The Interplay of Plasma Turbulence and Magnetic Reconnection in Producing Nonthermal Particles

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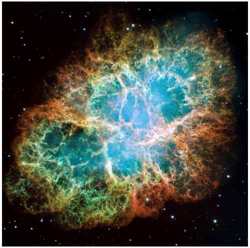
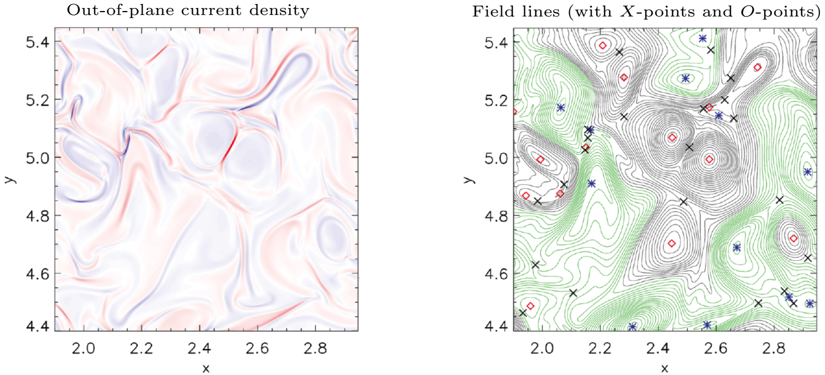
Outline

- Is turbulence in magnetically-dominated (i.e., relativistic) plasmas an efficient source of nonthermal particles?
- If so, how does the nonthermal spectrum depend on the system parameters?
- Mechanism of particle acceleration? Interplay with magnetic reconnection?


Nonrelativistic Turbulence (plus Reconnection)

- Plasma turbulence produces sheets of strong current density $\Rightarrow$ natural sites of magnetic reconnection

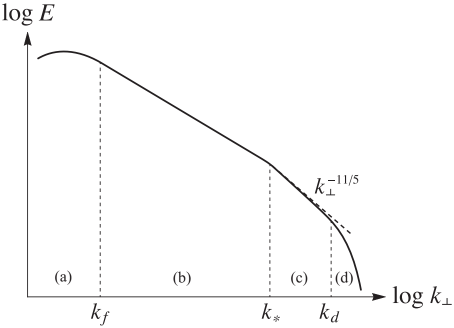


(Servidio *et al.* 2009/10/11)

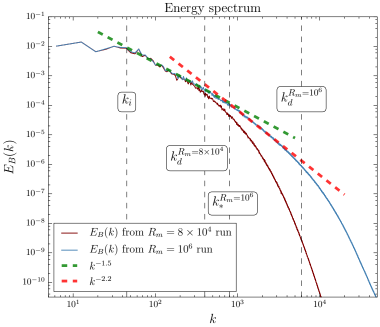
(also Matthaeus & Lamkin 1986, Politano *et al.* 1989, Biskamp 2003, Mininni *et al.* 2006, Wan *et al.* 2013, Zhdankin *et al.* 2013)

Nonrelativistic Turbulence (plus Reconnection)

- Magnetic reconnection leads to a steepening of the energy spectrum. What about particle acceleration?



(Comisso *et al.* ApJ 2018)



(Dong *et al.* PRL 2018)

(also Carbone *et al.* 1990, Carbone 1995, Cerri & Califano 2017, Franci *et al.* 2017, Mallet *et al.* 2017, Loureiro & Boldyrev 2017, Walker *et al.* 2018, ..)

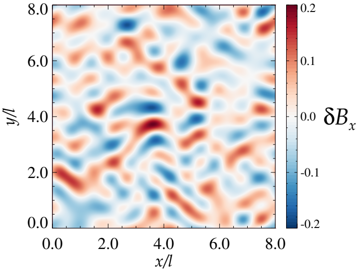
Tools and basic setup

- Fully-kinetic treatment:

  ⇒ we solve the coupled Vlasov-Maxwell system of equations through the PIC method

- PIC code TRISTAN-MP (Spitkovsky 2005)
- Decaying turbulence in relativistic pair plasmas
- 2D and 3D numerical simulations

Tools and basic setup (Relativistic "Servidio Problem")



- mean magnetic field $\langle \boldsymbol{B} \rangle = B_0 \hat{\boldsymbol{z}}$
- turbulence develops from uncorrelated magnetic fluctuations δB_x and δB_y in Fourier harmonics
- energy-carrying scale: $l = 2\pi/k_f$ (k_f is the wavenumber where the energy spectrum peaks)

