Efficient Nonthermal Ion and Electron Acceleration in 3D Magnetic Reconnection

Qile Zhang+ 2021 PRL

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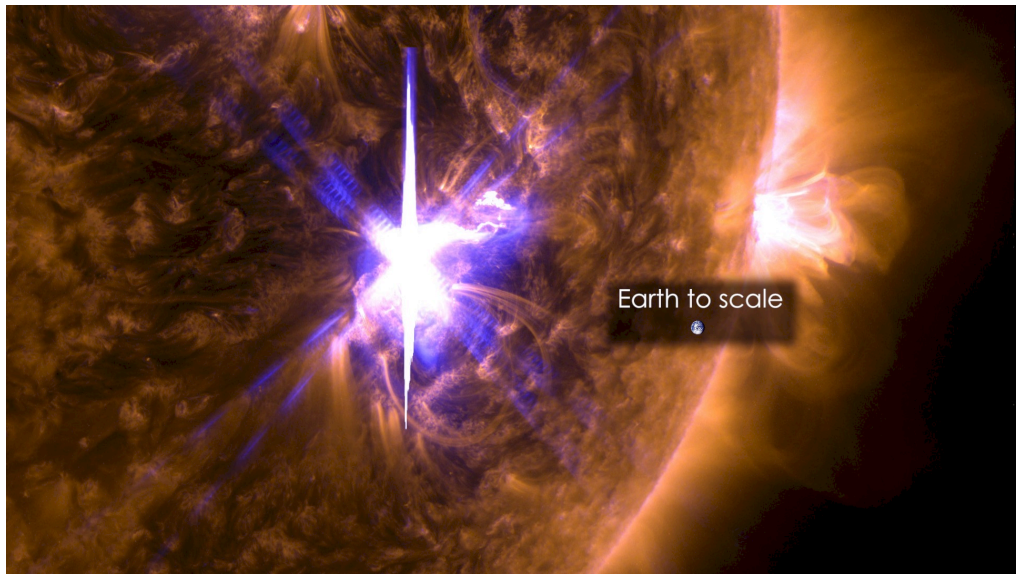
AGU Fall meeting 2021



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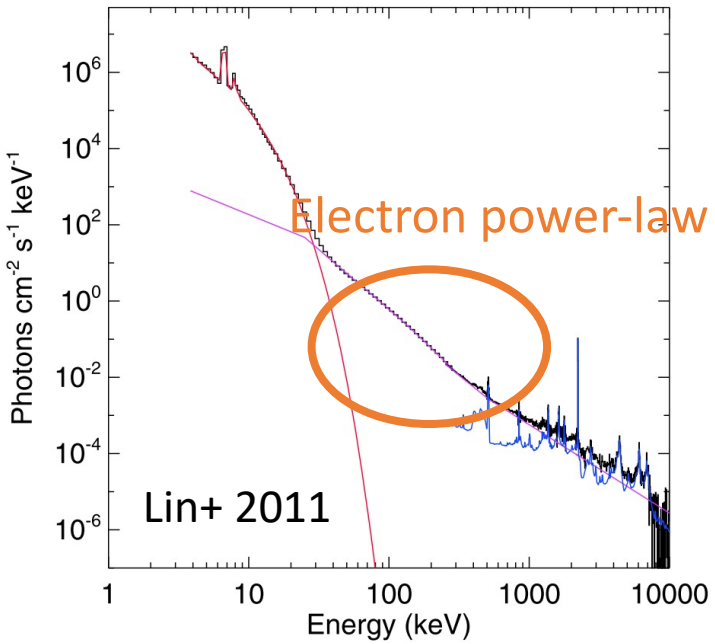
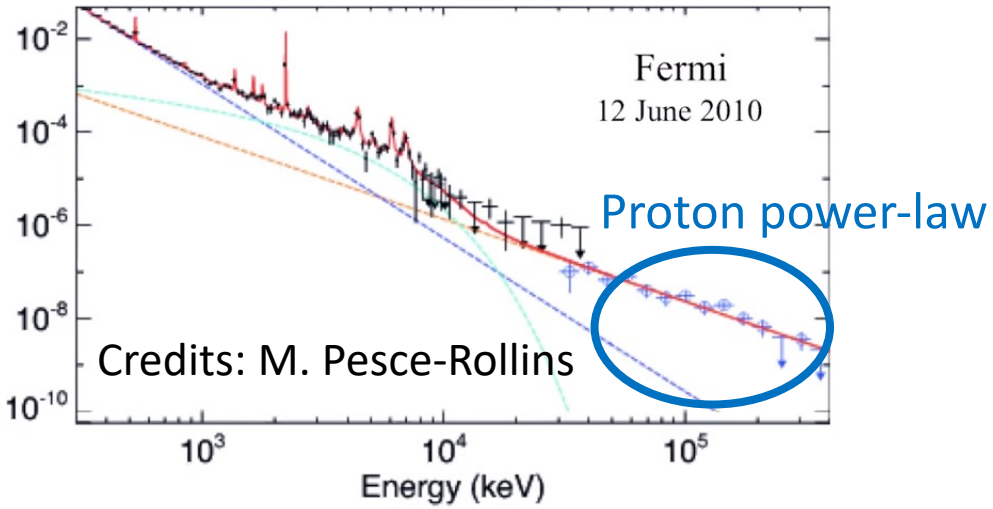
DARTMOUTH

