Heating and particle acceleration during magnetic reconnection

J. F. Drake	Maryland
S. Antiochos	GSFC
W. Daughton	LANL
J. Egedal	MIT
A. Lazarian	Wisconsin
R. P. Lin	Berkeley
T. D. Phan	Berkeley
D. Uzdensky	Colorado
M. Yamada	PPPL

Electron observations

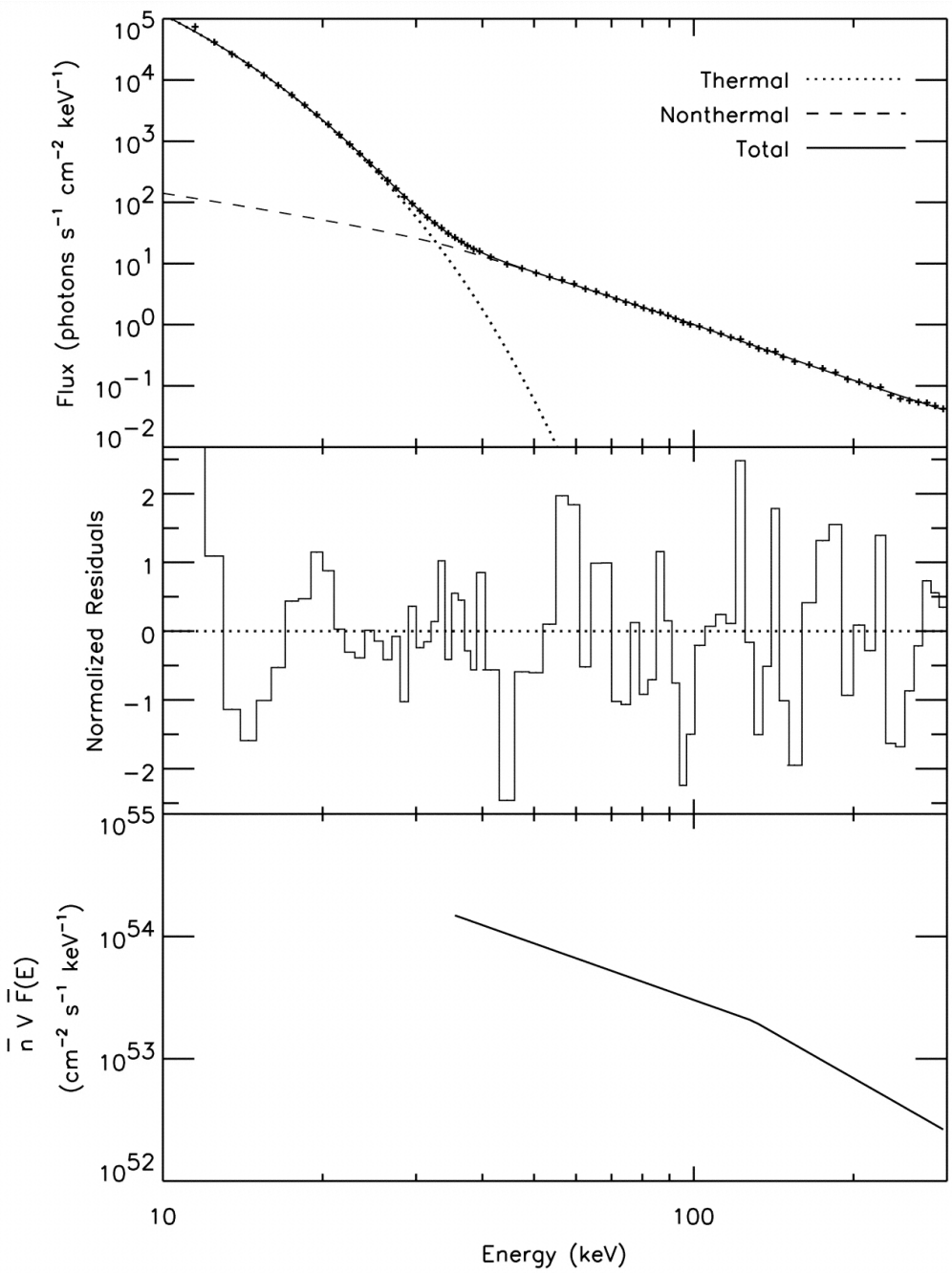
- Impulsive flare observations
  - In solar flares energetic electrons up to MeVs have been measured
    - A significant fraction of the released magnetic energy appears in the form of energetic electrons (Lin and Hudson '76, Emslie et al '05)
    - In some flares the pressure of the energetic electrons can approach that of the magnetic field (Krucker et al 2009) ➔Remarkable!!
- Earth's magnetosphere
  - See electrons up to 300keV peaked around the x-line during magnetotail reconnection (Oieroset et al 2002).
- Solar wind observations
  - No energetic electrons are seen in solar wind reconnection exhausts (Gosling et al 2005).
- Laboratory observations
    - Energetic electrons up to 100keV during sawteeth and disruptions in tokamaks (Savrukhin 2001)
    - Strong enhancement in x-ray emission during counter-helicity magnetic loops in the Caltech prominence experiment (Hansen et al 2004).
- Astrophysical systems -- γ-ray bursts, supernova shocks?

