# Kinetic Simulations of Collisionless Shock Formation in the Dark Sector

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with William DeRocco

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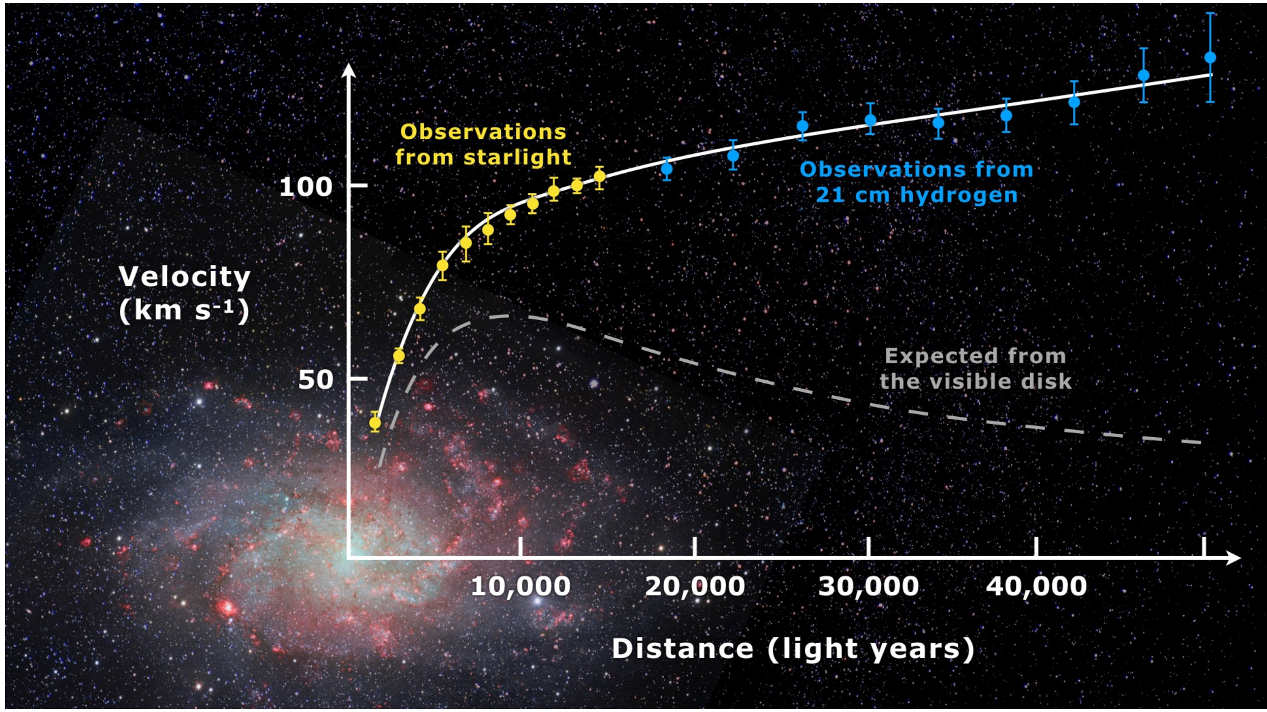
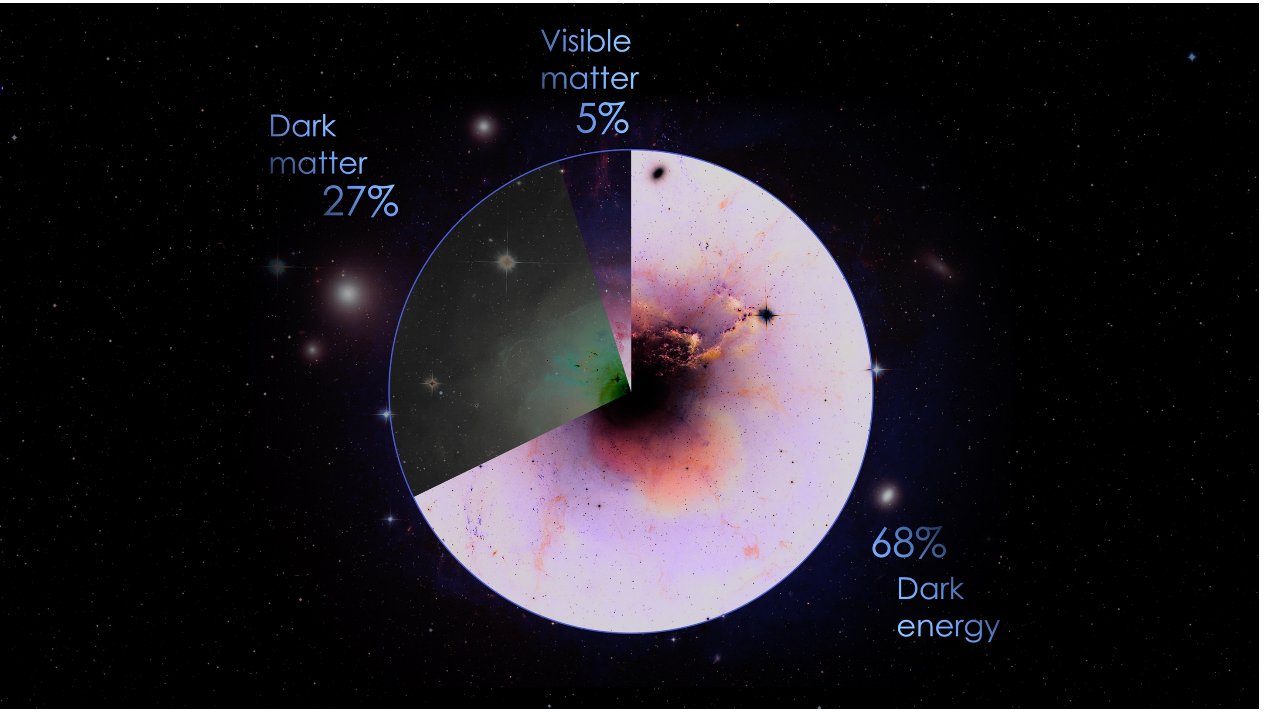
# Overview

- What is dark matter?
- How can plasma physics give new insights to dark matter phenomenology?
- Building a minimal testable model
- Huge implications for models with long-range effects

