Particle acceleration and the role of anisotropy in multi-island reconnection

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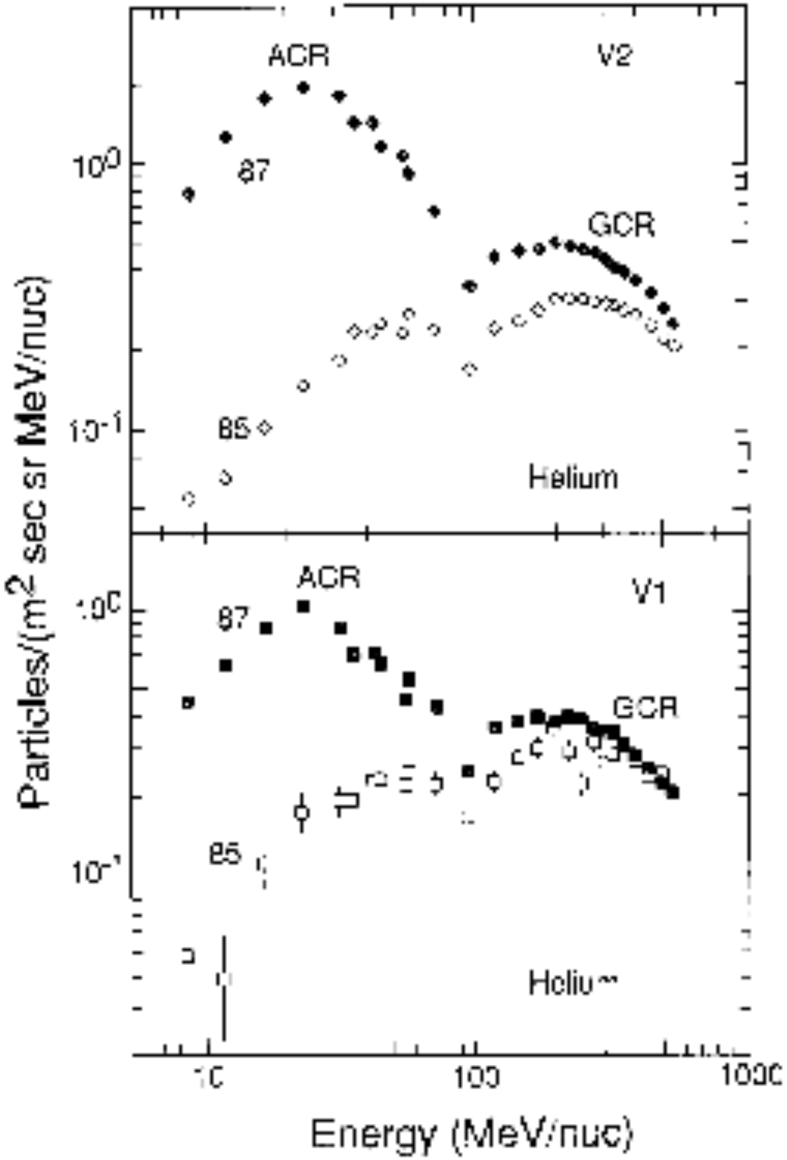
Some energetic particle observations in the heliosphere

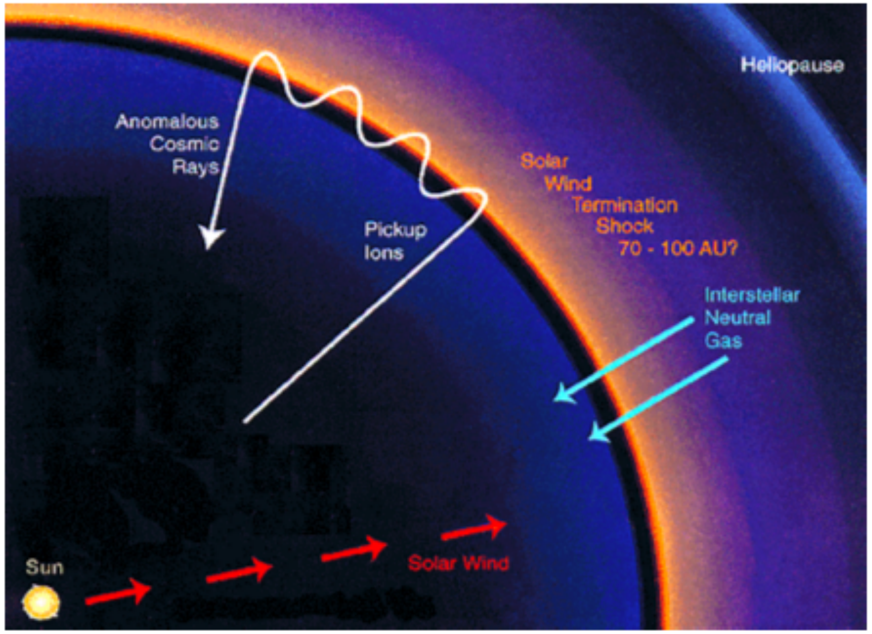
- In solar flares energetic electrons up to MeVs and ions up to GeVs are measured
  - A significant fraction of the released magnetic energy appears in the form of energetic electrons and ions (Lin and Hudson ‘76, Emslie et al ‘05)
    - Must explain such extraordinary efficiency and link particle energy gain to magnetic energy release
    - The energetic electron beta can approach unity in over-the-limb observations (Krucker et al 2010)
    - Correlation between > 300keV energetic electrons and > 30 MeV ions (Shih et al 2009)
      - Common acceleration mechanism?
- Is magnetic reconnection the source of Anomalous Cosmic Rays (ACRs)?
  - Interstellar neutrals are picked up in the solar wind, transported to the outer heliosphere and are accelerated up to 100MeV/nucleon in the heliosheath.
  - Is reconnection of the sectored heliospheric magnetic field the driver?

Anomalous Cosmic Rays (ACRs)

- 10-100MeV/nucleon particles
  - Energies just below those of galactic cosmic rays
- Voyager observations of He seen in 1985 and 1987 (Christian et al 1988)
  - Higher fluxes of ACRs with increasing distance from the sun



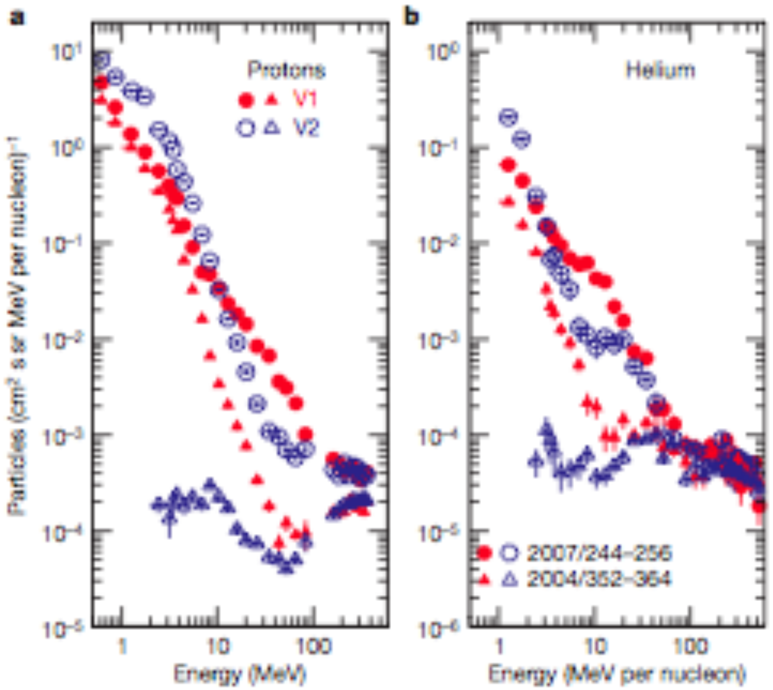
The classical model: acceleration of ACRs at the termination shock

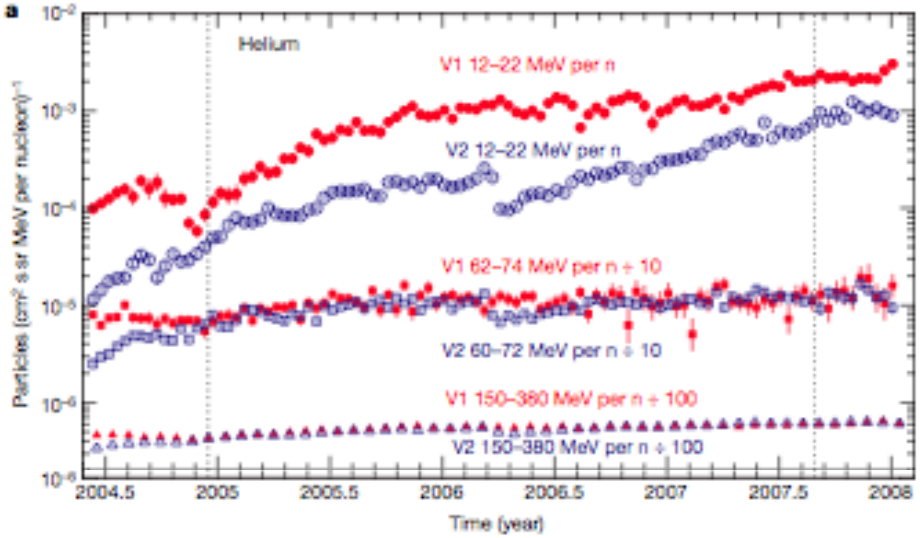


- The LISM neutrals are ionized and picked up deep within the heliosphere $T_i \sim m_i V_{sw}^2$
  - LISM pickup ions dominate the pressure in the outer heliosphere
- Carried by the solar wind out to the termination shock (TS) where they undergo diffusive shock acceleration (Fisk et al ‘74; Pesses et al ‘81)
  - LISM particles dominate the ACRs because they start with much higher energy than the solar wind ions

The source of ACRs

- The Voyager 1 & 2 spacecraft observations revealed that the ACRs do not peak at the TS but continue to increase in intensity as the spacecraft move further into the heliosheath
  - The local TS was not the source of the ACRs.



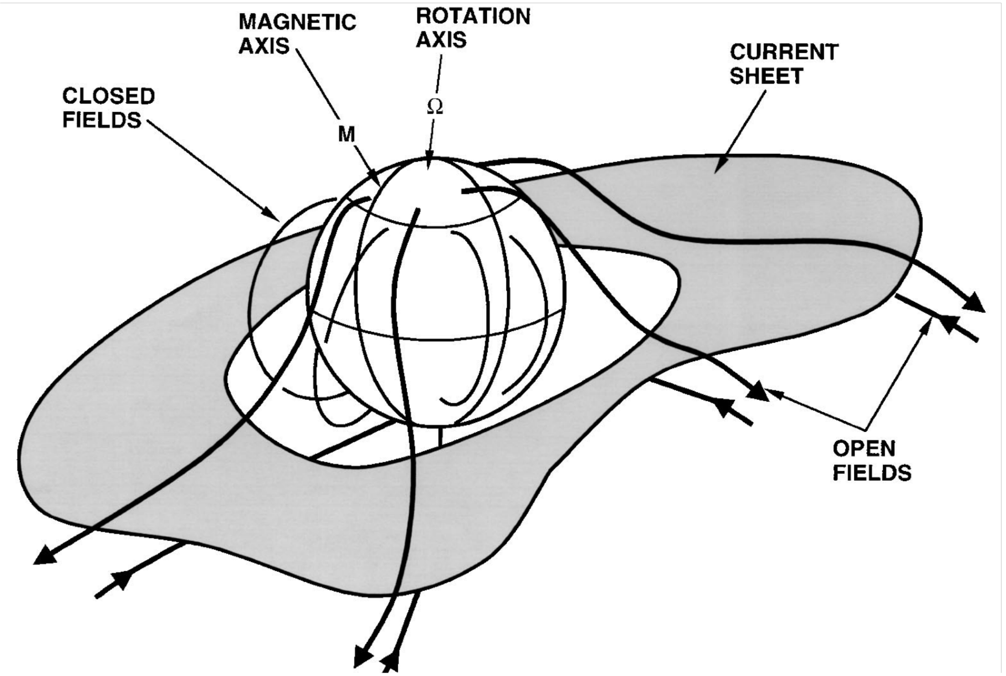


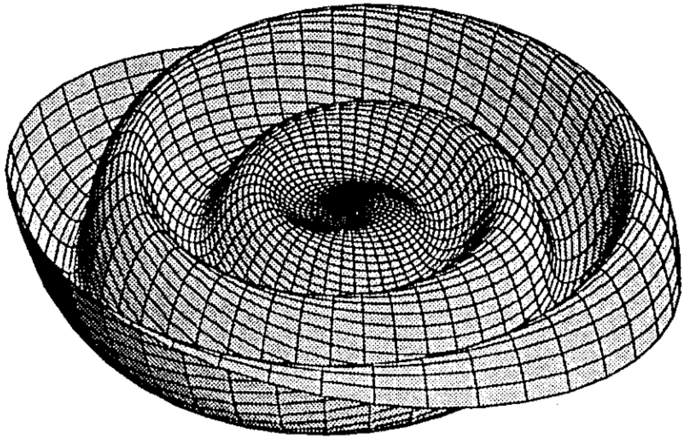
A reconnection model of the ACRs

- The tilt of the solar magnetic field with respect to solar rotation axis causes the heliospheric magnetic field to develop a sector structure in which the dominant azimuthal magnetic field periodically reverses sign with increasing distance from the sun
- The sectors compress downstream of the TS and continue to compress as they approach the heliopause (HP)
- Eventually the current sheet compresses sufficiently to trigger the onset of collisionless magnetic reconnection
  - The heliospheric current sheet is typically stable upstream of the TS because it is much wider than the ion inertial scale ~ 100 c/ω_{pi}
- Magnetic reconnection of the sectors dissipates most of the energy of the sectored field
- The LISM pickup particles gain most of the released energy
  - They initially have the highest energy
  - The acceleration mechanism is through Fermi reflection in contracting magnetic islands -- a first order Fermi process and therefore very efficient
  - Powerlaw spectra match the Voyager observations with no fudge factors

