Kinetic Simulations of Collisionless Shock Formation in the Dark Sector

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with Will DeRocco

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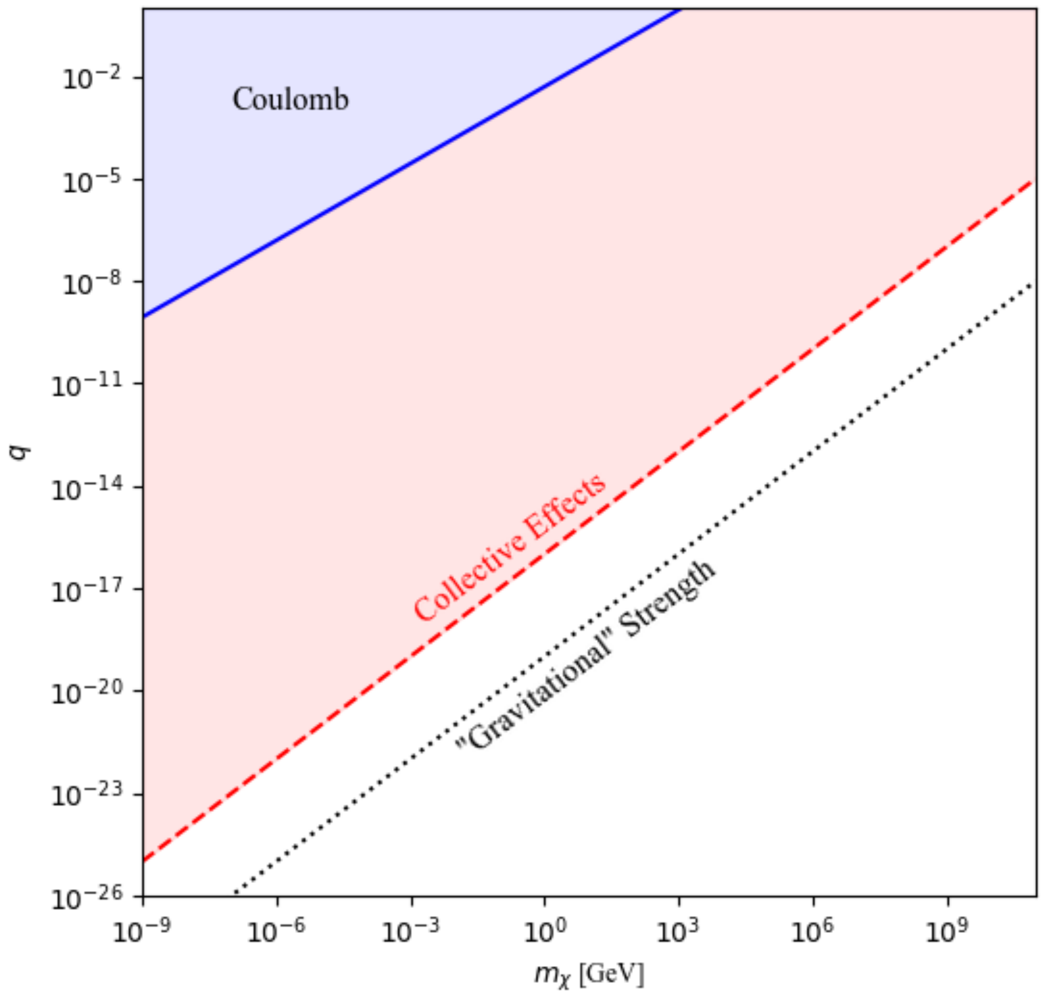
Long Range Effects

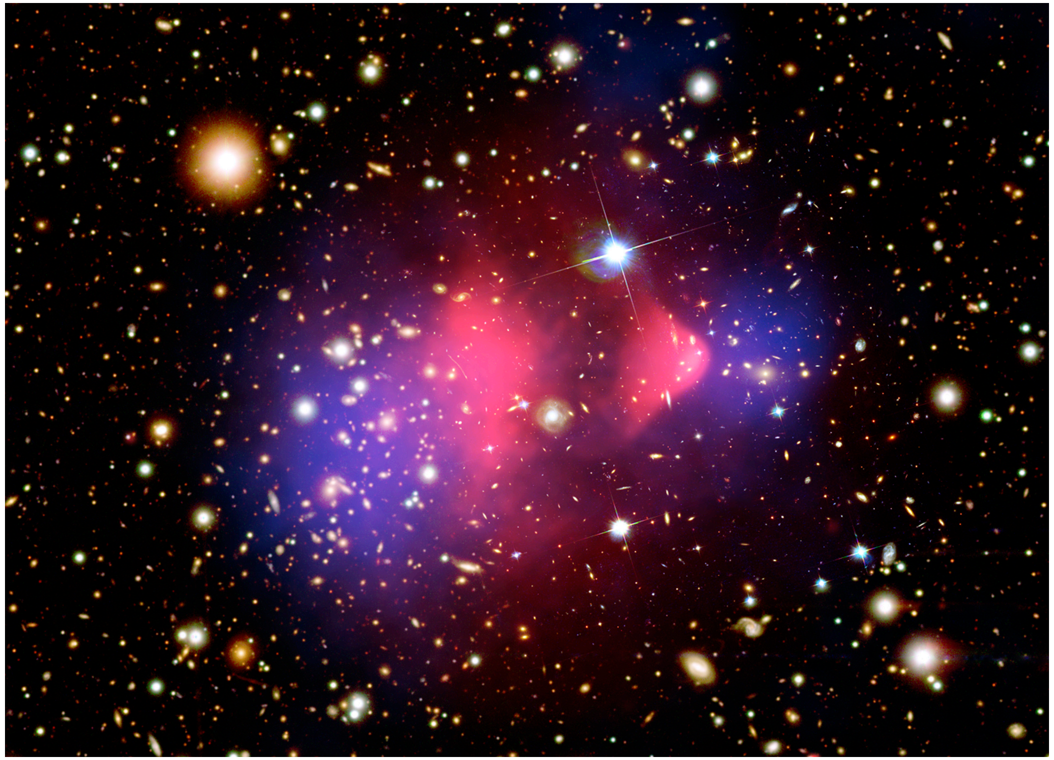
- Self-interacting dark matter is not only 2 → 2 scattering
- 99.9% of visible matter in the universe is a plasma, governed by many → many scattering
- Long range collective effects can probe many orders of magnitude deeper into parameter space



Current Constraints

- Some of the strongest 2→2 constraints come from dissociative cluster mergers such as the Bullet Cluster [1]
  - $\sigma/m \lesssim 1\ \mathrm{cm^2 g^{-1}}$

- Main Observables
  - Evaporation of dark matter halo
  - Offset of dark matter and standard model centers