RHESSI observations

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

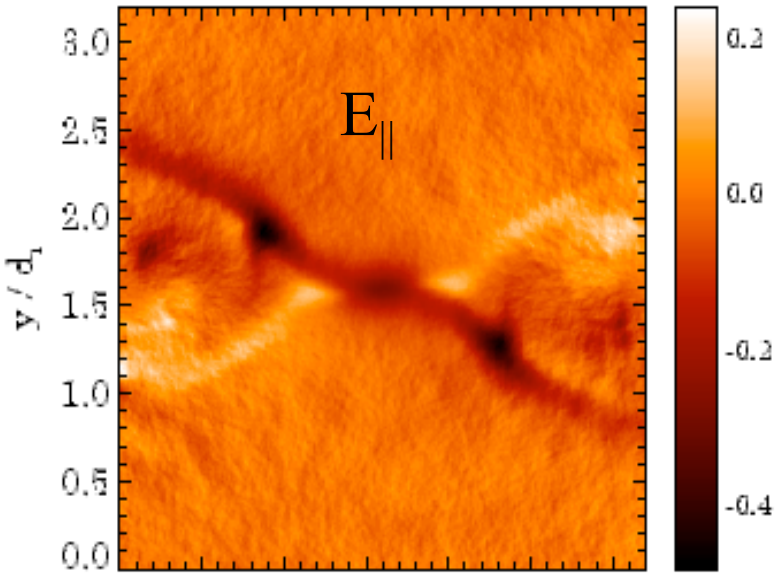
  1.5 (34-126 keV)

