Turbulence and Magnetic Reconnection in Relativistic Multi-Species Plasmas near Compact Objects

[1]**Mario Imbrogno**, [2]Claudio Meringolo, [3]Alejandro Cruz-Osorio, [2,4,5]Luciano Rezzolla, [6]Benoît Cerutti, [7,8]Francesco Pegoraro, [1]Sergio Servidio

[1]Department of Physics, Università della Calabria, Arcavacata di Rende, 87036, Italy - [2]Institut fur Theoretische Physik, Goethe Universitat, Max-von-Laue-Str. 1, D-60438 Frankfurt am Main, Germany - [3]Instituto de Astronomia, Universidad Nacional Autonoma de Mexico, AP 70-264, 04510 Ciudad de Mexico, Mexico - [4]CERN, Theoretical Physics Department, 1211 Geneva 23, Switzerland - [5]School of Mathematics, Trinity College, Dublin, Ireland - [6]Université Grenoble Alpes, CNRS, IPAG, 38000 Grenoble, France - [7]Department of Physics “Enrico Fermi”, Università di Pisa, Pisa, 56122, Italy - [8]AINAF-IAPS, via Fosso del Cavaliere 100, Roma, 00133, Italy

Corresponding author: mario.imbrogno@unical.it

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Introduction

Astrophysical turbulence characterizes a variety of systems, from the heliosphere to the interstellar medium and compact object environments, spanning a wide range of length- and timescales, from large-scale eddies to sub-electron structures. Although often associated to randomness and unpredictability, turbulence can generate persistent coherent structures that emerge from chaotic backgrounds and travel undisturbed over long timescales. While persistent structures have been extensively studied in classical viscous fluids, much less is known about their collisionless, magnetized counterparts, where such “magnetic vortices” may play a crucial role in particle energization and dissipation. Their internal structure remains poorly understood, primarily due to the complex coupling between macroscopic dynamics and characteristic plasma scales.The study of turbulent relativistic plasmas around compact objects, such as black holes and neutron stars, is key to integrating high-energy astrophysics, particle kinetics, and MHD. These plasmas may consist of multiple particle species, including electrons, protons, and positrons, with relative abundances that depend sensitively on the astrophysical context. While relativistic MHD captures large-scale dynamics, it fails to account for essential kinetic effects such as nonthermal particle distributions and fast magnetic reconnection. For this, PIC simulations offer the most accurate framework to study the dynamics of charged particles in electromagnetic fields. However, most PIC studies are limited to simplified two-species plasma models (electron-proton or electron-positron), neglecting the role of additional charge carriers. Including a third species can significantly influence local charge neutrality, current structures, and reconnection efficiency, yet remains largely unexplored.

Initial setup and parameters

Numerical code: *Zeltron* **[1]**;
Plasma mixture: trans-relativistic electron–proton plasma;
Initial magnetic field: 2D in-plane perturbation via random Fourier modes (from the out-of-plane vector potential);
Global and boundary conditions: periodic boundary conditions, global charge neutrality, strong turbulence regime, thermal equilibrium between species;
Parameters: magnetization & plasma beta consistent with accretion disk conditions **[2]**;
Units adopted: geometric units with $\mathbf{c = G = 1 = k_B = e}$.

$$\langle \delta \mathbf{b}_\perp \rangle / \mathbf{B}_{0,z} \approx 1$$

→ Root mean square of the in-plane magnetic field over the background magnetic field strength

$$\sigma = \frac{\mathbf{B}_{0,z}^2}{4\pi \mathbf{w}} \approx 1, \quad \mathbf{w} = (\rho_e + \rho_i)\mathbf{c}^2 + \Gamma_e \epsilon_e + \Gamma_i \epsilon_i$$

$$\beta_\alpha = \frac{8\pi n_\alpha k_B T_\alpha}{\mathbf{B}_{0,z}^2} \approx 3 \times 10^{-3}$$

$$\theta_\alpha = \frac{k_B T_\alpha}{m_\alpha c^2}$$

Rest-mass density; Enthalpy density; Internal energy density; Number density; Adiabatic index; → Adimensional temperature

