From Turbulence to Reconnection to Particle Acceleration: Connecting the Dots

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Particle Acceleration in Astrophysical Objects
Astronomical Observatory of Rome
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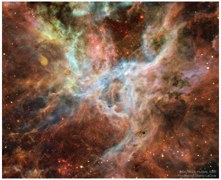
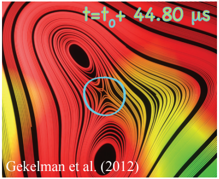
COLUMBIA UNIVERSITY
IN THE CITY OF NEW YORK

Outline

Turbulence

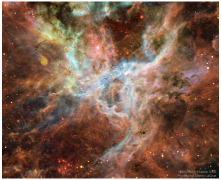


Magnetic Reconnection



Particle Acceleration

Turbulence



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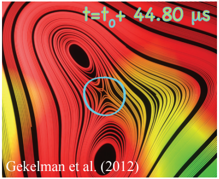
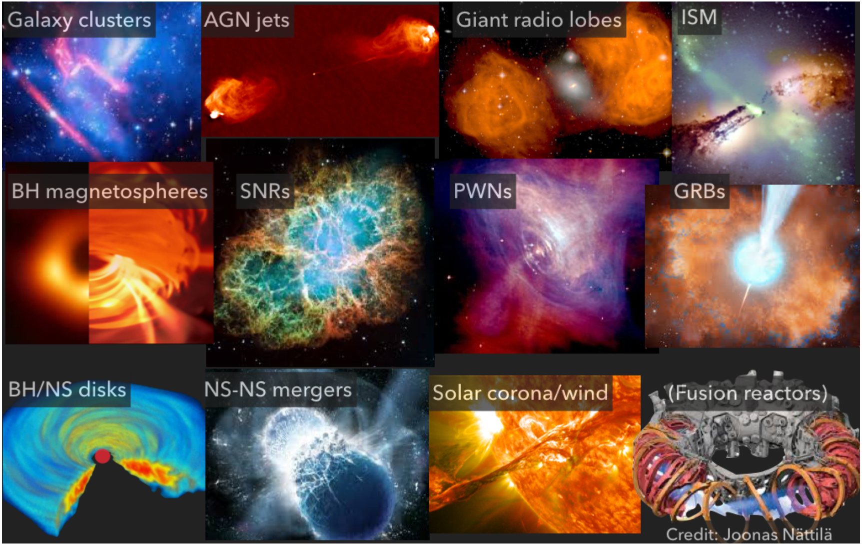
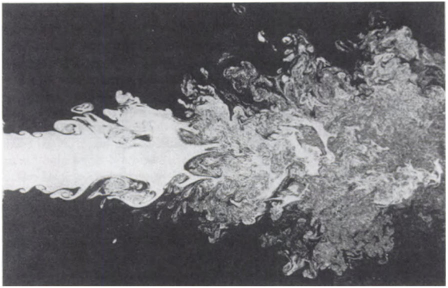


?

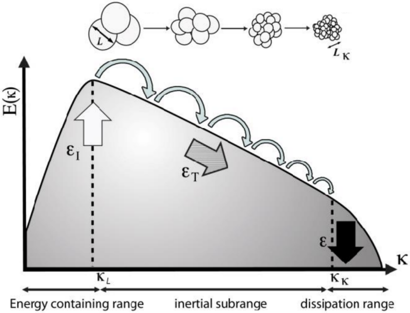
Particle Acceleration

Turbulent Plasmas are Ubiquitous





Gallery of Fluid Motion

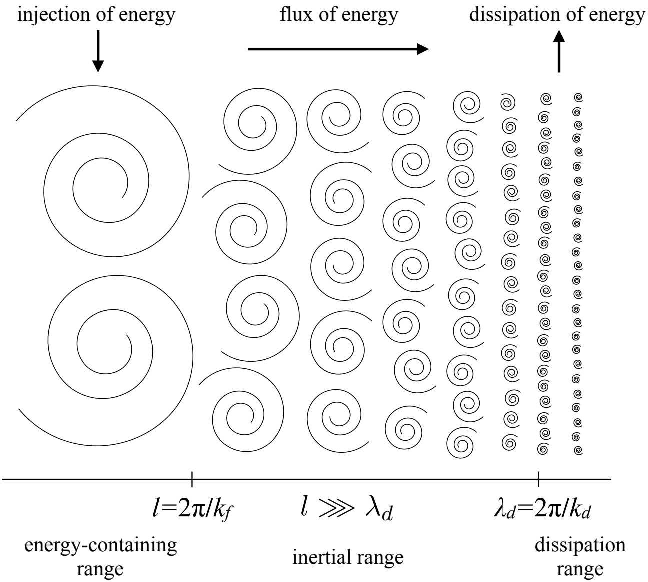


Sagaut et al. 2013

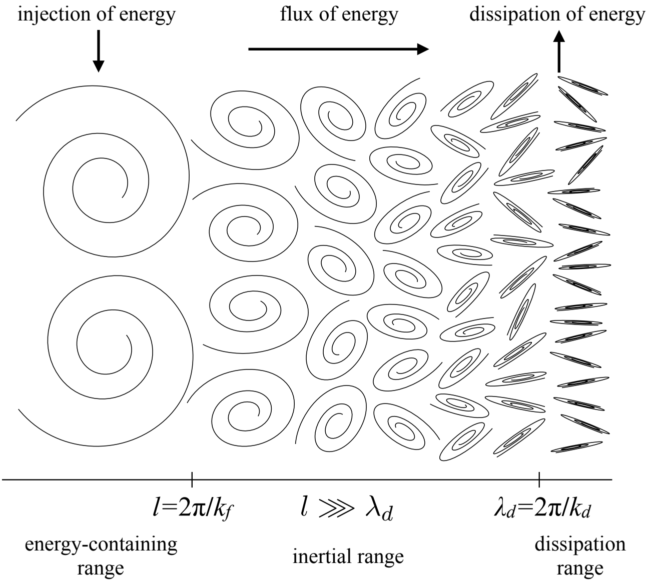
Big whirls have little whirls,
That feed on their velocity;
And little whirls have lesser whirls,
And so on to viscosity.

