Particle Acceleration in Magnetically Dominated Turbulence

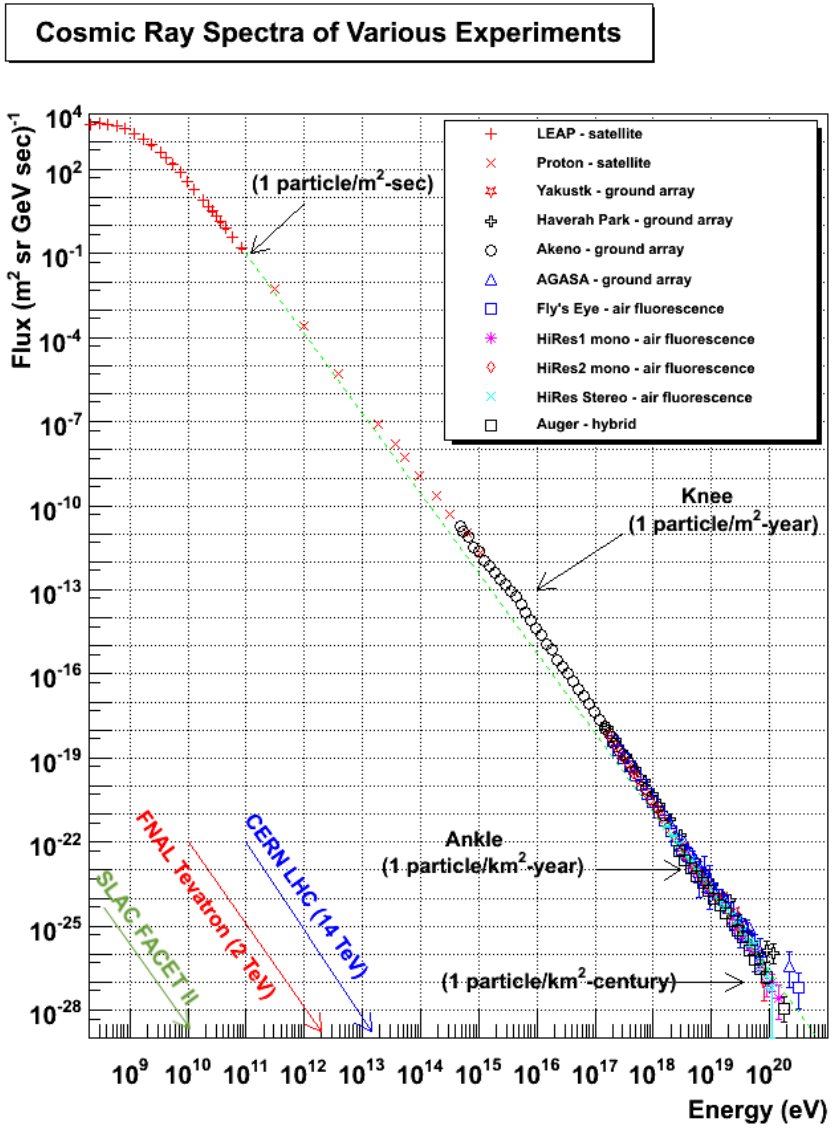
Luca Comisso

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

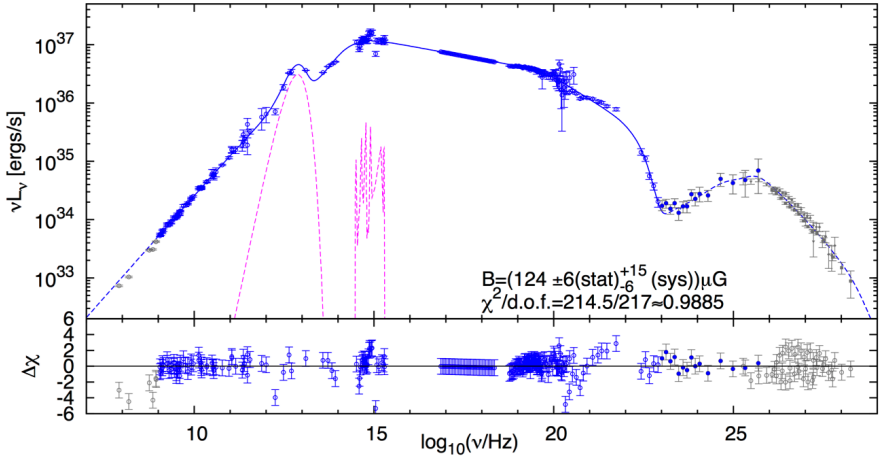
Princeton Center for Theoretical Sciences
October 30, 2020

COLUMBIA UNIVERSITY
IN THE CITY OF NEW YORK

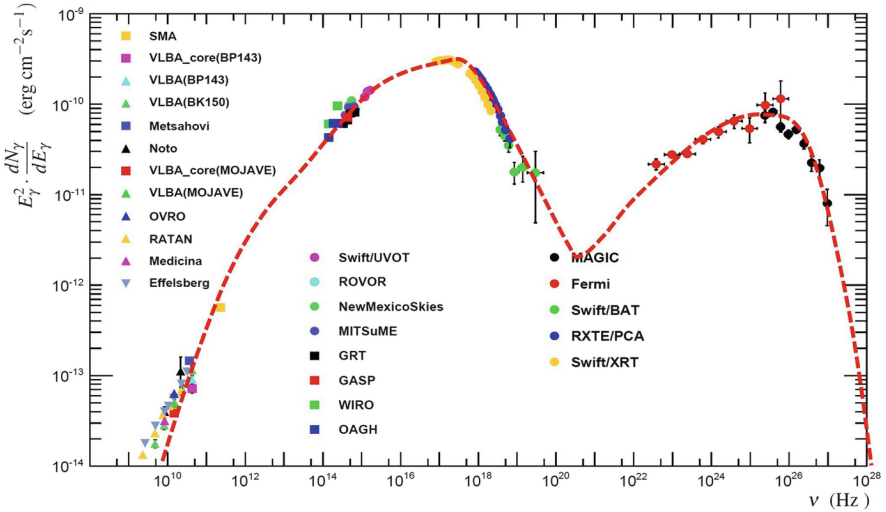
Some Prominent Non-Thermal Distributions



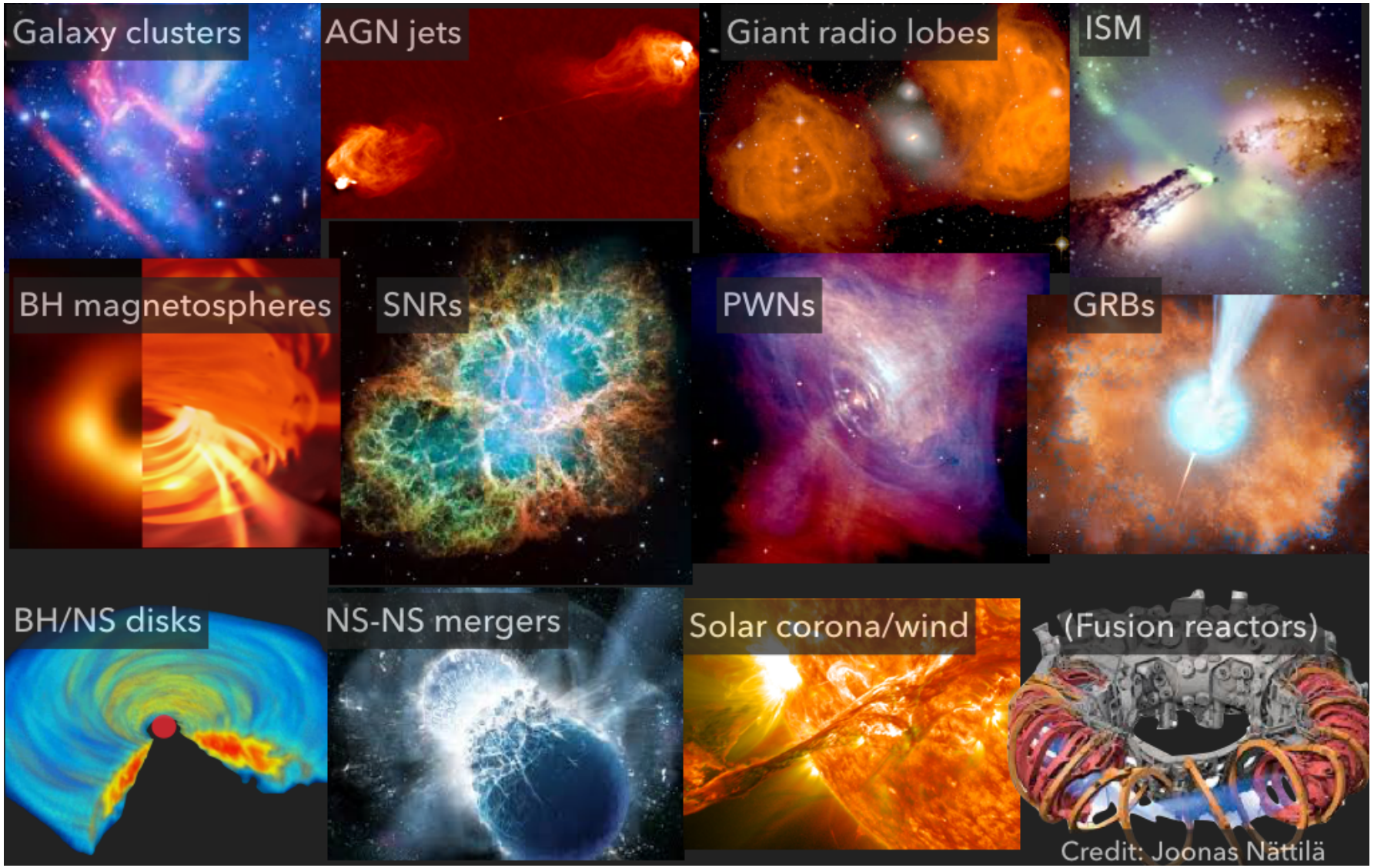
Pulsar Wind Nebulae (Meyer *et al.* 2010)



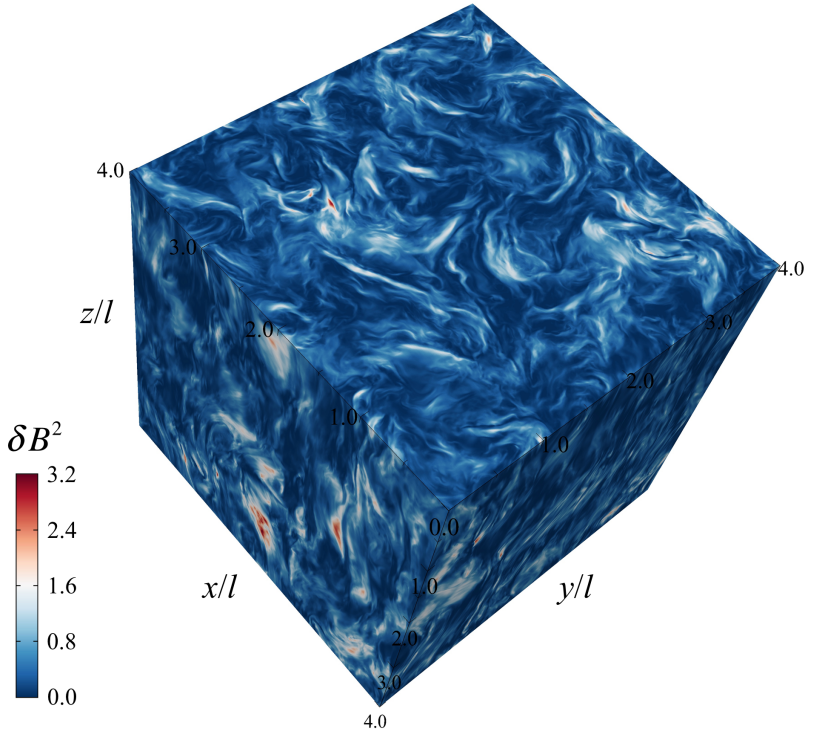
Blazars (Abdo *et al.* 2011)