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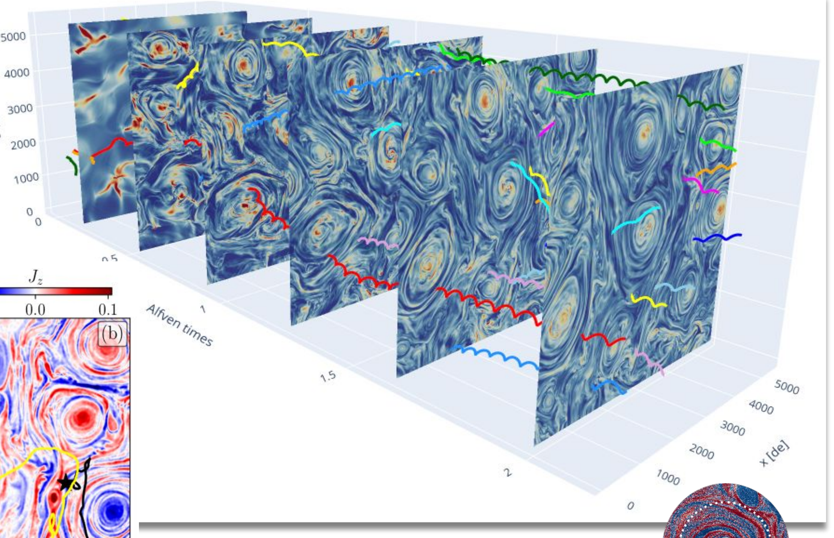
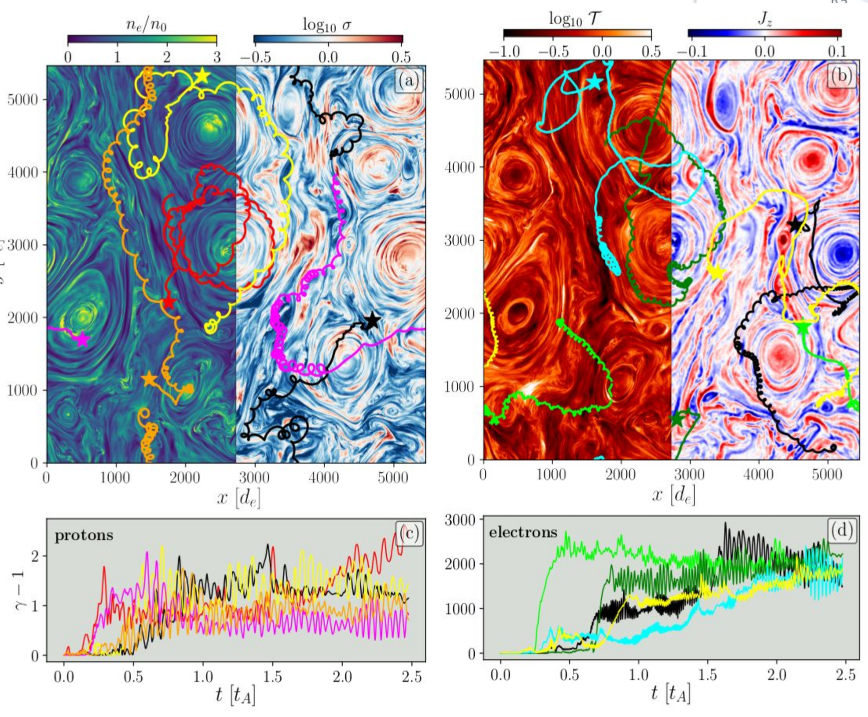
Turbulence-Driven Particle Acceleration

Coherent structures emerge from the turbulent landscape and interact,forming current layers where **magnetic energy is converted into particle kinetic energy**.



