Energy dissipation and particle acceleration during reconnection

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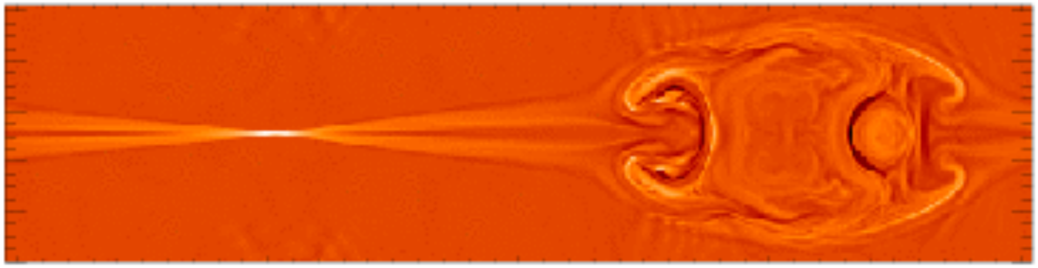
Energy release during reconnection

- 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 most of the magnetic energy is released



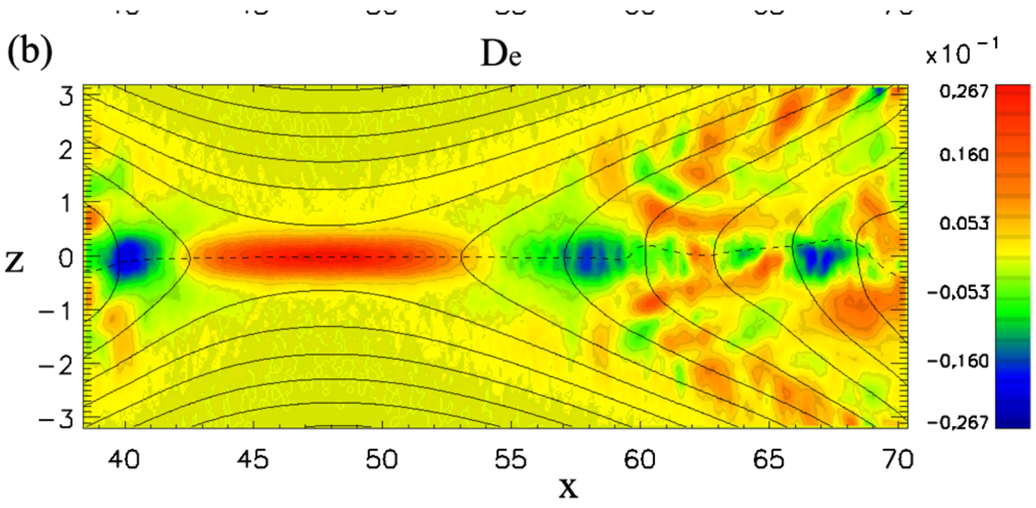
- Energy release primarily takes place downstream of the x-line where newly-reconnected field lines relax their tension
- How is magnetic energy dissipated in the reconnection exhaust?
  - What about the Zenitani et al dissipation measure, which peaks in the diffusion region and not in the exhaust?

The dissipation measure

- Zenitani et al proposed a dissipation measure that is defined by writing the dissipation in the electron frame

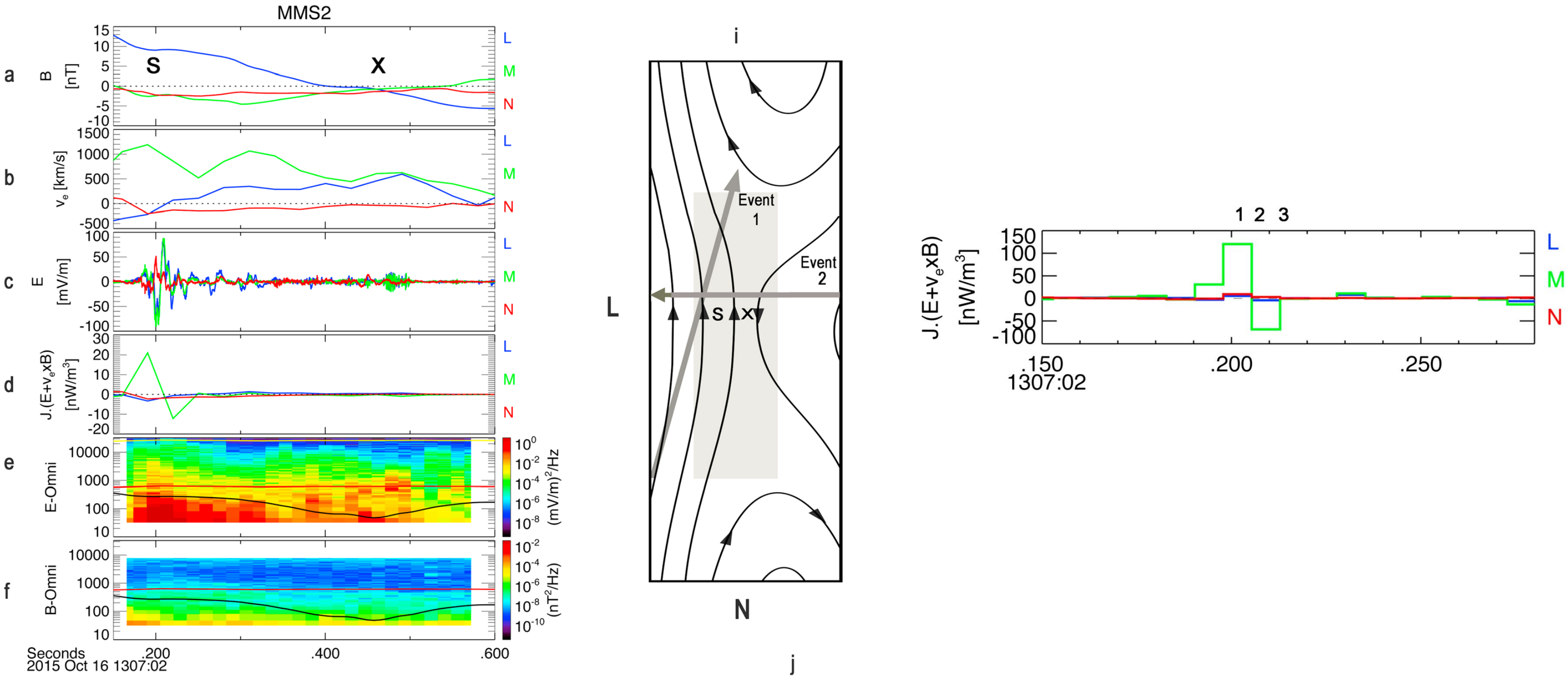
$$\vec{J} \bullet \vec{E}' = \vec{J} \bullet \left(\vec{E} + \frac{1}{c} \vec{v}_e \times \vec{B} \right)$$

