Turbulent particle energization in radiatively inefficient accretion flows

Vladimir Zhdankin

Princeton University

(previously JILA, University of Colorado at Boulder)

Dmitri Uzdensky, Greg Werner, Mitch Begelman

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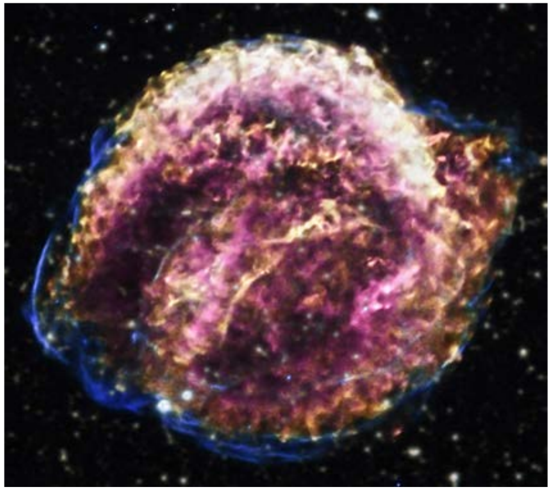
PRINCETON UNIVERSITY

High-energy astrophysical turbulence



Kepler's supernova (SNR)

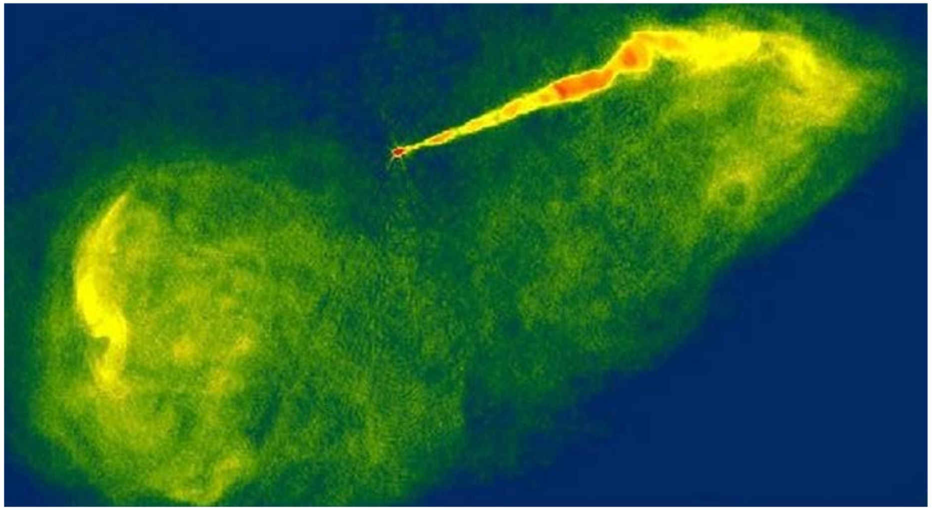
Turbulence is a **ubiquitous process** in high-energy astrophysics

Systems often comprise **radiative, relativistic, collisionless plasmas**

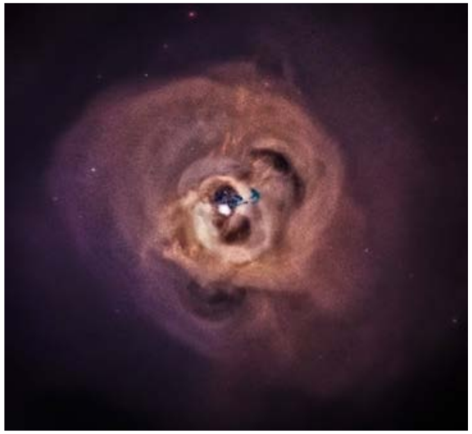
Small-scale turbulence important for understanding structure, spectra, etc.

NGC 4261 (accretion flow)

Crab nebula (PWN)



M87 (AGN jet)

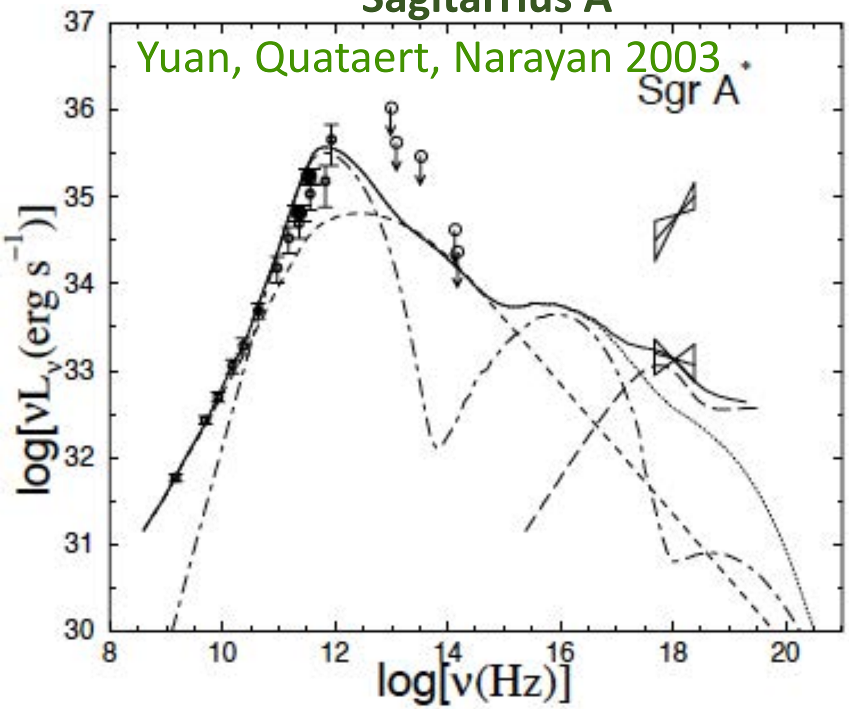


Perseus cluster (ICM)

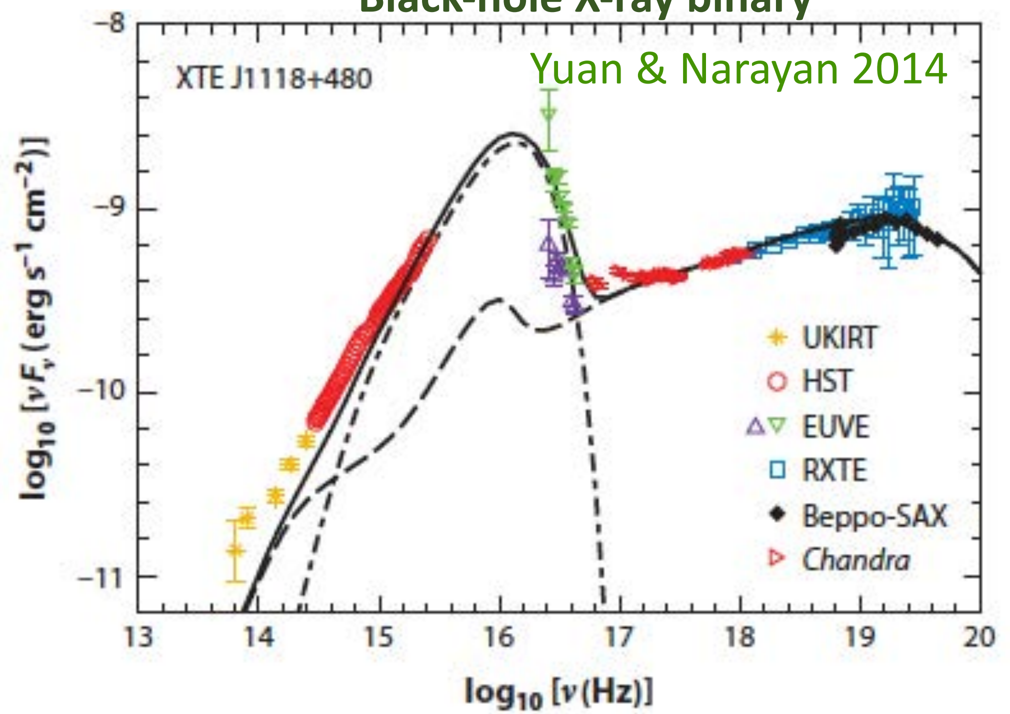
Radiatively inefficient accretion flows (RIAFs)

- Low-luminosity accretion state commonly observed around black holes, comprising geometrically thick, optically thin, hot tenuous plasma
- Expected to be highly turbulent due to magnetorotational instability
- Broadband radiation spectra indicate nonthermal particle acceleration
- Global models require "two-temperature" plasma, where ions are much hotter than electrons, for equilibrium (Yuan & Narayan 2014 for review)

Sagitarrius A*



Black-hole X-ray binary



Key questions about RIAFs

- Can collisionless dissipation of turbulence naturally establish a two-temperature plasma, as required by RIAF models?
- Are there any collective plasma physical effects that will prevent $T_i \gg T_e$?
- Can turbulent particle acceleration explain the observed presence of nonthermal energetic particles?
- What are the observable radiative signatures in such a setting, and what can they tell us about the system?

