Dark Plasmas in the Nonlinear Regime: Constraints from Particle-in-Cell Simulations

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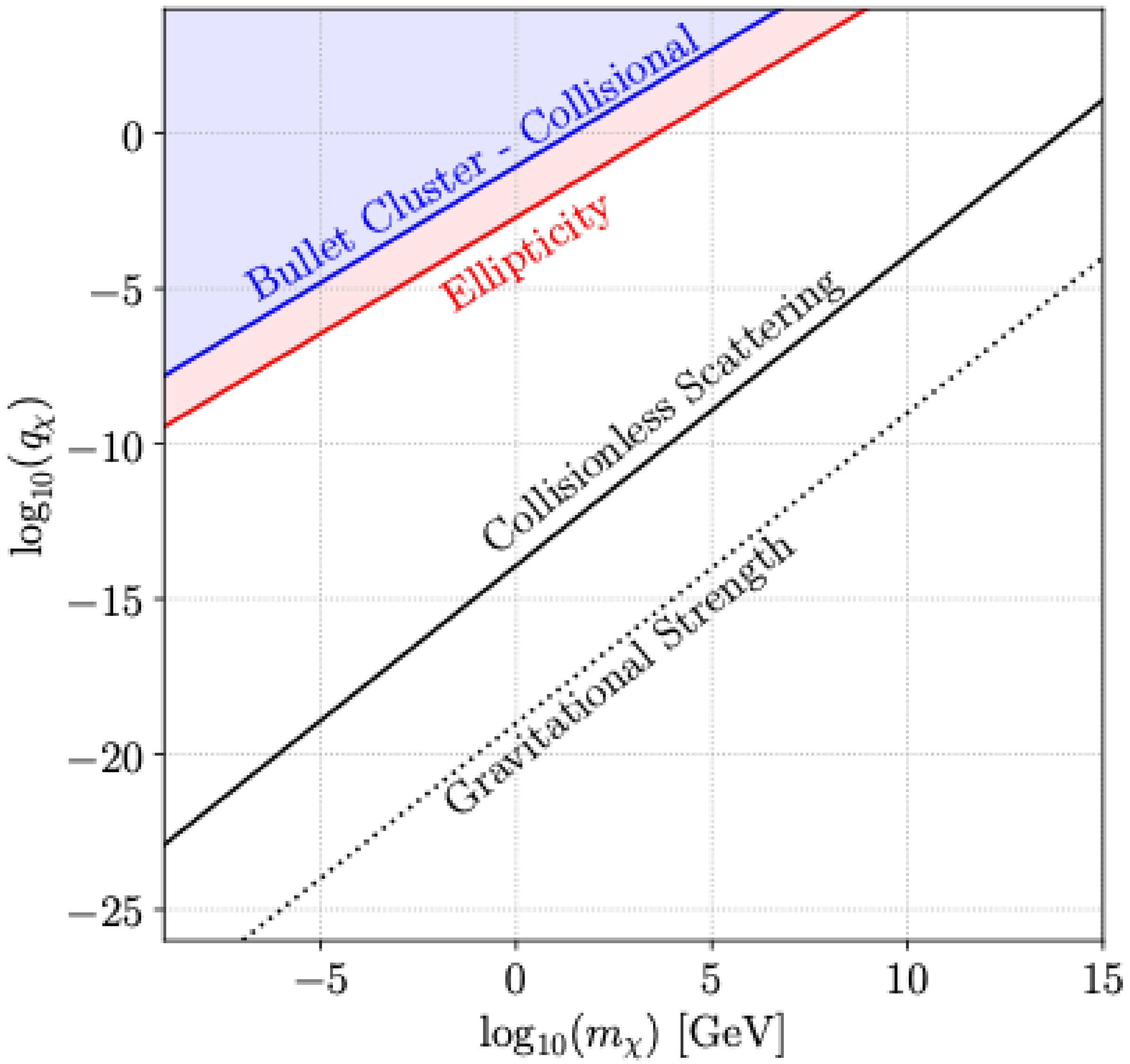
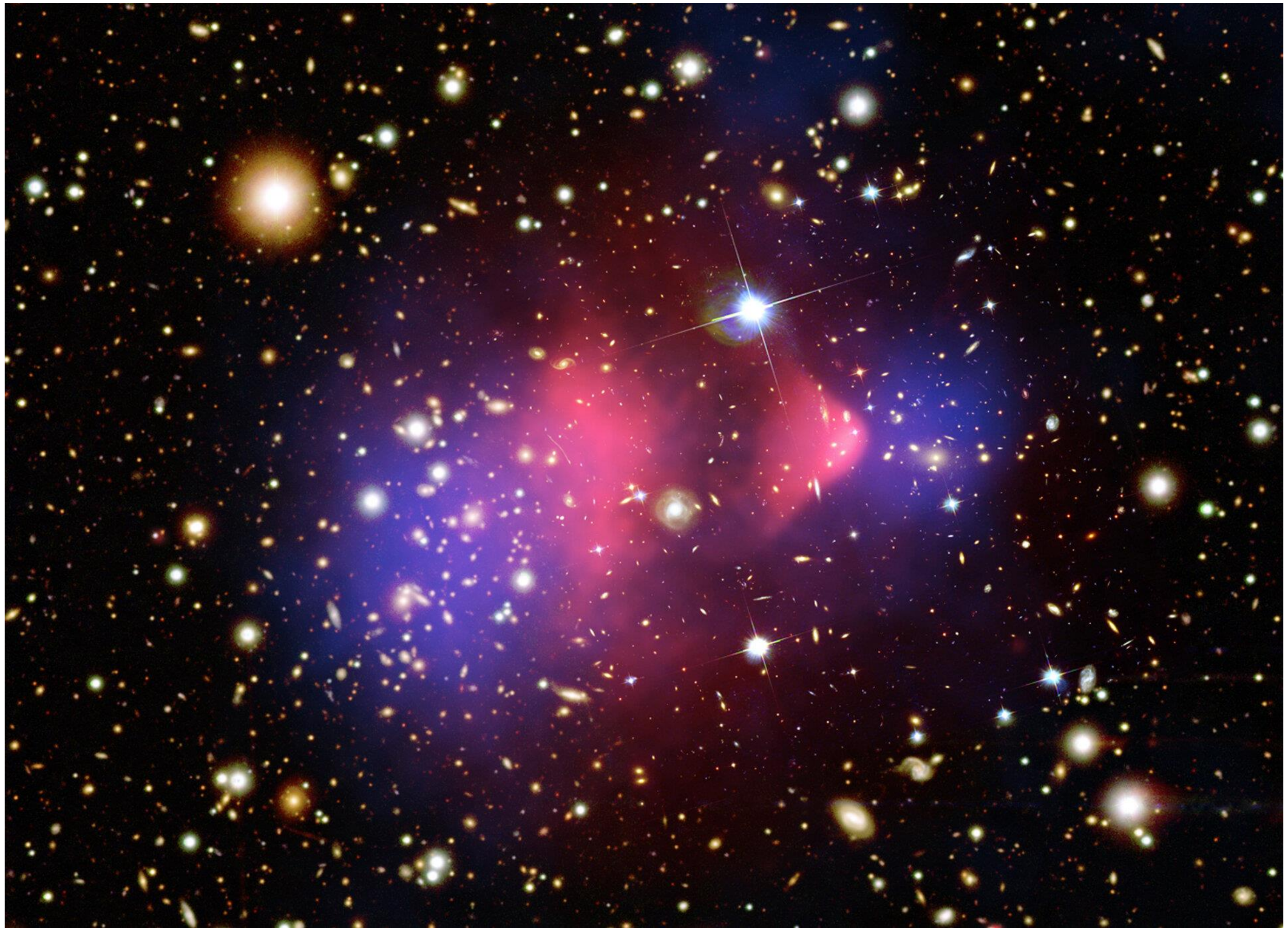
Long Range Effects

- 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
  - $\sigma/m \lesssim 1\ \mathrm{cm}^2/\mathrm{g}$
- Main Observables
  - Evaporation of dark matter halo
  - Offset of dark matter and standard model centers



Credit: European Space Agency

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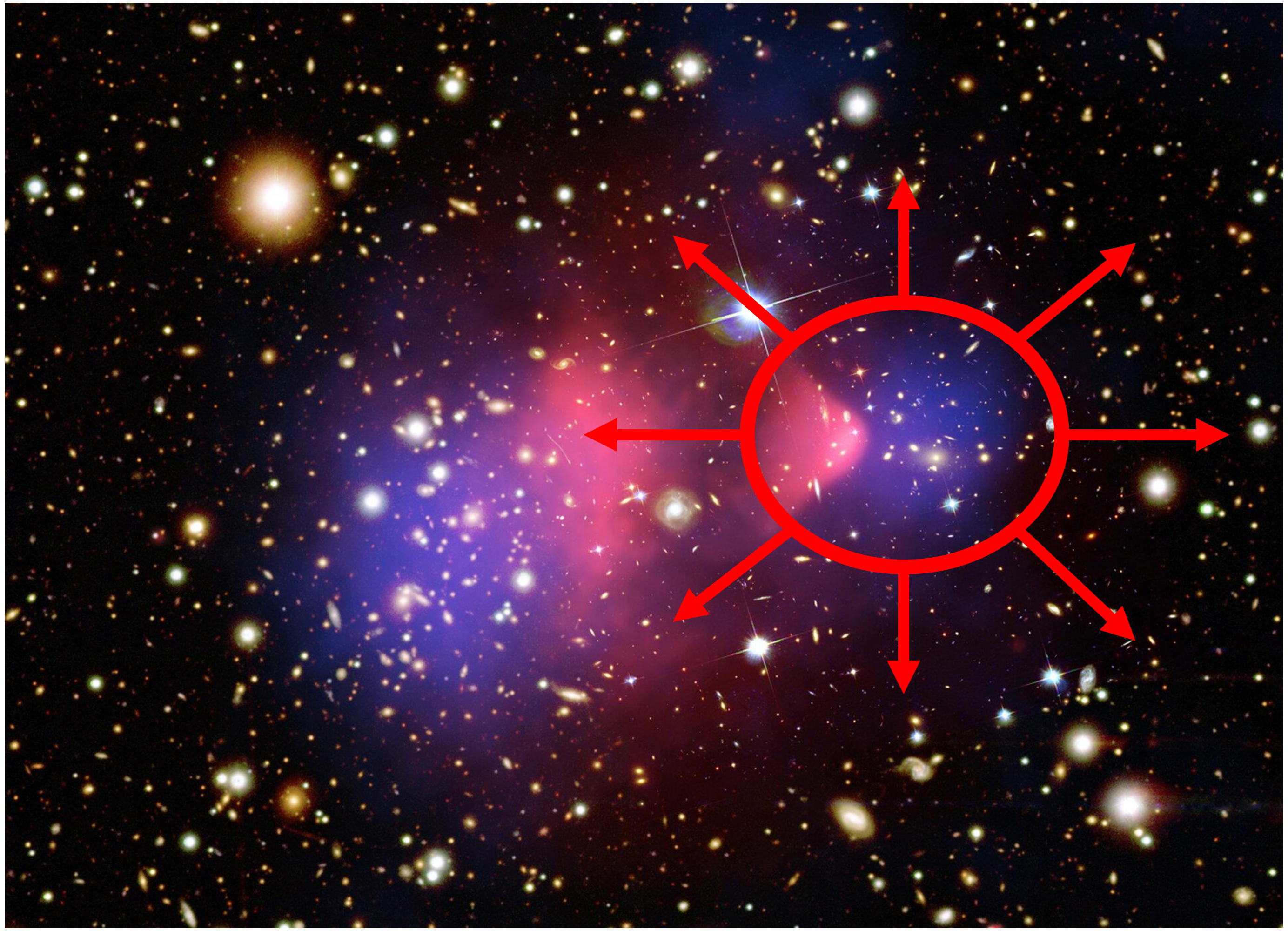

