Kinetic Simulations of Collisionless Shock Formation in the Dark Sector

Pierce Giffin

with Will DeRocco

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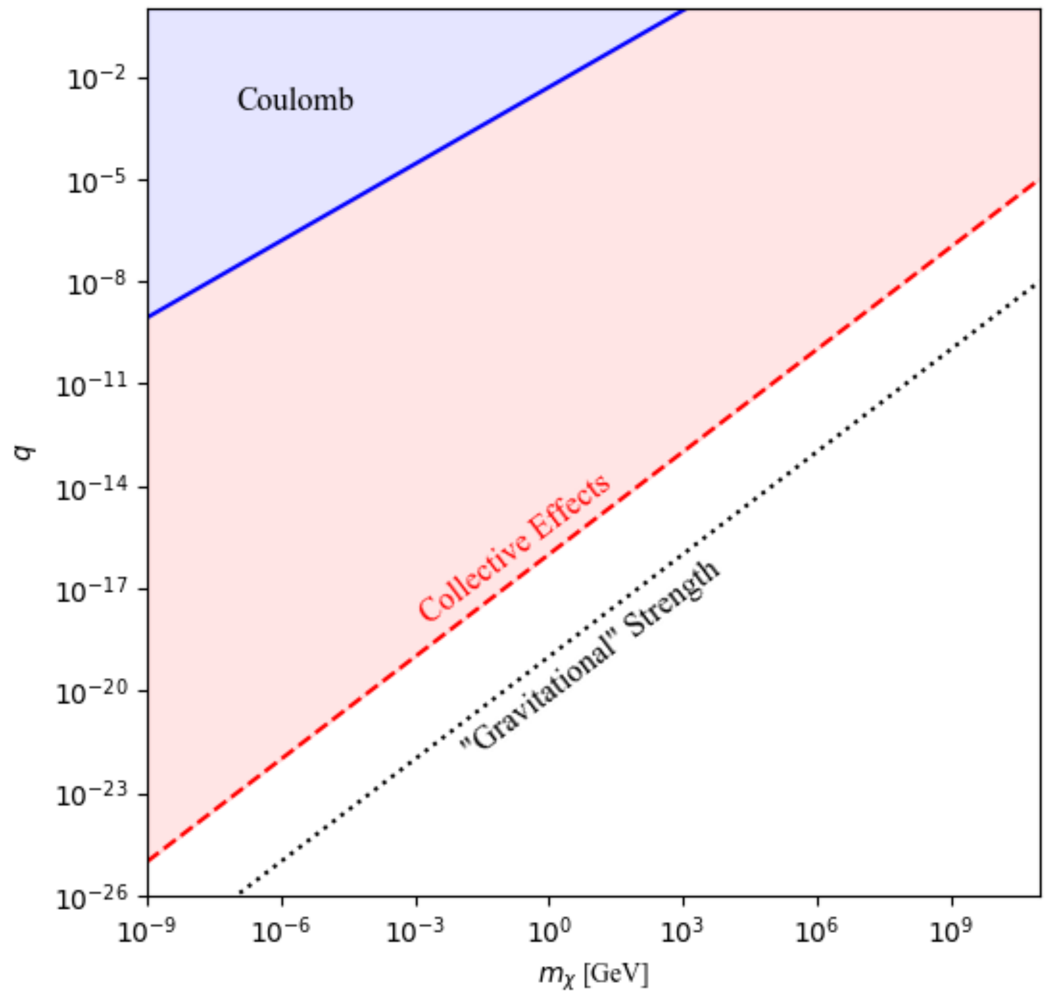
Long Range Effects

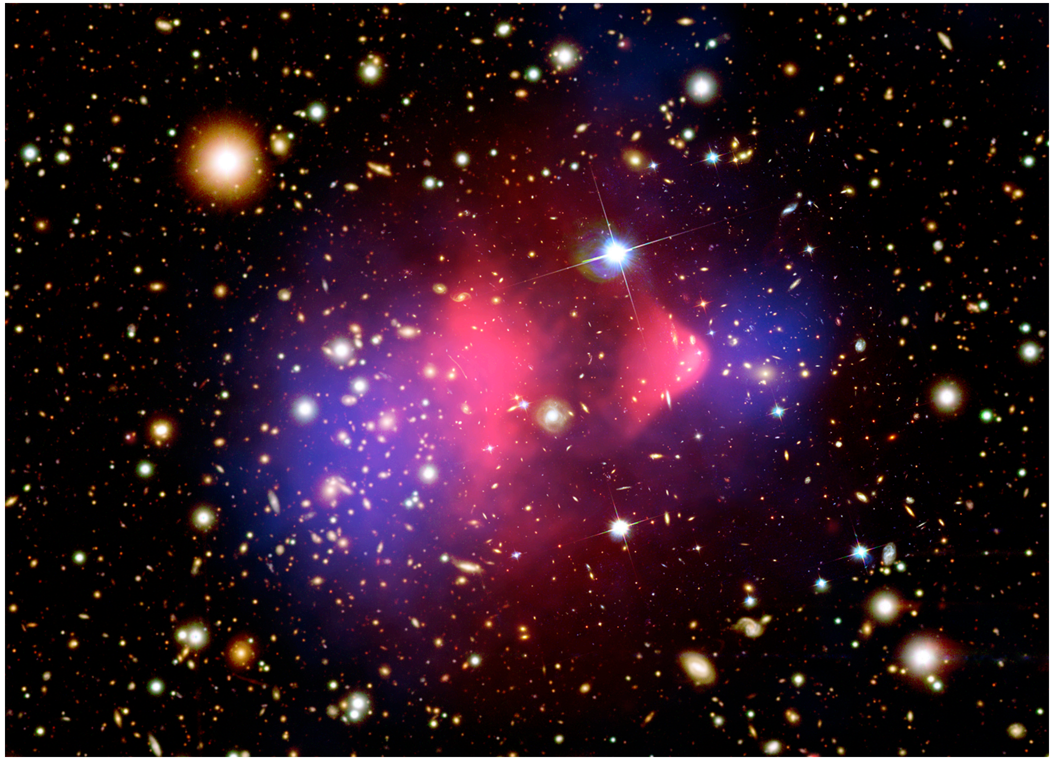
- Self-interacting dark matter is not only 2 → 2 scattering
- 99.9% of visible matter in the universe is a plasma, governed by many → many scattering
- Long range collective effects can probe many orders of magnitude deeper into parameter space



