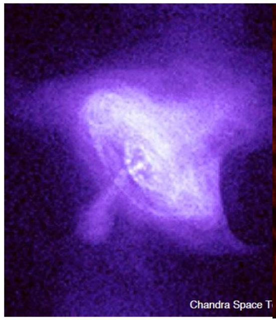
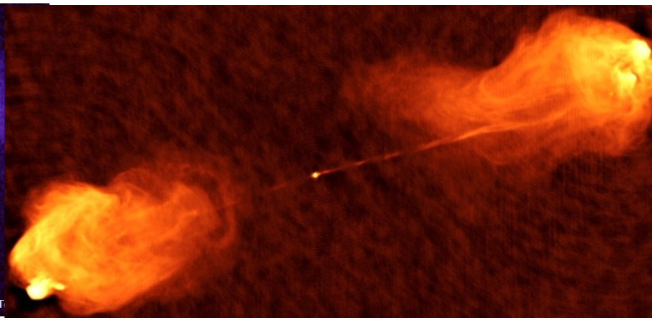
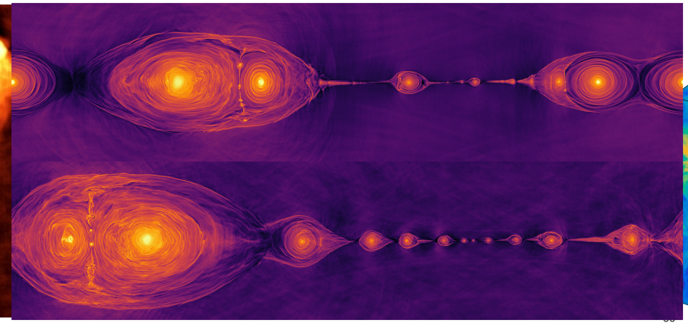
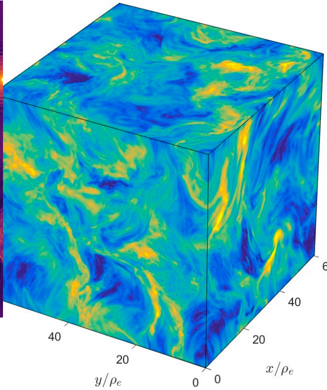








Nonthermal Particle Acceleration in Plasma Turbulence (~~and Magnetic Reconnection~~)

Dmitri Uzdensky

University of Colorado Boulder

Thanks:

Greg Werner, Mitch Begelman, Vladimir Zhdankin, Kai Wong

Support: NASA, NSF

Interconnections between the Physics of Plasmas and Self-gravitating Systems

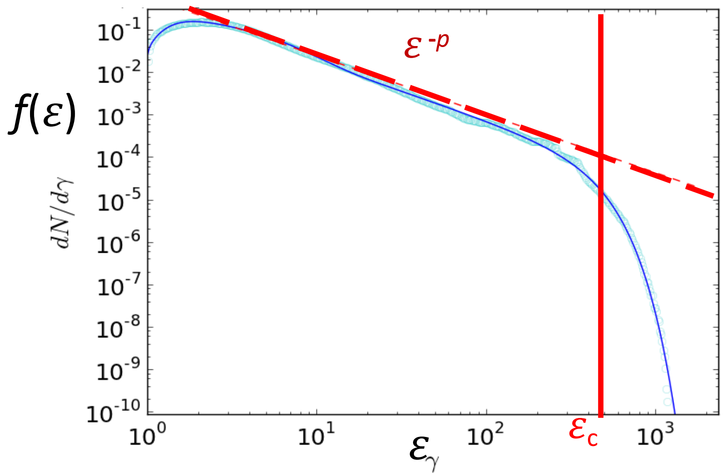
KITP, Santa Barbara, June 17, 2024

OUTLINE

- What is Nonthermal Particle Acceleration (NTPA)?
- Nonthermal Particle Acceleration in the Universe:
  - Space/Heliosphere: Solar Flares, Earth Magnetosphere
  - High-Energy Astrophysics: Cosmic Rays, Supernova Remnants, Accreting Black Holes, AGN jets, Pulsar Wind Nebulae
- Plasma Physics of NTPA: General Remarks
- Particle Acceleration in Turbulence:
  - Diffusive Fermi Acceleration
  - Quasi-Linear Theory (QLT) and the Fokker-Planck Equation
  - First-Principles Particle-in-Cell (PIC) Simulations of Kinetic Turbulence
- (Particle Acceleration in Magnetic Reconnection)
- Summary

Nonthermal Particle Acceleration (NTPA)

In Astrophysics, ***Nonthermal Particle Acceleration*** (***NTPA***) refers to production of extended (several decades) ***power-law*** particle energy distributions $f(\varepsilon) \sim \varepsilon^{-p}$



- **Goals:**
  - Understand physical mechanisms of NTPA and characterize it quantitatively across a broad parameter space.
  - Provide usable prescriptions for the astrophysics and space communities for NTPA parameters (p, ε_c) as functions of key system parameters:

    System parameters → → power-law index ***p*** and cutoff ε_c

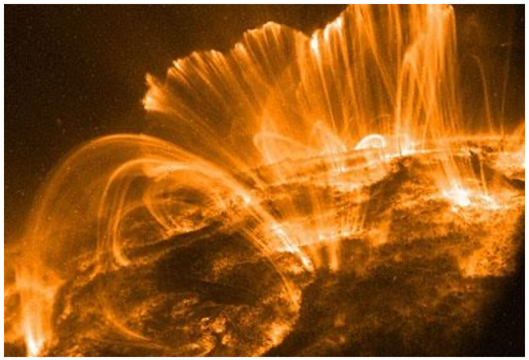
- **Tools:** Particle-in-Cell (PIC) Simulations + Analytical Theory

Space Motivation:

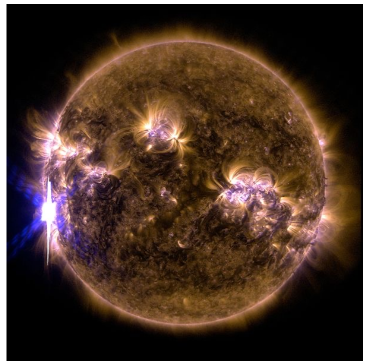
Nonthermal Particle Acceleration in the Solar System

Solar Flares

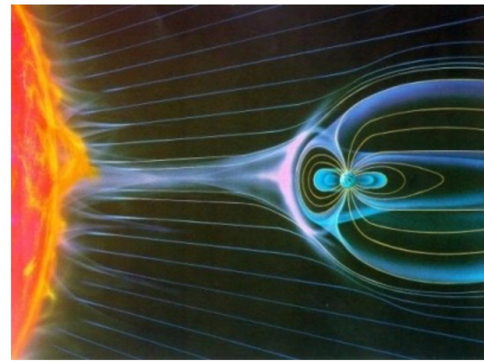
Earth Magnetosphere



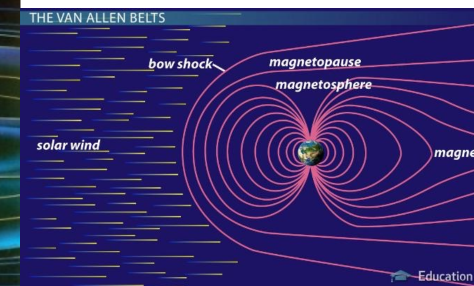
Active Solar Corona



Flaring Sun in X-rays

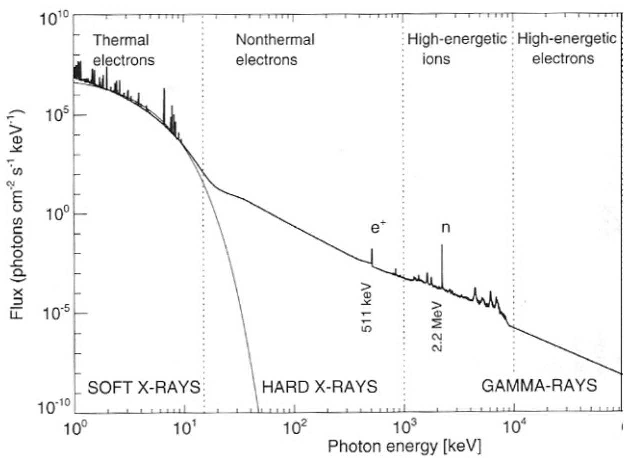


Sun-Earth Connection

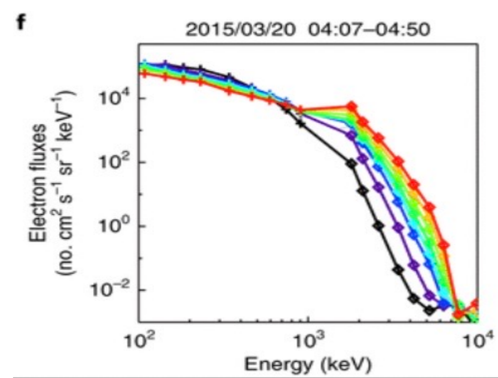


Earth Magnetosphere

Solar flares show nonthermal X-ray spectra



Electron Energy Spectrum in Earth's Magnetosphere

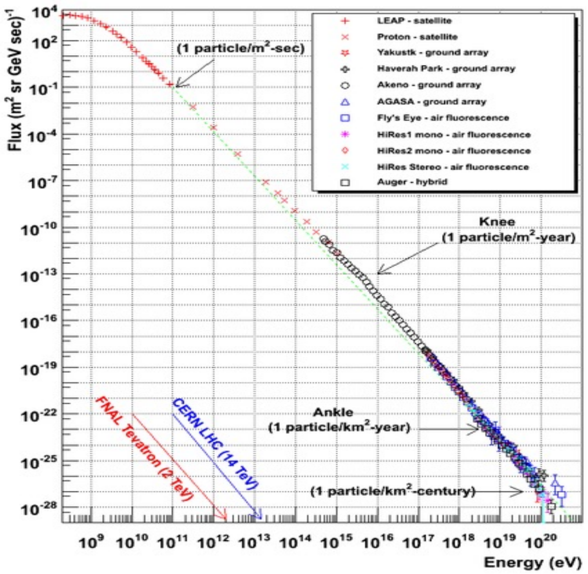


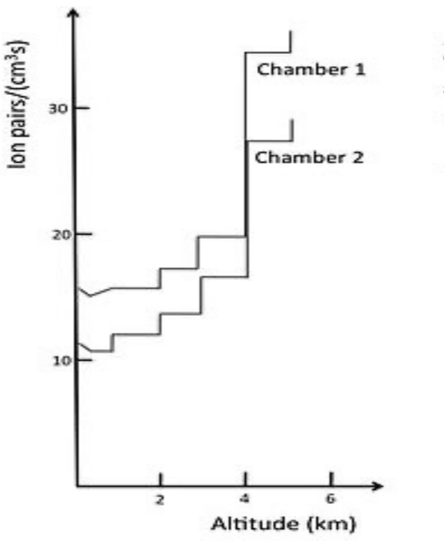
Astro Motivation:

