Large-scale Particle Acceleration during Magnetic Reconnection in Solar Flares

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Outline

1. Overview
   - Particle acceleration during solar flares
   - A framework for studying particle acceleration
2. Particle acceleration and transport
   - Acceleration mechanisms
   - The role of turbulence
3. A macroscopic energetic-particle model
   - Solving Parker's transport equation in 2D
   - Other preliminary results
4. Conclusions

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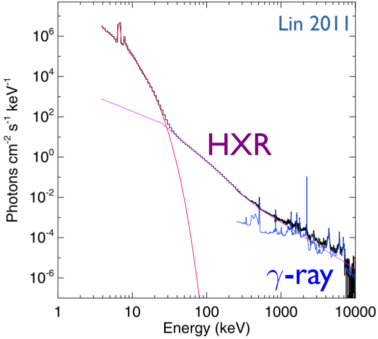
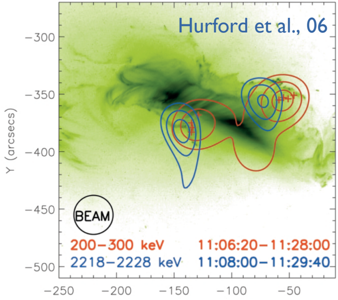
Nonthermal particle acceleration in solar flares

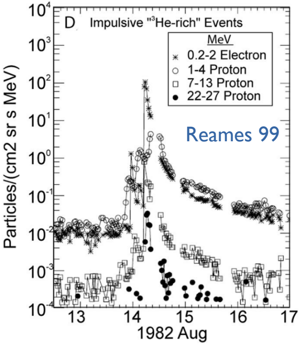
Evidence

- HXR: nonthermal electrons
- γ-ray: nonthermal ions
- Impulsive SEP events

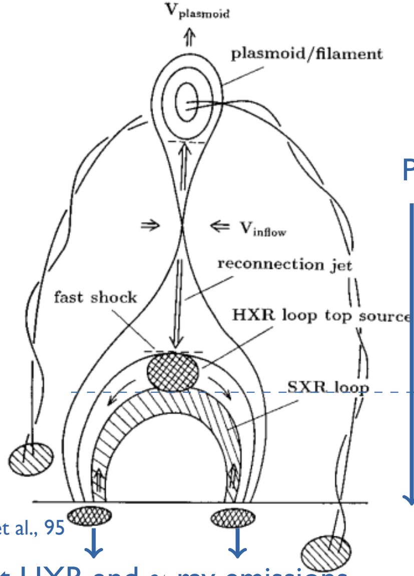
Photon energy spectrum







Possible particle acceleration sites



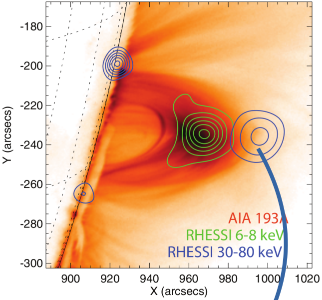
Shibata et al., 95

Most HXR and γ-ray emissions come from the footpoints

Particle precipitation

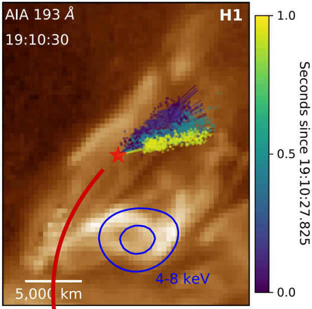
- Reconnection
- Reconnection-driven turbulence
- Termination shock
- Large-scale Alfvén waves in loops

