Plasmoids and Particle Acceleration in Relativistic Turbulent Systems

Luca Comisso and Lorenzo Sironi

Department of Astronomy, Columbia University
and
Columbia Astrophysics Laboratory, Columbia University

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Outline

- Is plasma turbulence an efficient source of non-thermal particles?
- What are the requirements to produce non-thermal particles with power-law energy distribution?
- How do the power-law characteristics depend on the system parameters?
- What are the mechanisms that produce the accelerated particles?

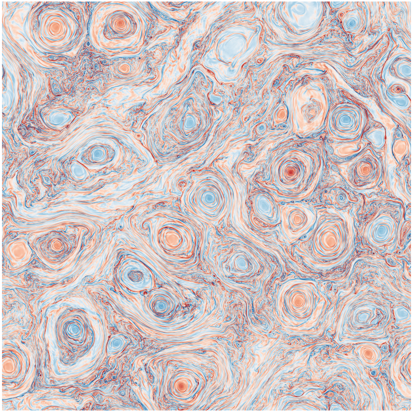
Tools and basic setup

- PIC Method using TRISTAN-MP code (Spitkovsky 2005)
- Numerical simulations of decaying turbulence
- 2D and 3D simulations initialized with uncorrelated magnetic field fluctuations in Fourier harmonics with random phases
- We consider an electron-positron plasma and uniform magnetic guide field B_0
- Simulations in the regime

$$\sigma = \frac{\delta B_{\rm rms}^2}{4\pi w} \gg 1, \qquad \theta = \frac{k_B T_e}{m_e c^2} \sim 1, \qquad \frac{1}{16} \le \frac{\delta B_{\rm rms}^2}{B_0^2} \le 1$$

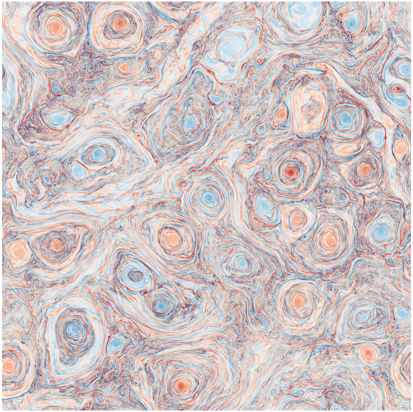
with $w = n m_e c^2 + [\Gamma/(\Gamma-1)]\, p$

Fully-developed turbulence state



2D contour plots of the current density j_z

Fully-developed turbulence state



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Numerical results seems to be consistent with an earlier model of turbulence

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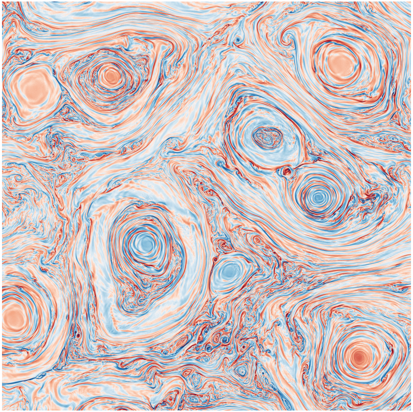

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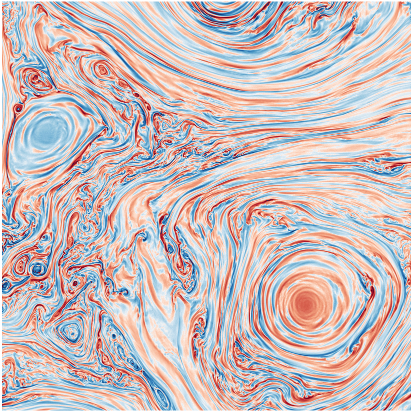

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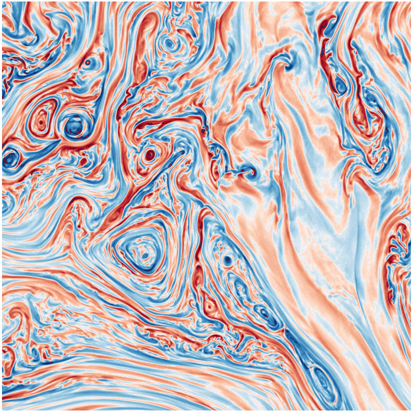

