

Particle Acceleration in Highly Magnetized Turbulent Plasmas

Luca Comisso

Columbia University

in collaboration with: L Sironi, E Sobacchi, B Jiang, G Farrar, M Muzio, D Fiorillo, E Peretti, M Petropoulou, M Lemoine, V Bresci, D Groselj

Astrophysics Seminar

Institute for Advanced Study

February 13, 2025

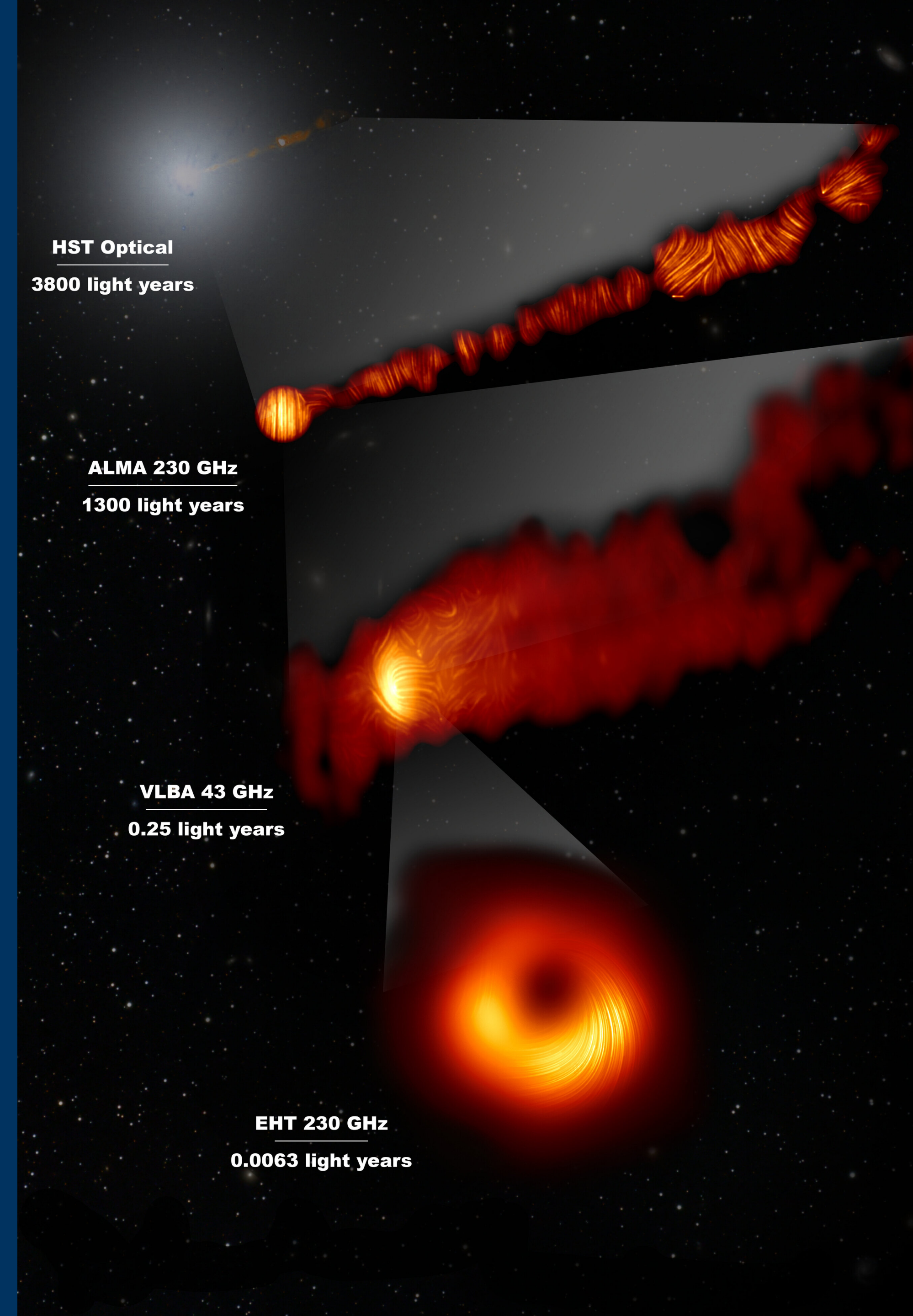


HST Optical
3800 light years

ALMA 230 GHz
1300 light years

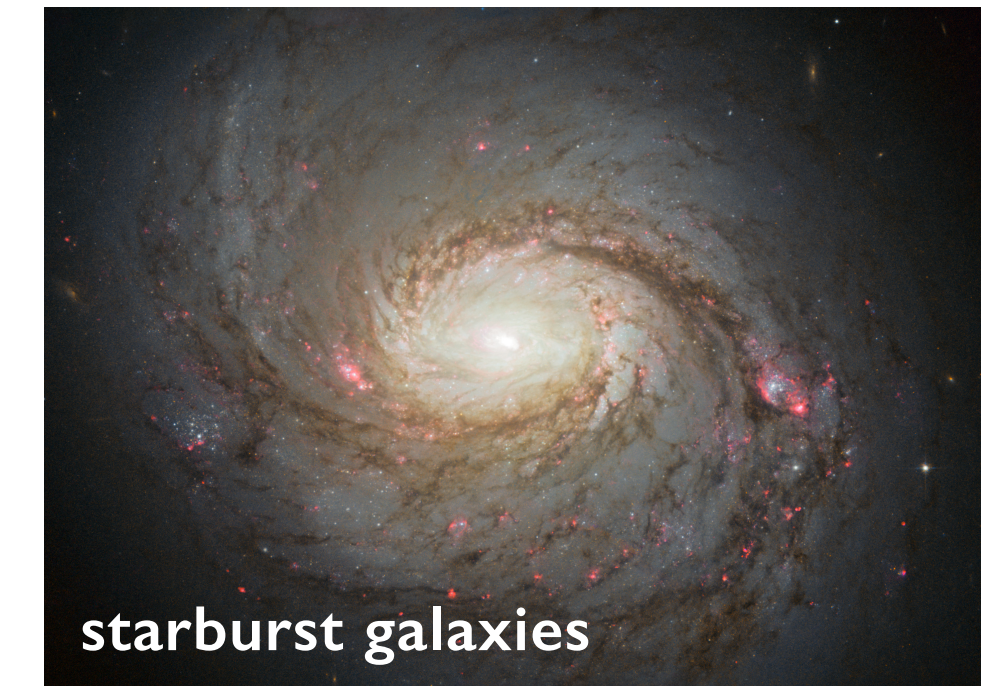
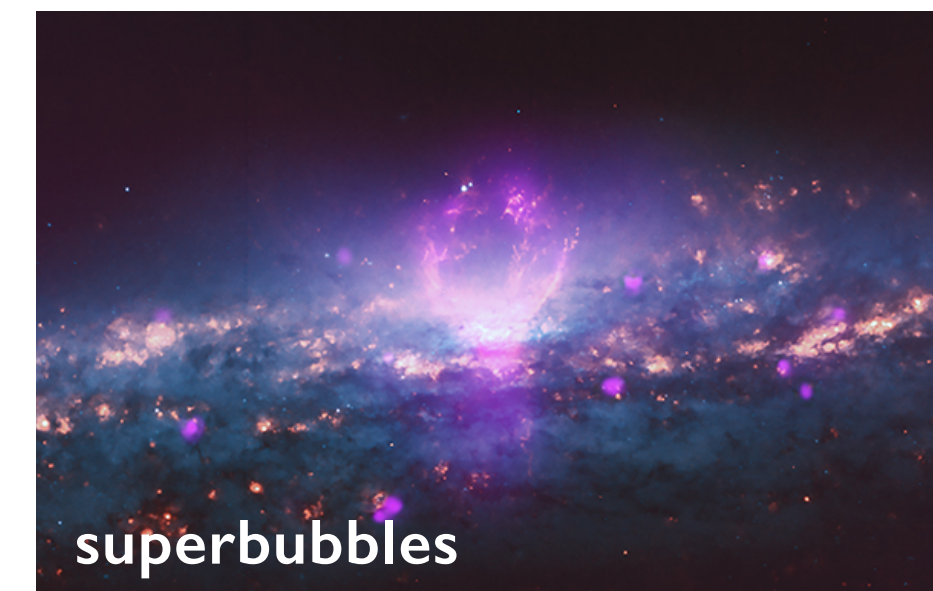
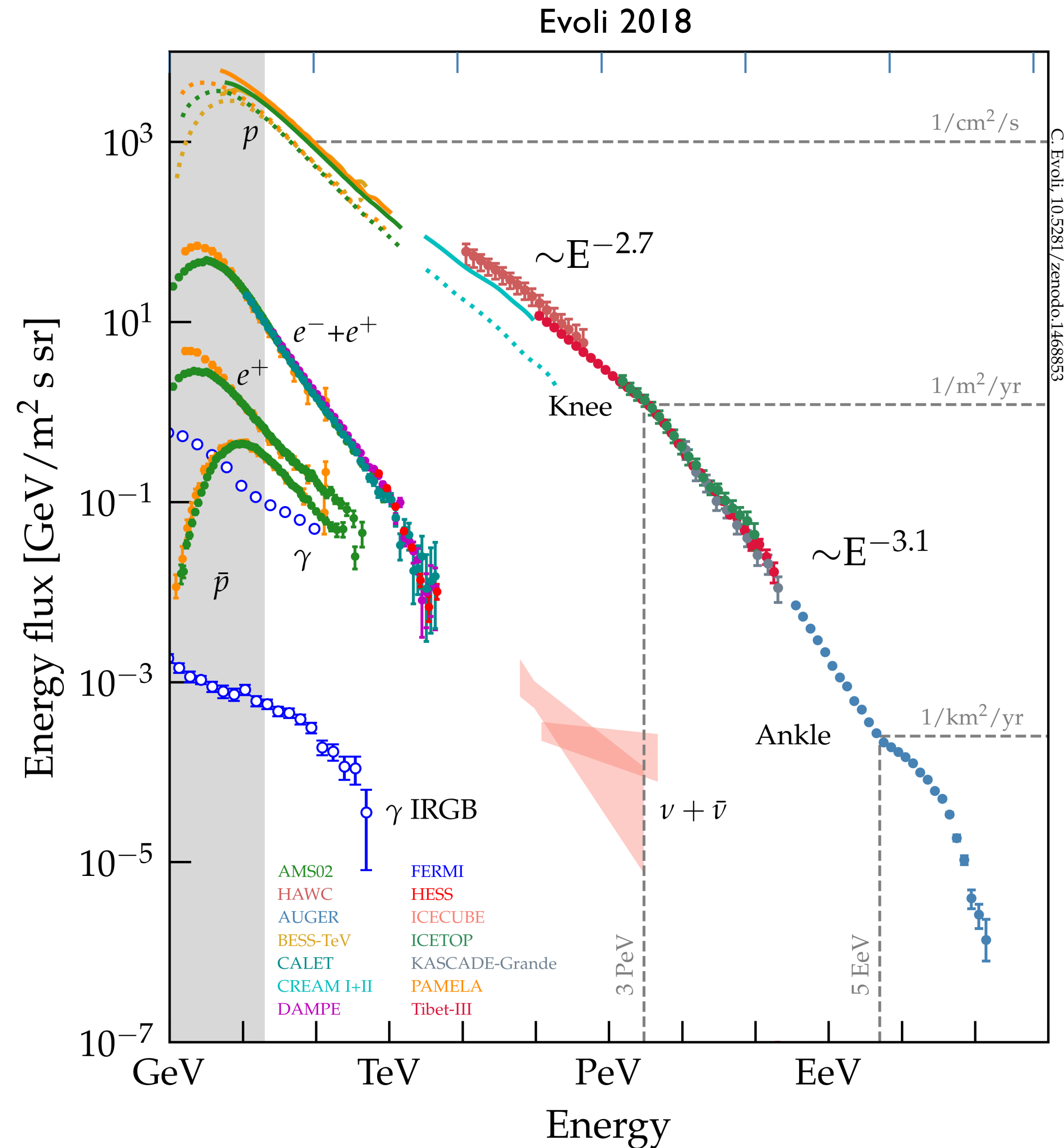
VLBA 43 GHz
0.25 light years

EHT 230 GHz
0.0063 light years

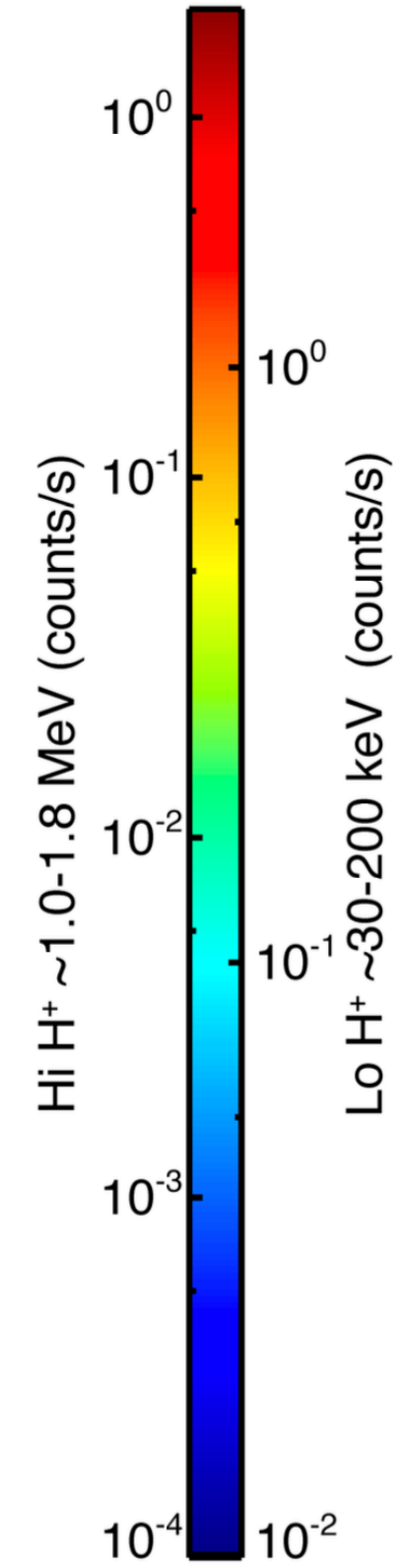
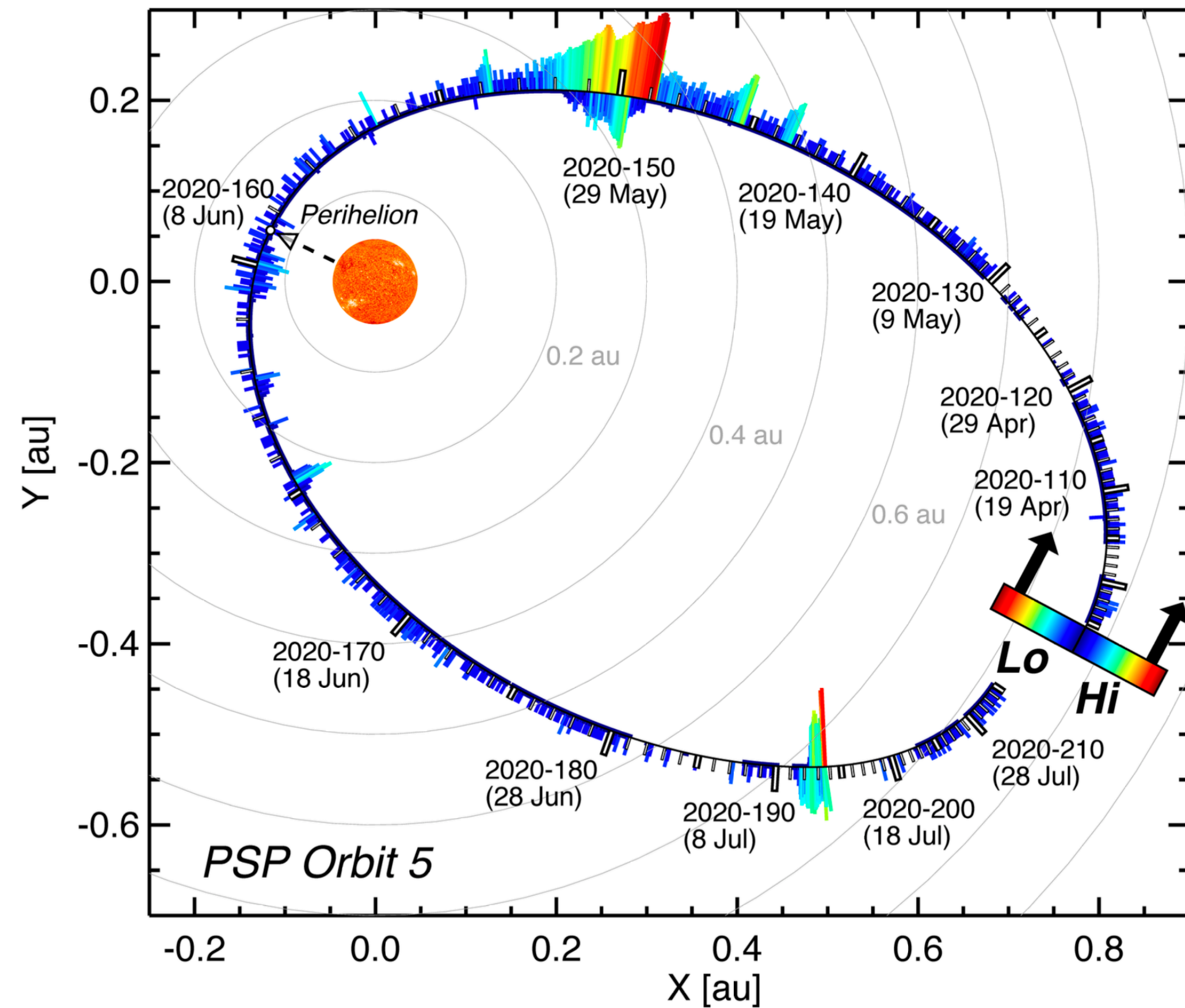


- The Non-Thermal Universe: Outstanding Cases
- Turbulence in Magnetized Plasmas
- Mechanisms of Particle Acceleration
- Generated Particle Energy Spectra
 - UHECR Acceleration via Relativistic Turbulence
- Emergent Pitch Angle Anisotropy
 - Implications for Emitted Radiation (PWNe, GRBs, etc.)
- A Few Key Takeaways

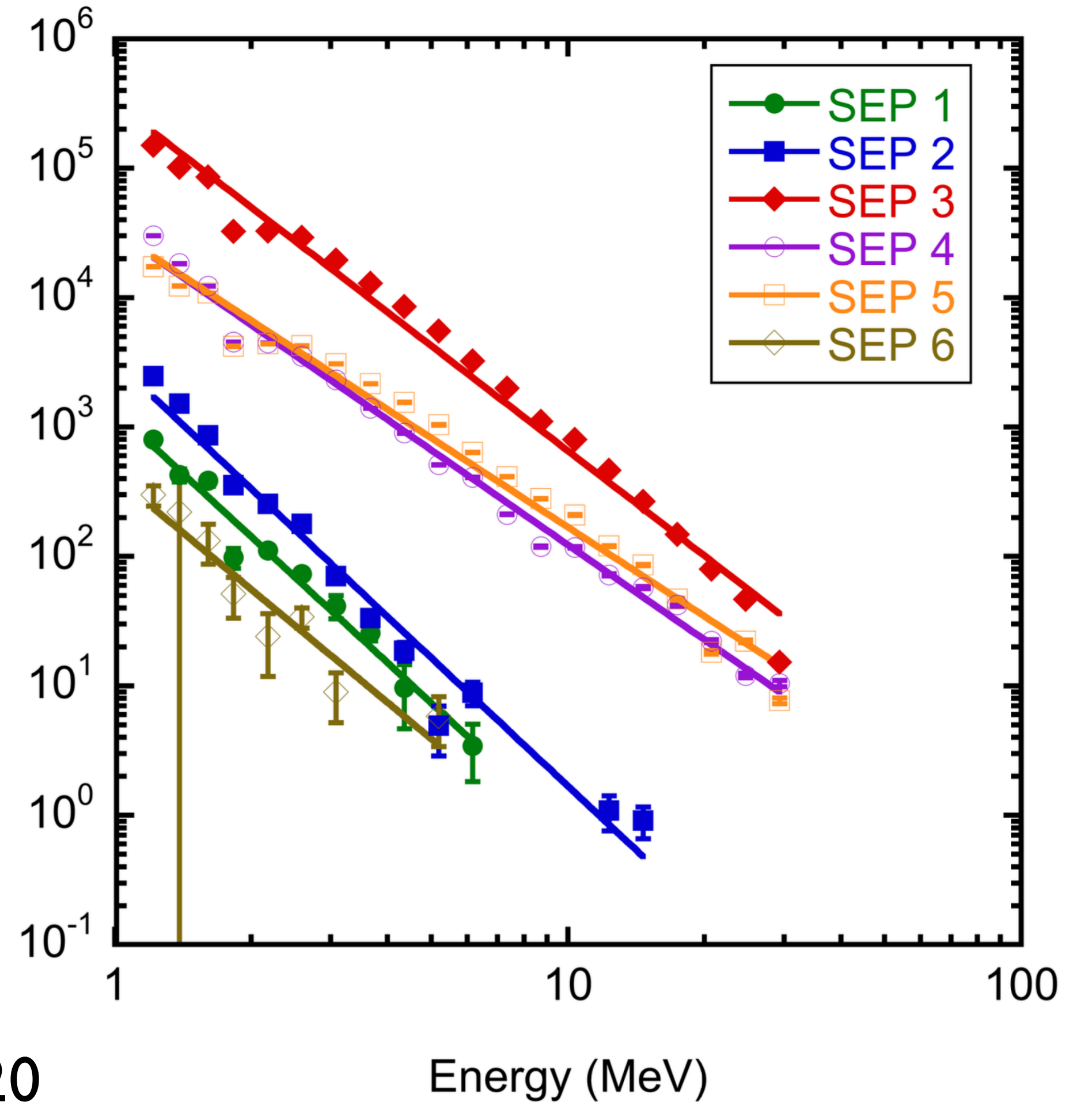
Energy Spectrum of Cosmic Rays



Direct Evidence: Solar Energetic Particles



Proton Fluence (cm² sr MeV)⁻¹

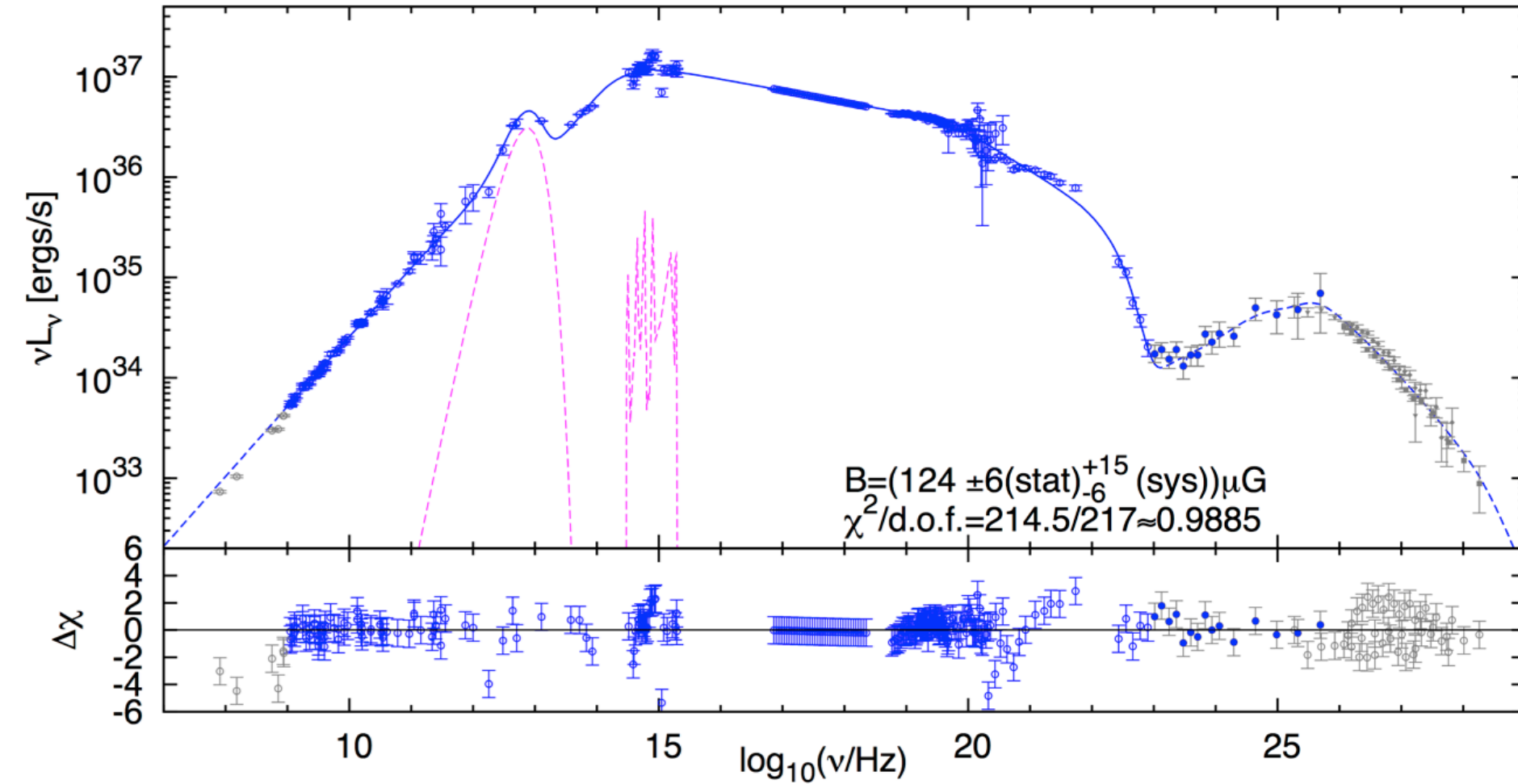


Cohen et al. 2020

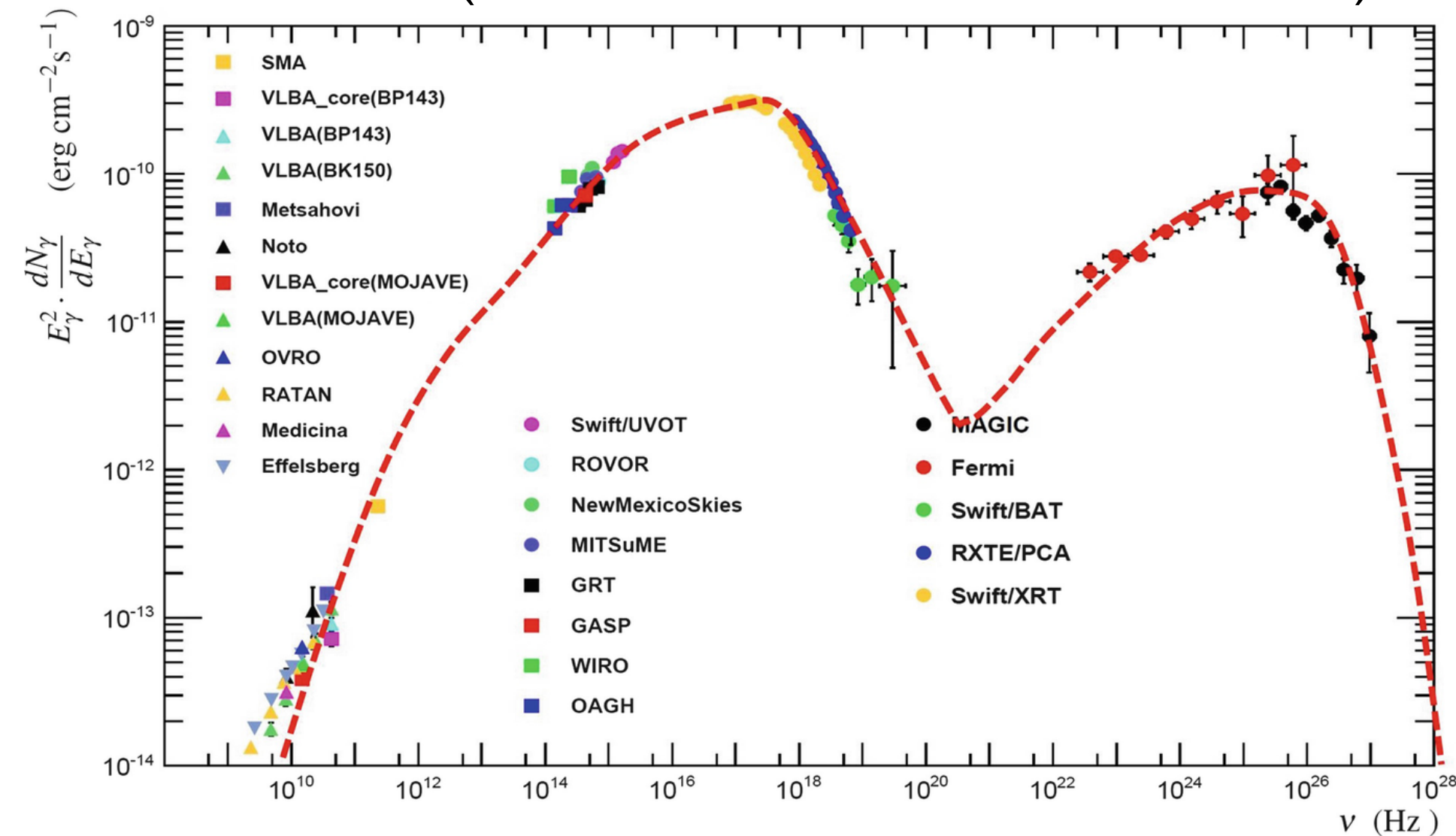
Direct measurements of non-thermal particles with power-law energy distributions

Indirect Evidence: Sources of Non-Thermal Radiation

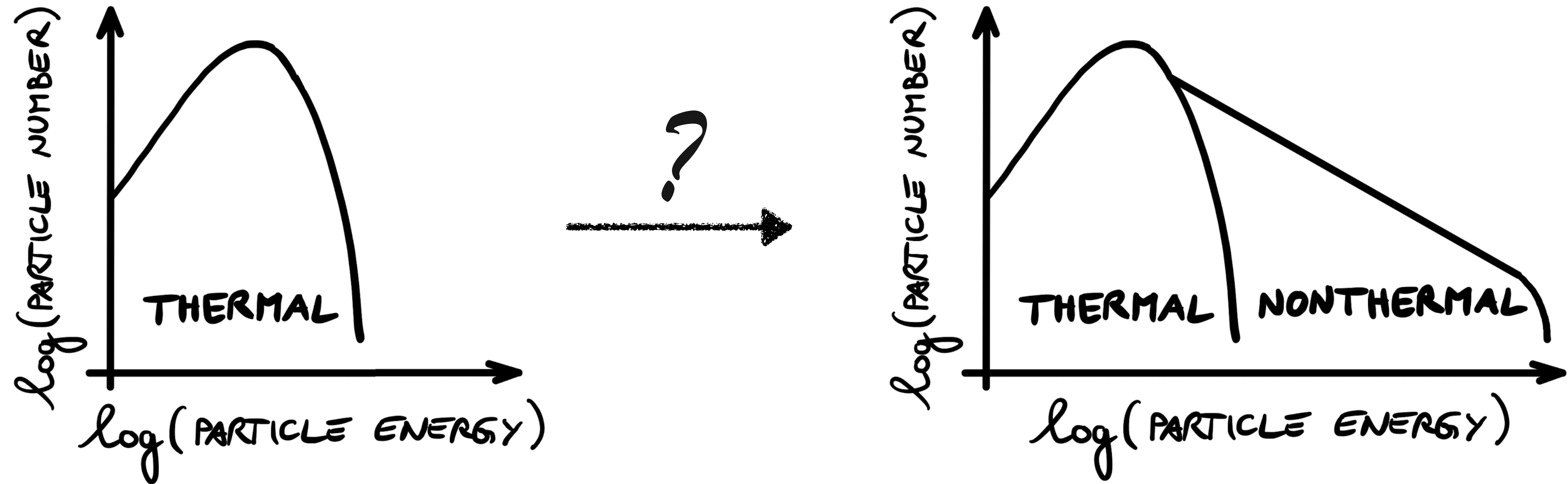
Pulsar Wind Nebulae (Crab; Meyer et al. 2010)



Blazars (Markarian 421; Abdo et al. 2011)



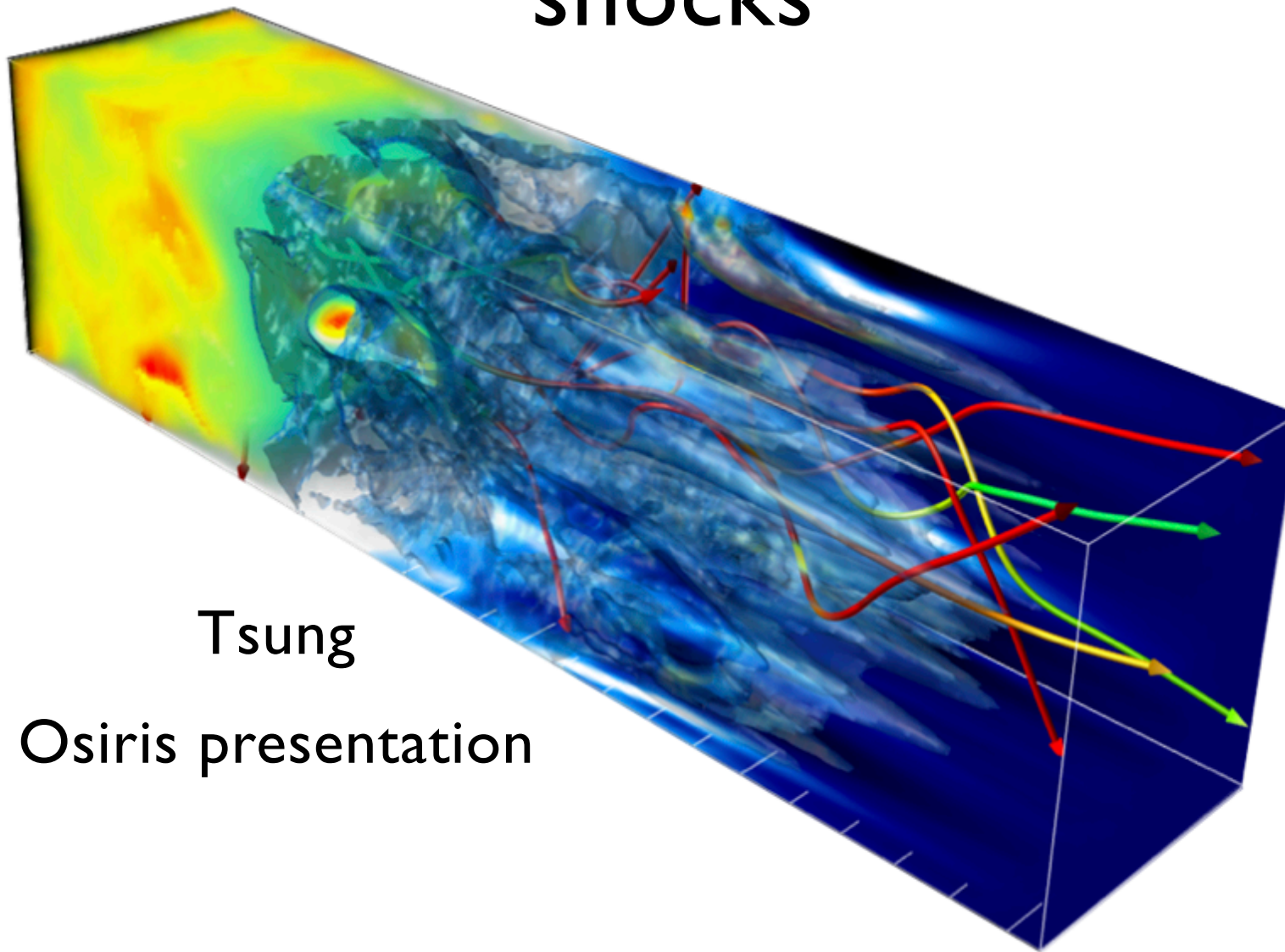
What Physical Processes Drive the Acceleration of Particles?



- The Maxwell distribution is the most probable distribution for a system in thermal equilibrium
 - What processes produce a non-thermal distribution of particles?

What Physical Processes Drive the Acceleration of Particles?