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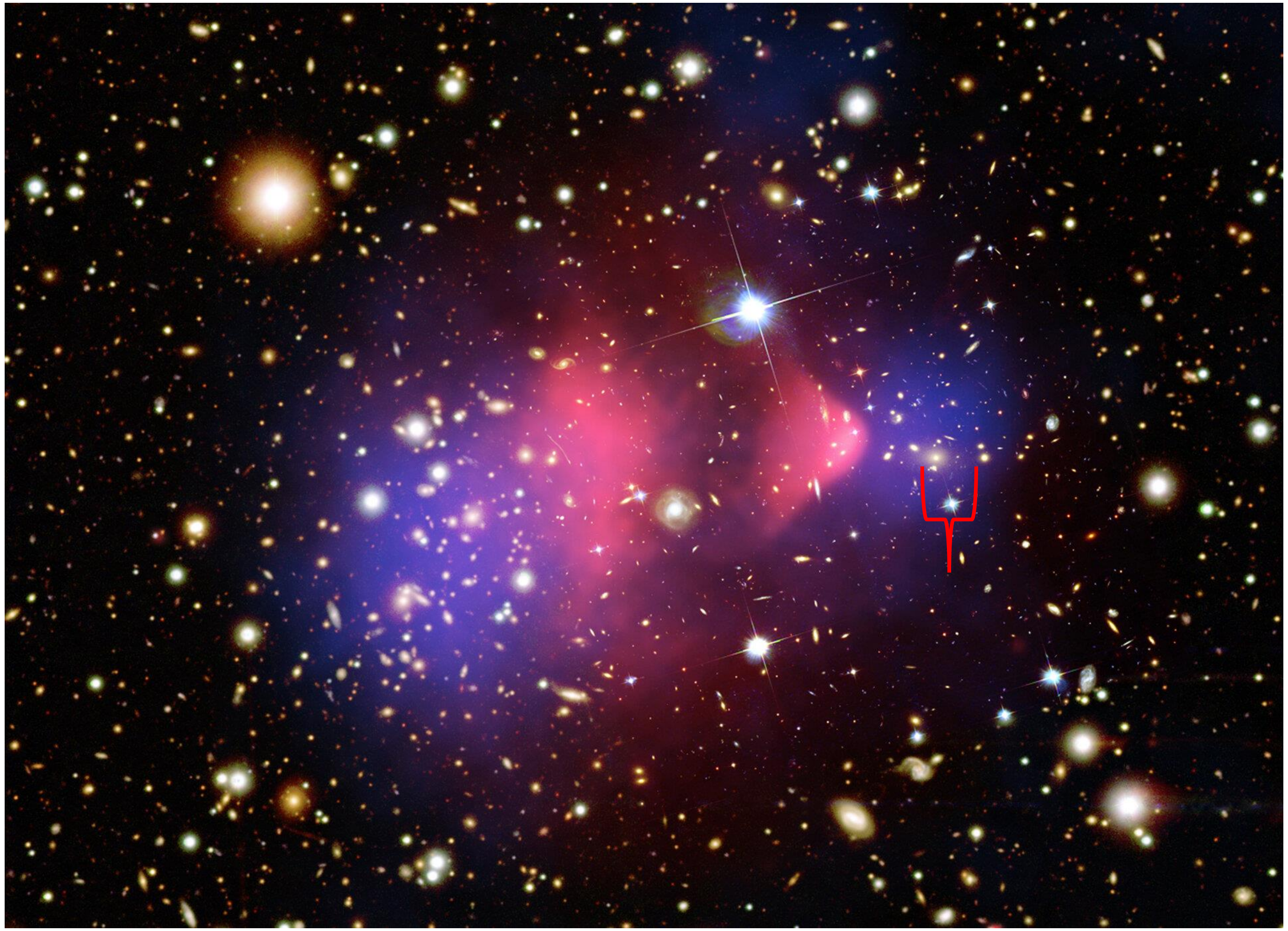


Credit: European Space Agency

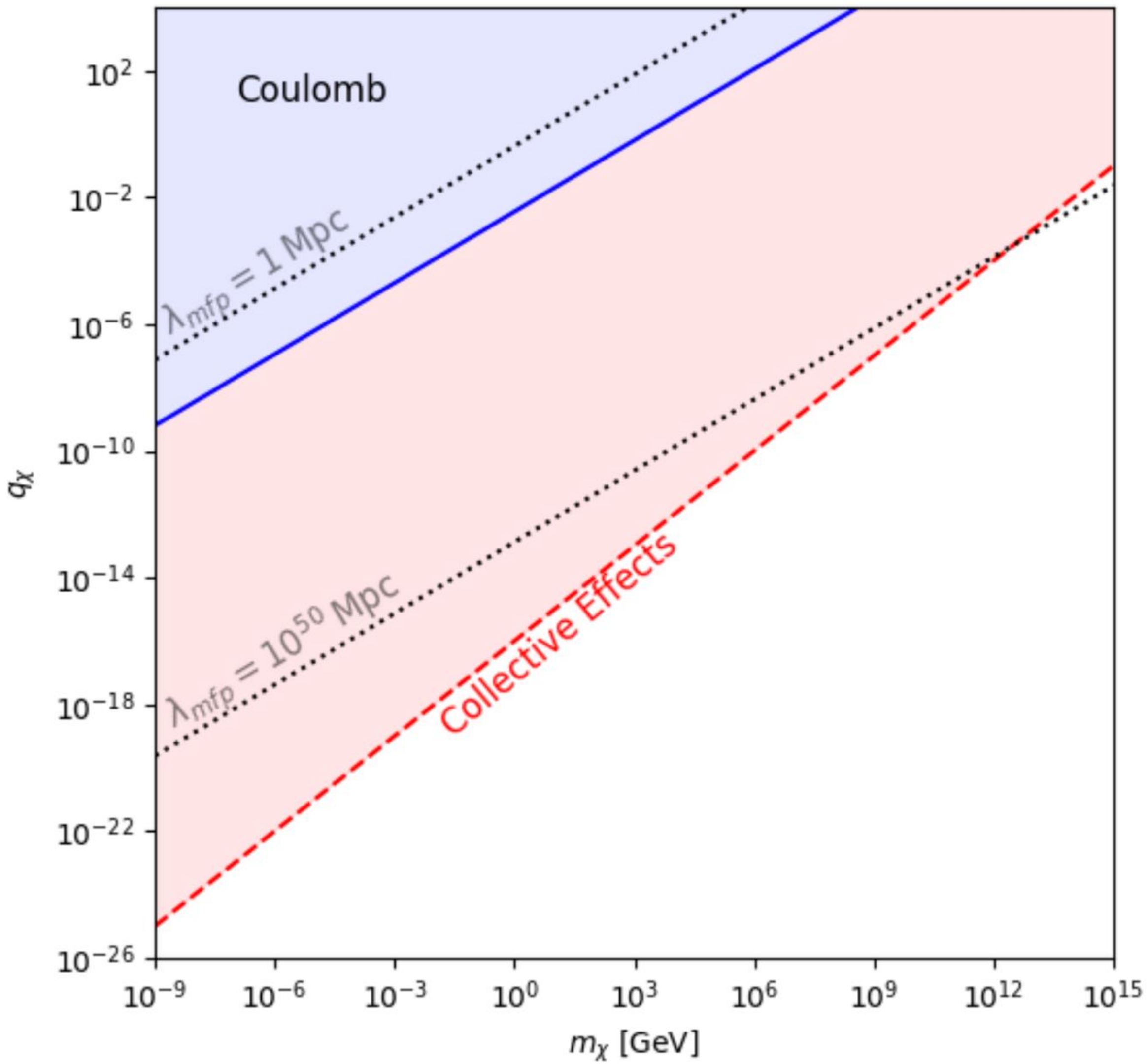
Collisionless Regime

- Introduce model

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

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

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



Plasma Dynamics

- Vlasov Equation

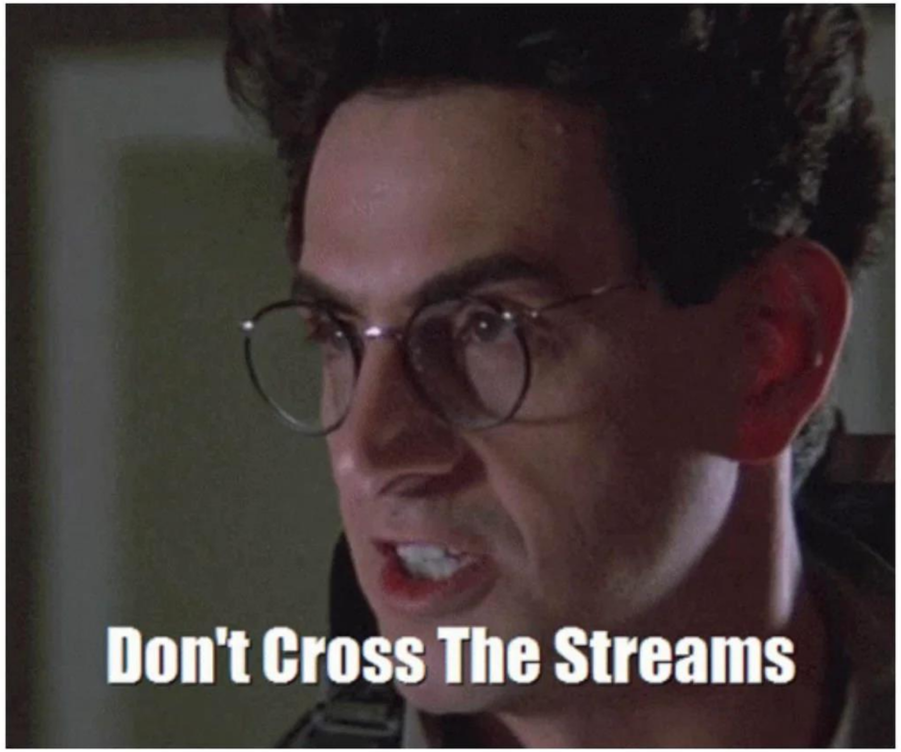
$$\left(\partial_t + \frac{q_s}{m_s}(\boldsymbol{E} + \boldsymbol{v} \times \boldsymbol{B}) \cdot \nabla_v + \boldsymbol{v} \cdot \nabla_x\right) f_s(\boldsymbol{x}, \boldsymbol{v}, t) = 0$$

- 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

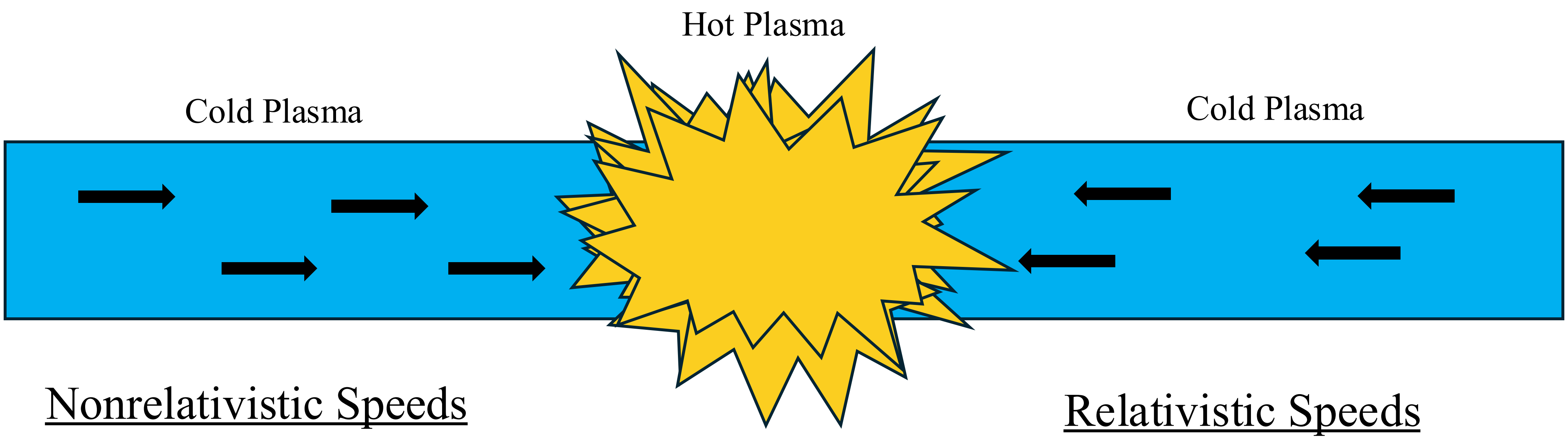
Simulations

- 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]