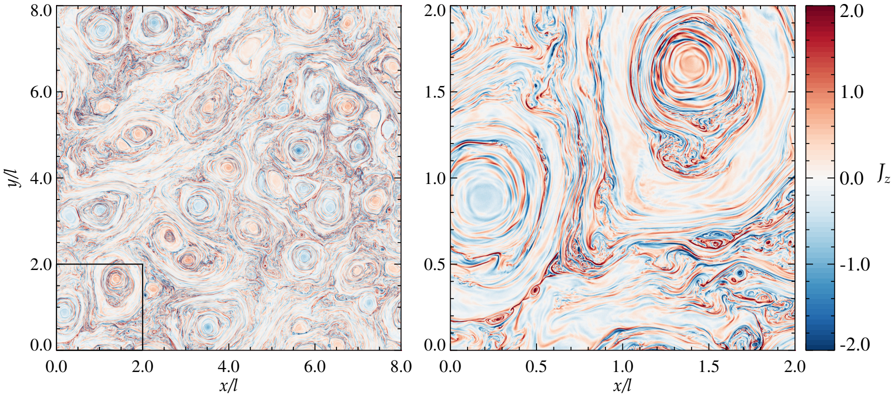
- Simulations in the magnetically-dominated regime

$$\sigma_0 = \frac{\delta B^2_{\rm rms0}}{4\pi w_0} \gg 1, \qquad \frac{1}{16} \leq \frac{\delta B^2_{\rm rms0}}{B_0^2} \leq 16, \qquad \theta = \frac{k_B T}{m_e c^2} \sim 1$$

with $w_0 = n m_e c^2 + n k_B T \left[\hat{\gamma}/(\hat{\gamma}-1)\right]$

Fully-developed turbulence state

2D simulation with $\sigma_0 = 10$, $\delta B_{\mathrm{rms0}}/B_0 = 1$, $L/d_{e0} = 3280$



- Copious presence of current sheets, plasmoids, and vortices

Fully-developed turbulence state

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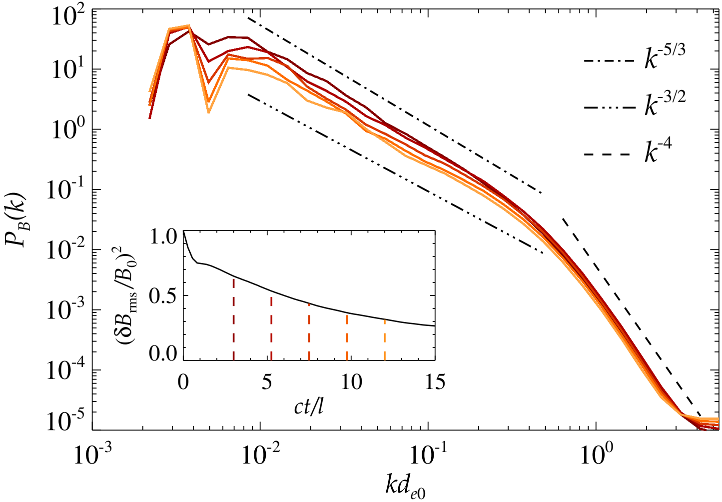
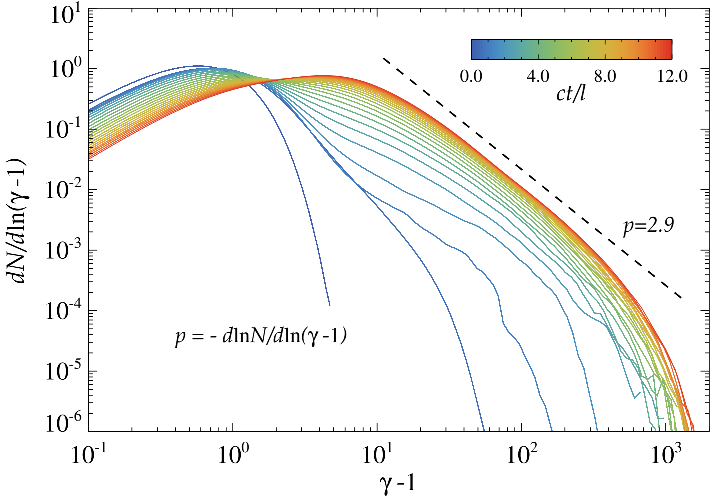
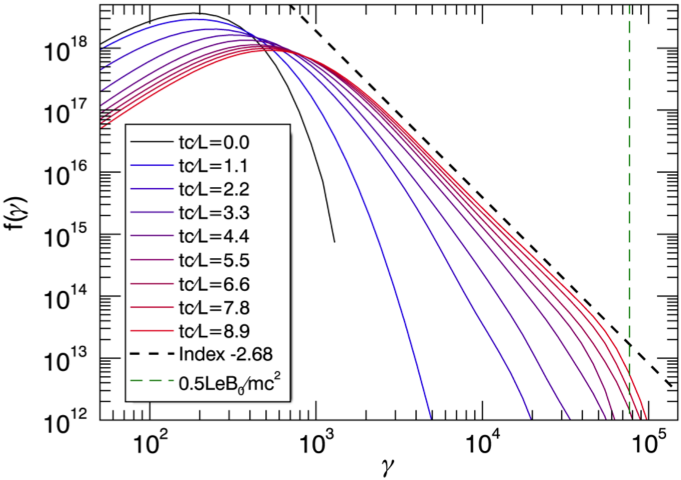


Particle Spectrum

2D simulation with $\sigma_0 = 10$, $\delta B_{\mathrm{rms0}}/B_0 = 1$, $L/d_{e0} = 3280$



Similar power-law particle energy distributions also in simulations by Zhdankin *et al.* 2017, 2018.



