Particle Acceleration via Magnetized Turbulence and Magnetic Reconnection

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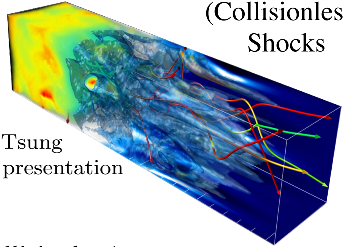
Outline

- A few words on the most commonly invoked plasma processes for particle acceleration
- I will argue that turbulence and magnetic reconnection should take place together in astrophysical plasmas
- Introduce the method (Fully Kinetic PIC) used to study particle acceleration
- Turbulence (with reconnection) as reproduced by Fully Kinetic PIC simulations
- Some hits on how particles are accelerated in Fully Kinetic PIC simulations of turbulence (with reconnection)
- Generation of power-law energy distribution from thermal distributions (focusing on protons)

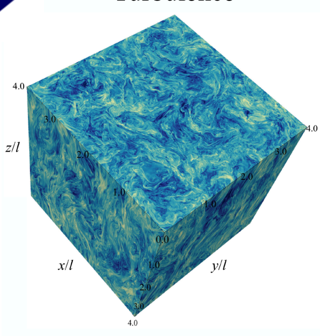
The Usual Suspects

(Collisionless)
Shocks



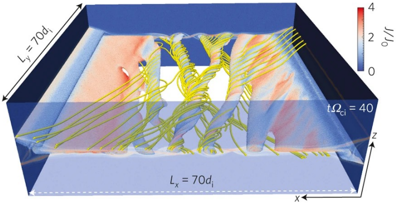
Tsung
Osiris presentation

(Collisionless)
Turbulence



Comisso & Sironi 2019

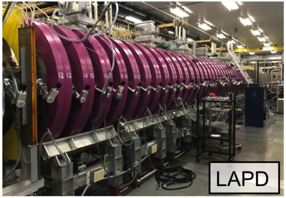
(Collisionless)
Magnetic Reconnection

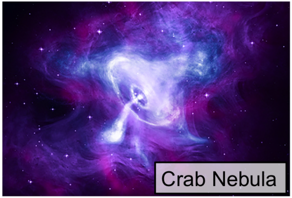


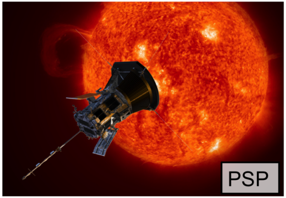
Daughton *et al.* 2014

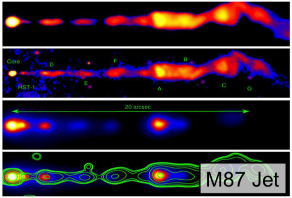
Magnetization Parameter

$\sigma \ll 1$ $\quad\quad$ $\sigma = \dfrac{B^2}{4\pi h}$ $\quad\quad$ $\sigma \gg 1$



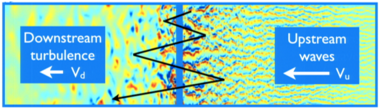




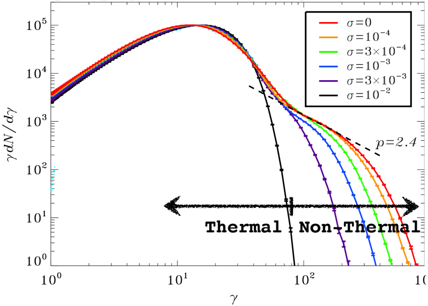


$$\sigma \gg 1 \implies v_A = c\sqrt{\sigma/(1+\sigma)} \simeq c \quad \text{(relativistic regime)}$$

Relativistic Shocks



Courtesy of F. Fiuza

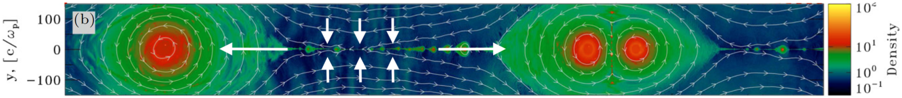


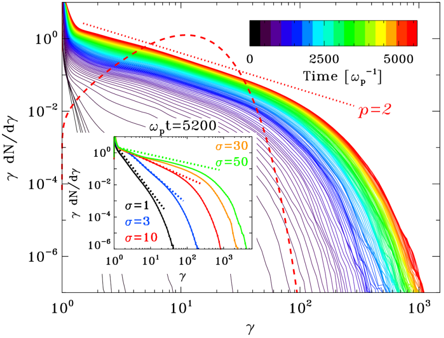
Sironi et al. 2013

- Shock acceleration: standard paradigm for many years
- Poor particle acceleration already for fairly modest plasma magnetizations

$\sigma \gtrsim 10^{-2} \Rightarrow$ no acceleration

See also Krymskii 1977, Axford *et al.* 1977, Blandford & Ostriker 1978, Bell 1978, Gallant *et al.* 1992, Spitkovsky 2008, Fiuza *et al.* 2012, ...





