

Cosmic-Ray Acceleration to Ultra-High Energies

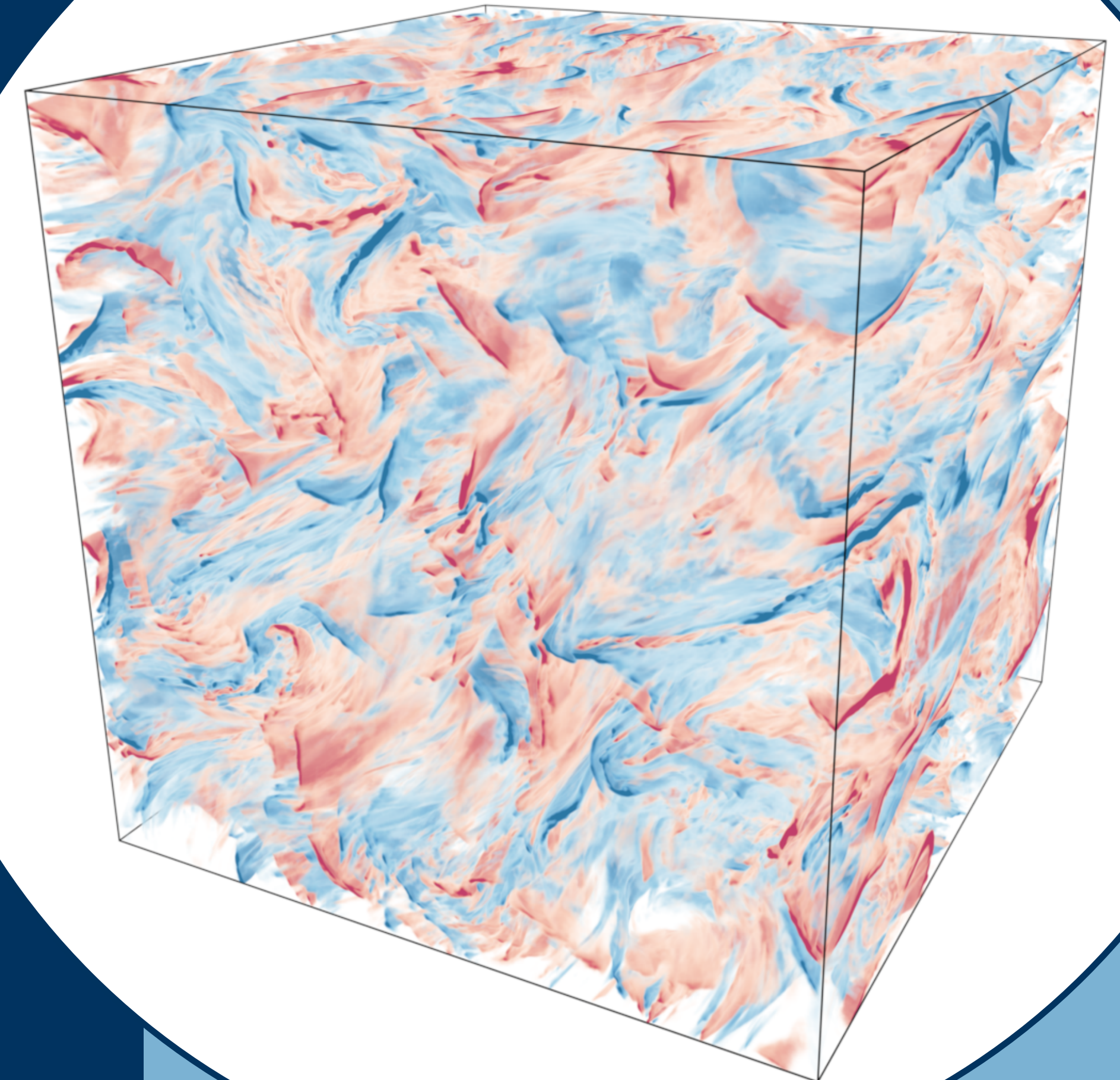
Luca Comisso

Columbia University

in collaboration with:

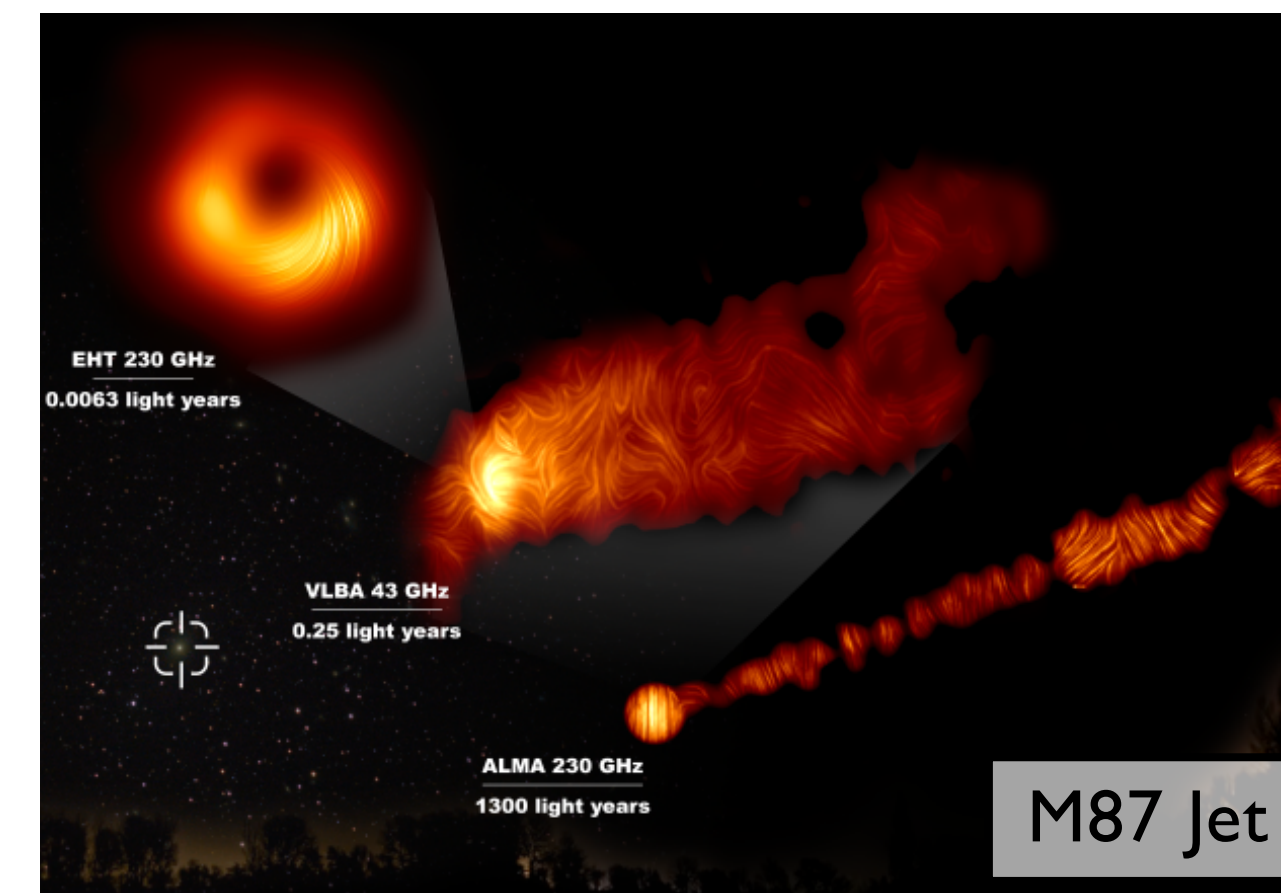
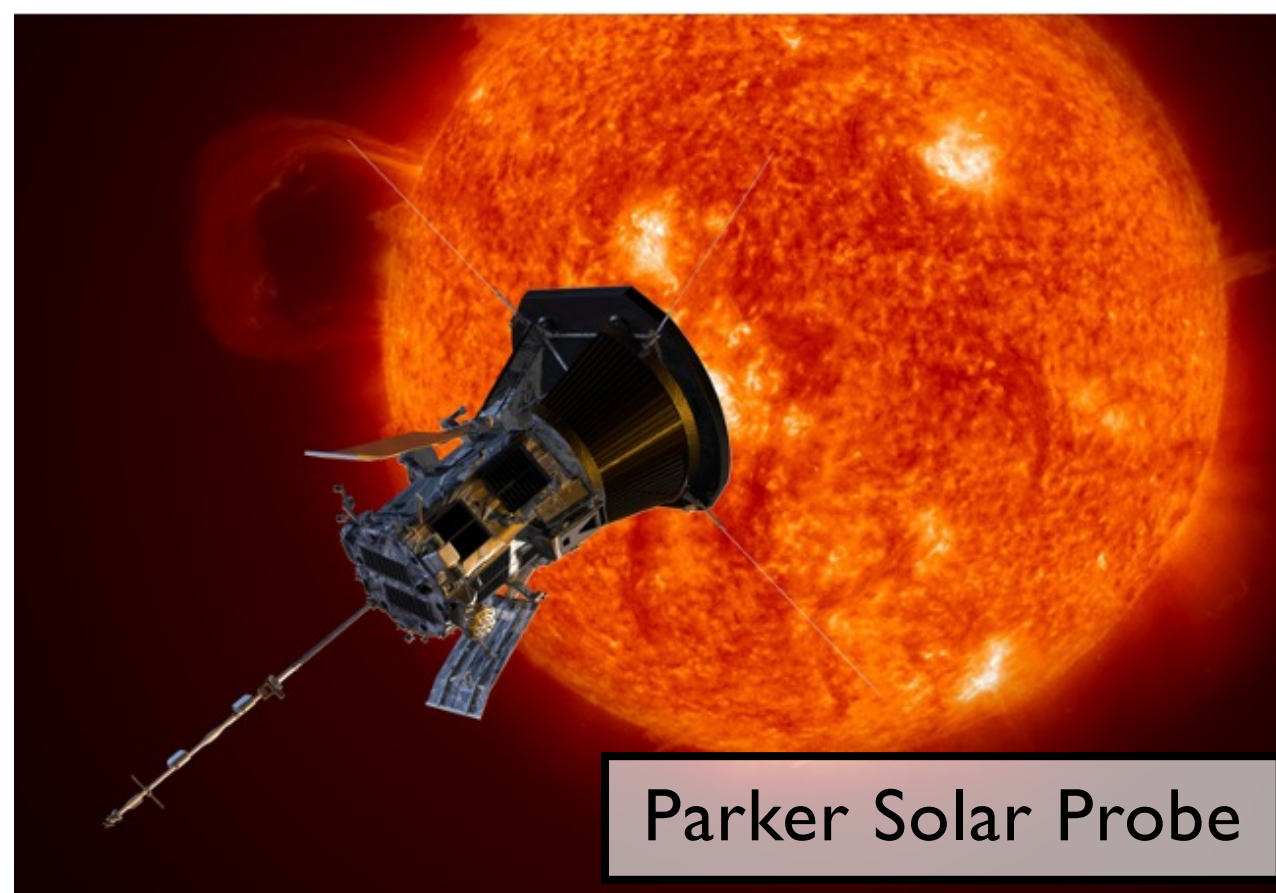
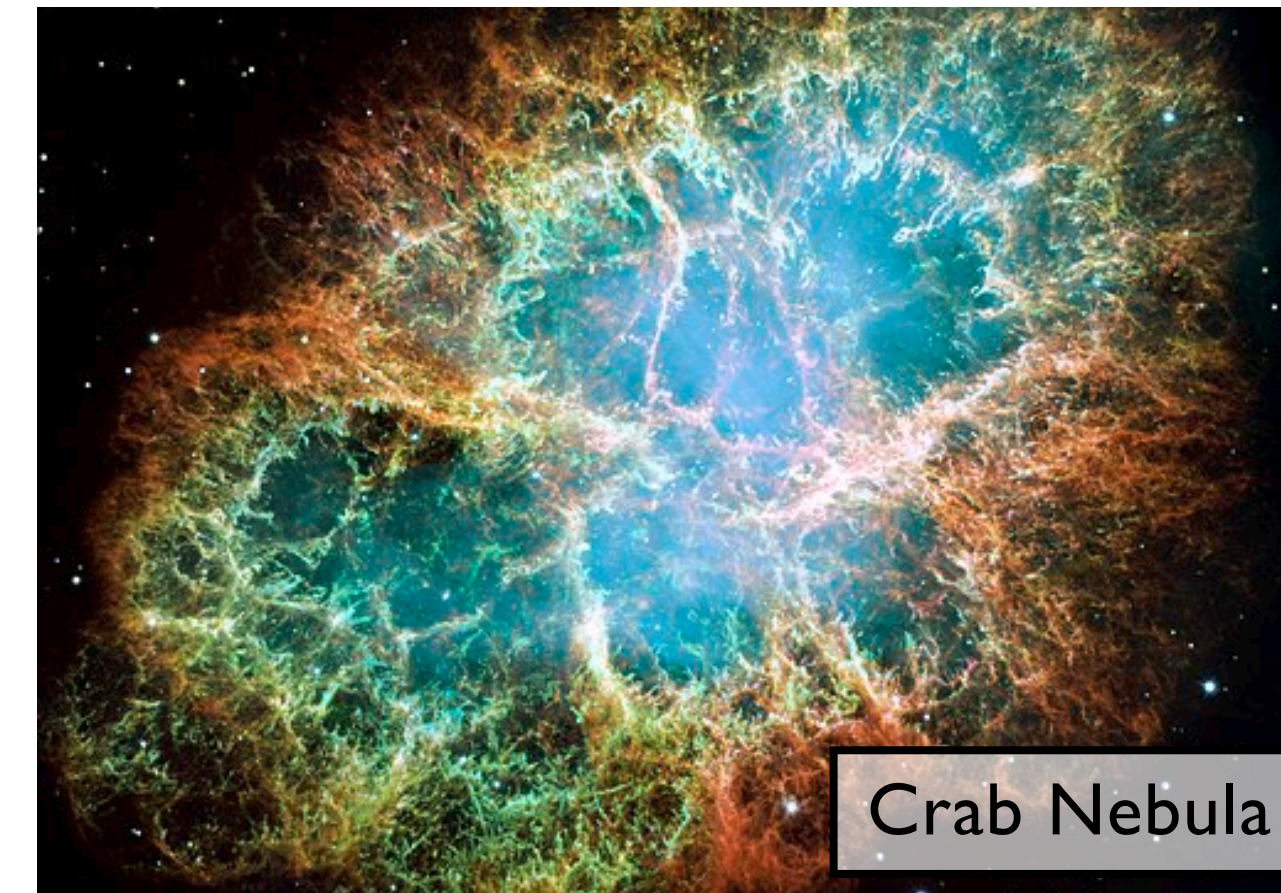
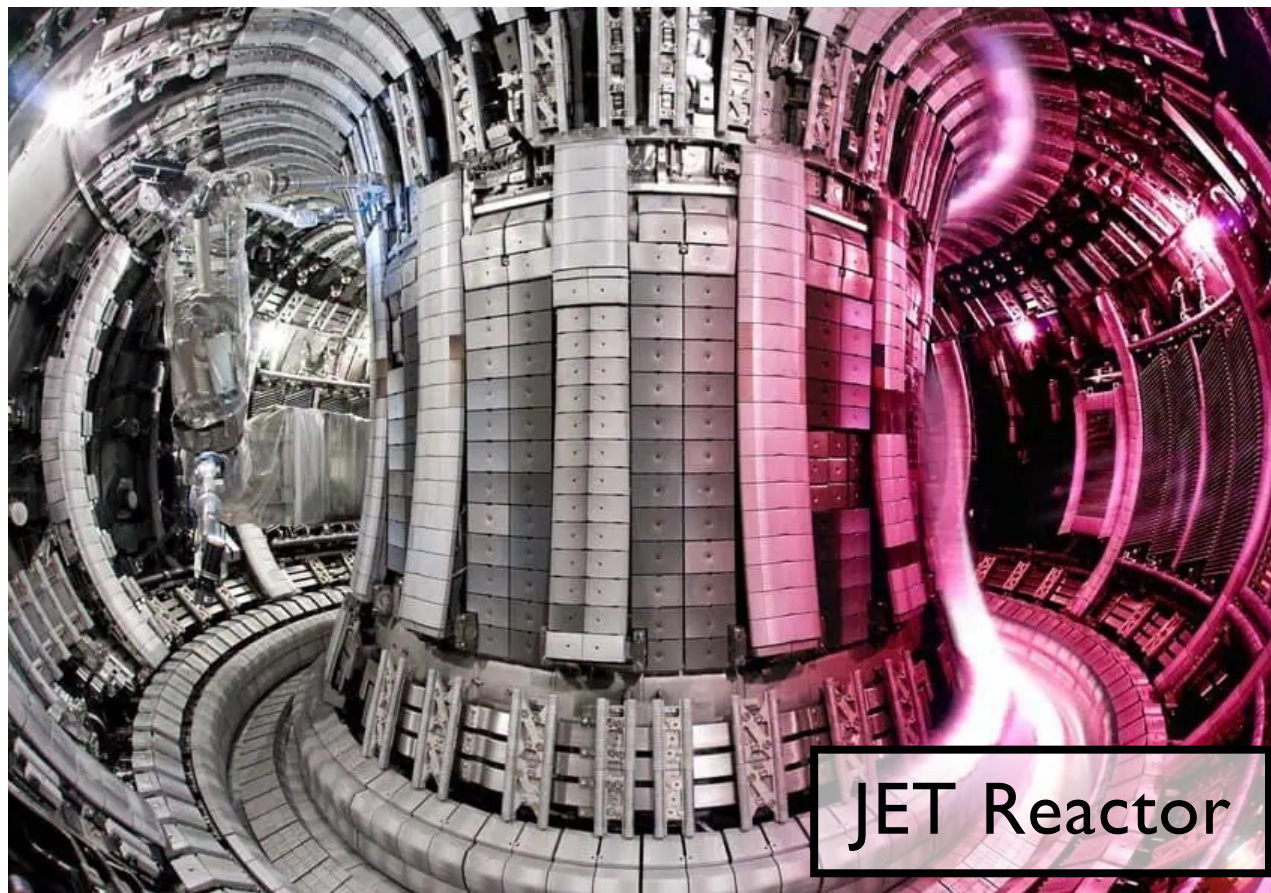
Z Davis, G Farrar, D Fiorillo, R Golant, C Haggerty,
B Jiang, P Kempski, M Muzio, E Peretti, M Petropoulou,
S Sebastian, L Sironi, E Sobacchi, X Sun, F Testagrossa

Institute for Fundamental Physics of the Universe (IFPU)
Trieste, September 7-11, 2026



Magnetized environments (nonrelativistic vs. relativistic regimes: $\frac{v_A}{c} = \sqrt{\frac{\sigma}{1+\sigma}}$)

$$\sigma \ll 1 \quad \sigma = \frac{B^2}{4\pi\rho c^2} \simeq \frac{4}{\beta} \frac{k_B T}{m_i c^2} \quad \sigma \gg 1$$



Fully Kinetic Treatment of the Plasma

- ▶ The evolution of the particle density $f_s(\mathbf{x}, \mathbf{p}, t)$ of species s in a collisionless plasma is described by the Vlasov equation

$$\frac{\partial f_s}{\partial t} + \frac{\mathbf{p}}{m_s \gamma_s} \cdot \nabla_{\mathbf{x}} f_s + \mathbf{F} \cdot \nabla_{\mathbf{p}} f_s = 0$$

where $\gamma_s^2 = 1 + \frac{|\mathbf{p}|^2}{m_s^2 c^2}$ and $\mathbf{F} = q_s \left(\mathbf{E} + \frac{\mathbf{p}}{\gamma_s m_s c} \times \mathbf{B} \right)$.

- ▶ $\mathbf{E}(\mathbf{x}, t)$ and $\mathbf{B}(\mathbf{x}, t)$ are determined from Maxwell's equations

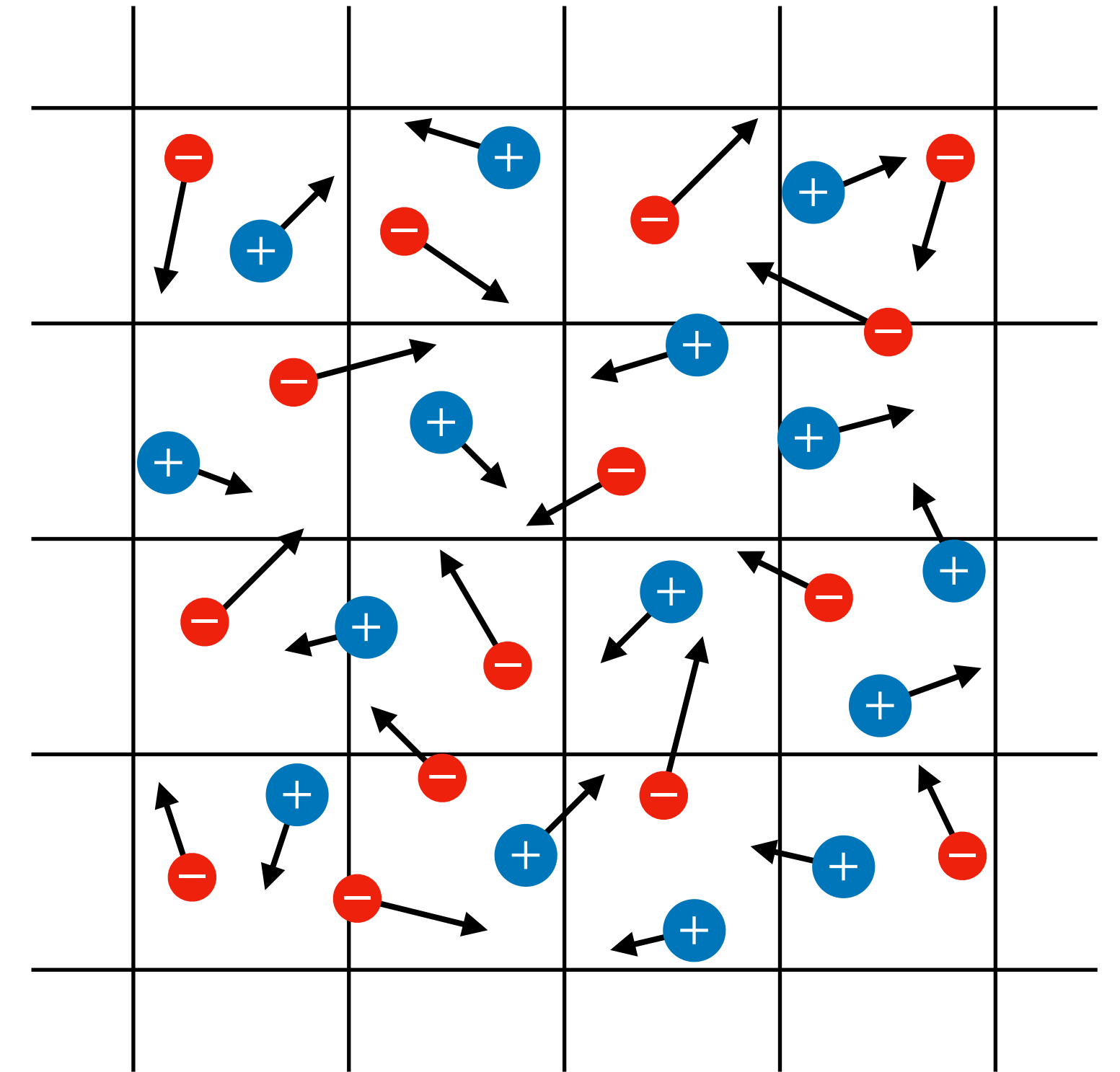
$$\frac{\partial \mathbf{E}}{\partial t} - c \operatorname{curl} \mathbf{B} = -4\pi \mathbf{J}, \quad \operatorname{div} \mathbf{E} = 4\pi \rho,$$

$$\frac{\partial \mathbf{B}}{\partial t} + c \operatorname{curl} \mathbf{E} = 0, \quad \operatorname{div} \mathbf{B} = 0,$$

where the source terms are computed by

$$\rho = \sum_s q_s \int_{\mathbb{R}^3} f_s d\mathbf{p}, \quad \mathbf{J} = \sum_s \frac{q_s}{m_s} \int_{\mathbb{R}^3} f_s \frac{\mathbf{p}}{\gamma_s} d\mathbf{p}.$$

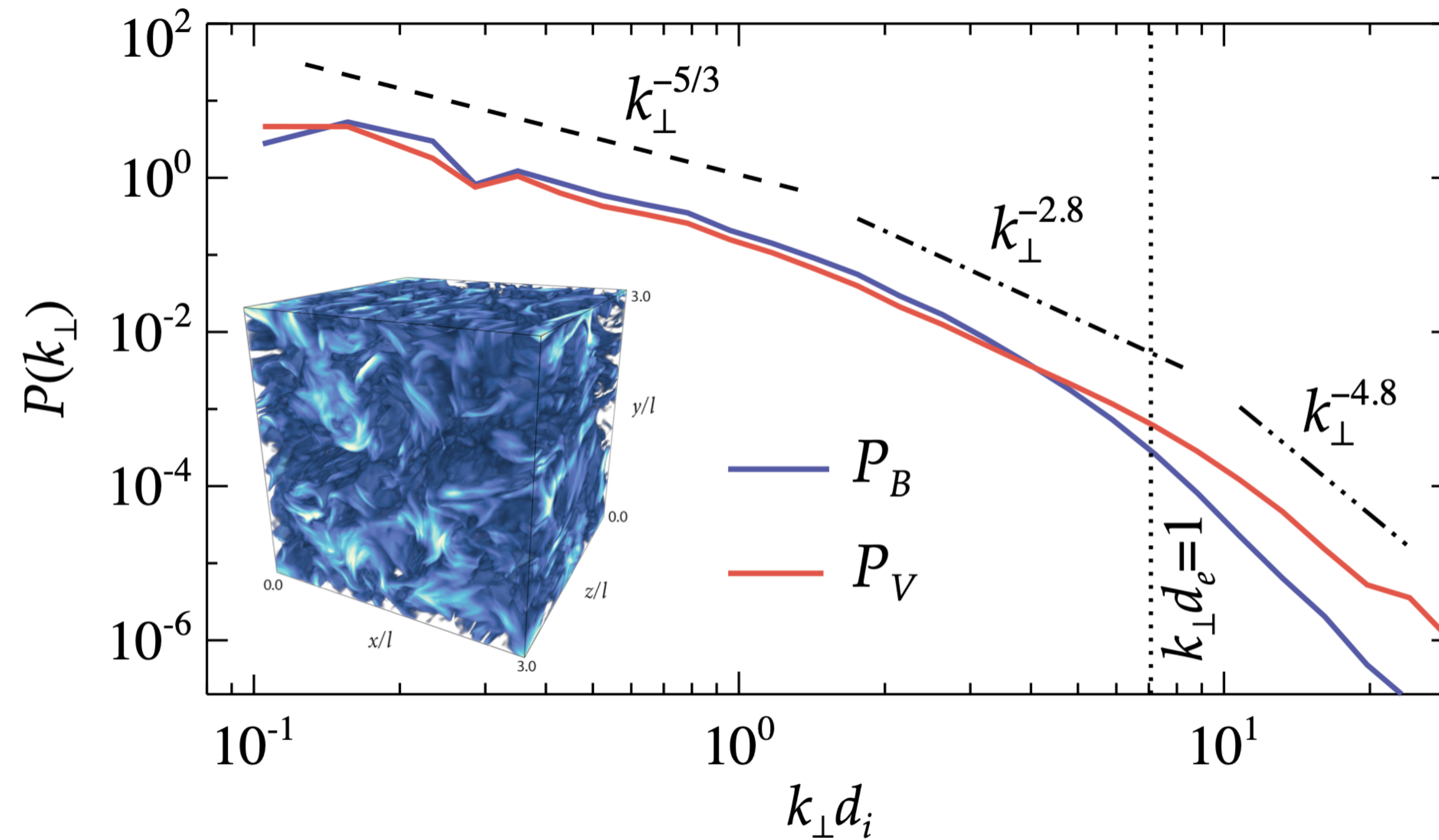
- ▶ Solution via particle-in-cell method