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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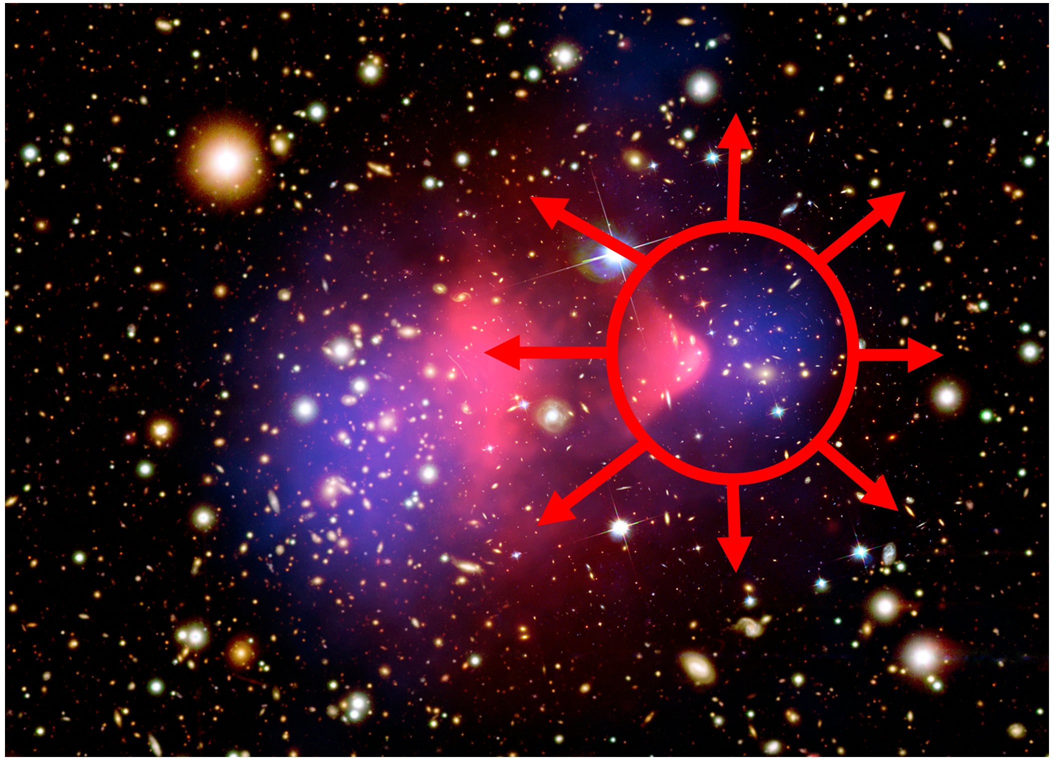

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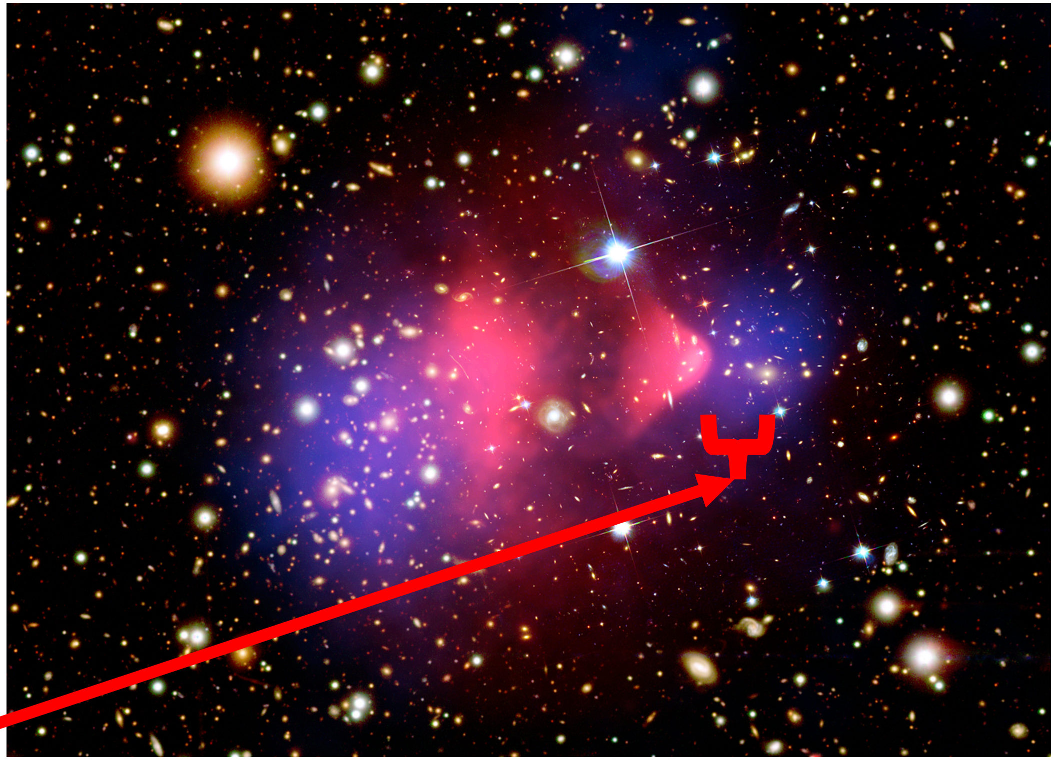

