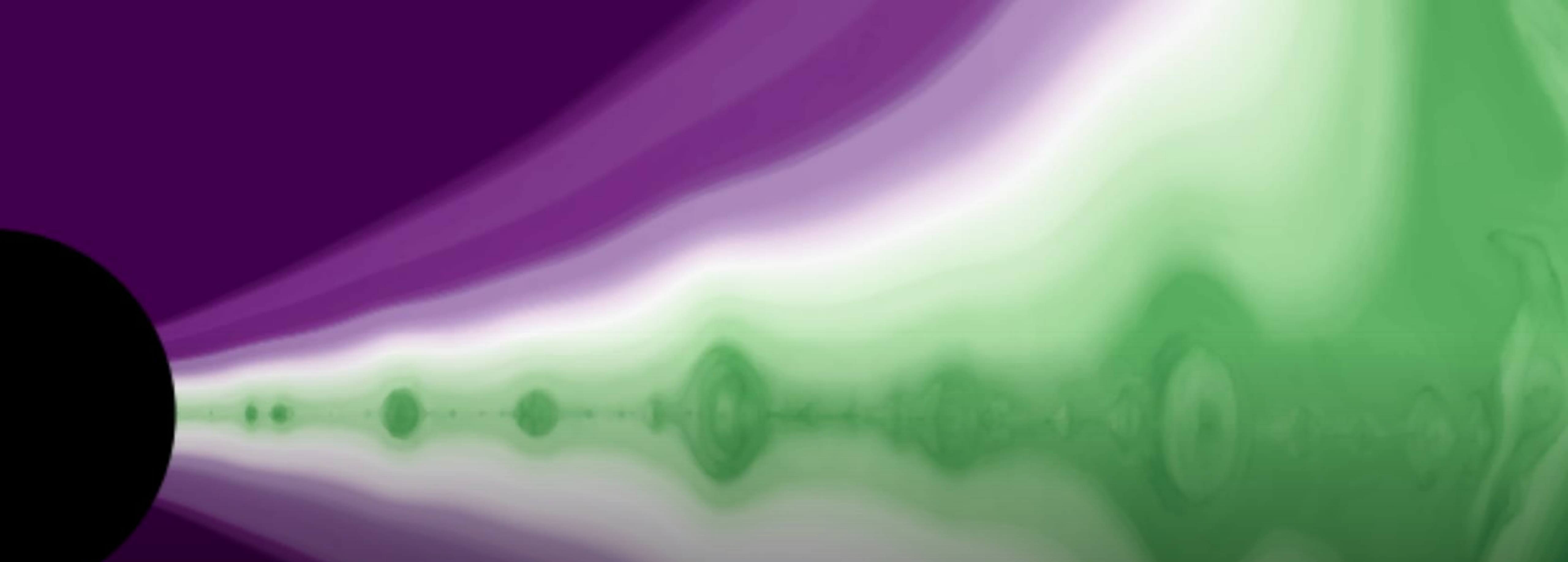

Energy Partition in Pair-Ion Relativistic Reconnection

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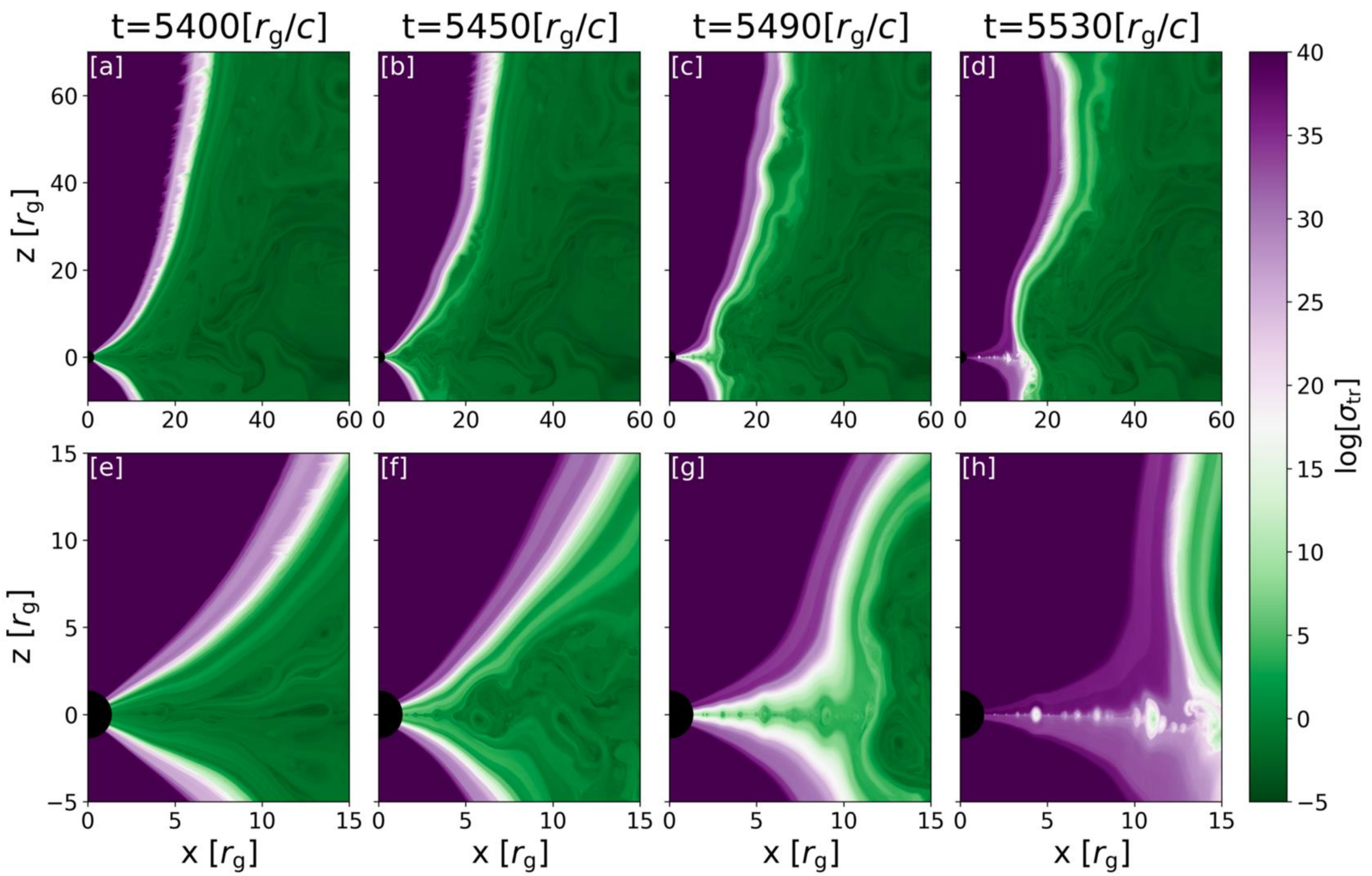
Astrophysical Motivation

- Relativistic Reconnection is invoked as acceleration mechanism to explain non-thermal emission from Black Holes.

- The actual reconnection site is uncertain: jet spine, boundary layer, magnetospheric equator...

- In all of these environments the plasma composition is unknown: pair-dominated or baryon-loaded?

- Our goal is to investigate how the **composition** of the plasma determines **energy partition** during reconnection