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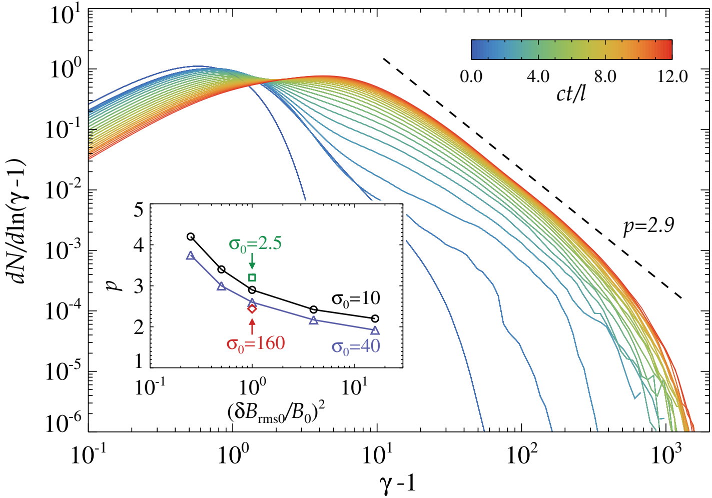
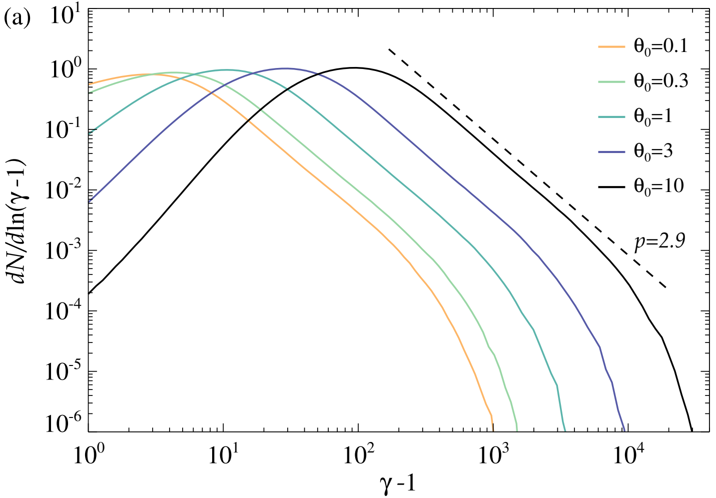


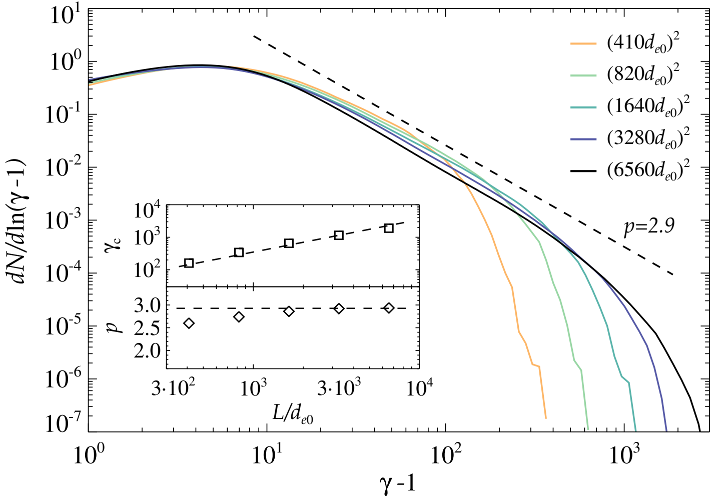
Particle Spectrum: initial temperature scan

2D simulation with $\sigma_0 = 10$, $\delta B_{\mathrm{rms}0}/B_0 = 1$, $L/d_{e0} = 3280$



