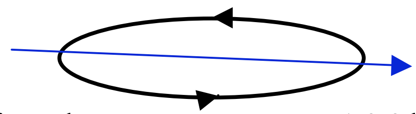
$T_{||}$



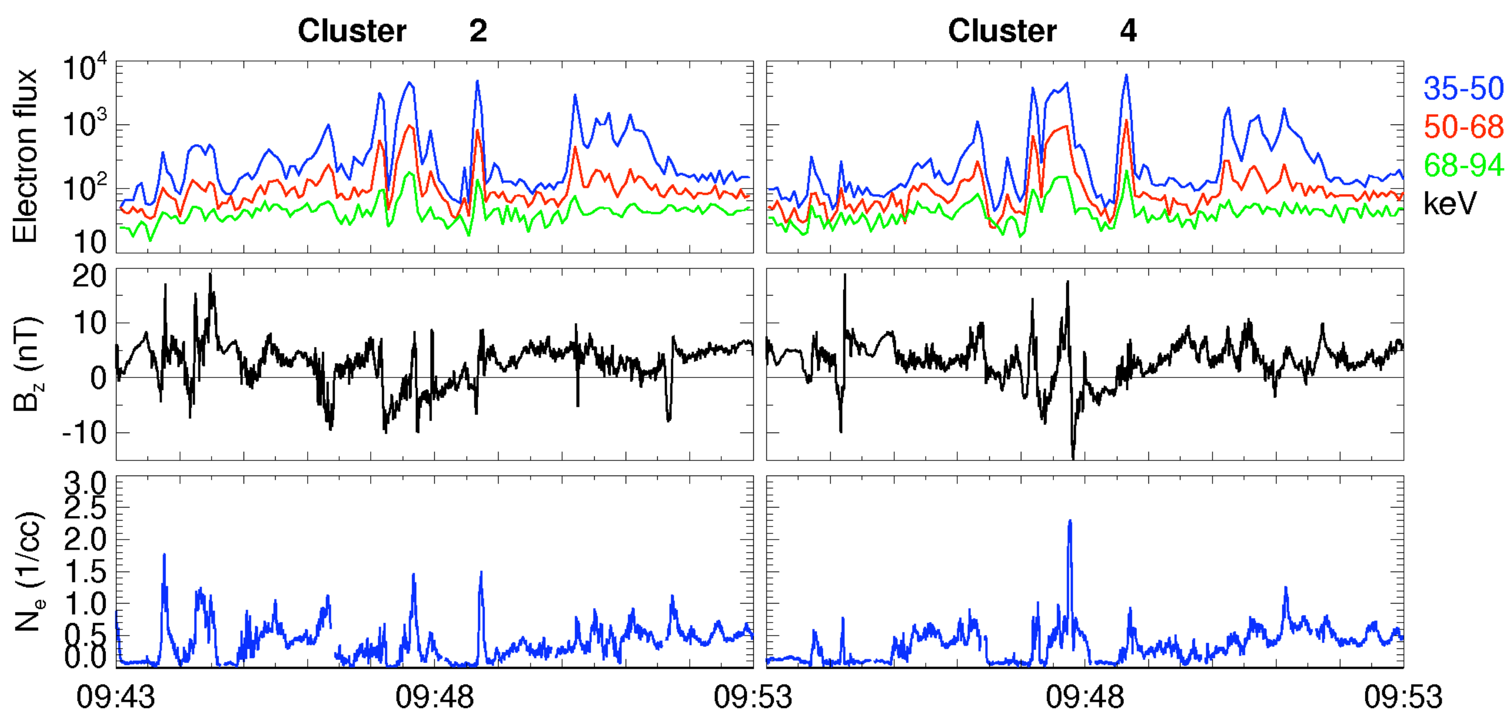
- Strong increase in $T_{||}$ inside the bundle during contraction
- 60% of released energy goes into electrons

Observational evidence for energetic electrons in magnetic islands

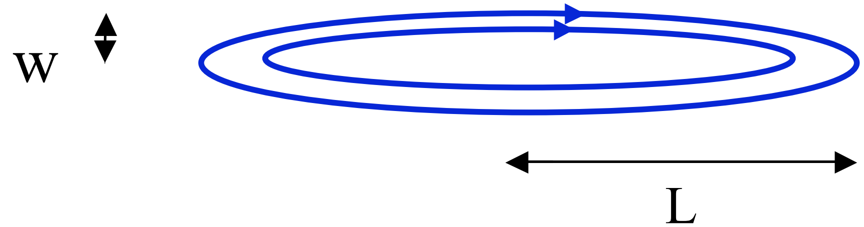
- Cluster magnetotail data during substorms (Chen, et al., 2007)
- Bipolar B_z and density peaks are signatures of magnetic islands



- Enhancement of energetic electrons up to 100keV within islands in the Cluster data