To address these questions, must understand nature of turbulence in relativistic, collisionless plasmas

Very challenging problem, but can be studied with numerical simulations

Particle-in-cell (PIC) simulations

- Solves Maxwell-Vlasov system of equations for collisionless plasma
- Plasma represented by "macroparticles" pushed by Lorentz force
- Electric and magnetic fields computed on a grid from charges/currents

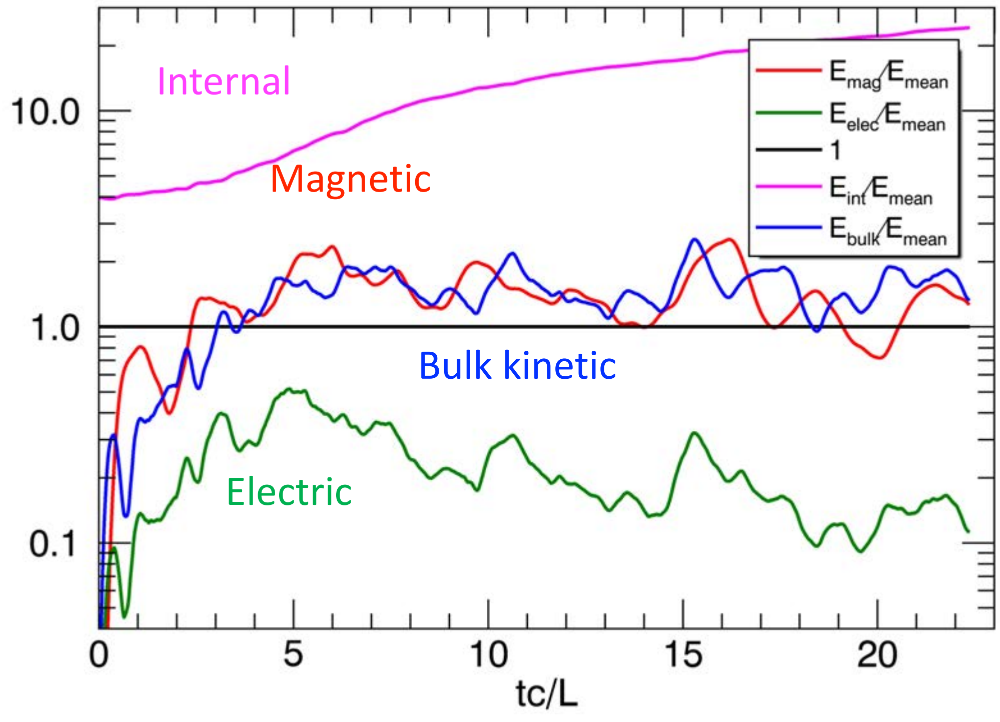
What is possible with PIC codes?

- "First-principles" solutions of collisionless plasma phenomena, including dissipation mechanisms and nonthermal particle acceleration
- Efficient for pair plasmas, relativistic plasmas; expensive for non-relativistic, electron-ion plasmas (disparity between electron and ion spatial scales, timescales)
- Widely used for studying collisionless shocks, magnetic reconnection, pulsar magnetospheres, plasma instabilities, turbulence, etc.

Numerical simulations

- Externally driven turbulence with PIC code *Zeltron* (Cerutti+ 2013)
- Periodic box (no particle escape, no energy sink)
- Initialize thermal plasma, apply large-scale driving (TenBarge+ 2014)
- Uniform guide field $B_0 \sim \delta B_{\rm rms}$, equal initial temperatures $T_i = T_e$

Energy evolution



Before looking at electron-ion plasmas…

- For simplicity, first consider ultra-relativistic pair plasma
- Mathematically identical to ultra-relativistic electron-ion plasma $(T \gg m_i c^2)$
- Relevant for pulsar wind nebulae and AGN jets
- Two physical parameters (fixing $T/m_e c^2 = 100$):

1) Magnetization (ratio of magnetic energy to total particle energy):

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

Alfvenic turbulence: $\frac{\delta v}{c} \sim \frac{v_A}{c} = \sqrt{\frac{\sigma}{\sigma + 4/3}}$

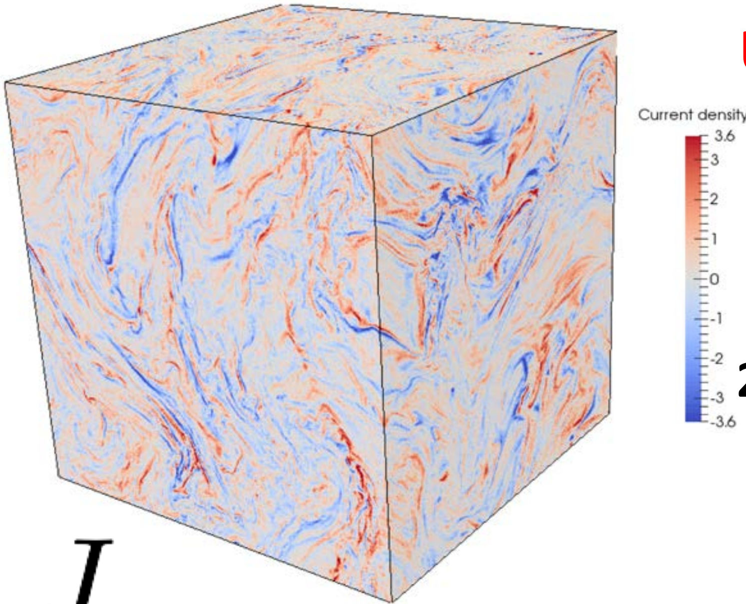
2) System size (ratio of driving scale to particle Larmor radius):

$$L/2\pi\rho_e \to 163$$

(MHD range recovered)