Lewis Fry Richardson

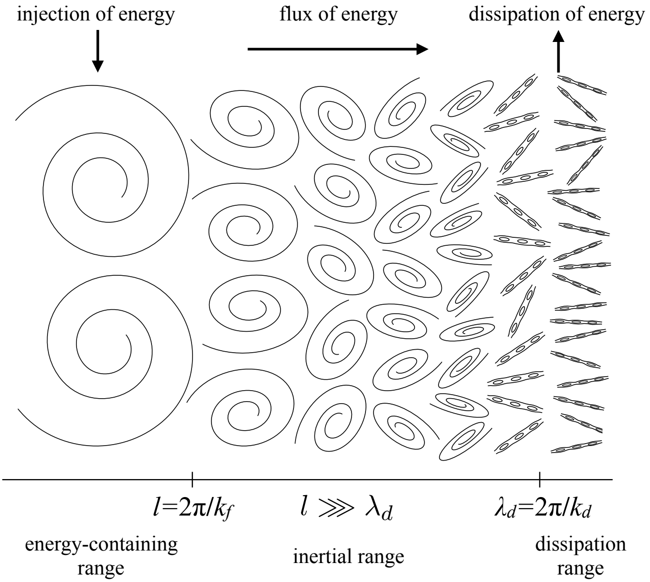
Turbulence Cascade à la Richardson



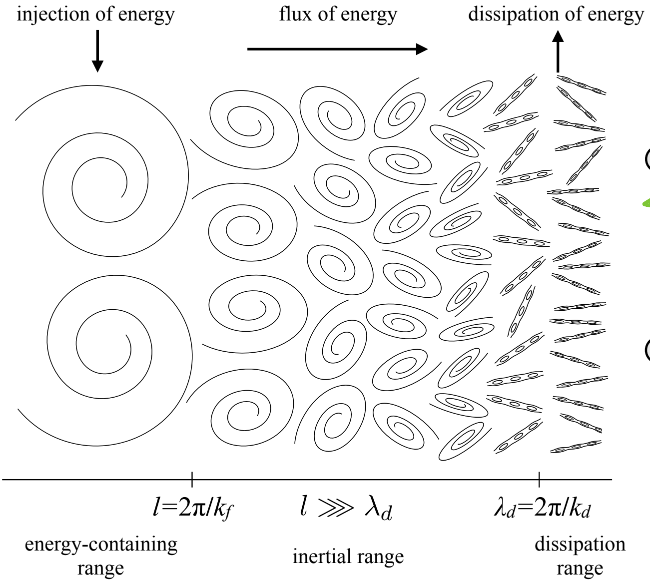
Turbulence Cascade with Magnetic Field

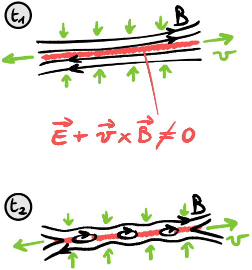


Turbulence Cascade with Magnetic Reconnection

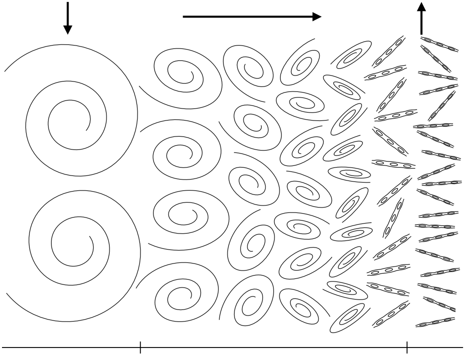


Turbulence Cascade with Magnetic Reconnection

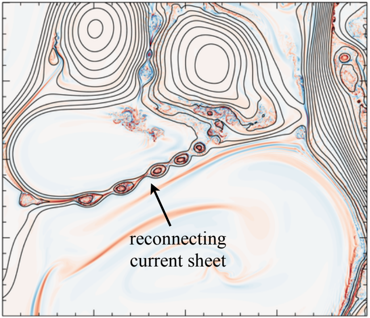




Turbulence Cascade with Magnetic Reconnection



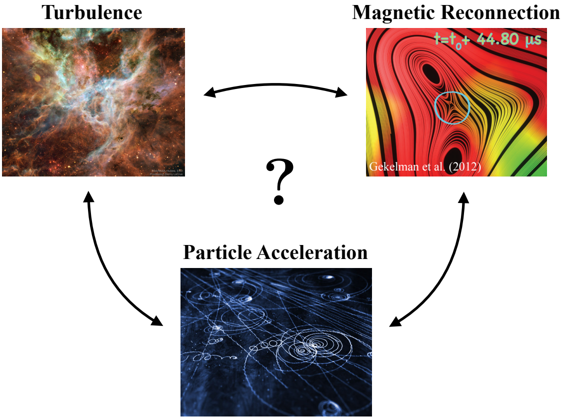
out-of-plane electric current density
(magnetic field lines superimposed)



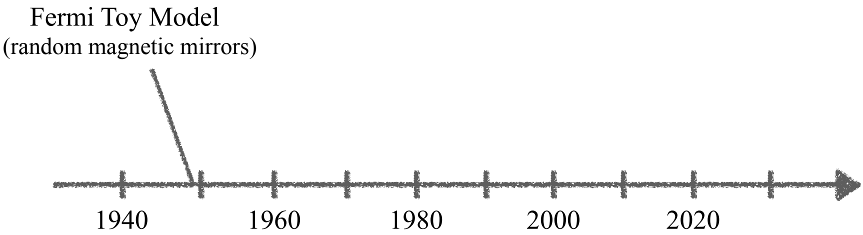
[zoomed-in subdomain from 2D turbulence simulation]

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

Turbulence + Reconnection + Particles:



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



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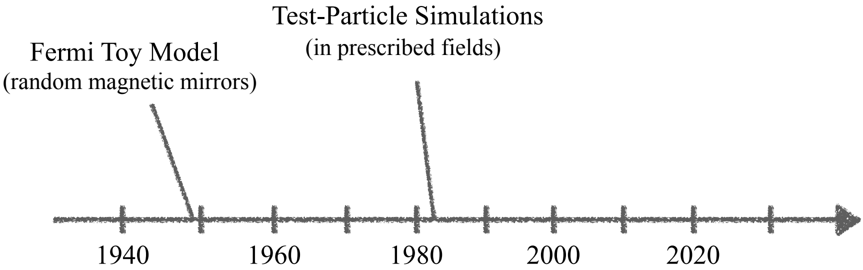
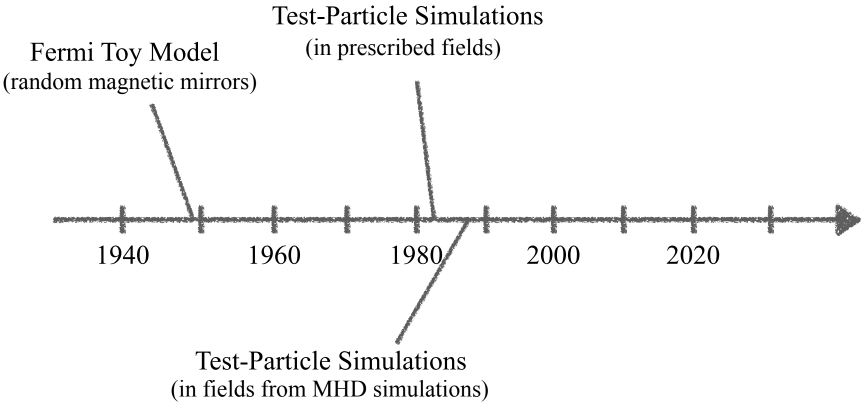


Solving the Full Problem: Timeline

Turbulence + ~~Reconnection~~ + Particles:

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



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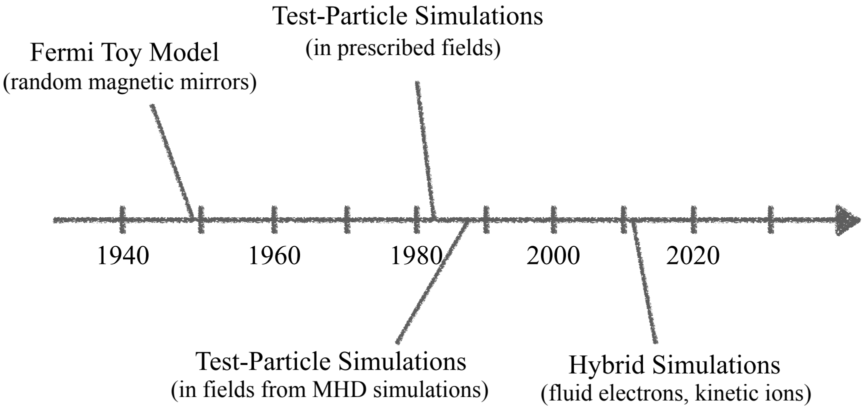
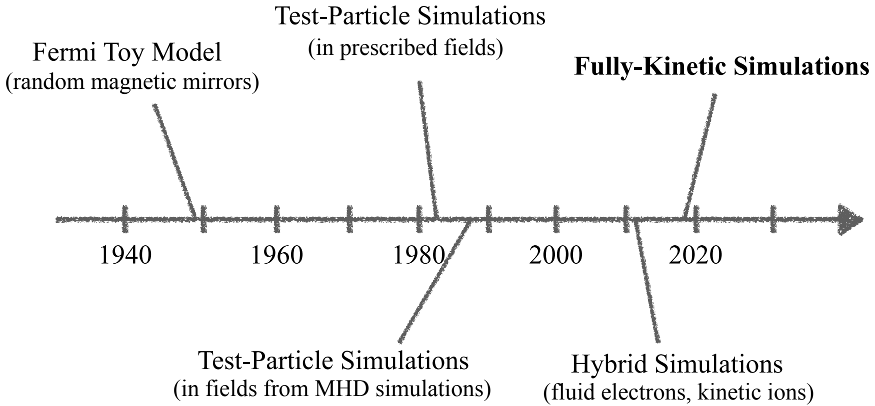


Solving the Full Problem: Timeline

Turbulence + Reconnection + Particles:

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



Fully-Kinetic Treatment - PIC Method

Solve Particle Equations of Motion:

$$\frac{d\boldsymbol{p}_p}{dt} = q_p \left(\boldsymbol{E} + \frac{\boldsymbol{p}_p}{\gamma_p m_p c} \times \boldsymbol{B} \right)$$

$$\frac{d\boldsymbol{x}_p}{dt} = \frac{\boldsymbol{p}_p}{\gamma_p m_p}$$

Extrapolate to Grid:

$$(\boldsymbol{x}, \boldsymbol{p})_p \to \boldsymbol{J}_i$$

Solve Maxwell's Equations

$$\frac{\partial \boldsymbol{E}}{\partial t} = c\, \boldsymbol{\nabla} \times \boldsymbol{B} - 4\pi \boldsymbol{J}$$

$$\frac{\partial \boldsymbol{B}}{\partial t} = -c\, \boldsymbol{\nabla} \times \boldsymbol{E}$$

Interpolate to Particles:

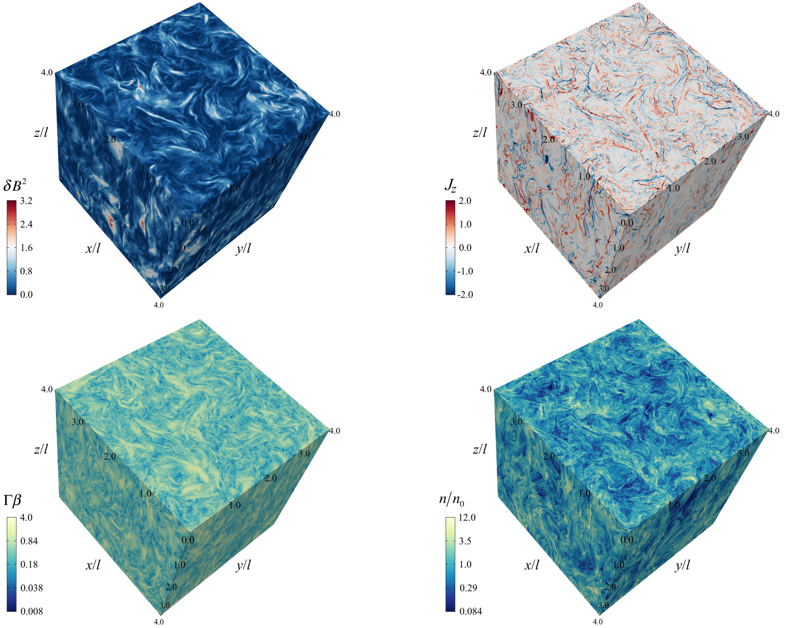
$$(\boldsymbol{E}, \boldsymbol{B})_i \to \boldsymbol{F}_p$$

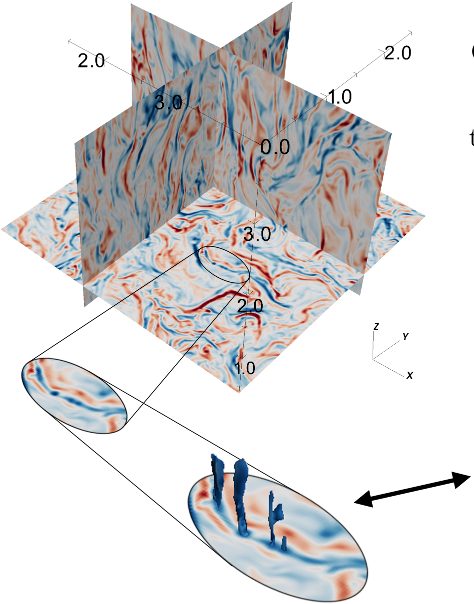
PIC code: TRISTAN-MP (Spitkovsky 2005)

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)

Turbulence Structures from PIC Simulations

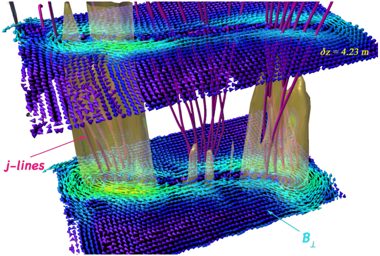




Comisso & Sironi, 2018, 2019

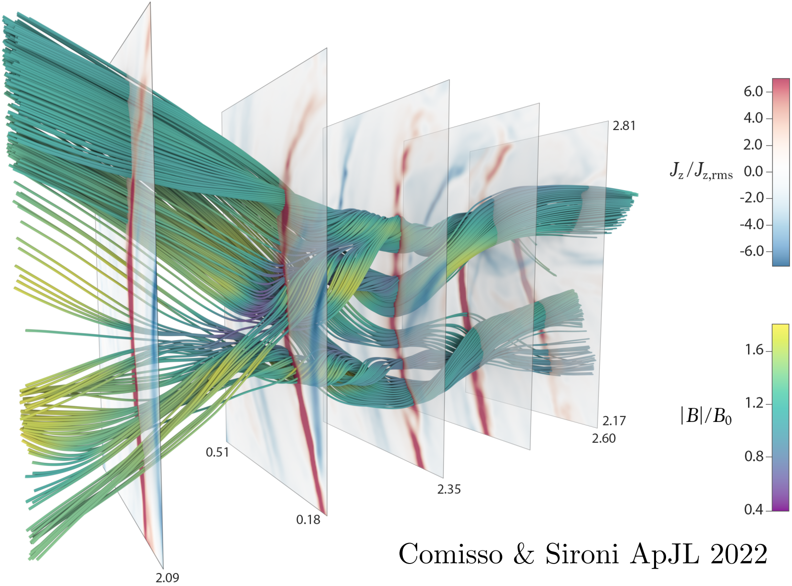
The large inertial range allows the development of reconnection layers with flux ropes

Reconnection with flux ropes in dedicated lab experiment



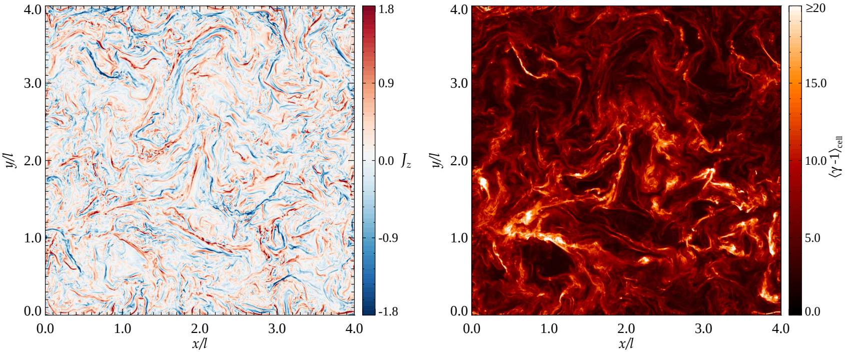
Gekelman *et al.* 2016

Reconnecting Current Sheets in Turbulence



Comisso & Sironi ApJL 2022

Reconnecting Current Sheets and Energization

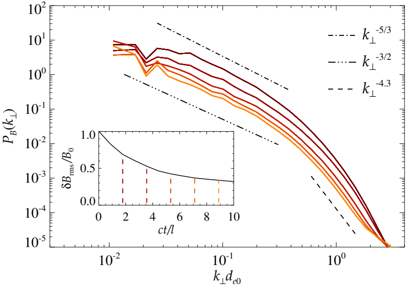


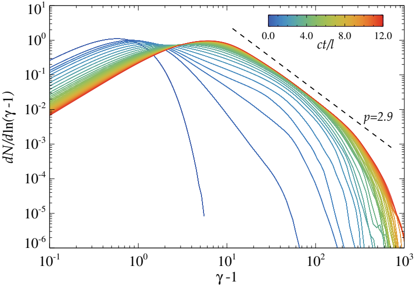
3D PIC turbulence simulation at 2460^3

- Reconnecting current sheets are sites of particle energization
  (only up to moderate energy, as we will see later)

Heating and Particle Acceleration

- Where does the dissipated turbulent energy go?