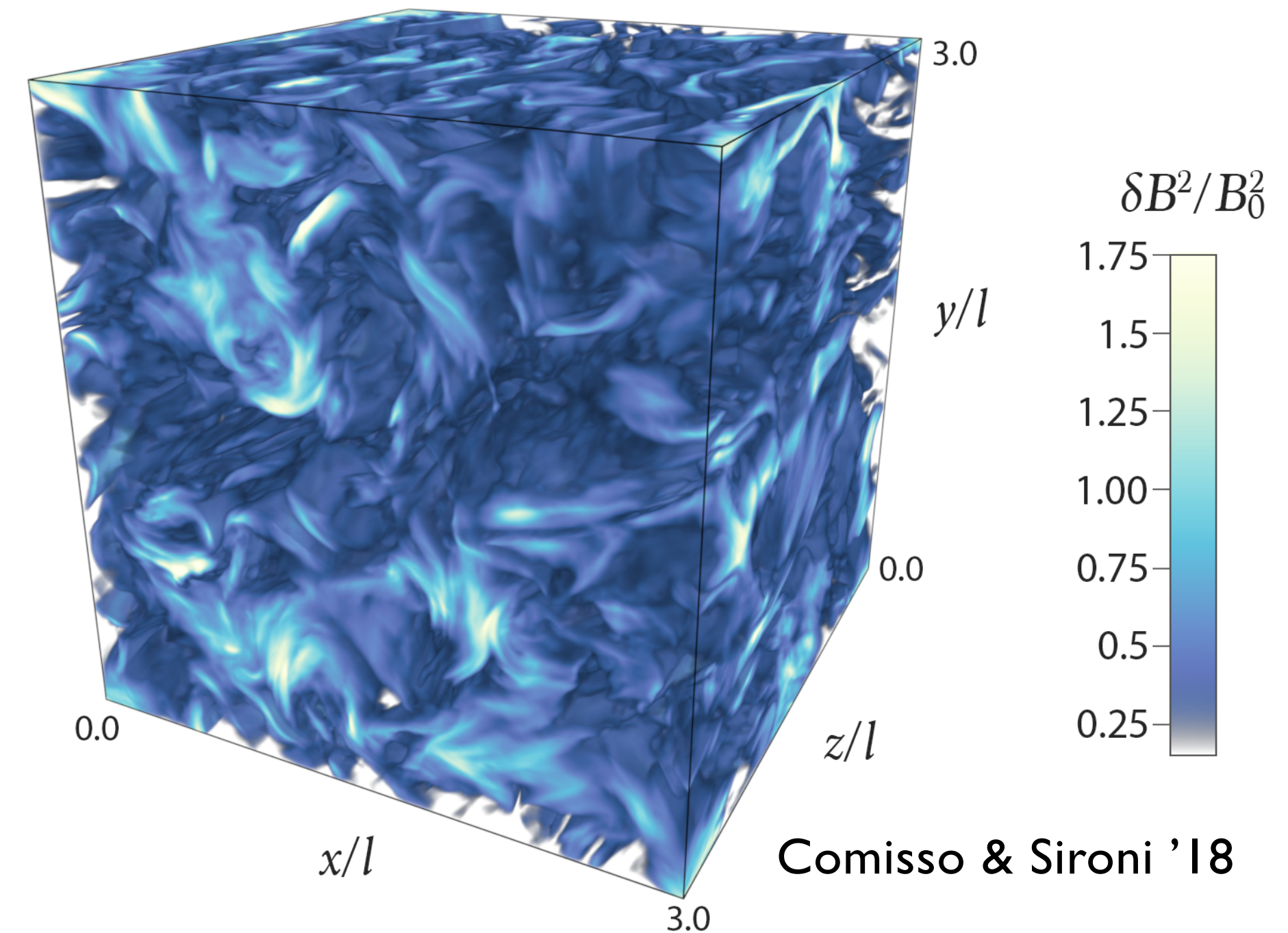
shocks



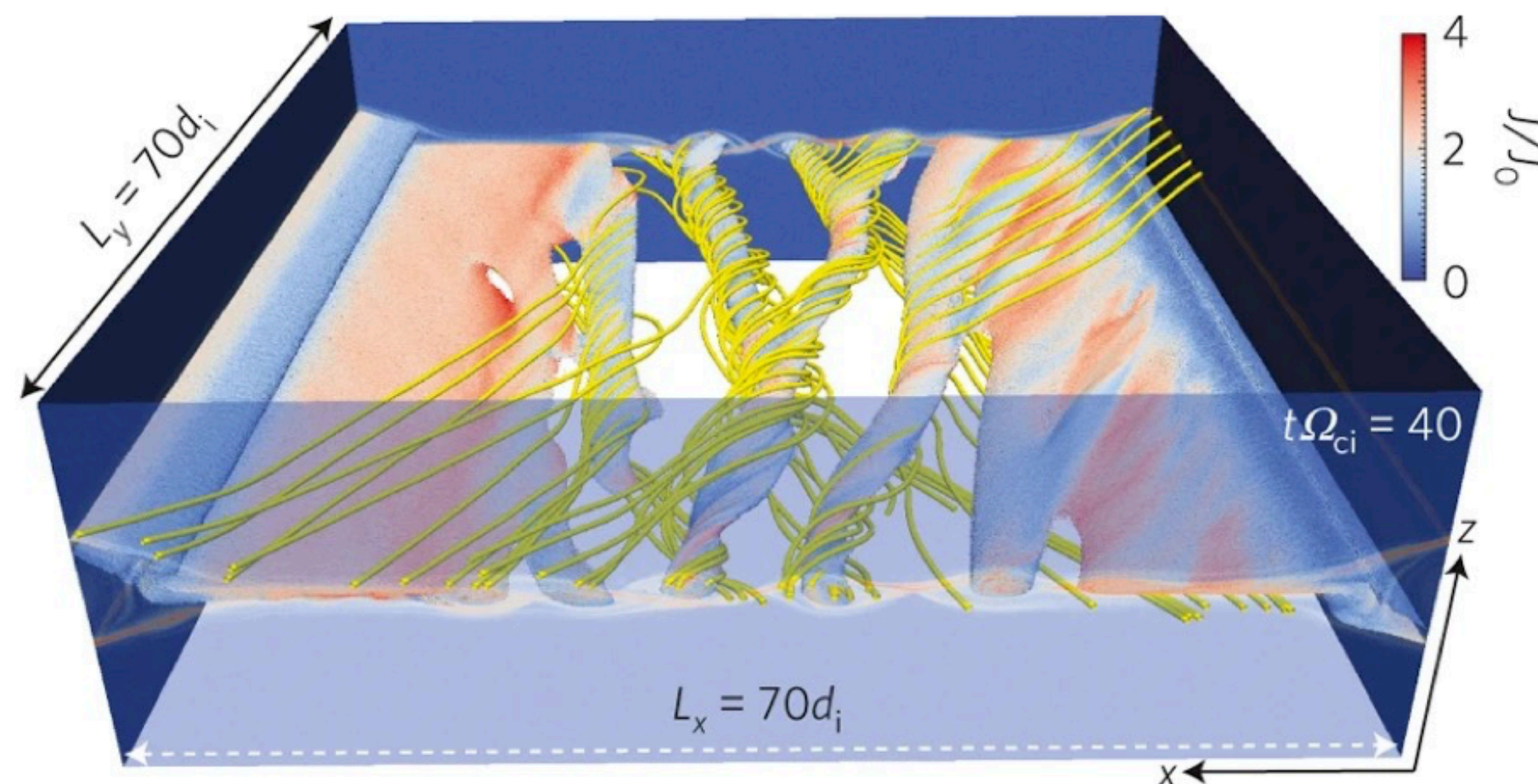
Tsung

Osiris presentation

magnetized turbulence



magnetic reconnection

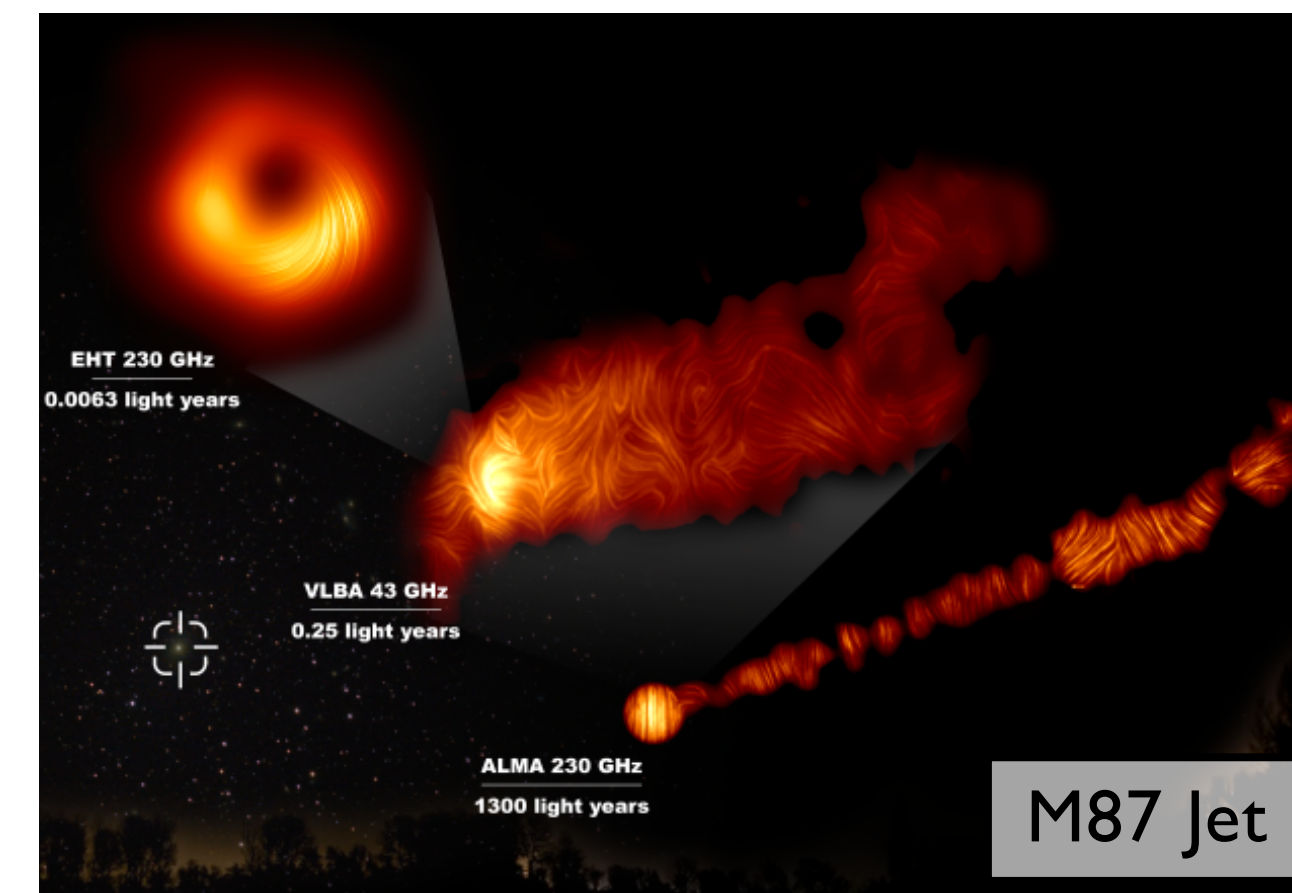
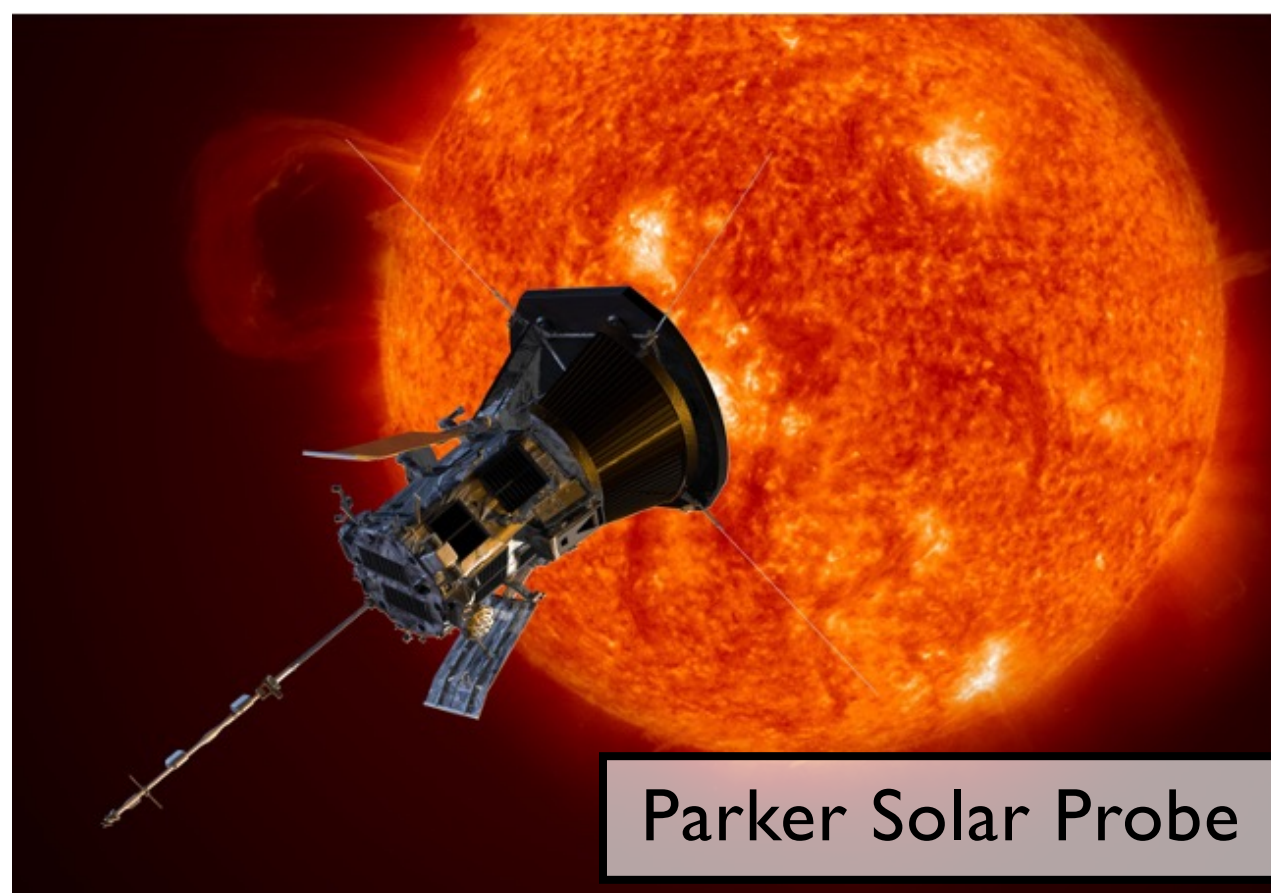
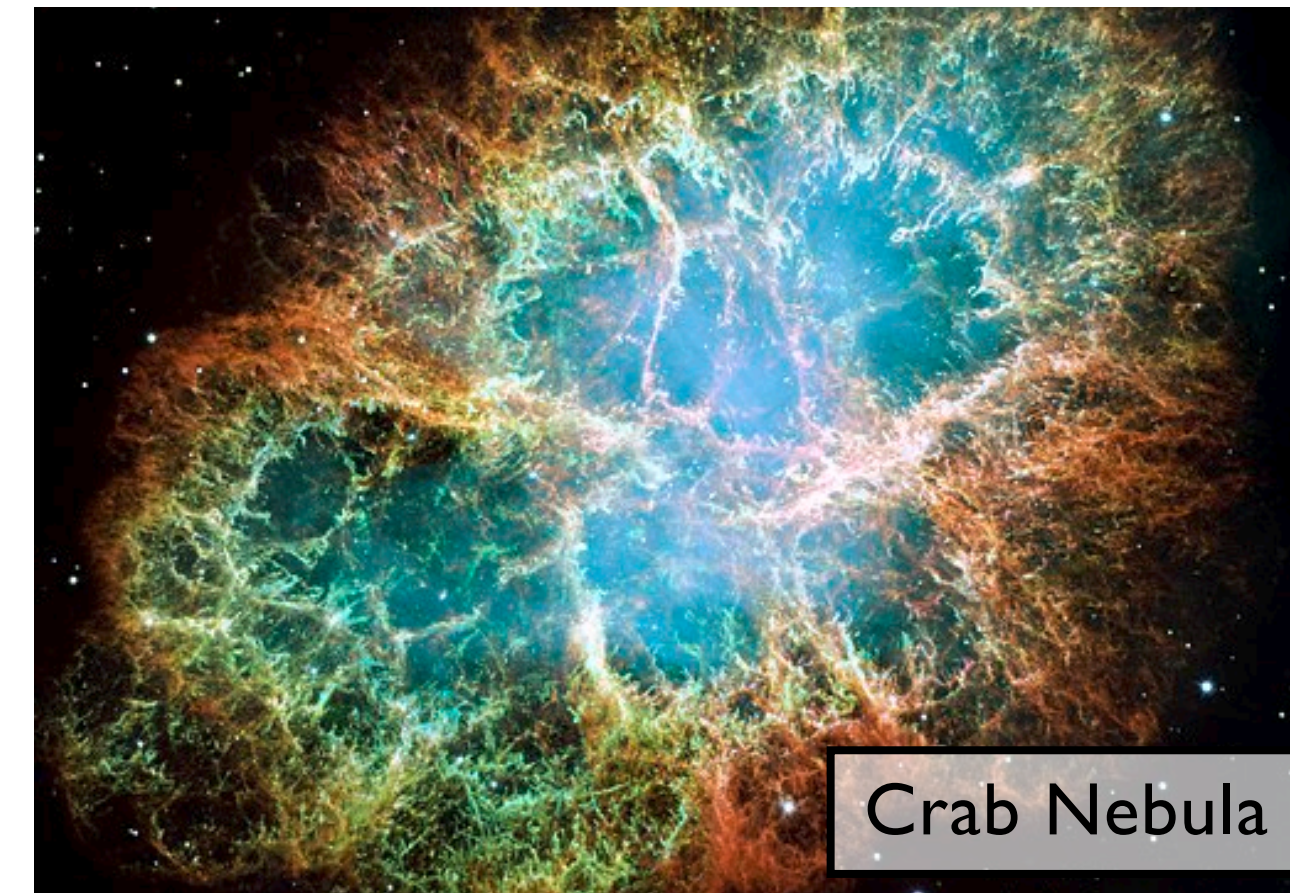
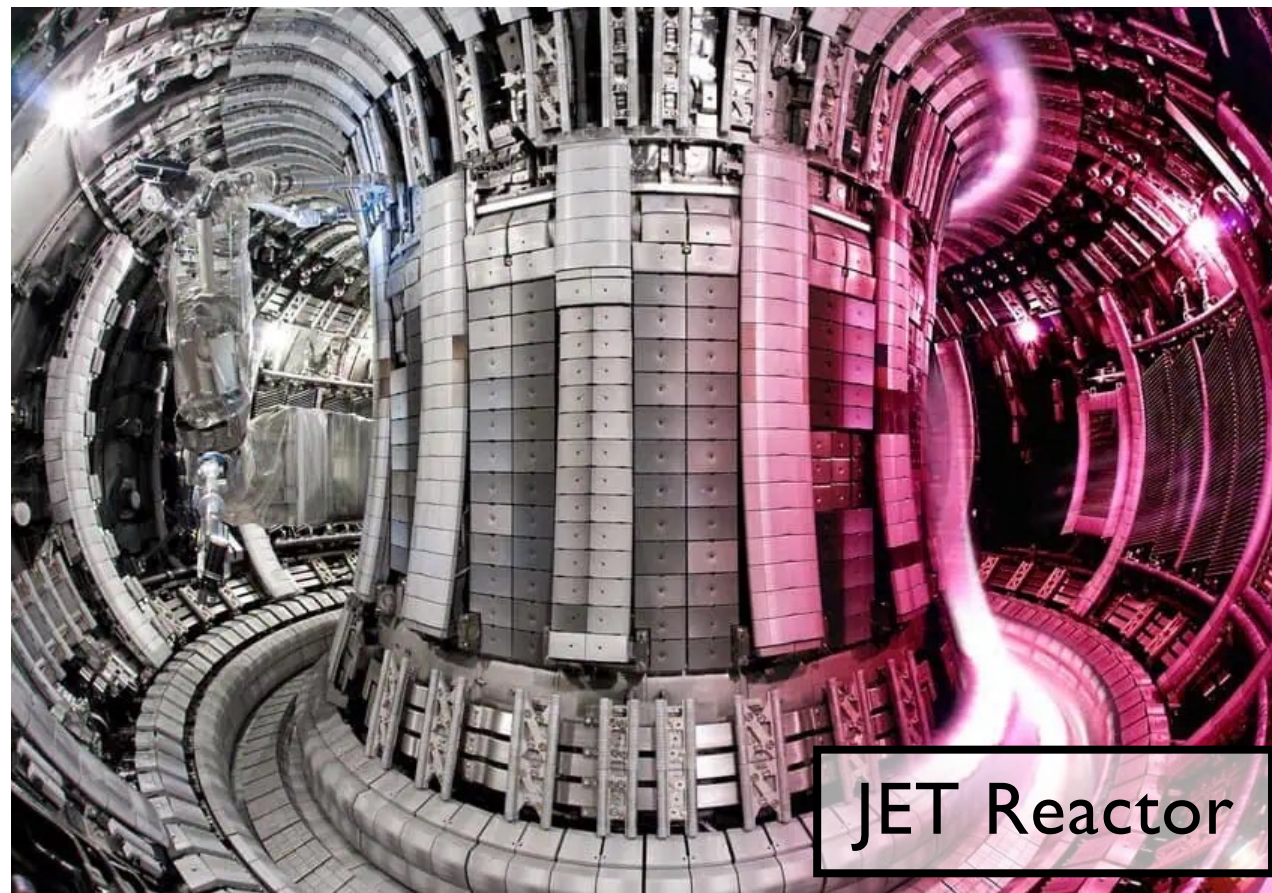


Daughton et al. '14

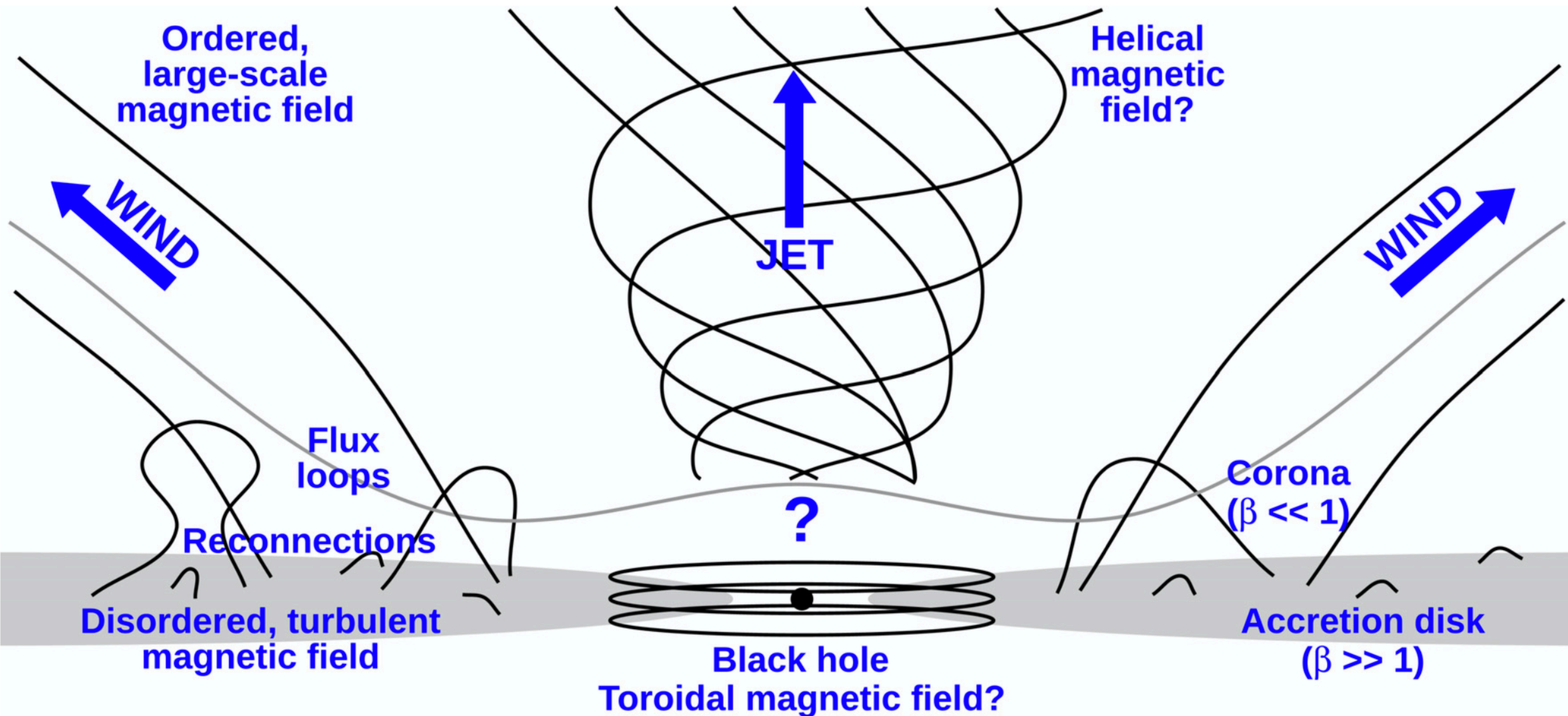
- sheared velocity flows
- magnetospheric gaps
- magnetized rotators
- and others...

Magnetized Environments (Nonrelativistic vs. Relativistic Regimes: $\frac{v_A}{c} = \sqrt{\frac{\sigma}{1+\sigma}}$)

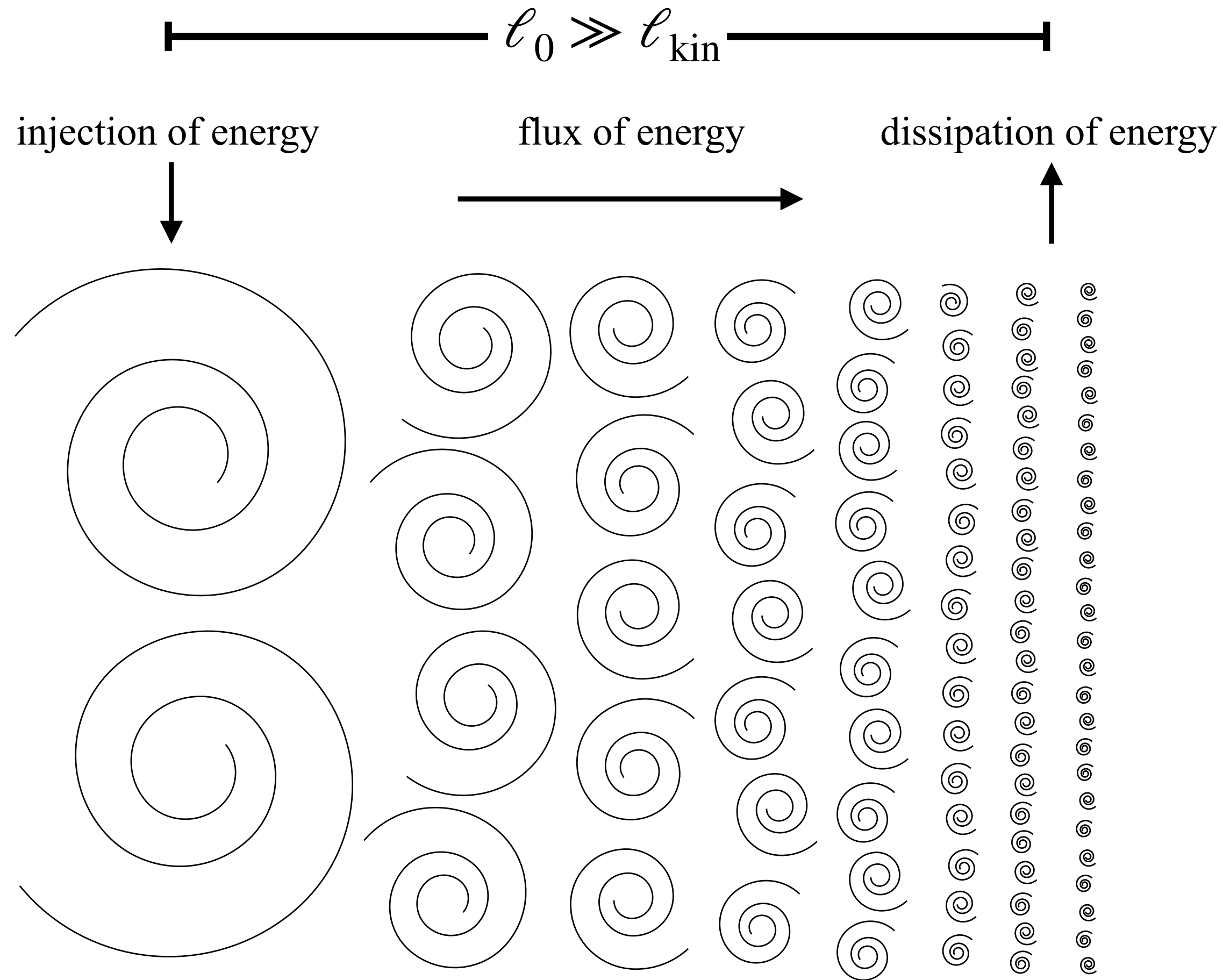
$$\sigma \ll 1 \quad \sigma = \frac{B^2}{4\pi\rho c^2} \simeq \frac{4}{\beta} \frac{k_B T}{m_i c^2} \quad \sigma \gg 1$$



Abundant Energy Reservoirs in Magnetic Fields

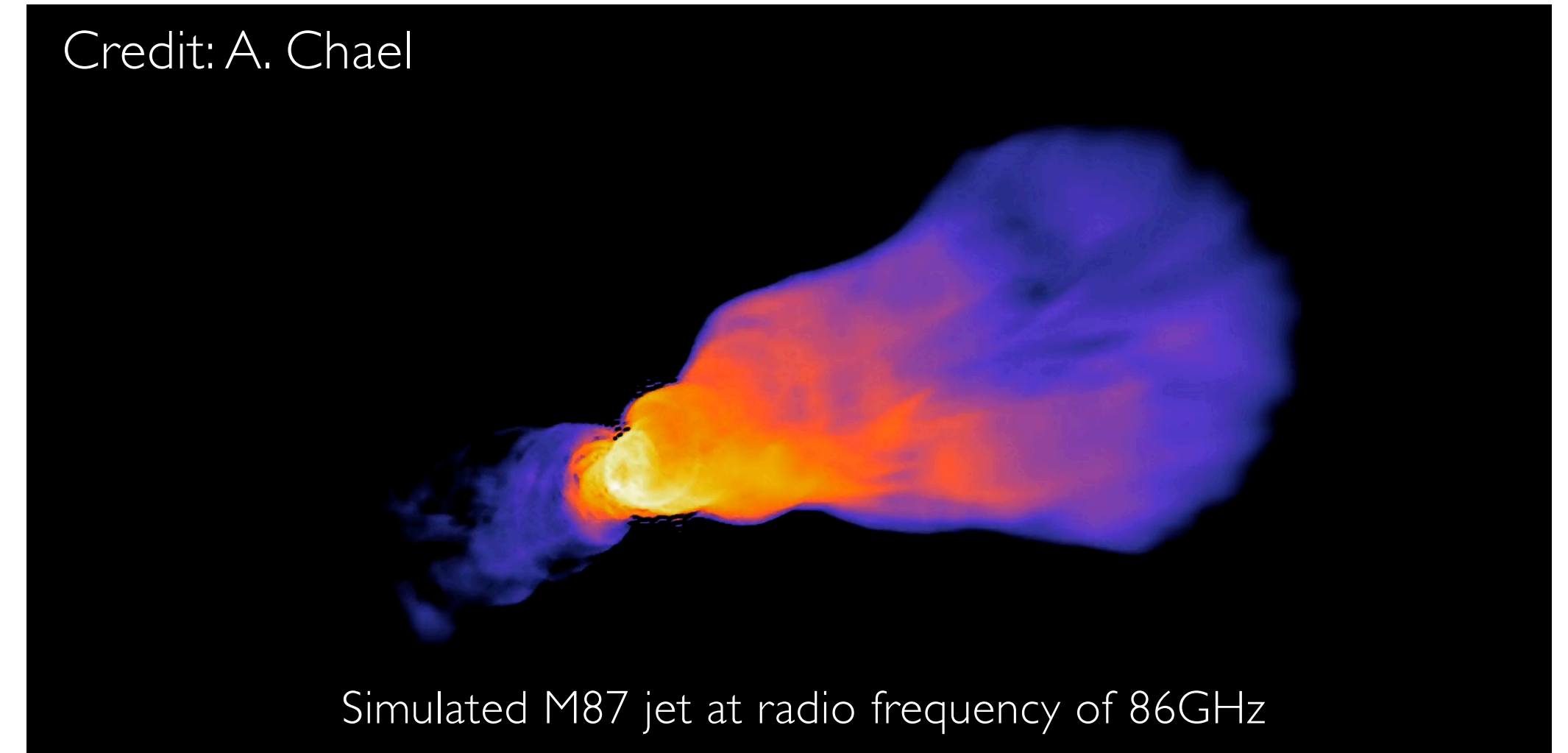


Expected Turbulence in Large-Scale (Astrophysical) Systems



Turbulence is likely to play a main role
in the **transfer of energy across scales**

Credit: A. Chael



M87's Corona (with large uncertainties):

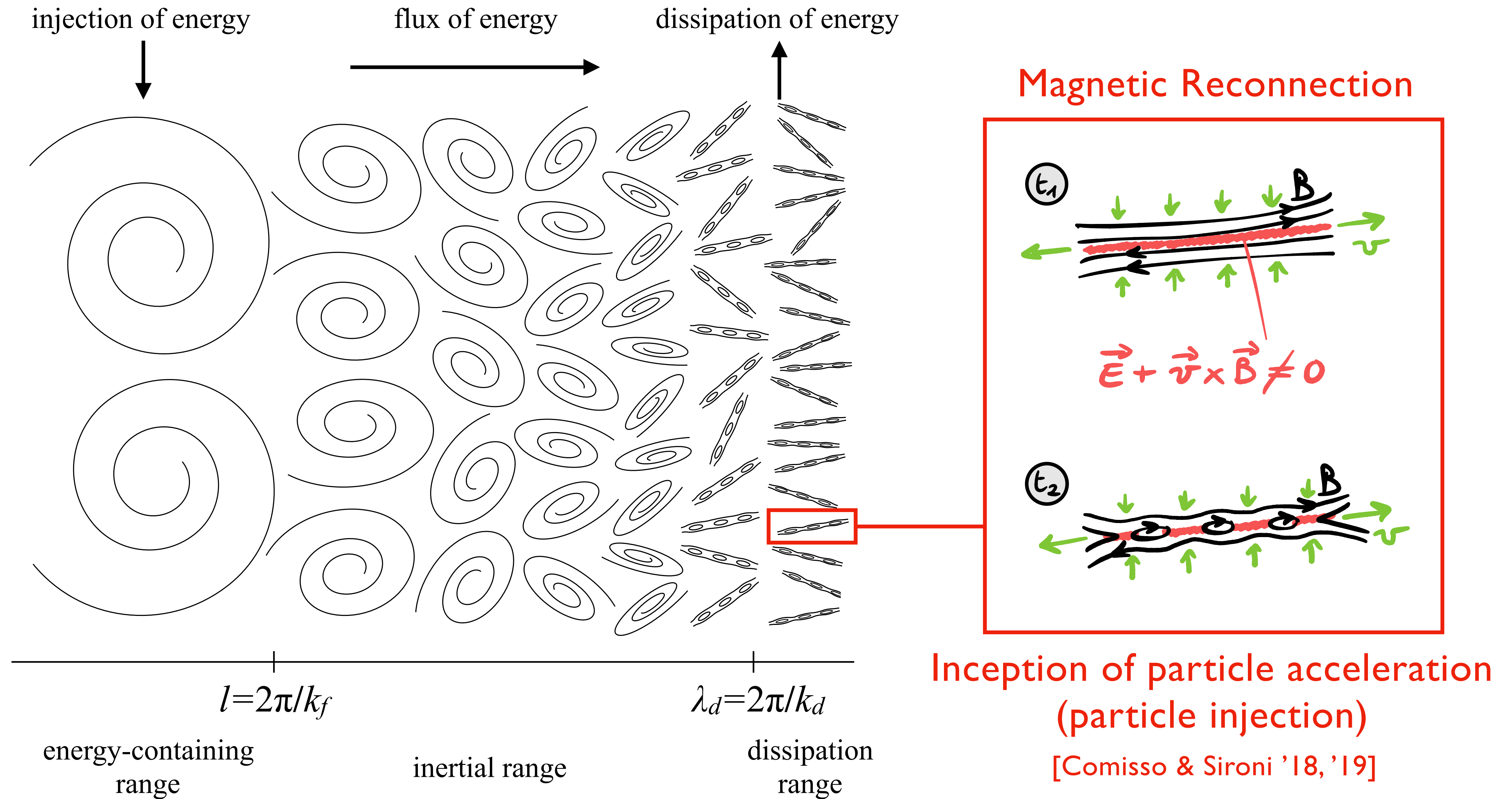
$$\ell_0 \gtrsim R_S = 2GM/c^2 \sim 2 \times 10^{12} \text{ m}$$

$$\ell_{\text{kin}} \sim \rho_p \sim 5 \times 10^3 \text{ m}$$

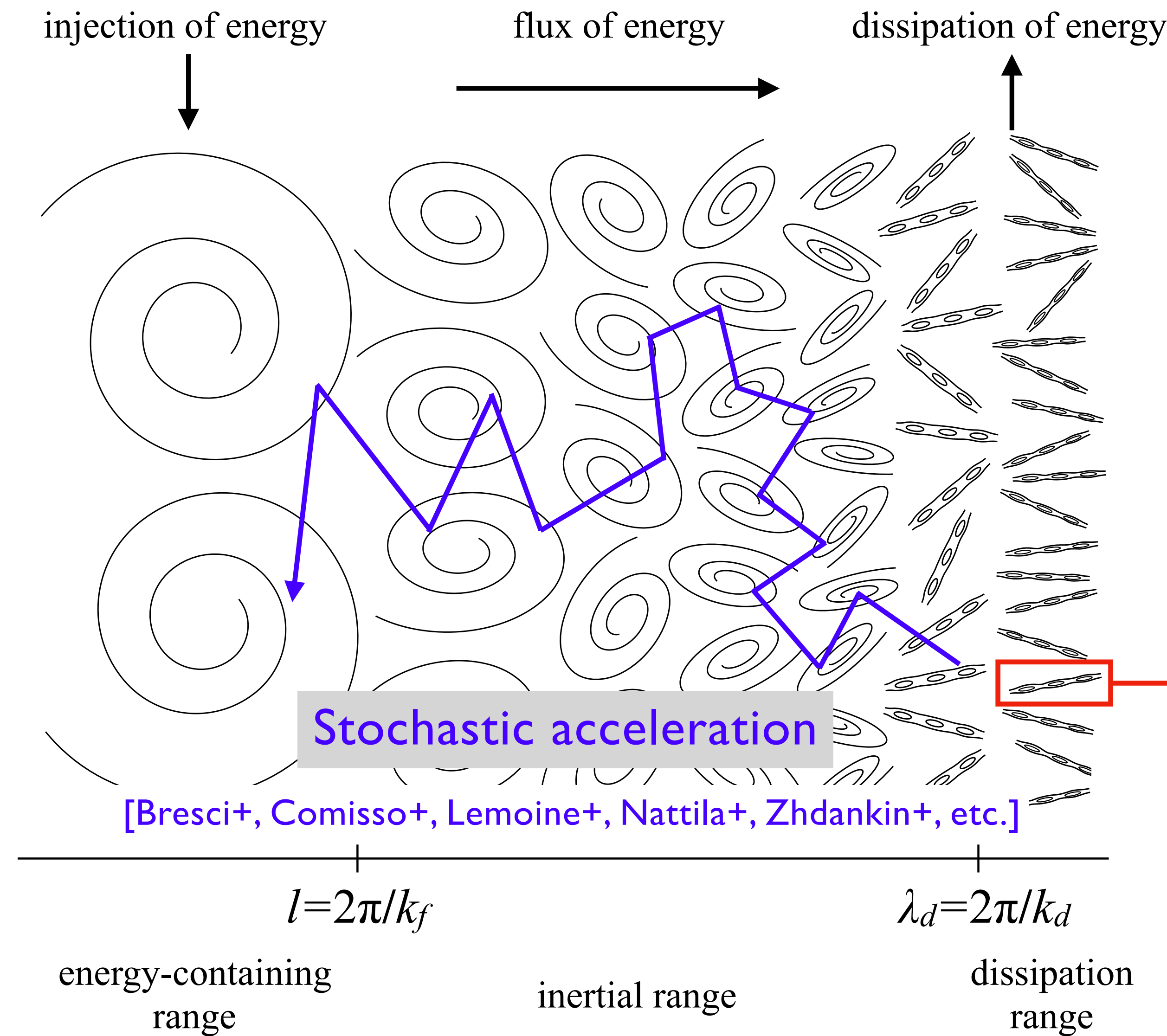
$$(\lambda_{\text{mfp},p} \sim 10^{20} \text{ m})$$

Estimates from EHT Collaboration 2019

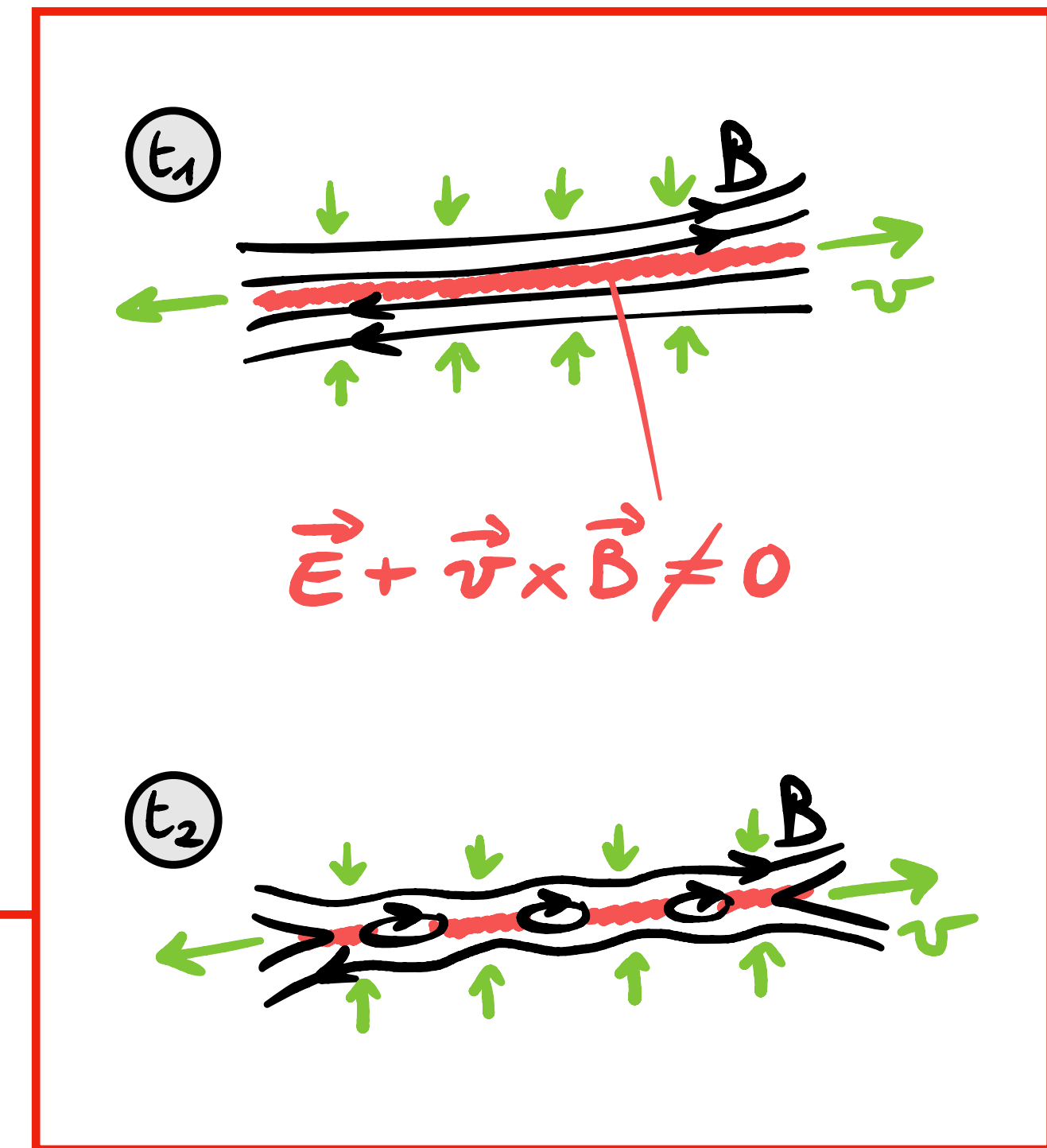
Turbulent Energy Cascade in Large-Scale Magnetized Systems



Turbulent Energy Cascade in Large-Scale Magnetized Systems



Magnetic Reconnection



Inception of particle acceleration (particle injection)

[Comisso & Sironi '18, '19]

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

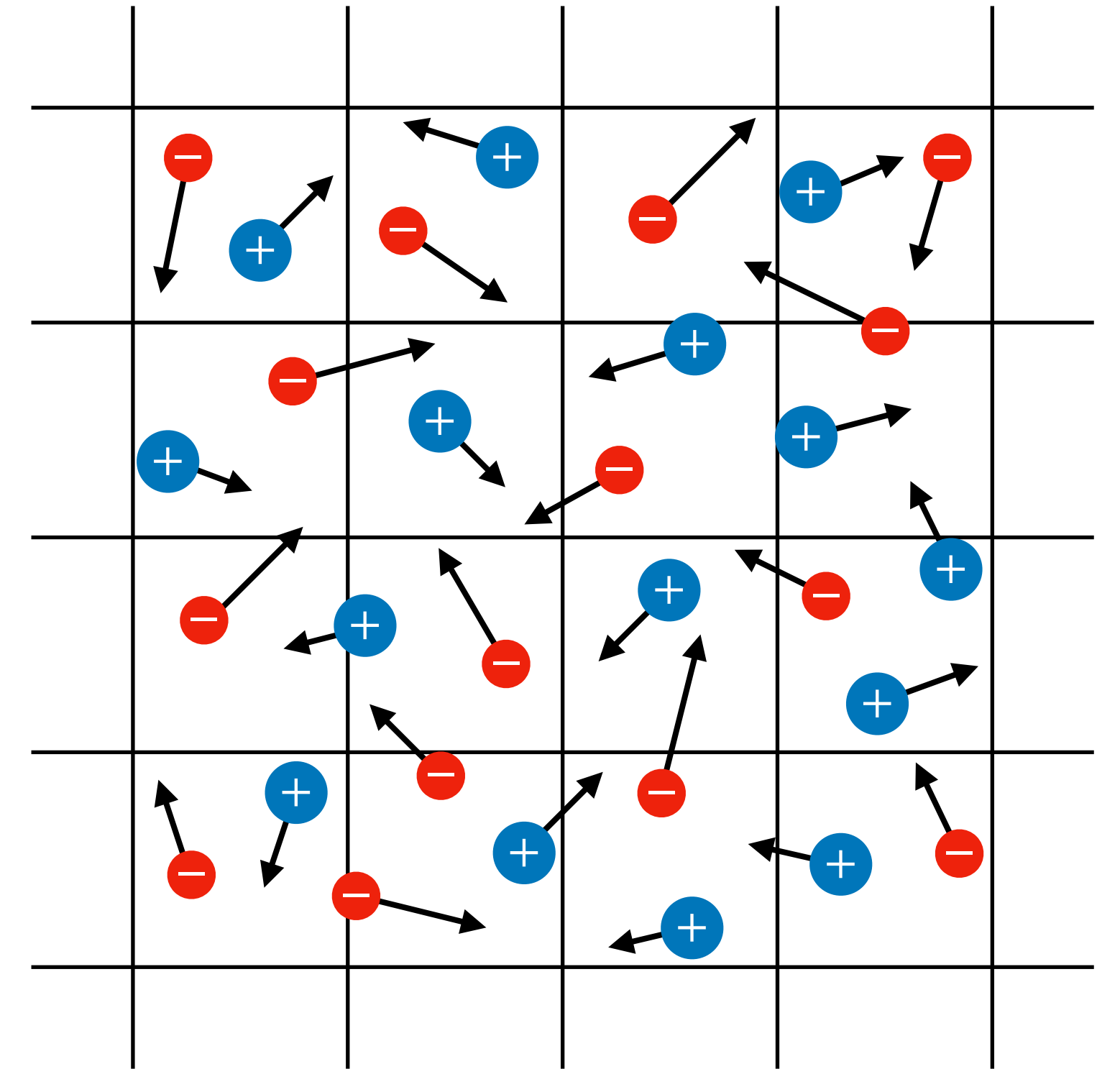
$$\frac{\partial \mathbf{E}}{\partial t} - c \operatorname{curl} \mathbf{B} = -4\pi \mathbf{J}, \quad \operatorname{div} \mathbf{E} = 4\pi \rho,$$