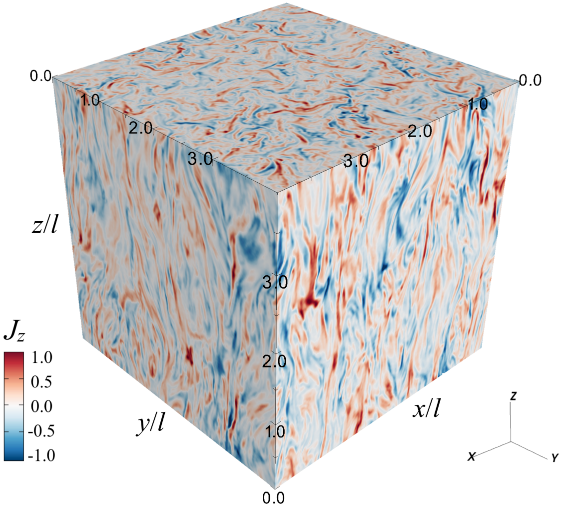
Particle Spectrum: system-size scan

2D simulations with $\sigma_0 = 10$, $\delta B_{\mathrm{rms0}}/B_0 = 1$

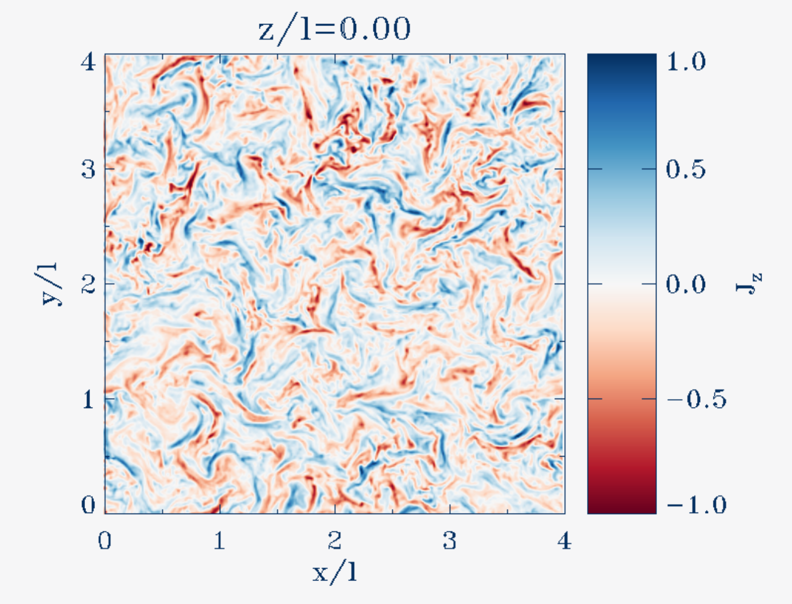


Current sheets in 3D

3D simulation with $\sigma_0 = 10$, $\delta B_{\mathrm{rms}0}/B_0 = 1$, $L/d_{e0} = 820$



Current sheets in 3D: slices of J_z



Current sheets in 3D: plasmoids/flux ropes

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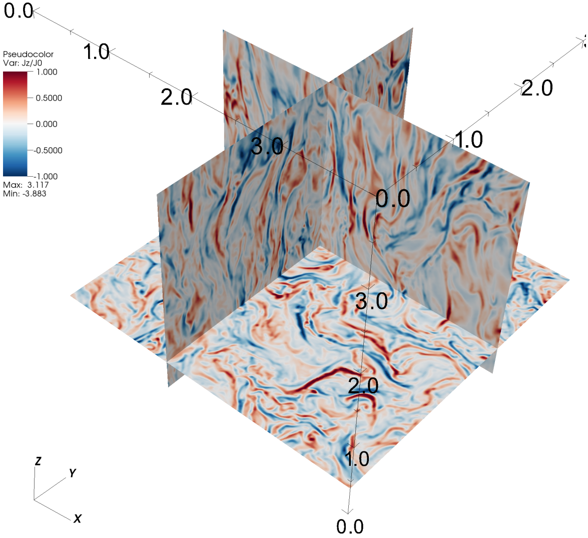

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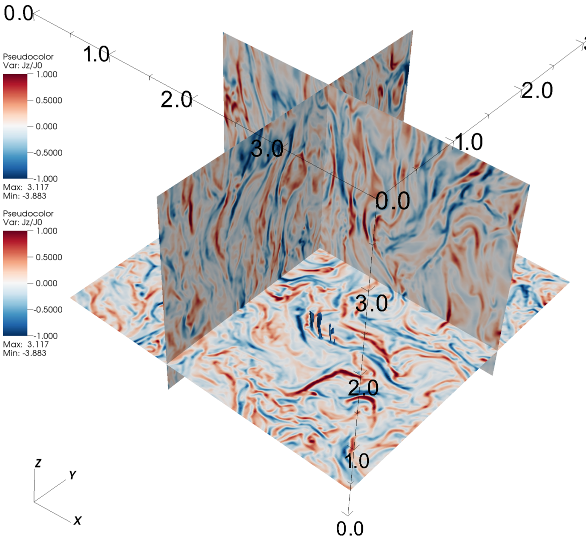