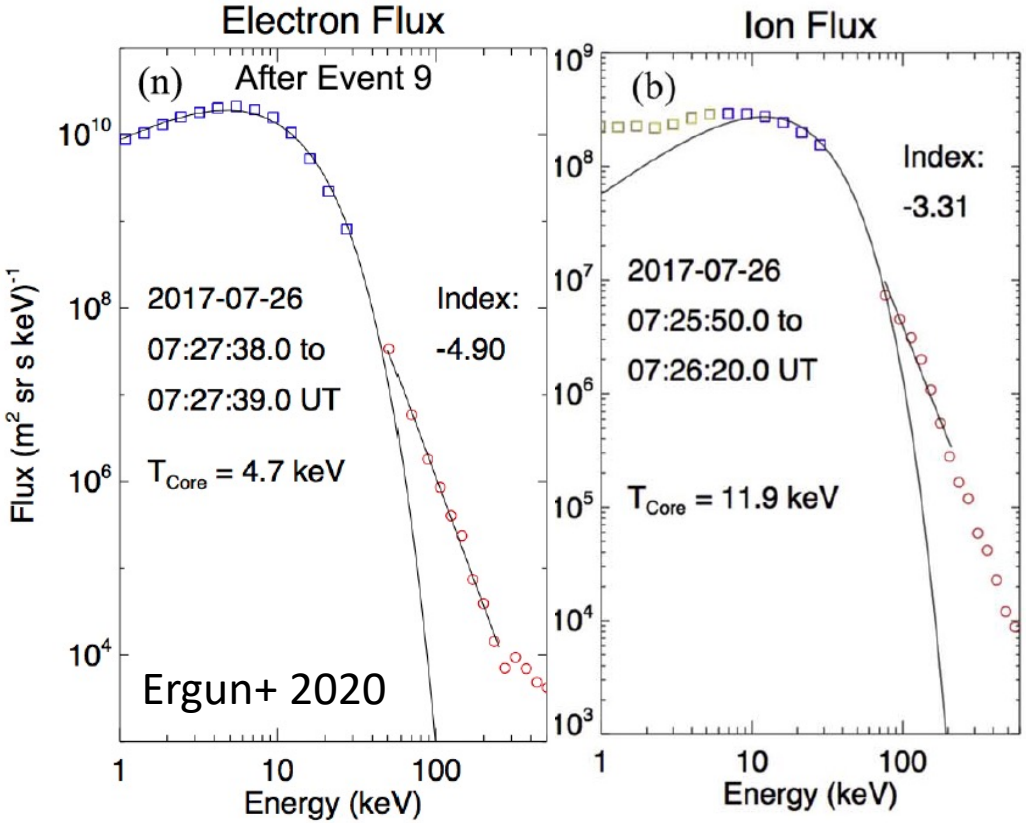
Ions and electrons are efficiently accelerated into power-laws

Solar flare remote sensing



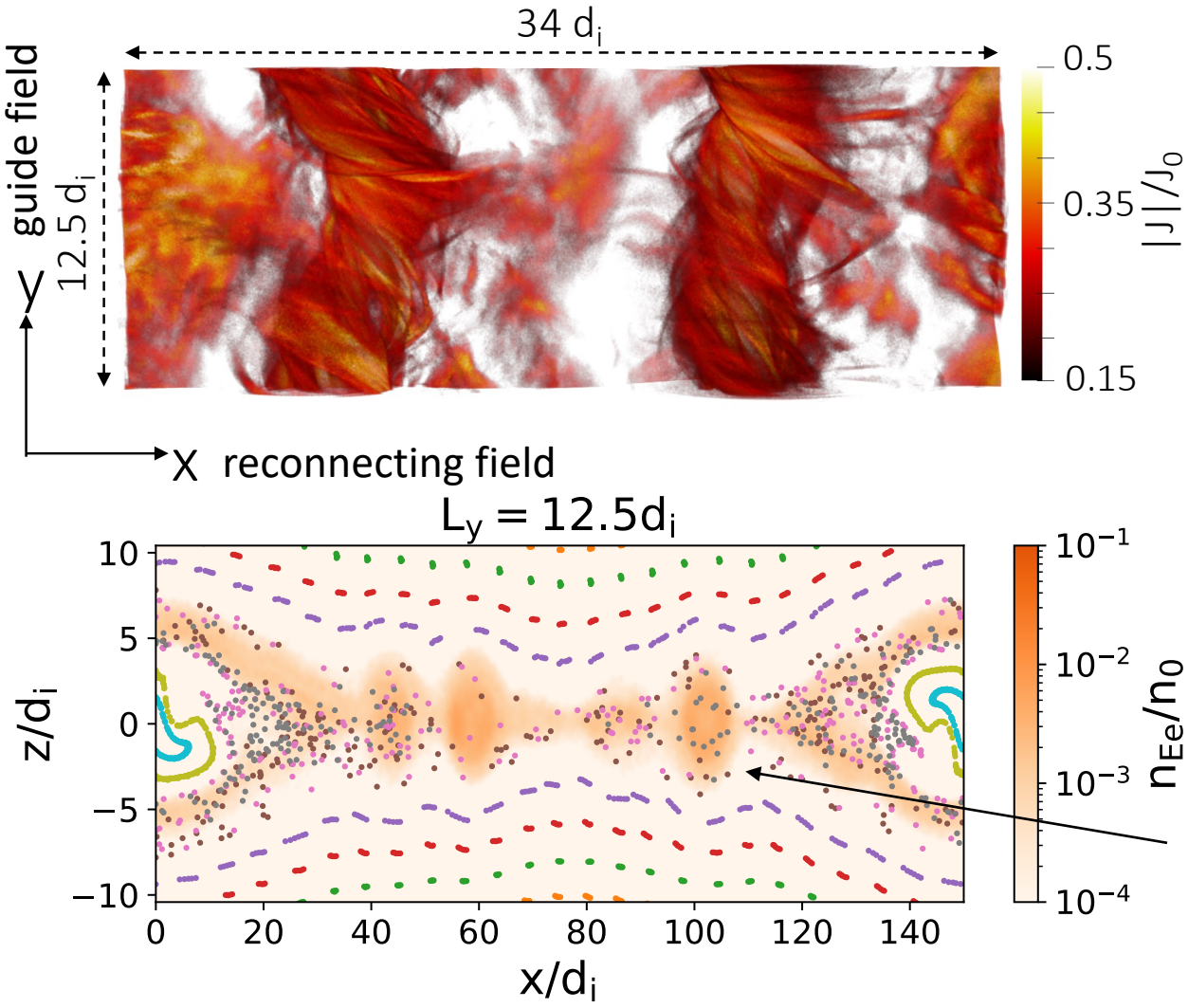


Magnetotail in-situ



But the underlying physics is not well understood.