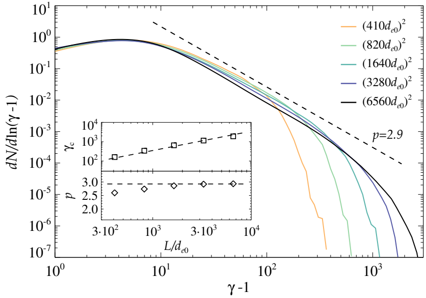
$$\text{Plasma Heating } (\Delta\gamma \sim \gamma_{th0}\sigma_0/2)$$

$$+$$

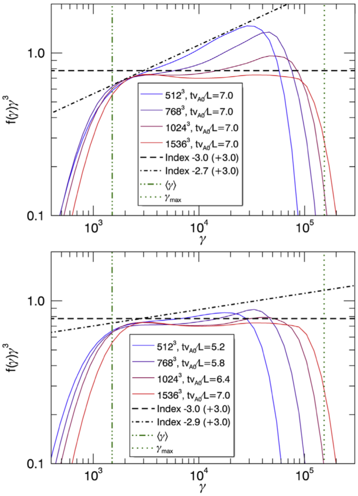
$$\text{Nonthermal Particle Acceleration } (\Delta\gamma \gg \gamma_{th0}\sigma_0/2)$$

Here $\sigma_0 = \dfrac{\delta B_0^2}{4\pi h_0}$, which is $\gg 1$ here. We also have $\dfrac{\delta B_0}{B_0} \sim 1$.

Generation of power-law particle energy distributions



Comisso & Sironi 2018

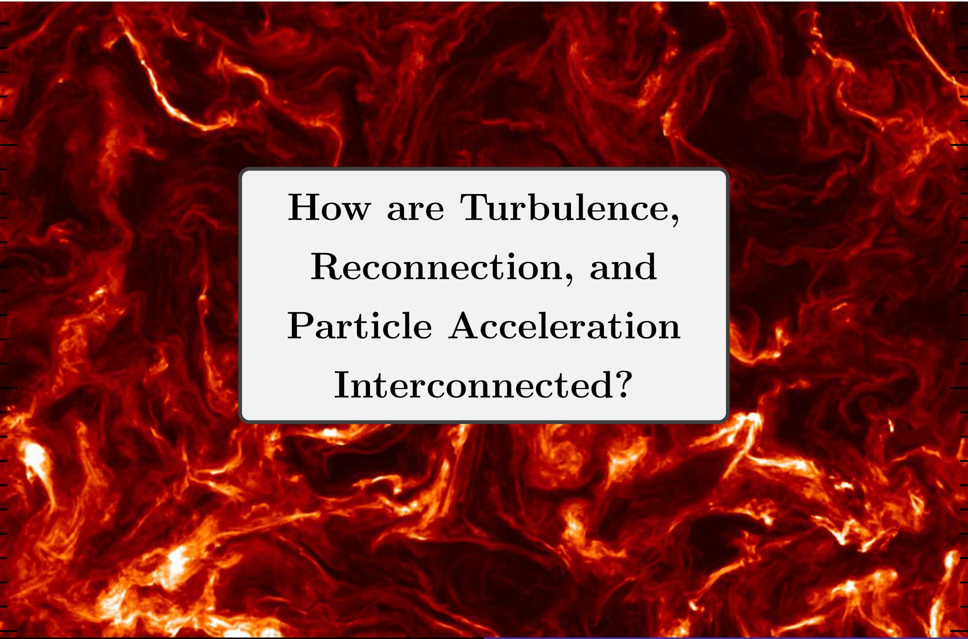


Zhdankin *et al.* 2018

- Turbulence produces robust power-law particle energy distributions for systems with

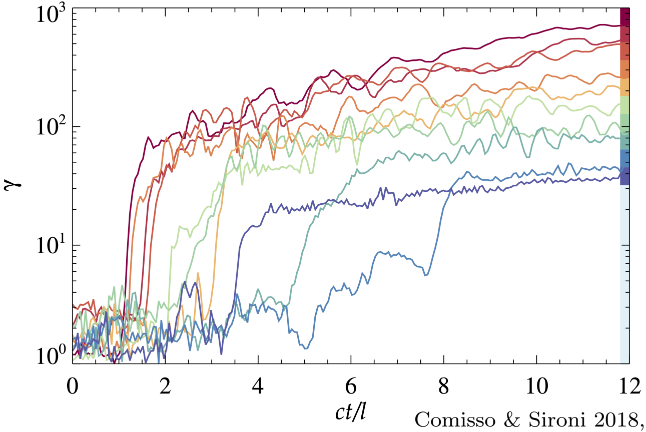
$$L \gg \text{kinetic scales}$$

Let’s Dive Into the Particle Acceleration Mechanism



How are Turbulence, Reconnection, and Particle Acceleration Interconnected?

