

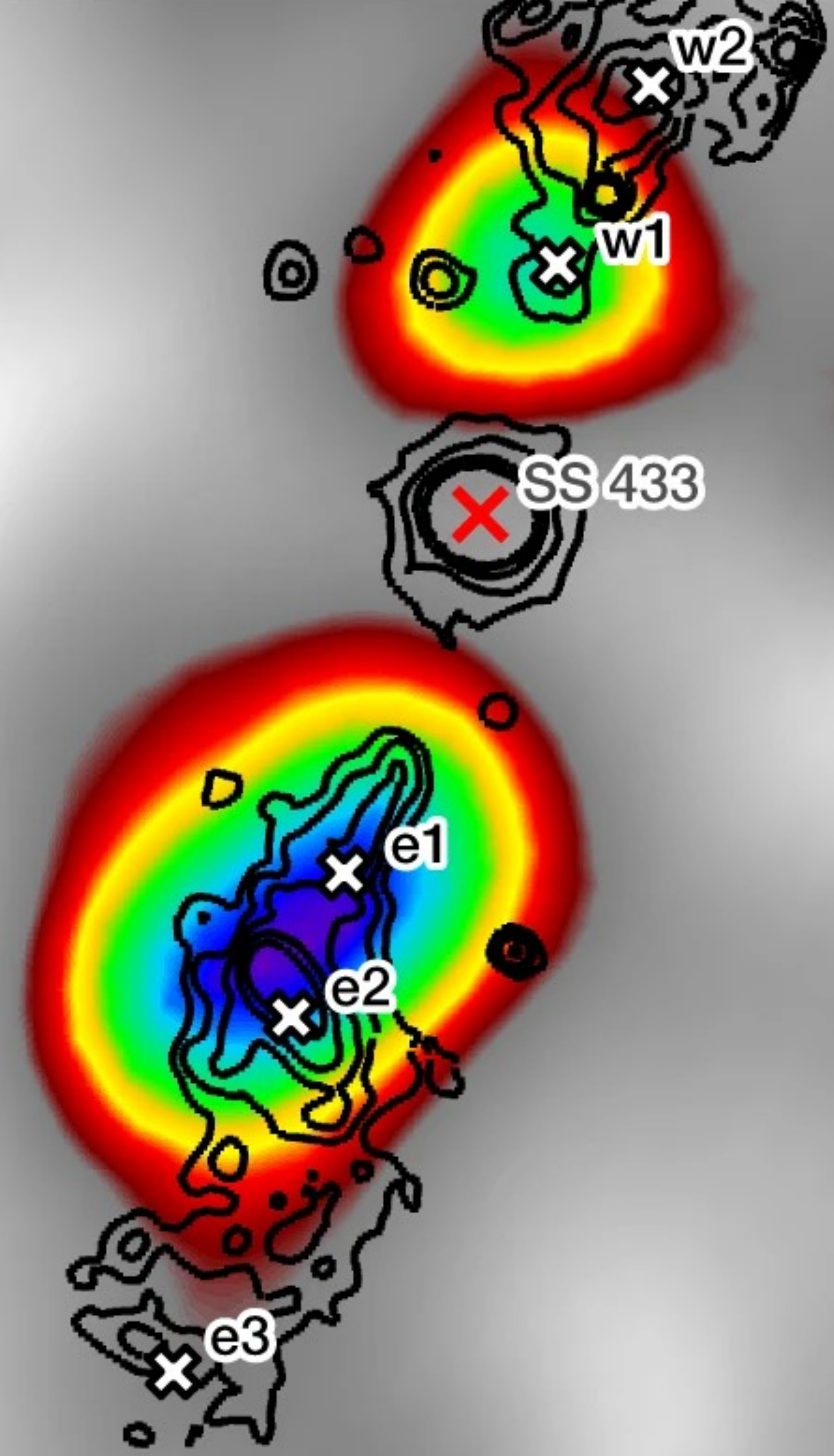
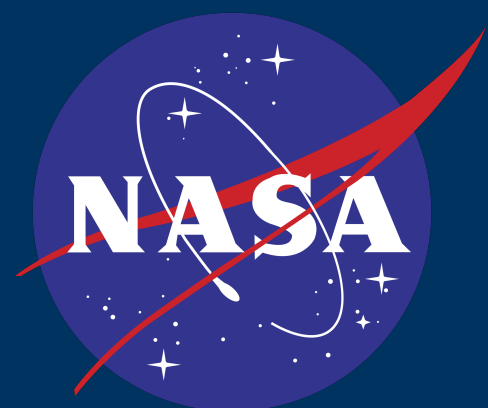
Cosmic Ray Acceleration in Turbulent Magnetized Plasmas