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

where the source terms are computed by

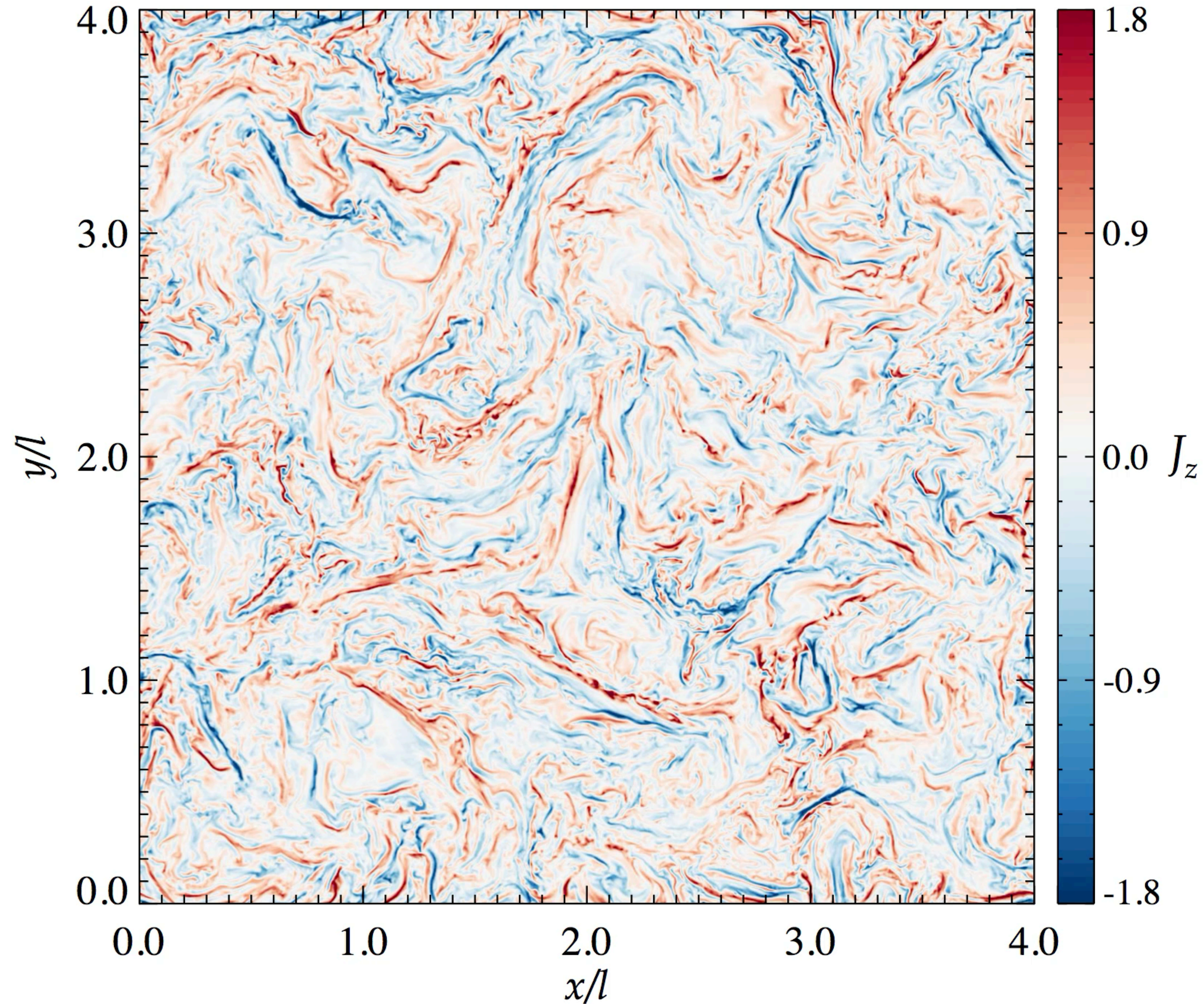
$$\rho = \sum_s q_s \int_{\mathbb{R}^3} f_s d\mathbf{p}, \quad \mathbf{J} = \sum_s \frac{q_s}{m_s} \int_{\mathbb{R}^3} f_s \frac{\mathbf{p}}{\gamma_s} d\mathbf{p}.$$

- ▶ Solution via particle-in-cell method



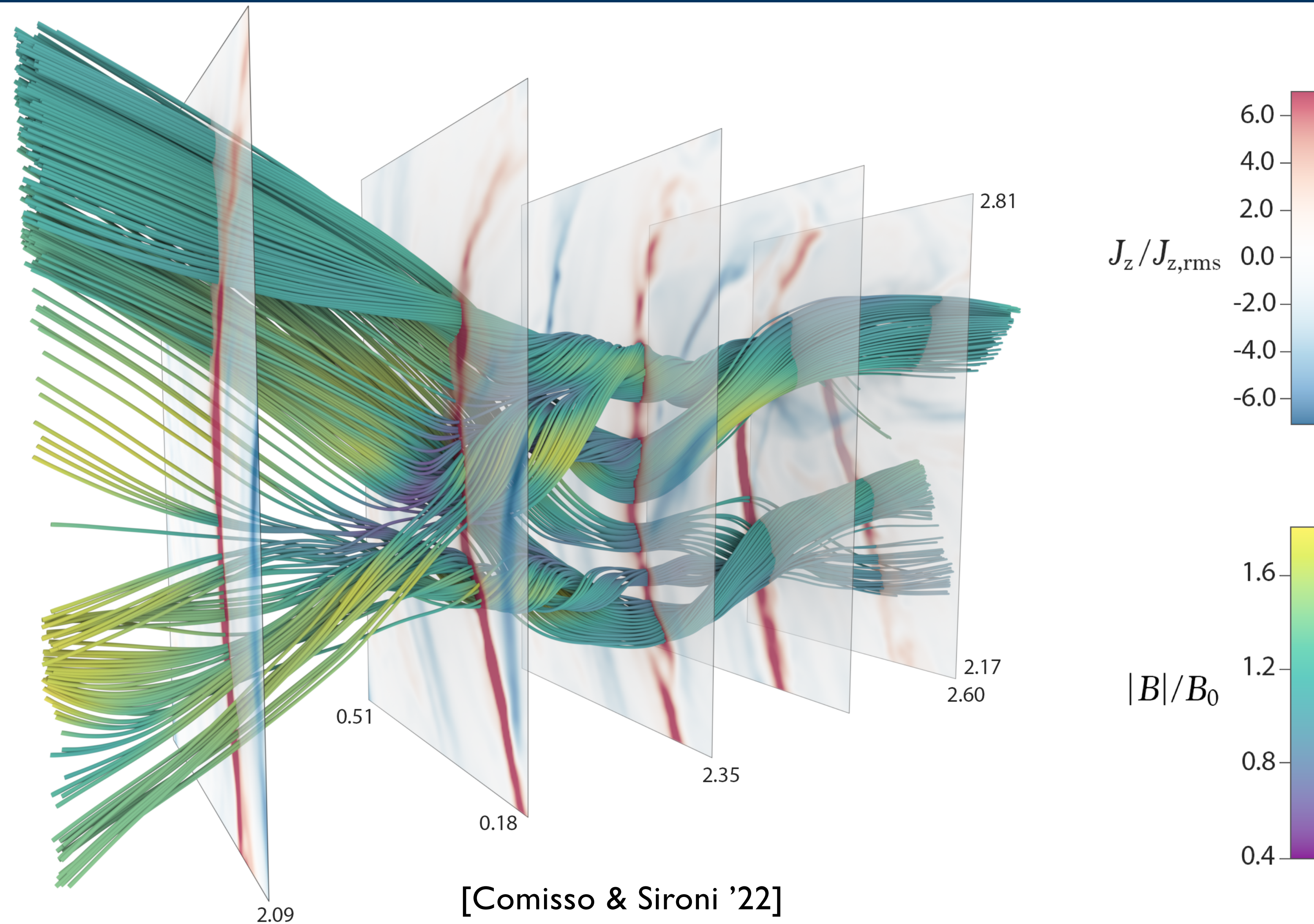
PIC code: TRISTAN-MP
(Spitkovsky 2005)

Flying Through Turbulence Along the Mean Magnetic Field Direction



PIC Turbulence

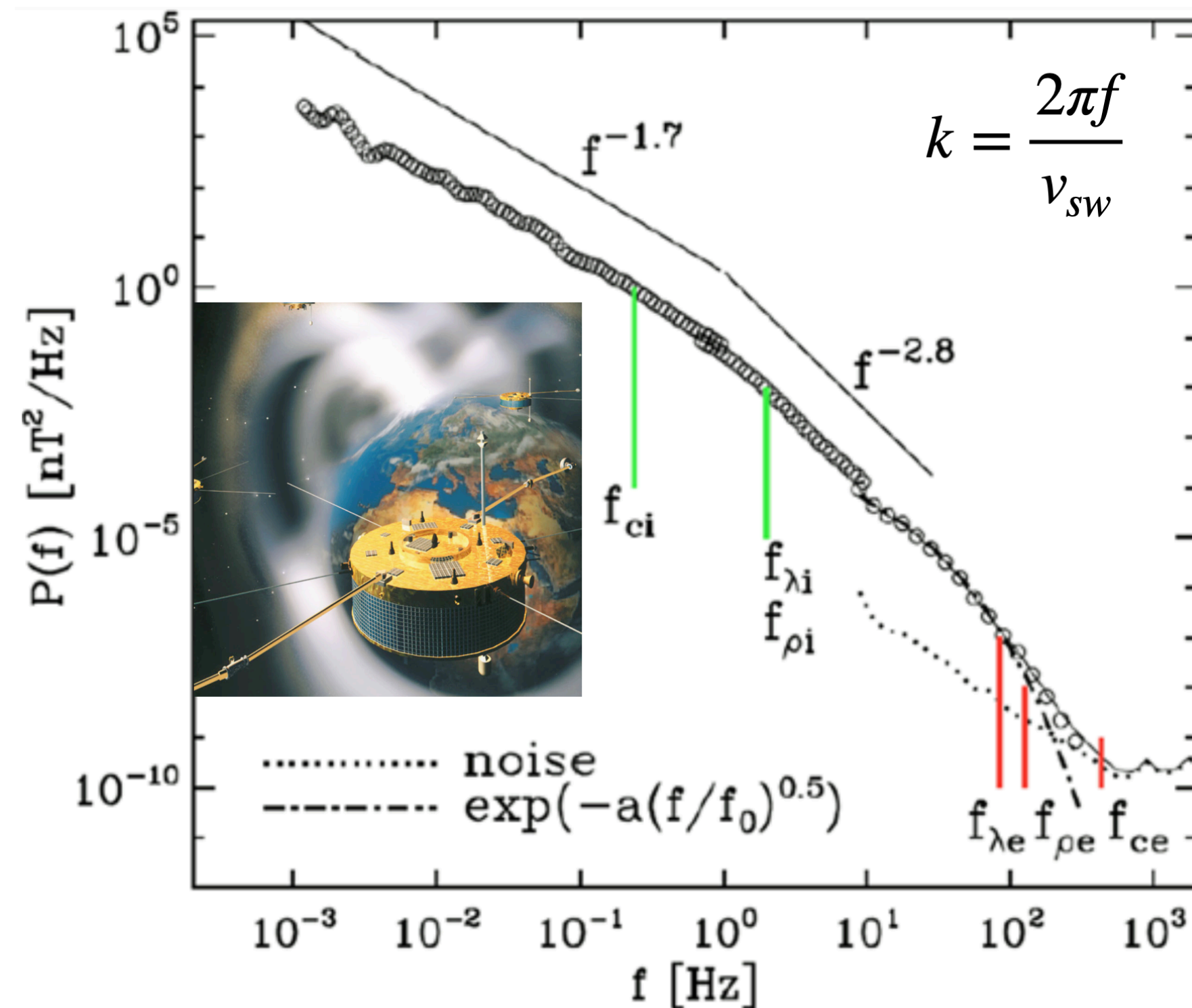
Magnetic Reconnection Within the Turbulent Cascade



Formation of flux ropes within the turbulent domain (PIC Turbulence)

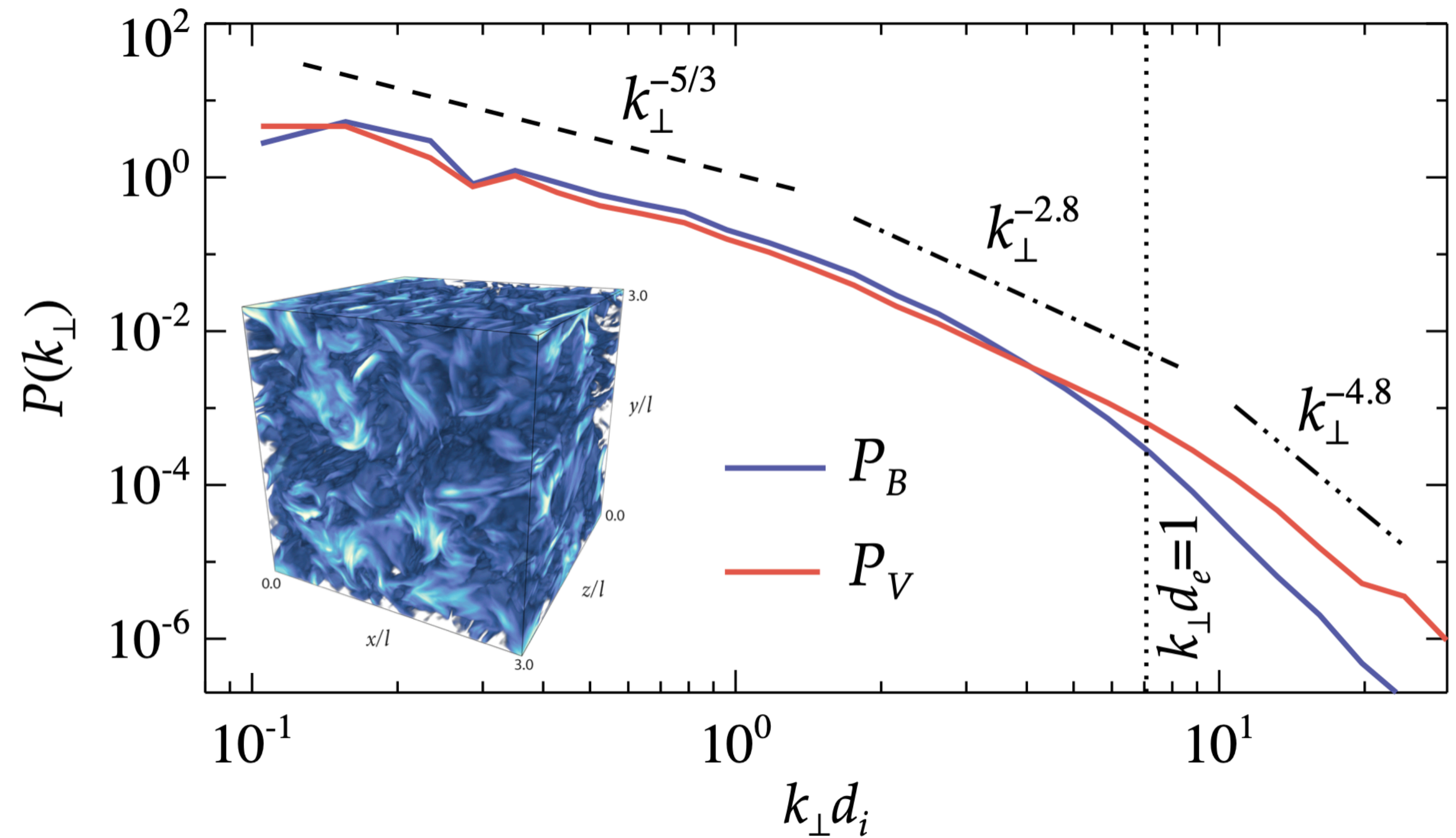
Power Spectrum: Comparison with Solar Wind Data

Magnetic power spectrum of Solar Wind



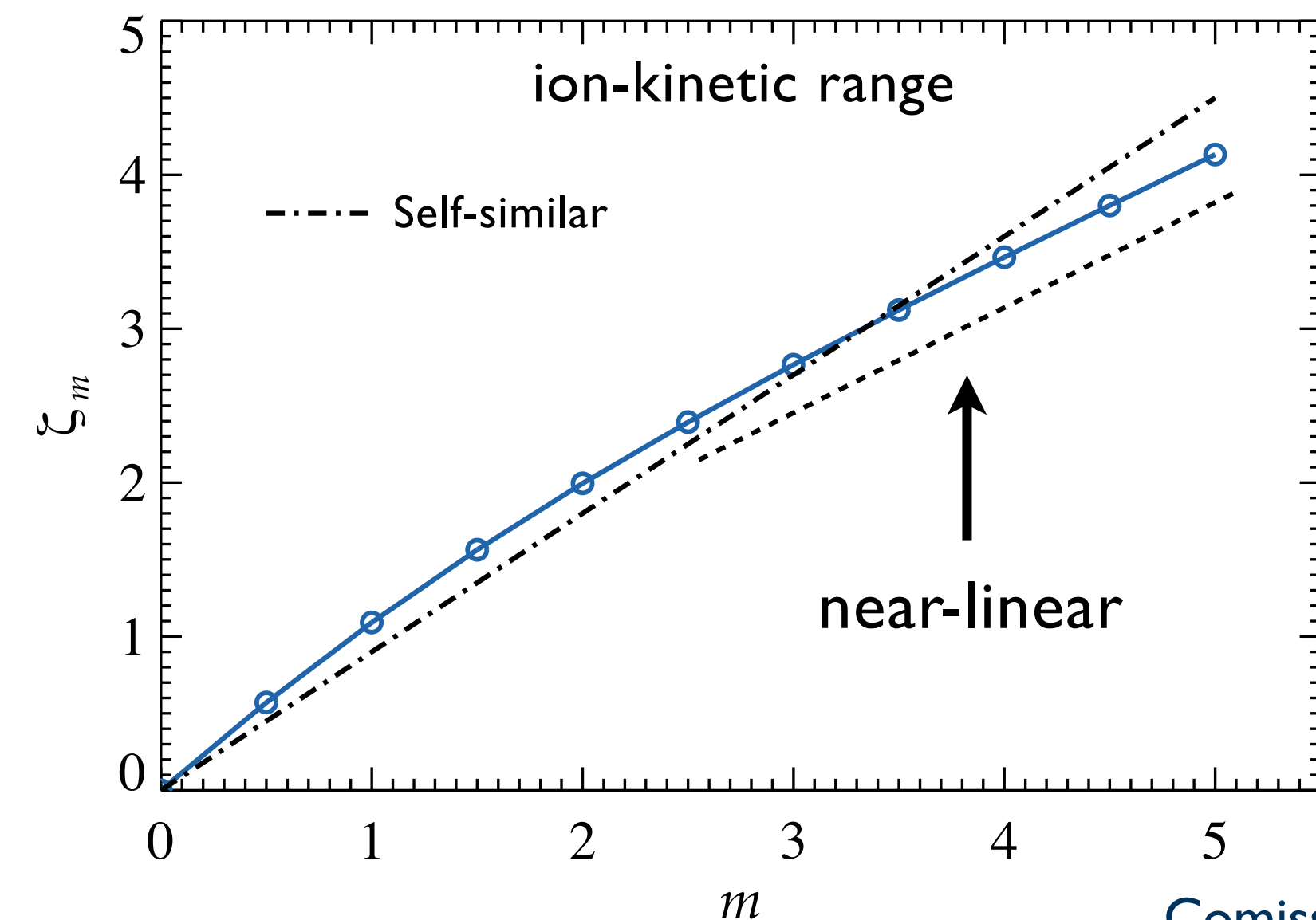
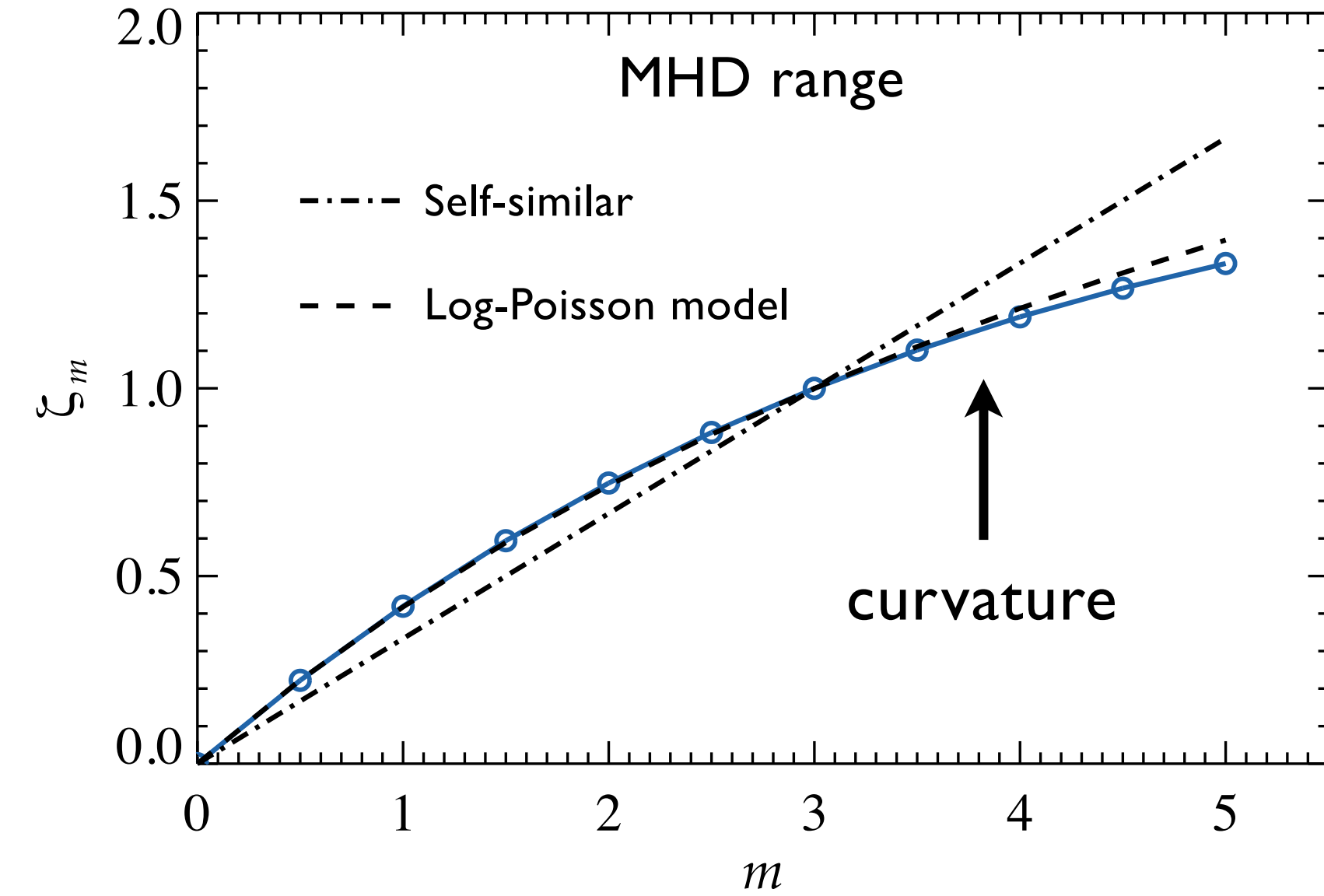
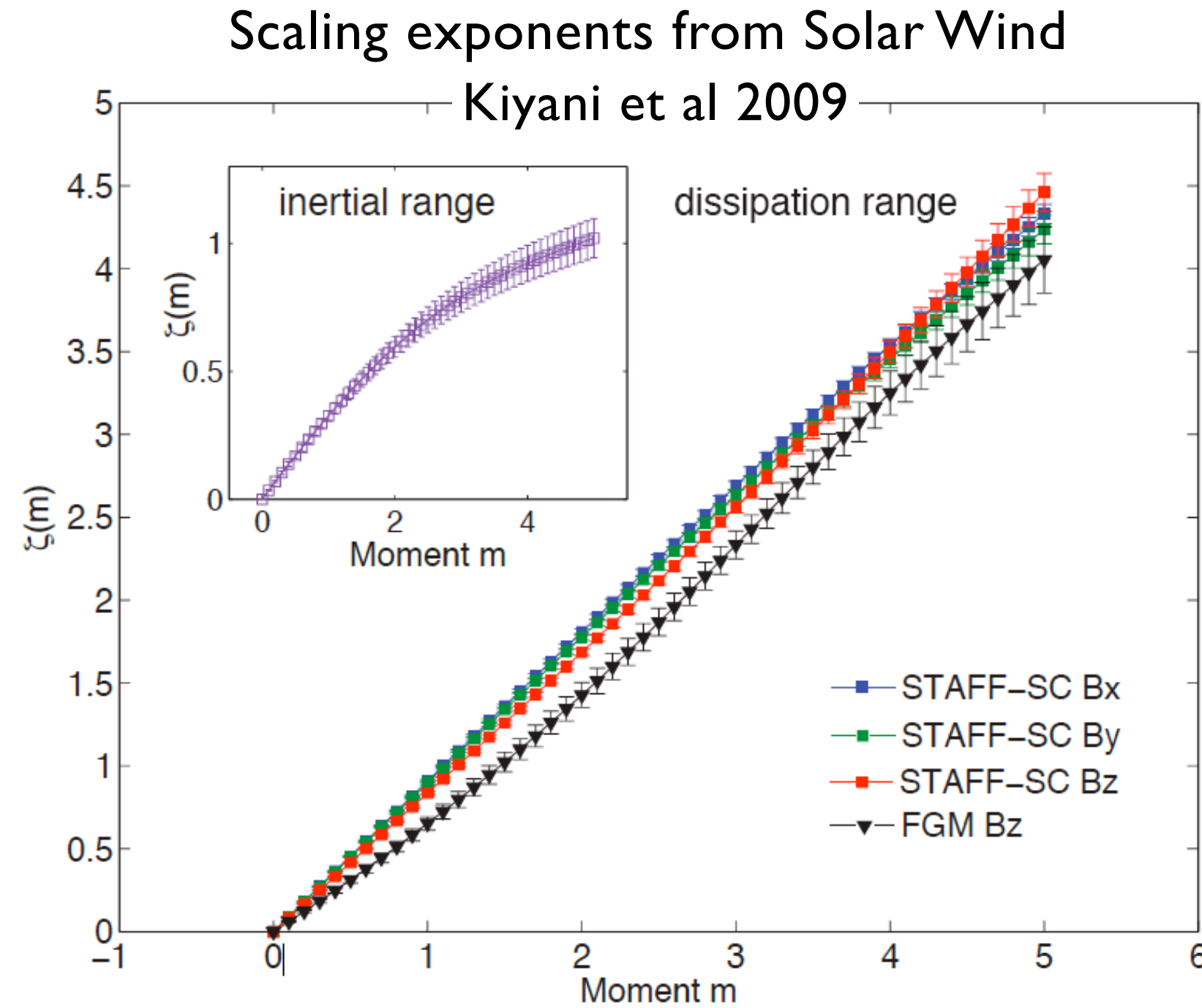
Alexandrova et al. 2013

Power spectra from low- β PIC simulation



Comisso and Sironi 2022

Higher-Order Statistics: Comparison with Solar Wind Data

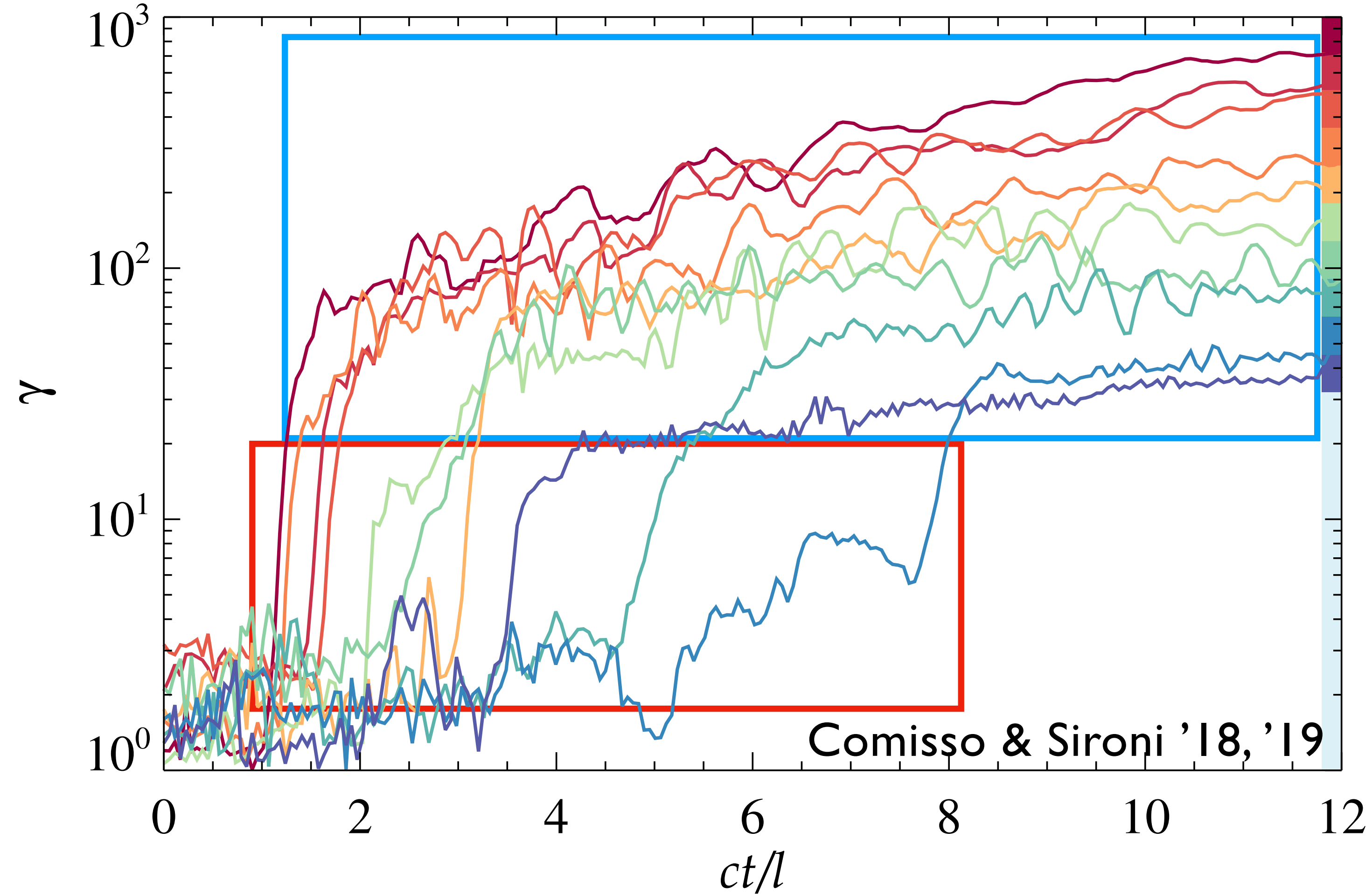


From the measure of the scaling exponents

$$S_m(\ell_{\perp}) = \langle |\Delta B_x(x, \ell_{\perp})|^m \rangle_x \propto \ell_{\perp}^{\zeta_m}$$

the MHD range is more intermittent than the kinetic range (consistent with solar wind)

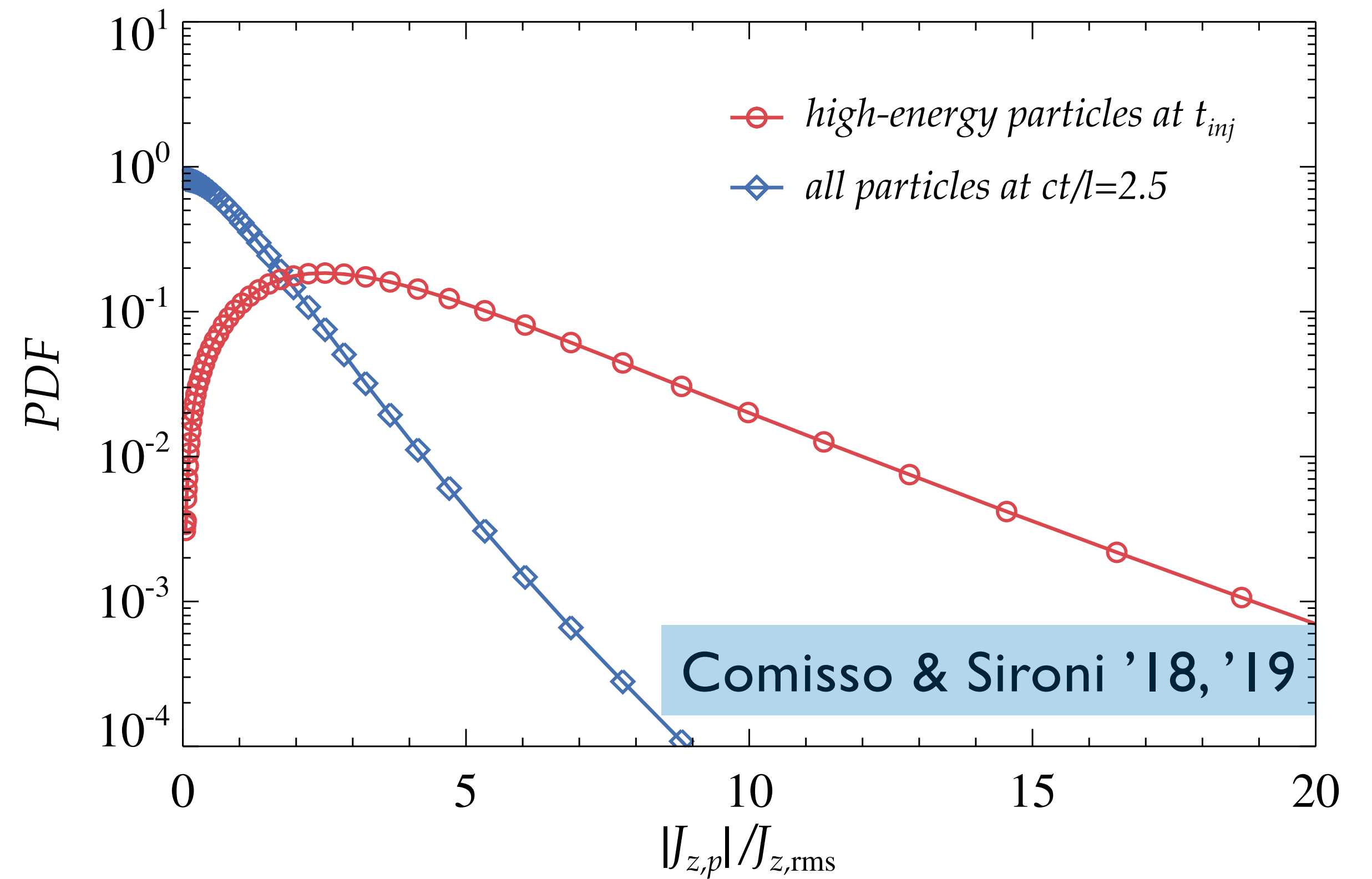
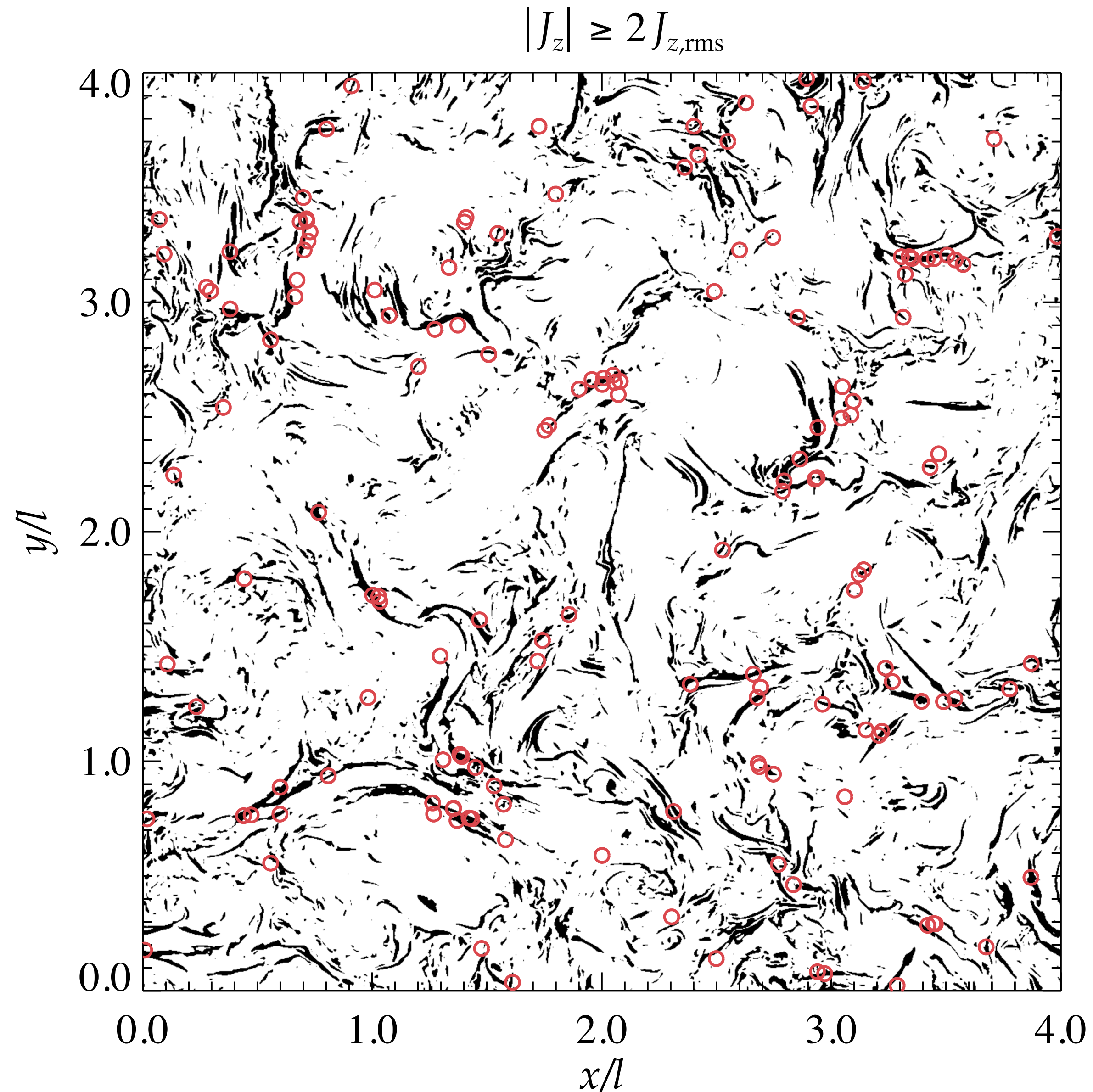
Particle Energization as a Two-Stage Process



Particle energization occurs via a two-stage acceleration process:

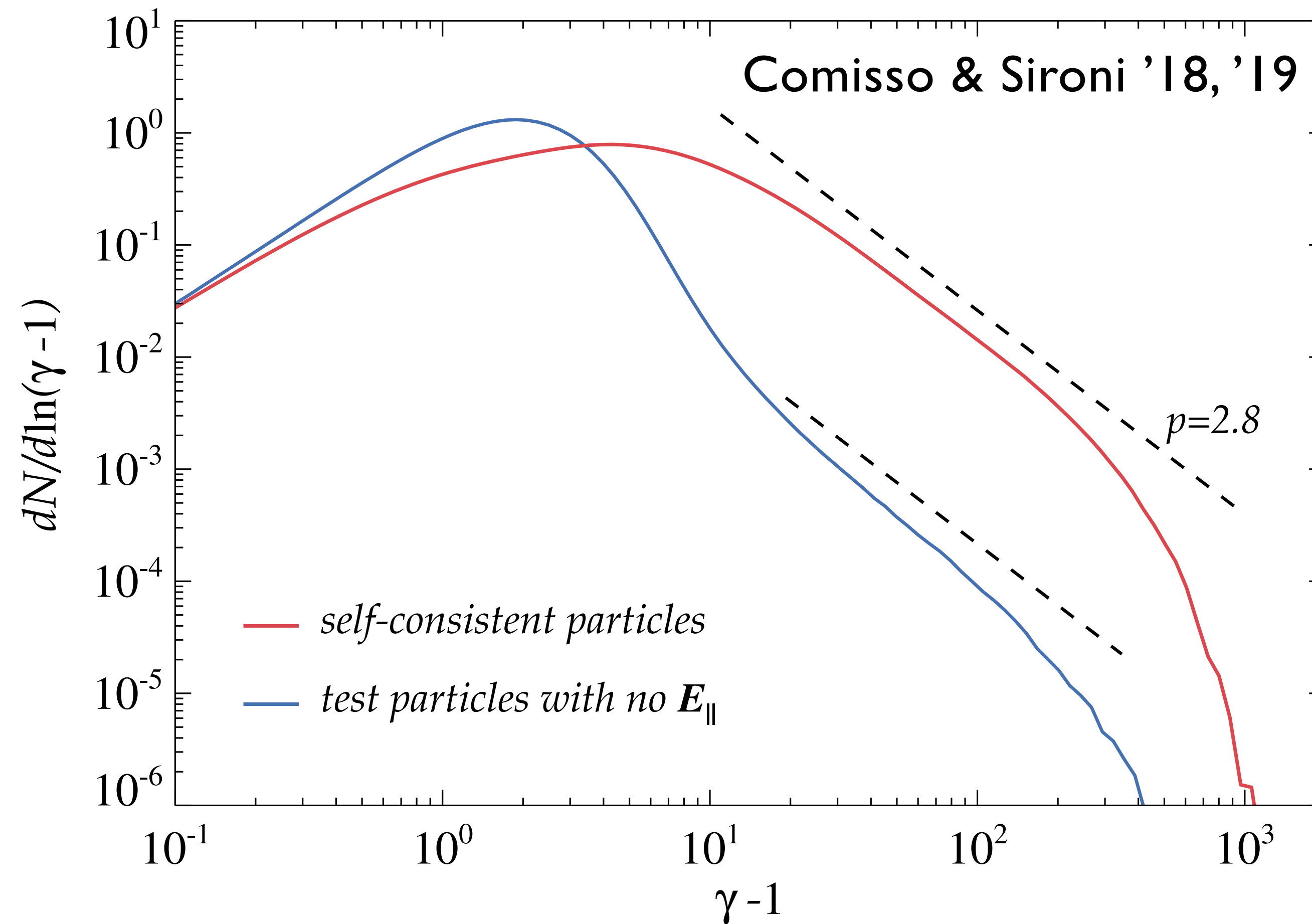
1. Particle injection (via magnetic reconnection layers)
2. Stochastic acceleration (via scatterings off larger scale turbulent fluctuations)

1st Stage: Particle “Injection”