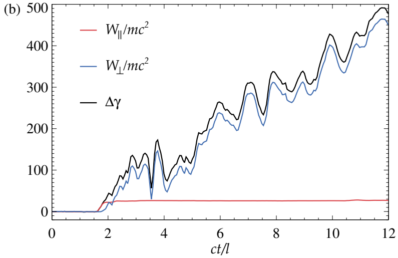
Two Stages of Particle Acceleration

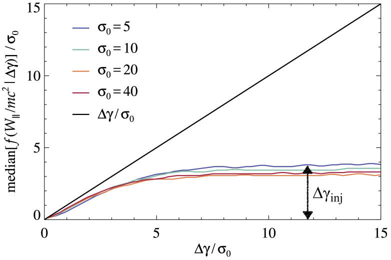


Comisso & Sironi 2018, 2019

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

1st Acceleration Stage ("Injection")



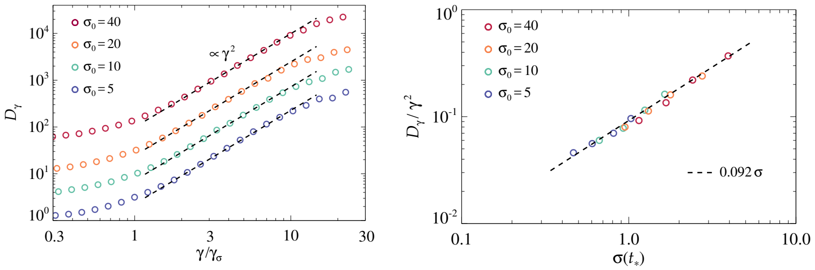


$$W_{\parallel,\perp}(t) = q \int_0^t \boldsymbol{E}_{\parallel,\perp}(t') \cdot \boldsymbol{v}(t')\, dt'$$

- $\Delta\gamma_{\rm inj} \sim W_{\parallel}/m_e c^2 \sim \sigma_0 \gamma_{th0}$ (Comisso & Sironi 2018, 2019)
- $\boldsymbol{v} \cdot \boldsymbol{E}_{\parallel}$ energization is important initially (low $\Delta\gamma$-range)

  ($\boldsymbol{v} \cdot \boldsymbol{E}_{\perp}$ energization is responsible for further acceleration)

2nd Acceleration Stage (Stochastic Fermi Acceleration)



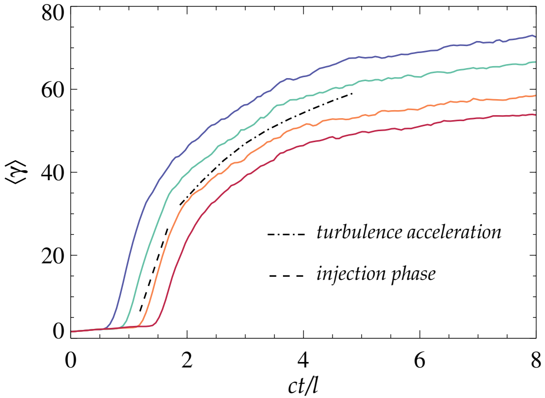
Comisso & Sironi 2019

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

- The PIC simulations are well fitted by $D_\gamma \sim 0.1\sigma \left(\frac{c}{l}\right) \gamma^2$

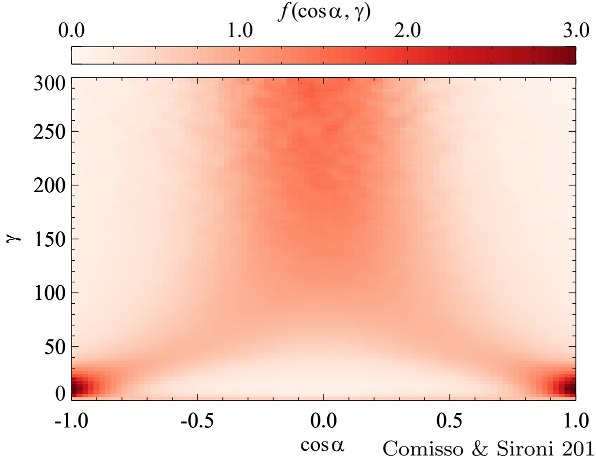
  (see also Wong et al. 2020 and Lemoine's talk)

Two-Stage Acceleration Process



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

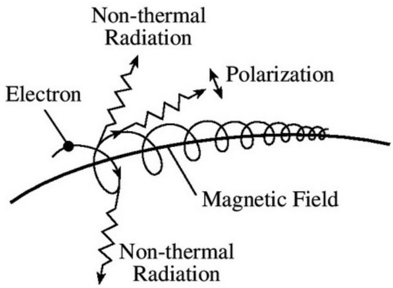
Anisotropy of the Pitch Angle Distribution



Comisso & Sironi 2019

- Here: $\cos\alpha = \dfrac{\boldsymbol{v}\cdot\boldsymbol{B}}{|\boldsymbol{v}|\,|\boldsymbol{B}|}$, $\int_{-1}^{1} f(\cos\alpha,\gamma)\, d(\cos\alpha) = 1$
- The two stage acceleration process produces an *energy-dependent pitch angle anisotropy.*

Importance for Synchrotron Radiation

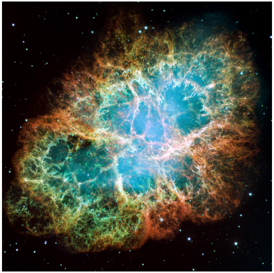


- The synchrotron power emitted by a single electron due to synchrotron radiation is (in the local comoving frame)

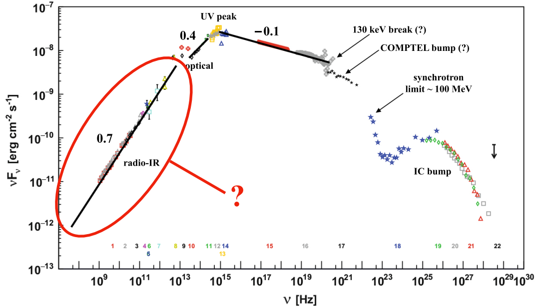
$$P_{\rm syn} = \frac{2e^4}{3m^2c^3} B^2 \gamma^2 \left(\frac{v}{c}\right)^2 \sin^2 \alpha$$

- The synchrotron power has a strong dependence ($\propto \sin^2 \alpha$) on the pitch angle.