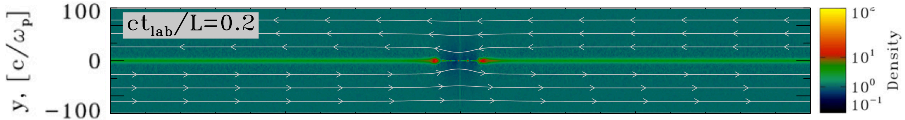
Sironi & Spitkovsky, 2014

- Efficient particle accelerator for fairly high plasma magnetizations

$\sigma \gtrsim 1 \Rightarrow$ acceleration

See also Zenitani & Hoshino 2001, Jaroschek *et al.* 2004, Lyubarsky & Liverts 2008, Cerutti *et al.* 2013, Guo *et al.* 2014, Werner *et al.* 2016, ...

Important Caveat

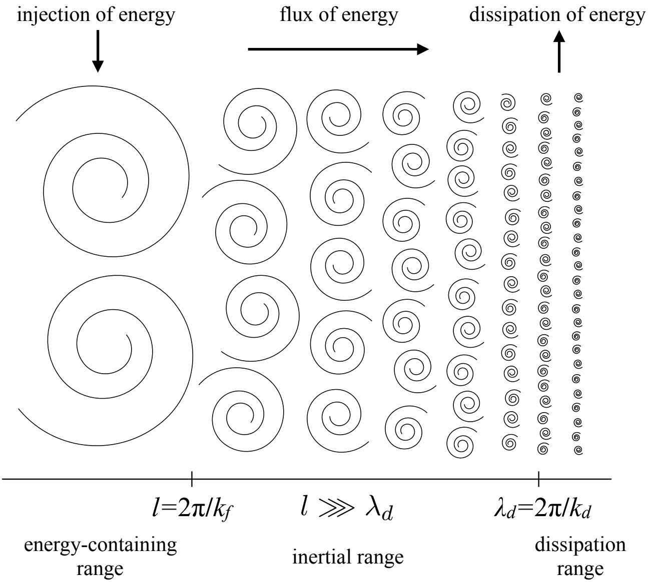


But simulations employ *ad hoc* (ultra-unstable) initial current sheets (having kinetic-scale thickness).

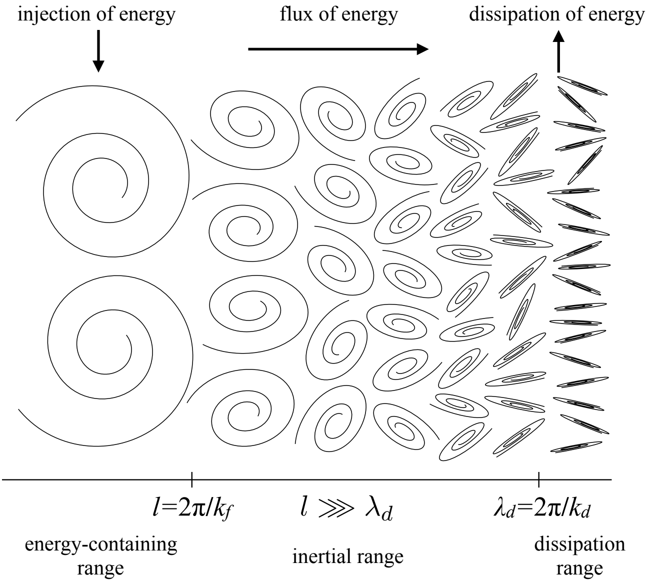
Astrophysical systems have large scale separation, $l \ggg \lambda_d$.

Under most circumstances, turbulence is inevitable (high Re).