Linking energy gain to magnetic energy released



- Basic conservation laws
  - Magnetic flux ⇒BW = const.
  - Area ⇒WL = const.
  - Electron action ⇒VL = const.
- Magnetic energy change with ΔL

$$\Delta W_B = \frac{B^2}{4\pi}\frac{\Delta L}{L} < 0$$

  - Island contraction is how energy is released during reconnection
- Particle energy change with ΔL

$$\Delta\varepsilon = -\varepsilon\frac{\Delta L}{L} > 0$$

- Island contraction stops when
  - Marginal firehose condition

$$\varepsilon \sim \frac{B^2}{4\pi} \Rightarrow \beta_{\parallel} \sim 1$$

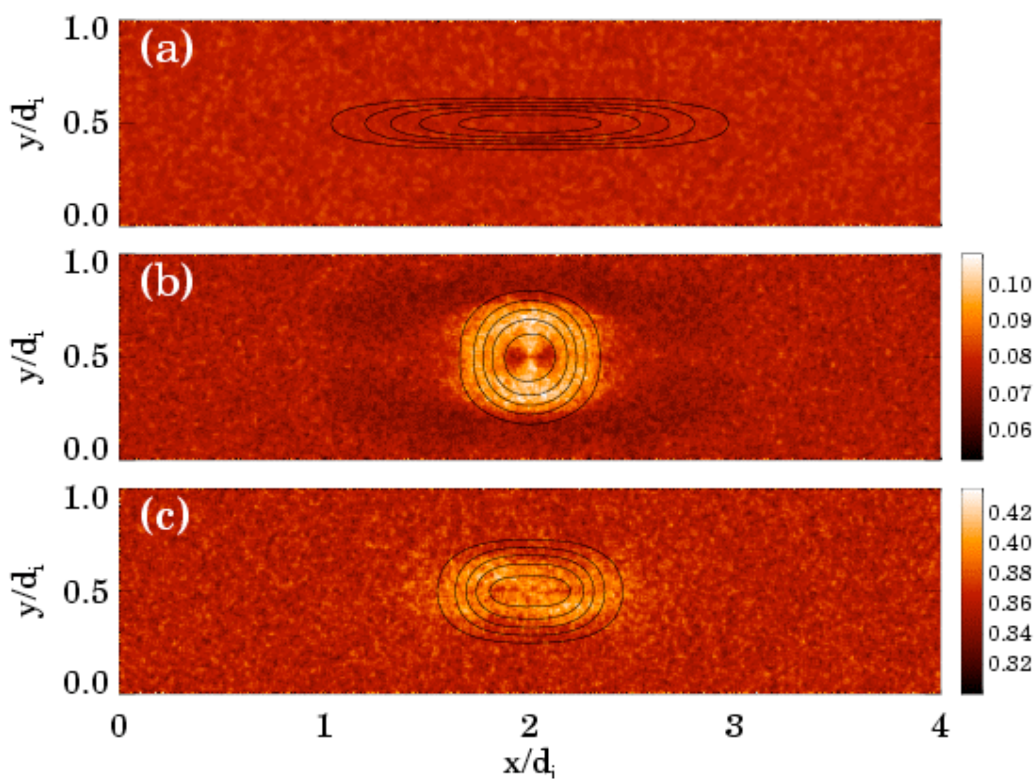
- Energetic electron energy rises until it is comparable to the released magnetic energy

Suppression of island contraction by energetic particle pressure

- Explore the impact of the initial β on the contraction of an initially elongated island
- With low initial β island becomes round at late time
- Increase in $p_{||}$ during contraction acts to inhibit island contraction when the initial β is high ⇒ contraction stops at firehose marginal stability

$\beta = 0.3$

$\beta = 1.2$



Key results

- Steady state kinetic equation for electrons

$$\vec{\nabla} \bullet \vec{u} f - \vec{\nabla} \bullet \kappa(v) \vec{\nabla} f = \frac{1}{3} A \left(1 - \frac{8\pi W}{3B^2}\right)^{1/2} \frac{dc_{Ax}}{dy} \frac{\partial}{\partial v} v f$$

- Electron energy gain linked to release of magnetic energy
- Powerlaw distributions of energetic electrons with spectral indices that depend on the incoming plasma β

