Magnetically-dominated plasma turbulence in the rapid synchrotron-cooling regime

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Abstract

Many high-energy astrophysical phenomena — such as gamma-ray bursts, black hole accretion flows, neutron-star merger precursors, and magnetar flares — can be powered by magnetically-dominated ($\sigma \gg 1$) plasma turbulence. Importantly, when the magnetic field strength is very high, the systems have an extremely short synchrotron cooling time that is comparable to plasma timescales. We study such ultra-efficient synchrotron-cooling plasma turbulence with advanced 2D and 3D particle-in-cell and ring-in-cell simulations.

Setup

A typically assumed isotropic synchrotron cooling time in a strong field can be very short

$$t_{\rm syn} \sim \frac{\gamma m_e c^2}{P_{\rm syn}} \sim \frac{m_e^3 c^5}{q^4 \gamma} B^{-2} \approx \frac{B_{15}^{-1}}{\gamma^2 \omega_B}. \quad (1)$$

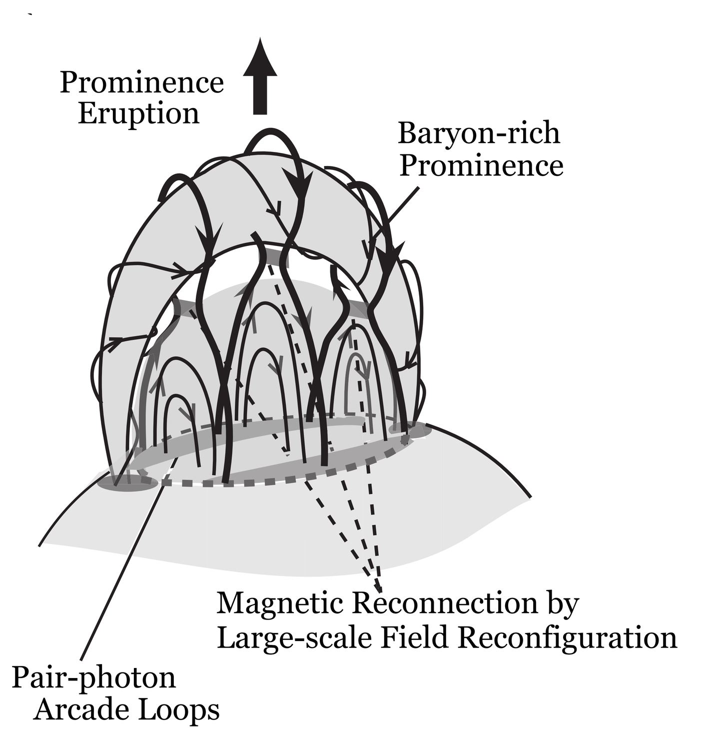

Figure 1. Magnetic Reconnection Model for a magnetar flare, example from Masada (2009). A possible environment for highly magnetized rapid synchrotron-cooling might be a nascent giant magnetar flare.

Naively, this is expected to prevent the formation of turbulent flow and non-thermal particle acceleration.

We test this assumption with numerical plasma simulations. We study highly magnetized plasmas with

$$\sigma \equiv \frac{U_B}{U_\pm} = \left(\frac{\omega_B}{\omega_p}\right)^2 = \frac{\delta B^2}{4\pi n_\pm m_e c^2} \gg 1 \quad (2)$$

In our simulations $\sigma_0 = 10$. We excite strong turbulence $\delta B \sim B_{\rm g}$ that decays.

In our numerical simulations of relativistic plasma turbulence, we use a ring-in-cell approach, but each time step we declare the magnetic moment $\mu = \frac{mu^2}{2B}$ of a particle to be zero, virtually nullifying the gyration radius of the particle. In this limit, only $E \times B$-drift plays a role in the particle pusher.

Non-thermal particle acceleration

The turbulent plasma in this regime is also able to accelerate non-thermal particles.