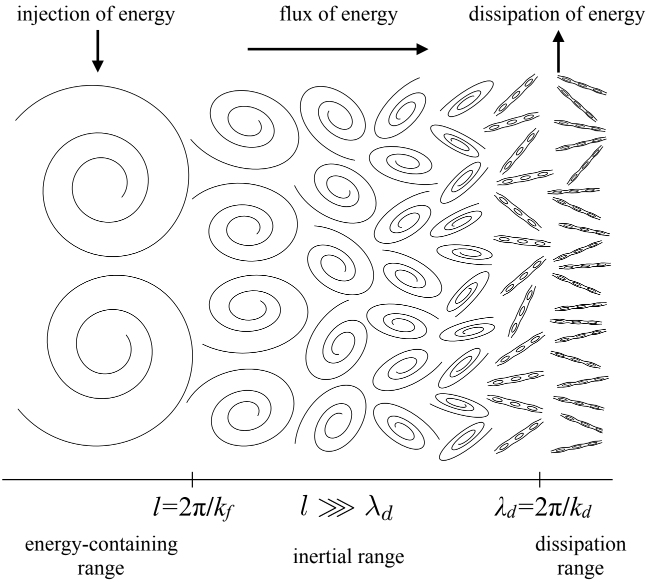
Turbulence Cascade à la Richardson



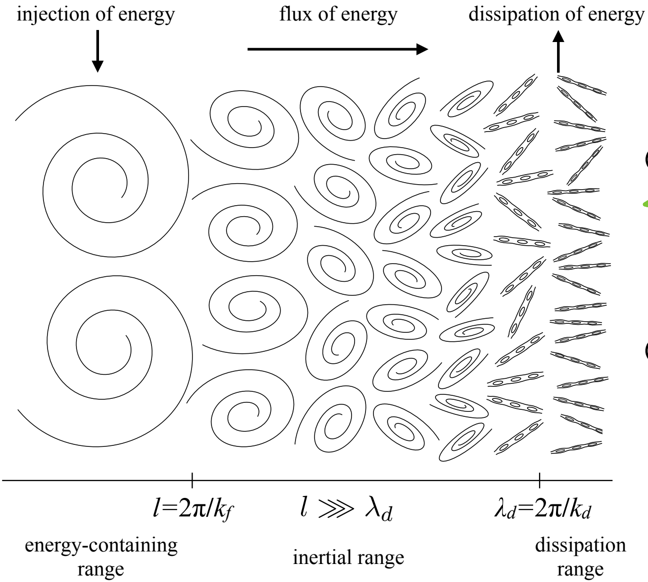
Turbulence Cascade with Magnetic Field

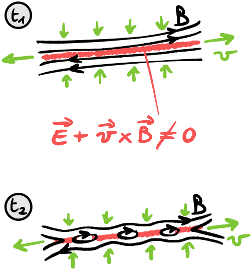


Turbulence Cascade with Magnetic Reconnection

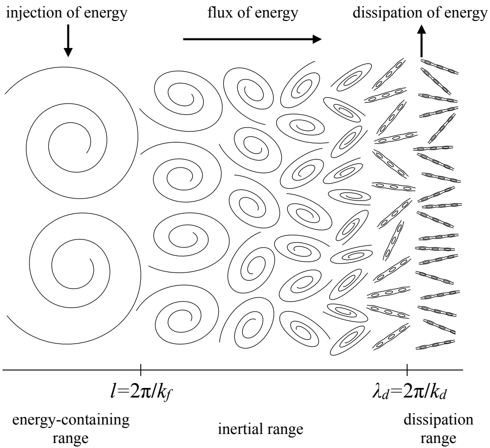


Turbulence Cascade with Magnetic Reconnection

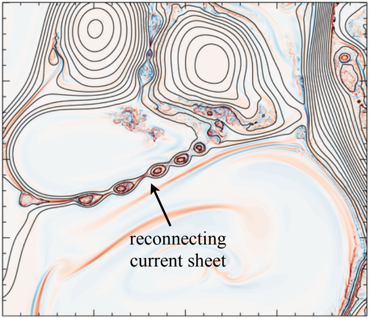




Turbulence Cascade with Magnetic Reconnection



out-of-plane electric current density
(magnetic field lines superimposed)

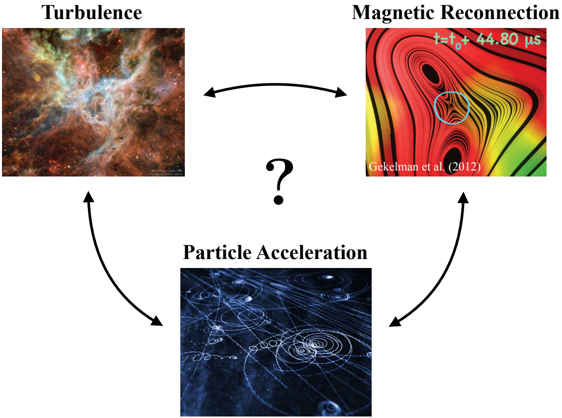


[zoomed-in subdomain from 2D turbulence simulation]

- Magnetic reconnection occurs in *intermittent current sheets*
  $\Rightarrow$ inevitable when $l \ggg \lambda_d$
  (essentially all astrophysical systems of interest here)

How Turbulence+Reconnection Accelerate Particles?