Luca Comisso

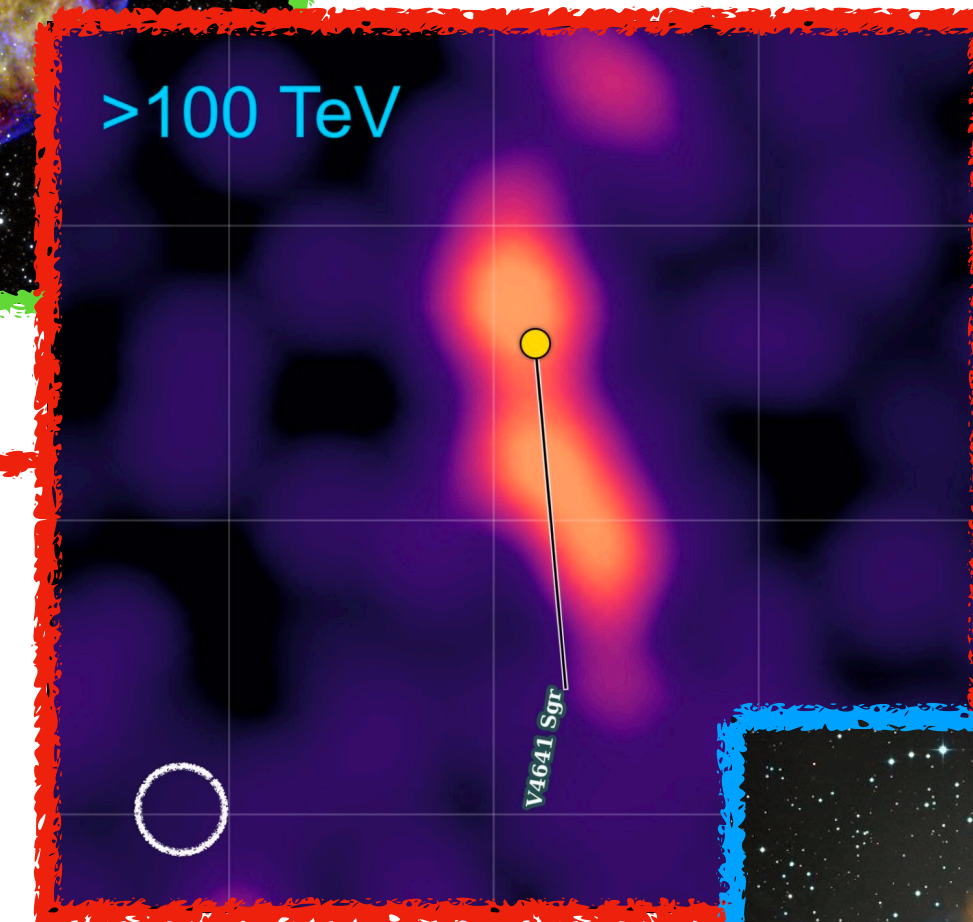
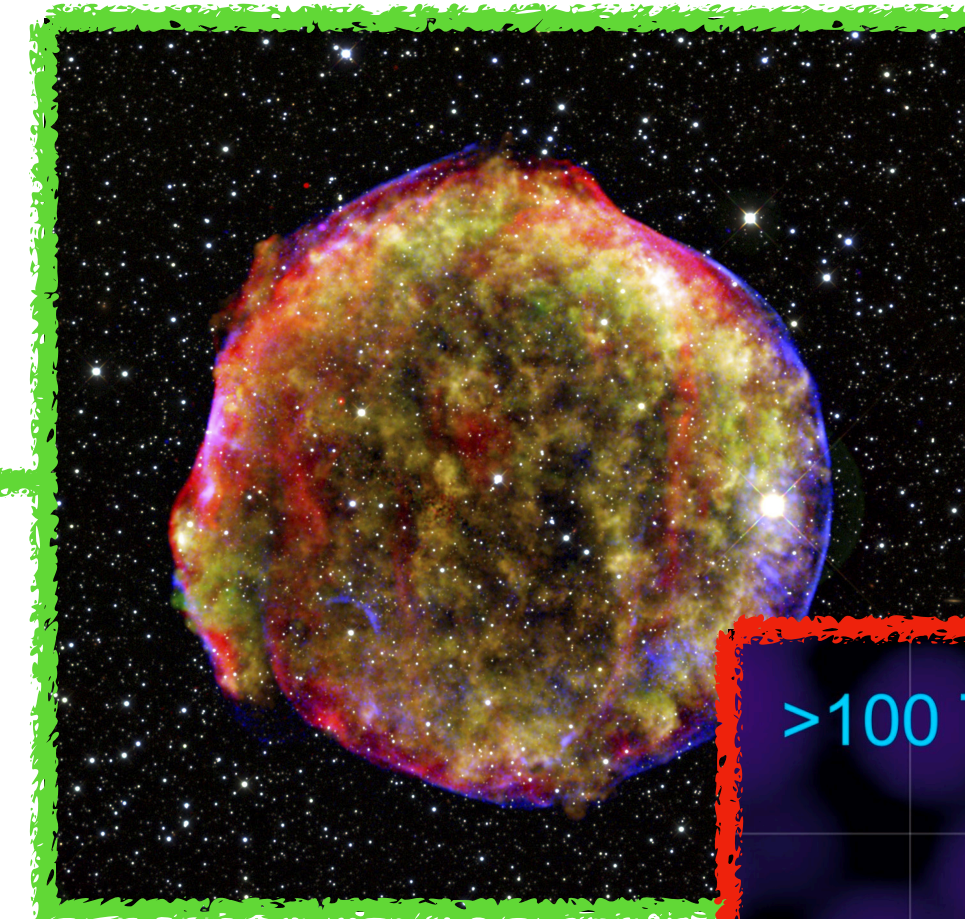
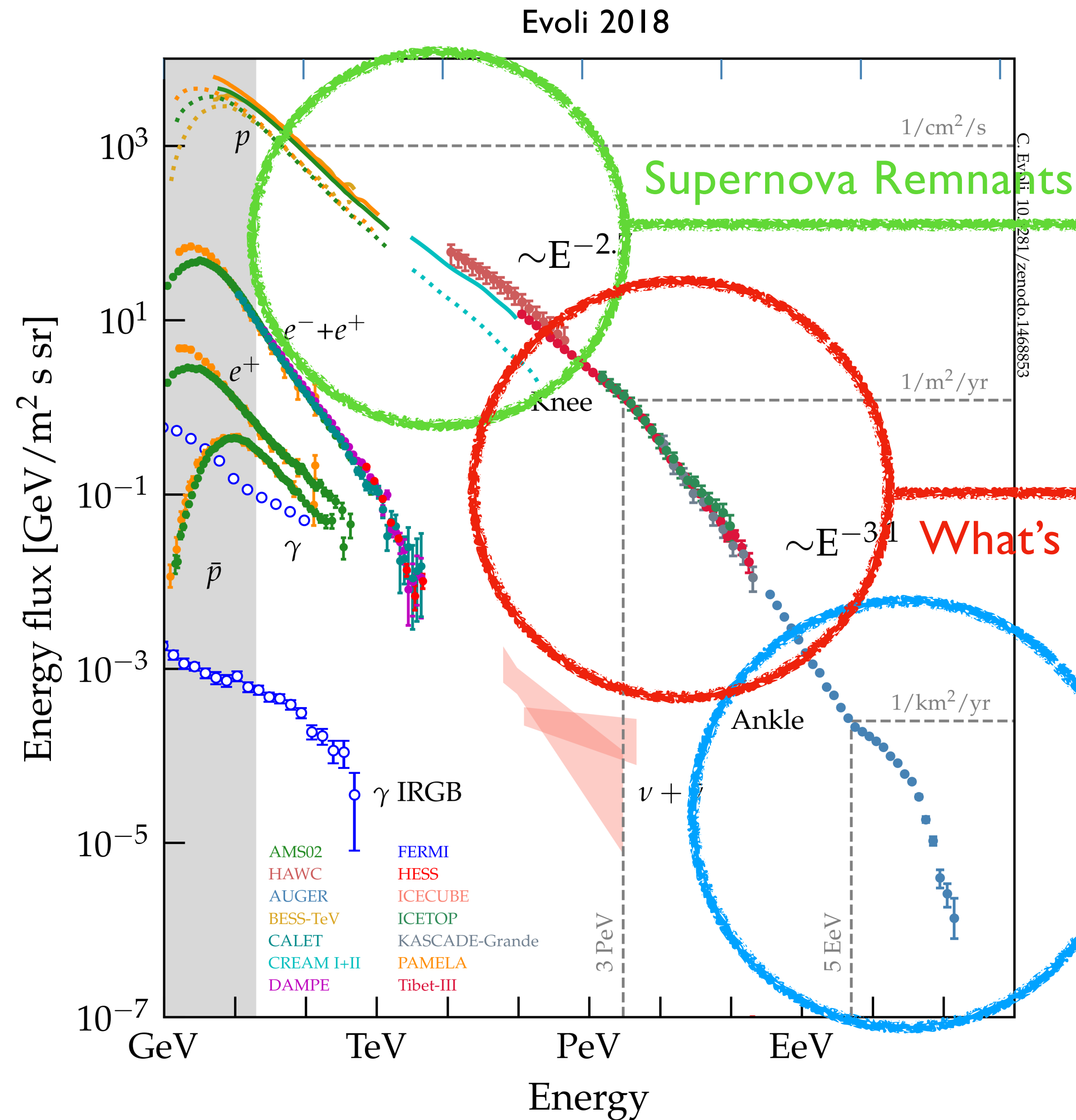
Columbia University

with L Sironi, E Sobacchi, G Farrar, M Muzio,
S Sebastian, Z Davis, D Giannios, B Jiang

