# Magnetic reconnection and particle acceleration in space and astrophysical systems

J. F. Drake    University of Maryland

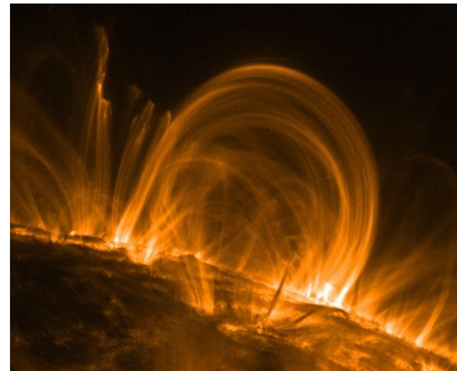
Ack: Drs. M. Swisdak, J. Dahlin, H. Arnold,
and the SolFER team

SolFER

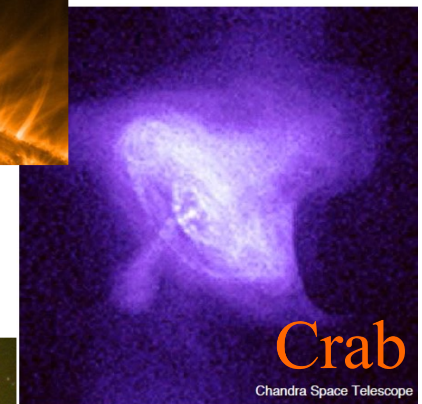
# Magnetic Energy Dissipation in the Universe

- Magnetic reconnection is the dominant mechanism for dissipating magnetic energy in the universe
- The conversion of magnetic energy to heat and high speed flows underlies many important phenomena in nature
- Known systems are characterized by a slow buildup of magnetic energy and fast release
  - Poorly understood
- A significant fraction of the released magnetic energy goes into energetic particles
  - Emerging understanding

# Astrophysical reconnection



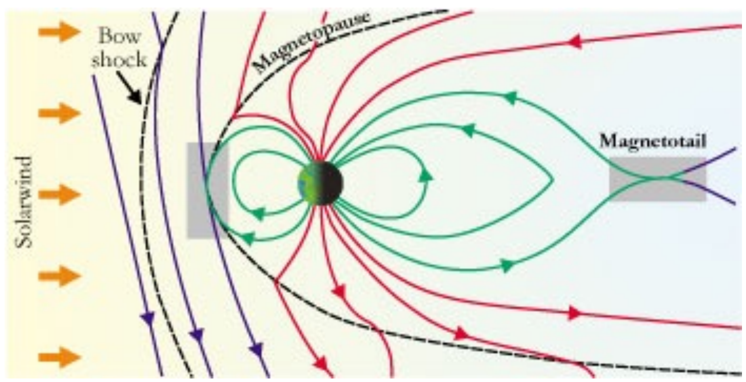
- Solar and stellar flares




- Pulsar magnetospheres, winds, PWNe


- AGN (e.g., blazar) jets, radio-lobes

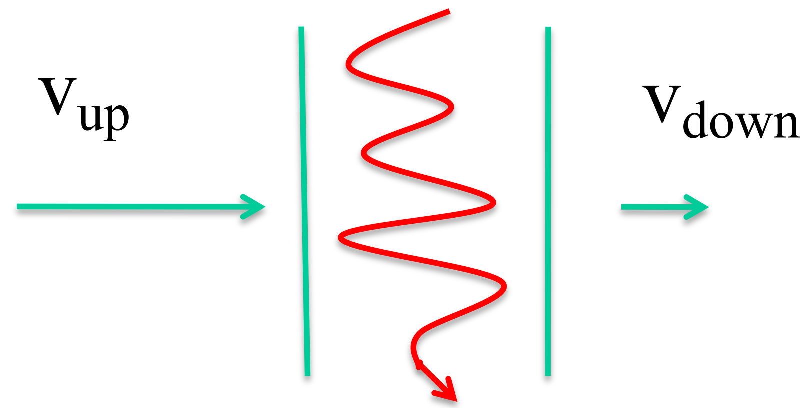

- Gamma-Ray Bursts (GRBs)
- Magnetosphere



# Mechanisms for particle acceleration

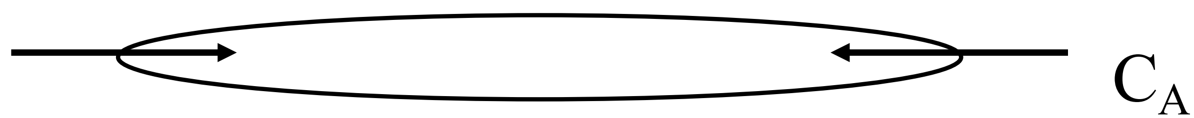
- Fast mode shocks

$$\frac{d\varepsilon}{dt} \sim \frac{\Delta v}{L}\varepsilon$$



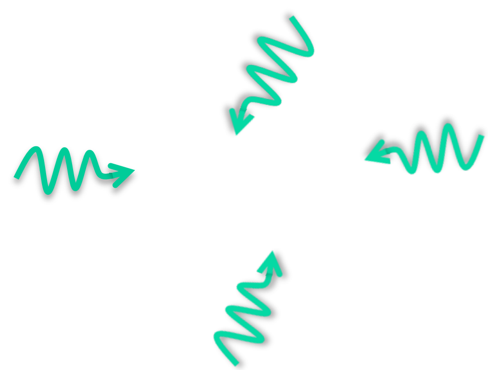

- Magnetic reconnection

$$\frac{d\varepsilon}{dt} \sim \frac{c_A}{L}\varepsilon$$



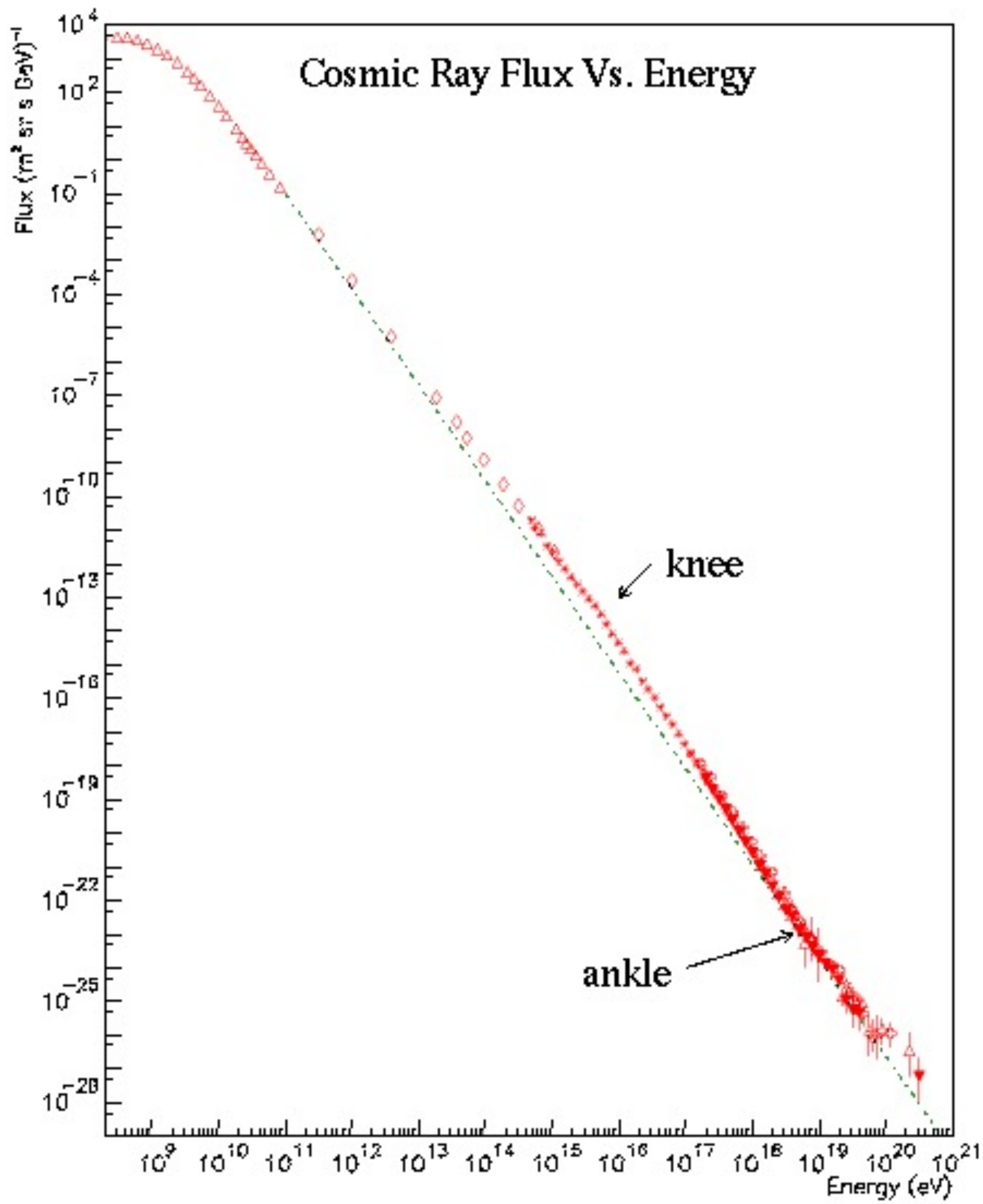

- Turbulence
  - Can gain or lose energy
  - See more waves head-on so net gain

$$\frac{d\varepsilon}{dt} \sim \frac{c_A^2}{Lv}\varepsilon$$



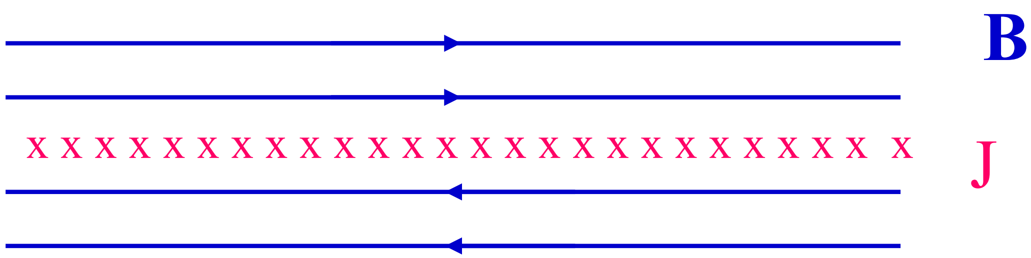
# Cosmic Ray Energy Spectrum

- Supernova shocks remain the favored mechanism for producing cosmic rays
  - Fermi reflection across the shock front
    - Converging flow at shock
  - Energies up to ~ $10^{15}$eV
    - Too small to contain higher energy particles
  - Powerlaw spectra close to observations
    - ~ $E^{-2.7}$
- Jets from active Galactic nuclei and associated radio lobes are large enough to produce particles above $10^{15}$eV
  - Open issue
- GZK cutoff at around $10^{20}$eV
  - Pion production due to scattering off the microwave background