–For Wind observations in magnetotail

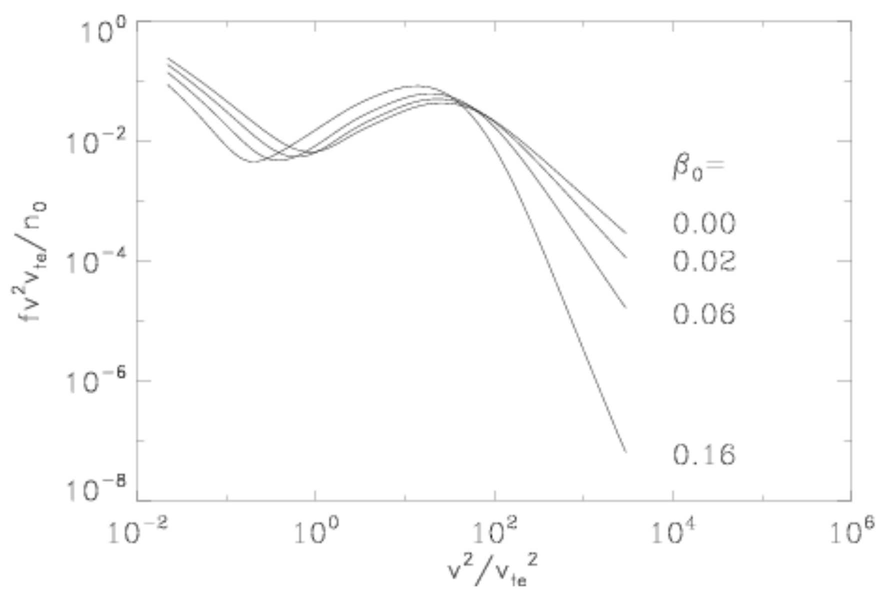
$f \sim v^2 F \sim E^{-3.6}$

–For the solar corona

$f \sim v^2 F \sim E^{-1.5}$

$F \sim v^{-5}$

- Universal spectrum for low β_0
- Consequence of firehose marginal stability



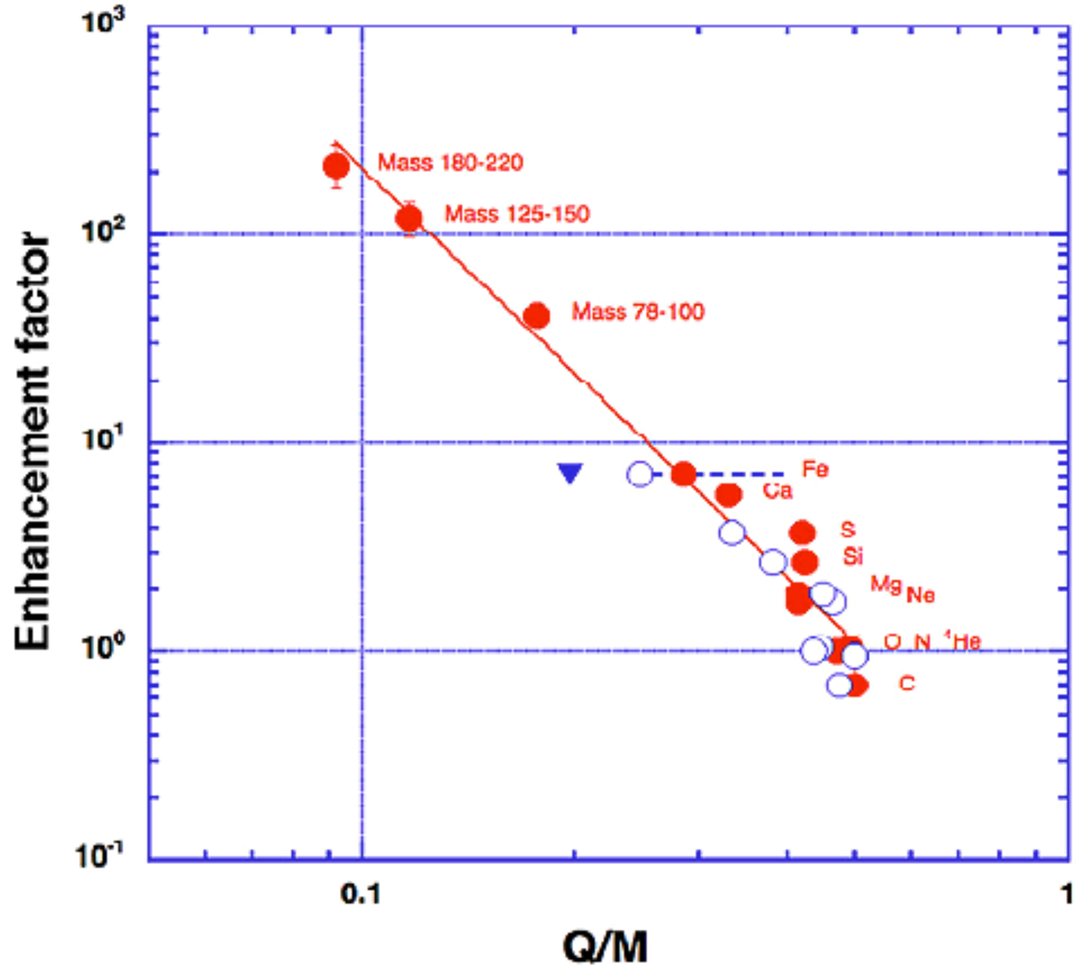
Ion acceleration in flares

- Ions gain significant energy through large-scale Alfvenic flows
  - Does not facilitate the production of particles in the 100MeV to GeV range in the corona $\Rightarrow$ energy gain is reversible
- Parallel electric fields are inefficient accelerators of ions
- Fermi contraction mechanism requires super-Alfvenic ions
  - Need seed mechanism
- What is the mechanism for the abundance enhancement of high M/Q ions in impulsive flares?

Impulsive flare energetic ion abundance enhancement

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

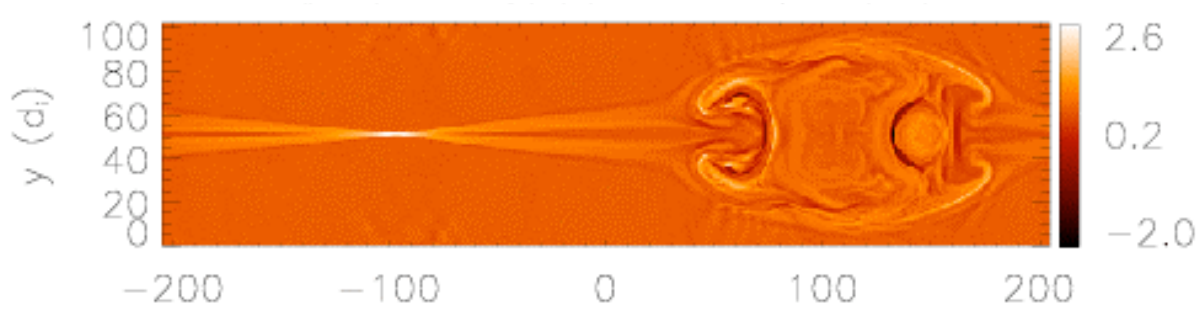
$$\propto \left(\frac{Q}{M}\right)^{-3.26}$$