With low guide fields, flux-rope kink instability drives field-line chaos

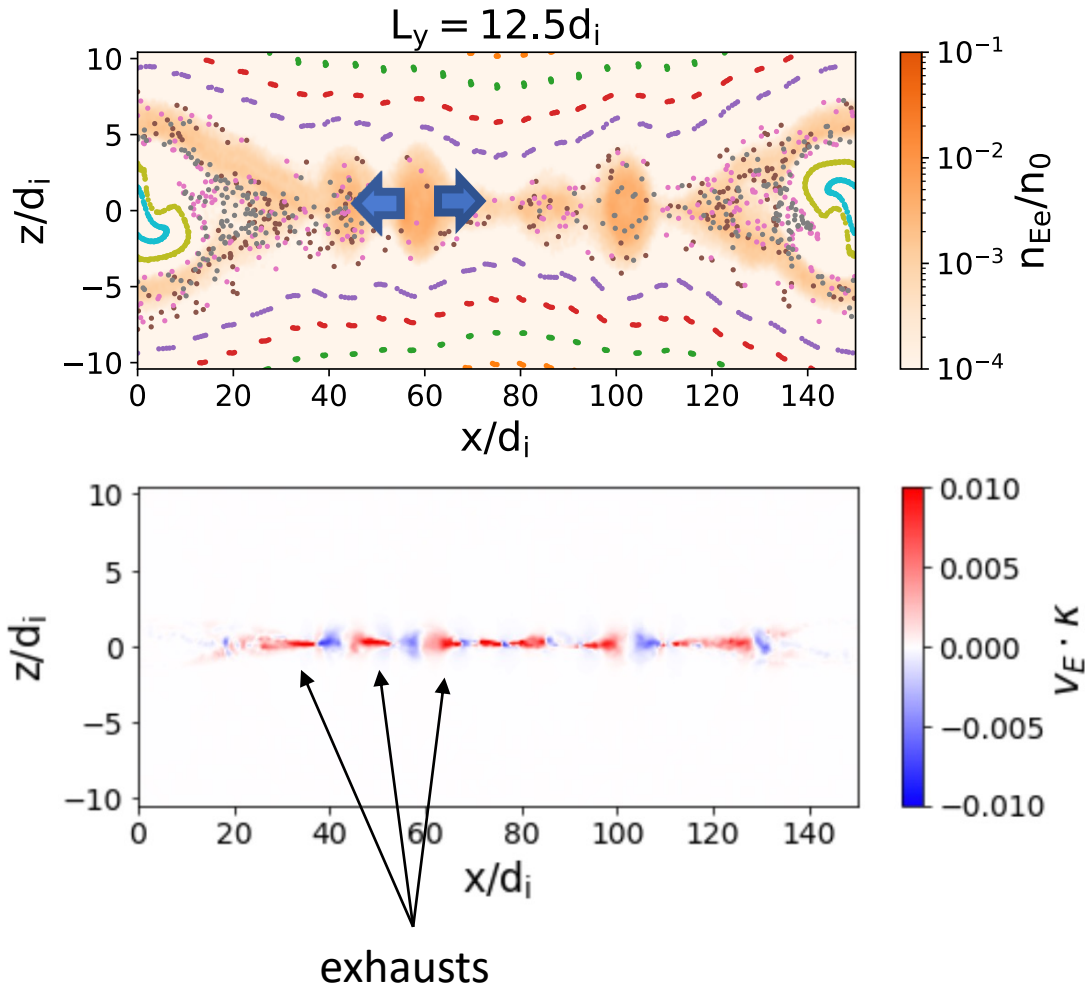


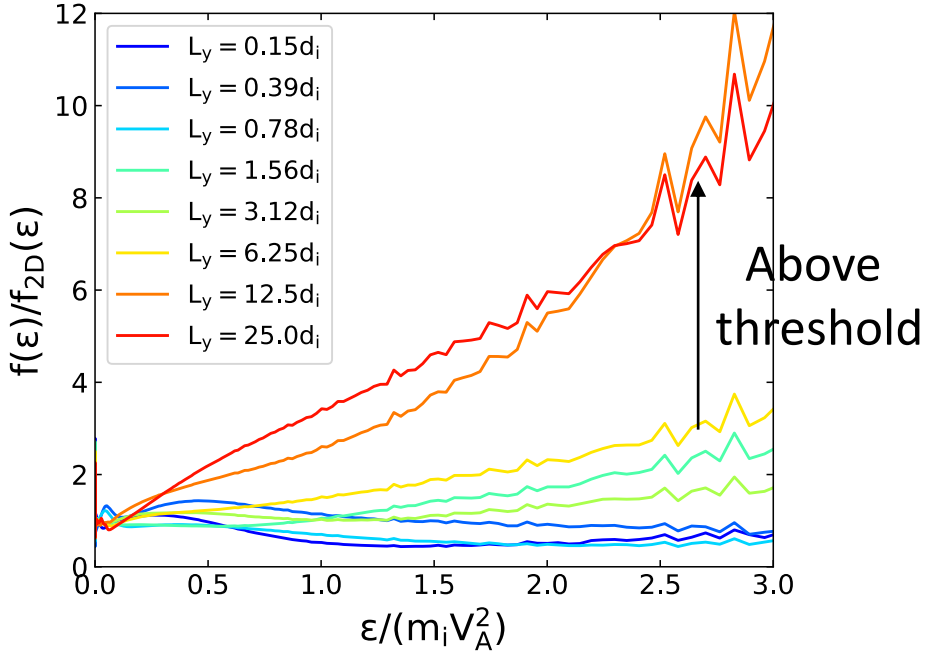
Kink instability criteria: safety factor q<1