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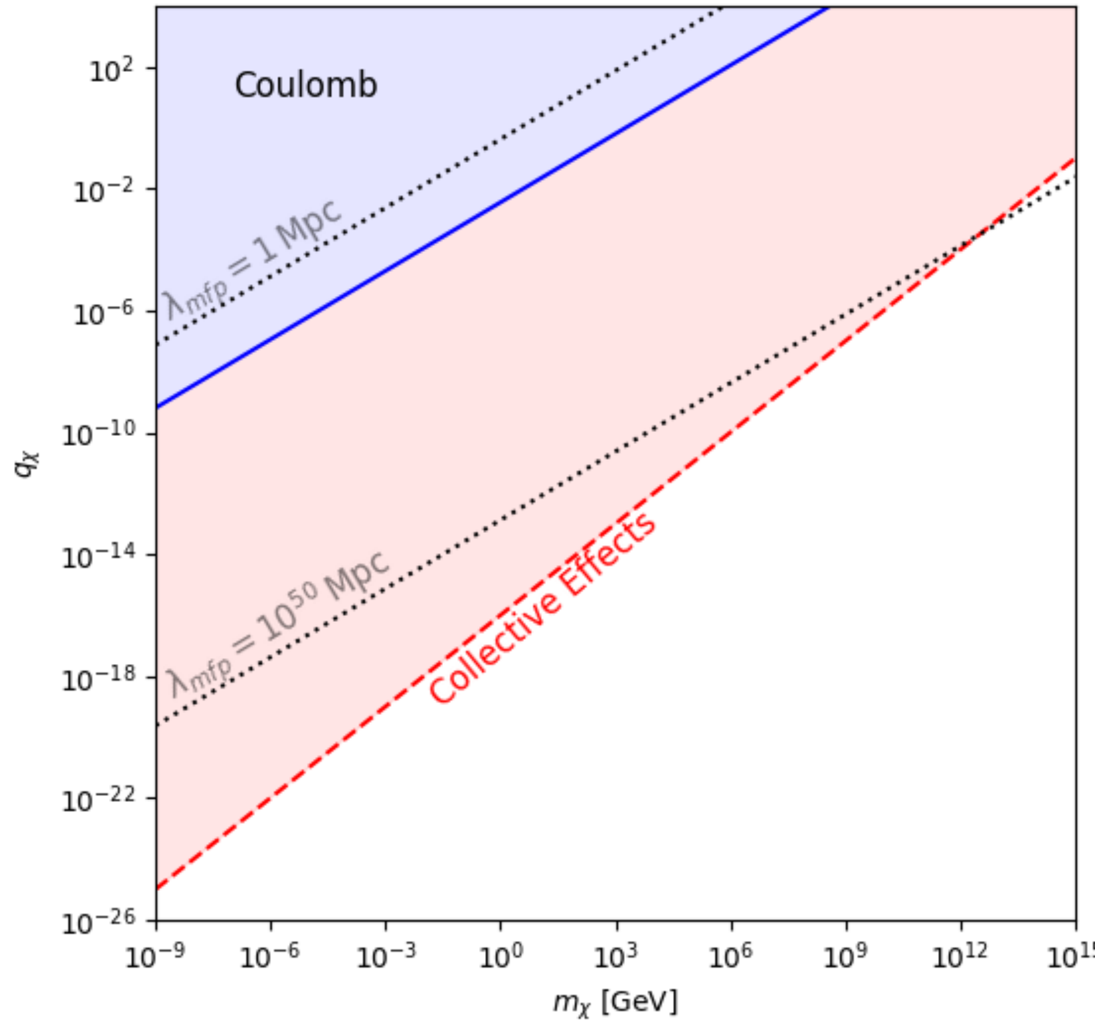
Collisionless Regime

- 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

$$\lambda \sim 300\ \mathrm{kpc}\left(\frac{v_{rel}}{0.01c}\right)^4\left(\frac{q_\chi}{q_e}\right)^{-4}\left(\frac{m_\chi}{\mathrm{GeV}}\right)^3\left(\frac{\rho_\chi}{0.01\ \mathrm{GeV/cm^3}}\right)$$



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
  - Analytical estimates break down as perturbations grow
  - In order to determine dynamics over long timescales, simulations are needed