Particle Spectrum

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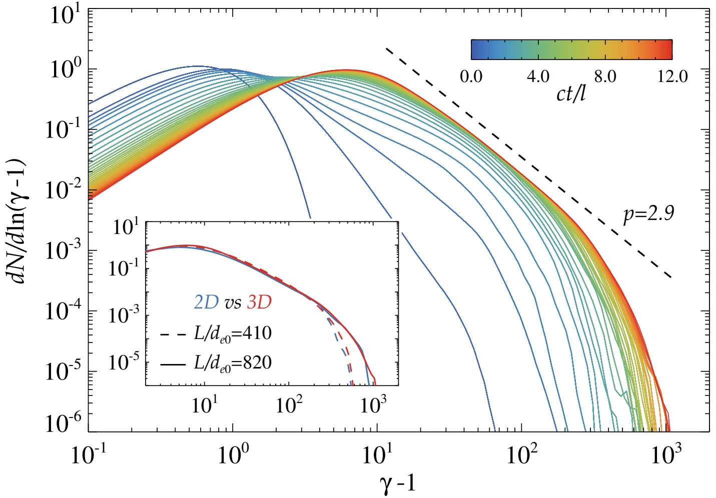
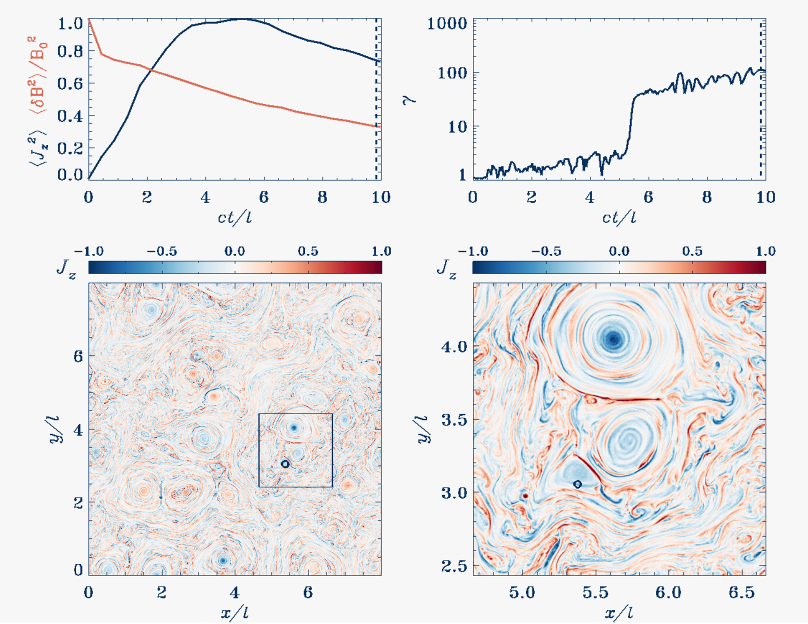
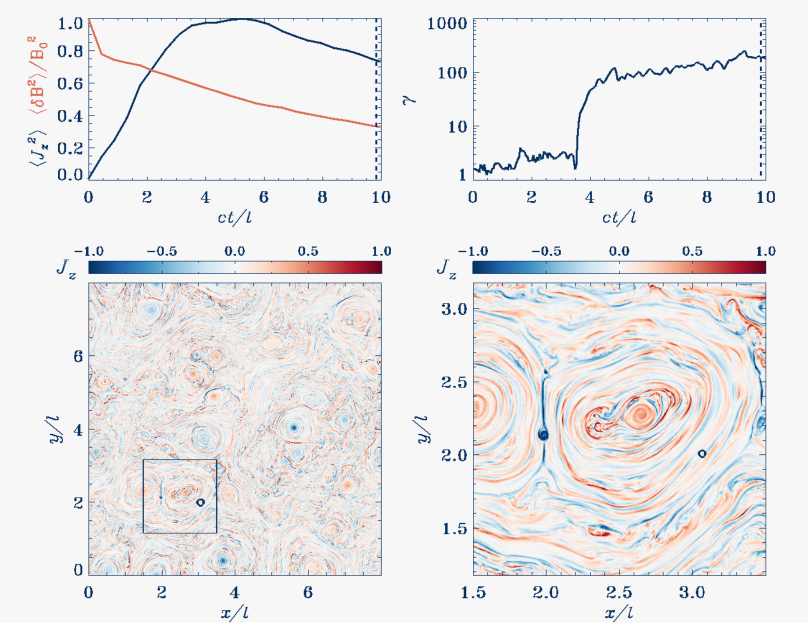


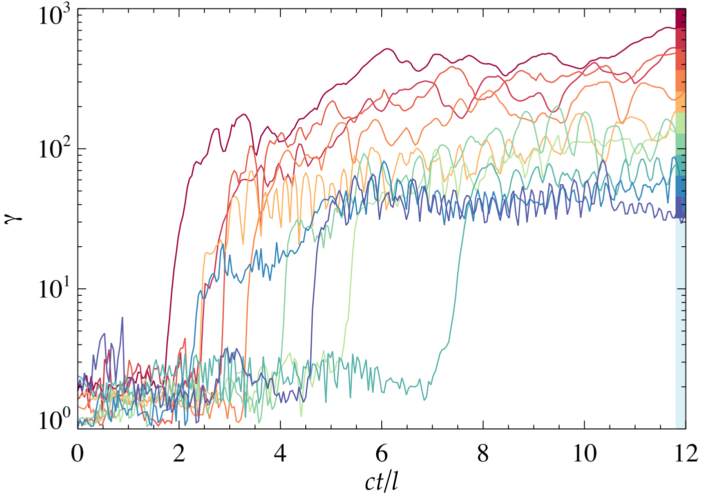
How are particles accelerated?



How are particles accelerated?

