A Bright Future for Dark Plasmas

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Introduction

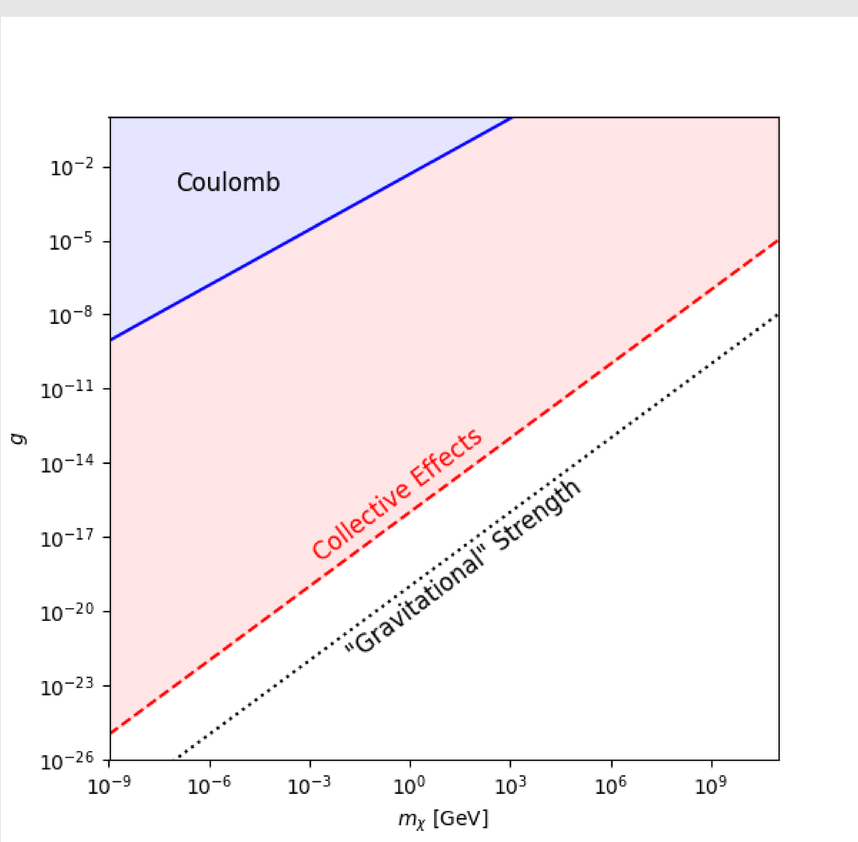
Historically, dark matter has been studied within the context of point-particle interactions. While an overwhelming majority of visible matter in the universe is composed of plasma governed by collective effects, collective effects in the dark sector have received little attention. Despite this, collective effects mediated by long-range interactions in the dark sector have dramatic consequences. In a large range of parameter space, plasma instabilities can lead to the formation of collisionless shocks which cause the dark matter to behave collisionally despite a long scattering mean free path. This is in severe tension with observations of dissociative cluster mergers such as the Bullet Cluster. In this work, we perform the first-ever simulations of collective interactions in the dark sector to study shock formation and collisionality in the nonlinear regime.

Motivation

One well-motivated model for dark matter is a single new particle that interacts via a massless $U(1)_D$ mediator.

$$\mathcal{L}_{\mathcal{D}} = \bar{\chi}(i\not{D} + m_\chi)\chi - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}$$

with $D_\mu = \partial_\mu - igA_\mu$ and $F^{\mu\nu}$ the field strength tensor for the mediator. In cases such as the Bullet Cluster, impacts on gravitational lensing would be dominated by collective effects instead of 2→2 Coulomb interactions. These new bounds could be as strong as $g \gtrsim 10^{-16} m_\chi/\mathrm{GeV}$ [1].



Dominant Instabilities

We aim to simulate two beams of cold, collisionless plasmas colliding at a non-relativistic relative velocity. It is well-known that the two dominant instabilities are the transverse Weibel instabilities and the electrostatic longitudinal two-stream instability. Analytical estimates [2, 3] for the growth rates of both of these instabilities have been made. The electrostatic two-stream instability to grow at nearly the same rate for all incident beam velocities,

$$\delta_{TS} \sim \frac{3^{1/2}}{2^{4/3}}\omega_p \approx 0.7\omega_p$$

However, the Weibel instabilities are velocity suppressed.

$$\delta_W \sim \left(2\beta_0\sqrt{\frac{2}{(1+\beta_0^2)^3}}\right)\omega_p,$$

where $\omega_p = \sqrt{qn_0/m}$ is the plasma frequency. Thus, the electrostatic instabilities dominate in the early timescales for low beam velocities and Weibel instabilities dominate in the highly relativistic cases.