Mason, 2007

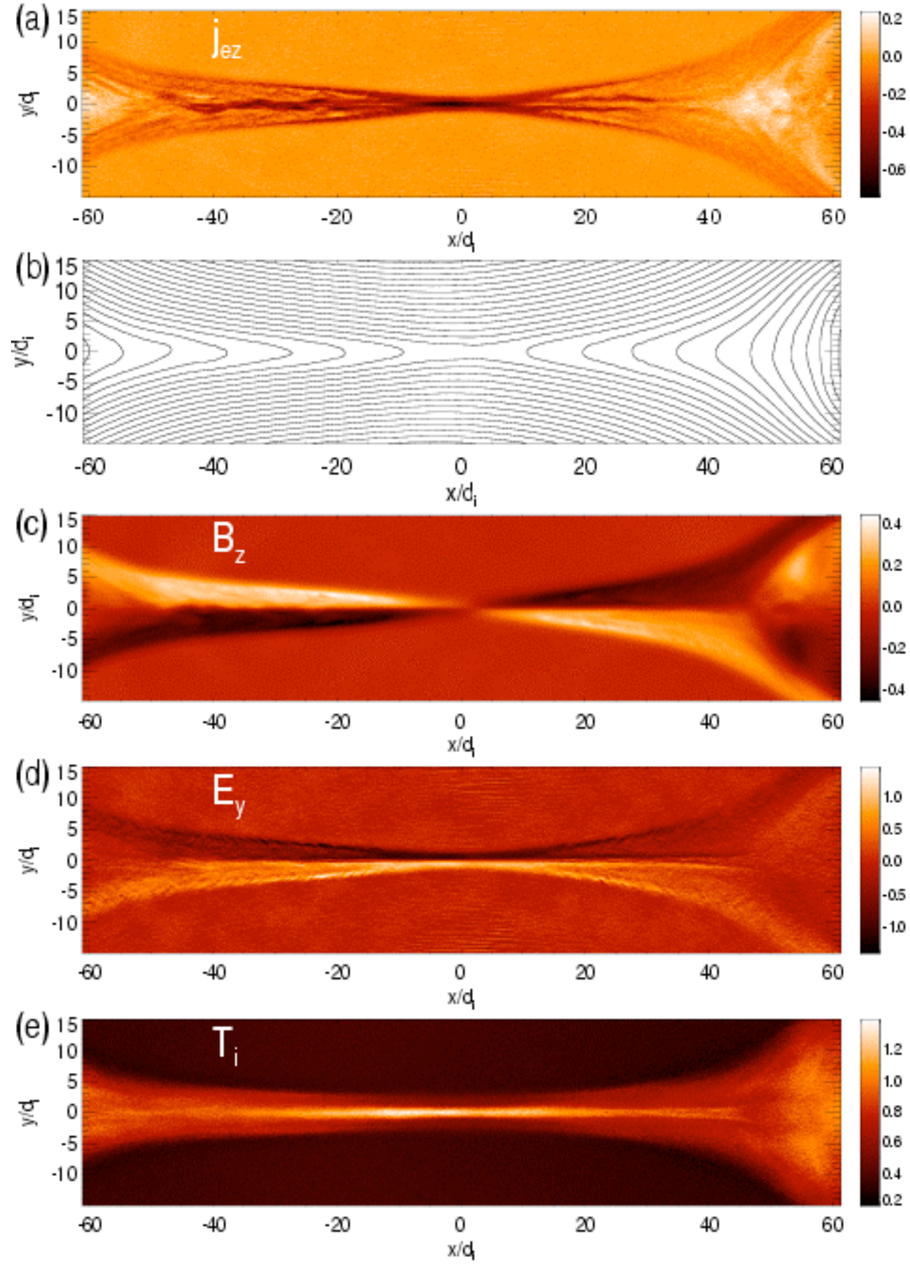
Seeding super-Alfvenic ions through pickup in reconnection exhausts

- 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 c_A
    - The result is roughly energy proportional to mass (Fujimoto and Nakamura, 1994)

