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Efficient Nonthermal Ion and Electron Acceleration in 3D Magnetic Reconnection

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Solar flare and Earth's magnetotail observations show simultaneous acceleration of ions and electrons into power-law energy distributions extending to high energy. This suggests a common magnetic-reconnection acceleration process but the underlying physics is not well understood.

During magnetic reconnection, energetic particles undergo a universal Fermi acceleration process, involving the curvature drift of particles within the electric field induced by the large-scale flows. However, the efficiency of this mechanism is limited by the trapping of energetic particles within magnetic flux ropes produced by reconnection.

Using 3D fully kinetic simulations, we demonstrate that the flux-rope kink instability (Figure 1) leads to field-line chaos in weak-guide-field regimes where the Fermi mechanism is most efficient, thus allowing particles to transport out of flux ropes and undergo further acceleration [1]. As a consequence, both ions and electrons form clear power laws (Figure 2) which contain a significant fraction of the released energy. The low-energy bounds, which control the nonthermal energy contents, are determined by the injection physics, while the high-energy cutoffs are limited only by the system size.

In contrast, in the higher-guide-field regimes, field-line chaos and efficient acceleration comes from 3D overlapping oblique tearing flux ropes of large sizes [2]. As a result, both species also form power laws consistent with Fermi acceleration, with indices softer than weak-guide-field regimes. Interestingly, these oblique flux ropes are also subject to kink instability.

These basic results have strong relevance to observations of nonthermal particle acceleration in both the solar corona and magnetotail.

References
[1] Qile Zhang et al., Physical Review Letters 127, 185101 (2021)
[2] Qile Zhang et al., 2022, in preparation

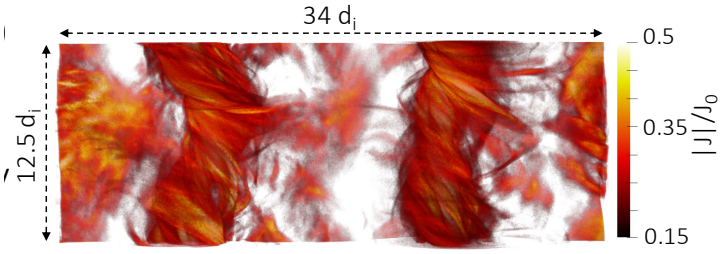

Figure 1. 3D current density, showing that magnetic flux ropes undergo flux-rope kink instability.

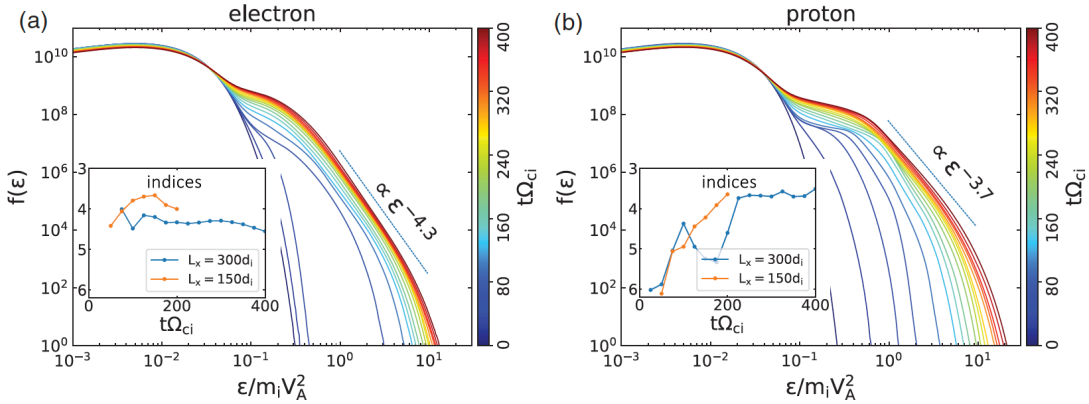

Figure 2. Evolution of energy spectra for electrons (a) and protons (b). Both electrons and protons form clear and sustainable power laws as a result of efficient acceleration in 3D.