Credit: European Space Agency

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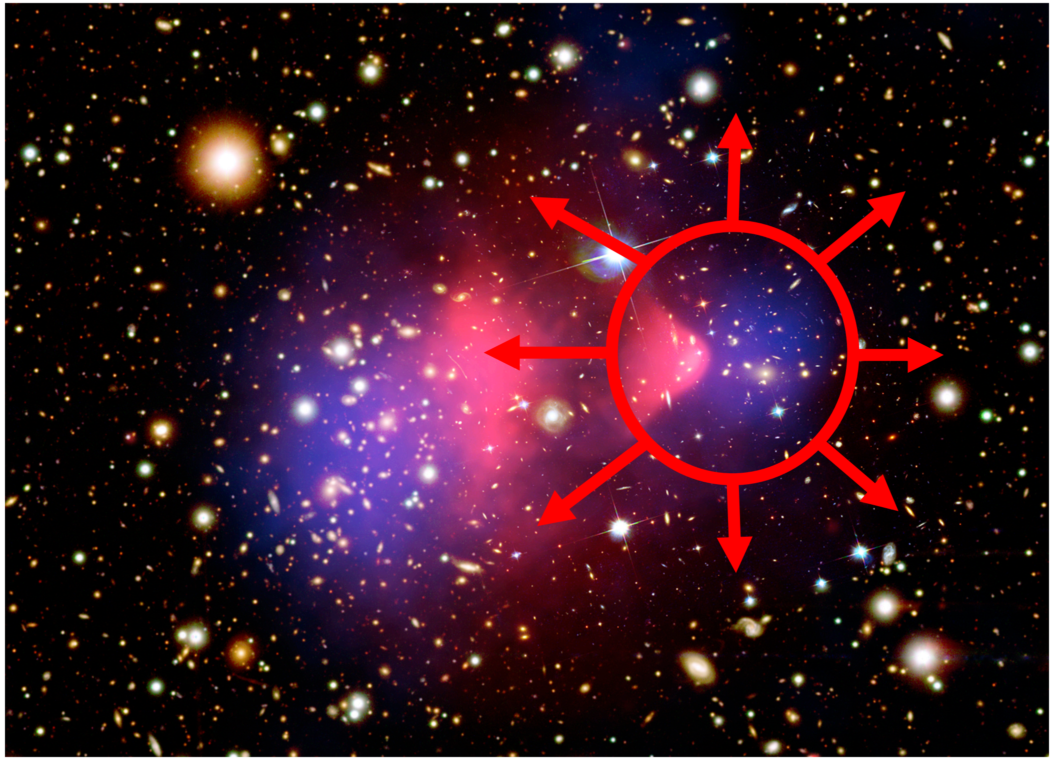

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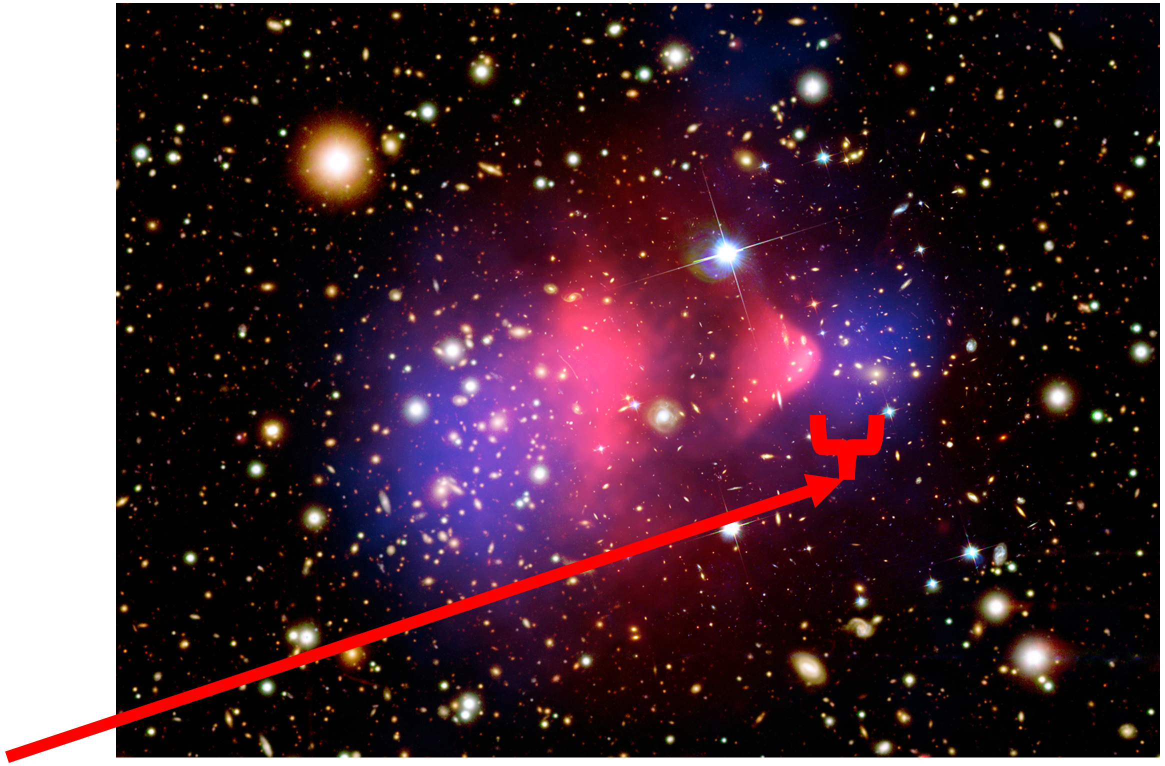