# What is Dark Matter?




https://en.wikipedia.org/wiki/Galaxy_rotation_curve

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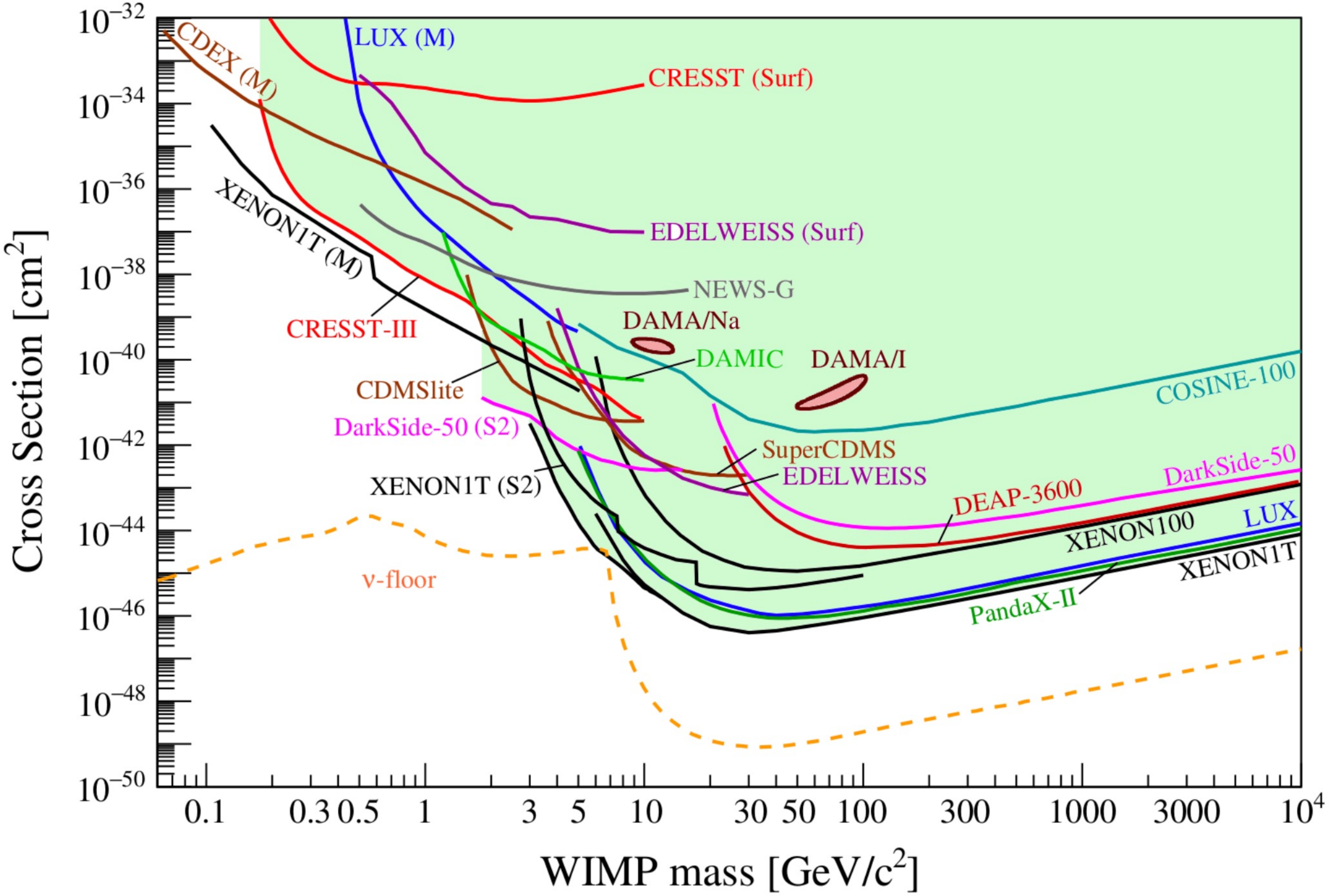
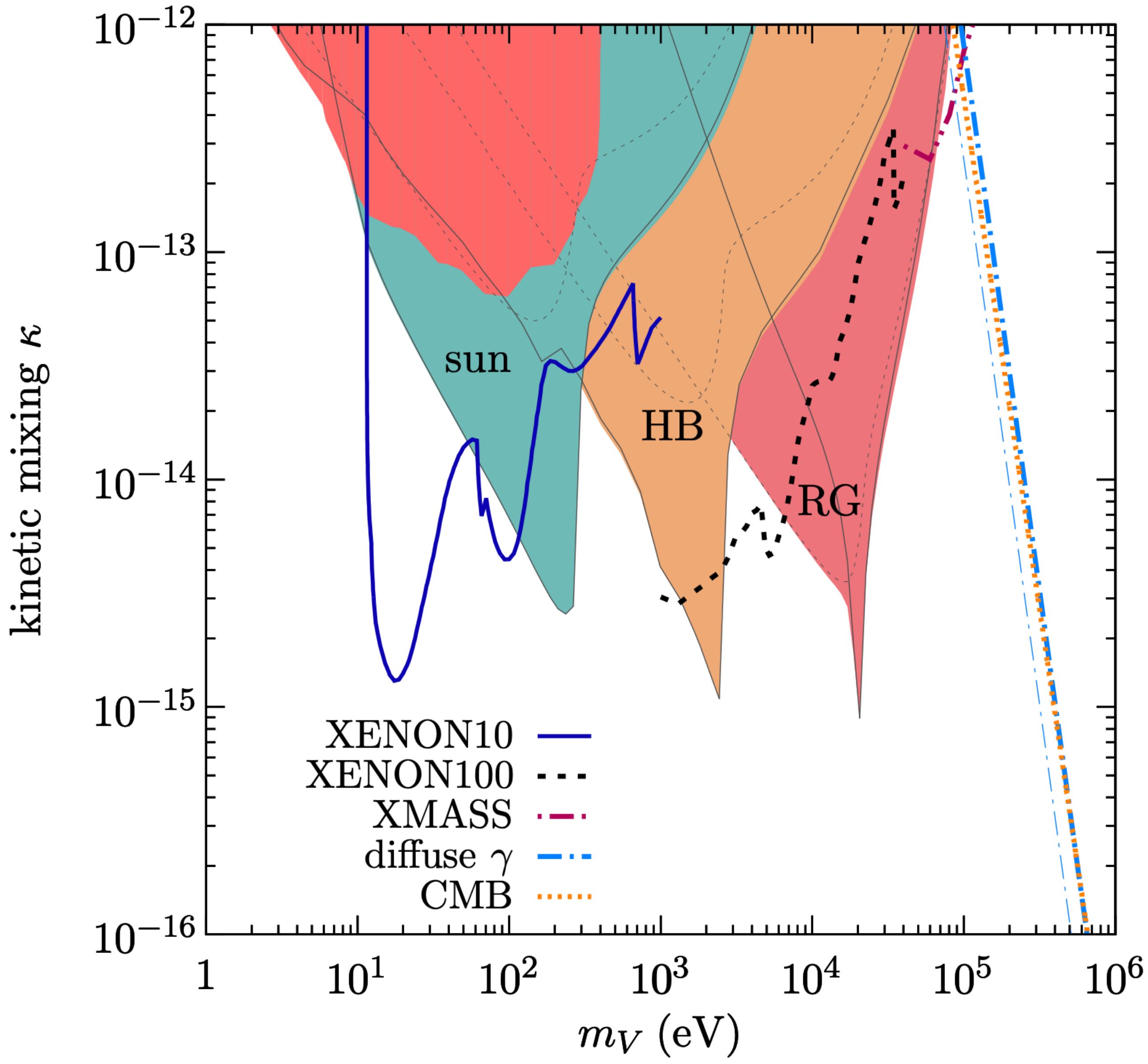