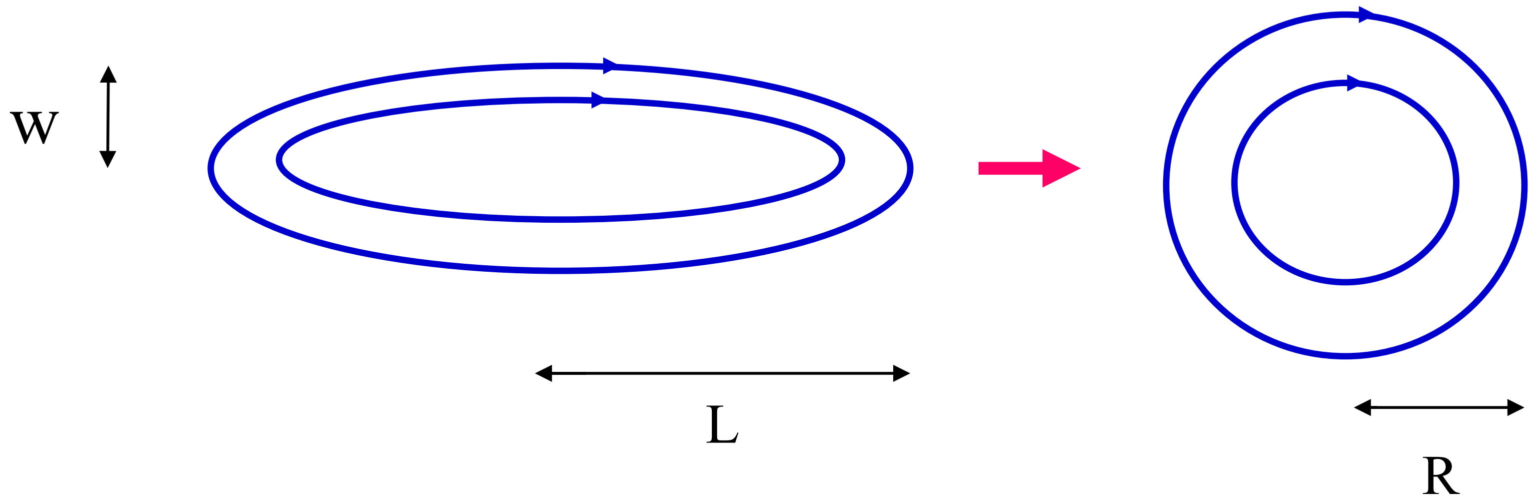
# Magnetic Free Energy

- A reversed magnetic field is a source of free energy




•Can imagine **B** simply self-annihilating
•What happens in a plasma?

# Energy Release from a Squashed Bubble




- Evaluate initial and final magnetic energies
  - use conservation law for ideal motion
    - magnetic flux conserved
    - area for nearly incompressible motion

$$W_f \sim (w/L)\, W_i \ll W_i$$

•Most of the magnetic energy is released

# Flow Generation

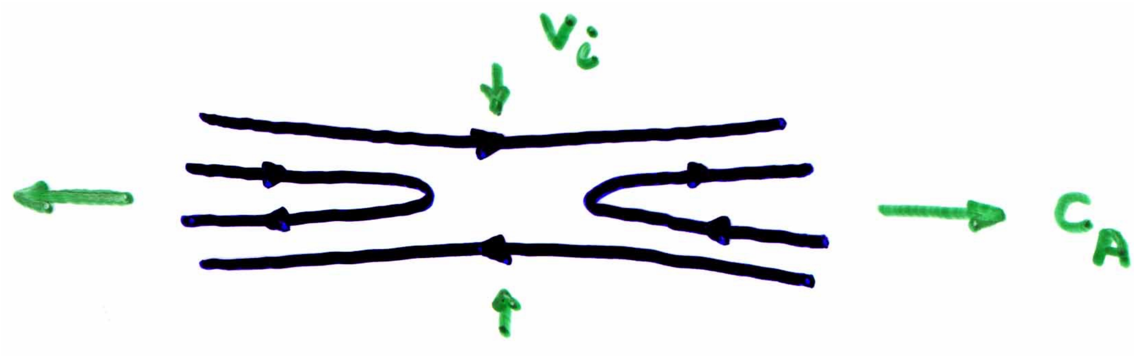
- Released magnetic energy is converted into plasma flow

$$\frac{1}{2}\rho v^2 = \frac{B^2}{8\pi}$$

$$v \approx c_A \equiv \left(\frac{B^2}{4\pi\rho}\right)^{1/2} \qquad \tau_A = L/c_A$$

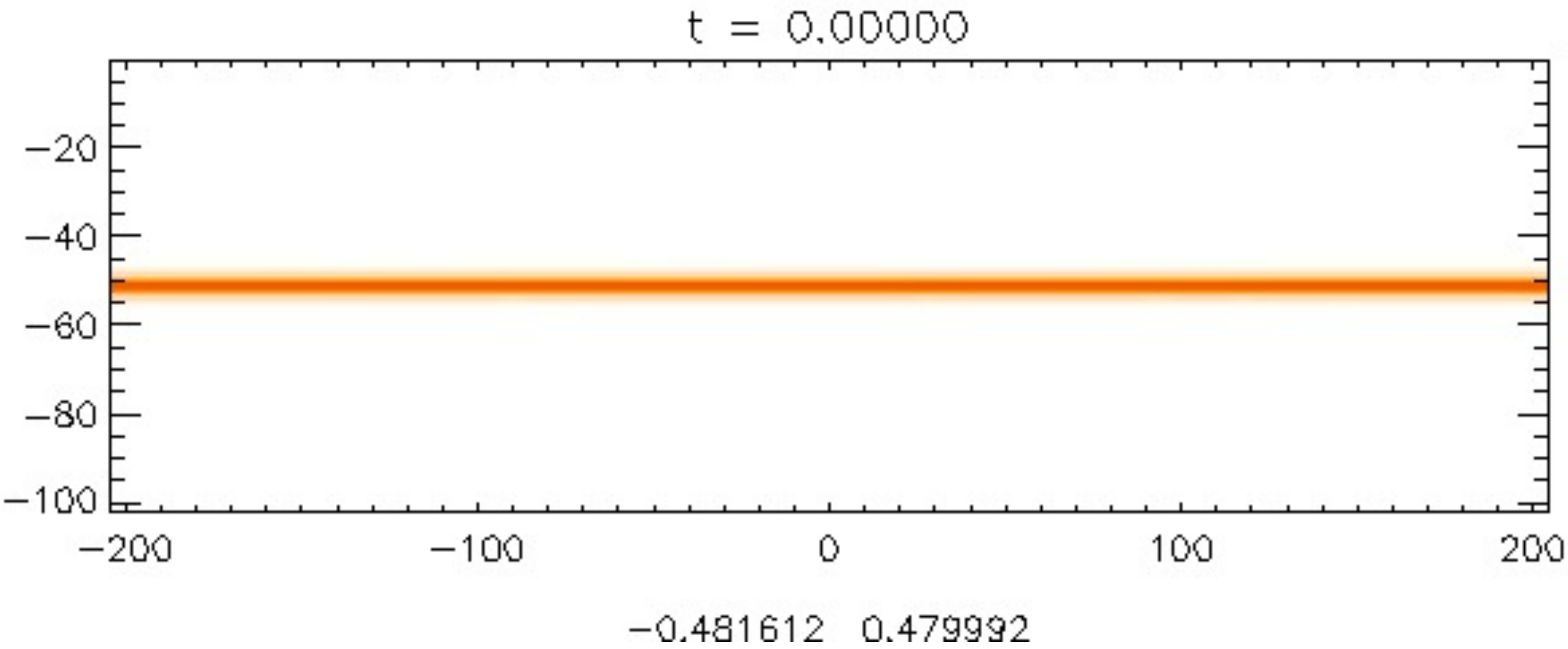
•Alfven time $\tau_A$ is much shorter than observed energy release time

# Magnetic Reconnection Basics




- Reconnection is driven by the magnetic tension in newly reconnected field lines
  - Drives outflow at the Alfven speed $c_A$
  - Pressure drop around the x-line pulls in upstream plasma
- Dissipation required to break field lines
  - At small spatial scales since dissipation is weak
- Reconnection is self-driven
  - No external forcing is required
- This picture is unaffected by an ambient magnetic field in the out-of-plane direction – the guide field
  - The guide field strongly impacts particle acceleration