CDHY PeVatron Workshop
October 8-10, 2025

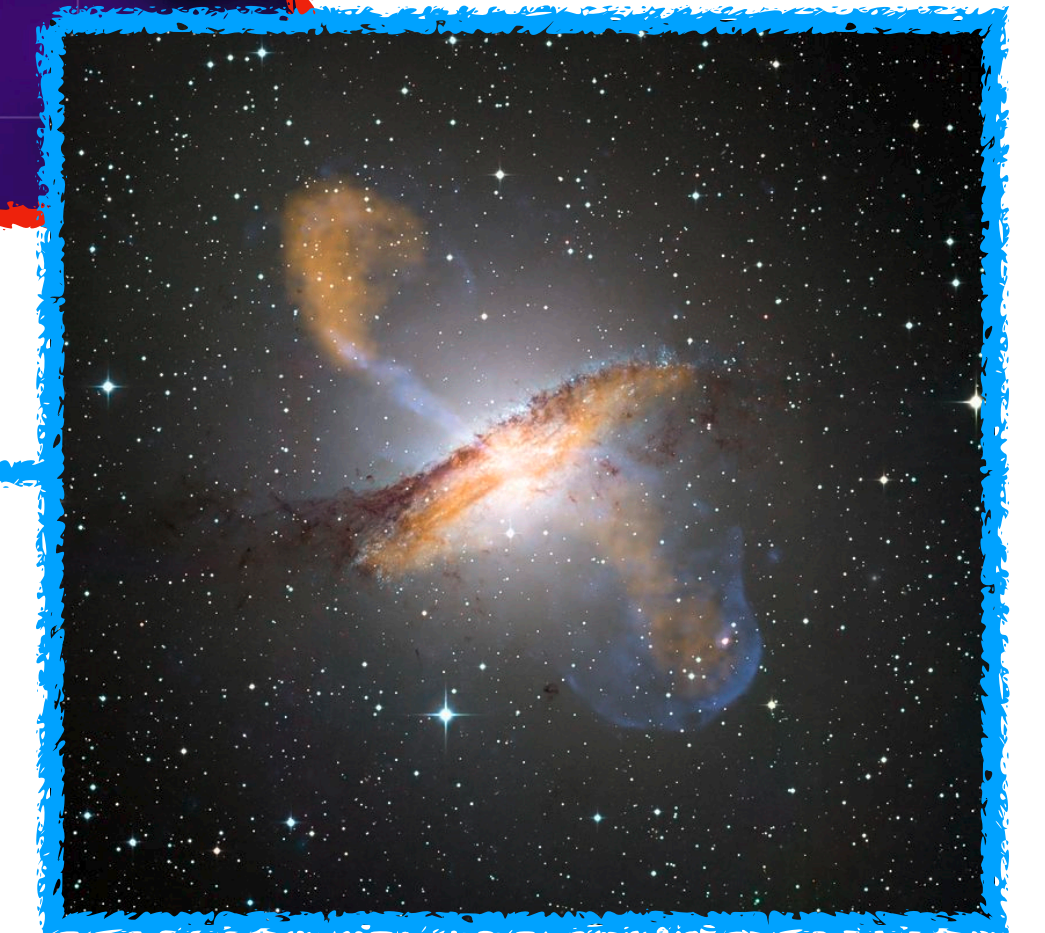


Where Do Cosmic Rays Come From?



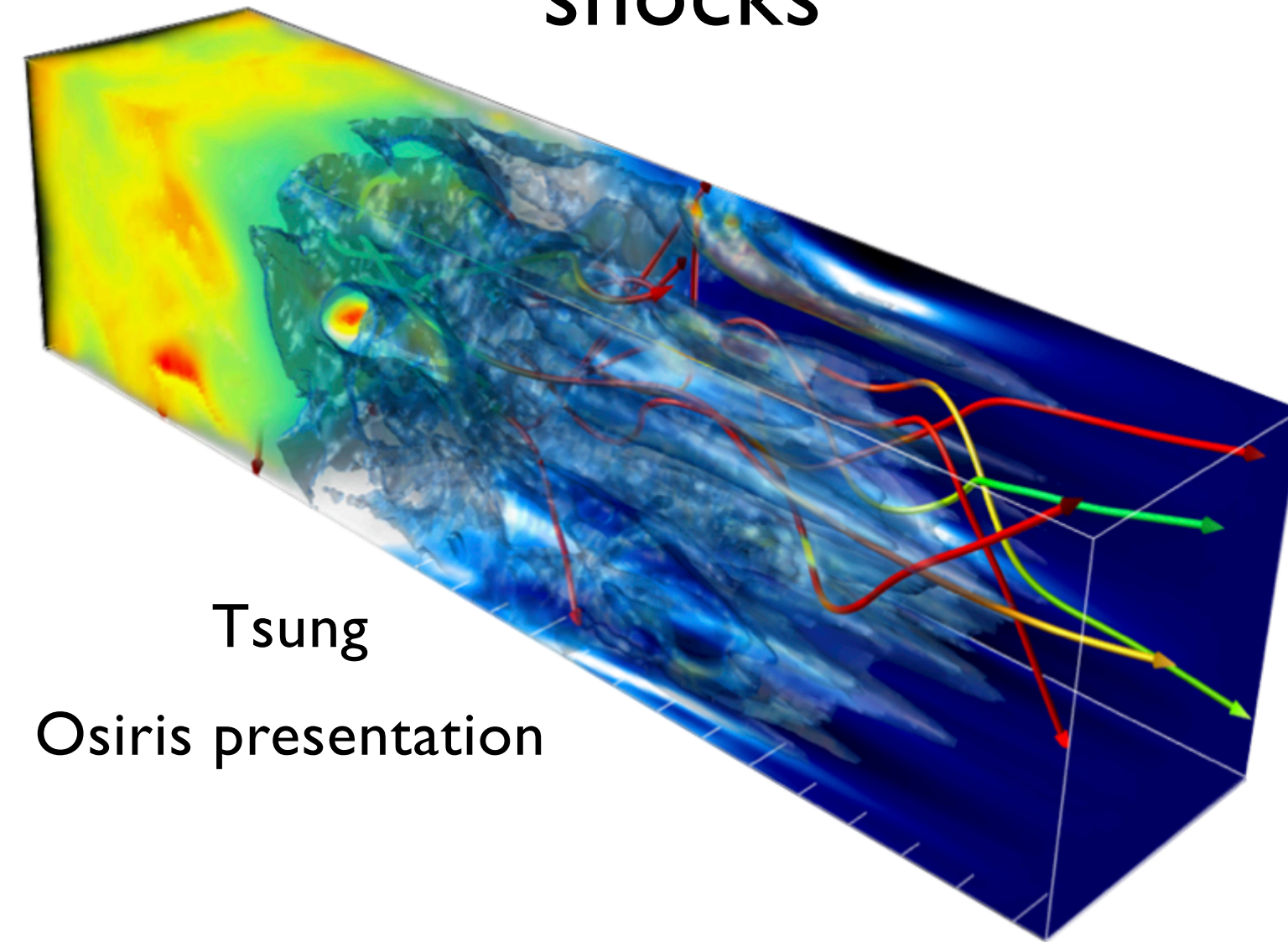
What's going on here?

What's going on also here?
(must be extragalactic)