Evidence for acceleration by reconnection



Krucker & Battaglia 14

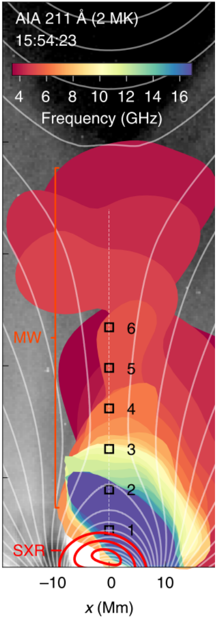
Above-the-looptop HXR emissions



Chen et al., 18

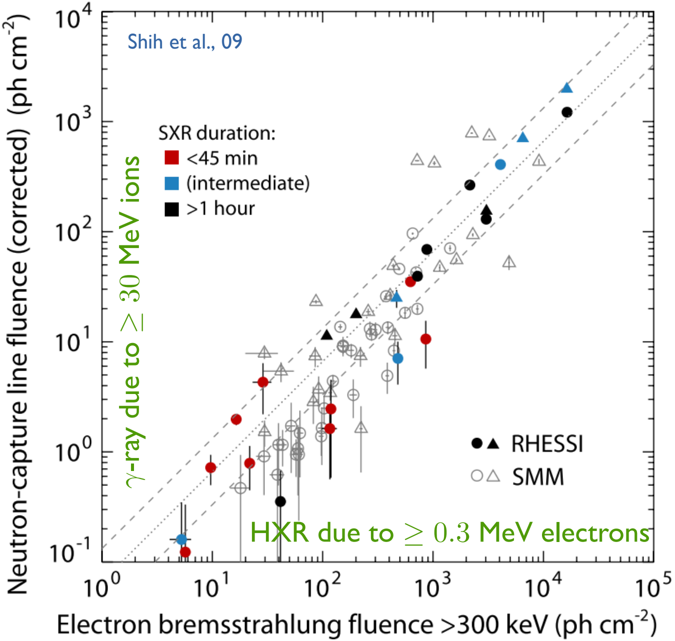
Electron beams originated from reconnection site

Microwave emissions filling up the reconnection region



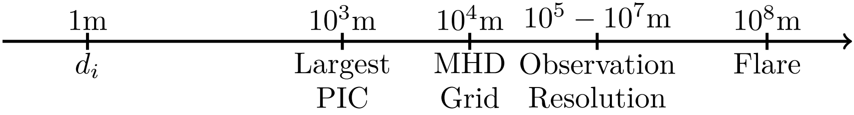
Chen et al., 20

Similar acceleration mechanism for ions

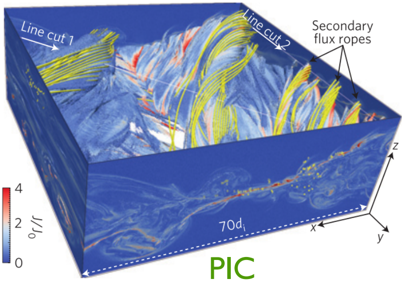


Challenges in modeling particle acceleration

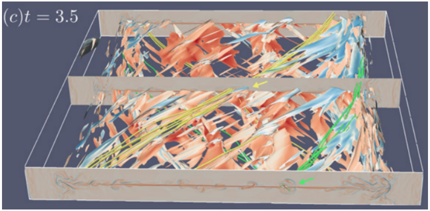
- The scale separation is enormous in flares.



- 3D physics in reconnection is complicated.



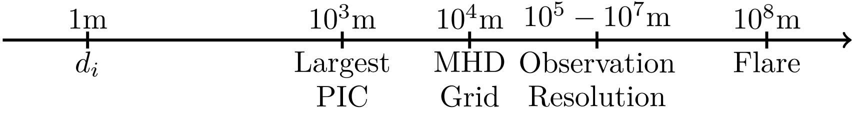
PIC
Daughton et al., 11



MHD
Huang et al., 16

- A larger number of particles are accelerated (Lin & Hudson 76, Krucker et al., 10).

Methods to model particle acceleration in flares



Kinetic simulations

- Self-consistent
- Suitable for studying acceleration mechanisms and turbulence properties
- Small size

Test-particle + MHD

- Capture large-scale dynamics
- No wave-particle interaction
- No feedback
- Energy spectrum is too hard

Combine these two in a framework?

