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Dark plasmas in the nonlinear regime: constraints from particle-in-cell simulations

If the dark sector possesses long-range self-interactions, these interactions can source dramatic collective instabilities even in astrophysical settings where the collisional mean free path is long. Here, we focus on the specific case of dark matter halos composed of a dark $U(1)$ gauge sector undergoing a dissociative cluster merger. We study this by performing the first dedicated particle-in-cell plasma simulations of interacting dark matter streams, tracking the growth, formation, and saturation of instabilities through both the linear and nonlinear regimes. We find that these instabilities give rise to local (dark) electromagnetic inhomogeneities that serve as scattering sites, inducing an effective dynamic collisional cross-section. Mapping this effective cross-section onto existing results from large-scale simulations of the Bullet Cluster, we extend the limit on the dark charge-to-mass ratio by over ten orders of magnitude. Our results serve as a simple example of the rich phenomenology that may arise in a dark sector with long-range interactions and motivate future dedicated study of such "dark plasmas."

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