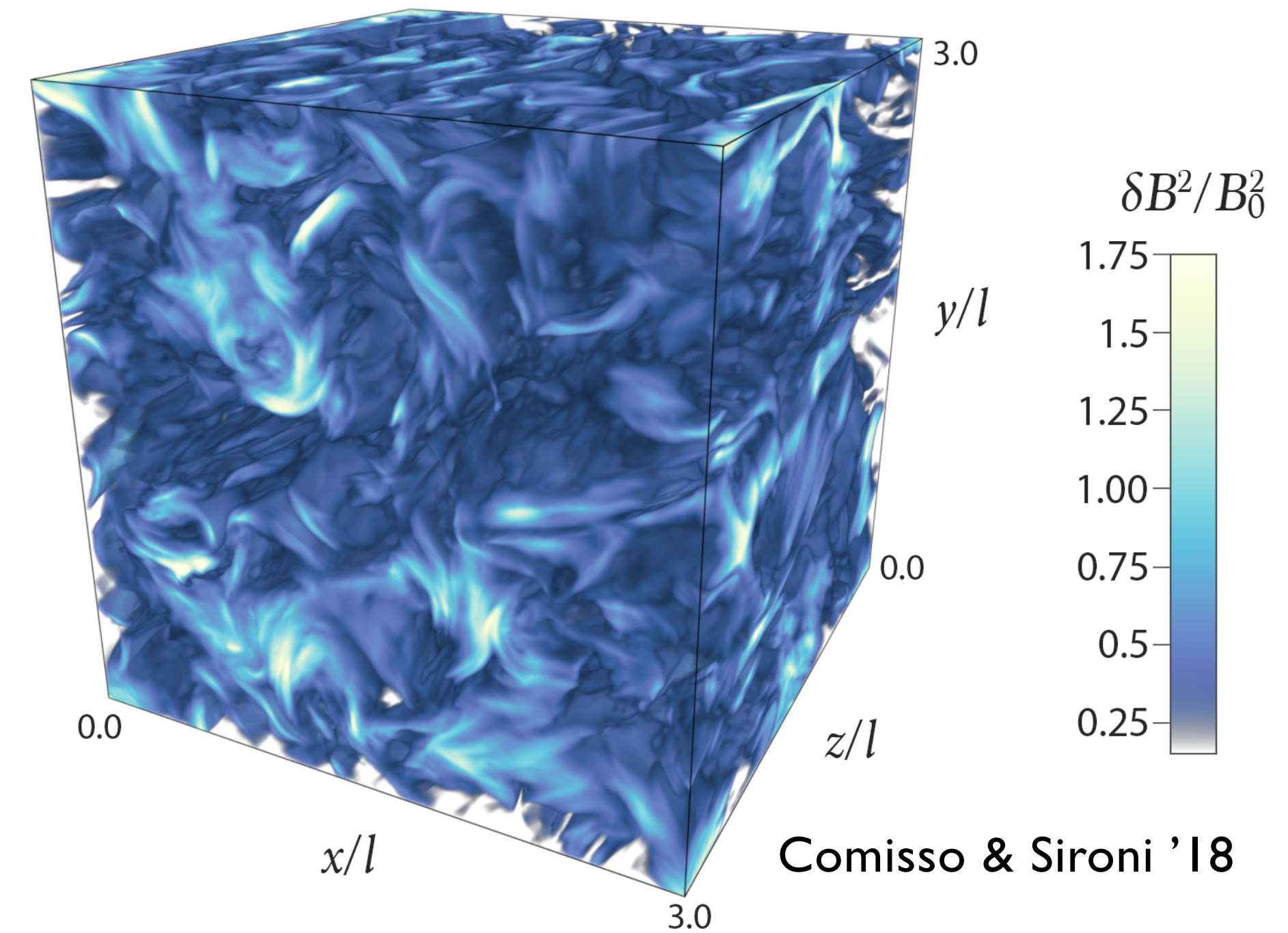


What Drives Particle Acceleration?