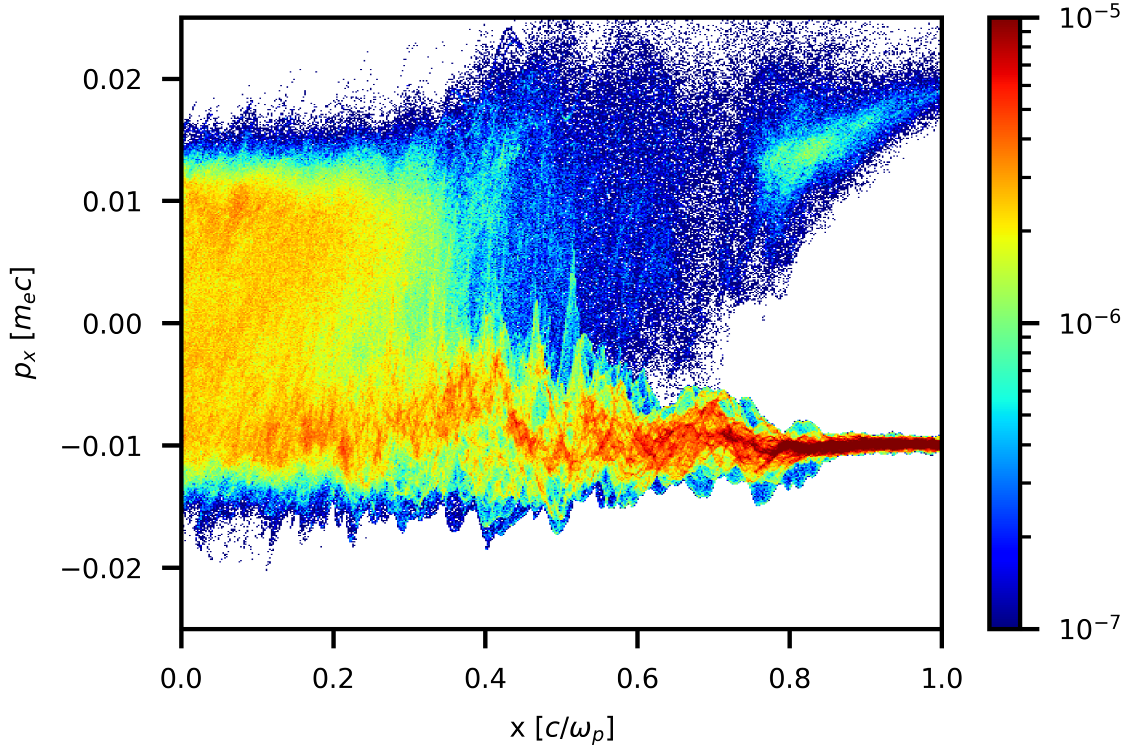
Simulations

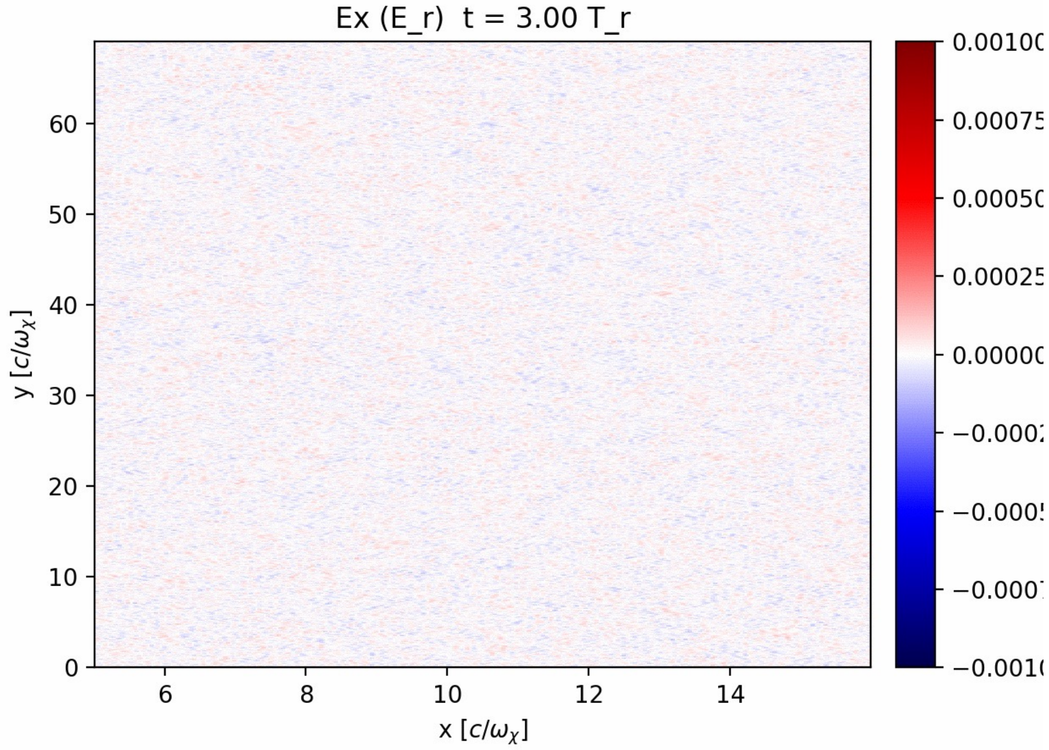
- Plasma frequency: $\omega_\chi = \sqrt{\frac{4\pi q_\chi^2 n_{0,\chi}}{m_\chi}} = \frac{q_\chi}{m_\chi}\sqrt{4\pi\rho_\chi}$

- "**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]

Smilei) v4.7

Plasma Shocks





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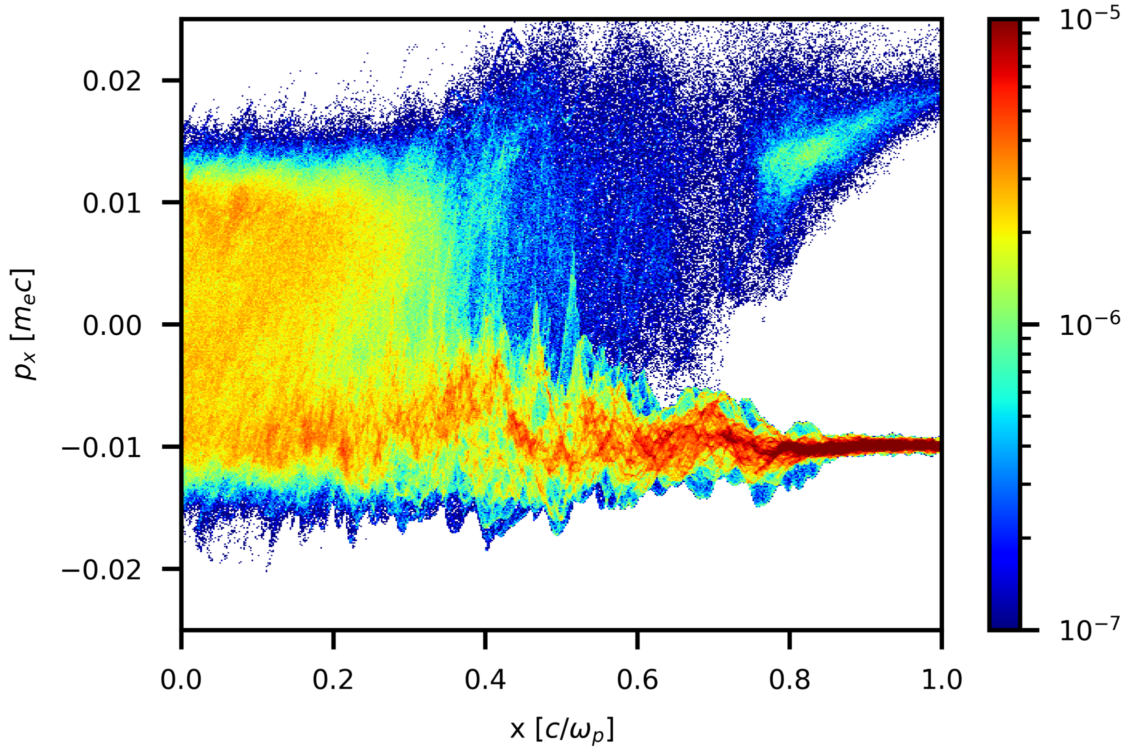