2D contour plots of the current density j_z

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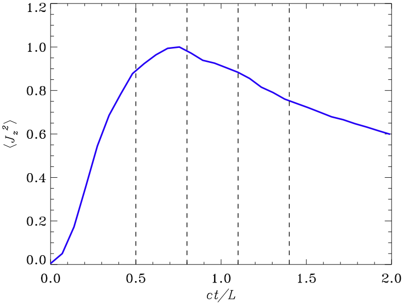
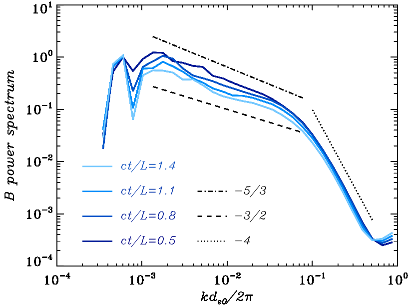
Fully-developed turbulence state

$2D : 3280 d_e \times 3280 d_e \, , \quad \sigma = 10$

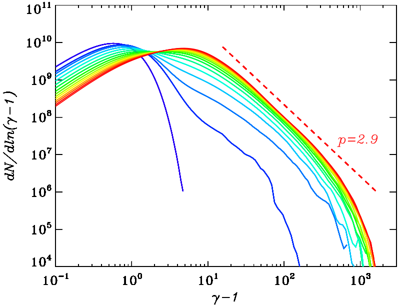


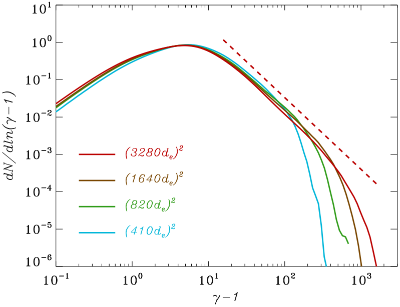


- Maximum turbulence activity identified by the peak of the mean squared current density $\langle j_z^2 \rangle (t)$
- Power spectrum similar to the non-relativistic regime (details not addressed in this talk)

Production of non-thermal particles

$$2D : 3280 d_e \times 3280 d_e \,, \quad \sigma = 10 \,, \quad \delta B_{\rm rms}^2 / B_0^2 = 1$$

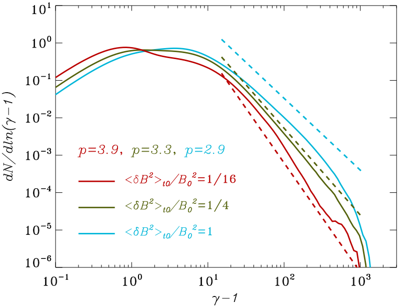


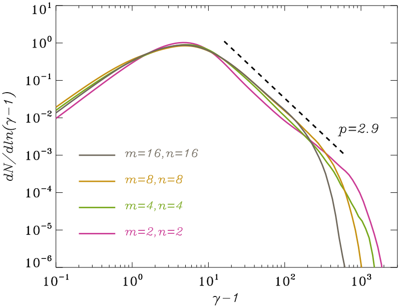


- The spectrum at late times resembles a power law
- The slope of the power law does not change for increasing system sizes
- The high energy cutoff increases with the system size

Production of non-thermal particles

$2D : 3280 d_e \times 3280 d_e \,, \quad \sigma = 10$

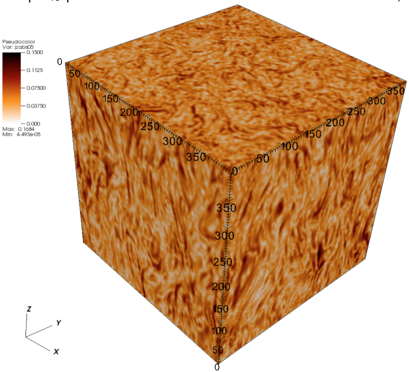


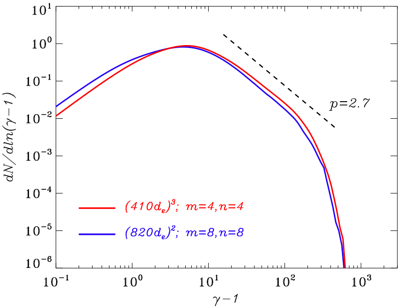


- The slope of the power-law depends on the fluctuations level
- Different magnetic field initial harmonics produce consistent results