- This dissipation parameter is effective in defining the location of the dissipation region



Oscillatory dissipation from MMS observations

- MMS data revealed that the electron frame dissipation could be very intense and could take on positive and negative values (Burch et al 2018)



- Negative excursion due to electron bounce motion in the intense E_N at the magnetopause (Swisdak et al 2018)

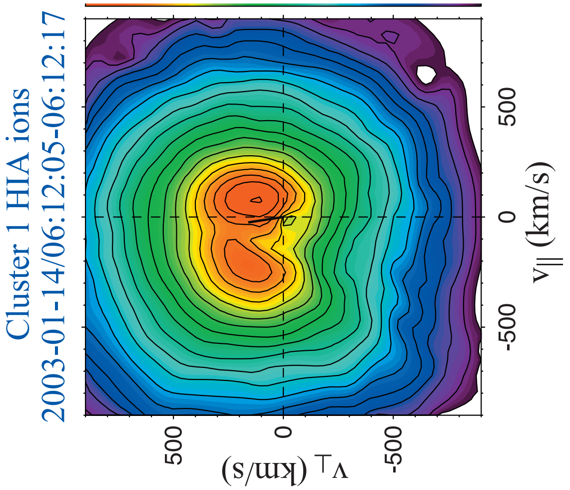
Ions dominate energy gain in magnetosphere observations

Hoshino et al '98
Gosling et al '05
Phan et al ' 07
Eastwood et al '13

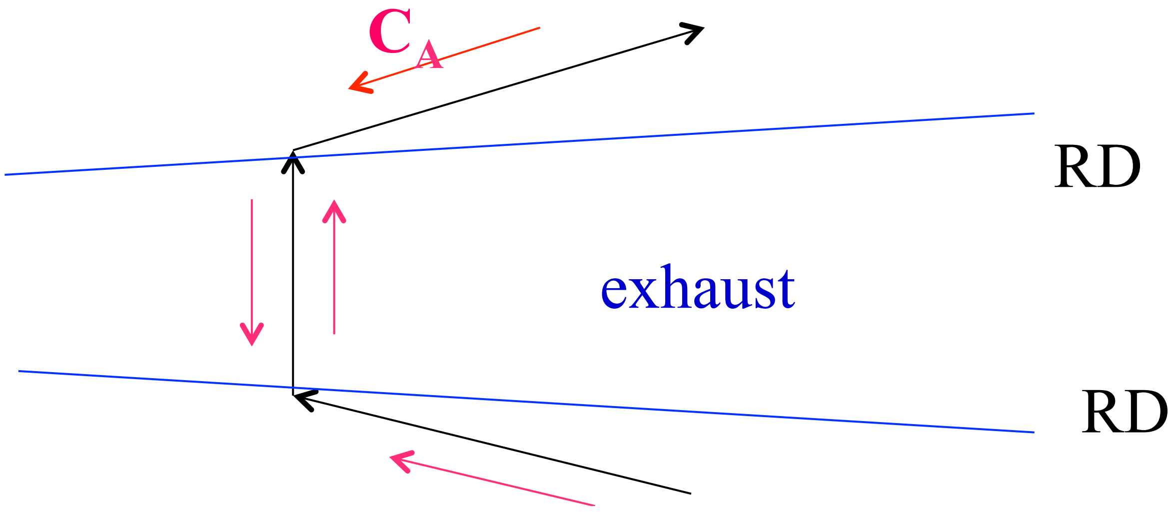
- Ion energy gain from Fermi reflection
  - leads to large parallel heating of ions
  - Measured throughout the magnetosphere
- Measured scaling of ion temperature consistent with Fermi reflection (Phan et al 2014)

$$\Delta T_i \sim 0.13 m_i c_A^2$$

- Ion energy gain would be zero in the ion moving frame



$$\Delta T \sim \frac{1}{3} m_i c_A^2$$



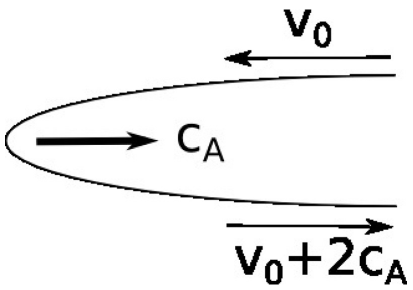
Basic mechanisms for particle energy gain during reconnection

- In the guiding center limit

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

- Curvature drift $\left(\sim J_{\perp} \bullet E_{\perp}\right)$
  - Slingshot term (Fermi reflection) increases the parallel energy