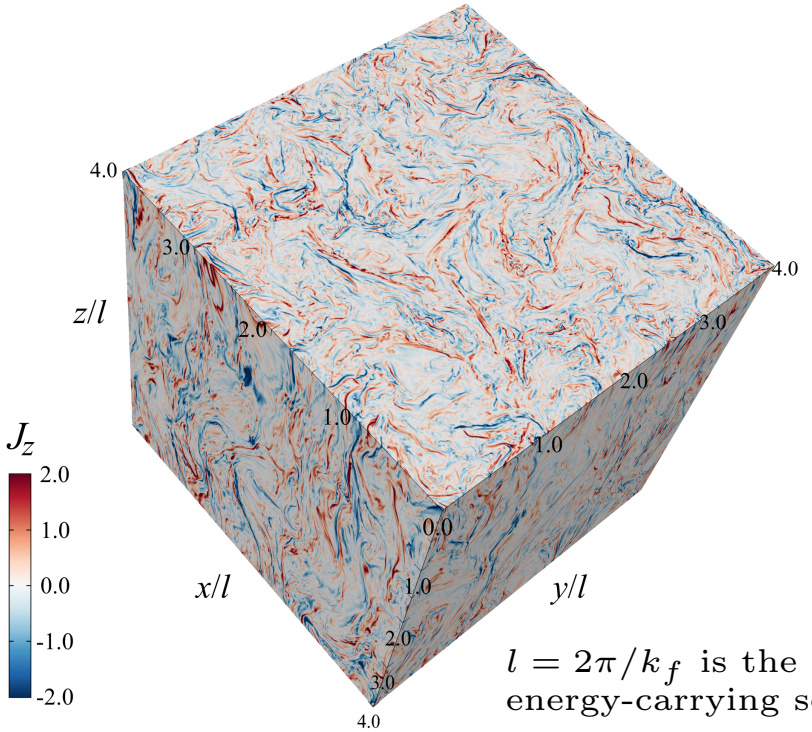


Examples of Turbulent Plasmas



Turbulence Cascade from Fully-Kinetic PIC Simulations





$l = 2\pi/k_f$ is the initial energy-carrying scale

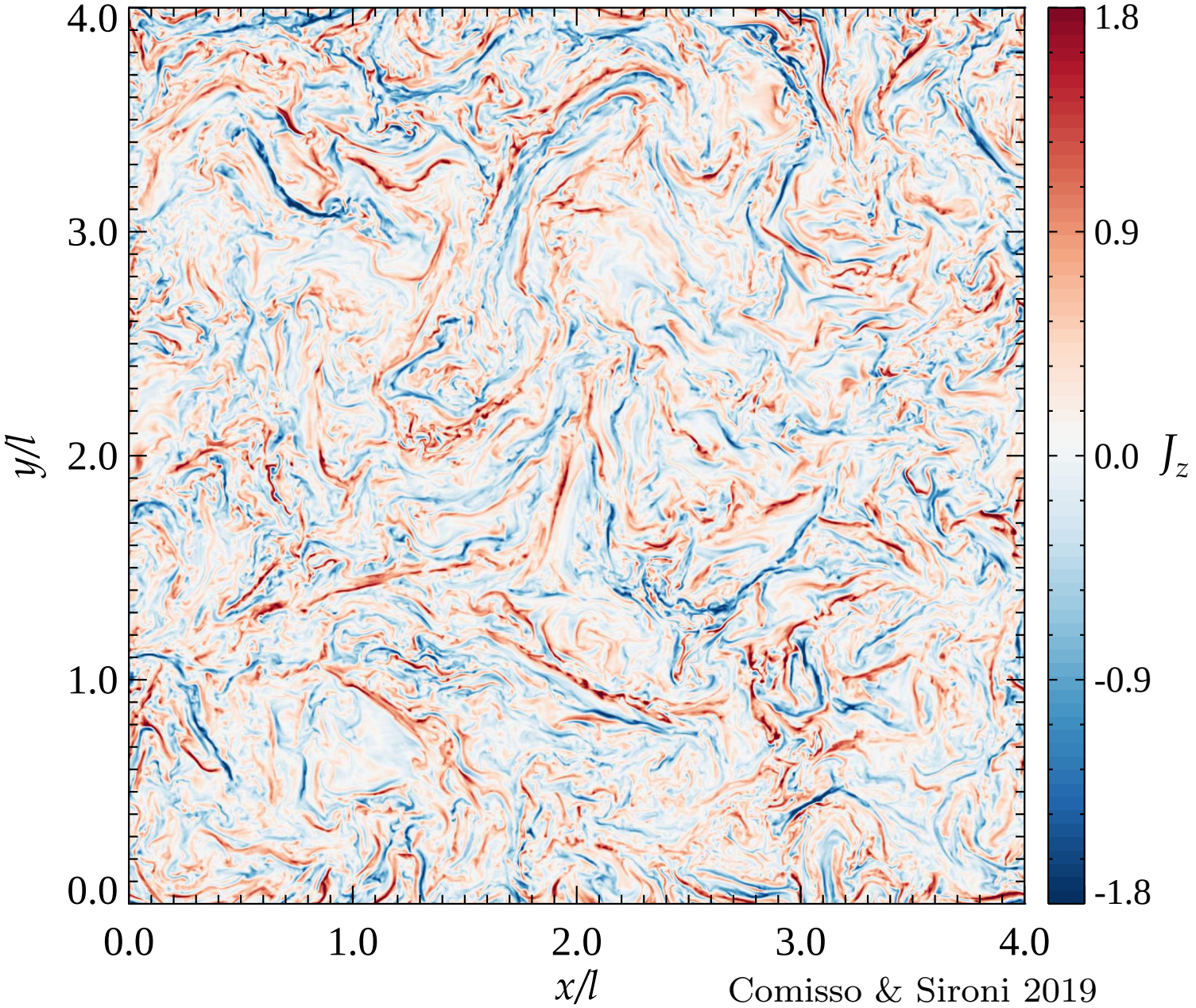
Turbulence develops from uncorrelated initial fluctuations $\boldsymbol{\delta B}$

Mean magnetic field $\langle \boldsymbol{B} \rangle = B_0 \hat{\boldsymbol{z}}$

$e^- e^+$ plasma with $\sigma_0 = \delta B_{\mathrm{rms0}}^2 / 4\pi h_0 \gg 1$

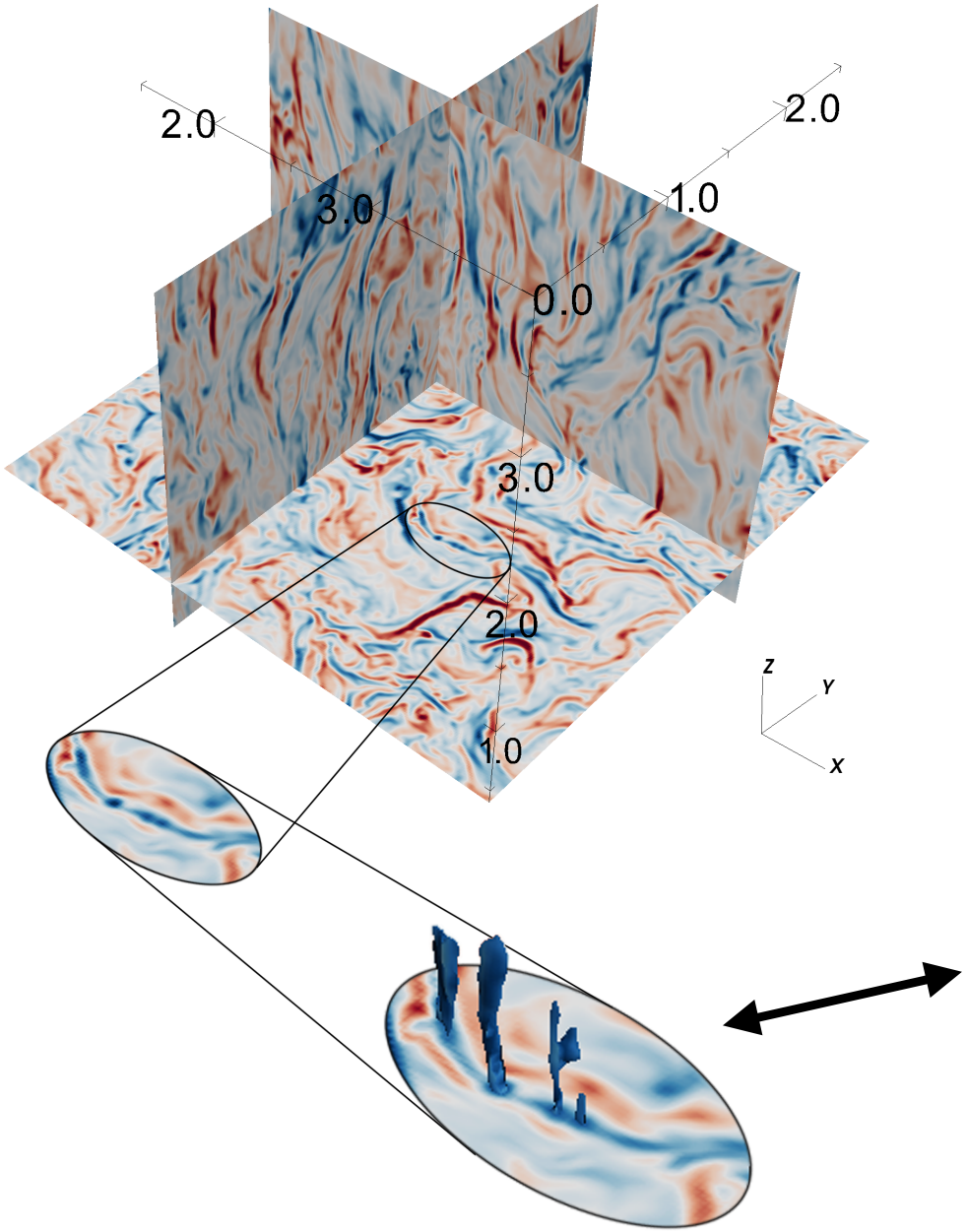
$$d_{e0} = \left(\frac{\gamma_{th} m_e c^2}{4\pi n e^2} \right)^{1/2}, \quad \frac{L}{d_{e0}} = 820 \Rightarrow 2460^3 \text{ cells}$$