Don't Cross The Streams

Beam Instabilities



<u>Nonrelativistic Speeds</u>

- Electrostatic forces
- Longitudinal modes
- Exponential growth rate

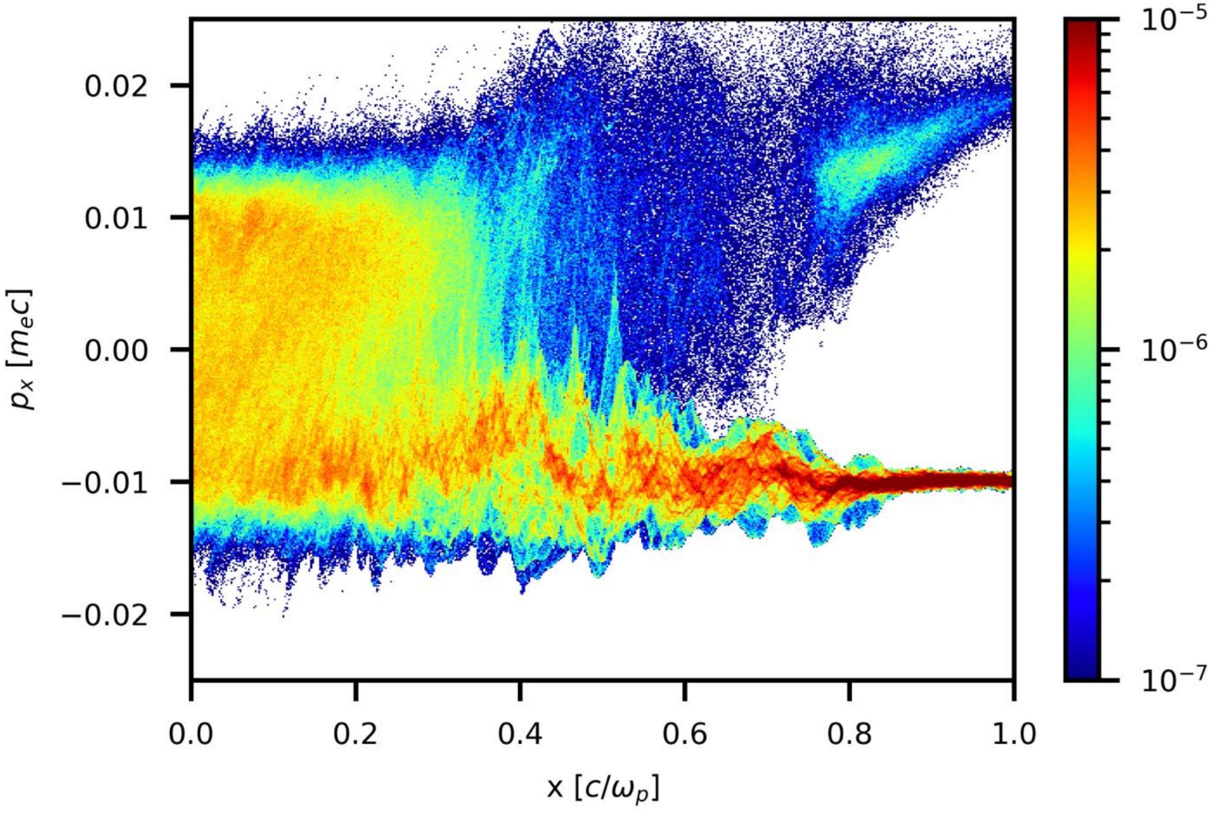
$$\Gamma \sim \omega_p^{-1}$$

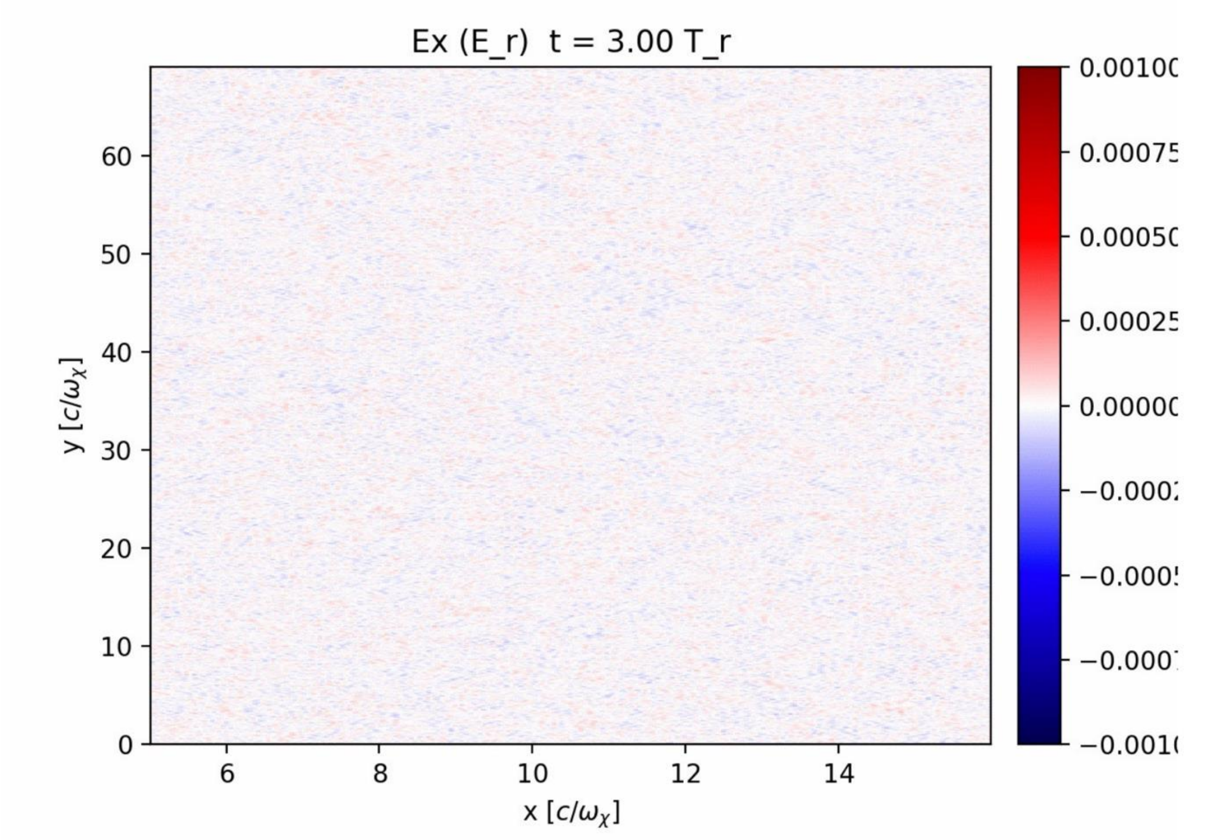
<u>Relativistic Speeds</u>

- Electromagnetic forces
- Transverse modes
- Exponential growth rate

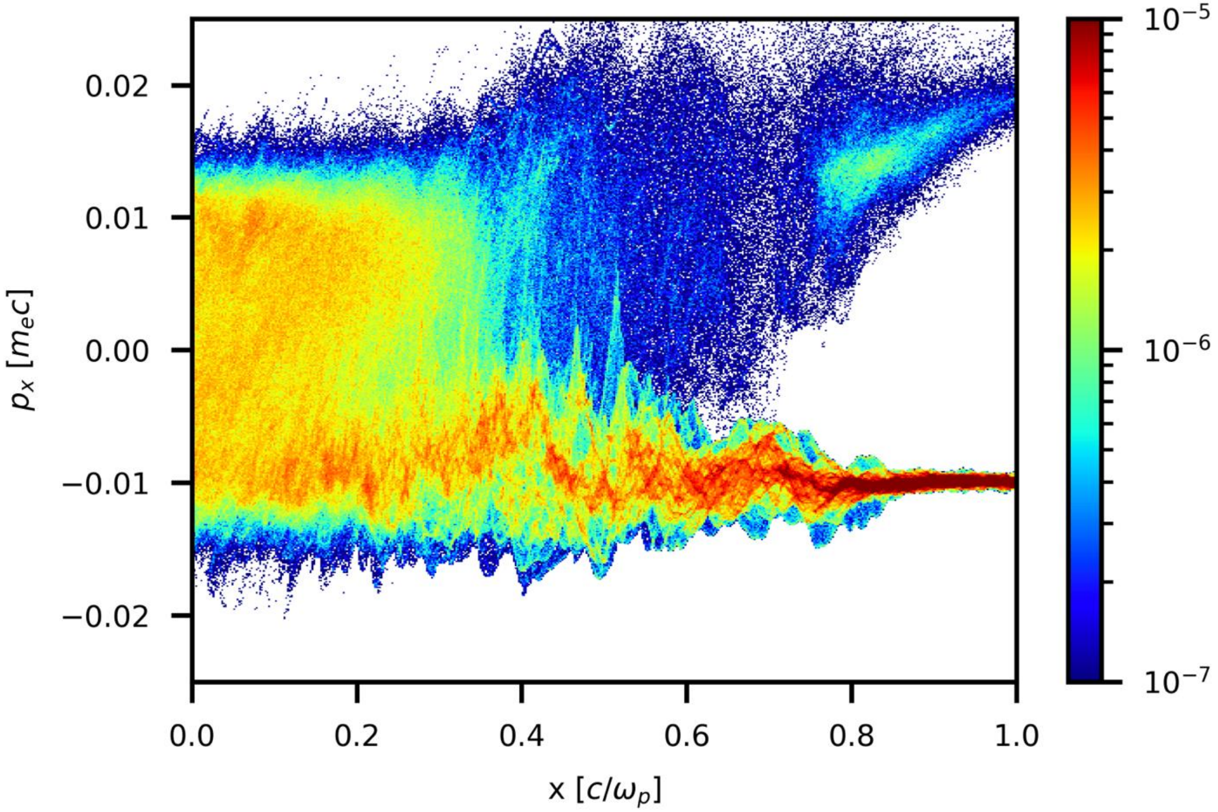
$$\Gamma \sim v_{\rm rel}\omega_p^{-1}$$