# Transition to fast reconnection

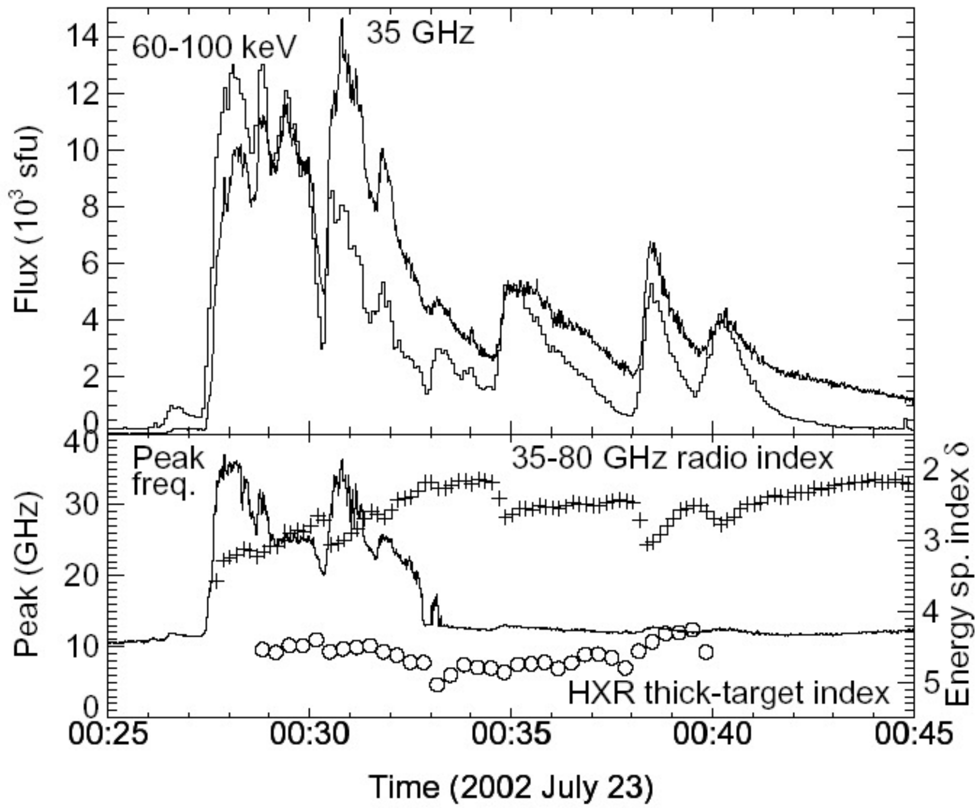



Reconnection inflow velocities around $0.1C_A$

Cassak et al 2005

# 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.

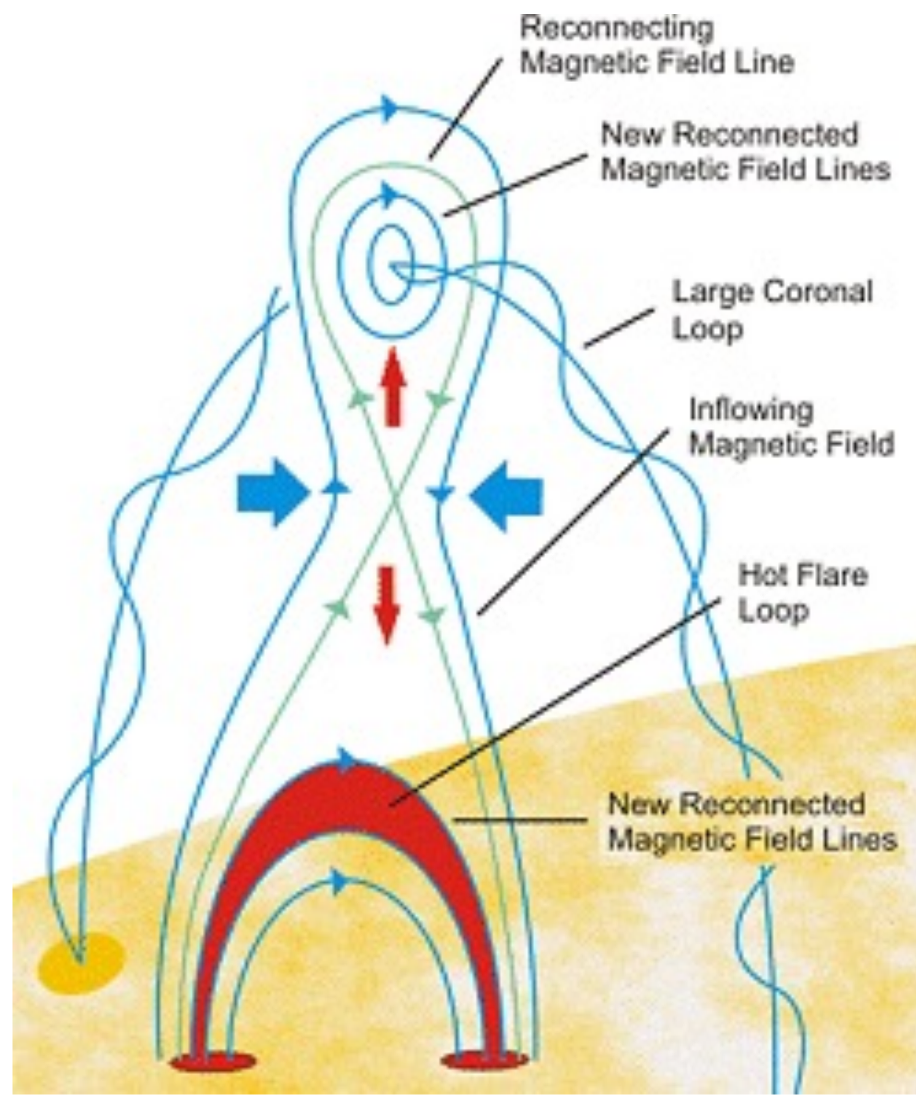



RHESSI and NoRH Data

(White et al., 2003)