Copious Formation of Current Sheets



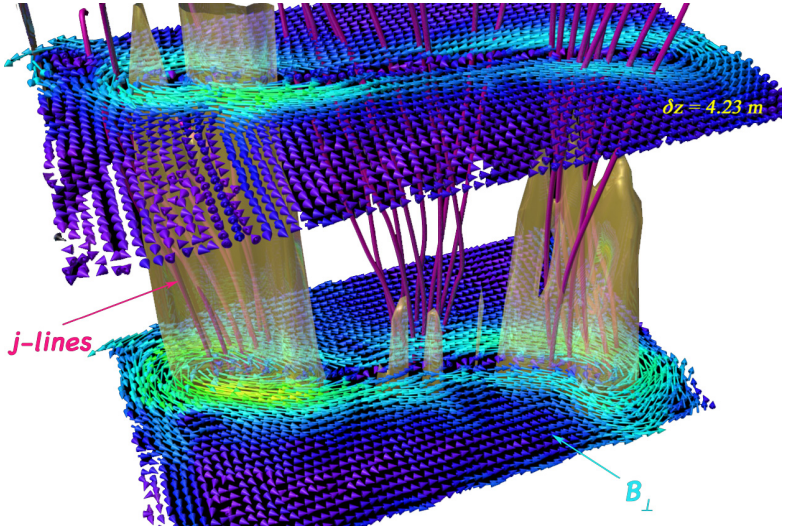
Comisso & Sironi 2019

Self-Consistent Development of Reconnection Layers



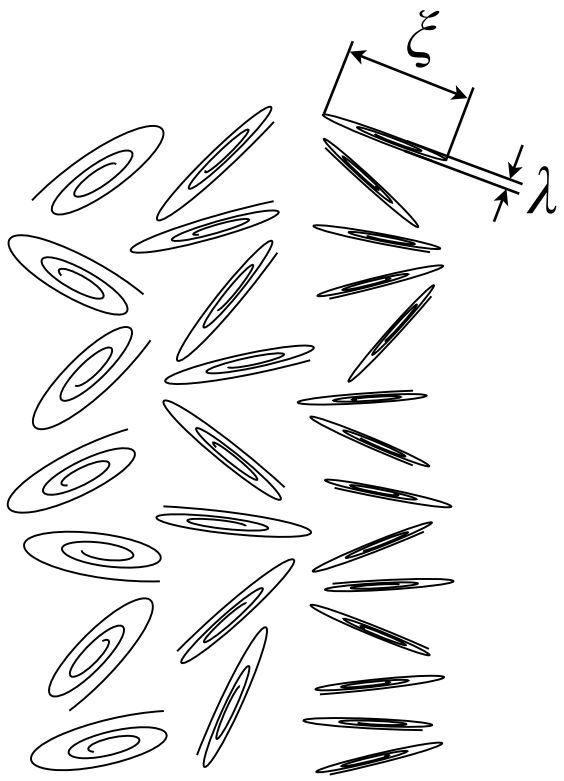
The large computational domain allows the turbulent cascade to develop reconnection layers with flux ropes/plasmoids

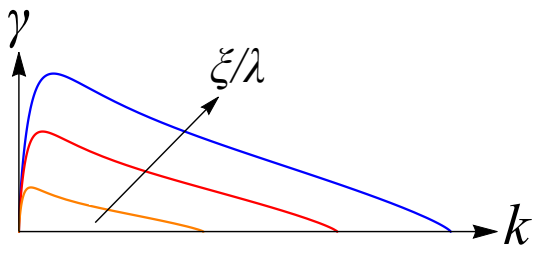
Reconnection with flux ropes in dedicated lab experiment



Gekelman *et al.* 2016

Conditions for Triggering Plasmoid-Mediated Recon.





Comisso & Sironi 2019

- Obtain relativistic tearing growth rate

$$\gamma^{1/2}\tau_H^{1/2}\left(\frac{\lambda}{d_e}\right)^{3/2}\frac{\Gamma\left[(\Upsilon-1)/4\right]}{\Gamma\left[(\Upsilon+5)/4\right]}=-\frac{8}{\pi}\Delta'$$

$$\tau_H=\frac{1}{k_\xi v_{A\lambda}},\ \Upsilon=\gamma\tau_H\frac{\lambda}{d_e}\ ,$$

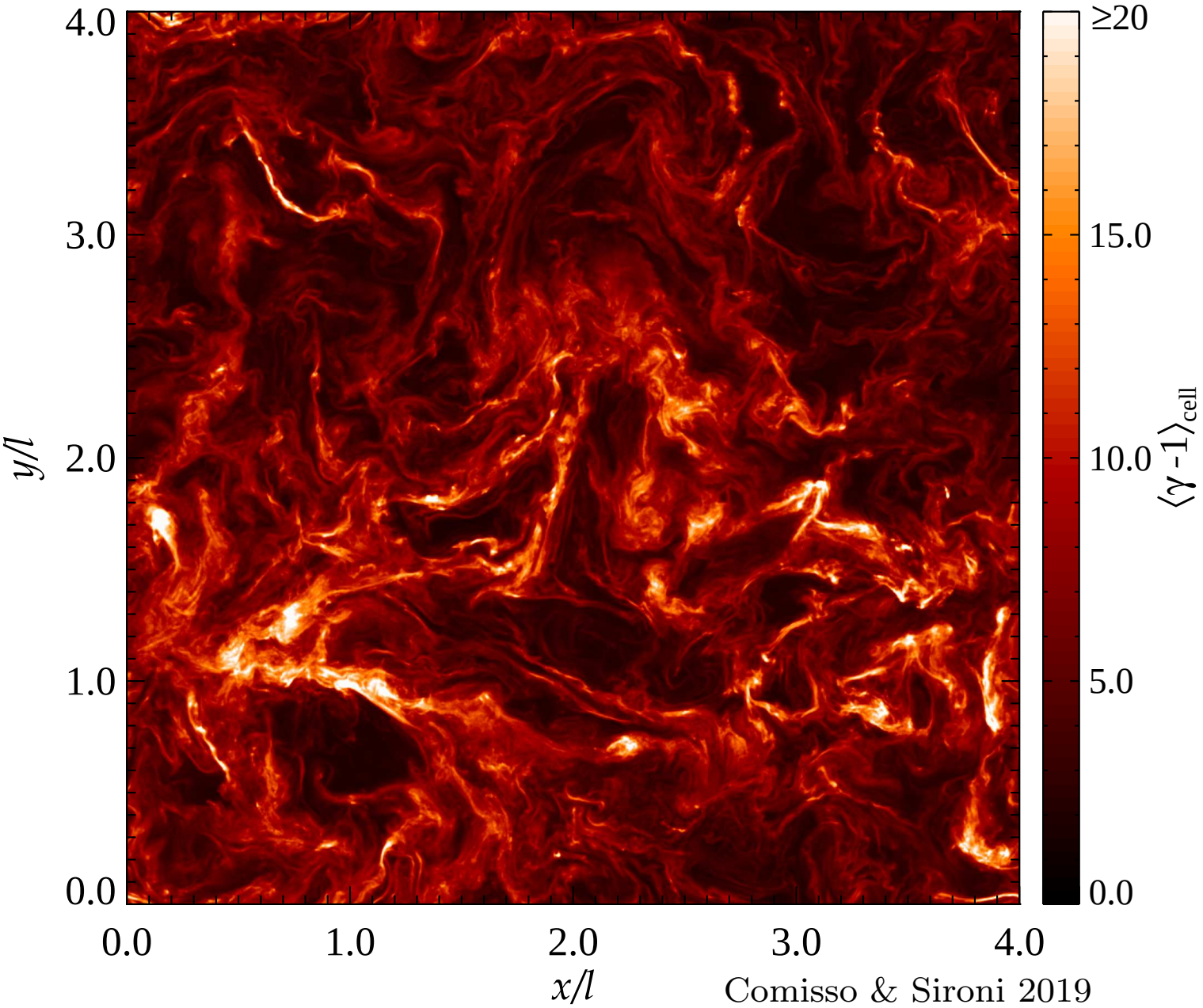
$$d_e=\left(\frac{\gamma_{th}m_ec^2}{4\pi ne^2}\right)^{1/2}$$

- Use principle of least time (Comisso *et al.* 2016) to obtain the conditions

$$\frac{\lambda}{\xi}\simeq\left(\frac{d_e}{\xi}\right)^{2/3}\left[\ln\left(\frac{1}{\sqrt{\varepsilon}}\left(\frac{d_e}{\xi}\right)^{\frac{4-\alpha}{6}}\right)\right]^{-1/3}$$

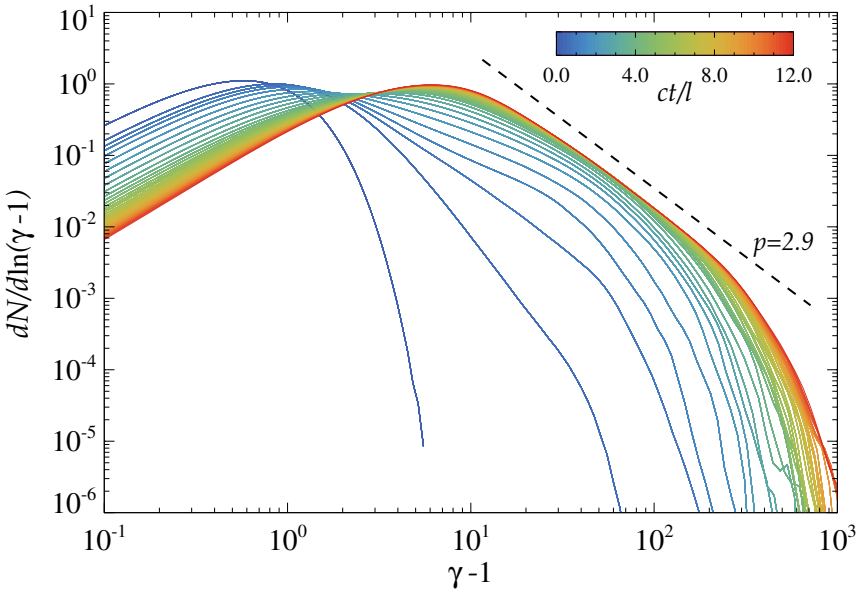
$$\gamma\frac{\xi}{v_{A\lambda}}\simeq\ln\left(\frac{1}{\sqrt{\varepsilon}}\left(\frac{d_e}{\xi}\right)^{\frac{4-\alpha}{6}}\right)\gg 1$$

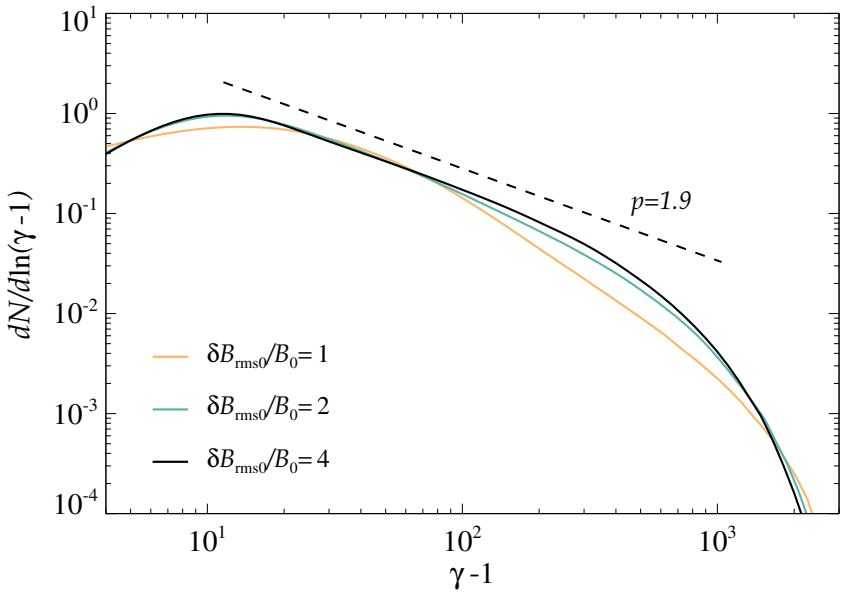
Reconnecting Current Sheets Energize Particles