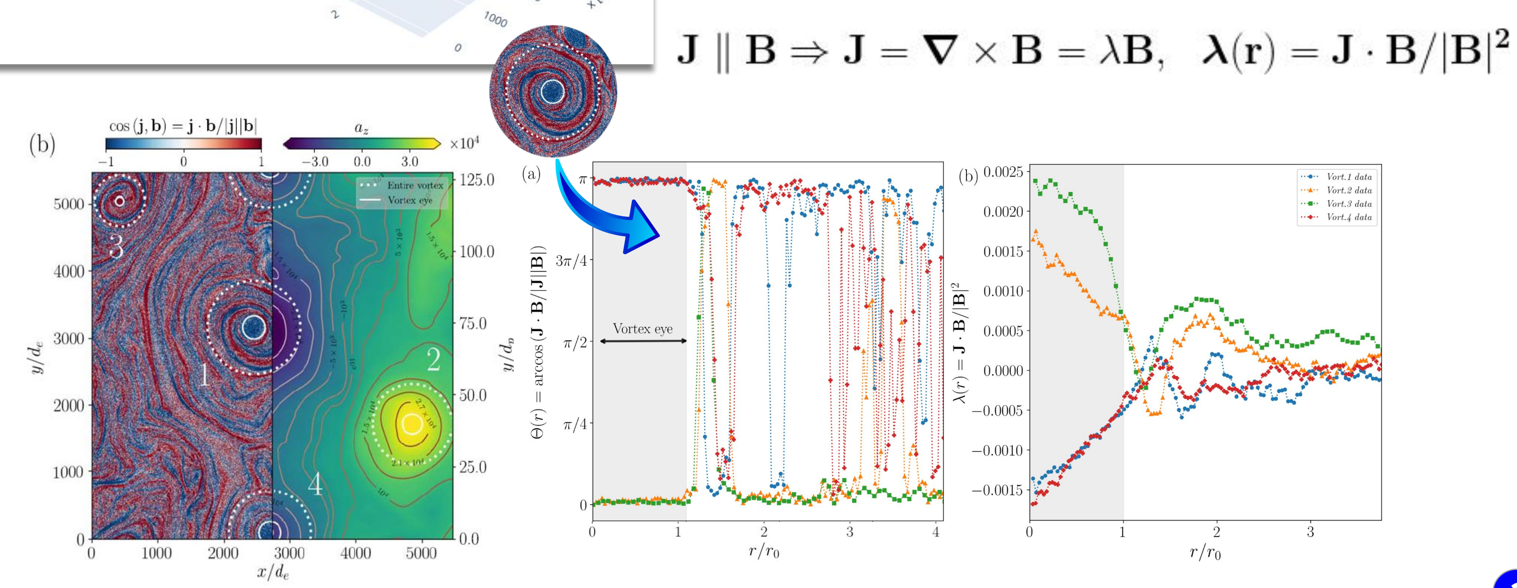


Electrons experiences huge accelerations **[3]**.

Within vortex cores, the current strongly aligns with the magnetic field, indicating a **tendency toward force-free states**.

Unlike classic constant-λ force-free states **[4]**, we observe a **strong radial dependence of λ(r)**, suggesting a more complex relaxation process.

$$\mathbf{J} \parallel \mathbf{B} \Rightarrow \mathbf{J} = \nabla \times \mathbf{B} = \lambda \mathbf{B}, \quad \lambda(\mathbf{r}) = \mathbf{J} \cdot \mathbf{B} / |\mathbf{B}|^2$$



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The Kinetic Vortex Reconstruction (KVR) model

Starting from the Vlasov equation, we assume a **stationary equilibrium in cylindrical coordinates**.
Inspired by the **Harris approach [5]**, the distribution function depends exponentially on energy ε_α and canonical momenta $P_{i,\alpha}$, with v_α^* and Ω_α^* as free parameters.

$$f_\alpha(\mathbf{x},\mathbf{v}) = f_{\alpha,0} \exp\left[-\frac{\varepsilon_\alpha - v_\alpha^* P_{z,\alpha} - \Omega_\alpha^* P_{\phi,\alpha}}{k_B T_\alpha}\right] \Rightarrow N_\alpha(r) = \int f_\alpha d^3 v = \exp[\gamma_\alpha(r)] =$$

$$= \exp\left[C_\alpha + \frac{q_\alpha}{c k_B T_\alpha}\left(v_\alpha^* A_z(r) + r\Omega_\alpha^* A_\phi(r) - c\psi(r)\right) + \frac{m_\alpha}{2 k_B T_\alpha}\left(r^2 \Omega_\alpha^{*2} + v_\alpha^{*2}\right)\right]$$

Central logarithmic density; Potential vector; Electrostatic potential

Maxwell's equations + Moment equations = KVR model:

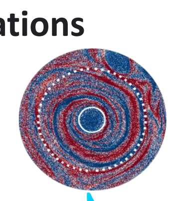
$$\frac{d A_z(r)}{dr} = -B_\phi(r)$$

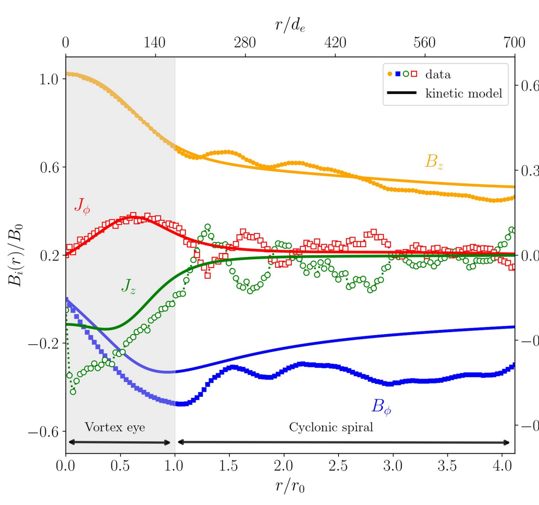
$$\frac{d A_\phi(r)}{dr} = -\frac{A_\phi(r)}{r} + B_z(r)$$

$$\frac{d B_z'(r)}{dr} = \frac{4\pi e}{c}(\Omega_e^* - \Omega_i^*) r\, e^{\gamma_e(r)} + \Omega_i^* \kappa r$$

$$\frac{d B_\phi(r)}{dr} = -\frac{B_\phi(r)}{r} + \frac{4\pi e}{c}(v_i^* - v_e^*)\, e^{\gamma_e(r)} - v_i^* \kappa$$

Fluctuations only; Charge separation





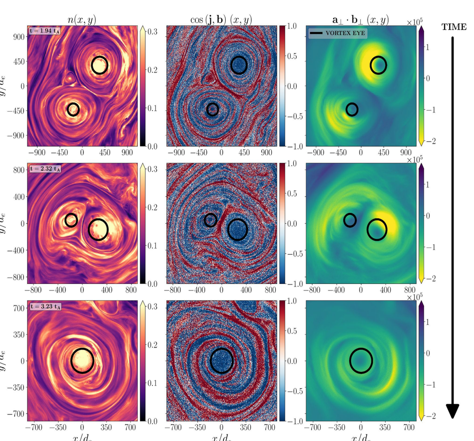
Based on data profiles, we impose negligible net charge density:
$v_p^* = -(T_p / T_e)\, v_e^*$ (Harris)
$\Omega_p^* = -(T_p / T_e)\, \Omega_e^*$ (NEW)
Vortex parameters v_e^* and Ω_e^* are set via a data-driven Monte Carlo method.

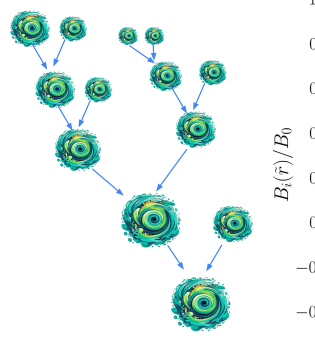
Magnetic islands are primarily governed by **magnetic forces**:

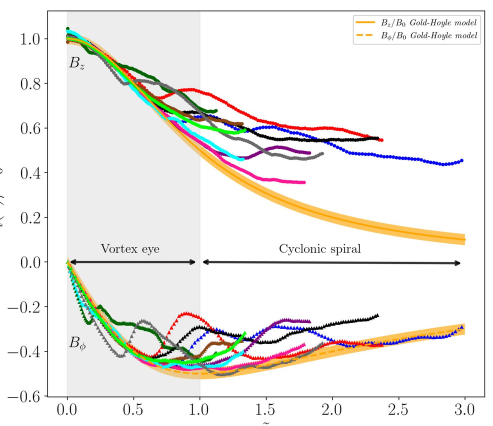
$$\mathbf{KVR} \Rightarrow \nabla \times \mathbf{B} \sim f(r)\, \mathbf{J}_0^*(r) \sim \lambda(r) \mathbf{B}(r), \quad \mathbf{J}_0^* = q_e[0, (\Omega_p^* - \Omega_e^*) r, (v_p^* - v_e^*)]$$