  2.5 (126-300 keV)
  - Typically see soft-hard-soft spectral evolution

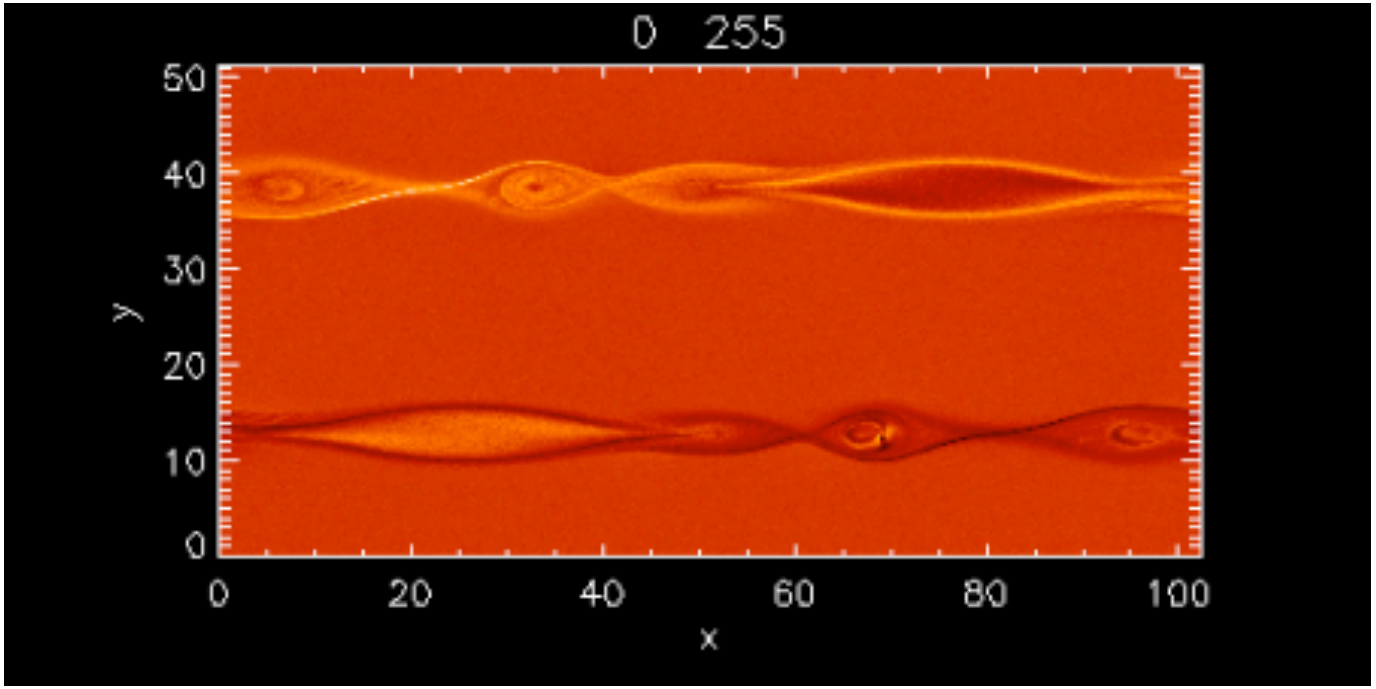


Electron acceleration by the parallel reconnection electric field

- 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.

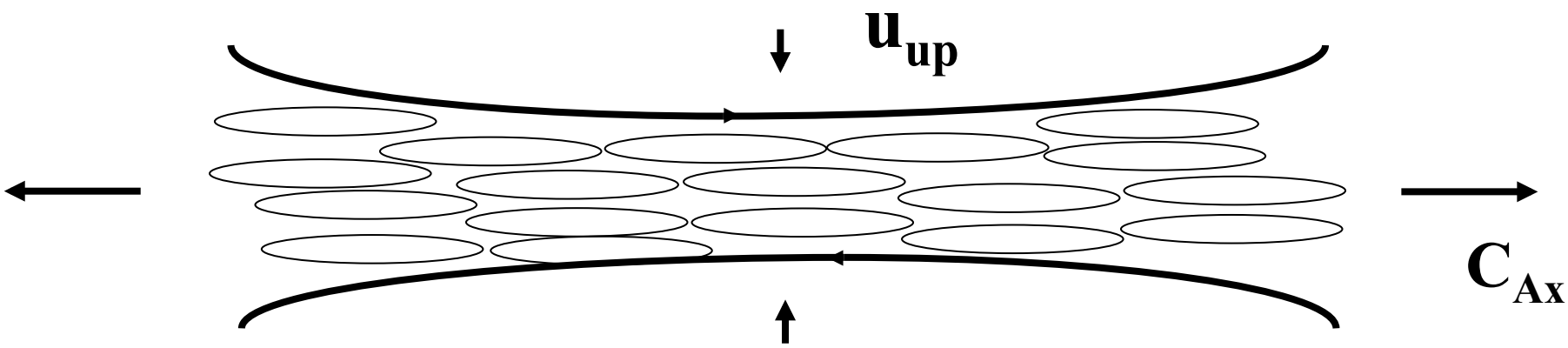


Secondary islands during reconnection with a guide field



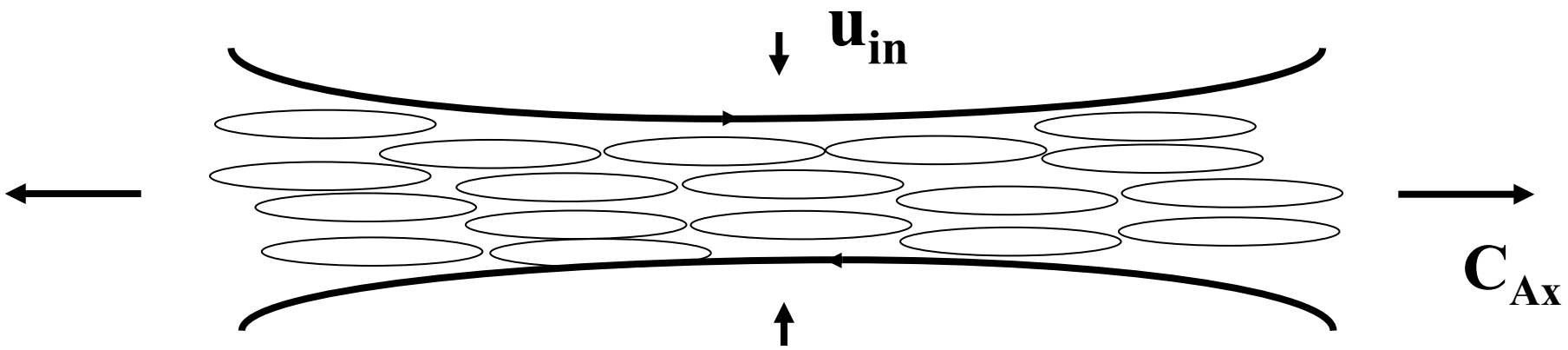
- Narrow current layers spawn multiple magnetic islands in reconnection with a guide field
  - Must abandon the classical single x-line picture!!