Comisso & Sironi 2019

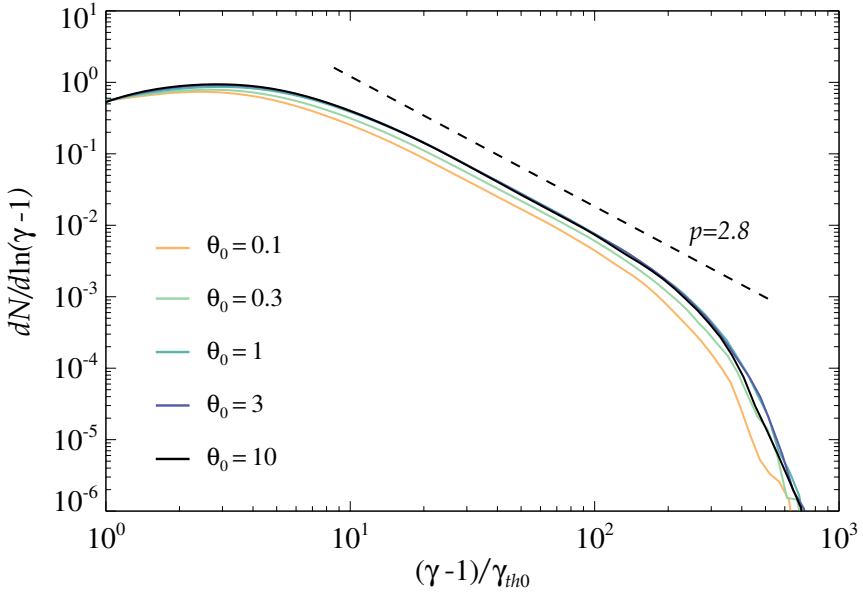
Development of Non-Thermal Particles





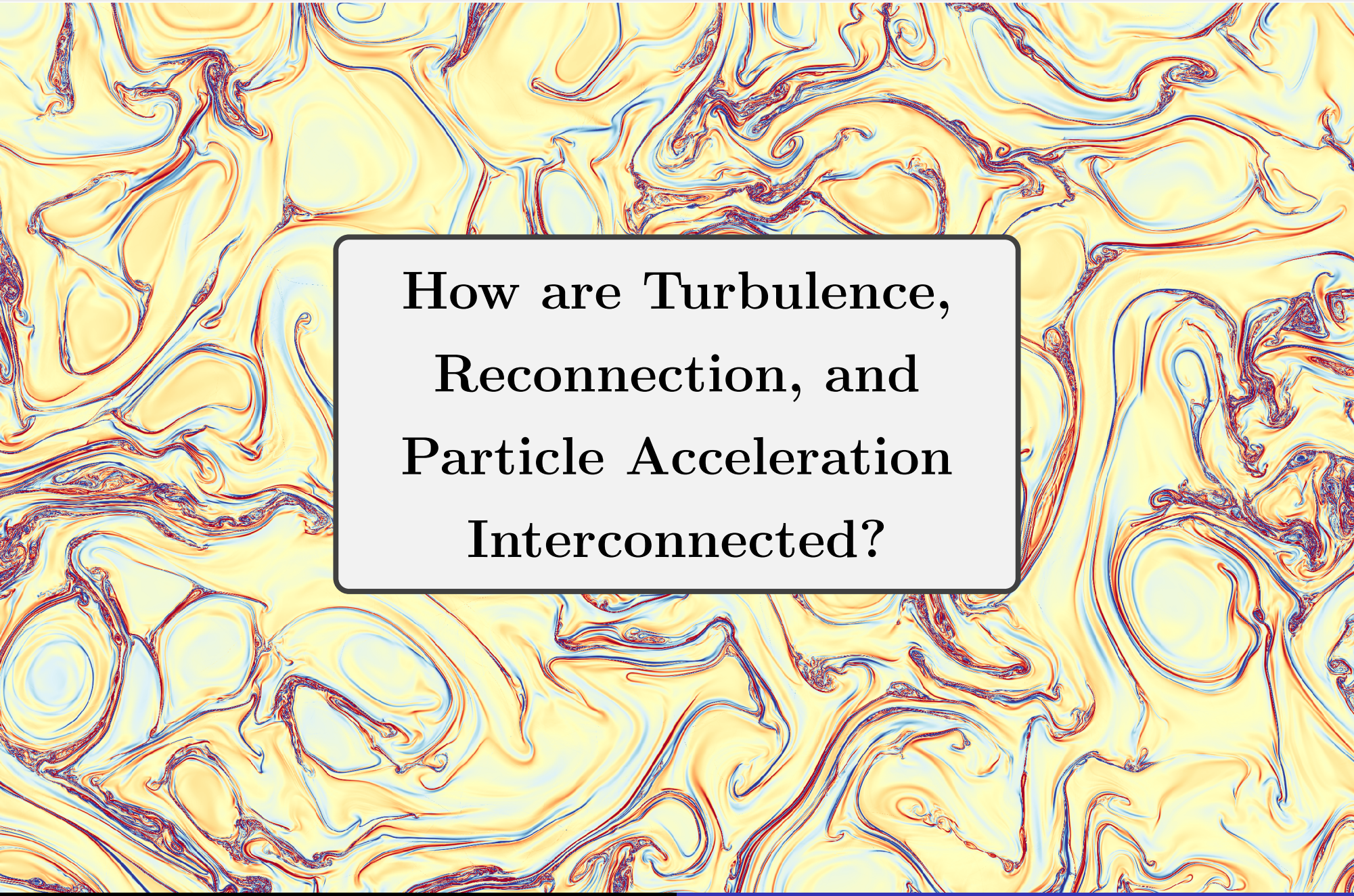
- Turbulence+Reconnection generate a nonthermal particle spectrum with a power-law energy range

Comisso & Sironi 2018, 2019



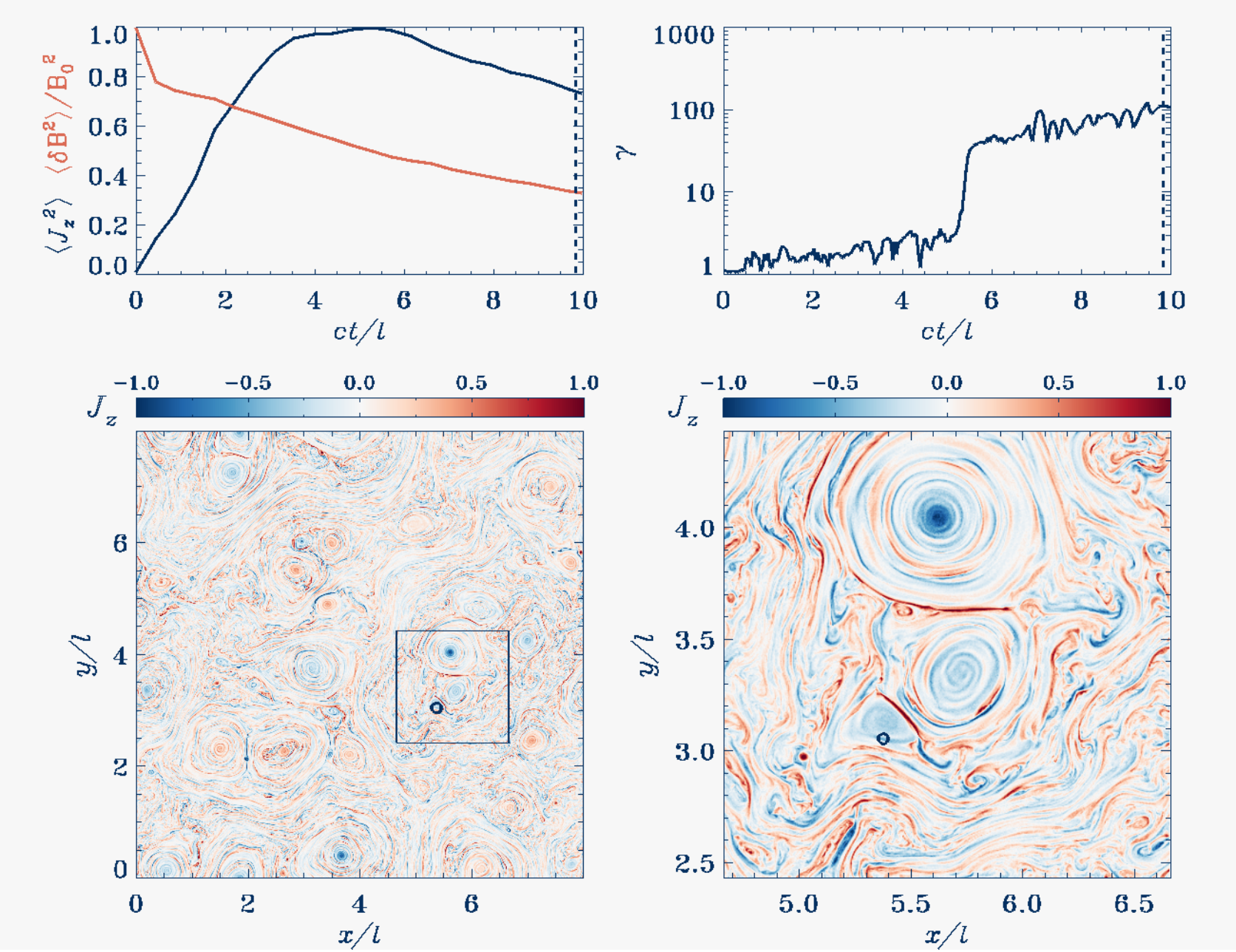
See also Zhdankin, Nättilä, Wong, *et al.*

Let's Dive Into the Generation of Non-Thermal Particles

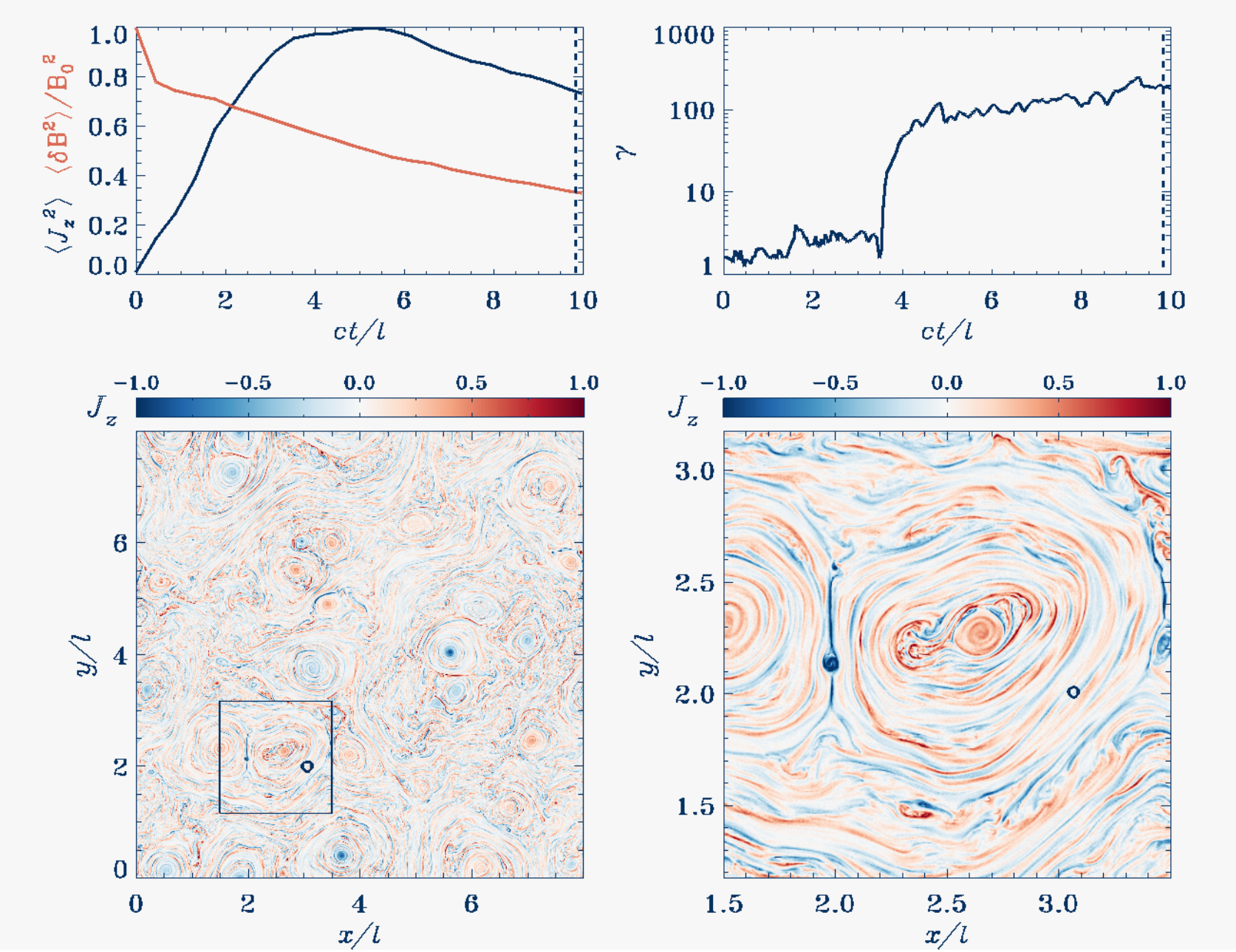


How are Turbulence, Reconnection, and Particle Acceleration Interconnected?