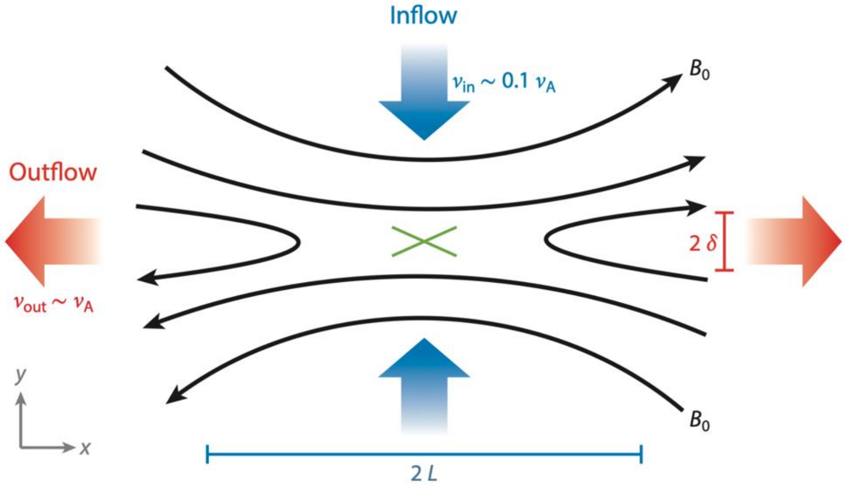


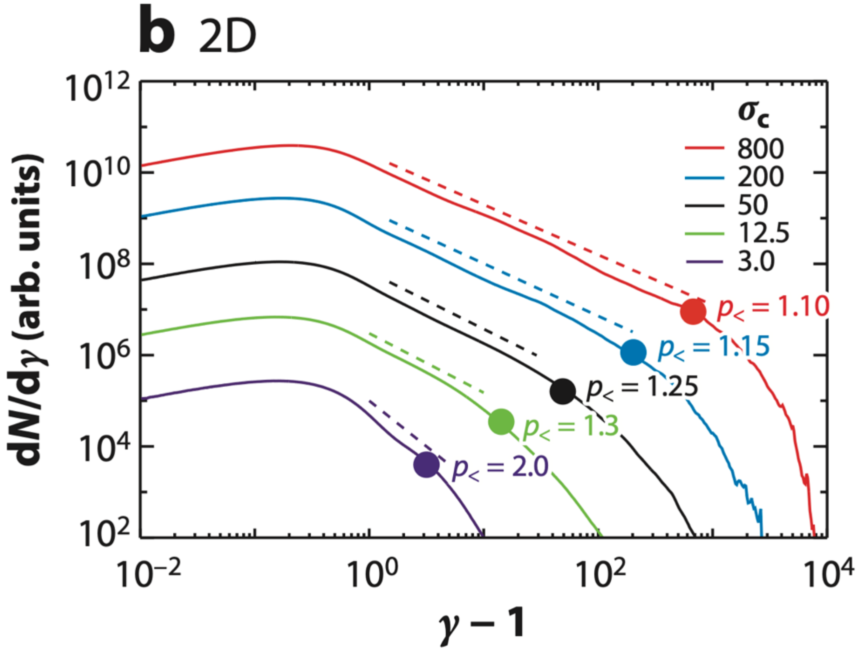
Chow et al. (in prep)

Relativistic Reconnection

Initial Magnetic Energy

- Internal Energy
  - Thermal
  - Non-Thermal
- Bulk Kinetic Energy





Plasma Magnetization

$$\sigma = \frac{B^2}{4\pi\rho c^2} >> 1$$

Alfvén speed

$$v_A = c\sqrt{\frac{\sigma}{1+\sigma}} \approx c$$

PIC Simulations

- Vlasov-Maxwell System:

$$\frac{\partial f_s}{\partial t} + \frac{\mathbf{p}}{m_s \gamma_s} \cdot \nabla_{\mathbf{x}} f_s + \mathbf{F} \cdot \nabla_{\mathbf{p}} f_s = 0$$

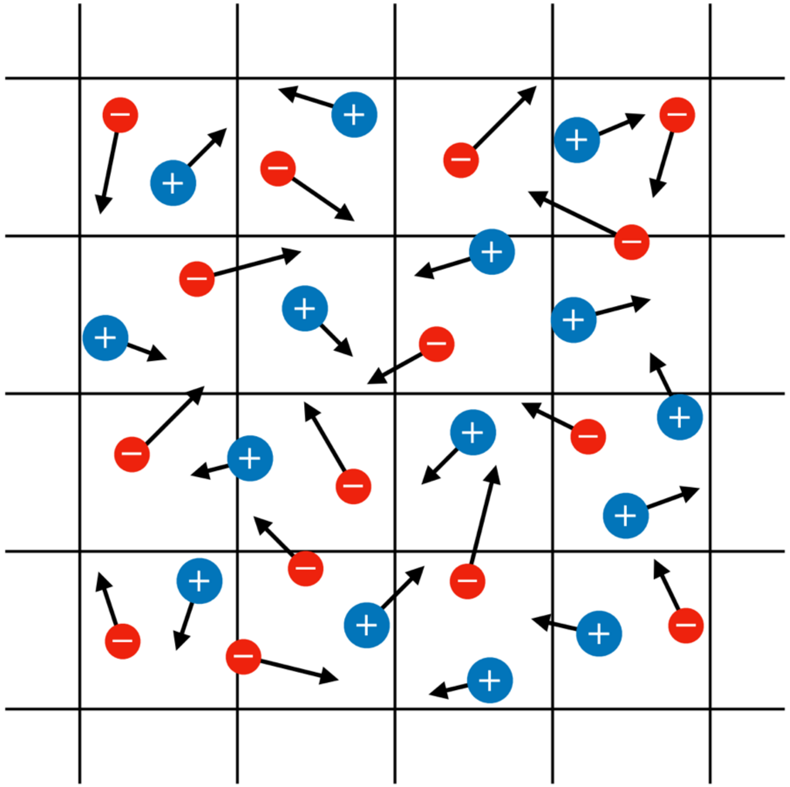
$$\gamma_s^2 = 1 + \frac{|\mathbf{p}|^2}{m_s^2 c^2}, \qquad \mathbf{F} = q_s \left(\mathbf{E} + \frac{\mathbf{p}}{\gamma_s m_s c} \times \mathbf{B} \right).$$

$$\frac{\partial \mathbf{E}}{\partial t} - c \nabla \times \mathbf{B} = -4\pi \mathbf{J}, \qquad \frac{\partial \mathbf{B}}{\partial t} + c \nabla \times \mathbf{E} = 0,$$

$$\rho = \sum_s q_s \int_{\mathbb{R}^3} f_s \, \mathrm{d}^3 p, \qquad \mathbf{J} = \sum_s \frac{q_s}{m_s} \int_{\mathbb{R}^3} f_s \frac{\mathbf{p}}{\gamma_s} \, \mathrm{d}^3 p.$$