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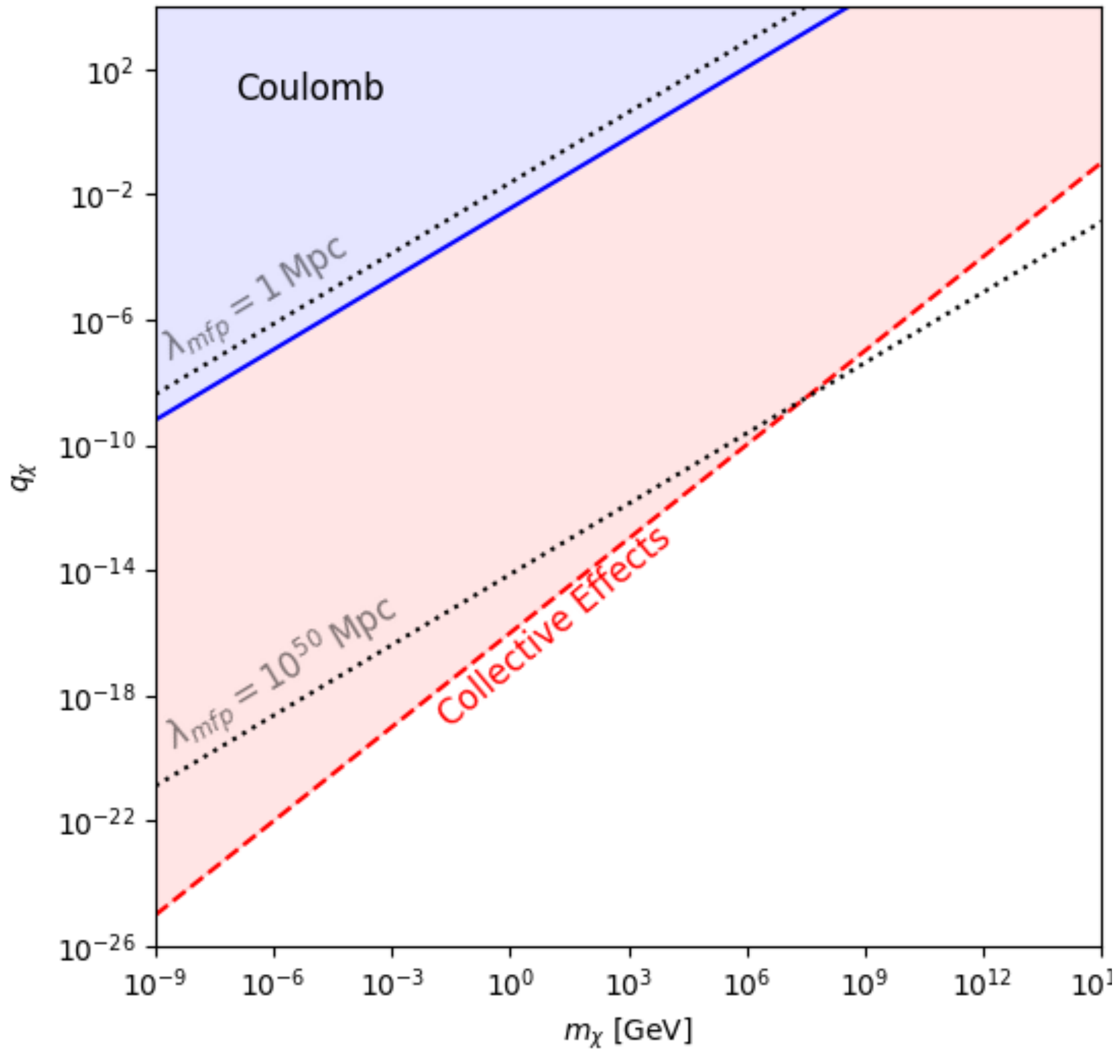
Collisionless Regime

- Introduce model

$$\mathcal{L} = \mathcal{L}_{SM} - \frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \bar{\chi}(\gamma^{\mu}(i\partial_{\mu} - qA') - m_{\chi})\chi$$

- Size of Bullet Cluster core ~100 kpc
- Mean free path of dark matter

$$\lambda \sim 30\ \mathrm{kpc}\left(\frac{v_{rel}}{0.01c}\right)^{4}\left(\frac{q_{\chi}}{q_e}\right)^{-4}\left(\frac{m_{\chi}}{\mathrm{GeV}}\right)^{3}\left(\frac{\rho_{\chi}}{0.01\ \mathrm{GeV/cm^3}}\right)$$



Plasma Dynamics

- Vlasov Equation

$$\left(\partial_t + \frac{q_s}{m_s}(\mathbf{E} + \mathbf{v} \times \mathbf{B}) \cdot \nabla_v + \mathbf{v} \cdot \nabla_x\right) f_s(\mathbf{x}, \mathbf{v}, t) = 0$$

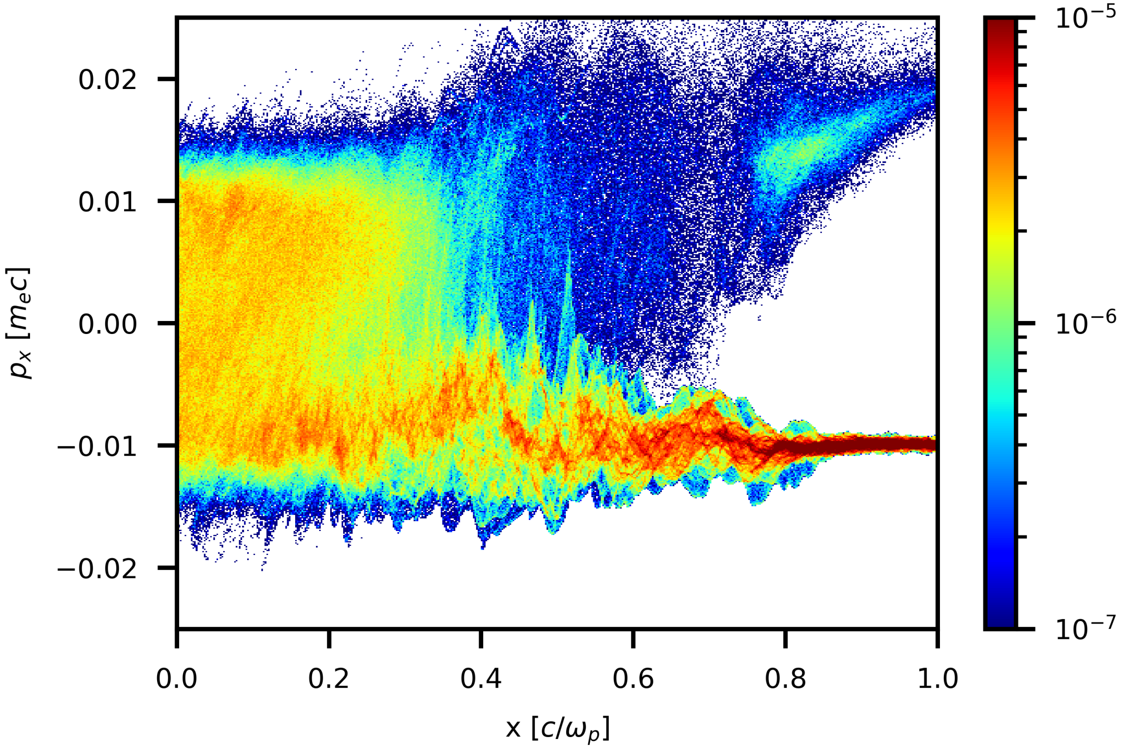
- Linear Regime
  - Analytical estimates predict growth rates and saturation times of instabilities
- Nonlinear Regime
  - Cannot be probed with analytics
  - Need for simulations