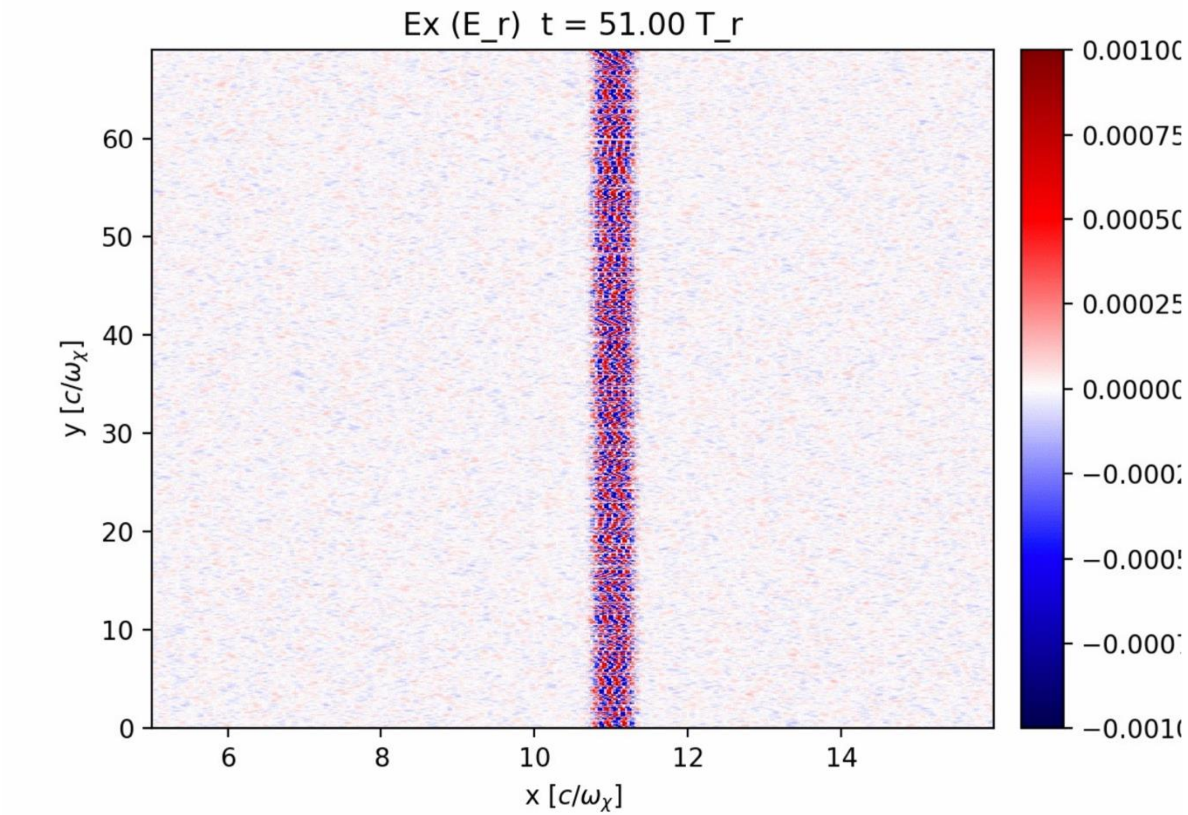
Plasma Shocks



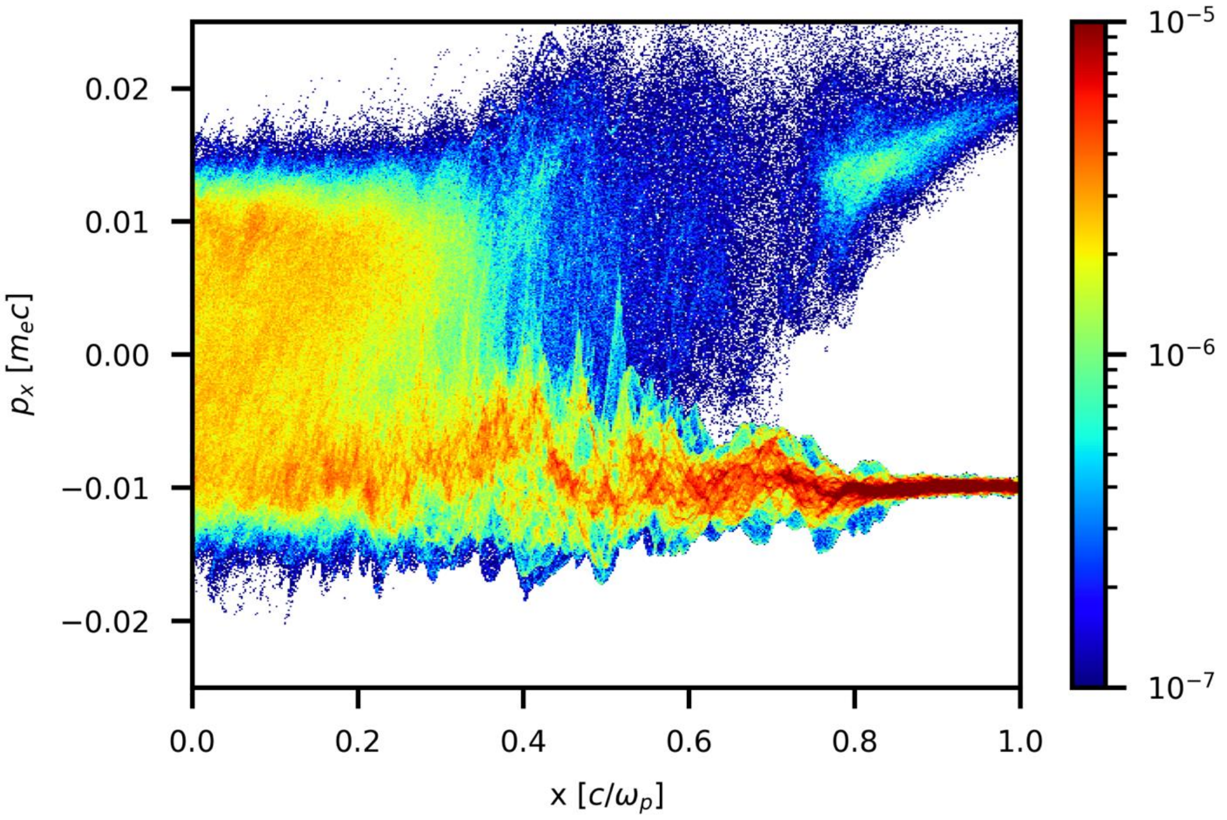


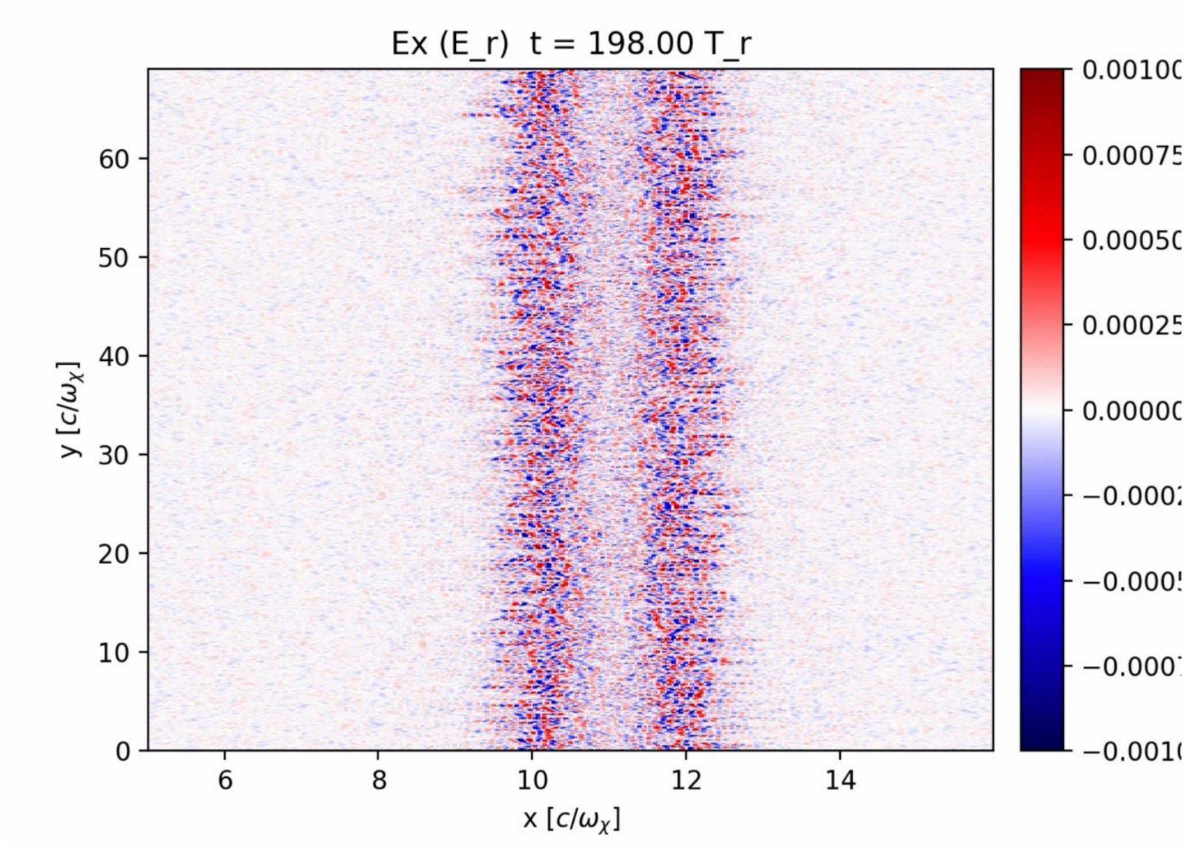
Plasma Shocks



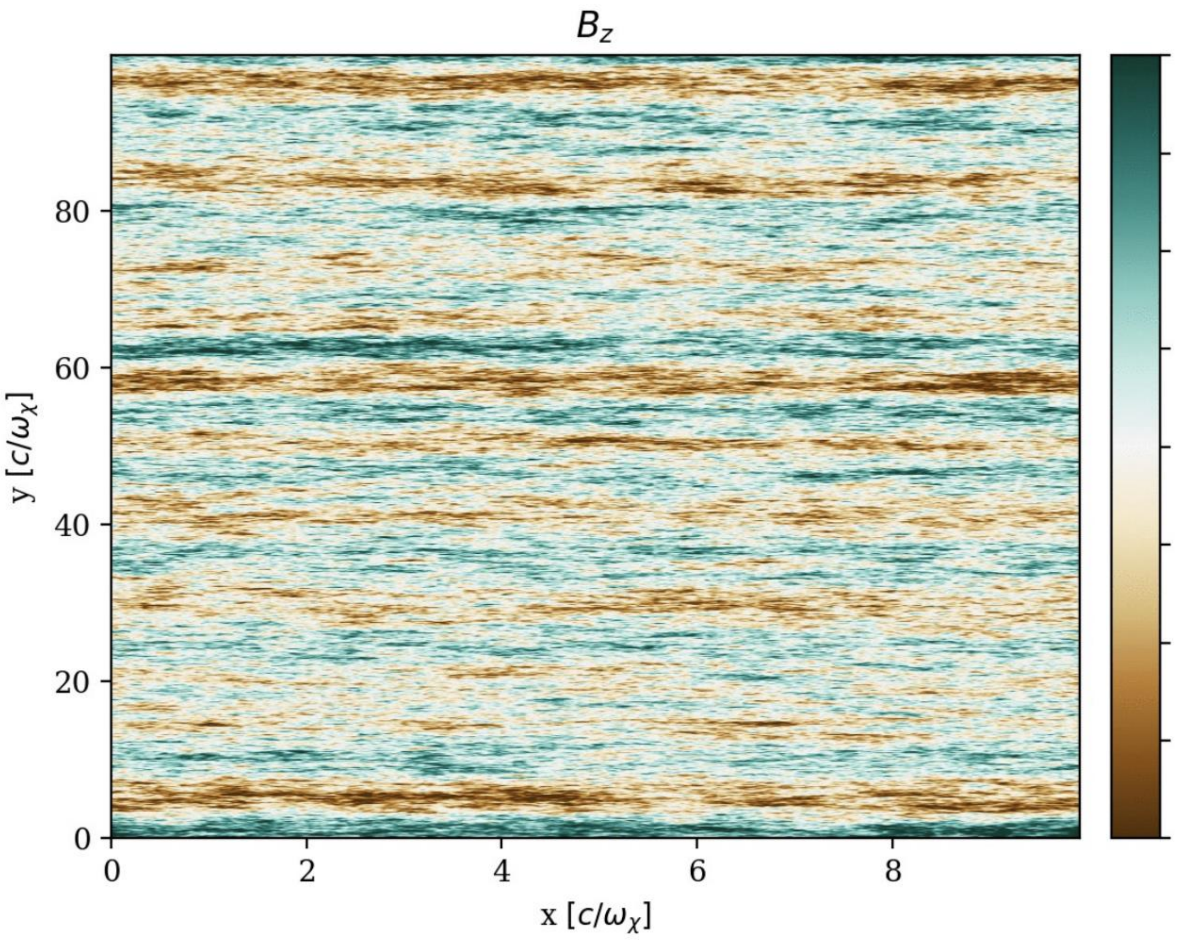


Plasma Shocks



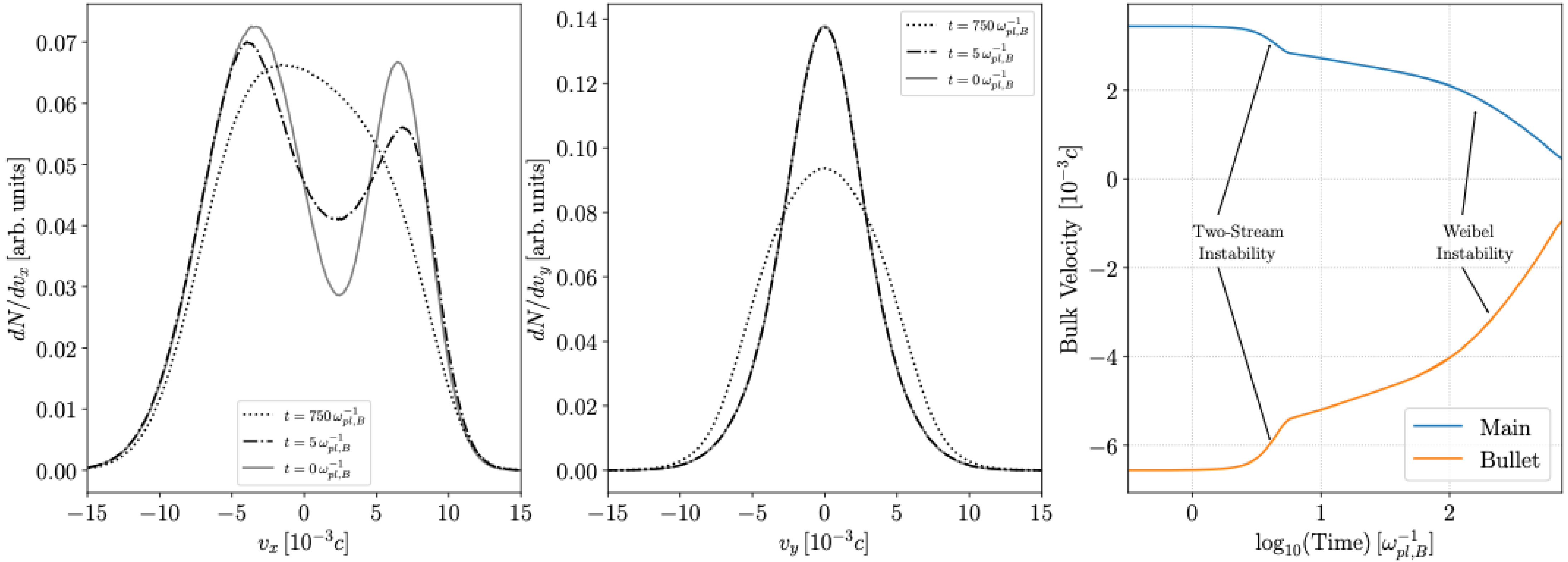


Effective Collisions



- 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