- Three-species Plasma: $s \in \{\mathrm{i}, e^+, e_-\}$
- No radiative cooling

Numerical Integration using the Particle-In-Cell (PIC) Method

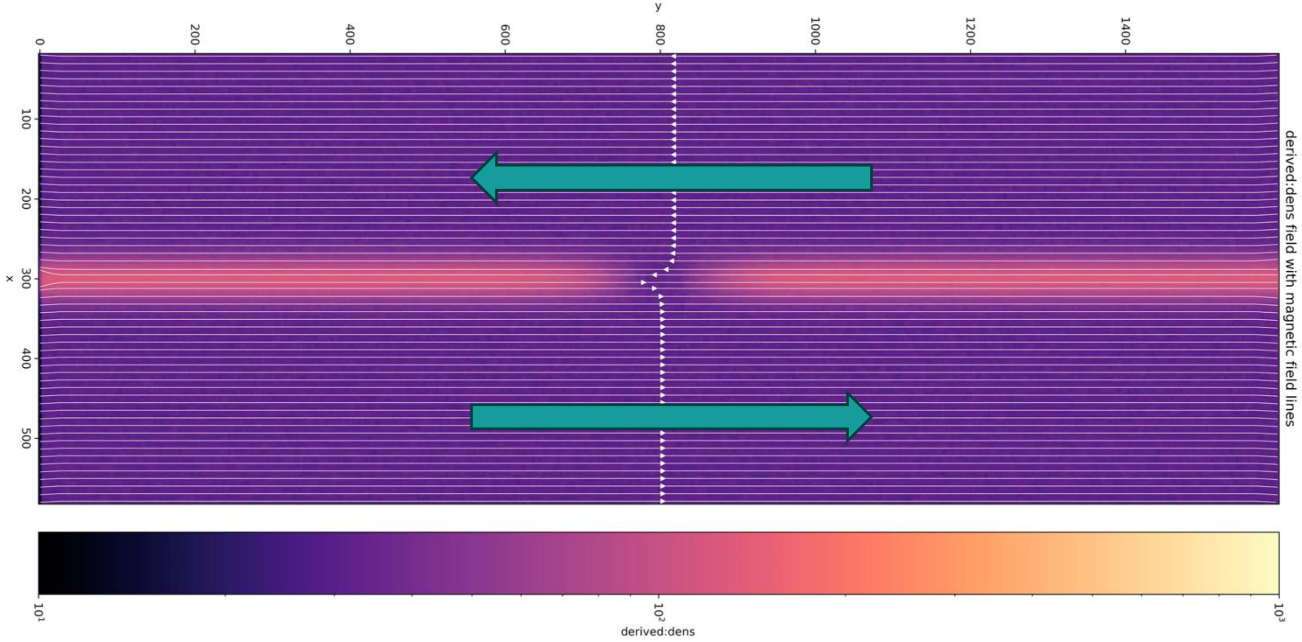


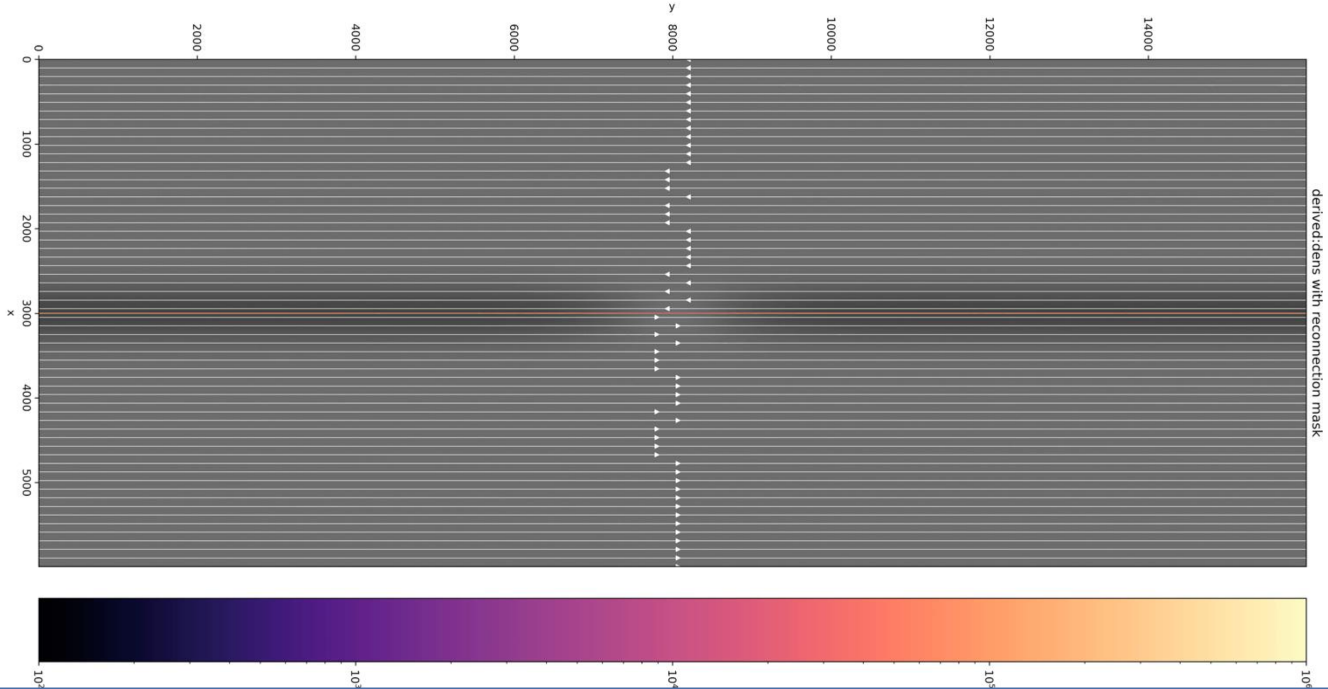
PIC Code: Tristan V2
(Hakobian H., Spitkovsky A.)

Simulation Setup

- 2D, antiparallel Harris Sheet
- Box size = 16000×6000 cells