A framework for studying particle acceleration

Kinetic simulations

- Acceleration mechanisms
- Turbulence properties

MHD simulations

- Flare geometry
- B-field and plasma flows

Macroscopic energetic-particle model

Spatially and temporally dependent energetic particle distributions

Emission modeling

Emission maps from different viewing perspectives

Observations

HXR and microwave emissions in different regions

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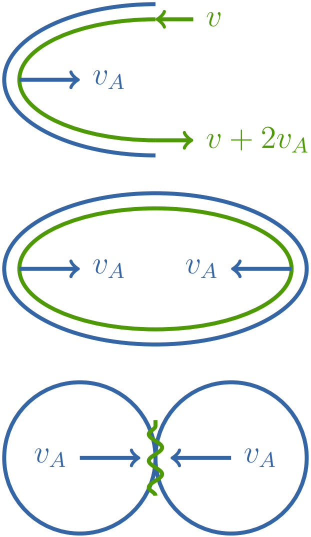
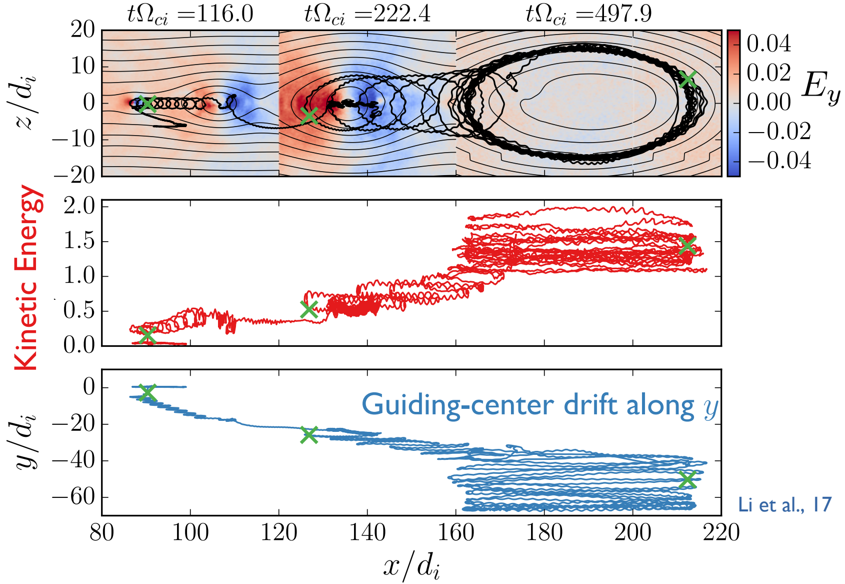
Fermi mechanism in reconnection



- One reflection off the reconnection outflow
- Multiple reflections off the reconnection outflow
  - Contracting magnetic islands (e.g., Drake et al. 06)
  - Merging magnetic islands (e.g., Oka et al. 10)
  - Trapping near the X-line (e.g., Egedal et al. 15)
  - Turbulence scattering (e.g., Li et al. 19)

One electron trajectory from 2D PIC simulation



Li et al., 17

Particle acceleration is associated with drift motions.

Drift along electric field ⇒ energization

- In the guiding-center approximation,

$$\langle d\varepsilon/dt \rangle_\phi = q\boldsymbol{E}\cdot \boldsymbol{v}_g + \mu \frac{\partial B}{\partial t},$$

Guiding-center drift motions

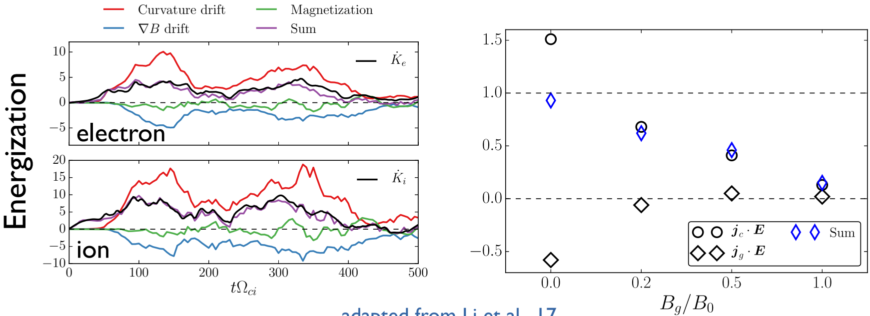
- Summing over one species leads to $\boldsymbol{j}_s \cdot \boldsymbol{E}$.

$$\boldsymbol{j}_{s\perp} \approx p_{s\parallel} \frac{\boldsymbol{B}\times(\boldsymbol{B}\cdot\nabla)\boldsymbol{B}}{B^4} + p_{s\perp}\frac{\boldsymbol{B}\times\nabla B}{B^3} + \cdots$$