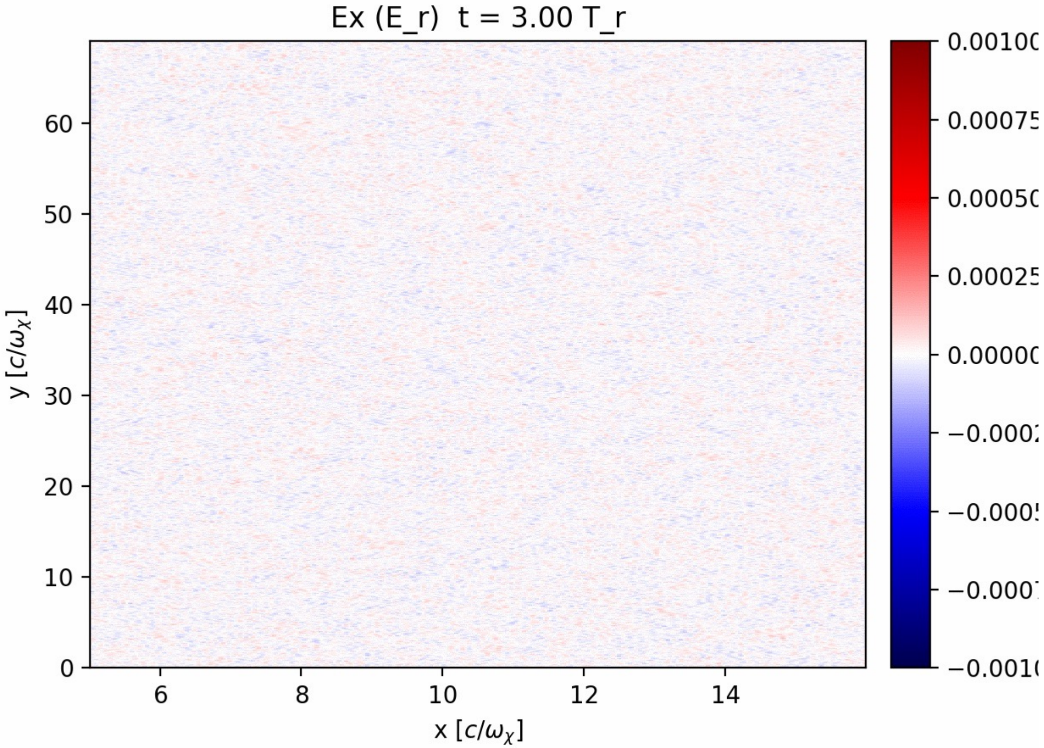
Simulations

- Plasma frequency: $\omega_\chi = \sqrt{\dfrac{q_\chi^2 n_{0,\chi}}{m_\chi \epsilon_0}} = \dfrac{q_\chi}{m_\chi}\sqrt{\dfrac{\rho_\chi}{\epsilon_0}}$

- "**Smilei** is a Particle-In-Cell code for plasma simulation. Open-source, collaborative, user-friendly and designed for high performances on super-computers, it is applied to a wide range of physics studies: from relativistic laser-plasma interaction to astrophysics."[2]

Plasma Shocks





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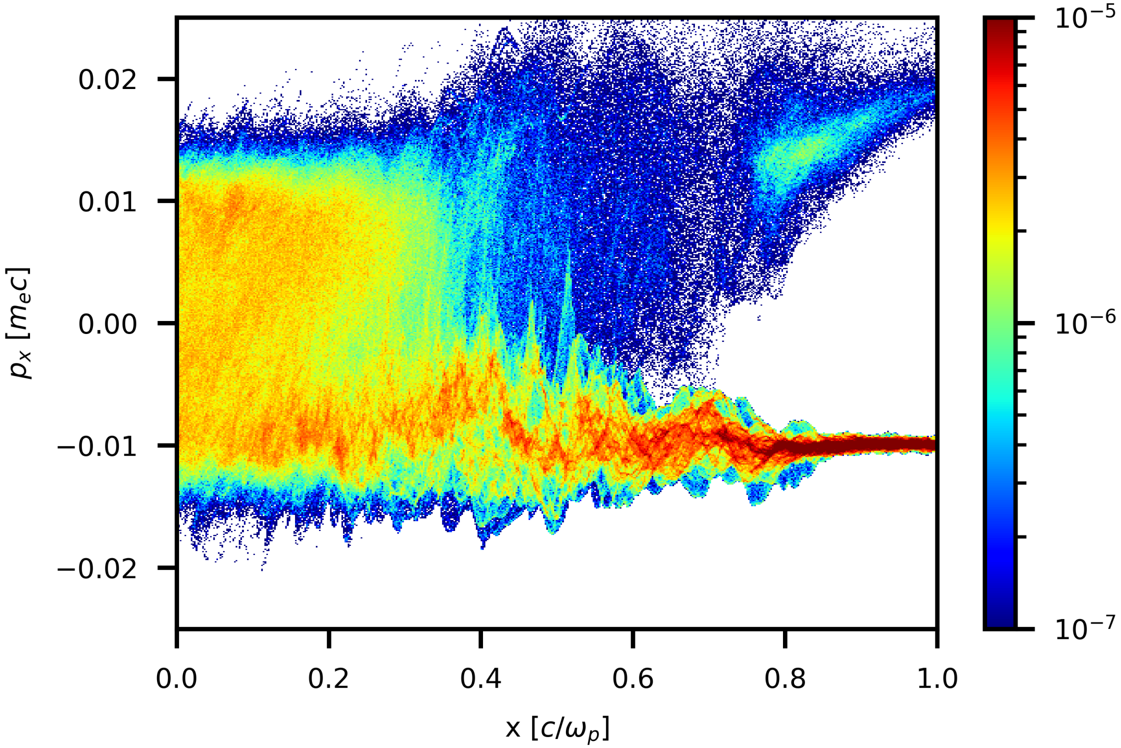