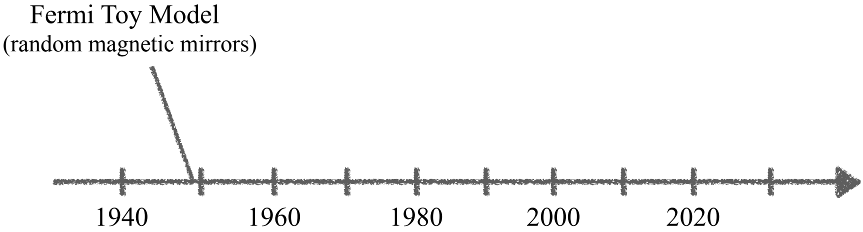
Turbulence + Reconnection + Particles:



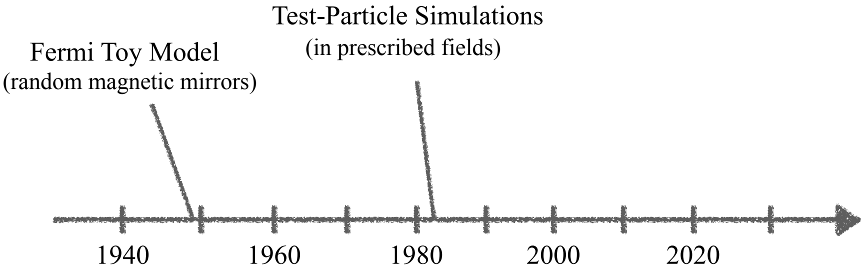
Solving the Full Problem: Timeline

Turbulence + ~~Reconnection~~ + Particles:

Complex, **Nonlinear**, **Multiscale** Problem



Turbulence + ~~Reconnection~~ + Particles:
Complex, **Nonlinear**, **Multiscale** Problem



Turbulence + ~~Reconnection~~ + Particles:

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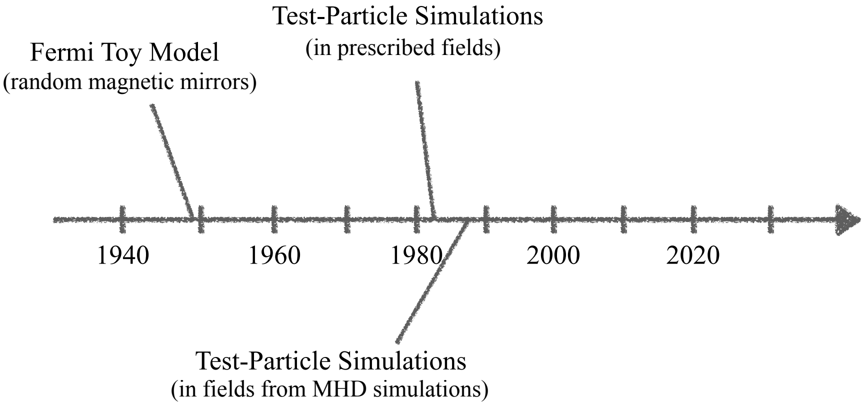