curvature drift
Fermi mechanism

∇B drift

2D PIC simulation results



adapted from Li et al., 17

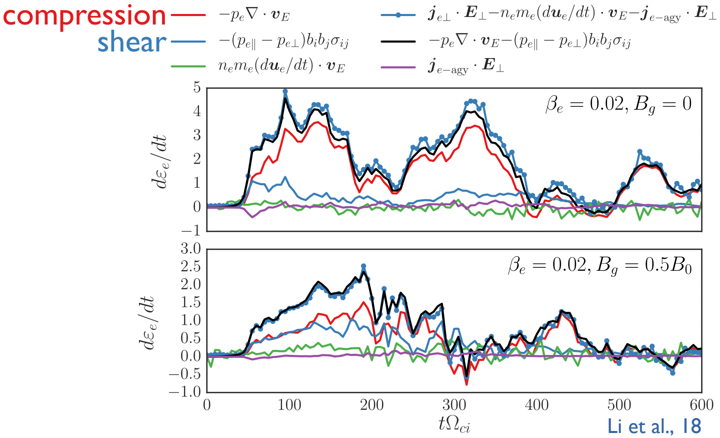
- $\beta_e = 0.02, B_g = 0$
- The primary acceleration is associated with curvature drift.

- Fermi mechanism becomes less efficient as guide field increases (see also Dahlin et al., 14).

Energization due to flow compression and shear

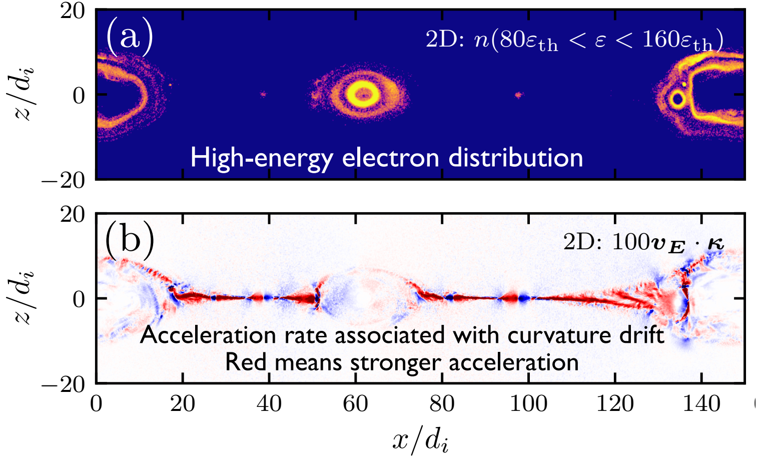
The energization associated with drift motions is equivalent to

$$\nabla \cdot (p_{s\perp}\boldsymbol{v}_E) - p_s \nabla \cdot \boldsymbol{v}_E - (p_{s\parallel} - p_{s\perp}) b_i b_j \sigma_{ij} + n_s m_s (d\boldsymbol{u}_s/dt) \cdot \boldsymbol{v}_E$$



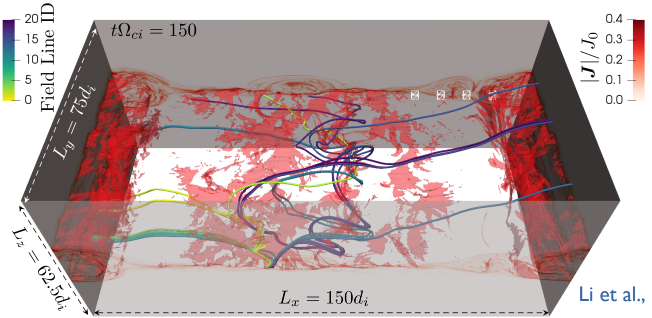
- Shear is only effective for anisotropic particle distributions.

One limitation of 2D simulations



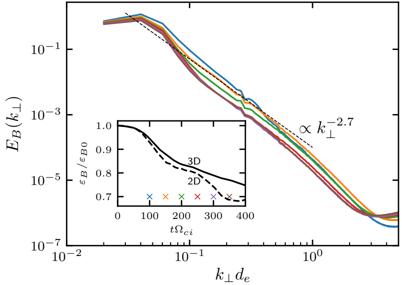
High-energy electrons cannot access the major acceleration regions when trapped in islands. (Dahlin et al. 17, Li et al. 17, 19)