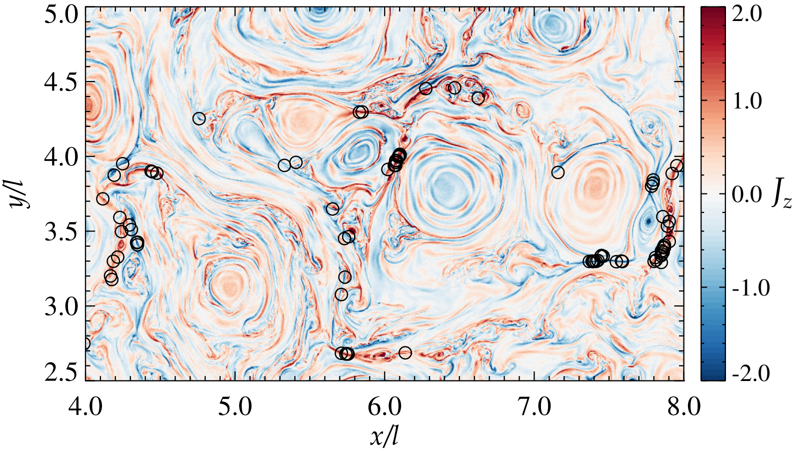


Particle Injection



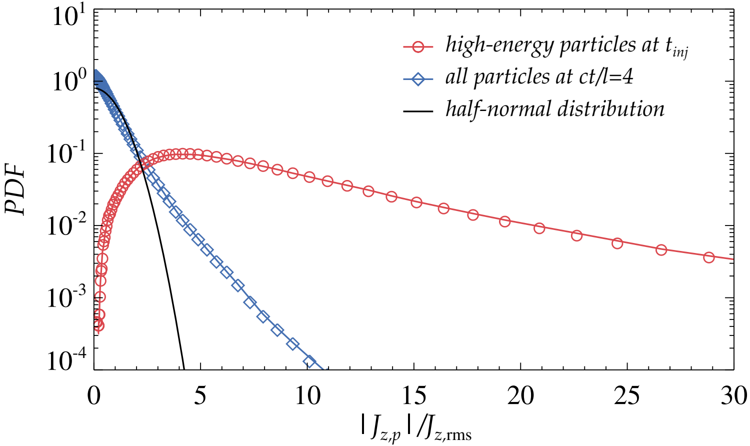
- $\sim 97\%$ of the particles belonging to the nonthermail tail experience a sudden energy jump from the thermal pool

Particle Injection



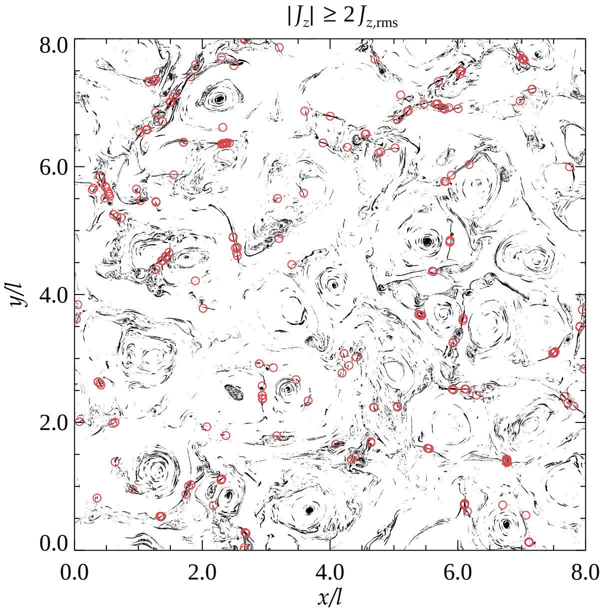
- Particle injection at reconnecting current sheets

Particle Injection

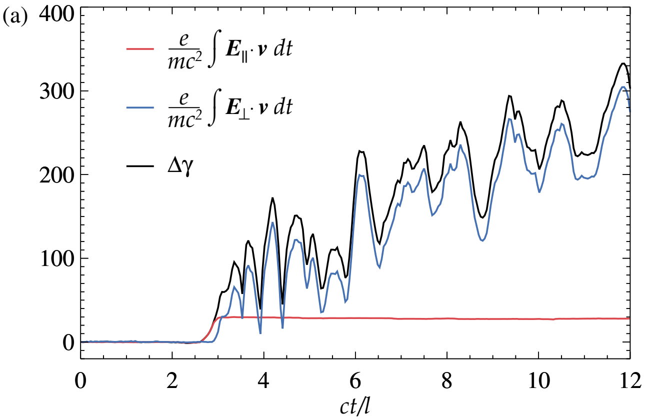


- $\sim 95\%$ of the high-energy particles reside at injection at $|J_{z,p}| \geq 2\, J_{z,\mathrm{rms}}$ (current sheets)

Particle Injection

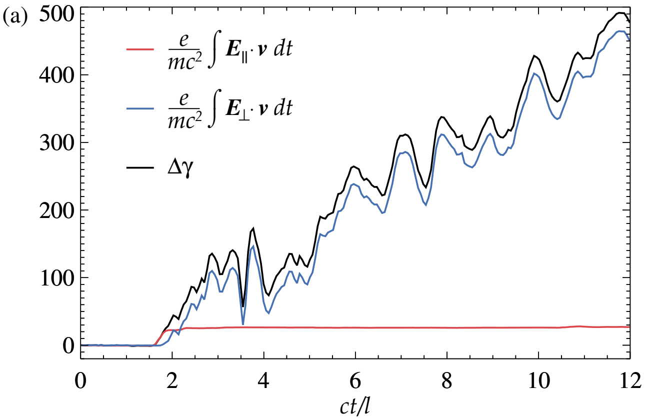


Particle energization



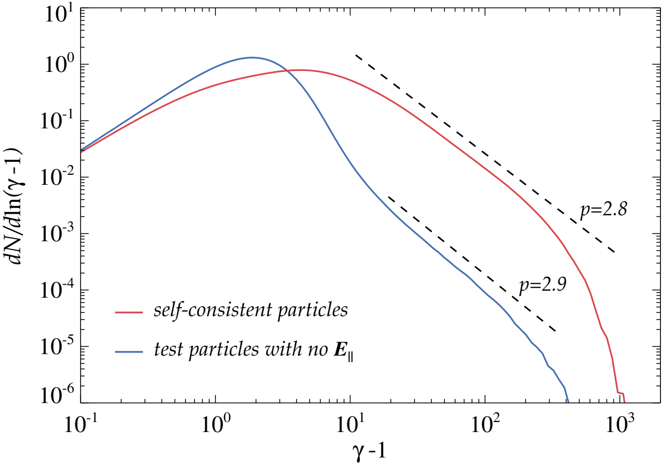
- Typical particle energization history (2D)