References

[1] R. Lasenby. *Long range dark matter self-interactions and plasma instabilities.* Journal of Cosmology and Astroparticle Physics, 11 (2020) 034

[2] S. Peter Gary. *Theory of space plasma microinstabilities.* Cambridge, Cambridge University Press, 1993

[3] A. Bret, A. Stockem, F. Fiuza, et al. *Collisionless shock formation, spontaneous electromagnetic fluctuations, and streaming instabilities.* Phys. Plasmas 20, (2013) 042102

[4] T. D. Arber et al. *Contemporary particle-in-cell approach to laser-plasma modeling.* Plasma Physics & Controlled Fusion, 57 (2015) 113001

Simulation

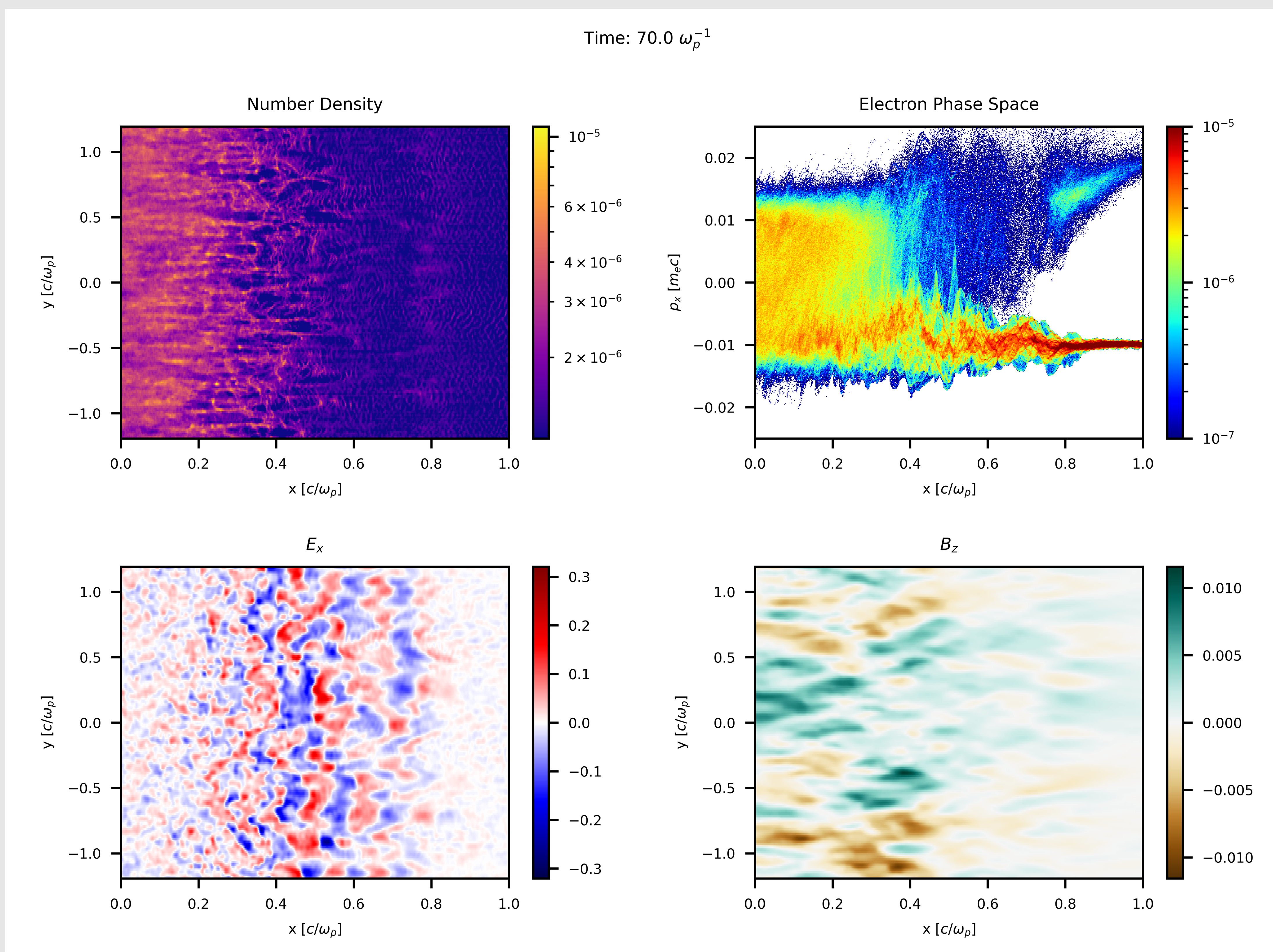
Our initial simulations were performed on parameter space still within Standard Model coupling ranges in order to confirm that the results reproduce analytic estimates in the non-relativistic regime. We therefore utilized the EPOCH [4] framework to simulate the collision of two beams of Standard Model electron-positron plasma using the following parameters:

- $n_0 = 5 \times 10^5\,\mathrm{m}^{-3}$
- $g = e$ and $m_\chi = m_e$ (Standard Model parameter space)
- $\beta_0 = 0.01$ ($\sim$ relative velocity of the Bullet Cluster merger)
- $T = 0.01\,\mathrm{eV}$ (for comparison to analytic estimates in the cold plasma limit)
- Simulation size of $10c/\omega_p \times 2.4\,c/\omega_p$ with 4750×190 cells
- 5 current smoothing iterations and 25 particles per cell (maintains control over numerical heating)

Additional simulations were performed to ensure that effects due to numerical heating were negligible compared to the amount of free energy available from the bulk velocity plasmas. It was found that the increase in thermal velocity remained below 1% of the bulk velocity for the timescales of interest.