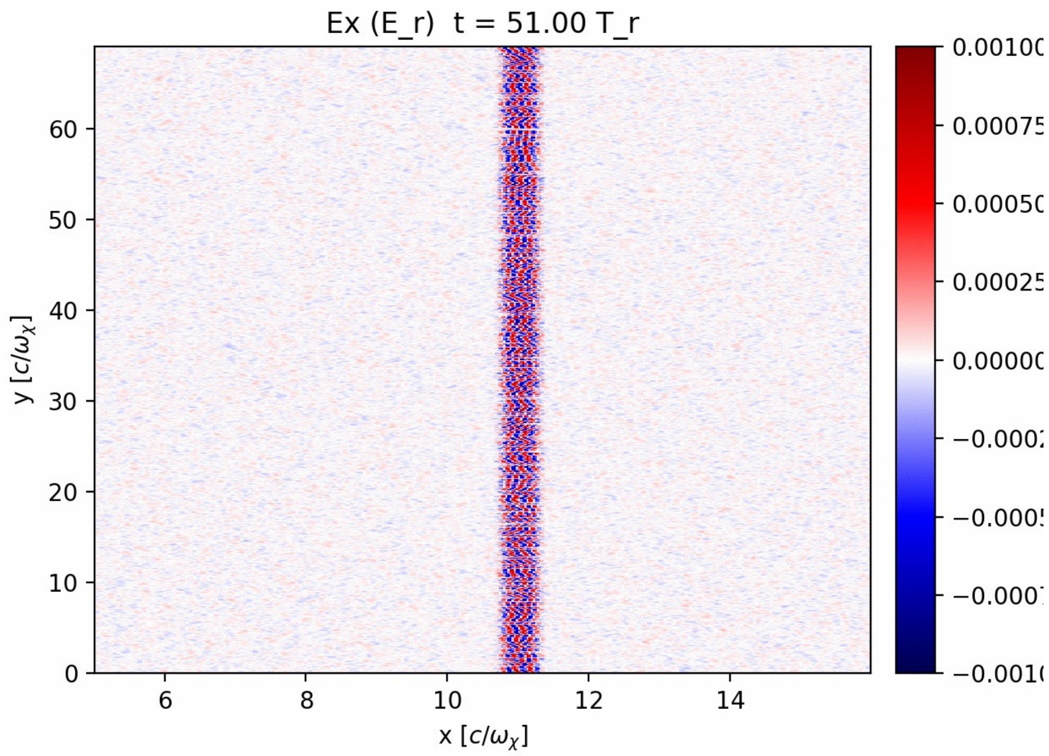

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