$$L_{th} \sim \pi b_g D \sim 0.1\pi b_g L_x$$

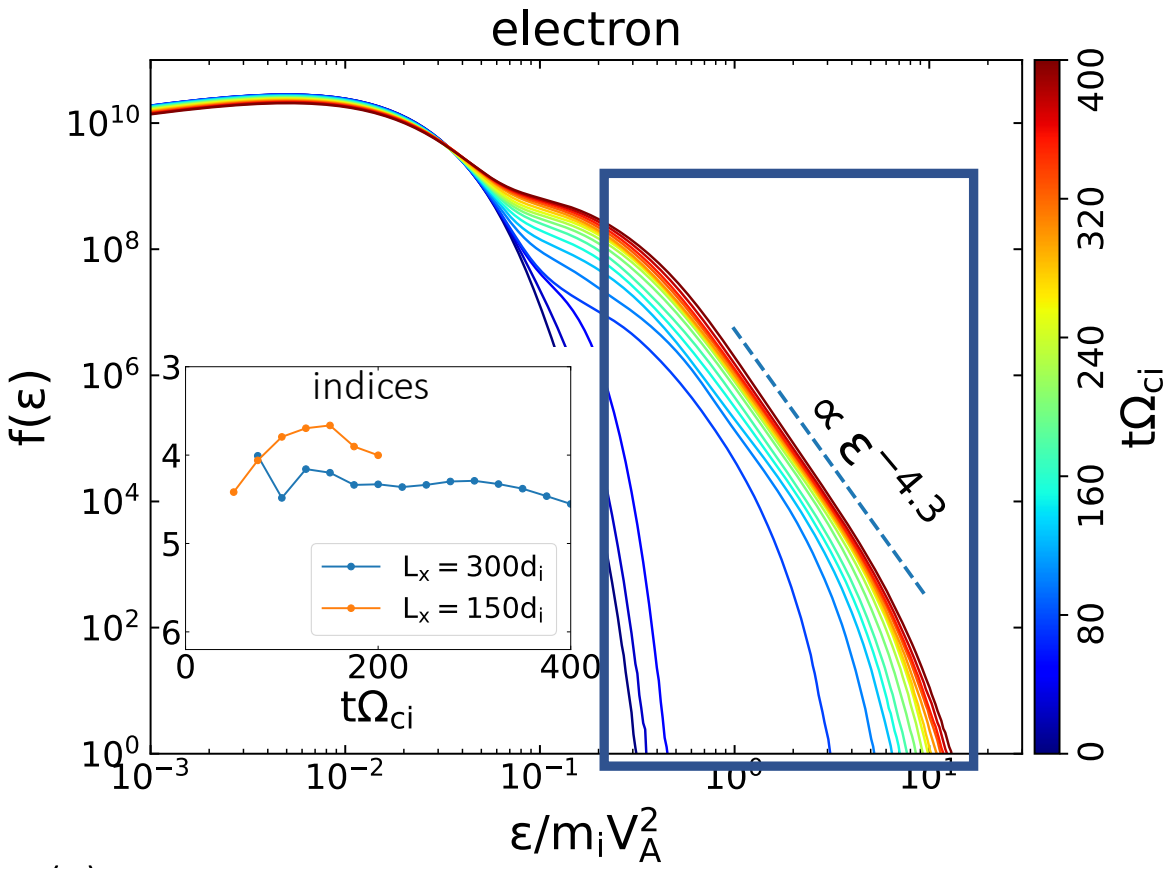
Field-line chaos
Particle spreading

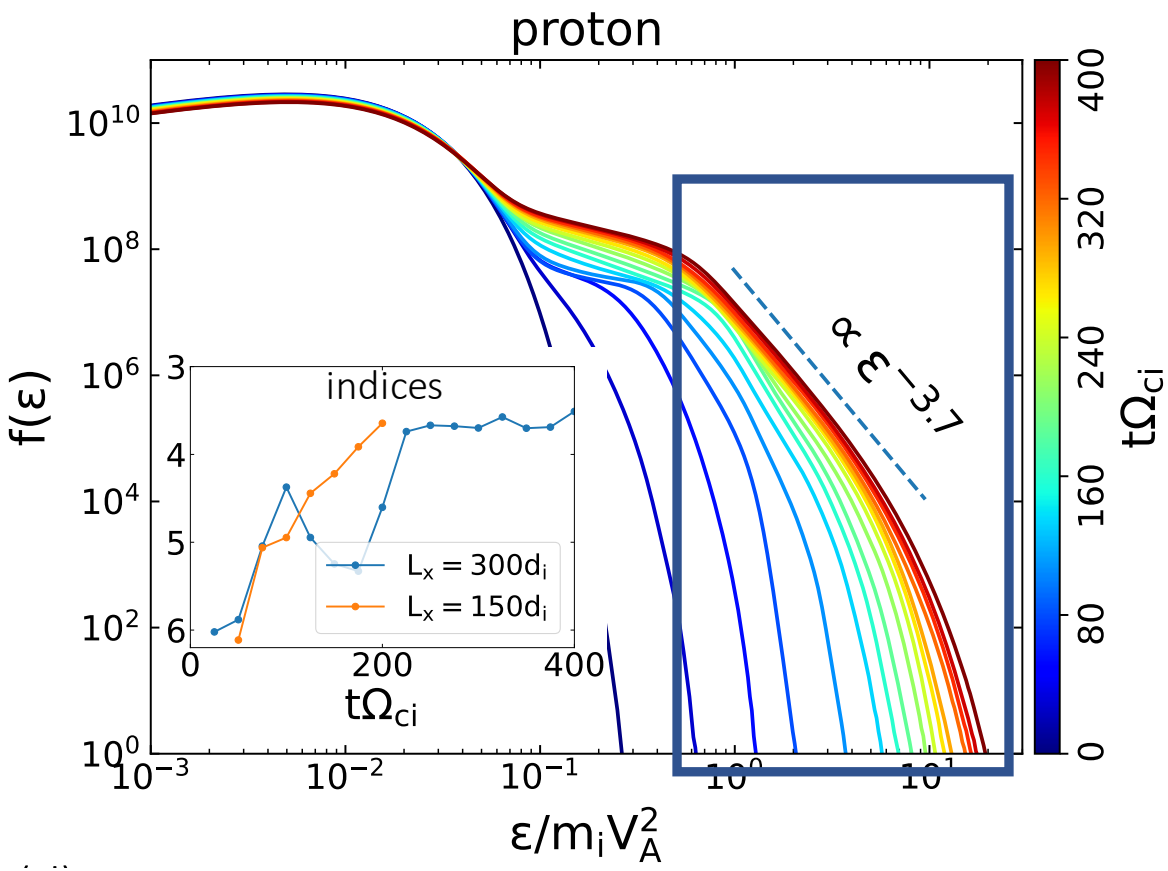
Field-line chaos leads to particle transport out of flux ropes, allowing more efficient acceleration