3D physics relevant to electron acceleration



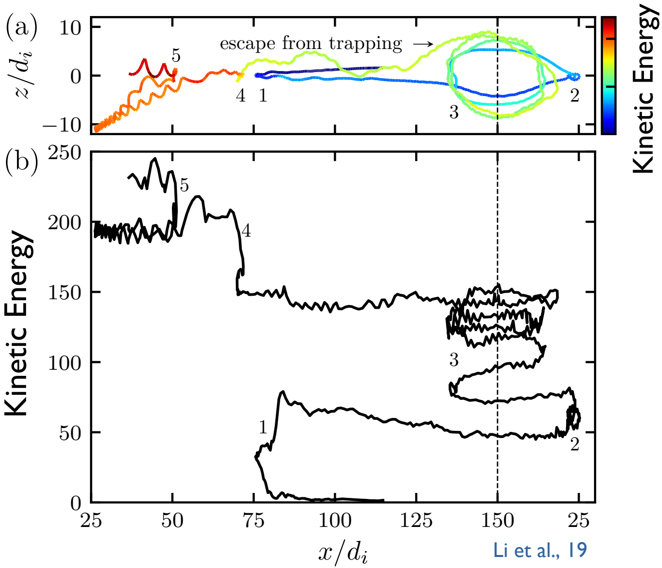
Li et al., 19

Magnetic power spectrum



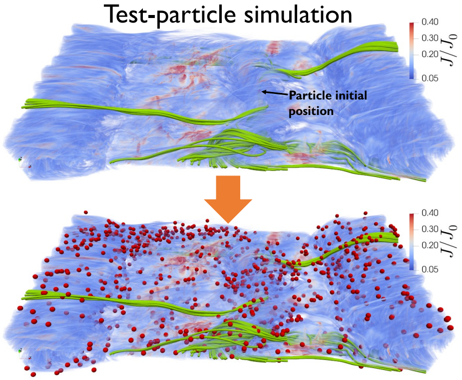
- Chaotic magnetic field lines.
- Self-generated turbulence, different from $k^{-5/3}$.

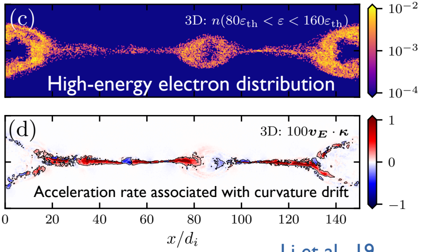
3D physics prevent electrons from being trapped



Li et al., 19

Fast electron transport in 3D

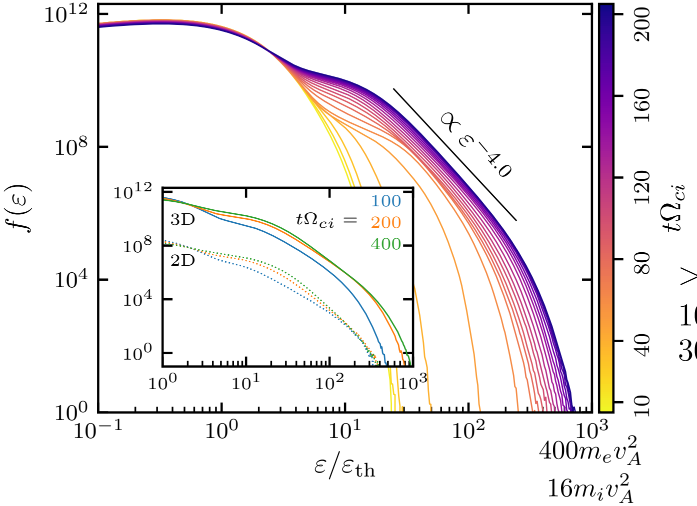




Li et al., 19

Energetic electrons can access major acceleration regions in 3D.

Power-law electron energy spectrum

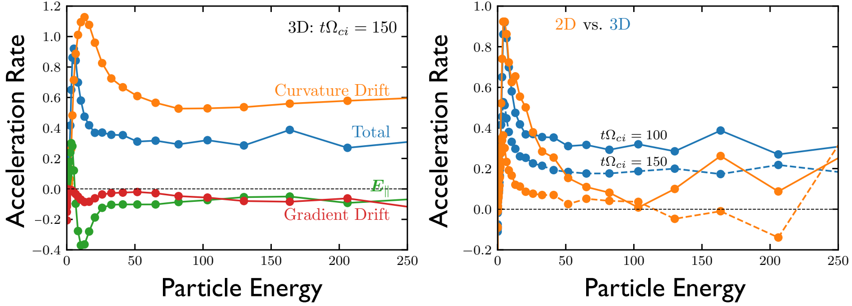


$> 20\varepsilon_{\rm th}$:
10% in number
30% in energy

- More efficient electron acceleration in 3D (see also Dahlin et al. 16, 17).
- The power-law spectrum persists throughout the simulation in 3D but not in 2D.