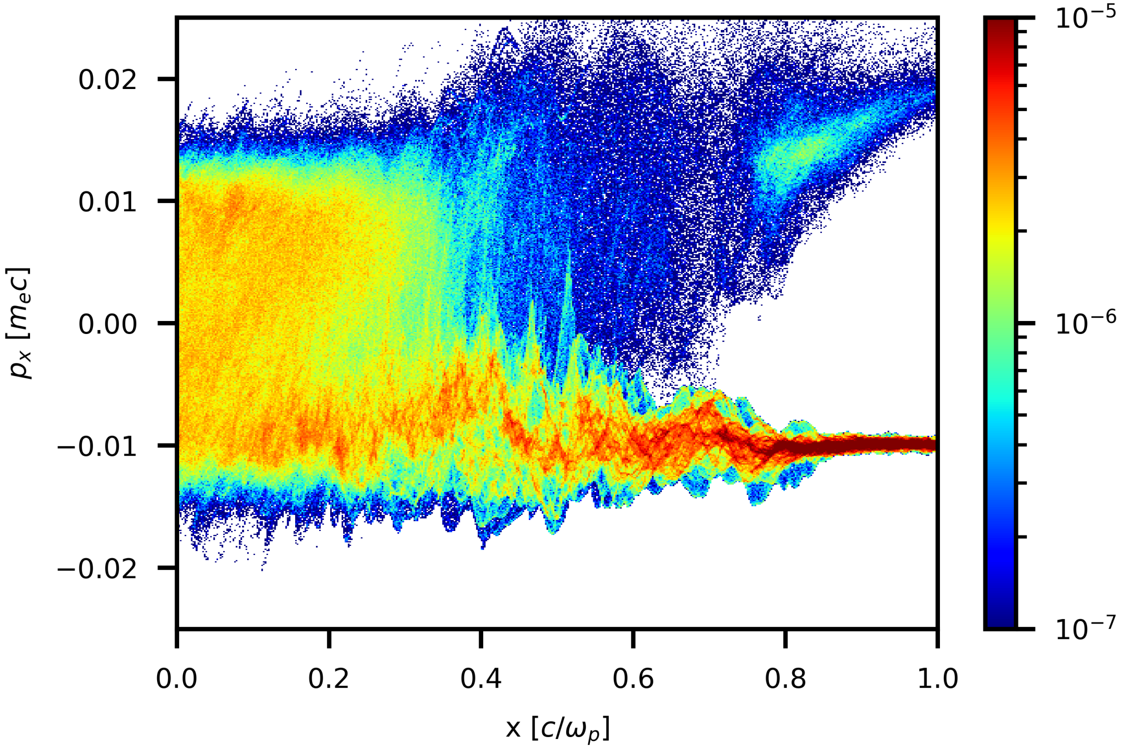
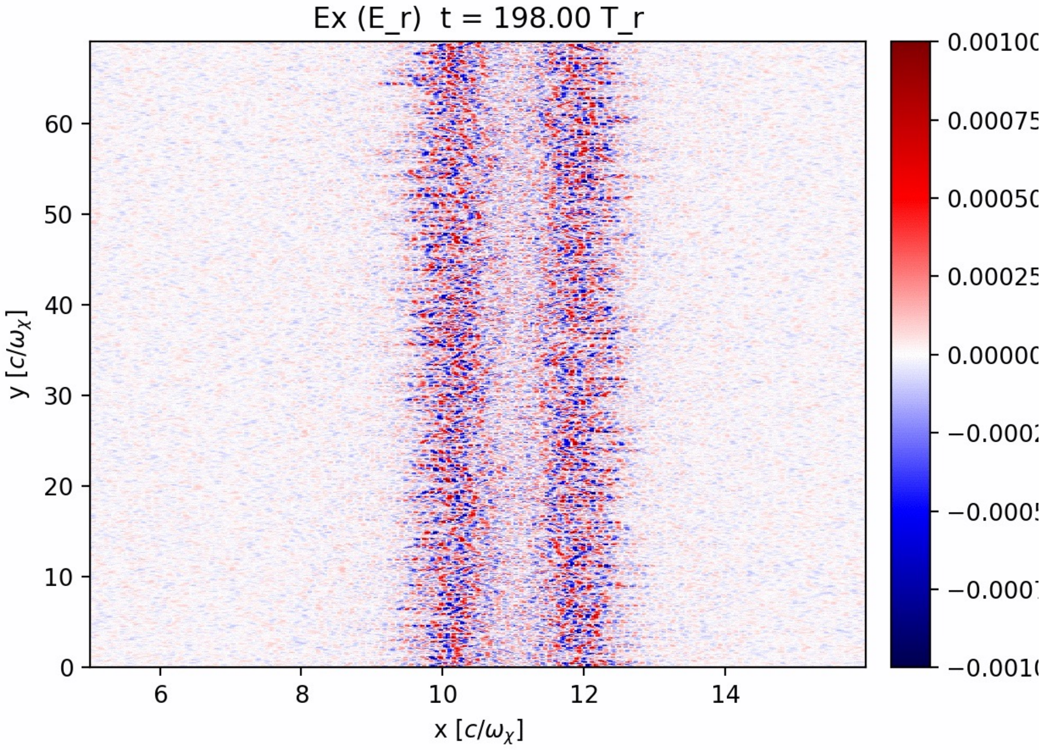
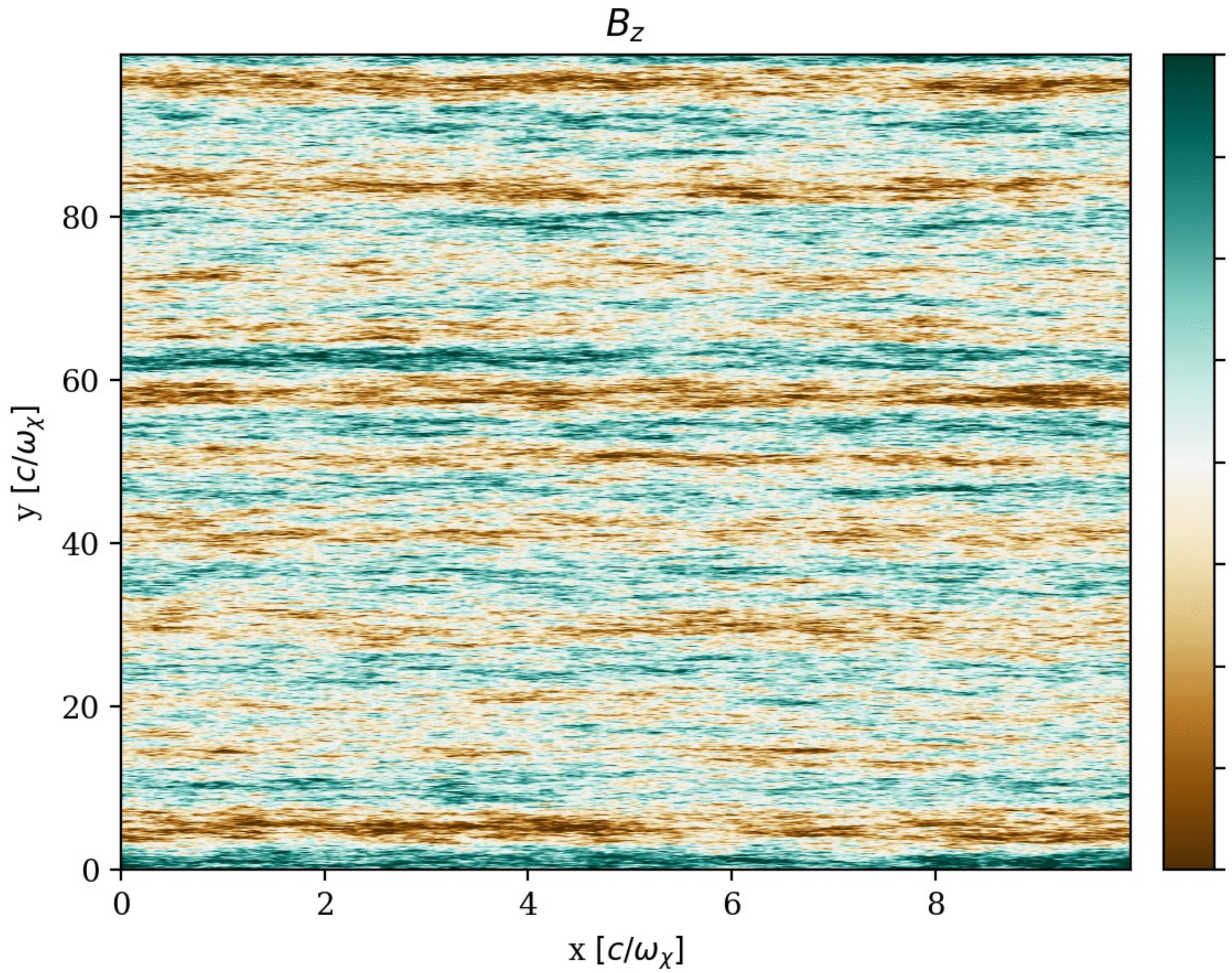