The Puzzling Radio Spectrum of the Crab Nebula



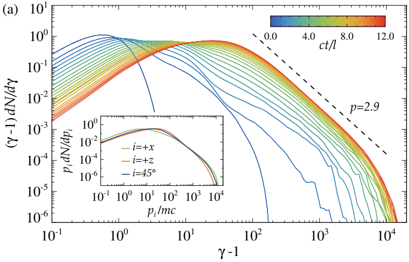
Credits: NASA, ESA

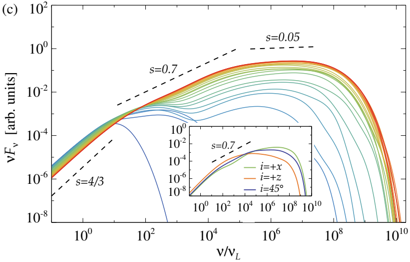


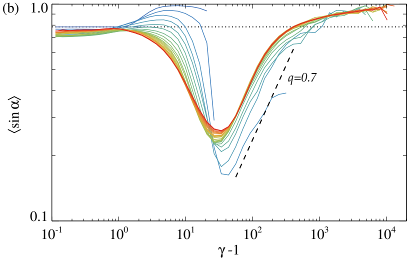
Zanin 2017, Lyutikov *et al.* 2019

- Isotropic distribution of electrons implies $dN/d\gamma \propto \gamma^{-1.6}$
- An anisotropic pitch angle distribution helps alleviate the requirement of a very hard particle distribution (even $p > 2$ can give $\nu F_\nu \propto \nu^{0.7}$).

Synchrotron spectrum hardened by the α anisotropy



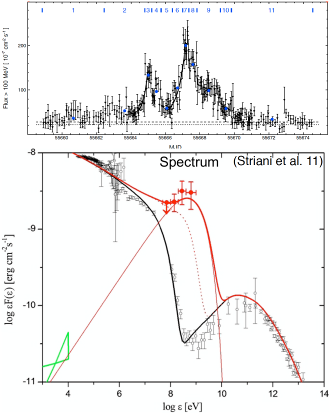




- Low frequencies: $\nu F_\nu \propto \nu^{4/3}$
- High frequencies: $\nu F_\nu \propto \nu^{(3-p)/2}$
- Intermediate frequencies: $\nu F_\nu \propto \nu^{(3-p+2q)/(2+q)}$

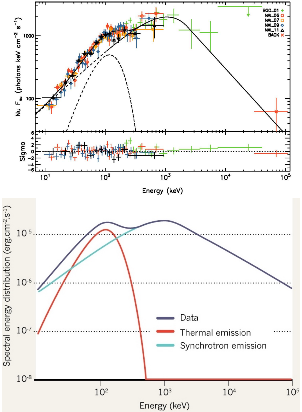
Comisso, Sobacchi, Sironi 2020

Striani *et al.* 2011, Buehler *et al.* 2012



- Origin of PWN gamma-ray flares exceeding the synchrotron burnoff limit?

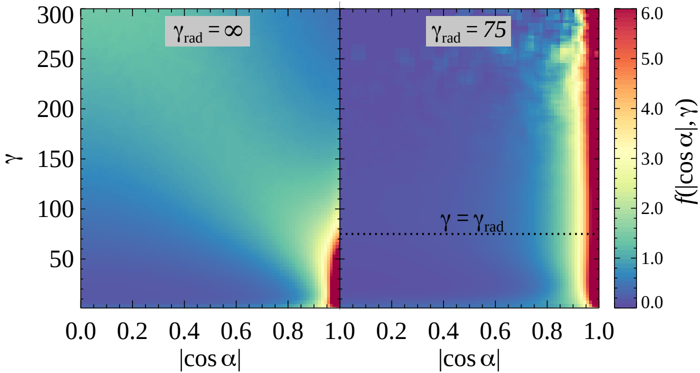
Axelsson *et al.* 2012, Hand 2012



- Origin of the steep spectrum in the prompt phase of GRBs?

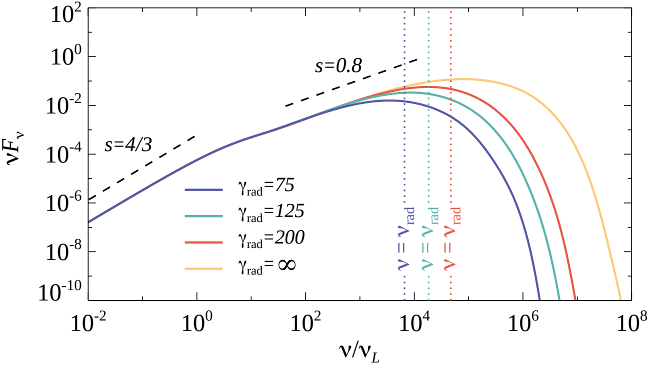
See Comisso & Sironi 2021 for Insights from Relativistic Turbulence

Particles exceeding the radiation reaction limit



- The highest-energy particles exceed the nominal radiation reaction limit γ_{rad} thanks to their small pitch angle.

Hard synchrotron spectrum



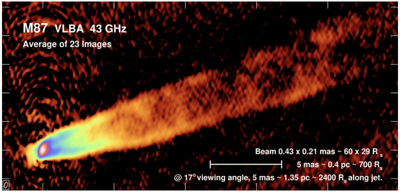
- Hard synchrotron spectrum: $\nu F_\nu \propto \nu^{0.8}$ up to $\nu_{\rm peak}$ ($s > 0.8$ for higher σ_0)
- Excess of synchrotron radiation ($\sim 35\%$) above the nominal radiation-reaction-limited frequency $\nu_{\rm rad}$

Relevance to other Astrophysical Systems

Plasma around BHs

Credits: EHT Collaboration

Jets from BHs



Credits: NRAO/Walker et al. (2018)

Solar Corona

Credits: NASA

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.
- Turbulence + Reconnection Generate Anisotropic Pitch Angle Distributions.
- Anisotropic Pitch Angle Distributions affect the Synchrotron Spectrum produced by the Energetic Particles.