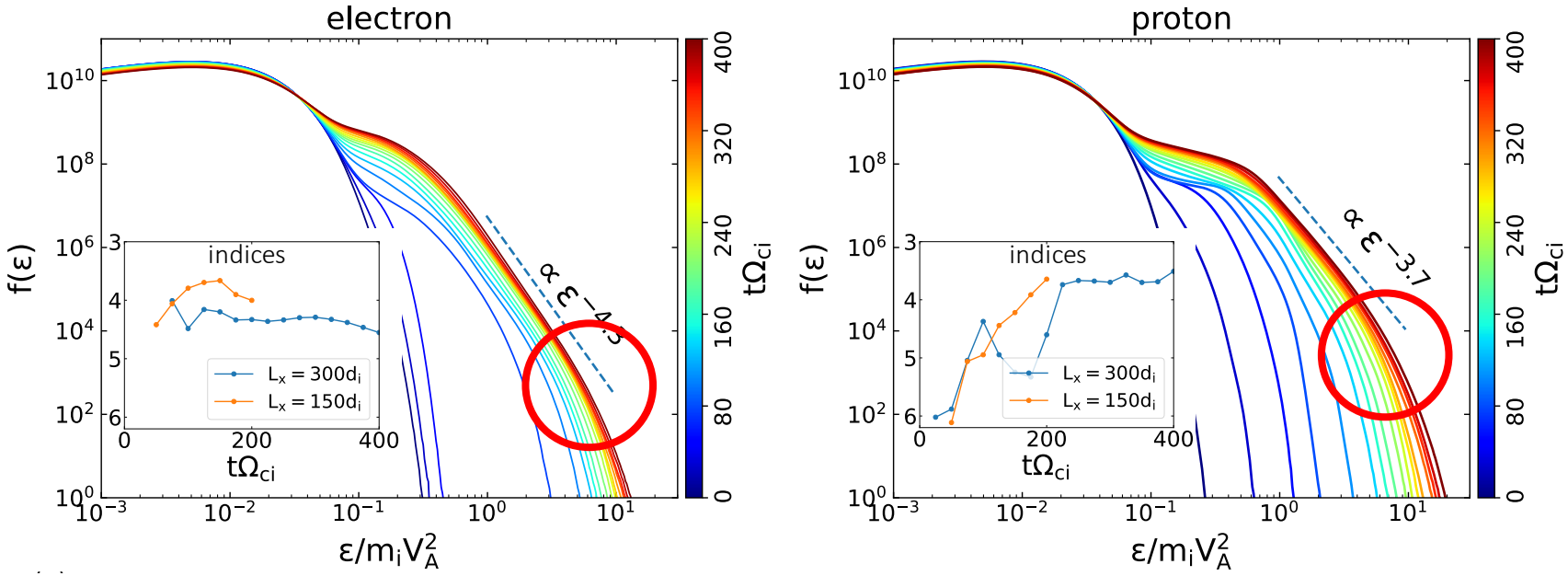
Electrons and protons form power-laws containing a large fraction of energy

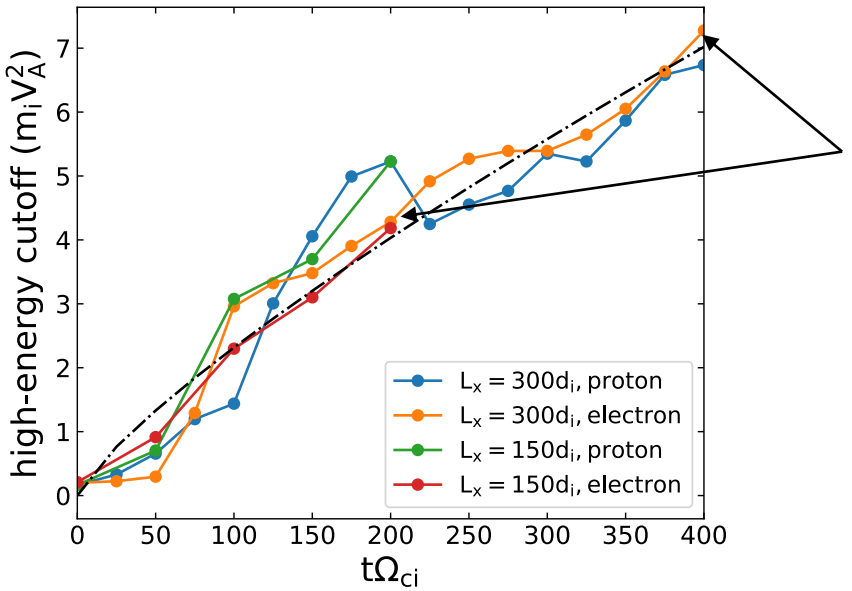




Nonthermal components: ~ 20% number, 50% energy

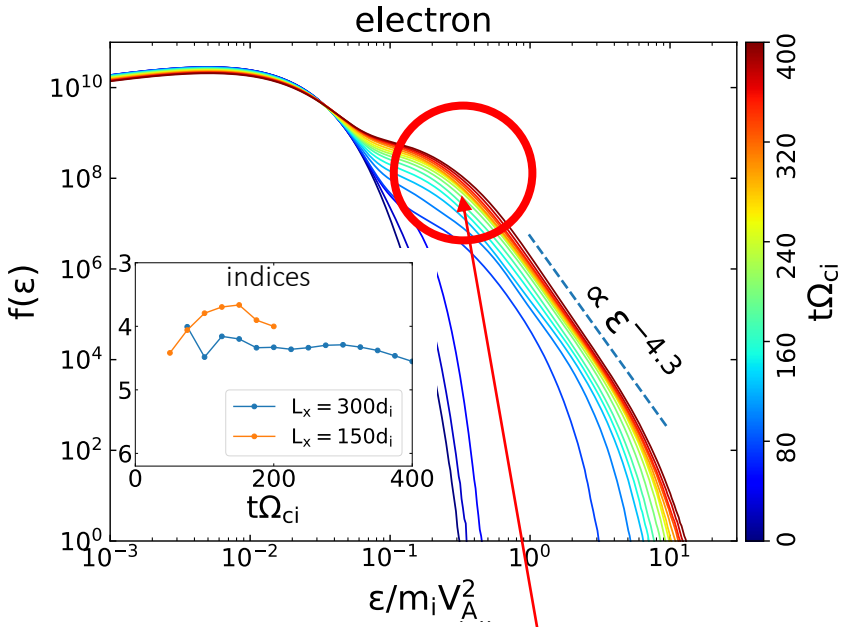
High-energy cutoff is limited by system size