Turbulence + Reconnection + Particles:
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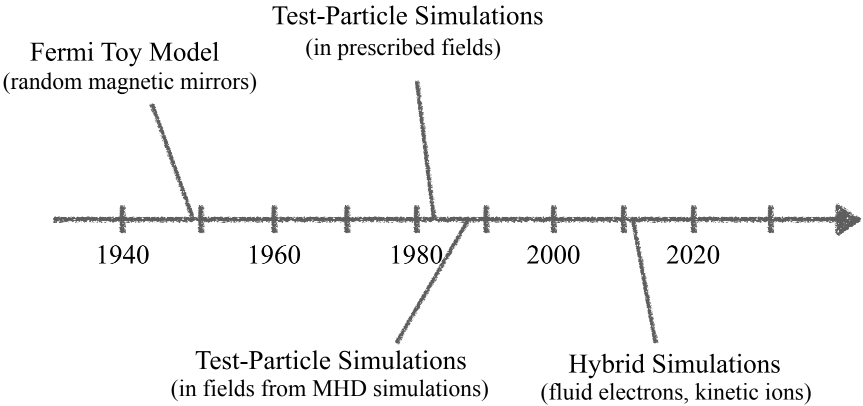
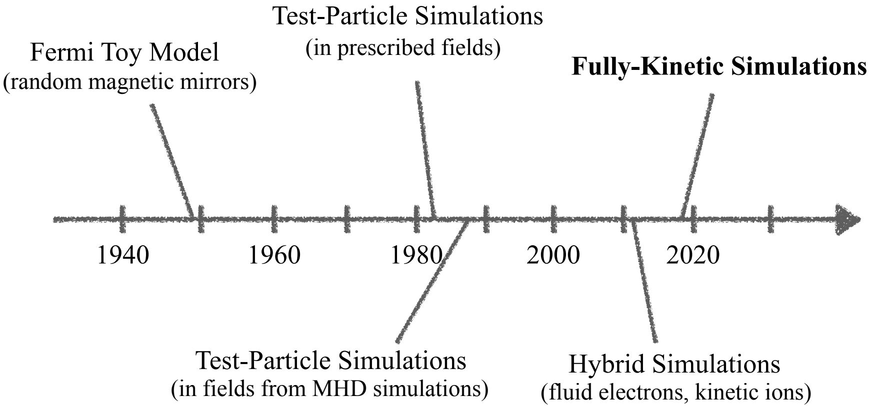
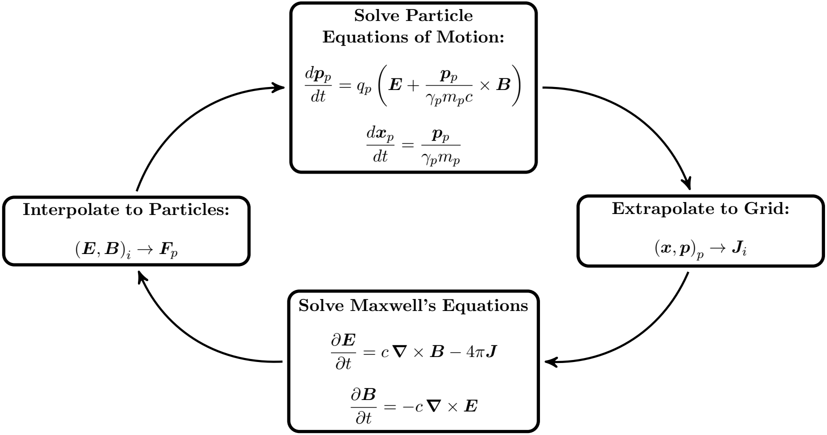


Turbulence + Reconnection + Particles:
Complex, **Nonlinear**, **Multiscale** Problem



Fully-Kinetic Treatment - PIC Method

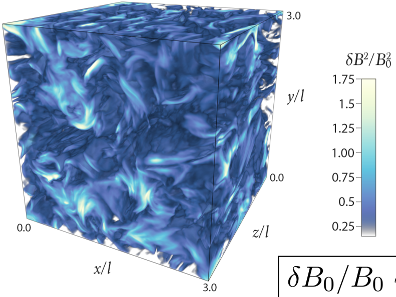


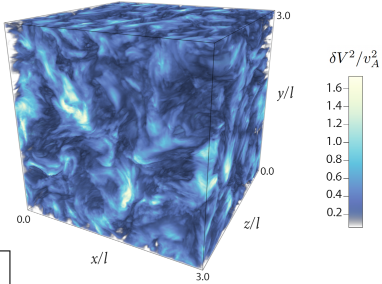
PIC code: TRISTAN-MP (Spitkovsky 2005)

Numerical Simulations with Massive Supercomputers

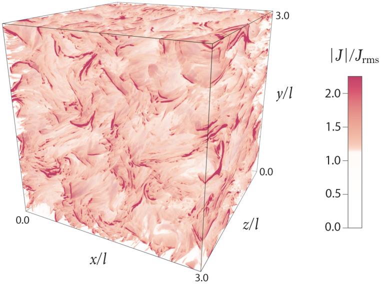
- This problem is hard (needs large separation of scales)
- We can do it now thanks to huge numerical simulations
  ($> 10^{10}$ cells, $> 2 \times 10^{11}$ particles)
- Here I'll present (scattered) results from simulations of: nonrealtivistic plasma turbulence, relativistic pair plasma turbulence, relativistic proton-electron plasma turbulence