PIC code: TRISTAN-MP
(Spitkovsky 2005)

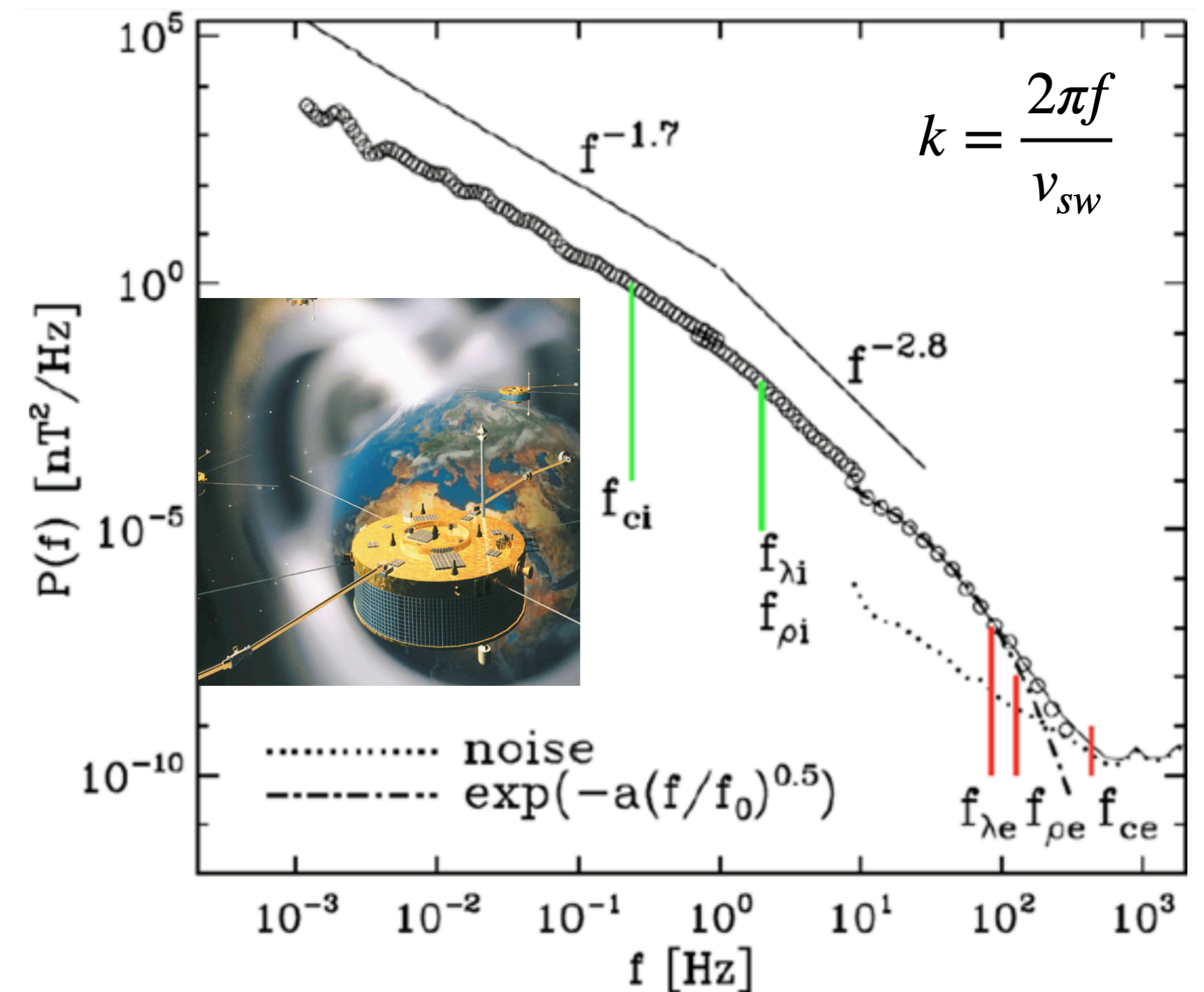
Fully Kinetic Turbulence on Supercomputers

Power spectra from low- β PIC simulation



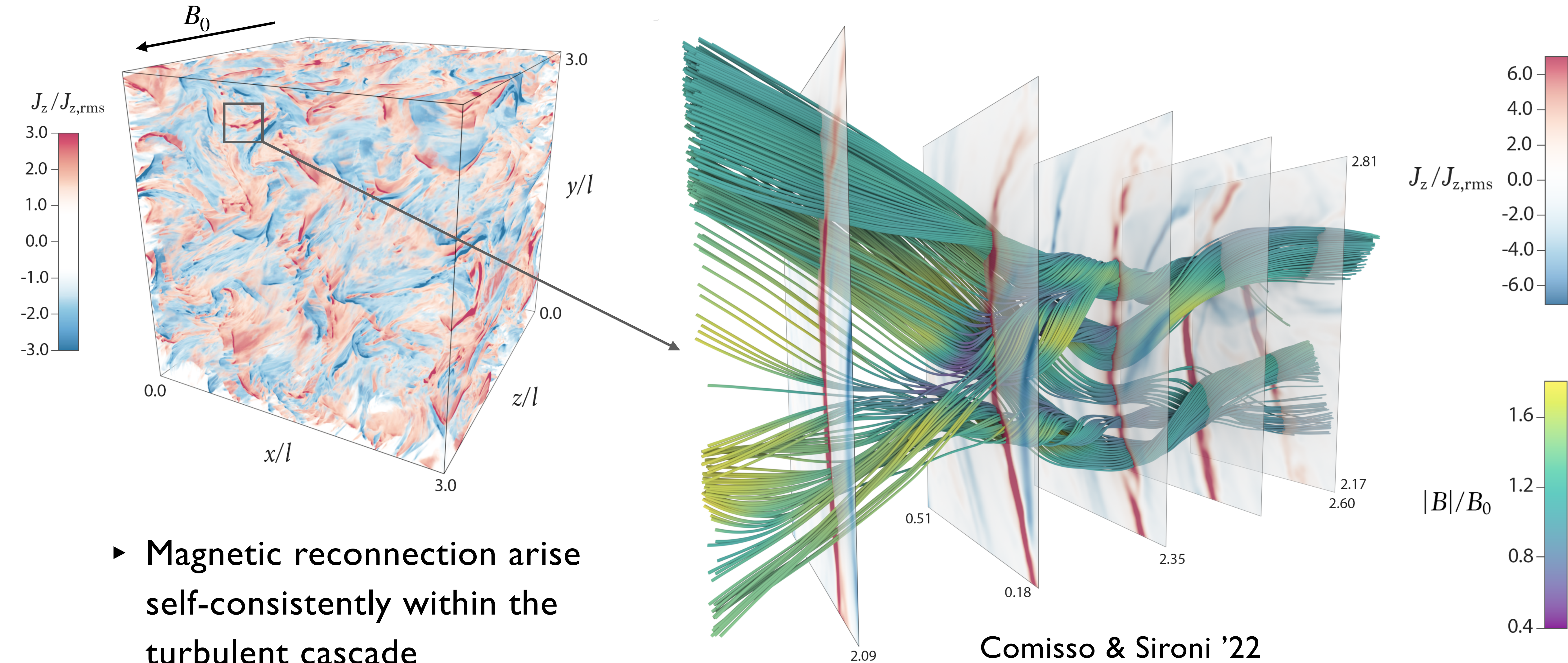
Comisso and Sironi 2022

Magnetic power spectrum of Solar Wind

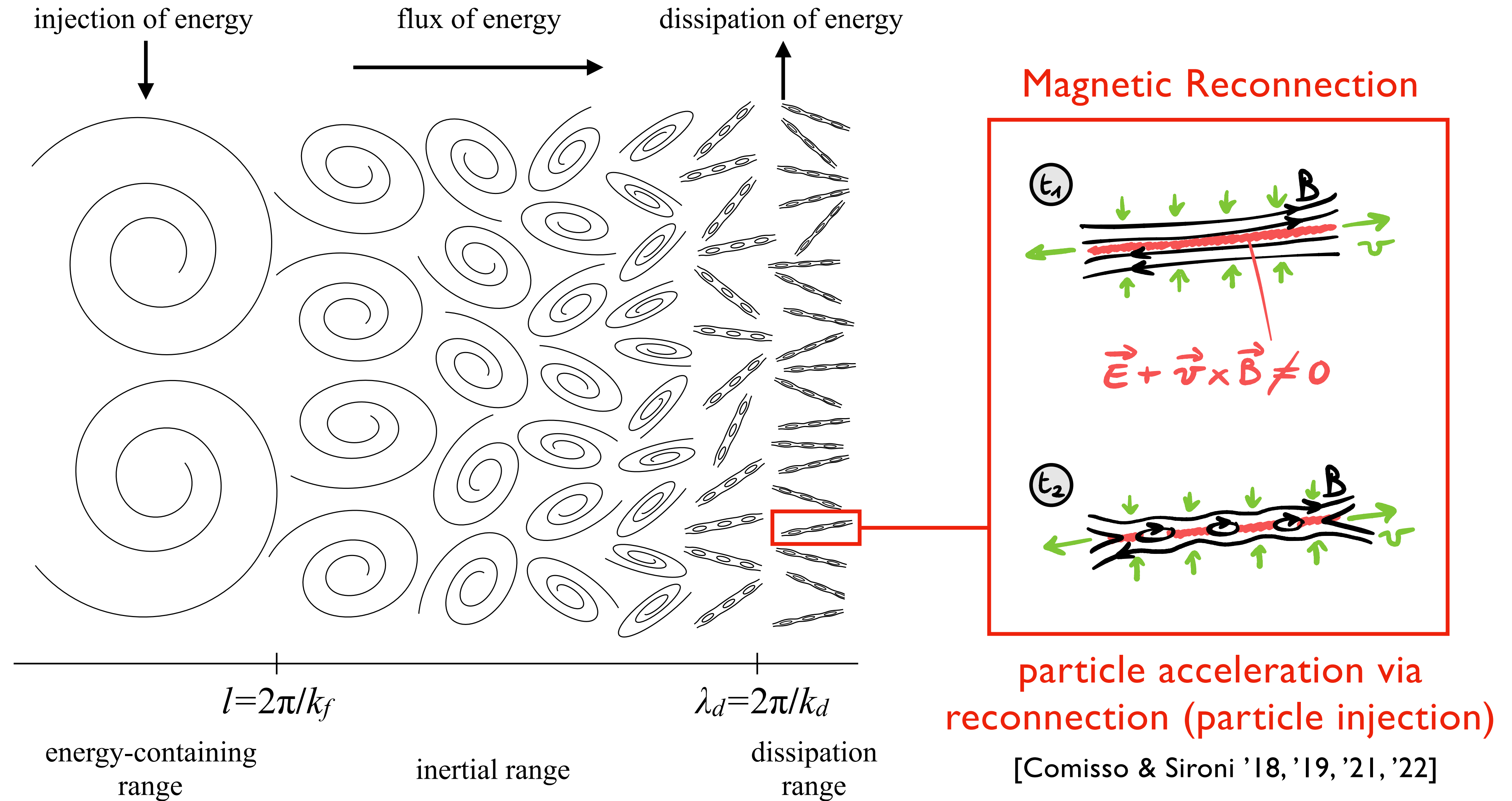


Alexandrova et al. 2013

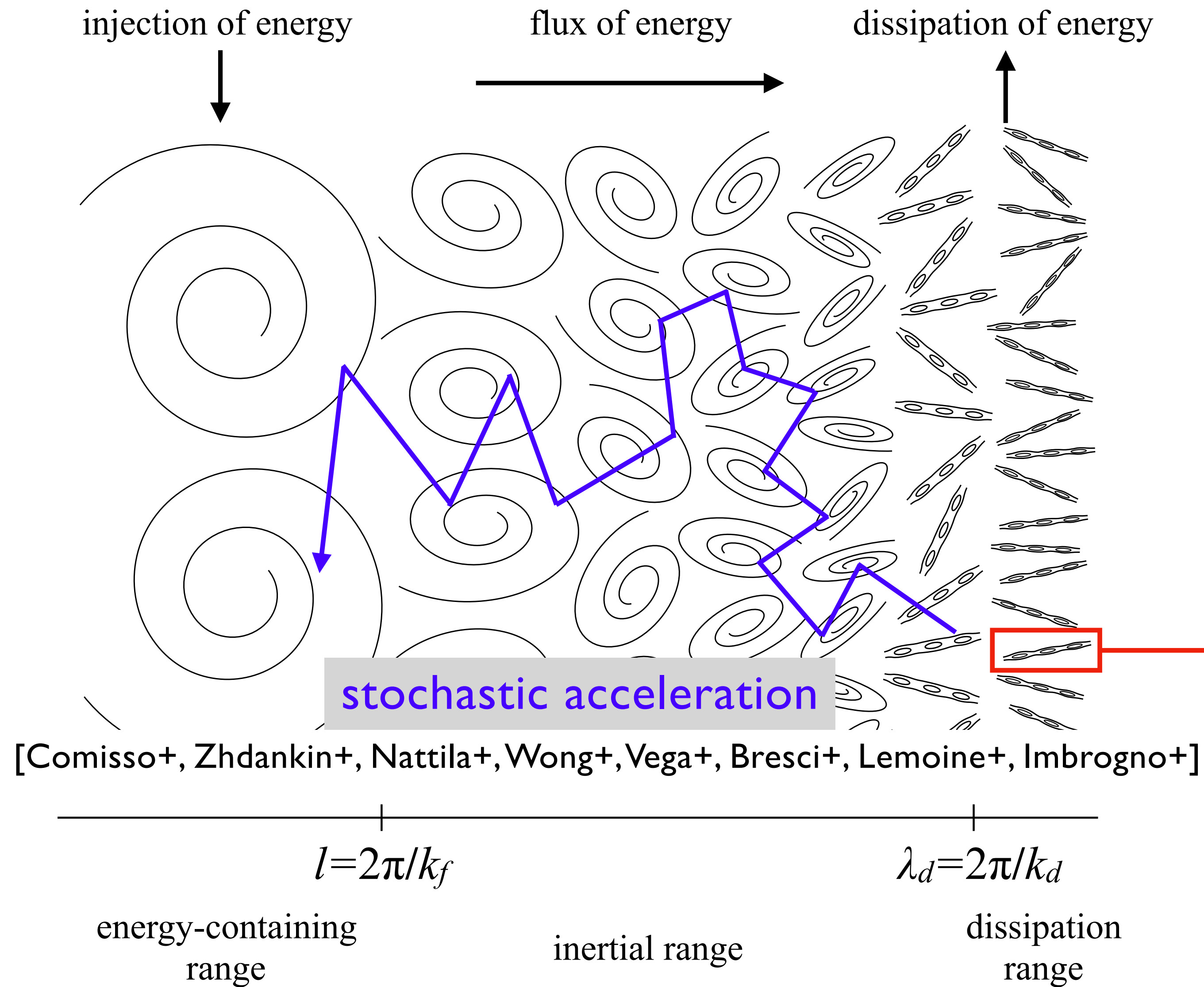
Fully Kinetic Turbulence on Supercomputers



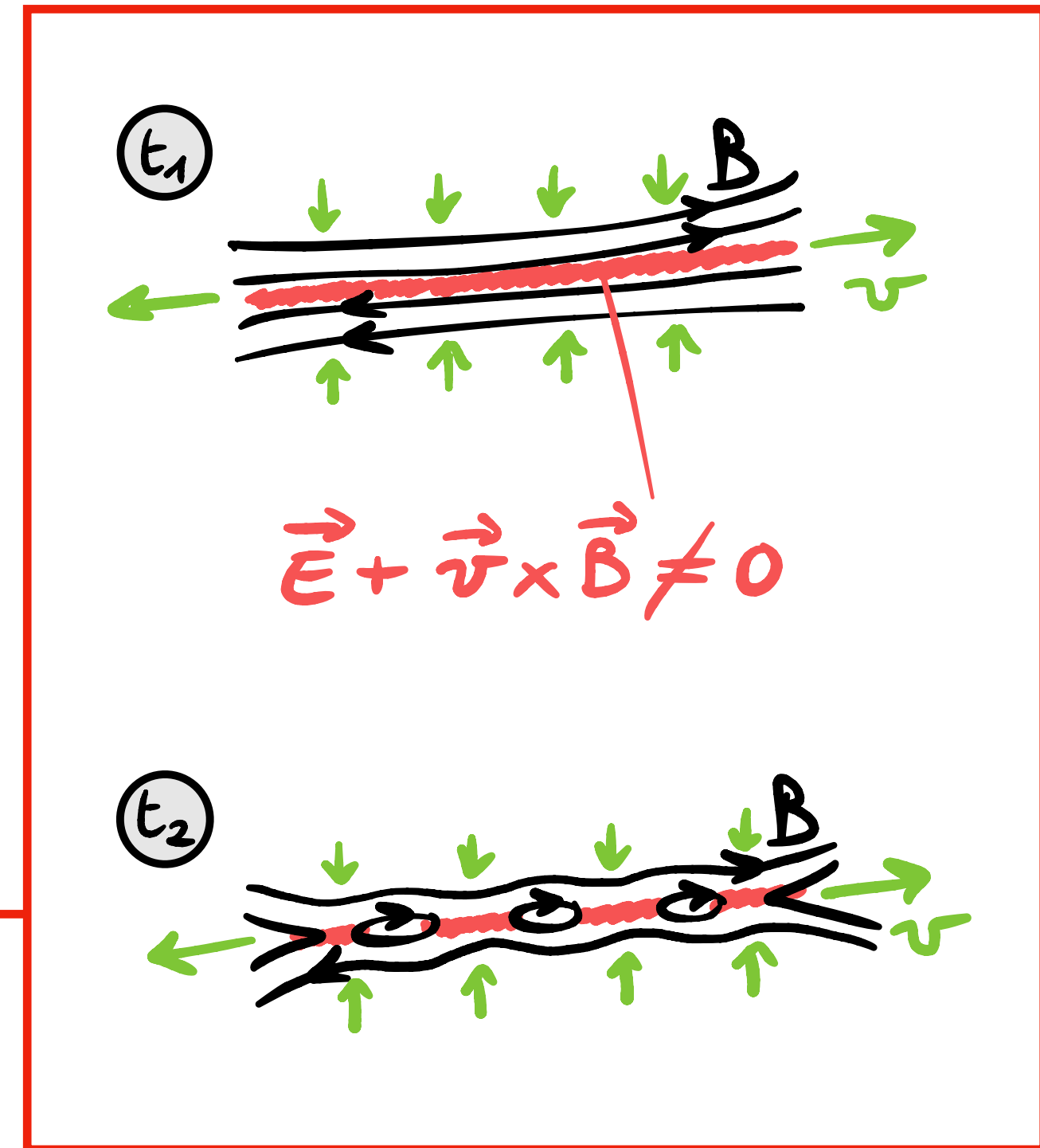
Particle acceleration in fully kinetic turbulence



Particle acceleration in fully kinetic turbulence



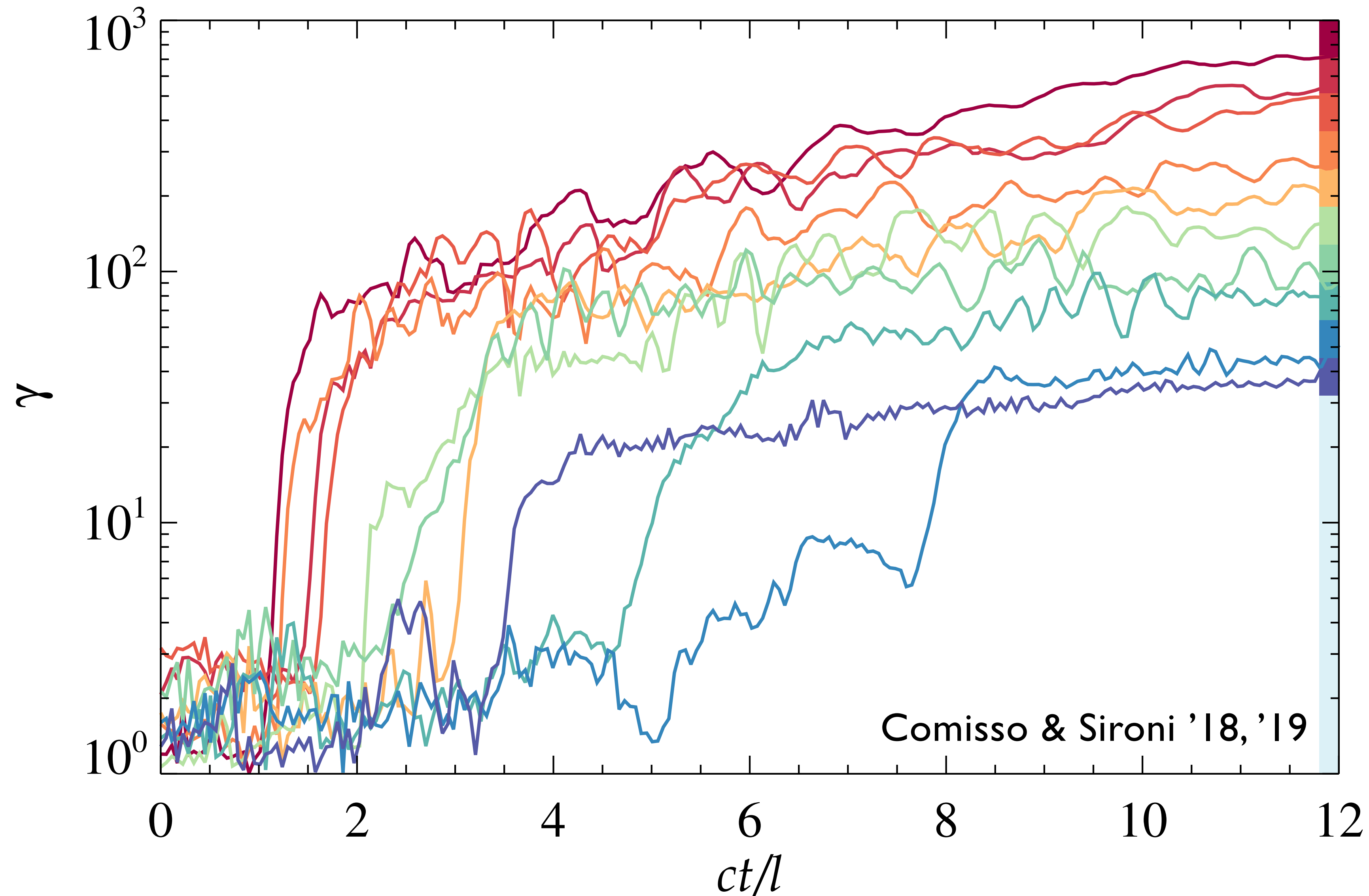
Magnetic Reconnection



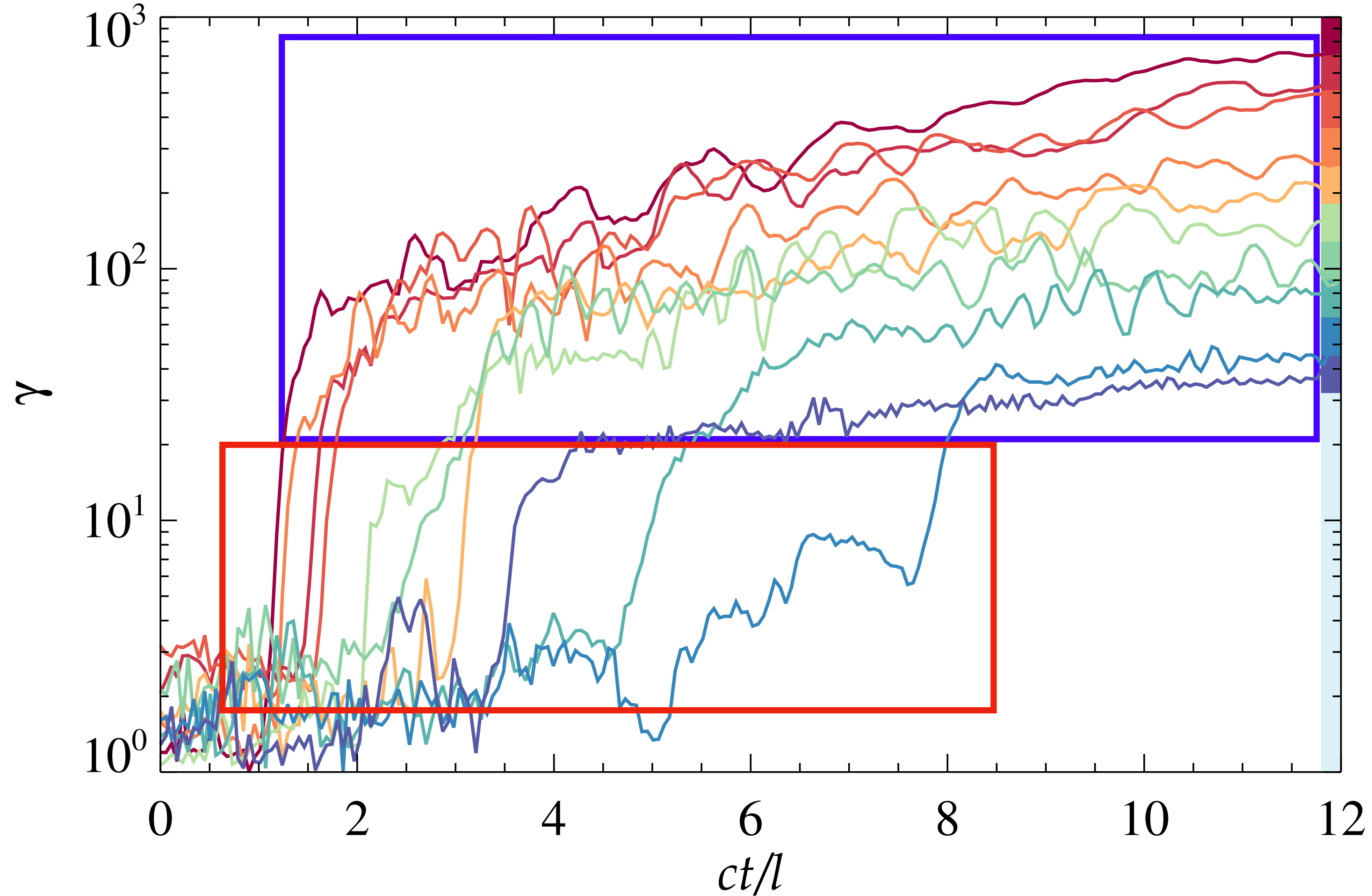
particle acceleration via reconnection (particle injection)

[Comisso & Sironi '18, '19, '21, '22]