$$\rho_e = \frac{\bar{\gamma} m_e c^2}{e B_{\rm rms}}$$

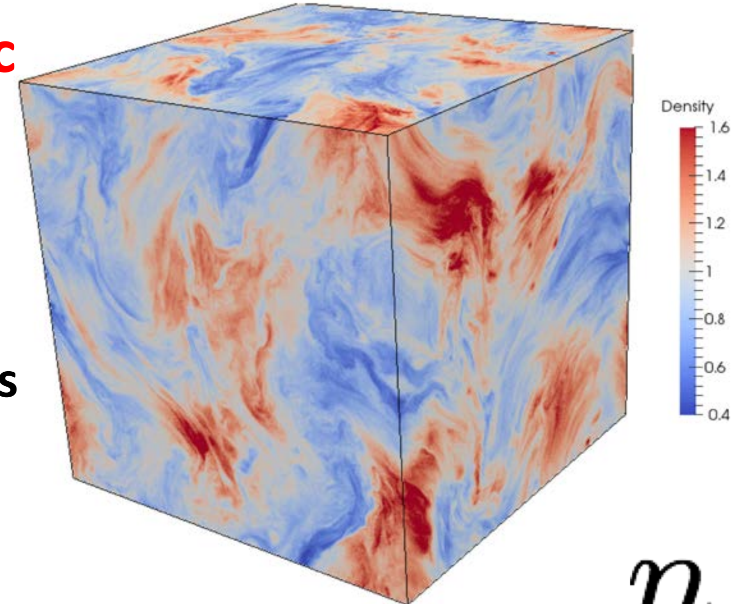
Ultra-relativistic pair plasma



J_z

up to
200 billion particles
1536^3 cells

$\sigma_0 = 0.5$



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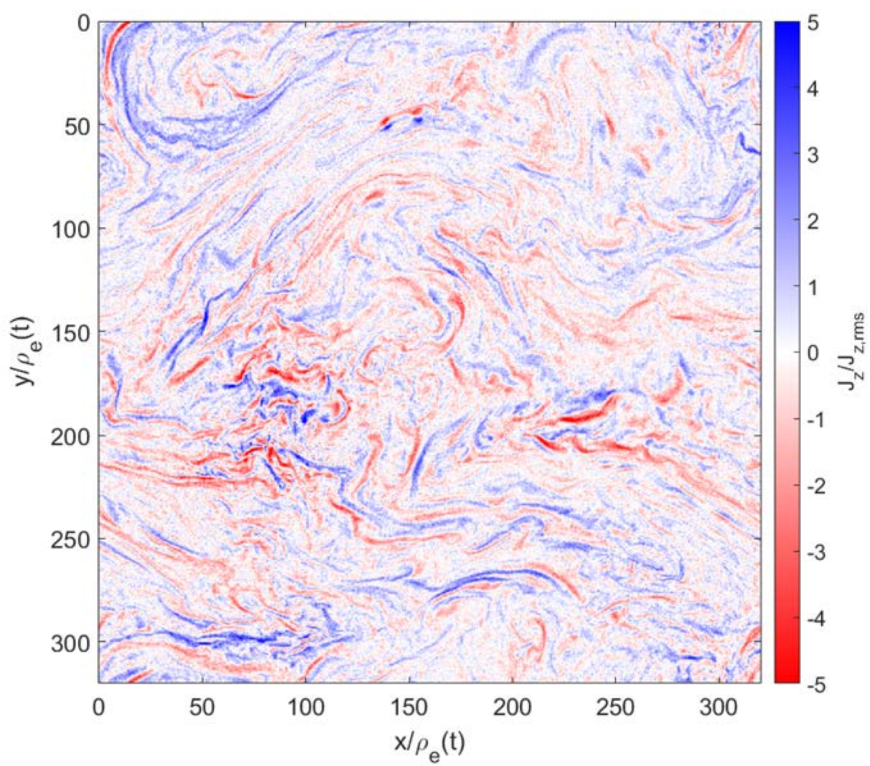
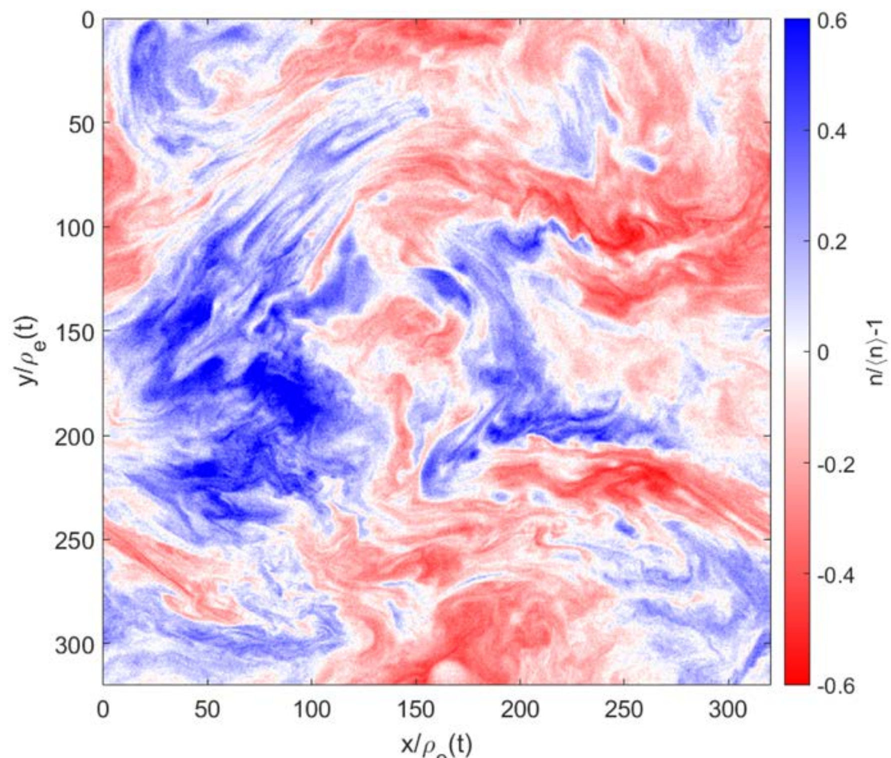
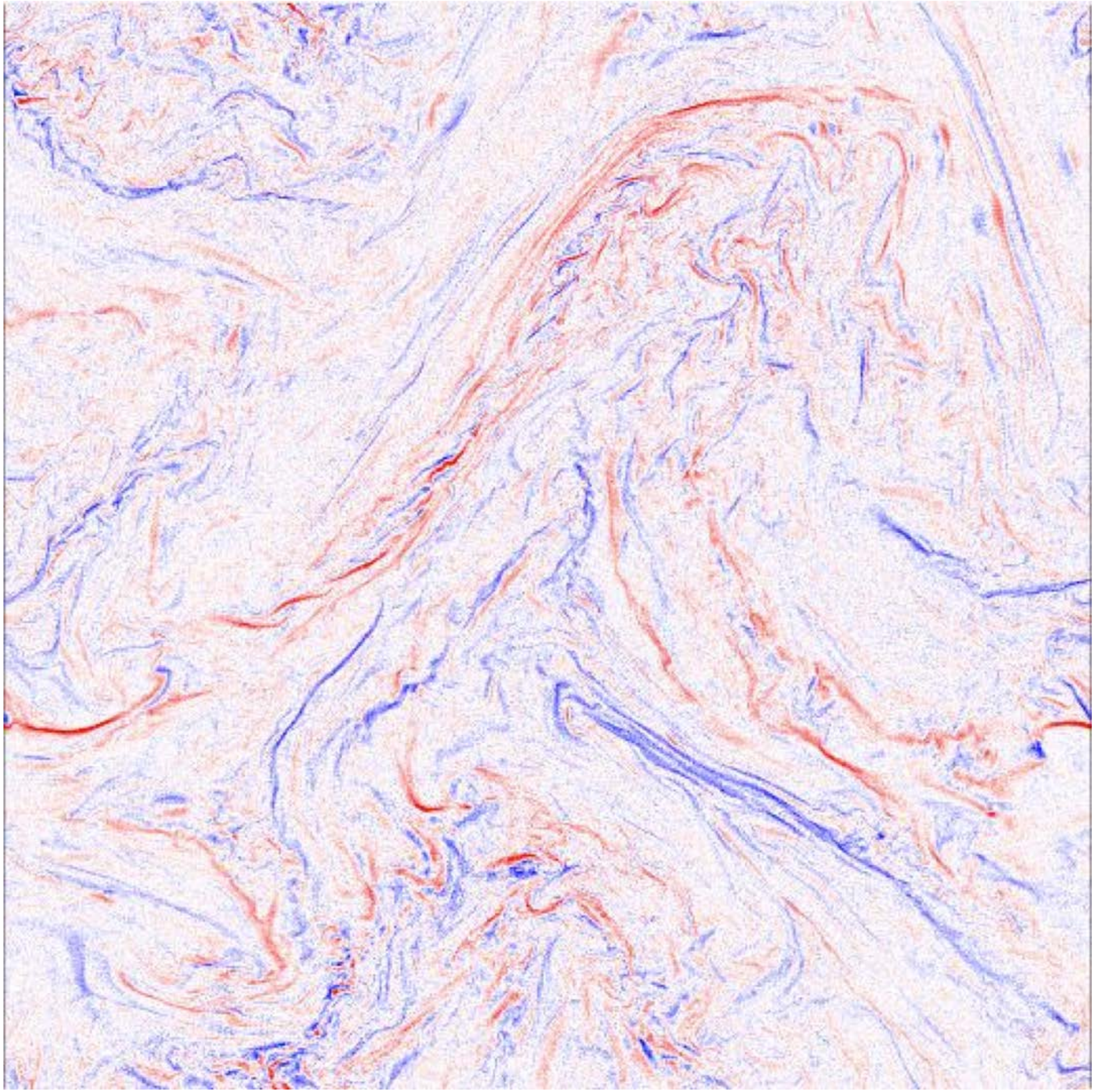