Sector structure of the heliospheric field

- The Parker spiral field (dominantly B_ϕ) produces the heliospheric current sheet
- Misalignment of the magnetic and rotation axes causes the current sheet to flap



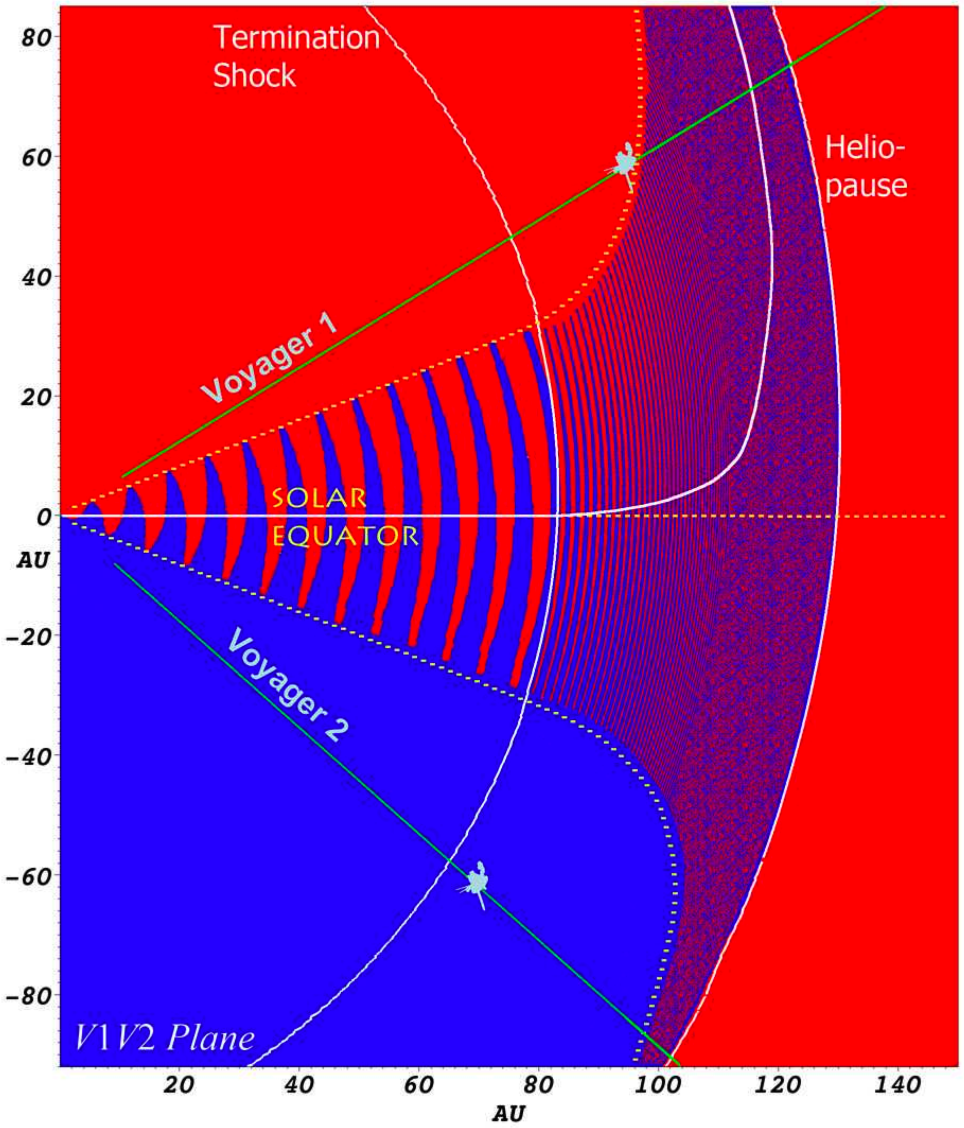


Heliospheric current sheet

Sector structure of the outer heliosphere

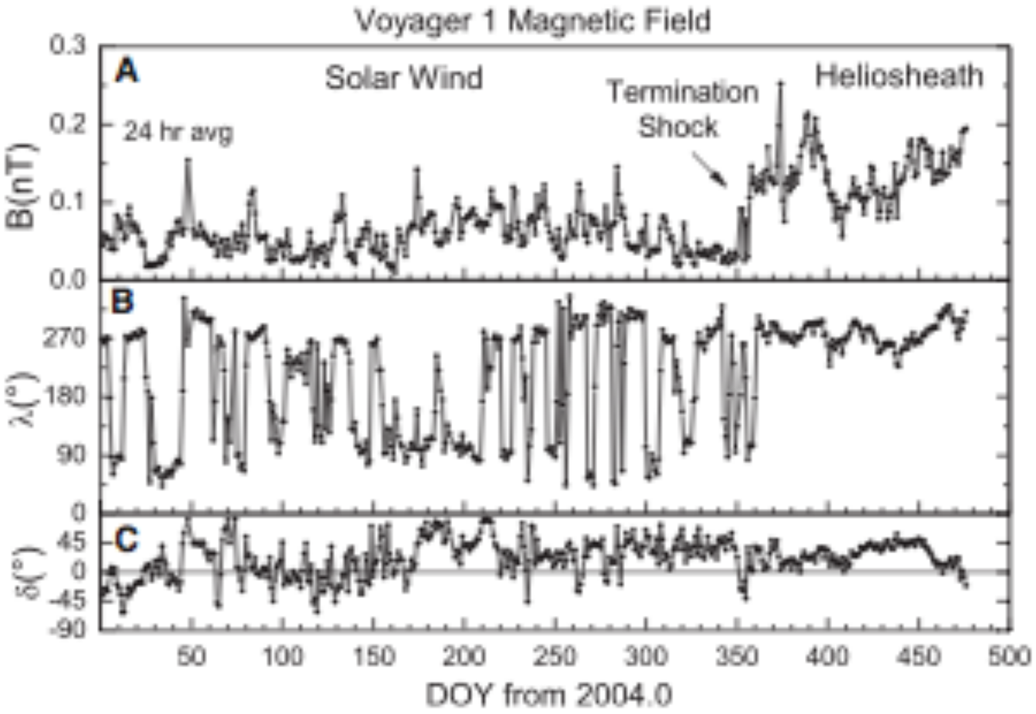
- MHD results from Borovikov and Pogorelov (BP)
- Voyager trajectories are within the sectored region

B_φ



Sector structure of the heliospheric field seen by Voyager 1

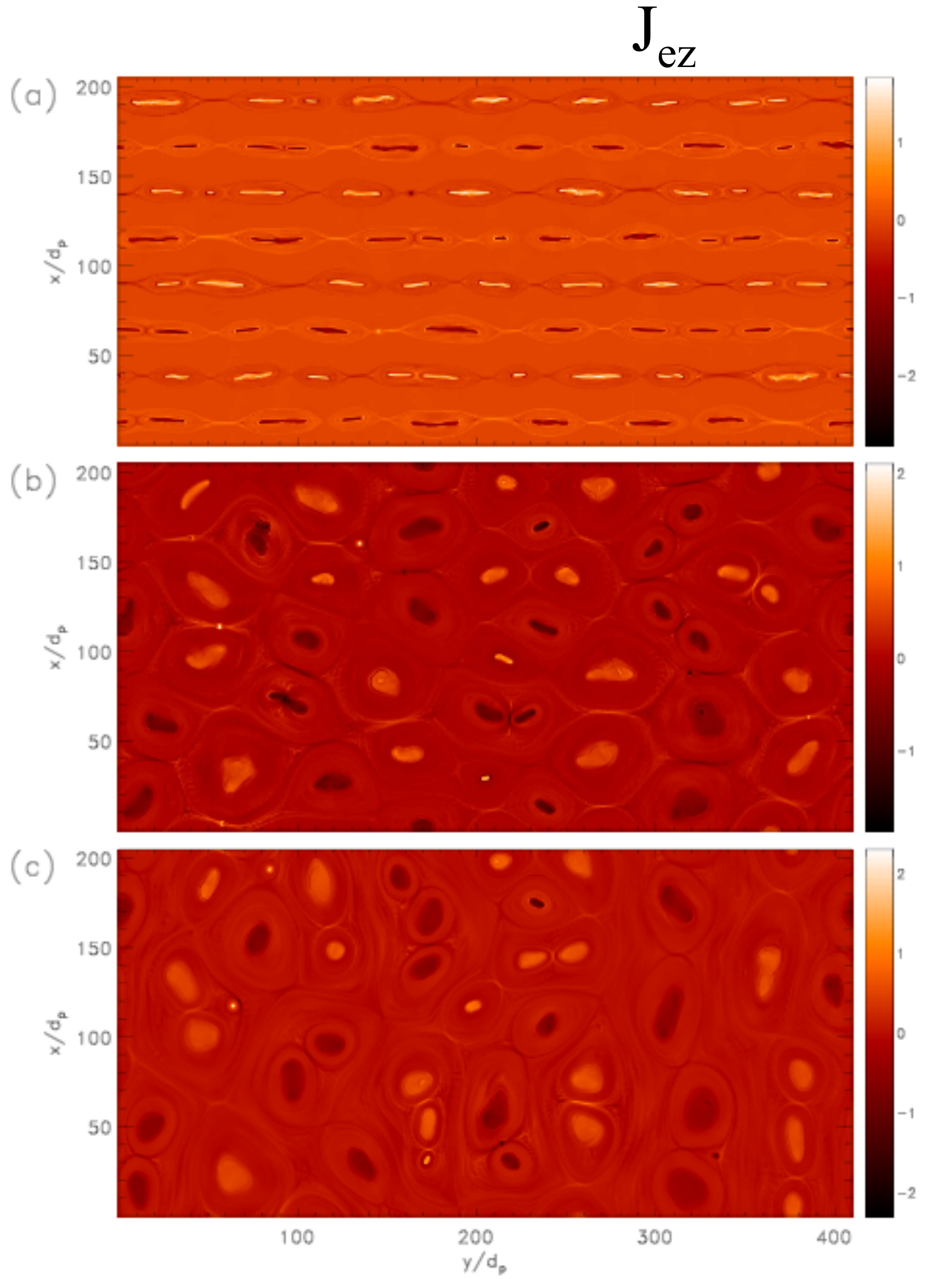
- The flapping current sheet produces a sectored magnetic field
  - Periodic reversal of B_ϕ



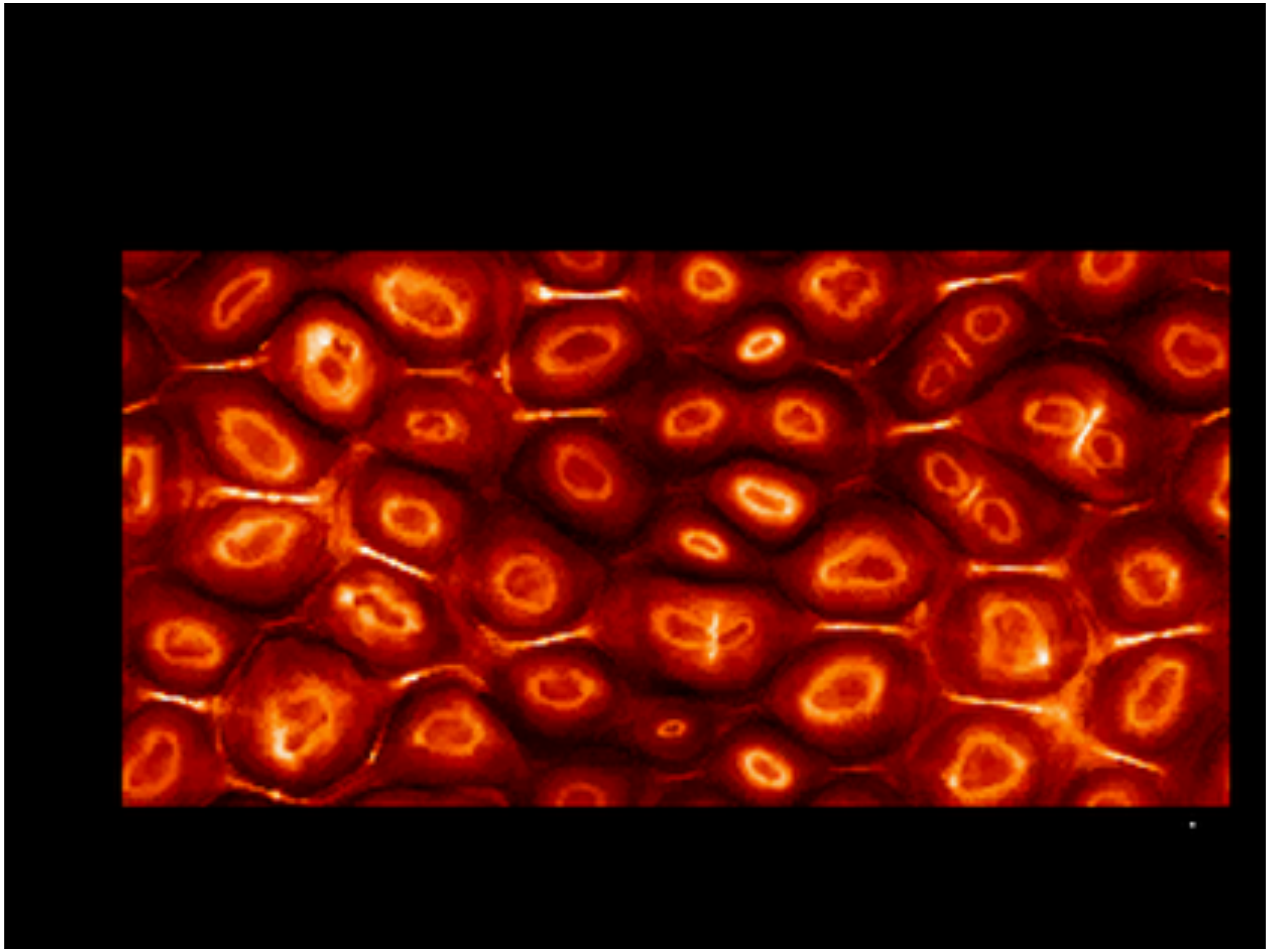
Burlaga et al 2005

Collisionless reconnection of the sectored heliospheric field

- The sectored field is stable to reconnection upstream of the TS because the width of the current sheet is much wider than the ion inertial length $\sim 100\ c/\omega_{pi}$.
  - Collisionless reconnection is very weak
- The current layers compress on their approach to the heliopause
  - This is well documented in the case of the Earth's magnetosphere
  - Inevitably have the onset of collisionless reconnection
  - Dissipation of nearly all of the magnetic energy ~ 85%