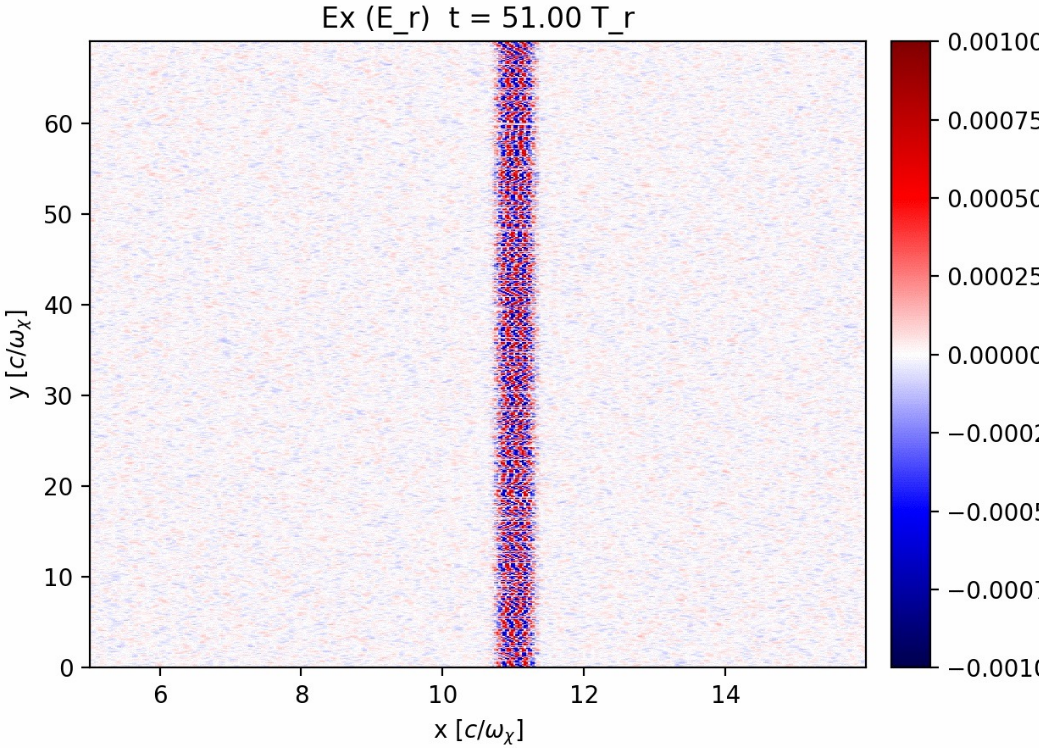

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