Nonthermal Radiation and Relativistic Particle Spectra are Ubiquitous in the Universe

I. Cosmic Rays

- Discovered by Victor Hess (1911-12) with hot-air balloon measurements
- Relativistic particles (mostly protons) with (broken) power-law energy spectrum from $m_p c^2$ = 1 GeV up to 10^{20} eV (>10 decades!)
- The original **Multi-Messenger Astrophysics** (non-EM)!
- Main driver of theoretical research of nonthermal particle acceleration



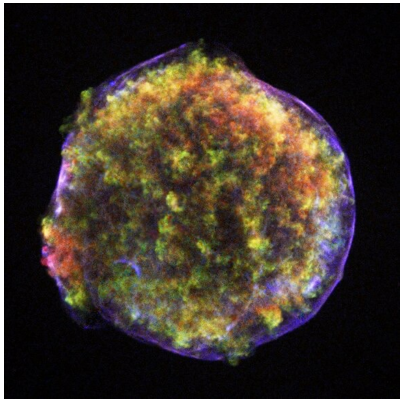


Astro Motivation:

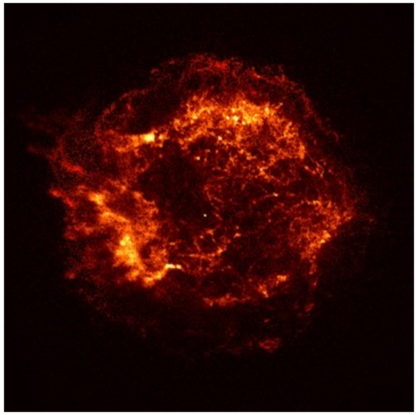
Nonthermal Radiation and Relativistic Particle Spectra are Ubiquitous in the Universe

II. EM Radiation from Supernovae & Pulsar Wind Nebulae

Supernova Remnants

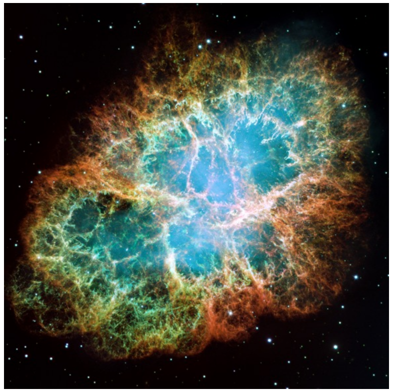


Tycho SNR 1572



Cas A SNR (~1690) X-rays

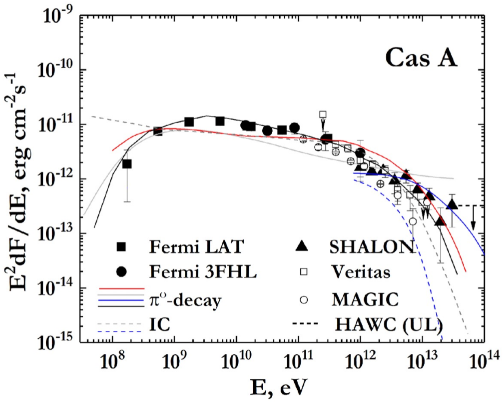
Pulsar Wind Nebulae

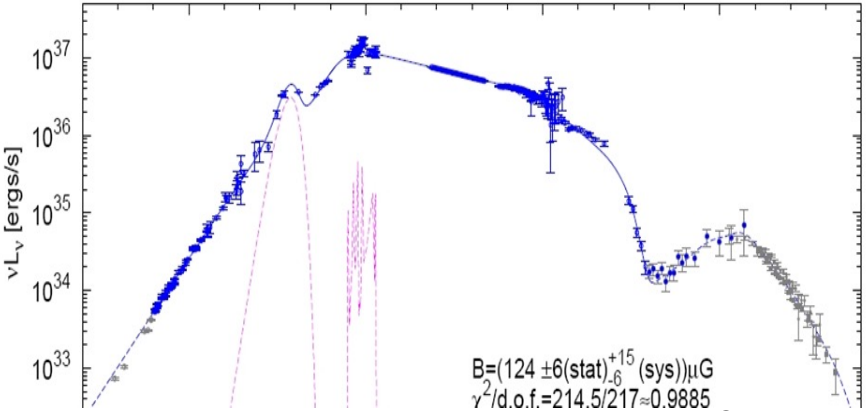


Crab Nebula (M1); HST

Crab Nebula; HST+Chandra

Supernova shocks
- main CR accelerator up to PeV.

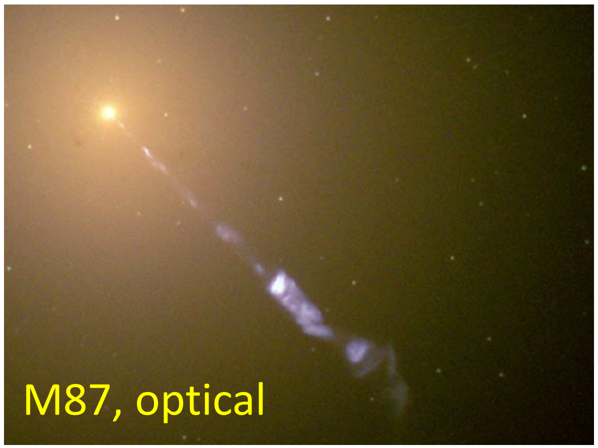


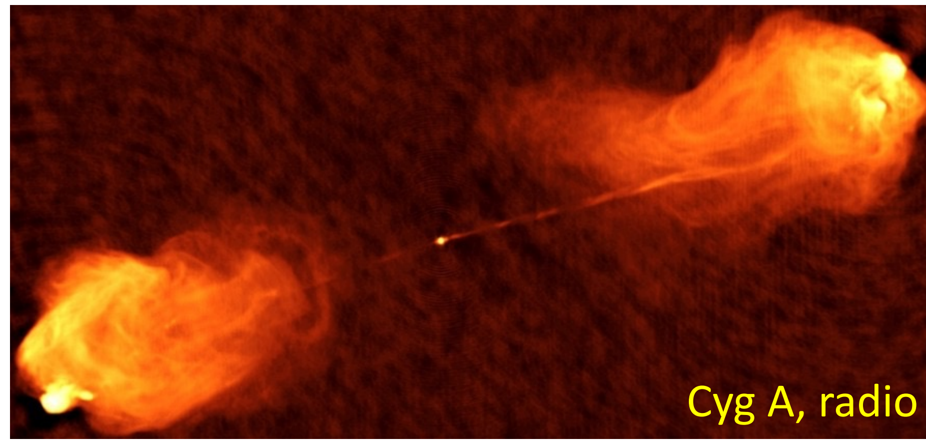


Astro Motivation:

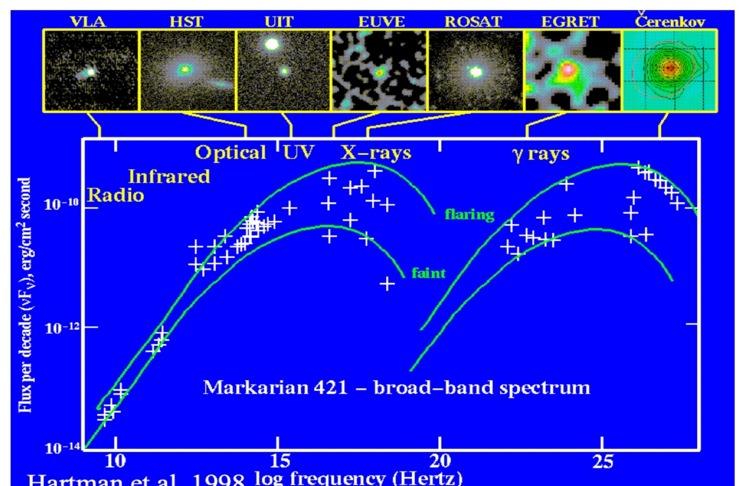
Nonthermal Radiation and Relativistic Particle Spectra are Ubiquitous in the Universe

III. Relativistic Jets driven by Supermassive Black Holes (SMBH) in Active Galactic Nuclei (AGN), including blazars



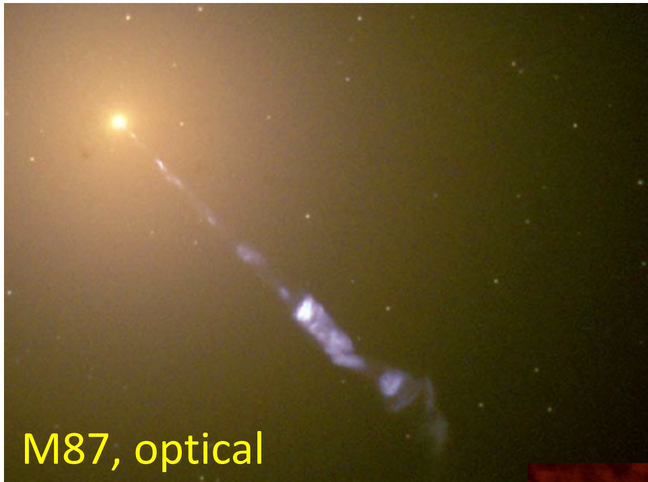


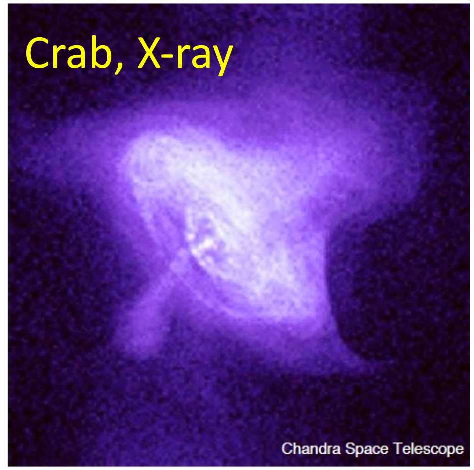
AGN jets - main CR accelerators beyond PeV.