Particle acceleration: two-stage process



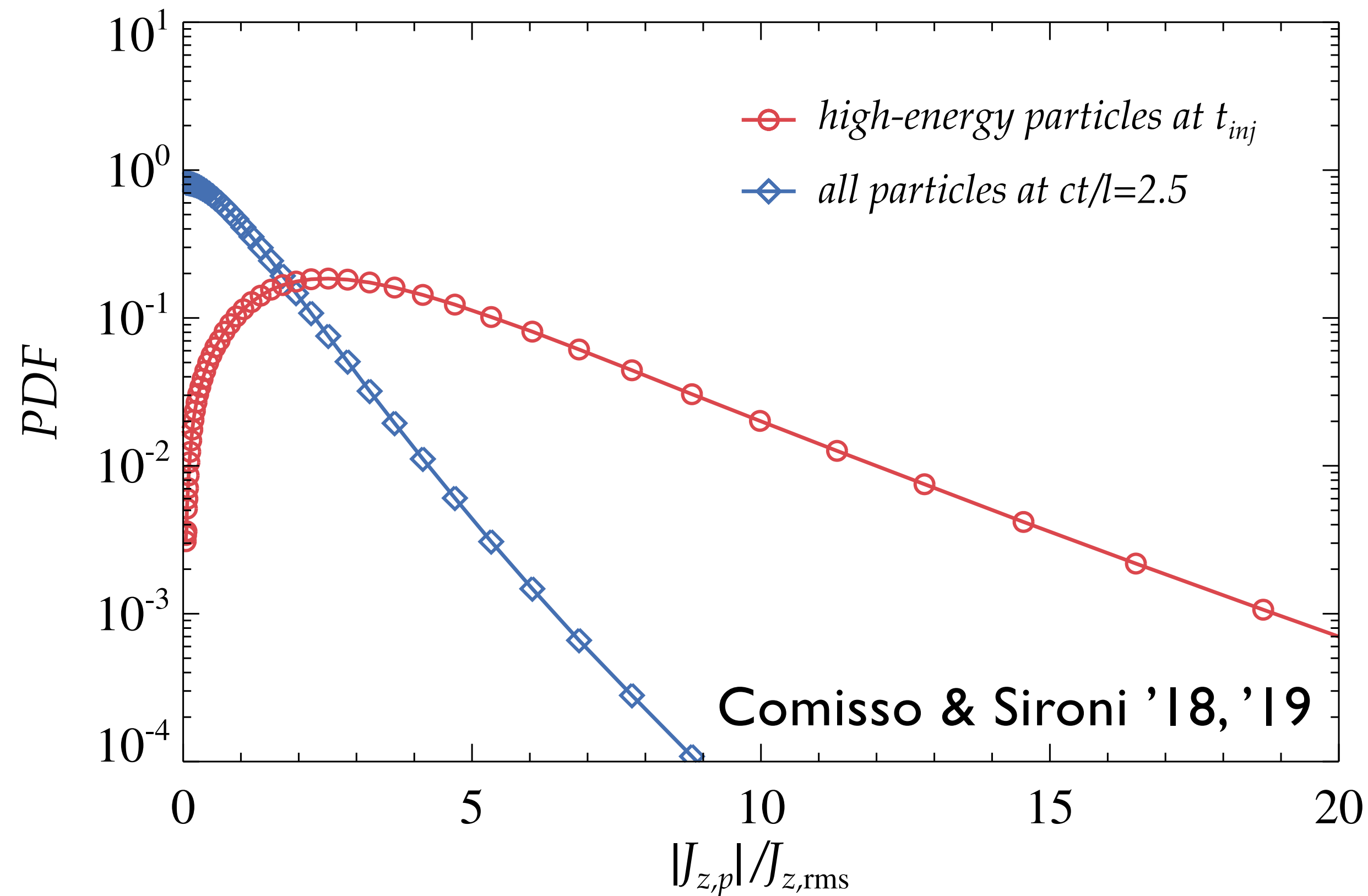
Particle acceleration: two-stage process



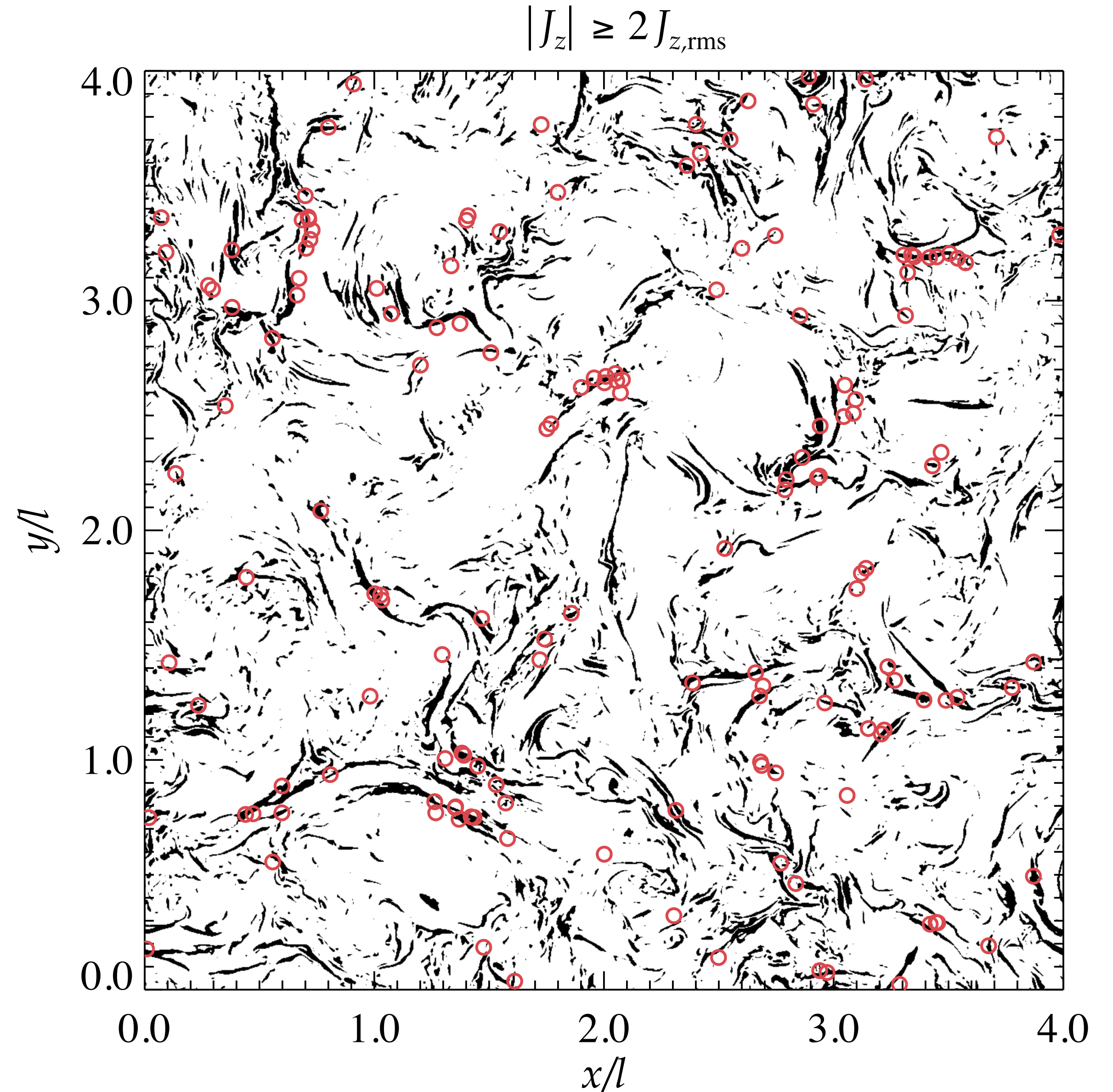
Particle energization occurs via a two-stage acceleration process:

1. Particle injection (via magnetic reconnection layers)
2. Stochastic acceleration (via scatterings off larger scale turbulent fluctuations)

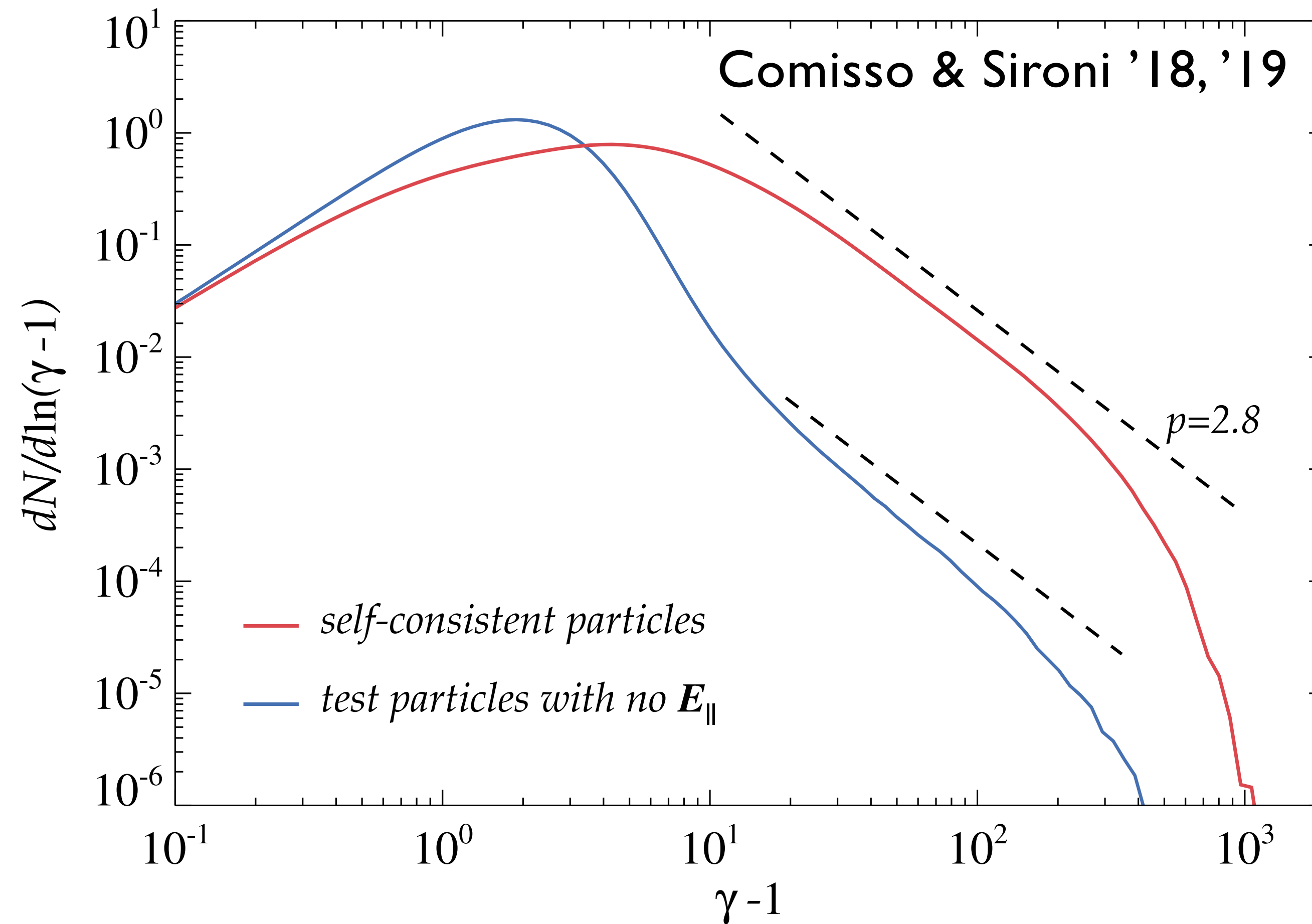
1st stage: particle “injection” by magnetic reconnection



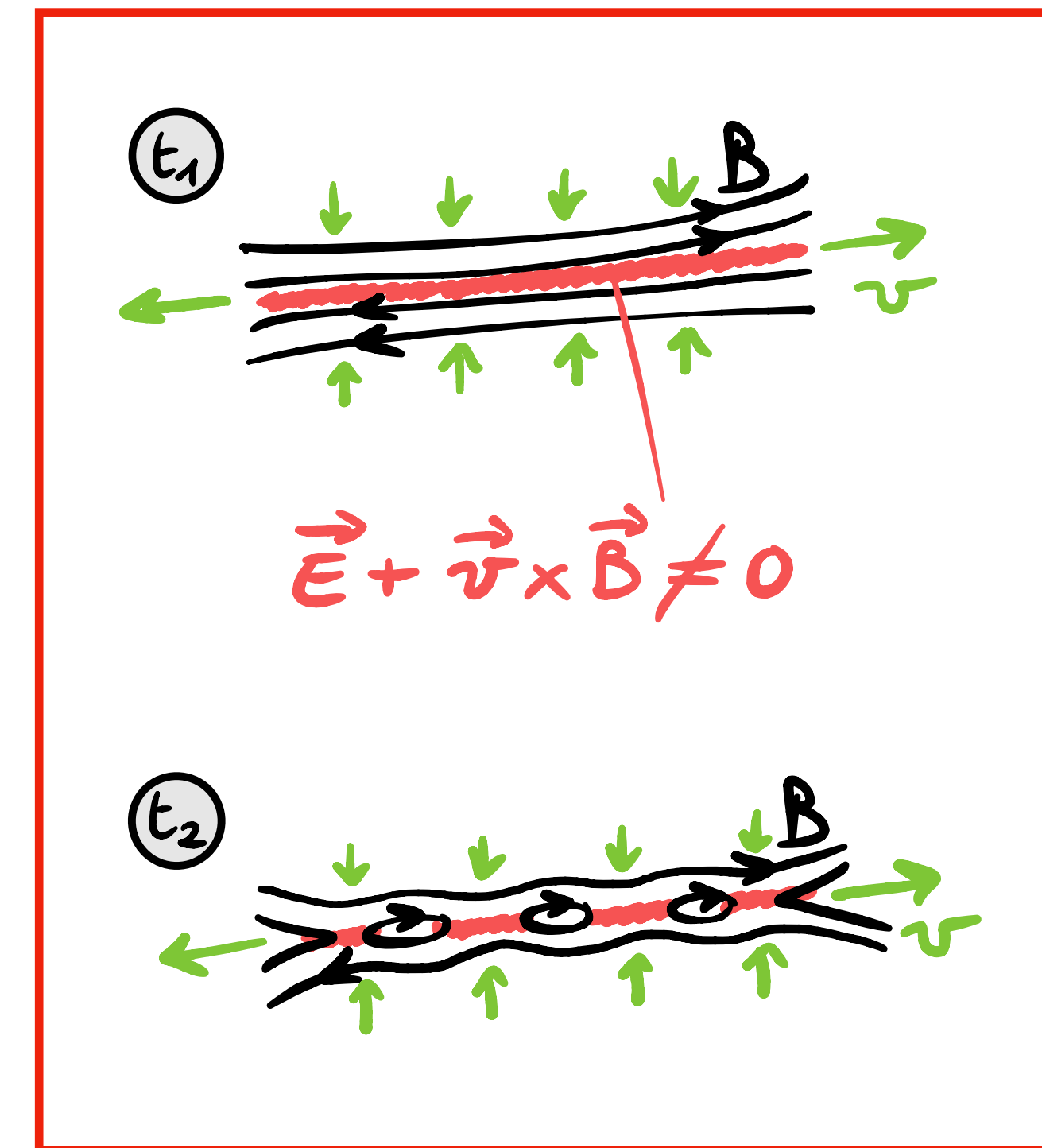
- ▶ particle “injection” occurs when particles are in current sheets



1st stage: particle “injection” by magnetic reconnection

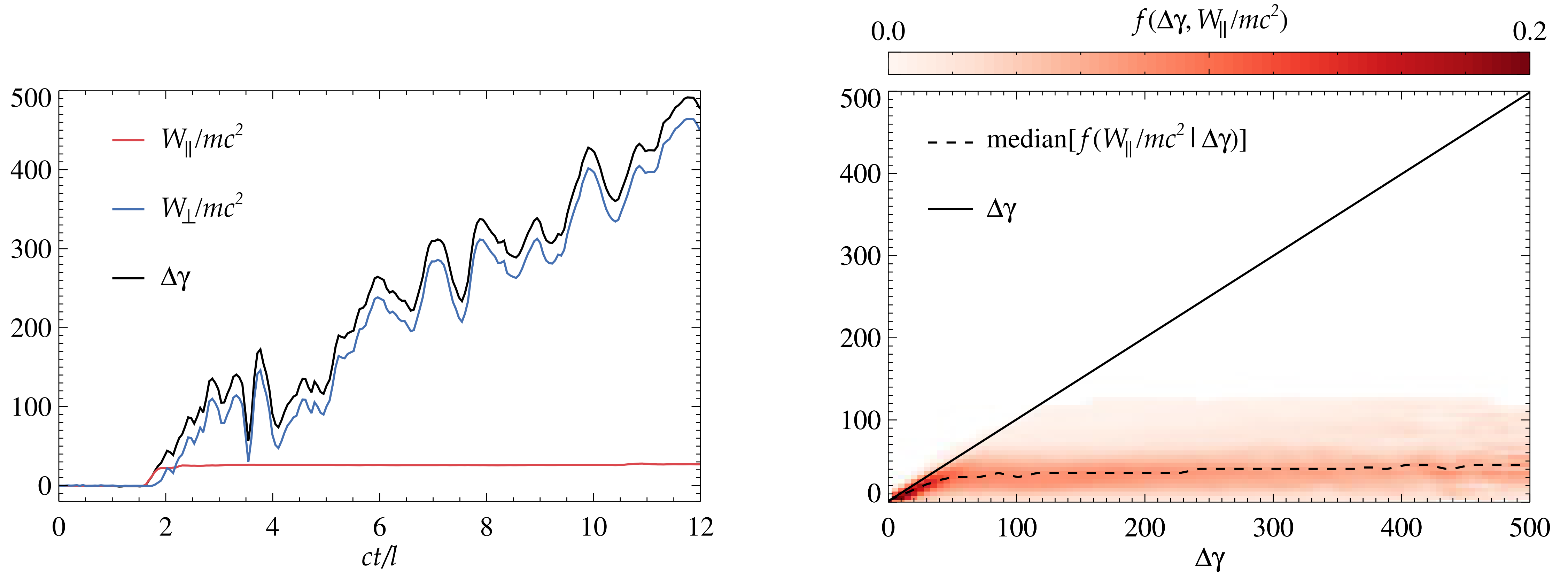


Magnetic Reconnection



- For particles that do not feel $E_{\parallel}$ (from reconnection layers), the normalization drops by 2 orders of magnitude (only $\sim 0.2\%$ vs $\sim 20\%$ of the particles in the non-thermal tail)

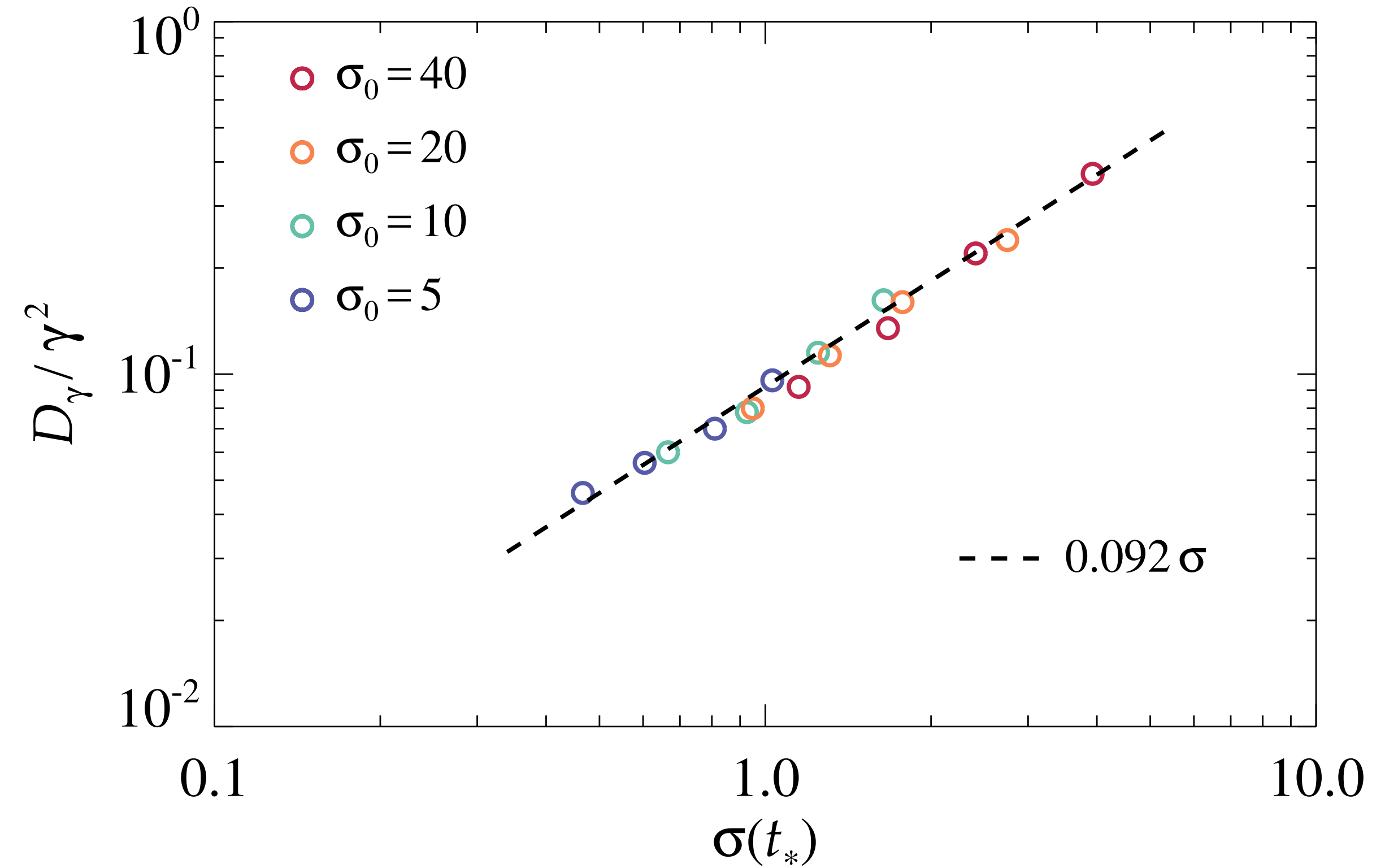
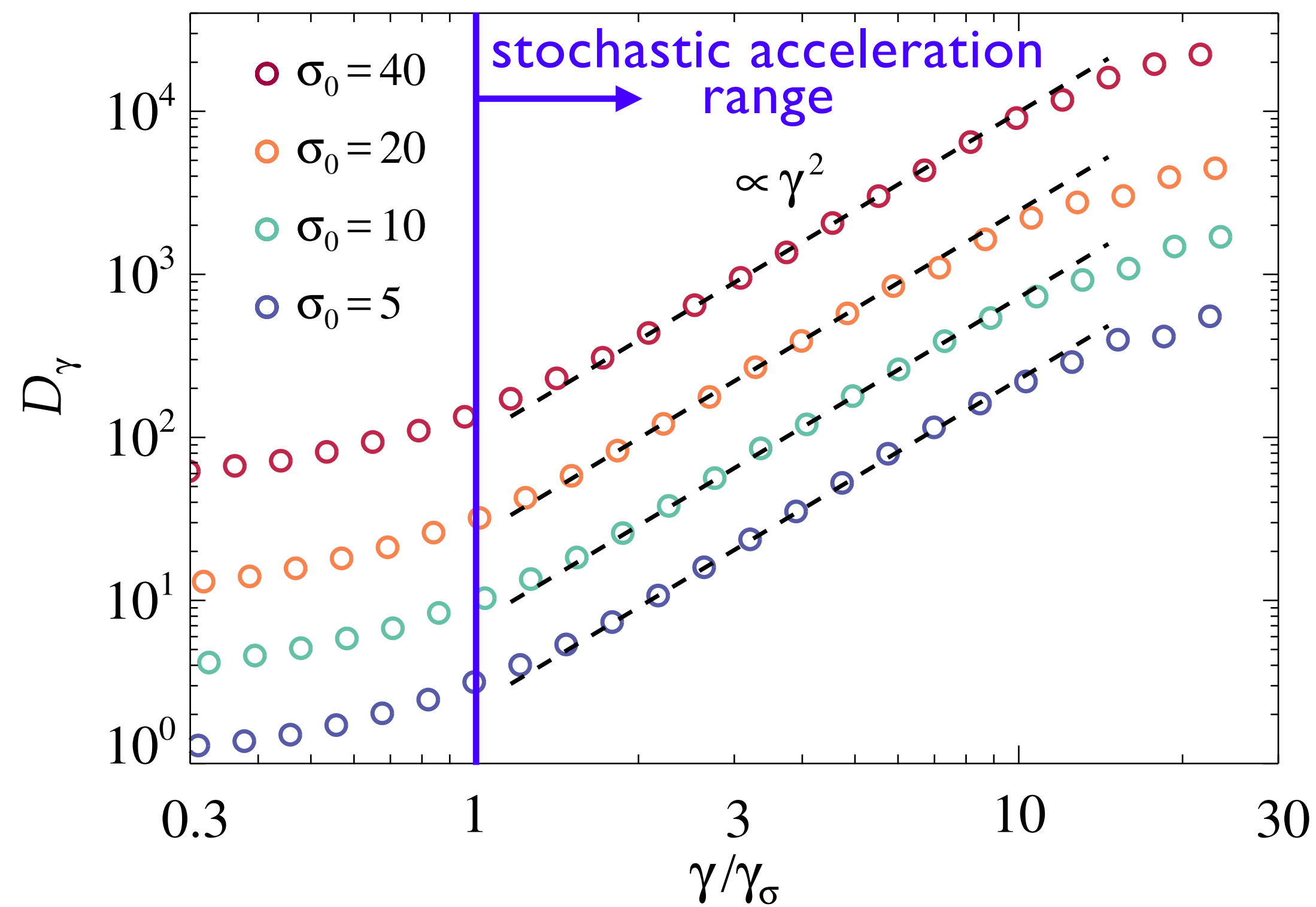
From the 1st to the 2nd stage: injection to stochastic acceleration



Comisso and Sironi '18, '19

- ▶ $\mathbf{v} \cdot \mathbf{E}_{||}$ energization critical initially (low $\Delta\gamma$ -range) $\longrightarrow \frac{d\gamma}{dt} \sim \frac{e}{m_e c} \beta_{\text{rec}} \delta B_{\text{rms}}$
- ▶ $\mathbf{v} \cdot \mathbf{E}_{\perp}$ energization responsible for most acceleration up to the confinement limit