- Through various nonlinear effects, particles exchange enough momentum to mimic a hard scattering

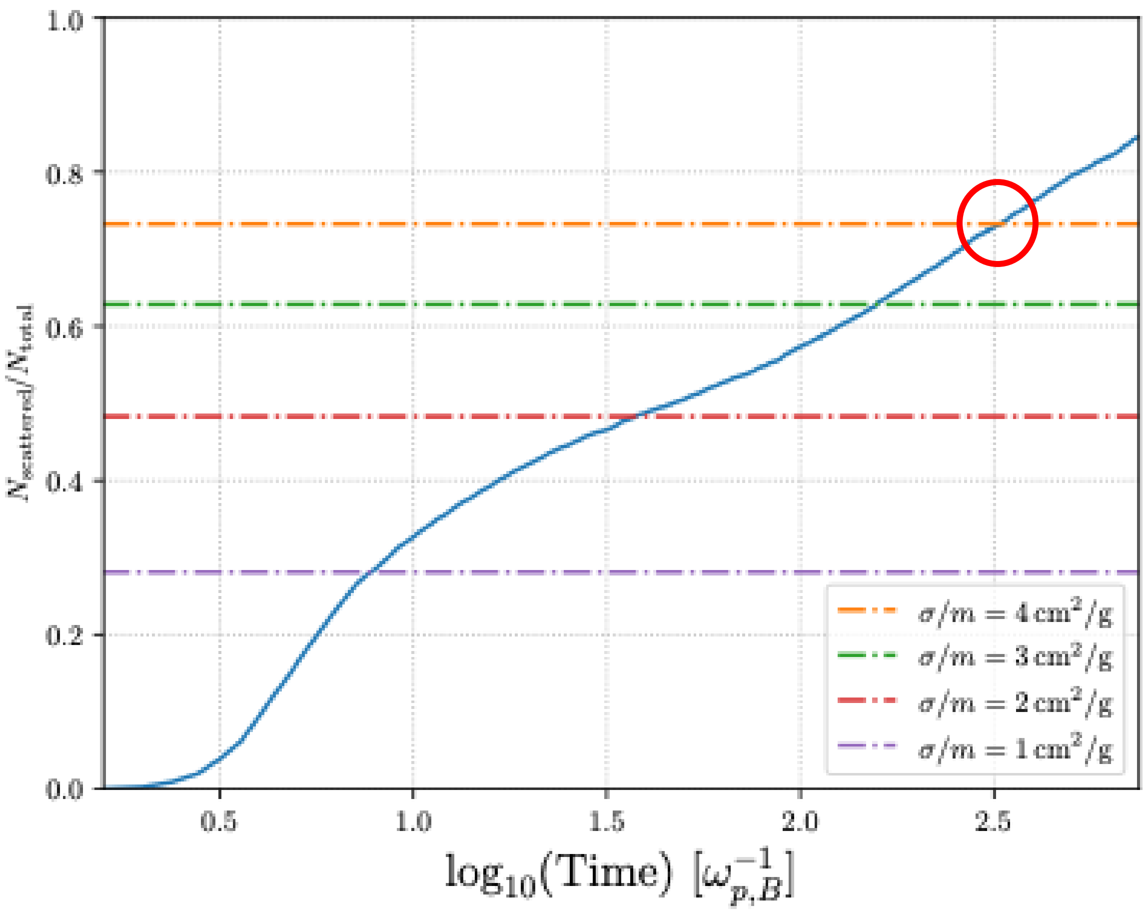
Towards Thermal Equilibrium

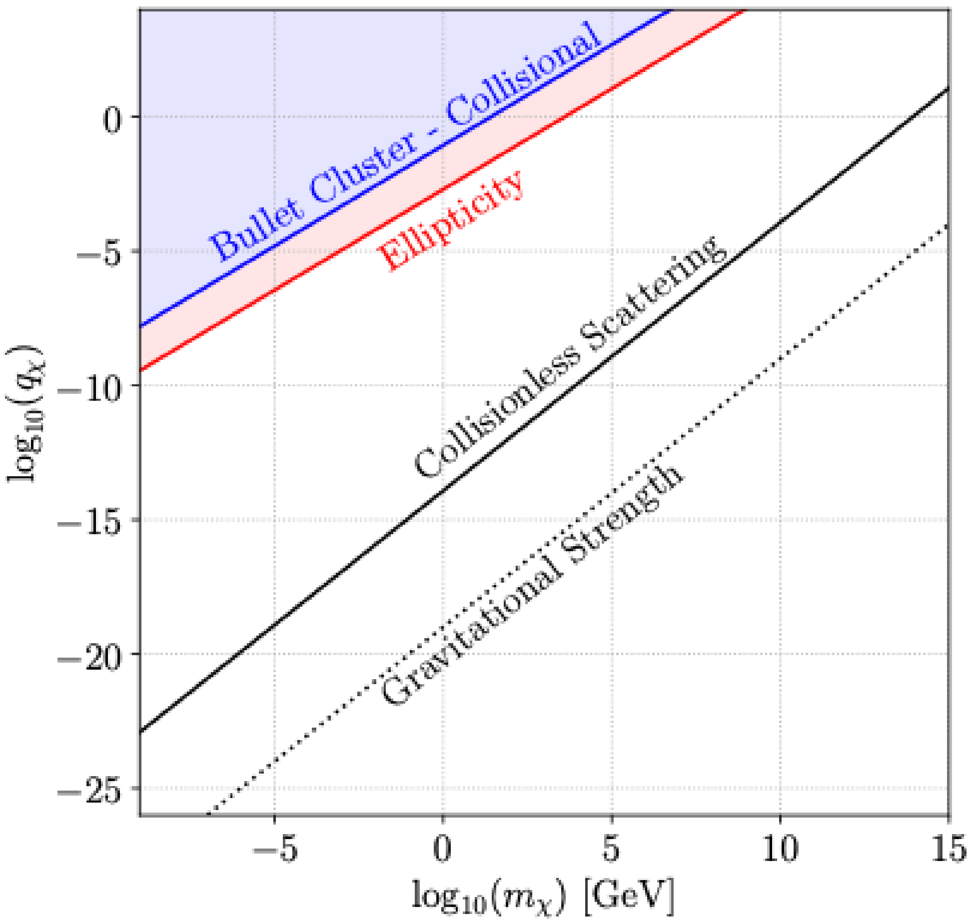


After tracking the fraction of particles that have undergone a significant change in momentum, we can determine an effective cross-section