Effective Collisions

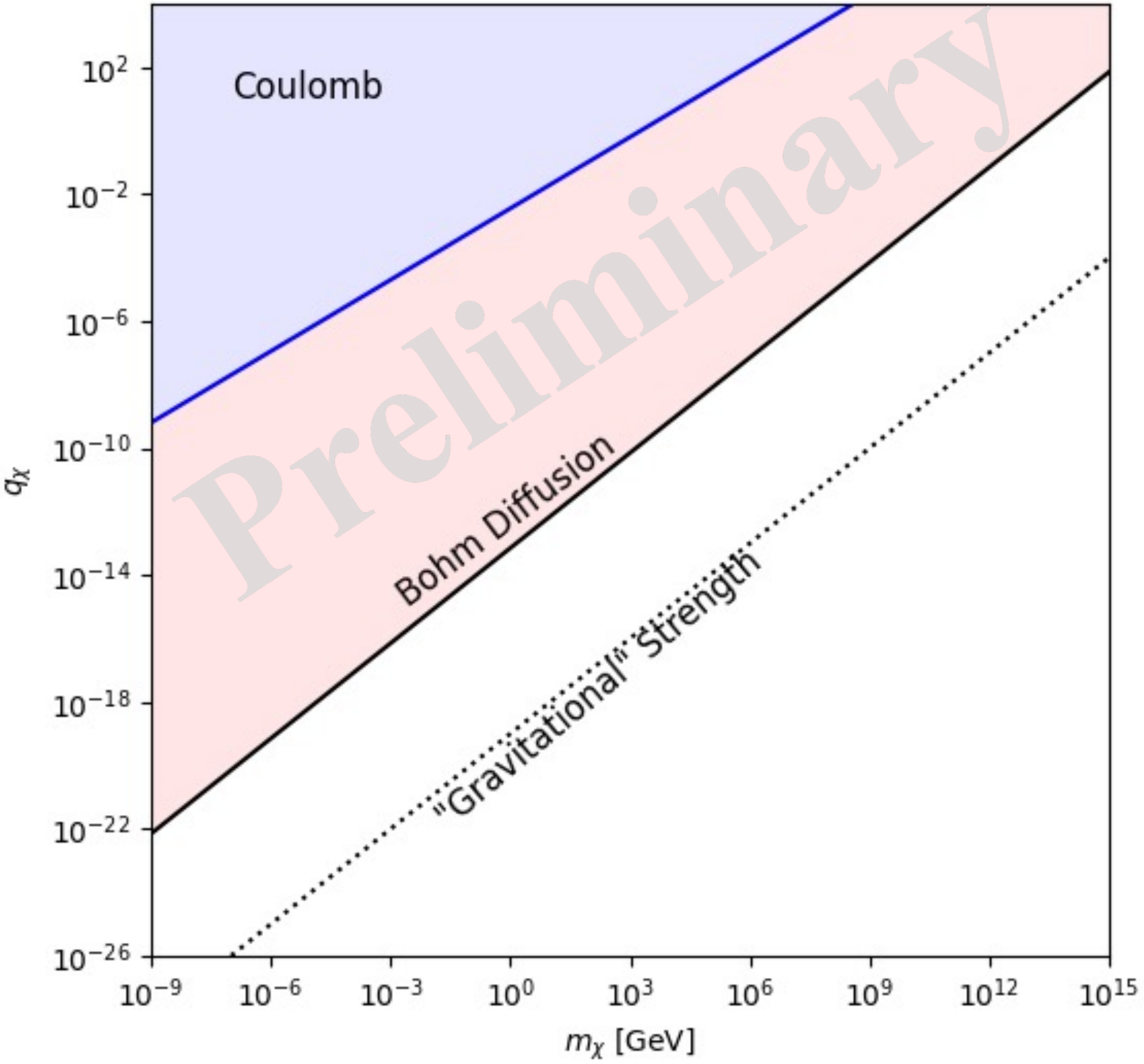


- After the electrostatic shock saturates, the beam's bulk velocity drastically decreases.
- The transverse electromagnetic mode continues to grow on very large timescales creating long filaments of strong magnetic fields.
- These fields saturate when the exponential growth rate approaches the bounce frequency

$$\omega_B = \left(\frac{q_\chi k_{max}}{m_\chi} v_T B\right)^{1/2}$$

- Regions of strong magnetic fields create Bohm-like diffusion

$$\nu_{eff} \sim \frac{q_\chi}{m_\chi} B$$



- Magnetic field at saturation

$$B_f \sim 2 \times 10^{-4} \frac{m_\chi}{q_\chi} \omega_\chi$$

- Parameters of Bullet Cluster core crossing

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

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

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

$$\sigma/m \lesssim 1 \text{ cm}^2\text{g}^{-1}$$

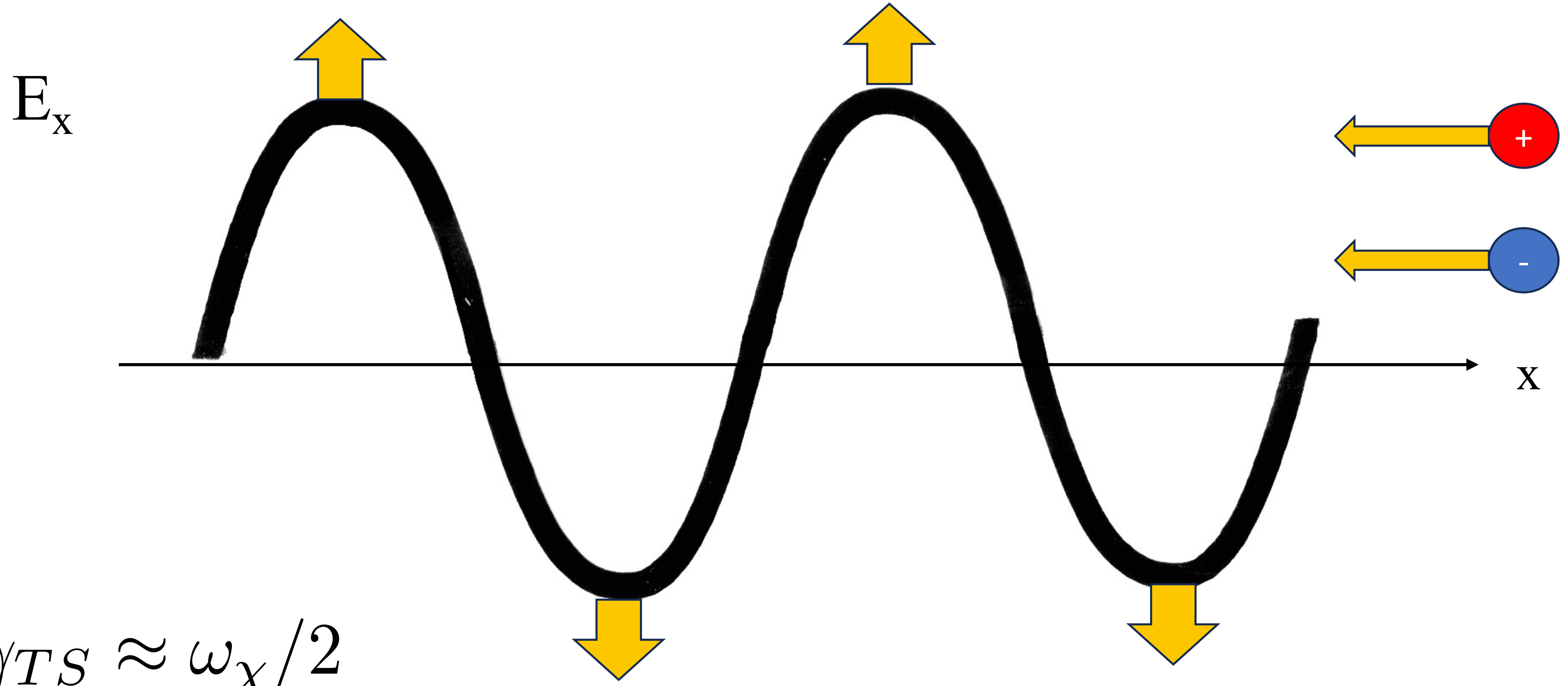
Conclusions

- Collective effects have potential to constrain several orders of magnitude of parameter space.
- Simulations are necessary to understand nonlinear behavior of plasmas.
- With more precise treatment and stronger computational power, further constraints can be placed.
- Future studies
  - Instabilities triggered from background magnetic fields
  - Exploration of other models such as 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)