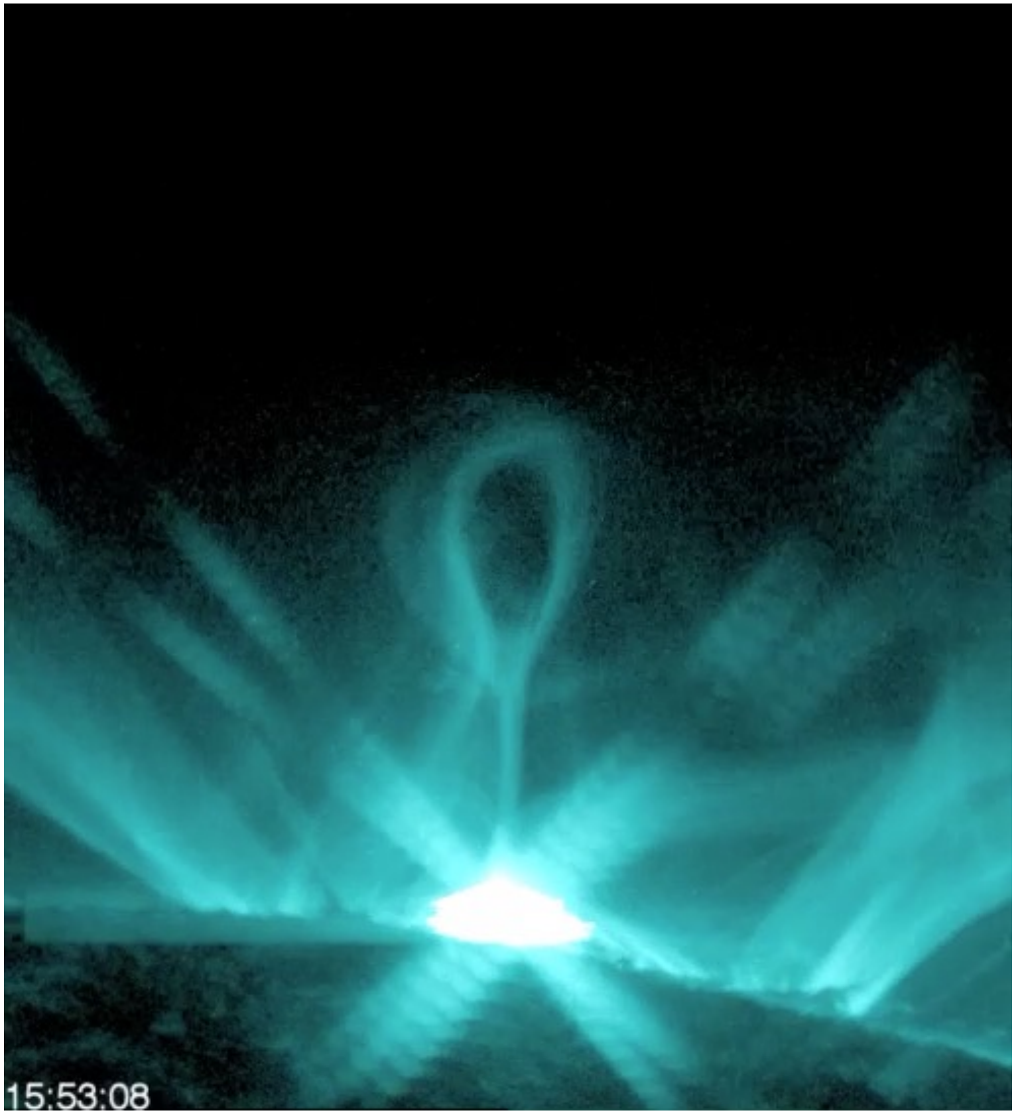
# Cartoon of solar flare reconnection

- Classic picture of reconnection during flare energy release



# Observation of large solar flare

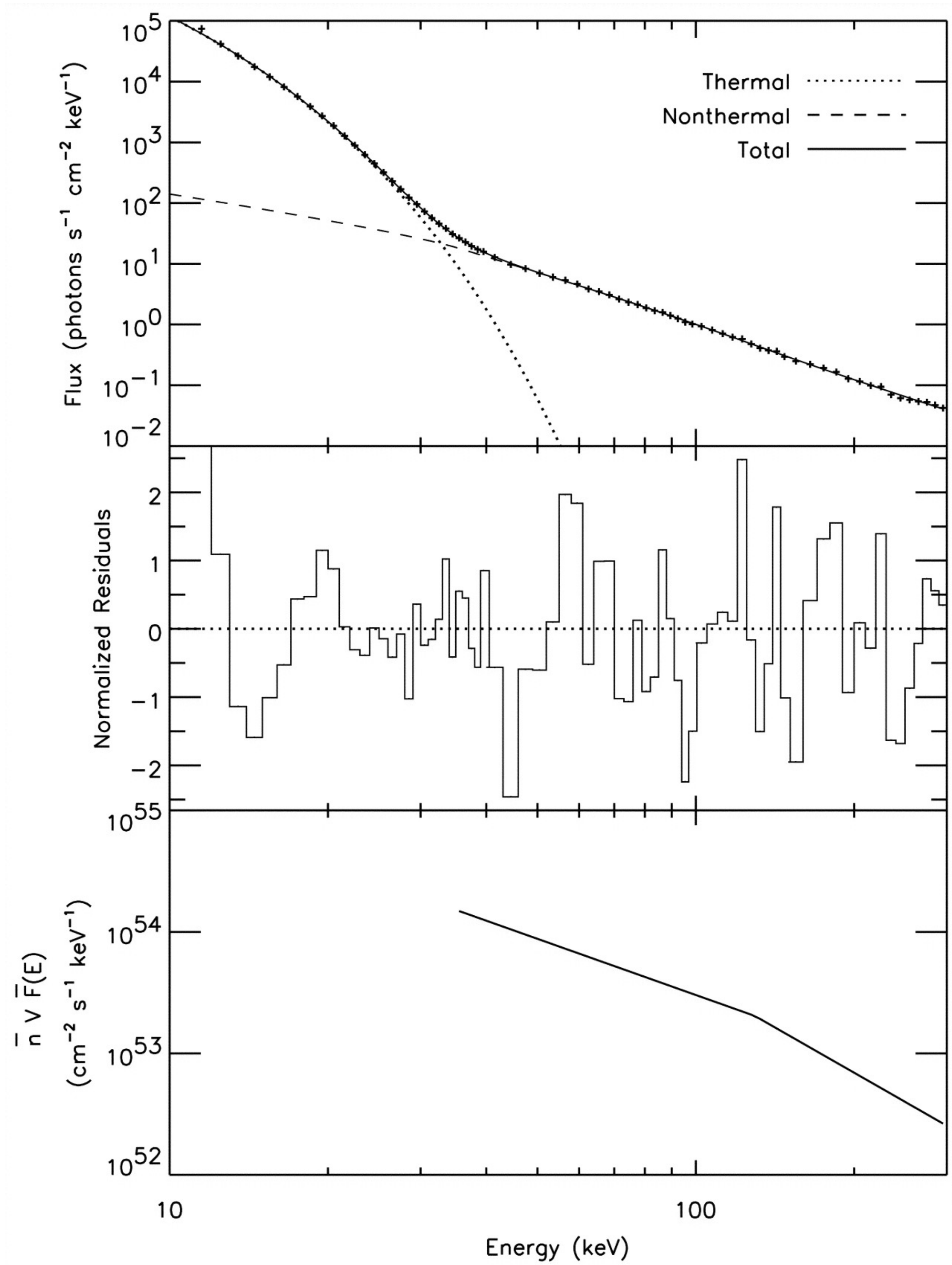
- September 10, 2017 X-class flare
- A limb flare
  - On the edge of the sun viewed from Earth
- Extreme ultra violet (EUV) imaging
- Consistent with classic flare cartoon



# Reconnection driven particle acceleration

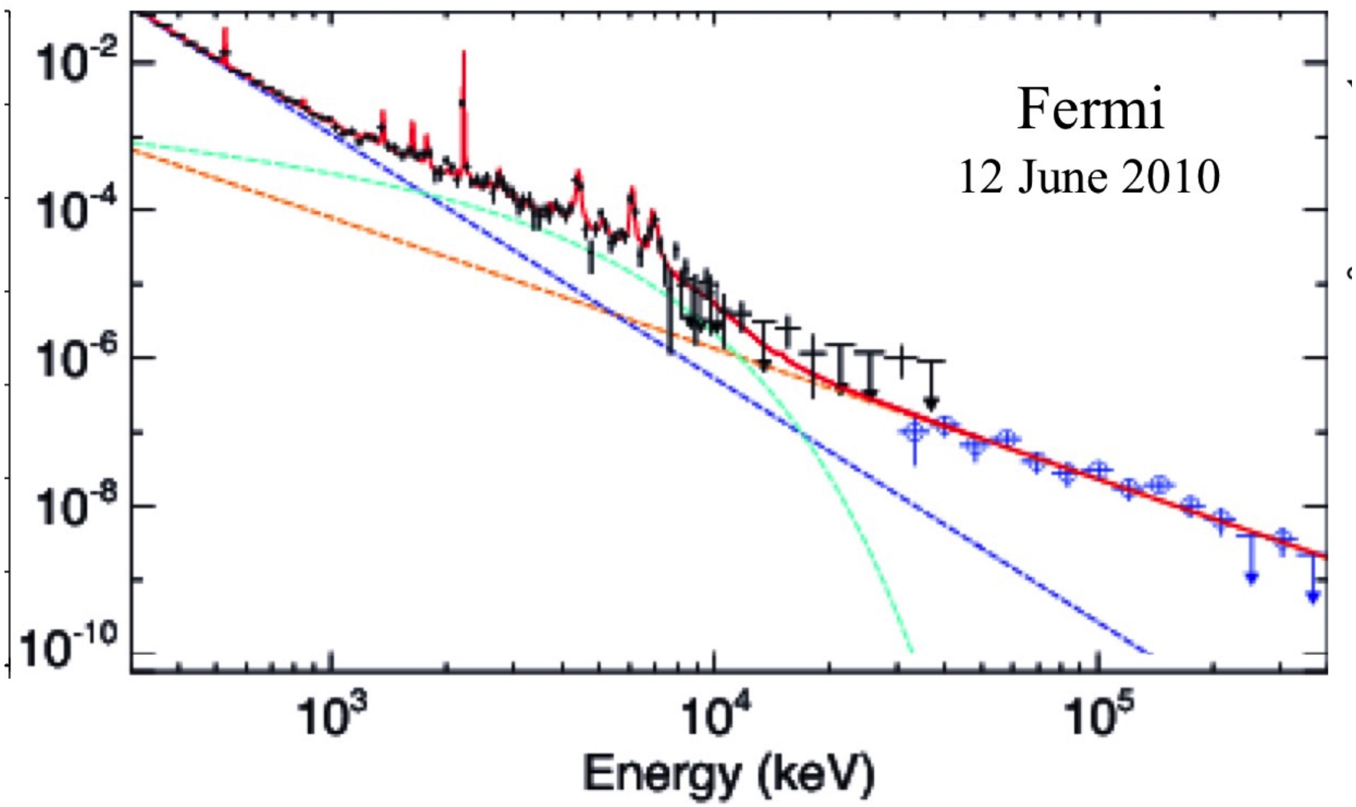
# RHESSI spacecraft observations

- 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)

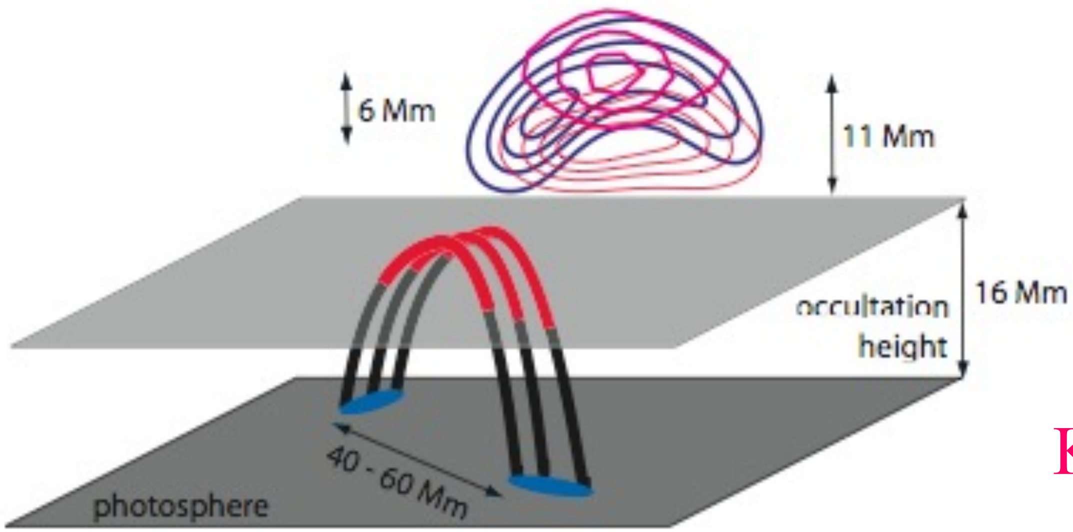


# Fermi solar flare observations

- June 12, 2010, γ-ray flare (Ackermann+ 2012)



# RHESSI occulted flare observations



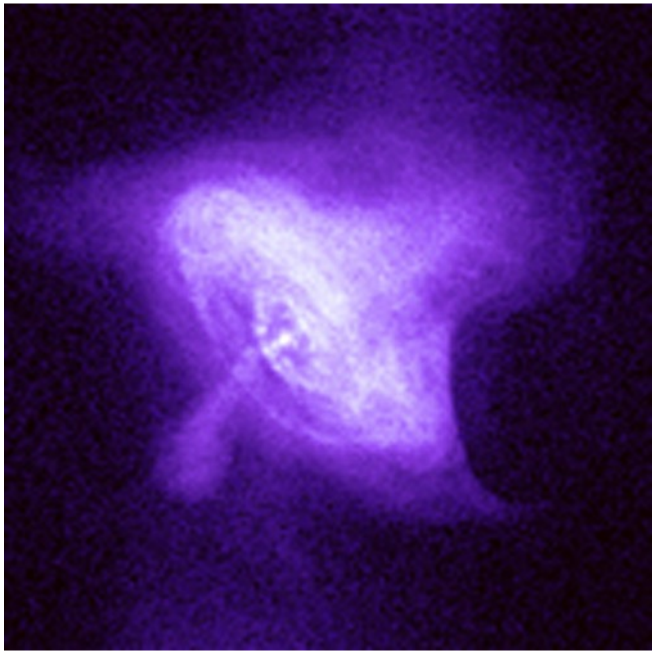

30-50keV

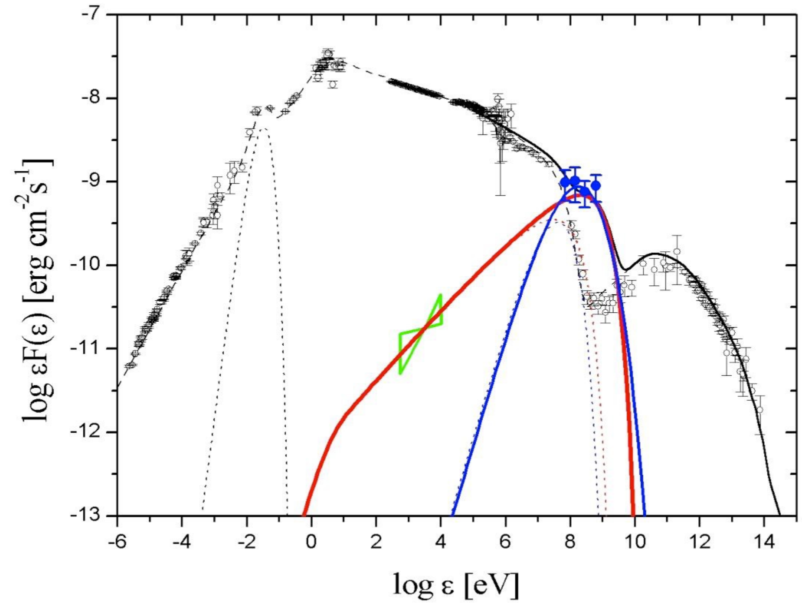
17GHz

Krucker et al 2010

- Direct observations of coronal x-ray sources are rare
  - Emission from energetic electrons striking the corona blinds the weaker source high in the corona where the plasma density is low
- 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

# Gamma-Ray Flares in the Crab






September 2010 AGILE/FERMI γ-flare

**Observational constraints:**

- Flare duration: $\tau = 1$ day --> $l \sim 3 \times 10^{15}$ cm
- Photon energy: > 100 MeV --> Particle energy ~ PeV
- Isotropic flare energy: $\sim 4 \times 10^{40}$ erg
- Reconnection mechanism? Shocks are too slow.