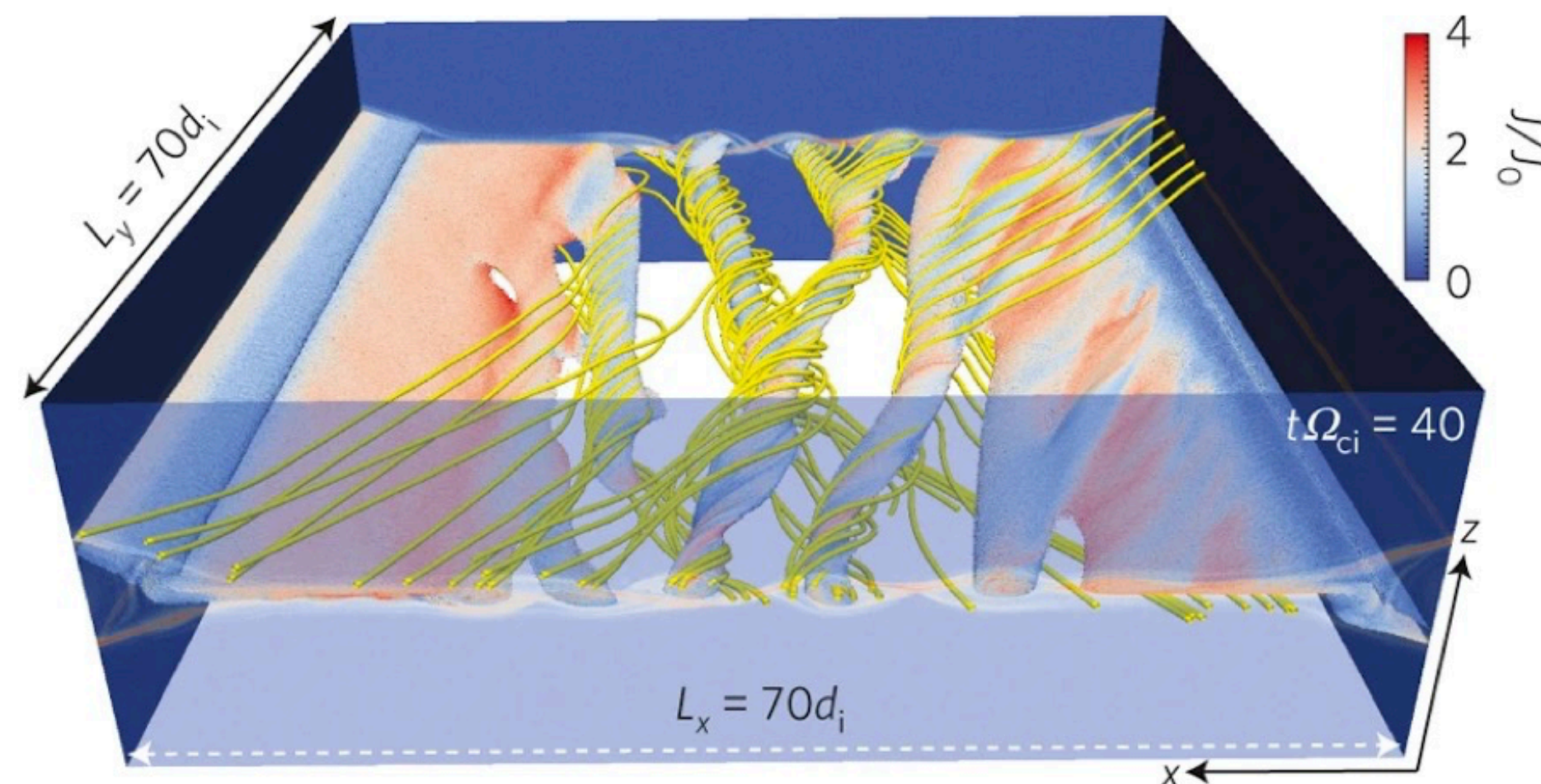
shocks



magnetized turbulence



magnetic reconnection

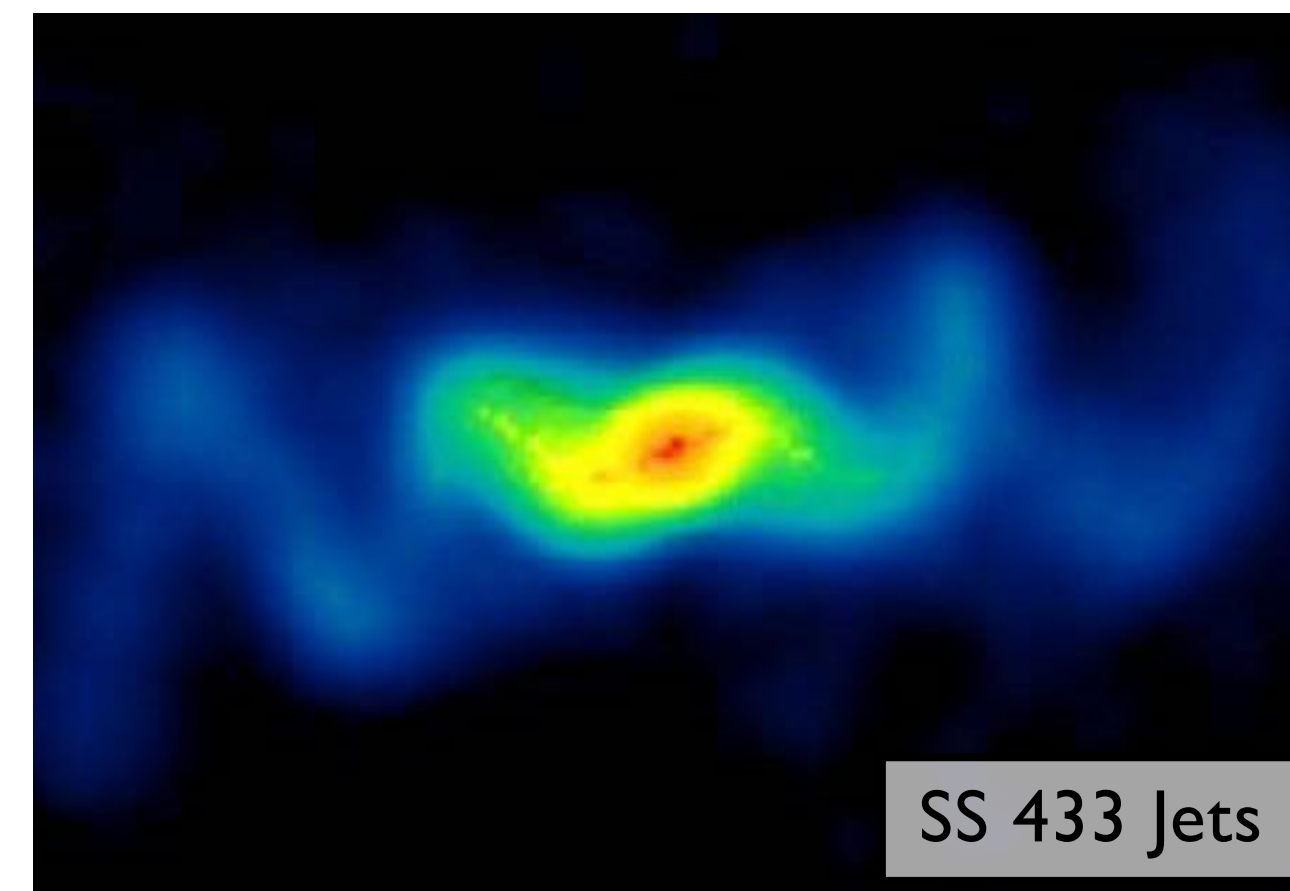