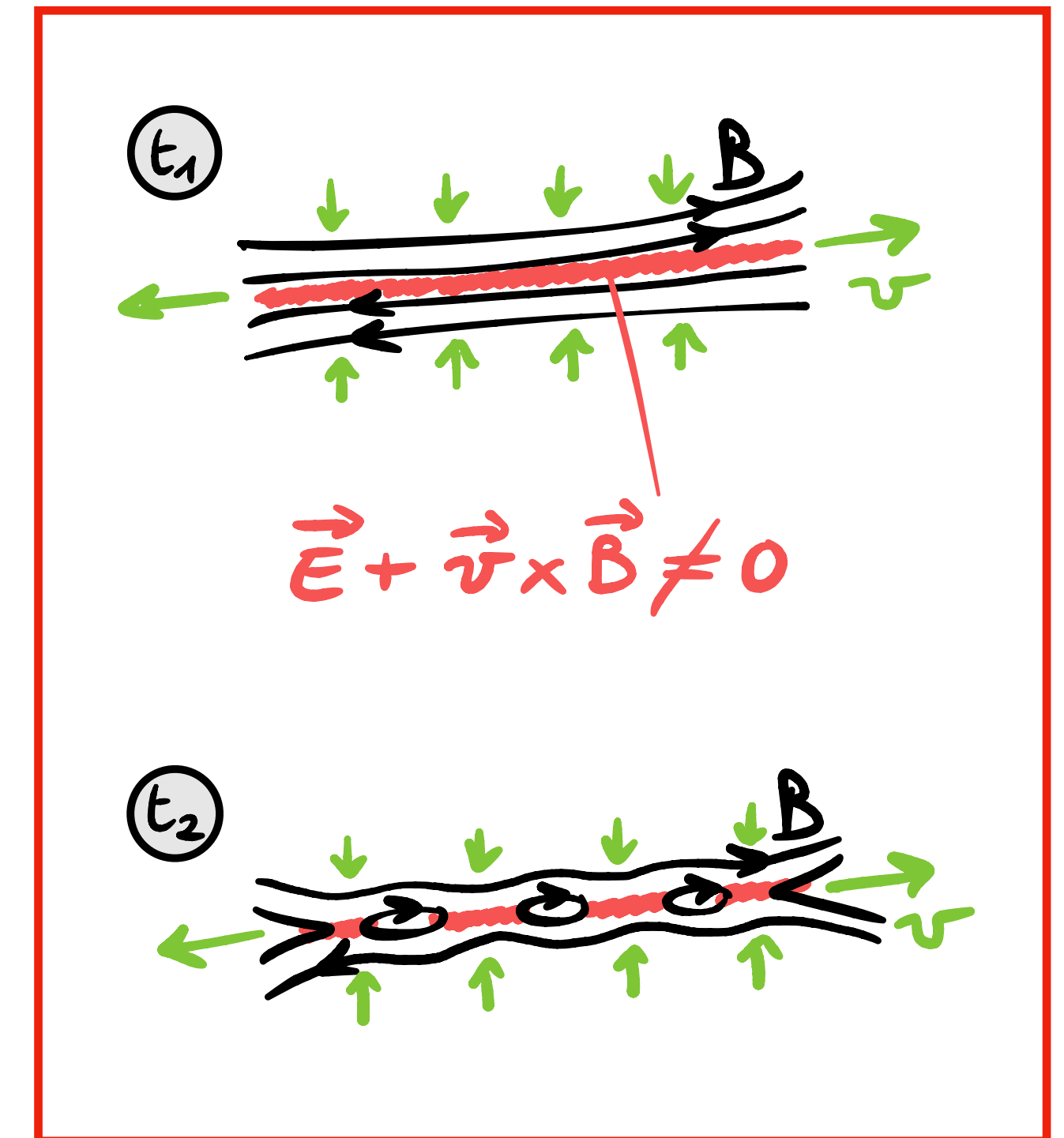


- Initial particle acceleration occurs when particles are in strong current sheets

Particle “Injection” via Magnetic-Field-Aligned Electric Fields

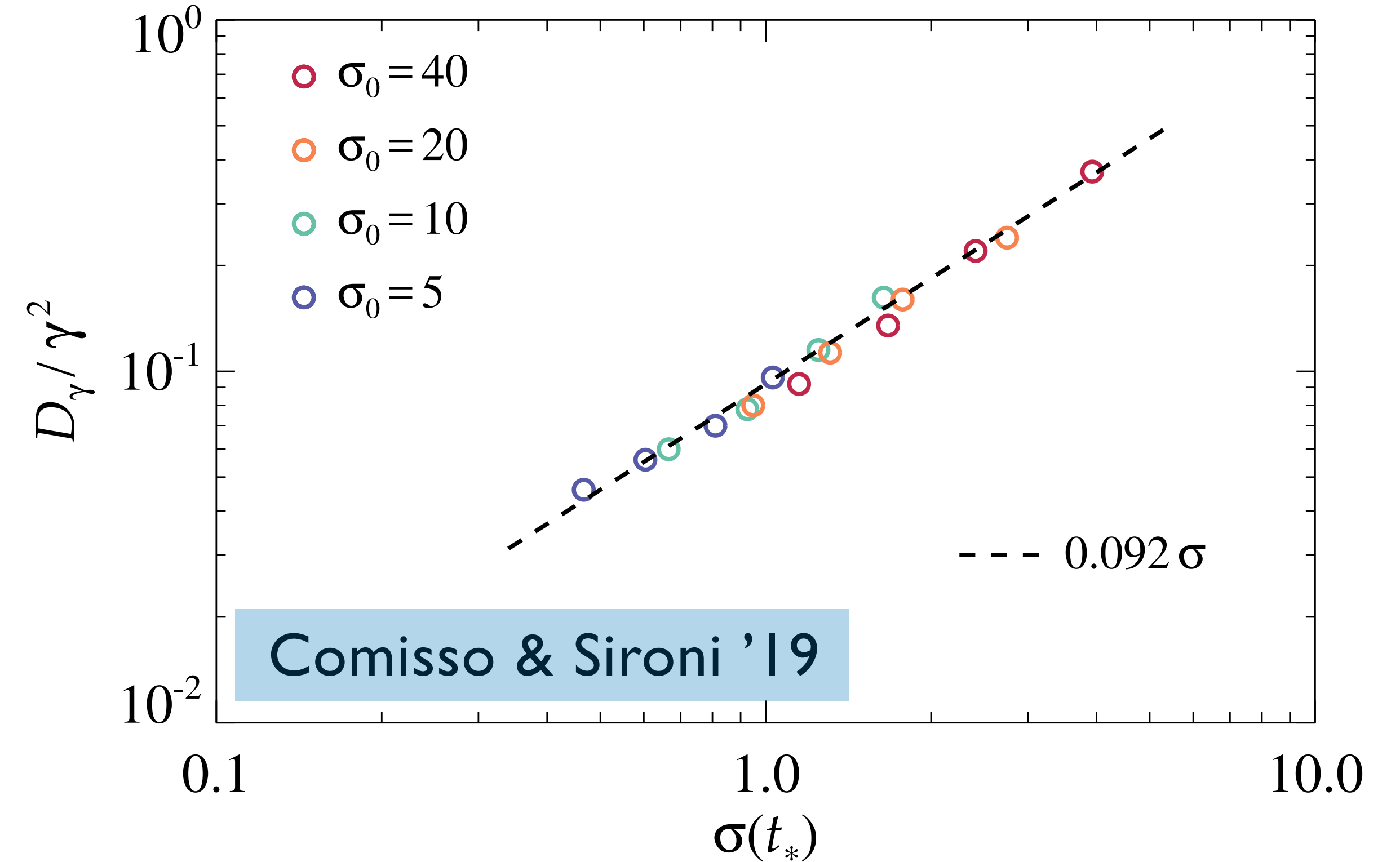
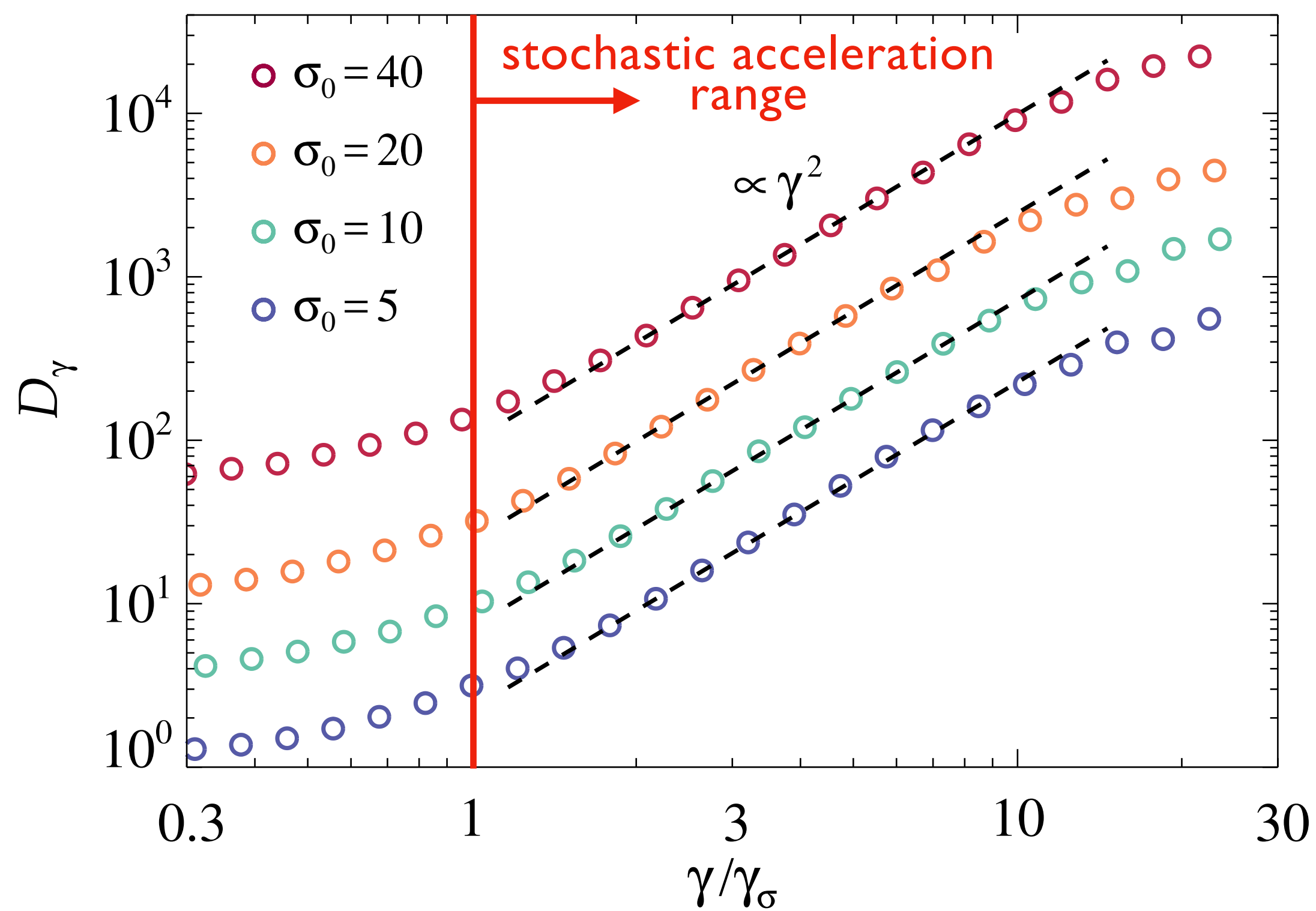


Magnetic Reconnection



- 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)

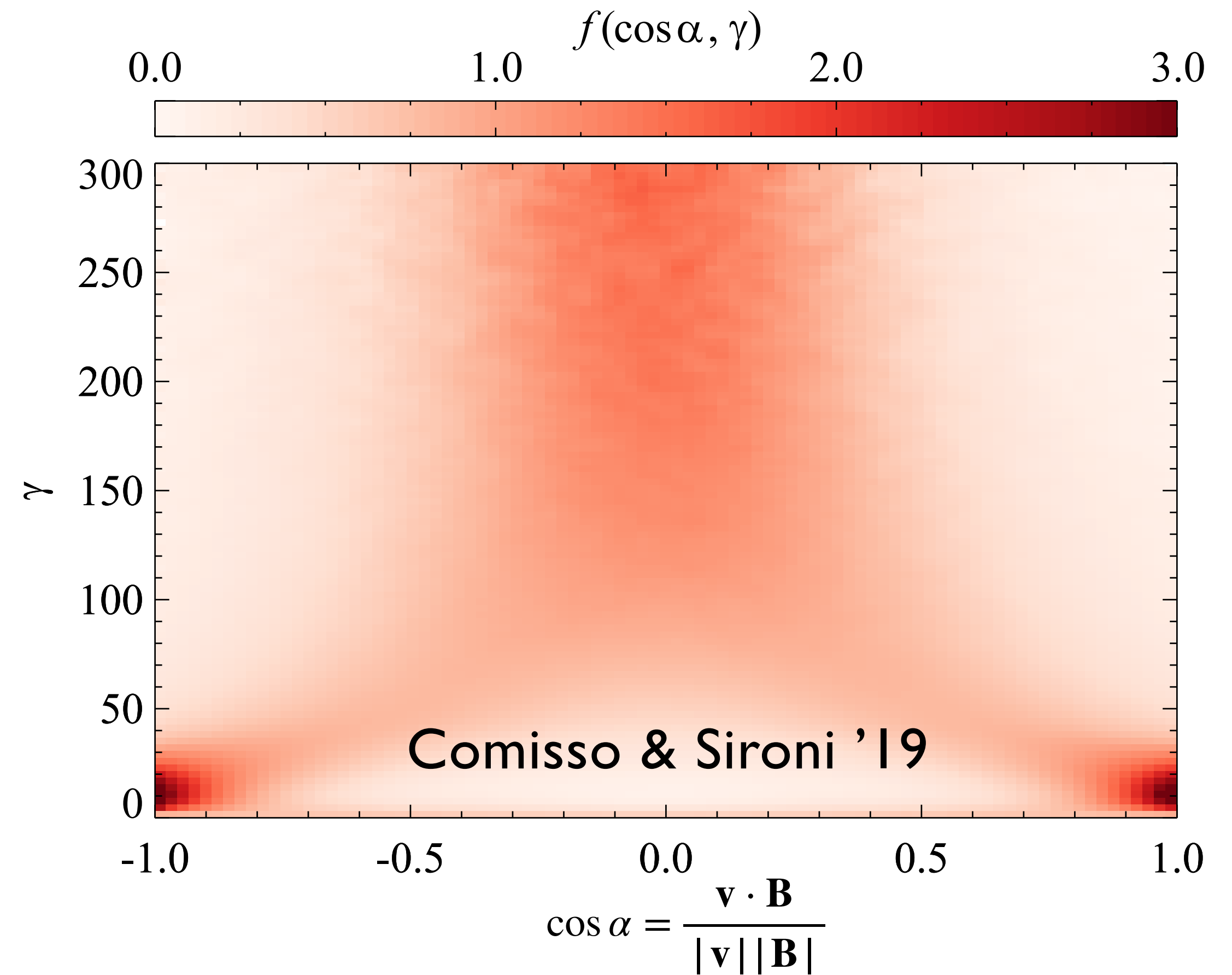
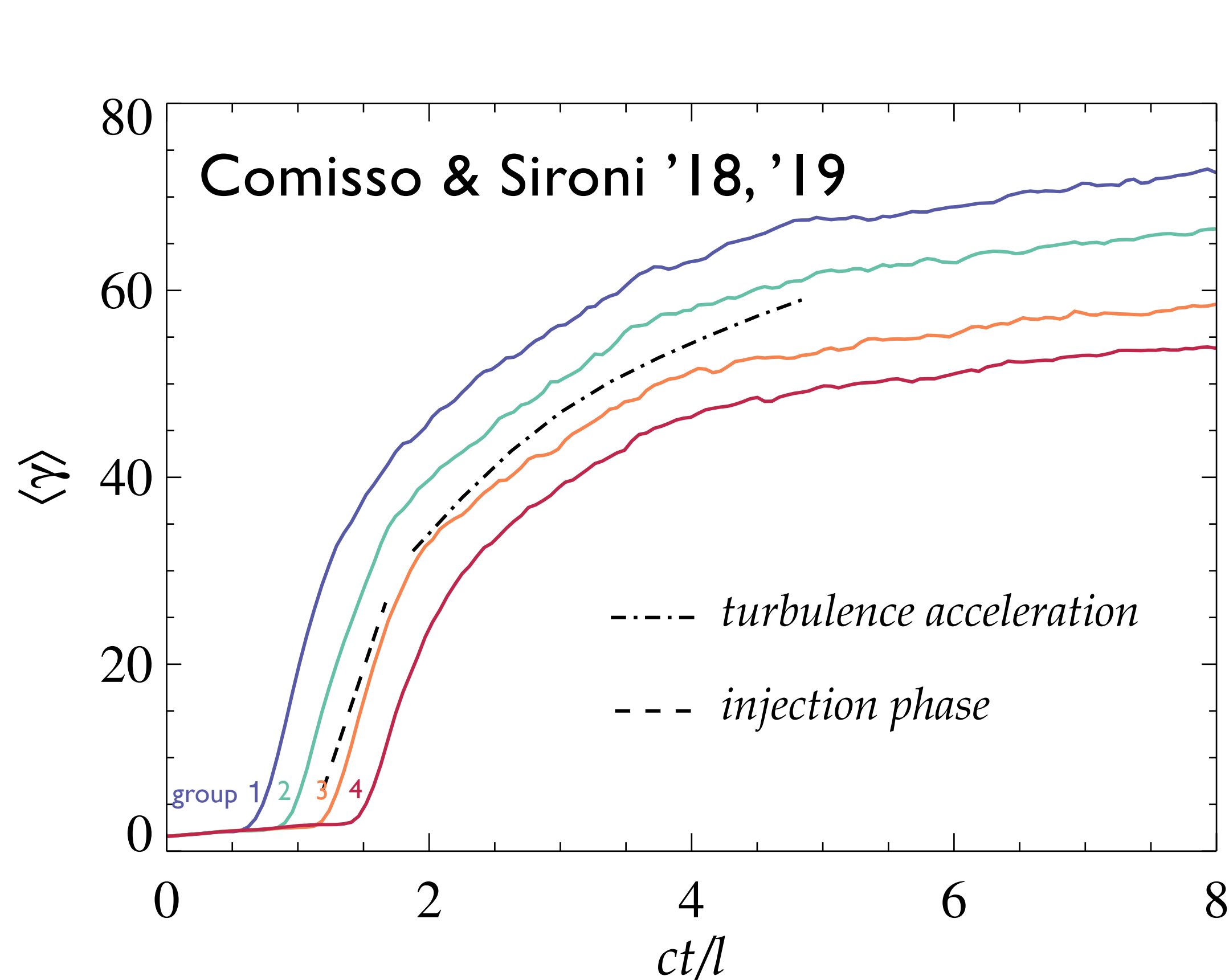
2nd Stage: Stochastic Particle Acceleration up to the “Hillas” Limit



- Mean rate of change of γ due to stochastic acceleration: $\frac{d\langle\gamma\rangle}{dt} = \frac{1}{\gamma^2} \frac{\partial}{\partial \gamma} \left(\gamma^2 D_\gamma \right)$
- PIC simulations give: $D_\gamma \sim 0.1 \sigma_{\text{tur}} \left(\frac{c}{\ell_c} \right) \gamma^2 \longrightarrow t_{\text{acc}} = \frac{\gamma^2}{D_\gamma}$

Nonresonant rather than gyro-resonant interactions (see also Wong+ '20, Lemoine '22, Bresci+ '22)

Two-Stage Acceleration Produces an *Energy-Dependent Pitch-Angle Anisotropy*

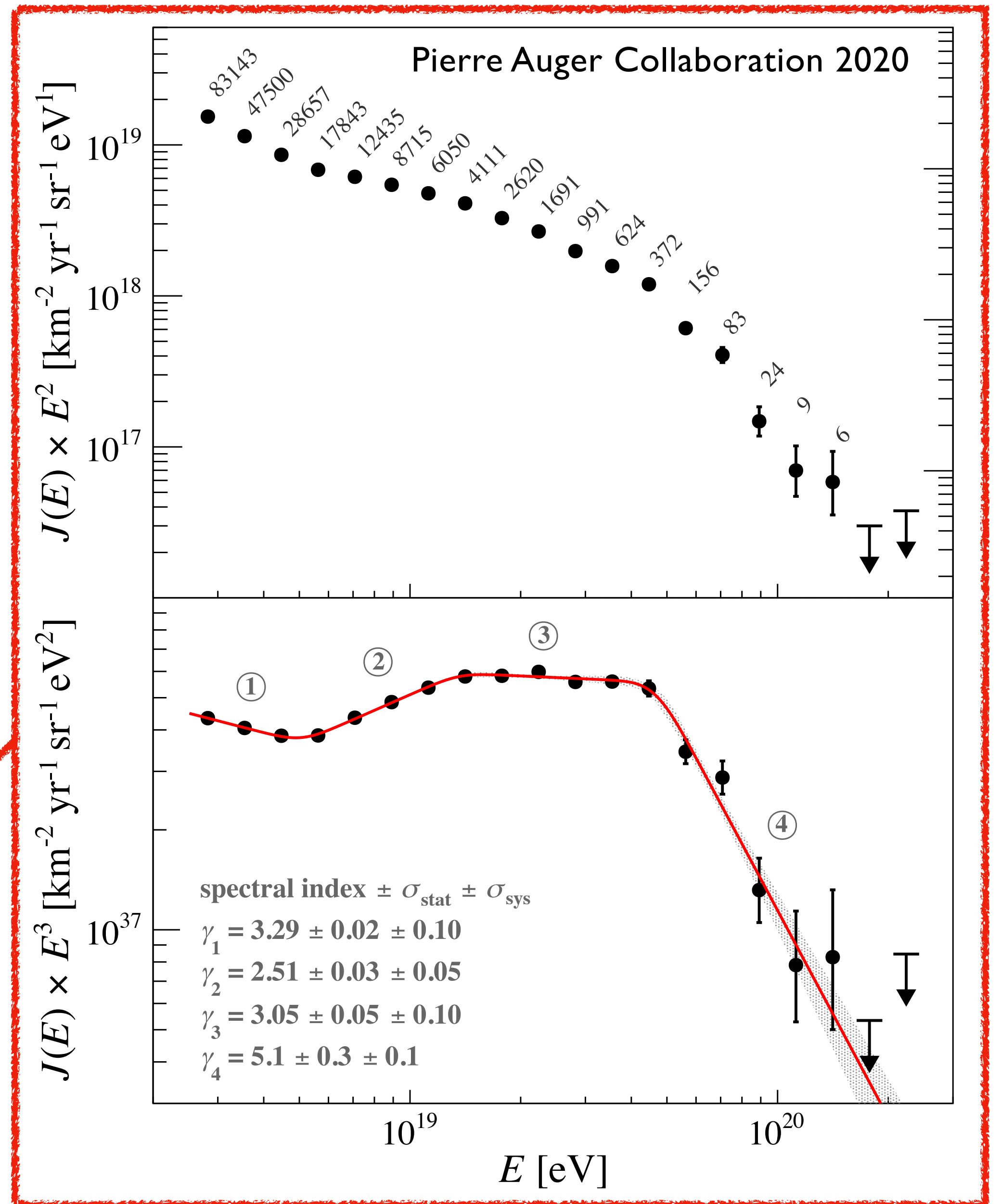
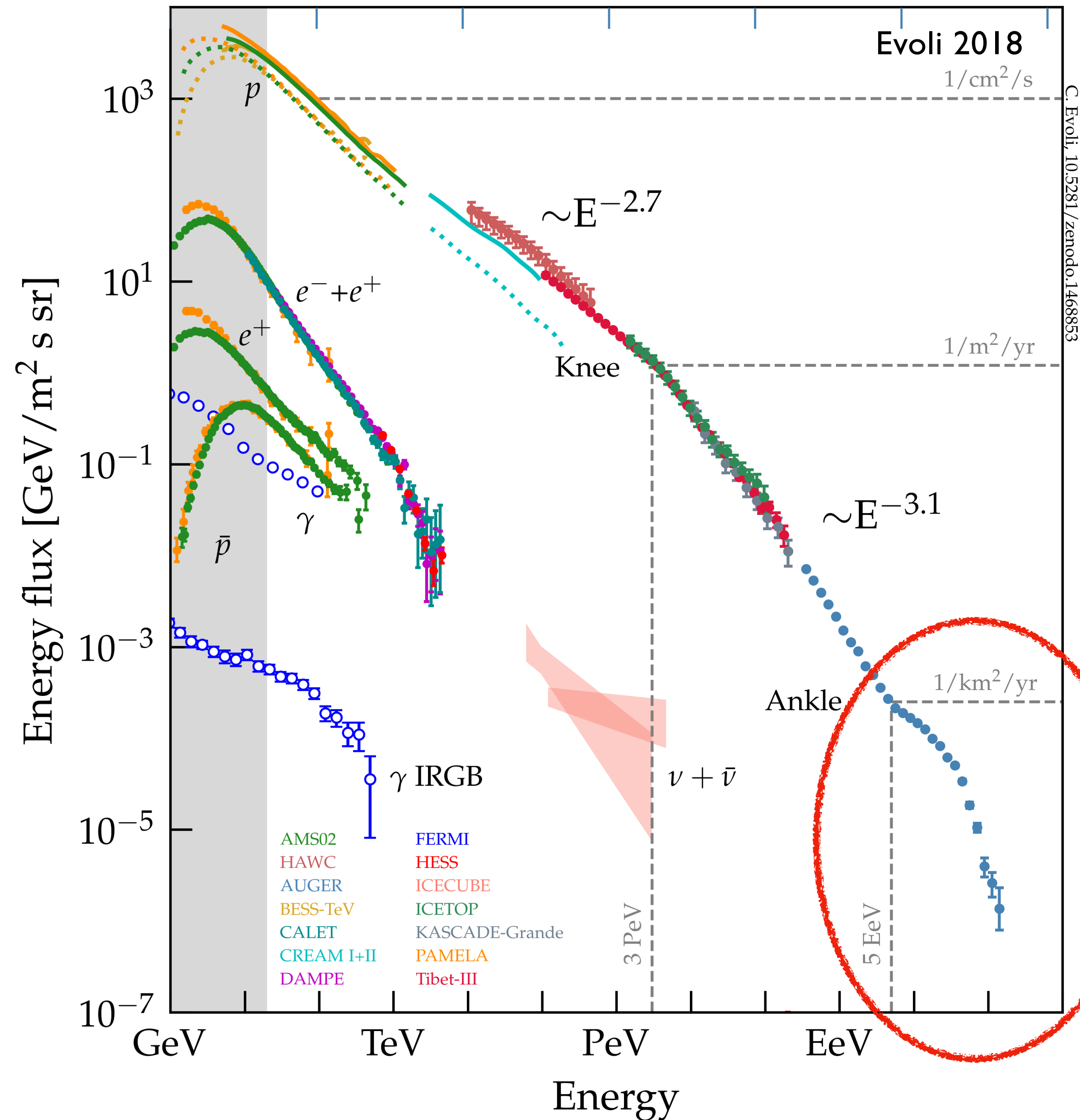


- injection phase: $\frac{d\langle \gamma \rangle}{dt} \sim \frac{e}{m_e c} \beta_{\text{rec}} \delta B_{\text{rms}}$
- stochastic acceleration: $\frac{d\langle \gamma \rangle}{dt} \sim 0.4 \sigma \left(\frac{c}{\ell_c} \right) \gamma$

@ low- γ , $\mathbf{v}$ strongly anti/aligned with $\mathbf{B}$

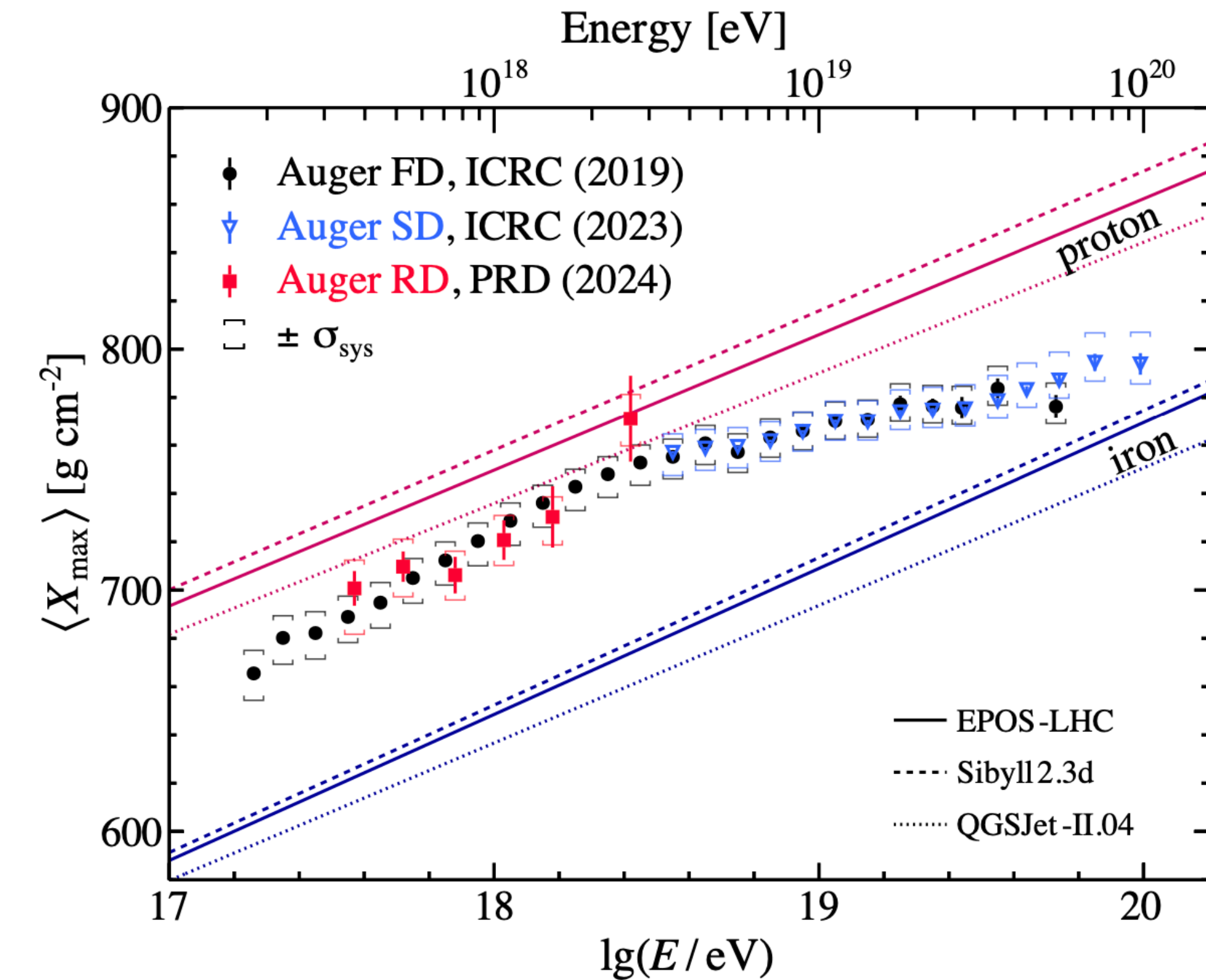
@ high- γ , $\mathbf{v}$ mostly perpendicular to $\mathbf{B}$

Magnetized Turbulence as a Mechanism for UHECR Acceleration?

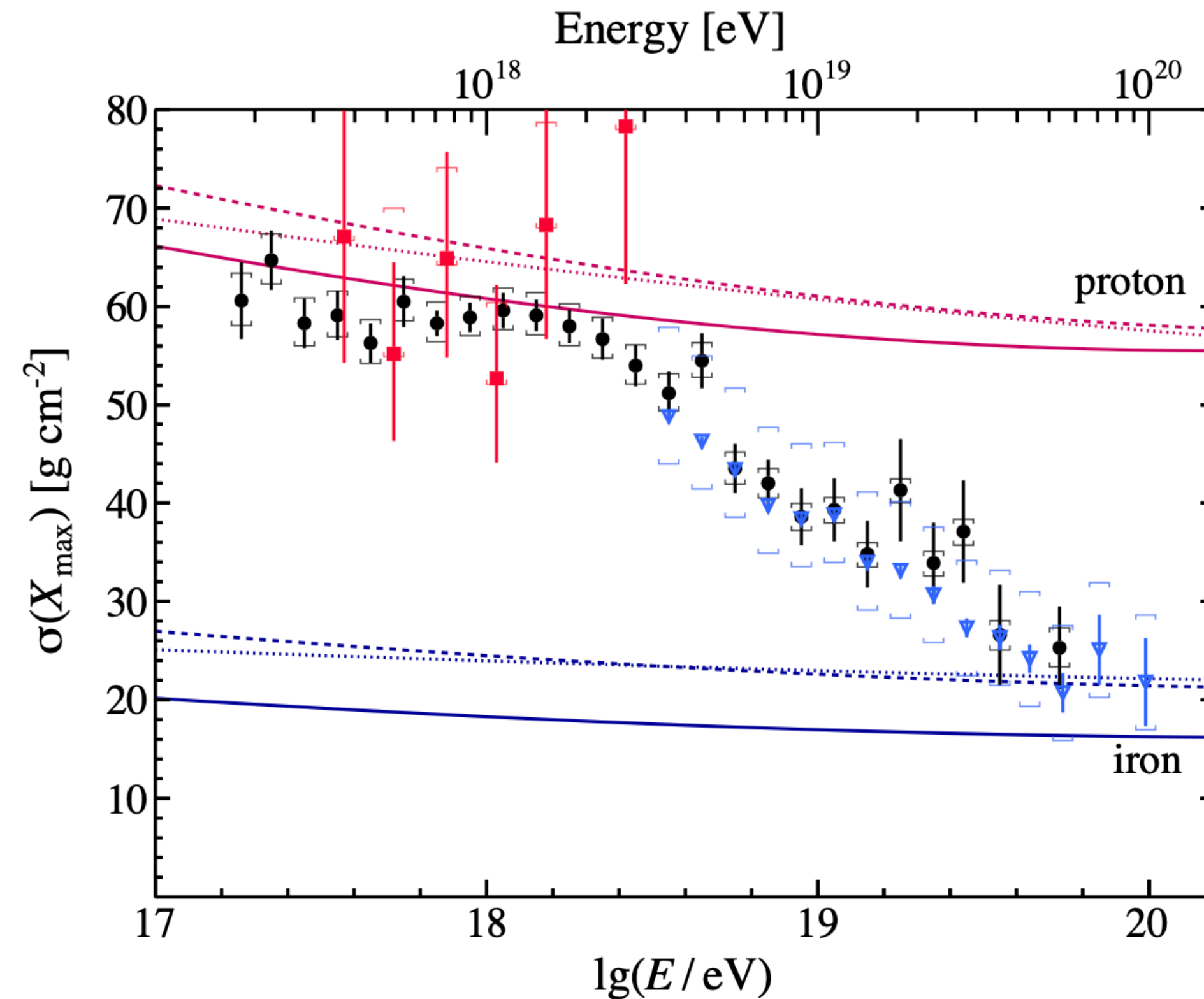


Detailed Statistics of UHECR Composition

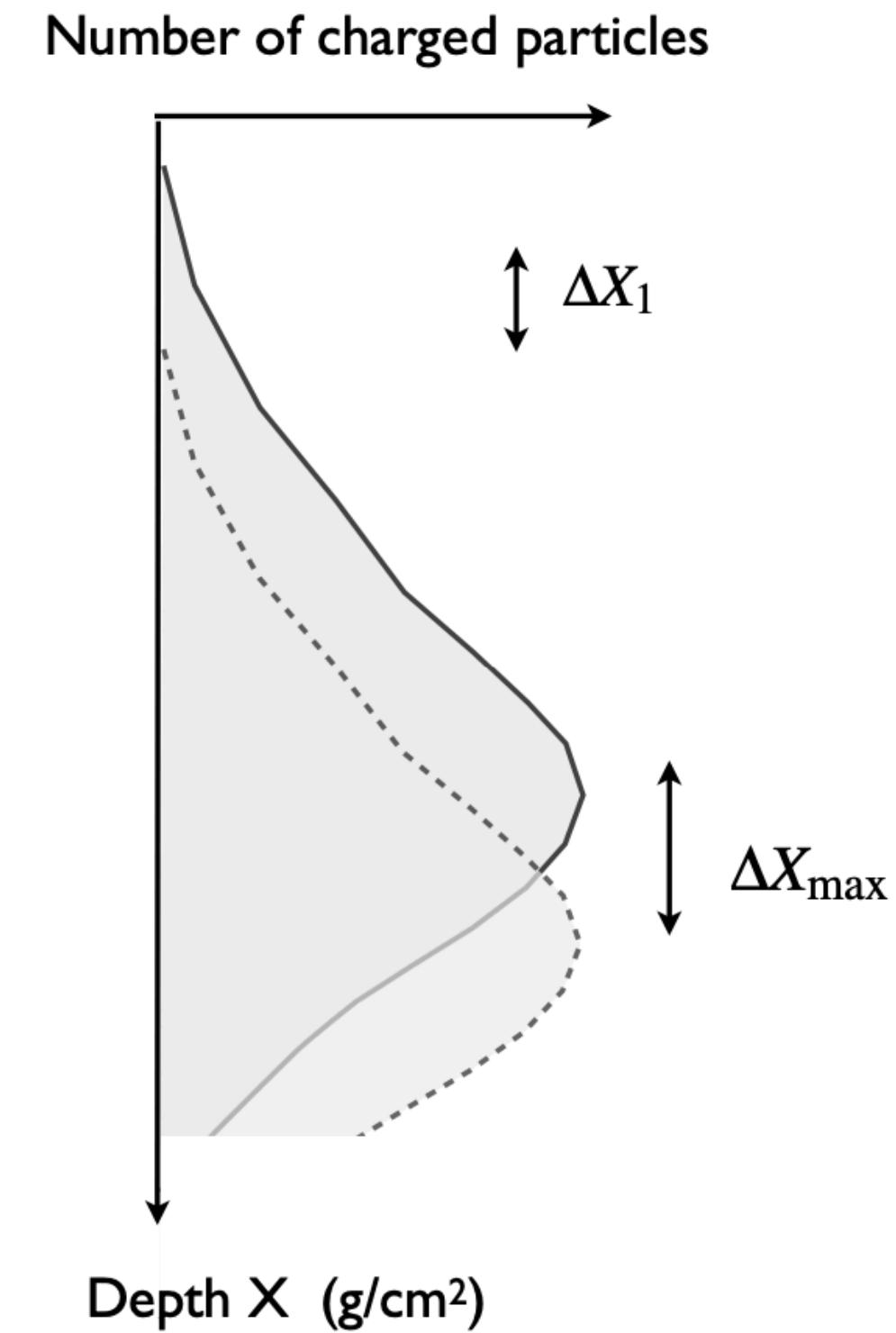
Mass composition results from the Pierre Auger Observatory [Engel 2024]:



(FD telescopes: PRD 90 (2014), 122005 & 122005, updated ICRC 2023)
(SD risetime: Phys. Rev. D96 (2017), 122003)



(AERA/radio: PRL & PRD 2023)
(SD DNN: to appear in PRL & PRD)



Challenges Posed by Smooth Energy Cutoffs

- ▶ The source energy cutoff is generally modeled as:

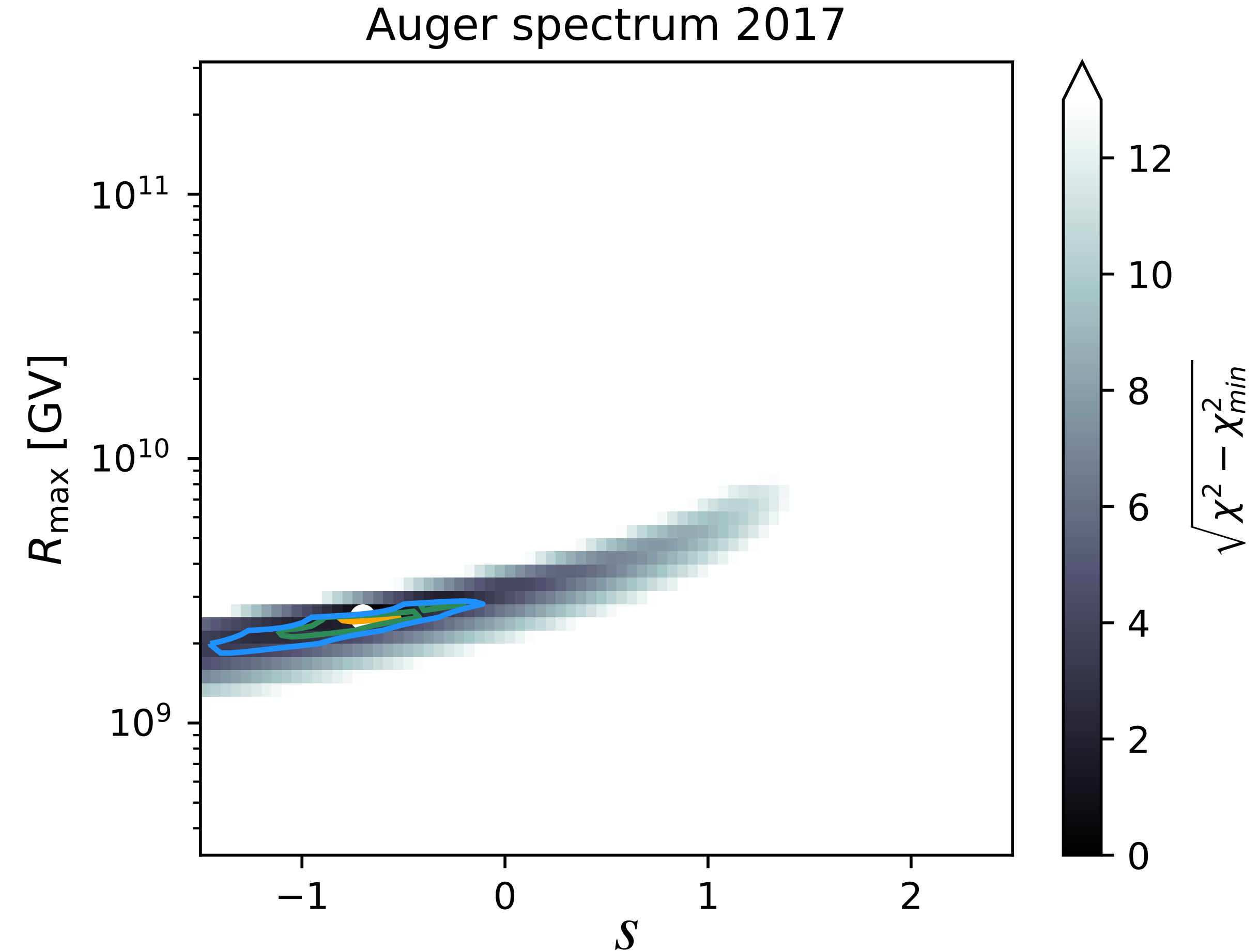
$$\phi(E) \propto E^{-s} \exp\left[-E/E_{\text{cut}}\right], \text{ with } s \geq 2$$

[e.g., Protheroe & Stanev 1999]

