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

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

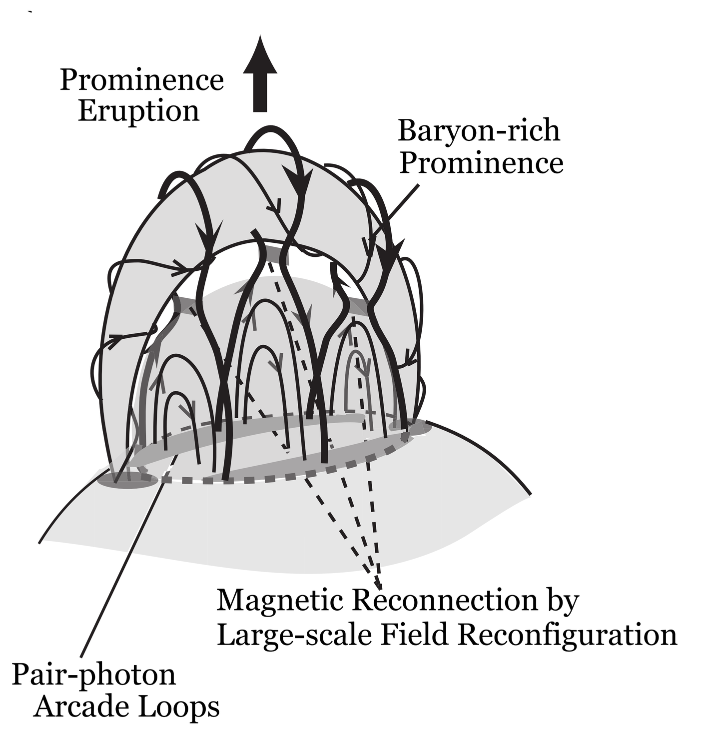

Figure 1. Magnetic Reconnection Model for a magnetar flare, example from Masada (2009). A possible environment for highly magnetized rapid synchrotron-cooling might be a nascent giant magnetar flare.

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, 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.