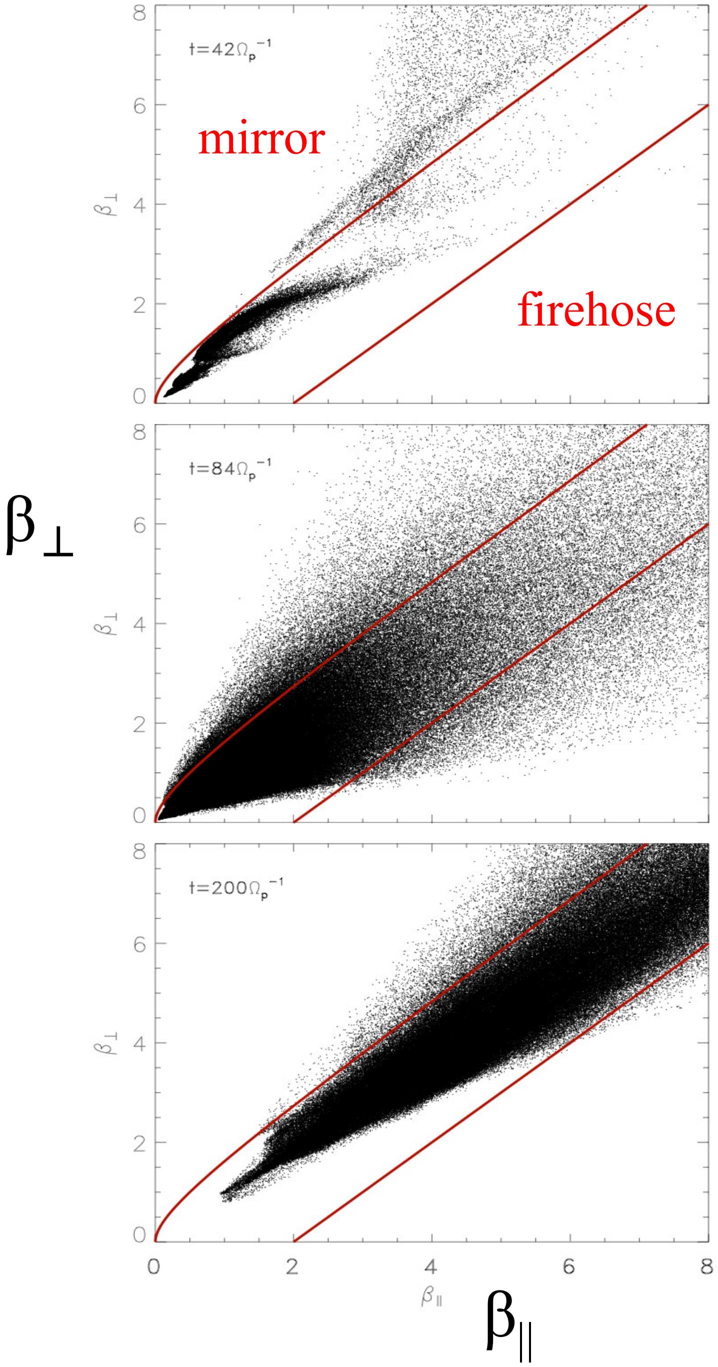
Reconnection dynamics



- First have reconnection on individual current layers
- Then merging of islands on adjacent layers

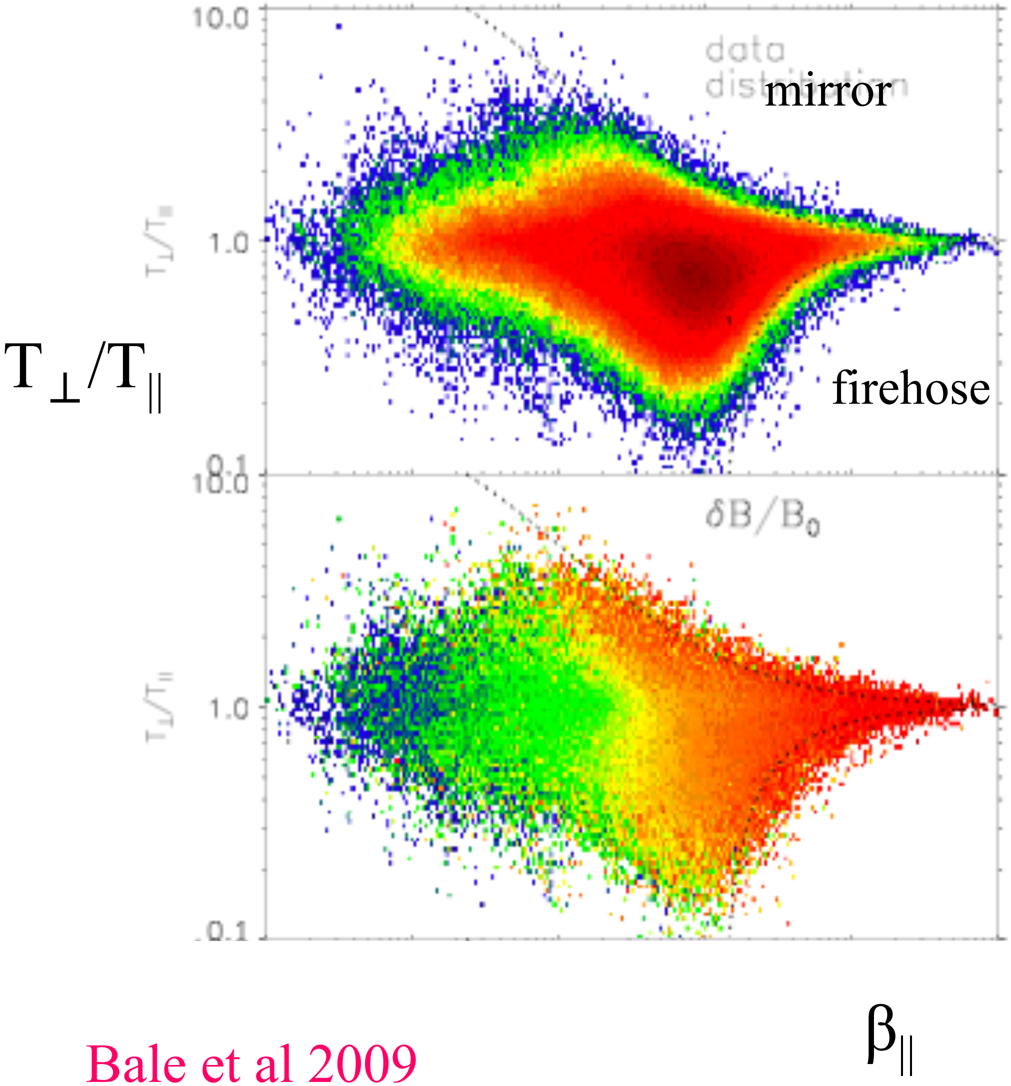
Mirror and firehose conditions

- Data from PIC simulations
  - Each point corresponds to a grid point in the simulation
- As reconnection strongly onsets both the firehose and mirror stability boundaries are violated
- At late time the firehose and mirror conditions act as constraints



Wind data on solar wind turbulence

- Solar wind turbulence bumps against the the firehose and mirror stability boundaries
- Very similar to the reconnection simulations
  - Why does this happen in the case of solar wind turbulence?



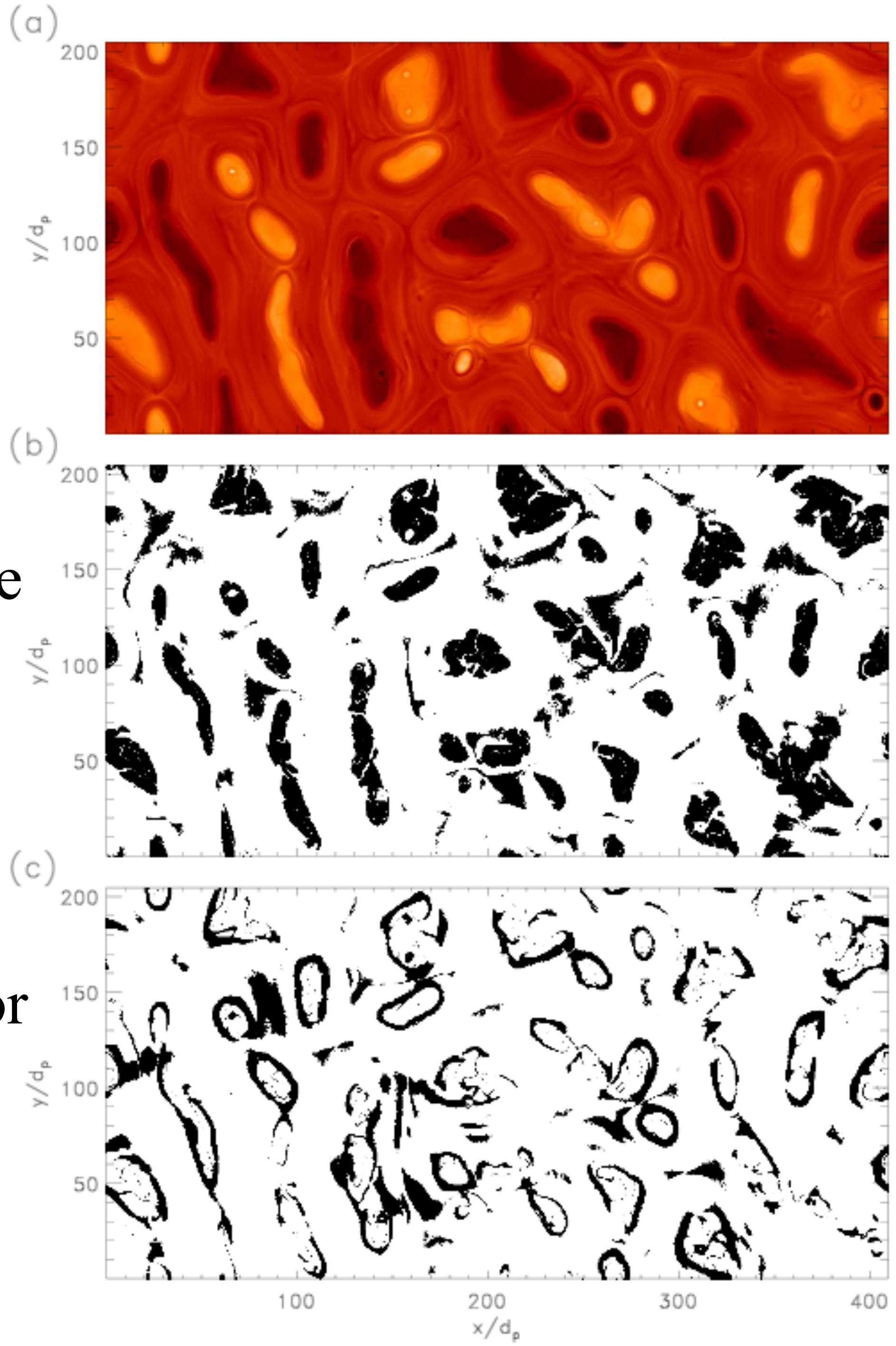
Bale et al 2009

Mirror and firehose conditions

- Within islands bump against the firehose condition
  - This condition limits island contraction
    - No tension in magnetic fields when the firehose condition is violated

$$\omega^2 = k_\parallel^2 c_A^2 \left(1 - \frac{1}{2}\beta_\parallel + \frac{1}{2}\beta_\perp\right)$$