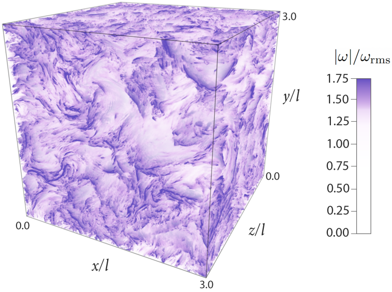
Turbulence Structures from PIC Simulations



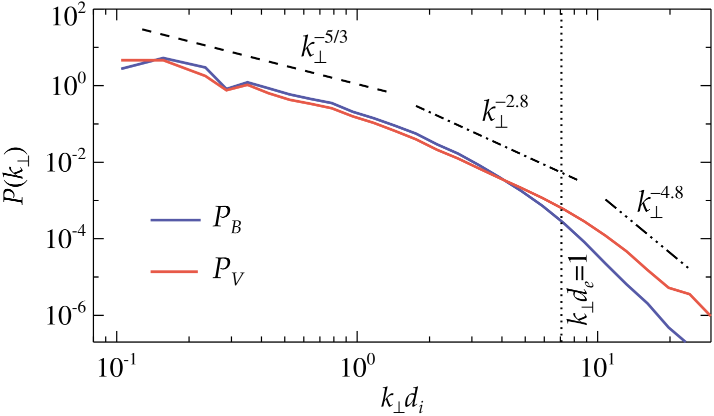


$$\delta B_0/B_0 \sim 1$$





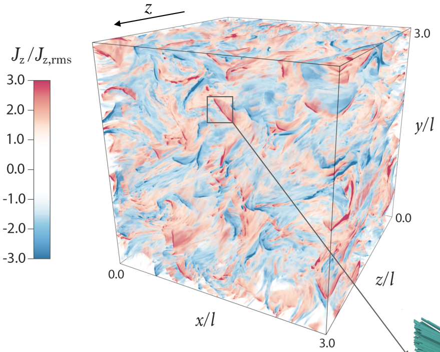
Turbulence Power Spectrum



Comisso & Sironi ApJL 2022

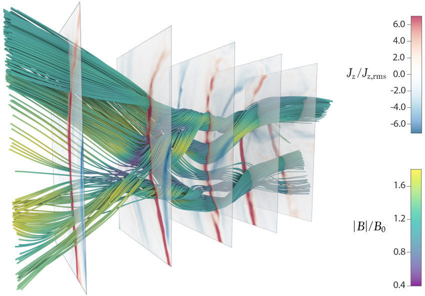
- The large computational domain allow us to capture both the MHD cascade at large scales and the kinetic cascade at small scales

Reconnecting Current Sheets in Turbulence

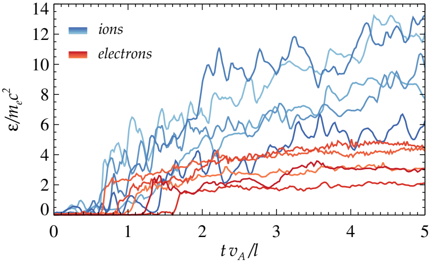


The large inertial range allows the development of reconnection layers with flux ropes

Comisso & Sironi 2022 (see also Comisso & Sironi 2018, 2019)

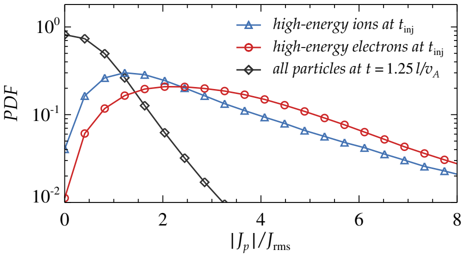


Current Sheets Initiate Particle Acceleration

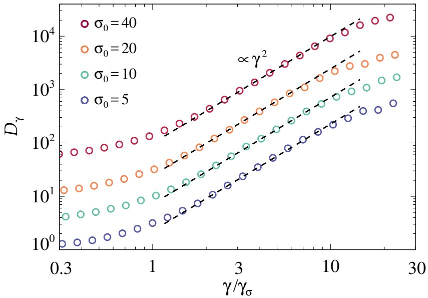


Sudden "injection phase" that brings particles to energies $\varepsilon \gg \varepsilon_{\rm th}$, followed by a more gradual stochastic Fermi acceleration phase