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

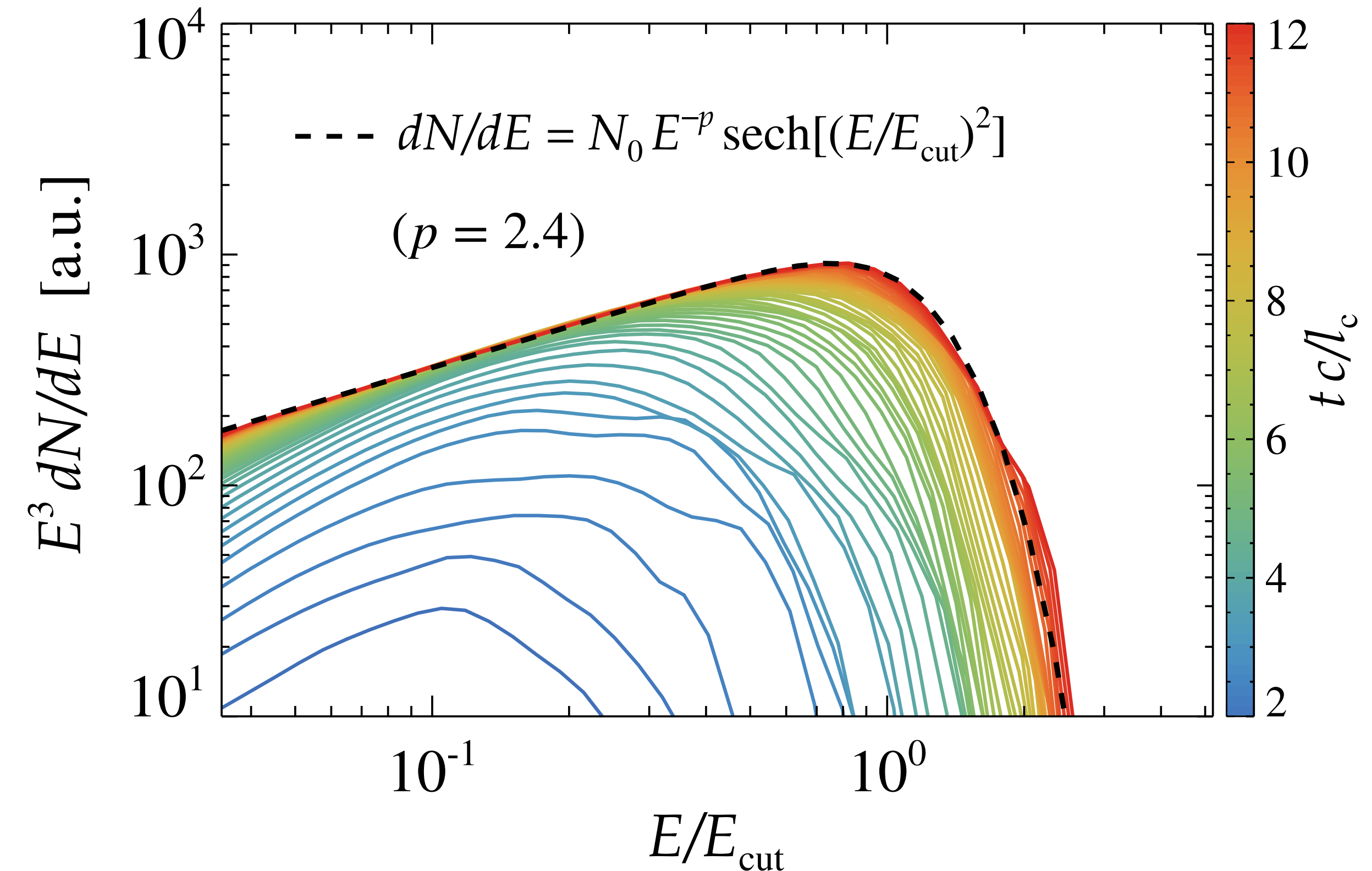
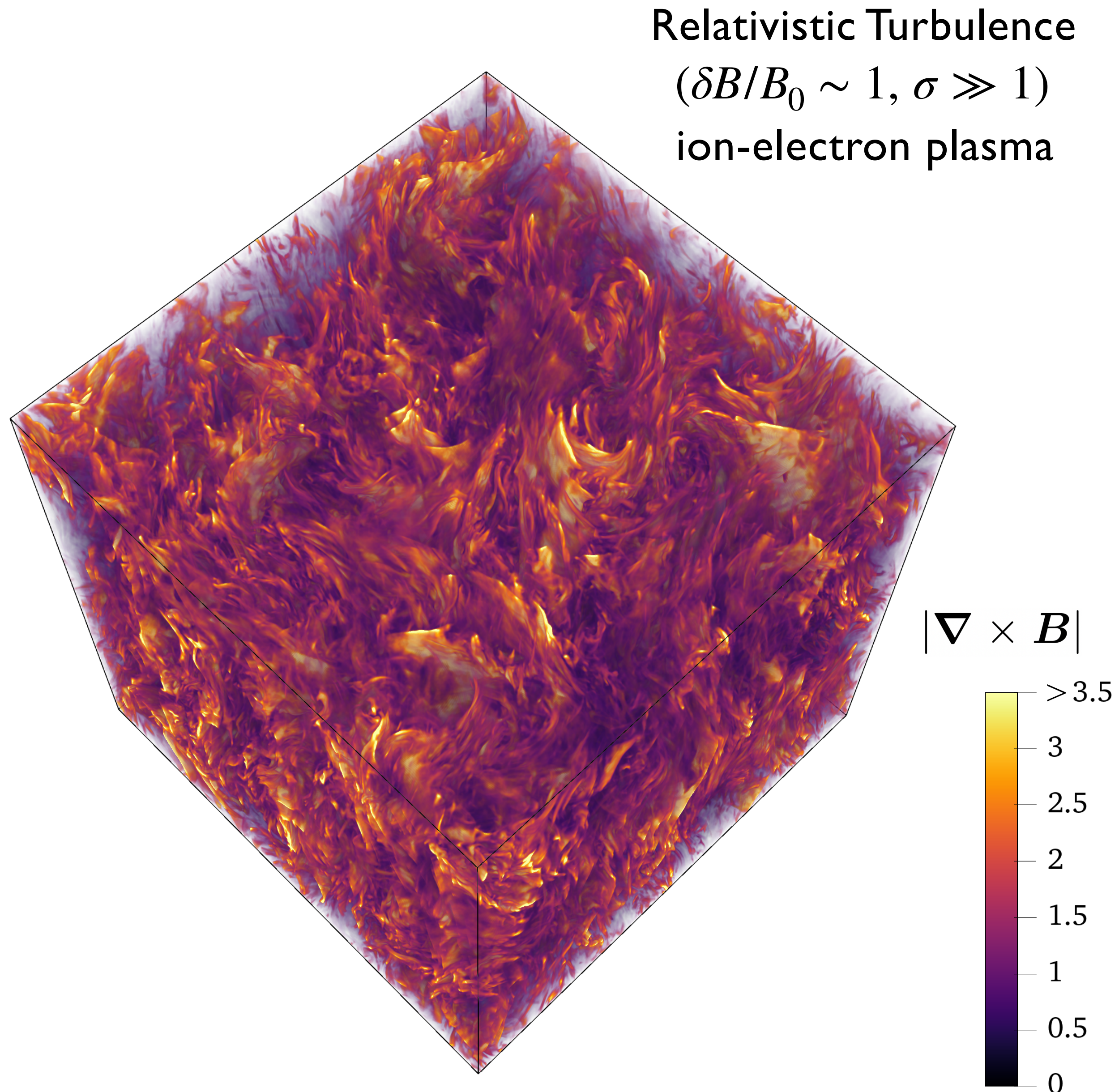
$$\phi(E) \propto E^{-s} \times \begin{cases} 1 & , E \leq E_{\text{cut}} \\ \exp\left[(1 - E/E_{\text{cut}})\right] & , E > E_{\text{cut}} \end{cases}$$

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



Heinze et al. 2019

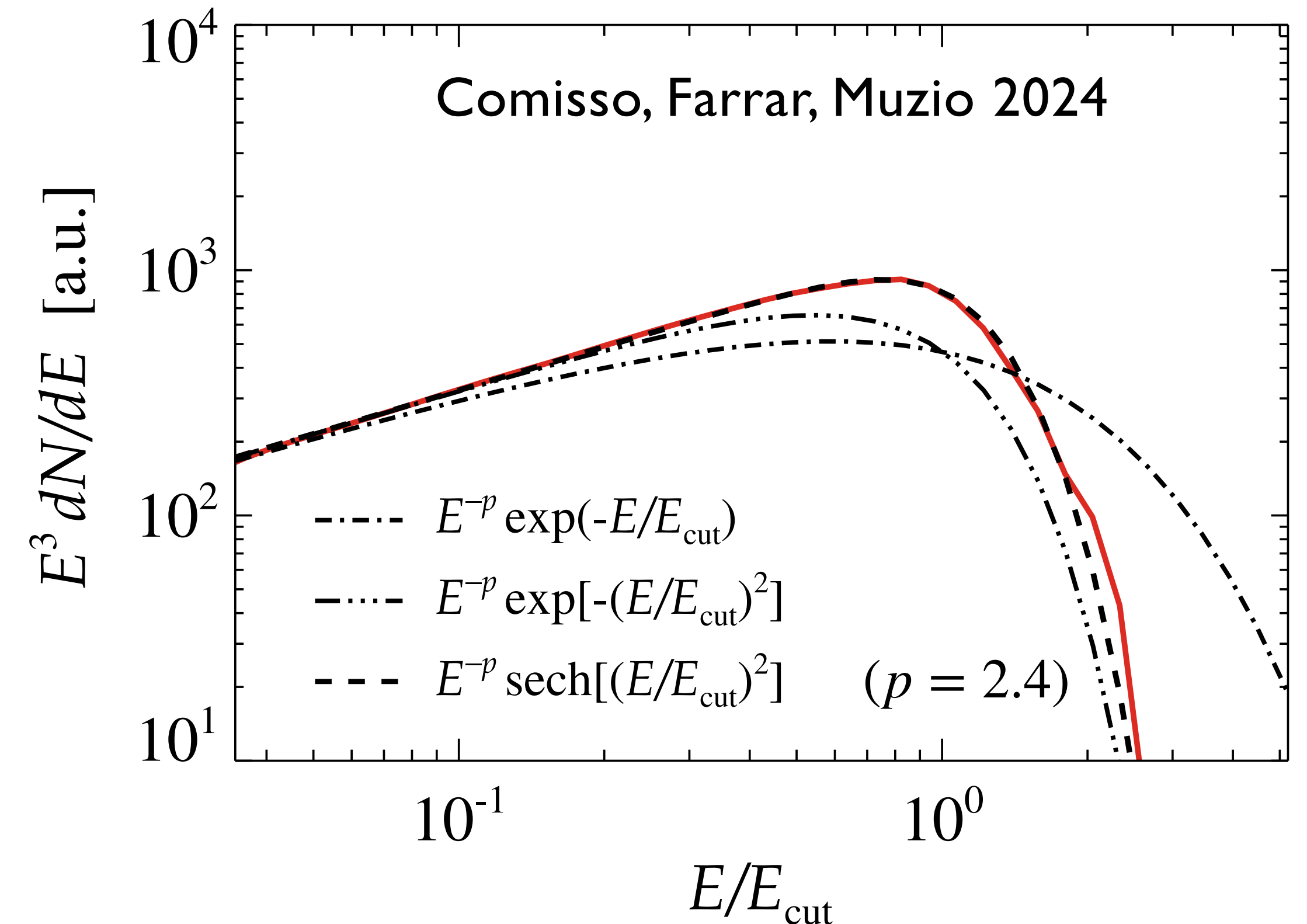
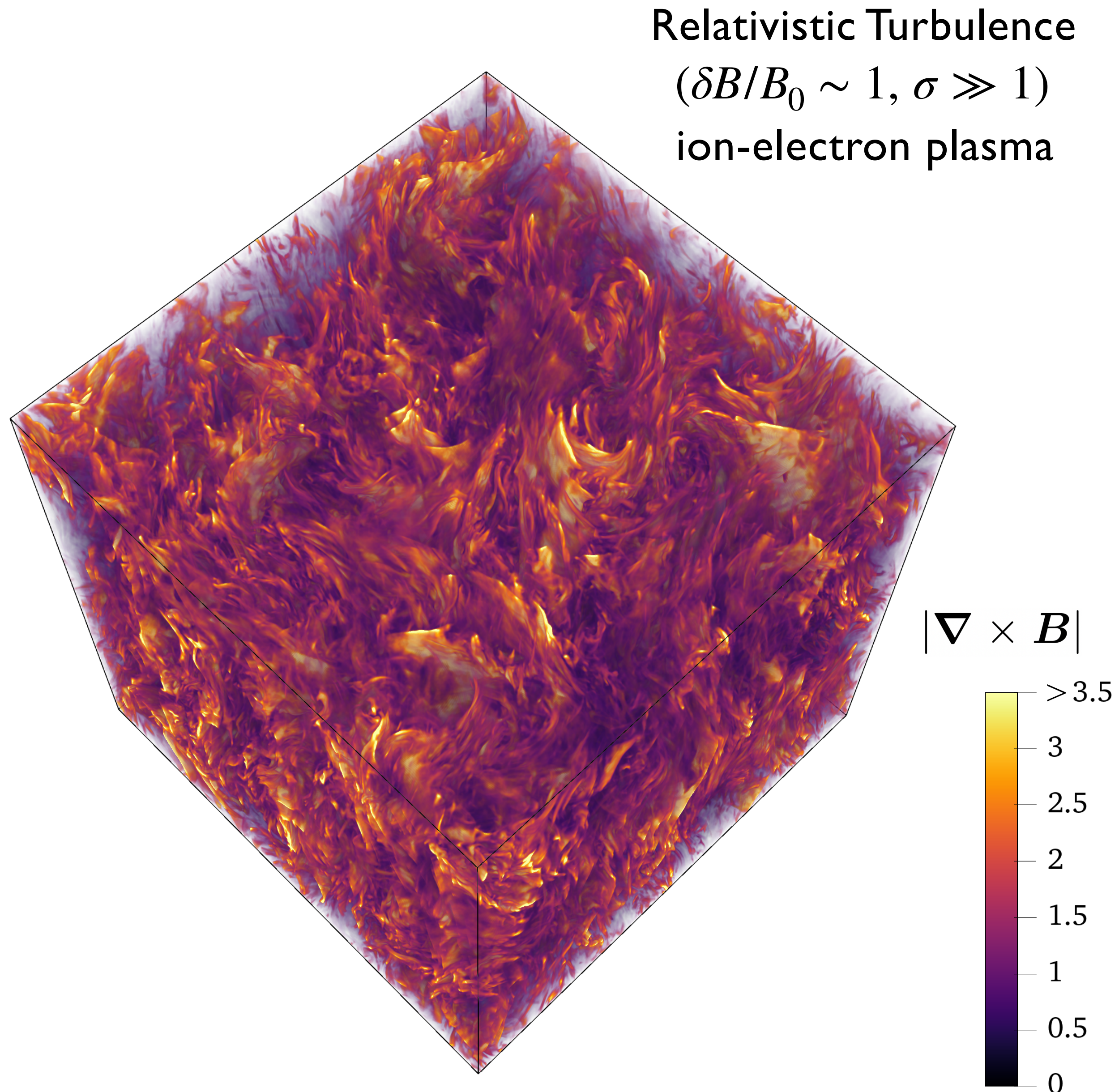
Ion Acceleration by Relativistic Turbulence



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

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

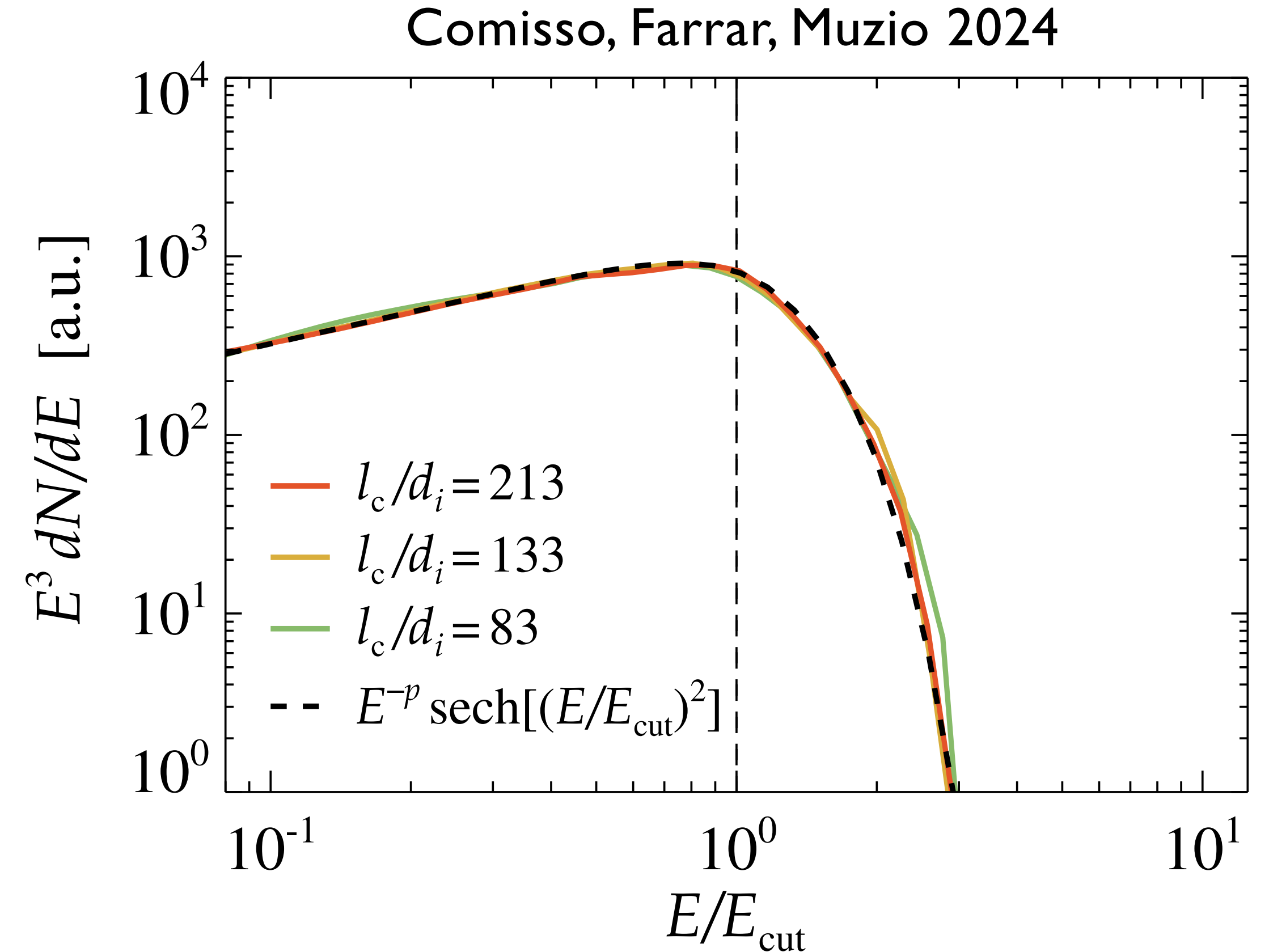
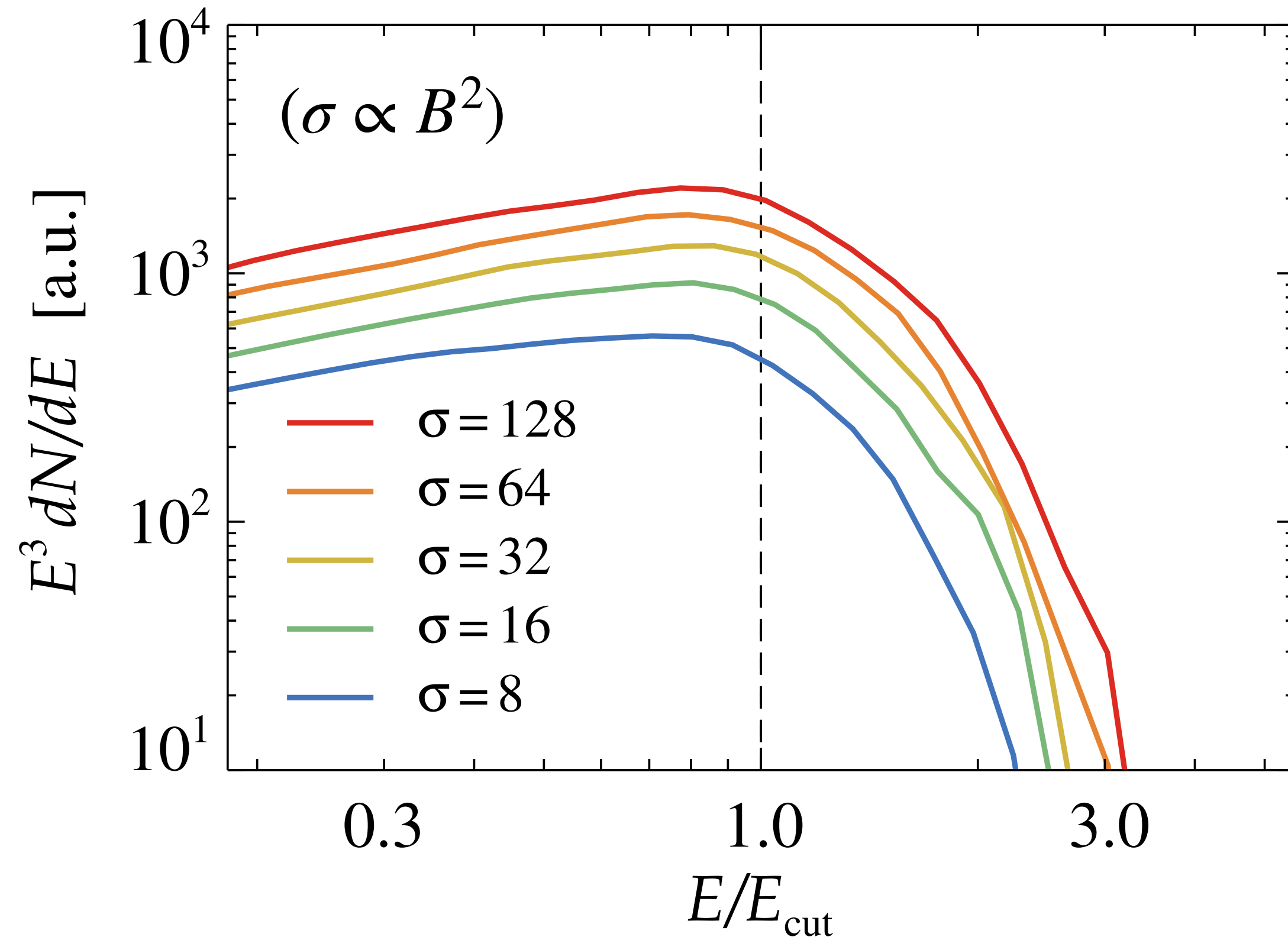
Ion Acceleration by Relativistic Turbulence



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

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

Ion Acceleration by Relativistic Turbulence: Cutoff Shape and Hillas Limit



- Cutoff $\text{sech}[(E/E_{\text{cut}})^2]$ scales with $E_{\text{cut}} = ZeR_{\text{cut}} = Ze(B_{\text{rms}}\kappa l_c)$, where $\kappa = 0.65$ from the fits
- Magnetized turbulence does accelerate particles to the “Hillas limit” if one assumes $l_c = R_{\text{size}}$

Ion Acceleration by Relativistic Turbulence: Particle Escape Timescale

- 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

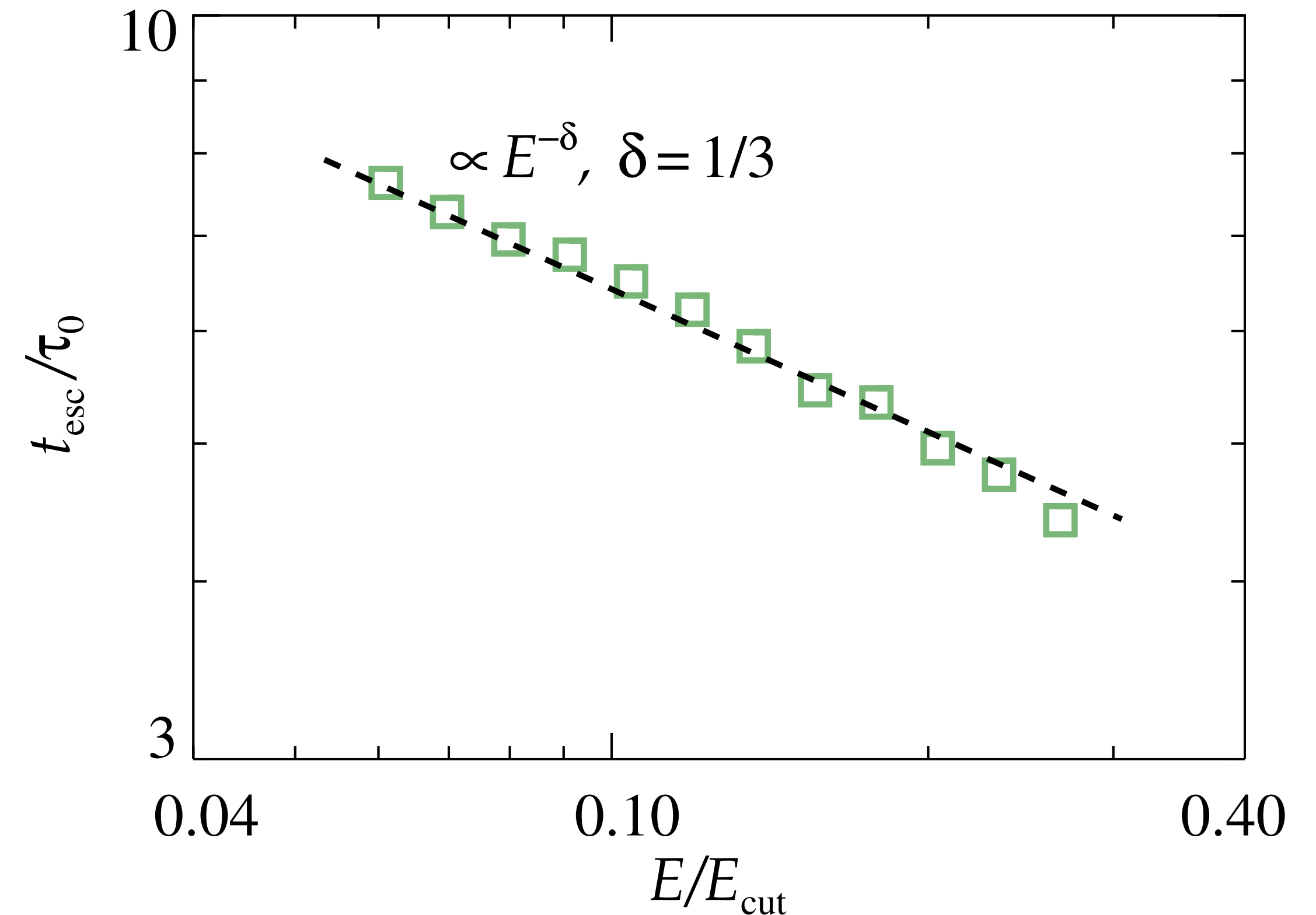
$$\phi(E) = \frac{dN}{dEdt} = \frac{1}{t_{\text{esc}}} \frac{dN}{dE} \propto E^{-s} \text{sech} \left[\left(E/E_{\text{cut}} \right)^2 \right]$$

with $s = p - \delta \sim 2.1$

$p \sim 2.4$

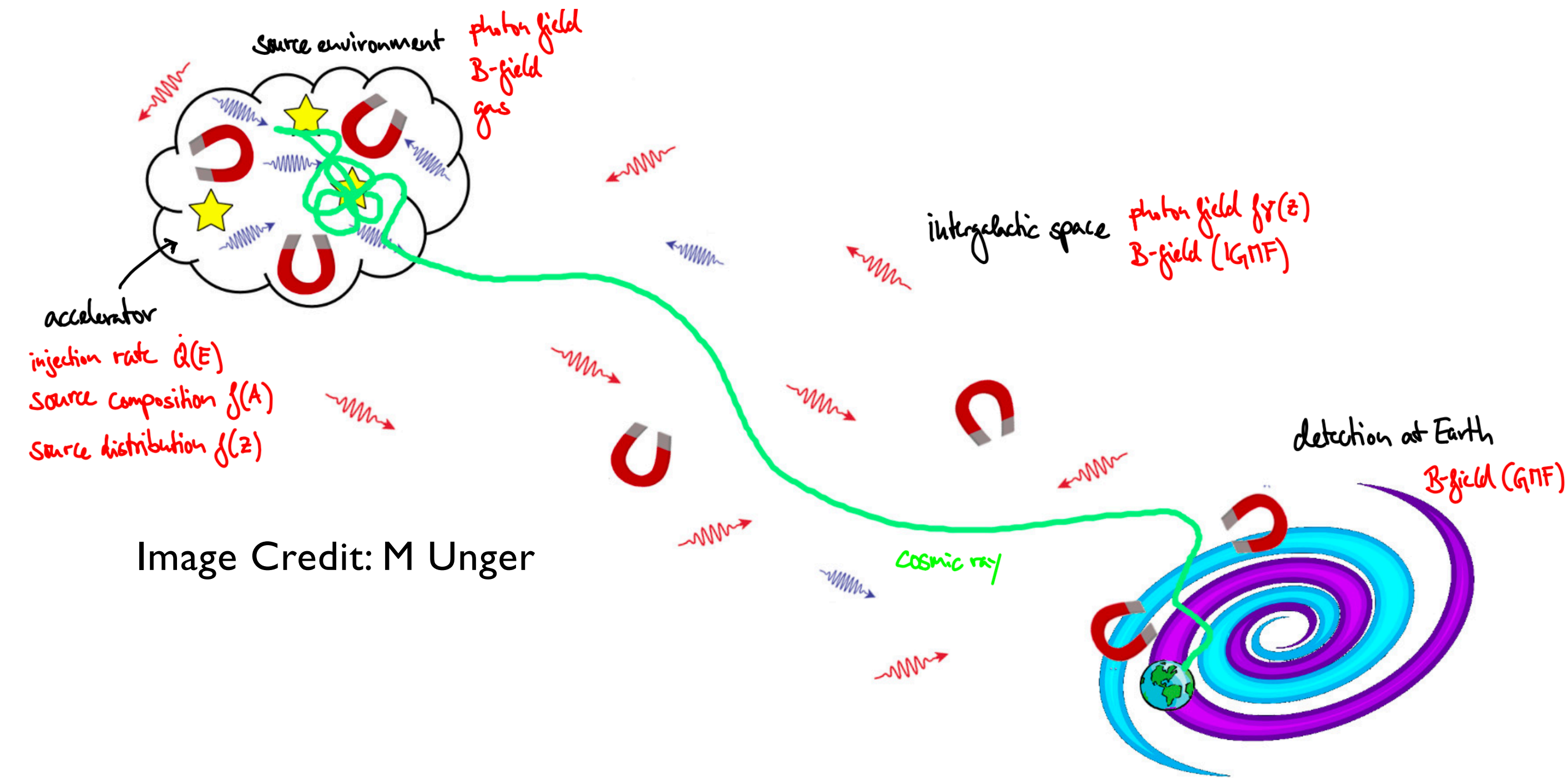
$\delta \sim 1/3$ from PIC simulations of highly magnetized ($\sigma \gg 1$) turbulence

Comisso, Farrar, Muzio 2024

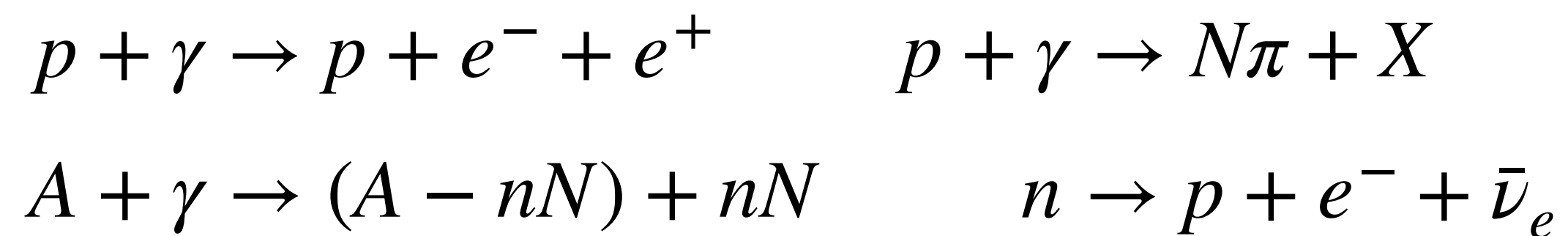


(see also test particle simulations of large amplitude turbulence, e.g. Casse+ 01, Pezzi+ 22, Lemoine 23)

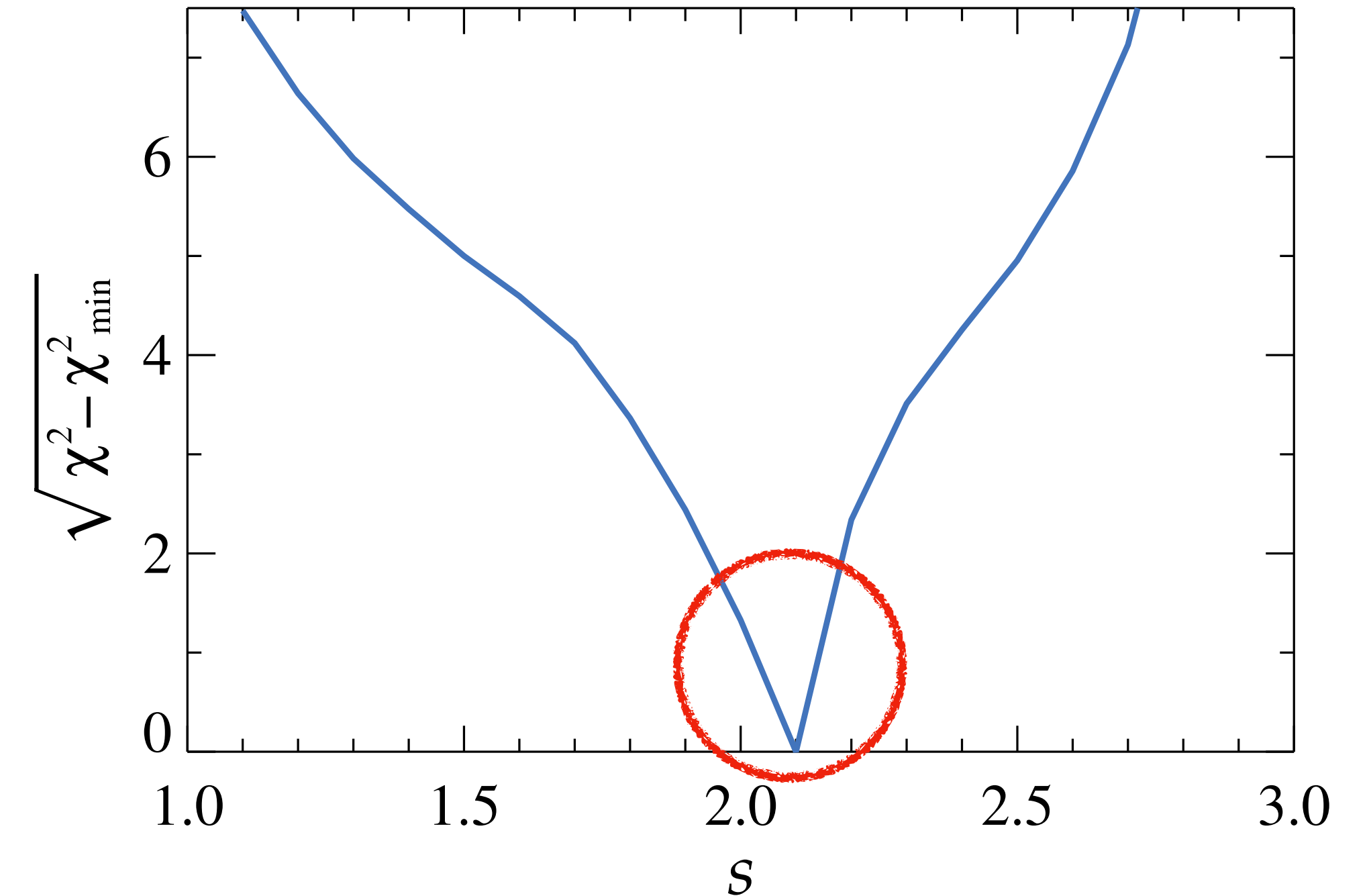
Ion Acceleration by Relativistic Turbulence: Matching UHECR Observations



- Particle propagation considering relevant particle interactions, e.g.:

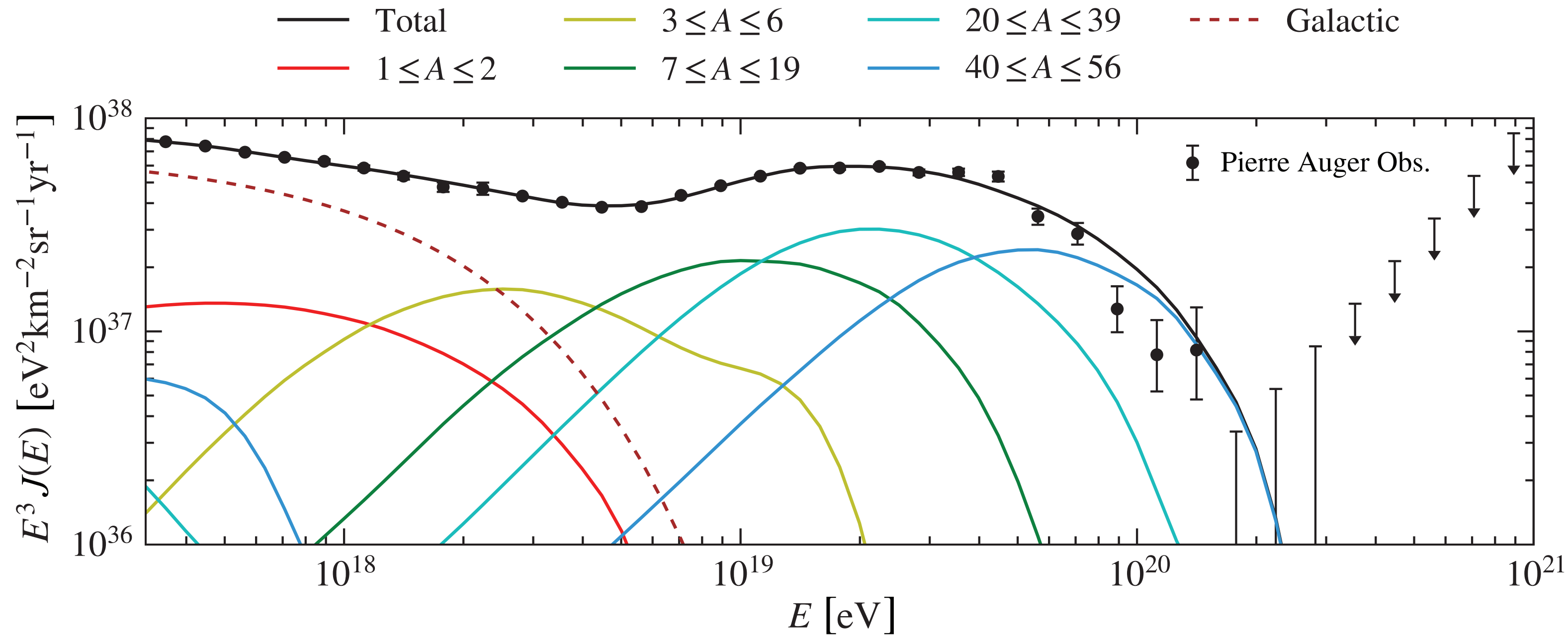


Comisso, Farrar, Muzio 2024



$$\chi^2 = \sum_i^{N_{\text{spec}}} \frac{(J_{m,i} - J_i)^2}{\sigma_{J,i}^2} + \sum_j^{N_{\text{comp}}} \frac{(\langle \ln A \rangle_{m,j} - \langle \ln A \rangle_j)^2}{\sigma_{\langle \ln A \rangle,j}^2} + \sum_j^{N_{\text{comp}}} \frac{(\text{Var}(\ln A)_{m,j} - \text{Var}(\ln A)_j)^2}{\sigma_{\text{Var}(\ln A),j}^2}$$

UHECR Spectrum and Composition Explained by Turbulent Acceleration Model



► The sharp cutoff restricts the energy range where each element group contributes significantly $\Rightarrow$ as required by the narrow $\ln A$ distribution