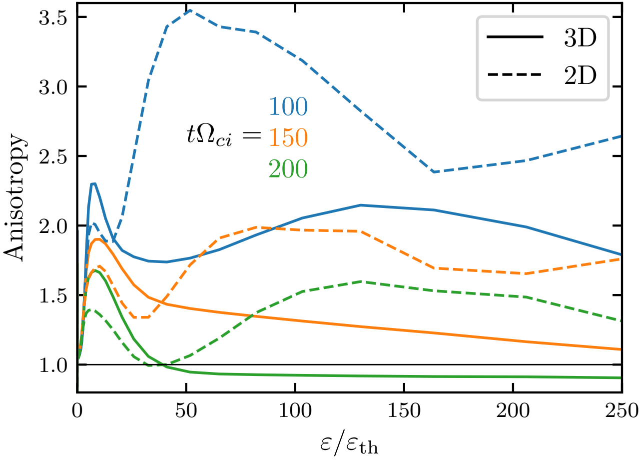
Why is there a power-law?

Acceleration rate $\alpha = \dot{\varepsilon}/\varepsilon$



1. Primary acceleration is due to a Fermi-type mechanism.
2. The acceleration rate α is nearly a constant in 3D.

Pitch-angle scattering of energetic electrons



- Anisotropy level is lower in 3D than that in 2D.

Summary on particle acceleration and transport

Kinetic simulations → Macroscopic modeling

- Acceleration mechanisms: flow compression and shear
- Fast spatial transport of energetic particles (diffusion?)
- Turbulence leads to more isotropic particle distributions?
- Turbulence spectrum is different from Kolmogorov?

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Solving Parker's transport equation

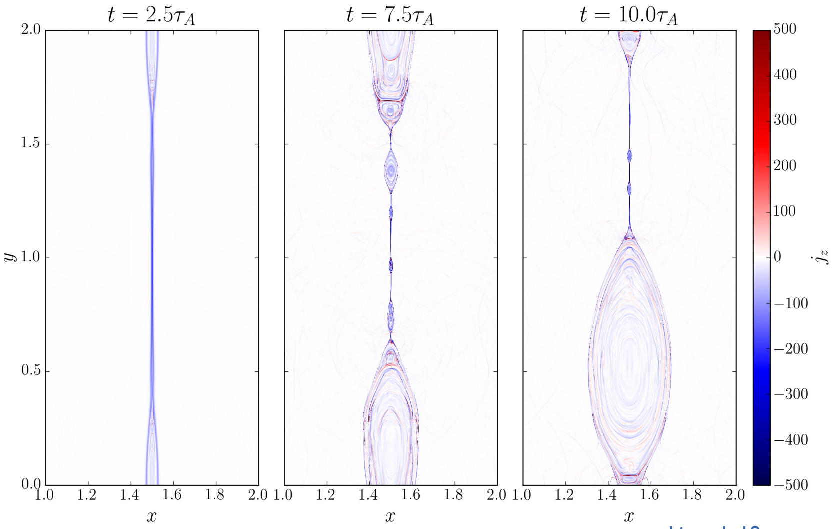
Kinetic simulations → Macroscopic modeling

- Flow compression and shear (2nd-order)
- Fast spatial transport of energetic particles (diffusion? Yes)
- Turbulence leads to more isotropic particle distributions? Yes
- Turbulence spectrum is different from Kolmogorov? No

$$\frac{\partial f}{\partial t} = \frac{\partial}{\partial x_i}\left[\kappa_{ij}\frac{\partial f}{\partial x_j}\right] - (U_i + V_{d,i})\frac{\partial f}{\partial x_i} + \frac{1}{p^2}\frac{\partial}{\partial p}\left(p^2 D_{pp}\frac{\partial f}{\partial p}\right) + \frac{p}{3}\frac{\partial U_i}{\partial x_i}\frac{\partial f}{\partial p} + Q$$