The initial particle acceleration is associated with locations of high current density (reconnecting sheets)



Stochastic Fermi Acceleration for $\gamma/\gamma_\sigma \gtrsim 1$



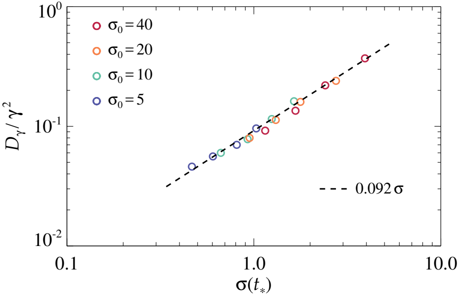
The power-law tail of the particle spectrum starts at $\gamma/\gamma_\sigma \gtrsim 1$

(γ_σ is the mean Lorentz factor after turbulent dissipation)

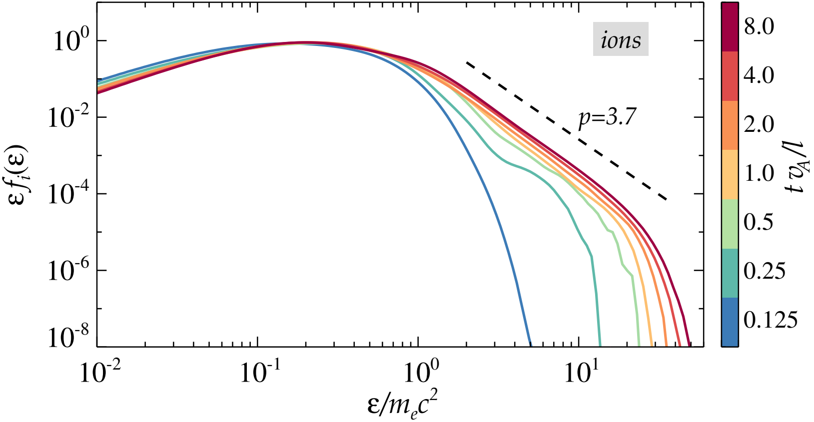
PIC simulations are well fitted by

$$D_\gamma \sim 0.1\sigma \left(\frac{c}{l}\right) \gamma^2$$

Comisso & Sironi 2019



Development of a Nonthermal Power-Law Tail



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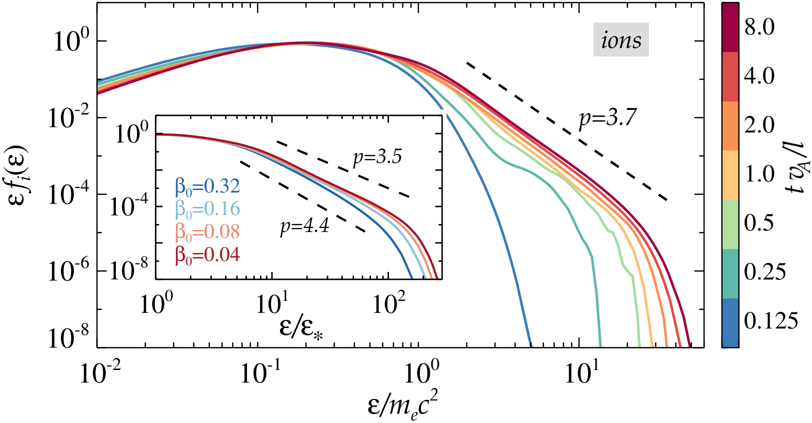
- Self-consistent formation of a nonthermal power-law tail. Here, $f_i(\varepsilon) = dN(\varepsilon)/d\varepsilon$, $\varepsilon = (\gamma - 1)m_ic^2$, $p = -d\ln f_i/d\ln\varepsilon$