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



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

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

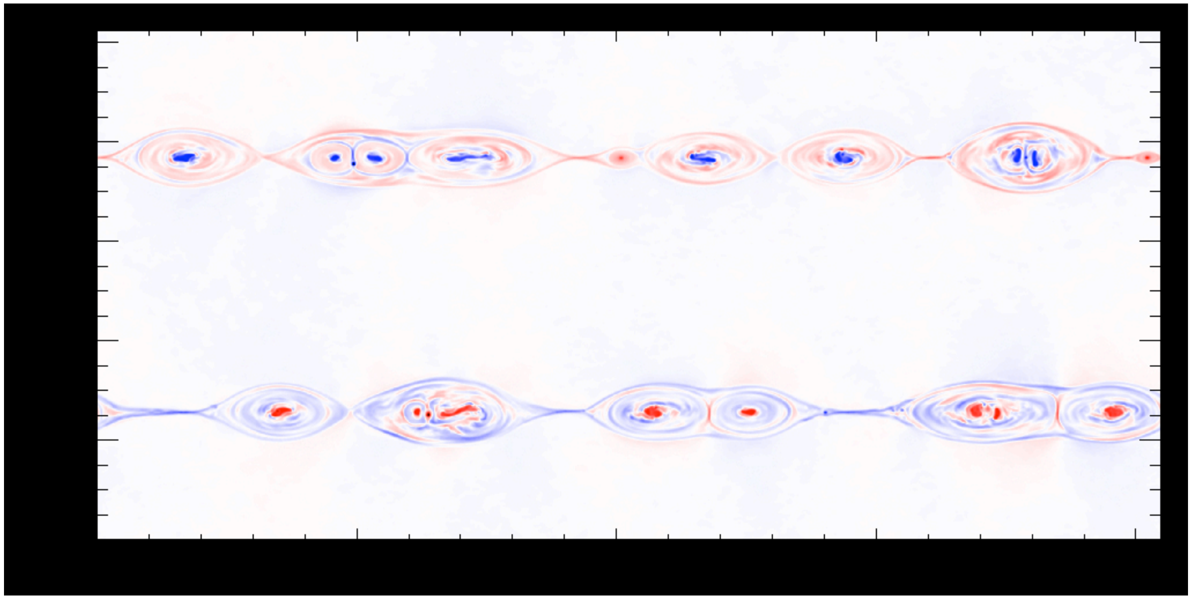
$$\mu = \frac{mv_{\perp}^2}{2B}$$

Electron heating during reconnection: dependence on guide field

- Carry out PIC simulations of reconnection with a range guide fields

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

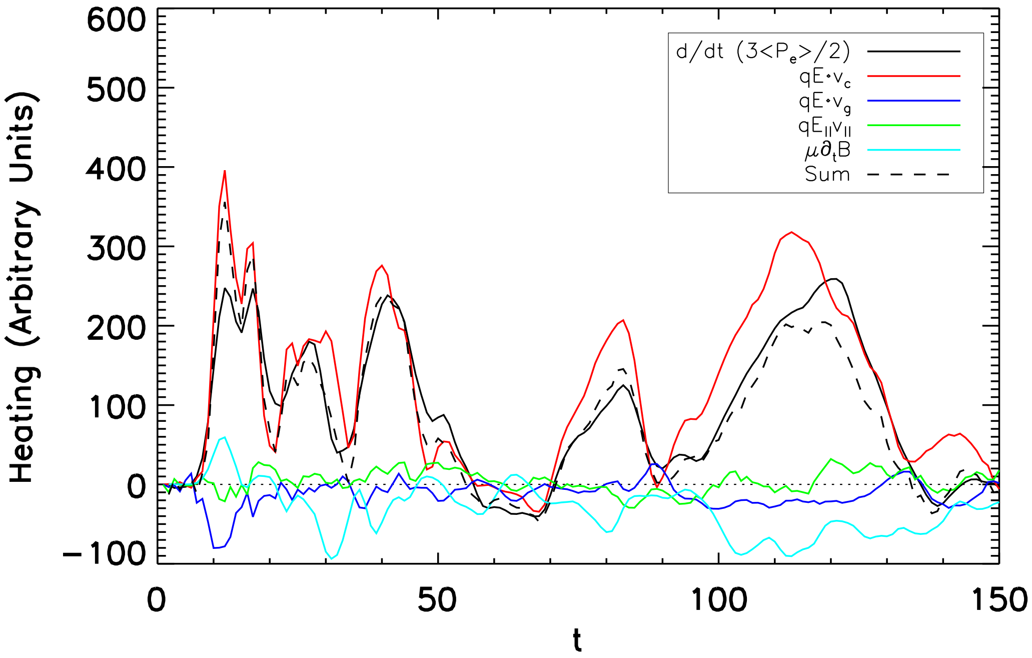
- Focus here on 2D -- 819.2d_i x 409.6d_i
  - Compare all of the heating mechanisms
  - Dahlin et al ’14, ’17