Multi-island reconnection and particle acceleration



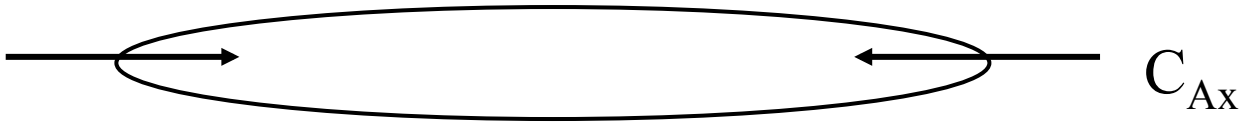
- Observations in the corona and magnetosphere also suggest that reconnection leads to interacting flux ropes
- Need to consider particle acceleration in a 3-D volume with multiple islands
  - Electrons can wander from island to island in the resulting stochastic magnetic field

Multi-island particle acceleration



- How are electrons accelerated in a multi-island environment?
  - Parallel electric fields are now viable
  - Fermi reflection in contracting magnetic islands (Kliem 94, Drake et al 2006)
    - Rate of energy gain independent of particle mass
    - Same for electrons and super-Alfvenic protons
    - A first order Fermi mechanism

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



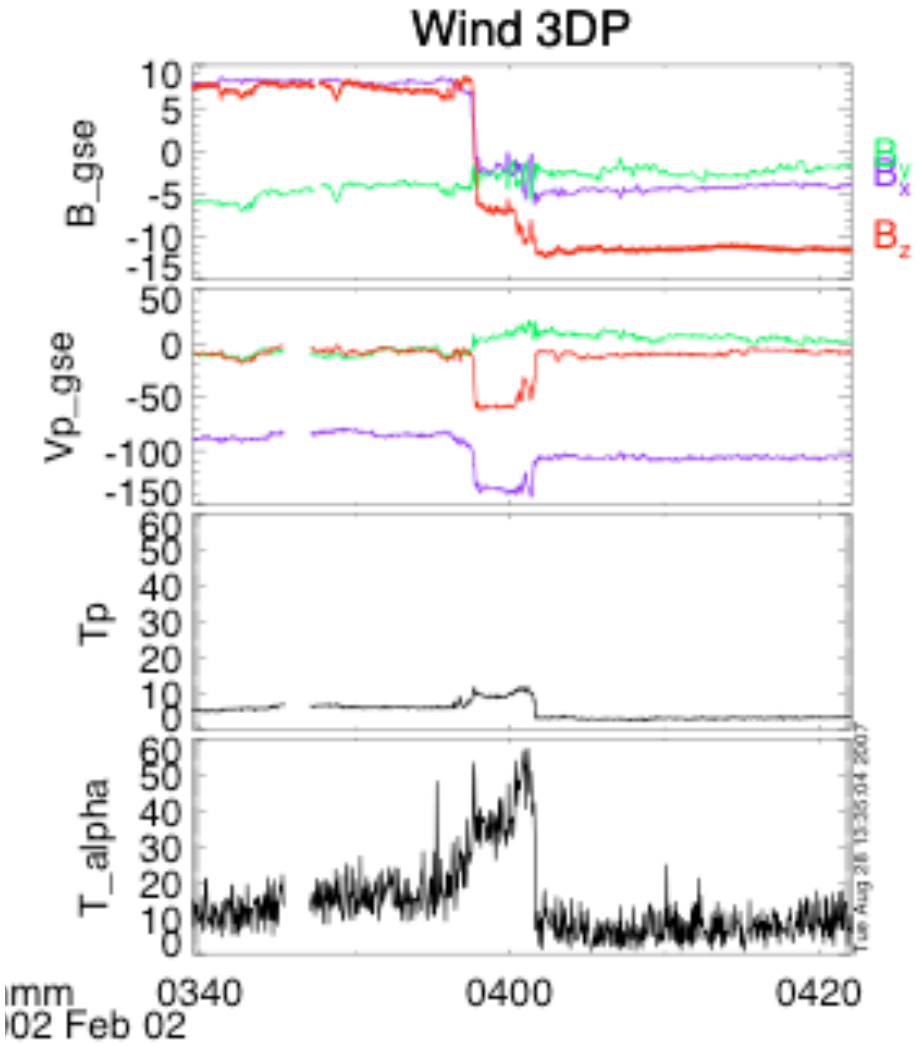
Ion Observations

- Impulsive flare observations
  - In solar flares energetic ions up to GeVs have been measured
    - A significant fraction of the released magnetic energy appears in the form of energetic ions (Emslie et al '05)
  - In impulsive flares see enhancements of high M/Q ions (Mason '07)
- Earth's magnetosphere
  - Often see counter-streaming ion beams linked to reconnection (Phan et al 2007).
- Solar wind observations
  - Ion heating in solar wind reconnection exhausts (Gosling et al 2005, Phan et al 2006) but no energetic particles.