$$\sigma/m = -(0.33\,\mathrm{g/cm^2})^{-1}\log(1-p)$$

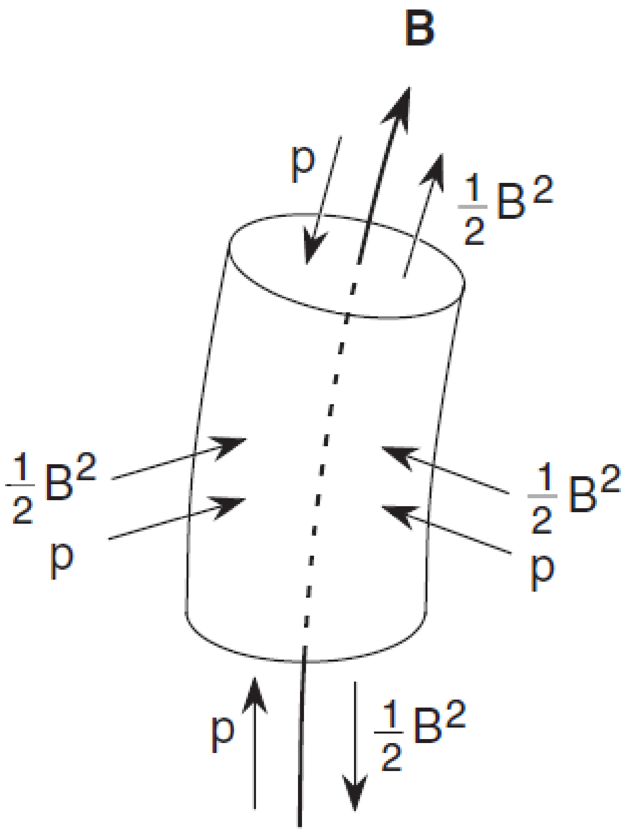
Effective Collisions



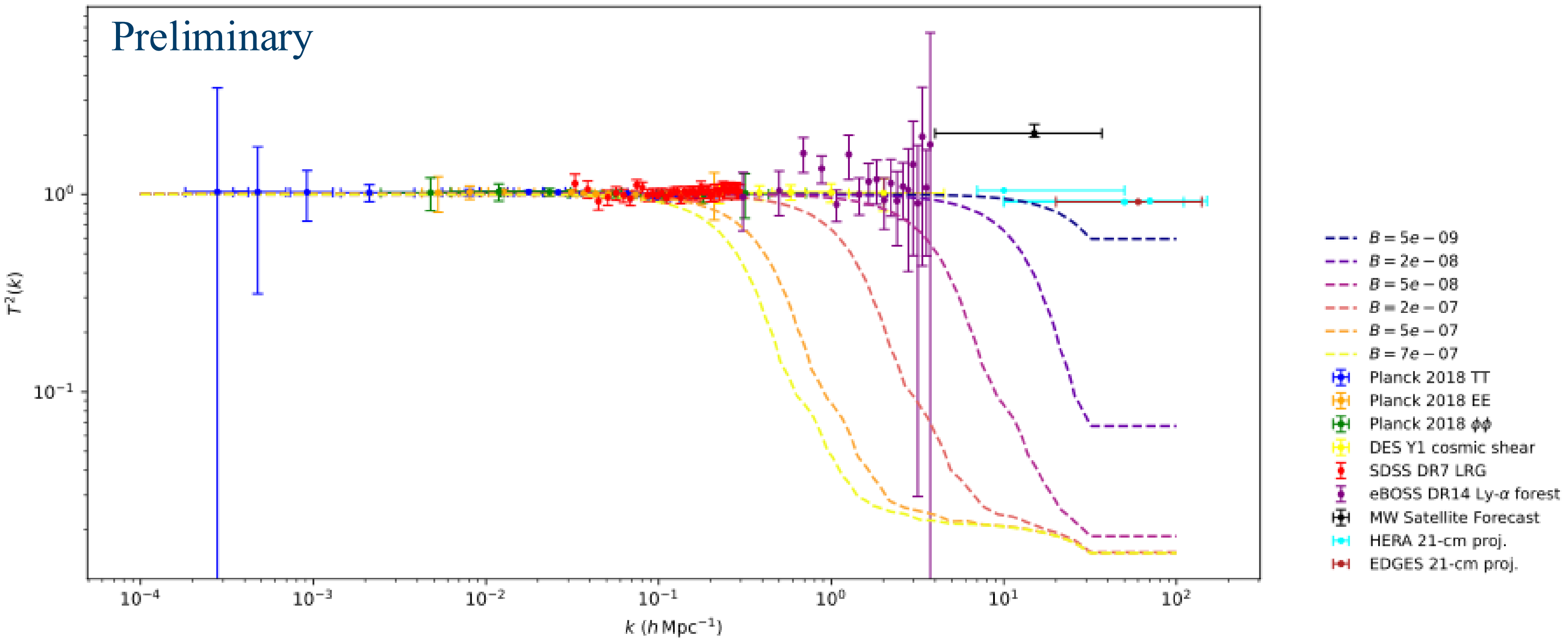


After reaching a conservative effective collisional cross-section 4 cm^2/g, we place our constraint when saturation occurs in less that 1% of the Bullet Cluster crossing time.

Further Directions



Principles of Magnetohydrodynamics by
Hans Goedblood & Stefaan Poedts

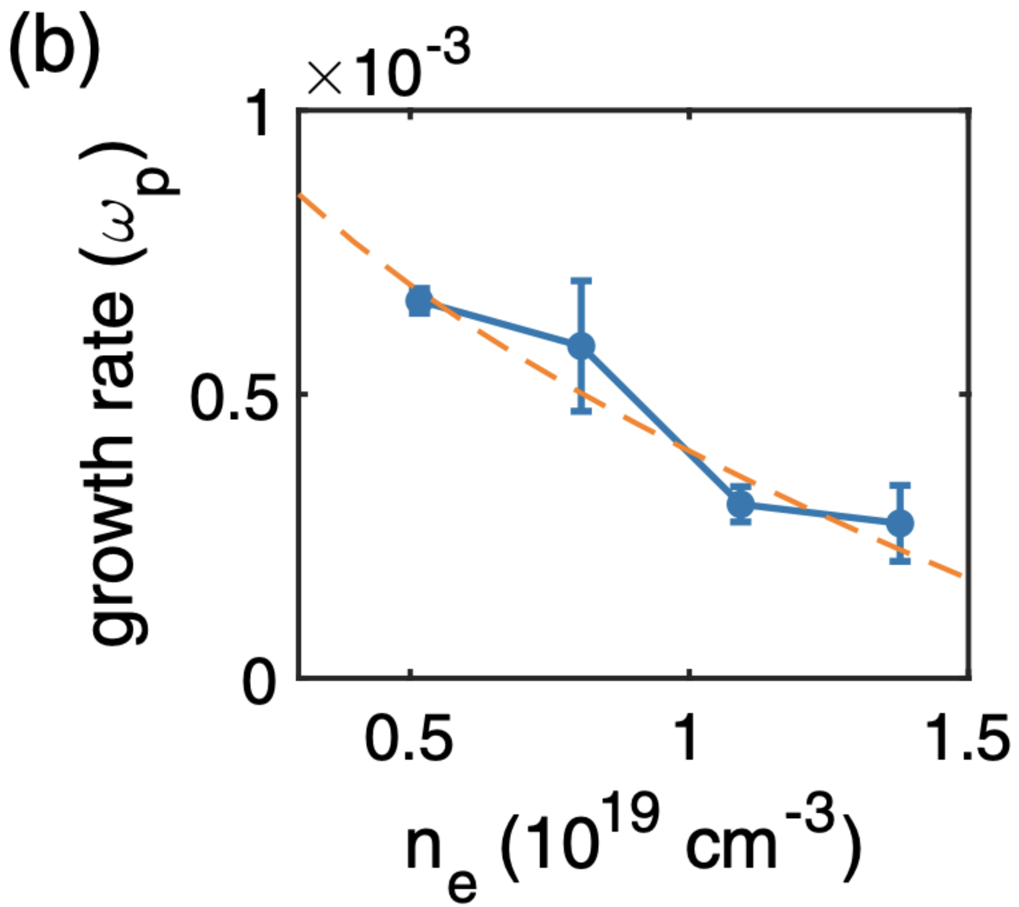


- Dark magnetic fields provide "magnetic pressure" to suppress structure formation in the early universe.
- Couples plasma dynamics to gravitational interactions.

Further Directions

$$\nabla \cdot E = \rho - g_{a\gamma\gamma} B \cdot \nabla a$$
$$\nabla \cdot B = 0$$
$$\nabla \times E = -\partial_t B$$
$$\nabla \times B = \partial_t E + J + g_{a\gamma\gamma}(B\partial_t a - E \times \nabla a)$$
$$\partial_t^2 a - \nabla^2 a + m_a^2 a = -g_{a\gamma\gamma} E \cdot B$$

- Presence of ultralight axionic dark matter alters plasma dynamics.
- Various earth-based plasma experiments may be sensitive to axions altering instability dynamics.



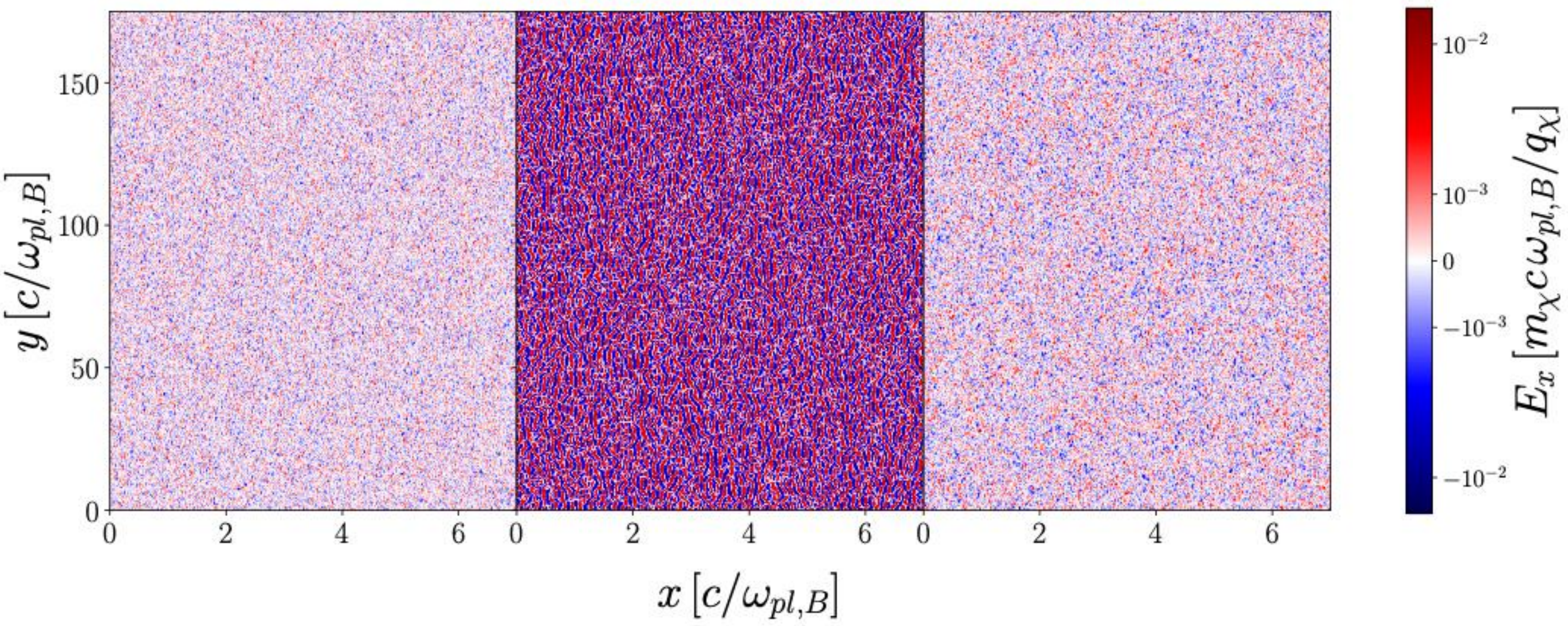
Zhang, C., Huang, CK. & Joshi, C. Self-organization of photoionized plasmas via kinetic instabilities. *Rev. Mod. Plasma Phys.* **7**, 34 (2023).