Among the solutions, the “**Gold–Hoyle equilibrium**” **[6,7]** stands out.
Strong magnetic reconnection occurs between merging islands.
Spiraling arms encode the interaction history, while **magnetic helicity in the vortex core** can be reliably estimated as:

$$\mathbf{H_m} = \mathbf{V}^{-1} \int_V \mathbf{A}_\perp \cdot \mathbf{B}_\perp d^3 x = 10^{-1} \mathbf{B}_0^2 \mathbf{r}_0$$







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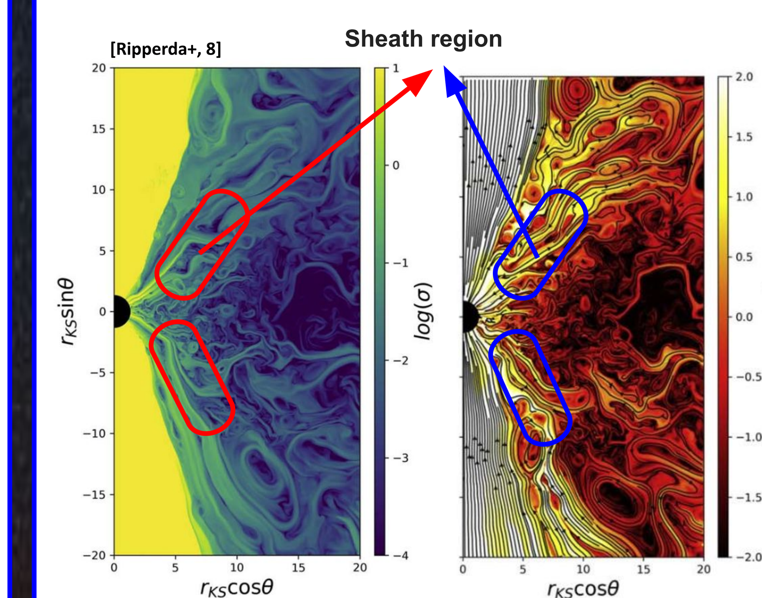
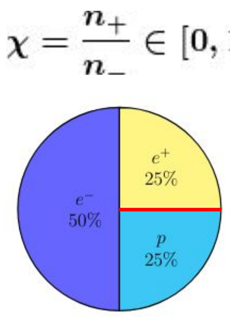
A Multi-Species Plasma

Electrons, protons, and positrons coexist in many astrophysical environments, as in black hole sheaths.
Using GRMHD data **[8]**, we fix magnetization, total plasma beta, and enforce global charge neutrality.



Positron-to-electron concentration ratio:

$$\chi = \frac{n_+}{n_-} \in [0, 1]$$



Global plasma parameters: $\sigma \approx 1$, $\beta_{tot} \approx 0.1, 0.2$

Debye length

Run	χ	β_+	β_p	θ_e	θ_p	B_0	$PP\lambda_{D,-}^2$	$\lambda_{D,-}/\Delta x$	$\lambda_{D_+}/\Delta x$
I	0.1	1×10^{-2}	9×10^{-2}	137.79	7.50×10^{-2}	52.50	6195	8.80	27.84
II	0.5	5×10^{-2}	5×10^{-2}	76.63	4.17×10^{-2}	39.15	3453	6.57	9.28
III	0.9	9×10^{-2}	1×10^{-2}	15.46	8.42×10^{-3}	17.58	696	2.95	3.11

4

Magnetic Reconnection in Multi-Species Plasmas

As χ → 1, a **larger number of plasmoids appear between the main structures**. The dissipation range in the electric and magnetic spectra shifts to smaller scales.
In quasi-pair plasmas, reduced effective mass ($m_p \gg m_e$) yields smaller gyroradii and enhances small-scale energy transfer.
From the relativistic generalization of Vlasov equation, we derive a **generalized Ohm’s law for a three-species plasma**:

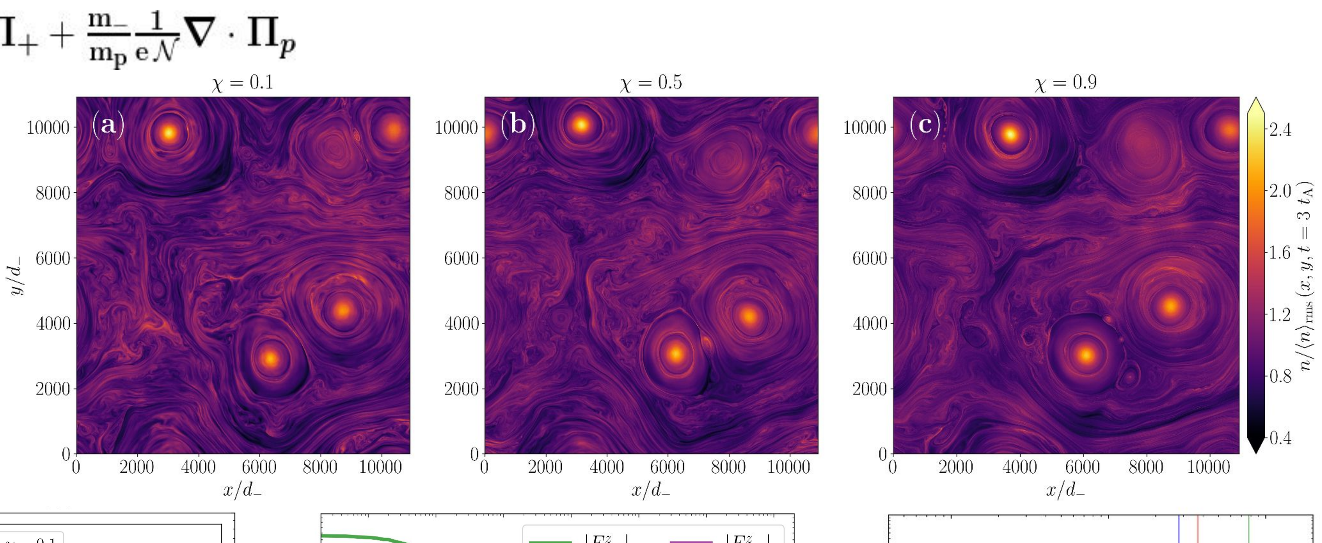
$$\mathbf{E} = \frac{m_-}{e^2 \mathcal{N}} \partial_t \mathcal{J} - \frac{1}{\mathcal{N}}(n_+ \mathbf{V}_+ + n_- \mathbf{V}_-) \times \mathbf{B} - \frac{1}{\mathcal{N}} n_p \mathbf{V}_p \times \mathbf{B} - \frac{1}{e\mathcal{N}} \nabla \cdot \Pi_- + \frac{1}{e\mathcal{N}} \nabla \cdot \Pi_+ + \frac{m_-}{m_p} \frac{1}{e\mathcal{N}} \nabla \cdot \Pi_p$$

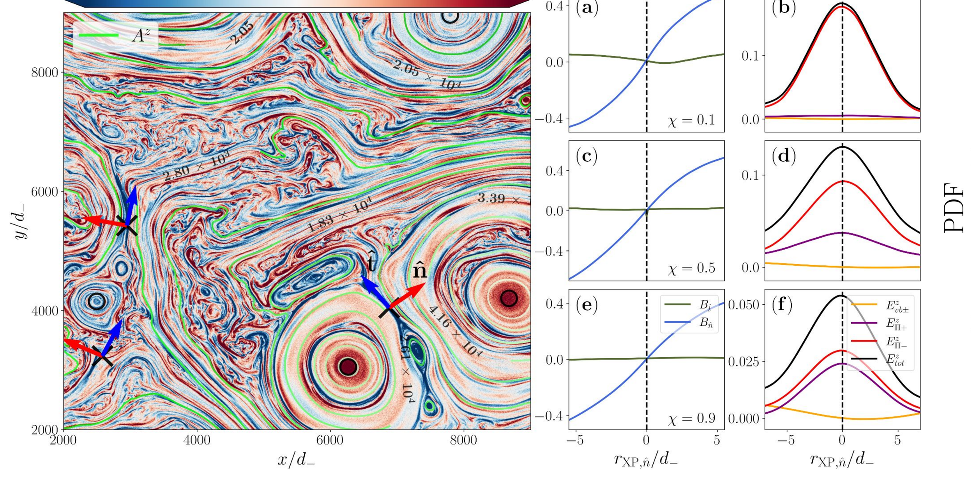
$$= \mathbf{E}_{\partial_t} + \mathbf{E}_{vb\pm} + \mathbf{E}_{vbp} + \mathbf{E}_{\Pi-} + \mathbf{E}_{\Pi+} + \mathbf{E}_{\Pi p}$$