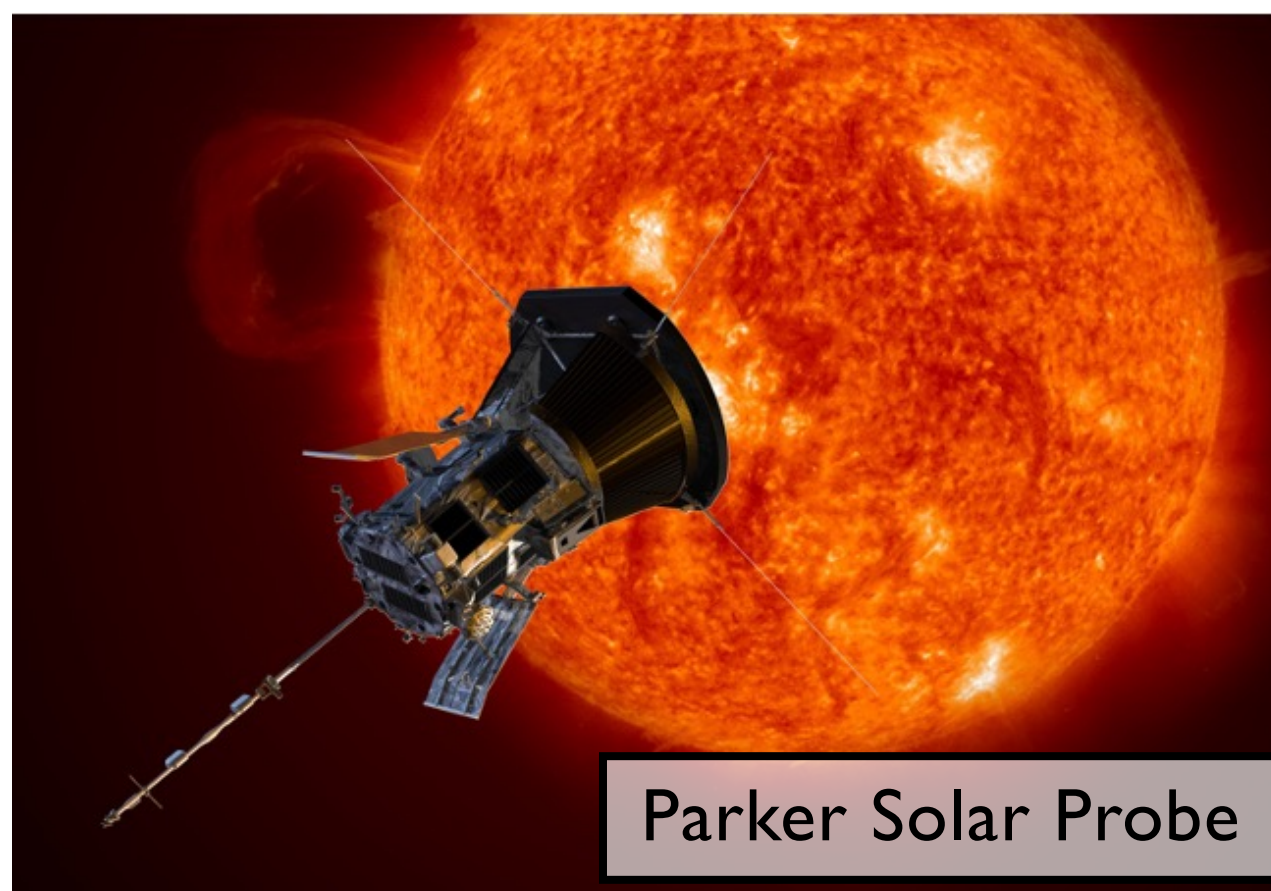
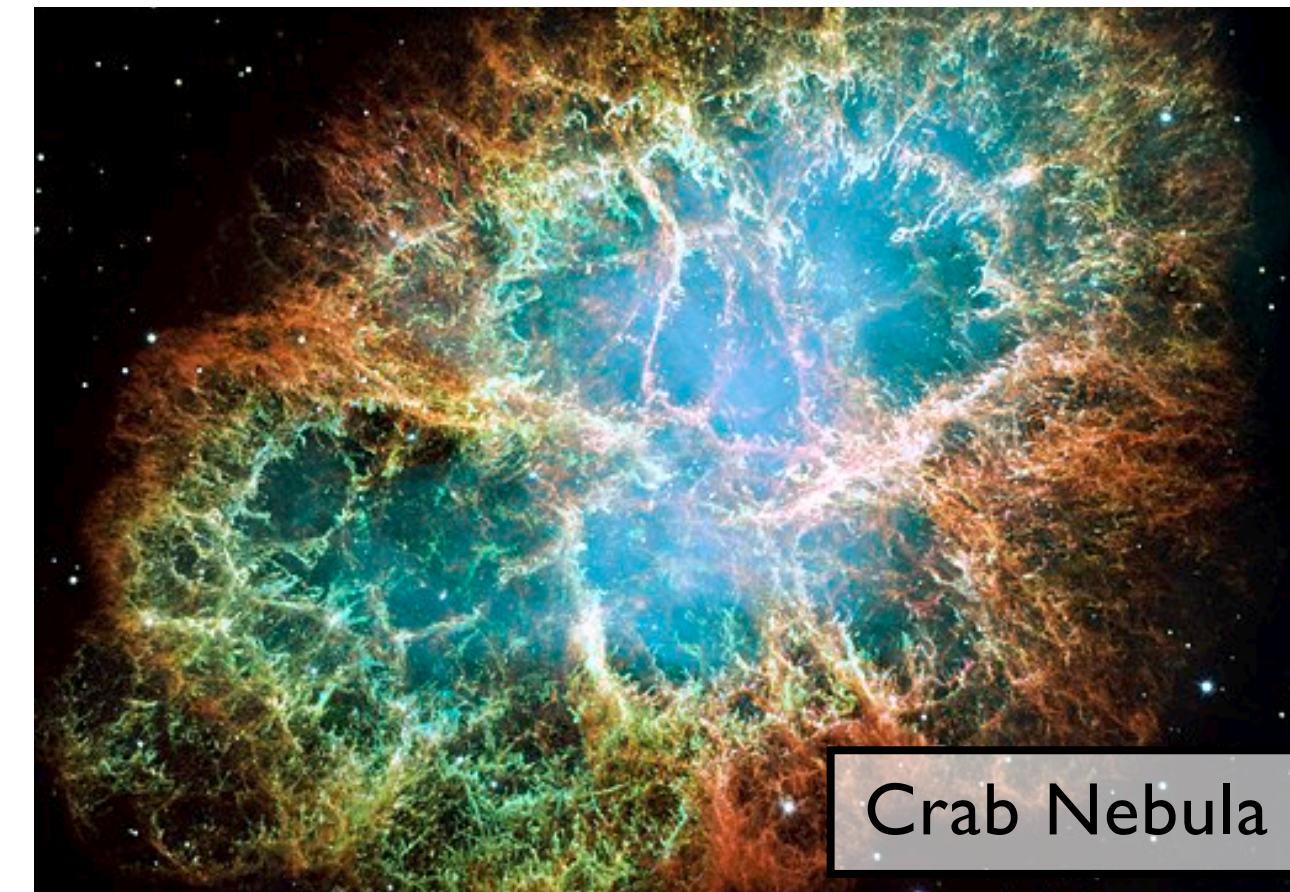
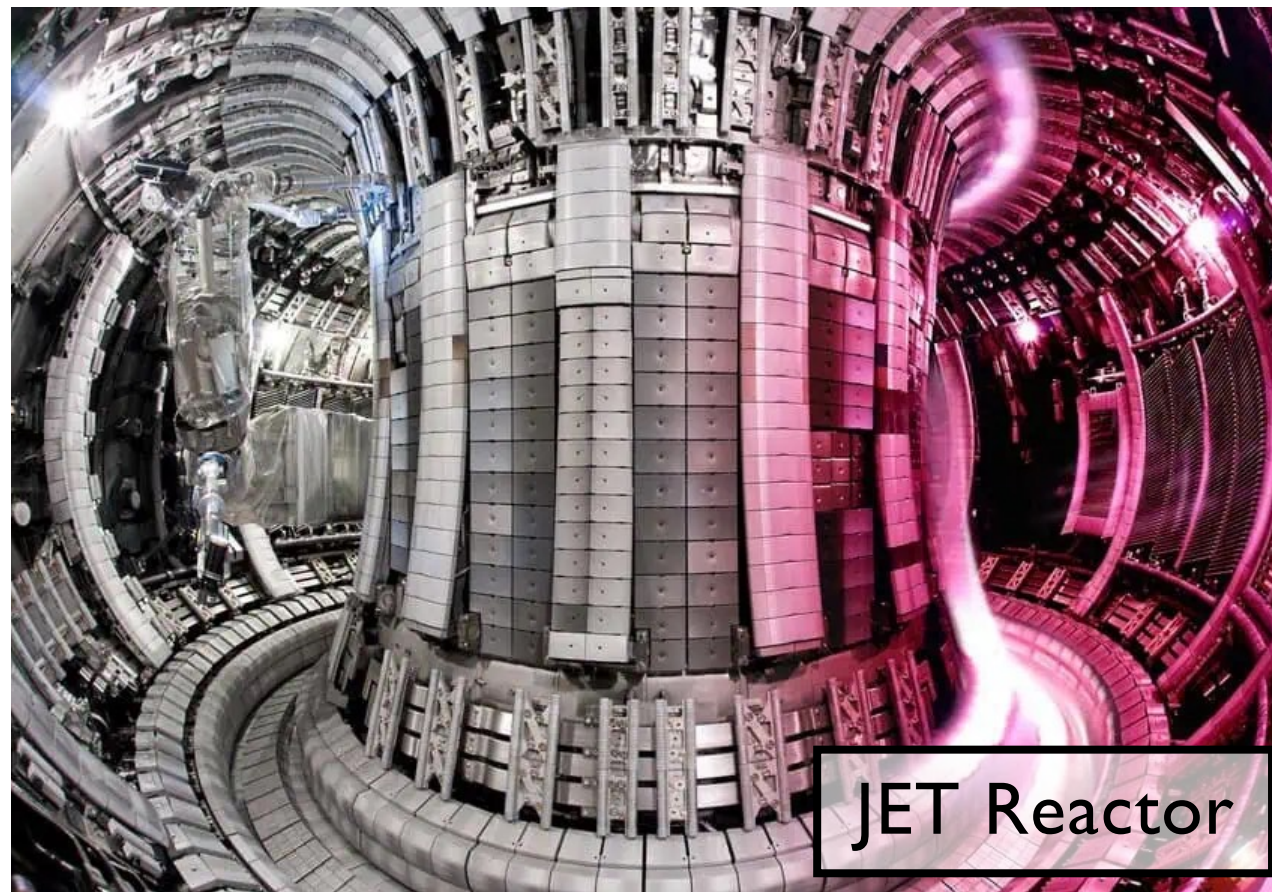