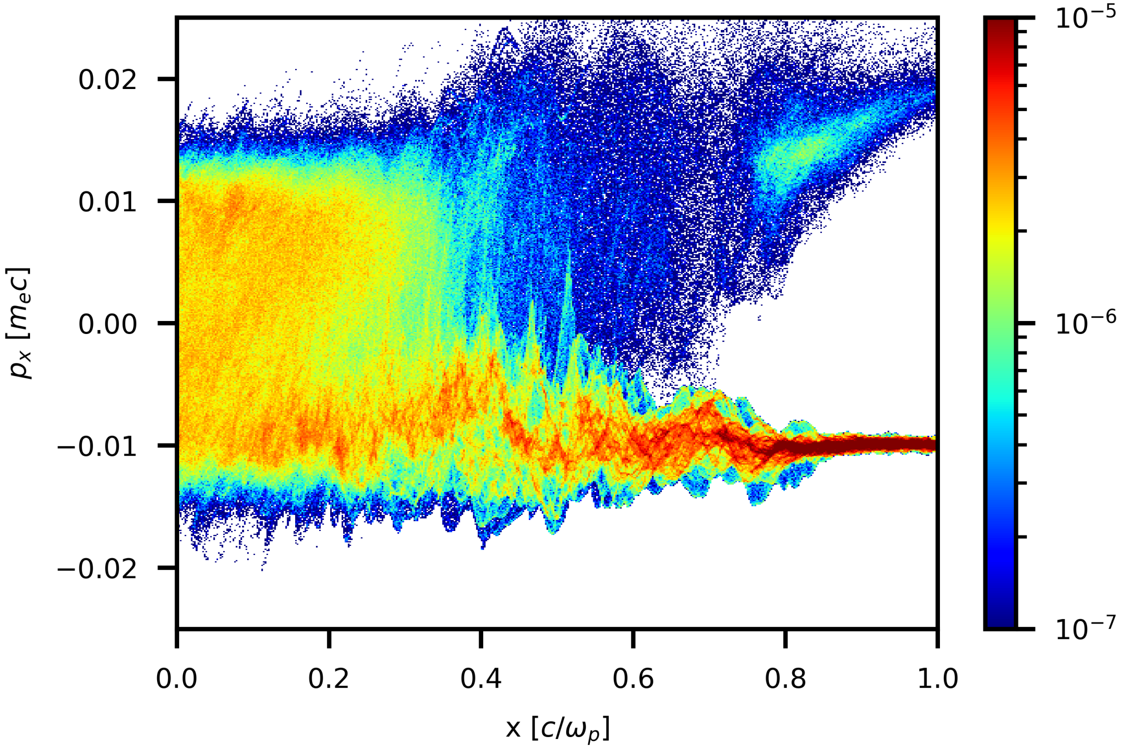
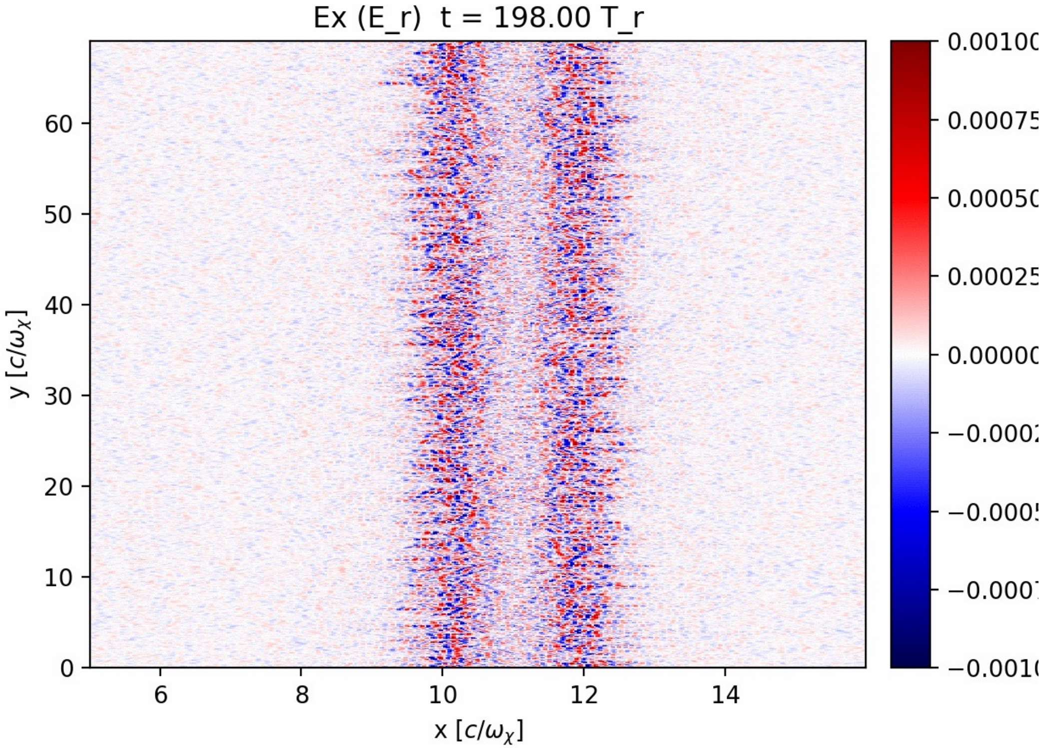
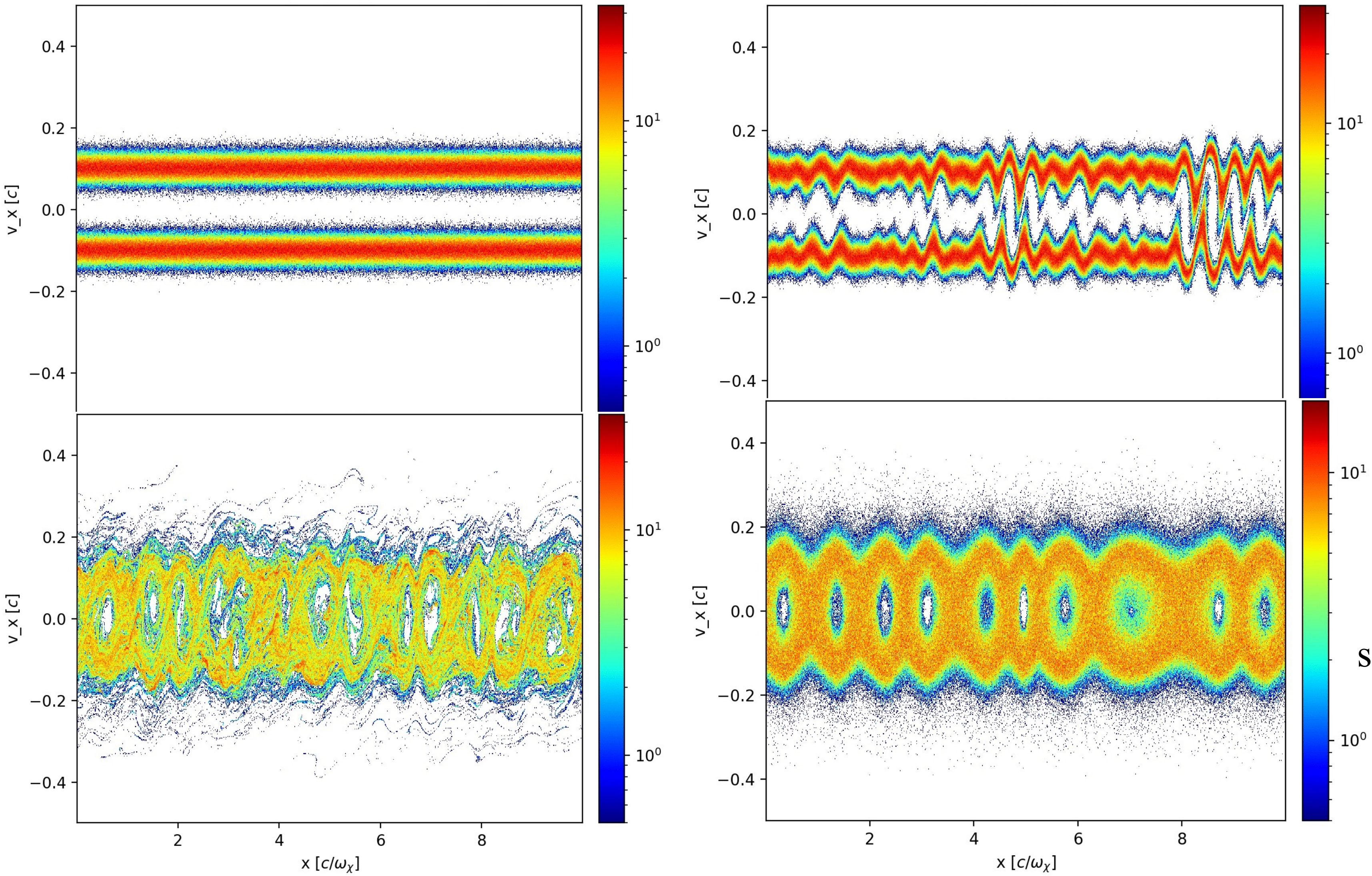