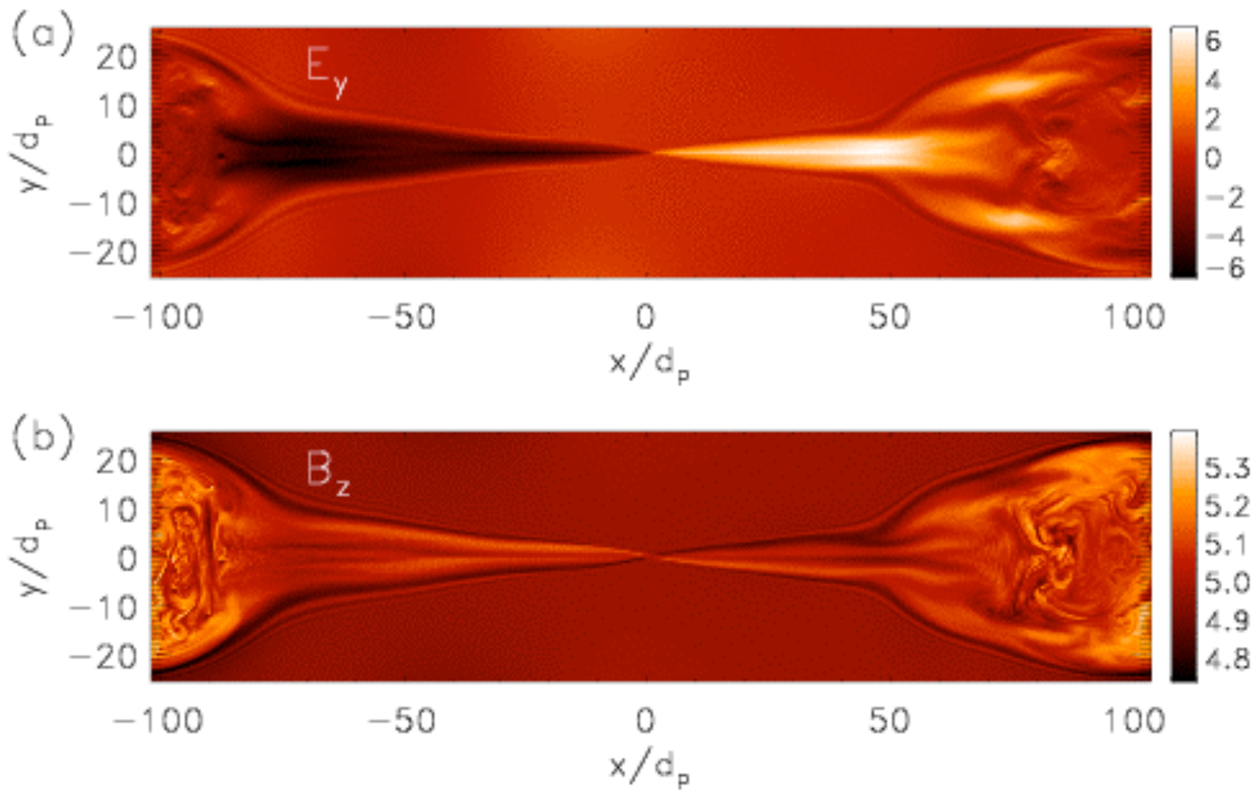


Ion acceleration during reconnection

- PIC simulation with $m_i/m_e=25$
- Focus on ion heating well downstream of the x-line?
- Sharp increase of T_i in the exhaust



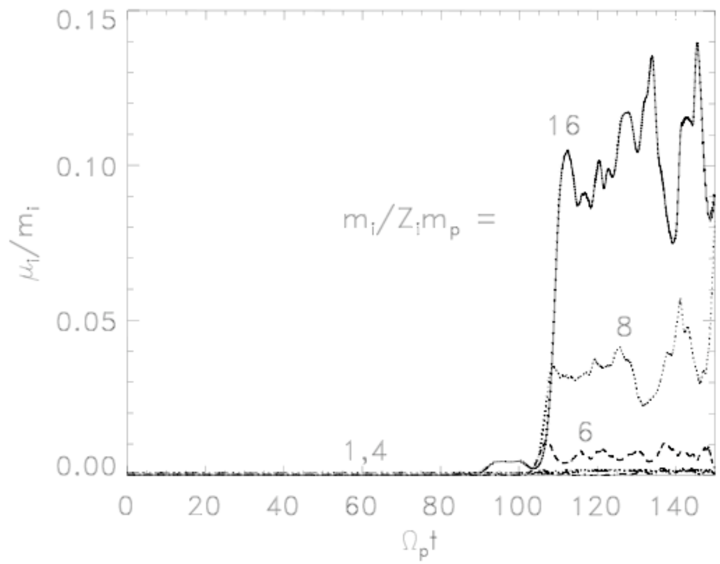
Ion acceleration with a guide field

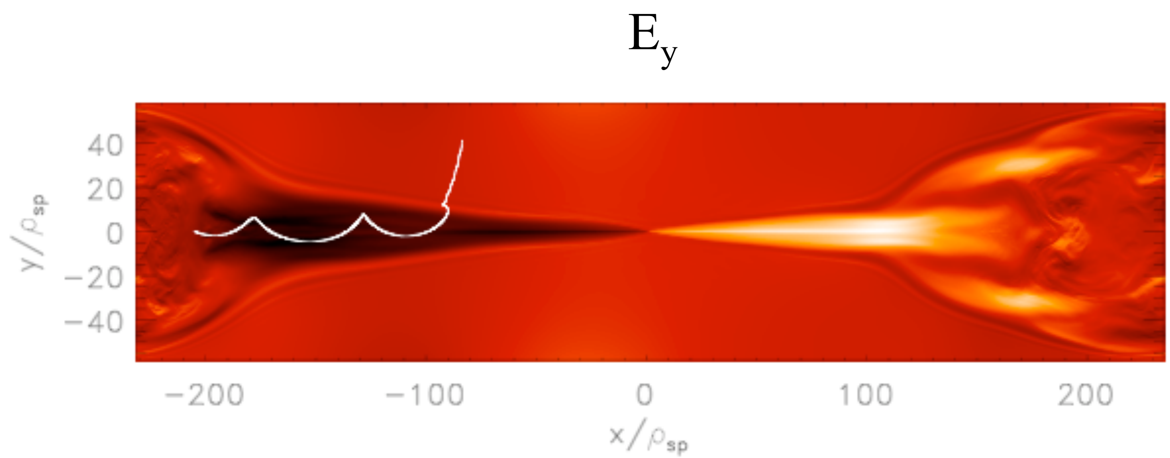


- A narrow boundary layer bounds the outflow exhaust
  - Large E_y drives the outflow ($cE_y/B_z=c_{Ax}$)
- Large guide field can magnetize the protons
  - μ conserved for protons