Electron heating mechanisms: weak guide field

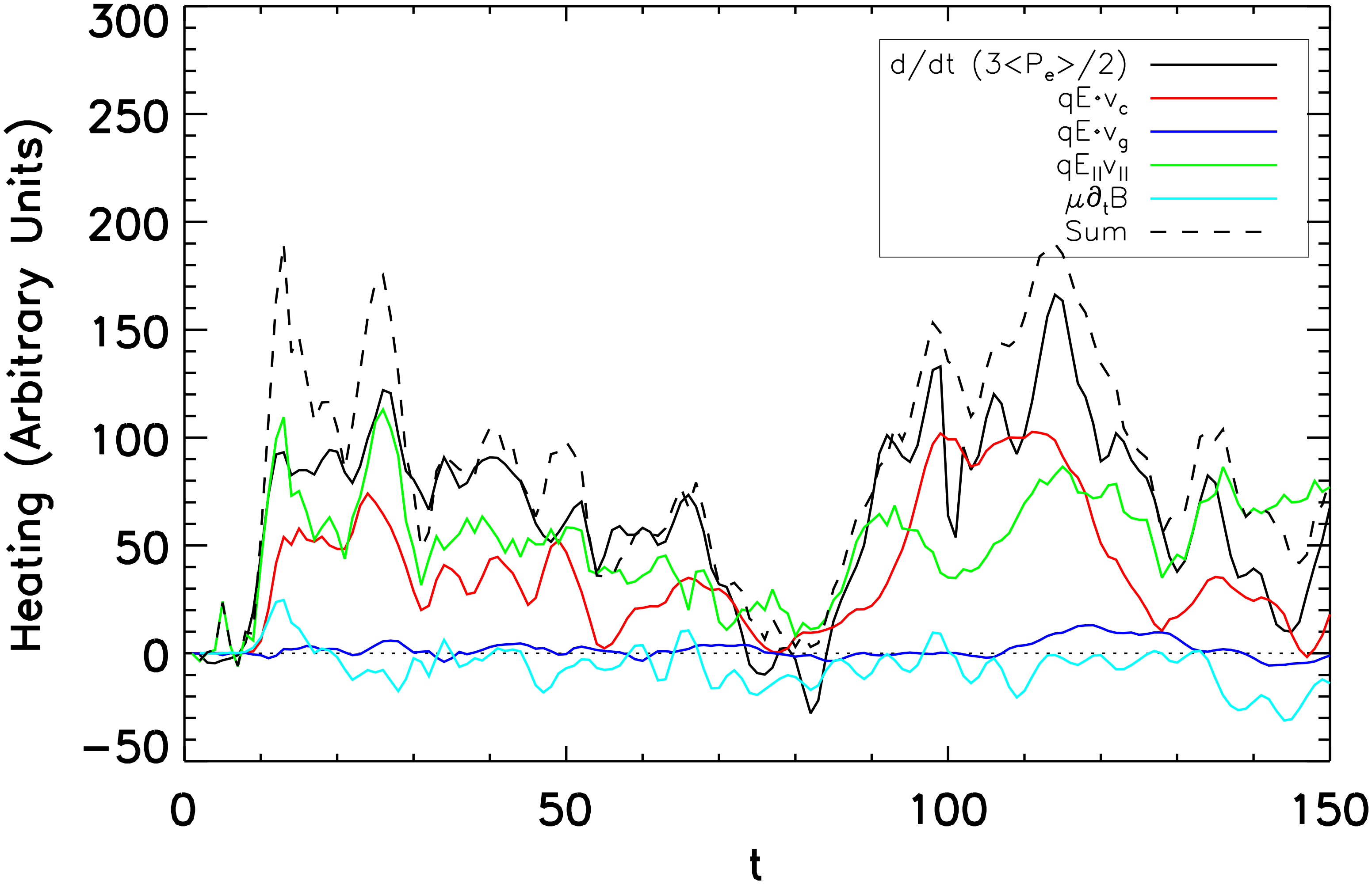
- Slingshot term dominates (Fermi reflection)
- Parallel electric field term small – a surprise
- Grad B term is an energy sink
  - Electrons entering the exhaust where B is low lose energy because μ is conserved.

$B_g=0.2B_r$



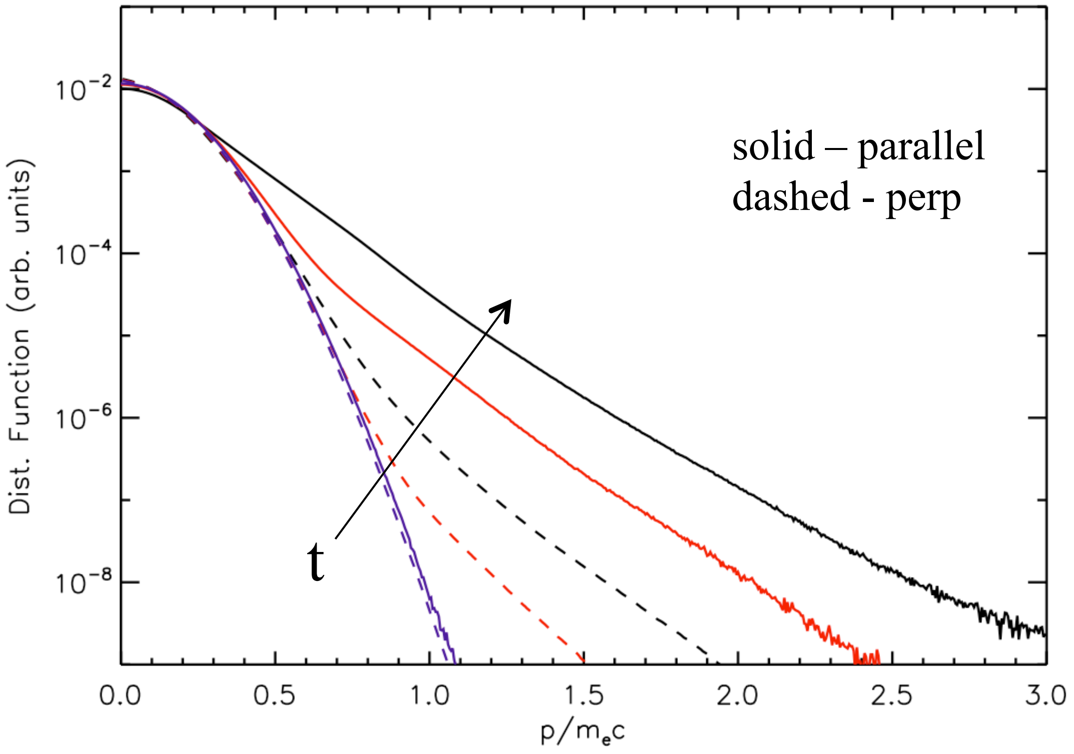
Electron heating mechanisms: strong guide field