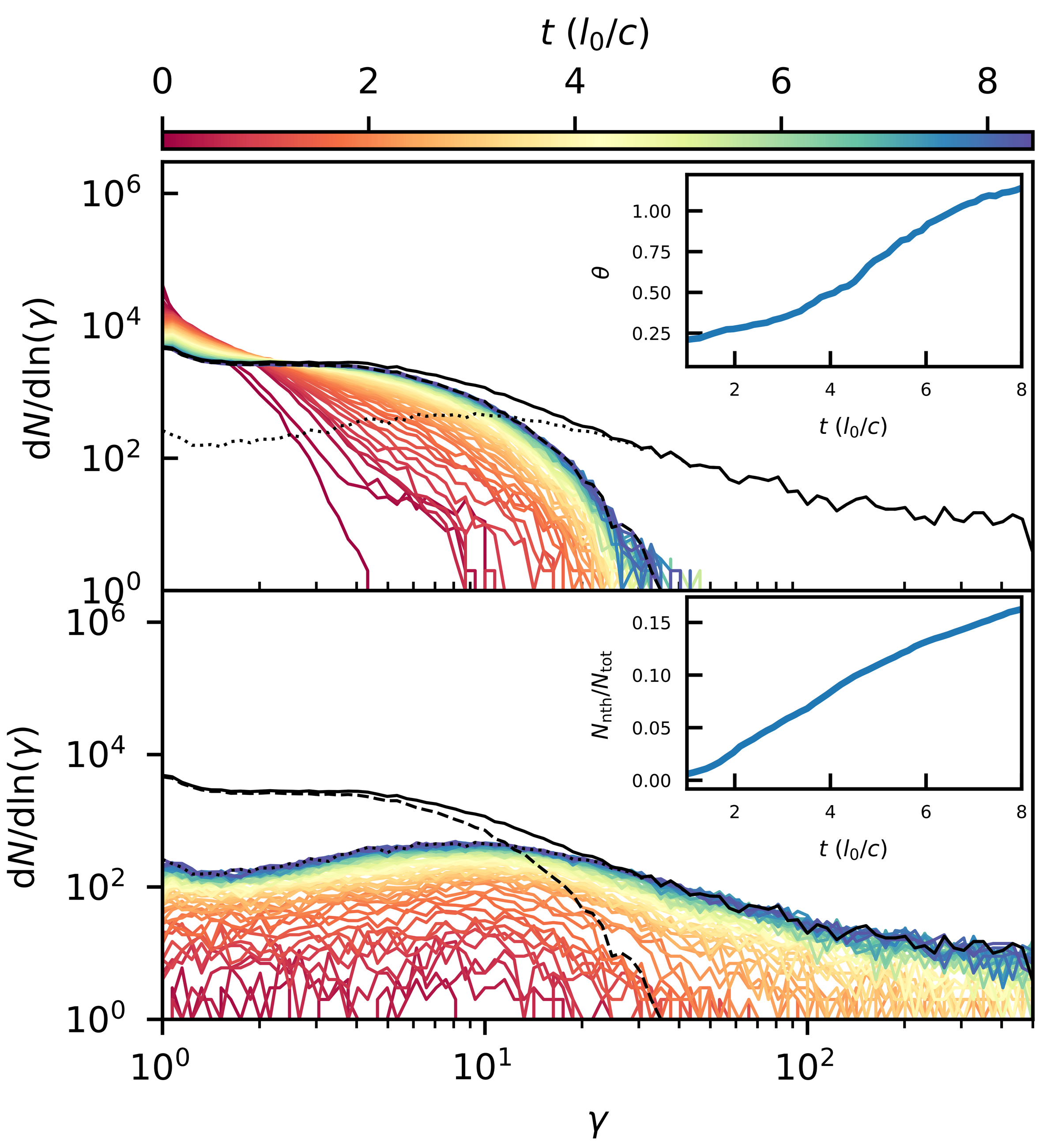

Figure 2. The evolution of particle distribution in magnetized plasma turbulence with numerical synchrotron cooling. Color represents evolution time scaled light-crossing times according to the colormap. Both panels represent the same one simulation, but we distinguish the particles into two populations: thermal (top panel) and non-thermal (bottom panel). The top mini-panel shows the temperature evolution of the thermal particles, while the bottom mini-panel represents the rise of the fraction of non-thermal particles.

Results and discussion

- We find that turbulence can persist even as synchrotron cooling time approaches zero.
- The turbulence in this radiation regime is still able to sustain non-thermal particle acceleration.

However, in this simulations particles can get trapped in a current sheet for an indefinitely long time accelerating to unusually high Lorentz factors ($> 3\sigma$). These simulations also neglect the processes (photons, pair creation) which in reality would prevent particles from unbound acceleration. This contributes to our understanding of plasma dynamics in extreme environments like those around binary neutron stars and magnetars.