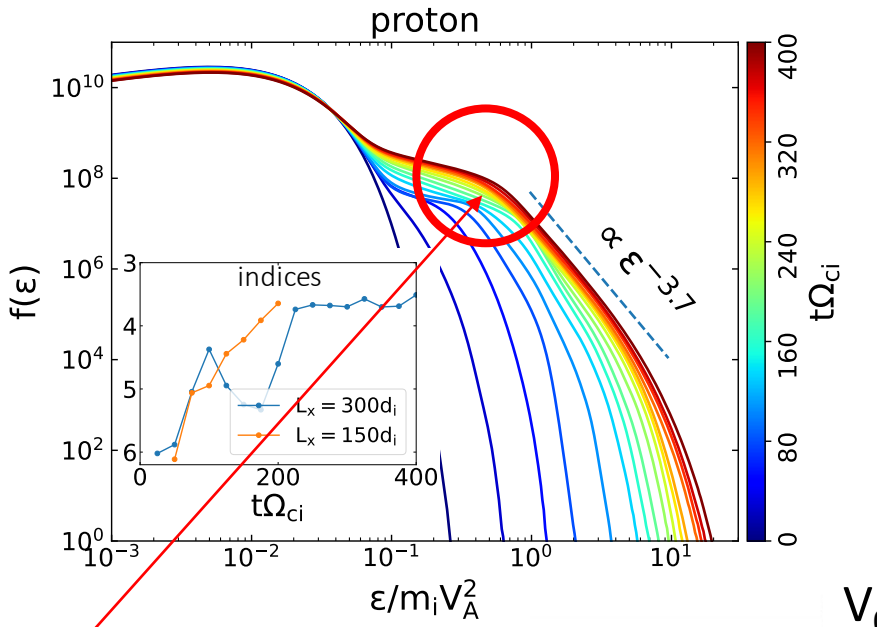


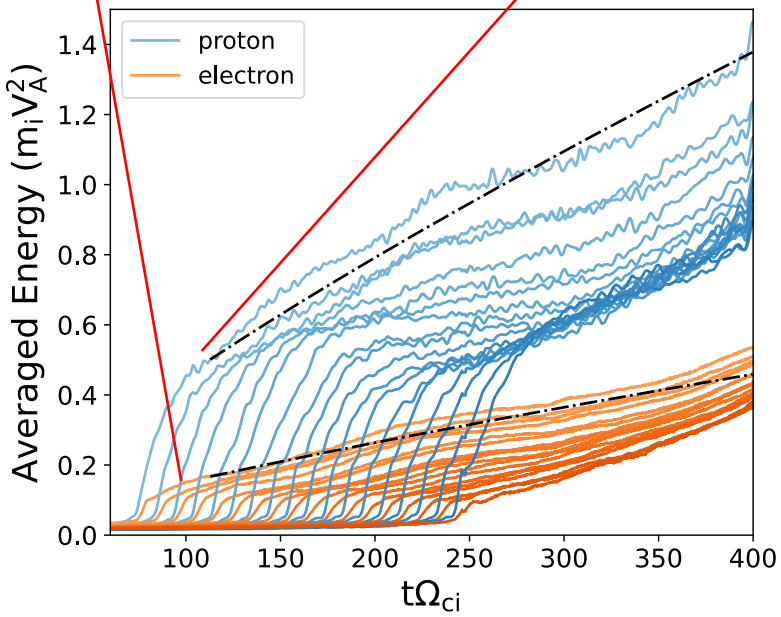


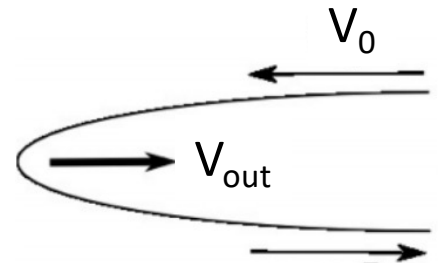
Increase with system sizes

Low-energy bound is determined by injection









$$\varepsilon_{li} \sim 0.5 m_i V_A^2$$

The Fermi acceleration process can be elucidated by a scaling analysis

Fermi acceleration at exhausts + particle acceleration theory gives:

$$p \sim 1 + \frac{B_x}{B_z}\frac{\Delta_z}{L}(1 + \frac{B_g^2}{B_x^2}).$$

$$\alpha \equiv \dot{E}/E \sim \frac{B_z V_{Ax} B_x^2}{B_x(B_x^2 + B_g^2)\Delta_z}.$$