- Fermi and parallel electric field term dominate
  - Longer current layers where $E_{\|} \neq 0$ with a guide field



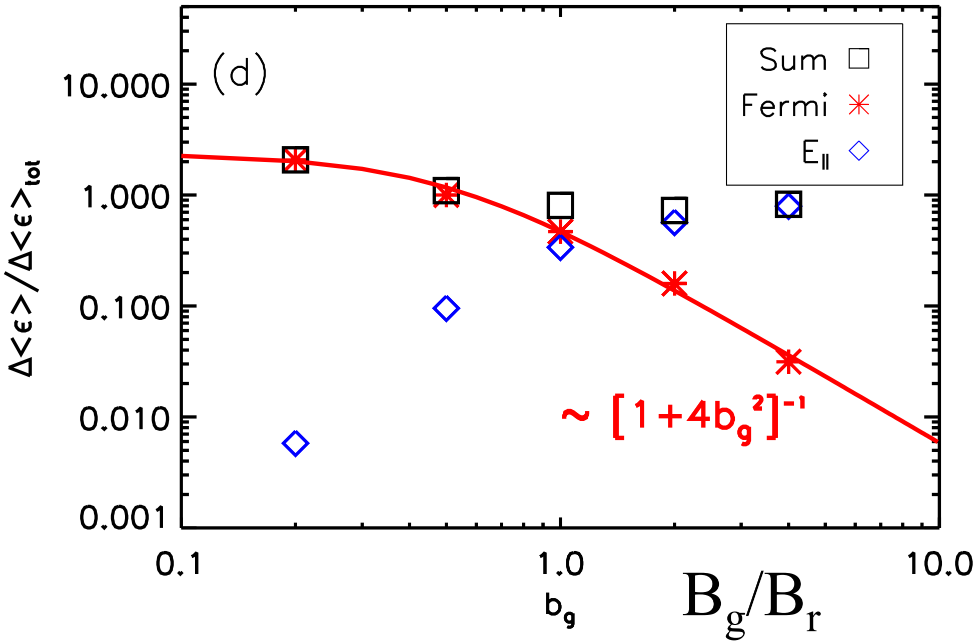
Electron spectral anisotropy

- The dominant acceleration mechanisms accelerate electrons parallel to the local magnetic field – Fermi slingshot and $E_{||}$
  - Extreme anisotropy in the spectrum of energetic electrons



Electron heating: dependence on the guide field

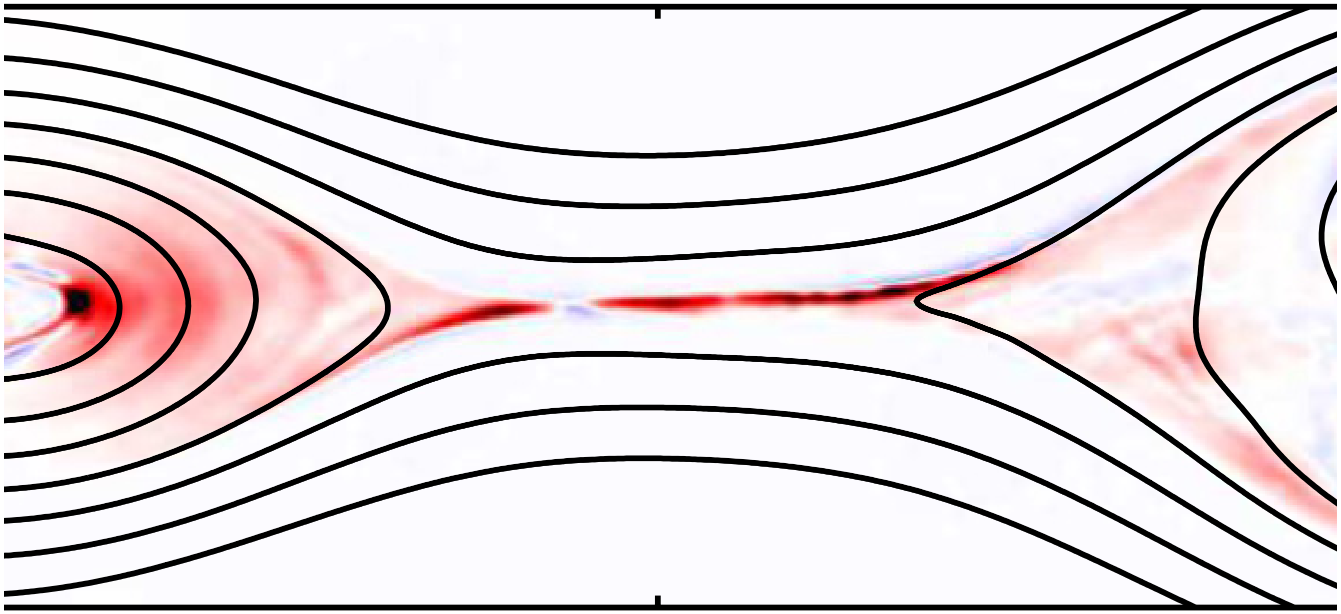
- Fermi reflection dominates for weak guide field
  - Drops off sharply with increasing guide field
    - Magnetic field radius of curvature increases with guide field
- $E_{||}$ dominates for strong guide field
  - Why does $E_{||}$ heating increase with the guide field?
- Trend consistent with Wilder et al. 2018