# Energy release during reconnection

- The change in magnetic topology for reconnection takes place in the "diffusion" region
  - A very localized region around the x-line
  - This is not where significant magnetic energy is released

- Energy release primarily takes place downstream of the x-line where newly-reconnected field lines relax their tension
- Mechanisms for particle heating and energization can not be localized in the "diffusion region"

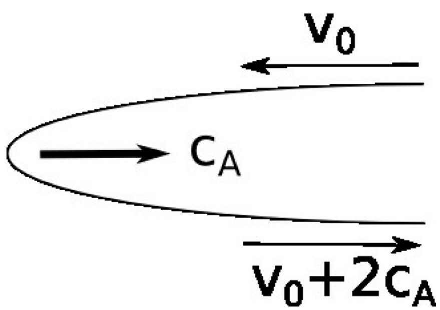
# Basic mechanisms for particle energy gain during reconnection

- In the guiding center limit

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

- Curvature drift
  - Slingshot term (Fermi reflection) increases the parallel energy

$$v_c = \frac{v_{\parallel}^2}{\Omega}\vec{b}\times(\vec{b}\bullet\vec{\nabla}\vec{b})$$




- Grad B drift
  - Betatron acceleration increases perpendicular energy – μ conservation

$$v_B = \frac{v_{\perp}^2}{2\Omega}\vec{b}\times\frac{\vec{\nabla}B}{B} \qquad \mu = \frac{mv_{\perp}^2}{2B}$$

# Particle-in-cell (PIC) simulation: basics

- The algorithm
  - Throw a bunch of particles on a grid
    - Electrons and protons or electrons and positrons
  - Advance the particle motion in electric and magnetic fields
  - Calculate the currents from the particles
  - Advance **E** and **B** using Maxwell's equations
- The constraints
  - The model must resolve all kinetic scales
  - The Debye length of order 0.1cm for coronal parameter

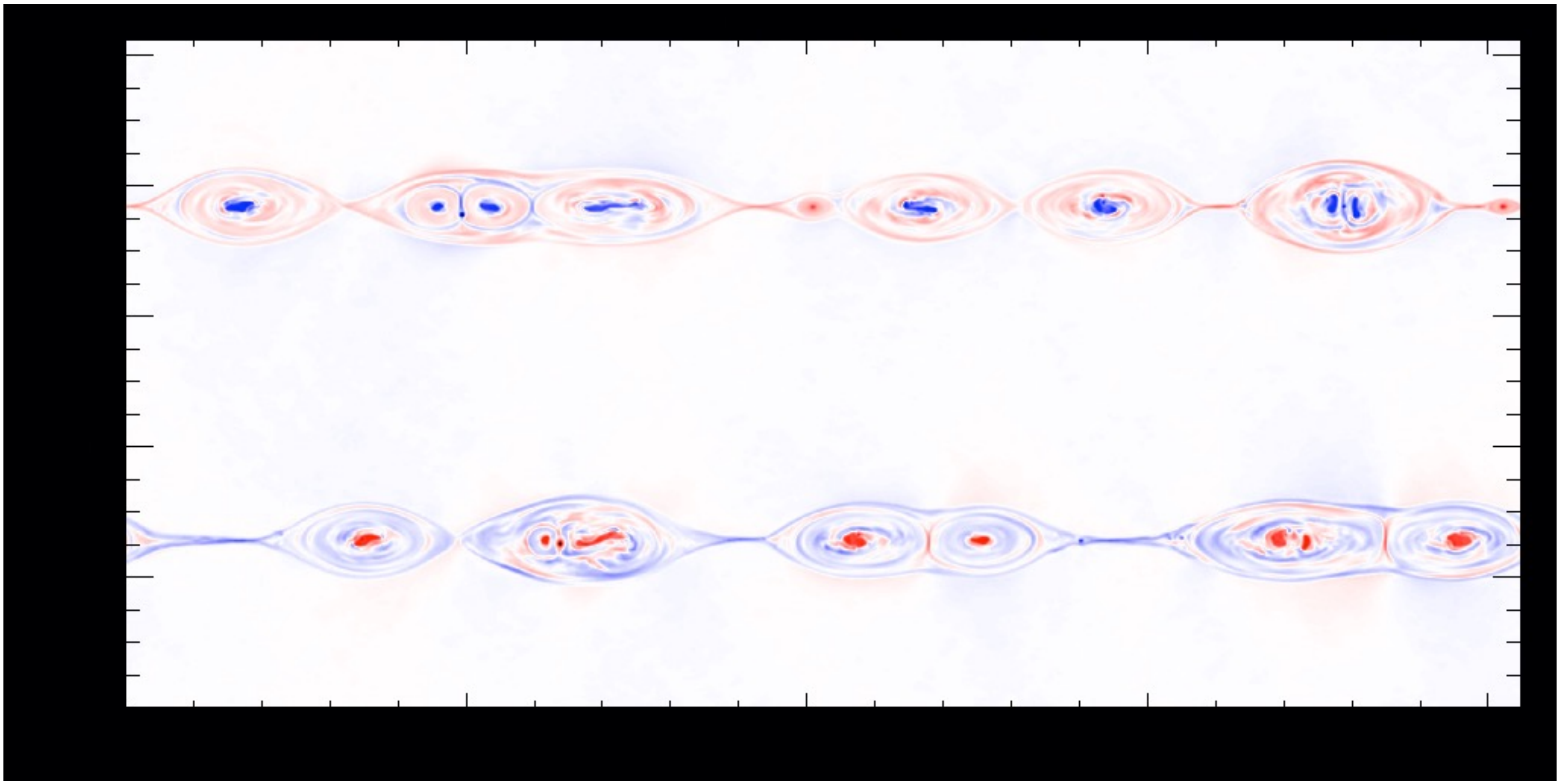
$$\lambda_{De} = \frac{v_{te}}{\omega_{pe}}$$

  - Characteristic flare sizes around $10^4$ km
- PIC models can only explore very small domains
  - Scale lengths of meters

# Electron heating during reconnection

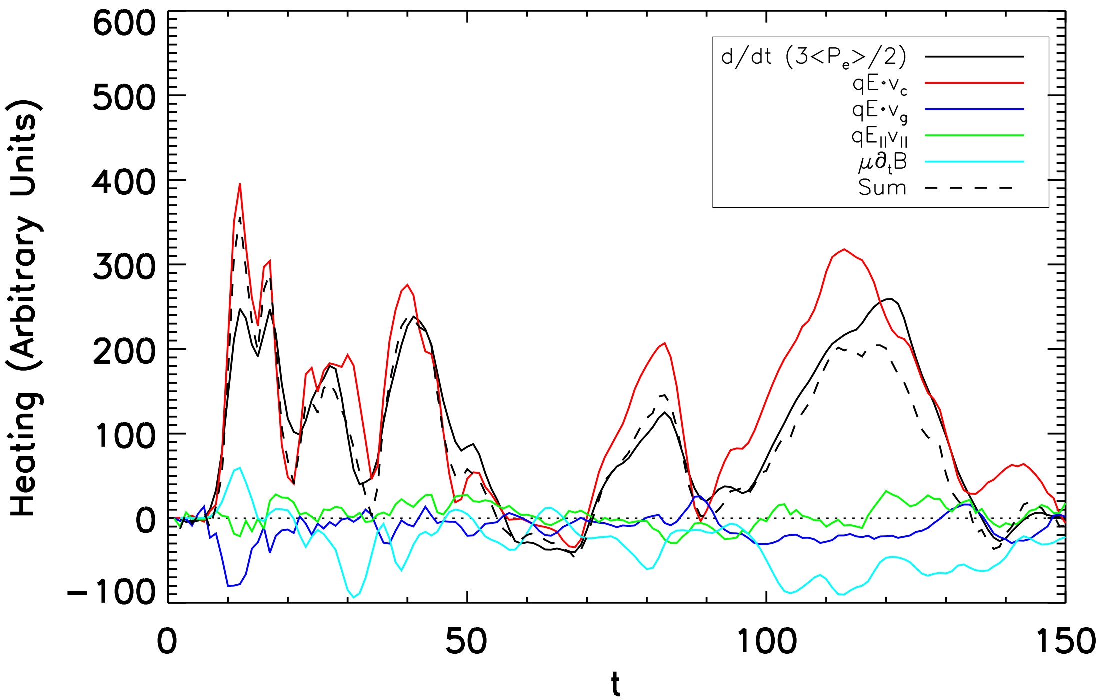
- Carry out 2-D PIC simulations of electron-proton system with a weak and strong guide fields (0.2 and 1.0 times the reconnection field)
  - $819.2d_i$ x $409.6d_i$ with $d_i$ the ion inertial length
  - Compare all of the heating mechanisms
  - Dahlin et al '14