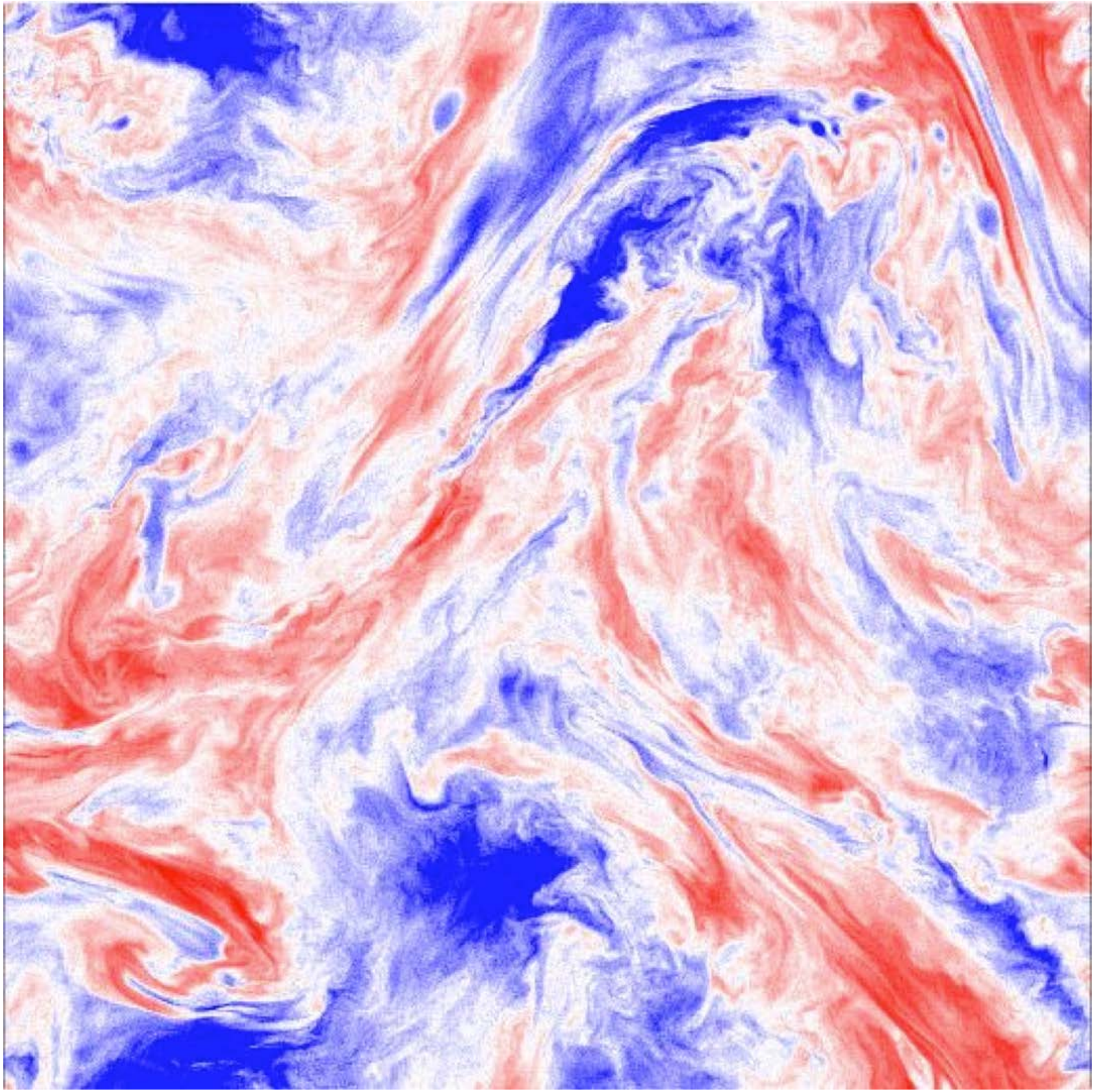
Fixed time fly through

J_z



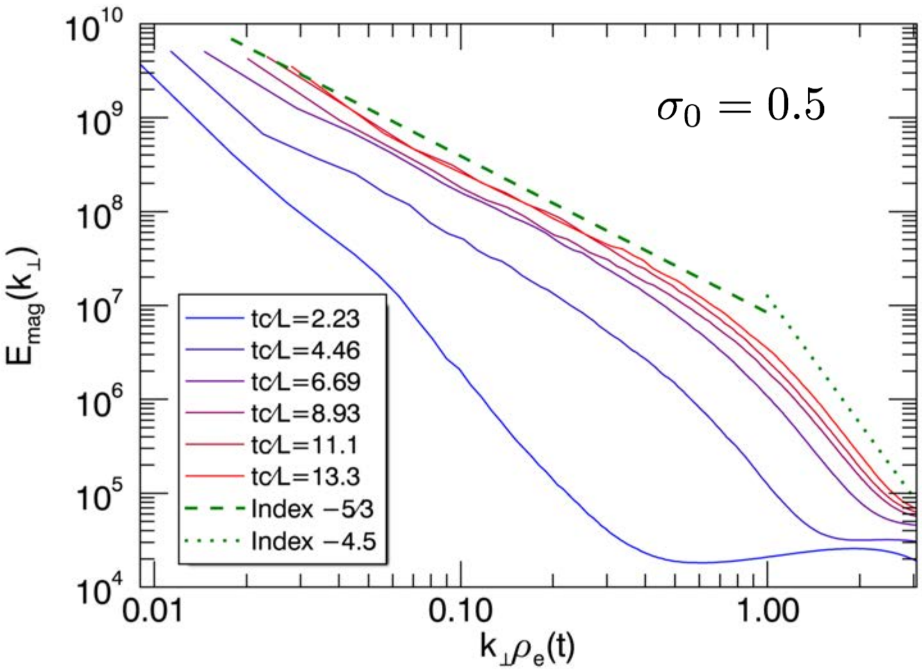
Fixed
time
fly
through

δn

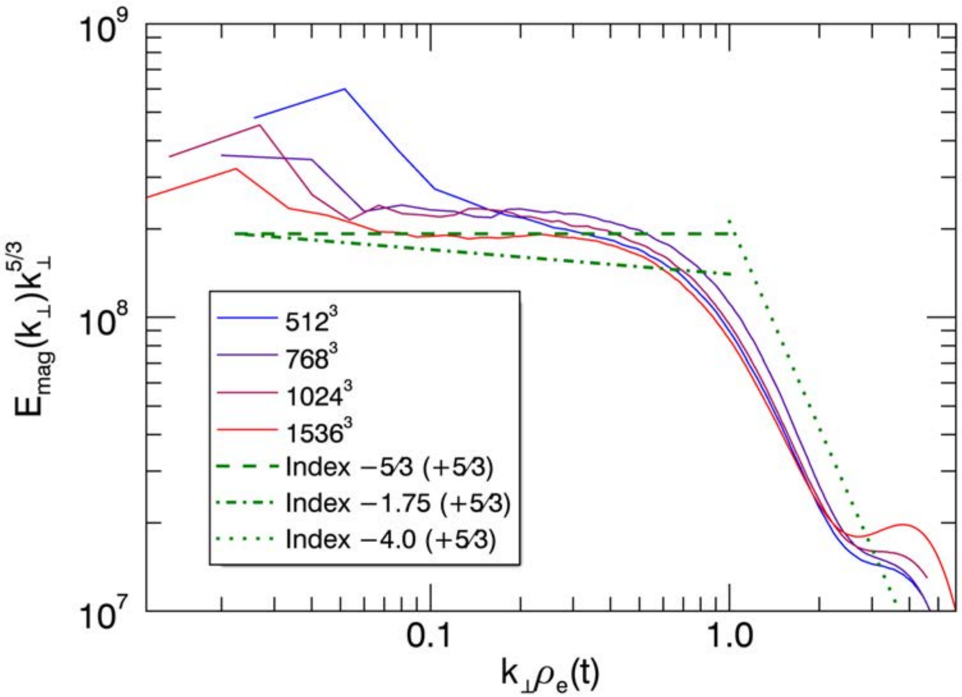


Magnetic energy spectrum

Spectrum evolution (1024^3)



Compensated, averaged spectrum



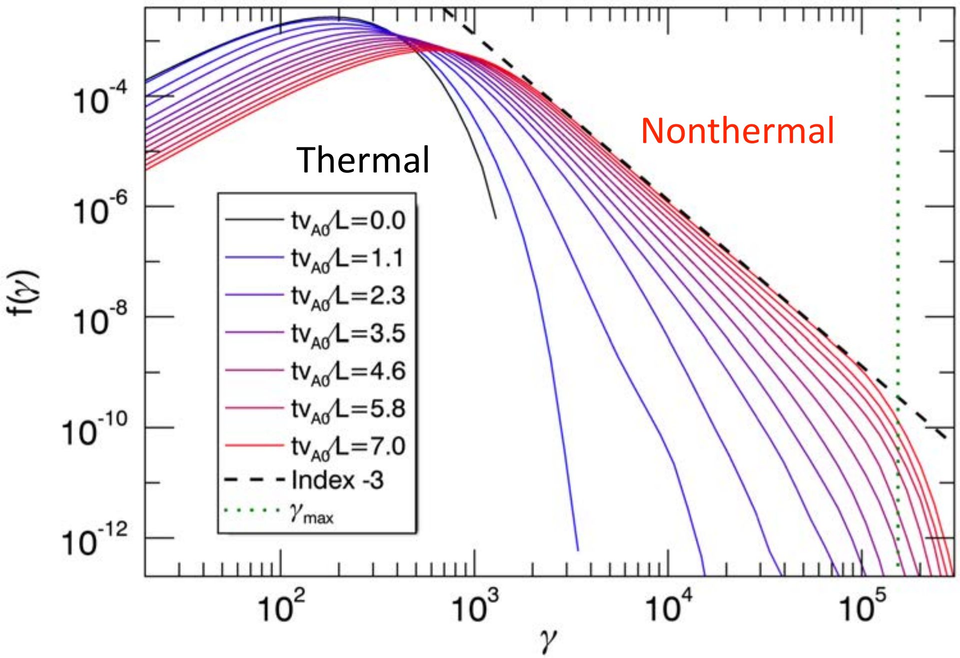
Inertial range essentially converged for 768^3 and larger $(L/2\pi\rho_{e0} \gtrsim 80)$

MHD range -5/3 index (Goldreich & Sridhar 1995, Thompson & Blaes 1998)