Development of a Nonthermal Power-Law Tail



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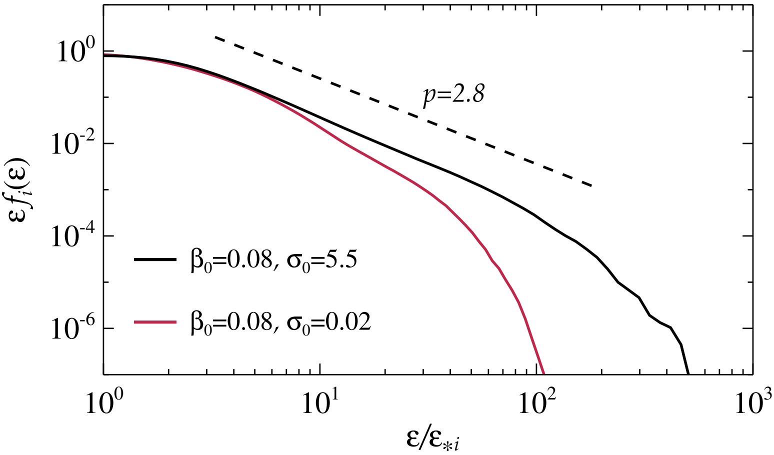
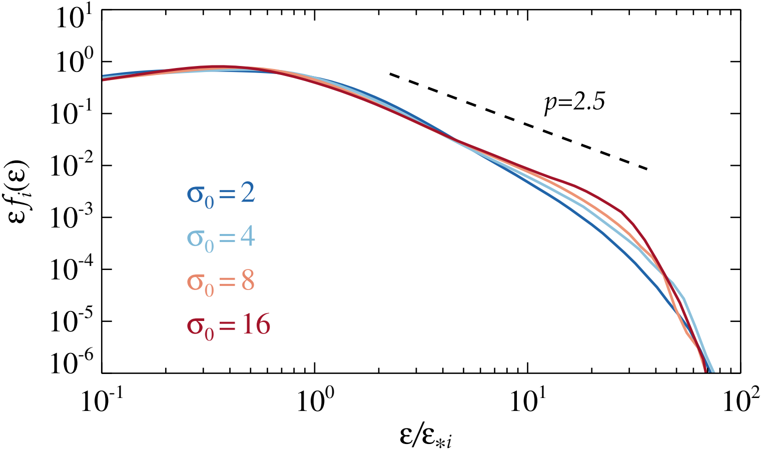
- Self-consistent formation of a nonthermal power-law tail. Here, $\beta_0 = \beta_{i0} + \beta_{e0}$, with $\beta_{i0} = \beta_{e0} = 8\pi n_0 k_B T_0 / B_0^2$

The Spectrum Hardens for Increasing σ_0



- Here, $\varepsilon_{*i} = (3/2)k_B T_0 + \kappa_i \, \Delta\bar{\varepsilon}_{i,e} = (3/2 + 2\kappa_i/\beta_0)k_B T_0$ is the mean energy per particle after turbulent dissipation

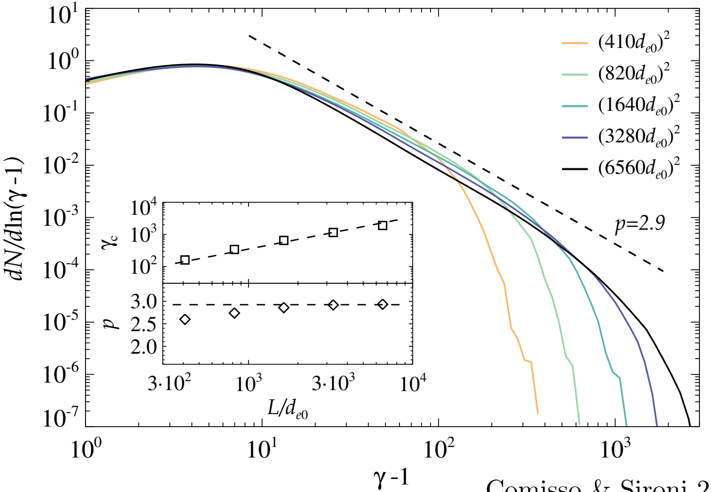
Hardening of the Ion Spectrum for Increasing σ_0



- Hardening of the ion energy spectrum for increasing plasma magnetization (relativistic regime $\sigma_0 \gtrsim 1$)

Acceleration up to $\rho_L \sim$ outer scale eddy size

Here shown for a pair plasma...



Comisso & Sironi 2018

Summary

- *Fully Kinetic Simultaneous Treatment* of Turbulence, Reconnection, and Particle Acceleration.

- High-Energy Particles are Generated Self-Consistently as a By-Product of Turbulence + Reconnection.

- Particle Acceleration Follows a Two-Stage Process.

- Self-consistent Formation of a Nonthermal Power-Law Tail (starting from a thermal distribution) up to $\rho_L \sim$ outer scale eddy size.

- Hardening of the Proton Energy Spectrum for Higher Plasma Magnetization (Relativistic Regime).