- ▶ sheared velocity flows
- ▶ magnetospheric gaps
- ▶ magnetized rotators
- and others...

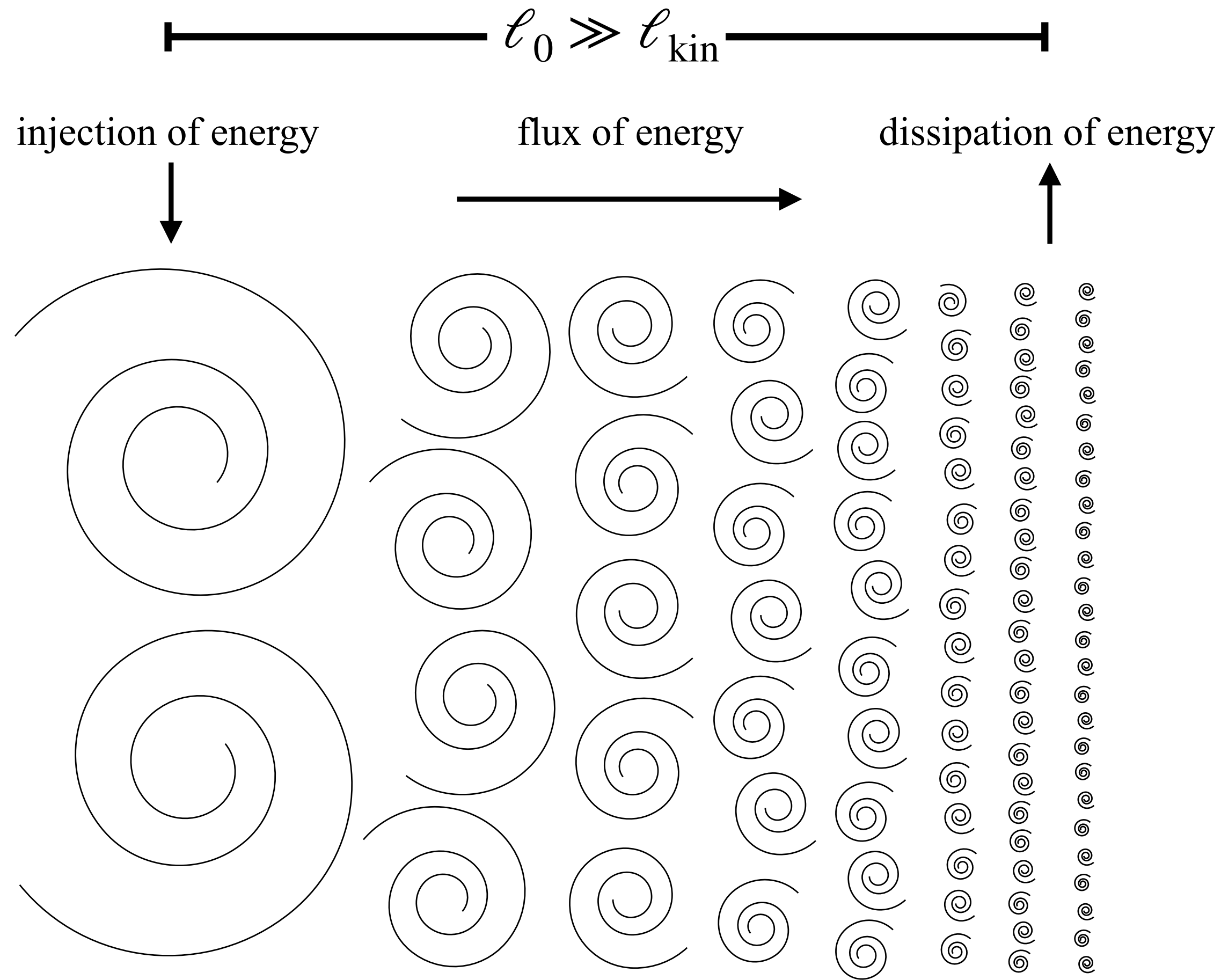
Daughton et al. '14

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

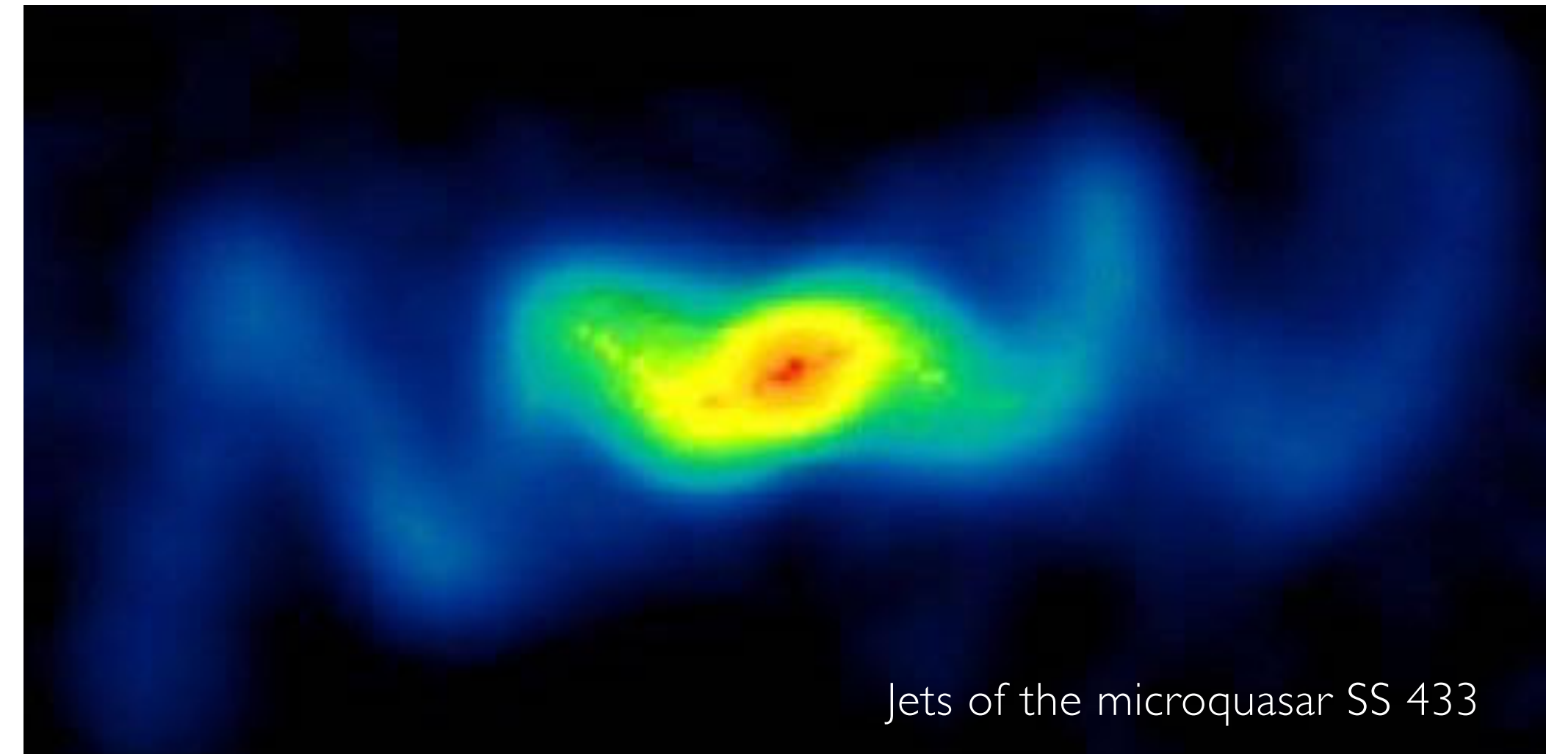
$$\sigma < 1 \qquad \sigma = \frac{B^2}{4\pi\rho c^2} \simeq \frac{4}{\beta} \frac{k_B T}{m_i c^2} \qquad \sigma > 1$$



Expected Turbulence in Large-Scale (Astrophysical) Systems



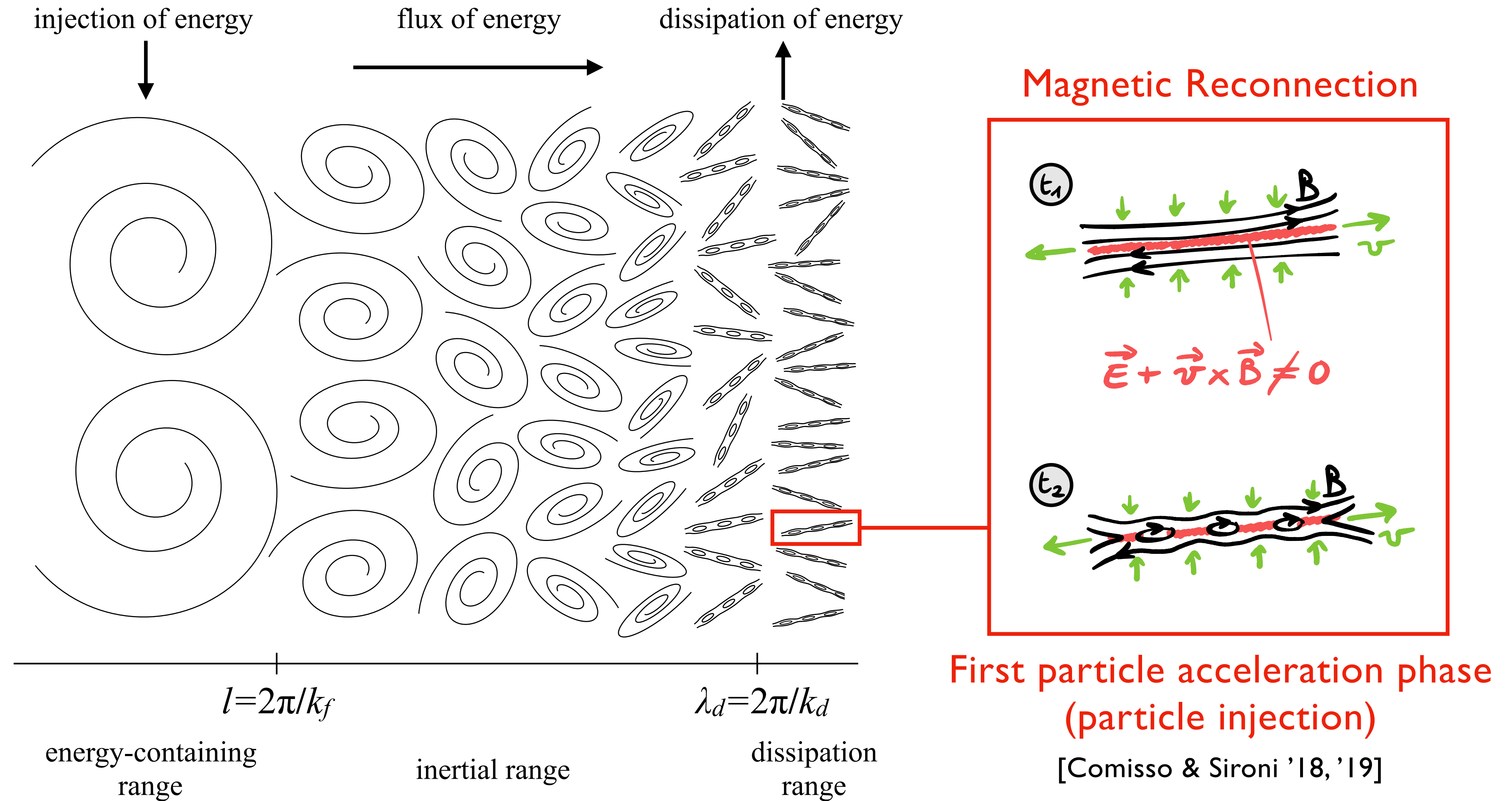
Turbulence is likely to play a main role in the transfer of energy across scales