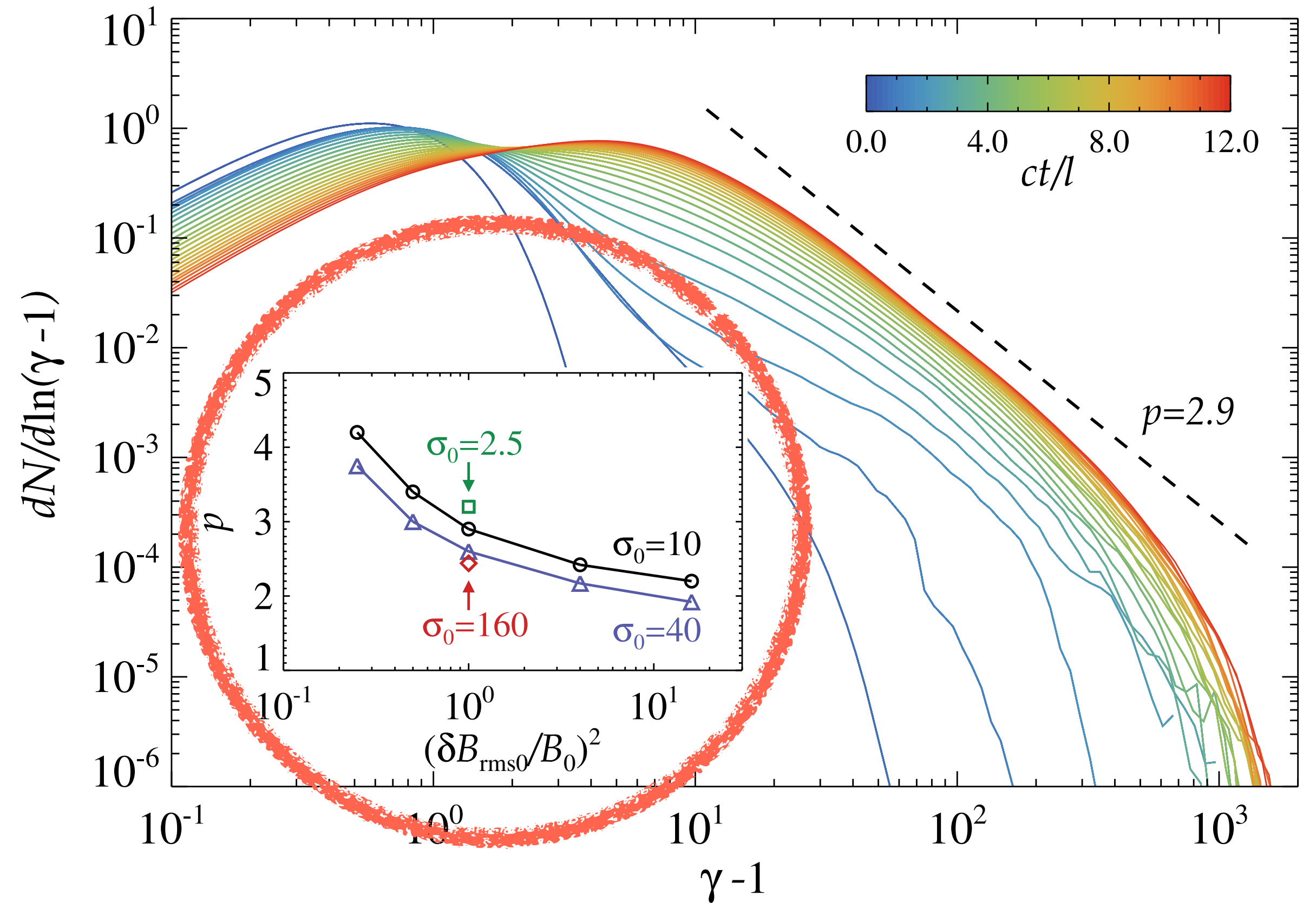
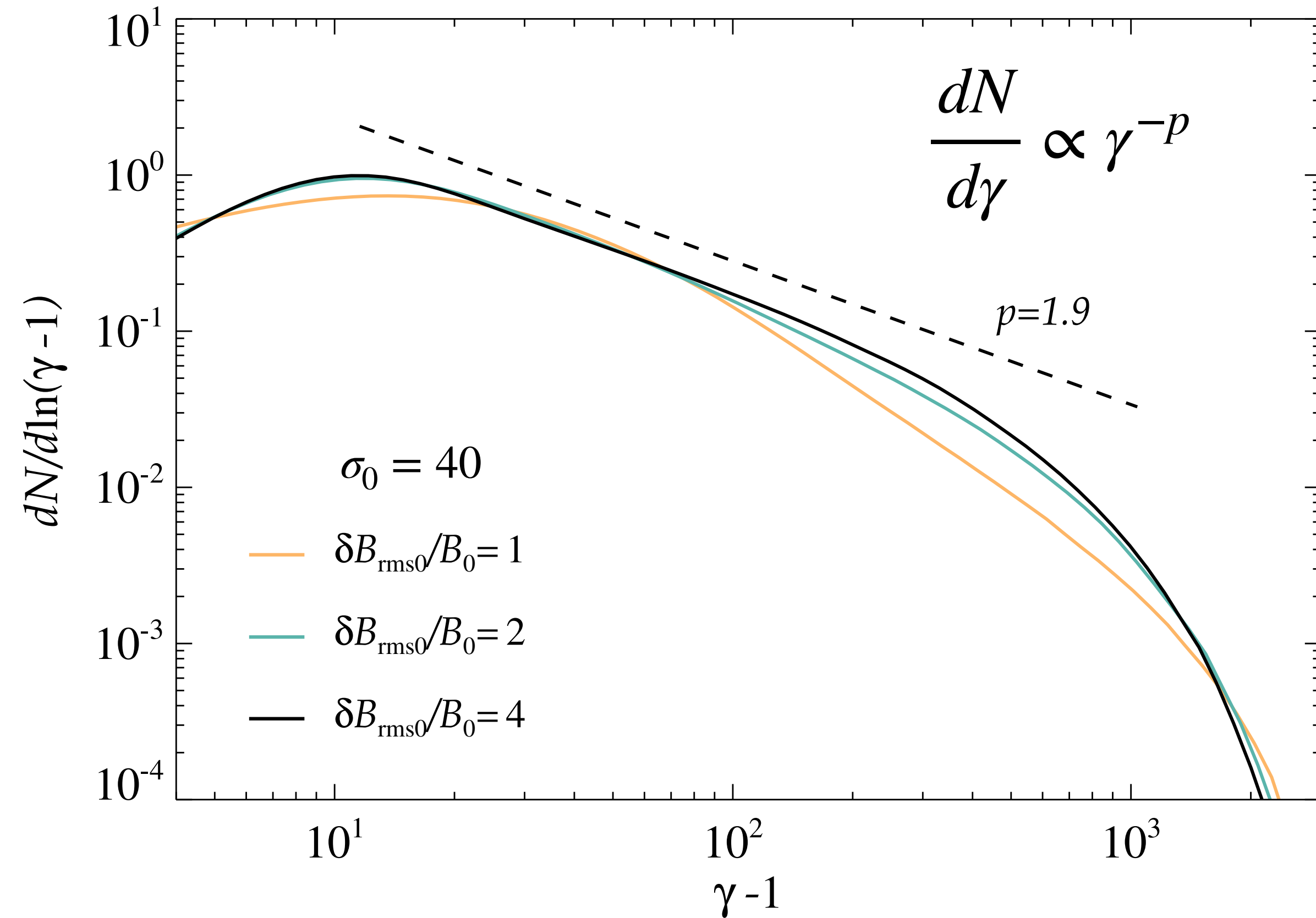
2nd stage: stochastic acceleration by scatterings off larger scale fluctuations



- Diffusion coefficient in energy space: $D_\gamma \simeq \kappa_{\text{acc}} \sigma \frac{\delta B_{\text{rms}}^2}{B_{\text{rms}}^2} \frac{c}{l_c} \gamma^2$ $\longleftarrow \kappa_{\text{acc}} \simeq 0.1$
- (Comisso & Sironi '19)

- Mean particle acceleration time: $t_{\text{acc}} = \frac{\gamma}{d\gamma/dt} = \frac{\gamma^2}{4D_\gamma}$

2nd stage: stochastic acceleration by scatterings off larger scale fluctuations



Comisso & Sironi '18, '19

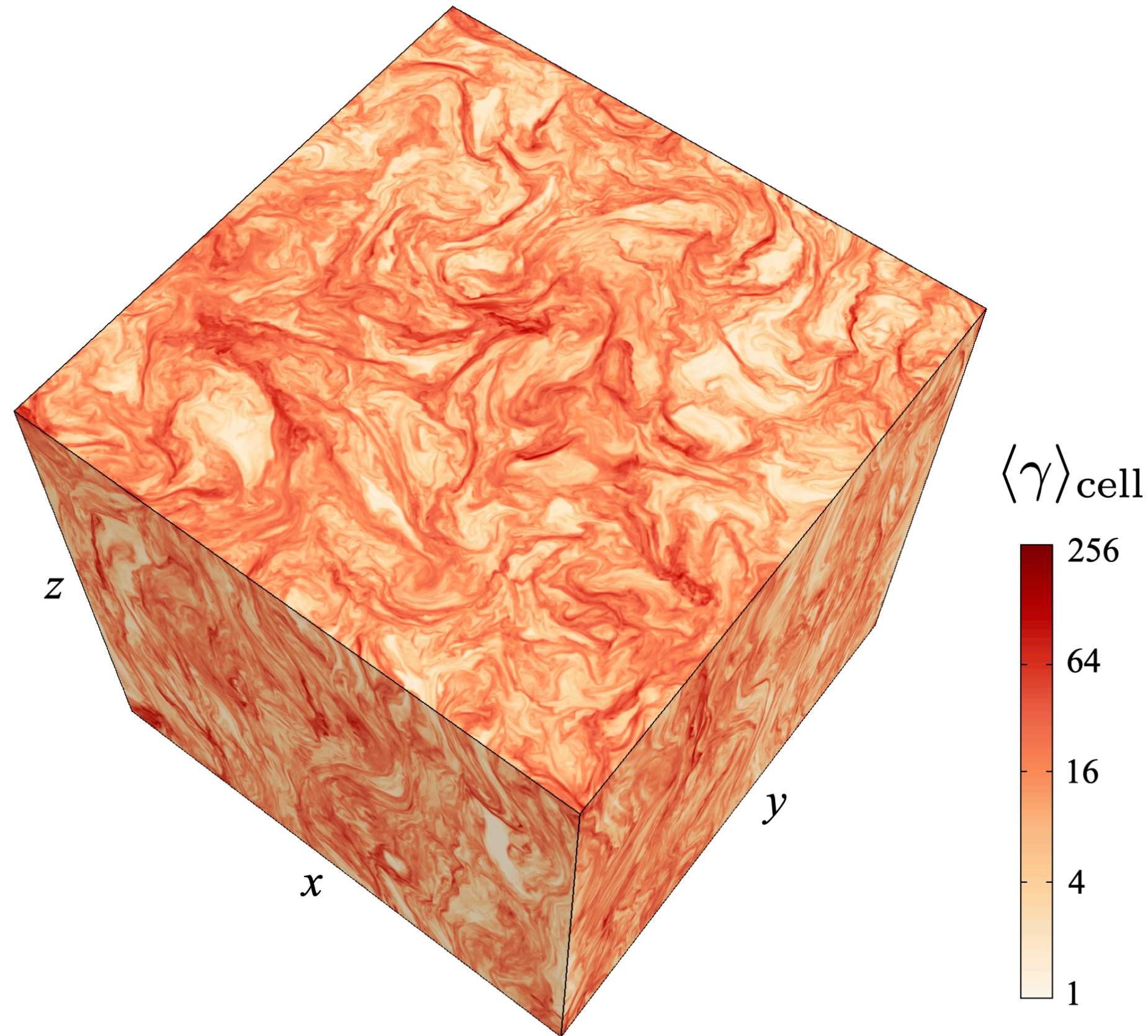
- Particle energy distribution depends on guide field strength and magnetization

Fully kinetic simulations of synchrotron-cooled turbulence

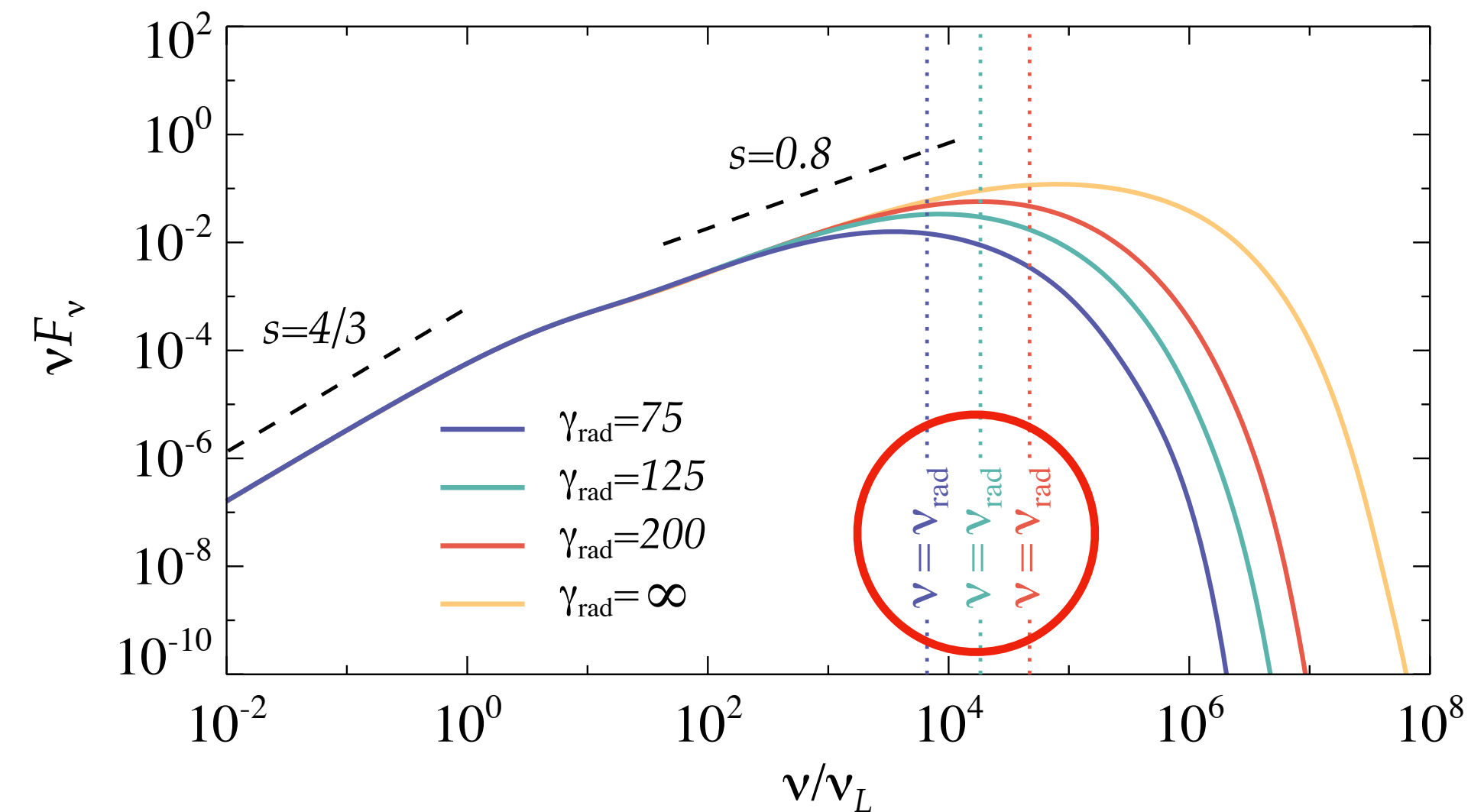
$$\mathbf{F}_{RR} = \frac{2}{3}r_0^2 \left[(\mathbf{E} + \boldsymbol{\beta} \times \mathbf{B}) \times \mathbf{B} + (\boldsymbol{\beta} \cdot \mathbf{E})\mathbf{E} \right] - \frac{2}{3}r_0^2\gamma^2\boldsymbol{\beta} \left[(\mathbf{E} + \boldsymbol{\beta} \times \mathbf{B})^2 - (\boldsymbol{\beta} \cdot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

- Strength of $\mathbf{F}_{RR}$ parametrized by γ s.t. $\mathbf{F}_{RR} = \mathbf{F}_{acc}$
- For ultra-relativistic particles ($\gamma \gg 1, \beta \simeq 1$):

$$\gamma_{rad} = \sqrt{\frac{3m_e^2 c^4}{2e^3} \frac{E}{B_{\perp}^2}}$$

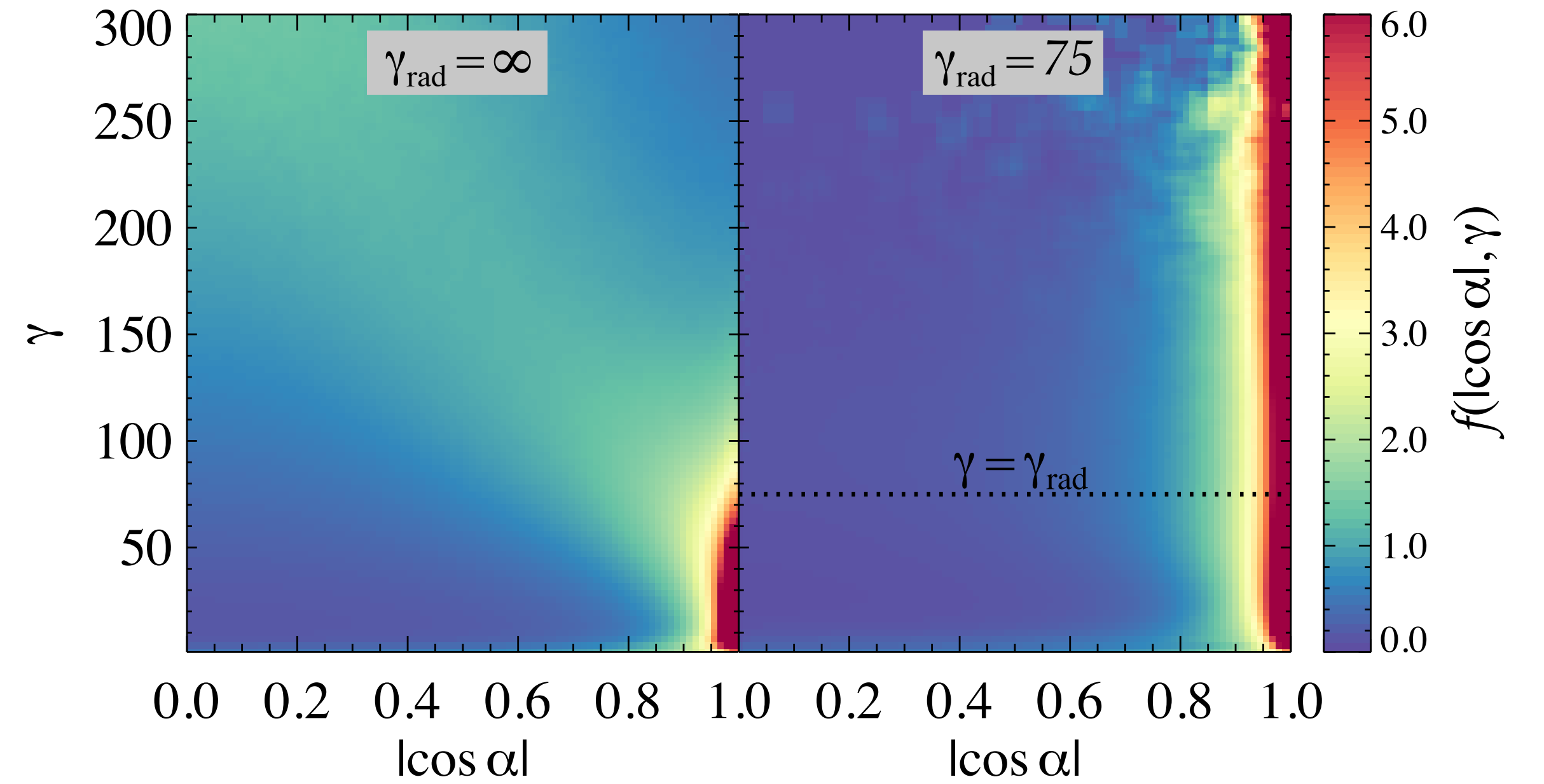
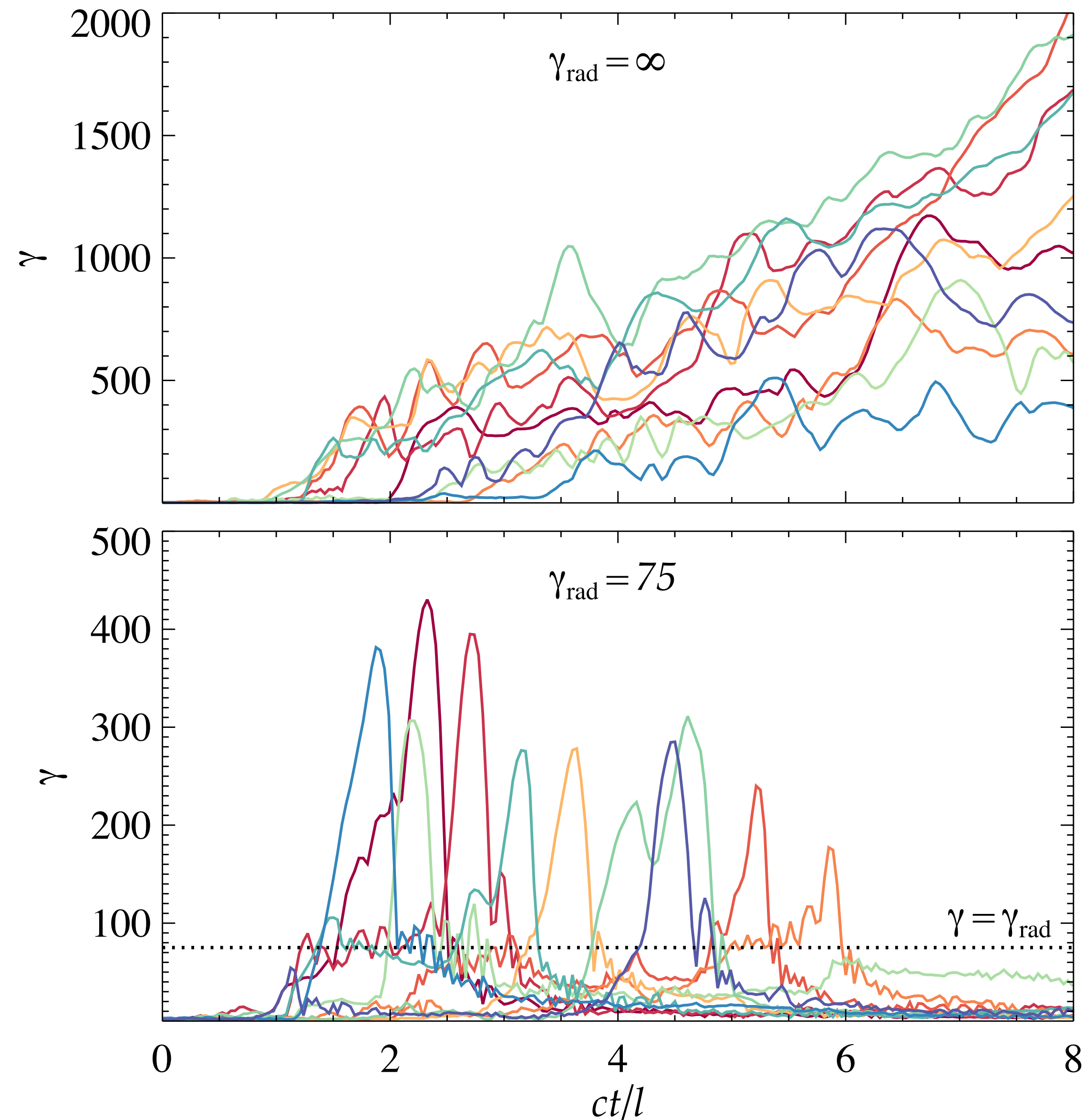


PIC simulations with 3072^3 cells
($L/d_e = 1024$)



Comisso & Sironi '21

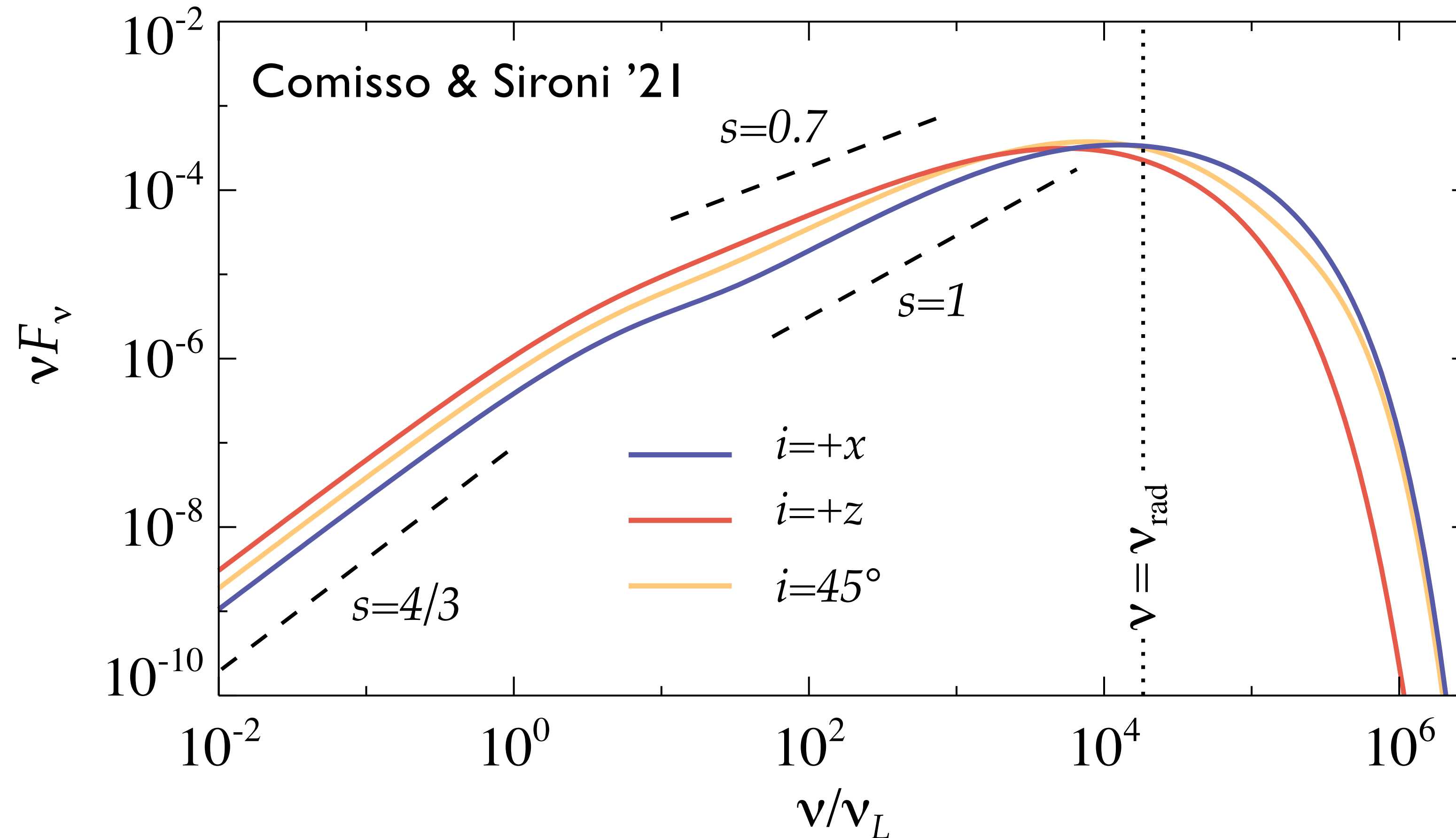
Extreme particle acceleration and abrupt cooling