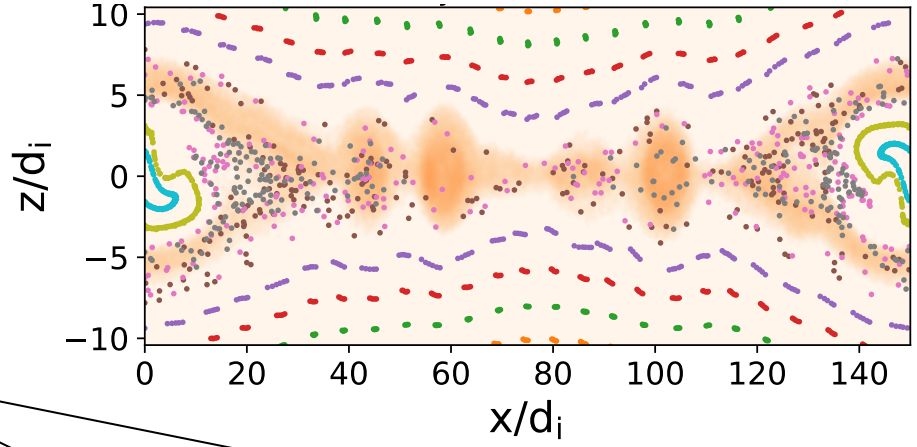
$$p \sim 4$$

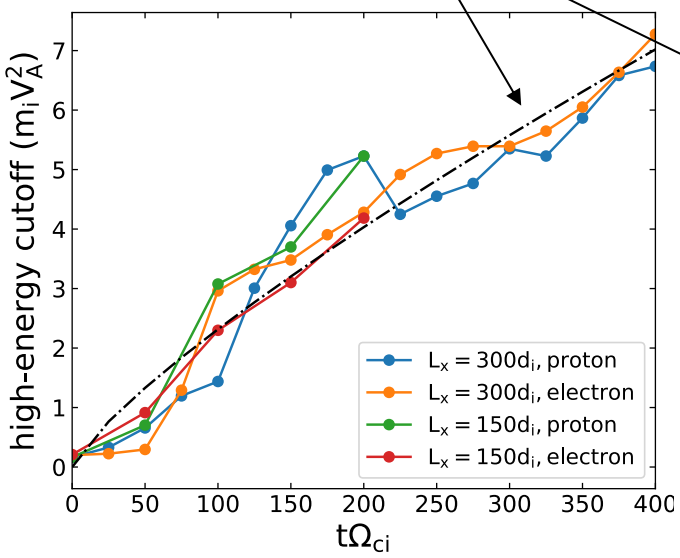
$$\alpha \sim C/t$$

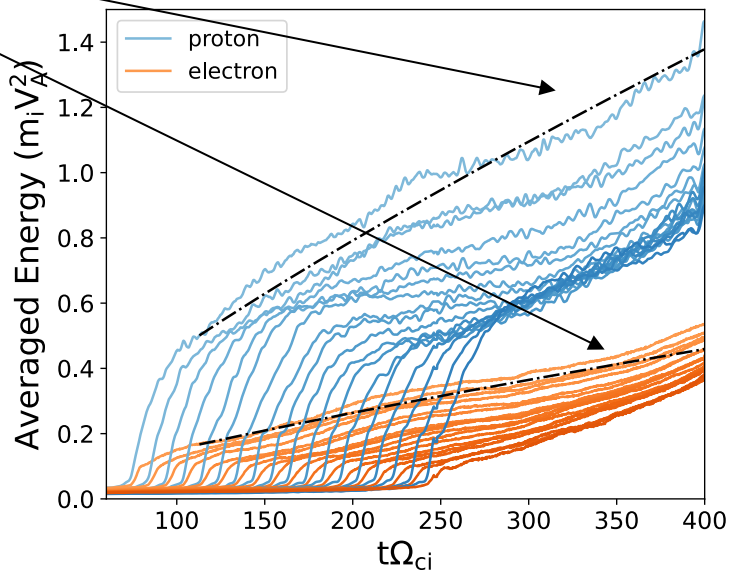
$$C \sim 0.8$$

$$E \propto t^C \sim t^{0.8}$$

$t^{0.8}$







Results are roughly consistent with observations

Solar flares

- Power-law indices p~4: Electrons: x-ray (Oka+ 2018), microwave (Gary+ 2018)

  Protons: gamma-ray (Omodei+ 2018), solar energetic particles (Cohen+ 2020)
- Significant nonthermal fraction (Oka+ 2015, Aschwanden+ 2016)

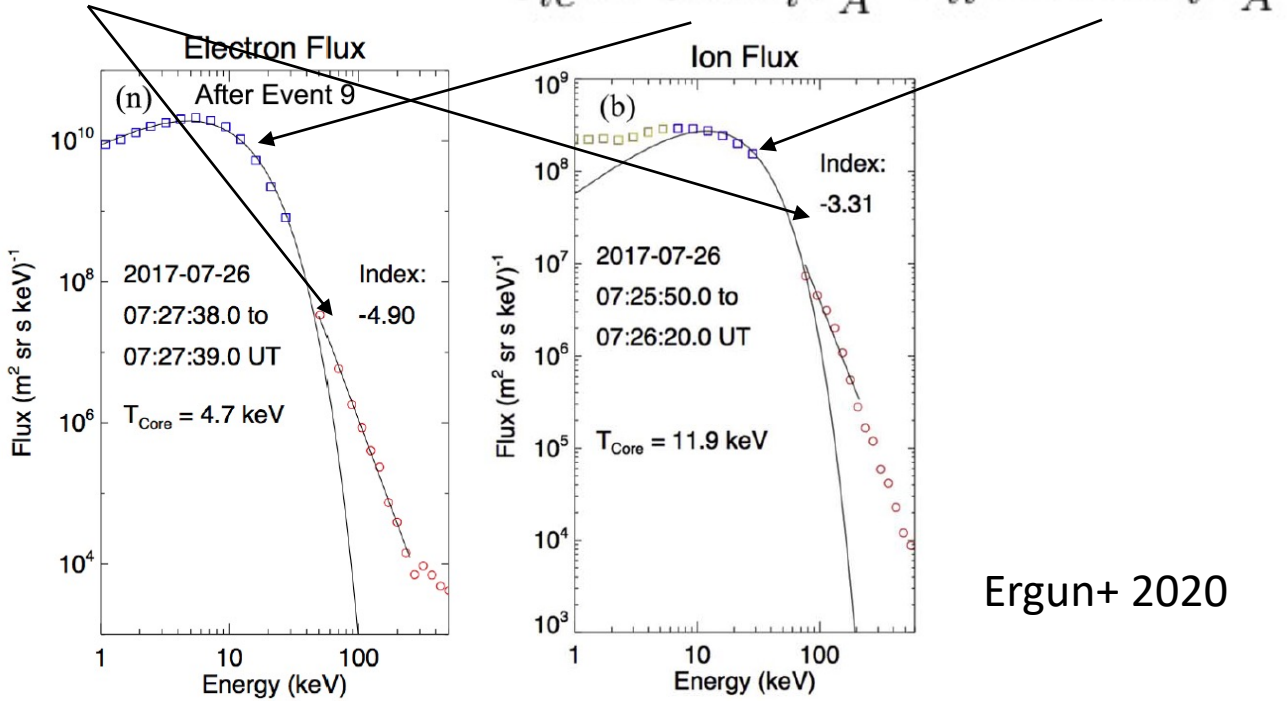
Magnetotail

In-situ spectra for both species

Power-law indices p~4

Low-energy bound "shoulder"