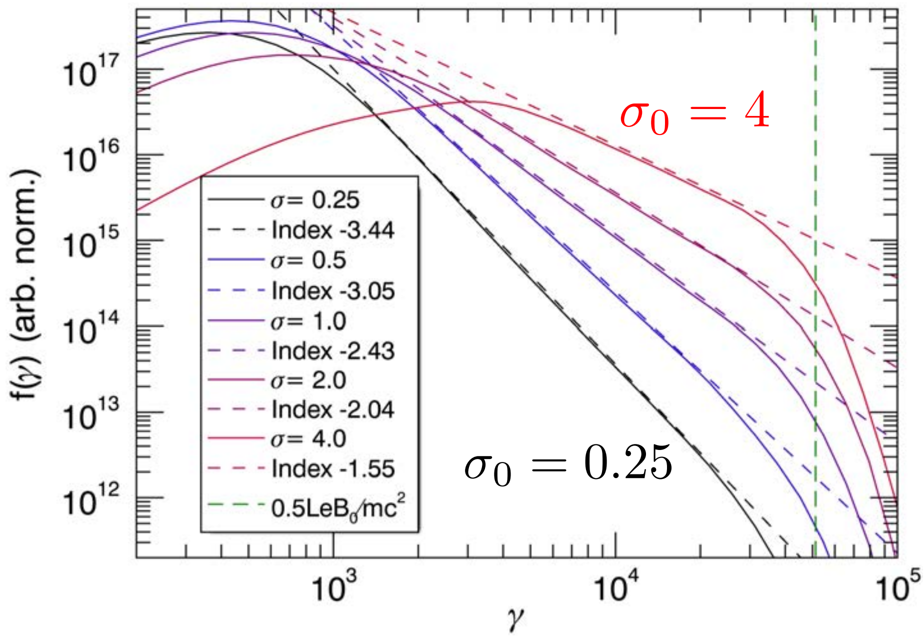
Kinetic range -4.5 index (kinetic cascade? Schekochihin+ 2009)

Nonthermal particle acceleration

Energy distribution evolution



Magnetization scan



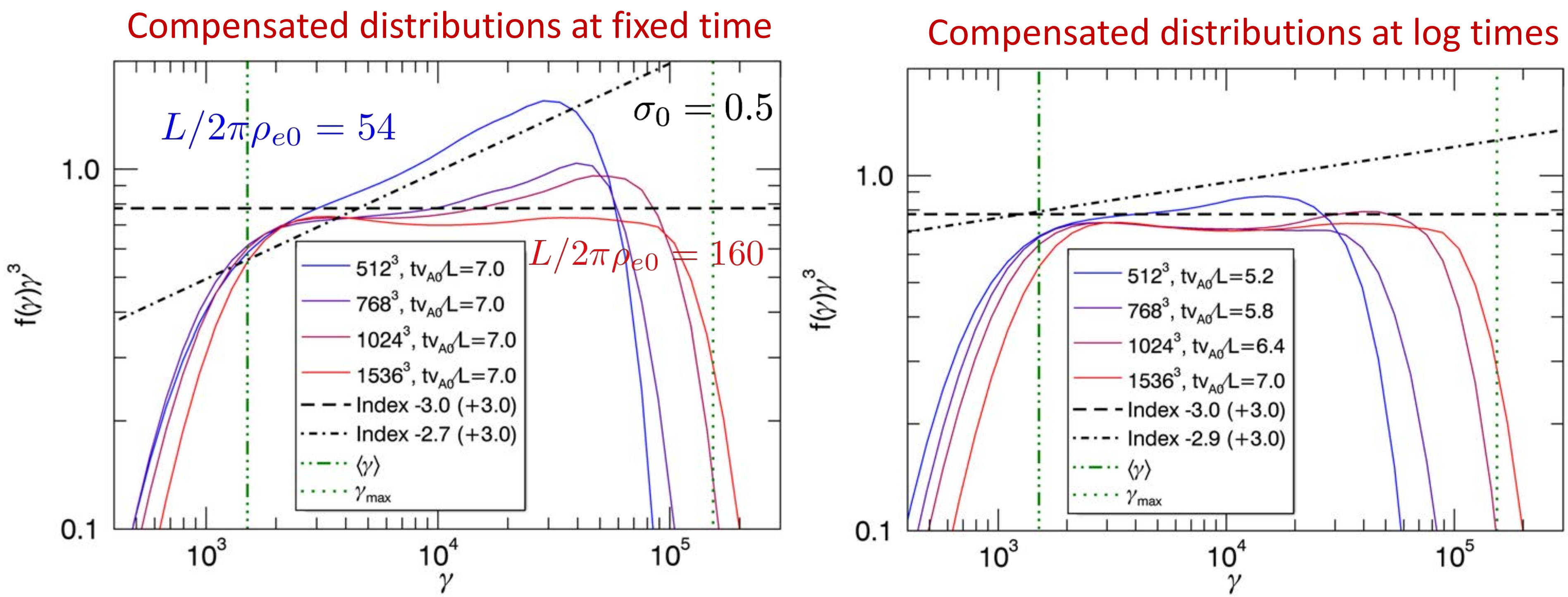
Power law tail: $f(\gamma) \sim \gamma^{-\alpha}$ $\quad (\gamma = E/m_e c^2)$

Spans from mean energy $\langle \gamma \rangle$ to system-size limited energy $\gamma_{\max} = LeB/2mc^2$

Hardens with increasing magnetization: empirical formula $\alpha \sim 1 + C_0 \sigma_0^{-1/2}$

Zhdankin, Werner, Uzdensky & Begelman PRL 2017

System-size dependence?



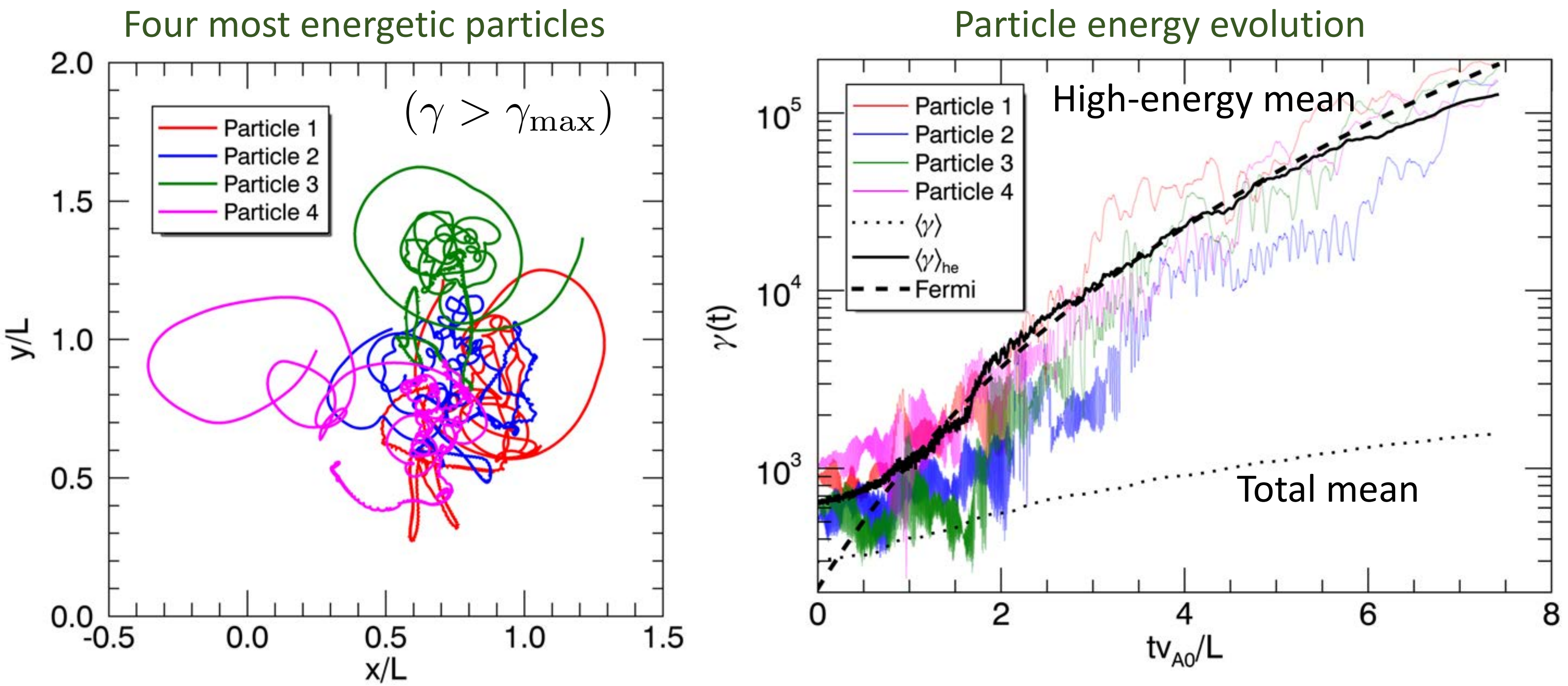
Weak system-size dependence (up to size $L/2\pi\rho_e \sim 160$)

Convergence when compared at times scaling logarithmically with system size

Proposal: nonthermal distribution formation delayed in larger simulations

(Zhdankin+ arXiv:1805.08754; see also Comisso & Sironi arXiv:1809.01168)

Mechanism of acceleration?