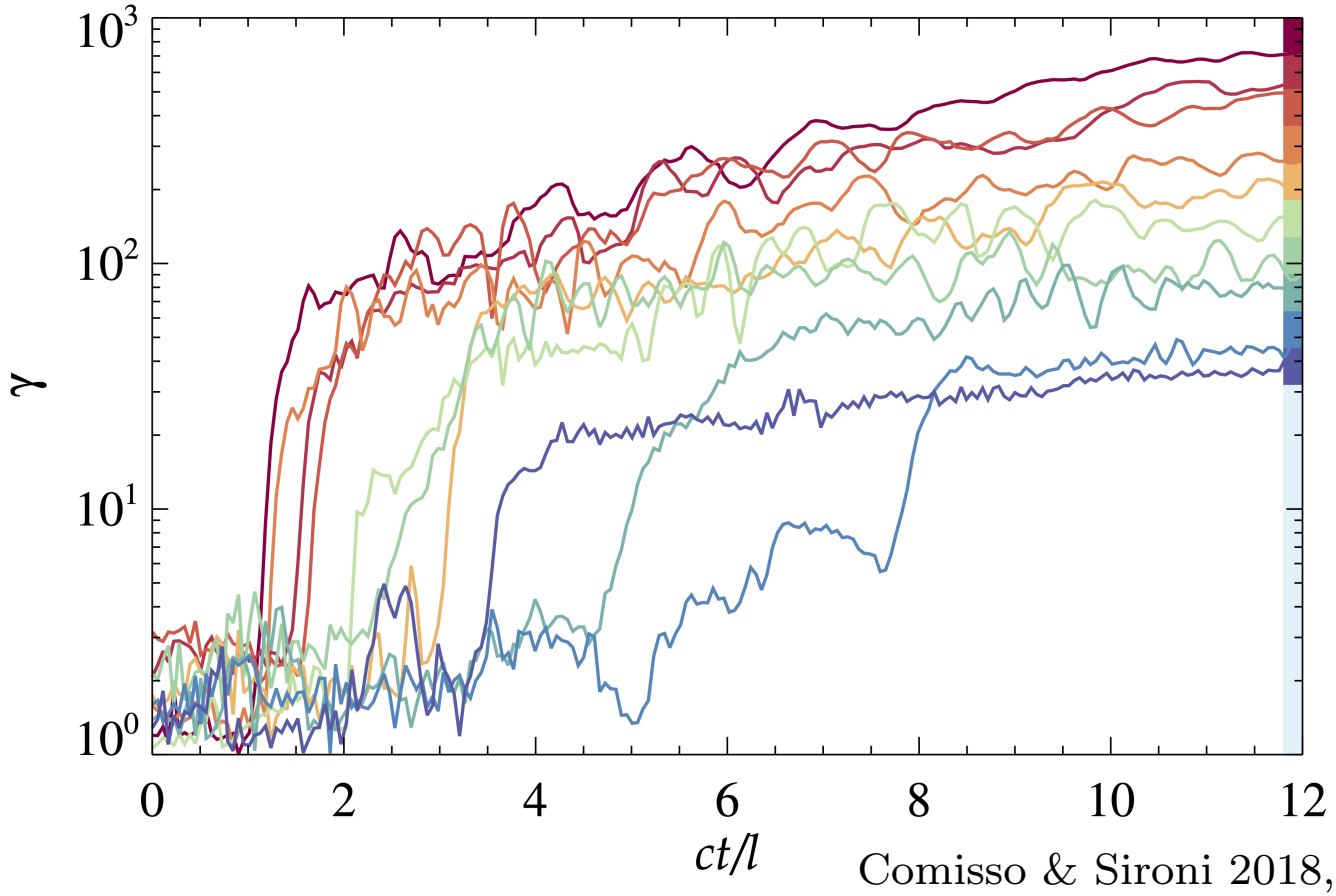
Energization History for a Typical Particle



Energization History for Another Typical Particle



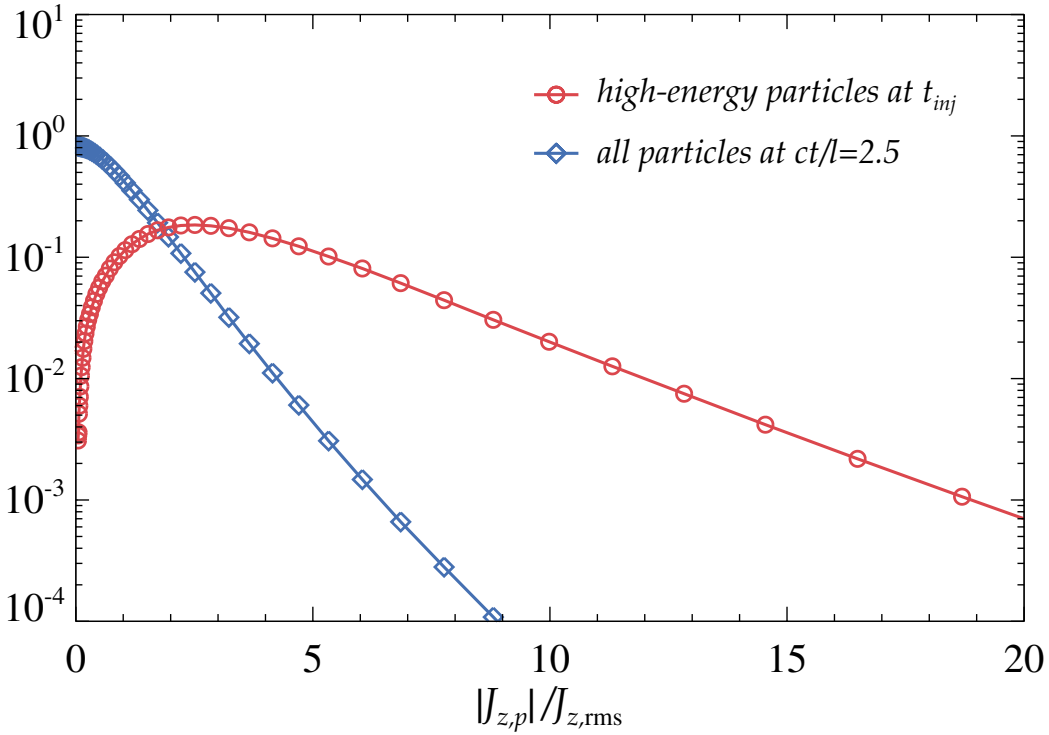
Two Stages of Particle Acceleration

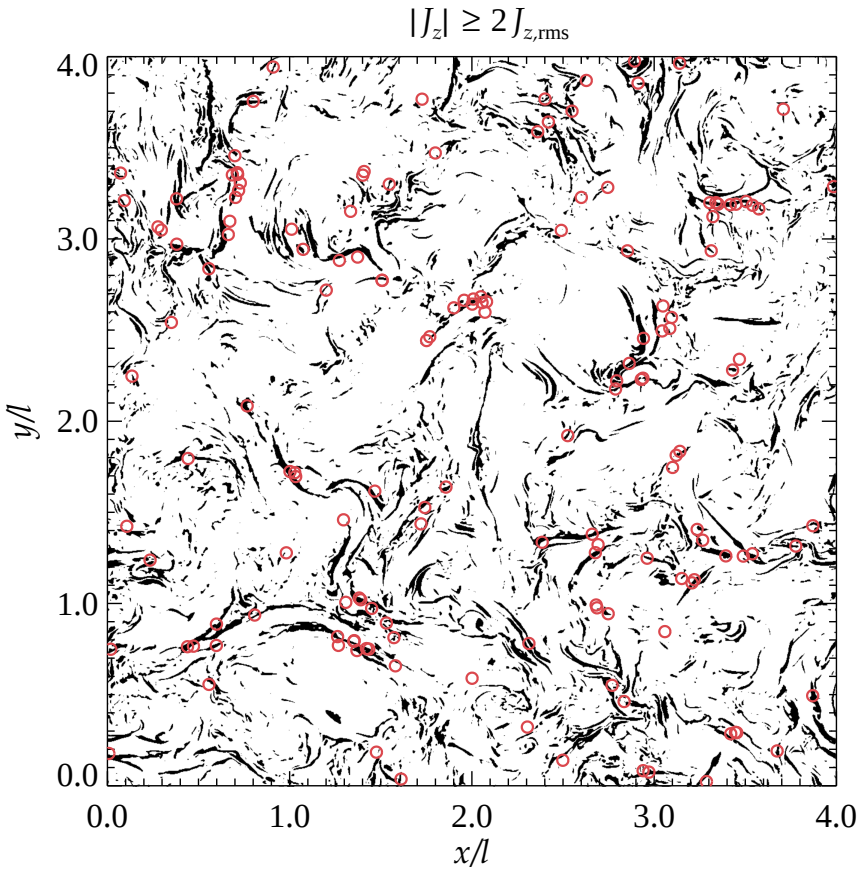


Comisso & Sironi 2018, 2019

- Particles belonging to the non-thermal tail experience a sudden energy jump from $\gamma \sim \gamma_{th}$ to $\gamma \sim \sigma_0 \gamma_{th} \gg \gamma_{th}$
- Particle continue to gain energy with a slower rate from $\gamma \sim \sigma_0 \gamma_{th}$ to much higher energies (up to $\gamma \sim \gamma_{\rm cutoff}$).