Plasma Turbulence

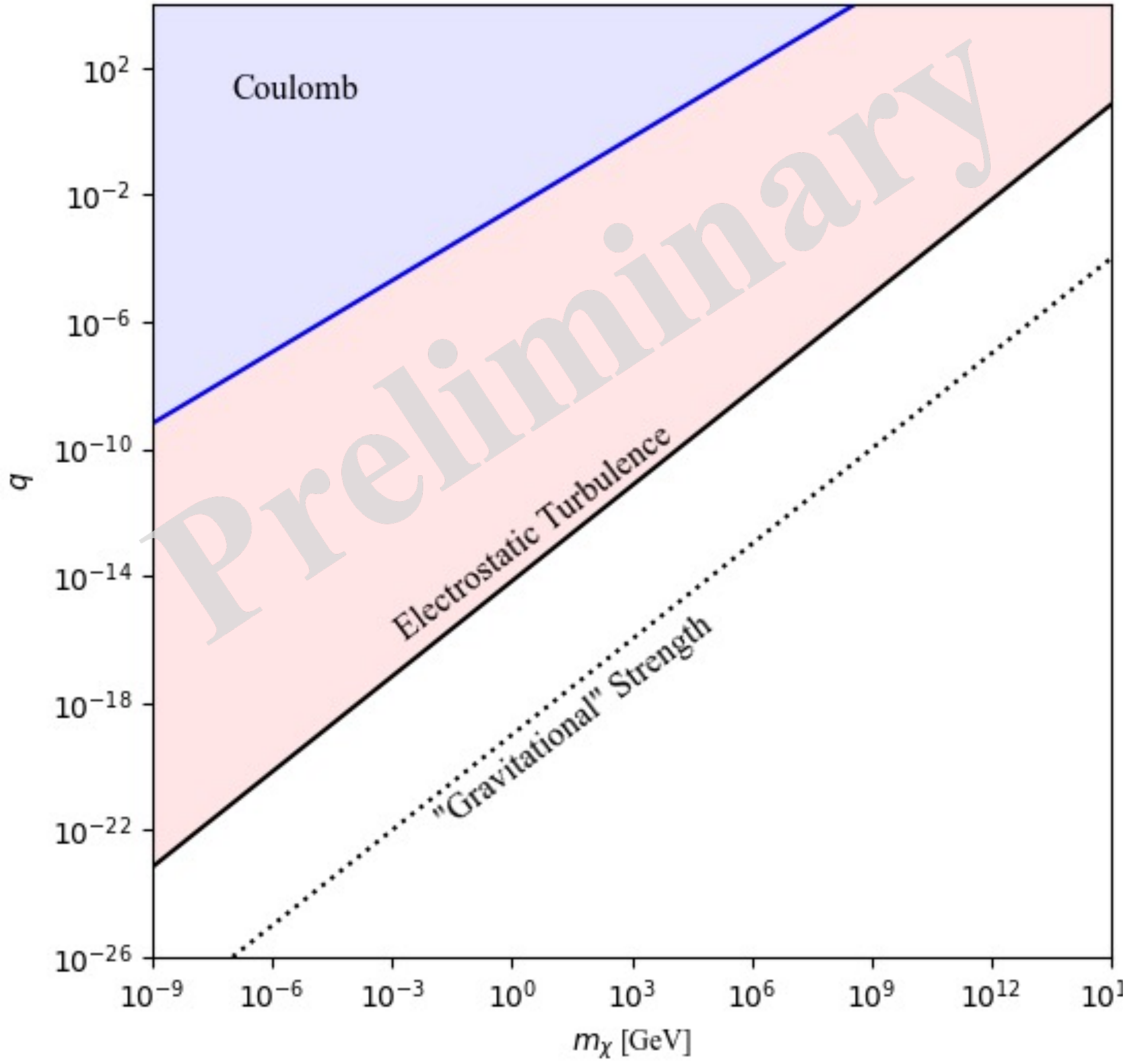
Initial Configuration
$t = 0\ \omega_p$

Small instabilities set in
$t \sim 10\ \omega_p$



Structure begins to form
$t \sim 100\ \omega_p$

Long lasting structure remains
$t > 1000\ \omega_p$



- Drag coefficient
  - Fit from simulations of bulk velocity slowdown from turbulence

$$c_d \sim -8 \times 10^{-4} \omega_\chi$$

- Parameters of Bullet Cluster core crossing

$$\rho_\chi \sim 0.01\ \mathrm{GeV/cm^3}$$

$$v_{rel} \sim 0.01c$$

$$t_{cross} \sim 3 \times 10^7\ \mathrm{yr}$$

$$\Delta x \gtrsim 50\ \mathrm{kpc}$$

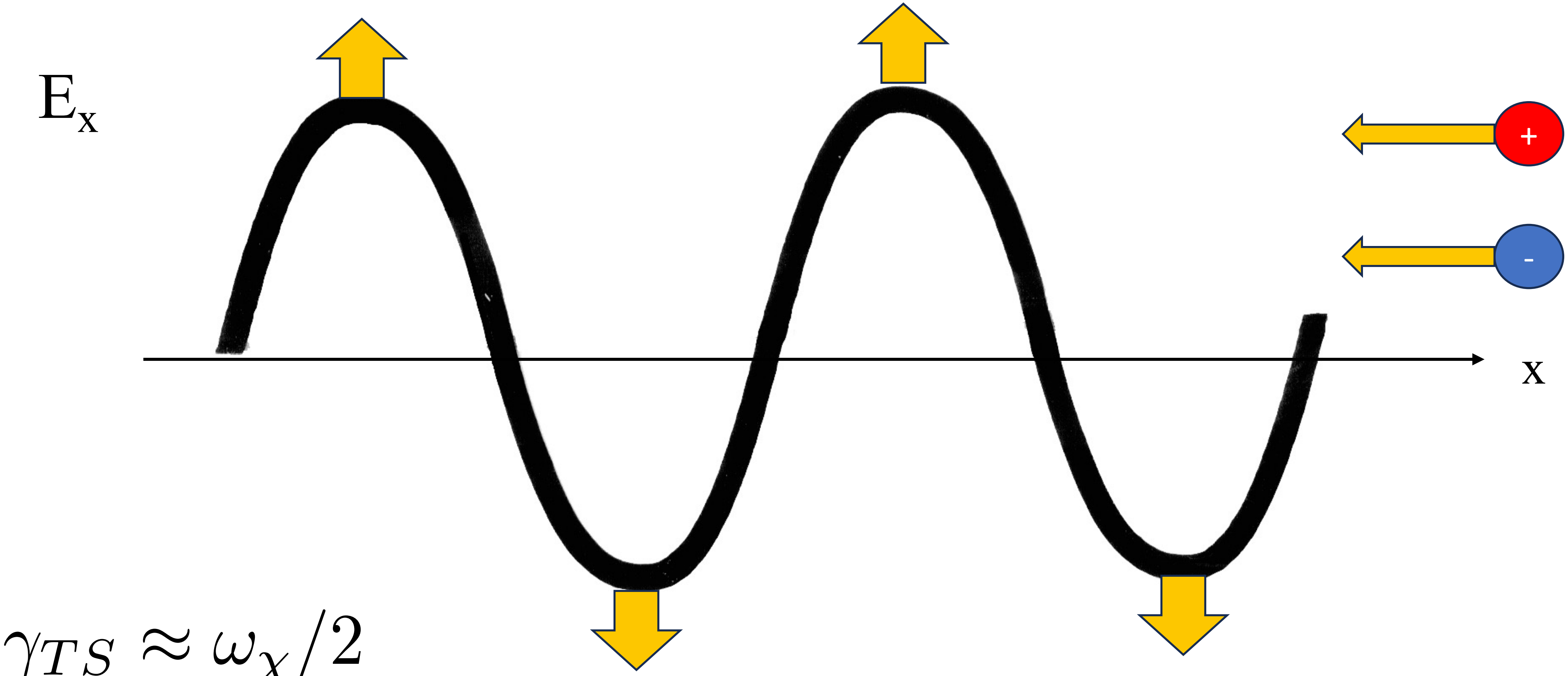
Conclusions

- Collective effects have potential to constrain several orders of magnitude of parameter space.
- Simulations are necessary to understand nonlinear behavior of plasmas.
- Currently unclear if shocks form in the Bullet Cluster or if turbulence is the dominant behavior.
- Future studies
  - Magnetized plasmas
  - Millicharged particles

References

- [1] A. Robertson, R. Massey, V. Eke, *What does the Bullet Cluster tell us about self-interacting dark matter?*, MNRAS, 465, 569-587 (2017)
- [2] J. Derouillat, A. Beck, F. Pérez, T. Vinci, M. Chiaramello, A. Grassi, M. Flé, G. Bouchard, I. Plotnikov, N. Aunai, J. Dargent, C. Riconda, M. Grech, *SMILEI: a collaborative, open-source, multi-purpose particle-in-cell code for plasma simulation*, Comput. Phys. Commun. 222, 351-373 (2018)
- [3] P. Agrawal, F-Y. Cyr-Racine, L. Randall, J. Scholtz, *Make Dark Matter Charged Again*, JCAP, 2017, 5 (2017)