Comisso & Sironi '21

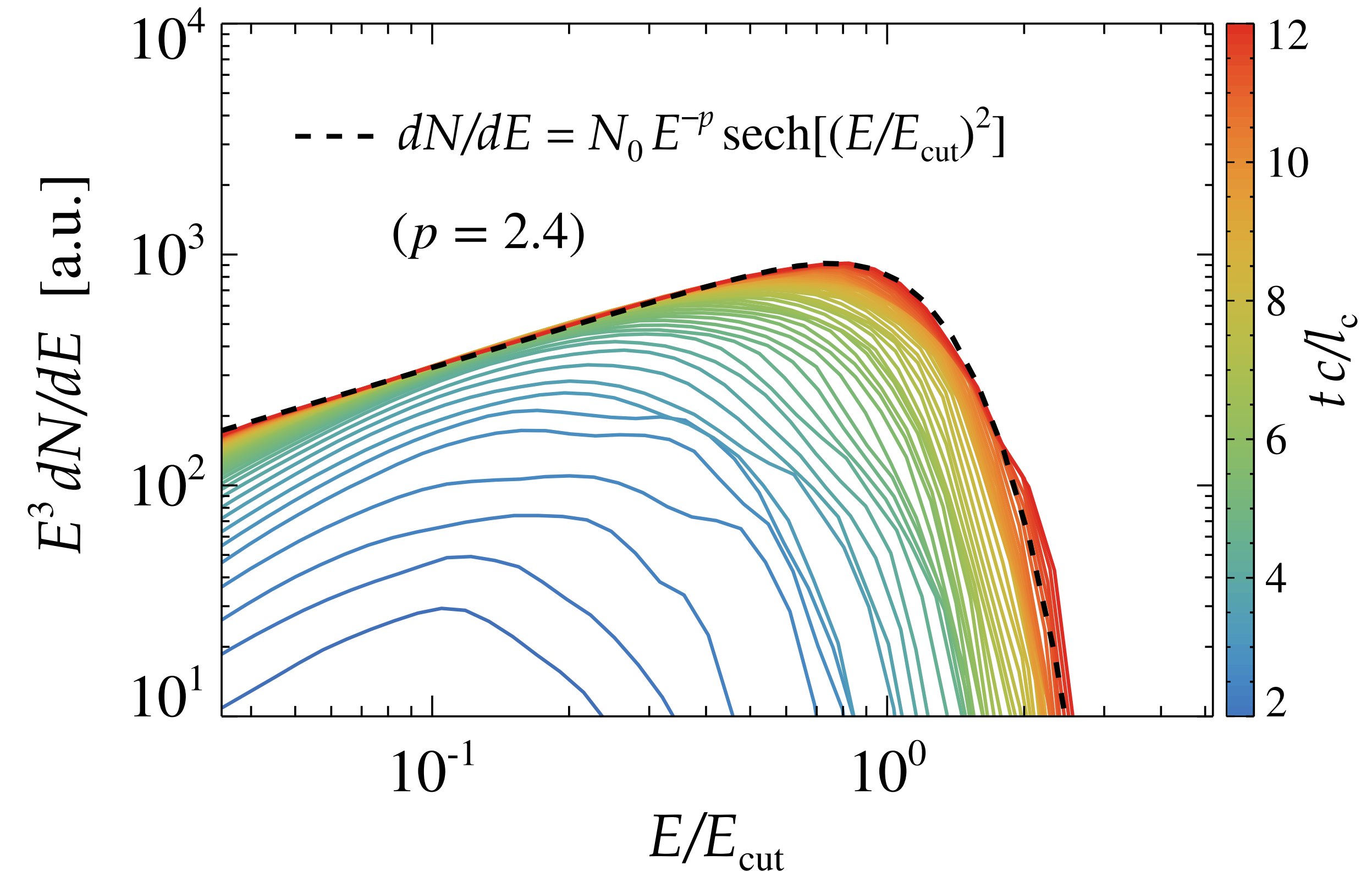
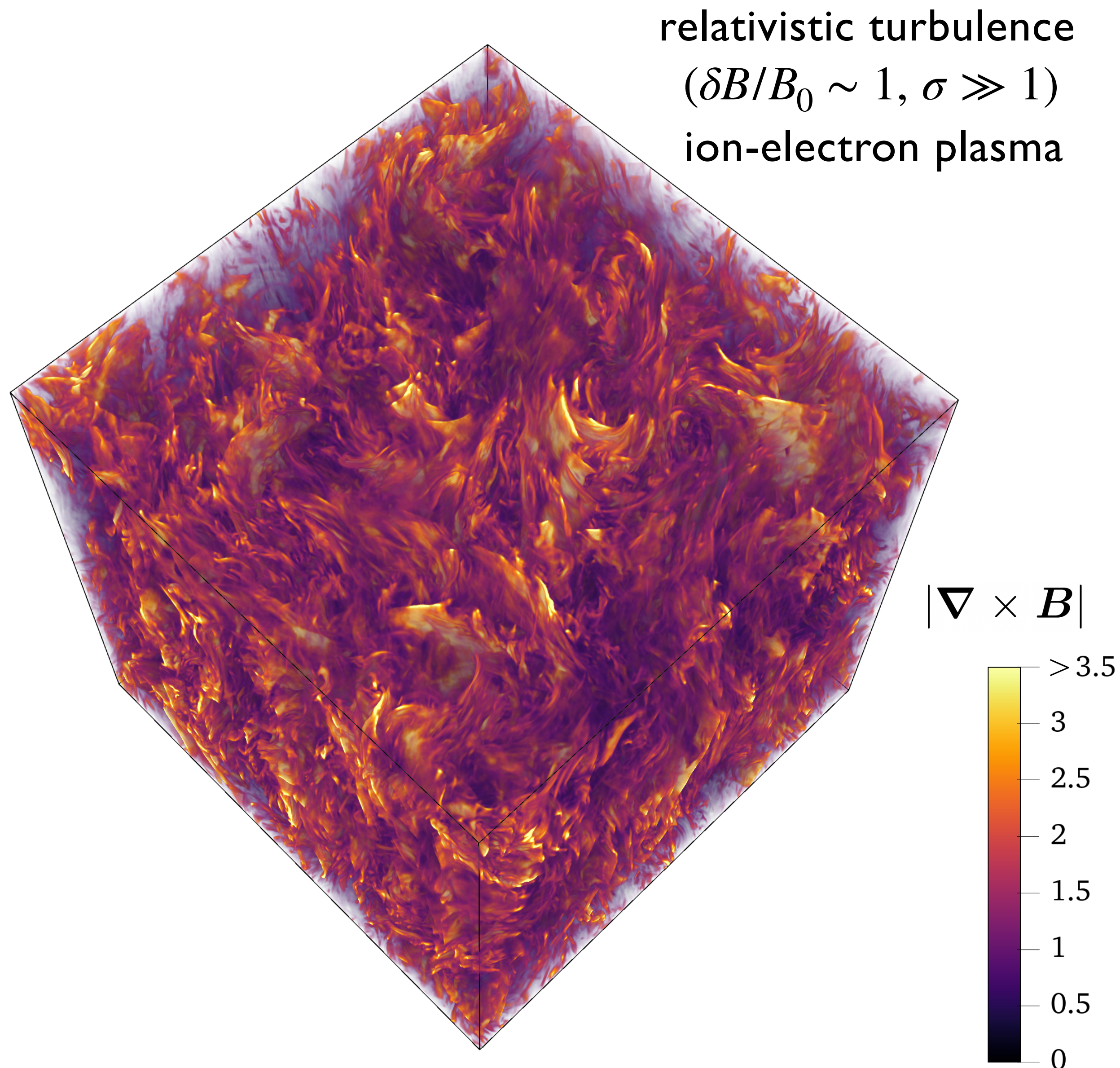
- Particles exceed $\gamma \gg \gamma_{\text{rad}}$ with $|\cos\alpha| \sim 0$
- Energy radiate away in fraction of gyroperiod:
 $\tau_{\text{cool}}(\gamma \gg \gamma_{\text{rad}}) \ll \gamma_{\text{rad}}/(\omega_L E/B)$ when $\sin\alpha \sim 1$

Synchrotron spectrum in synchrotron-cooled fully-kinetic turbulence



- ▶ Excess of synchrotron radiation above the nominal radiation-reaction-limited frequency ν_{rad}
- ▶ Hard synchrotron spectrum $\nu F_\nu \propto \nu^s$ with $s > 1/2$ (exceeds the “naive limit” $s = 1/2$) up to ν_{peak}

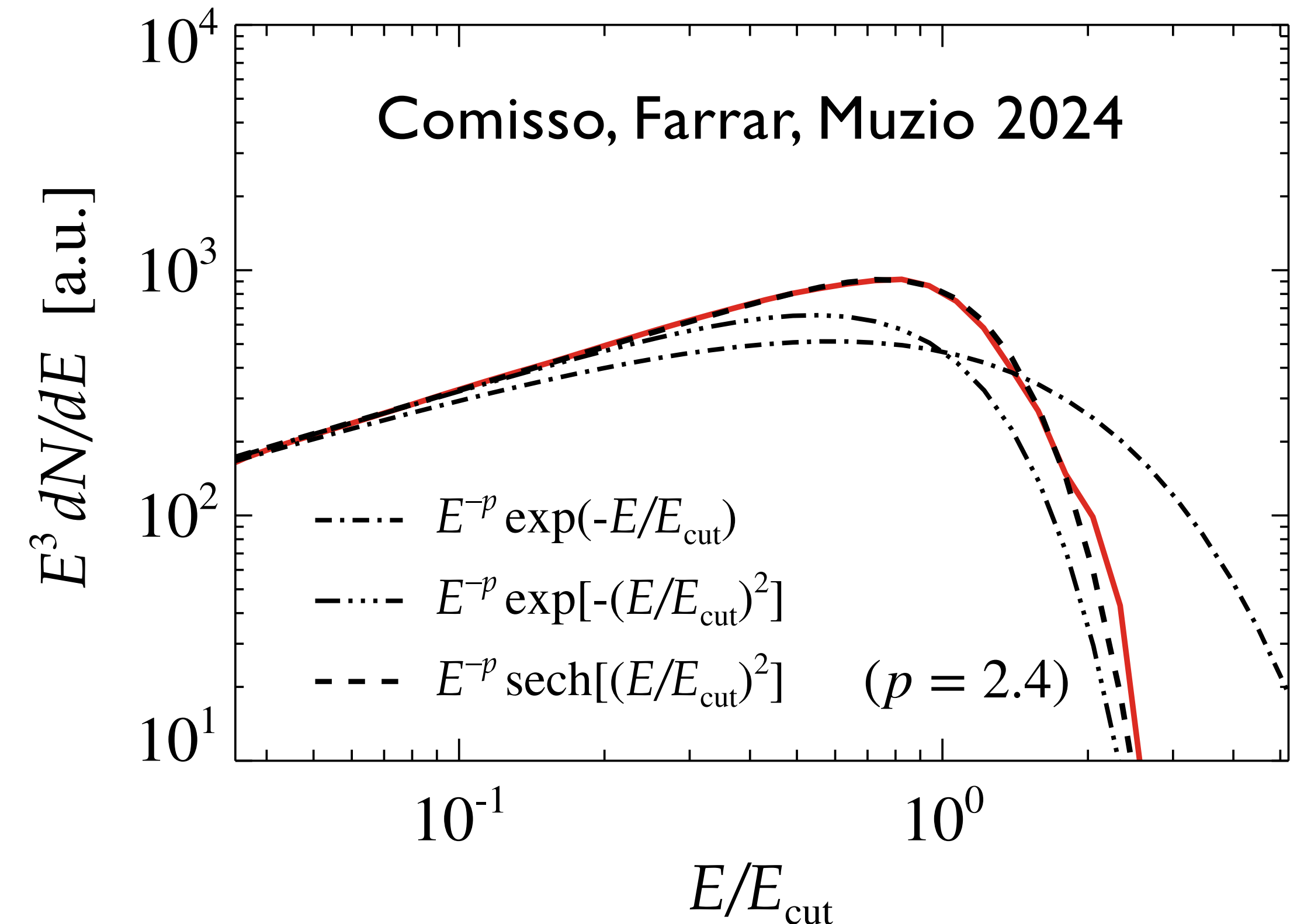
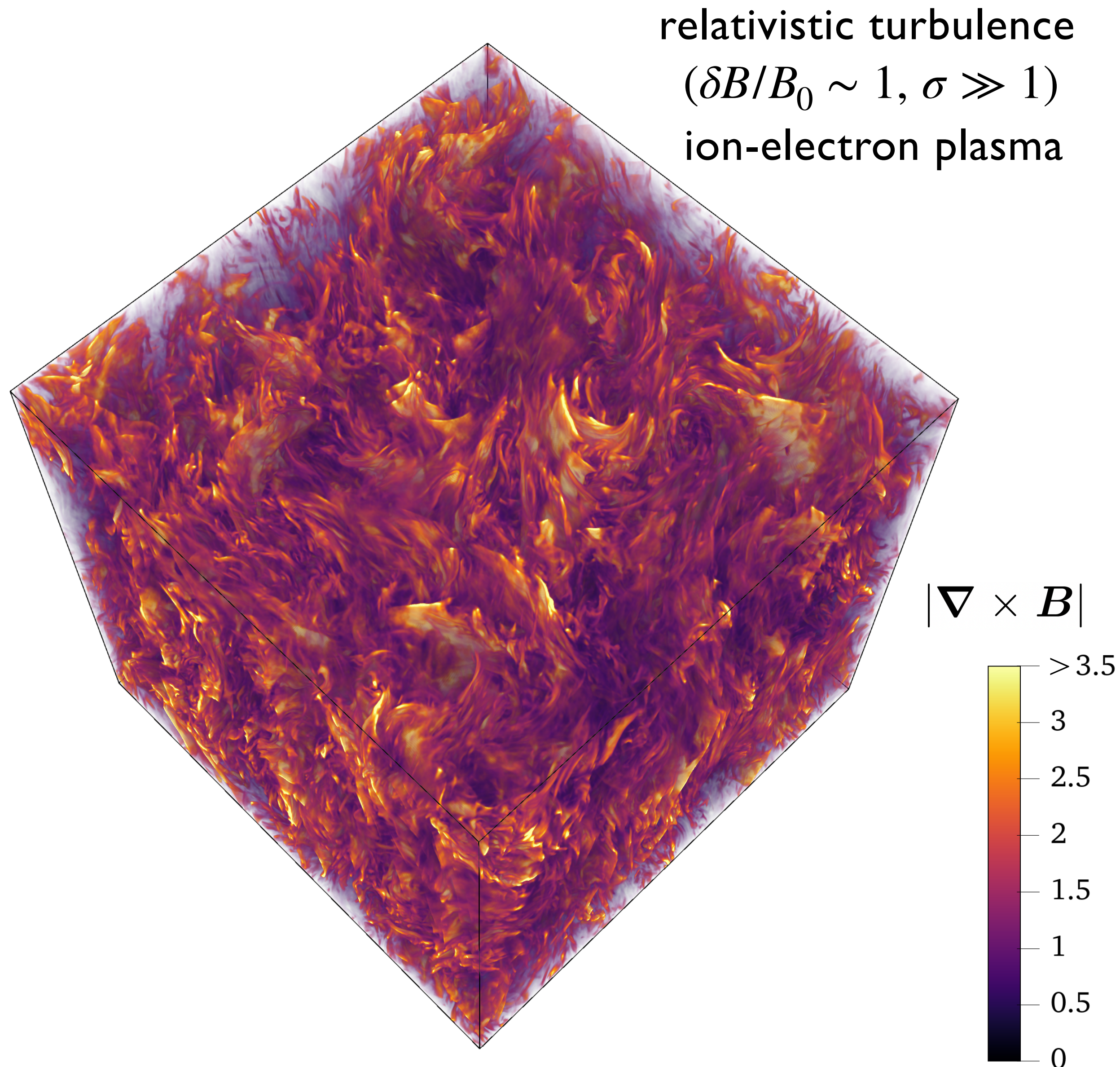
Fully kinetic simulations of cosmic-ray acceleration in turbulence



- Magnetized turbulence accelerates particles into a spectrum of the form:

$$\frac{dN}{dE} = N_0 E^{-p} \text{sech} \left[\left(E/E_{\text{cut}} \right)^2 \right]$$

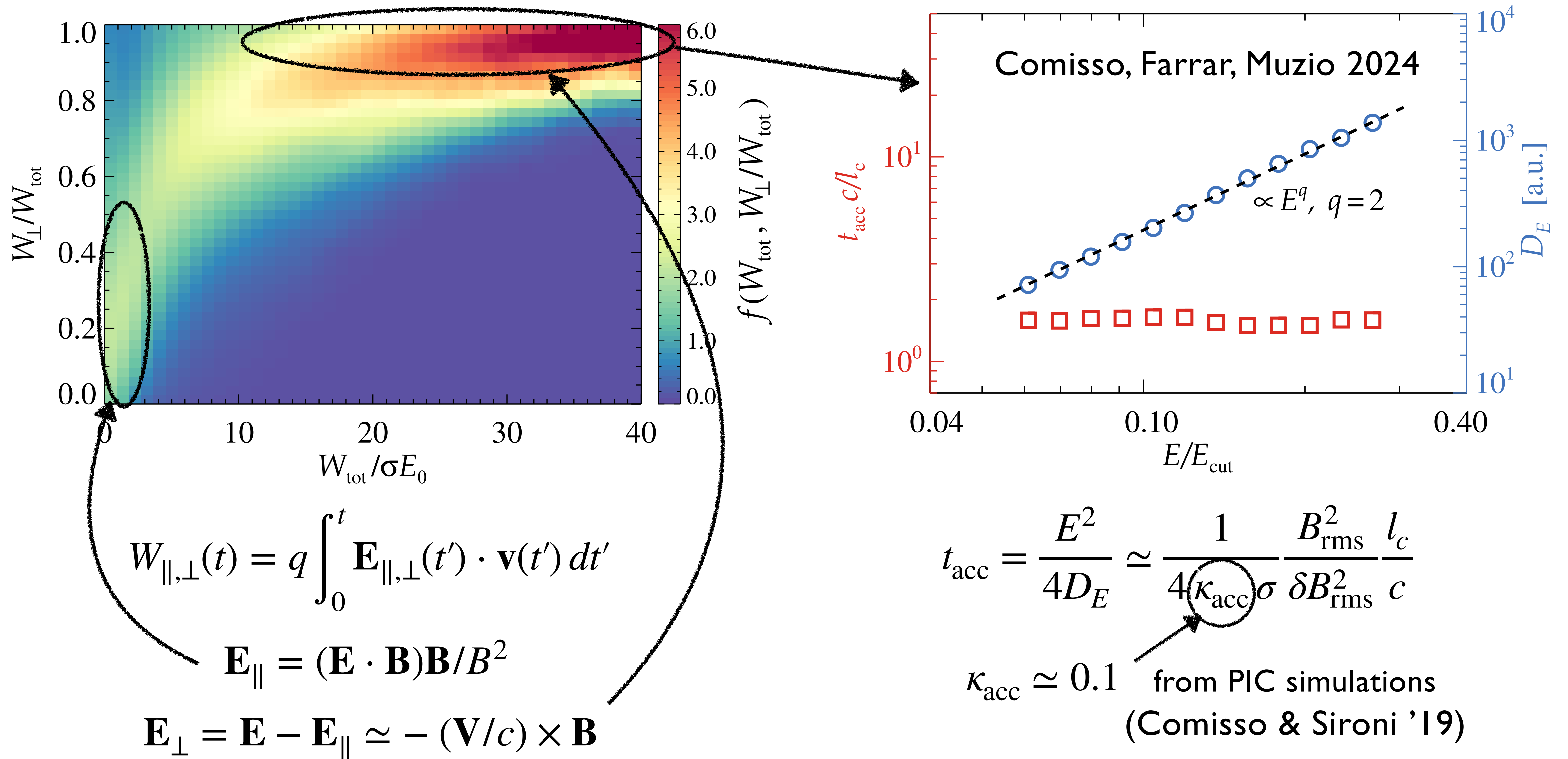
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Fully kinetic simulations of cosmic-ray acceleration in turbulence



Flux of cosmic rays escaping the accelerator in fully-kinetic turbulence

- Residence time within the accelerator:

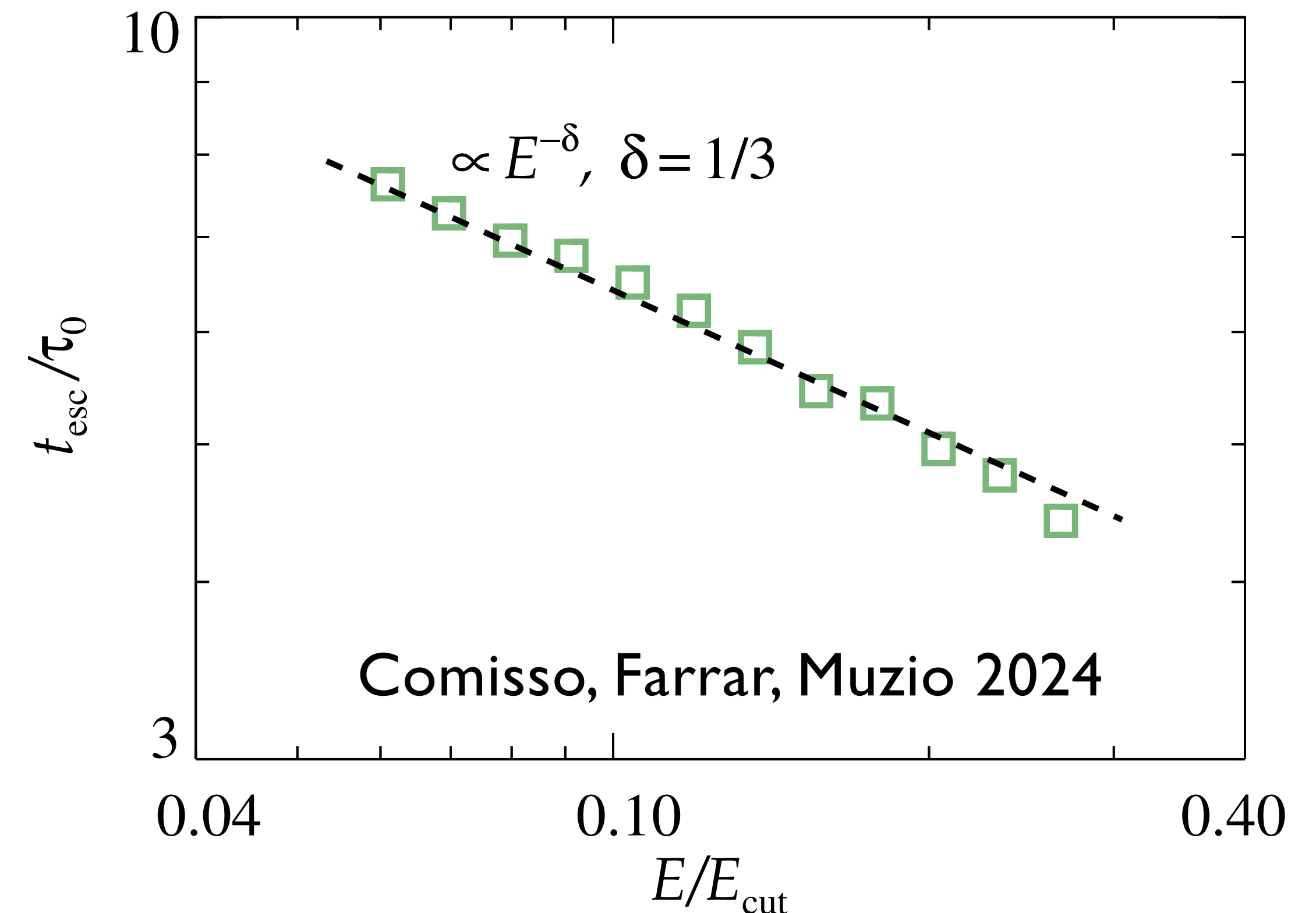
$$t_{\text{esc}} \simeq \frac{L^2}{\lambda_s c} \simeq \frac{L^2}{l_c c} \left(\frac{E_{\text{cut}}}{E} \right)^\delta \propto E^{-\delta}$$

- Flux of particles escaping the accelerator is given by

$$\phi(E) = \frac{dN}{dEdt} = \frac{1}{t_{\text{esc}}} \frac{dN}{dE} \propto E^{-s} \text{sech} \left[\left(E/E_{\text{cut}} \right)^2 \right]$$

with $s = p + \delta \sim 2.1$ from fully-kinetic PIC simulations of highly magnetized turbulence

$p \sim 2.4$ $\delta \sim 1/3$



The issue with smooth source energy cutoffs

- ▶ The source energy cutoff is generally modeled as:

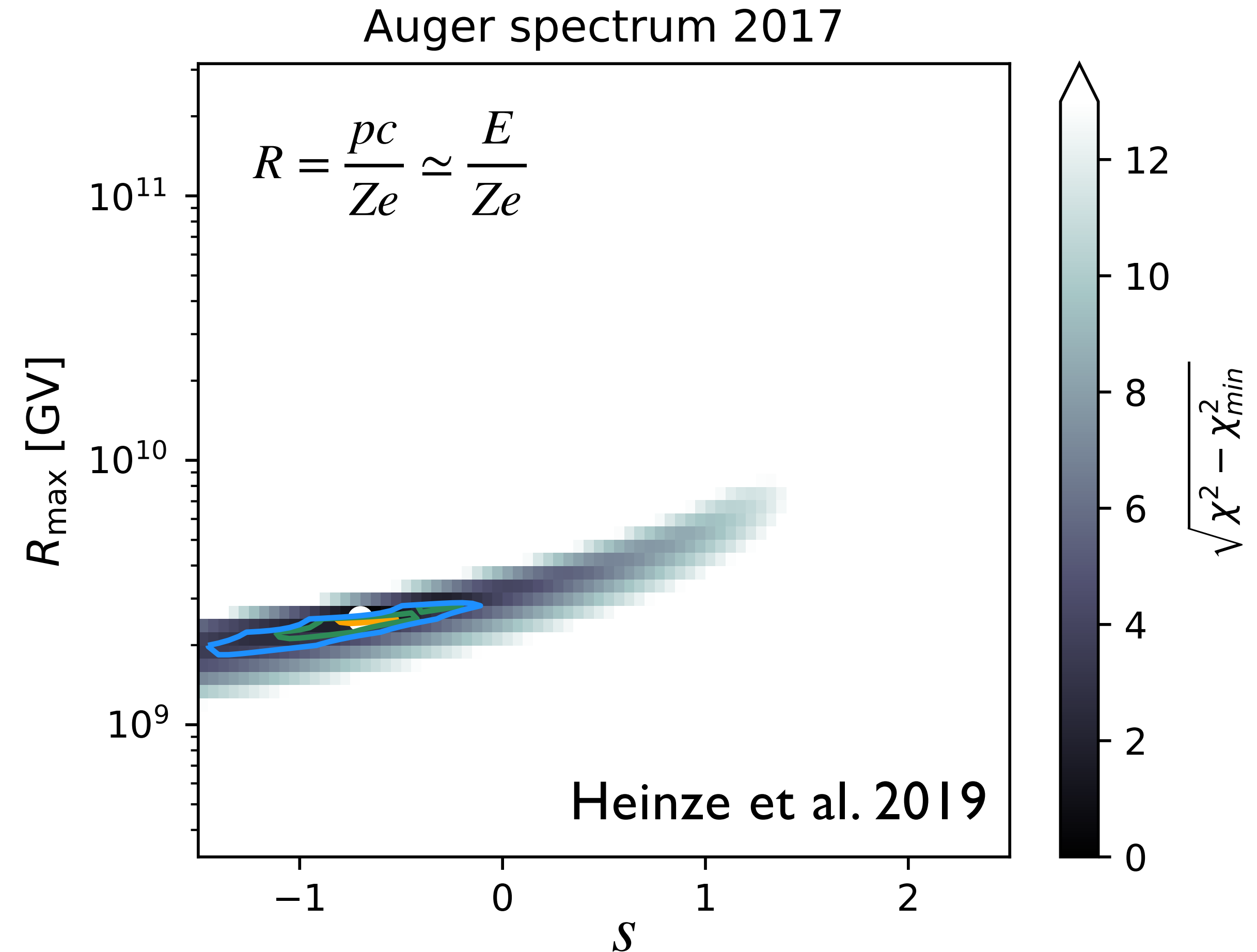
$$\phi(E) \propto E^{-s} \exp\left[-E/E_{\text{cut}}\right]$$