    - Note the abnormally long islands compared with early time
  - Controls particle spectra
- In current layers and along separatrices bump against mirror mode limit
- Self-consistency is crucial in exploring particle acceleration



firehose

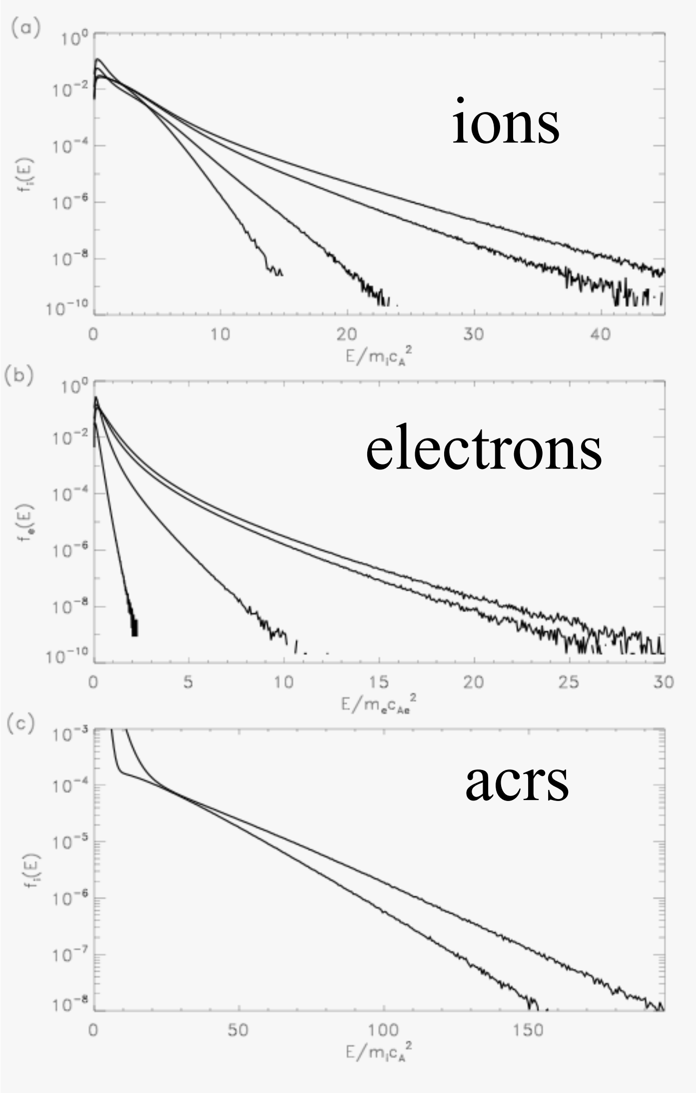
mirror

Electron and ion energy spectra

- Both ions and electrons gain energy
- Include 5% population of pickup particles to simulate the production of ACRs
  - These particles are super-Alfvenic in the initial state
- A key feature is that the rate of energy gain of particles increases with energy

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

⇒ first order Fermi

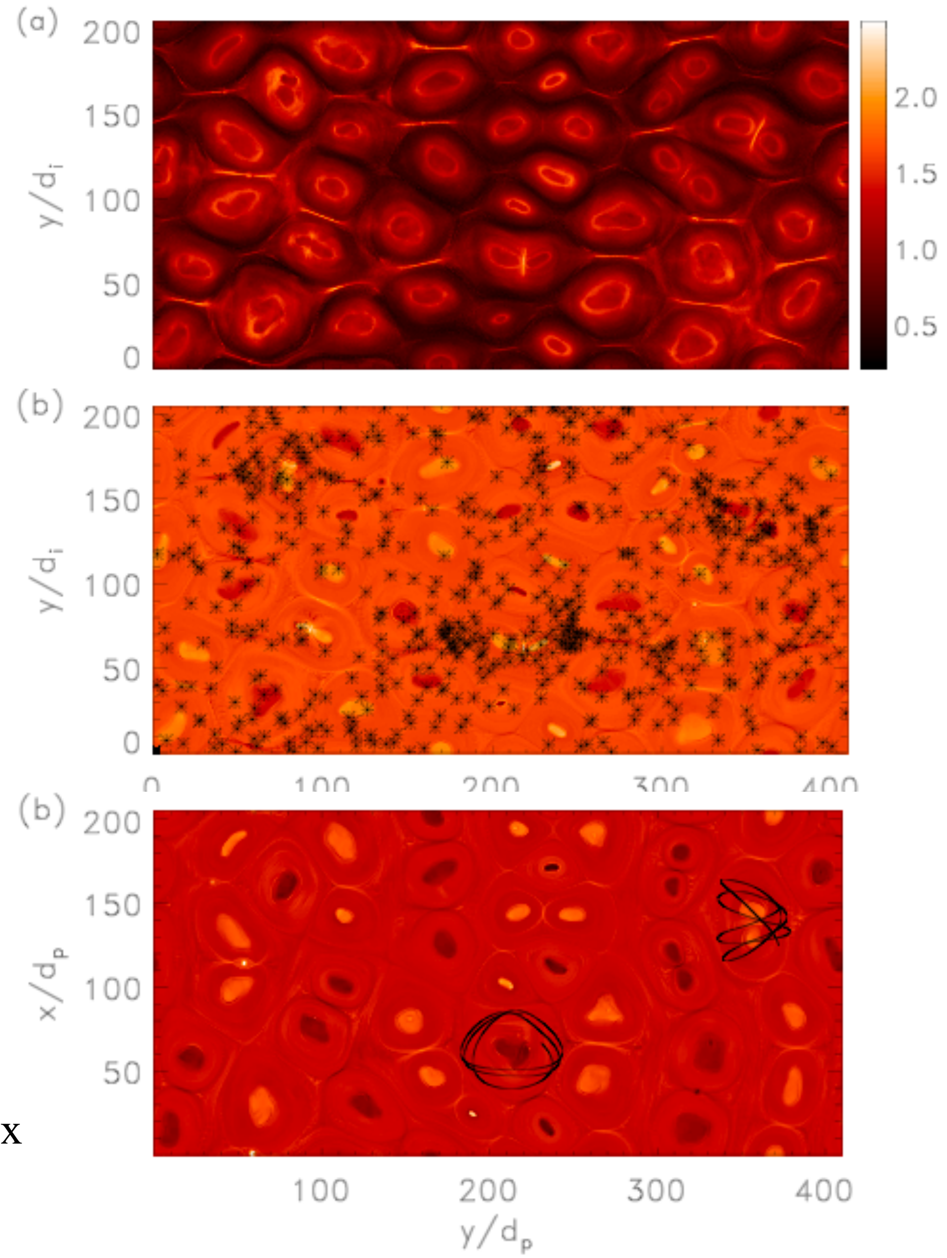


Distribution of most energetic ions

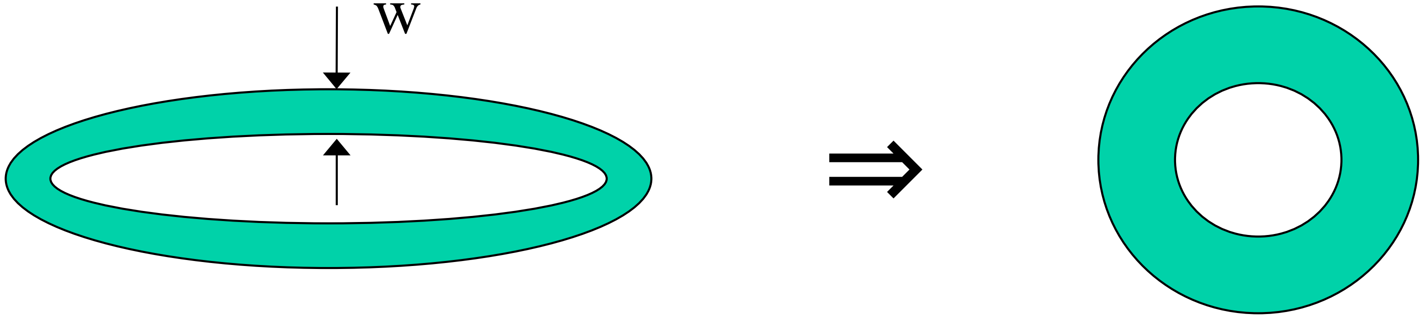
- The most enegetic ions are located in regions of island merging which leads to contraction of a very large island
- The particles circulate in the contracting islands and gain energy as they reflect from the ends of the island
  - Same as mechanism proposed earlier for electrons (Drake et al 2006)
  - A first order Fermi process
  - No seed ion heating mechanism needed since the pickup particles are super-Alfvenic

C_{Ax}

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



Fermi acceleration in contracting islands



- Area of the island Lw is preserved

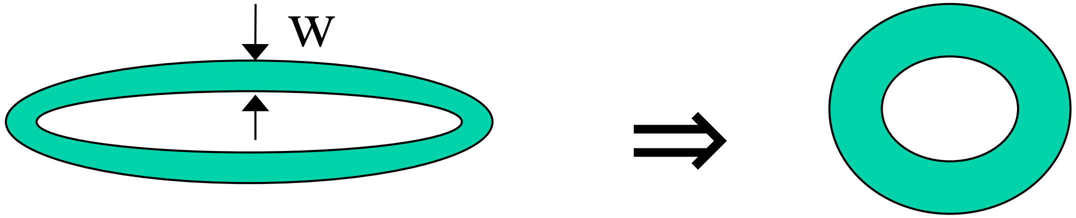
  ⇒ incompressible dynamics

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

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

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

Fermi acceleration in contracting islands



- Area of the island Lw is preserved
- Magnetic flux Bw is preserved $W_B = \frac{B_0^2}{8\pi}\frac{L^2}{L_0^2}$
- Particle conservation laws
  - Magnetic moment $\mu = mv_\perp^2 / B$
  - Parallel action $V_{||}L$
- Energy gain for initially isotropic plasma

$$W_p = \frac{1}{2}mv_0^2\left(\frac{2L}{3L_0} + \frac{L_0^2}{3L^2}\right)$$

  - No energy gain for infinitesimal change in L ⇒ consistent with Parker
  - Significant energy gain for finite contraction
    - Parker equation is missing some important physical processes

Linking magnetic energy release to particle energy gain

- A key flare observation is that energetic particle energy gain is linked to the released magnetic energy. Why?
- Island contraction continues until the firehose marginal stability condition is reached. At this point

$$\frac{dW_B}{dt} + \frac{dW_p}{dt} = 0$$

  - The rate of particle energy gain equals the rate of release of magnetic energy
  - This establishes the key linkage between particle and magnetic energy seen in flares
- Magnetic energy released depends on β_0
  - Low β_0 $\qquad \Delta W_B \sim -W_{B_0}$
  - High β_0 $\qquad \Delta W_B \sim -W_{B_0} / \sqrt{\beta_0}$

1-D Model equations

- Rate of energy gain: first order Fermi

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

Reduction of contraction rate due to firehose condition

- Model equation for the omnidirectional distribution function

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

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

- Above the source energy this is an equidimensional equation

$\Rightarrow$ powerlaw solutions

Distributions and spectral indices

- Exact steady state solutions for F(v)

$$F(v) = (\gamma - 1) v^{-\gamma} \int_0^v ds s^{\gamma - 1} F_0(s)$$

- Spectral index

$$(\gamma - 1)\left(1 - \frac{4\pi p_0}{B^2} \frac{\gamma - 1}{\gamma - 3}\right)^{1/2} = \frac{\tau_h}{\tau_L}$$

- Heliopause limit $\tau_h << \tau_L$ since $L >> L_w$

$$\gamma = 3 + \beta_0$$

⇒ spectral index controlled by marginal firehose condition

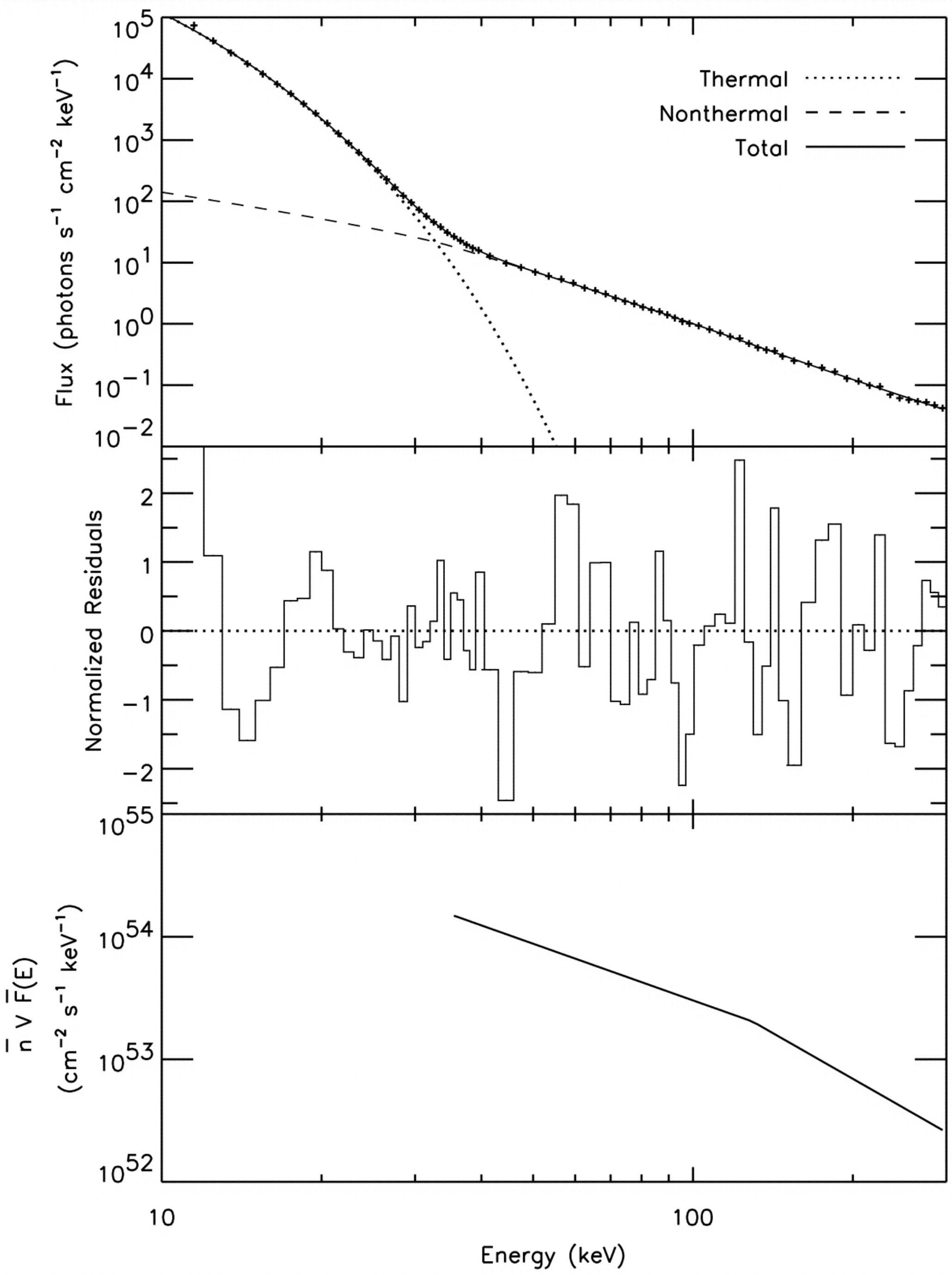
⇒ consistent with spectral indices from Voyager