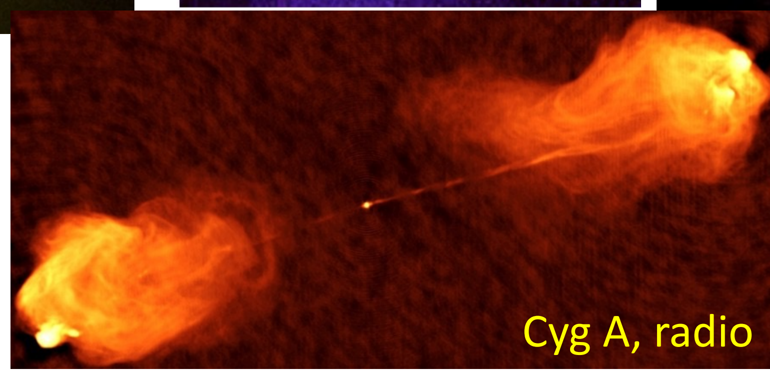


Astro Motivation:

High-Energy Particle Acceleration and Emission in Astrophysical Plasmas







- Astrophysical plasmas ***shine***.
- Extremely ultra-relativistic particles pervade the Universe and emit high-energy radiation
- Radiative cooling time << travel time from central engine → *in-situ particle acceleration.*

Plasma Physics of NTPA: General Remarks

- Astrophysical environments are diverse, exhibit wide range of conditions, including high-T, low-density collisionless plasmas → favorable for NTPA.
- Most space/astro plasmas are magnetized:
  - Plasma-β = $P/(B^2/8\pi)$ ranges from 10^{-3} to >> 1, including dynamically important magnetic fields ($\beta < 1$)
  - Even in high-β situations, plasma particles are well-magnetized:

    small Larmor radius: $\rho_L \lll L, \lambda_{mfp}$
- Particle Equation of Motion: $d\boldsymbol{p}/dt = \boldsymbol{F} = q\,(\boldsymbol{E} + \boldsymbol{v} \times \boldsymbol{B}/c)$
  - Magnetic force is ⊥ to ***v*** ⇒ magnetic field does not do work on particles and hence cannot directly increase their energy!
  - Particle acceleration requires electric field ***E*.**
- (ideal) Magnetohydrodynamics (MHD) equations*:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0$$

$$\rho\left(\frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u}\cdot\nabla)\mathbf{u}\right) = \frac{1}{\mu_0}(\nabla \times \mathbf{B}) \times \mathbf{B} - \nabla p$$

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{u} \times \mathbf{B})$$

$$\nabla \cdot \mathbf{B} = 0$$

$$p = p(\rho)$$

E-field does not appear explicitly, but it is still there:

$$\boldsymbol{E}_\perp = -\,[\boldsymbol{u} \times \boldsymbol{B}]/c,$$

i.e., fluid moves with ExB drift velocity.

(*special nonideal regions with finite $E_{||}$, e.g., in reconnection)

Plasma Physics of NTPA: General Remarks

- Particle Equation of Motion: $d\boldsymbol{p}/dt = \boldsymbol{F} = q\,(\boldsymbol{E} + \boldsymbol{v} \times \boldsymbol{B}/c)$
- MHD Electric Field: $\boldsymbol{E}_\perp = -\,[\boldsymbol{u} \times \boldsymbol{B}]/c$
- Characteristic strength of electric field: $|E| \sim uB/c$

Corollaries: *Efficient NTPA is helped by:*

- Strong B!
- Fast bulk motions $\boldsymbol{u} \Rightarrow$ violent, dynamic processes!
- Especially relativistic motions: $u \sim c \Rightarrow E \sim B$
- Electric field coherent over long scales, preferably $> \rho_L$
- Particles interact most strongly with EM fields on scales $\sim\rho_L$

  For non-relativistic particles: $\rho_L = v_\perp m\, c/eB \sim \epsilon^{1/2}$

  For relativistic particles ($\gamma >> 1$): $\rho_L = \gamma\, m\, c^2/eB \sim \epsilon$

  $\epsilon = \gamma\, m\, c^2$
- Hence, higher-energy particles interact with larger-scale EM fields
- Power-law particle-energy spectrum $\Rightarrow$ power-law distribution in $\rho_L \Rightarrow$

  NTPA -- multiscale problem: power-law EM field fluctuation spectrum (e.g., turbulence)
- Maximum (*Hillas '84*) particle energy (extreme acceleration): $\epsilon_{max} = eBL$ ($\rho_L = L$)

Dissipation and Particle Acceleration Mechanisms

In Astrophysics, particles are accelerated by nonlinear ***collective plasma processes***.

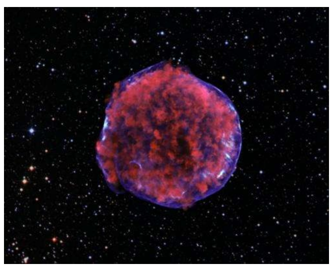
AVAILABLE FREE ENERGY

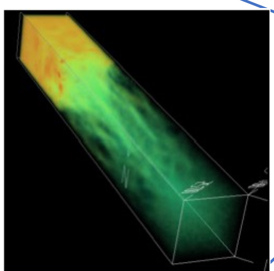
Bulk Kinetic

Magnetic (Poynting flux)

- longitudinal:

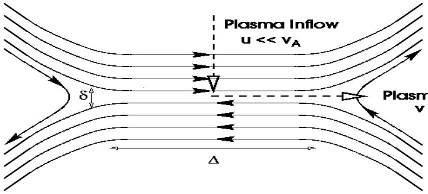
shocks



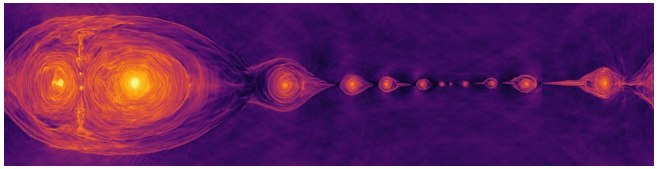


SINGULAR STRUCTURE

current sheets:



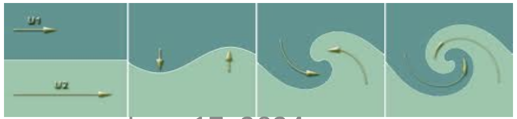
Magnetic reconnection

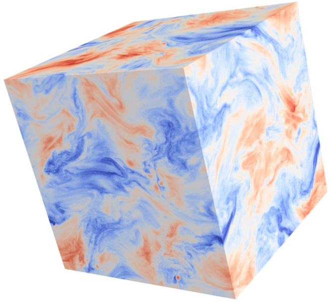


TURBULENCE

- transverse:

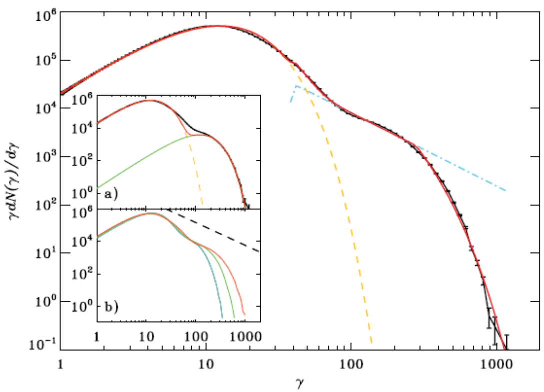
shear (KH) instability



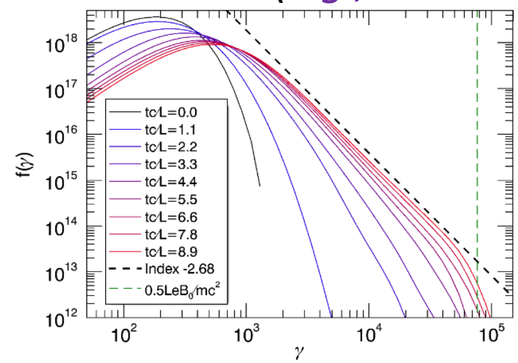


Nonthermal Particle Acceleration (NTPA) in PIC simulations

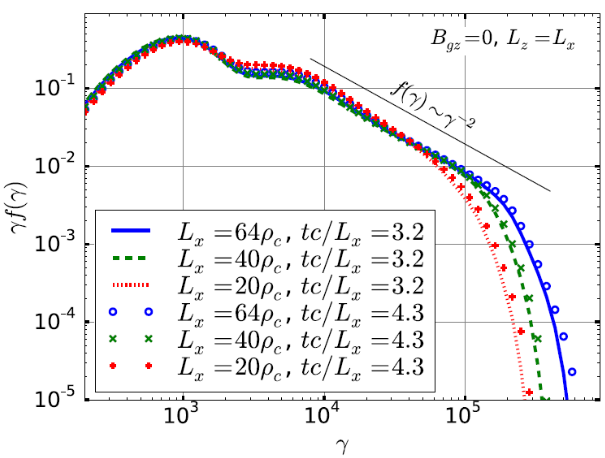
Collisionless shocks (*e.g., Spitkovsky+ 2008*)