Conclusions

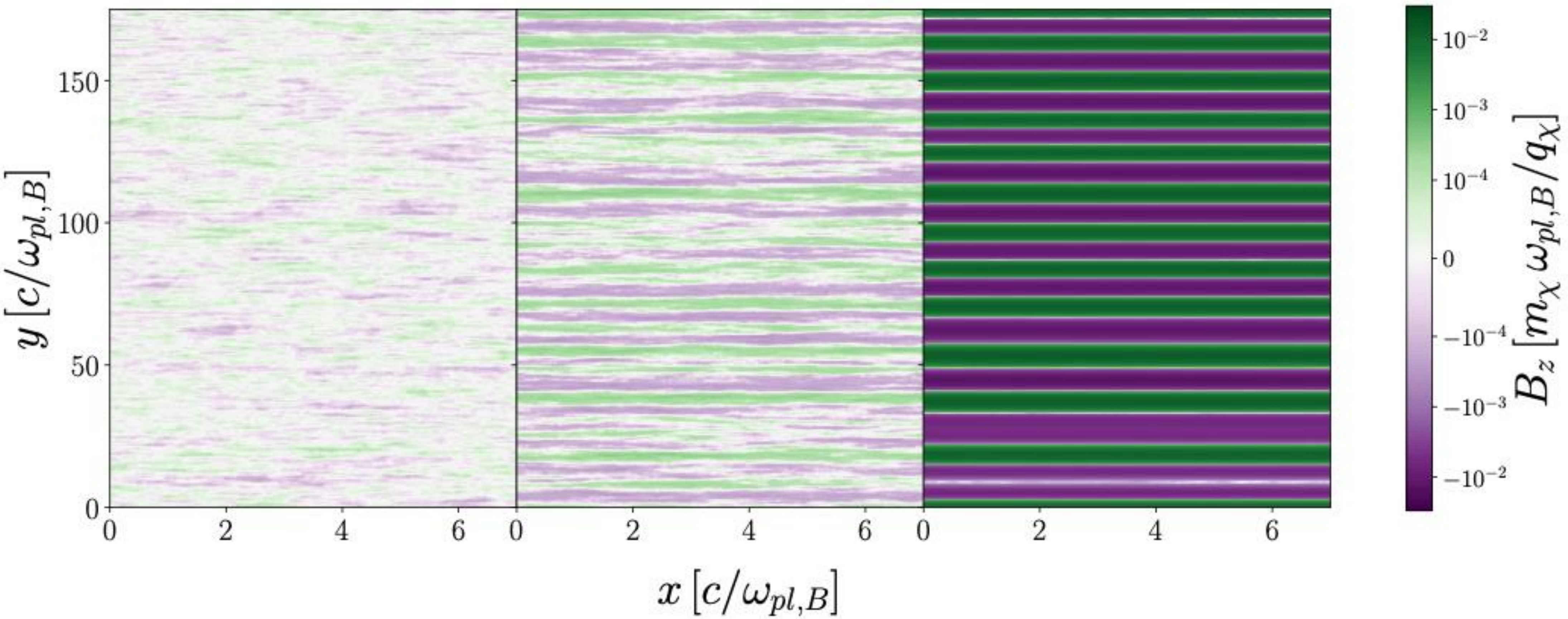
- Collective effects can constrain many orders of magnitude of parameter space.
- Simulations are necessary to understand nonlinear behavior of plasmas.
- With more precise treatment and stronger computational power, further constraints can be placed.
- Many new opportunities to study well-motivated models that can exhibit collective effects.

References

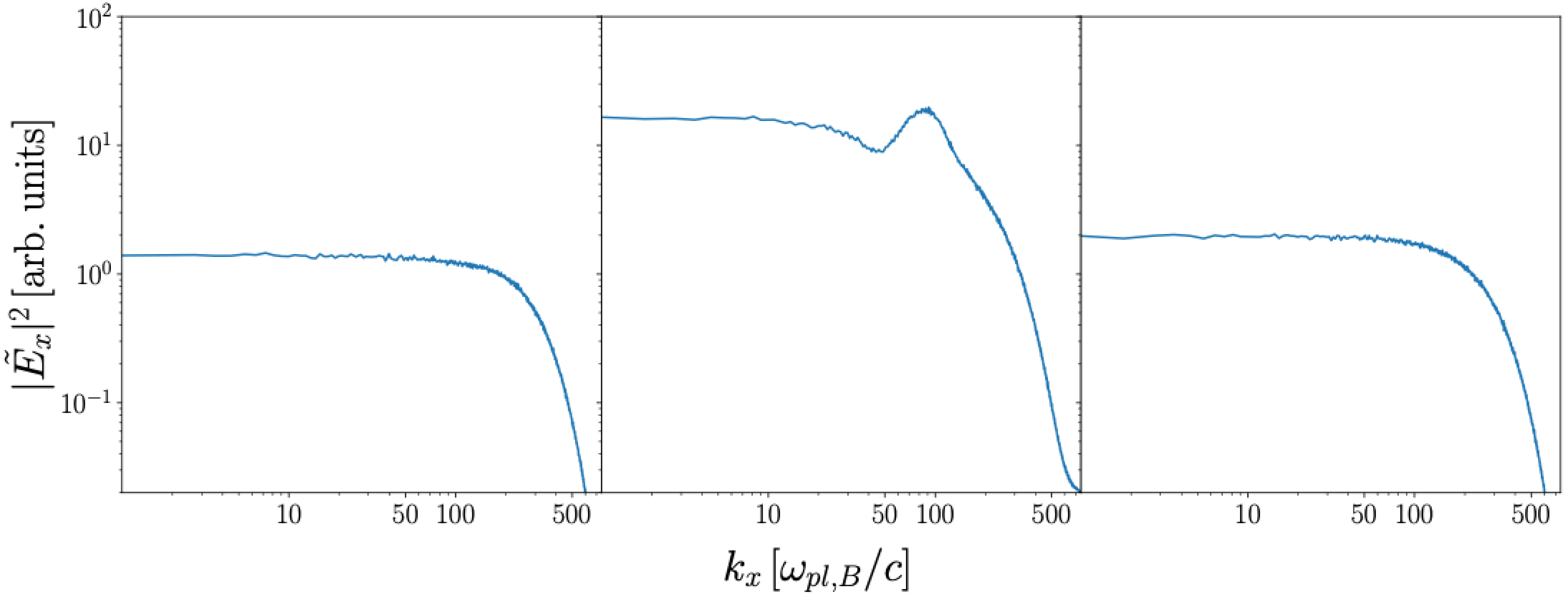
- [1] A. Robertson, R. Massey, V. Eke, *What does the Bullet Cluster tell us about self-interacting dark matter?*, MNRAS, 465, 569-587 (2017)
- [2] J. Derouillat, A. Beck, F. Pérez, T. Vinci, M. Chiaramello, A. Grassi, M. Flé, G. Bouchard, I. Plotnikov, N. Aunai, J. Dargent, C. Riconda, M. Grech, *SMILEI: a collaborative, open-source, multipurpose 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)



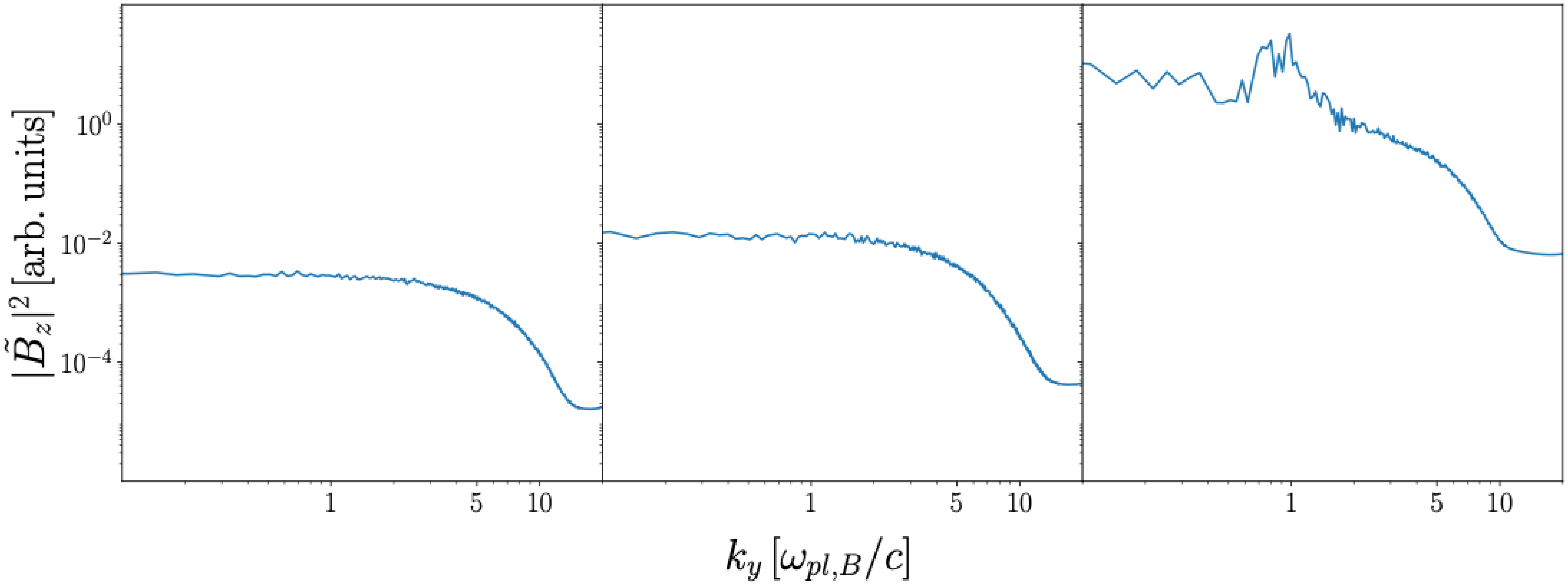
$y\,[c/\omega_{pl,B}]$
150
100
50
0
0
2
4
6
0
2
4
6
0
2
4
6
$x\,[c/\omega_{pl,B}]$
10^{-2}
10^{-3}
0
-10^{-3}
-10^{-2}
$E_x\,[m_\chi c\,\omega_{pl,B}/q_\chi]$



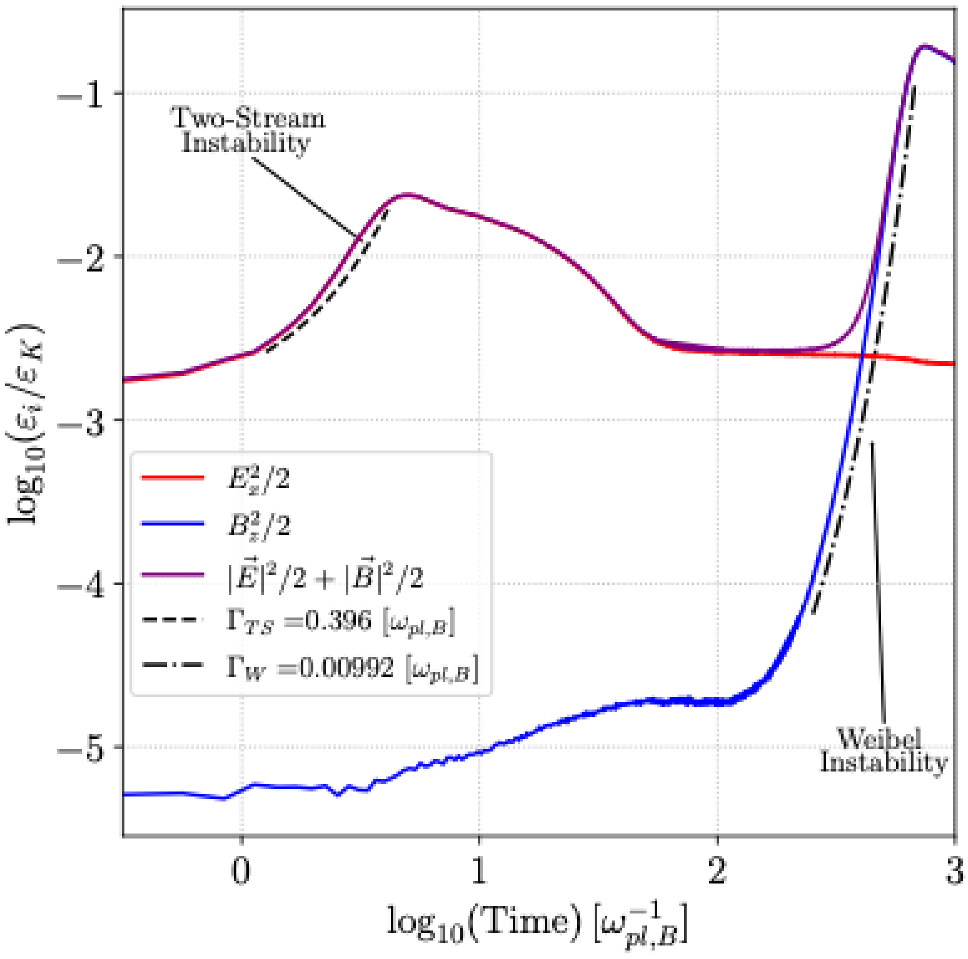
$y\,[c/\omega_{pl,B}]$
150
100
50
0
0
2
4
6
$x\,[c/\omega_{pl,B}]$
10^{-2}
10^{-3}
10^{-4}
0
-10^{-4}
-10^{-3}
-10^{-2}
$B_z\,[m_\chi\,\omega_{pl,B}/q_\chi]$