High-energy particles consistent with second-order Fermi acceleration (Fermi 1949):

$$\frac{d\gamma}{dt} \sim \frac{\gamma}{\tau_{\rm acc}(t)} \qquad \tau_{\rm acc} \propto \frac{Lc}{v_A^2(t)}$$

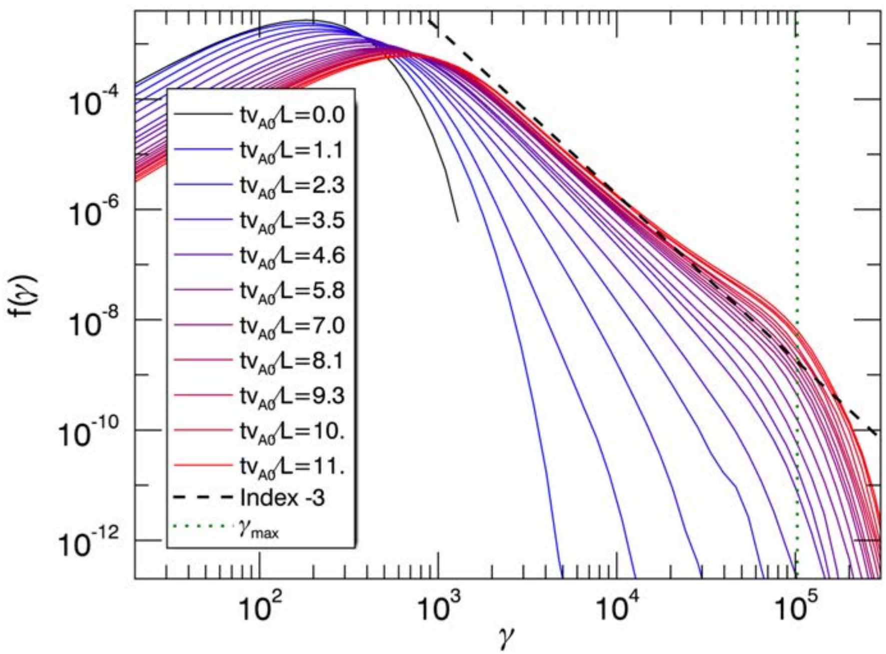
Implications of Fermi acceleration

"Inflection time" (time required for particles to reach system-size energy limit) is logarithmic function of system size:

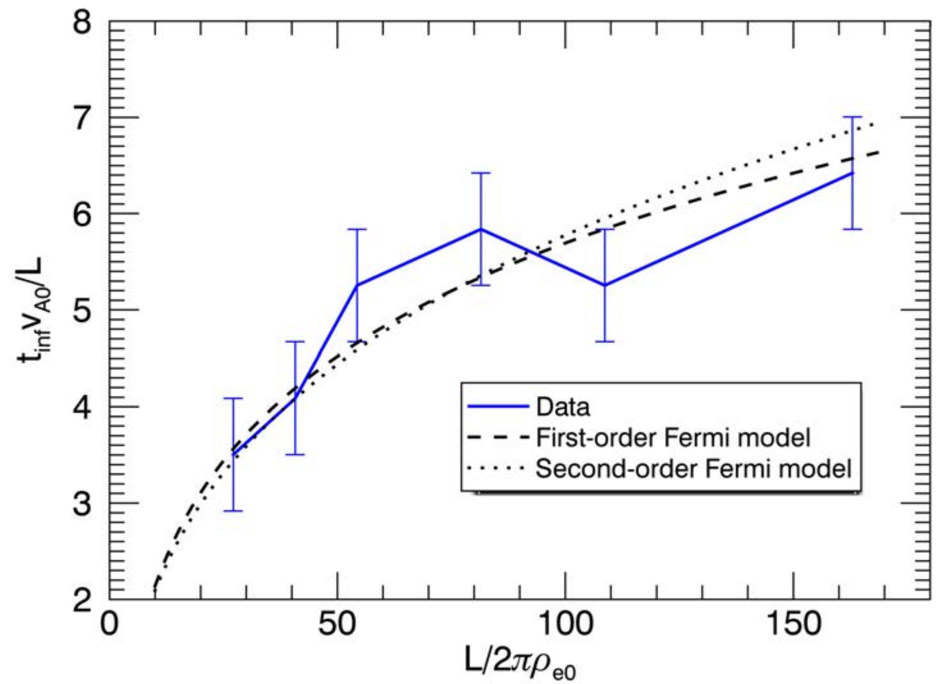
$$\gamma \sim \gamma_i \exp\left(t/\tau_{\rm acc}\right) \implies t_{\rm inf} \sim \tau_{\rm acc} \log\left(\gamma_{\rm max}/\gamma_i\right) \sim \tau_{\rm acc} \log L/\rho_{e0}$$

Distribution is fully developed until inflection time is reached

Pileup forms at "inflection time"



Inflection time vs system size



Electron-ion simulations

- Focus on temperatures such that ions (protons) are sub-relativistic and electrons are ultra-relativistic (transrelativistic or "semirelativistic" case):

$$m_e c^2 < T < m_i c^2 \qquad (0.5 \text{ MeV} \lesssim T \lesssim 1 \text{ GeV})$$

- Electrons have large effective mass due to relativistic effects, reducing scale separation relative to ions
- Three physical parameters:

1) Temperature relative to ion rest mass: $\theta_i = T/m_i c^2$

   Relativistic (pair plasma) regime: $\theta_i \gg 1 : \rho_i \sim \rho_e$

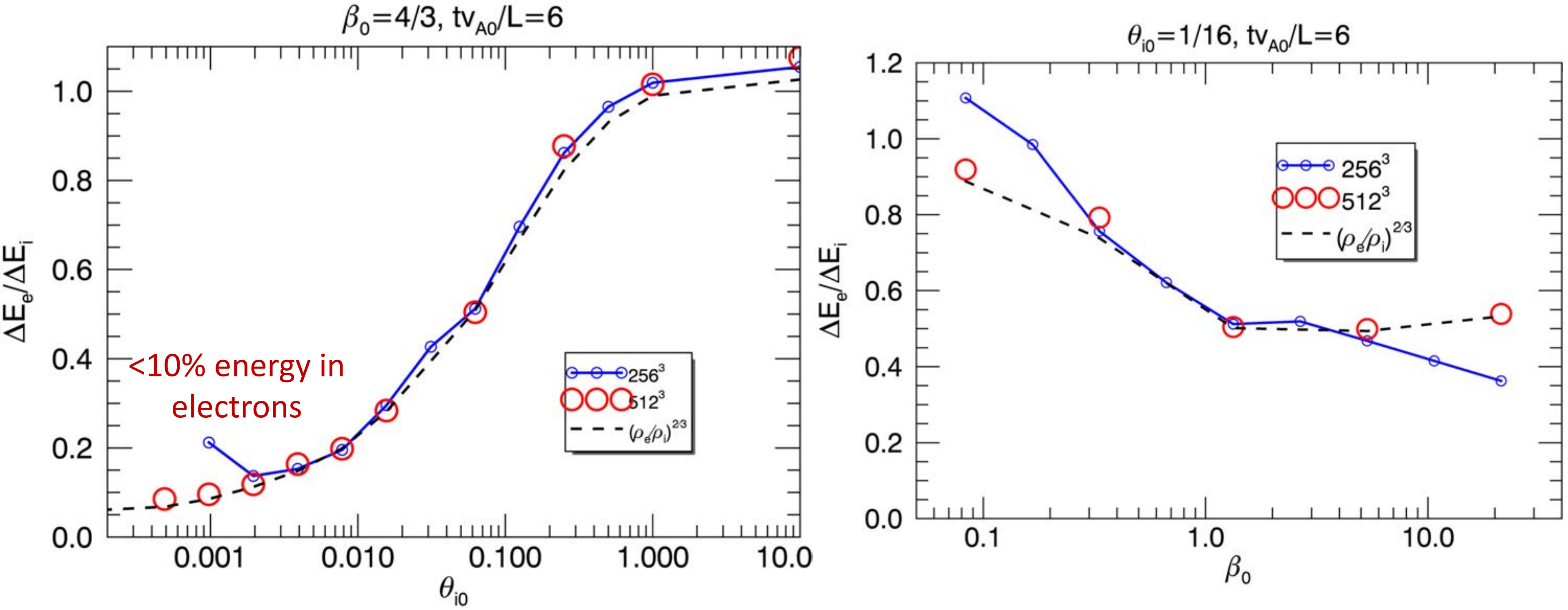
   Semirelativistic regime: $10^{-3} \ll \theta_i \ll 1 : \rho_i \sim \theta_i^{-1/2} \rho_e$

2) Plasma beta: $\beta = \dfrac{16\pi n_0 T}{B_{\rm rms}^2}$ (thermal pressure/magnetic pressure)

3) System size relative to ion Larmor radius: $L/2\pi\rho_i$ $\qquad \rho_s = \dfrac{\gamma_s m_s v_s c}{e B_{\rm rms}}$