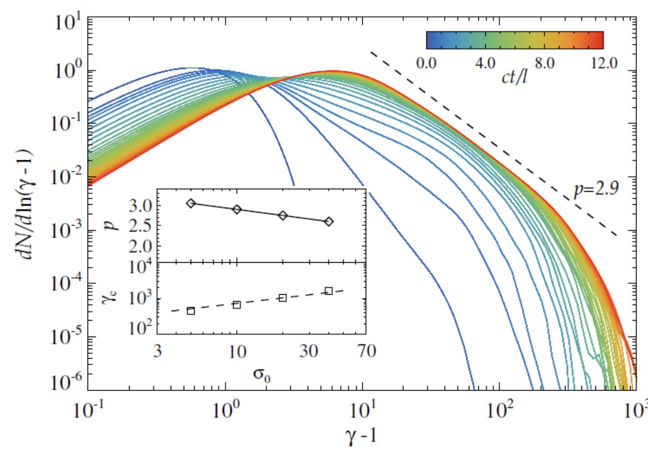
- Driven turbulence (*e.g., Zhdankin+ 2017*)



Reconnection (*e.g., Werner+ 2016*)



- Decaying turbulence (*e.g., Comisso+ 2018*)

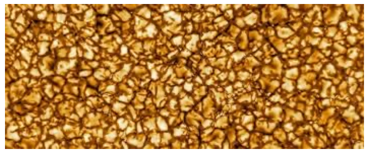


Astro Motivation:

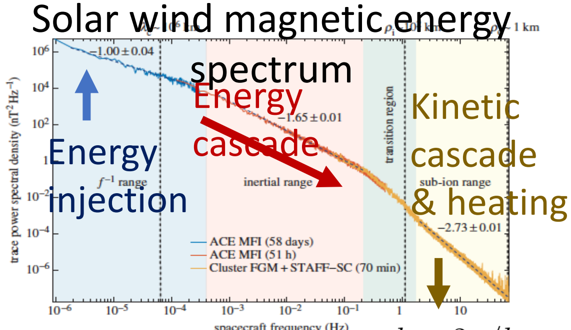
Turbulence is Ubiquitous in the Universe

Astrophysical plasmas are generally manifestly turbulent

- Solar/Stellar Convection Zone

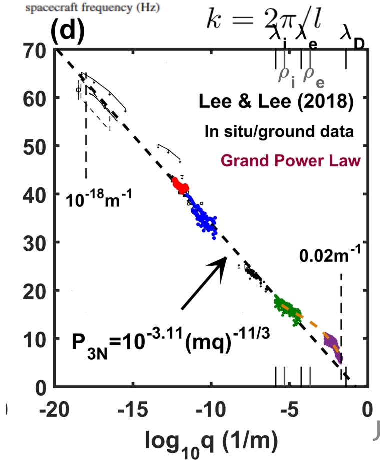


- Solar Wind:

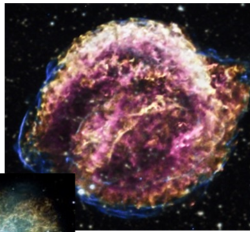


- ISM:

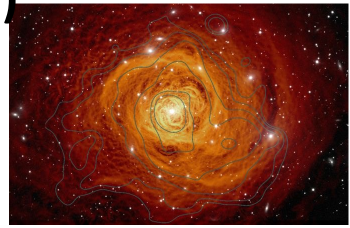
Big Power Law In the Sky



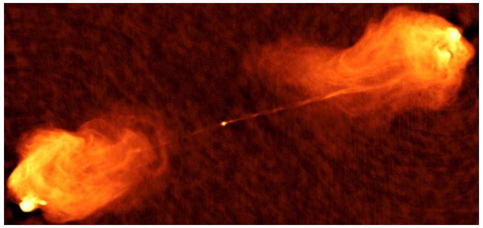
- SN remnants, PWN




- Galaxy Clusters (ICM)



- AGN jets



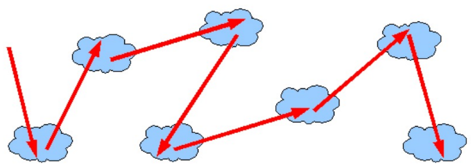
- Black-Hole Accretion Disks, Advection-Dominated Flows

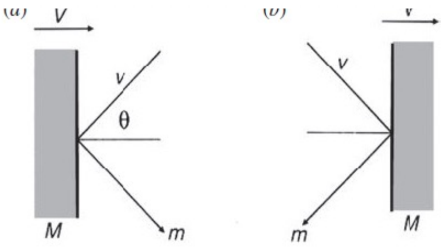
Theory:

Theory of Turbulent Relativistic Nonthermal Particle Acceleration (NTPA)

I. Fermi Acceleration:

Diffusive, 2nd-order Fermi ('49, '54) Acceleration of CRs:





- Particles scatter off randomly moving magnetic clouds
- Particle momentum performs biased random walk
- Head-on collisions (gaining energy) more probable than tail collisions (losing energy)
- Average energy gain ∝ cloud velocity squared, $\left(\frac{v}{c}\right)^2$
- Generalised to any scatterer type: plasma waves, turbulence, …
- In combination with particle escape, particle spectrum develops power law: $f(\gamma) \sim \gamma^{-p}$, with slope $p = 1 + \tau_{acc} / \tau_{esc}$

$$\epsilon = \gamma\, m\, c^2$$

Fermi's ideas have guided turbulent particle acceleration research ever since.
Astrophys. applications of turb NTPA are diverse, but most theory work done for CRs.

But what are these scattering centers, how rapidly do they move, how do they scatter particles?

Theory:

Theory of Turbulent Relativistic Nonthermal Particle Acceleration (NTPA)

What are these scattering centers, how rapidly do they move, how do they scatter particles?

II. Quasi-Linear Theory (QLT) of Wave-Particle Interaction:

The Language of the (analytical) Realm!

Basic idea:

- Turbulence is ensemble of EM perturbations, (e.g., Alfven, Fast, Slow MHD waves)
- Wave properties [dispersion relation ω(k), polarization] described by linear theory
- Particle momentum distribution is split into the slowly evolving spatially and gyro-average part and rapidly fluctuating part: $f(t,\mathbf{x},\mathbf{p}) = f_0(t,p,\mu) + f_1(t,\mathbf{x},\mathbf{p})$ ($\mu = \cos\theta$)
- $f_1(t,\mathbf{x},\mathbf{p})$ governed by linearizing relativistic Vlasov equation: $\frac{\partial f_e}{\partial t} + \mathbf{v}_e \cdot \nabla f_e - e\left(\mathbf{E} + \frac{\mathbf{v_e}}{c} \times \mathbf{B}\right) \cdot \frac{\partial f_e}{\partial \mathbf{p}} = 0$

evolves due to product of fluctuating EM fields and *momentum derivative of f_0*

- $f_0(t,\mathbf{p})$ evolves slowly (2^{nd} order), due to correlation between fluctuating EM fields and momentum derivative of *momentum derivative of f_1*
- Generic Result: QLT evolution equation for $f_0(t,\mathbf{p})$ is a Fokker-Planck *diffusion equation* in momentum space.

Theory:

Theory of Turbulent Relativistic Nonthermal Particle Acceleration (NTPA)

QLT motivates **Fokker-Planck** approach to stochastic particle acceleration, yielding practical, convenient, and widely used prescriptions for NTPA (esp. for CRs)

Fokker-Planck equation:

- Derived from Vlasov equation using QLT for given spectrum of EM perturbations (waves, turbulence)
- Describes slow evolution of the space- and gyro-averaged momentum distribution, as a function of particle momentum magnitude p and pitch angle θ: $f_0(t,p,\mu)$, due to wave-particle interactions, including pitch-angle scattering.
- General form: diffusion equation in momentum space:

$\mu = \cos\theta$

$$\frac{\partial f}{\partial t} = \frac{\partial}{\partial \mu}\left(D_{\mu\mu}\frac{\partial f}{\partial \mu}\right) + \frac{\partial}{\partial \mu}\left(D_{\mu p}\frac{\partial f}{\partial p}\right) + \frac{1}{p^2}\frac{\partial}{\partial p}\left[p^2\left(D_{p\mu}\frac{\partial f}{\partial \mu} + D_{pp}\frac{\partial f}{\partial p}\right)\right]$$

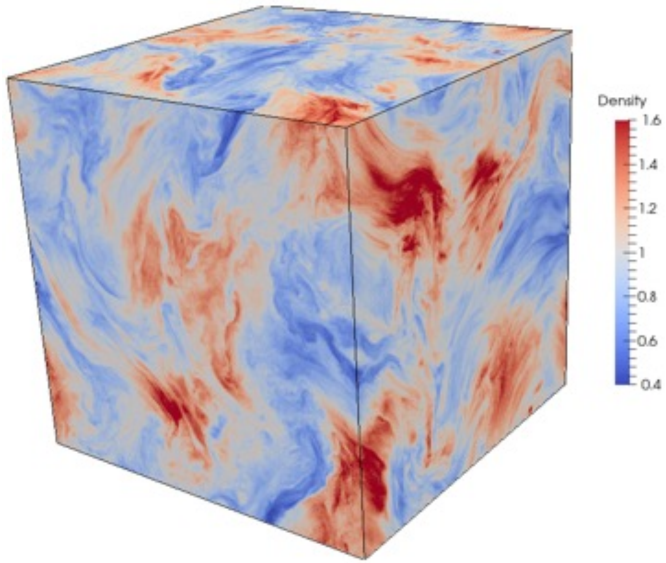
- Simplified form: pitch-angle-averaged; diffusion in energy space only:

$$\partial_t f = \partial_\gamma\left(D\partial_\gamma f\right) - \partial_\gamma(Af)$$

$\gamma = \epsilon/mc^2 = p/mc$

- $f(\gamma, t)$: particle energy distribution
- $D(\gamma, t)$: energy diffusion coefficient – second-order acceleration
- $A(\gamma, t)$: energy advection coefficient – first-order acceleration

Numerical Studies of Relativistic Turbulent NTPA



Three numerical approaches:

- Test particles in synthetic turbulent EM fields
- Test particles in MHD simulations
- **Particle-in-Cell (PIC) kinetic simulations**

Types of Turbulence:

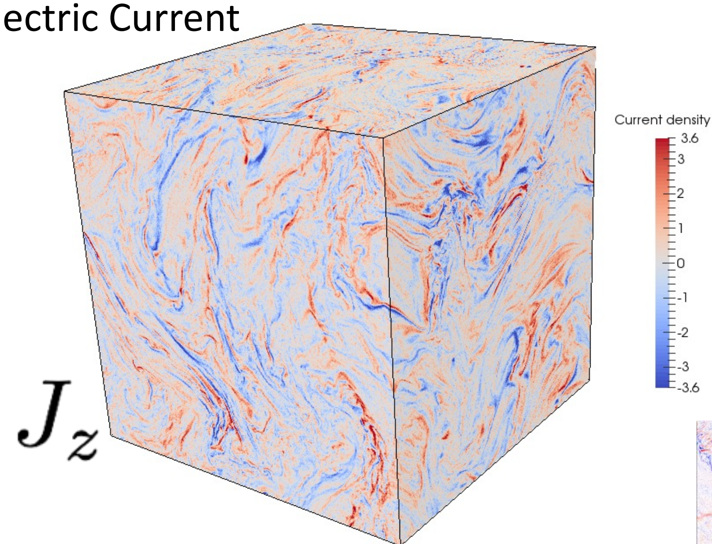
- **Driven (e.g., Zhdankin et al)**
- Decaying (e.g., Comisso)

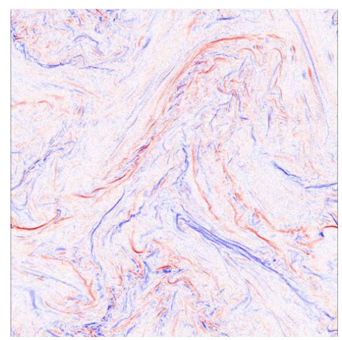
Simulation:

3D Kinetic (PIC) Simulations of Driven Turbulence in Relativistic Collisionless Plasmas

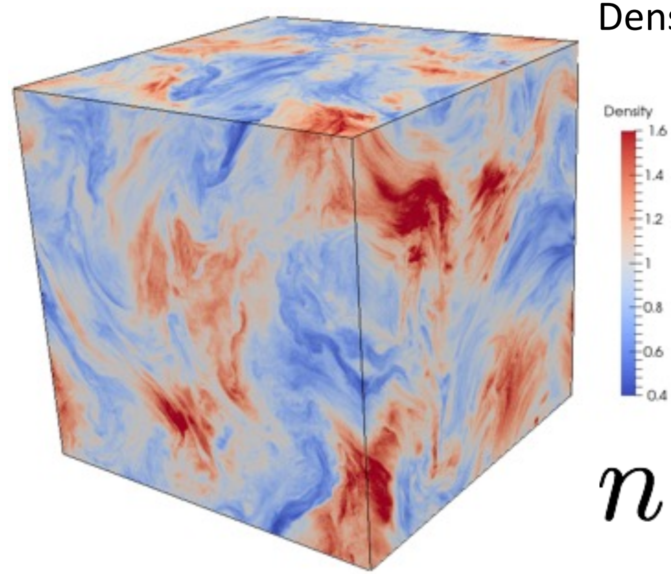
***V. Zhdankin**, K. Wong, A. Hankla, G. Werner, D. Uzdensky, M. Begelman (2017-2024)*

Electric Current





Density



Key Questions:

- What are the statistical properties of turbulence: **power spectra** in inertial (MHD) range (***l* > *ρ***) and sub-Larmor (kinetic) range (***l* < *ρ***)?
- **Is turbulence a viable mechanism for nonthermal particle acceleration?**

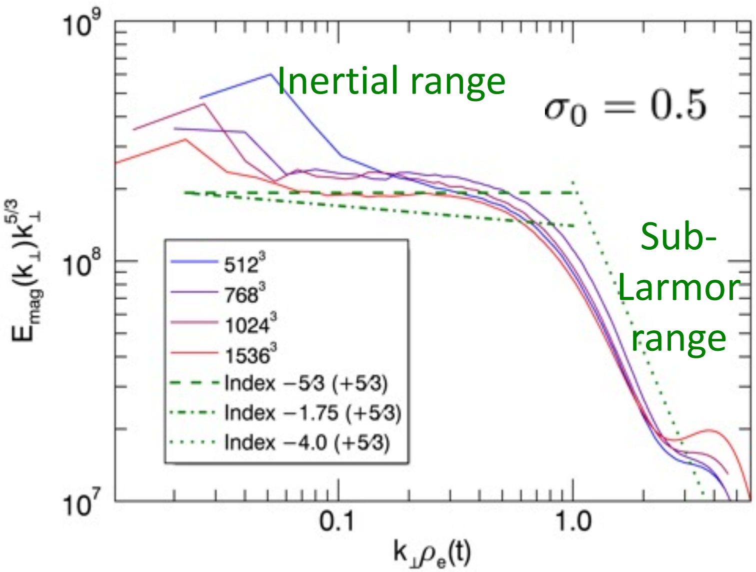
- **3D periodic box; Zeltron PIC code**
- **Relativistically hot pair plasma**
- **Driven magnetized plasma turbulence**
- **Uniform guide field:** $B_0 \sim \delta B_{\rm rms}$
- **System size:** $L/2\pi\rho_e \rightarrow 163$
- **Up to** 1536^3**-cell grids**
- **Hundreds of billions macroparticles**

Simulation:

3D PIC Simulations of Driven Relativistic Collisionless Turbulence in Pair Plasmas

(Zhdankin, Werner, Uzdensky, Begelman 2017-2018)

Turbulent magnetic energy spectrum



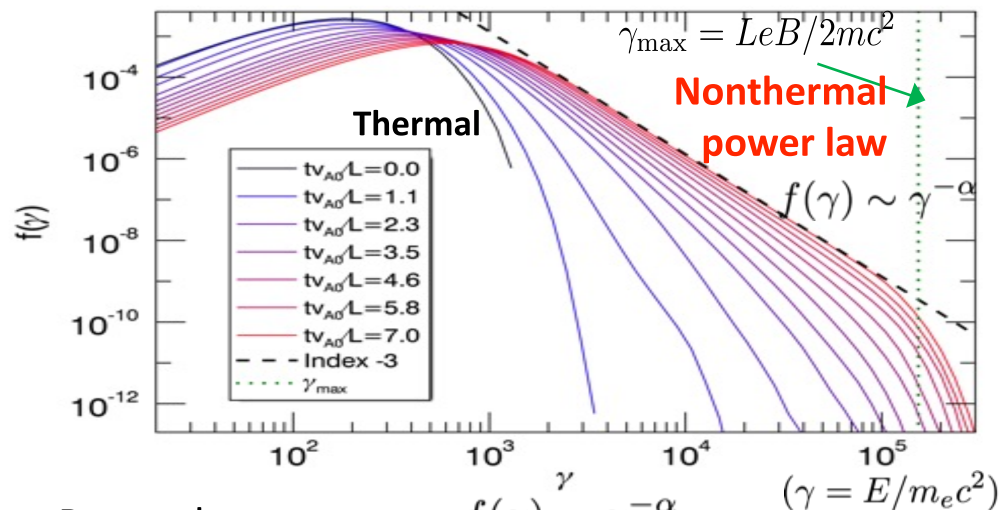
Turbulent magnetic fluctuations spectrum:

- **E(k)~k $^{-5/3}$** in inertial range ($k_\perp < \rho_e^{-1}$)
- **E(k)~k $^{-4}$** in kinetic range ($k_\perp > \rho_e^{-1}$)

Two dimensionless parameters:

- Length-scale separation: ***L/ρ_0***
- Initial Magnetization: **$\sigma_0 = B_{rms}^2/(4\pi\ n\ \gamma mc^2)$**

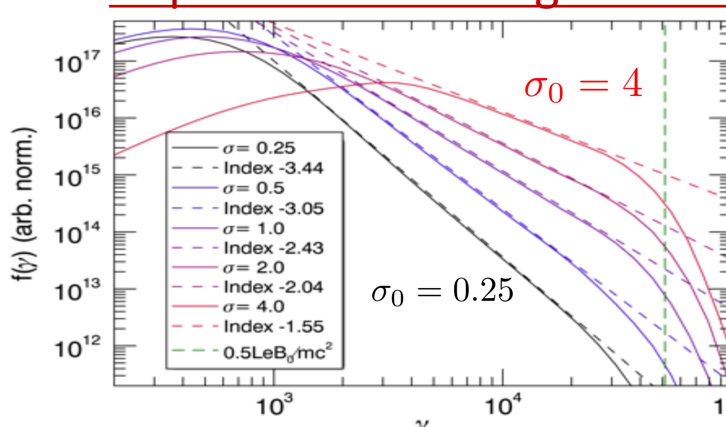
Nonthermal Particle Acceleration (NTPA)



Power-law segment: $f(\gamma) \sim \gamma^{-\alpha}$

reaches system-size-limit: $\gamma_{max} = LeB/2mc^2$ $(\rho_e \sim L/2)$

Dependence on Magnetization



$$\sigma \equiv \frac{B_{rms}^2}{4\pi n_0 \bar{\gamma} m_e c^2}$$

Spectrum hardens with σ

$\alpha = C_1 + C_2 \sigma^{-1/2}$

Simulation:

Direct Numerical (PIC) Test of Fokker-Planck Model for Turbulent Particle Acceleration

K. Wong, V. Zhdankin, D. Uzdensky, G. Werner, M. Begelman 2020, 2024

(also Comisso & Sironi 2019)

Questions:

- Is turbulent particle acceleration indeed diffusive?
- Do particle energies undergo random walks?
- Is Fokker-Planck (FP) framework an appropriate mathematical description of turbulent NTPA?
- How do the Fokker-Planck coefficients $D(\gamma)$, $A(\gamma)$ depend on σ (magnetization), L/ρ_e (system size)?