Particle Injection at Reconnecting Current Sheets



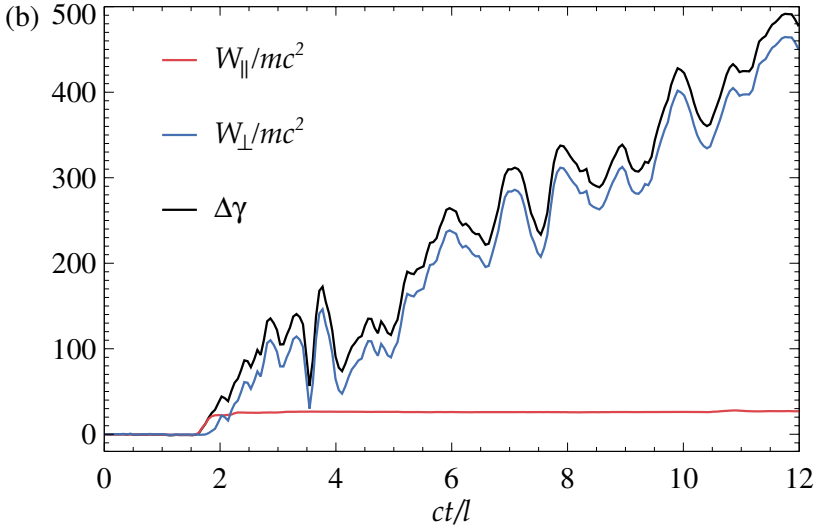


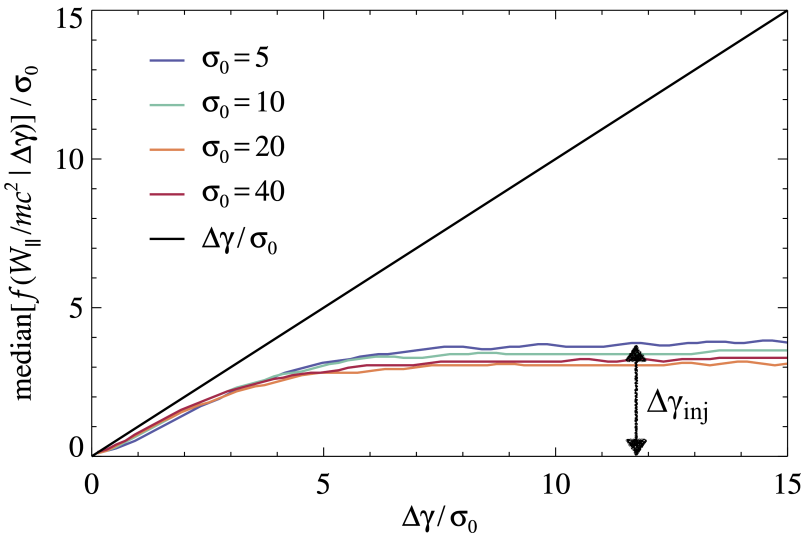
Comisso & Sironi 2018, 2019:

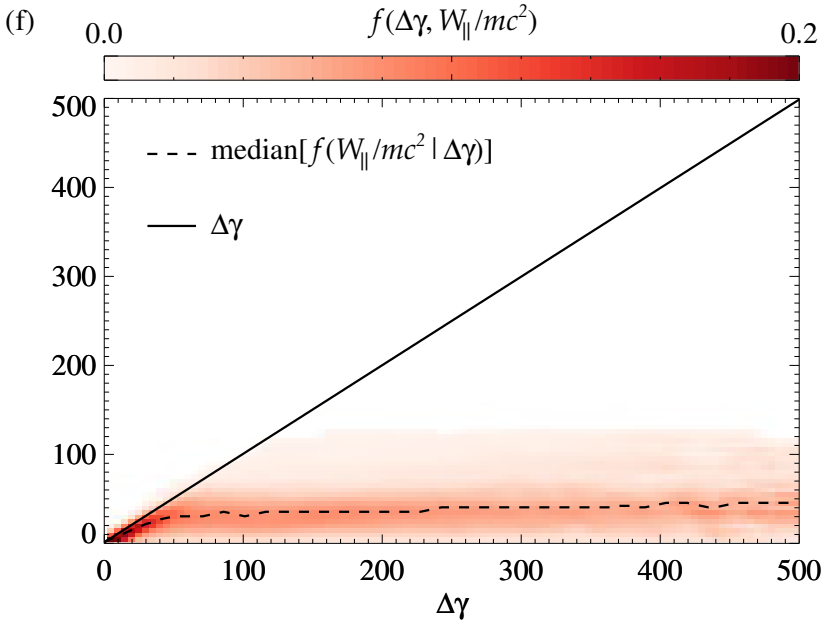
- At injection, most of the particles reside at $|J_{z,p}| \geq 2\,J_{z,\mathrm{rms}}$
- Locations with $|J_{z,p}| \geq 2\,J_{z,\mathrm{rms}}$ are strong current sheets

Particle Energization

$\left(W_{\parallel,\perp}(t) = q \int_0^t \boldsymbol{E}_{\parallel,\perp}(t') \cdot \boldsymbol{v}(t')\, dt' \right)$



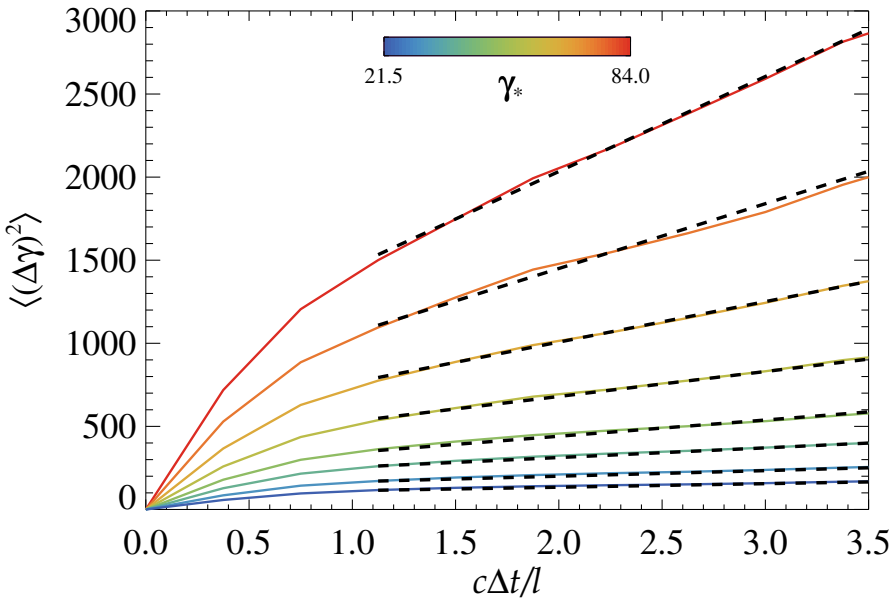


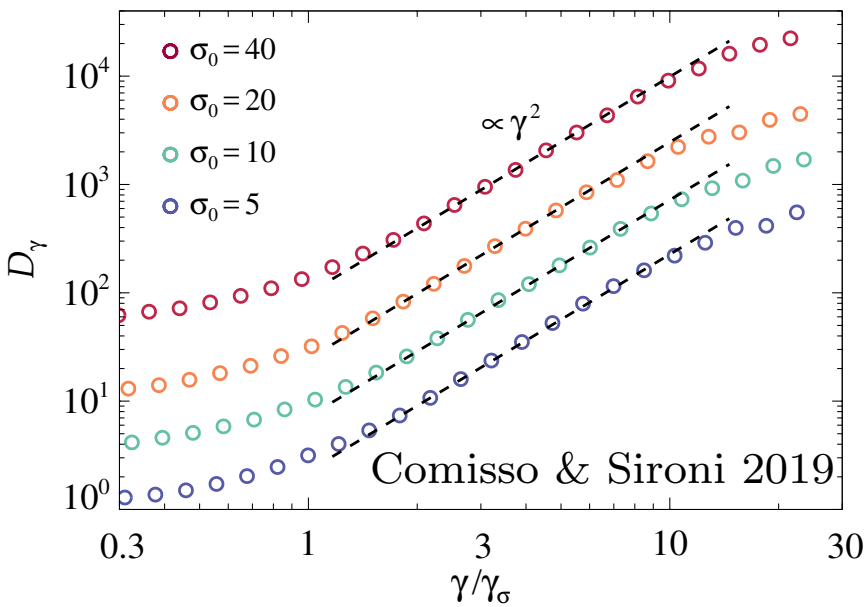


- $\Delta\gamma_{\rm inj} \sim W_\parallel/m_e c^2 \sim \sigma_0 \gamma_{th0}$
- $\boldsymbol{v} \cdot \boldsymbol{E}_\parallel$ energization is important initially (low $\Delta\gamma$-range)
- $\boldsymbol{v} \cdot \boldsymbol{E}_\perp$ energization gives the majority of particle energy

Comisso & Sironi 2019

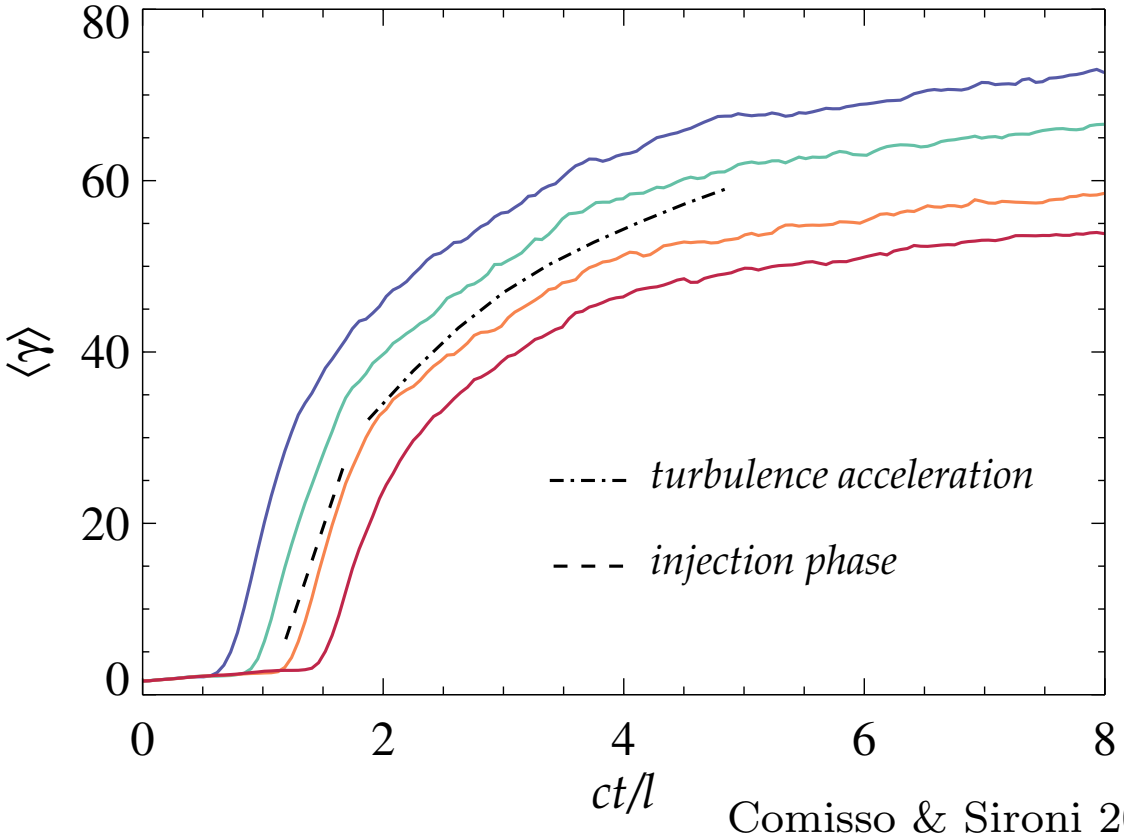
Stochastic Particle Acceleration





- From the self-consistent particles evolution we find (for $\gamma_* \gtrsim \gamma_\sigma$):
  $$\langle(\Delta\gamma)^2\rangle \propto \Delta t \;\Rightarrow \text{Diffusive behavior in energy space}$$
- The energy diffusion coefficient (in units of c/l) can be calculated as $D_\gamma = \dfrac{\langle(\Delta\gamma)^2\rangle}{2\Delta t}$ (see also Wong et al 20 for similar PIC results)
- The power-law tail of the particle spectrum starts at $\gamma/\gamma_\sigma \gtrsim 1$