Dahlin et al ‘16

Spatial distribution of heating rate from Fermi reflection

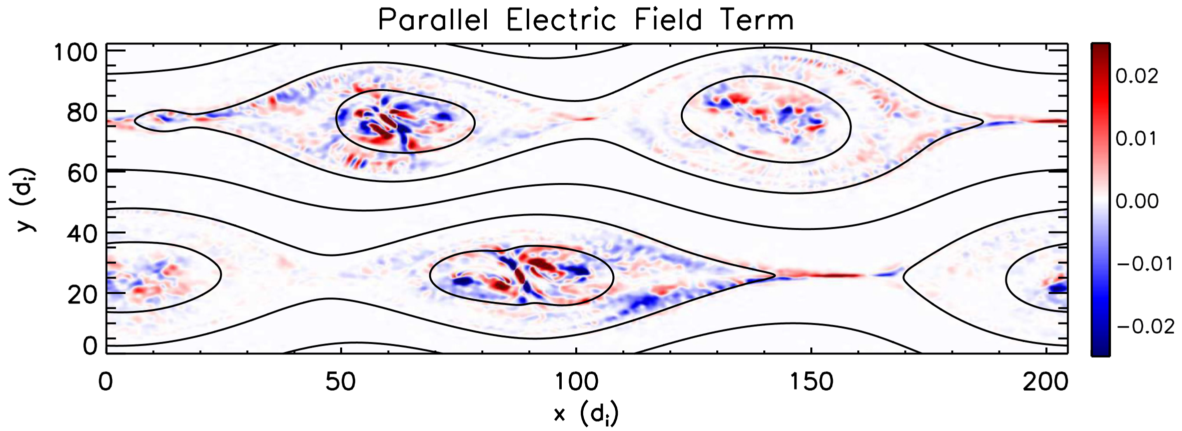
- Electron heating rate from Fermi reflection
  - Fills the entire exhaust
  - Not localized to narrow boundary layers at small spatial scales
  - Dissipation in collisionless plasma is very different from that in fluids



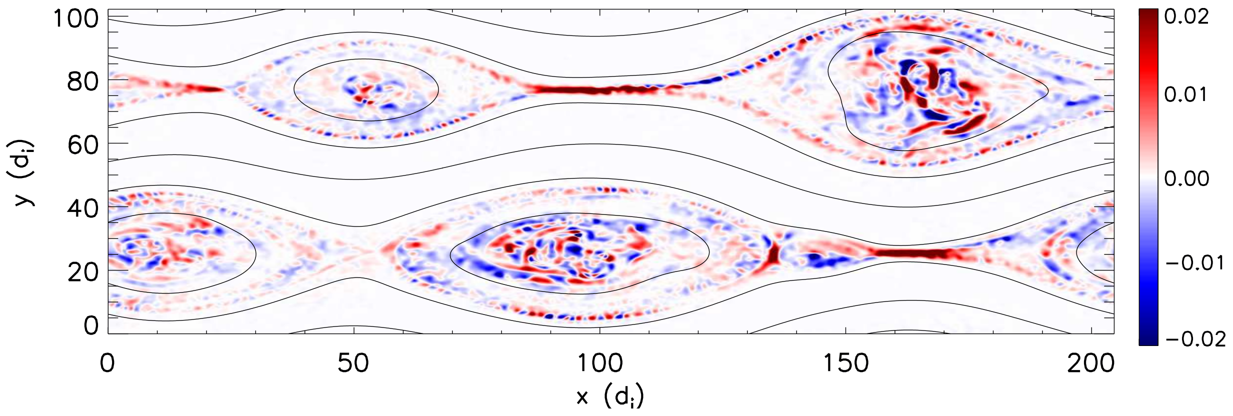
Spatial distribution of heating from $E_{||}$

- $E_{||}$ heating localized around the x-line
  - Very little net heating from electron holes along the separtrices
- Current layers become more elongated with incresing guide field