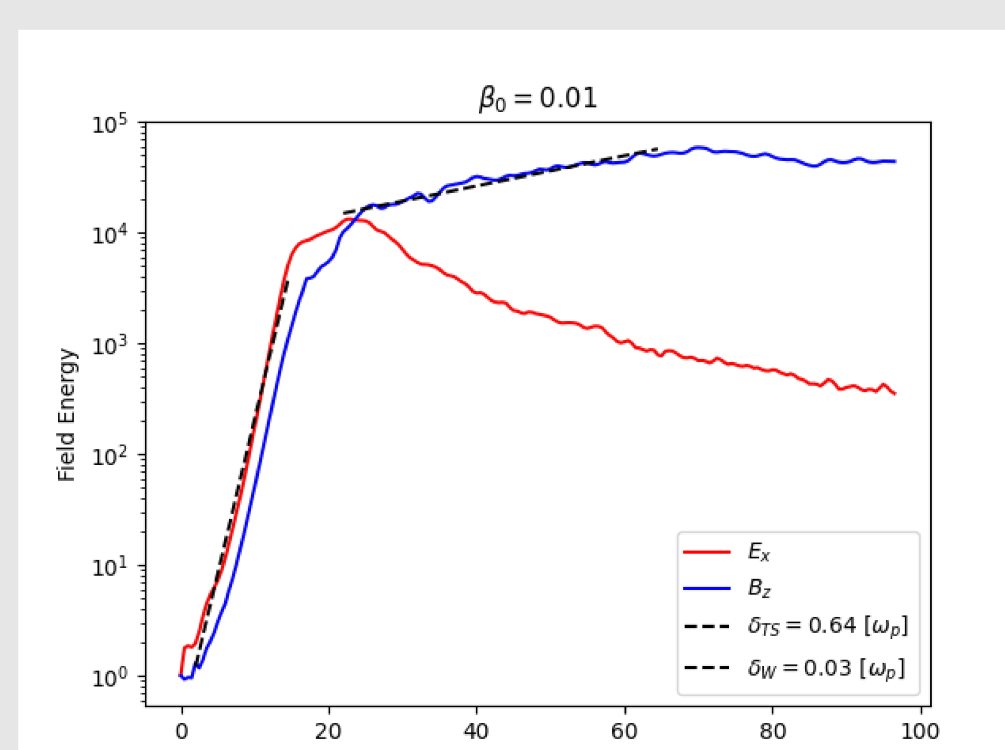
Characteristics of Instabilities

When the counter-streaming beams are each given initial velocities of 0.01c, we see signatures from both the longitudinal electrostatic instability as well as the transverse Weibel instability. Along the shock front, we see a powerful bipolar pulse from the longitudinal component of the electric field visible at $x = 0.5c/\omega_p$ in the lower left plot. As electrons and positrons enter these regions, they will oscillate in the longitudinal direction as they cross between these regions. This creates a phase space vortex seen at the same coordinate in the upper right plot. These phase space vortices arrest shock formation and lead to a saturation of the instability. Additionally, we see the characteristic transverse filamentation of the Weibel instability in the transverse magnetic field. This can be seen in the lower right plot.



Growth Rates of Instabilities

Analytic estimates predict that the electrostatic instability grows the fastest, with an exponential growth rate of $\delta_{TS} \approx 0.7\omega_p$ compared to the Weibel instability at $\delta_W \approx 0.028\omega_p$. Although the initial mode is slightly oblique, the early timescale is dominated by the electrostatic instability. However, this quickly saturates and allows the Weibel instability to continue growing at a much slower rate. From the numerical simulation, exponential models were fit to the data. They found $\delta_{TS} \approx 0.64\omega_p$ and $\delta_W \approx 0.03\omega_p$ which agree well with the analytical estimates. In order to compare our simulations with existing literature, additional simulations were performed with relativistic beam velocities. We found the instabilities in these simulations additionally matched well with analytic approximations.



Future Work

This work has studied the relevant dynamics and instabilities in cold, Standard Model plasmas in the non-relativistic regime. In the future, we plan to simulate warm plasmas with low relative velocities, a regime that has never previously been studied numerically in the literature. As a next step, the thermal velocity will be increased to $10^{-3}c$ in order to better model the conditions of the Bullet Cluster merger. Additionally, the constituent particles' charge, mass, and number density will be altered to fit values currently unconstrained in the parameter space of dark-$U(1)$ models.