RHESSI observations

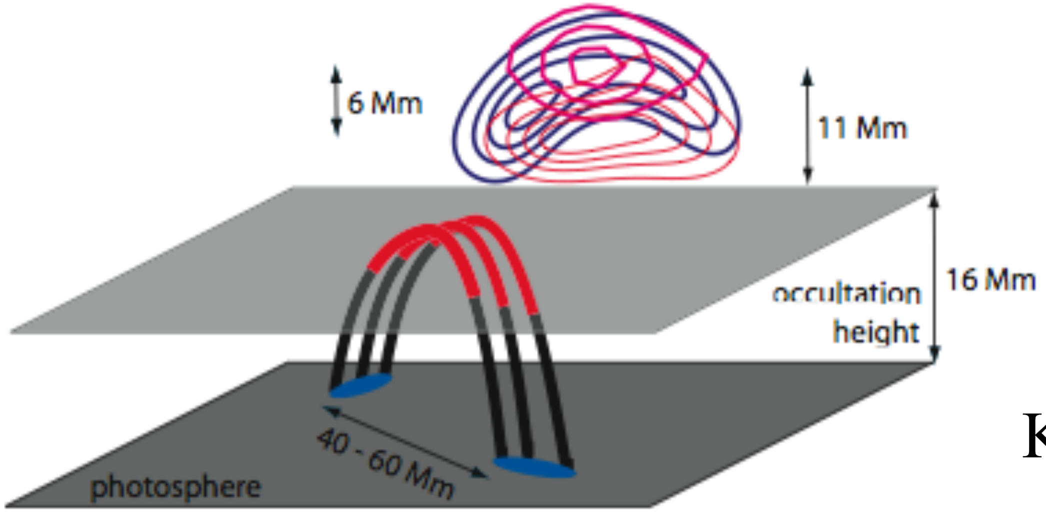
- July 23 γ-ray flare
- Holman, *et al.*, 2003
- Double power-law fit with spectral indices:

  1.5 (34-126 keV)

  2.5 (126-300 keV)



RHESSI occulted flare observations



30-50keV

17GHz

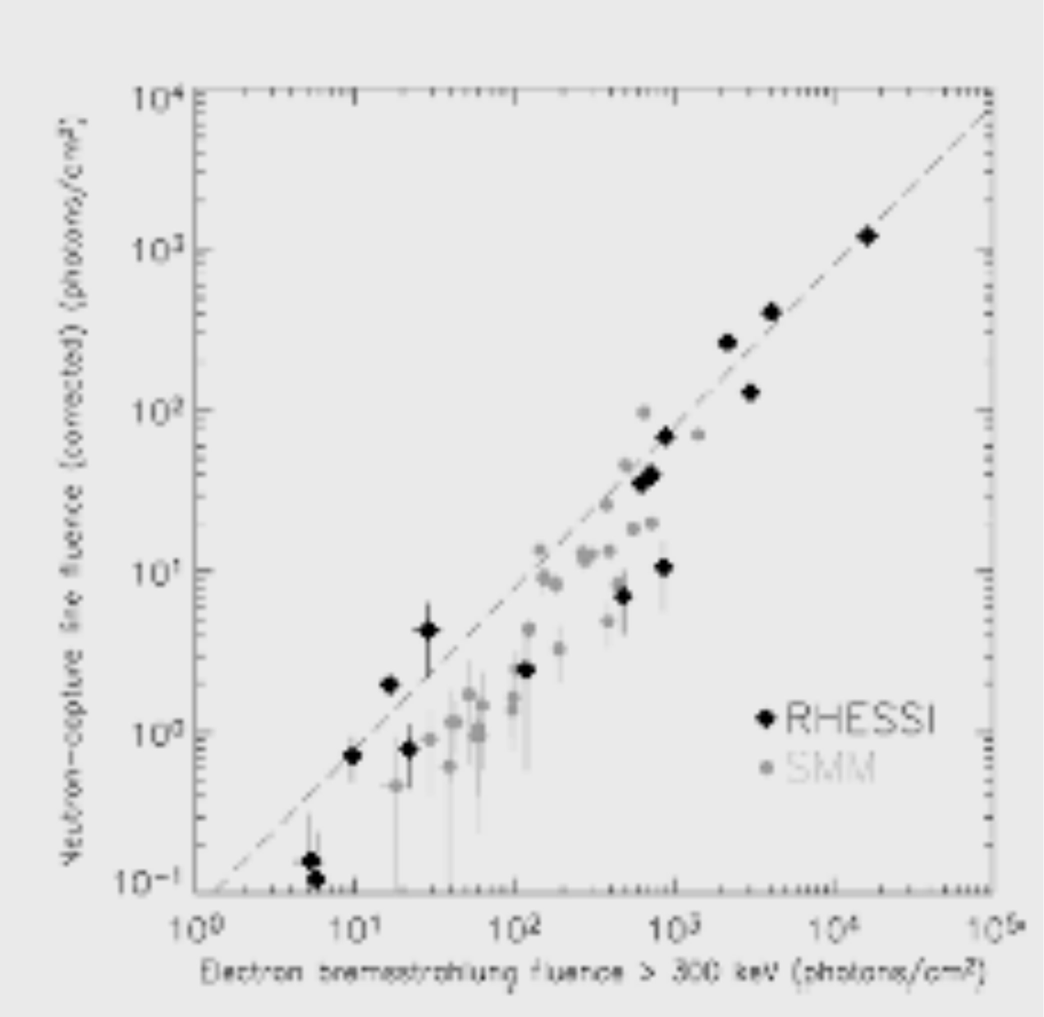
Krucker et al 2010

- Observations of a December 31, 2007, flare are remarkably consistent with the model
  - 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
  - Remarkable observations!

Energetic electron and ion correlation

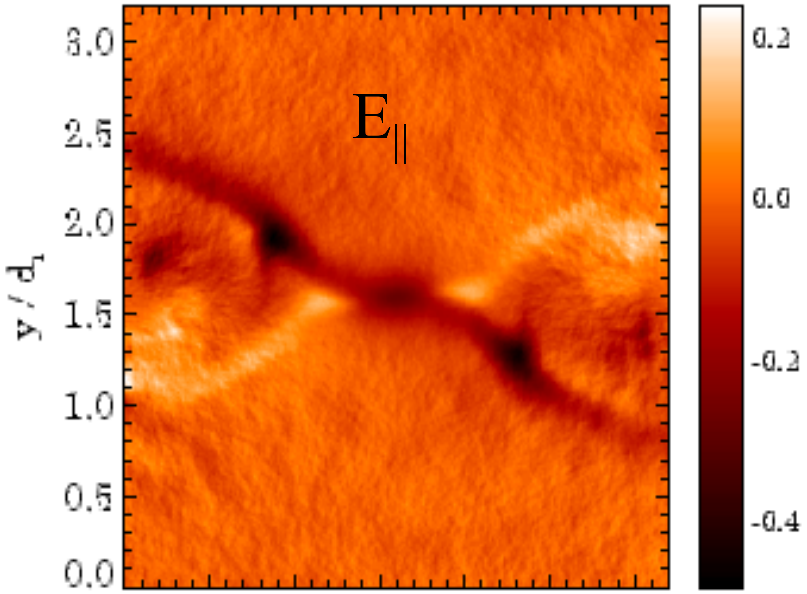
- > 300keV x-ray fluence (electrons) correlated with 2.23 MeV neutron capture line (> 30 MeV protons)
- Acceleration mechanisms of electrons and protons linked?

Shih et al 2008

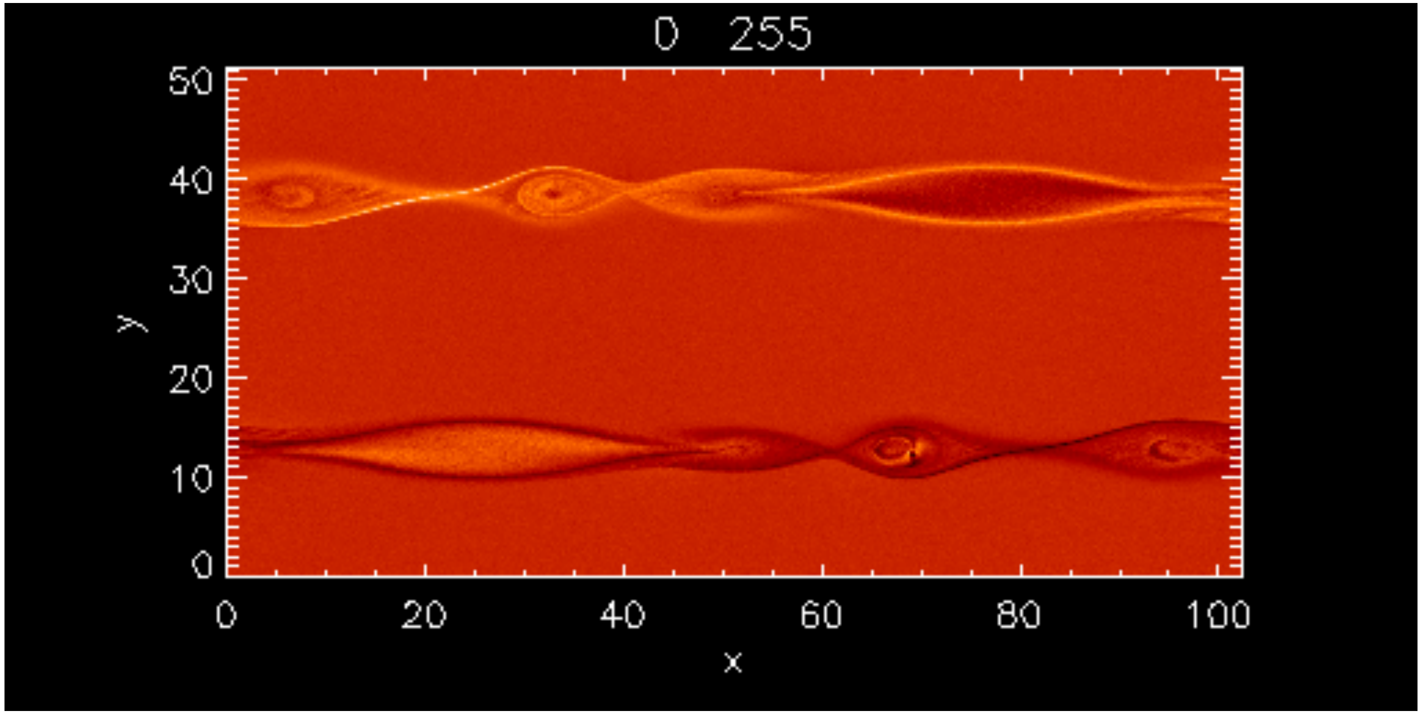


Electron acceleration by the parallel reconnection electric field

- Parallel electric fields during reconnection are typically highly localized near the x-line and along separatrices
- A single x-line model can not explain the large numbers of electrons seen in flares
  - Parallel electric fields are too spatially localized to be a significant source of large numbers of energetic electrons
  - The electron flux would produce currents that exceed the coronal fields by orders of magnitude
  - Finally, the x-line is not where magnetic energy is released.

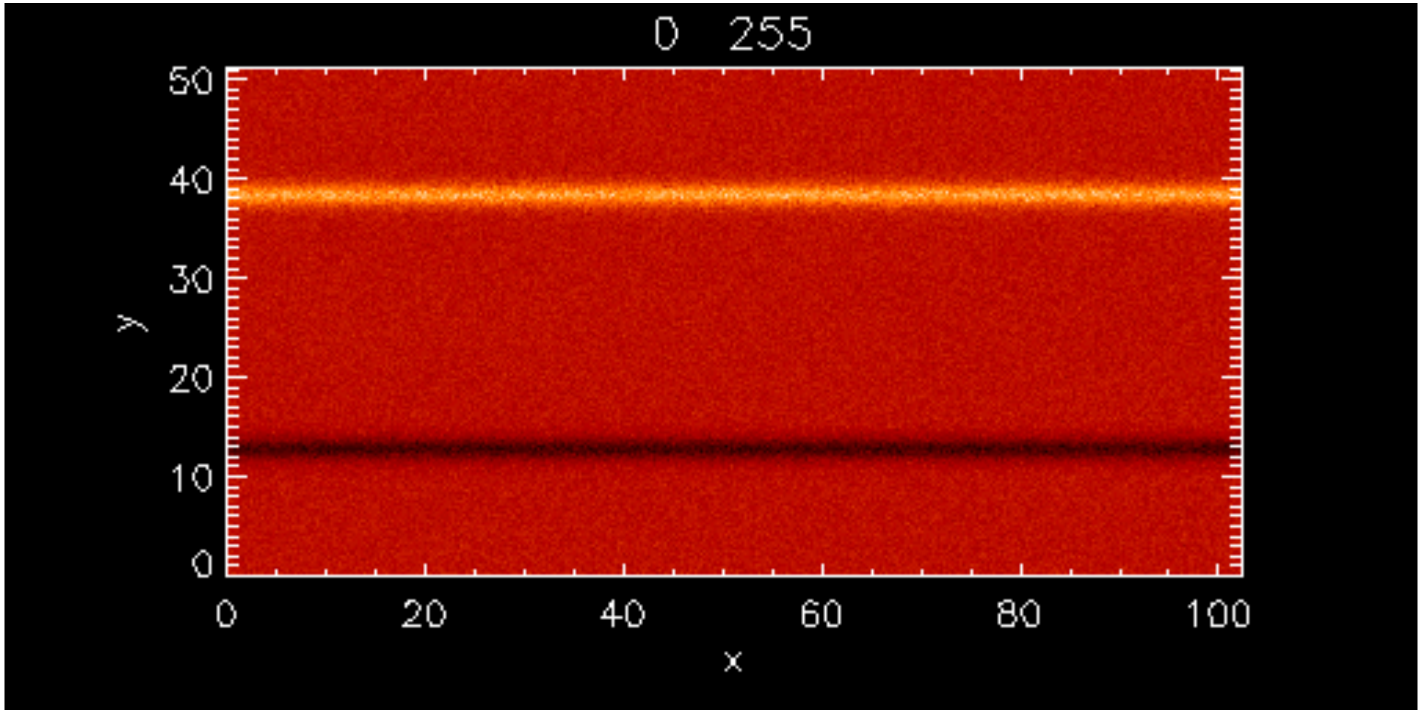


A multi-island acceleration model



- Narrow current layers spawn multiple magnetic islands in reconnection with a guide field
  - Must abandon the classical single x-line picture!!