$B_{z0} = 5.0$

Test particles in Hall MHD reconnection fields





$B_{z0} = 5.0$

- Protons and alpha particles remain adiabatic (μ is conserved)
  - Only mass 6 and above behave like pickup particles
    ⇒ because of large guide field
- For large mass ions

$$\Delta T_i \simeq \frac{1}{3} m_i c_{Ax}^2$$

- Ion energy gain
  - Irreversible portion

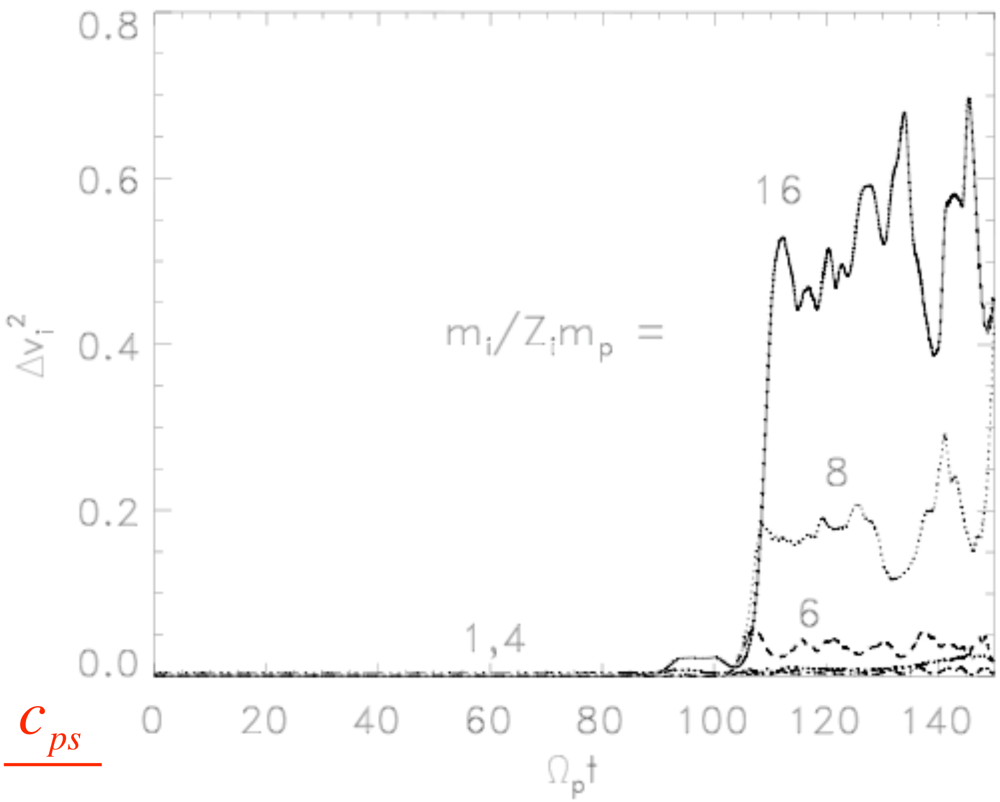
$$\Delta\vec{v}_i = \vec{v}_i - \vec{v}_{E\times B}$$

- The ions that act like pickup particles -- those with high M/Q -- gain much more energy
- What is the threshold for acting like a pickup particle?

$$\frac{v_{iy}}{\Delta} \approx \frac{0.1c_{Apx}}{\rho_{sp}} > \Omega_i \Rightarrow \frac{m_i}{Z_i m_p} > 10\frac{c_{ps}}{c_{Apx}}$$