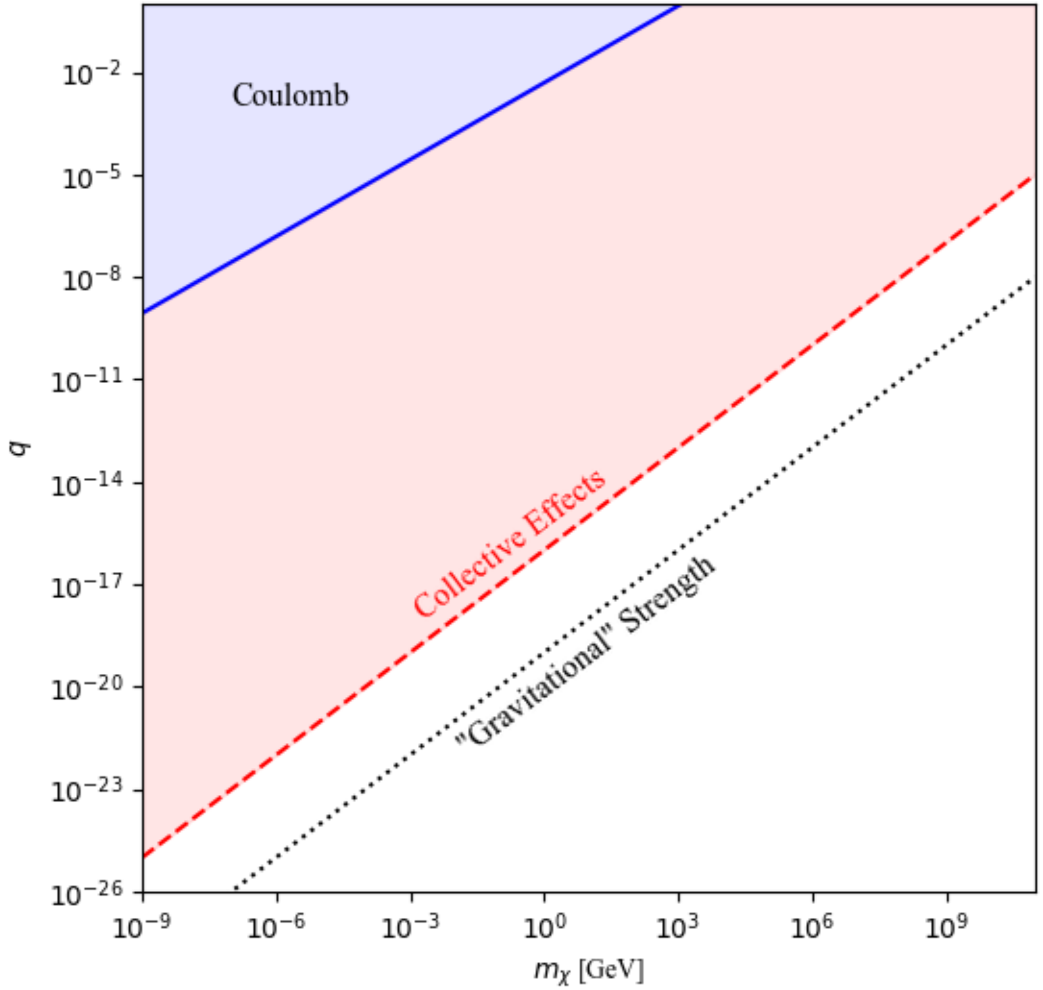

arXiv: 2104.07634




arXiv: 1412.8378

# Long Range Effects

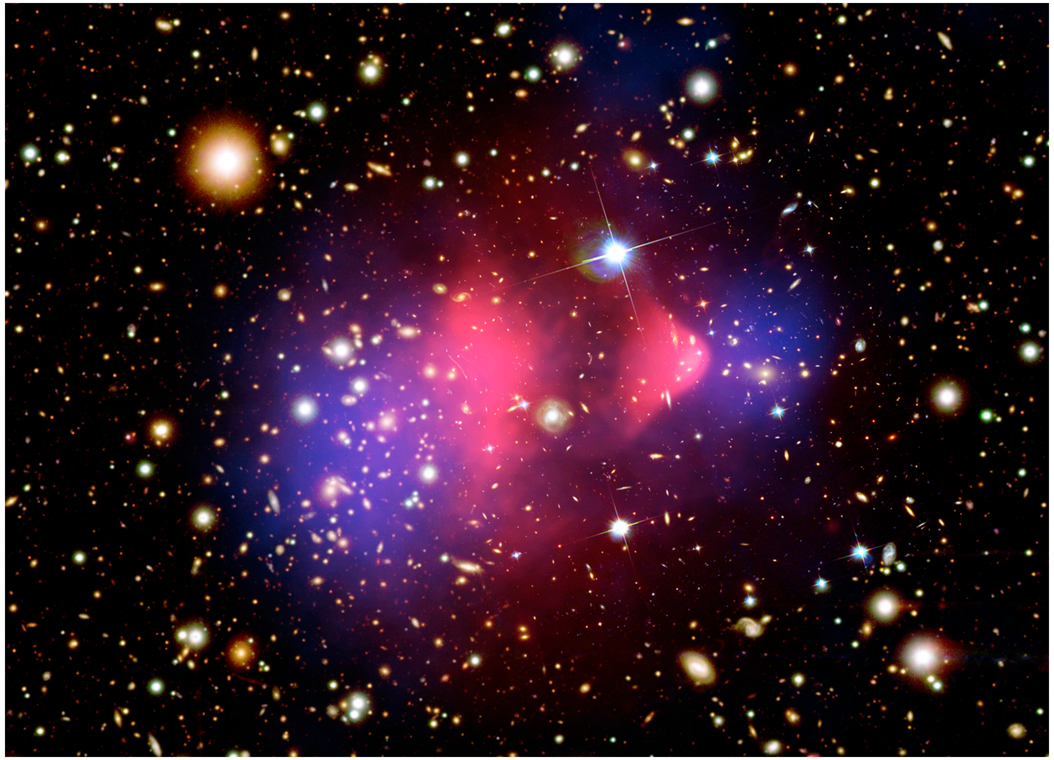
- Self-interacting dark matter is not only 2 → 2 scattering
- 99.9% of visible matter in the universe is a plasma, governed by many → many scattering
- Long range collective effects can probe **many** orders of magnitude deeper into parameter space



# 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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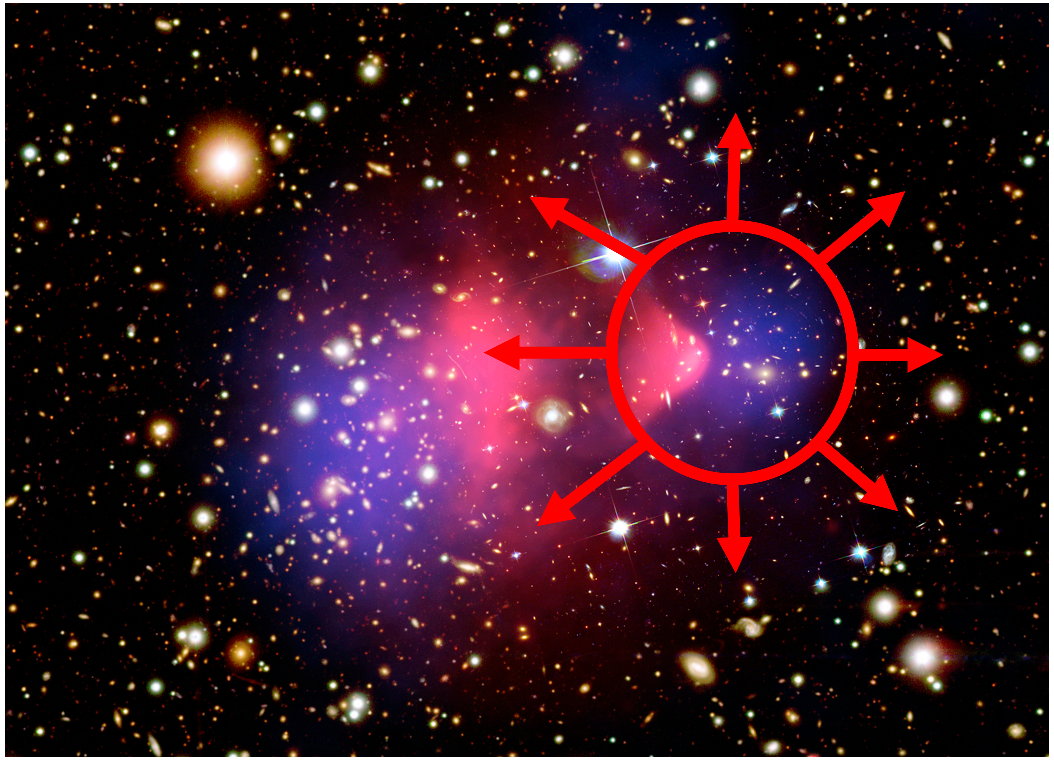