A multi-island acceleration model



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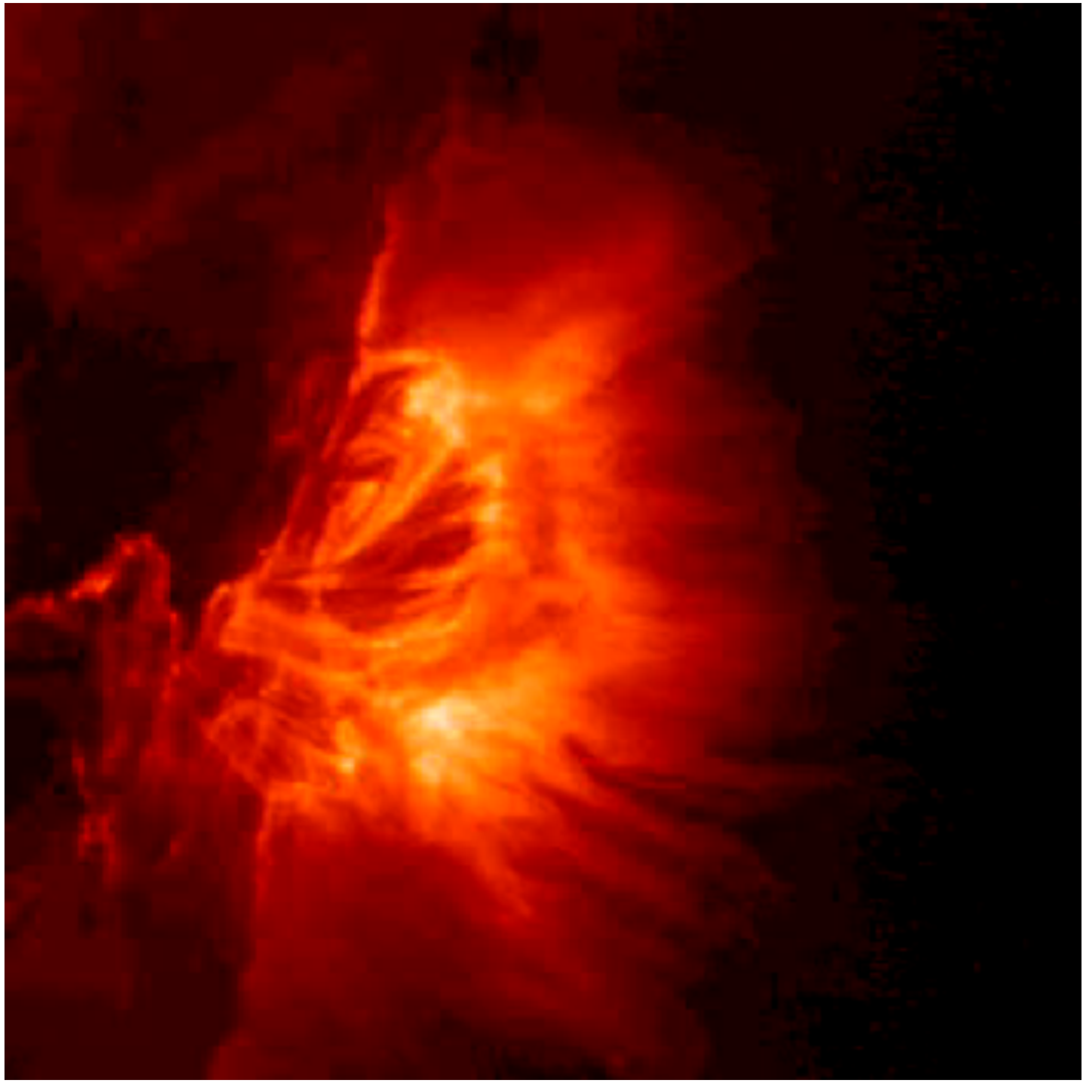
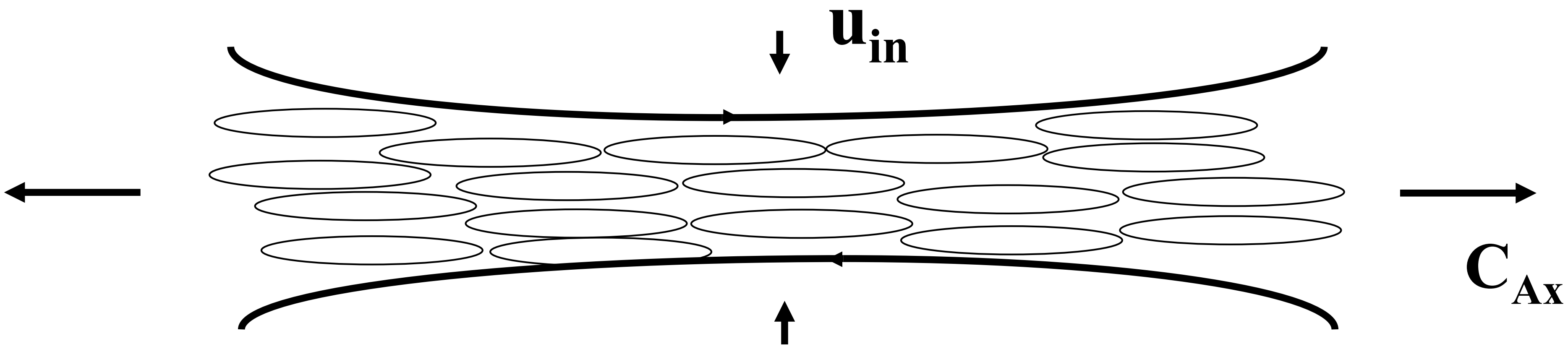
TRACE observations of downflow blobs

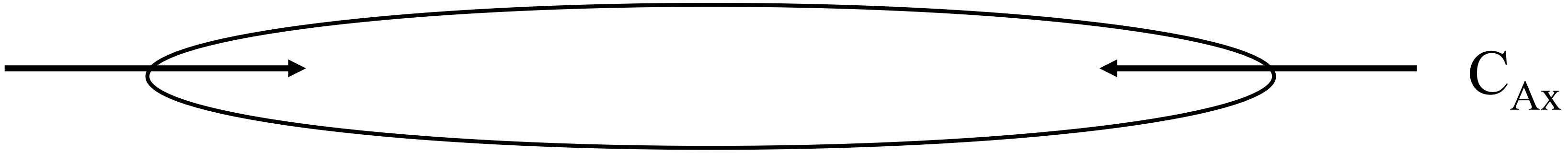
- Data from the April 21, 2002, X flare
- Interpreted as patchy reconnection from overlying reconnection site (Sheeley et al 2004, Linton and Longcope 2005)



Multi-island reconnection



- Give up single x-line model
- As in ACRs must explore Electrons and ion acceleration in a multi-island environment?
  - Fermi reflection in contracting magnetic islands increase the parallel particle energy



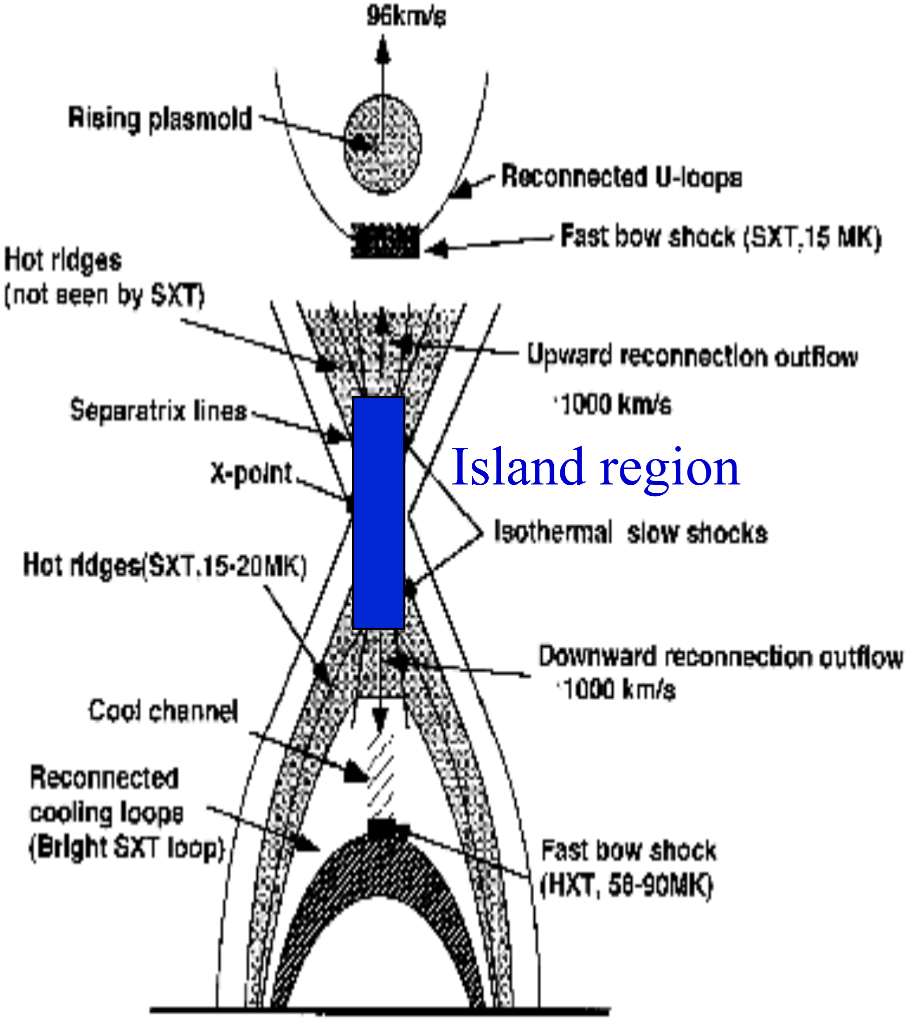
$$\frac{d\varepsilon_{\|}}{dt} \sim 2\varepsilon_{\|}\frac{c_A}{L_x}$$

  - Rate of energy gain independent of particle mass

    ➔ Thermal protons are not fast enough to bounce since are sub-Alfvenic -- need seed heating mechanism

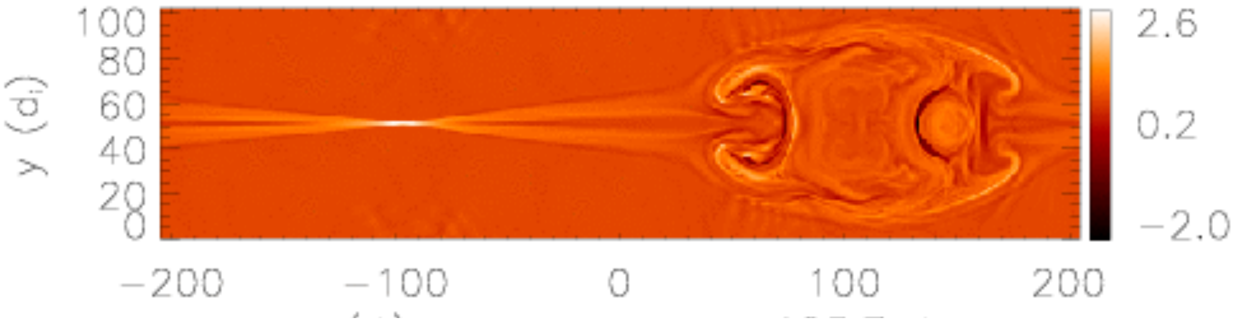
Critical issues in explaining the solar observations

- The electron numbers problem
  - The contracting island region must be macroscopic
- Energetic particles must gain a large fraction of the magnetic energy released