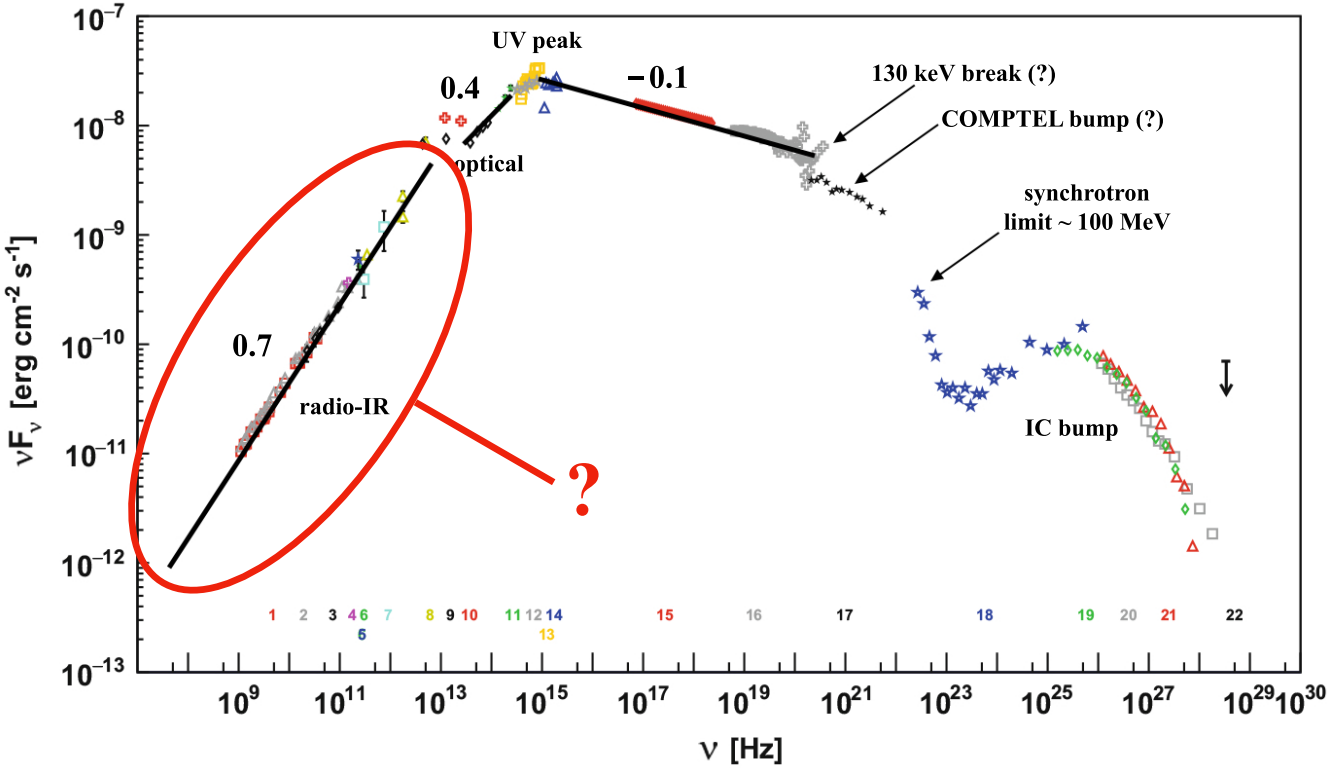
Two-Stage Acceleration Process



Comisso & Sironi 2018, 2019

- Injection phase controlled by $E_{\parallel} \Rightarrow \dfrac{d\langle\gamma\rangle}{dt} = \dfrac{e}{mc}\beta_R \delta B_{\rm rms}$
- Stochastic Acc. controlled by $D_\gamma \Rightarrow \dfrac{d\langle\gamma\rangle}{dt} = 0.4\sigma\left(\dfrac{c}{l}\right)\gamma$

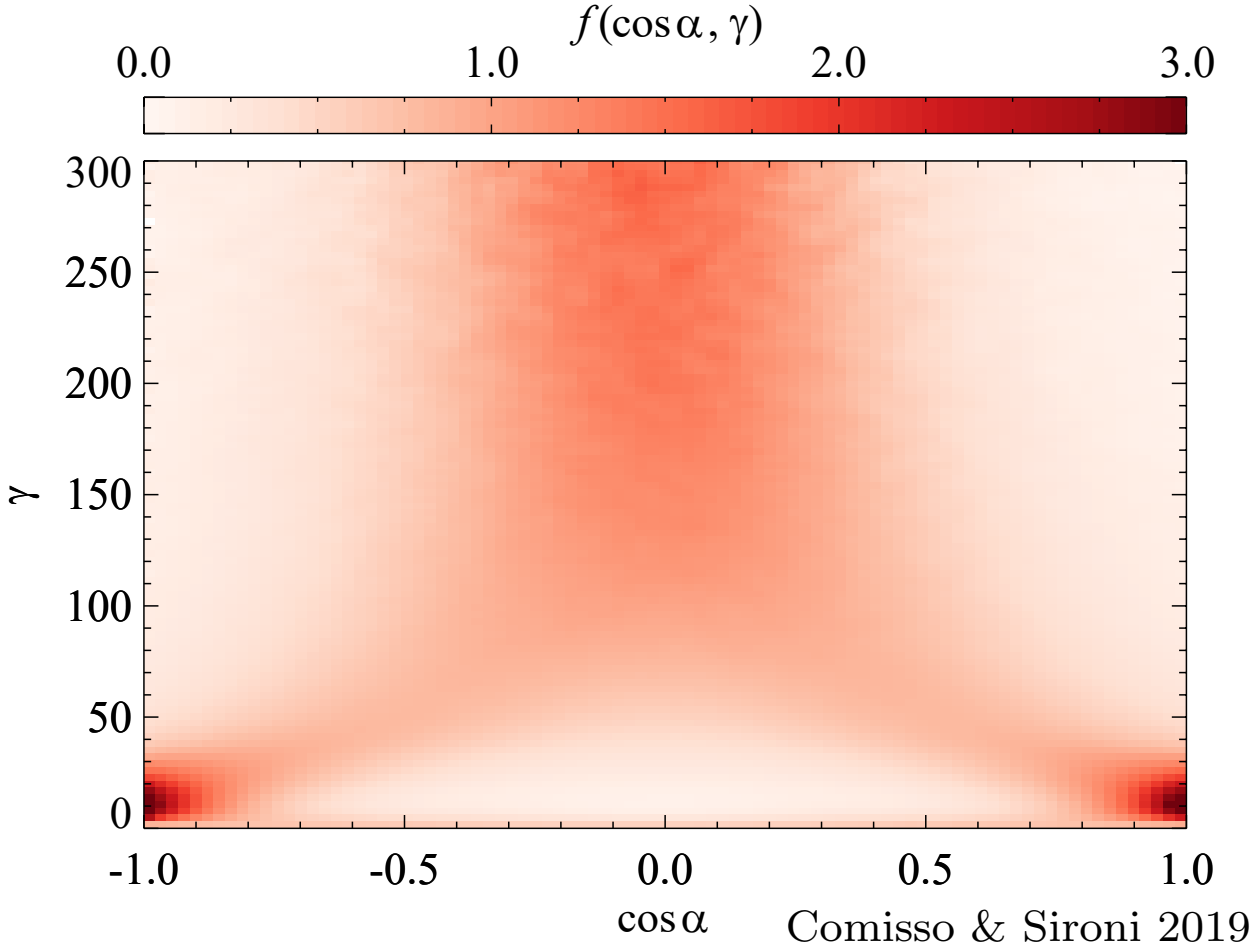
The Puzzling Radio Spectrum of the Crab Nebula



Zanin 2017, Lyutikov *et al.* 2019

- Why the spectrum in the radio is so hard ($\nu F_\nu \propto \nu^{0.7}$) ?
- Isotropic distribution of electrons implies $dN/d\gamma \propto \gamma^{-1.6}$
- An anisotropic distribution modifies this "requirement"

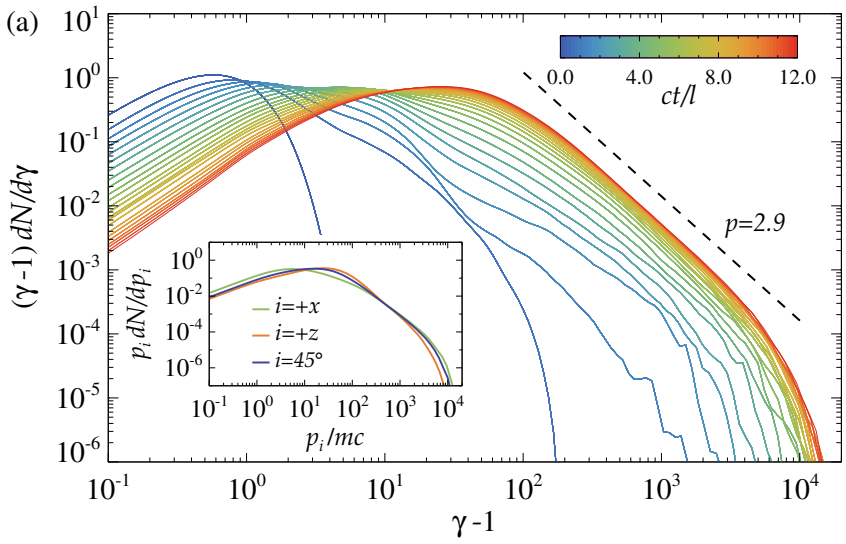
Anisotropy of the Pitch Angle Distribution