Simplest energy-space Fokker-Planck eqn:

advection-diffusion equation in energy:

$$\partial_t f = \partial_\gamma (D \partial_\gamma f) - \partial_\gamma (A f)$$

- $f(\gamma, t)$: particle energy distribution
- $D(\gamma, t)$: energy diffusion coefficient
- $A(\gamma, t)$: energy advection coefficient

$(\gamma = E/m_e c^2)$

Method:

- PIC (Zeltron) simulation of driven 3D relativistic pair-plasma turbulence.
- ~8x10^5 tracked particles:

Position, momentum, local $\boldsymbol{E}$ & $\boldsymbol{B}$ recorded at fine time intervals.

- Directly measure stat. properties of particle acceleration:

FP coefficients $D(\gamma, t)$, $A(\gamma, t)$

and their dependence on $\sigma, L/\rho_e$, etc.

<u>System parameters:</u>

Relativistically hot pair plasma:

$\langle\gamma\rangle_{\text{init}} = 300$

Initial plasma magnetization:

$\sigma_0 = B_0^2/16\pi n_0 T_0 = 3/8$

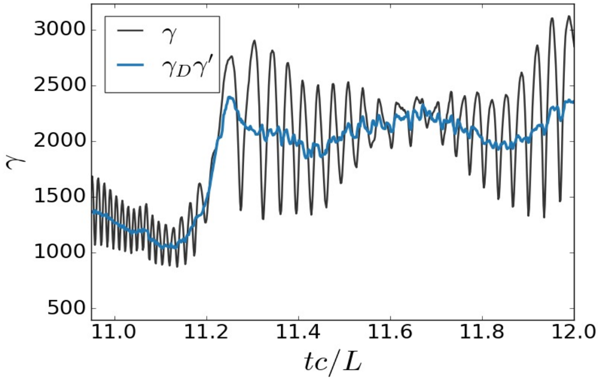
Simulation:

Direct Numerical (PIC) Test of Fokker-Planck Model for Turbulent Particle Acceleration

Wong et al. 2020

Technical Details

Removing energy oscillations



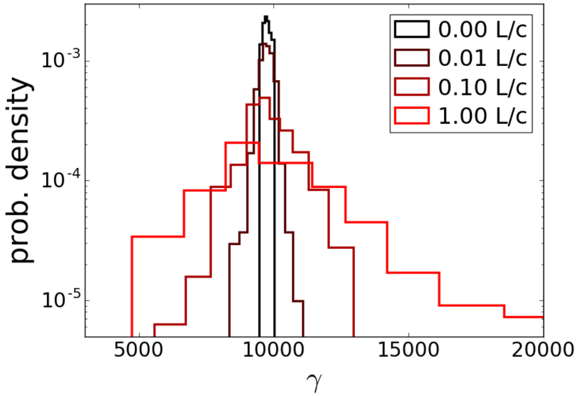
Relativistic turbulence: $E_{rms} \sim B_{rms}$

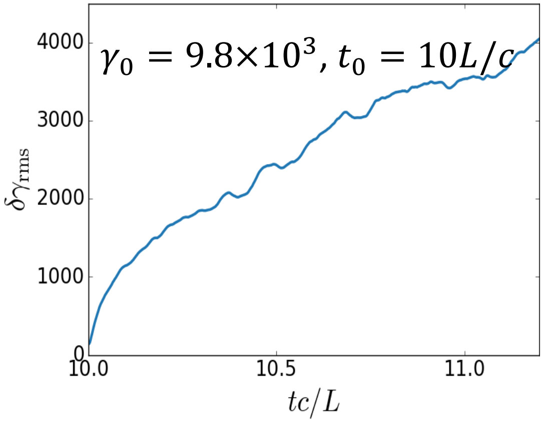
An electron gyrating in the presence of strong E_{rms} experiences order-unity energy oscillations over Larmor period.

We smooth over the oscillations to study random-walk in energy

Establishing energy diffusion and measuring FP coefficients: $\partial_t f = \partial_\gamma (D \partial_\gamma f) - \partial_\gamma (A f)$

- At $t = t_0$ after turbulence is established, select a group of particles in a narrow (1-5%) energy bin around γ_0.
- Calculate the average energy $\bar{\gamma}$ and standard deviation of $\delta\gamma_{rms}$ over subsequent time Δt.
- Extract $D(\gamma_0)$: $\delta\gamma_{rms} = \sqrt{2D\Delta t}$
- Extract $A(\gamma_0)$: $\Delta\bar{\gamma} = (A + \partial_\gamma D)\Delta t$
- Repeat for particle bins at other γ_0 and t_0





Simulation:

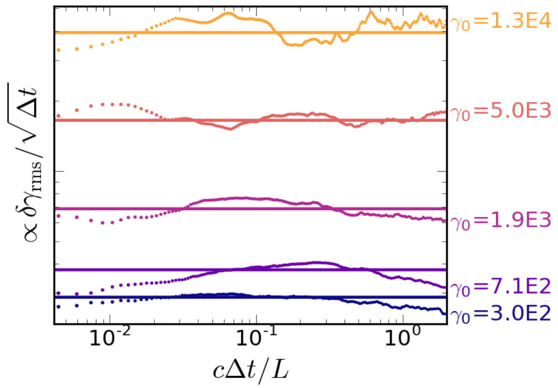
Direct Numerical (PIC) Test of Fokker-Planck Model for Turbulent Particle Acceleration

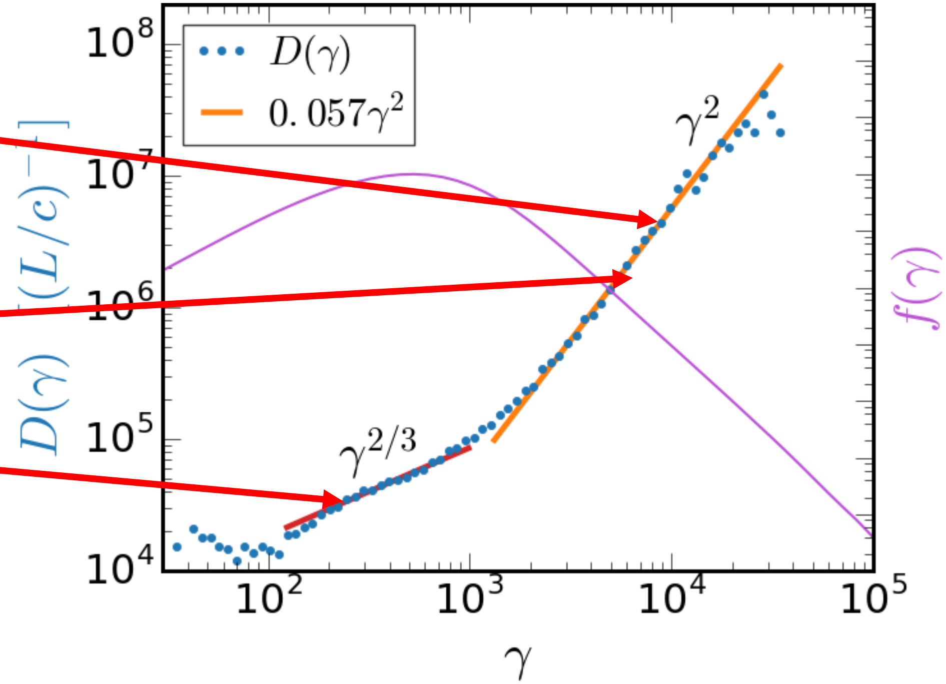
Results:

Wong et al. 2020

Random walk in energy and energy-diffusion coeff.

- Changes in energy consistent with random walk: $\delta\gamma_{rms} \sim \sqrt{\Delta t}$
- Extract Diffusion Coefficient: $D = \frac{\delta\gamma_{rms}^2}{2\Delta t}$
- $D(\gamma) \sim \gamma^2$ in the nonthermal tail, corresponding to inertial range of turbulence.
- 2nd-order Fermi Accel: $D(\gamma) = D_0\,\gamma^2$
- Much shallower of $D(\gamma)$ scaling at low energies…





Simulation:

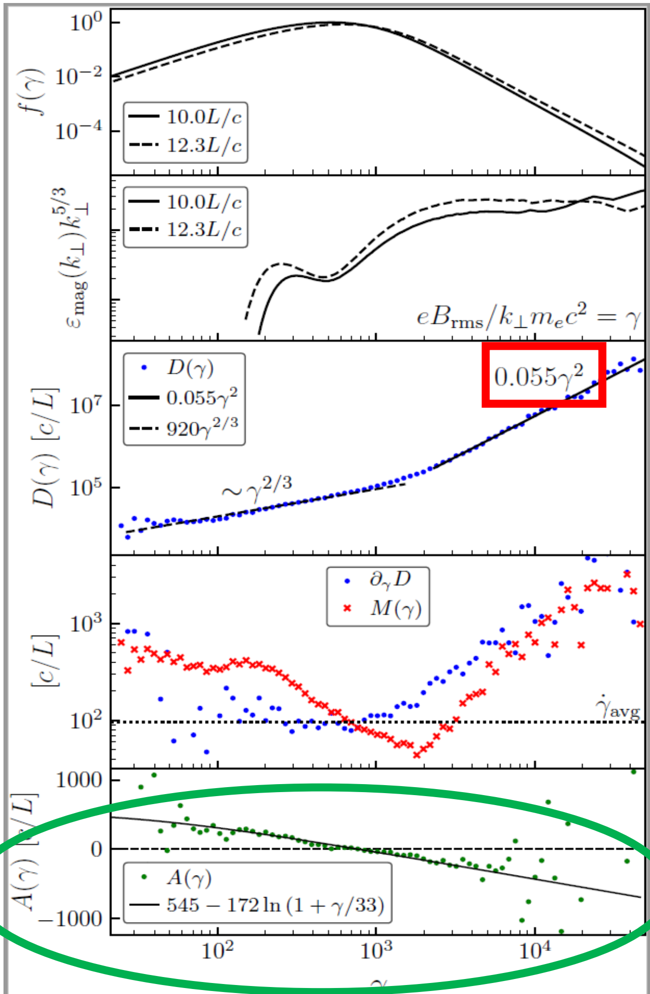
Direct Numerical (PIC) Test of Fokker-Planck Model for Turbulent Particle Acceleration

Results:

Wong et al. 2020

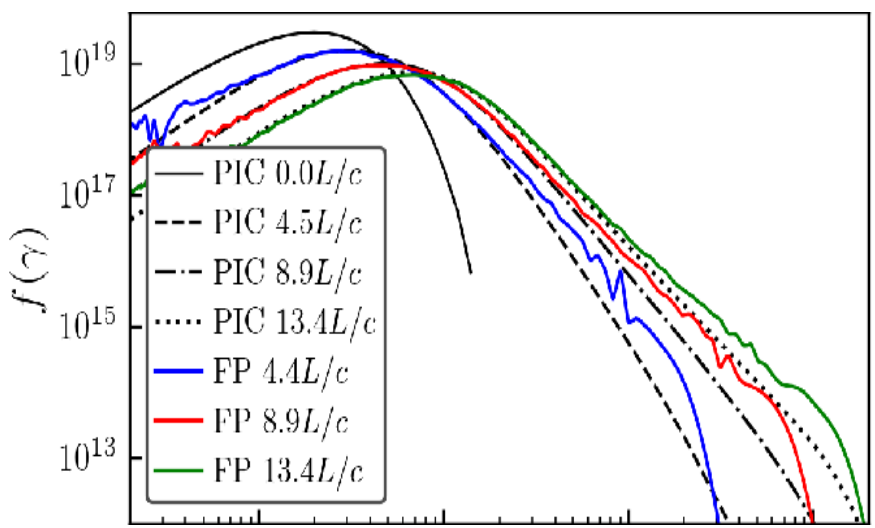
$$\partial_t f = \partial_\gamma (D \partial_\gamma f) - \partial_\gamma (A f)$$

Advection term is essential!



Fokker-Planck Framework works well!

Fokker-Planck Evolution vs. actual PIC

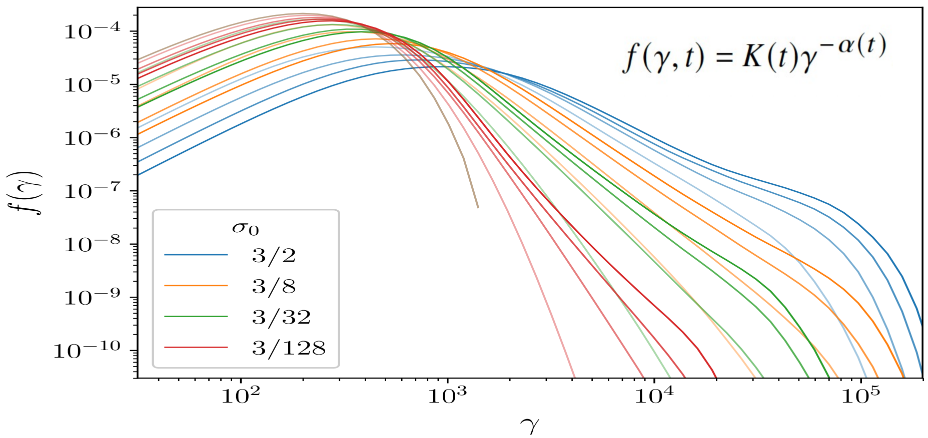


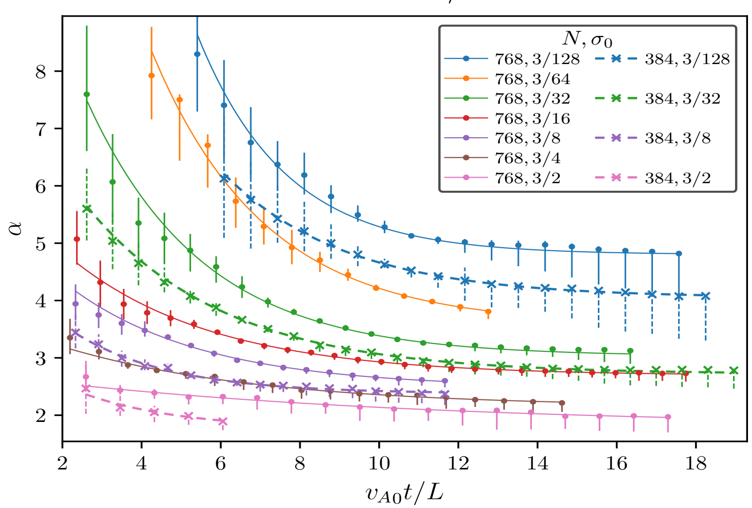
Simulation:

Energy Diffusion and Advection Coefficients in Kinetic Simulations of Relativistic Plasma Turbulence

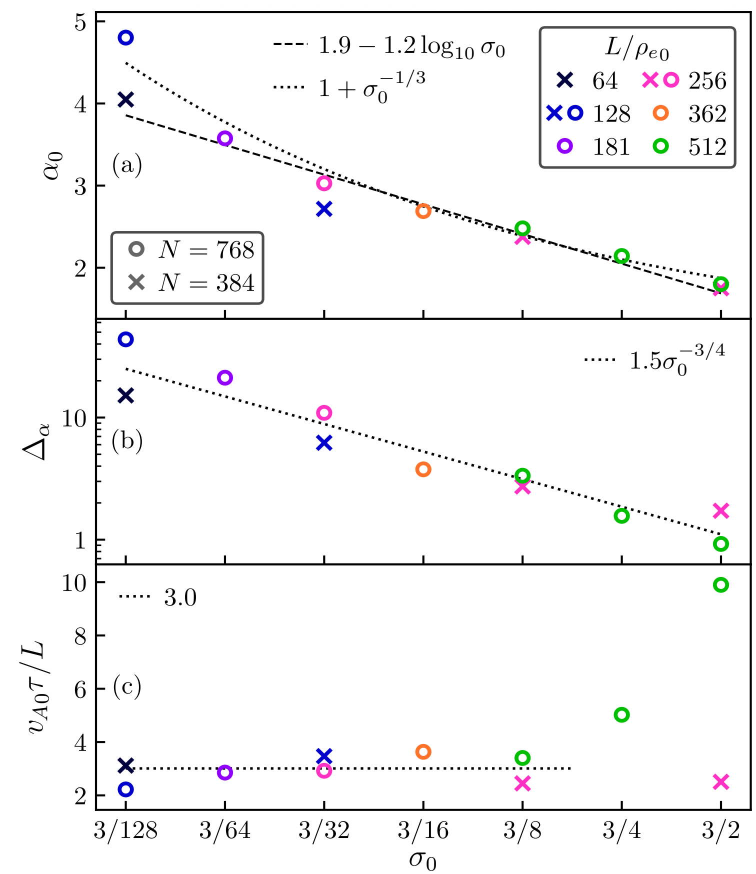
Wong et al. 2024 in prep

How are energy-space FP coefficients $D(\gamma)$ and $A(\gamma)$ related to the spectral evolution, e.g., power-law index $\alpha(t)$?





$$\alpha(t) = \alpha_\infty + \Delta_\alpha \exp(-t/\tau)$$

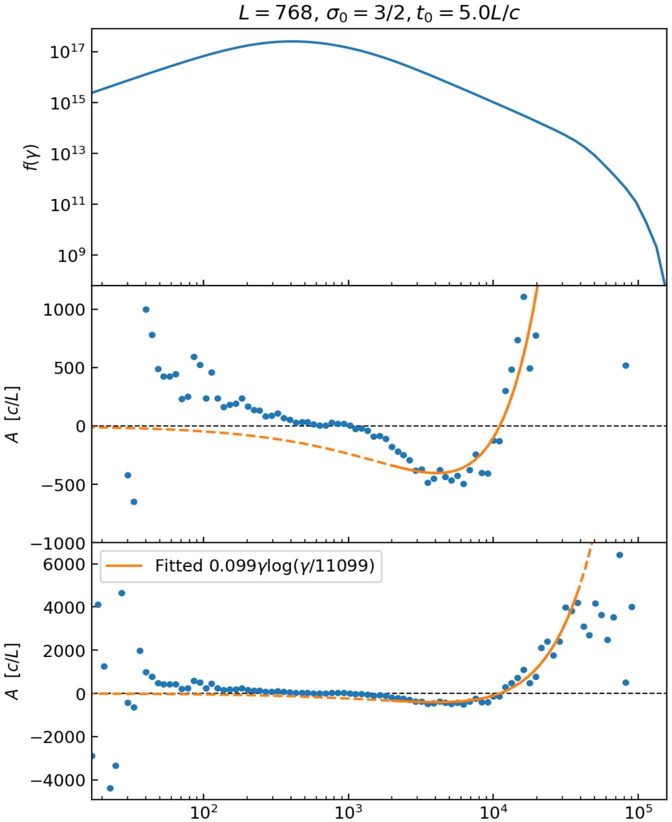


Simulation:

Energy Diffusion and Advection Coefficients in Kinetic Simulations of Relativistic Plasma Turbulence

Wong et al. 2024 in prep

Can the evolution of the spectral index $\alpha(t)$ be reproduced with a FP model?