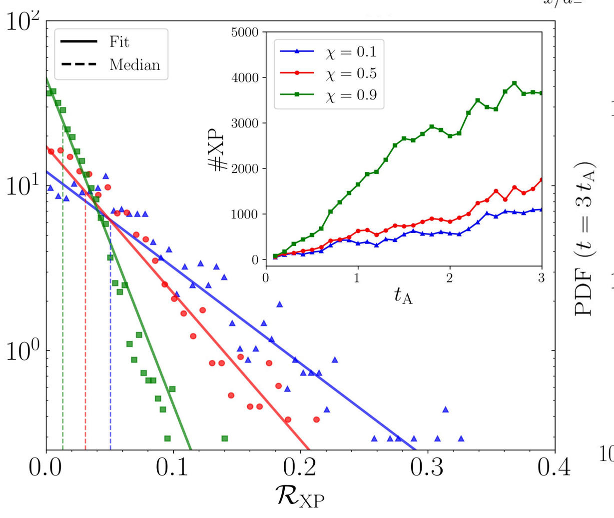
$$\Pi_\alpha = P_\alpha + m_\alpha n_\alpha V_\alpha U_\alpha = \int d^3 u\, m_\alpha \frac{\mathbf{uu}}{\gamma} f_\alpha$$ → Total relativistic kinetic pressure

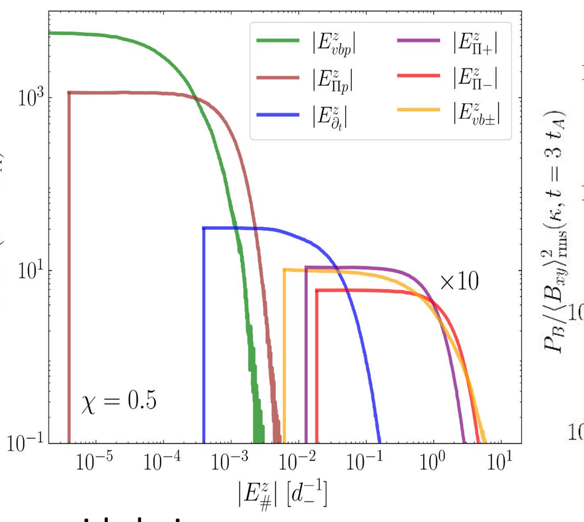
$$\mathcal{N} = n_p m_- / m_p + n_+ + n_-$$ → Total weighted number density

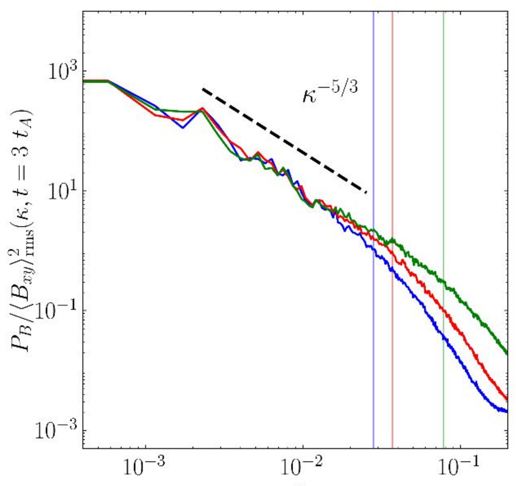
We define the **reconnection ratio** as $\mathcal{R}_{XP} = \mathbf{E_z}(\text{X-point}) / \langle \mathbf{B}_\perp \rangle_{rms}$
For χ → 0, the electron pressure gradient dominates.
For χ → 1, electron and positron pressure gradients become comparable.











As χ → 1, reconnection sites become more numerous over time, though typically weaker, forming plasmoid chains.

5

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