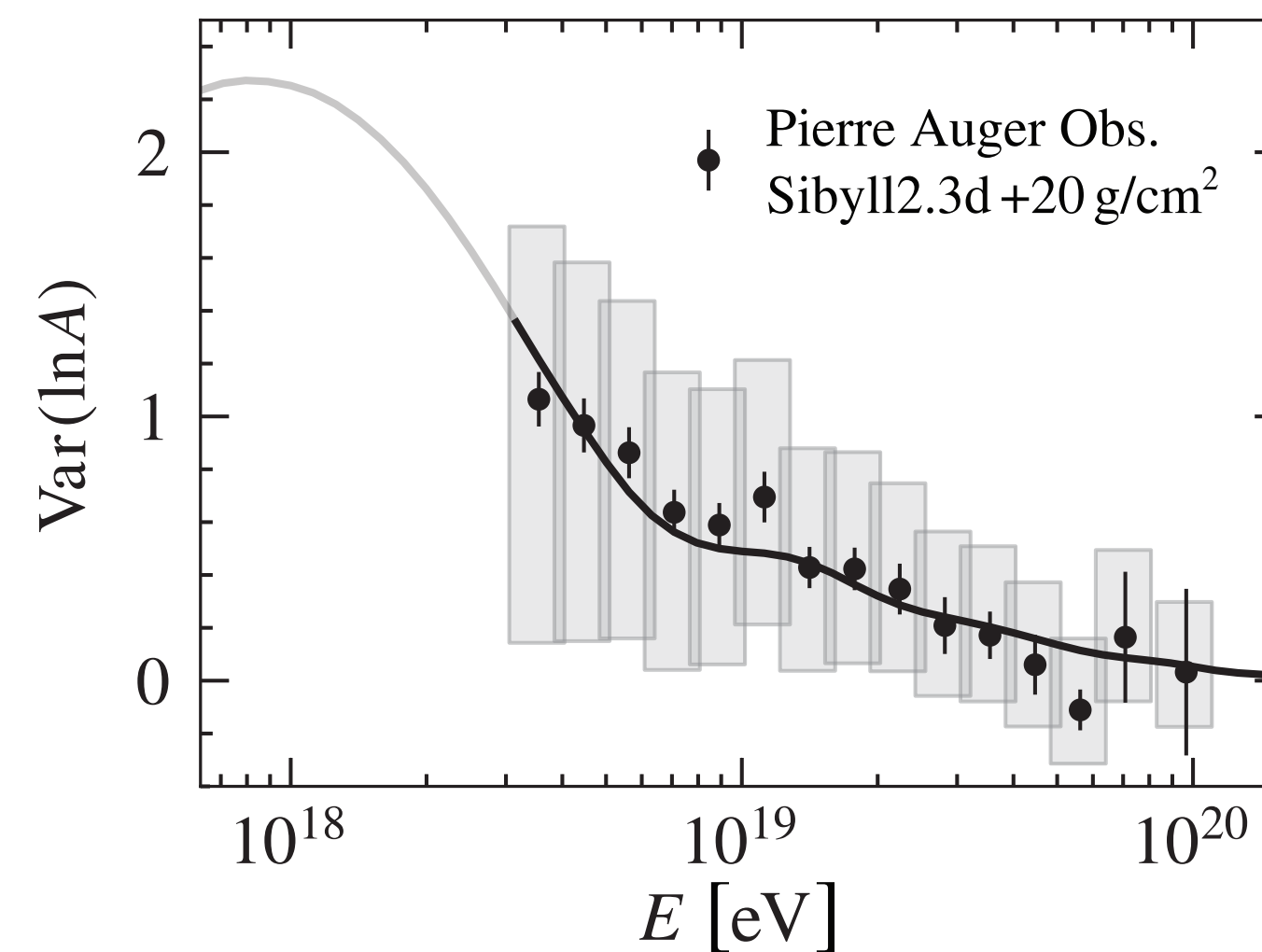
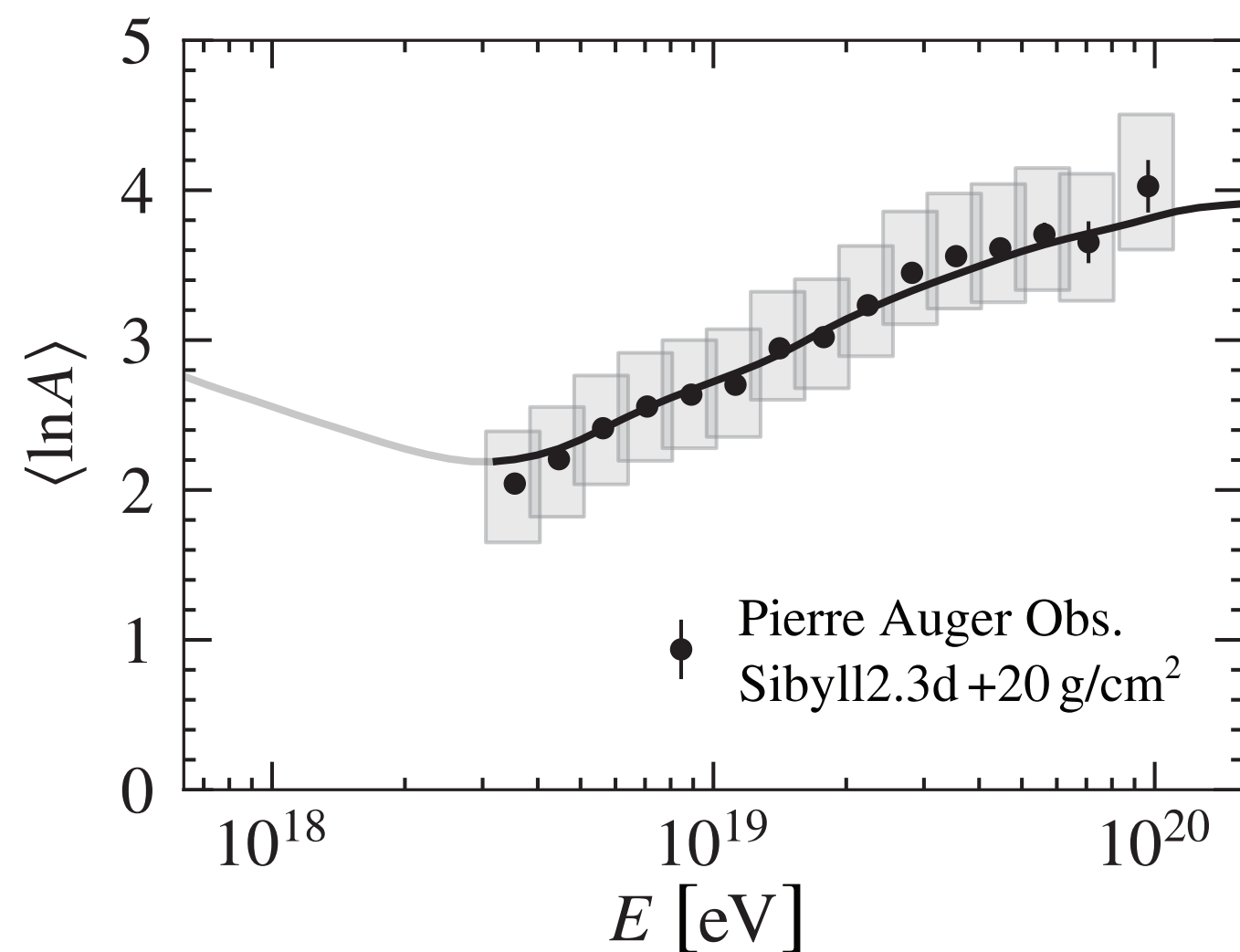
► The resulting best fit yields:

$$s \simeq 2.1$$

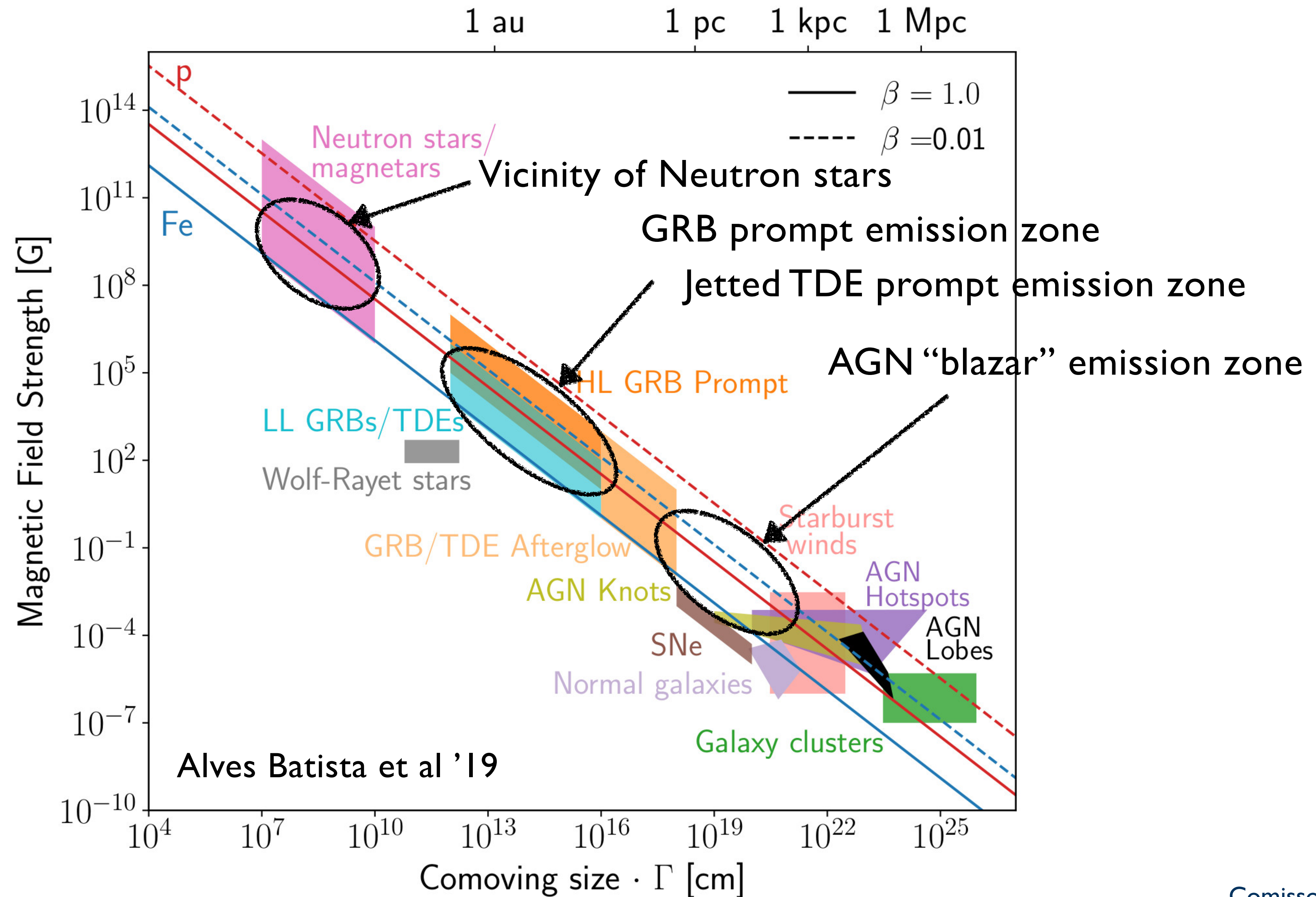
$$R_{\text{cut}} \simeq 6.3 \times 10^{18} \text{ V}$$

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

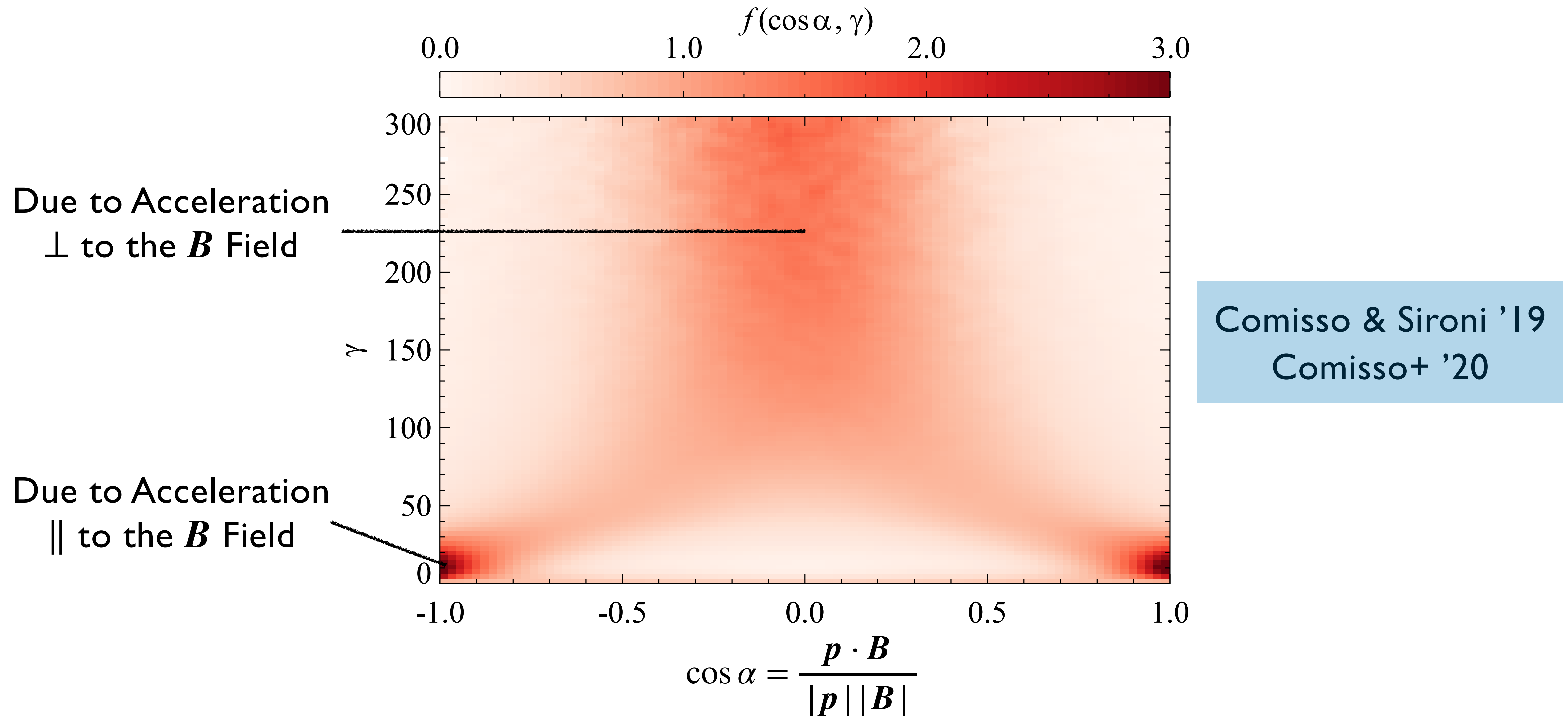
Comisso, Farrar, Muzio 2024



Potential Hosts of Magnetically Dominated Turbulence

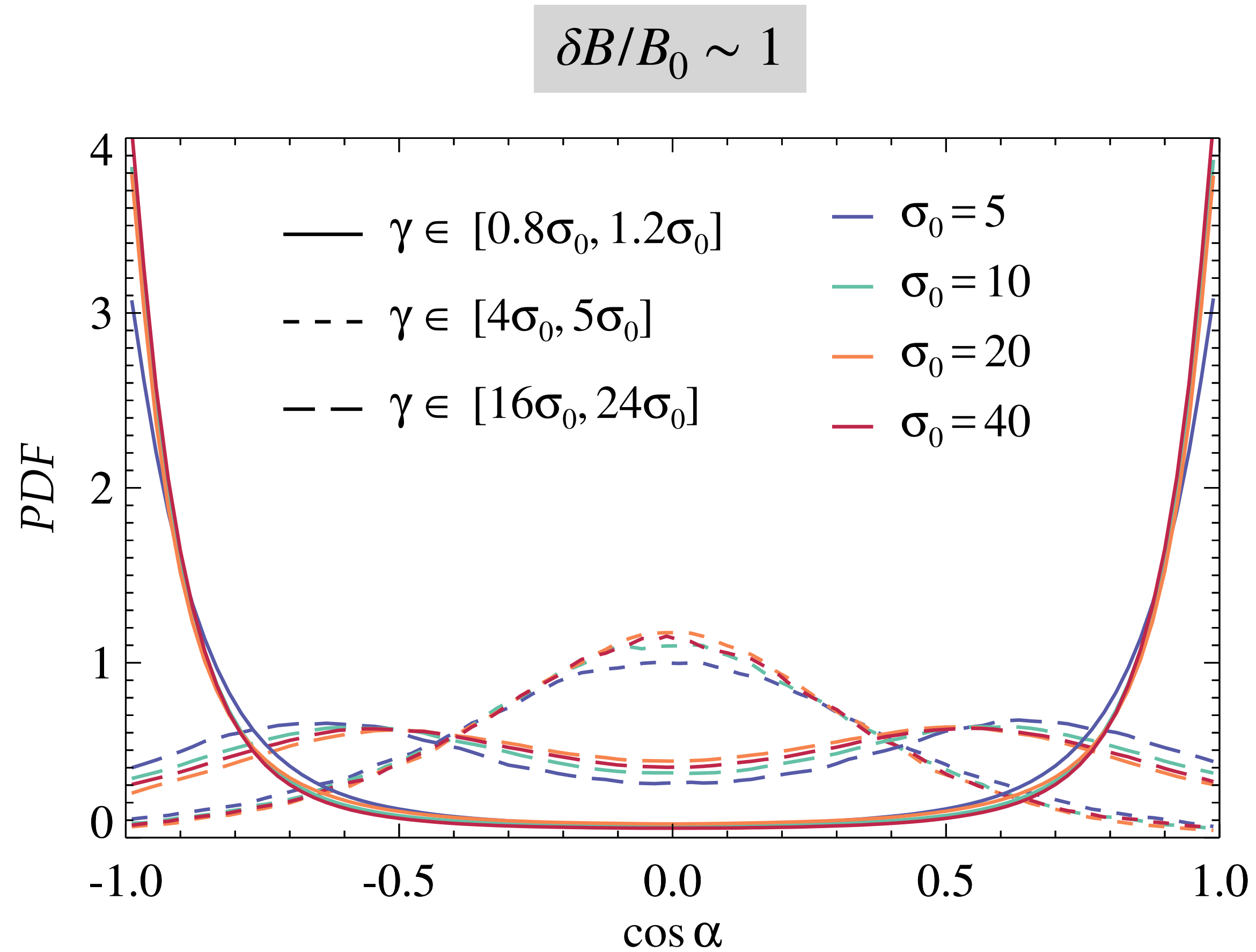


Particle Acceleration by Magnetized Turbulence: back to Pitch-Angle Anisotropy

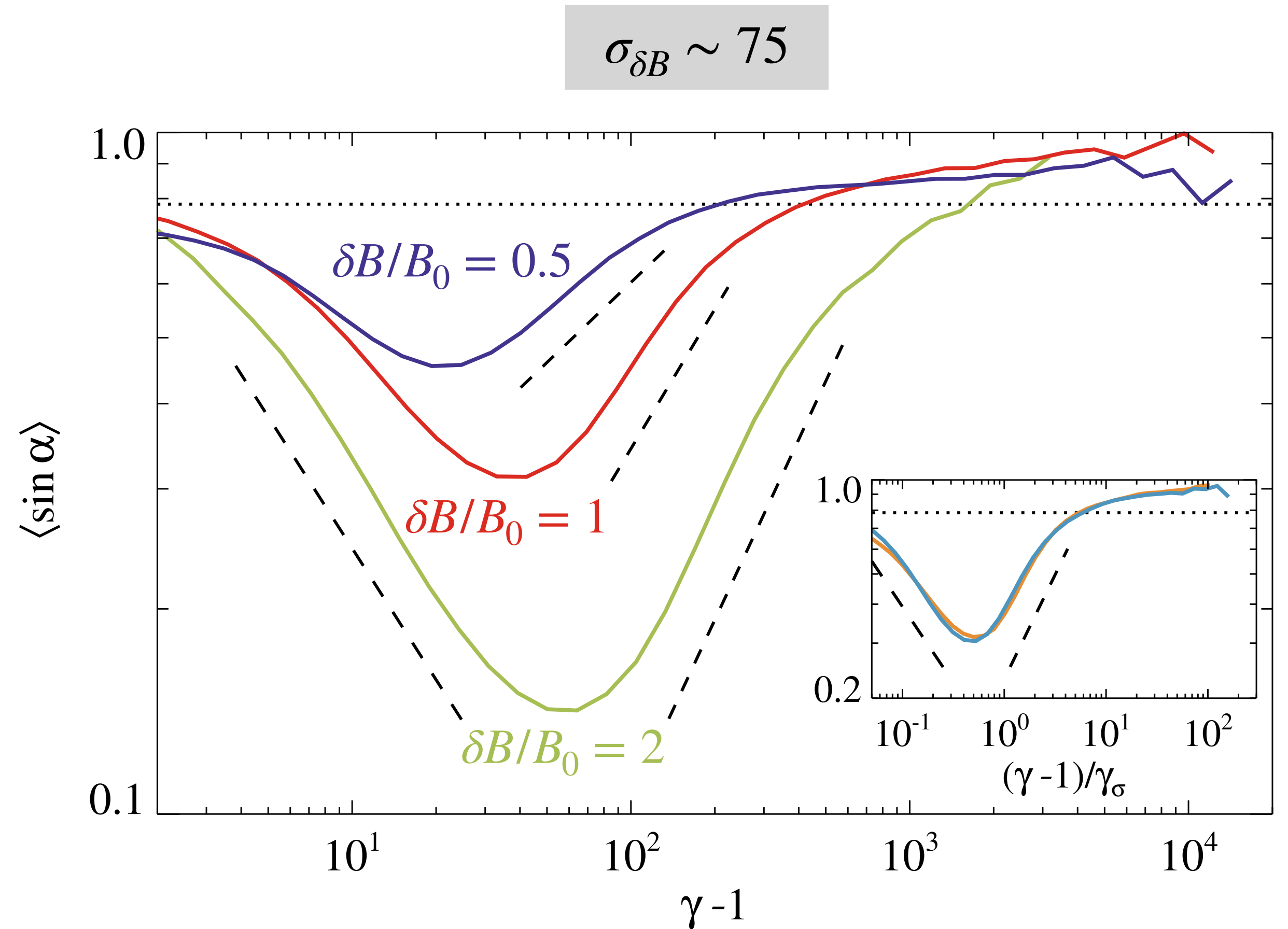


- Strongly Magnetized Turbulence Produces Anisotropic Pitch-Angle Distributions

Pitch-Angle Anisotropy Controlled by Magnetization and Guide Field Strength



Comisso & Sironi '19

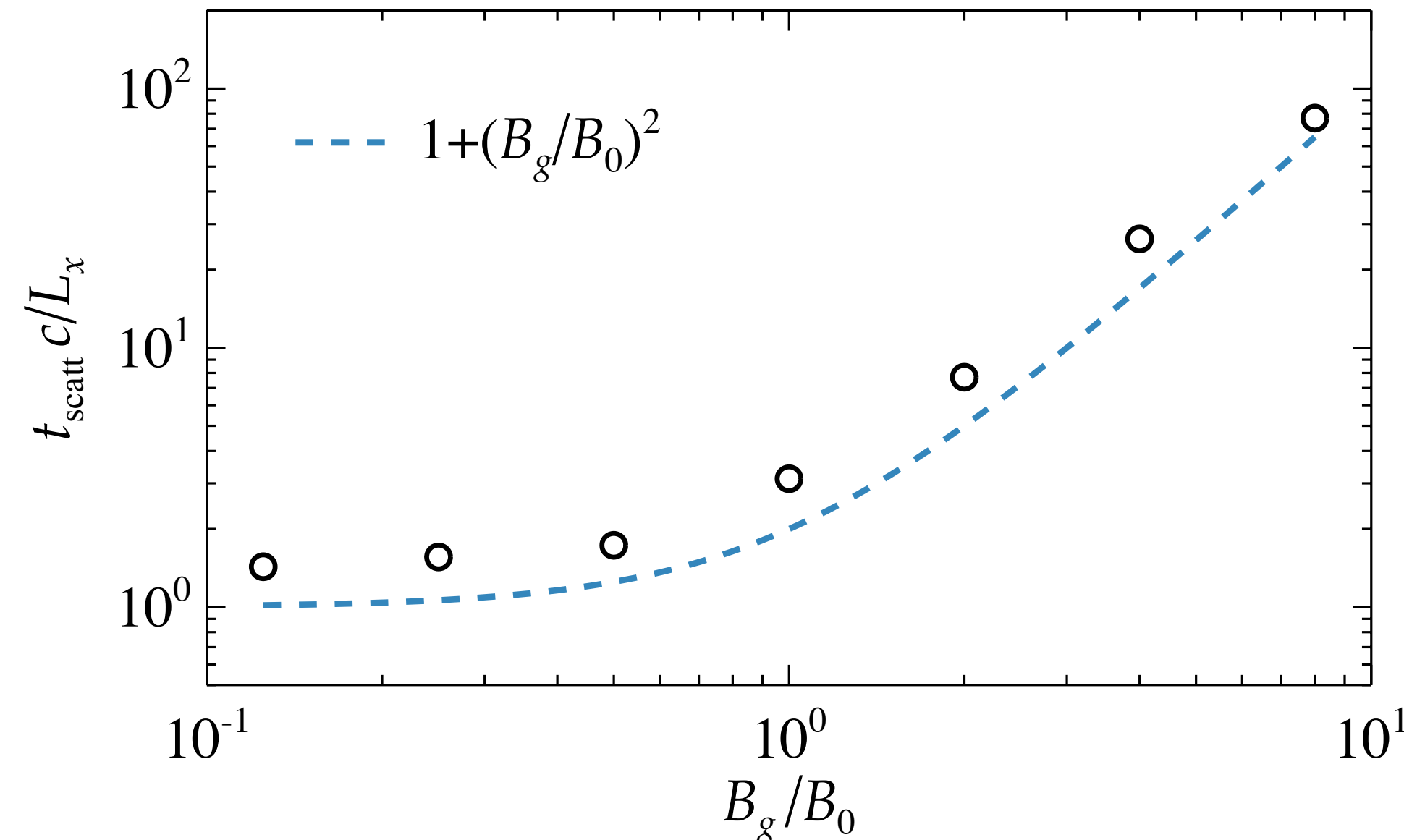
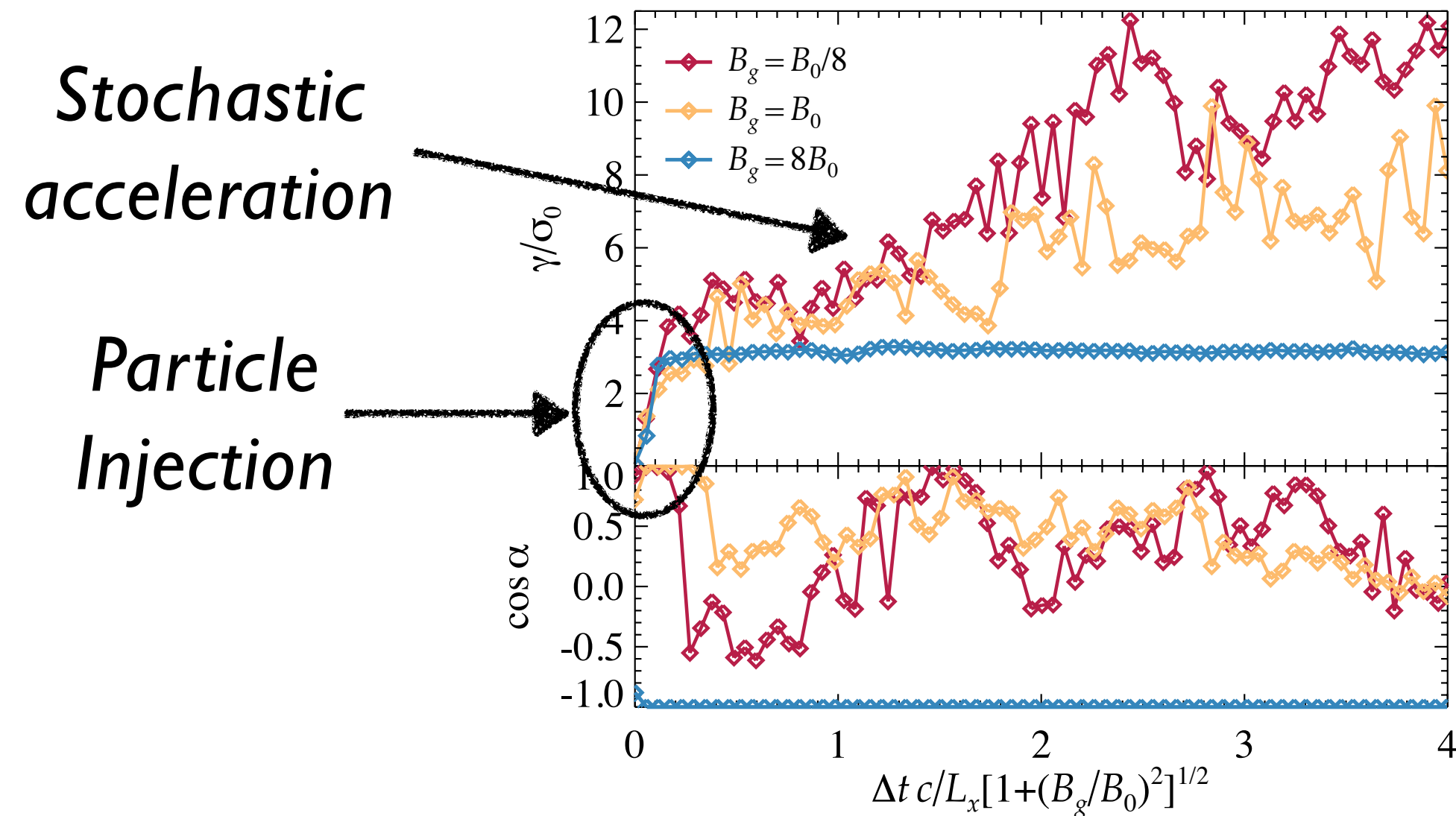
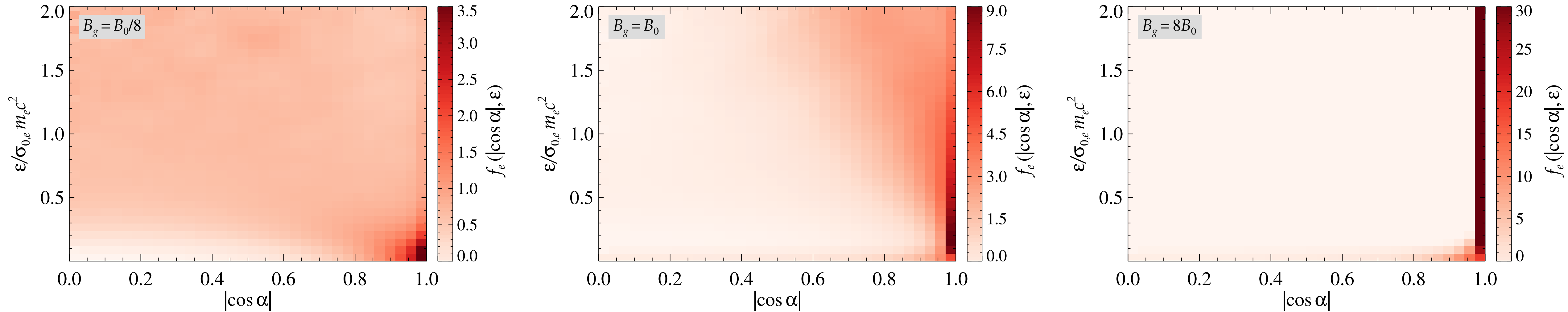


Comisso+ '20

- The pitch-angle anisotropy increases with the magnetization and stronger guide magnetic fields

Pitch-Angle Anisotropy Imprinted by Magnetic Reconnection

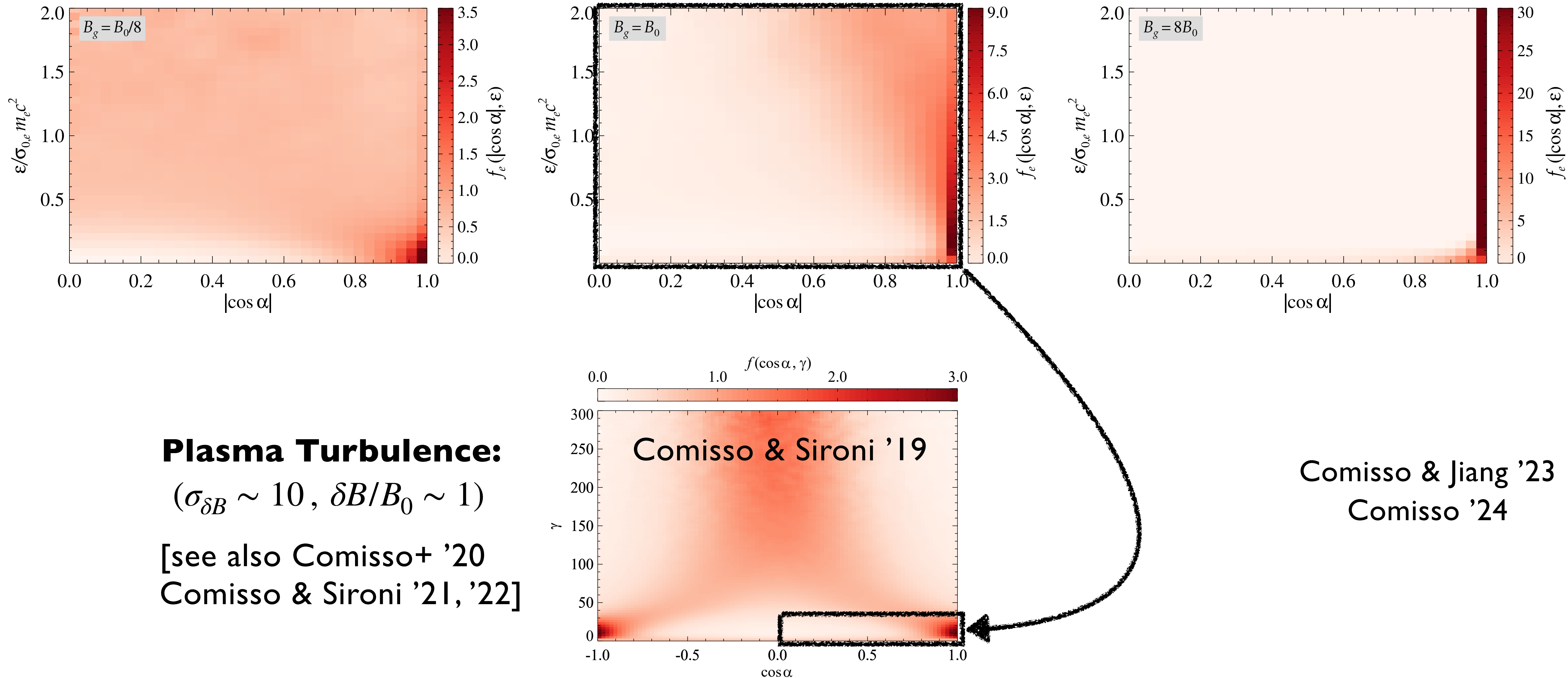
Anisotropic Pitch-Angle Distributions Produced by **Magnetic Reconnection**:



Comisso & Jiang '23
Comisso '24

Pitch-Angle Anisotropy Imprinted by Magnetic Reconnection

Anisotropic Pitch-Angle Distributions Produced by **Magnetic Reconnection**:



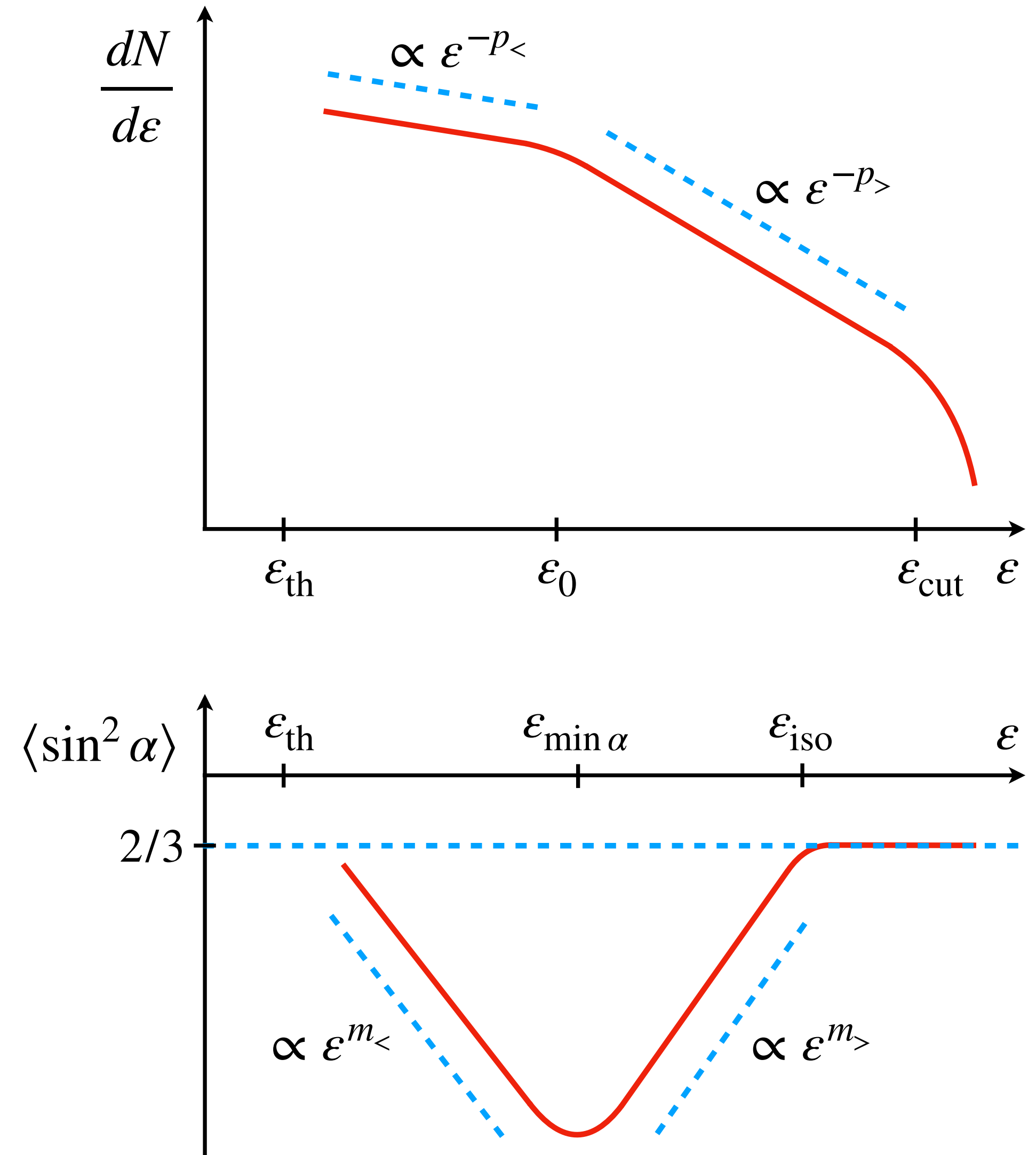
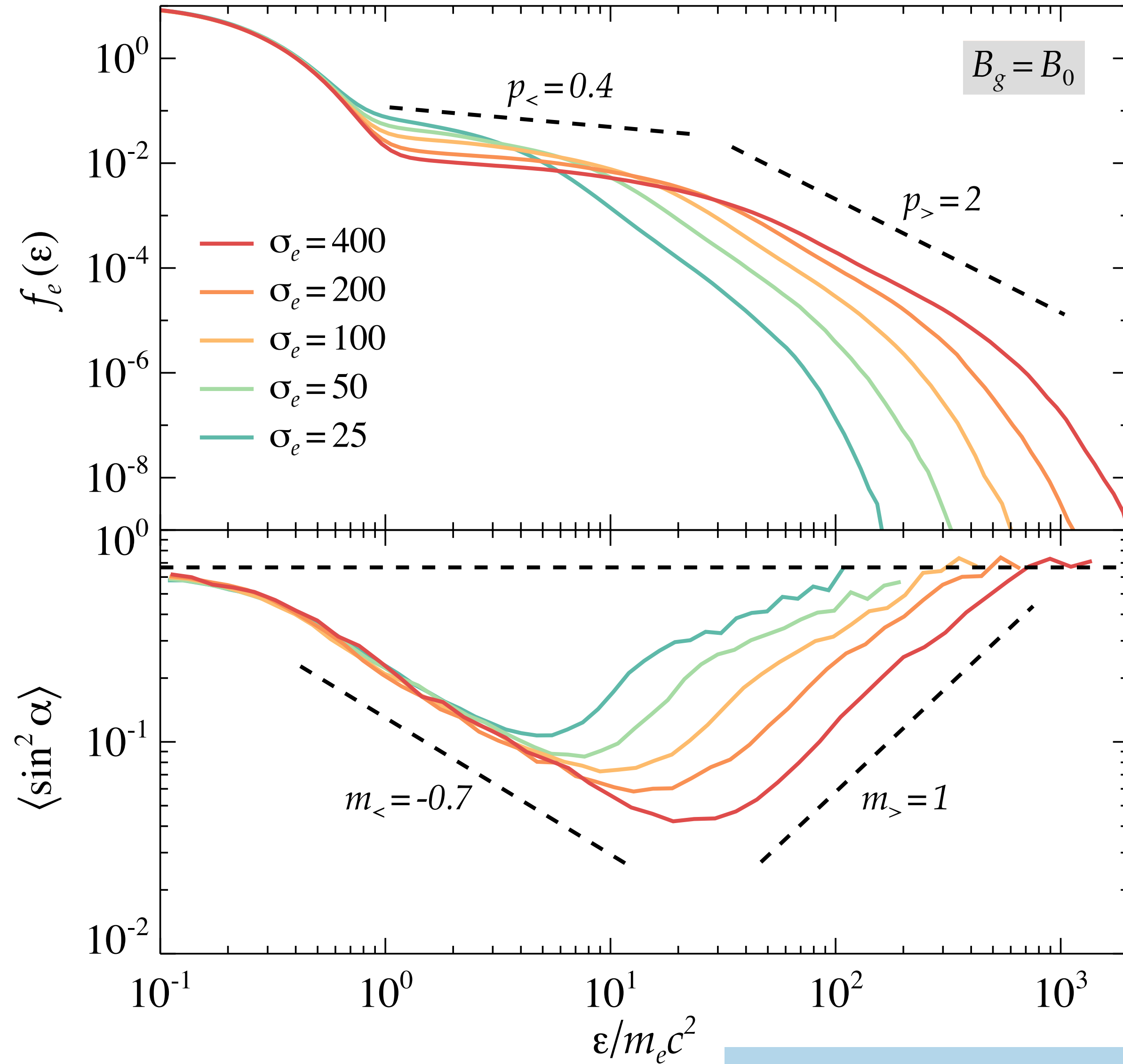
Plasma Turbulence:

$(\sigma_{\delta B} \sim 10, \delta B/B_0 \sim 1)$

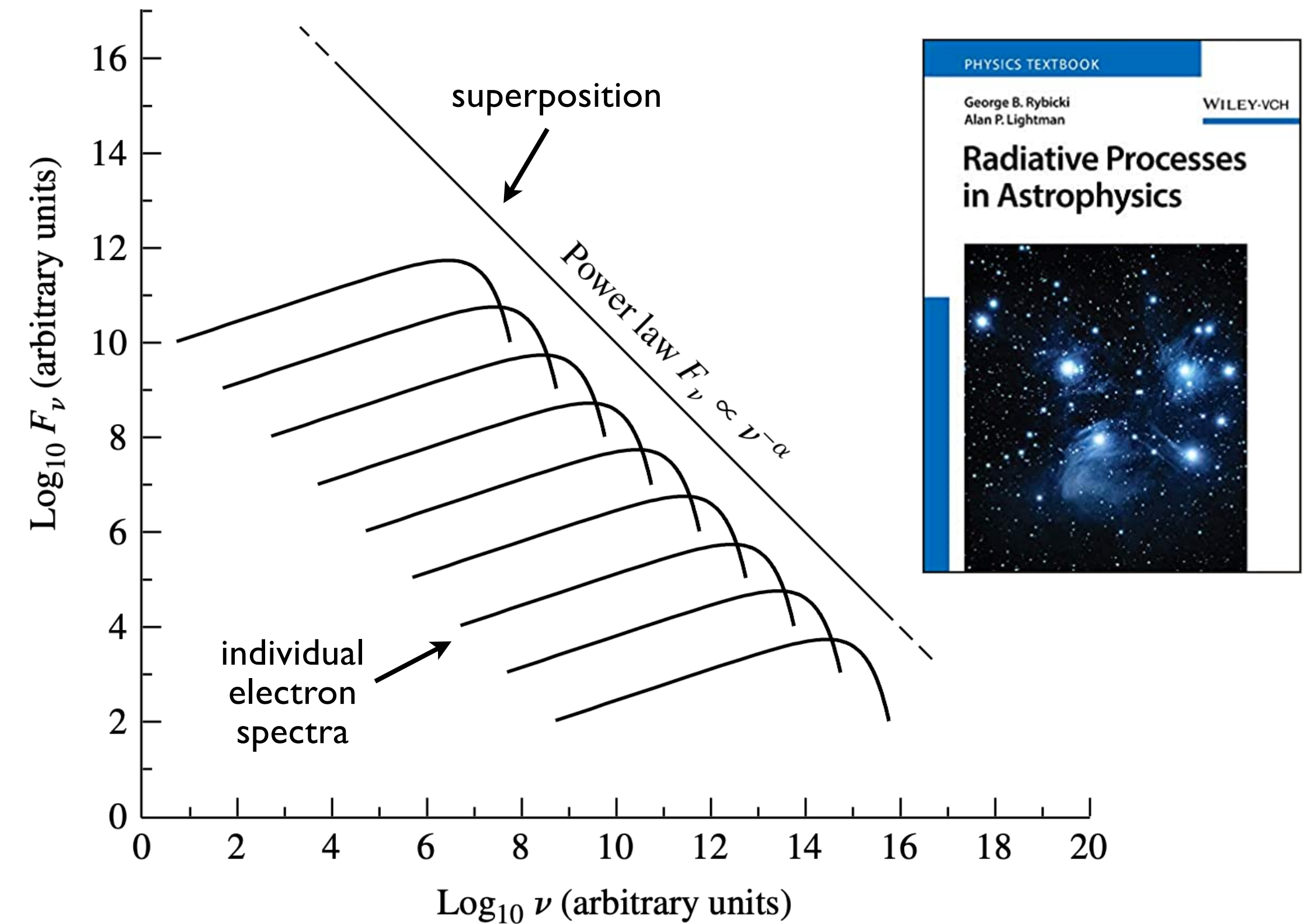
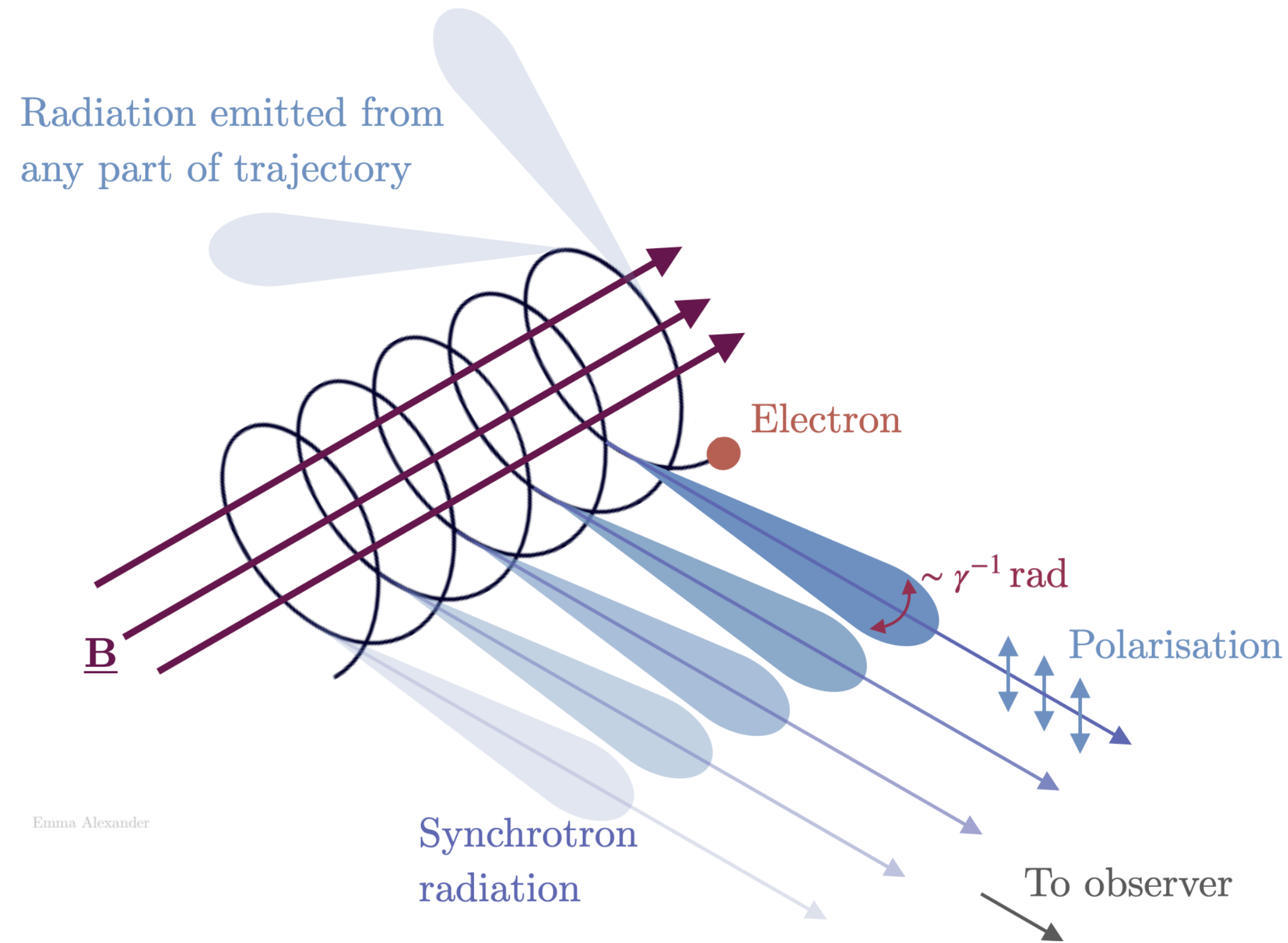
[see also Comisso+ '20
Comisso & Sironi '21, '22]

Comisso & Jiang '23
Comisso '24

Concurrent Particle Acceleration and Pitch-Angle Anisotropy



Synchrotron Radiation from the Accelerated Electrons



Synchrotron power radiated by one electron:

$$P_{\text{syn}} = 2\sigma_T c (B^2/8\pi) \gamma^2 \sin^2 \alpha$$

Typical frequency of synchrotron photons:

$$\nu \sim \gamma^2 \nu_L \sin \alpha \quad (\nu_L = eB/2\pi m_e c)$$

Particles distributed as

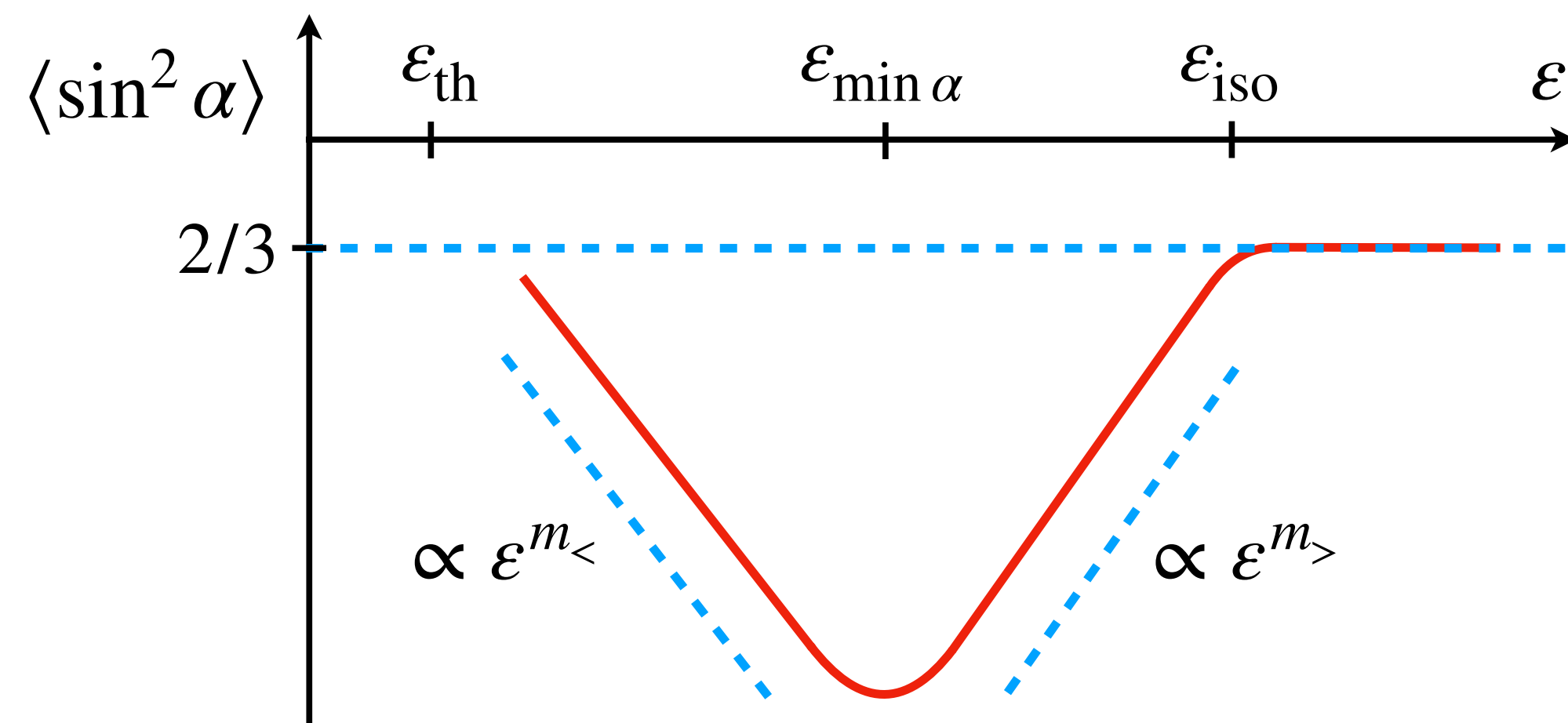
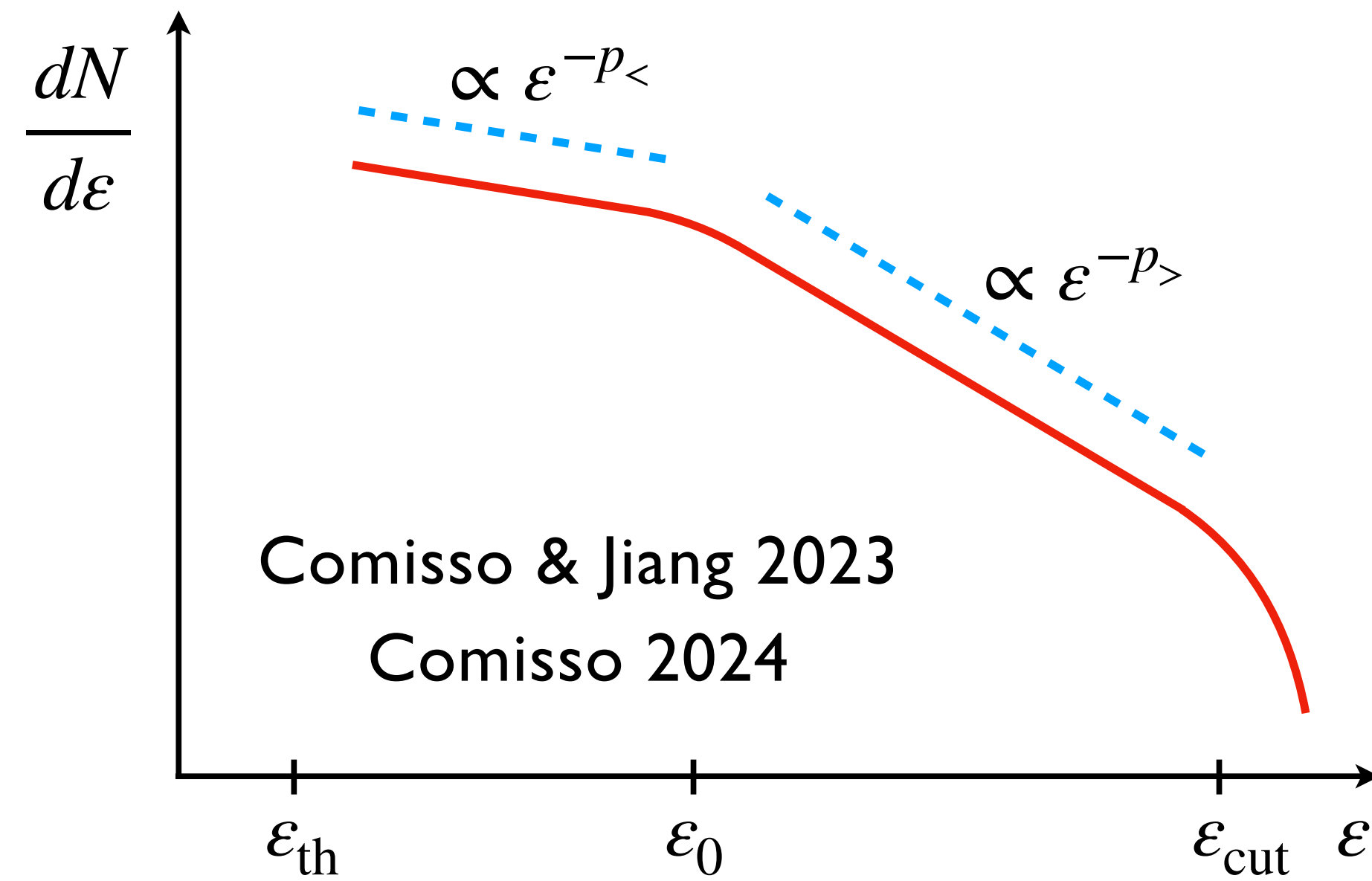
$$dN/d\gamma \propto \gamma^{-p}$$

lead to synchrotron energy flux

$$\nu F_\nu \propto \nu^{(3-p)/2}$$

(Hp: $\sin \alpha$ doesn't depend on γ)

Modification of the Spectral Energy Distribution



For ultra-relativistic particles ($\gamma \gg 1$):

$$N_\gamma \sim \gamma(dN/d\gamma) \propto \gamma^{1-p}$$

$$P_{\text{syn}} = 2\sigma_T c (B^2/8\pi) \gamma^2 \sin^2 \alpha \propto \gamma^{2+m}$$

$$\nu F_\nu \sim N_\gamma P_{\text{syn}} \propto \gamma^{3-p+m}$$

$$\nu \sim \gamma^2 \nu_L \sin \alpha \propto \gamma^{2+m/2} \quad (\nu_L = eB/2\pi m_e c)$$

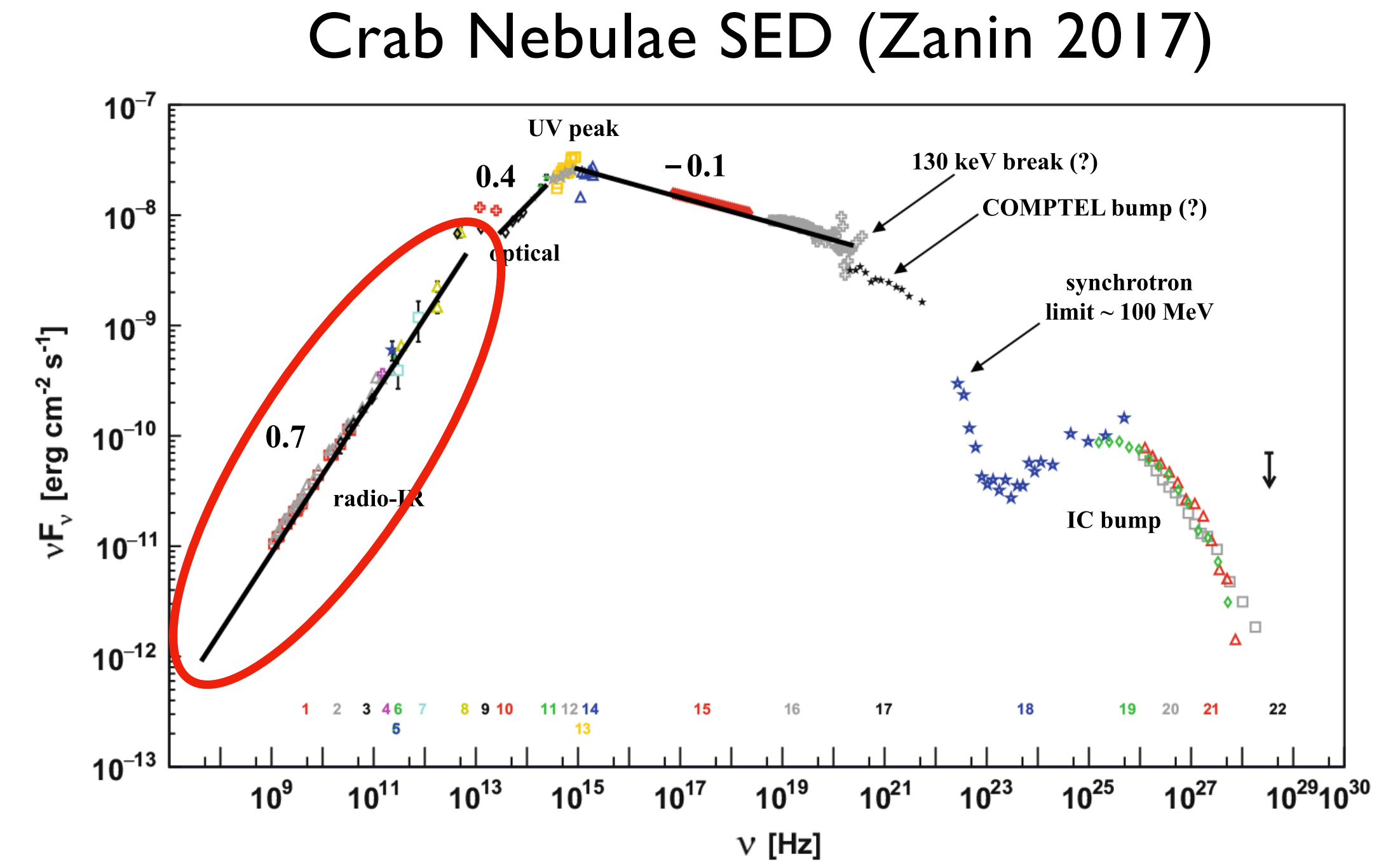
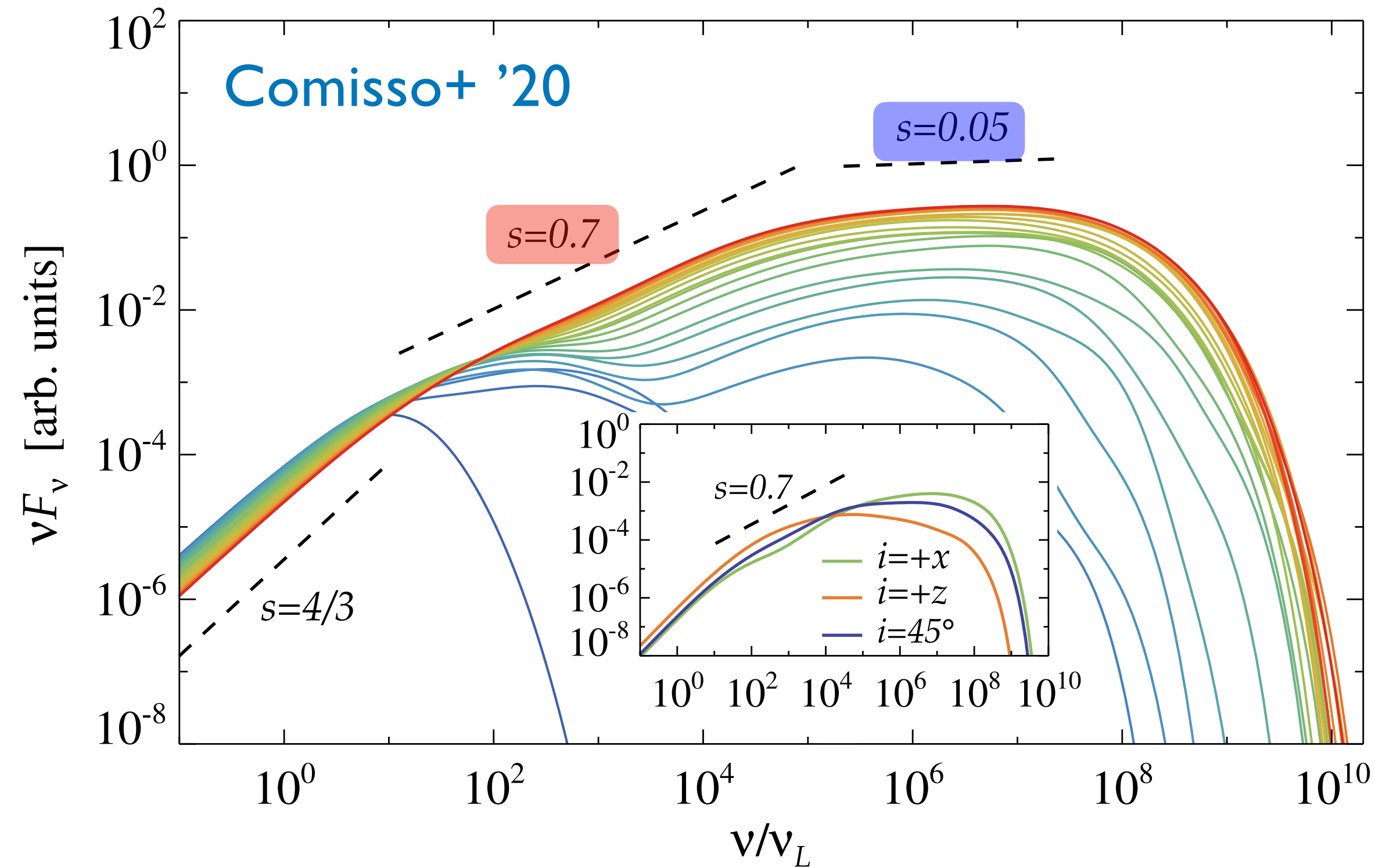
$$\nu F_\nu \propto \nu^{(3-p+m)/(2+m/2)} \quad \text{for } \nu_{\text{min } \alpha} < \nu < \nu_{\text{iso}} \sim \gamma_{\text{iso}}^2 \nu_L$$

$$\nu F_\nu \propto \nu^{(3-p)/2} \quad \text{for } \nu_{\text{iso}} < \nu < \nu_{\text{cut}} \sim \gamma_{\text{cut}}^2 \nu_L$$

(standard “textbook case” when $m = 0$)

Explanation of hard radio spectra of PWNs? (Comisso+ '20)

Modification of the Spectral Energy Distribution



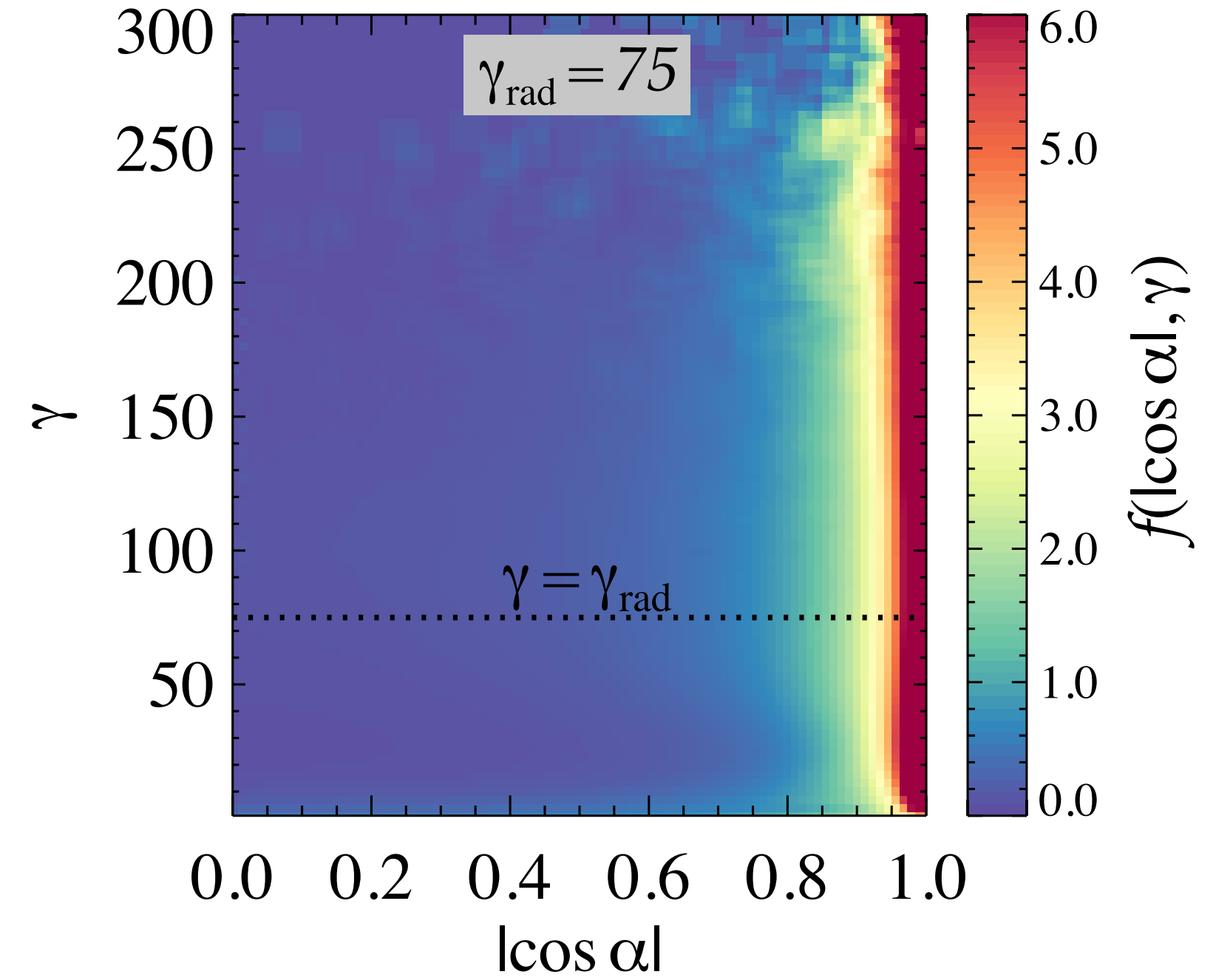
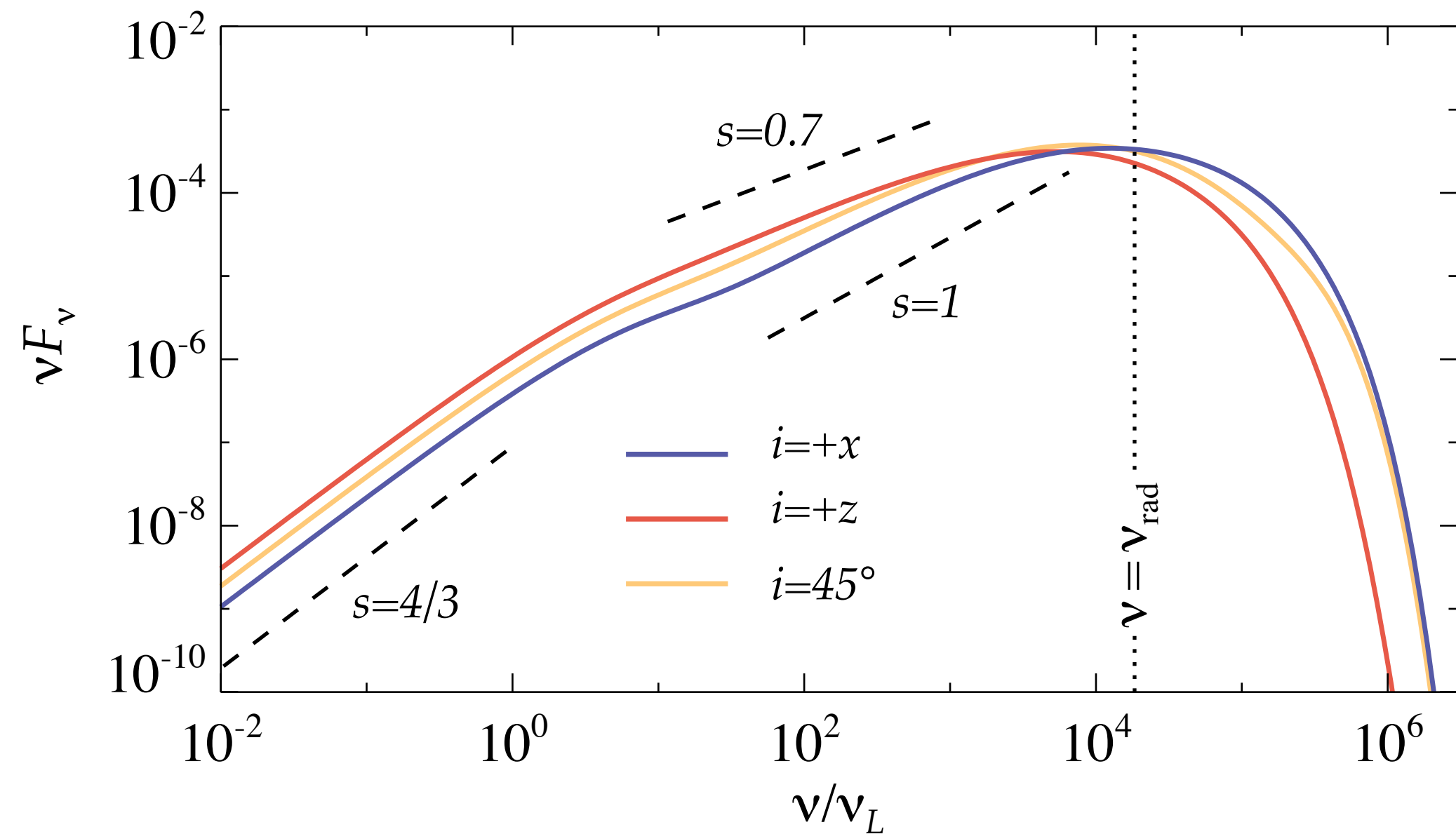
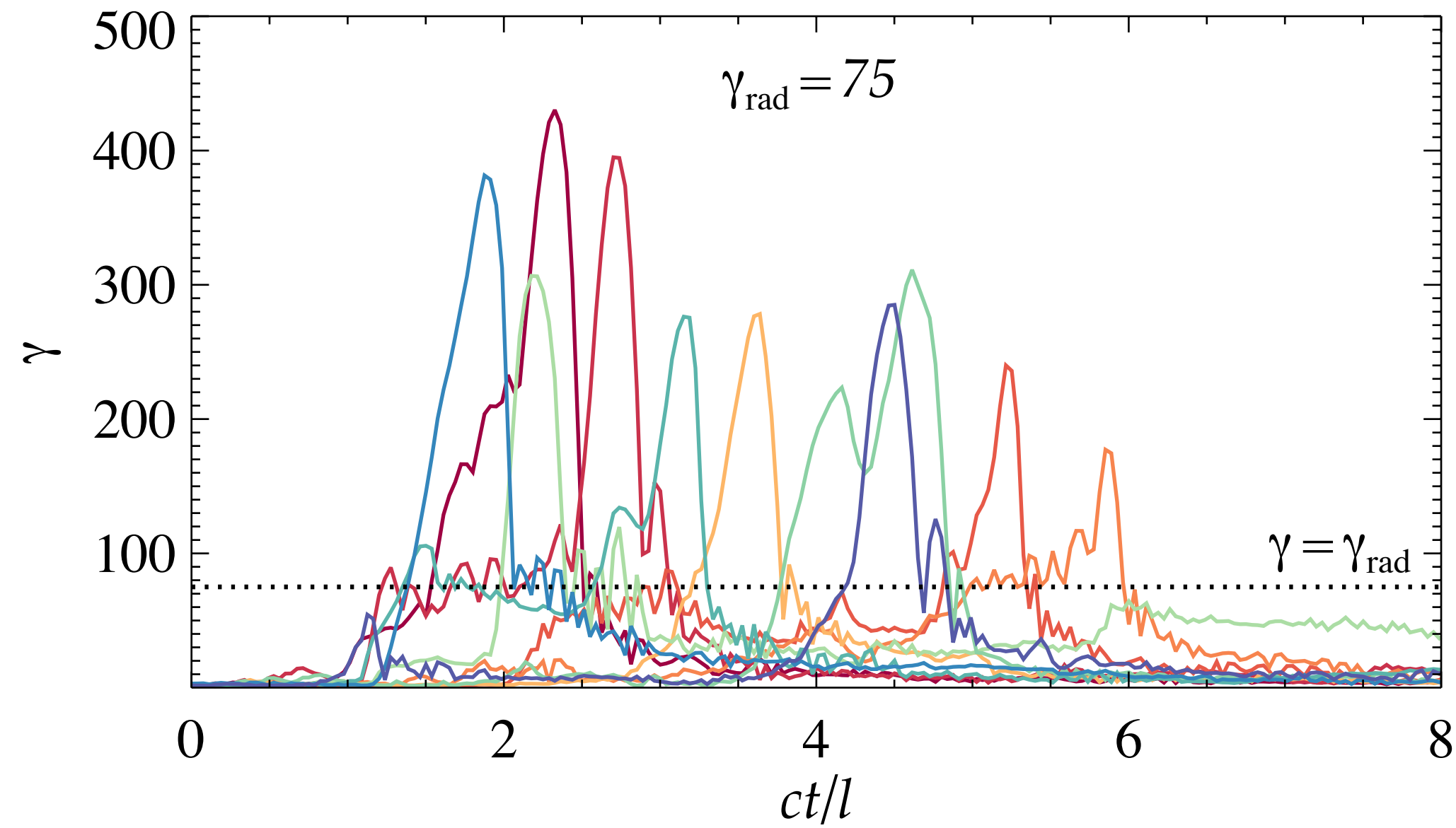
$$\nu \sim \gamma^2 \nu_L \sin \alpha \propto \gamma^{2+m/2} \quad (\nu_L = eB/2\pi m_e c)$$

$$\nu F_\nu \propto \nu^{(3-p+m)/(2+m/2)} \quad \text{for } \nu_{\min \alpha} < \nu < \nu_{\text{iso}} \sim \gamma_{\text{iso}}^2 \nu_L$$

$$\nu F_\nu \propto \nu^{(3-p)/2} \quad \text{for } \nu_{\text{iso}} < \nu < \nu_{\text{cut}} \sim \gamma_{\text{cut}}^2 \nu_L$$

- ▶ Resulting radio spectra with $s \sim 0.7$ for a significant energy range
- ▶ Radio spectra with $s \sim 0.7$ or a bit harder are typical of PWNe

Relaxation of Synchrotron Cooling Constraints



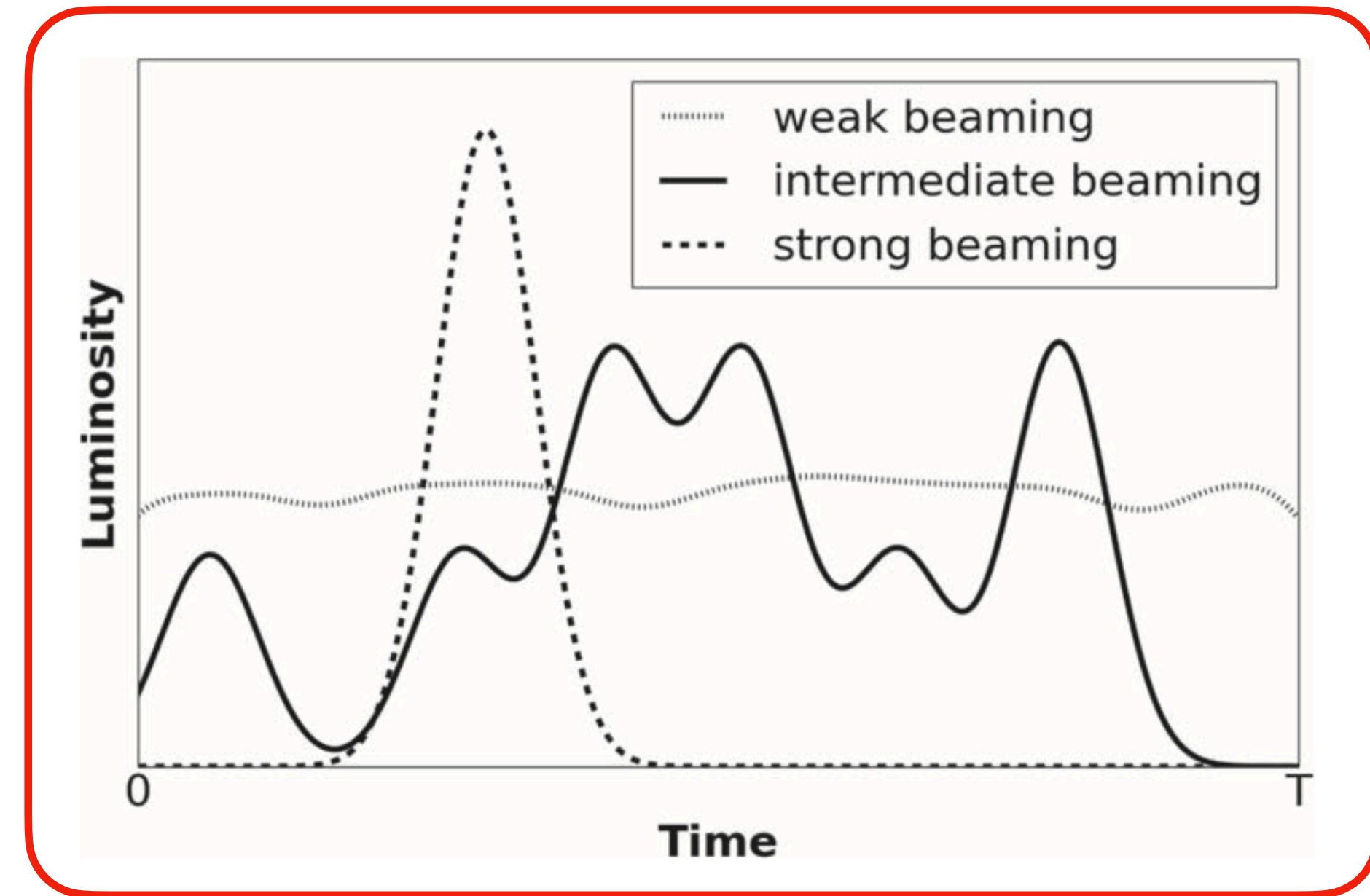
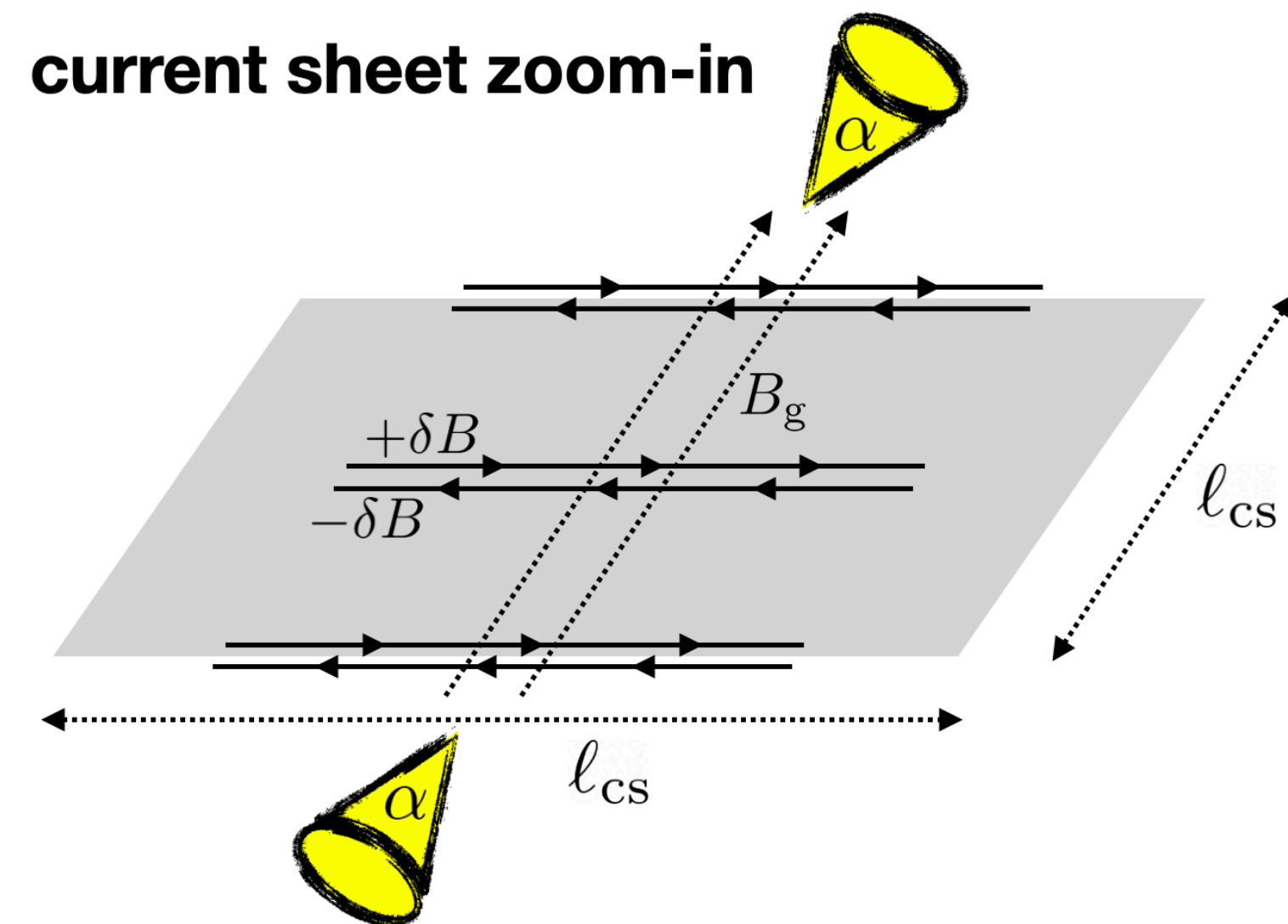
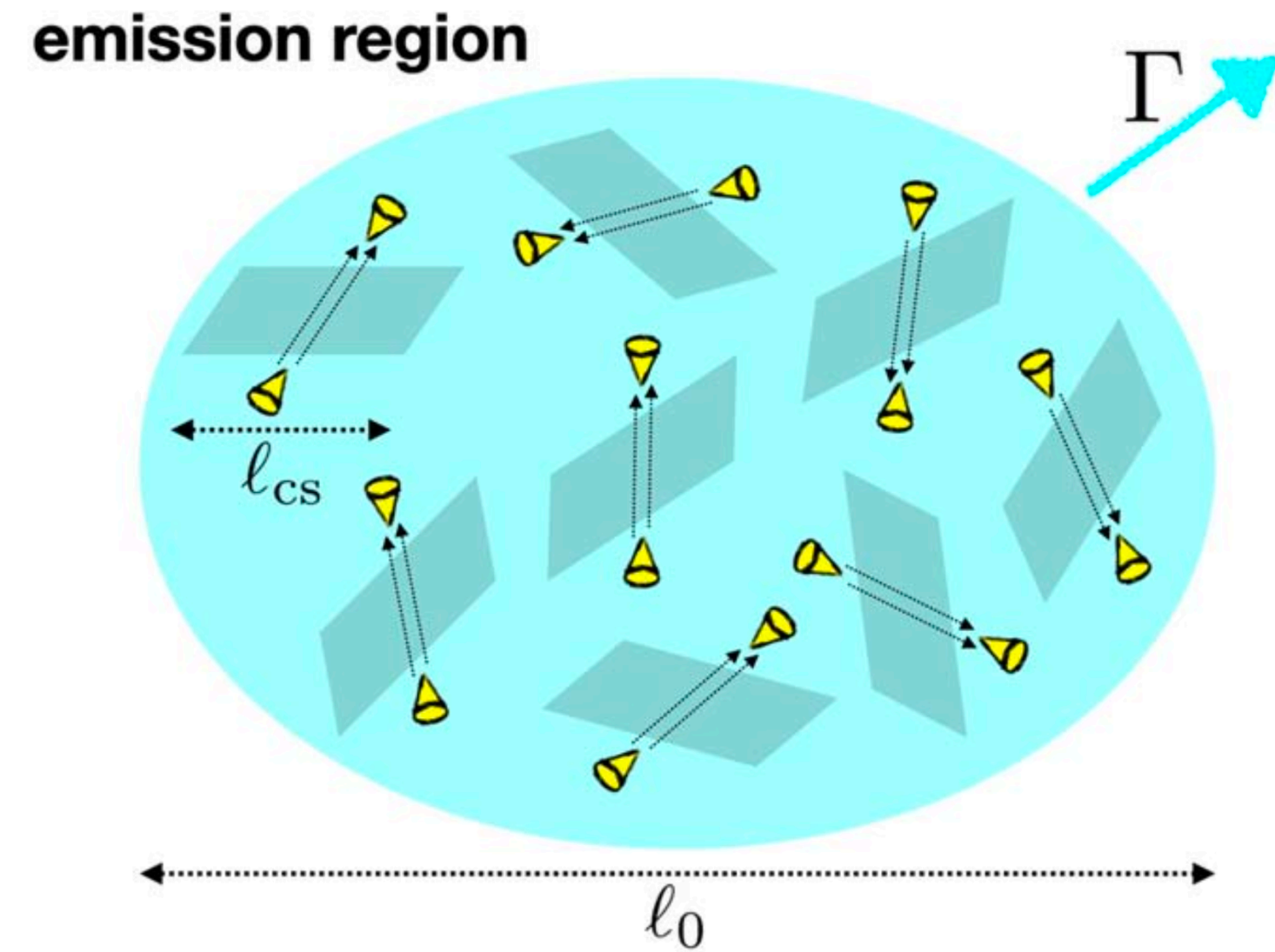
$$\gamma_{\text{rad}} = \left(\frac{eE}{2\sigma_T U_B \sin^2 \alpha} \right)^{1/2}$$