- ▶ Often the spectrum is modeled (with no good physical reason) as a broken exponential cutoff:

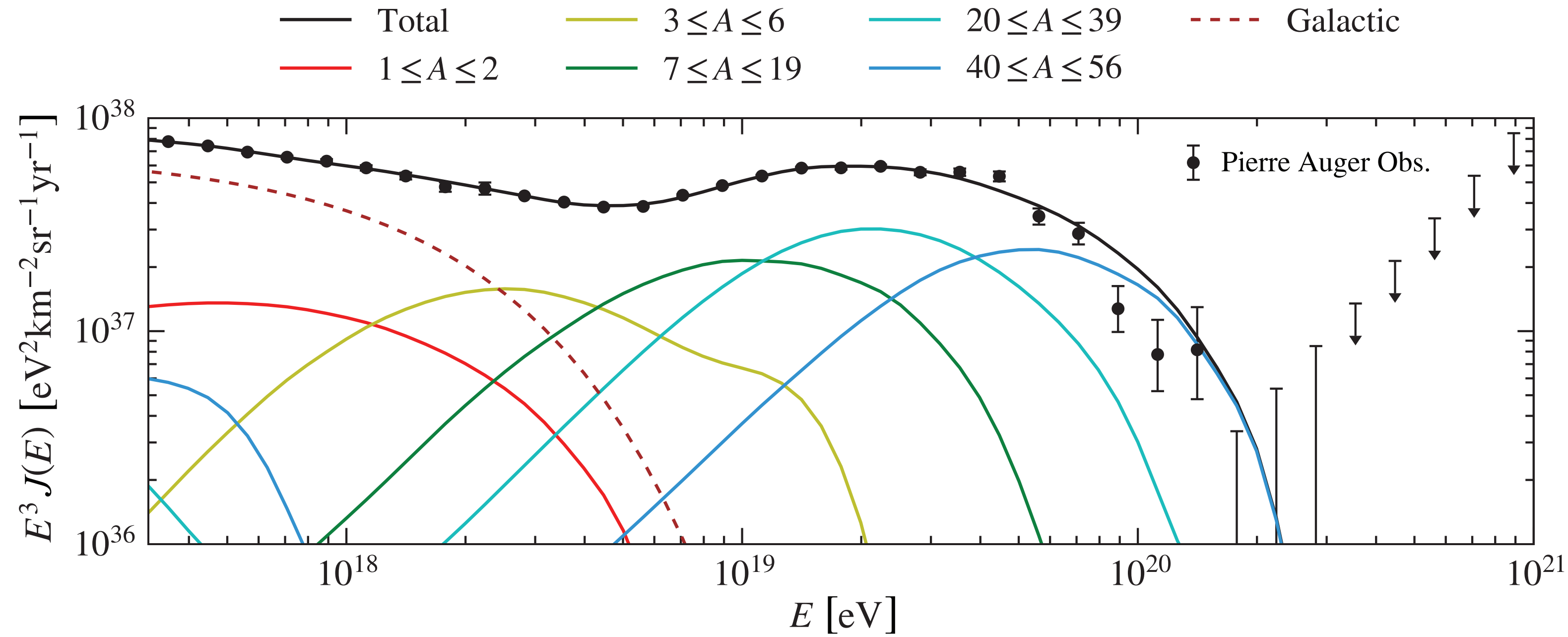
$$\phi(E) \propto E^{-s} \times \begin{cases} 1 & , E \leq E_{\text{cut}} \\ \exp\left[1 - E/E_{\text{cut}}\right] & , E > E_{\text{cut}} \end{cases}$$

- ▶ Fits to UHECR spectrum and composition data return $s \lesssim 1$ (which is difficult to achieve)

- ▶ A diverse source population makes it even more challenging (Ehlert+ 2023)



From turbulent acceleration to the observed UHECR spectrum and composition



Adopting the Unger-Farrar-Anchordoqui (UFA '15) transport framework, the turbulent acceleration model restricts the energy range where each element group contributes significantly

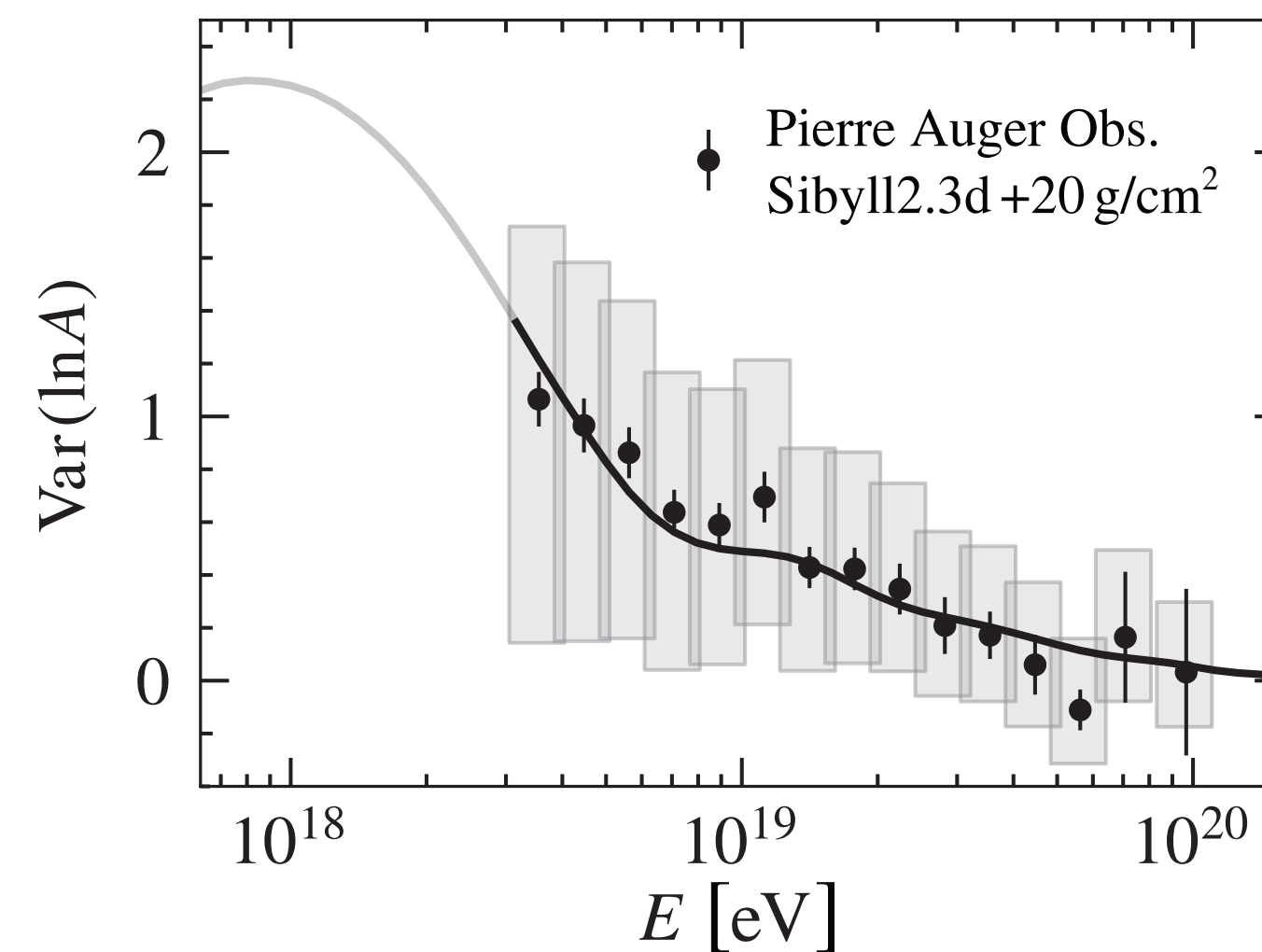
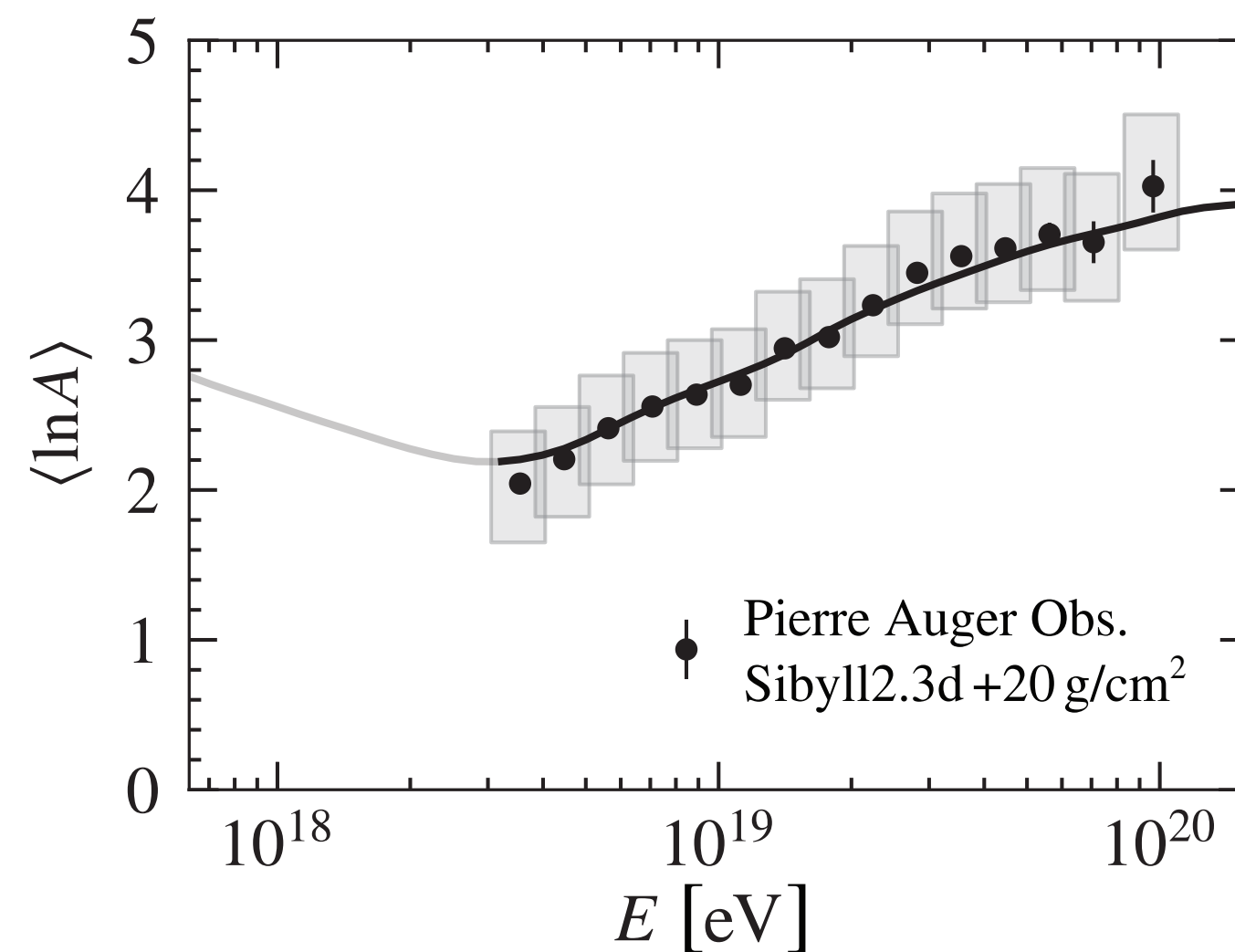
The resulting best fit yields:

$$s \simeq 2.1$$

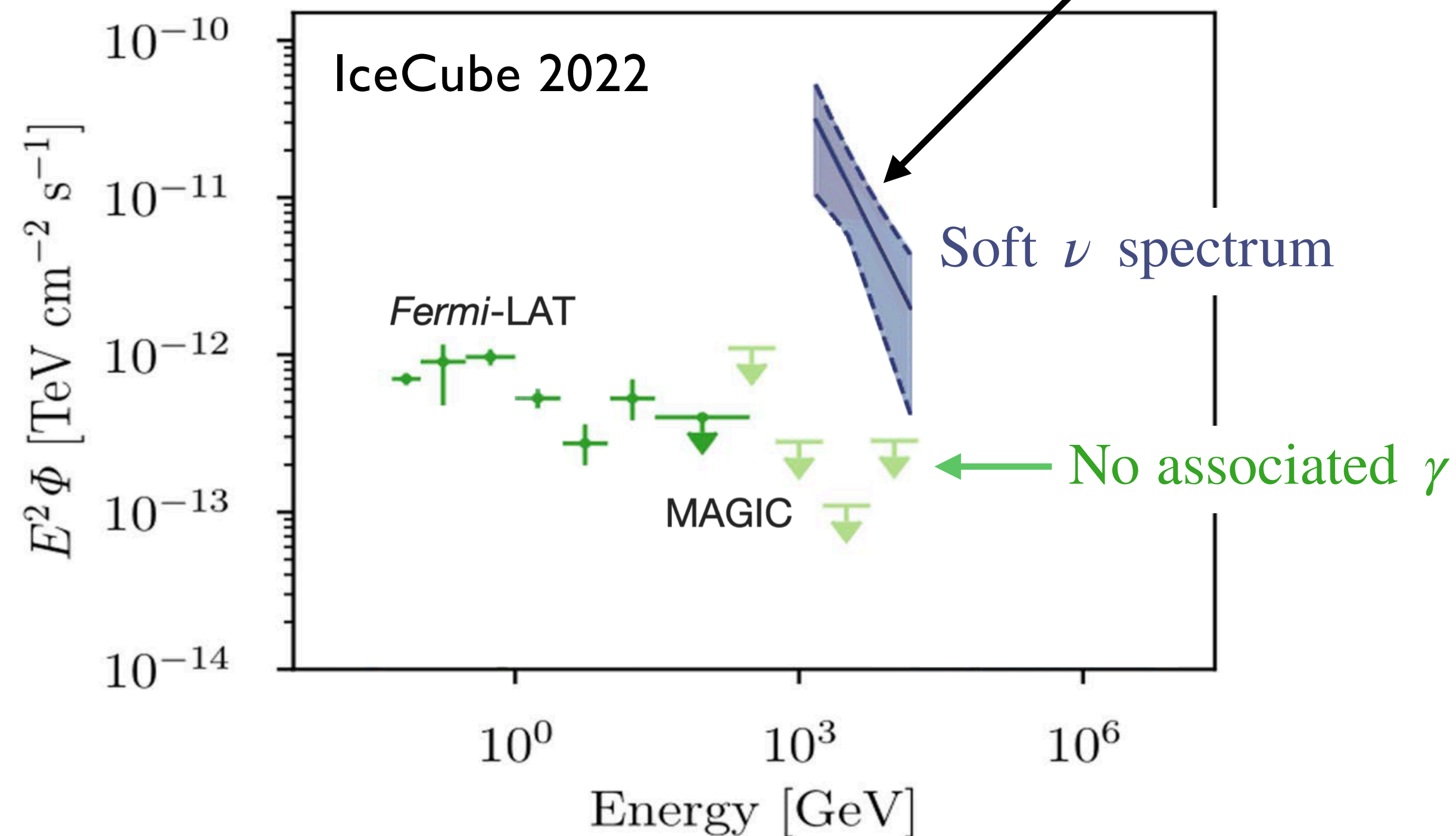
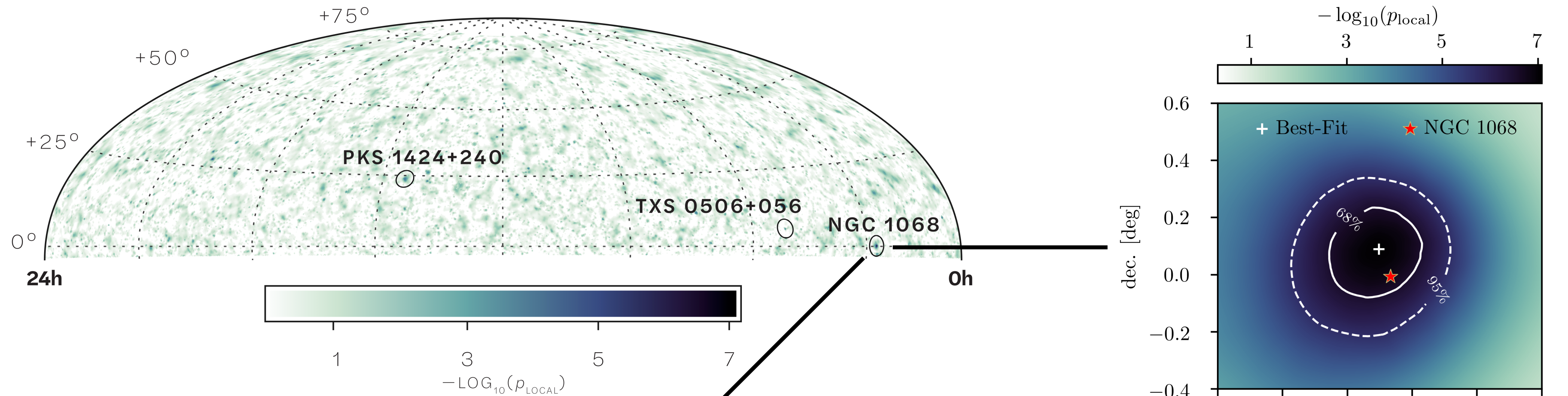
$$R_{\text{cut}} \simeq 6.3 \times 10^{18} \text{ V}$$

$$\mathcal{L}_{\text{UHECR}} \simeq 0.7 \times 10^{45} \text{ erg Mpc}^{-3} \text{ yr}^{-1}$$

Comisso, Farrar, Muzio 2024



Neutrino production in black-hole coronae



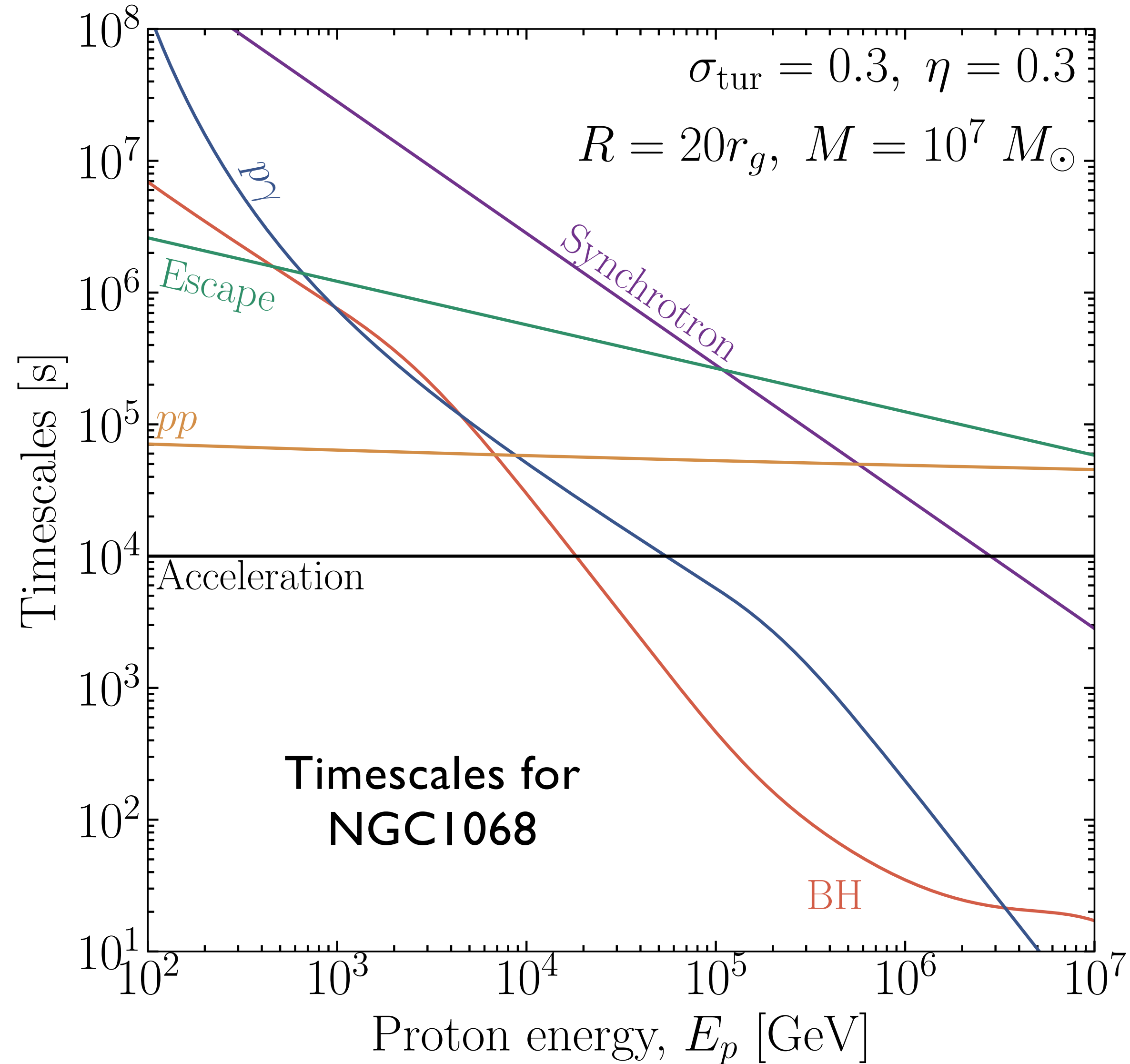
$$p + \gamma \rightarrow \begin{cases} n + \pi^+ \\ p + \pi^0 \end{cases} \quad p + p \rightarrow \begin{cases} \pi^+ + \text{anything} \\ \pi^- + \text{anything} \\ \pi^0 + \text{anything} \end{cases}$$

$$\pi^0 \rightarrow \gamma + \gamma$$

$$\pi^+ \rightarrow \mu^+ + \nu_\mu \quad \text{and} \quad \mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu \quad \text{and} \quad \mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$$

Acceleration, escape, and cooling in the black-hole corona



$$\left(\eta = \frac{\ell_c}{R} \right)$$

Fiorillo et al. '24, '25

- $$t_{\text{acc}} \simeq \frac{1}{\kappa_{\text{acc}} \sigma} \frac{B_{\text{rms}}^2}{\delta B_{\text{rms}}^2} \frac{l_c}{c} \quad (\text{From PIC Turbulence})$$

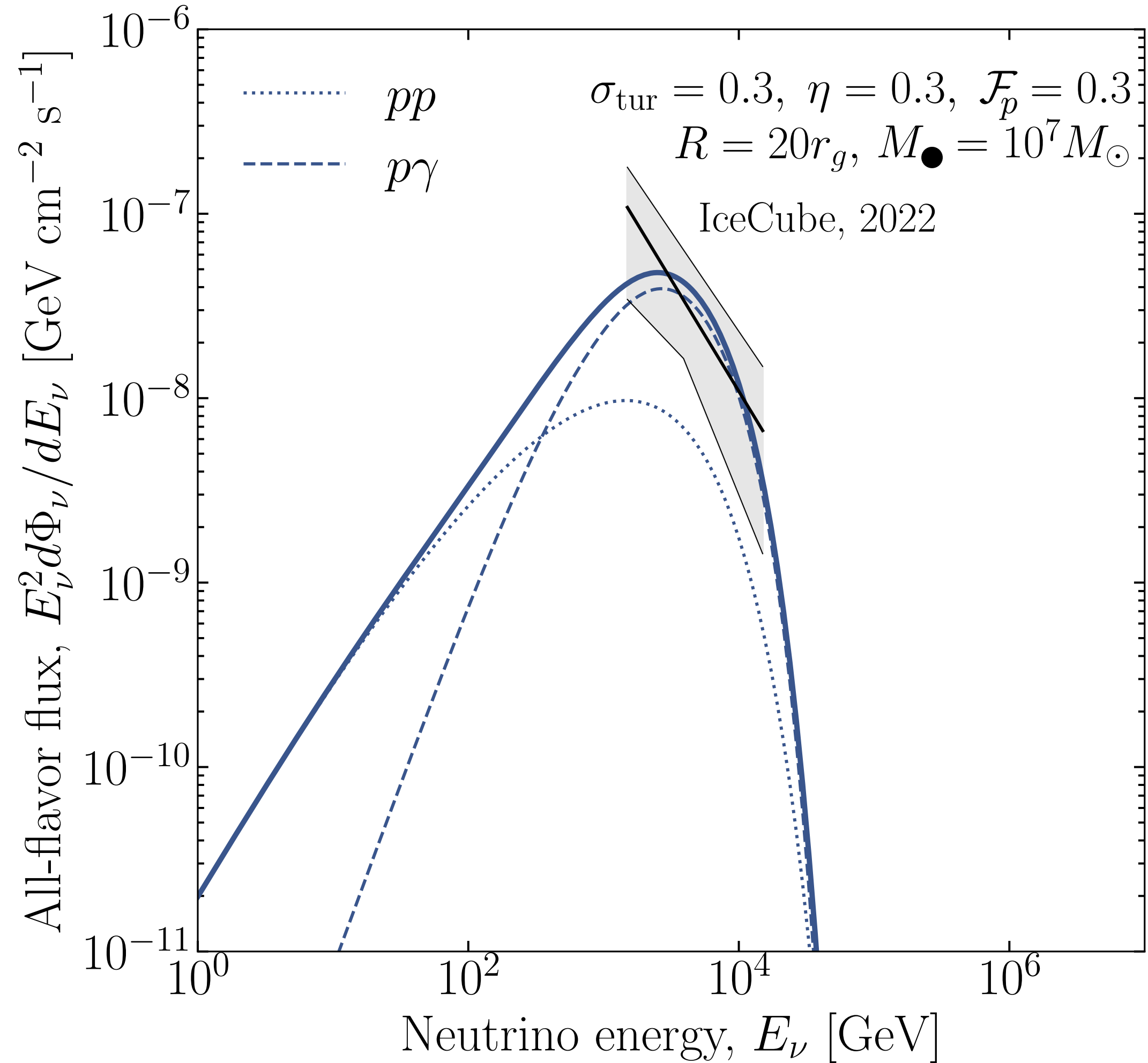
- $$t_{\text{esc}} \simeq \frac{L^2}{l_c c} \left(\frac{E_{\text{cut}}}{E_p} \right)^{1/3} \propto E_p^{-1/3}$$

- Bethe-Heitler cooling limits proton energy to 20 TeV (requires sufficiently compact corona)