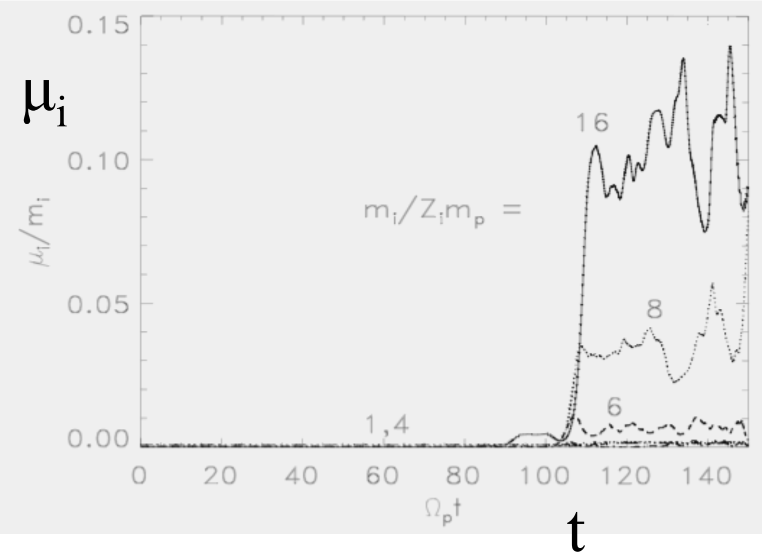


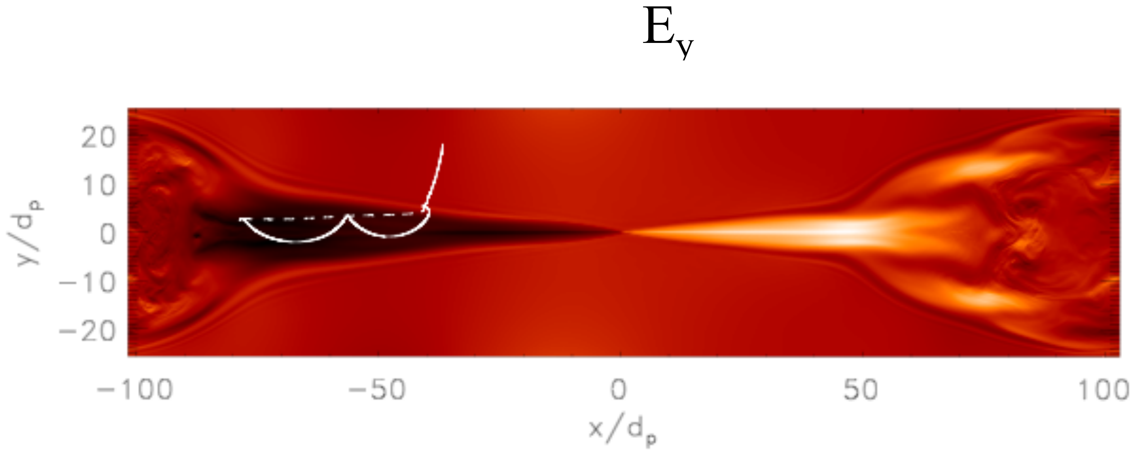
Seeding super-Alfvenic ions through pickup in reconnection exhausts

- 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 $T_i \sim m_i c_A^2$
    - Energy proportional to mass (Fujimoto and Nakamura, 1994; Drake et al 2009)



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

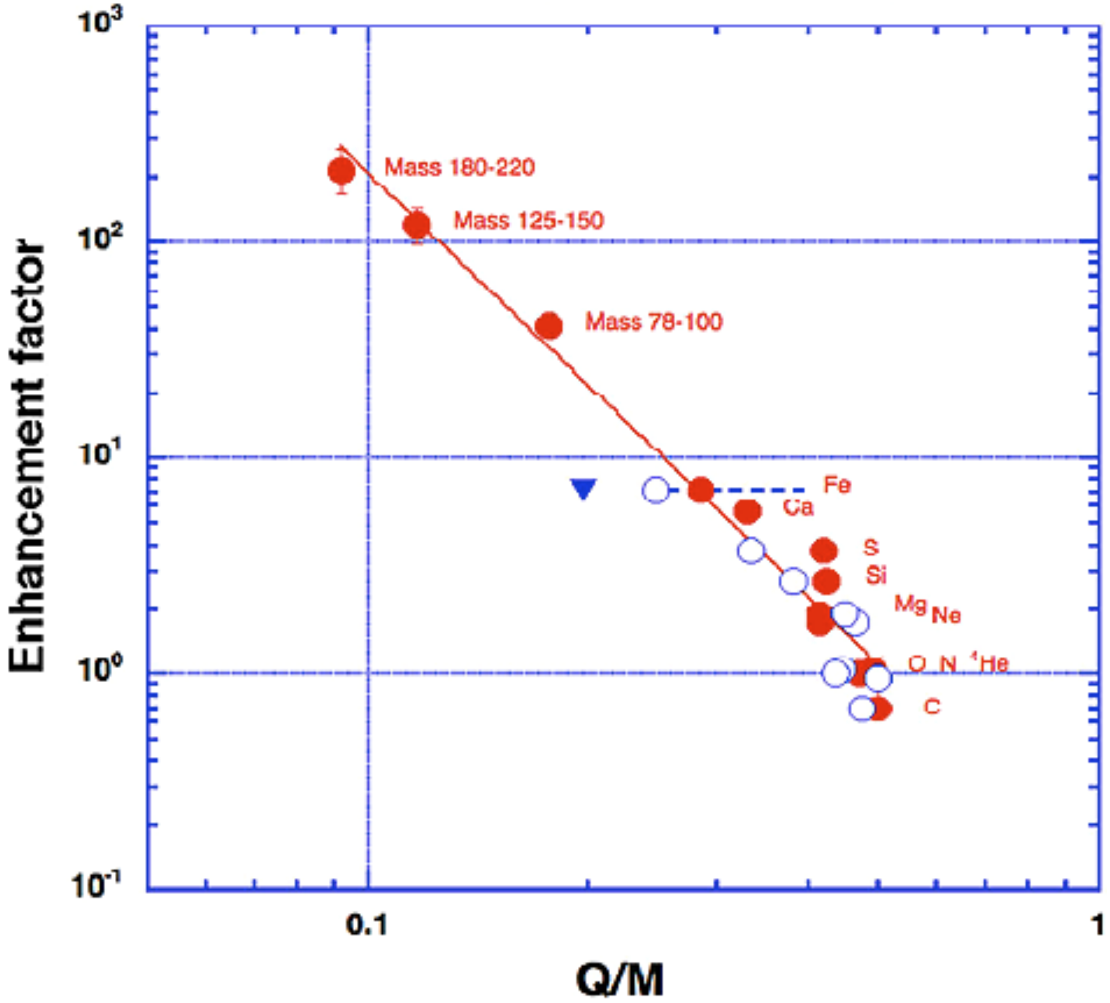
$$\frac{v_{iy}}{\Delta} \approx \frac{0.1 c_{Apx}}{\rho_{sp}} > \Omega_i \Rightarrow \frac{m_i}{Z_i m_p} > \beta_{px}$$

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

Impulsive flare energetic ion abundance enhancement

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

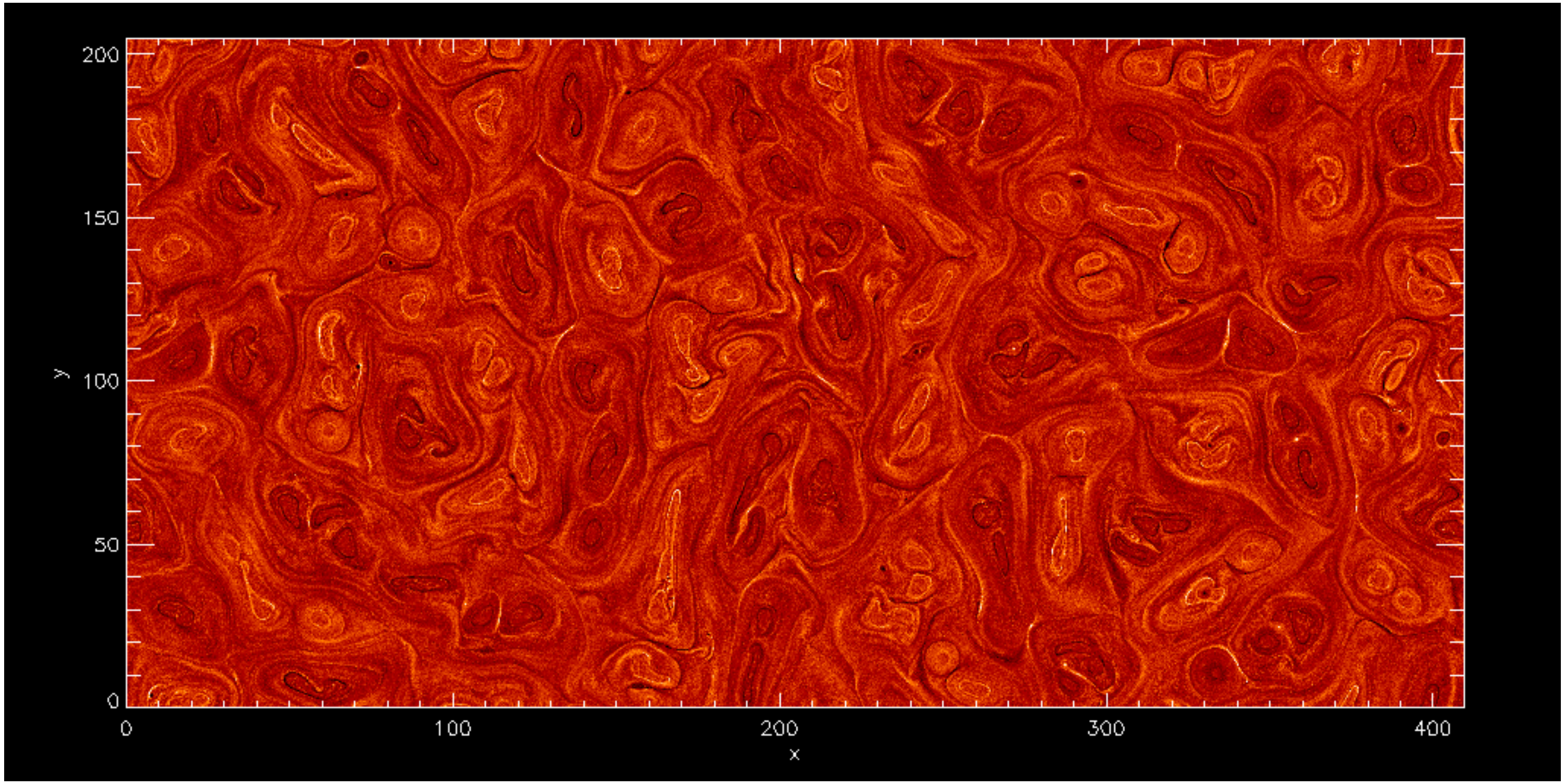
$$\propto \left(\frac{Q}{M}\right)^{-3.26}$$



Mason, 2007

Particle acceleration in a periodic magnetic field

- Simulations of particle acceleration in a realistic sheared magnetic field is intrinsically 3-D -- Not feasible in PIC model
- Treat a system with periodic reversals as a test bed
  - Can study particle acceleration in a true multi-island environment with a PIC model
- Low initial beta with a strong guide field to mimic the corona