Fully-Kinetic Treatment including Radiation Reaction

Solve Particle Equations of Motion:

$$\frac{d\boldsymbol{p}_p}{dt} = q_p\left(\boldsymbol{E} + \boldsymbol{\beta}_p \times \boldsymbol{B}\right) + \boldsymbol{F}_{RR}$$

$$\frac{d\boldsymbol{x}_p}{dt} = \frac{\boldsymbol{p}_p}{\gamma_p m_p}$$

Extrapolate to Grid:

$$\left(\boldsymbol{x}, \boldsymbol{p}\right)_p \rightarrow \boldsymbol{J}_i$$

Solve Maxwell's Equations

$$\frac{\partial \boldsymbol{E}}{\partial t} = c\,\boldsymbol{\nabla} \times \boldsymbol{B} - 4\pi \boldsymbol{J}$$

$$\frac{\partial \boldsymbol{B}}{\partial t} = -c\,\boldsymbol{\nabla} \times \boldsymbol{E}$$

Interpolate to Particles:

$$\left(\boldsymbol{E}, \boldsymbol{B}\right)_i \rightarrow \boldsymbol{F}_p$$

$$\boldsymbol{F}_{RR} = \frac{2}{3} r_0^2 \Big[(\boldsymbol{E} + \boldsymbol{\beta} \times \boldsymbol{B}) \times \boldsymbol{B} + (\boldsymbol{\beta} \cdot \boldsymbol{E})\boldsymbol{E}\Big] - \frac{2}{3} r_0^2 \gamma^2 \boldsymbol{\beta} \Big[(\boldsymbol{E} + \boldsymbol{\beta} \times \boldsymbol{B})^2 - (\boldsymbol{\beta} \cdot \boldsymbol{E})^2\Big]$$

PIC code: TRISTAN-MP (Spitkovsky 2005)

Radiation-Reaction-Limited Lorentz Factor

- The cooling regime can be parametrized by the value of the particle Lorentz factor ($\gamma_{\rm rad}$) for which the radiation drag force balances the accelerating force.
- For ultra-relativistic particles ($\gamma \gg 1$, $\beta \simeq 1$)

$$\boldsymbol{F}_{RR} \simeq -\frac{2}{3} r_0^2 \gamma^2 \boldsymbol{\beta} \left[(\boldsymbol{E} + \boldsymbol{\beta} \times \boldsymbol{B})^2 - (\boldsymbol{\beta} \cdot \boldsymbol{E})^2 \right]$$

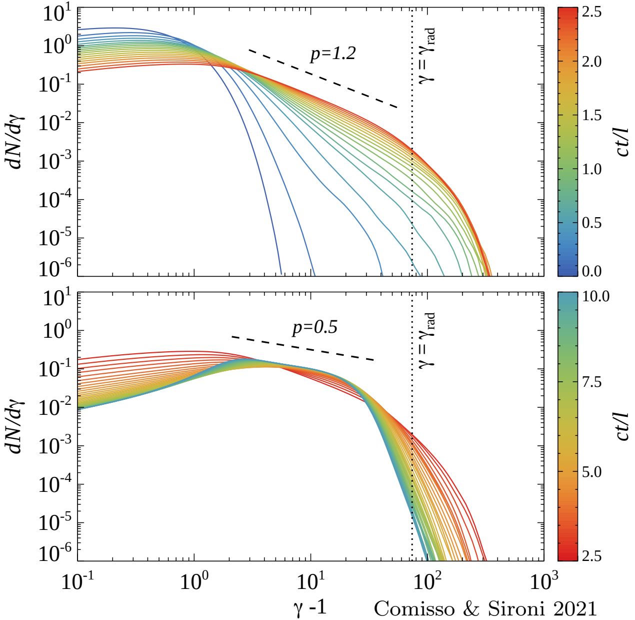
- Then the radiation-reaction-limited Lorentz factor is given by

$$F_{RR}^{\rm sync} = F_{\rm acc}$$

$$(2/3) r_0^2 \gamma^2 B^2 \sin^2 \alpha = eE$$

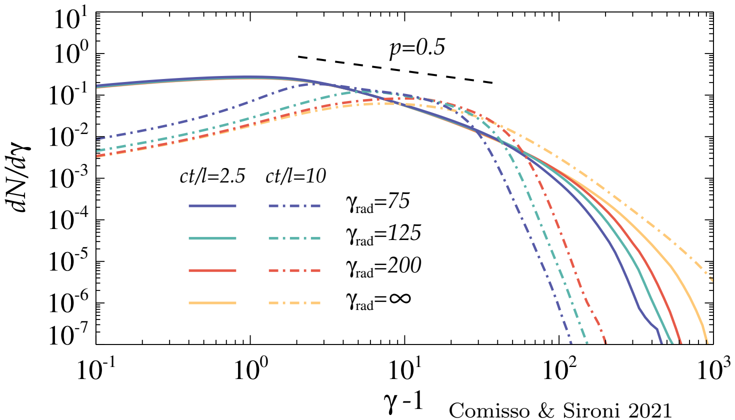
$$\Rightarrow \gamma_{\rm rad} = \sqrt{\frac{3 m_e^2 c^4}{2 e^3} \frac{E}{B^2}}$$

Formation of a hard non-thermal particle spectrum



Comisso & Sironi 2021

Particle Cooling Modifies the Particle Spectrum



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- Particles cool at different rates ($P_{\rm syn} \propto \gamma^2 \sin^2 \alpha$).
- The particle spectrum becomes harder because the *pitch angle anisotropy is energy dependent*