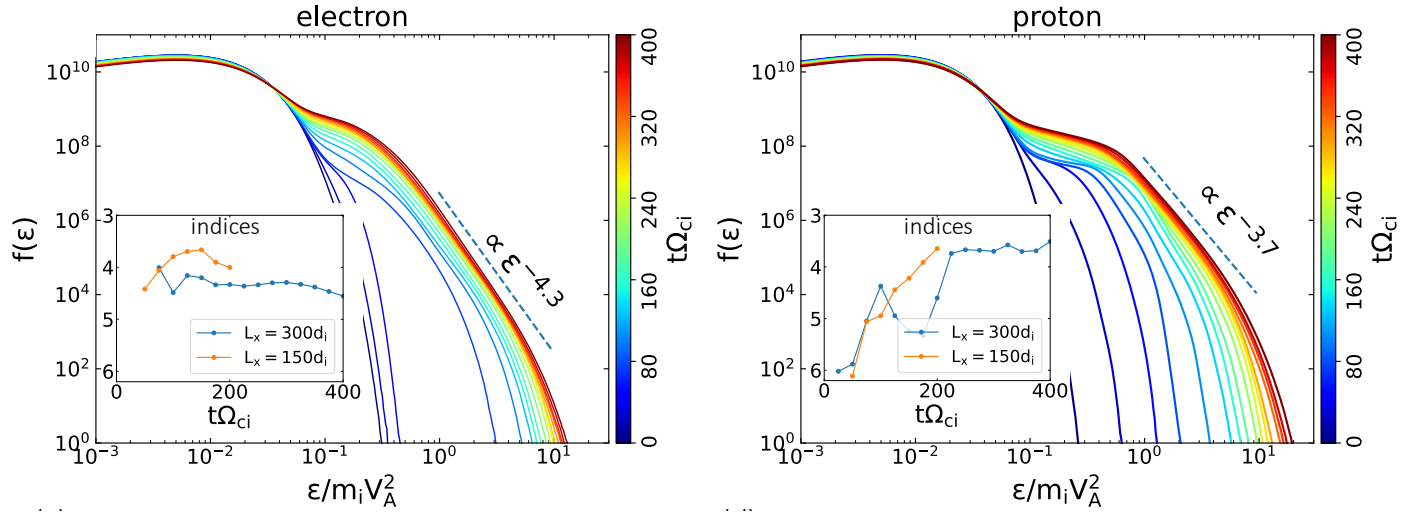
$\varepsilon_{le} \sim 0.2 m_i V_A^2 \quad \varepsilon_{li} \sim 0.5 m_i V_A^2$

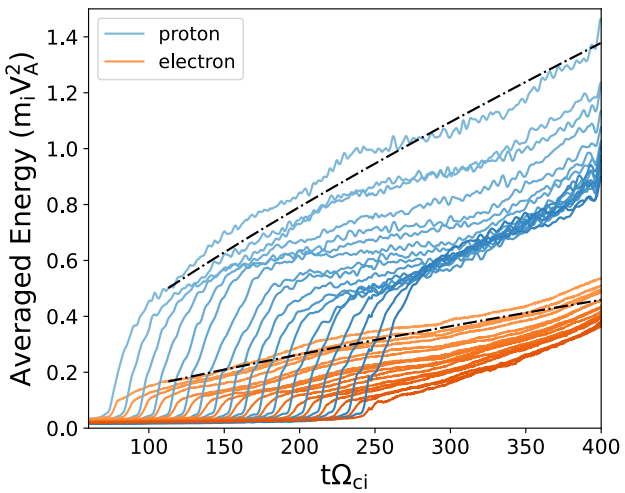


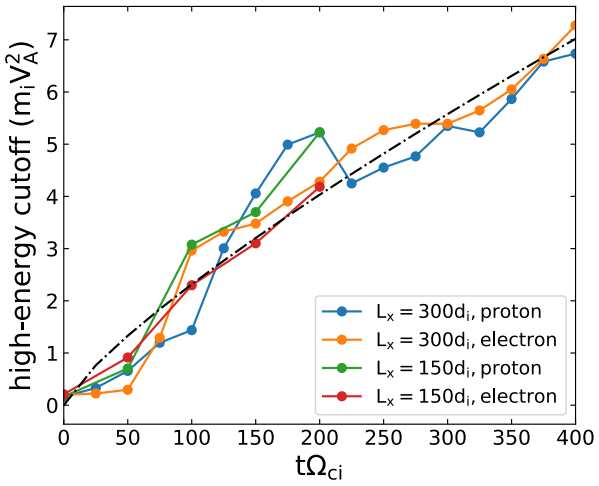
Ergun+ 2020

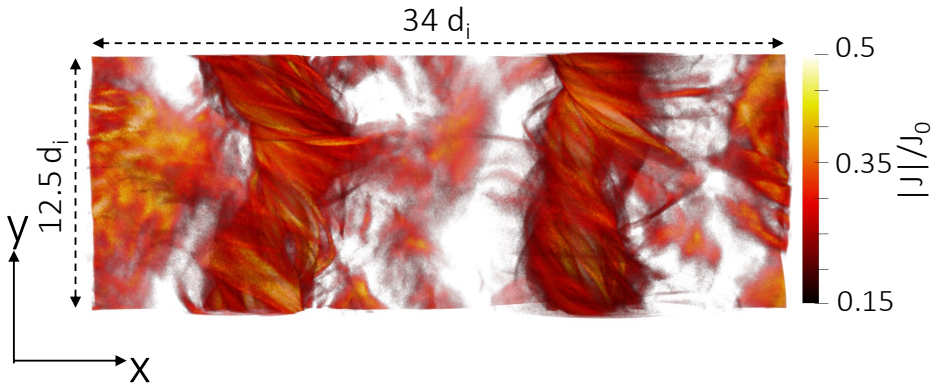
Take-aways

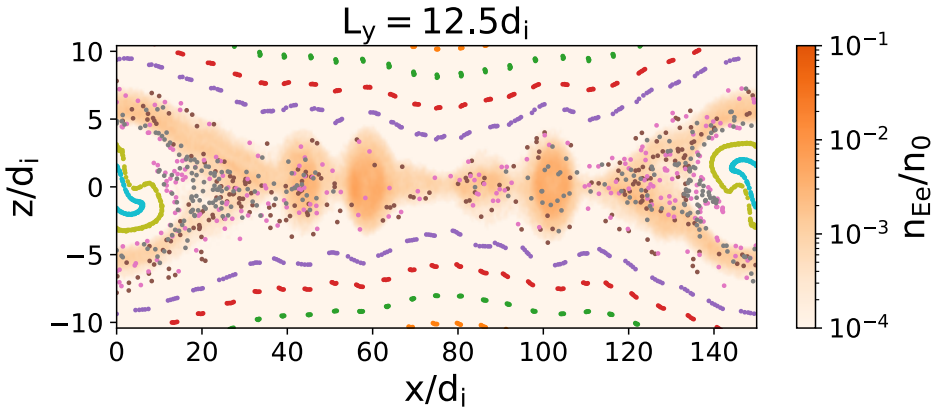
- 3D reconnection drives efficient nonthermal acceleration for both protons and electrons.
- Efficient Fermi acceleration is enabled by field-line chaos driven by flux-rope kink instability.
- Low-energy bound is determined by injection; high-energy cutoff grows with system size.











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