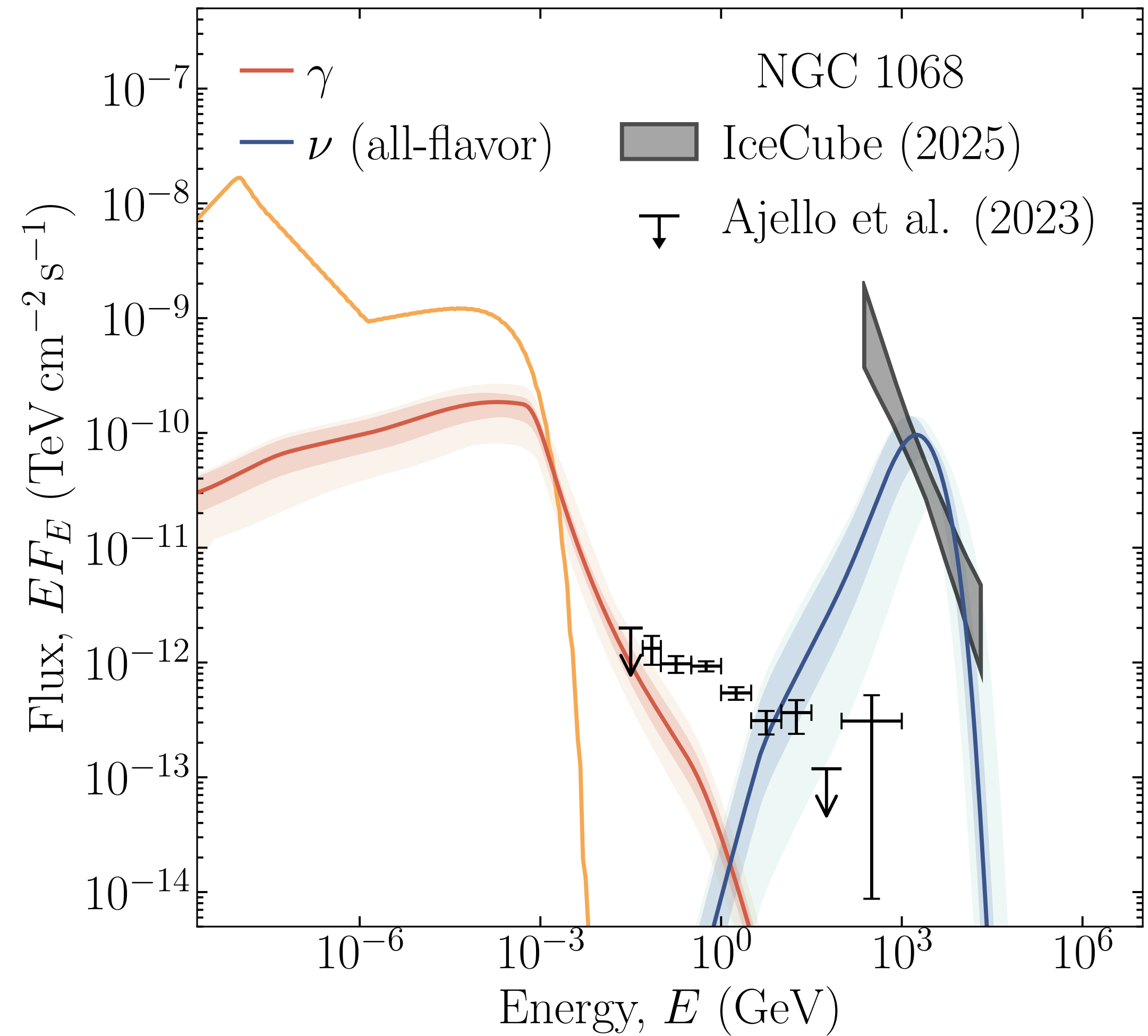
See also earlier model by Murase et al. '20

Probes of a turbulent black-hole corona

Fiorillo et al. 2024, 2025



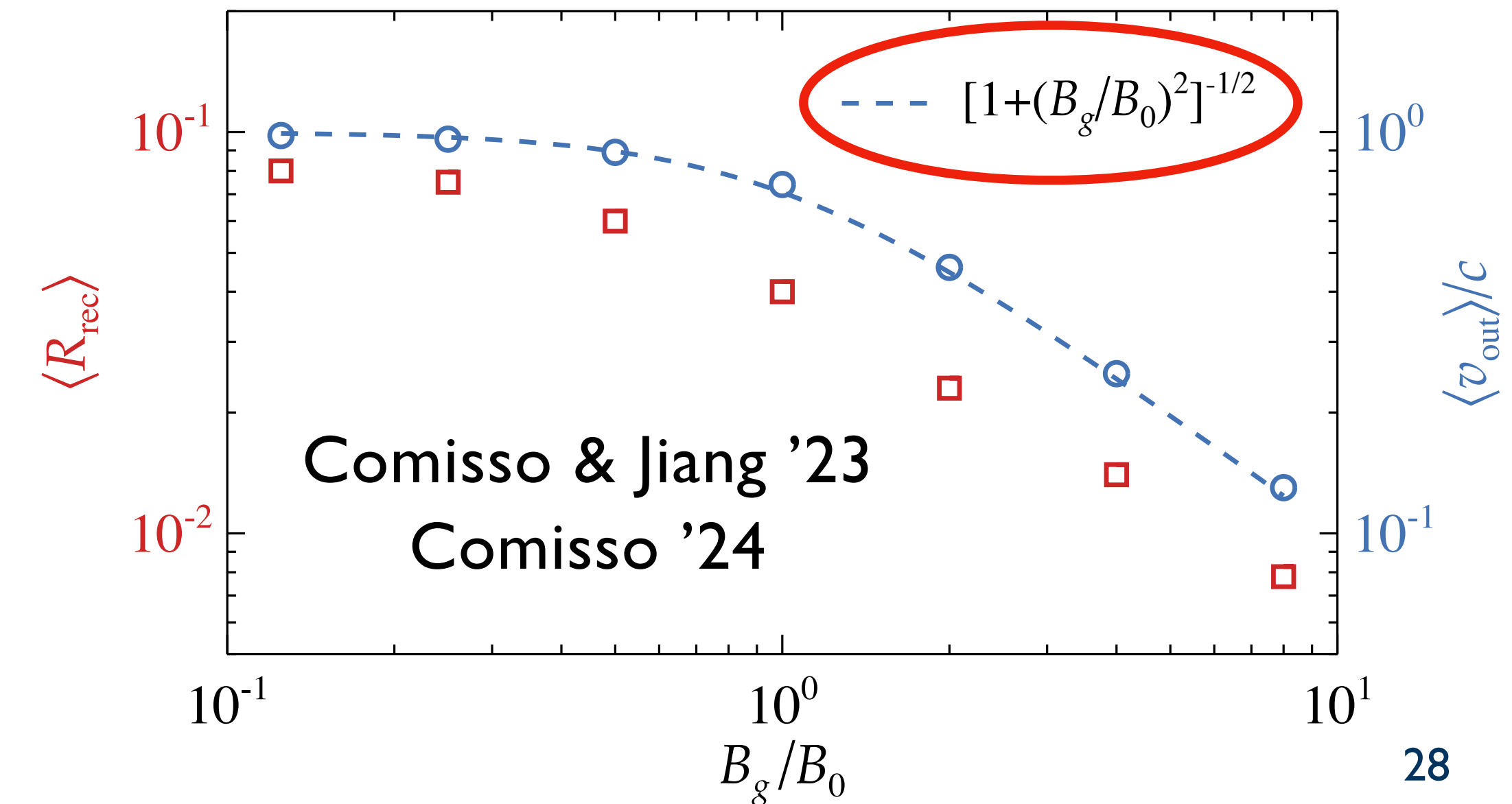
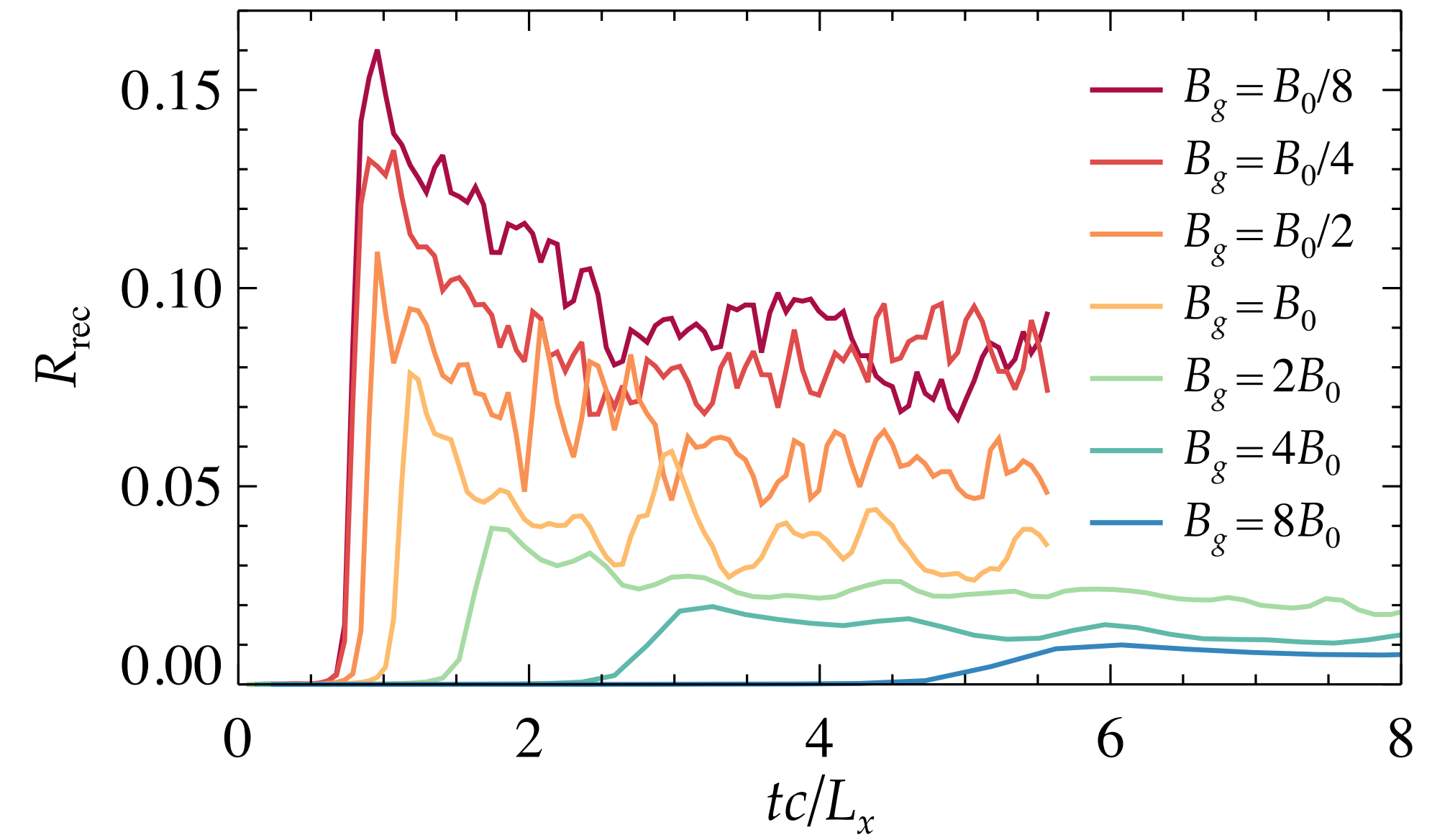
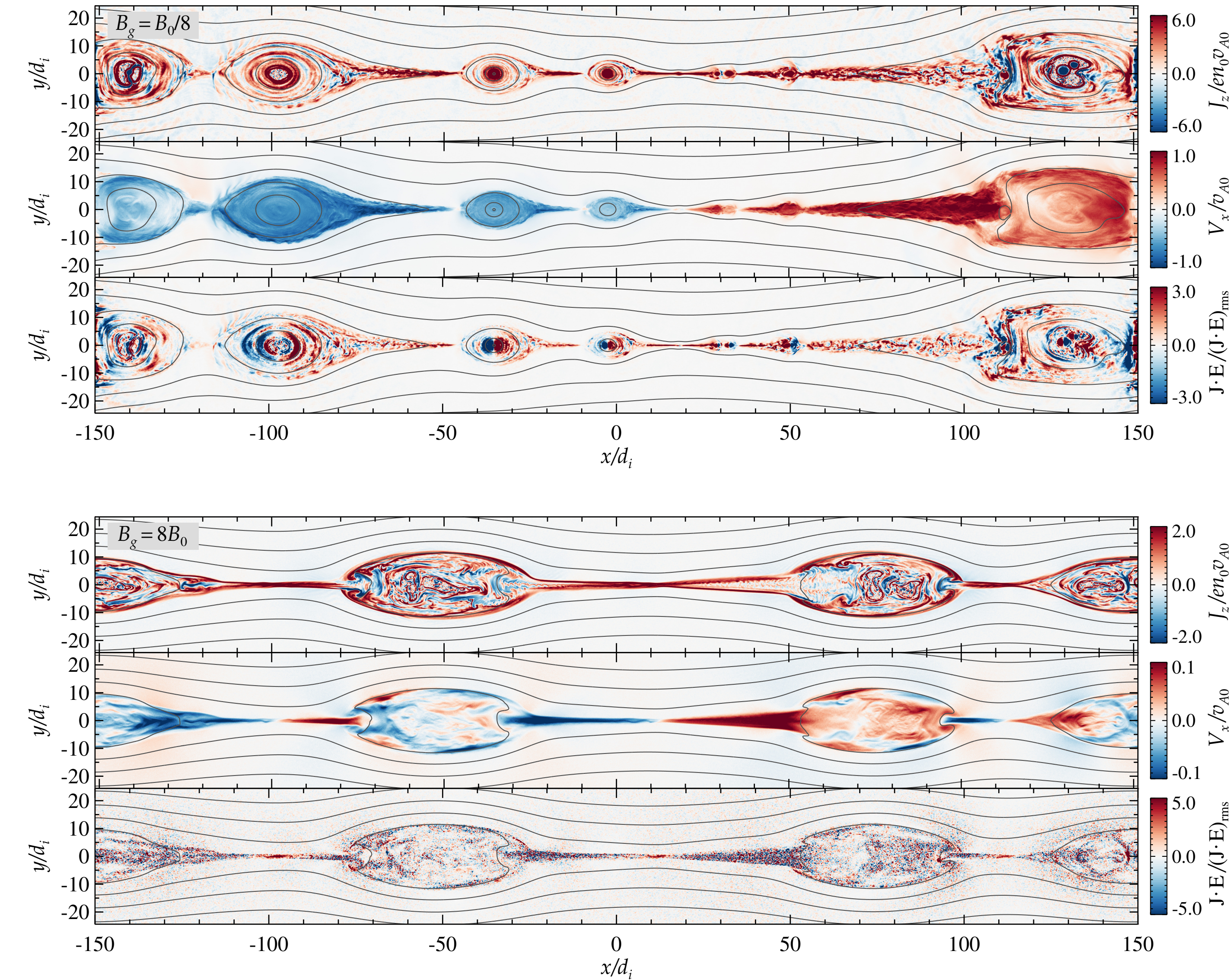
Testagrossa et al. 2026



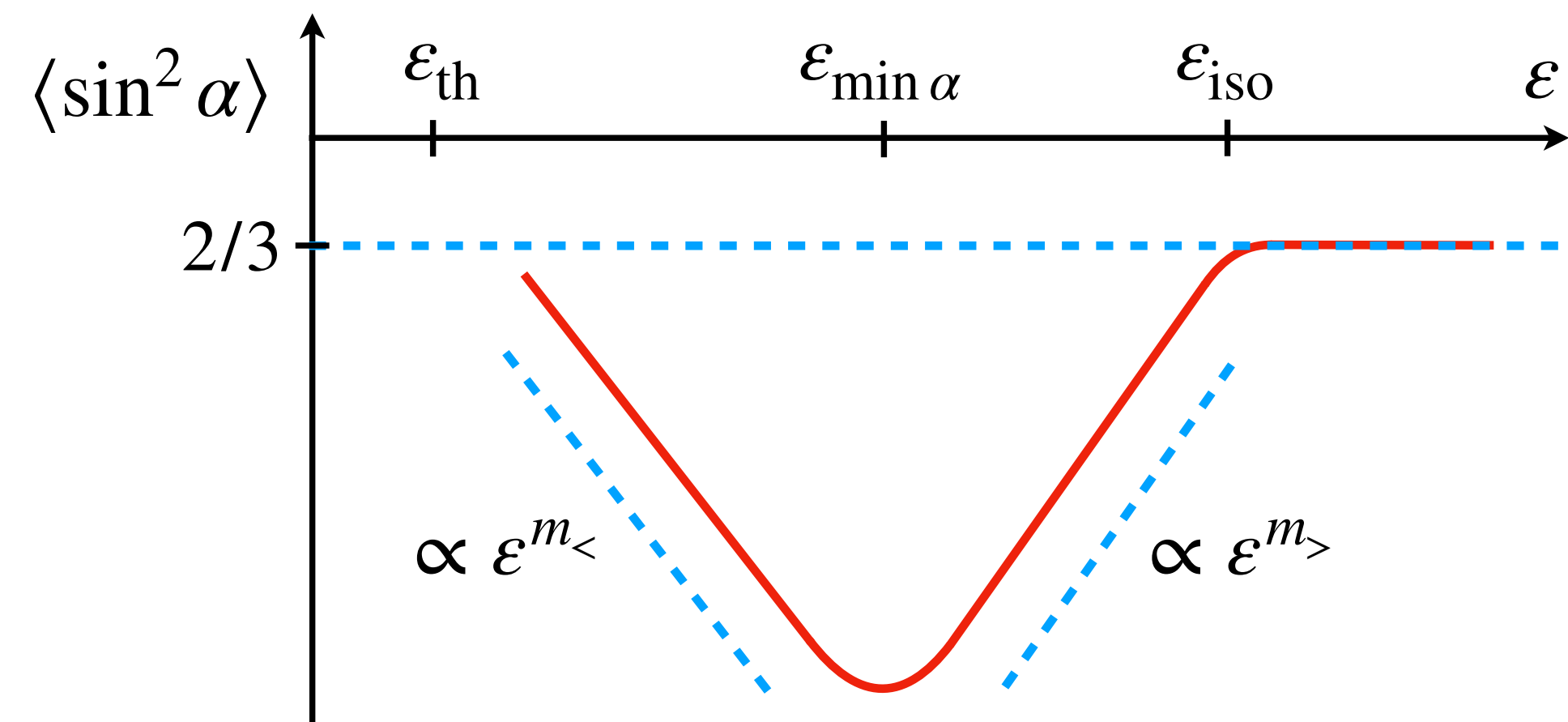
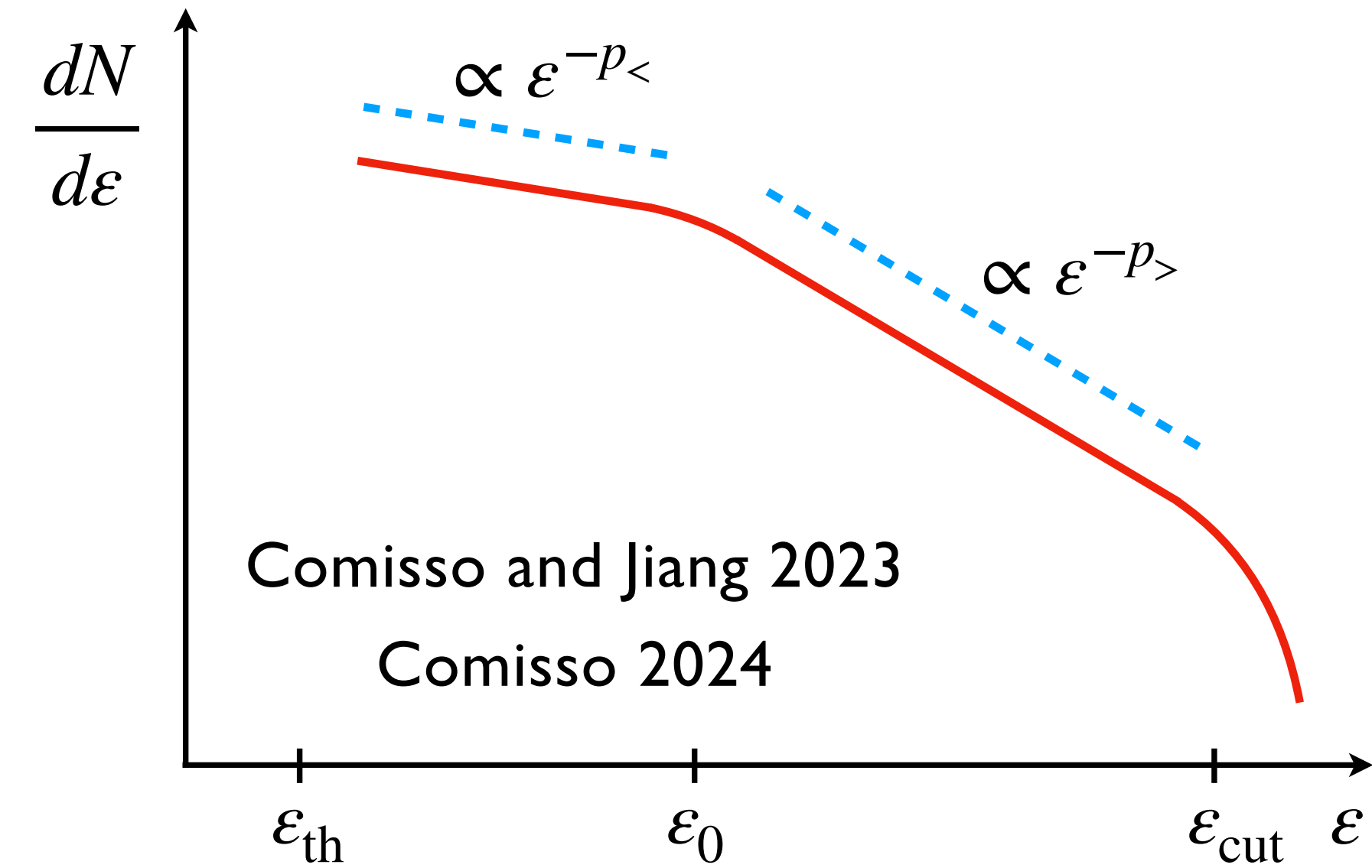
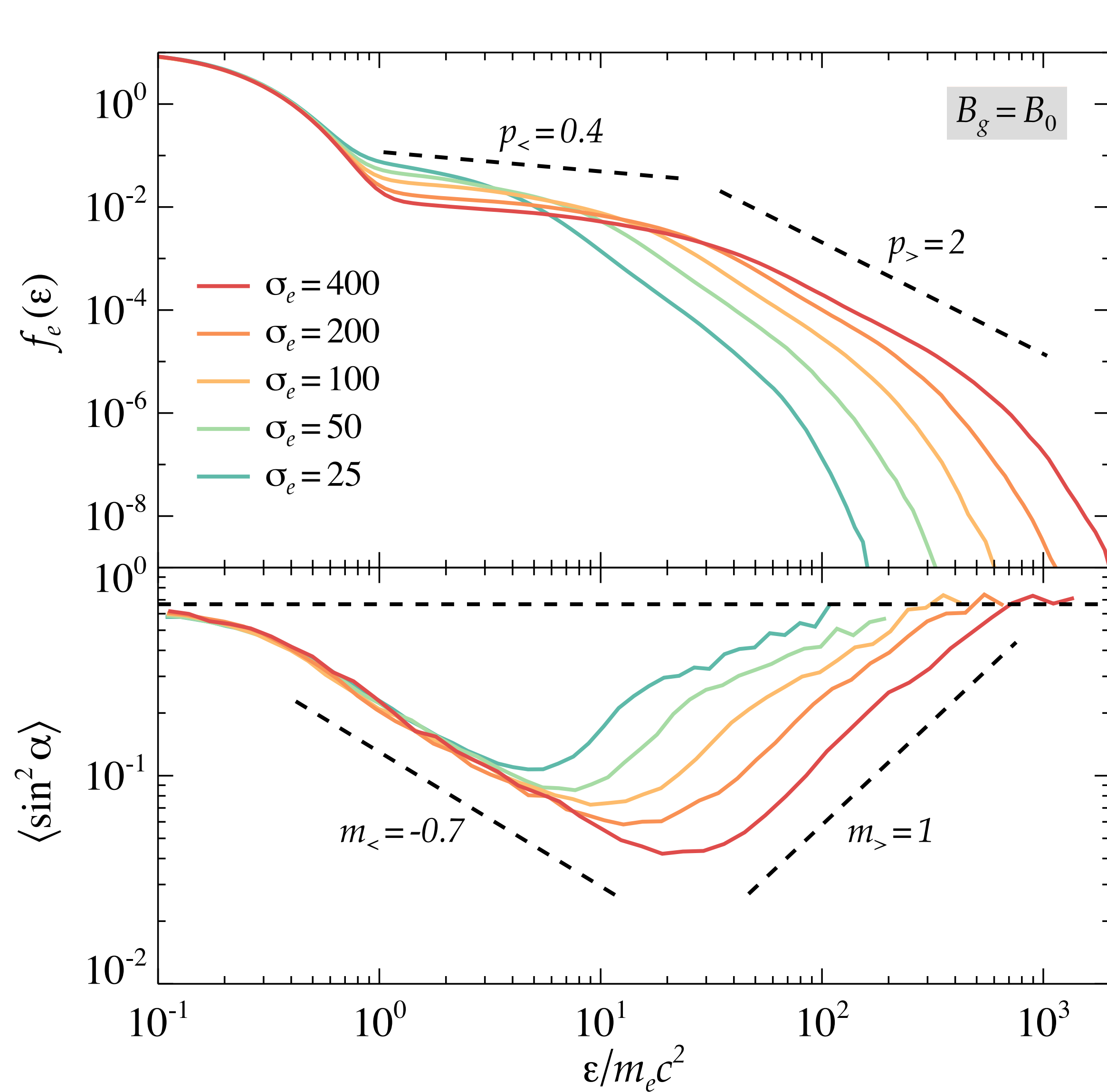
- The combined neutrino–gamma-ray constraints favor $R \sim 10 r_g$, $\sigma_{\text{tur}} \sim 1$, $l_c/R \sim 0.5$, $F_p \sim 0.5$

- ▶ **From kinetic to macroscopic scales**
PIC simulations are necessarily limited in scale. How do we connect first-principles kinetic results to the much larger scales accessible to MHD simulations?
- ▶ **From idealized simulations to realistic source geometries**
Source geometry can strongly affect particle acceleration and transport. How do we embed the physics learned from simulations into realistic astrophysical environments?
- ▶ **From first principles to observables**
How do we translate particle acceleration and plasma physics into robust predictions for spectra, composition, variability, and multimessenger signals?