- Energy **advection-diffusion** FP equation:

$$\partial_t f = \partial_\gamma(D\partial_\gamma f) - \partial_\gamma(Af)$$

  - $f(\gamma,t)$: particle energy distribution
  - $D(\gamma,t)$: energy diffusion coefficient
  - $A(\gamma,t)$: energy advection coefficient
- Nonthermal power law: $f(\gamma,t) = K(t)\gamma^{-\alpha(t)}$
- Diffusion Coefficient: $D(\gamma,t) = D_0(t)\gamma^2$
- What should $A(\gamma,t)$ be?
- Prediction for γ-functional form of A:

$$\boldsymbol{A = A_0\,\gamma\,\log(\gamma/\gamma_A^*)}$$

$$A_0(t) = \frac{\dot\alpha}{1-\alpha} = -\frac{d\log(\alpha-1)}{dt},\quad \gamma_A^*(t) = \exp\left[\frac{\dot K/K + D_0(\alpha-\alpha^2)}{\dot\alpha} + \frac{1}{1-\alpha}\right]$$

Simulation:

Energy Diffusion and Advection Coefficients in Kinetic Simulations of Relativistic Plasma Turbulence

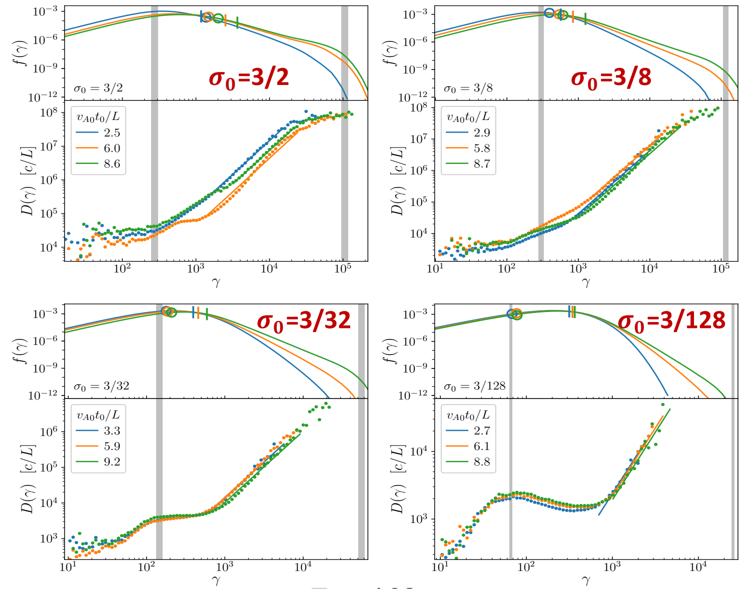
Wong et al. 2024 in prep

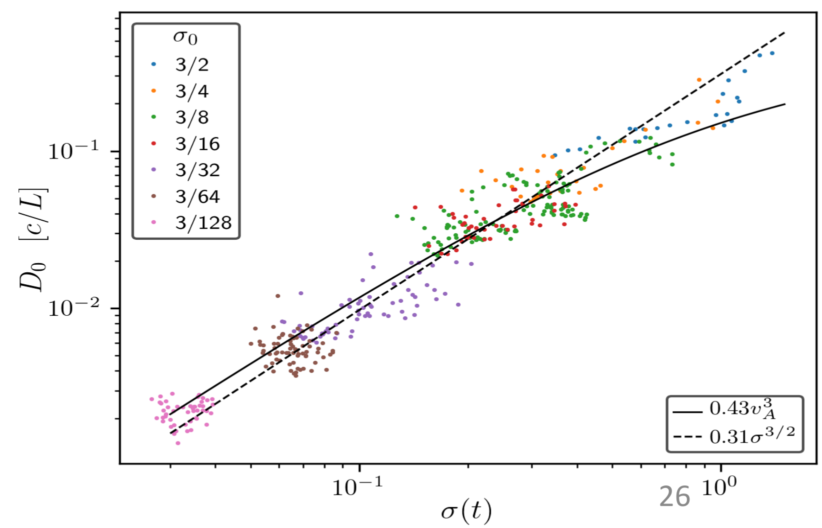
$\sigma_0 = B_0^2/16\pi n_0 T_0$

Dependence of $D(\gamma, t)$ on magnetization $\sigma(t)$

- Multiple runs with varying initial magnetization σ_0.
- Universal $D(\gamma) \sim \gamma^2$ in high-γ nonthermal tail $\gamma \gg \gamma_{\text{peak}}$, but non-universal σ_0-dependent slope at lower γ.
- Measure D_0 at many time instances.
- Magnetization decreases over time as plasma heats up.
- D_0 depends mainly on instantaneous $\sigma(t)$, not initial σ_0.
- D_0 scales as $\sigma^{3/2}$ or V_A^3 instead of σ or V_A^2.
- Agrees with *Demidem et al 2020*:

  Extra power of V_A from resonance broadening
- Knowing $D_0(\sigma)$ helps us:
  - discriminate among NTPA theories
  - predict $f(\gamma, t)$ given $\sigma(t)$





SUMMARY

- Turbulent Relativistic NTPA is ubiquitous in the Universe
- Quasi-Linear Theory (QLT) has been a leading theoretical approach, informed by advances in theory of MHD turbulence
- PIC simulation is the main working horse of modern numerical studies
- Relativistic magnetized plasma turbulence is a robust particle accelerator, producing extended (to Hillas limit) power-law spectra.
- Validation of energy-space Fokker-Planck (FP) model of turbulent relativistic particle acceleration using direct PIC measurements:
  - Demonstrated that relativistic NTPA is diffusive.
  - FP agrees well with the PIC evolution of $f(\gamma, \mathrm{t})$ in fully-developed turbulence.
- Measuring $D(\gamma)$, $A(\gamma)$:
  - $D(\gamma) \sim \gamma^2$ in the nonthermal tail, much shallower scaling at low energies.
  - Dependence on magnetization is $D_0 \sim \sigma^{\frac{3}{2}}$
  - Energy Advection Coefficient $A(\gamma)$ is essential

THANK YOU!

EXTRA SLIDES

Theory:

Theory of Turbulent Relativistic Nonthermal Particle Acceleration (NTPA)

Analytical QLT of Turbulent NTPA: Historical Development (1960-90s)

- Kennel and Engelmann (1966); Lerche(1968): "*Quasilinear Theory of Resonant Diffusion in a Magneto-Active, Relativistic Plasma*"
- Kulsrud & Pearce (1969), Kulsrud & Ferrari (1971): relativistic QLT for Alfven-wave MHD turbulence starting with relativistic Vlasov equation.

(Interlude: important parallel developments in 1st-order Fermi shock acceleration 1977-1978: Krymskii '77, Axford etal '77, Bell '78, Blandford & Ostriker '78; see Blandford & Eichler 1987 review)

- Schlickeiser (1989-1993): detailed QLT for spatial and momentum diffusion for gyro-averaged $f_0(p,\mu)$ for (slab) Alfven waves (parallel or antiparallel to background $\boldsymbol{B_0}$, $k_\perp = 0$) with a power-law $k_\parallel$ -spectrum.

What do we need to know about MHD turbulence to determine QL diffusion coefficient? Subsequent development of QLT of turbulent particle acceleration was influenced by advances in theory of magnetized plasma turbulence itself.

Theory:

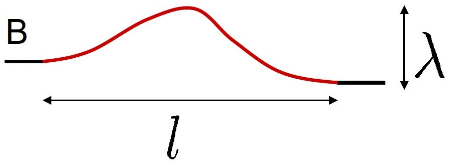
Theory of Turbulent Relativistic Nonthermal Particle Acceleration (NTPA)

Important development in incompressible MHD turbulence theory: Goldreich-Sridhar 1995, 1997

(*cf. Shebalin et al 1983; Higdon 1984, Ng & Bhattacharjee*)

- Strong Alfvenic MHD Turbulence is **anisotropic**: $k_\perp >> k_\parallel$
- Critical Balance: $\tau_{lin} = \omega_A = k_\parallel V_A \sim \tau_{nl} = 1/(k_\perp u_\perp)$

  Here, $l = k_\parallel^{-1}$ and $\lambda = k_\perp^{-1}$



- Result: GS95 spectral scalings:

$$E(k_\perp) \sim \varepsilon^{2/3} k_\perp^{-5/3}$$
$$k_\parallel \sim \varepsilon^{1/3} v_A^{-1} k_\perp^{2/3}$$
$$E(k_\parallel) \sim \varepsilon v_A^{-1} k_\parallel^{-2}$$

Chandran (2000):

updated Alfvenic-turbulence QLT accounting for GS95 theory.

Key findings: strong $k_\perp >> k_\parallel$ anisotropy suppresses strong pitch-angle scattering and NTPA.

But in MHD Turbulence truly Alfvenic?

Theory:

Theory of Turbulent Relativistic Nonthermal Particle Acceleration (NTPA)

But is MHD turbulence truly Alfvenic?

- General MHD turbulence is not limited to incompressible Alfven waves; also includes compressible Fast and Slow MS waves.
- Standard view: (nonrel.) MHD turbulence divides into two decoupled cascades:
  - Solenoidal (Alfvenic, Goldreich & Sridhar 1995)
  - Compressive (fast mode, Cho & Lazarian 2002+)
- QLT analyses of CR transport/acceleration by compressible F/S-mode turbulence: transit-time damping (n=0) + gyroresonant ($n \neq 0$) wave-particle interactions
  - Fast modes are more efficient particle accelerators
  - Schlickeiser & Miller (1998): isotropic fast-mode turbulence with Kolmogorov spectrum
  - Yan & Lazarian (2002), Cho & Lazarian (2003, 2006): strong and weak MHD turbulence with slow and fast modes
  - Chandran (2003), Chandran & Maron (2004): slow-mode compressible MHD turbulence (solar flares)
  - Demidem, Lemoine, Casse (2020): detailed relativistic QLT for stochastic NTPA in relativistic MHD general (fast, slow, and Alfvenic) turbulence.

Theory:

Theory of Turbulent Relativistic Nonthermal Particle Acceleration (NTPA)

Beyond Quasilinear Theory: New Theoretical Ideas

- Role of strong intermittent, coherent dissipative structures, e.g. reconnecting current sheets (Vlahos et al. 2004, Isliker et al. 2017, Zhdankin et al. 2013, Lemoine 2021, Comisso & Sironi 2018, 2019)
- Generalized Entropies, Casimir Invariants (Zhdankin 2021, 2022)
- Lynden-Bell's stat. mech. framework (Ewart et al. 2023)
- Interplay between pitch-angle scattering and trapping in accelerating structures (Vega, Boldyrev, Roytershteyn, Medvedev 2022)

Theory of Turbulent Relativistic Nonthermal Particle Acceleration (NTPA)

Some Modern Challenges and Opportunities:

- Update QLT for modern picture of MHD turbulence reflecting recent theoretical advances: dynamic alignment (Boldyrev 2006); plasmoid-mediated turbulence and role of small-scale reconnection (Mallet et al. 2017; Loureiro & Boldyrev 2017)
- QLT for turbulence with radiative cooling
- QLT for turbulence driven by small/intermediate-scale instabilities
- Beyond QLT: role of large, intense, reconnecting current sheets
- Embedding QLT/FP prescriptions into global MHD models
- Explore prospects for laboratory experimental studies.