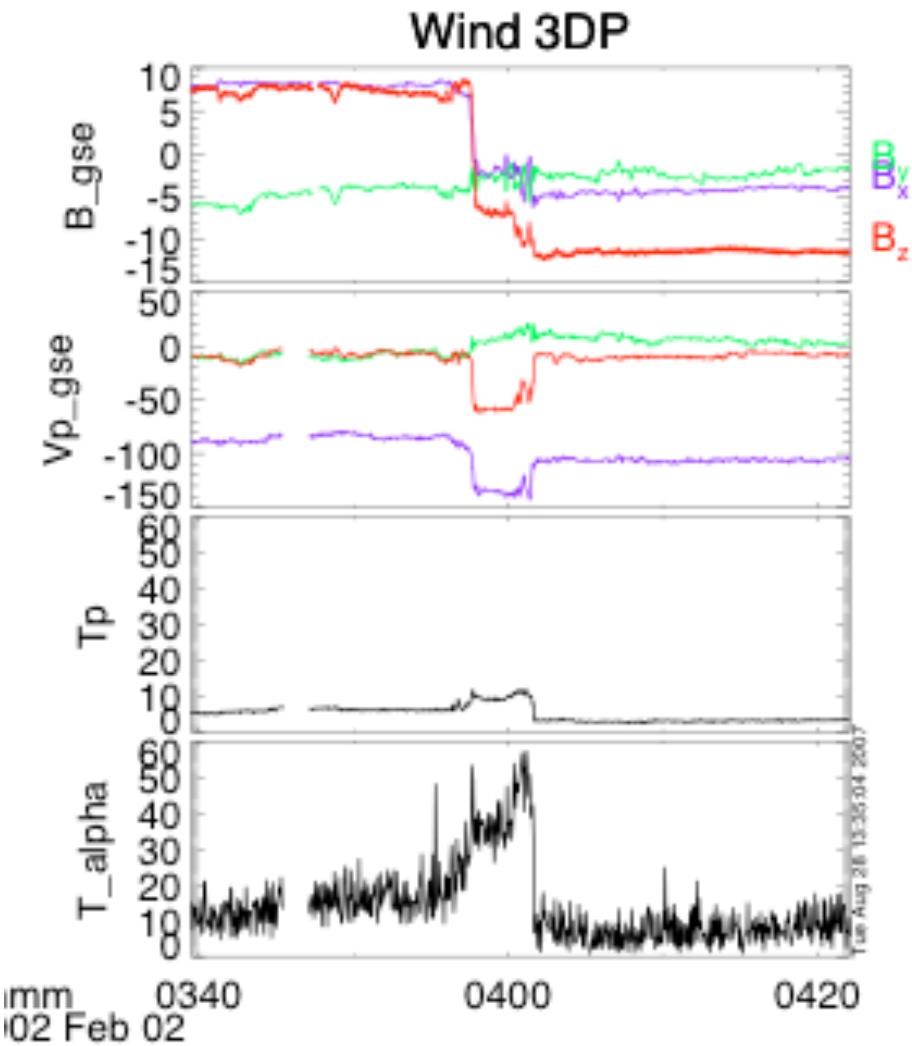
- For coronal parameters ($n \sim 3\times10^9/cm^3$, $T \sim 3\times 10^6$ °K) proton threshold is 60G

Ion energy gain



Only ions that act like pickup particles gain significant energy

Wind observations of solar wind exhaust



- $300R_E$ event (Phan et al., 2006)
- Exhaust velocity ~ 70km/s
- ΔT_p ~ 9eV (measured ~ 7eV)
- ΔT_α ~ 36eV (measured ~ 30eV)

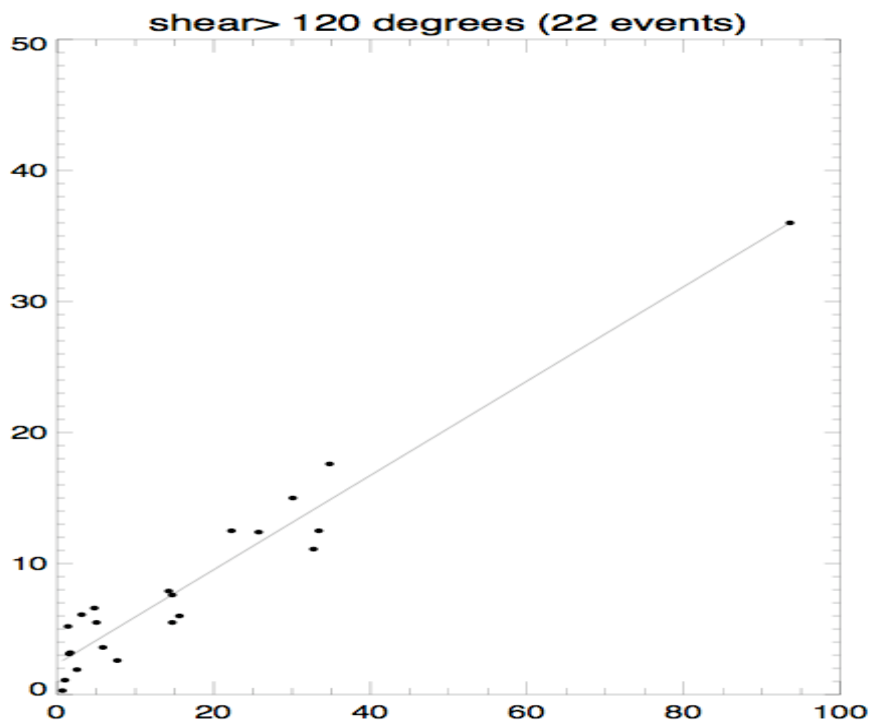
$$\frac{\Delta T_\alpha}{\Delta T_p} = \frac{m_\alpha}{m_p}$$

Wind solar wind exhaust data

- Data from 22 solar wind reconnection exhaust encounters
- Proton temperature increase in exhaust is given by

$$3\Delta T_p \simeq 0.39 m_p \Delta v^2$$

$3\Delta T_p$(eV)



$m_p\Delta v^2$(eV)

Production of energetic ions during flares

- Ions are seeded to super-Alfvenic velocities through interaction with reconnection exhausts
- Once the ions are super-Alfvenic the Fermi island contraction mechanism also acts on ions
  - Produces v^{-5} ($E^{-1.5}$) distribution as for electrons?
  - Are the v^{-5} distributions seen by the Fisk/Gloeckler in the solar wind related related?
- What about abundance enhancements of high M/Q ions?
  - Linked to the threshold for pickup behavior