  - Near universal super-Alfvenic ion tails in the slow solar wind $f \sim v^{-5}$ (Fisk and Gloeckler 2006)
  - Anomalous Cosmic Rays
    - ions with energy 10-100MeV whose source is in the vicinity of the heliospheric termination shock/heliosheath

Ion Observations (cont.)

- Laboratory experiments
  - Ion heating during sawtooth events in the Wisconsin reversed-field-pinch experiment (MST)
  - Strong ion heating during reconnection in the Swarthmore reconnection experiment
- Astrophysical systems
  - What role does reconnection play in producing the cosmic ray spectrum?

Wind observations of solar wind exhaust

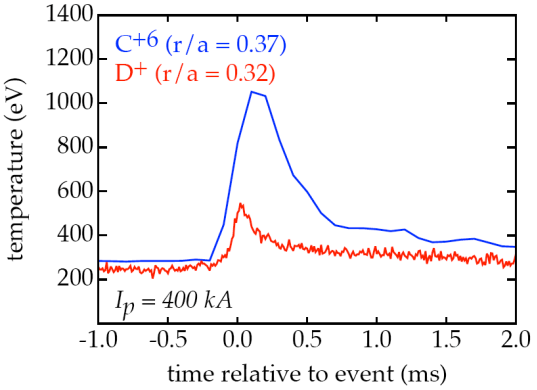


- 300R_E event (Phan et al., 2006)

$$\Delta T_i \sim m_i v_A^2$$

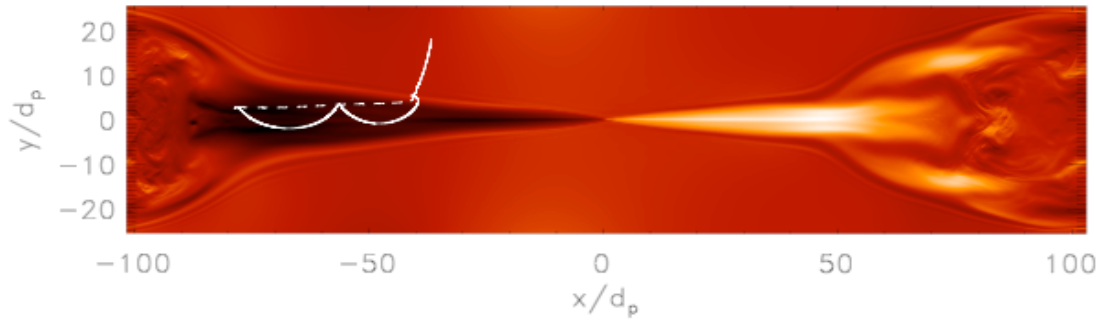
$$\frac{\Delta T_\alpha}{\Delta T_p} = \frac{m_\alpha}{m_p}$$

Sawtooth heating in MST



Ion pickup in reconnection exhausts

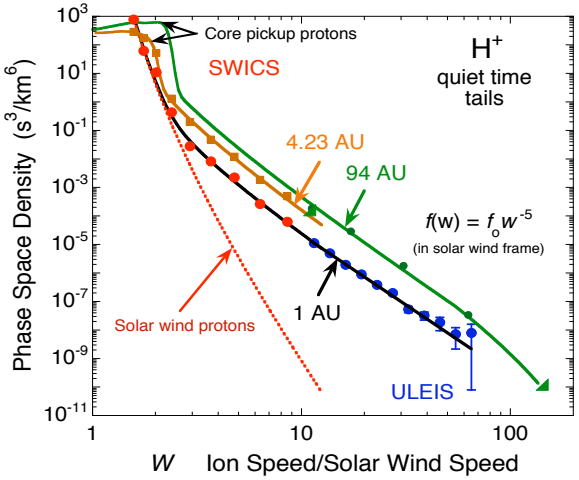
- Ions move from upstream cross a narrow boundary layer into the Alfvenic reconnection exhaust
- The ion can then act like a classic "pick-up" particle, where it gains an effective thermal velocity equal to the Alfvenic outflow $\Delta T_i \sim m_i c_A^2$
  - In the corona $\Delta T_i \sim 1$keV
  - Seed heating mechanism for shocks acceleration?