Particle energization



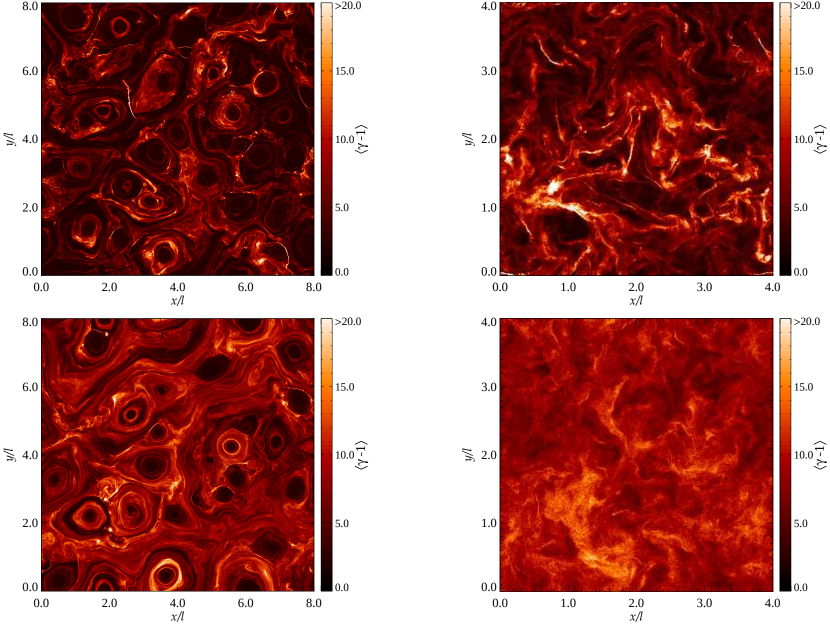
- Typical particle energization history (3D)

Test particle spectrum

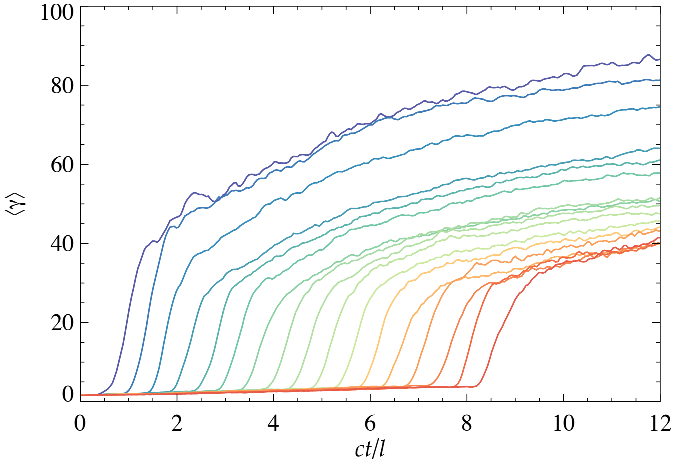


- For test particles that do not feel $E_{\|}$, there is a dramatic drop of particles in the nonthermal tail (while p is similar)

Particle mixing

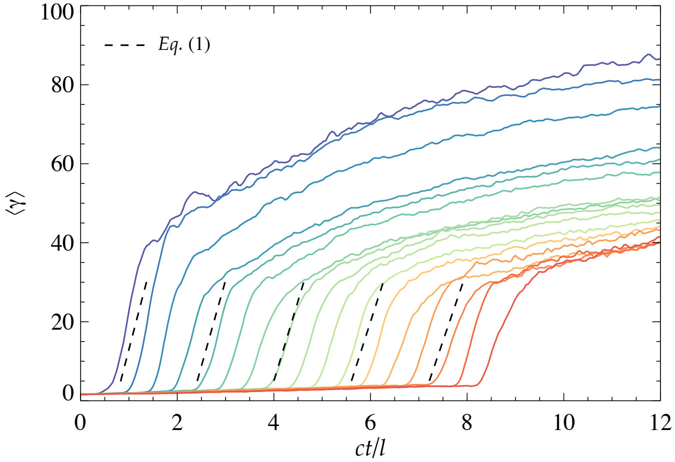


Energization mechanisms



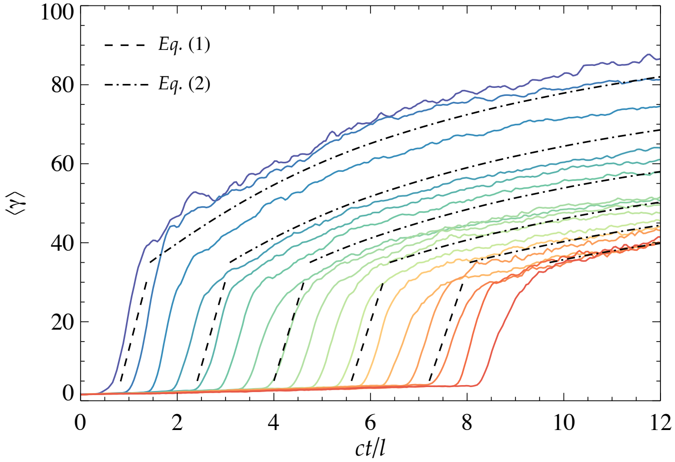
- Particles energization occurs in a two-stage process