Abundance enhancements in impulsive flares

- Ion pickup criterion can be rephrased as a threshold on magnetic island width w_c.

$$\frac{m_i}{Z_i m_p} > 10 \frac{c_{sp}}{c_{Axp}} \qquad c_{Axp} \simeq c'_{Axp} w_c > 10 c_{sp} \left(\frac{Z_i m_p}{m_i} \right)$$

  – Higher M/Q ions have lower island width thresholds

- Rate of production of pickup ions

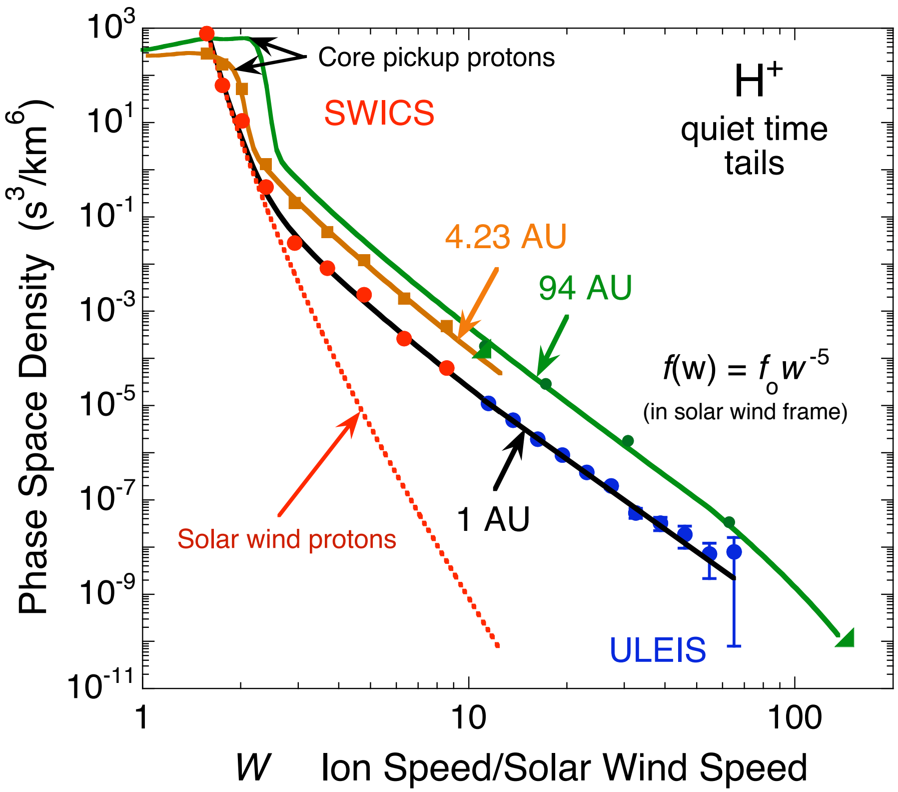
$$\frac{dN_i}{dt} \sim \sum_{w > w_c} 0.1 c_{Ax} L_w \sim \sum_{w > w_c} w^2 \sim \int_{w_c}^{\infty} dw w^2 P(w)$$

  – Take powerlaw distribution of island widths: $P(w) \sim w^{-\alpha}$

$$\frac{dN_i}{dt} \sim w_c^{3-\alpha} \sim \left(\frac{Z_i m_p}{m_i} \right)^{3-\alpha}$$

  – Match the observations if $\alpha \sim 6.26 \Rightarrow$ reasonable

Universal ion spectrum in the quiet solar wind



Gloeckler et al, 2006

- Proton spectra of the form $f \propto v^{-5}$ are often observed
- Similarity to spectra from the Fermi mechanism is striking

Conclusions

- Coupling to dispersive waves at small spatial scales facilitates fast magnetic reconnection in large systems at rates that are insensitive to dissipation
- Reconnection is bistable for a huge range of resistivity (a factor of 10^6 in the case of the solar corona)
  - A slow Sweet-Parker and fast Hall reconnection solutions exist for the same parameters
  - Below a critical resistivity the slow solution disappears causing an increase in the rate of reconnection by six orders of magnitude
    - ⇒Reconnection occurs as an explosion
- Stellar coronae may be in a state of self-organized criticality at the boundary defining the onset of fast reconnection

Conclusions (cont.)

- High energy particle production during magnetic reconnection involves the interaction with many magnetic islands
  - Not a single x-line
- Acceleration of high energy electrons is controlled by a Fermi process within contracting magnetic islands
- Particle distributions of energetic electrons take the form of powerlaws
  - Low initial pressure as in the solar corona yields harder spectra than in the magnetosphere
  - Universal spectrum with a spectral index of 1.5
- Electrons gain is linked to the energy released during magnetic reconnection

Conclusions (cont.)

- Ion interaction with the reconnection exhaust seeds them to super-Alfvenic velocities.
  - Ions that act as pickup particles as they enter reconnection exhausts gain most energy
    - M/Q threshold for pickup behavior
    - Gain a thermal velocity given by the Alfven speed
    - Wind and ACE observations support this picture
- Interaction with reconnection exhausts should enable energetic ions to be accelerated through Fermi contraction
  - Possibly leading to the $f \sim v^{-5}$ distributions?

Magnetic Reconnection Simulation