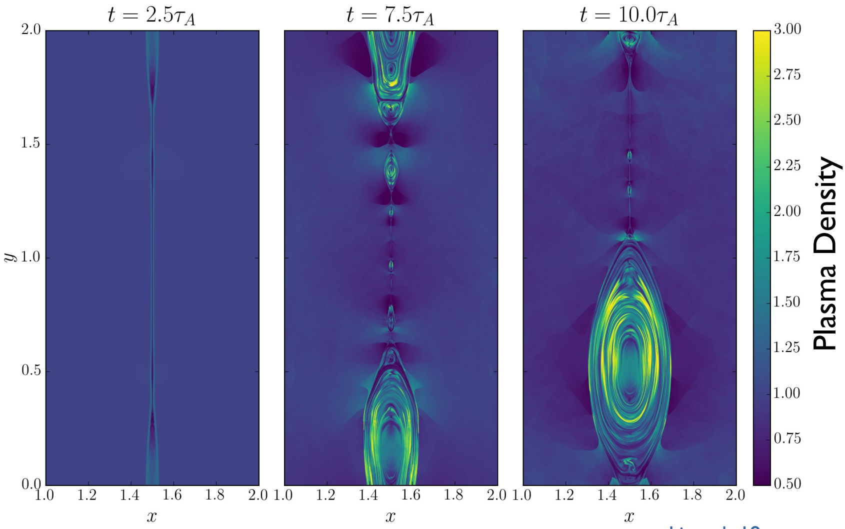
- Solve the equation using stochastic integration (e.g., Zhang 99)
- Magnetic field and flow are provided by MHD simulations.

2D MHD simulation ($B_g = 0$)



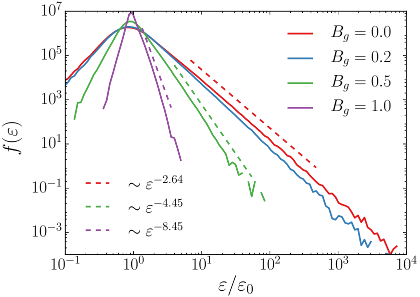
Li et al. 18

Compressible reconnection layer

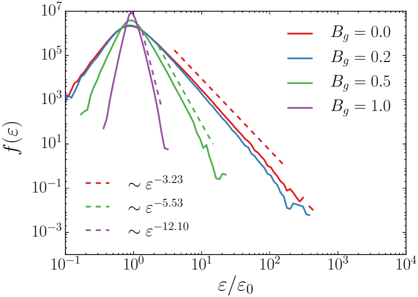


Li et al. 18

Energy spectra (constant $\kappa_\parallel$ and $\kappa_\perp$)



Proton

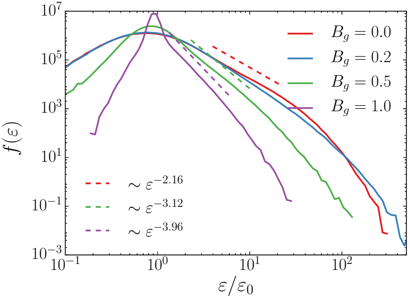


Electron

- The dependence on guide field is consistent with solar flare observations (Qiu et al. 2010).

Energy spectra ($\kappa_\perp/\kappa_\parallel = 0.01$)

- $\kappa_\parallel \sim \kappa_\perp \sim p^{4/3}$, according to quasi-linear theory (e.g. Jokipii 1966)



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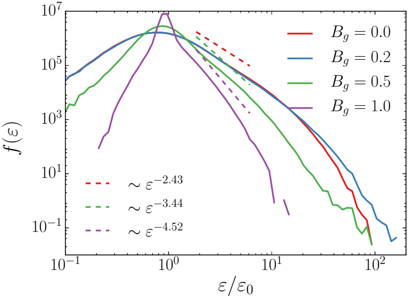
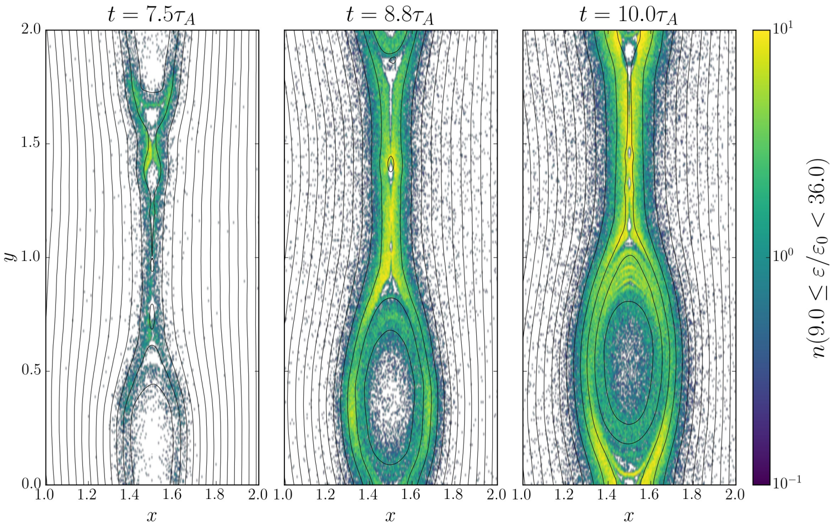


Electron

- Power-law indices are consistent with observations (Effenberger et al. 2017; Oka et al. 2018).