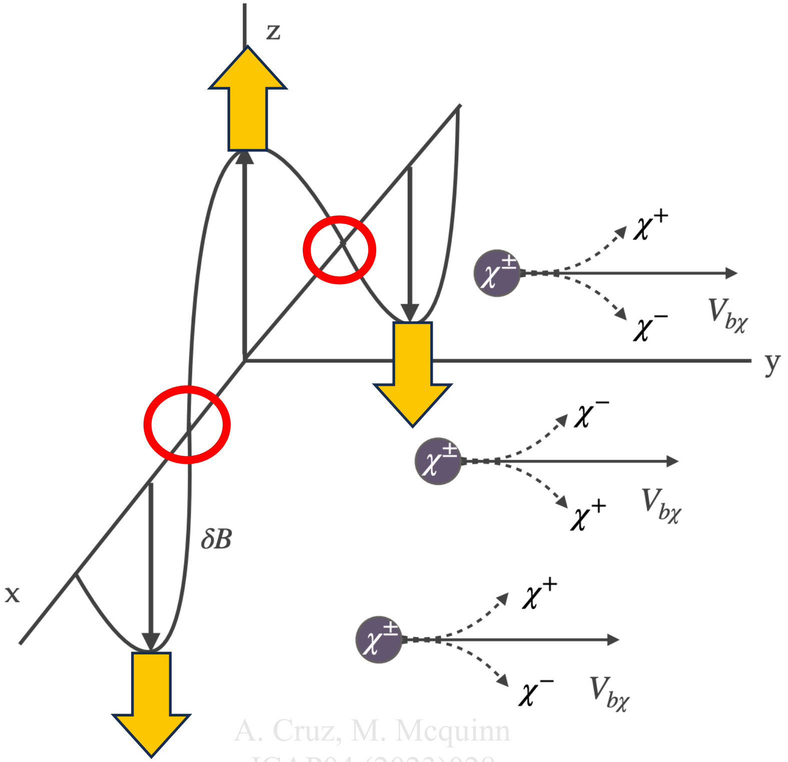
Longitudinal Instabilities



$$\gamma_{TS} \approx \omega_\chi/2$$

Transverse Instabilities

- Small perturbations in the transverse magnetic field attract particles to nodes
- Current sheets form as particles collect near nodes
- Current sheets induce a magnetic field that strengthens the initial perturbation
- Expected growth rate: $\gamma_W \approx v_{rel}\omega_\chi$



A. Cruz, M. Mcquinn
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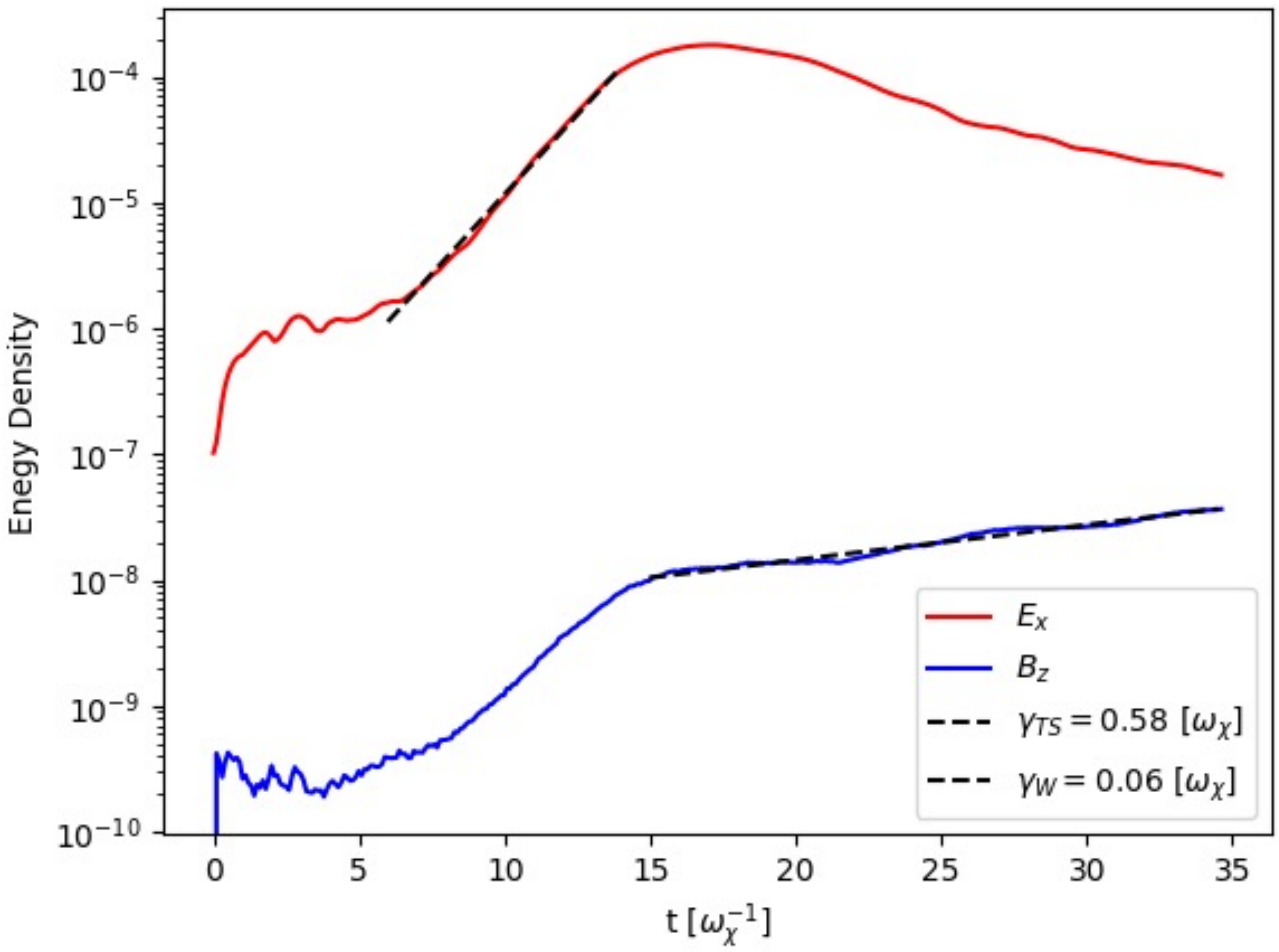

Enegy Density
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
0
5
10
15
20
25
30
35
t $[\omega_\chi^{-1}]$
E_x
B_z
$\gamma_{TS} = 0.58\ [\omega_\chi]$
$\gamma_W = 0.06\ [\omega_\chi]$