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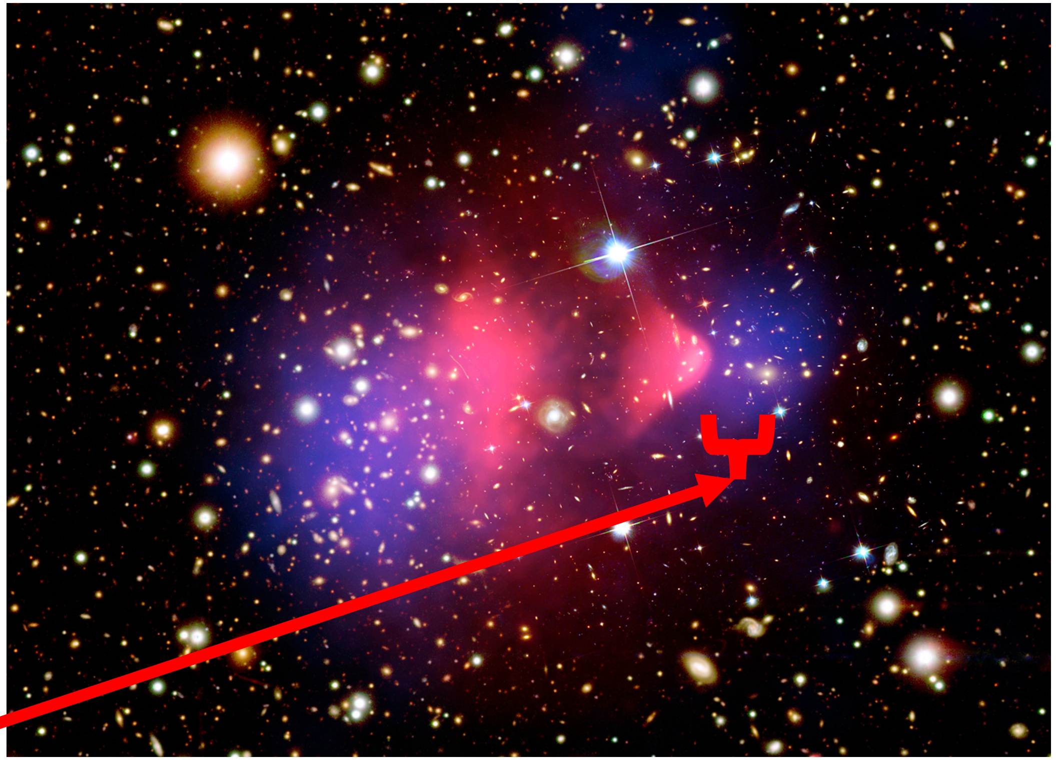


Credit: European Space Agency

# Collisionless Regime

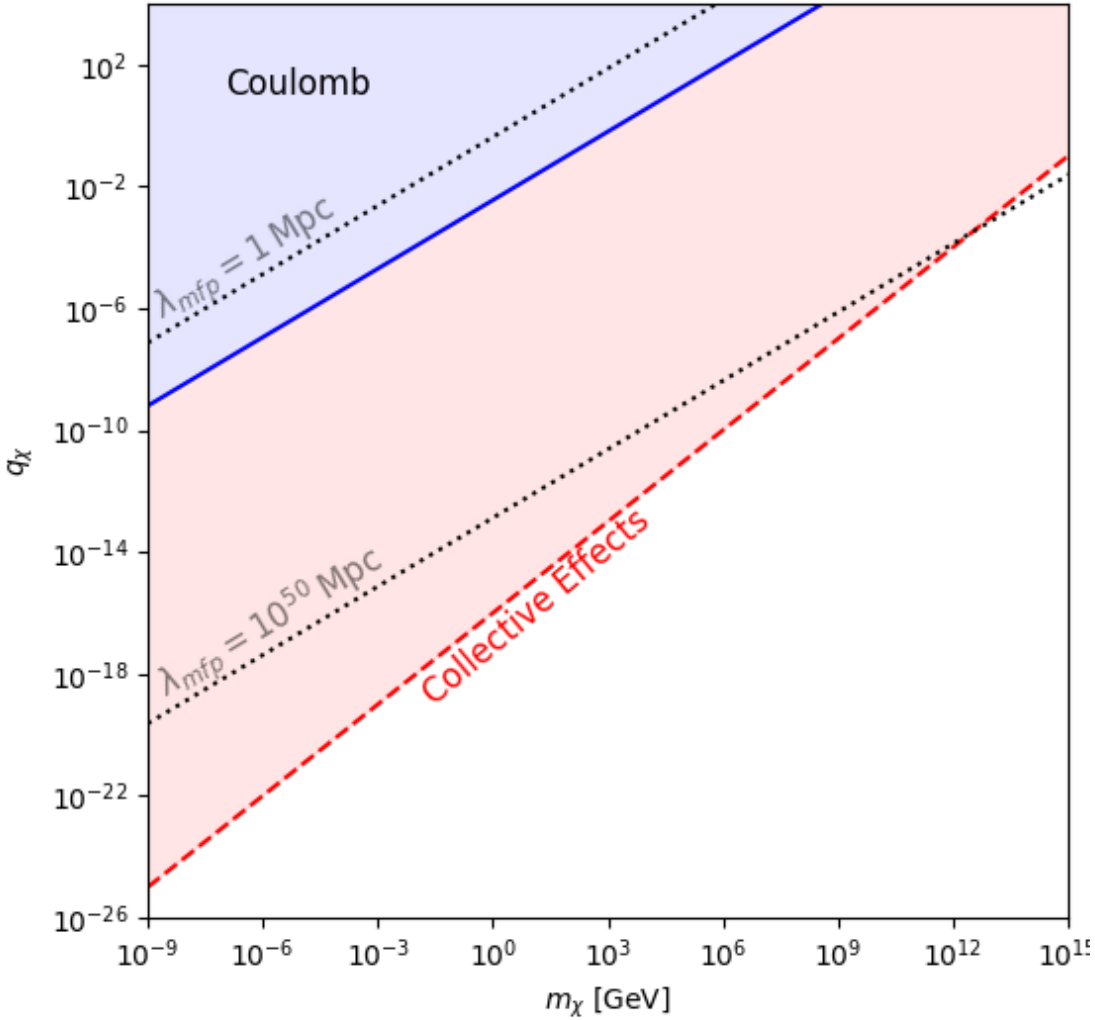
- Introduce model

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

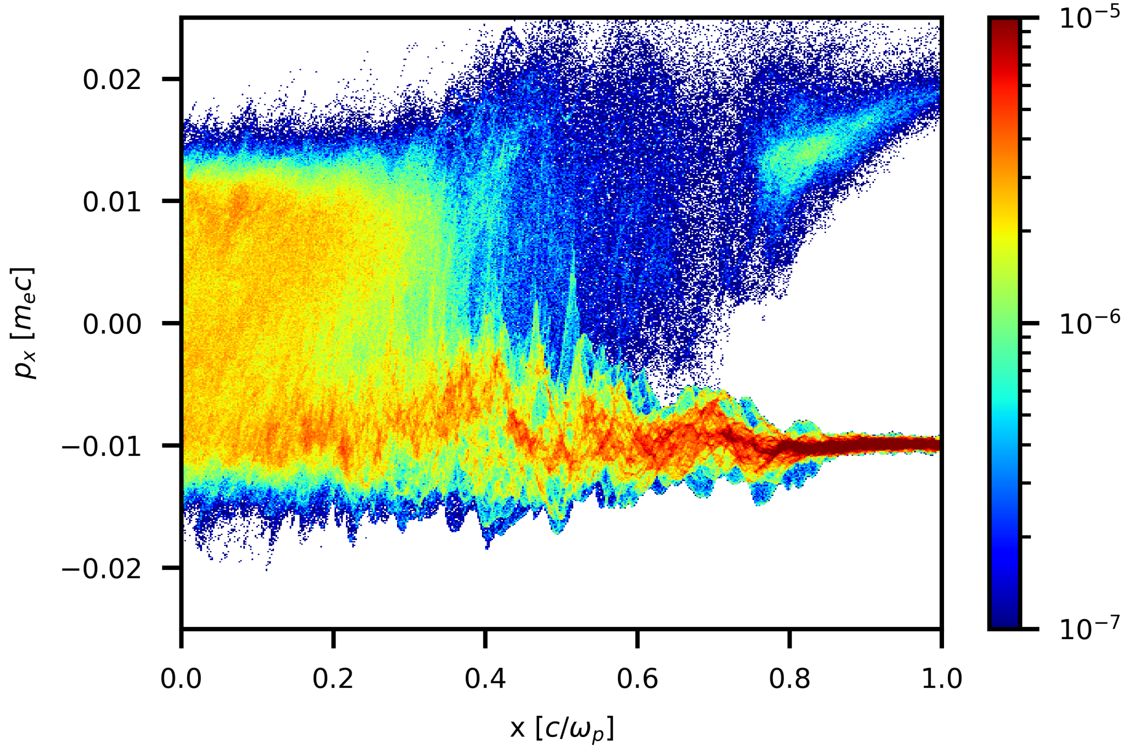
- Size of Bullet Cluster core ~100 kpc
- Mean free path of dark matter