$$d_i = \frac{c}{\omega_{pi}}$$



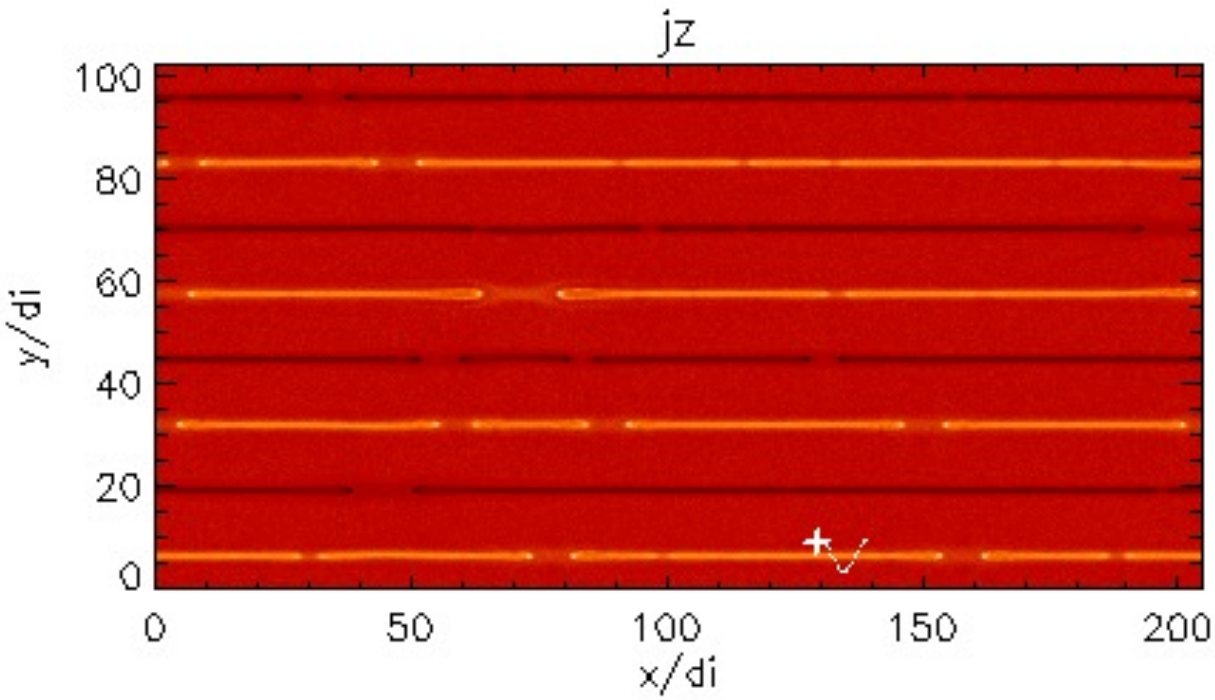
# Electron heating mechanisms: weak guide field

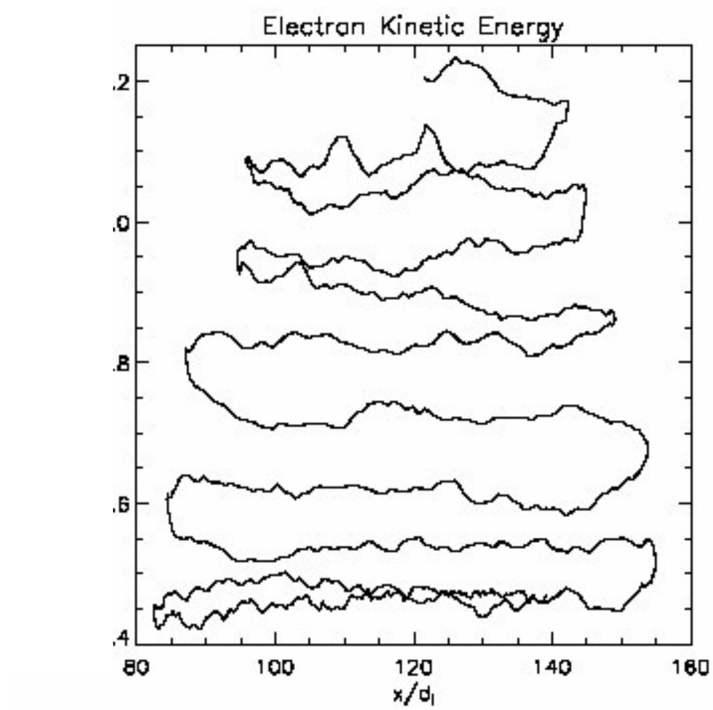
- Slingshot term dominates (Fermi reflection)
- Parallel electric field term small – a surprise
- Grad B term is an energy sink
  - Electrons entering the exhaust where B is low lose energy because μ is conserved.



# Electron Fermi acceleration

- How do the most energetic electrons gain energy?




Schoeffler et al 2011

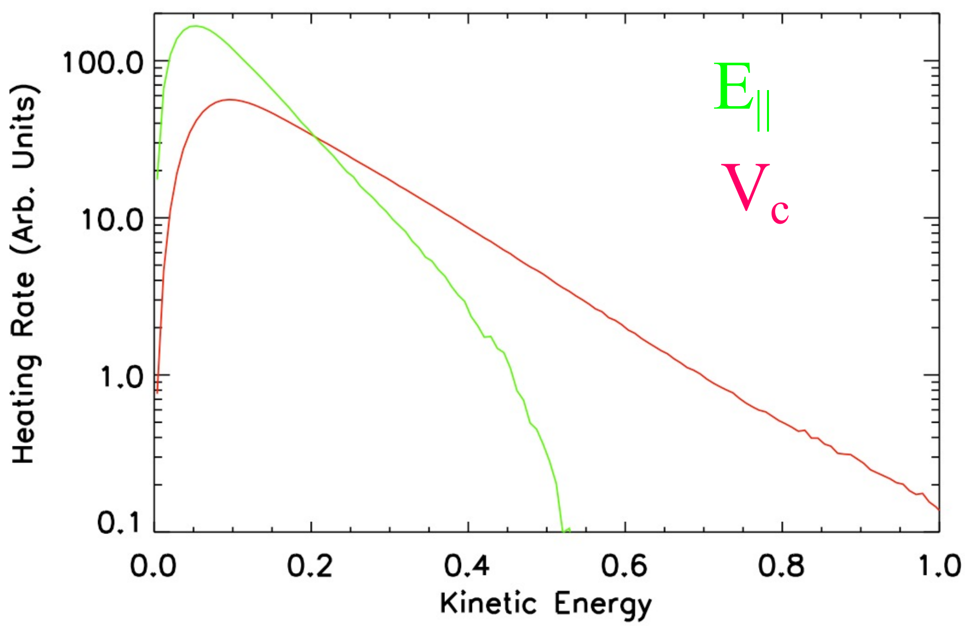
# Acceleration mechanism for highest energy electrons

- Fermi reflection dominates energy gain for highest energy electrons

$$\frac{d\varepsilon}{dt} \sim q v_{\parallel} E_{\parallel} + q \vec{v}_c \bullet \vec{E}$$

  - Where $v_c \sim v_{\parallel}^2$

- Recent simulations of pair and relativistic reconnection also see the dominance of Fermi reflection (Guo+ '14, Alfves+ '18)



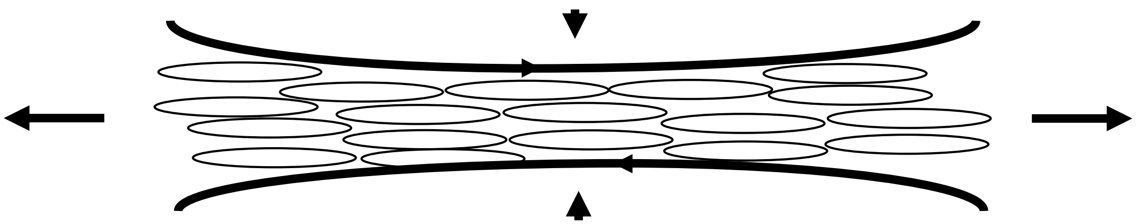
# Magnetic energy per particle

- The available magnetic energy per particle is a key parameter in both non-relativistic and relativistic reconnection
  - Non-relativistic: $W_0 = B^2/4\pi n = m_i C_A^2$
    - Around 20keV for flares
  - Relativistic: $\sigma = B^2/4\pi nmc^2$
    - Can be large in many astrophysical systems
- The available magnetic energy per particle is not sufficient to explain the most energetic particles in flares

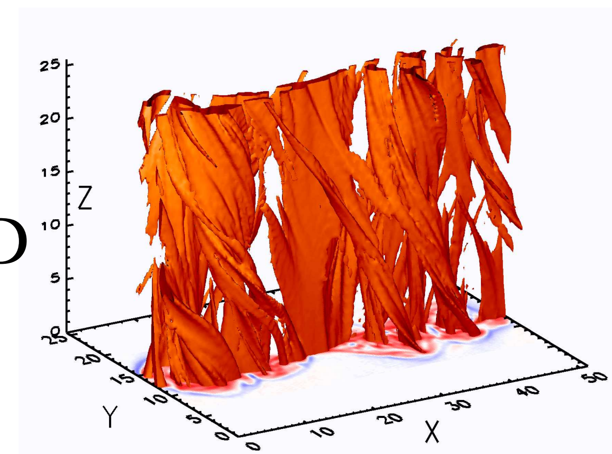
# Particle acceleration in multi-island reconnection

- Single x-line reconnection can not explain the most energetic particles seen in flares
  - Energy gain limited to around 10keV in solar flares
- Greater energy gain in contracting and merging magnetic islands

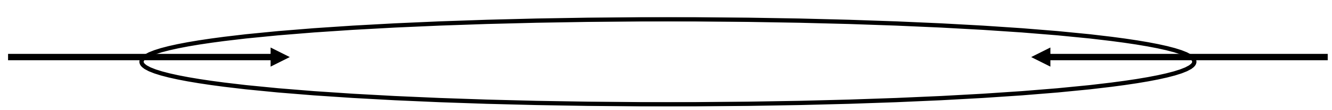
Tajima and Shibata '97
Drake et al '06
Oka et al '10
Dahlin et al '15