- Particles with $\gamma \gg \gamma_{\text{rad}}$ thanks to $|\cos\alpha| \sim 0$

Comisso & Sironi '21

(see also Cerutti+ '13, Yuan+ '16, Hakobyan+ '19, Chernoglazov+ '23)

Beamed Radiation and Frequency-Dependent Variability



Sobacchi, Piran, Comisso 2023

- Other variability model associated with pitch-angle anisotropy (via Landau damping) by C. Thompson (2006)
- Alternative variability models associated with ultrarelativistic bulk motions (Lyutikov 2006; Narayan & Kumar 2009; Lazar et al. 2009; Giannios et al. 2009)

Modification of the Linear Polarization Degree

(3) *Polarization.* We evaluate the degree of linear polarization for particles following power-law distributions in both energy and pitch angle, as described by Equations (4) and (5). The linear polarization degree can be calculated as

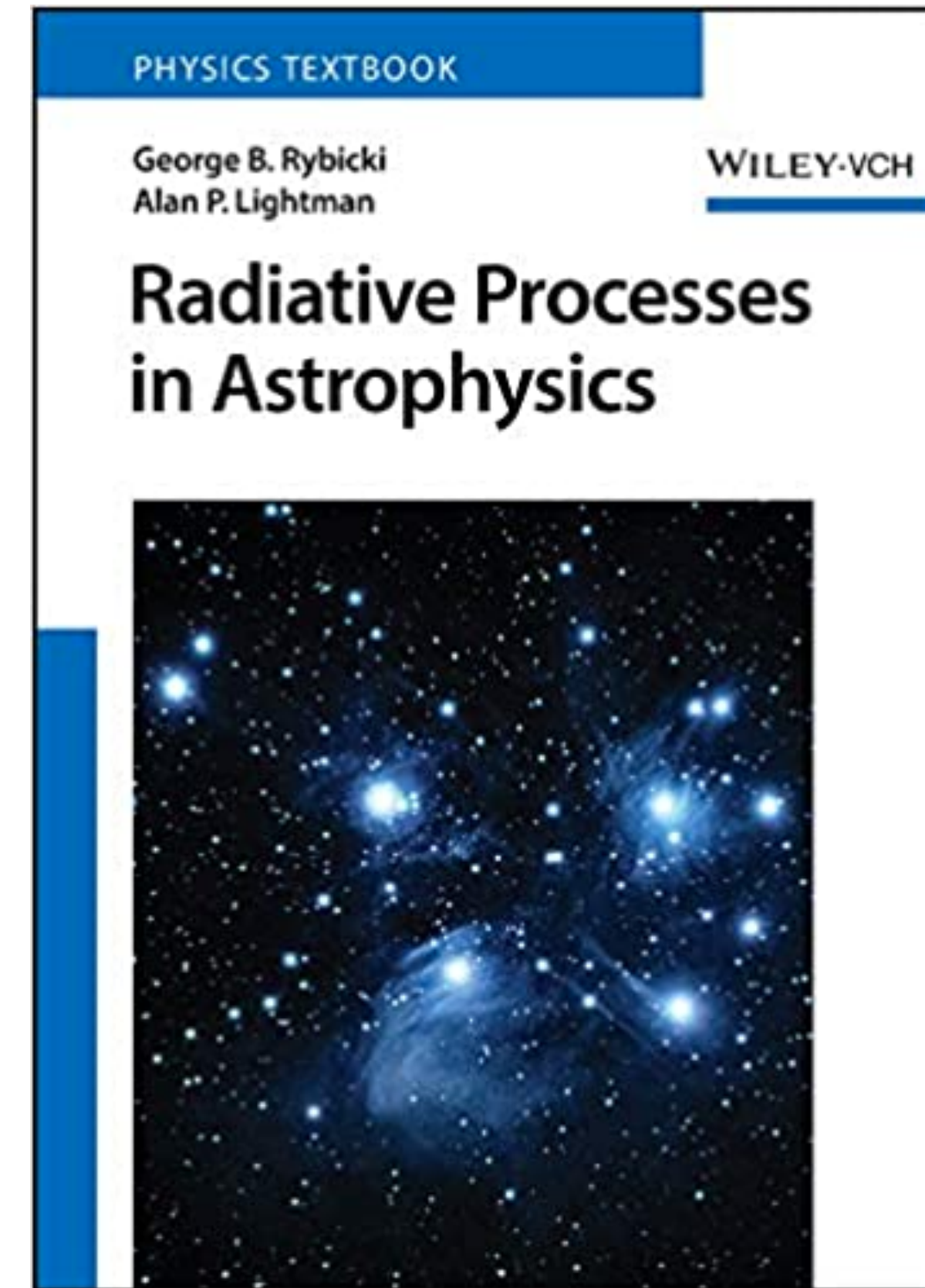
$$\Pi_{\text{lin}} = \frac{\int G_{\text{sync}}(x) \langle \sin \alpha \rangle \frac{dN}{d\gamma} d\gamma}{\int F_{\text{sync}}(x) \langle \sin \alpha \rangle \frac{dN}{d\gamma} d\gamma}. \quad (11)$$

Here, we have defined $F_{\text{sync}}(x) = x \int_x^\infty K_{\frac{5}{3}}(\xi) d\xi$ and $G_{\text{sync}}(x) = x K_{\frac{2}{3}}(x)$, with $x = \nu/\nu_c$ (Rybicki & Lightman 1979), where $K_{\frac{5}{3}}$ and $K_{\frac{2}{3}}$ are modified Bessel functions of orders 5/3 and 2/3, respectively. Therefore, after computing the integrals we obtain

$$\Pi_{\text{lin}} = \frac{p + 1}{p + 7/3 + m/3}. \quad (12)$$

The result for an isotropic population of particles is recovered for $m = 0$. Pitch-angle anisotropy reduces the degree of linear polarization in the $m = m_>$ range, while it increases it in the $m = m_<$ range.

Comisso & Jiang 2023



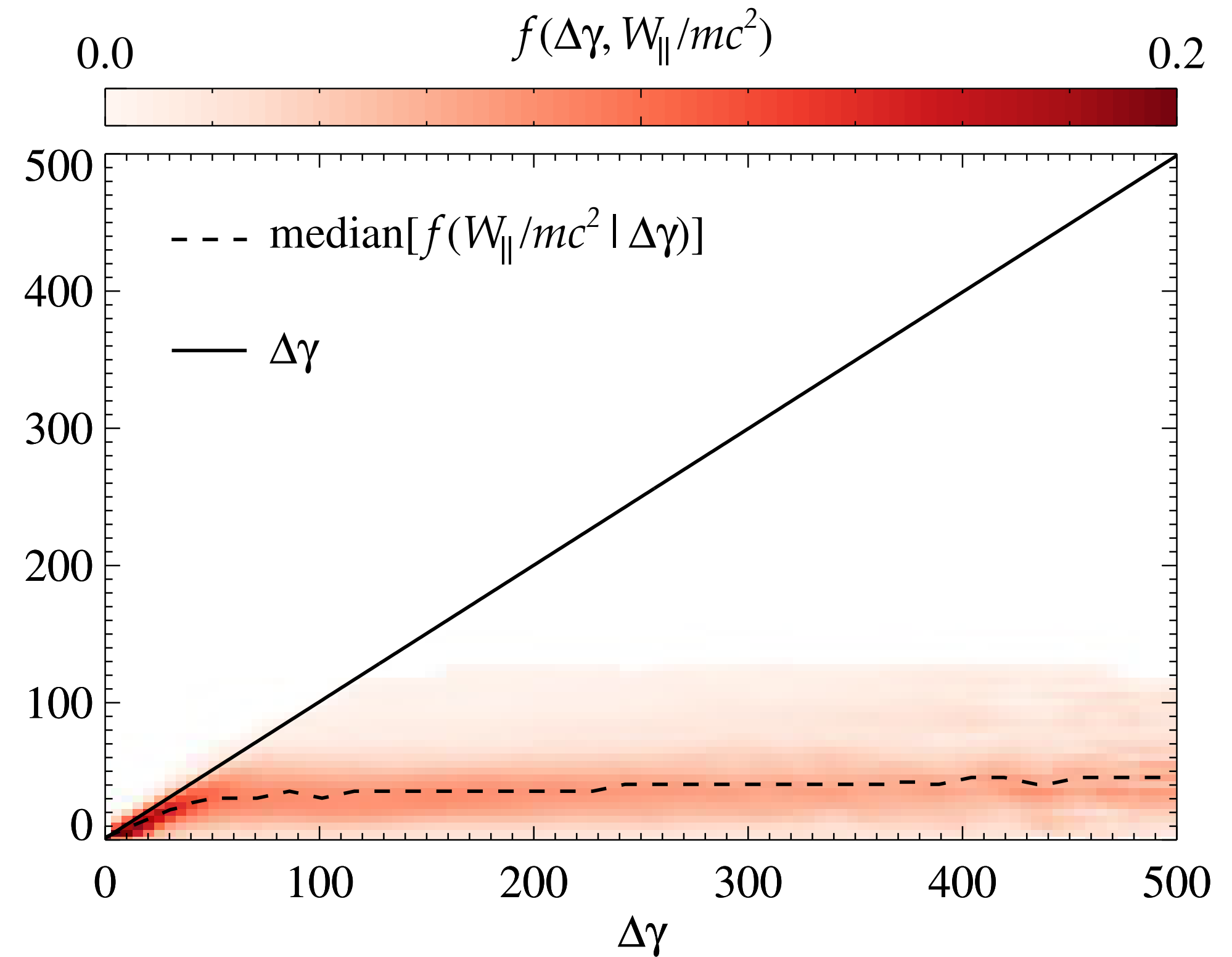
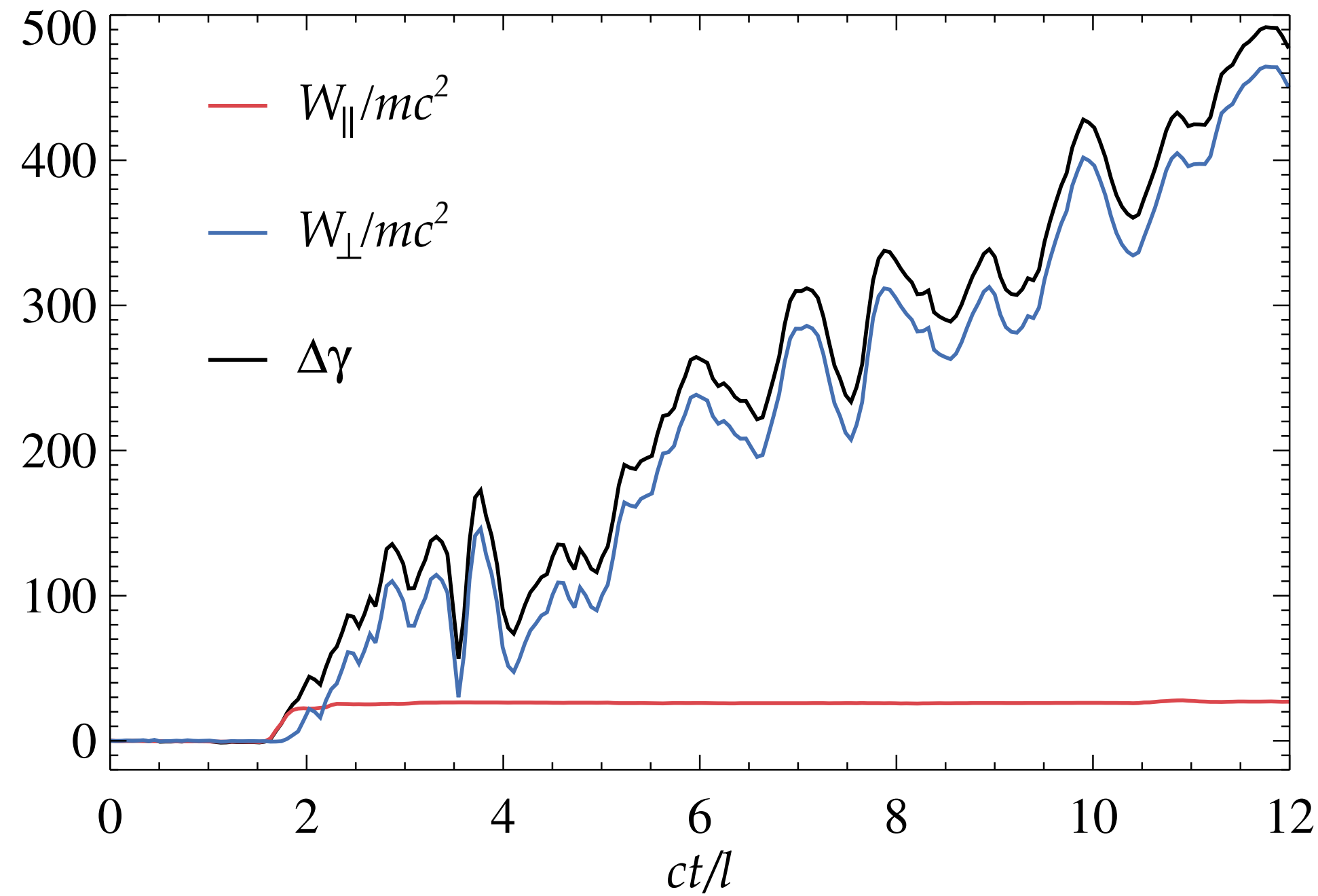
$$\Pi = \frac{p + 1}{p + \frac{7}{3}} \quad (6.38)$$

(isotropic assumption)

A Few Key Takeaways

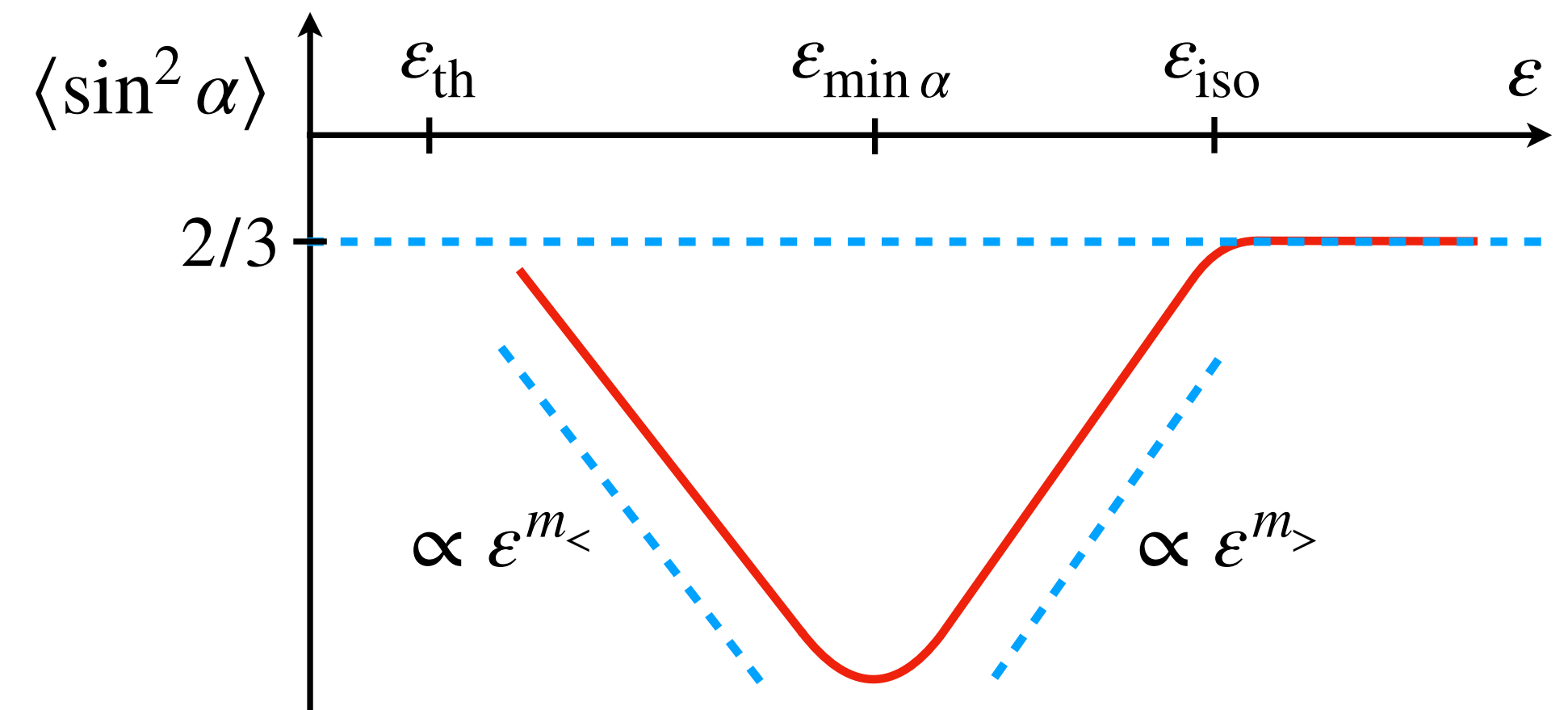
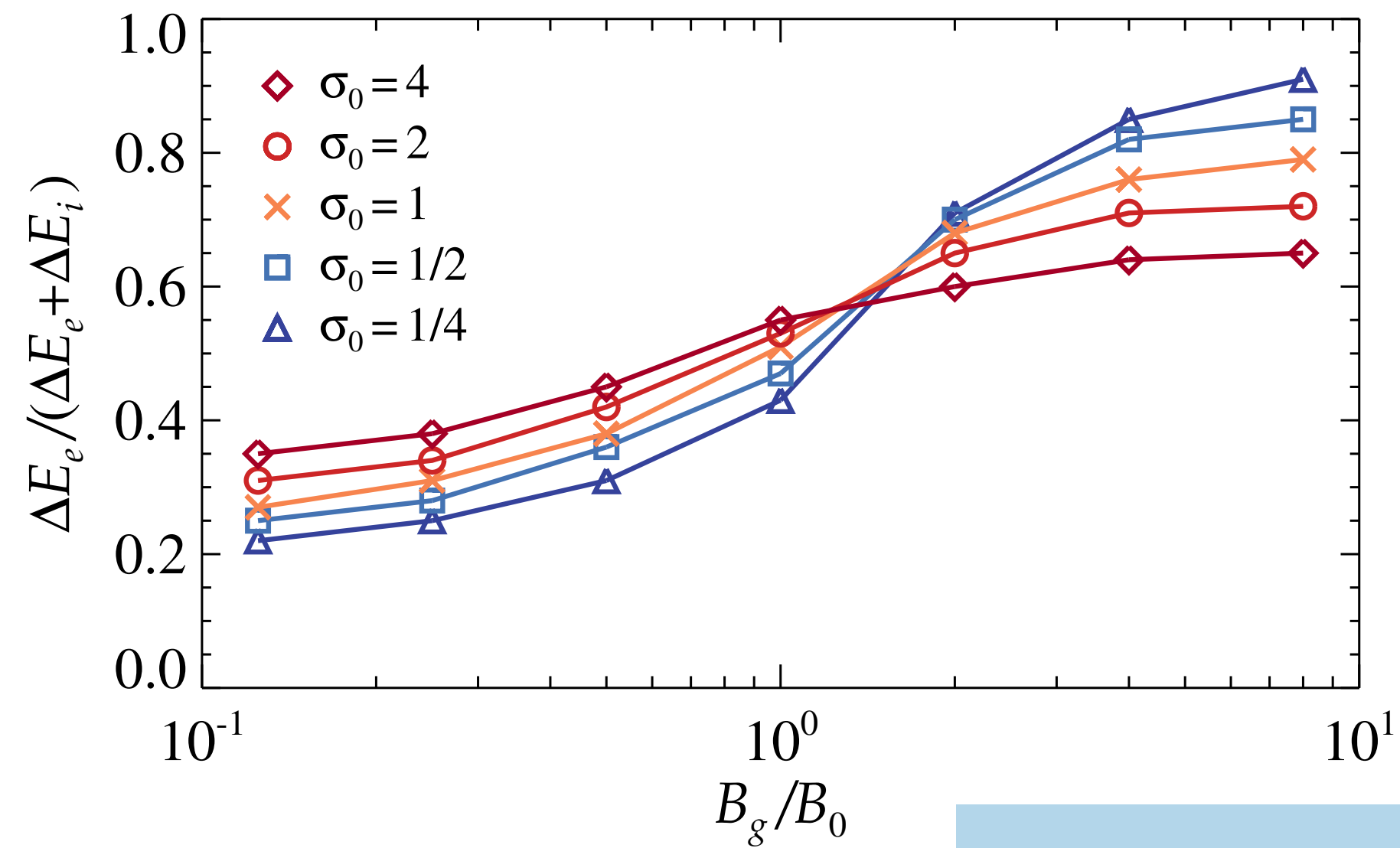
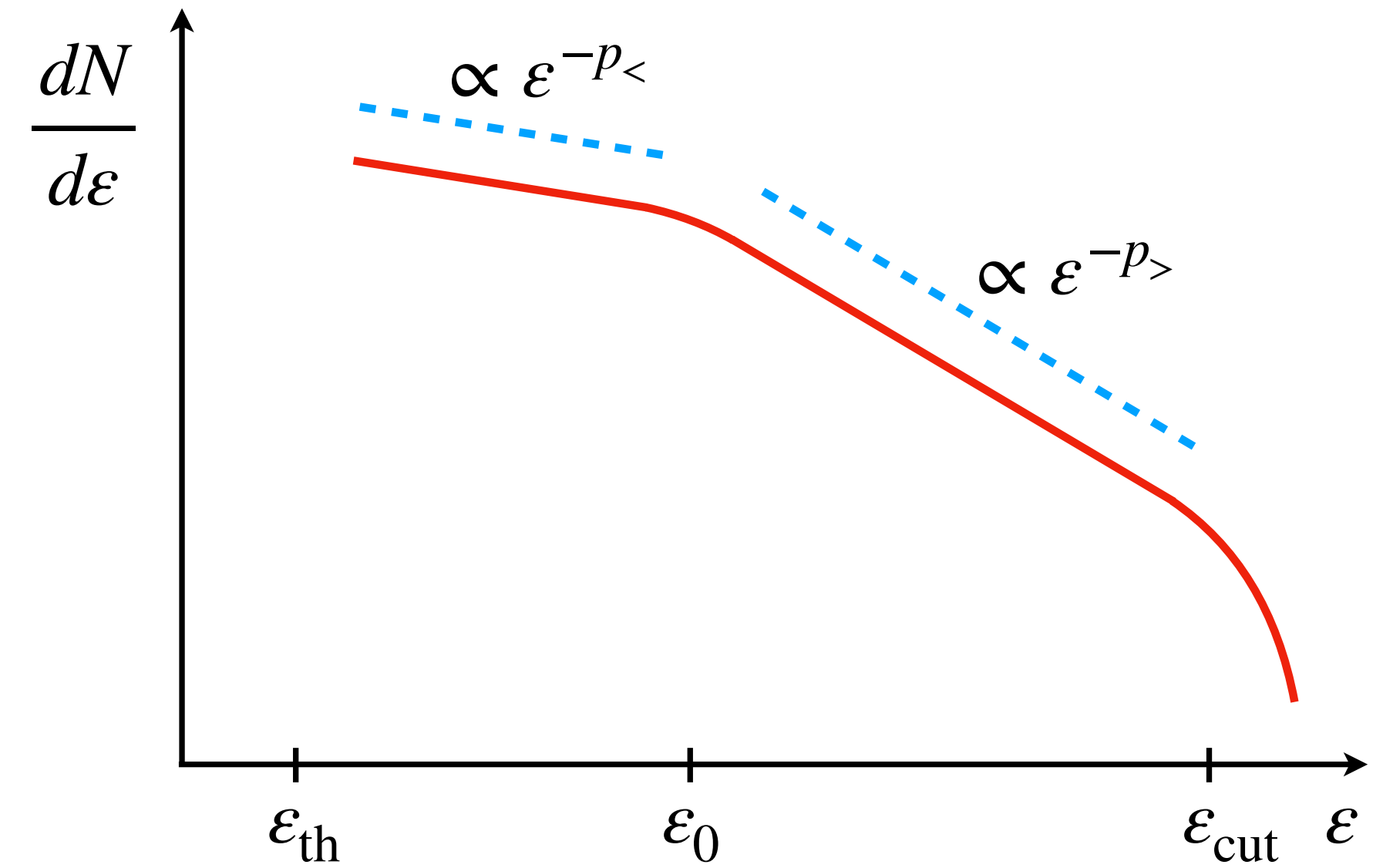
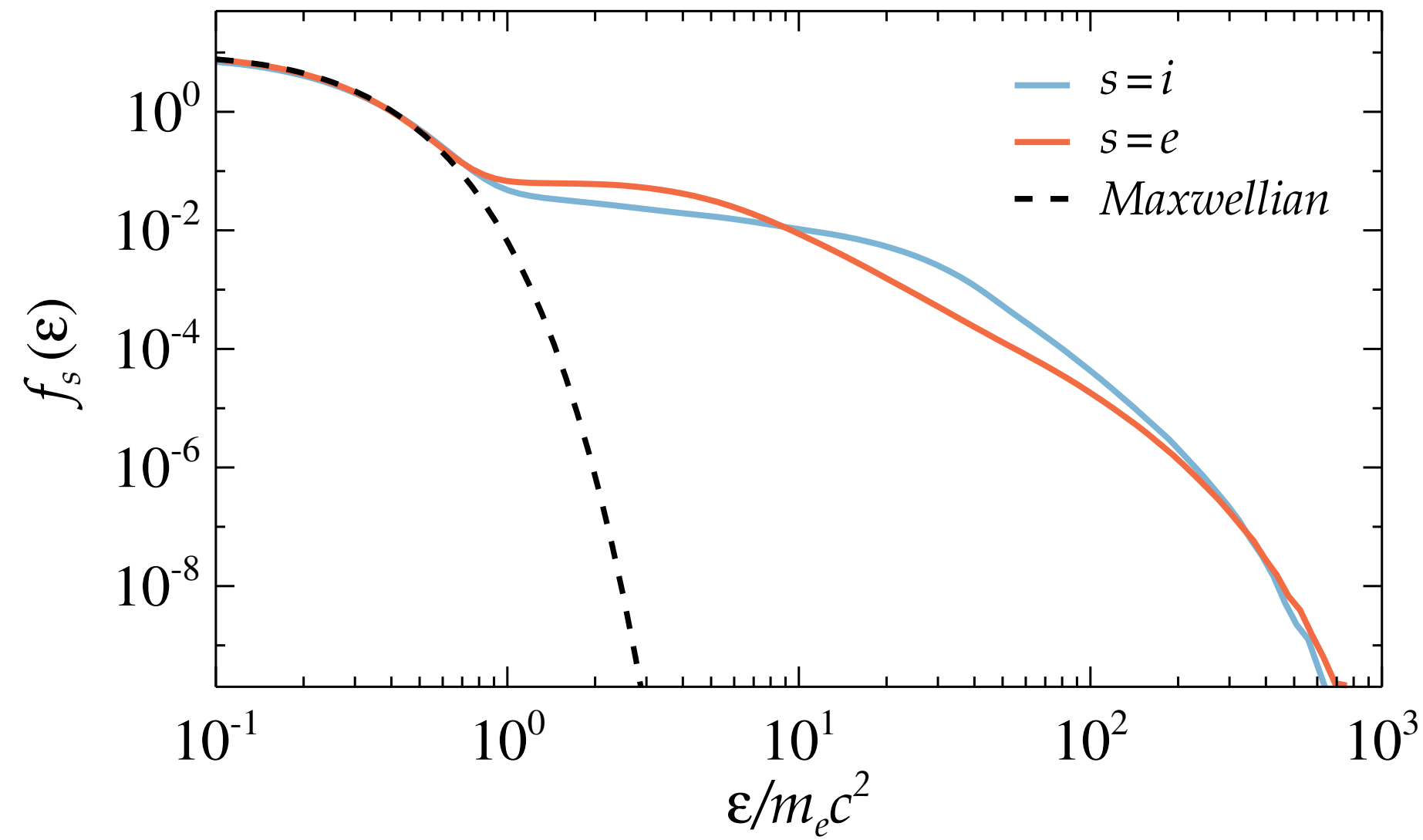
1. Magnetized turbulence and magnetic reconnection co-occur
2. Particle acceleration from the thermal pool is a two-stage process
3. Turbulence acceleration produces $dN/dEdt \propto E^{-s} \text{sech}[(E/ZeR_{\text{cut}})^2]$ with $R_{\text{cut}} \sim B_{\text{rms}} l_c$ and $s \sim [2 - 2.2]$ for $\sigma \gg 1$ (matches nicely UHECR data)
4. In magnetically dominated collisionless plasmas, pitch angle anisotropy is the norm rather than the exception
5. Understanding both particle energy spectrum and pitch-angle anisotropy is key to interpreting radiation signatures from energized particles

Appendix I - $E_{\parallel}$ vs. $E_{\perp}$ Energization

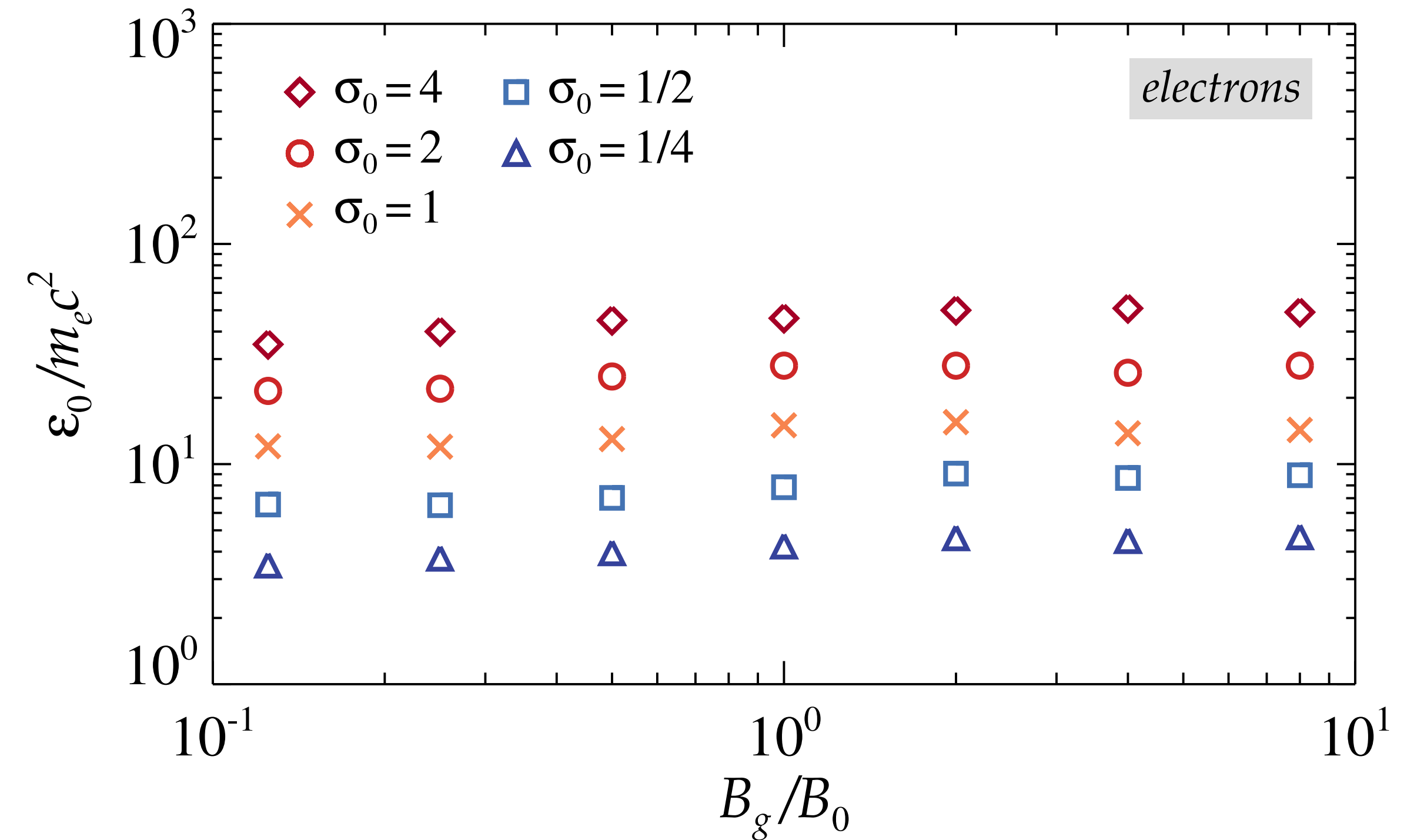
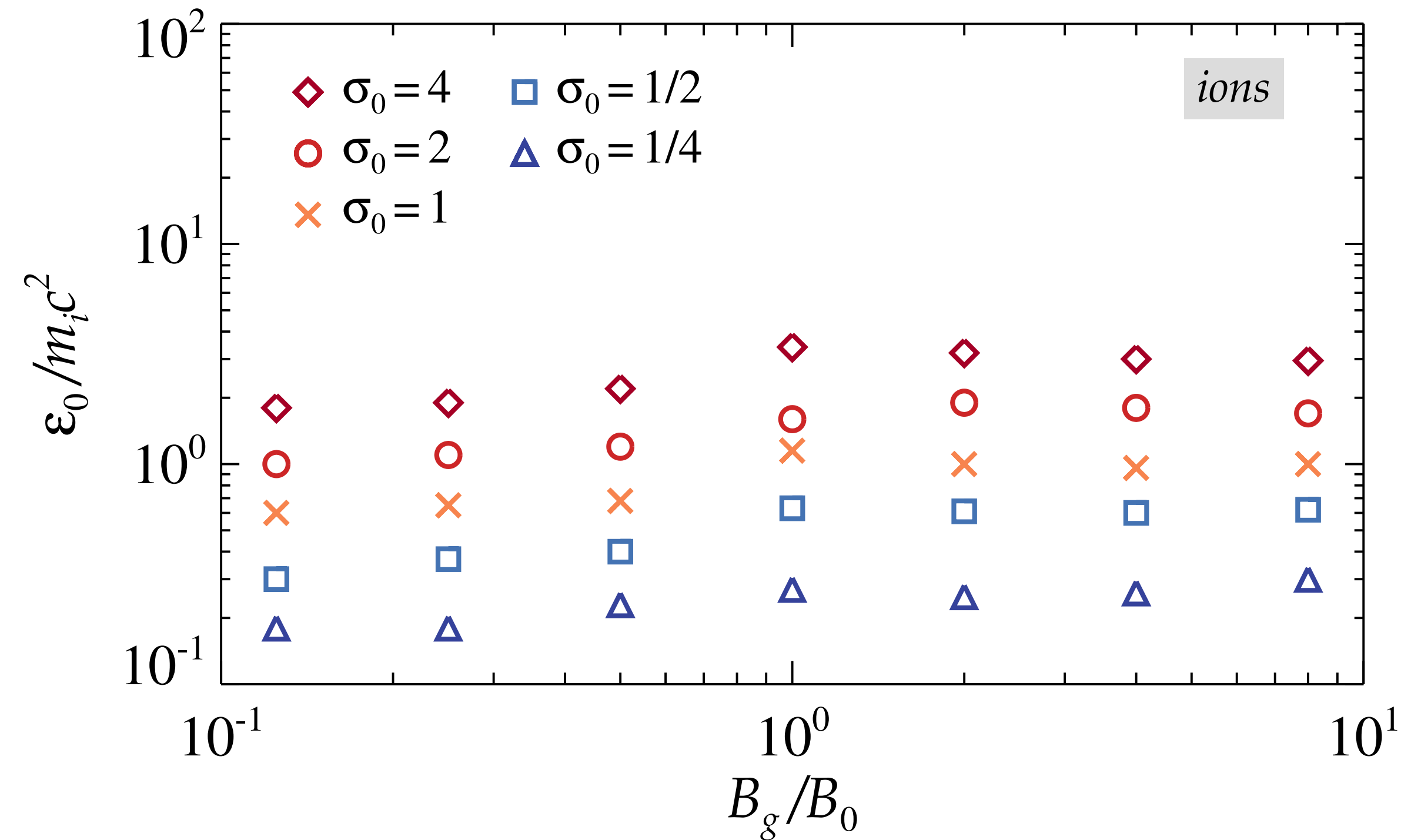


- The injection stage gives $\Delta\gamma_{\text{inj}} \sim 3\sigma_0$ (Comisso & Sironi '18, '19)
- $\mathbf{v} \cdot \mathbf{E}_{\parallel}$ energization is critical initially (low $\Delta\gamma$ -range) $\longrightarrow \frac{d\gamma}{dt} \sim \frac{e}{m_e c} \beta_{\text{rec}} \delta B_{\text{rms}}$
- $\mathbf{v} \cdot \mathbf{E}_{\perp}$ energization is responsible for further acceleration up to “Hillas” limit

Appendix 2 - Broken Power Laws and Energy Partition



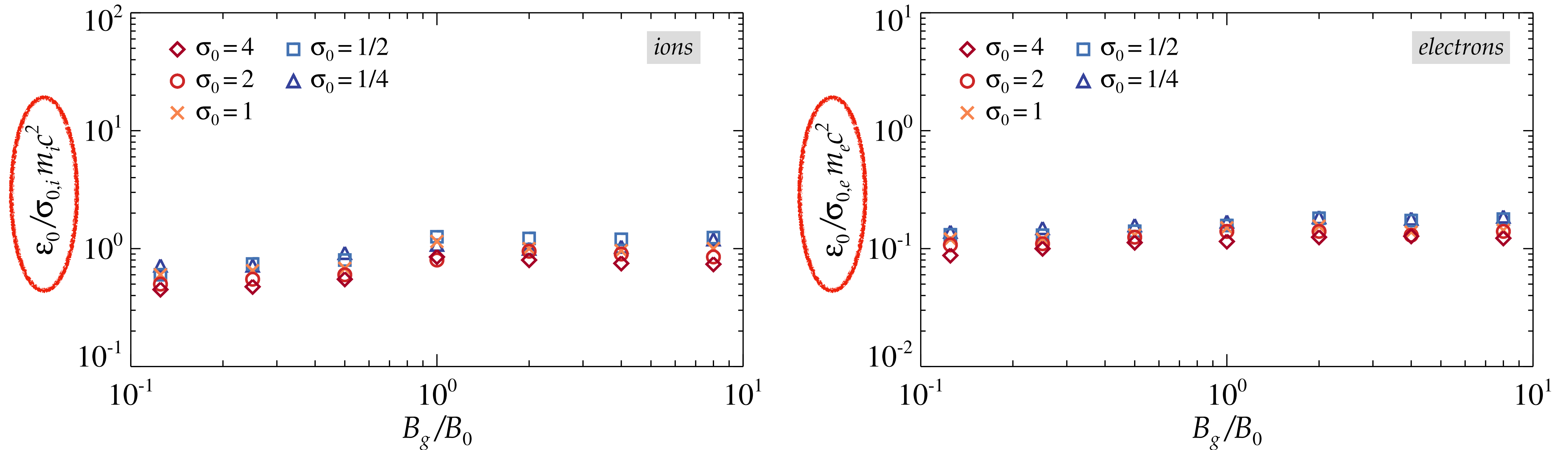
Appendix 3 - Characteristic Break Energies



Comisso 2024

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

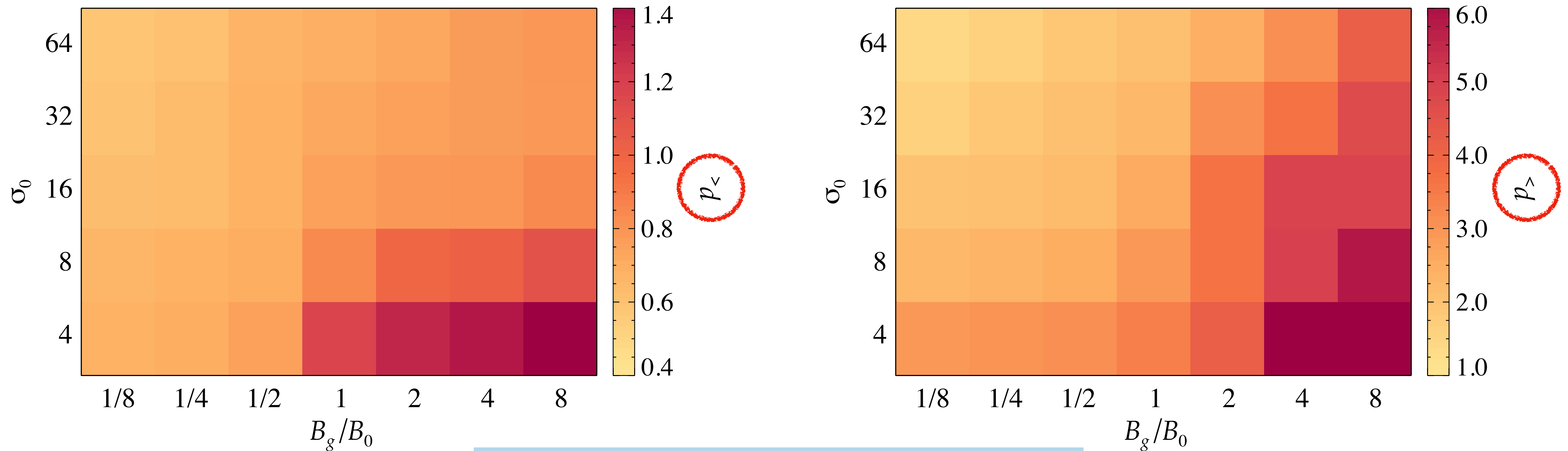
Appendix 3 - Characteristic Break Energies



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 4 - Slopes of the Broken Power Laws



Comisso & 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 $p_> \sim 2$