Turbulence in rapid synchrotron-cooling regime

We run 2D plasma simulation in this regime with `runko` (Nättilä 2022). We observe the turbulence developing over light-crossing times.

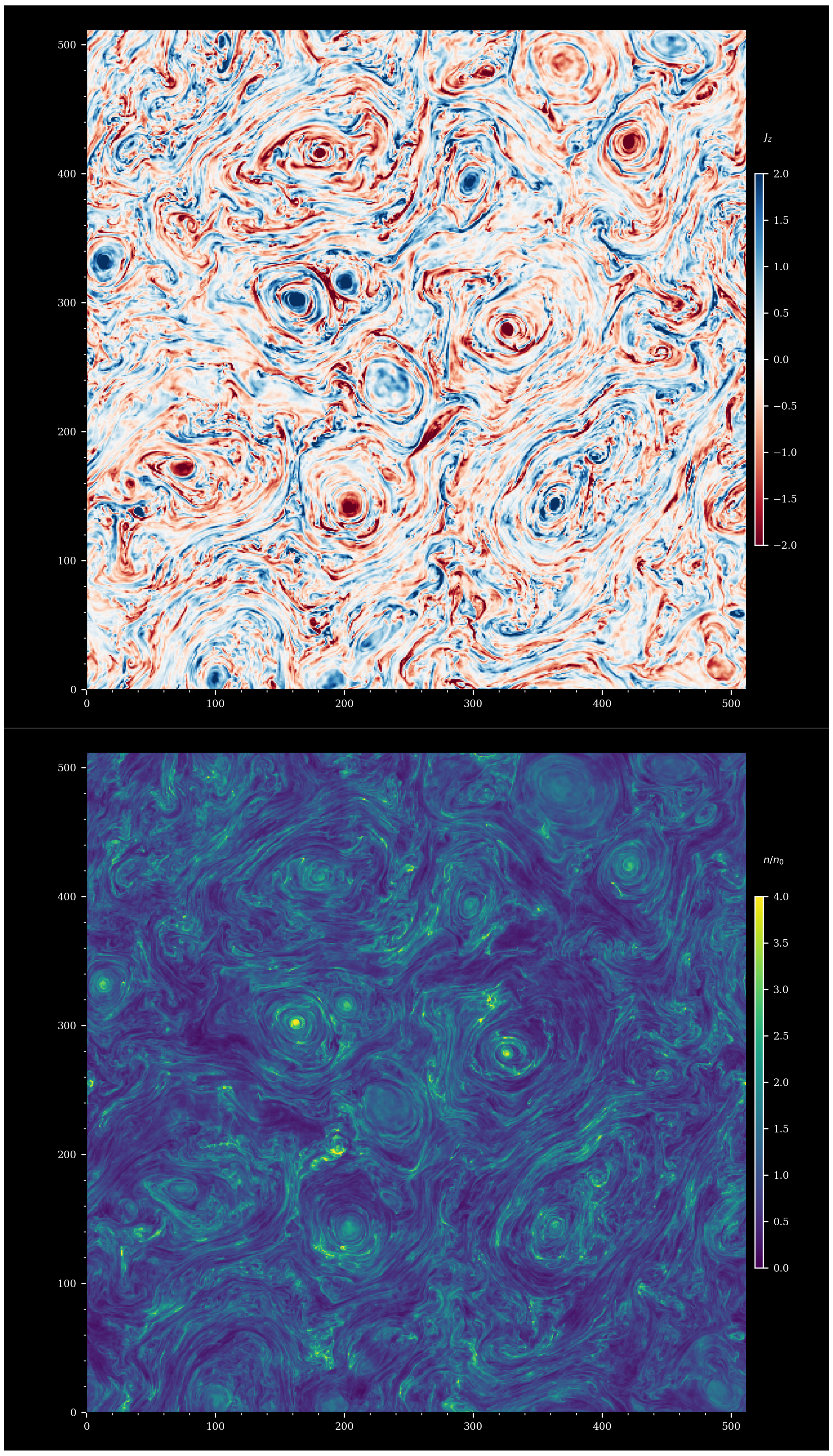

Figure 3. Simulation snapshot at about 7 light-crossing times. Current density (top) and number density (bottom), normalized to total number density. One unit in scale corresponds to the plasma skin depth ($c/\omega_{\rm p}$).