J_{ez}

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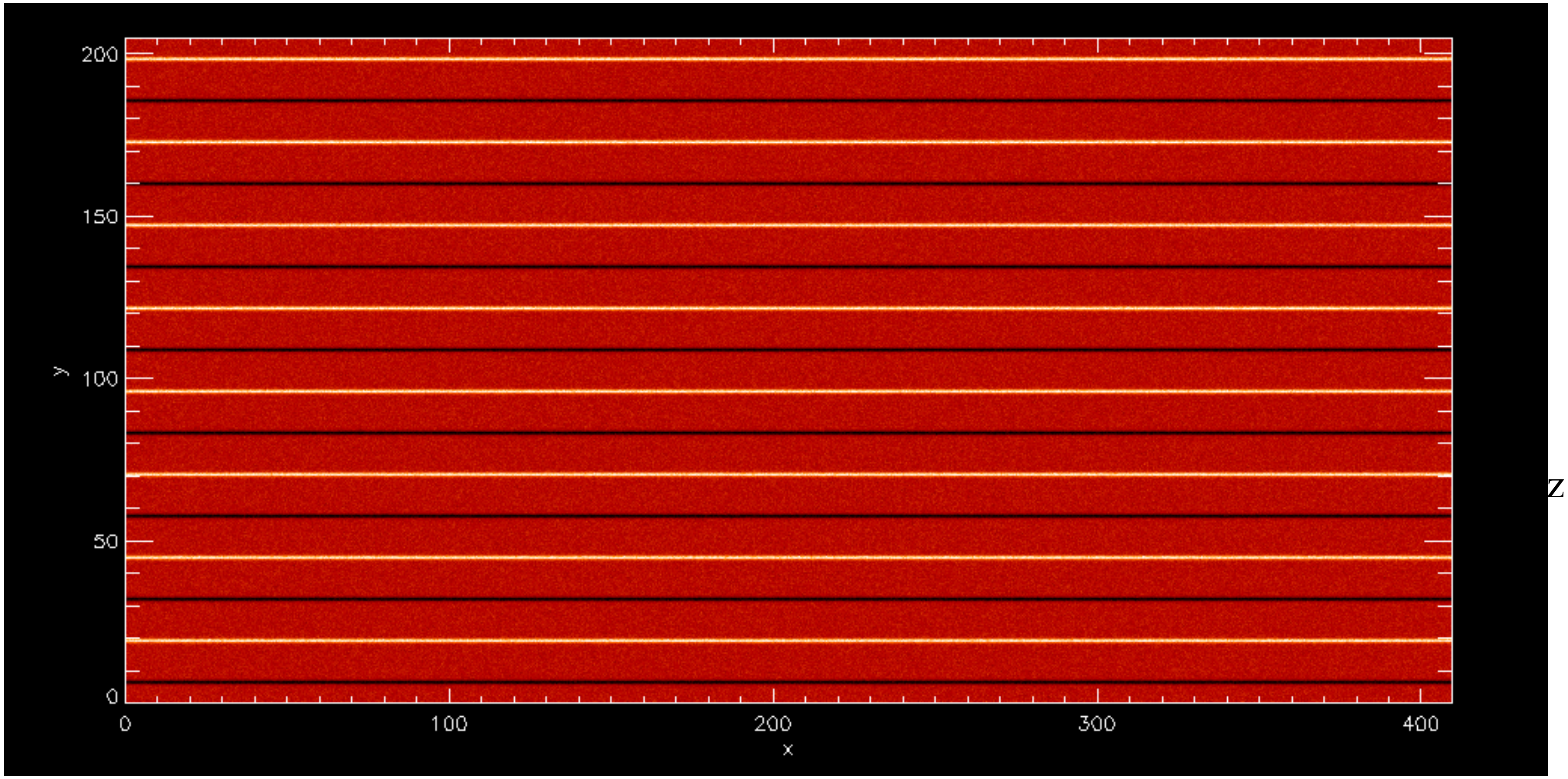
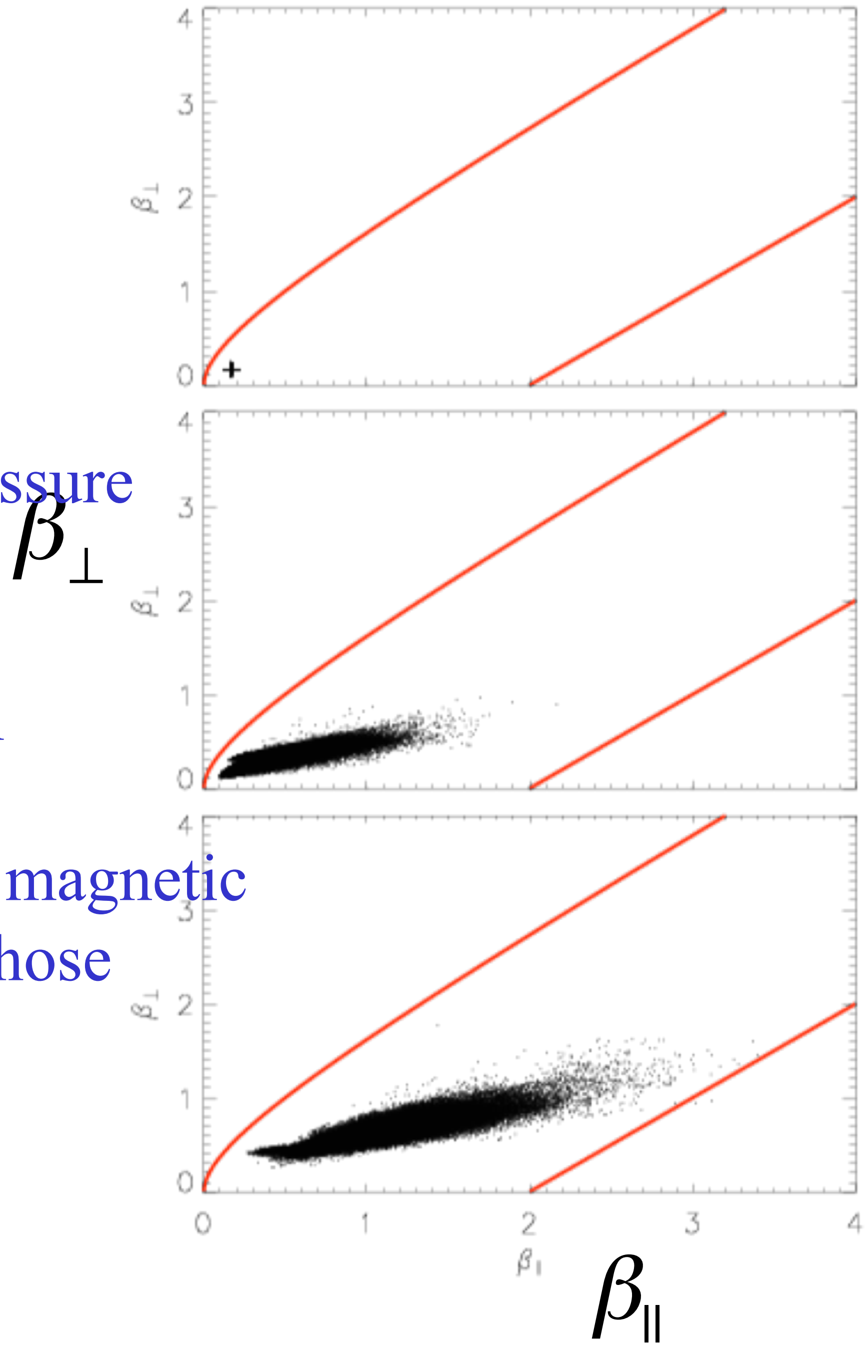


z

Development of pressure anisotropy

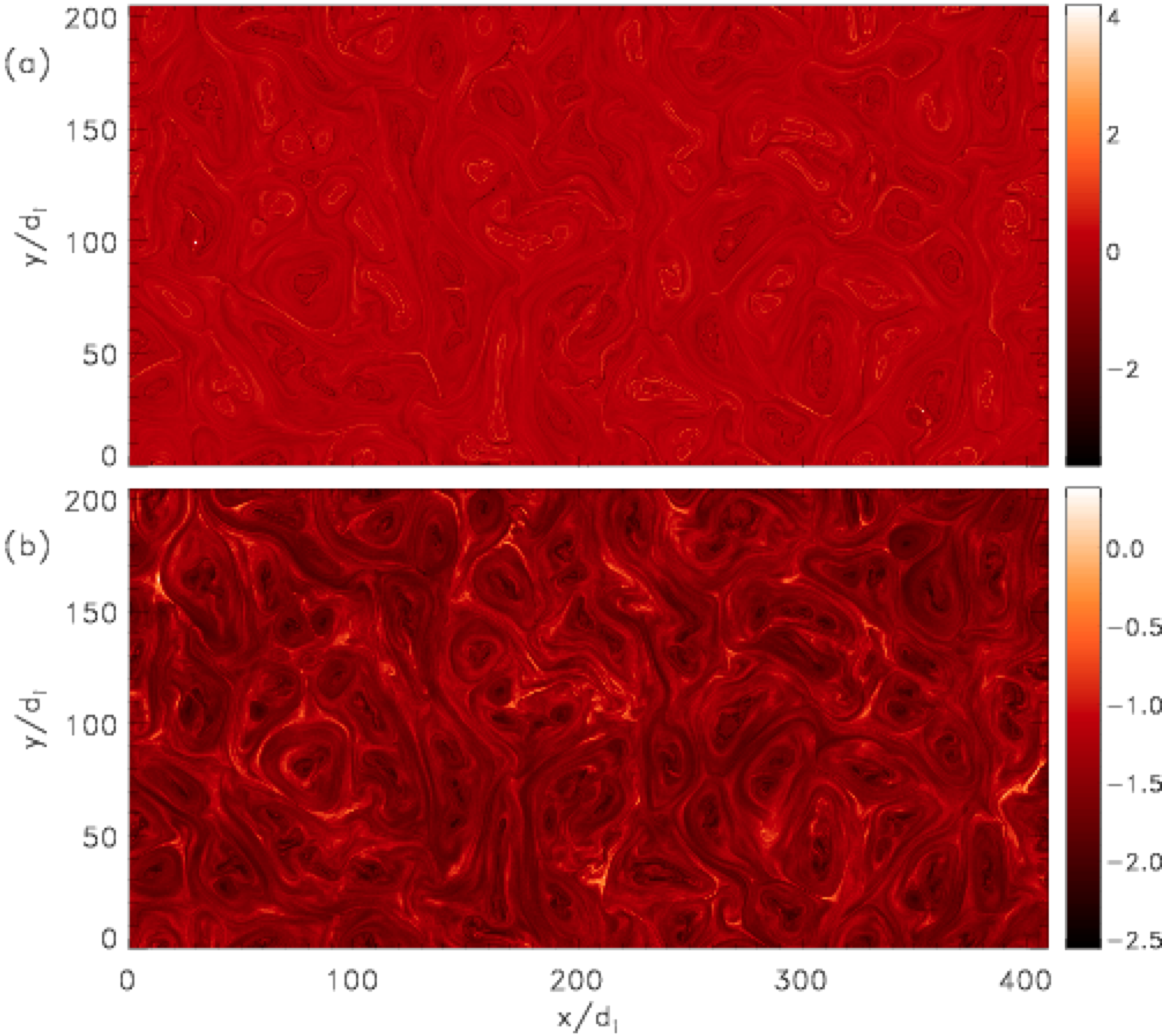
- The parallel pressure increases faster than the perpendicular pressure consistent with the Fermi mechanism.
- System approaches the marginal firehose condition at late time
- Shuts off reconnection (?) since magnetic fields have no tension at the firehose marginal limit



Firehose condition

- More complex than the case of anti-parallel reconnection
- Within islands and along separatrices bump against the firehose condition
  - Does this condition limits island contraction?
- Self-consistency is crucial in exploring particle acceleration

J_{ez}



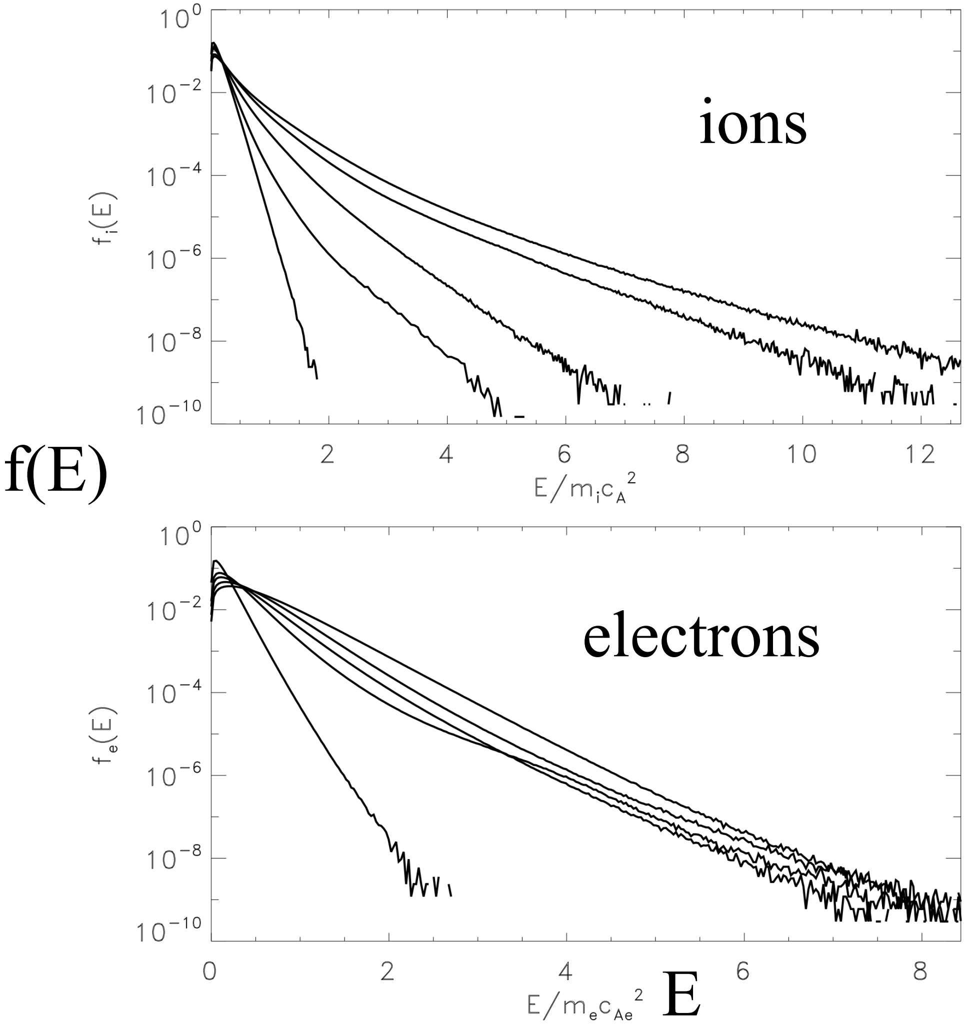
$$\beta_{\parallel} - \beta_{\perp} - 2$$

Electron and ion energy spectra

- Both ions and electrons gain energy
  - Electrons gain energy first and then saturate. Why?
  - Ions pickup at early time and Fermi at late time?
- The rate of energy gain of particles increases with energy
  - first order Fermi

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

- Ongoing study of acceleration mechanisms



Conclusions

- The sectored heliospheric magnetic field compresses and increases in strength as it approaches the heliopause
    - β falls below unity
    - Collisionless reconnection inevitably onsets and dissipates the sectored field energy
        - large reservoir of energy
        - Preferential heating of LISM pickup particles
- Efficient heating of interstellar pickup ions through a first order Fermi process during the contraction of reconnecting magnetic islands
    - **The Parker equation misses the particle energy gain in contracting islands**
    - Most of the magnetic energy goes into the ACRs
    - Balance of contraction drive and convective loss yields powerlaw solutions
    - Spectral indices are controlled by the approach to firehose stability
        - Limiting spectral index of 1.5

Conclusions (cont.)

- The single x-line model can not explain the large number of energetic electrons seen in flares
- Magnetic reconnection with a guide field as in the corona naturally leads to a multi-x-line configuration
  - High energy particle production during magnetic reconnection involves the interaction with many magnetic islands
- Electron acceleration is dominated by a Fermi-like reflection in contracting magnetic islands
- 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
    - Yields abundance enhancement of high M/Q ions

Conclusions (cont.)

- Efficient heating of super-Alfvenic ions through magnetic island contraction
- Balance of contraction drive and convective loss yields powerlaw solutions for all species
  - Spectral indices are controlled by the approach to firehose stability
- M/Q threshold for pickup behavior is a possible explantation of impulsive flare heavy ion abundance enhancements
  - This hypothesis can be tested with PIC simulations