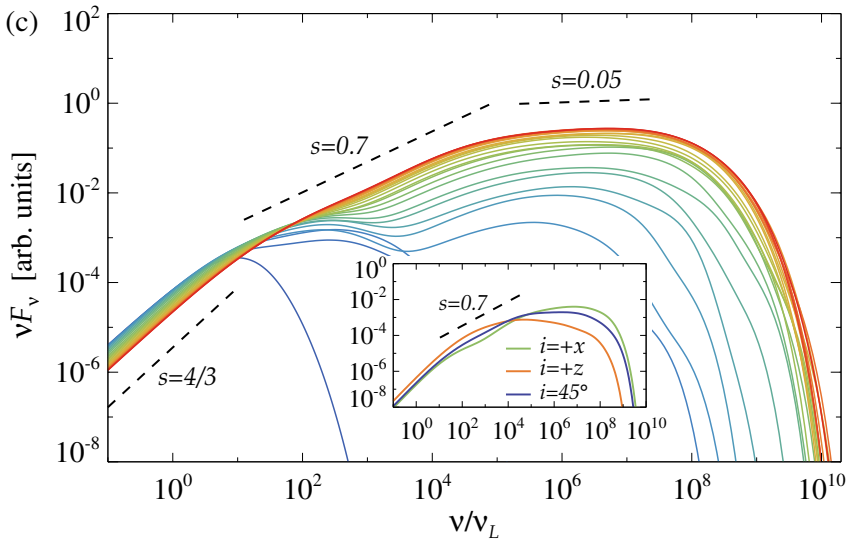


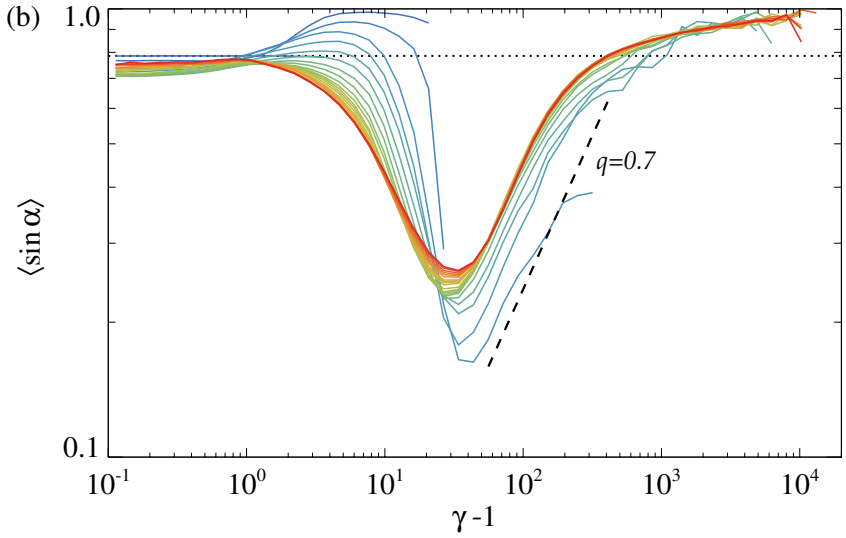
Comisso & Sironi 2019

- Here: $\cos\alpha = \dfrac{\boldsymbol{v}\cdot\boldsymbol{B}}{|\boldsymbol{v}|\,|\boldsymbol{B}|}\,, \quad \int_{-1}^{1} f\left(\cos\alpha, \gamma\right) d(\cos\alpha) = 1$
- The two stage acceleration process leads to anisotropic pitch angle distributions.

Hardened Synchrotron Spectrum







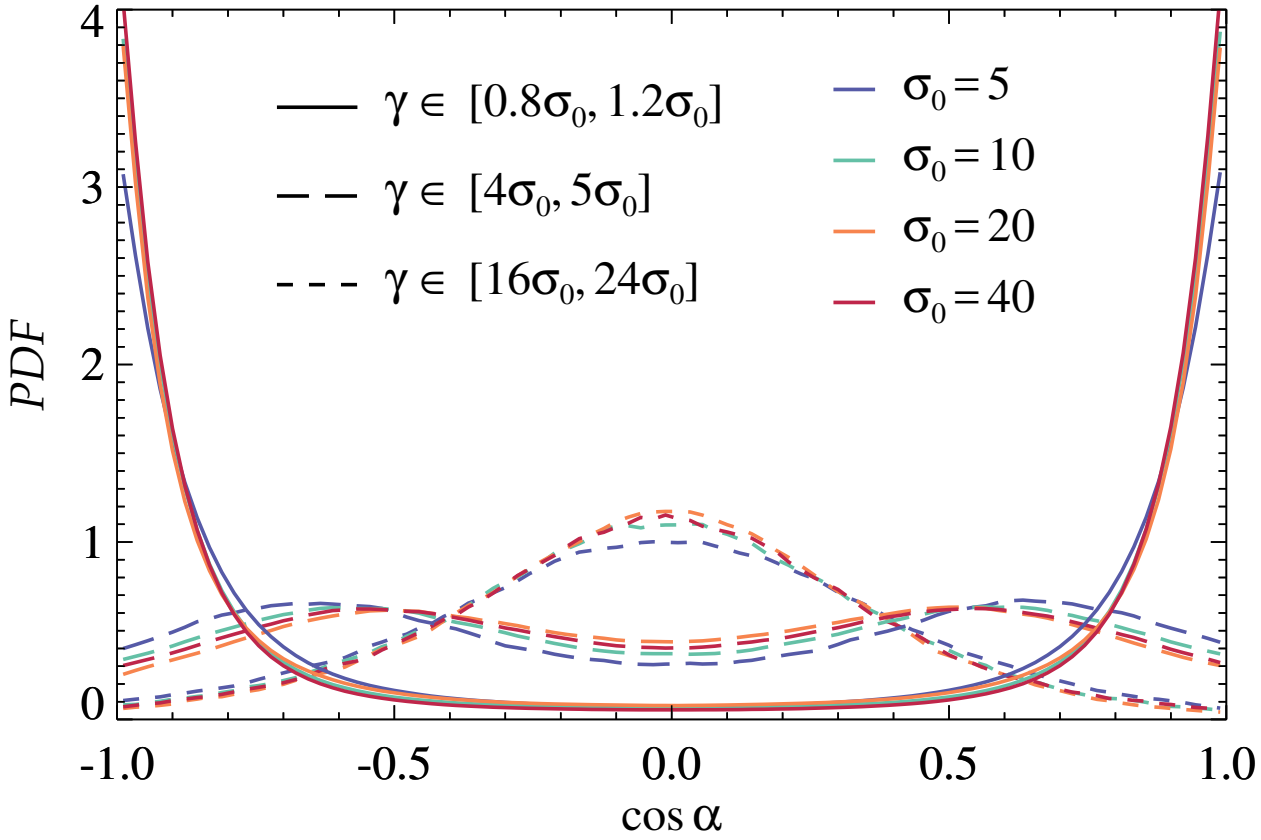
- Low frequencies: $\nu F_\nu \propto \nu^{4/3}$
- Intermediate frequencies: $\nu F_\nu \propto \nu^{(3-p+2q)/(2+q)}$
- High frequencies: $\nu F_\nu \propto \nu^{(3-p)/2}$

Comisso, Sobacchi, Sironi 2020

Summary

- Fully Kinetic Simultaneous Treatment of "Turbulence + Reconnection"
- High-Energy Particles are Generated Self-Consistently as a By-Product of Turbulence + Reconnection
- Particle Acceleration Follows a Two-Stage Process: Acceleration from Reconnection followed by Stochastic Acceleration by scattering off Turbulent Fluctuations
- Turbulence + Reconnection Generate Anisotropic Pitch Angle Distributions (Important for the Synchrotron Emission)

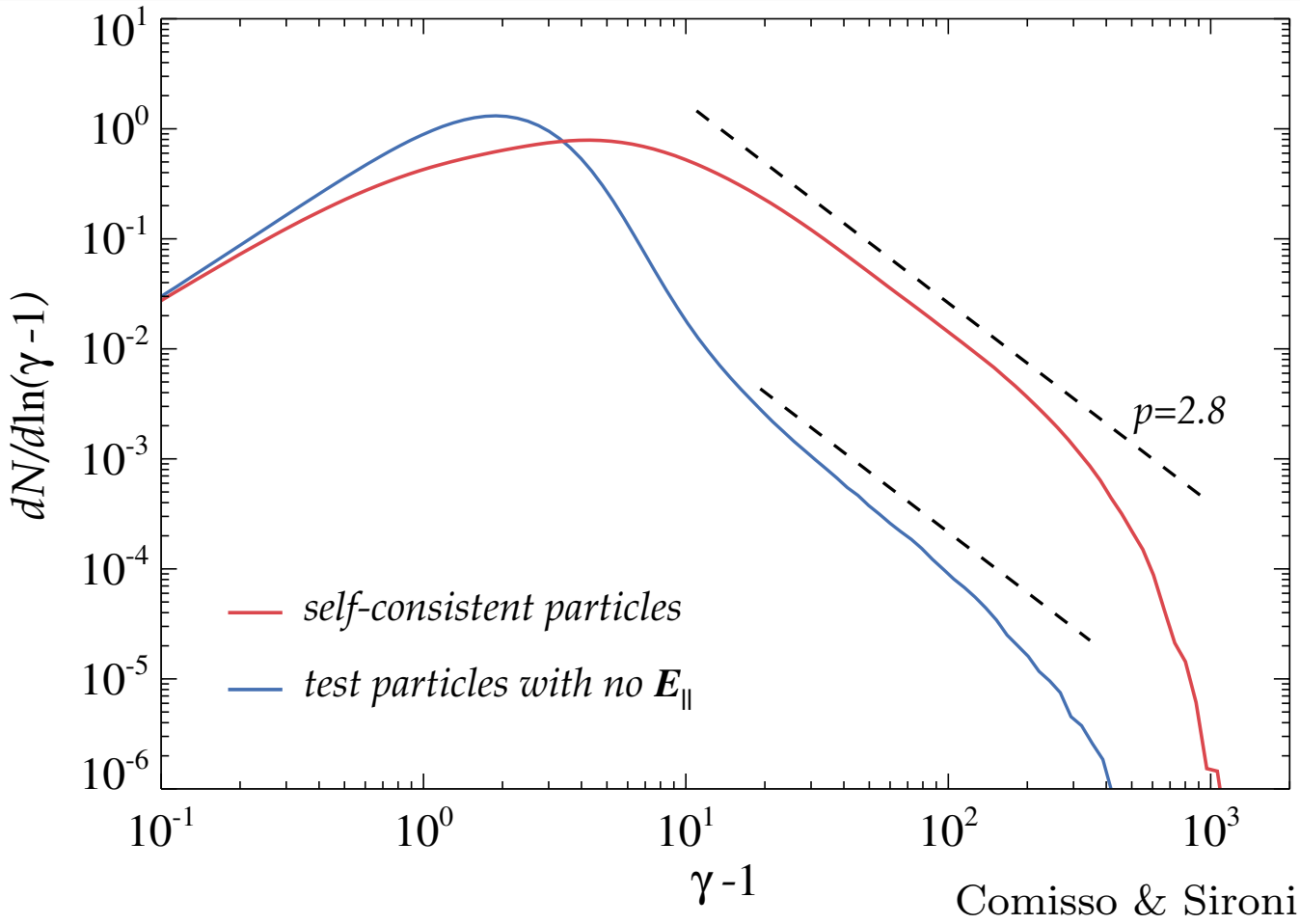
The anisotropy ranges are magnetization dependent



Comisso & Sironi 2019

- $\gamma \sim (\sigma_0/2)\gamma_{th0} \Rightarrow$ particles $\boldsymbol{v}$ are strongly anti/aligned with $\boldsymbol{B}$
- $\gamma \sim 5(\sigma_0/2)\gamma_{th0} \Rightarrow$ distribution with minima at $\cos\alpha = \pm 1, 0$
- $\gamma \gg 5(\sigma_0/2)\gamma_{th0} \Rightarrow$ particles $\boldsymbol{v}$ are mostly perpendicular to $\boldsymbol{B}$

What if we artificially remove $\boldsymbol{E}_{\parallel}$?



Comisso & Sironi 2019

- The normalization drops by 2 orders of magnitude (only $\sim 0.2\%$ of the particles in the non-thermal tail)
- On the other hand, the slope p is similar, as the high-energy particles "forget" their initial conditions

Biased Random Walk in Momentum Space

Fokker-Planck equation in energy space:

$$\frac{\partial N}{\partial t} = -\frac{\partial}{\partial \gamma}\left(A_\gamma N\right) + \frac{\partial^2}{\partial \gamma^2}\left(D_\gamma N\right)$$

The convection coefficient A_γ is related to the diffusion coefficient in energy space as

$$A_\gamma = \frac{d\langle\gamma\rangle}{dt} = \frac{1}{\gamma^2}\frac{\partial}{\partial \gamma}\left(\gamma^2 D_\gamma\right)$$

Using the previously obtained $D_\gamma = 0.1\sigma\left(\frac{c}{l}\right)\gamma^2$ we get

$$\frac{d\langle\gamma\rangle}{dt} = 0.4\sigma\left(\frac{c}{l}\right)\gamma$$