$B_g=0.2$

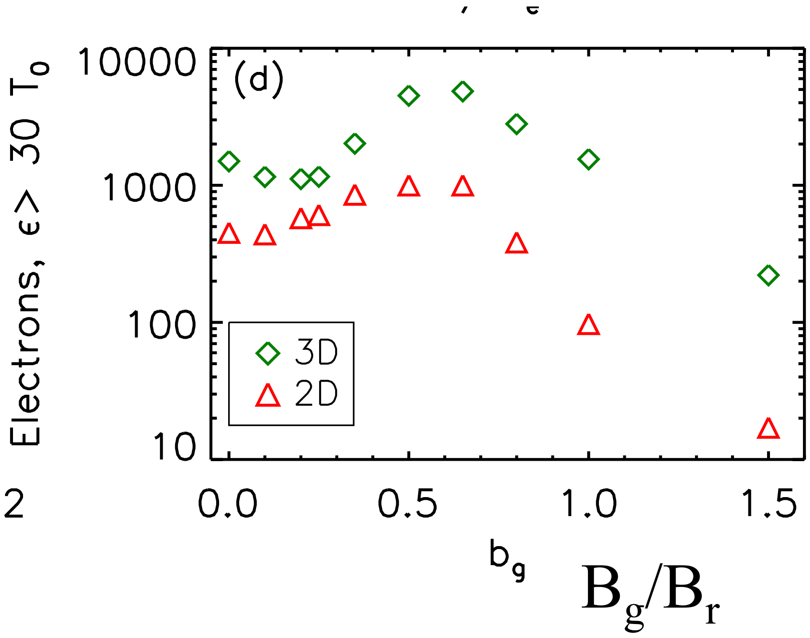


$B_g=1.0$



Production of energetic electrons: versus guide field

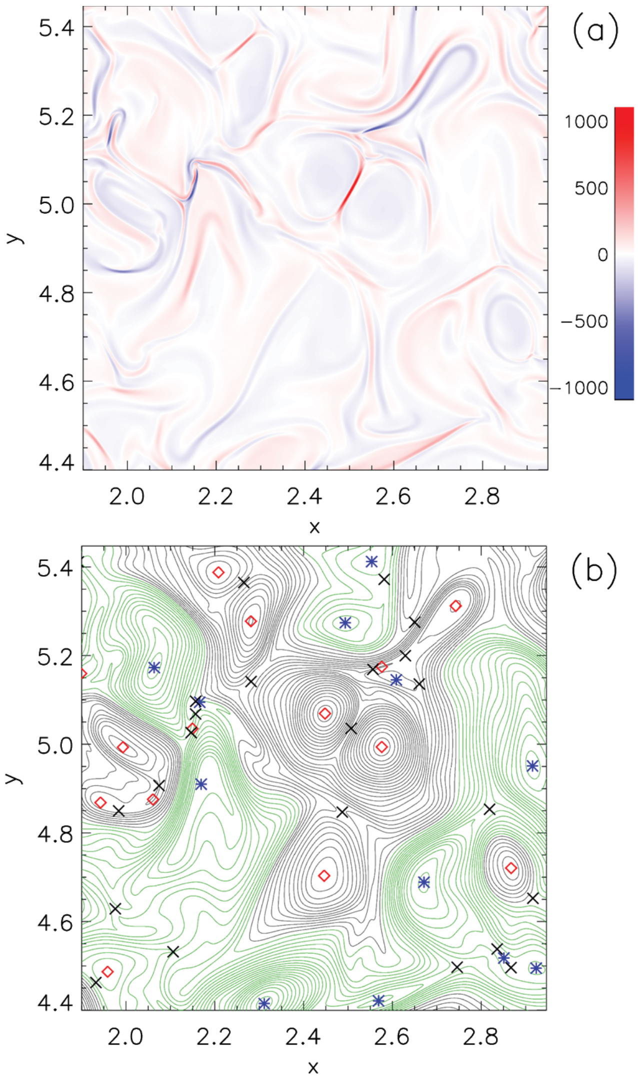
- Compare the production of energetic electrons versus the strength of guide field
  - Weak to modest guide field Fermi dominates
  - Large guide field $E_{||}$ dominates
- Virtually no energetic particles produced in strong guide field reconnection
- Parallel electric fields are not the driver of the most energetic electrons



Dahlin+ ’17

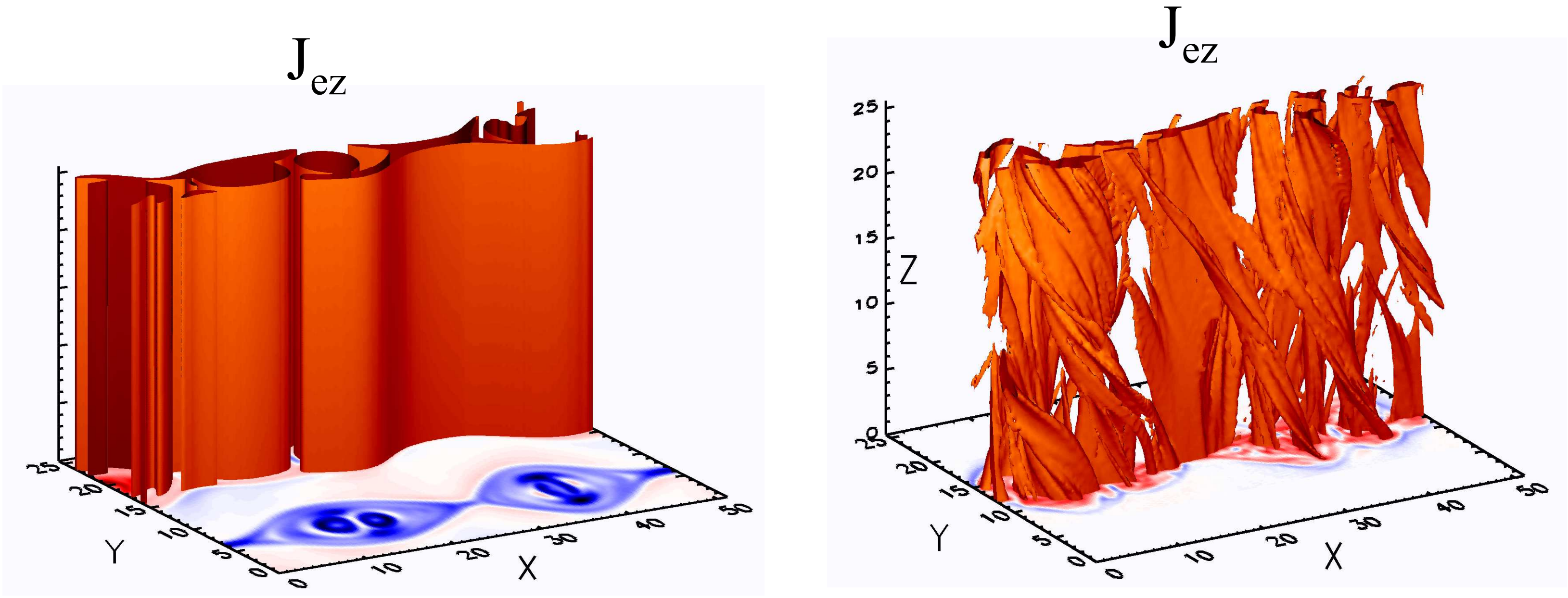
Diagnosing reconnection in turbulent environments

- In the solar wind and in the magnetosheath downstream of a parallel bow shock there are many current layers
  - Diagnosing reconnection is challenging even in 2D simulations of turbulence
  - Flux surfaces don't exist in 3D reconnecting systems
  - Are current layers undergoing reconnection?