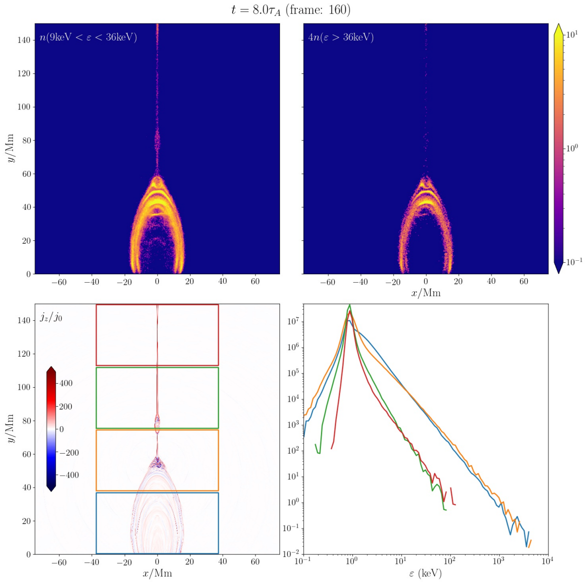
2D particle distributions



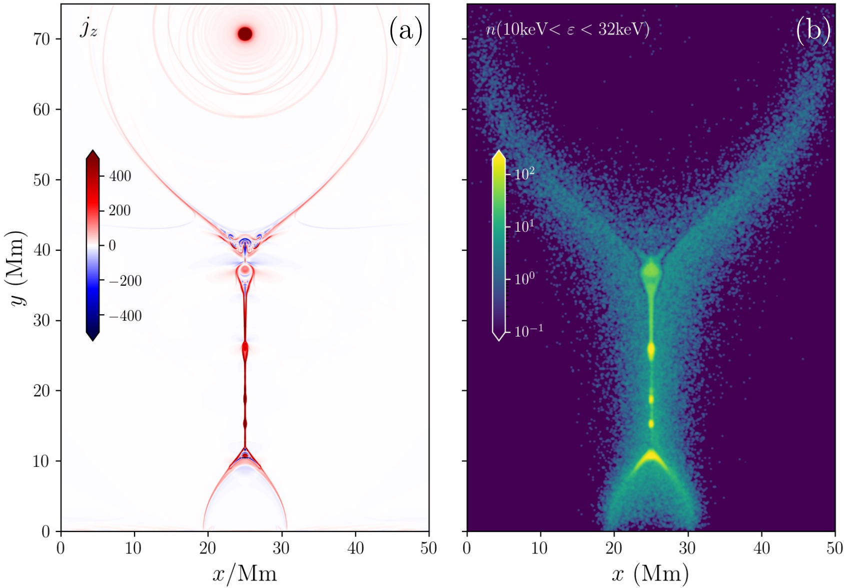
Li et al. 18

- Spatially and temporally dependent
- They can be input for nonthermal emission modeling (e.g., by `GX_Simulator`).

2D simulations with line-tied boundary (preliminary)



2D Forbes-Lin model



Li et al. in preparation

Summary on the macroscopic kinetic model

- In the diffusion limit, solving Parker's transport equation leads to the formation of power-law energy distributions.
- The model produces spatially and temporally dependent particle distributions.

Ongoing works

- Include momentum diffusion terms due to flow shear and wave-particle interactions.
- Include spatially dependent particle injection and turbulence properties.
- Extend the model to 3D.

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Takeaways

- Primary acceleration mechanisms: flow compression and shear
- Self-generated turbulence is important for particle acceleration and transport.
- A macroscopic model, including compression acceleration and spatial diffusion, can lead to efficient particle acceleration.
- Such a model can produce observable signatures.

Publications on building the macroscopic model

- Li et al., ApJ, 884, no. 2 (2019): 118.
- Li et al., ApJ, 879, no. 1 (2019): 5.
- Li et al., ApJ, 866, no. 1 (2018): 4.
- Li et al., ApJ, 855:80 (2018)
- Li et al., ApJ, 843.1 (2017): 21.
- Li et al., ApJL, 811:L24 (5pp), 2015 October 1