3D




2D

$C_{Ax}$

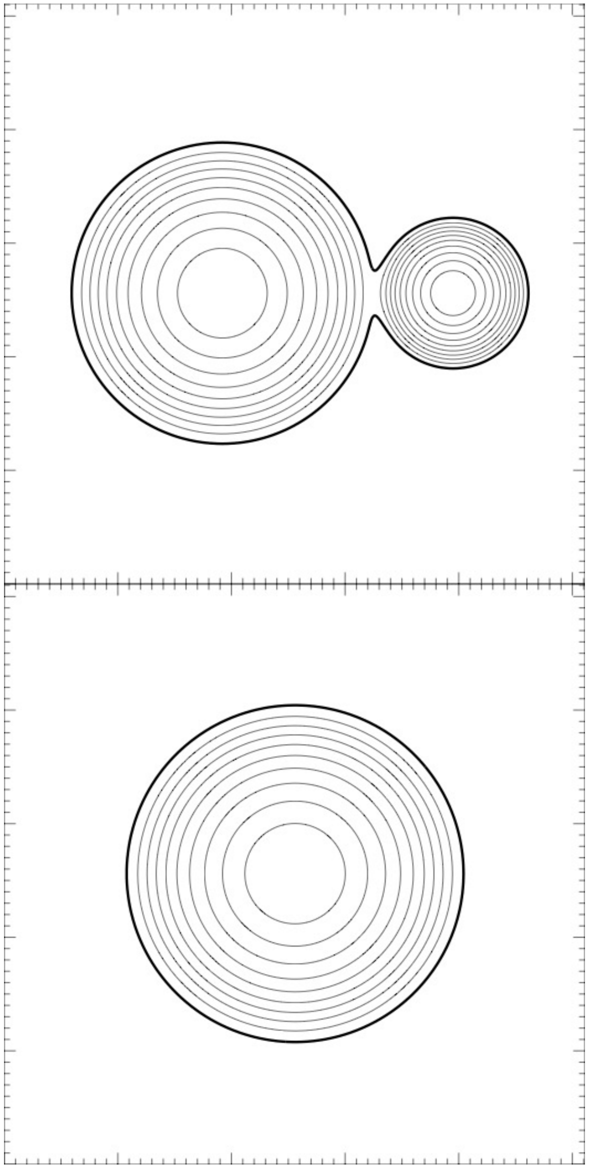
# Energy gain during the merging of islands

- Total area preserved during merger
- Magnetic flux is preserved
- Merging islands shorten field lines
- Parallel action is conserved $p_{||} L$
  - L goes down during merger so $p_{||}$ goes up
- The merger of two equal sized islands doubles the parallel energy of particles within the islands
- Time scale of island merging

$$t_{merge} \sim \frac{r}{0.1 c_A}$$

- Rate of particle energy gain

$$\frac{dW}{dt} \sim \frac{W}{t_{merge}}$$



Drake et al ’13
Montag et al ‘17

# MeV electrons in a coronal hard x-ray source

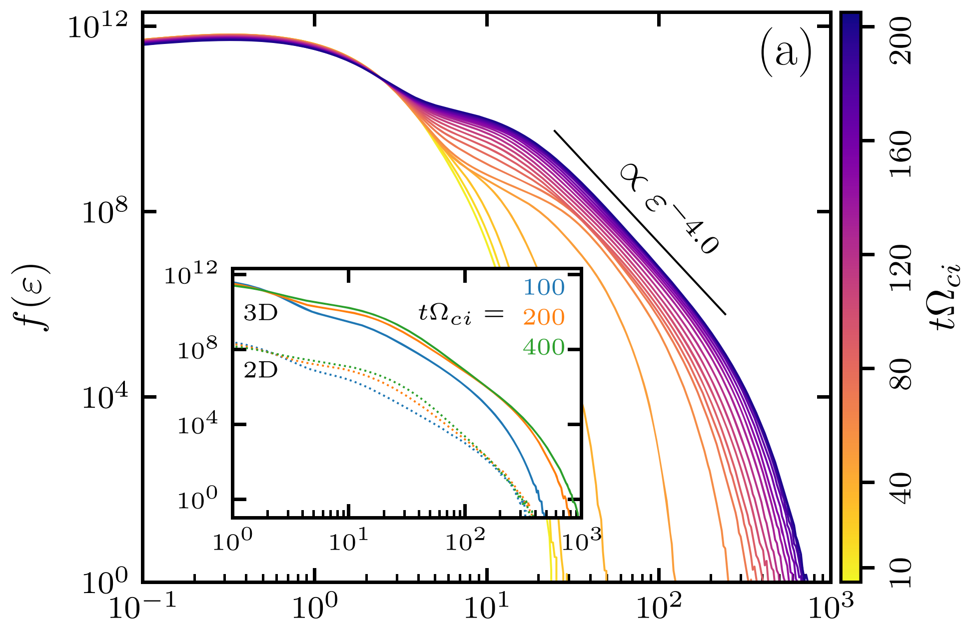
- How to get MeV electrons in the corona?
  - A two-step process – heating in single x-line reconnection following by island merging
- First step: single x-line reconnection splits released energy between electrons, ions and bulk flow
  - $T_e \sim 0.25 m_i C_A^2$
  - For B ~ 50G, with n ~ $10^9 cm^{-3}$, obtain $T_{hot} \sim$ 10keV
- Second step: island mergers
  - Each merger doubles the electron energy – field line shortening
  - How many island mergers takes 10keV electrons to 1MeV?

$$15 keV \times 2^N = 1 MeV \Rightarrow N = 6$$

  - Take typical island of size W ~ $10^3$km
  - Two island merging time $t_{merge} \sim (W/2)/0.1 c_A \sim 1.5 s$
  - 1MeV electrons in $t_{1MeV} \sim 6 t_{merge} = 9 s$

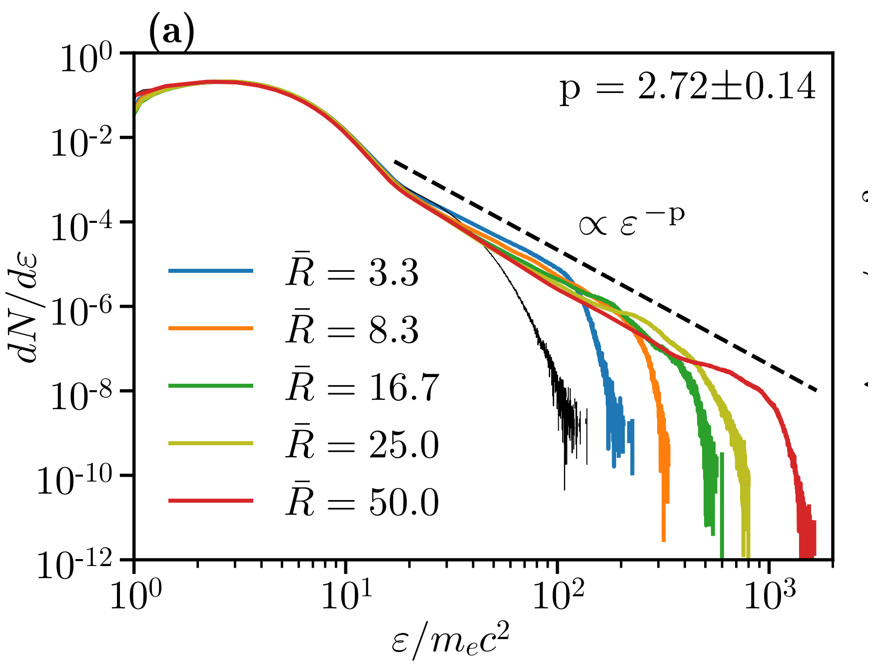
# Powerlaw spectra from 3D PIC reconnection simulations: non-relativistic

- Simulations of reconnection and particle acceleration
  - Turbulent reconnection in 3D systems
  - Powerlaw limited to around a decade in energy
  - PIC models are not producing the extended powerlaws seen in observations
  - Why?



# Powerlaw spectra from 3D PIC reconnection simulations: non-relativistic

- PIC simulations of astrophysical jets (Alfves+ 2018)
  - $\sigma = 5$
  - Limited range of the powerlaw because of limited PIC domain



# Modeling particle acceleration in macrosystems: the *kglobal* model

- PIC models have insufficient separation between kinetic and the system size
  - The scale size of structure that develop are at spatial scales that are too
  - Small structures scatter particles when the particle gyroradius reaches the size of the structure
    - Rate of energy gain strongly reduced once particles are demagnetized
- The *kglobal* simulation model eliminates these deficiencies
  - Eliminates kinetic scale boundary layers
  - Includes electron particles on a grid as in the PIC model
  - Includes the feedback of energetic particles on the plasma dynamics
- Can now simulate particle acceleration in macro-systems