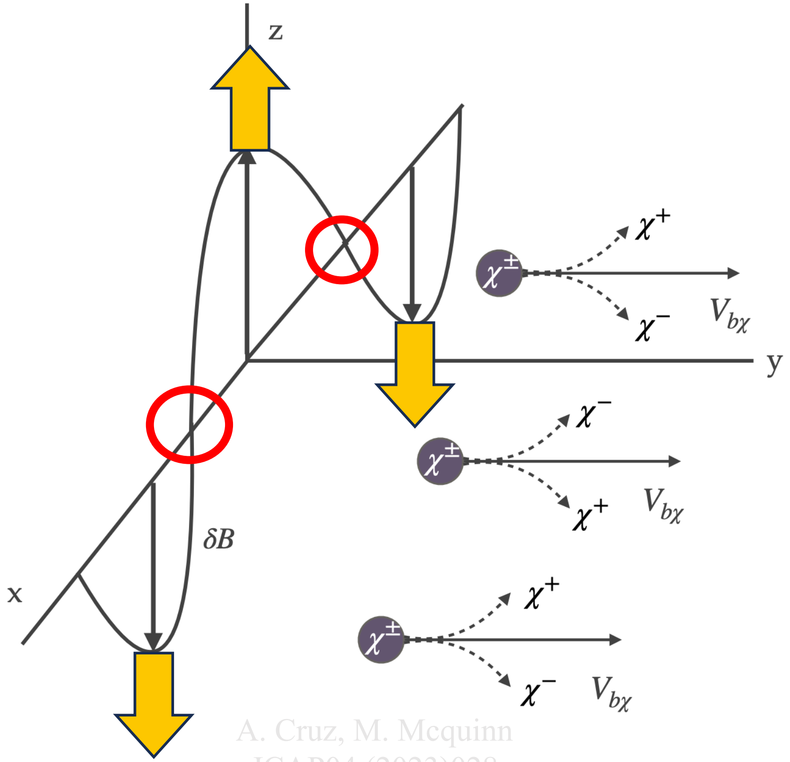
Longitudinal Instabilities



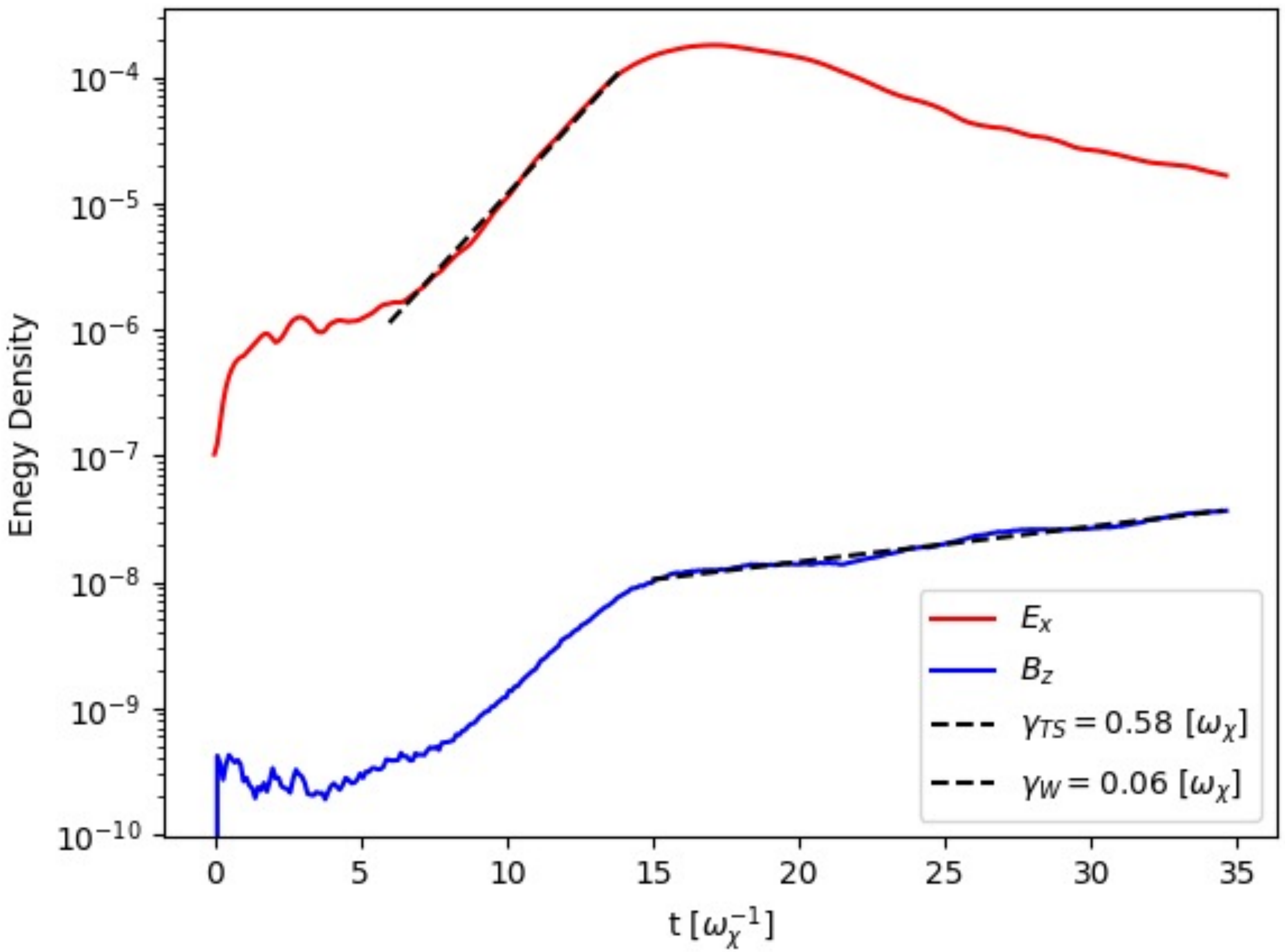
$$\gamma_{TS} \approx \omega_\chi/2$$

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
JCAP04 (2023)028


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
$\gamma_{TS} = 0.58\ [\omega_\chi]$
$\gamma_W = 0.06\ [\omega_\chi]$