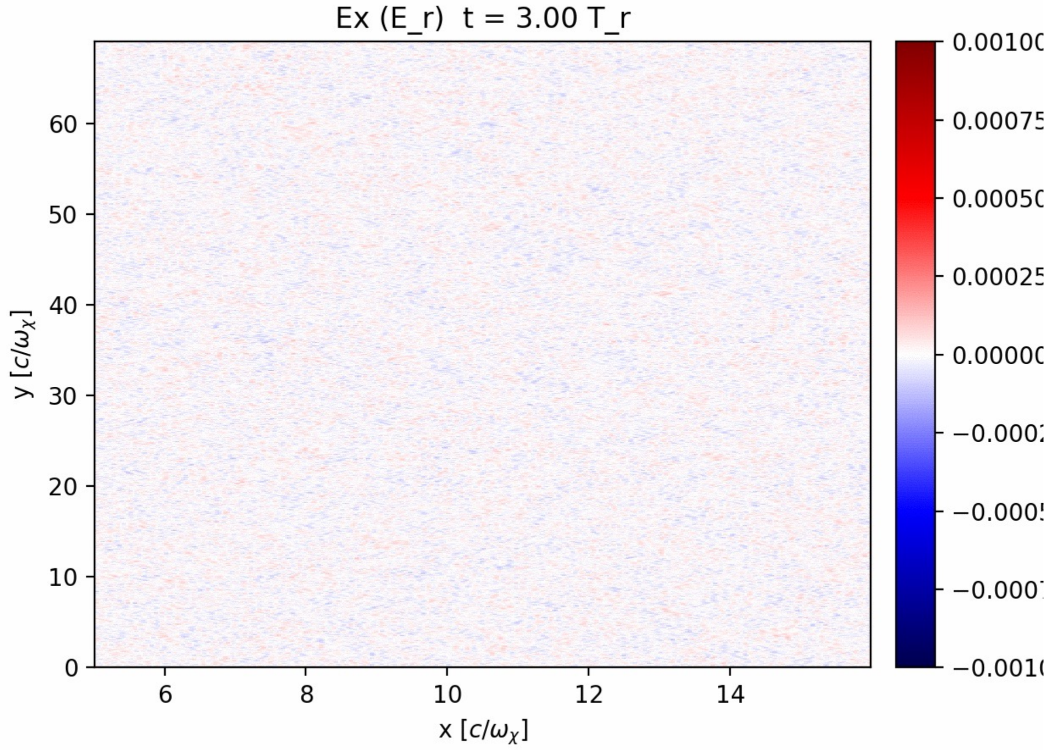
$$\lambda \sim 300\ \text{kpc}\left(\frac{v_{rel}}{0.01c}\right)^4\left(\frac{q_\chi}{q_e}\right)^{-4}\left(\frac{m_\chi}{\text{GeV}}\right)^3\left(\frac{\rho_\chi}{0.01\ \text{GeV/cm}^3}\right)$$

$$\omega_{p,\chi} = \sqrt{\frac{q_\chi^2 n_{0,\chi}}{m_\chi \epsilon_0}} = \frac{q_\chi}{m_\chi}\sqrt{\frac{\rho_\chi}{\epsilon_0}}$$



# Plasma Shocks



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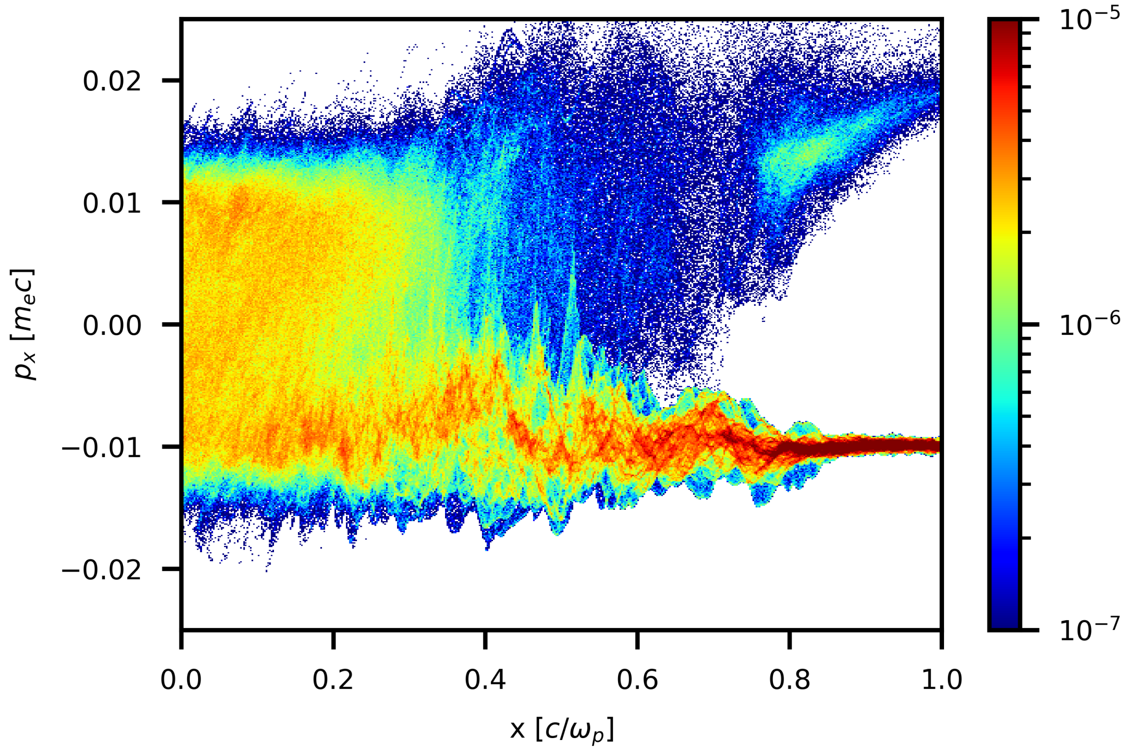