Drake+ '19, Arnold+ 19, Arnold+ '21

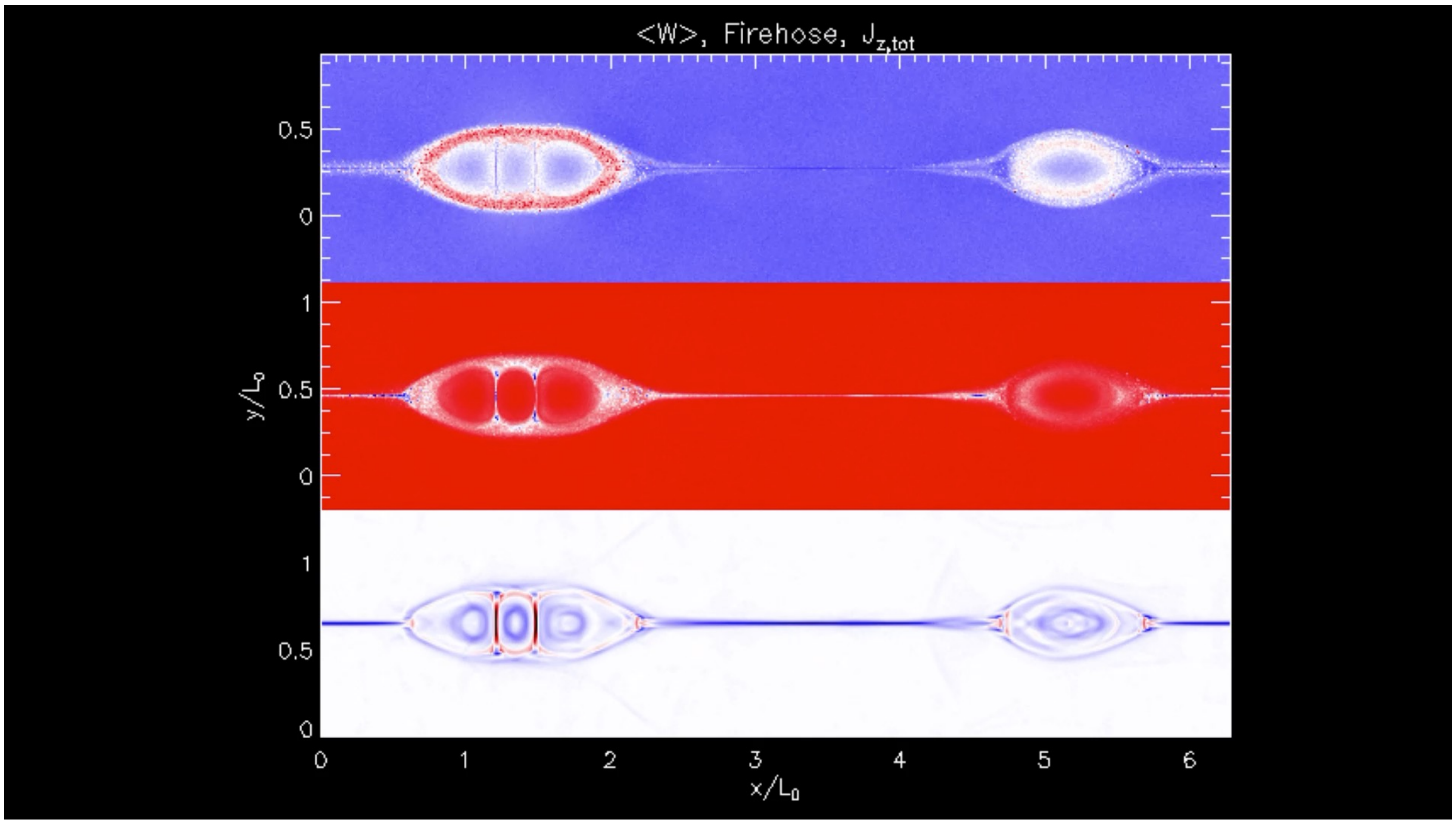
# *kglobal* reconnection results

- Time development of reconnection with electron acceleration in a macro-system
  - Simulation domain ~ $10^4$ km

Electron Energy

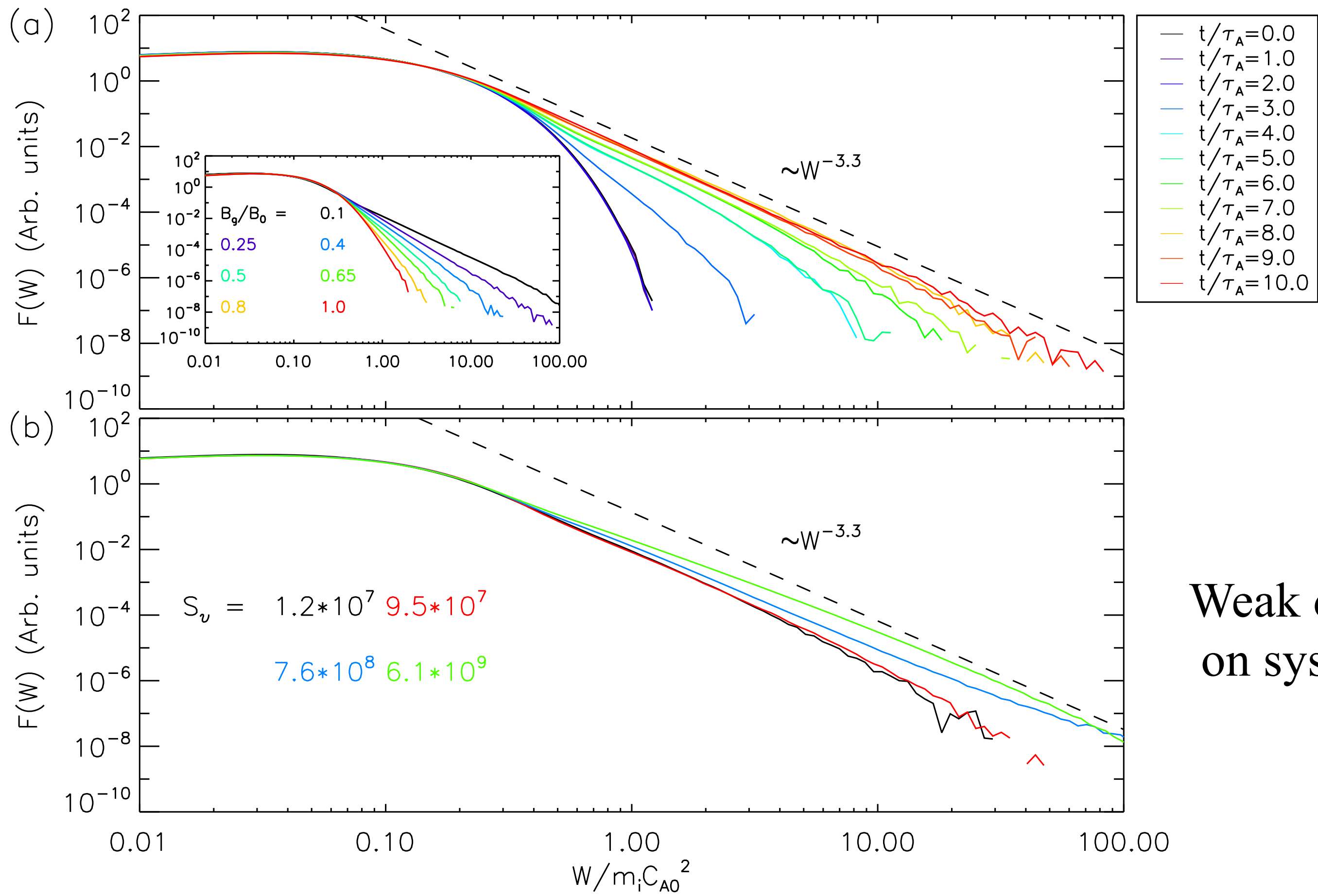
Firehose parameter

Current



# Electron energy spectra

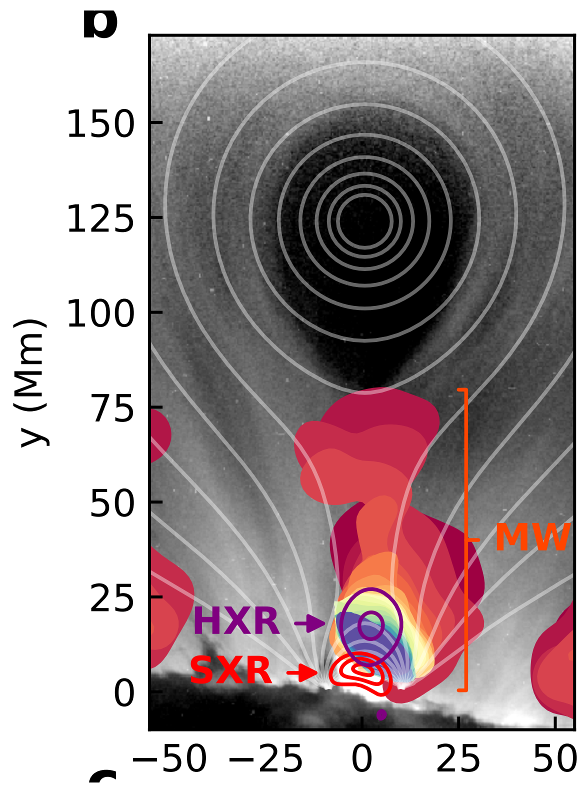
- Electron powerlaw spectra from *kglobal*
  - Powerlaws extend nearly three decades in energy
  - Strong dependence on the ambient out-of-plane magnetic field
    - Suppresses field line contraction

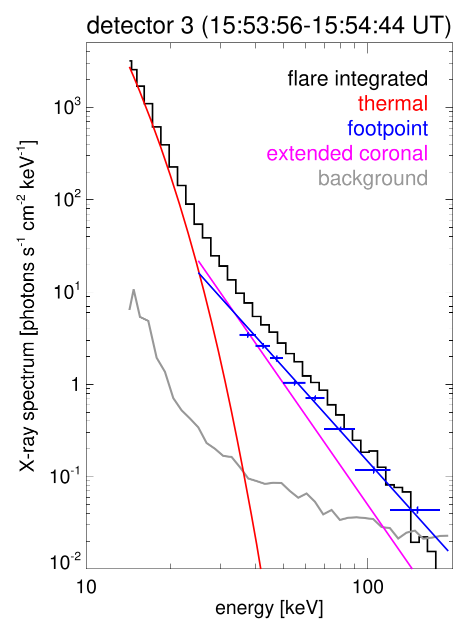



Weak dependence on system size

# Comparison with a large limb solar flare

- An X-class limb flare occurred on Sept. 10, 2017
  - Gyro-synchrotron emission from the Expanded Owens Valley Solar Array
    - Space/time evolution of energetic electron spectral indices and coronal magnetic field
  - X-ray data from RHESSI
  - Comparison of spectral indices
    - RHESSI 3.9
    - Kglobal 3.5
    - No free parameters



# Main Points

- Solar observations suggest that magnetic energy conversion into energetic electrons is extraordinarily efficient
- Acceleration of energetic particles dominated by Fermi reflection in both relativistic and non-relativistic reconnecting systems
- Multi-x-line reconnection is required to produce the energetic component of the particle spectrum
  - PIC simulations have not been able to produce the extended power tails of energetic electrons seen in observations
    - Small simulation domains distort the dynamics of particle energy gain
  - *kglobal* simulations produce extended powerlaw tails
    - Powerlaw indices sensitive to the ambient guide field
- An analytic model based on magnetic island merger reproduces the key results of the *kglobal* simulations
- An upgrade is planned to include particle ions in the model