- Skin depth = 5 cells
- $\sigma = 10$
- Cold plasma: $\frac{k_B T}{m_e c^2} = 0.01$
- Parameters:

$$\mu = \frac{m_i}{m_e}\ , \qquad q = \frac{n_i}{n_{e^-}}$$





Energy Partition

Definitions:

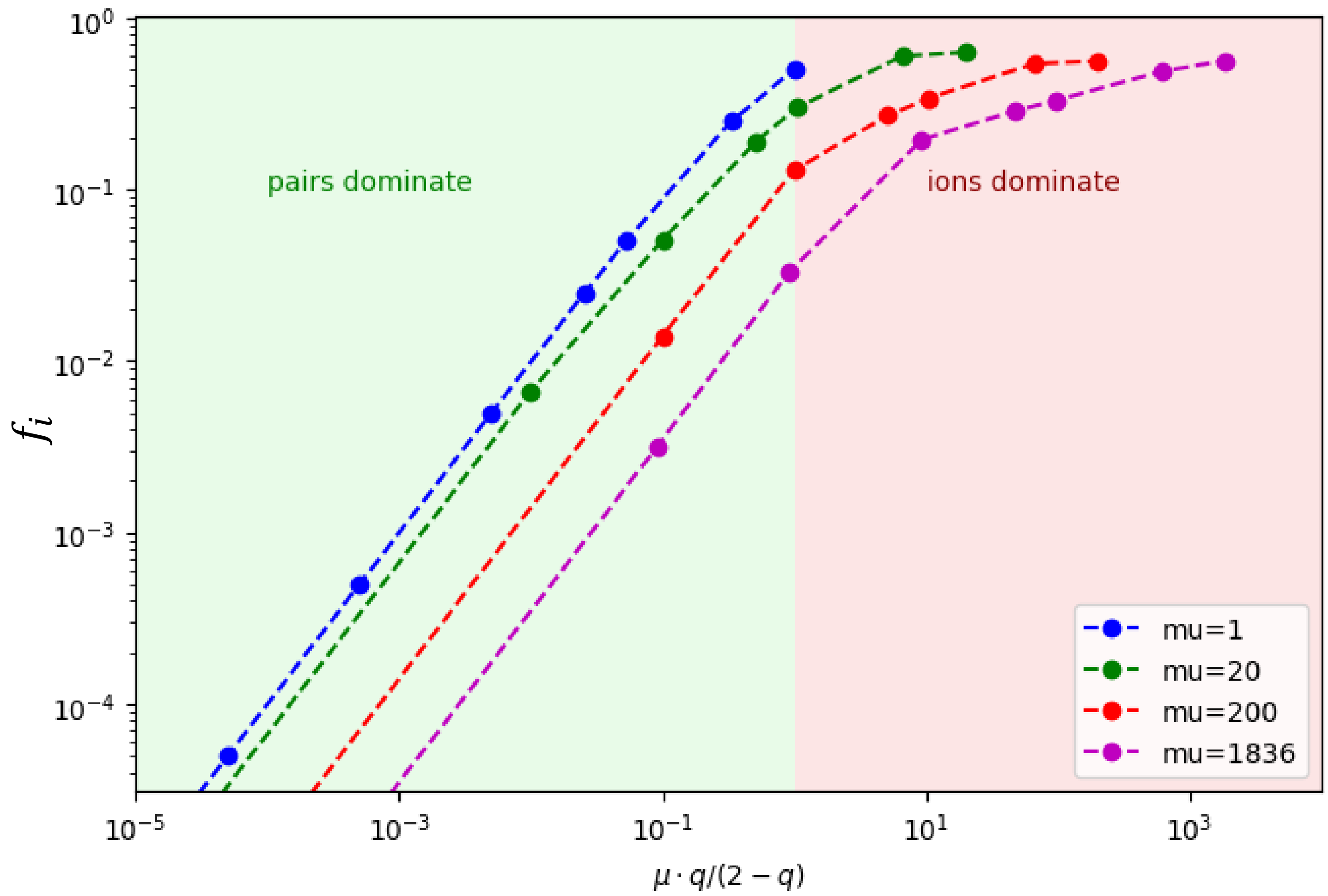
$$\mu = \frac{m_i}{m_e}, \quad q = \frac{n_i}{n_{e^-}}, \quad f_i = \frac{E_i}{E_i + E_{e^\pm}}$$