Particle acceleration in 3D reconnection

- In a 3D system with a guide field magnetic reconnection becomes highly turbulent (Daughton et al. ‘11)
  - No magnetic islands or flux surfaces
  - Chaotic field line wandering and associated particle motion
  - Diagnosing reconnection is a challenge


J_{ez}

J_{ez}

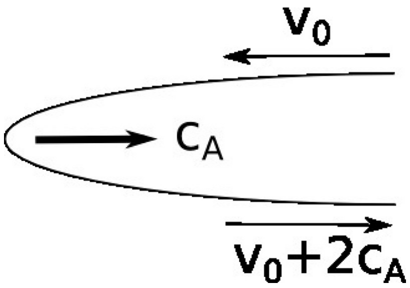
Dahlin et al ’15

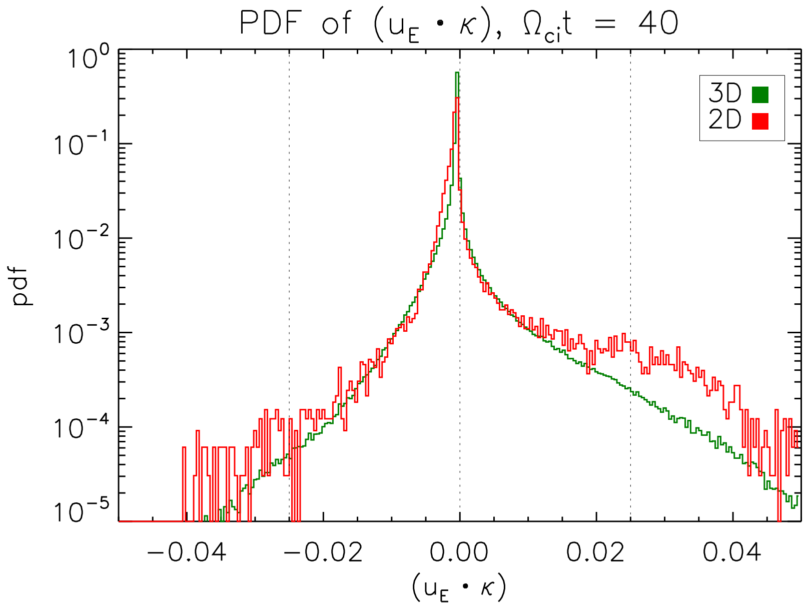
Establishing reconnection in a turbulent system

- A measure of the rate of magnetic energy release and particle acceleration is the parameter

$$\vec{\kappa} \bullet \vec{V}_{ExB} = (\vec{b} \bullet \vec{\nabla}\vec{b}) \bullet \frac{c\vec{E} \times \vec{B}}{B^2}$$

  - Dominantly positive and a reconnecting system and negative in a dynamo systems
  - The dominance of positive values establishes that particle acceleration in a turbulent reconnection is a first order Fermi process

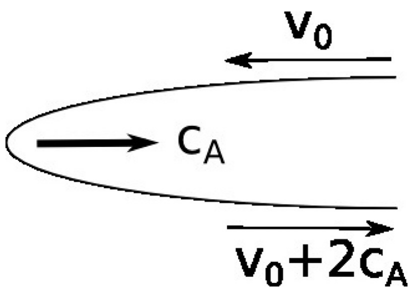




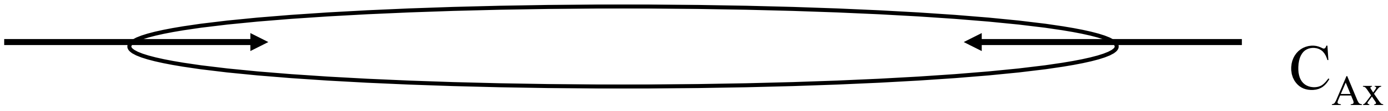
Dahlin et al ‘17

Frame invariance of magnetic reconnection measure in contracting islands

- What happens to $\vec{\kappa} \bullet \vec{V}_{ExB}$ under frame shifts?
  - A single bent field is sensitive to a frame shift



- Contracting islands are not sensitive to frame shifts
  - The sum of $\vec{\kappa} \bullet \vec{V}_{ExB}$ from the two ends is invariant
  - Perhaps the mean flow in a system with turbulent reconnecting islands does not impact the reconnection measure



Conclusions

- Most of the energy release during reconnection takes place in the reconnection exhaust
  - The plasma frame (electron or ion) dissipation measure is not adequate to measure energy conversion
  - The dominant heating mechanism for electrons is controlled by the guide field
    - Weak guide field Fermi reflection $\left(J_\perp \bullet E_\perp\right)$
    - Strong guide field parallel electric field $(J_{\|}E_{\|})$
- In turbulent systems can diagnose reconnection activity with the scalar parameter

$$\vec{\kappa} \bullet \vec{V}_{ExB} = (\vec{b} \bullet \vec{\nabla}\vec{b}) \bullet \frac{c\vec{E} \times \vec{B}}{B^2}$$

  - Potentially useful in the turbulent magnetosheath and the solar wind or anywhere
  - No need to carry out uncertain coordinate transformations