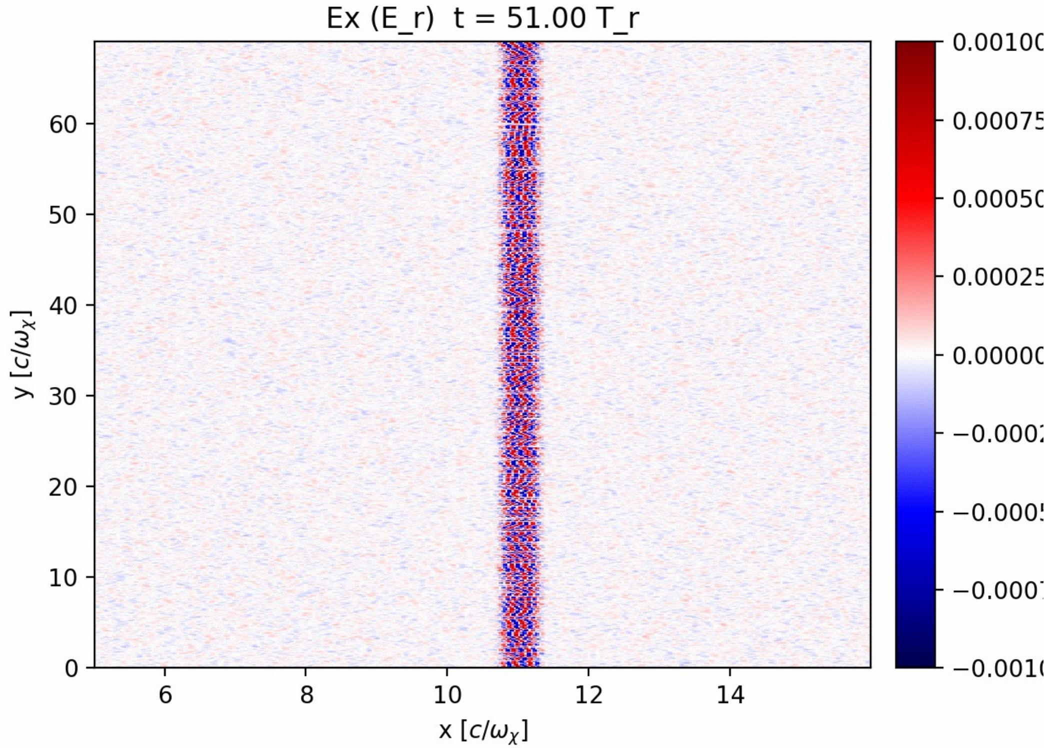

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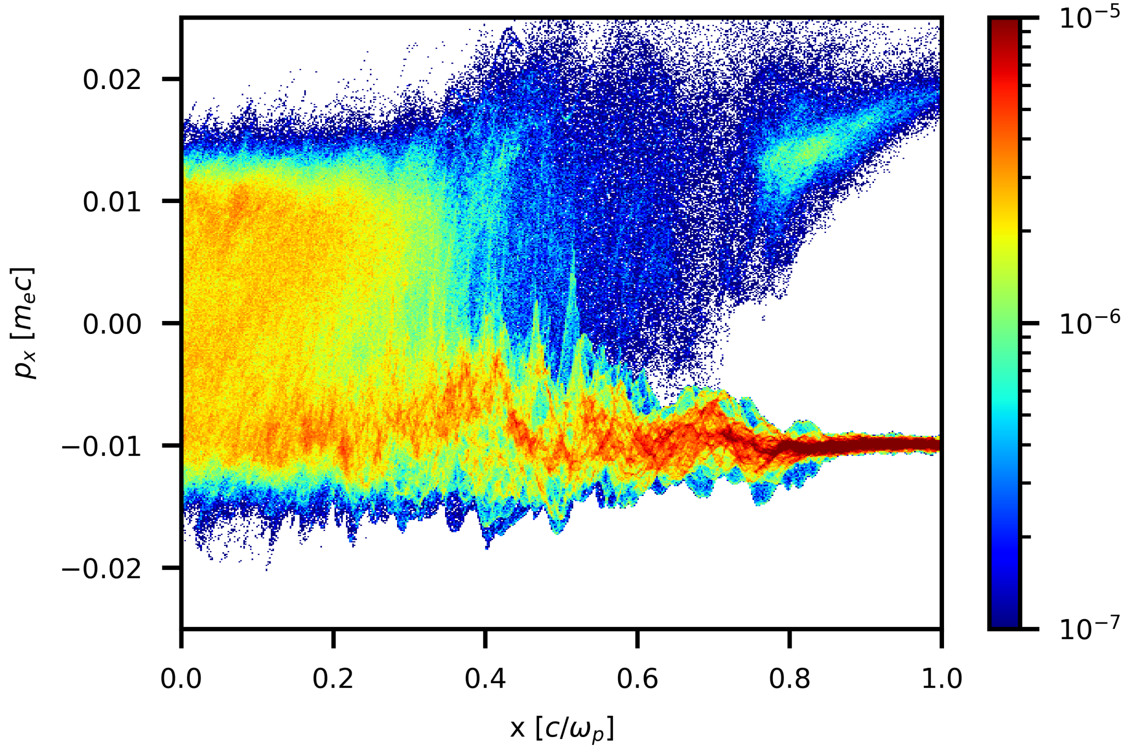
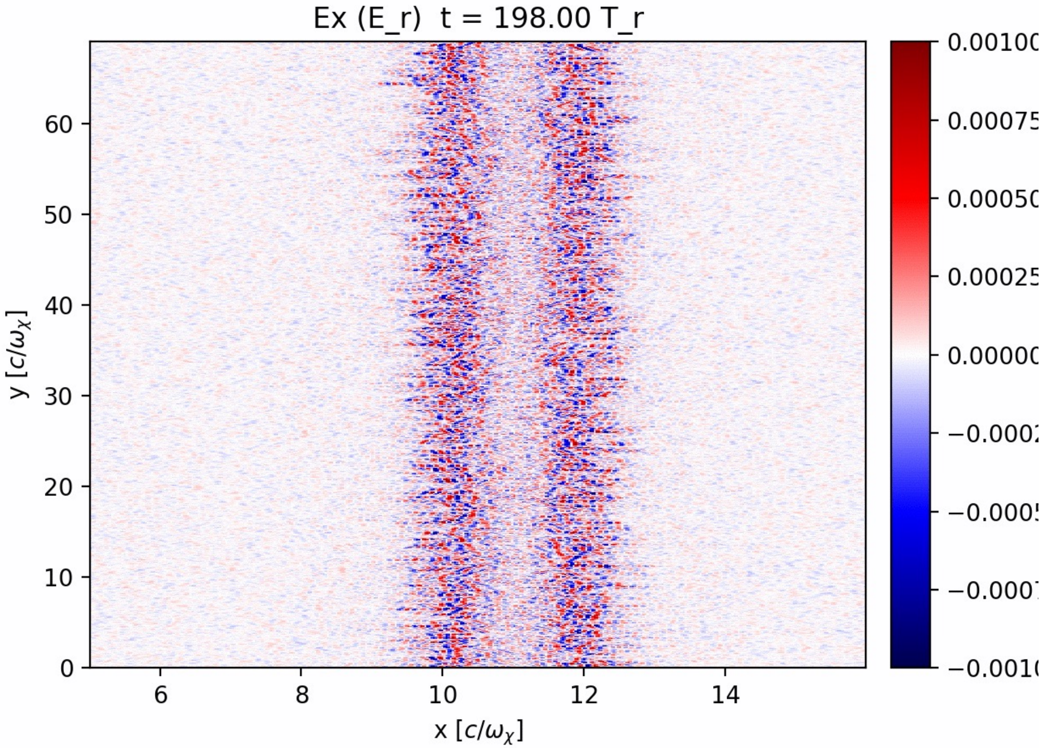
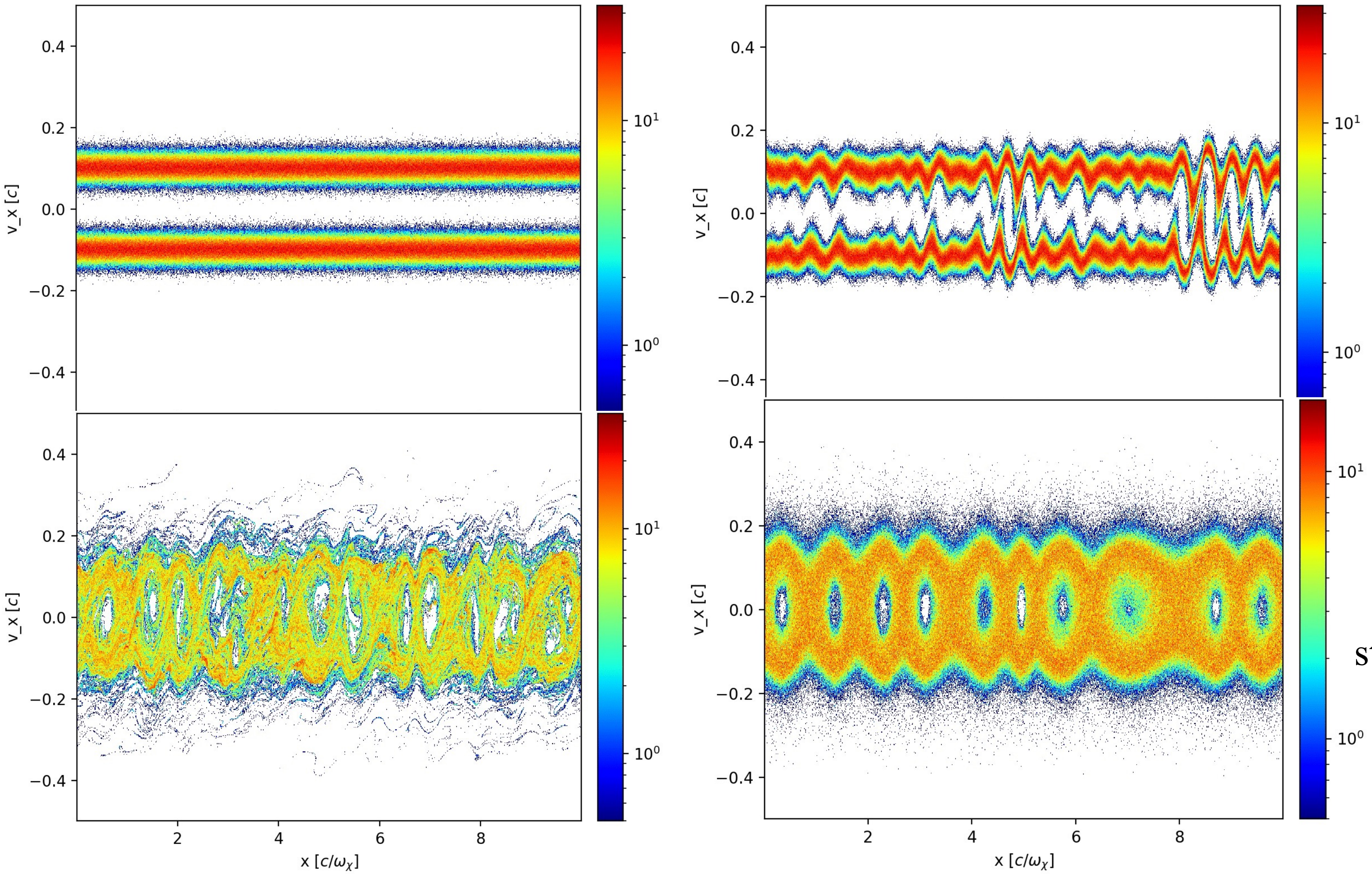