Key Result:

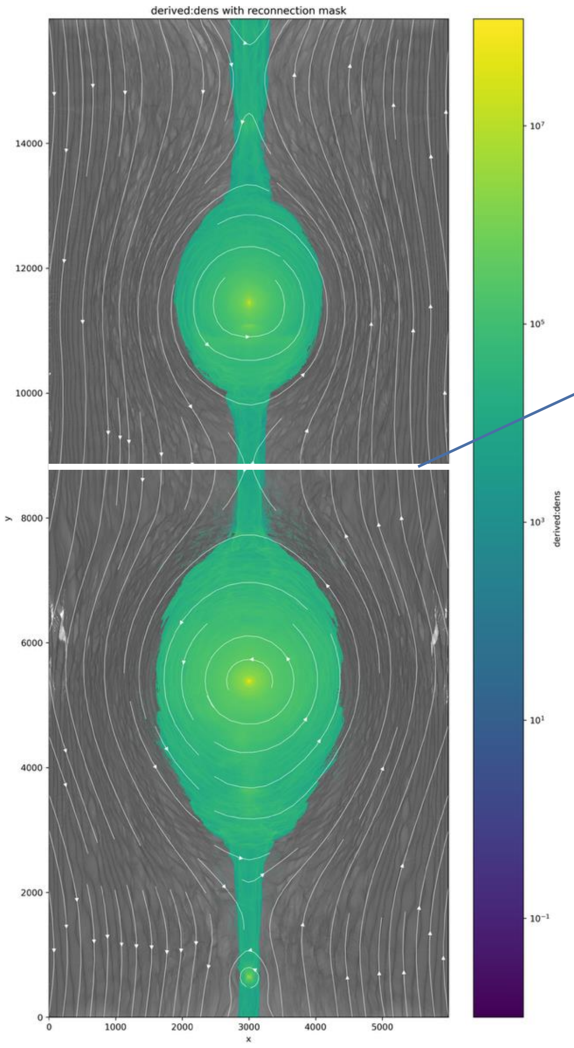
Equipartition between ions and pairs is achieved only when ions dominate the rest mass (right region of the plot).