Particle spectrum in 3D

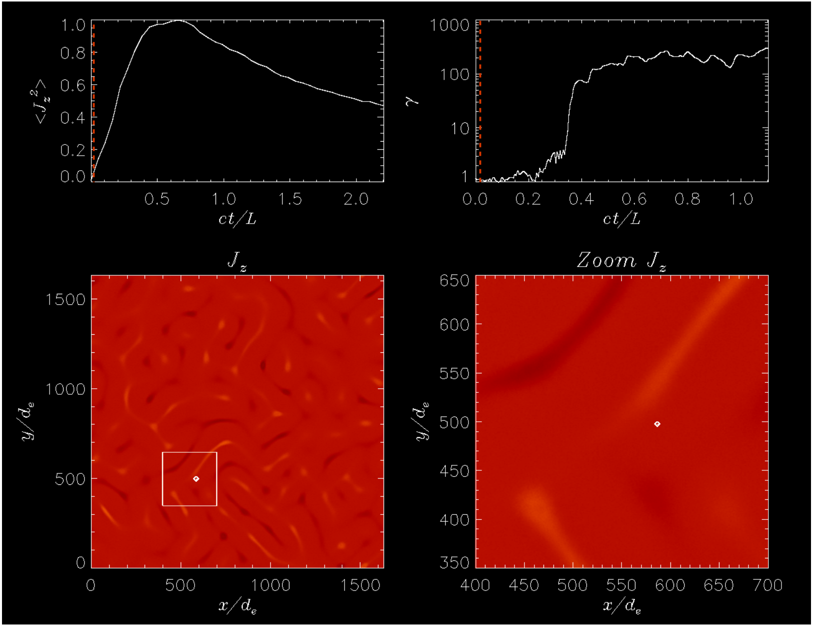
$|\mathbf{J}_z|$ $\qquad$ $\sigma = 10\,, \quad \delta B_{\rm rms}^2/B_0^2 = 1$





- The particle spectrum in 3D is essentially similar to 2D
- Slightly harder power-law in 3D

How particles are accelerated?



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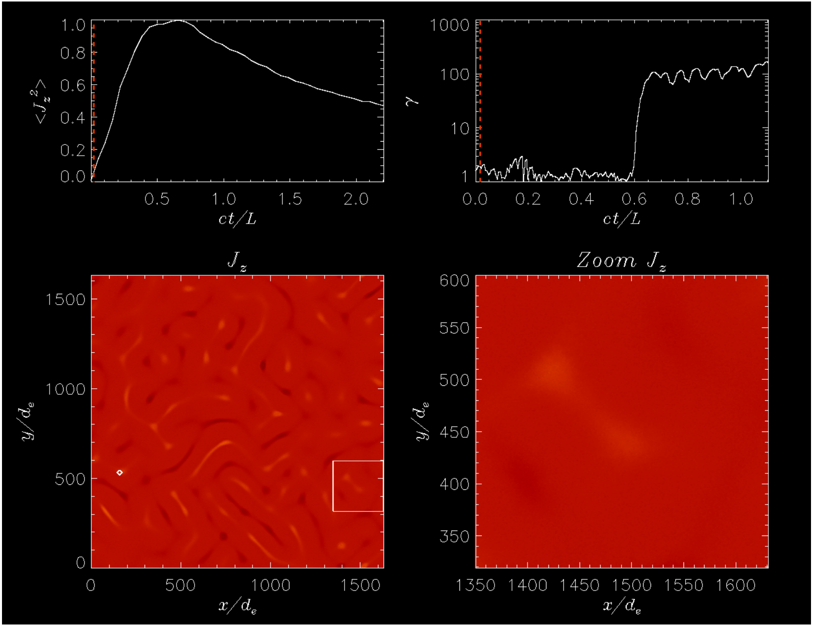
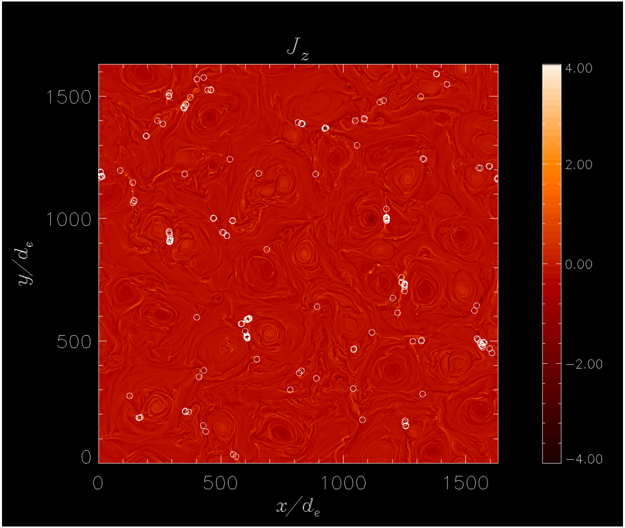