# Plasma Turbulence

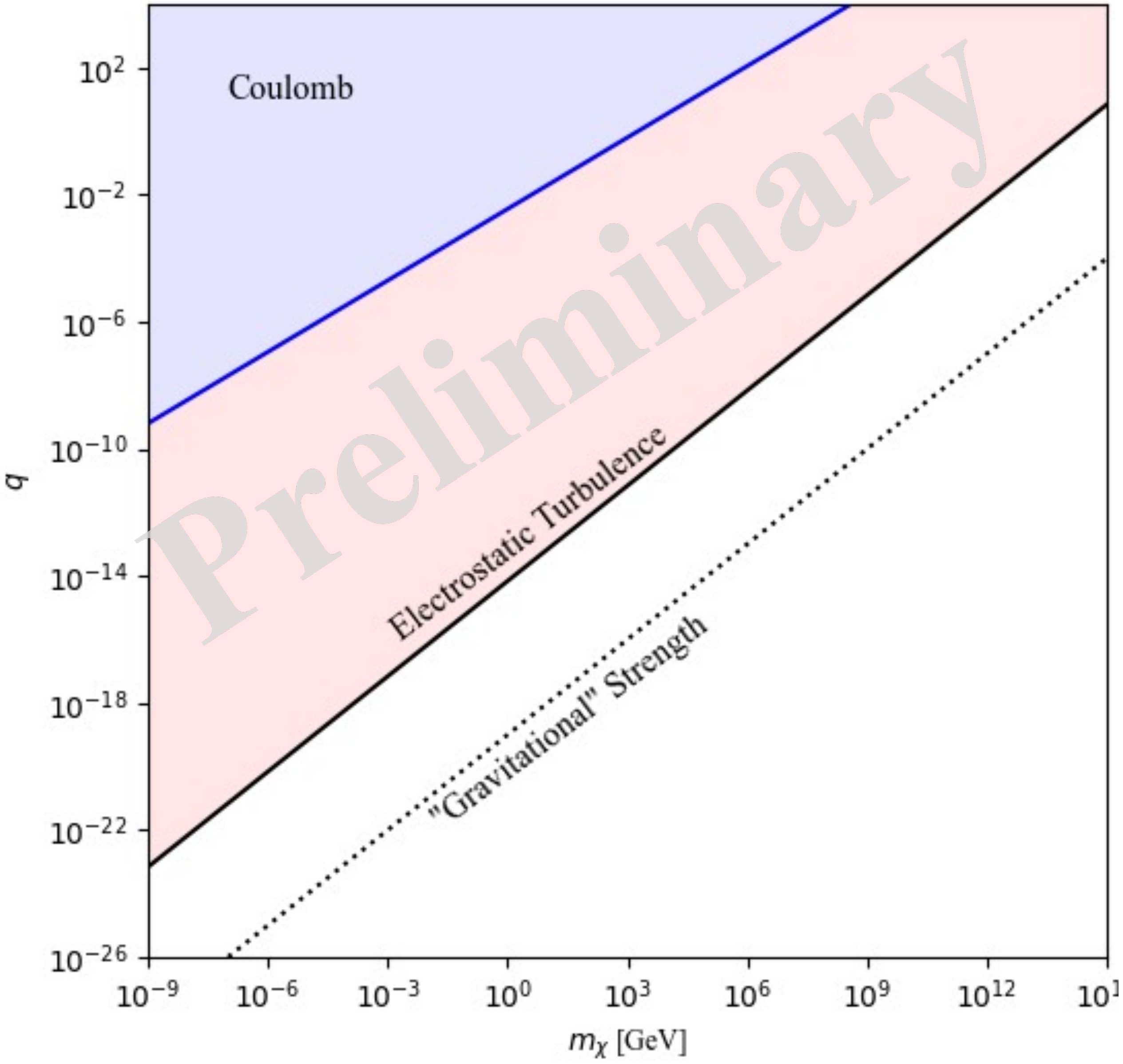
Initial Configuration
$t = 0\ \omega_p$

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

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

- Parameters of Bullet Cluster core crossing

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

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

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

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

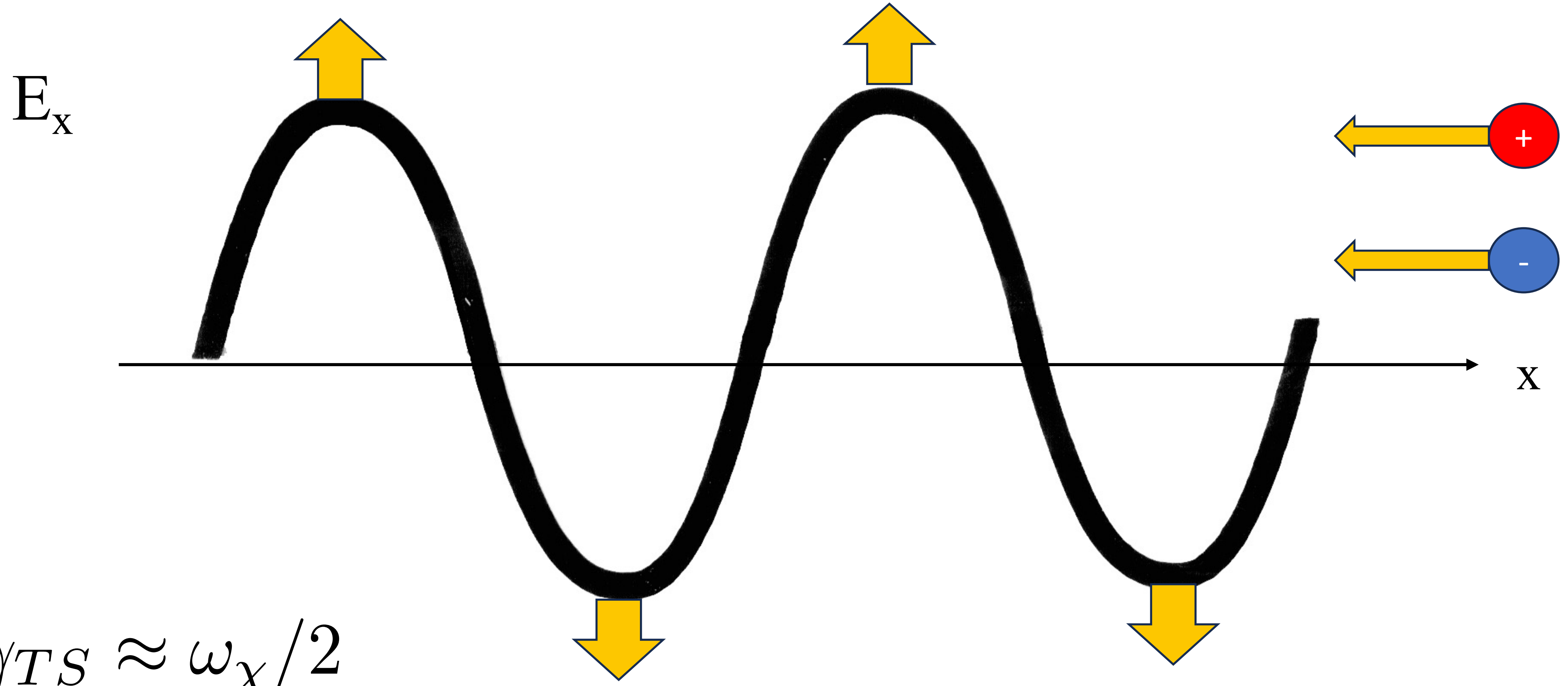
# Conclusions

- Collective effects have potential to yield new insights to the microscopic behaviors of dark matter
- Plasma instabilities and anomalous drag can contribute to observable displacements in dissociative cluster mergers