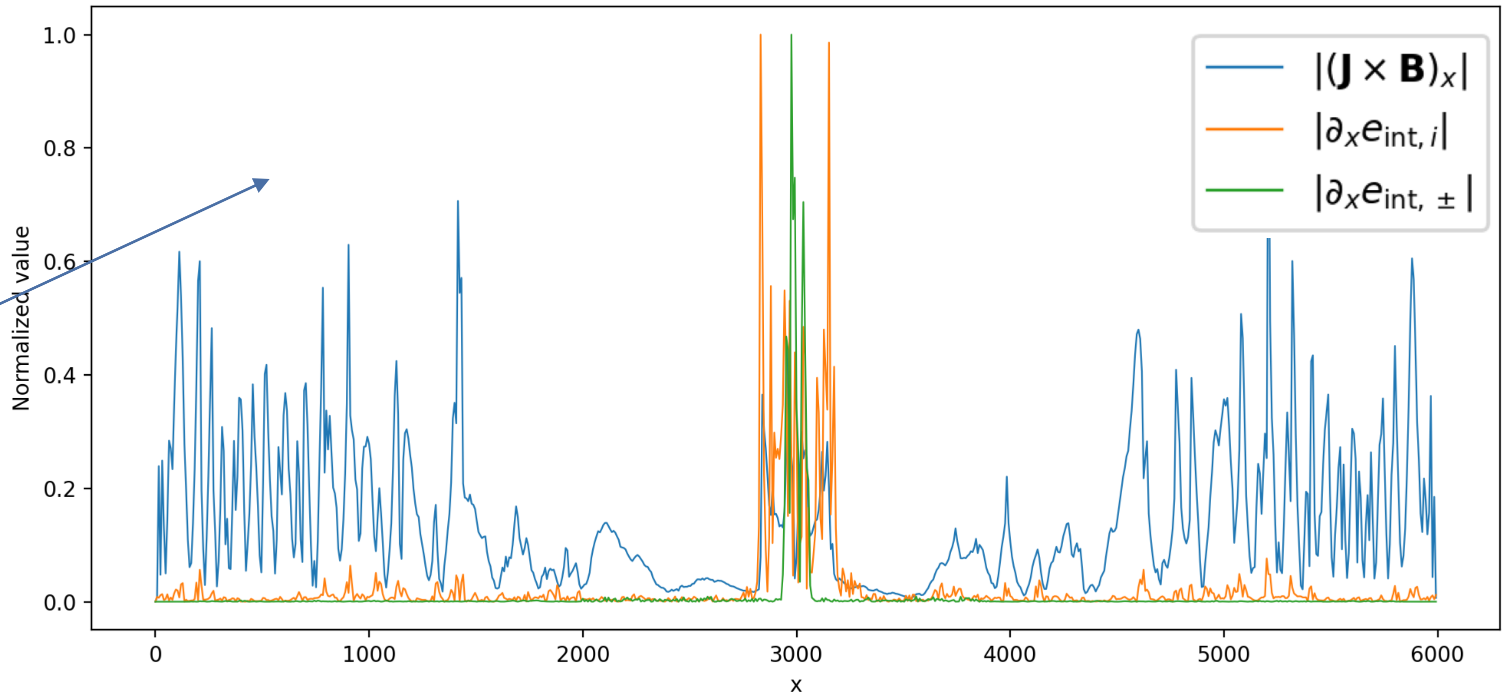
In the pair-dominated regime, ions behave as test particles, and the characteristic ion energy is fixed. Thus, the ion energy fraction scales with the number of ions. The usual scaling breaks down:

$$\langle \gamma_i \rangle \cancel{\propto} \sigma_i = \frac{B^2}{n_i m_i c^2}$$



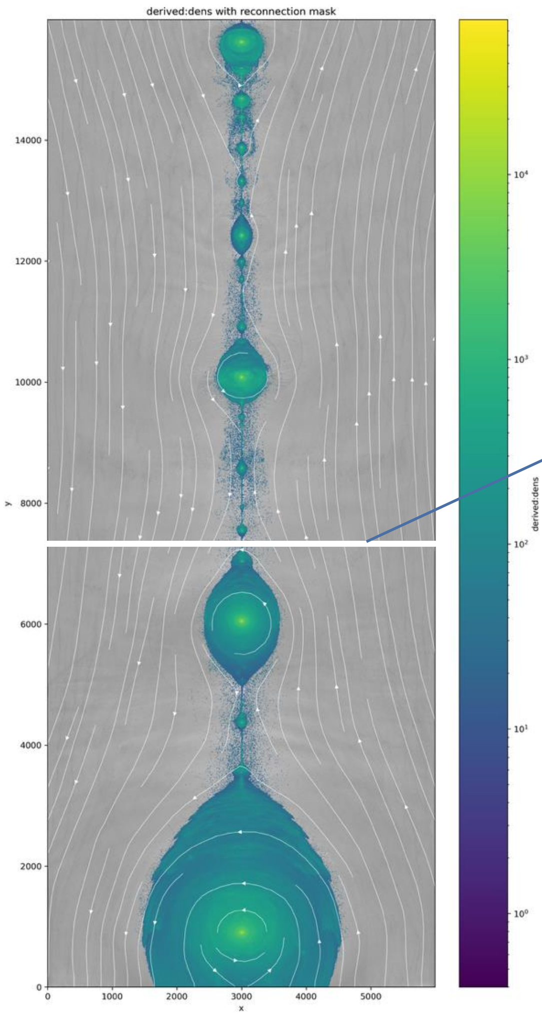
Force Balance: Electron-Ion Plasma

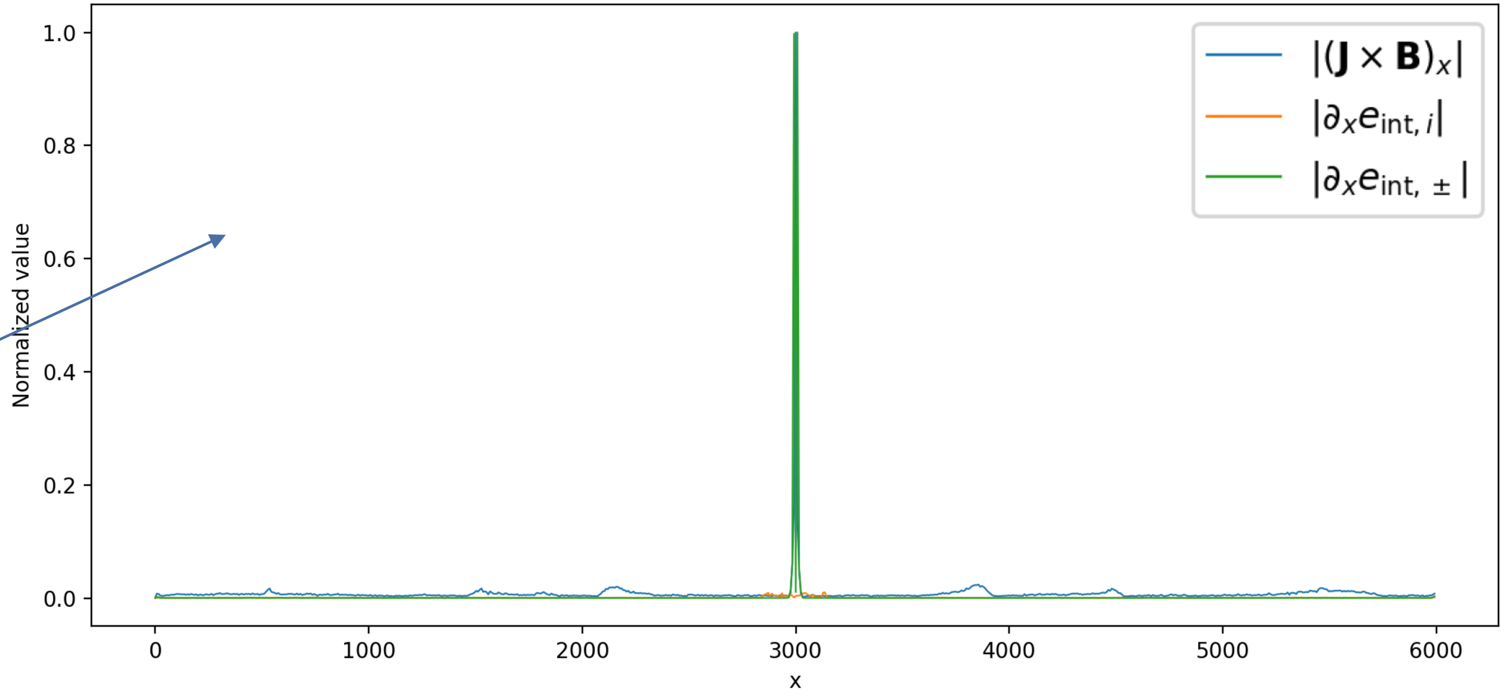




In an electron-ion (q=1) reconnection layer, the ions balance out the magnetic pressure.

Force Balance: Pair-dominated plasma





In pair-dominated reconnection, the ions are no longer dynamically important, and pressure balance is only reached in the electron layer.

Conclusions

- **Relativistic magnetic reconnection** is a prime candidate for **non-thermal particle acceleration** near black holes.
- In these systems (**AGN magnetosphere, microquasar**), the **plasma composition remains uncertain** – pair-dominated or baryon-loaded?
- We perform **kinetic simulations** of reconnection across **varying compositions** to quantify **energy partition** among species.
- **Key result:**
    1. The **equipartition ansatz** (comparable energy in all species) holds **only when ions dominate the inertia**.
    2. When **pairs dominate**, ions behave as **passive test particles**, unable to maintain pressure balance, and each ion gains a fixed amount of energy.

Next Steps:

- Extend the analysis to 3D simulations, explore the effects of a guide field, include radiative cooling.