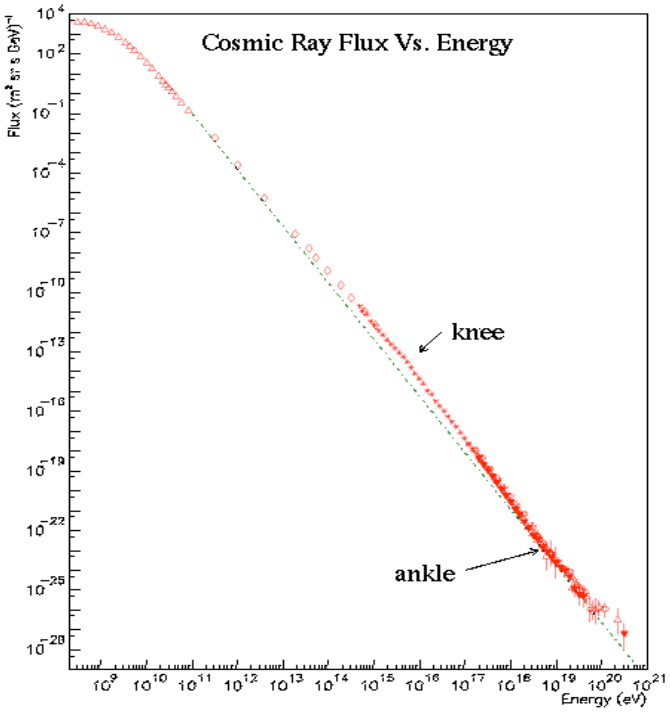


Power-law spectra of super-Alfvenic ions

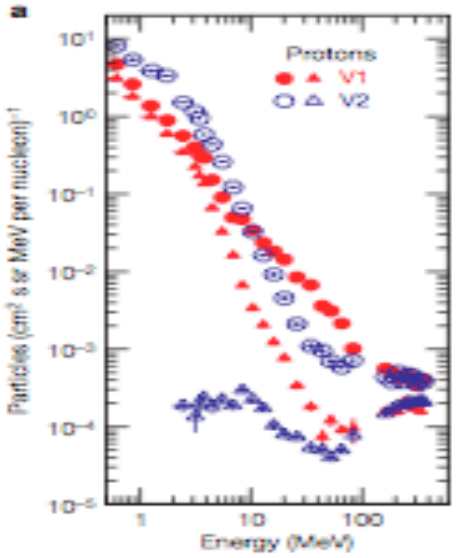
- What is the role of reconnection in producing these powerlaw spectra?
- Is there a reconnection "universal spectrum" like that of shocks?