Non-thermal particle acceleration

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

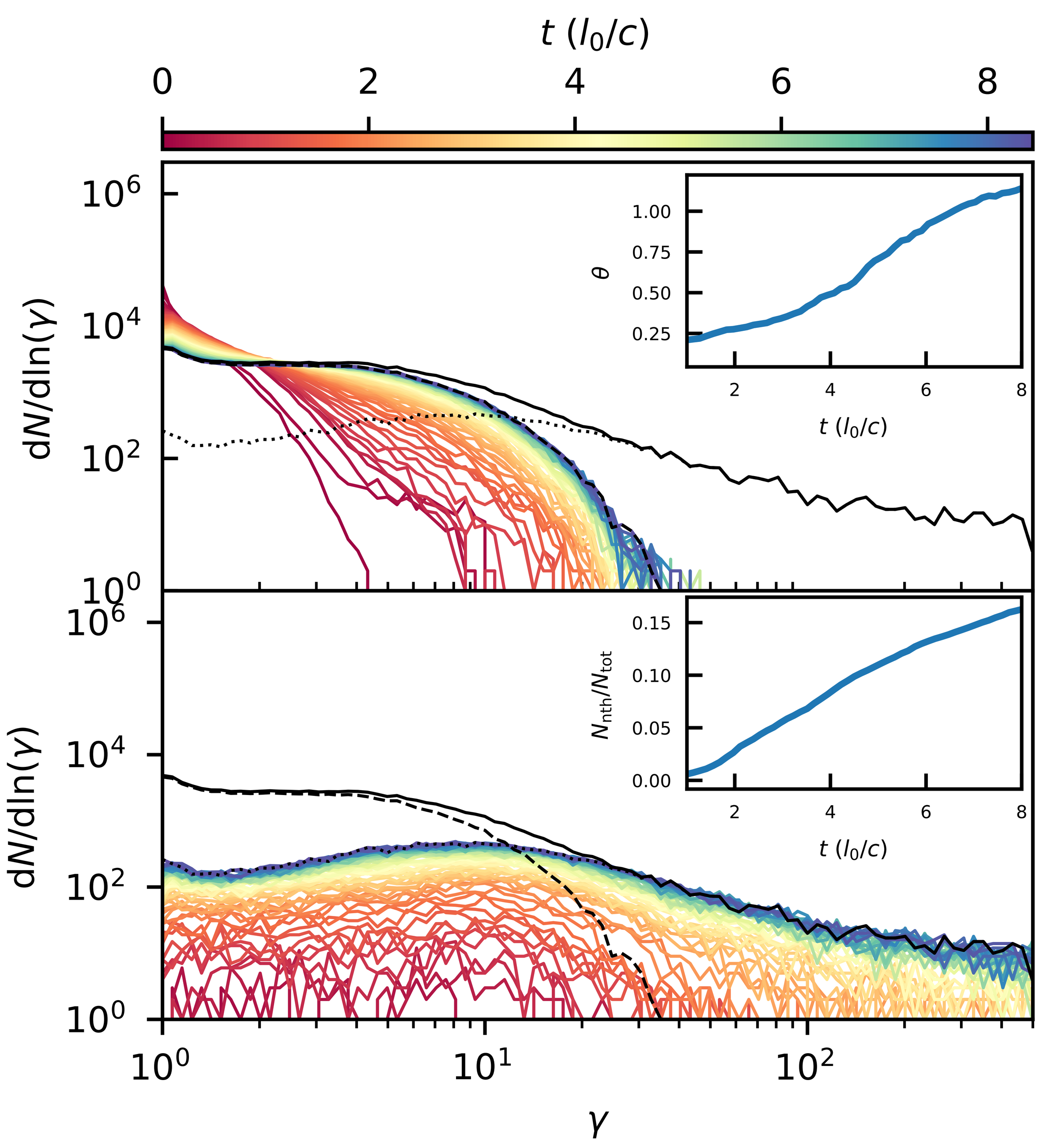

Figure 2. The evolution of particle distribution in magnetized plasma turbulence with numerical synchrotron cooling. Color represents evolution time scaled light-crossing times according to the colormap. Both panels represent the same one simulation, but we distinguish the particles into two populations: 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.

These discoveries contribute 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.

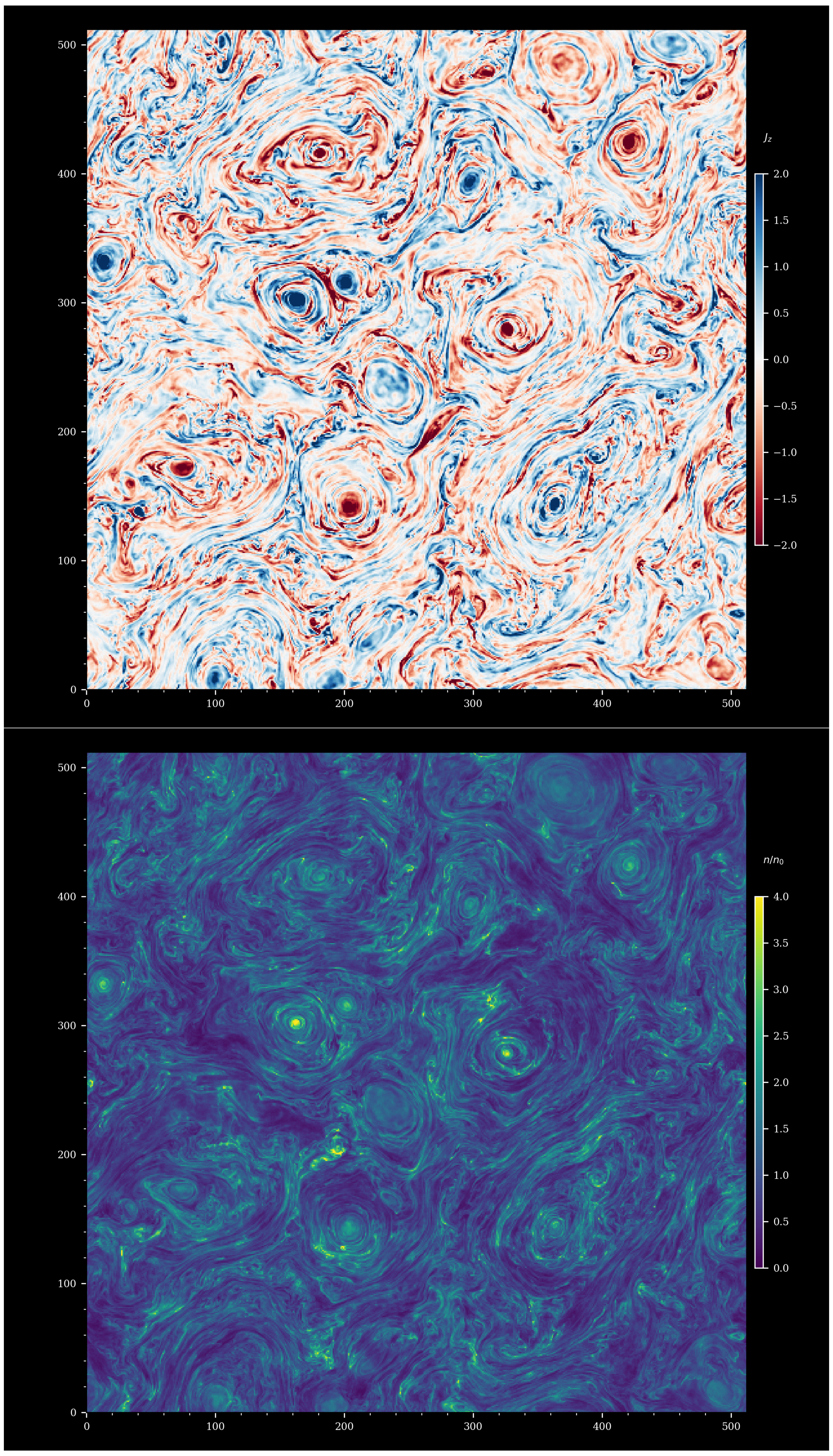

Figure 3. Simulation snapshot at about 7 light-crossing times. Current density (top) and number density (bottom), normalized to total number density. One unit in scale corresponds to the plasma skin depth ($c/\omega_{\rm p}$).

Author's [1] web page (but there is no more info on this particular project there yet)

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