Electron-ion energy partition

Preferential ion heating (up to 90% energy) in most of parameter space

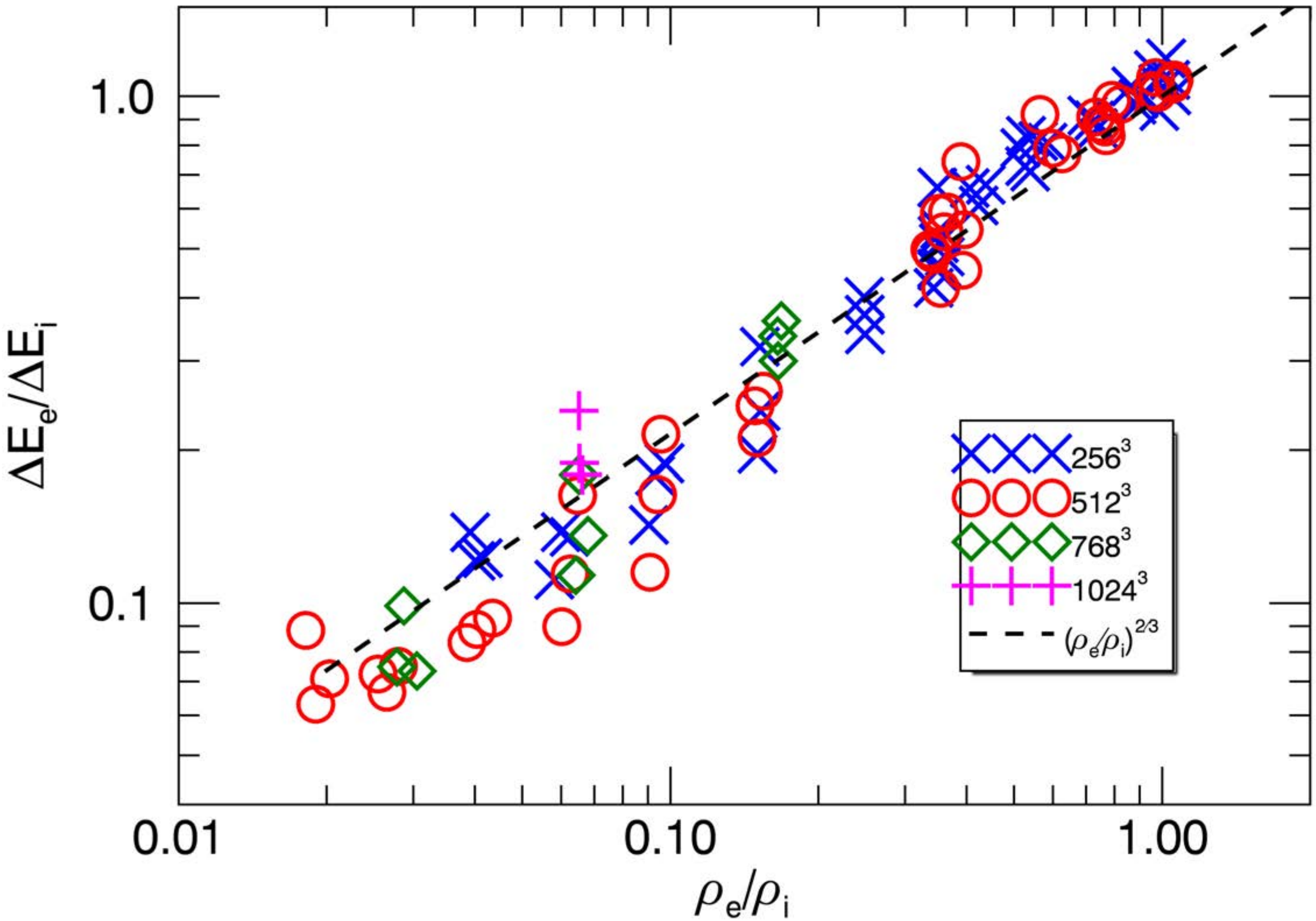


Empirical fitting formula: $\Delta E_e/\Delta E_i \sim (\rho_e/\rho_i)^{2/3}$

Zhdankin, Uzdensky, Werner & Begelman arXiv:1809.01966

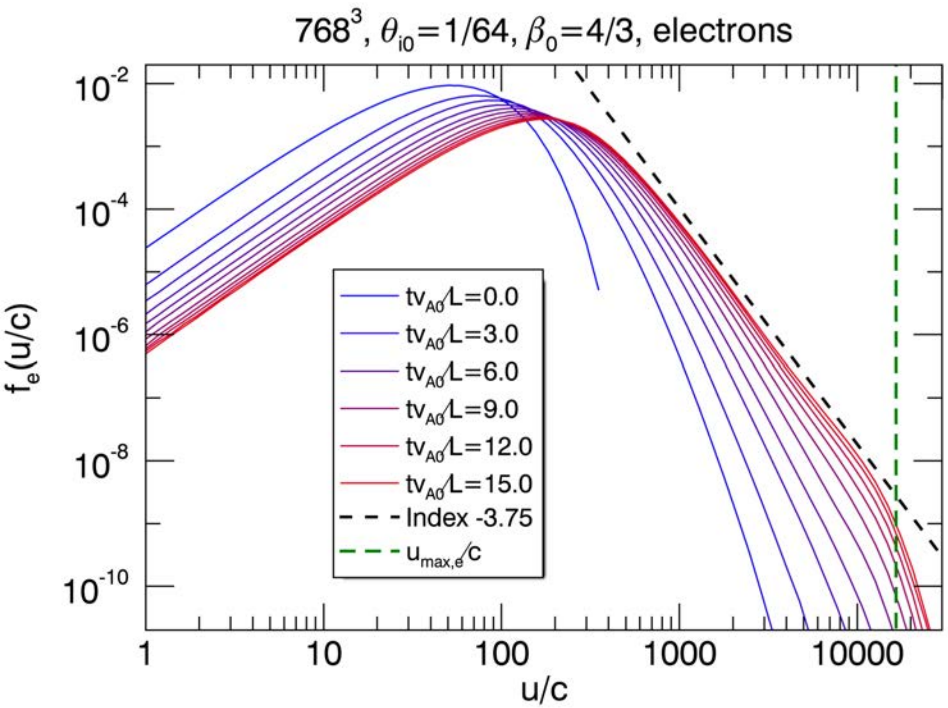
Empirical formula

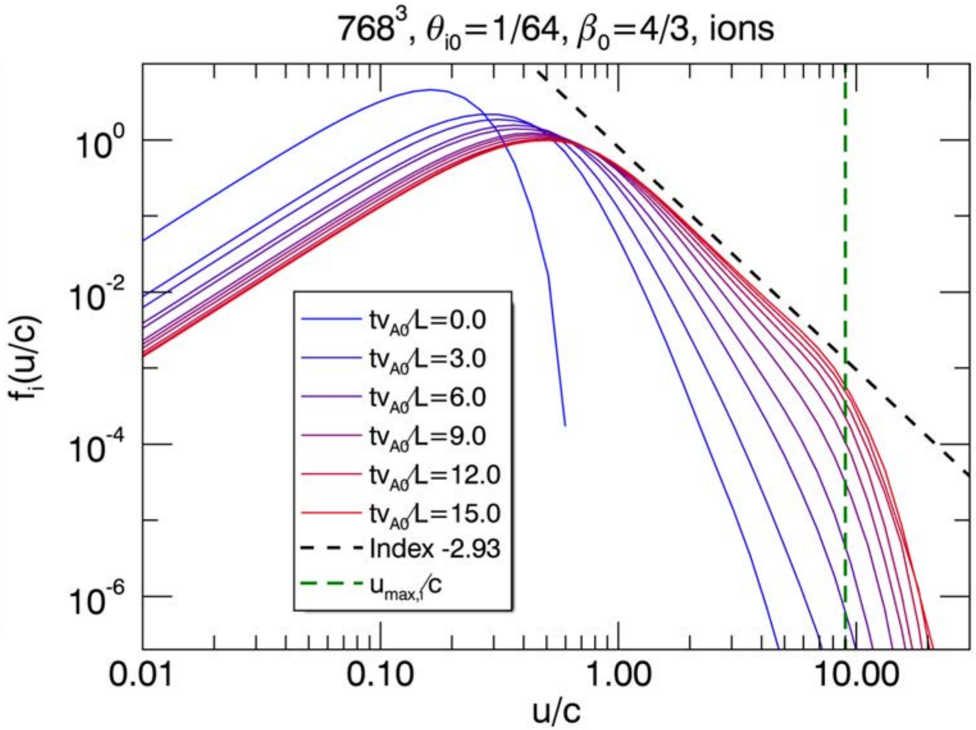
Suggestive trend of energy partition with Larmor scale separation