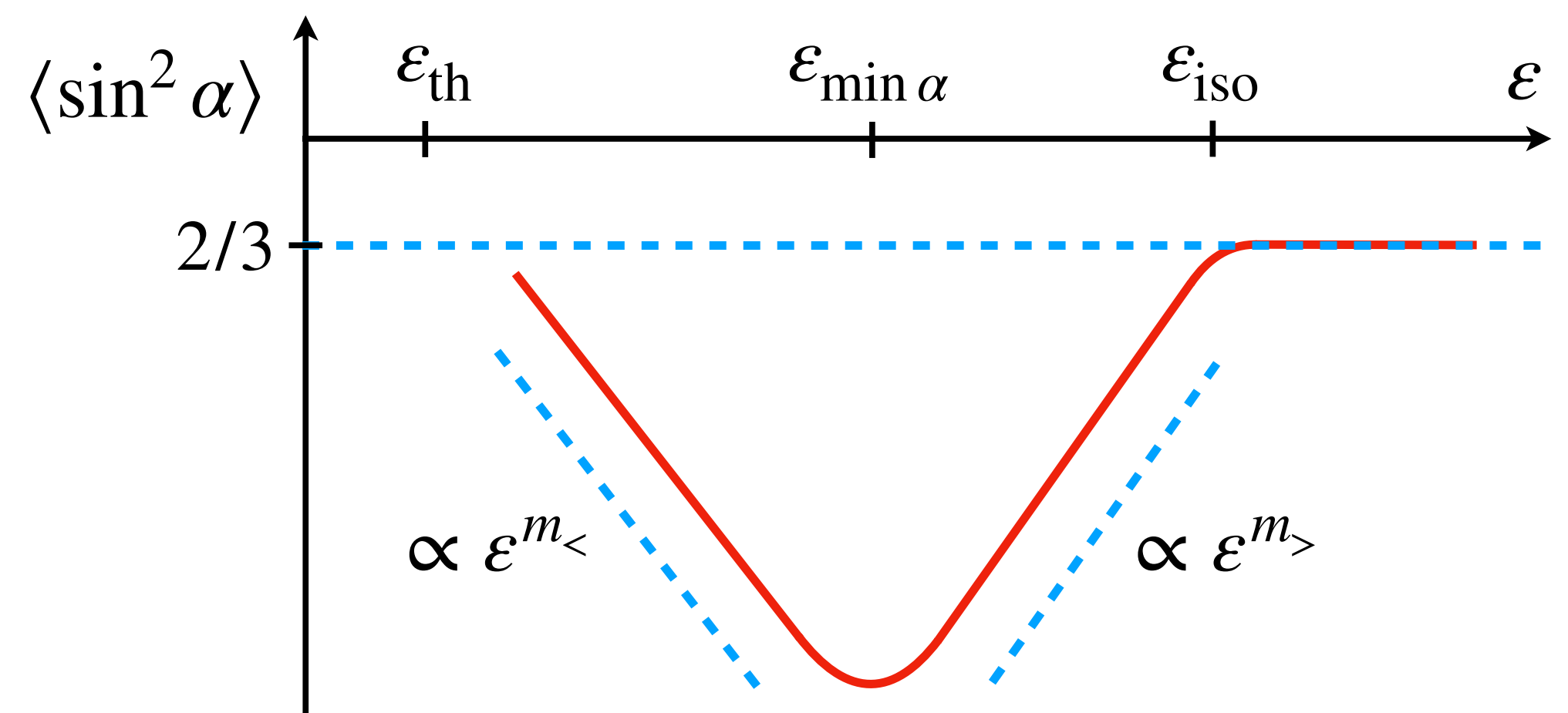
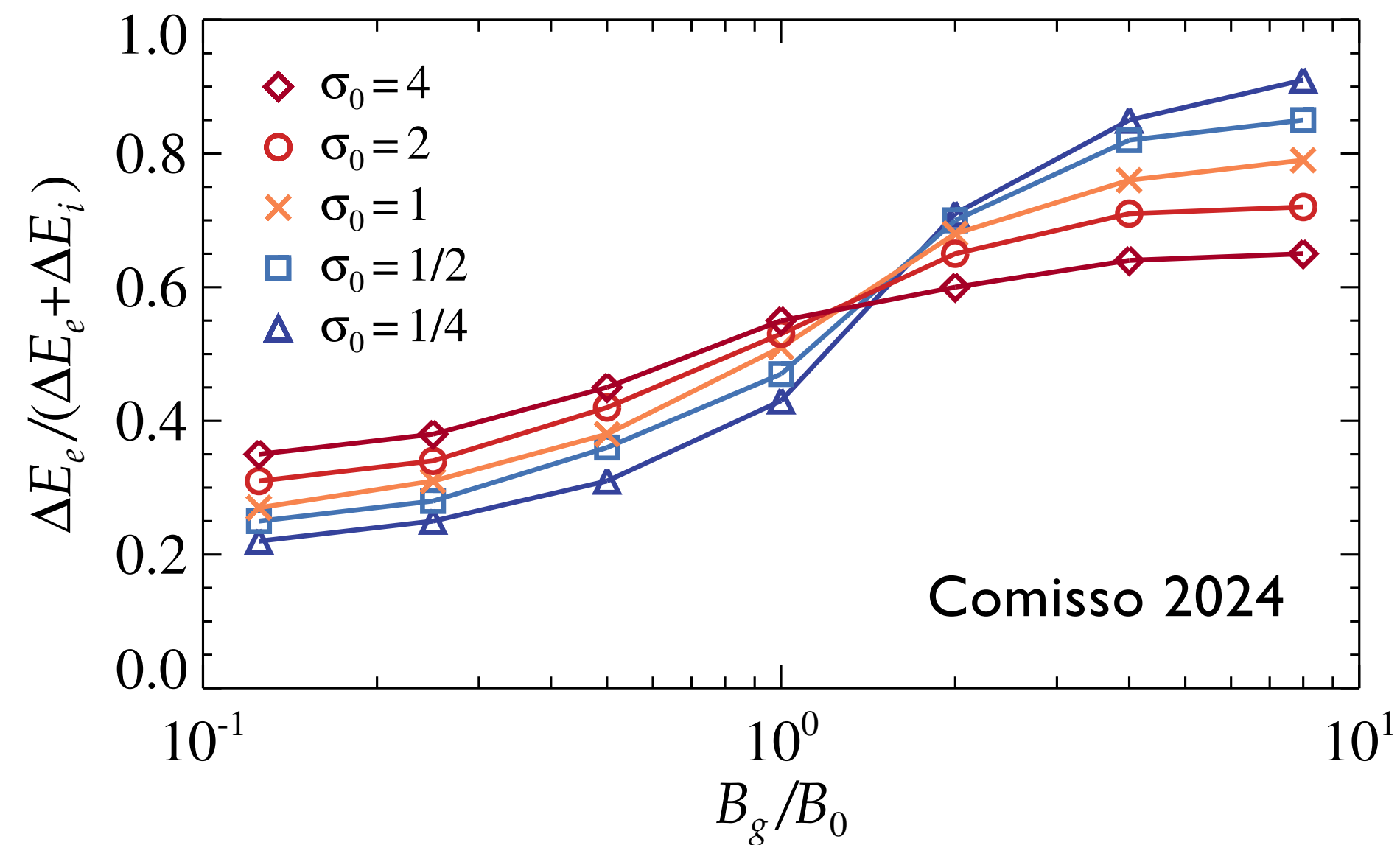
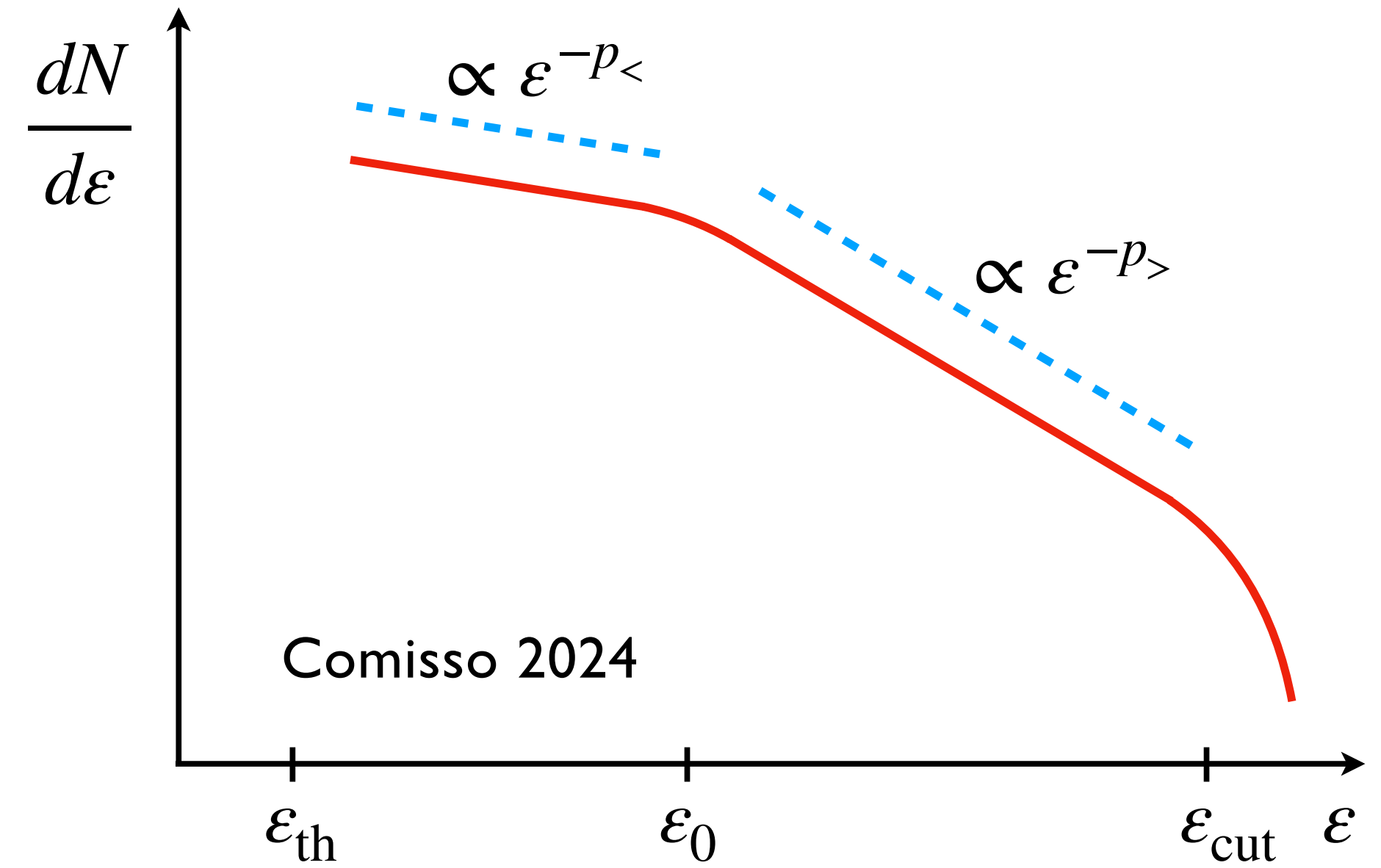
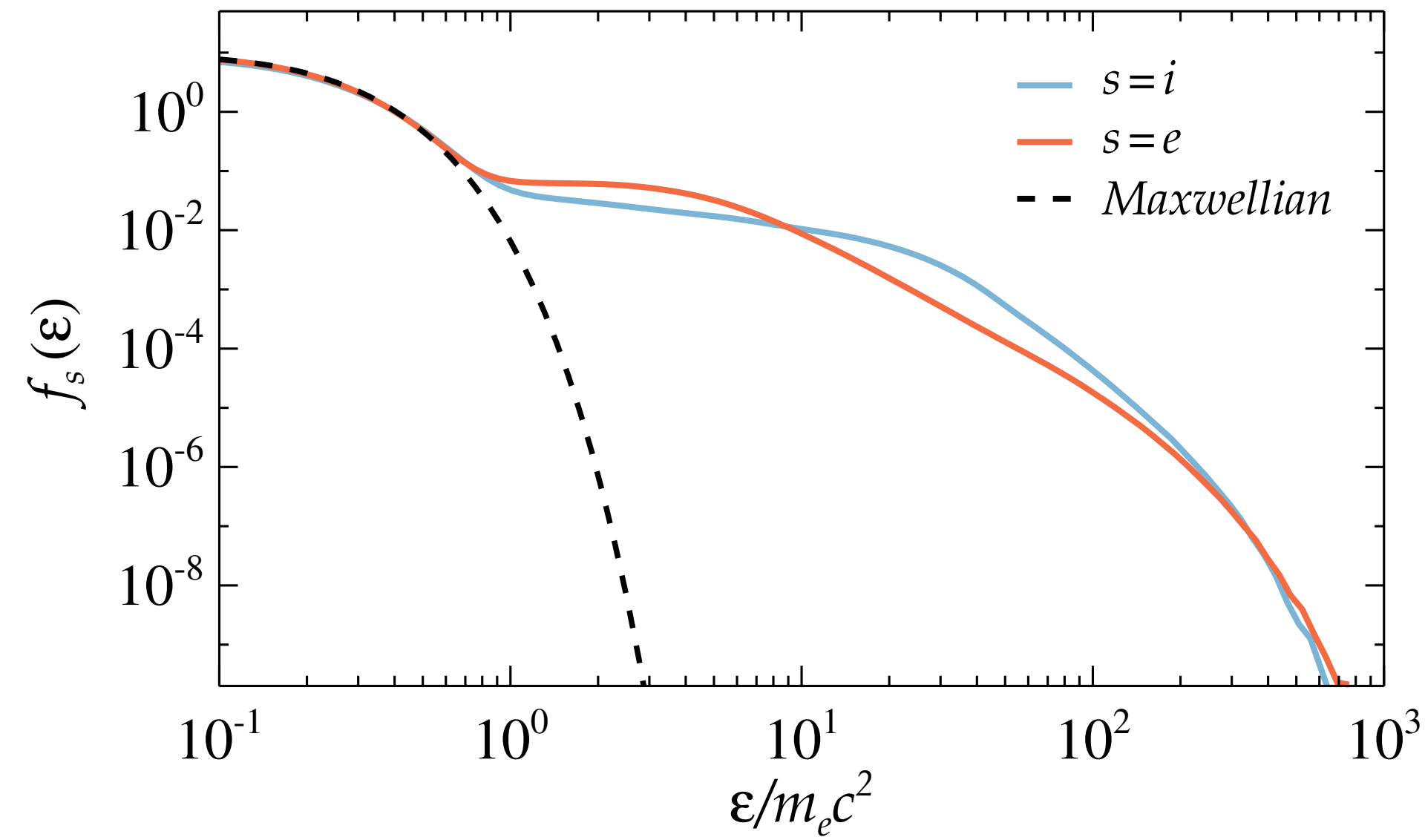
Appendix: guide-field dependence of magnetic reconnection



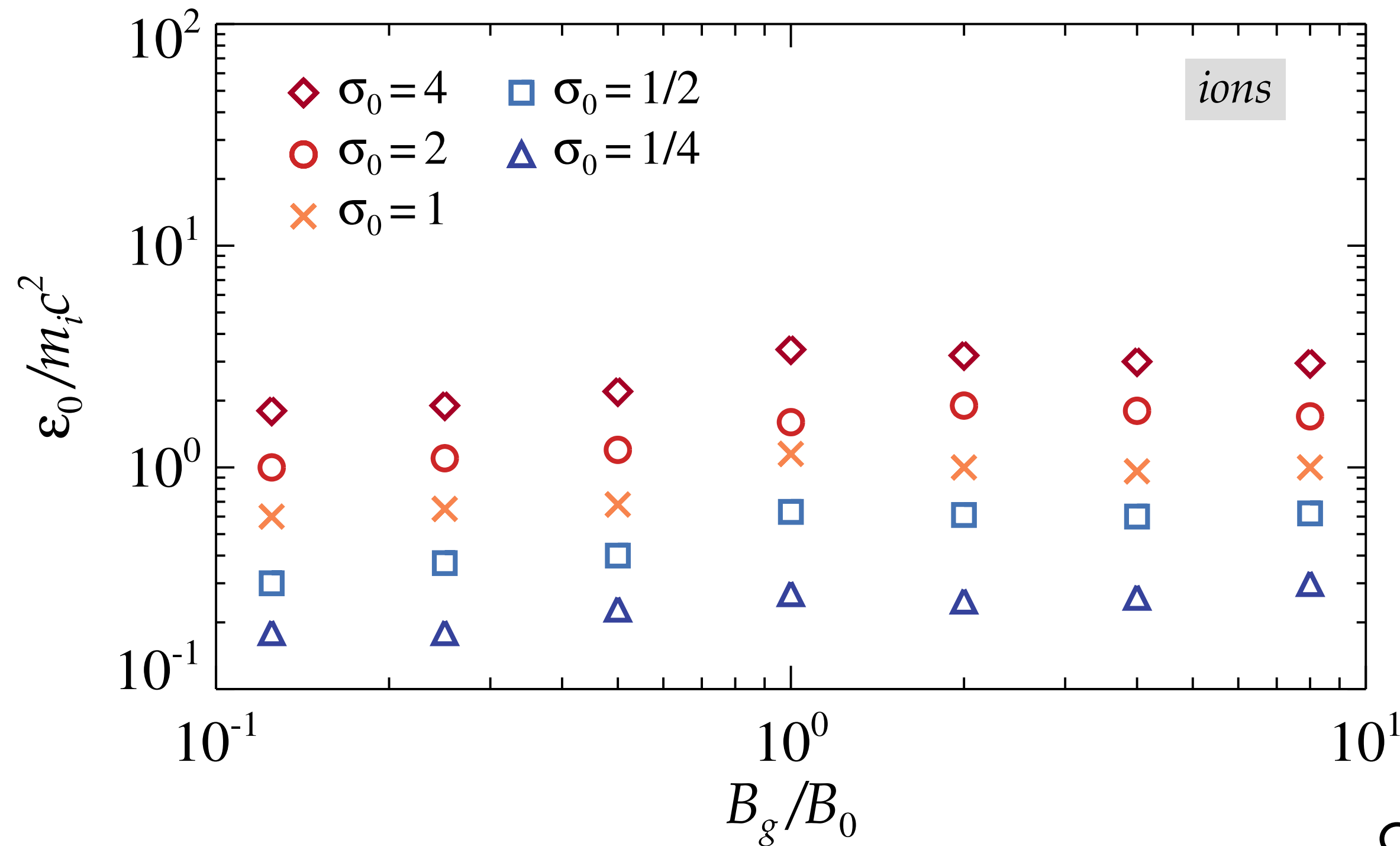
Appendix: particle acceleration in magnetic reconnection layers



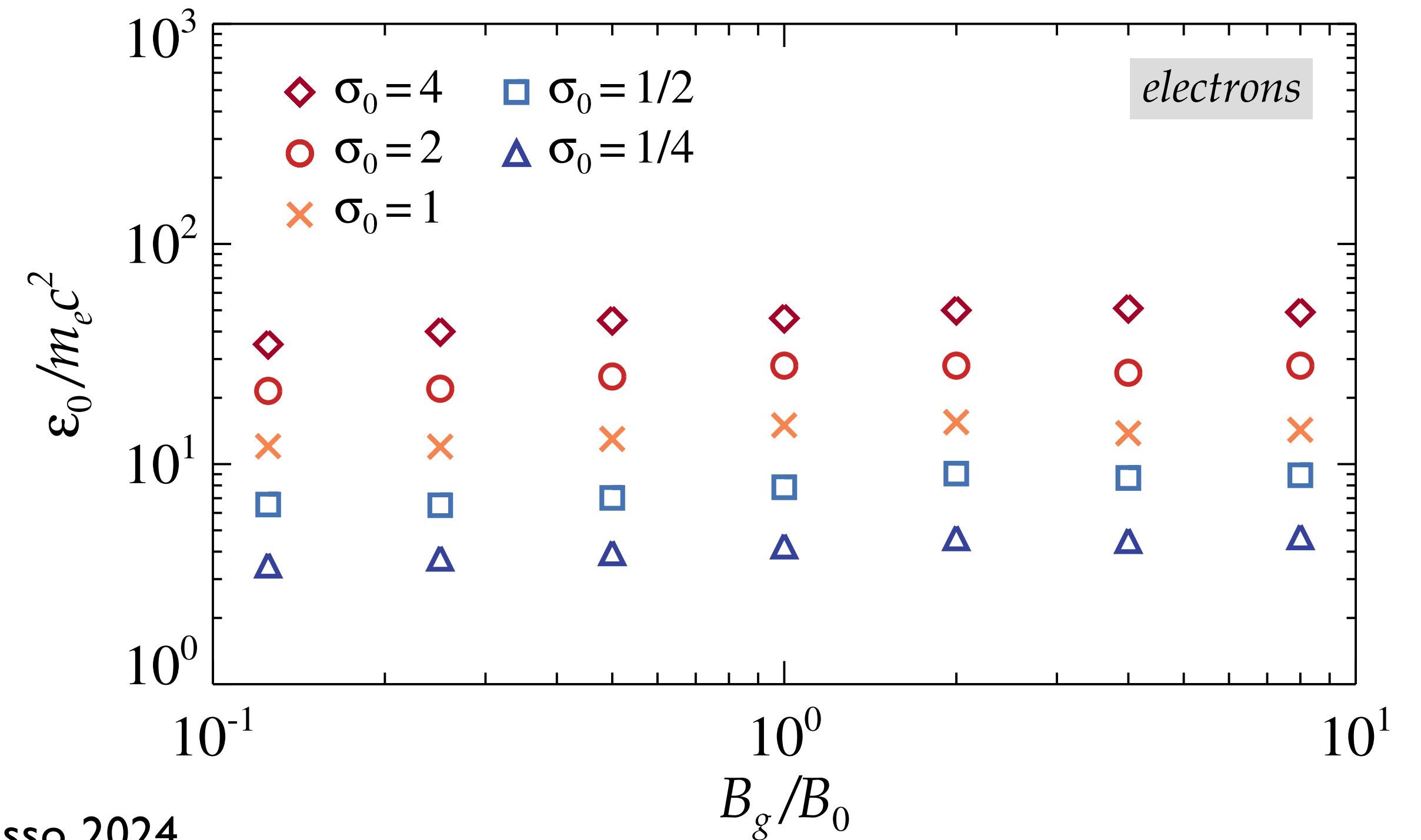
Appendix: particle acceleration in magnetic reconnection layers



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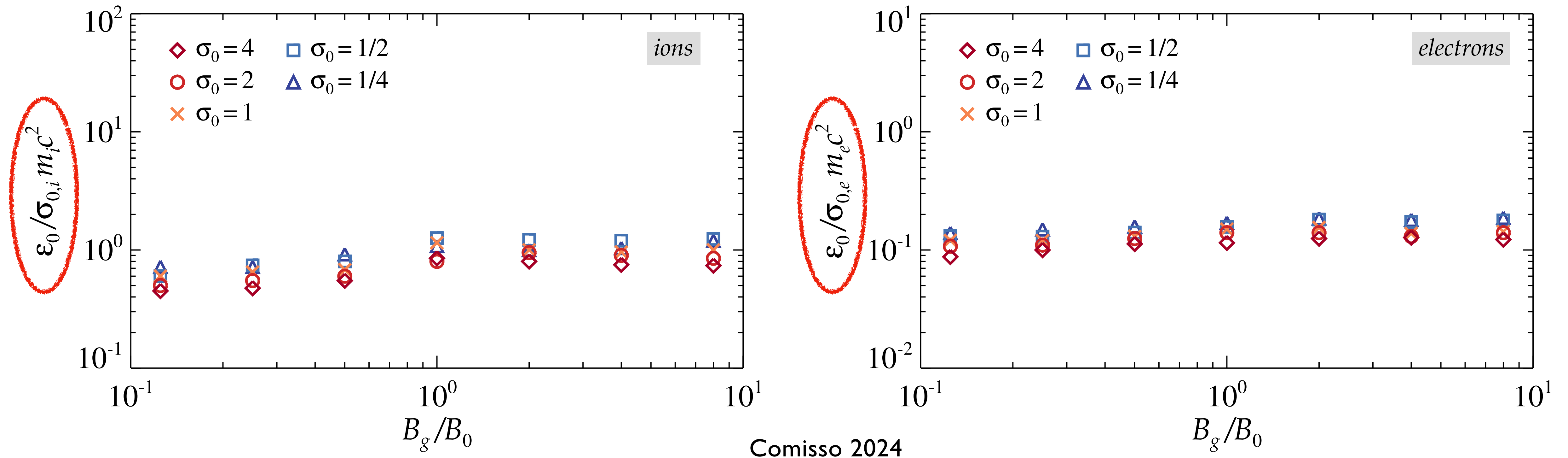


Comisso 2024



- Break energies for the particle energy spectrum (separating $p_<$ and $p_>$)
- Break energies scale with the magnetization of each particle species $\sigma_{0,s}$

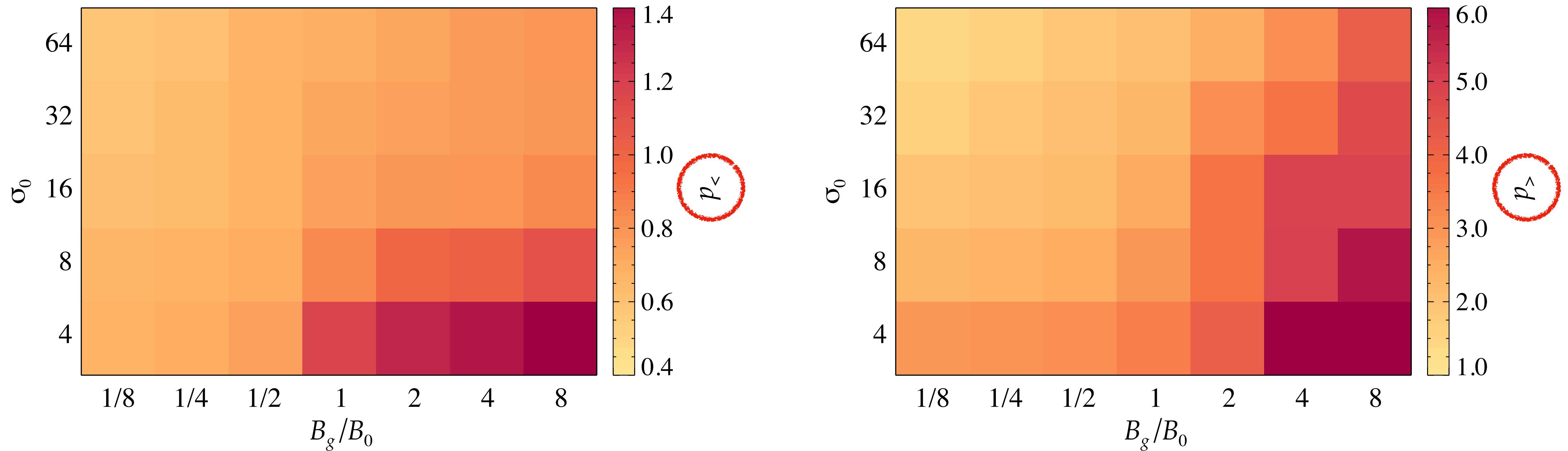
Appendix: particle acceleration in magnetic reconnection layers



- Break energies for the particle energy spectrum (separating $p_{<}$ and $p_{>}$)
- Break energies scale with the magnetization of each particle species $\sigma_{0,s}$

Appendix: particle acceleration in magnetic reconnection layers

Comisso and Jiang 2023; Comisso 2024



- ▶ Below the injection break energy, $p_< \lesssim 1$ for any B_g/B_0 and $\sigma_0 \gtrsim 1$
- ▶ Above the injection break energy, $p_> \gtrsim 2$, displaying high sensitivity to both B_g/B_0 and σ_0
- ▶ For $B_g/B_0 \ll 1$ and $\sigma_0 \gg 1$, $p_< \lesssim 1$ and $p_> \sim 2$