Energization mechanisms: injection



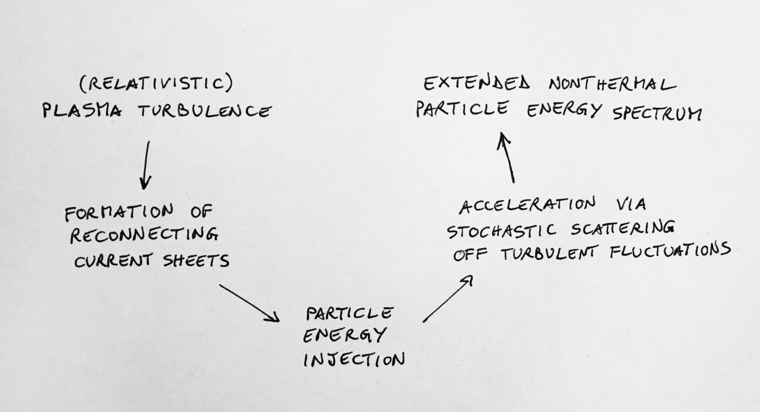
$$(1) \quad \frac{d\langle\gamma\rangle}{dt} = \frac{e}{mc}\,\beta_R\,\delta B_{\rm rms}$$

Energization mechanisms: stochastic acceleration



$$(2) \quad \frac{d\langle\gamma\rangle}{dt} = \frac{1}{\gamma^2}\frac{\partial}{\partial\gamma}\left[\gamma^2 D_p\right] , \quad D_p = \frac{1}{3\kappa}\frac{\delta V_{\rm rms}^2}{c^2}\frac{\delta B_{\rm rms}^2}{B_0^2}\gamma^2\omega_c$$

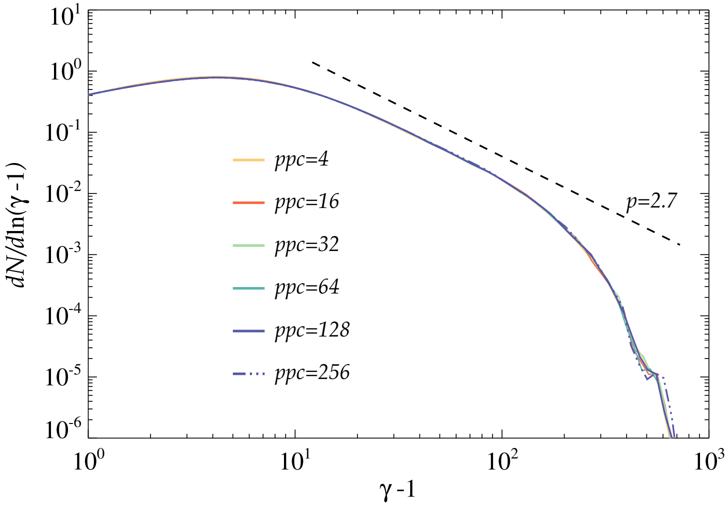
Summary



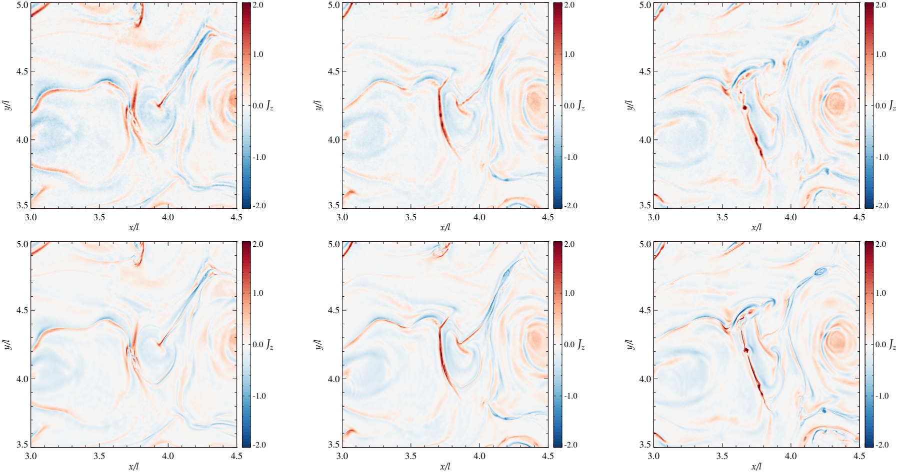
More details in Comisso & Sironi, PRL 121, 255101 (2018)

Particle Spectrum: particles per cell scan

2D simulation with $\sigma_0 = 10$, $\delta B_{\rm rms0}/B_0 = 1$, $L/d_{e0} = 820$



Plasmoid formation: different spatial resolutions



From two 2D simulations with 3 cells per d_{e0} (top row) and 10 cells per d_{e0} (bottom row).

Movie - time evolution of J_z