Nonthermal particle acceleration

Ions accelerated more efficiently than electrons as temperature decreased





u : particle four-velocity

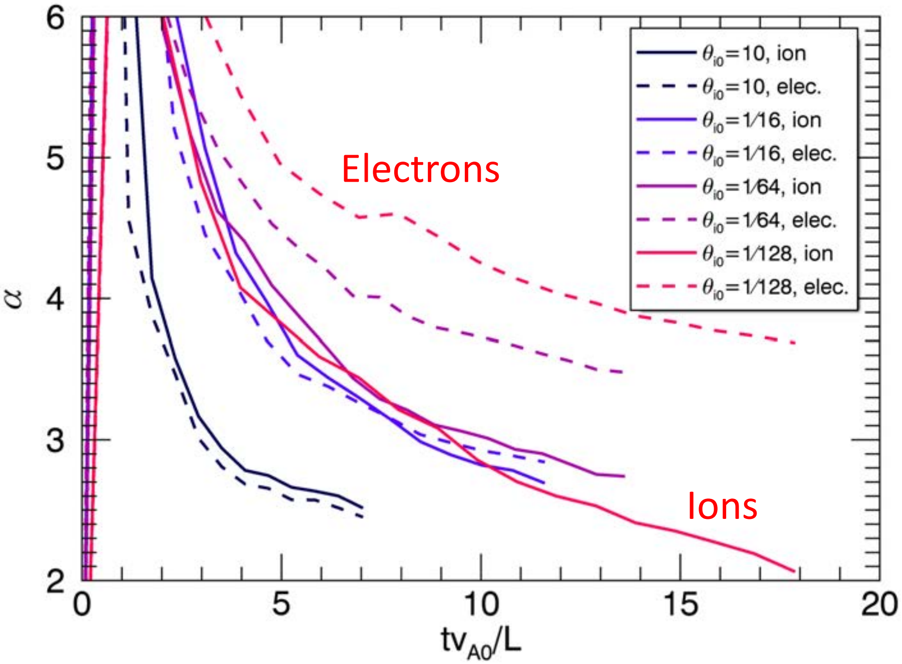
Contributes to cosmic ray population

Need high temperatures for nonthermal electron radiative signatures

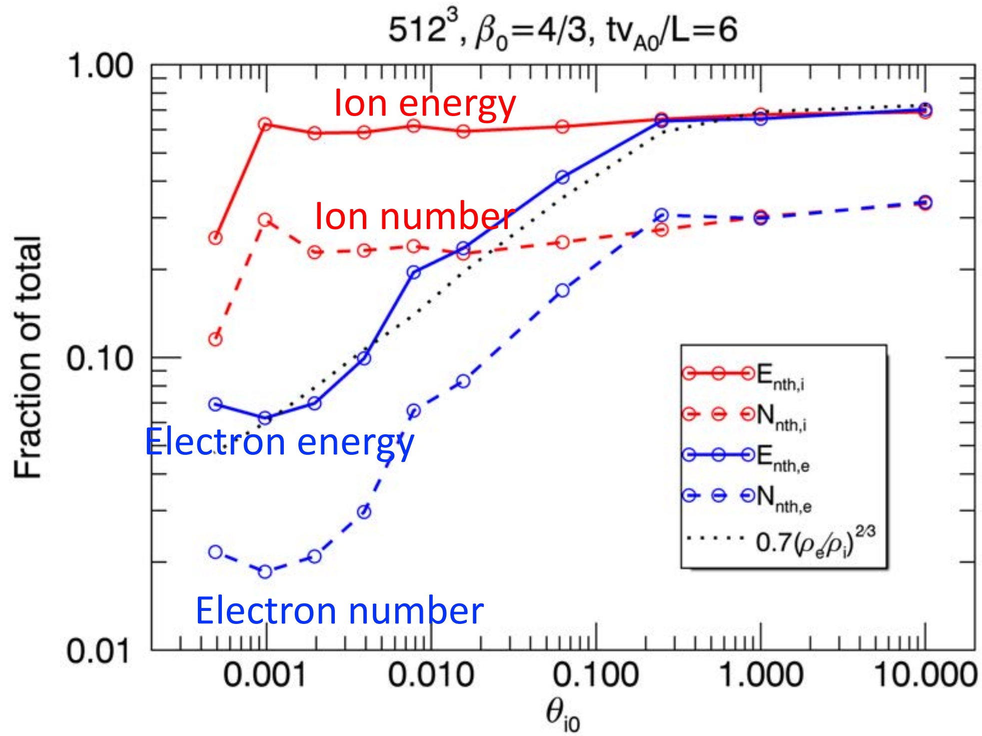
Particle distribution properties

- Distributions harden in time (eventually affected by high-energy pileup)
- Electron distribution steepens at lower temperatures

Spectral index evolution



Nonthermal population fraction



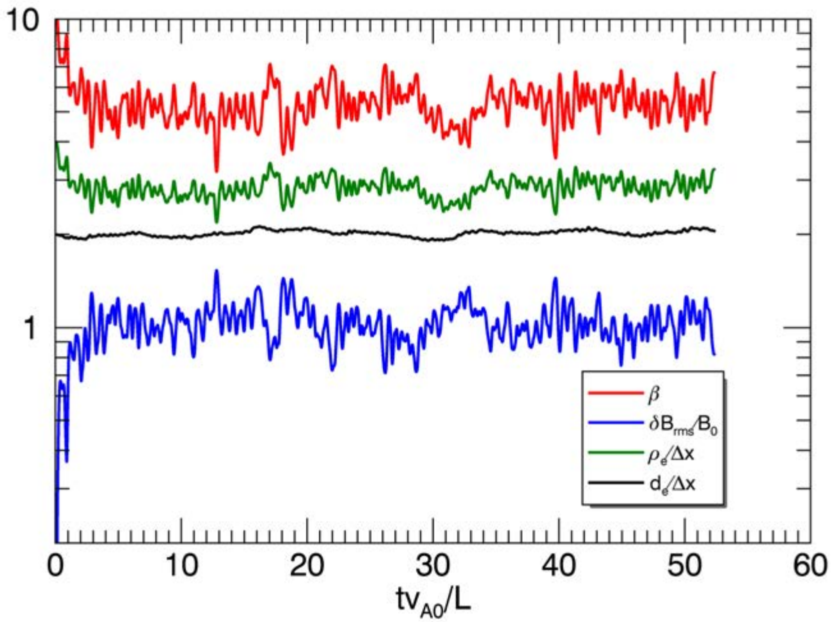
Conclusions

- PIC simulations are ideal for exploring 3D collisionless plasma turbulence in regimes relevant for high-energy astrophysics
- Turbulence can be viable and efficient astrophysical particle accelerator
- Ions gain more energy and are more efficiently accelerated than electrons in most of explored parameter space; this is described by empirical scaling relations
- Results broadly support RIAF models, but more work must be done for careful comparison
- Future directions: mechanisms of electron-ion heating, analytic modeling, radiative cooling/signatures, electron-ion thermal coupling, implementation to global simulations

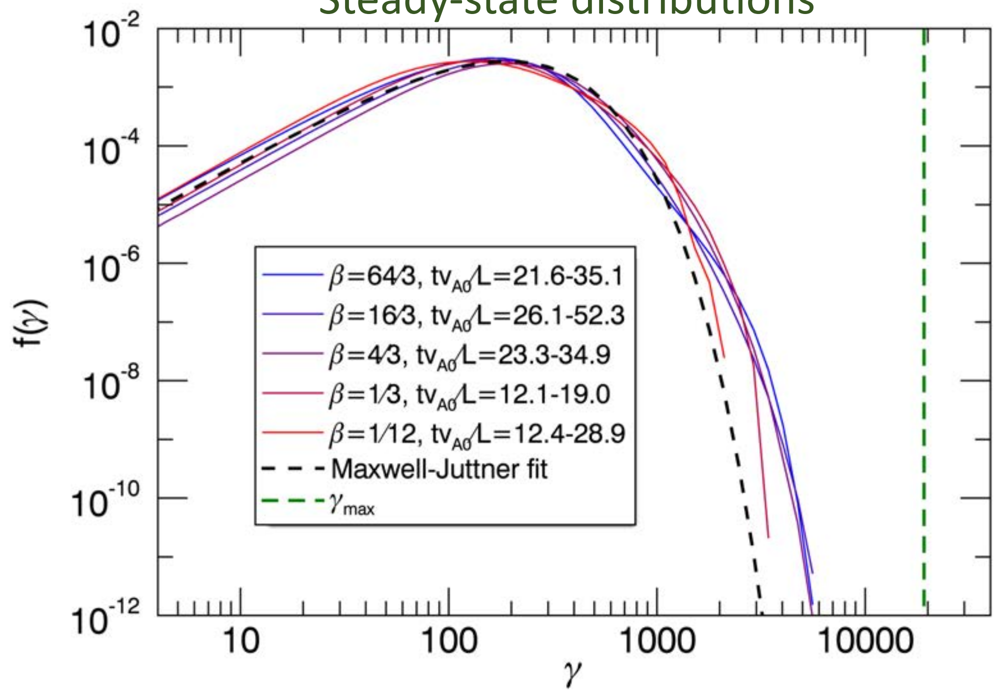
Future direction: radiatively cooled turbulence

- Incorporate optically thin synchrotron, inverse Compton radiative cooling
- In steady state, radiative cooling thermalizes distributions (Schlickeiser 1985)

Steady-state turbulence (pair plasma)



Steady-state distributions



- Ideal setting to explore electron-ion thermal coupling…