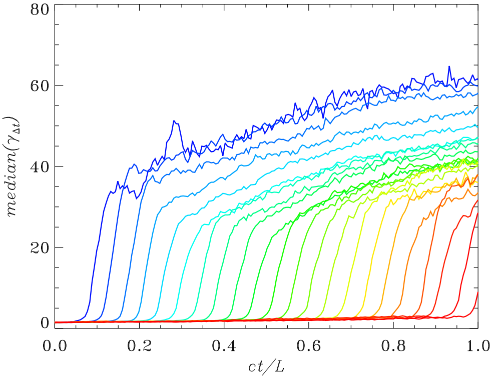
Where does particle injection occurs?

$$\frac{\Delta\gamma}{\Delta t} > C \frac{q}{m_e c} E_{rec} \quad \text{and} \quad \gamma_i < \gamma_{thr_i} \quad \text{and} \quad \gamma_f > \gamma_{thr_f}$$



Further acceleration

- Particles are grouped in slices of Δt depending on their injection time



- Particles are first accelerated in reconnecting current sheets, then they are accelerated by scattering with turbulent fluctuations

Summary

- Large fluctuations and magnetization are required to produce power-law energy distributions

- The power-law slope doesn't change for increasing system size
- The high-energy cutoff increases steadily with the system size
- First particle acceleration at current sheets
- Second particle acceleration by scattering with turbulent fluctuations

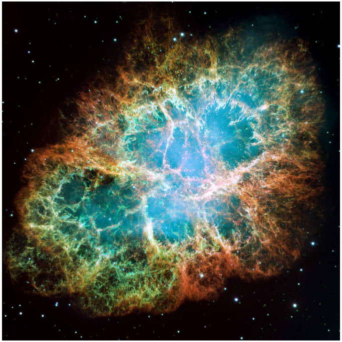
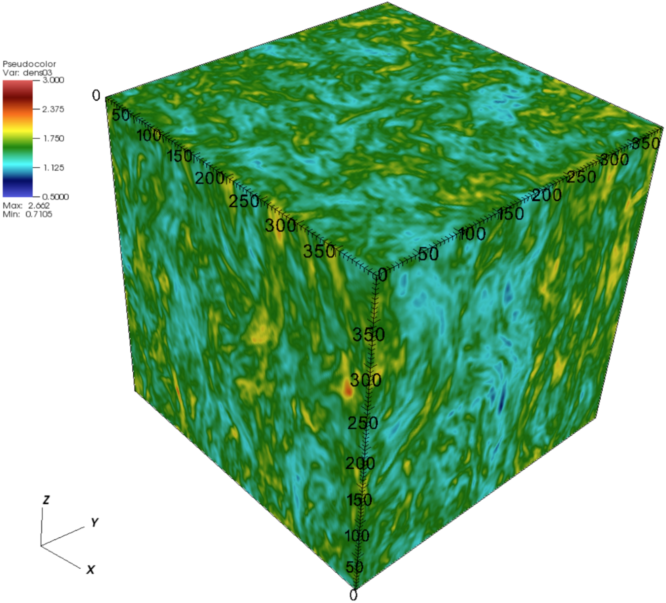


Image Credit: NASA, ESA, J. Hester, A. Loll (ASU)

Appendix 1: particle density



Appendix 2: slices of $|\mathbf{J}_z|$