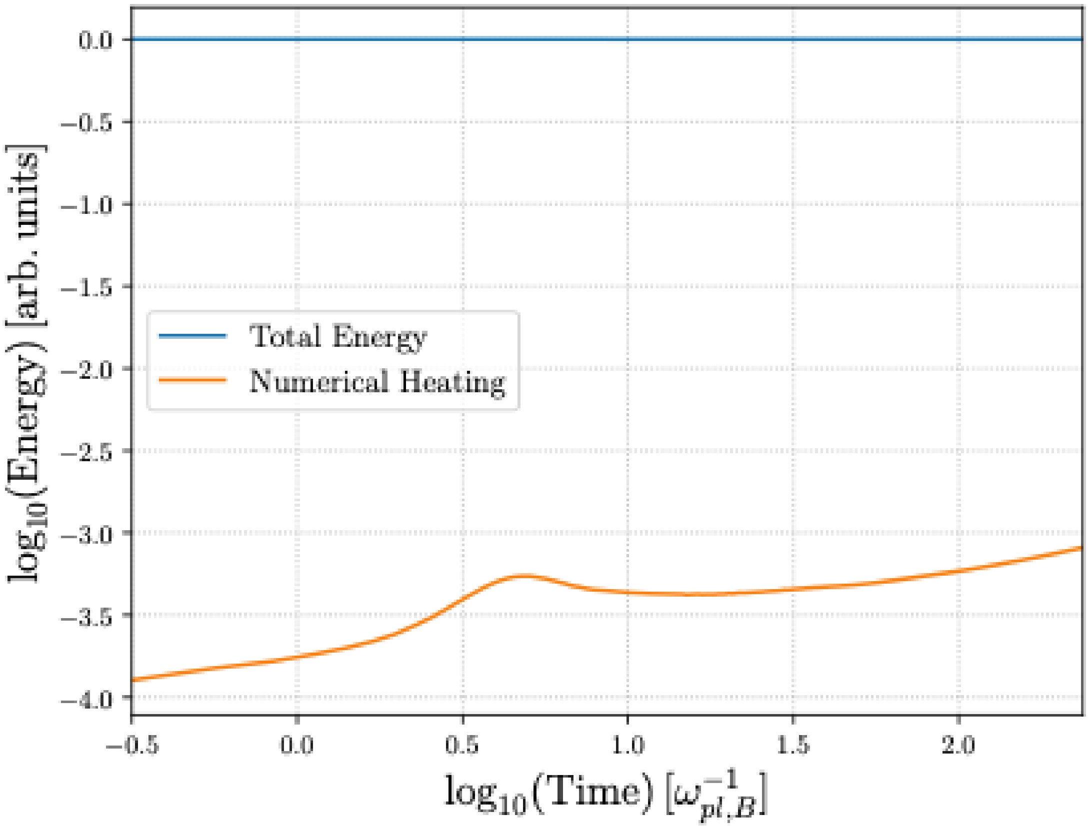
10^2
10^1
10^0
10^{-1}
$|\tilde{E}_x|^2$ [arb. units]
10
50
100
500
$k_x\,[\omega_{pl,B}/c]$



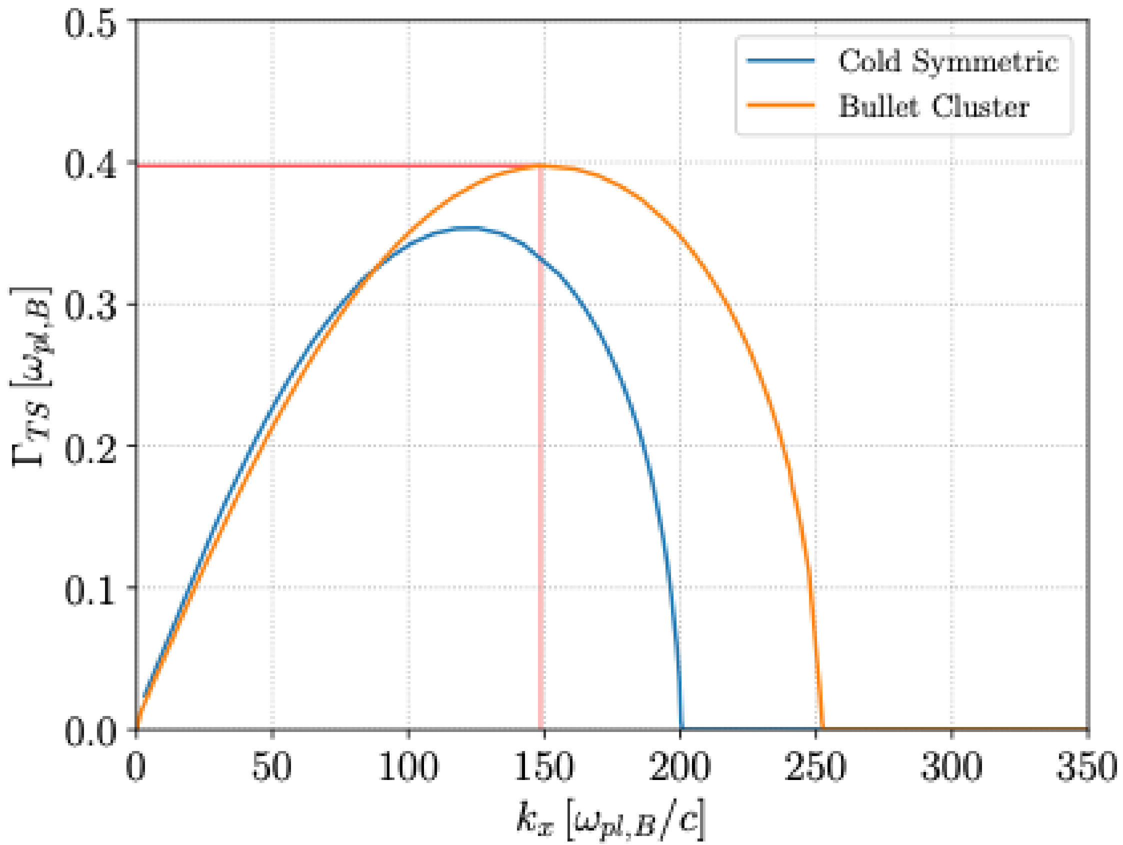
$|\tilde{B}_z|^2$ [arb. units]
10^0
10^{-2}
10^{-4}
1
5
10
$k_y\,[\omega_{pl,B}/c]$

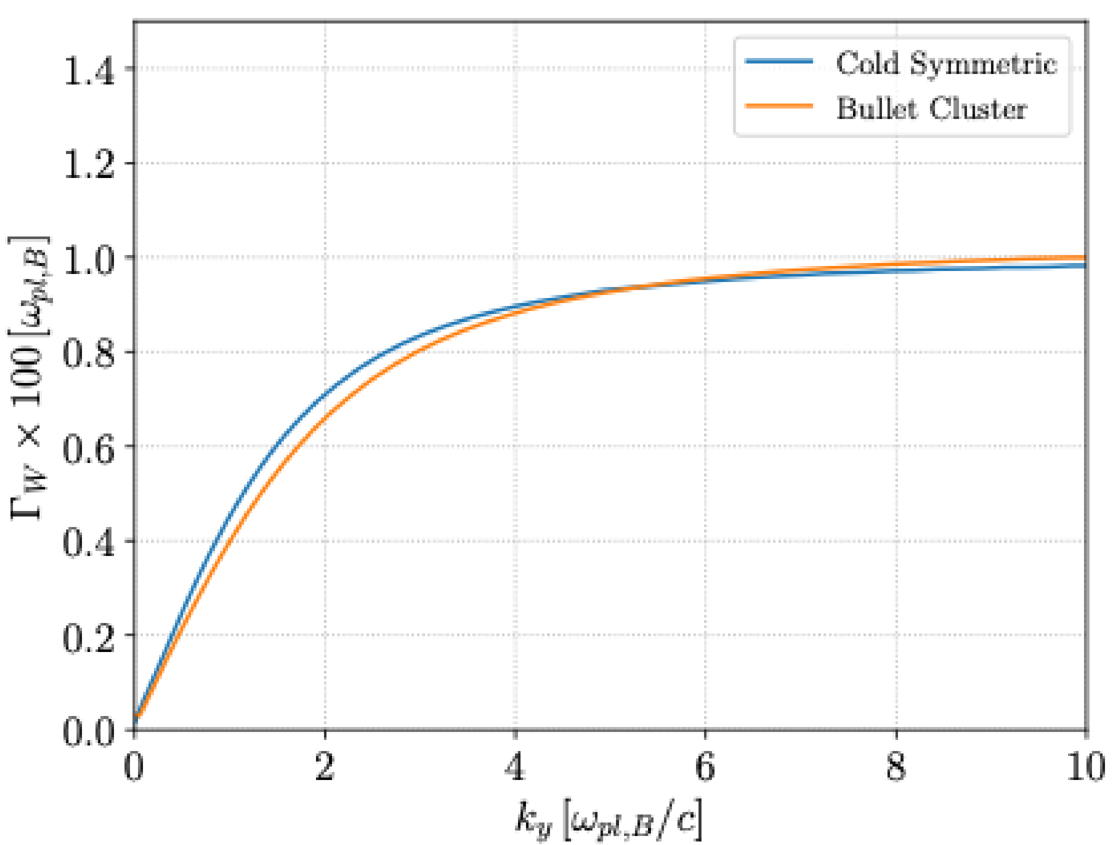


Two-Stream Instability
Weibel Instability
$E_z^2/2$
$B_z^2/2$
$|\vec{E}|^2/2 + |\vec{B}|^2/2$
Γ_{TS} =0.396 [$\omega_{pl,B}$]
Γ_W =0.00992 [$\omega_{pl,B}$]
$\log_{10}(\varepsilon_i/\varepsilon_K)$
$\log_{10}(\mathrm{Time})$ [$\omega_{pl,B}^{-1}$]



Total Energy
Numerical Heating
$\log_{10}(\mathrm{Energy})$ [arb. units]
$\log_{10}(\mathrm{Time})$ [$\omega_{pl,B}^{-1}$]


Cold Symmetric
Bullet Cluster
$\Gamma_{TS}\,[\omega_{pl,B}]$
$k_x\,[\omega_{pl,B}/c]$
0.0
0.1
0.2
0.3
0.4
0.5
0
50
100
150
200
250
300
350


Cold Symmetric
Bullet Cluster
$\Gamma_W \times 100\,[\omega_{pl,B}]$
$k_y\,[\omega_{pl,B}/c]$
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
0
2
4
6
8
10