- More systems can be probed with plasma physics
  - Magnetized plasmas
  - Millicharged particles
  - Axion dark matter

# 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)

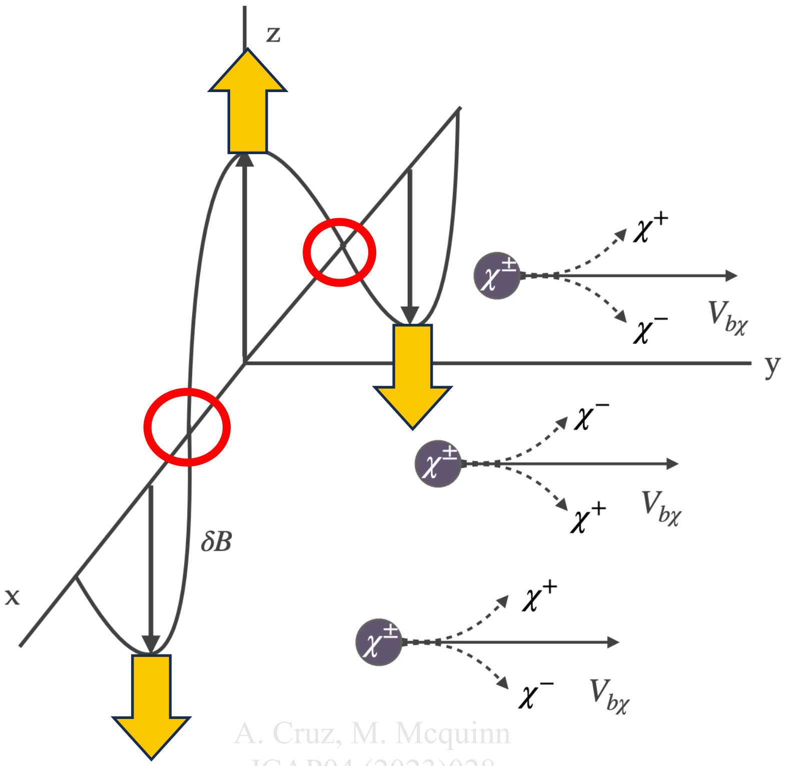
# Longitudinal Instabilities




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

# 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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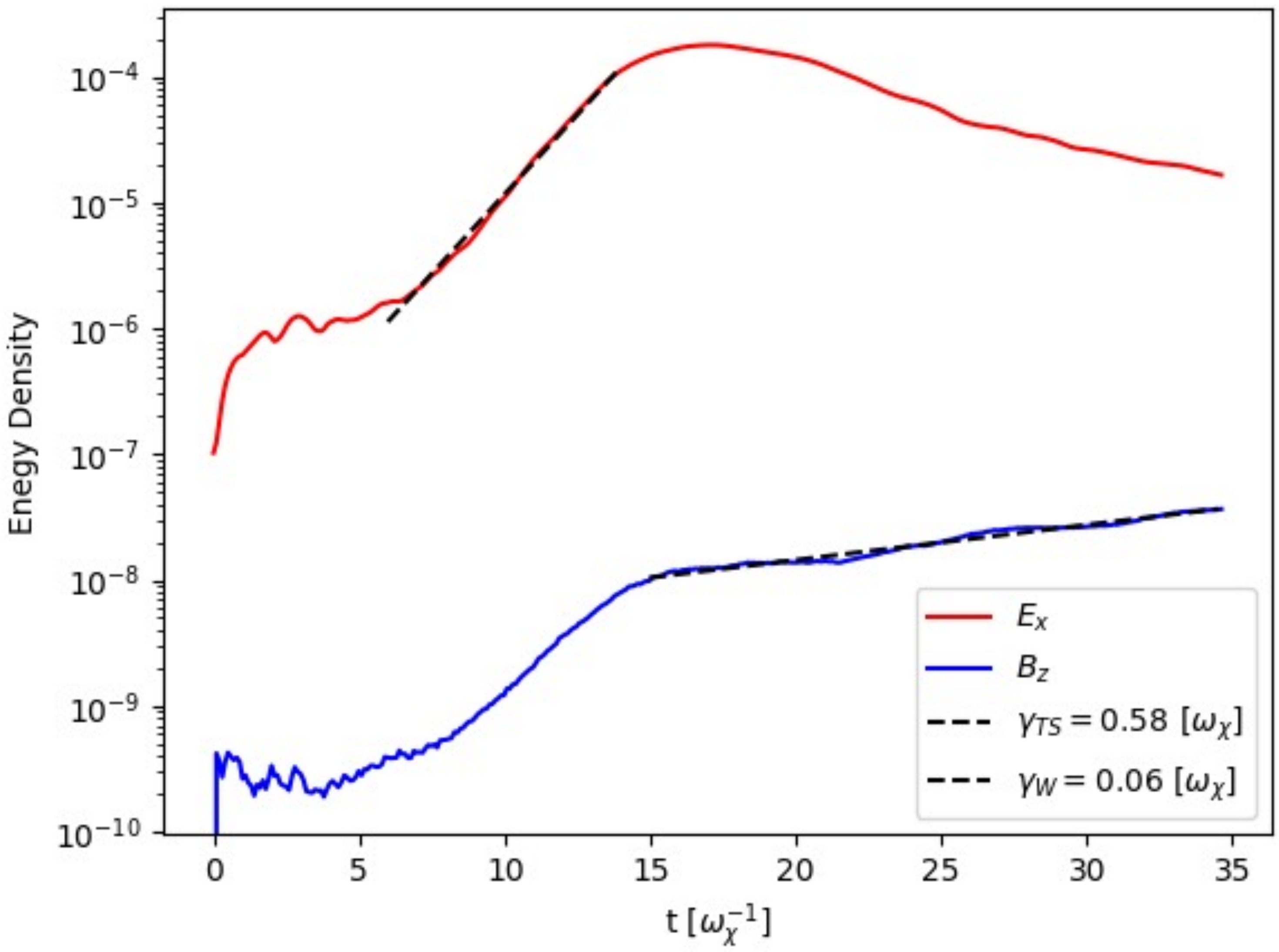

Enegy Density
$10^{-4}$
$10^{-5}$
$10^{-6}$
$10^{-7}$
$10^{-8}$
$10^{-9}$
$10^{-10}$
0
5
10
15
20
25
30
35
$t\ [\omega_\chi^{-1}]$
$E_x$
$B_z$
$\gamma_{TS} = 0.58\ [\omega_\chi]$
$\gamma_W = 0.06\ [\omega_\chi]$