Solar Wind



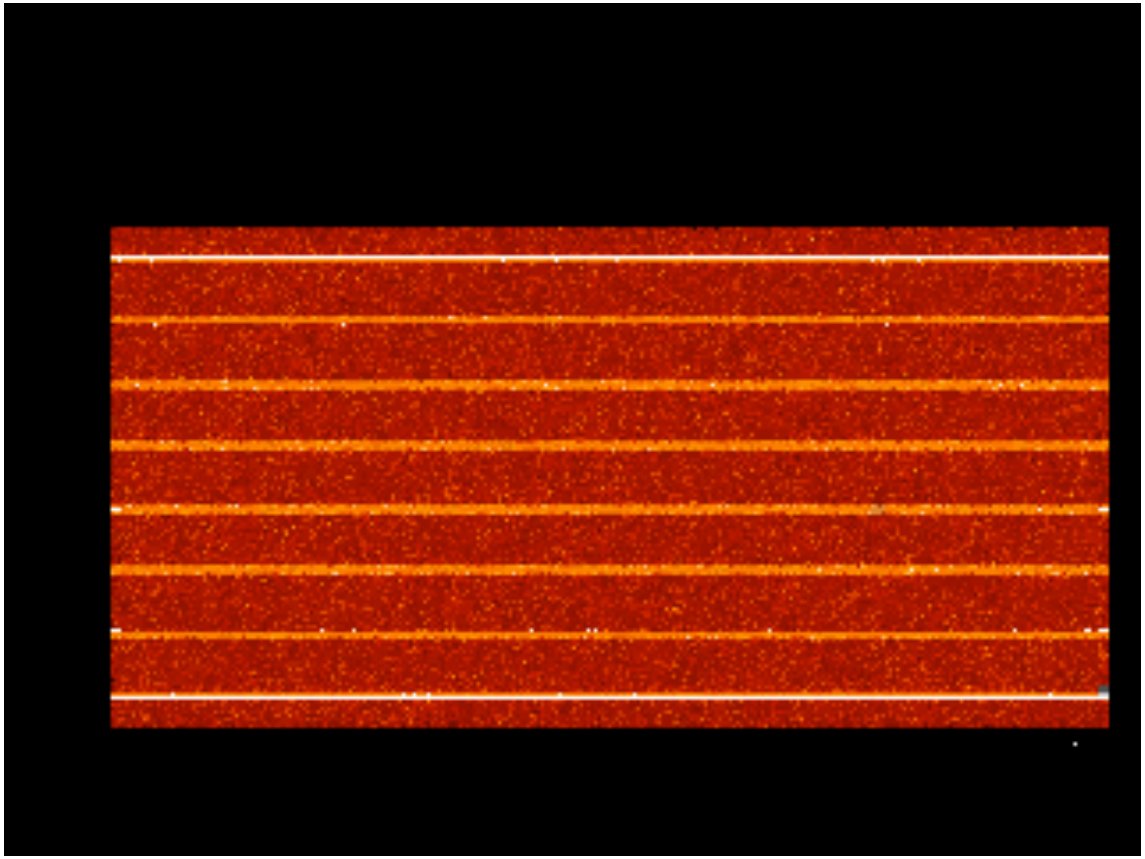


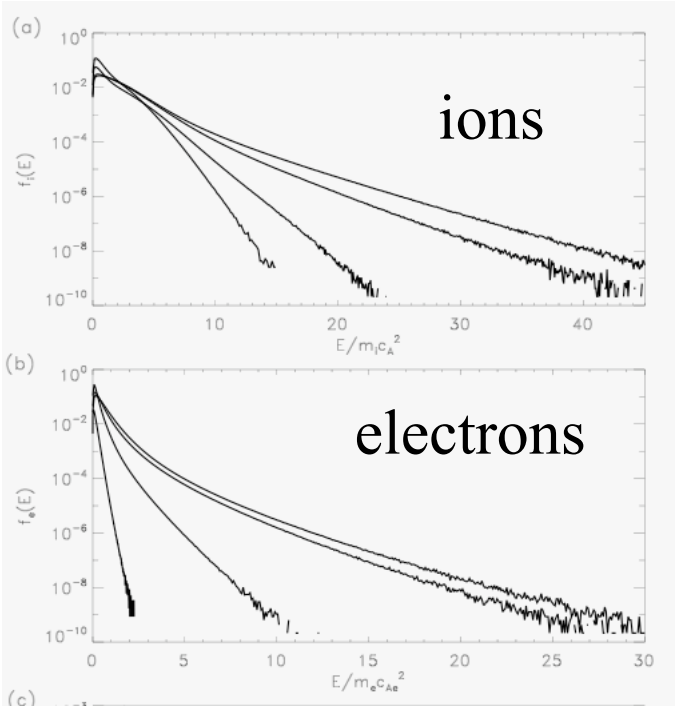
ACRs



Exploring reconnection-driven particle acceleration on the cheap

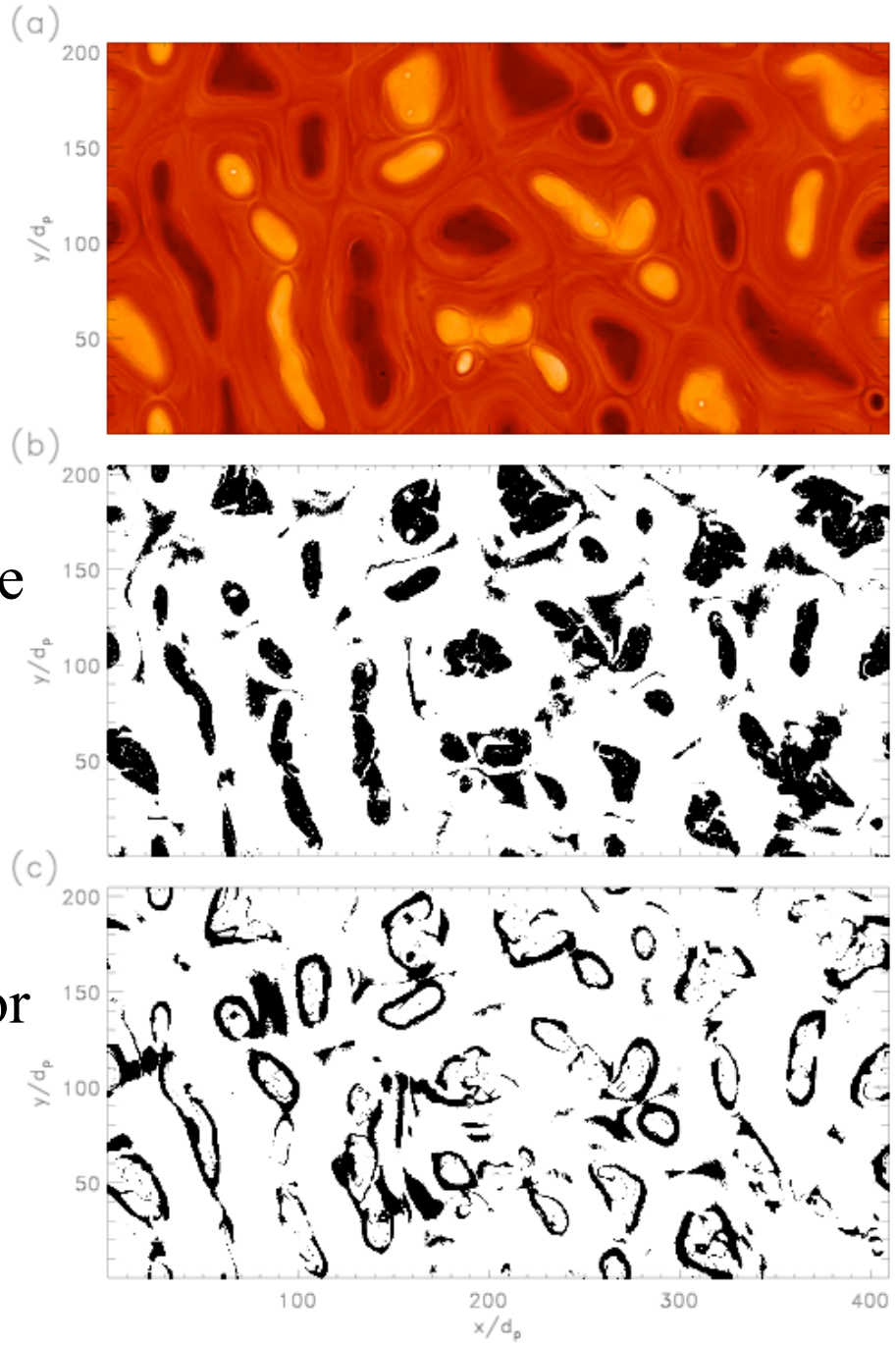
- Investigate multi-island acceleration in a 2-D multi-current layer geometry





The self-consistency problem is critical

- Within islands bump against the firehose condition
  - This condition limits island contraction
    - No tension in magnetic fields when the firehose condition is violated
- In current layers and along separatrices bump against mirror mode limit
- Self-consistency is crucial in exploring particle acceleration



firehose

mirror

Making progress on particle acceleration

- What are the relative roles of parallel electric fields and island contraction in driving electron acceleration?
- What are the relative roles of pickup and island contraction in driving ion acceleration? Or something else?
- Exploring 3-D kinetic reconnection in a multi-island environment is beyond the capacity of present computers
  - Need around $(200c/\omega_{pi})^3$ simulations
  - Can learn important physics in 2-D multi-current layer systems
- Present dedicated laboratory reconnection experiments are too constrained to explore multi-island reconnection.
  - Can an experiment be designed to explore multi-island particle acceleration?
- Magnetospheric satellites only occasionally see reconnection driven energetic electrons and link to energetic ions is tenuous.
  - NASA's two-spacecraft Artemis mission will likely produce important data since the deep tail seems to be a better environment for particle acceleration
  - Upcoming Solar Probe Plus mission will also provide important data since the environment around 10 solar radii is low β more like the sun than the magnetosphere and solar wind