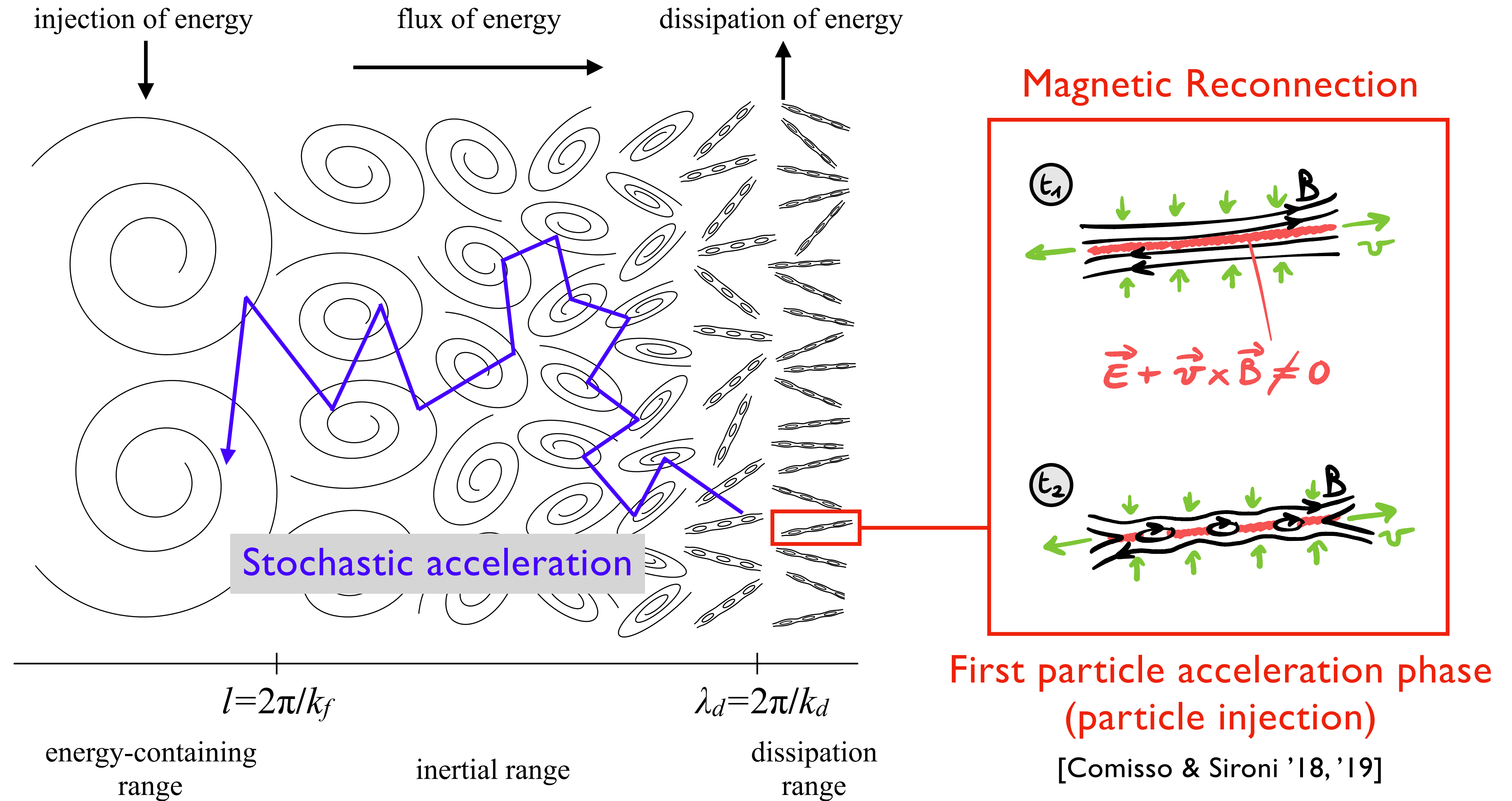
Jets of the microquasar SS 433

- Thermal proton gyro-scale $\lll$ jet diameter
(typically $\ell_{\text{kin}} \sim \rho_p \sim 10^{-9} - 10^{-7} R_{\text{jet}}$
for microquasar jets)

Turbulent Energy Cascade in Large-Scale Magnetized Systems



Turbulent Energy Cascade in Large-Scale Magnetized Systems



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

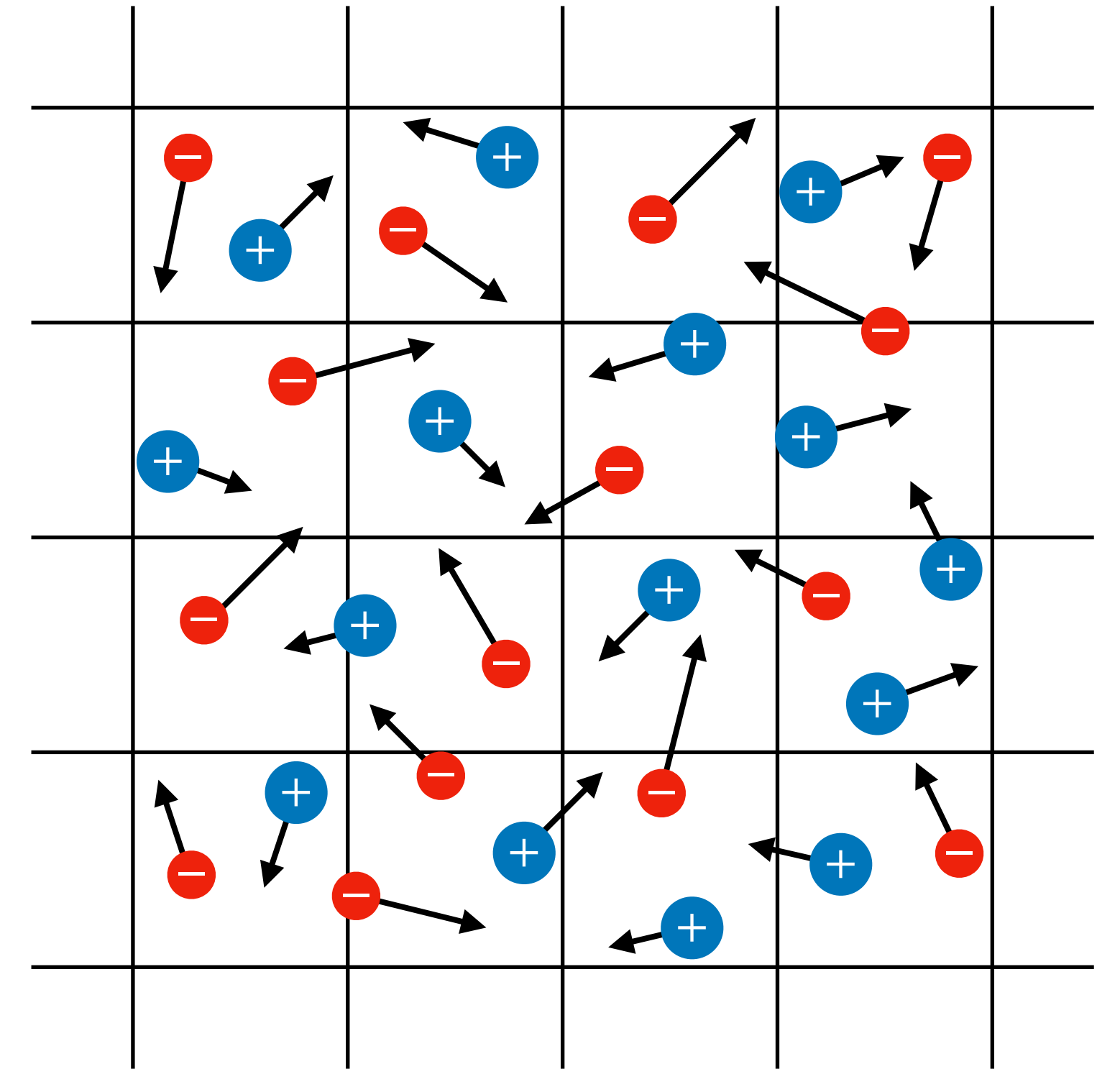
$$\frac{\partial \mathbf{E}}{\partial t} - c \operatorname{curl} \mathbf{B} = -4\pi \mathbf{J}, \quad \operatorname{div} \mathbf{E} = 4\pi \rho,$$

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

where the source terms are computed by

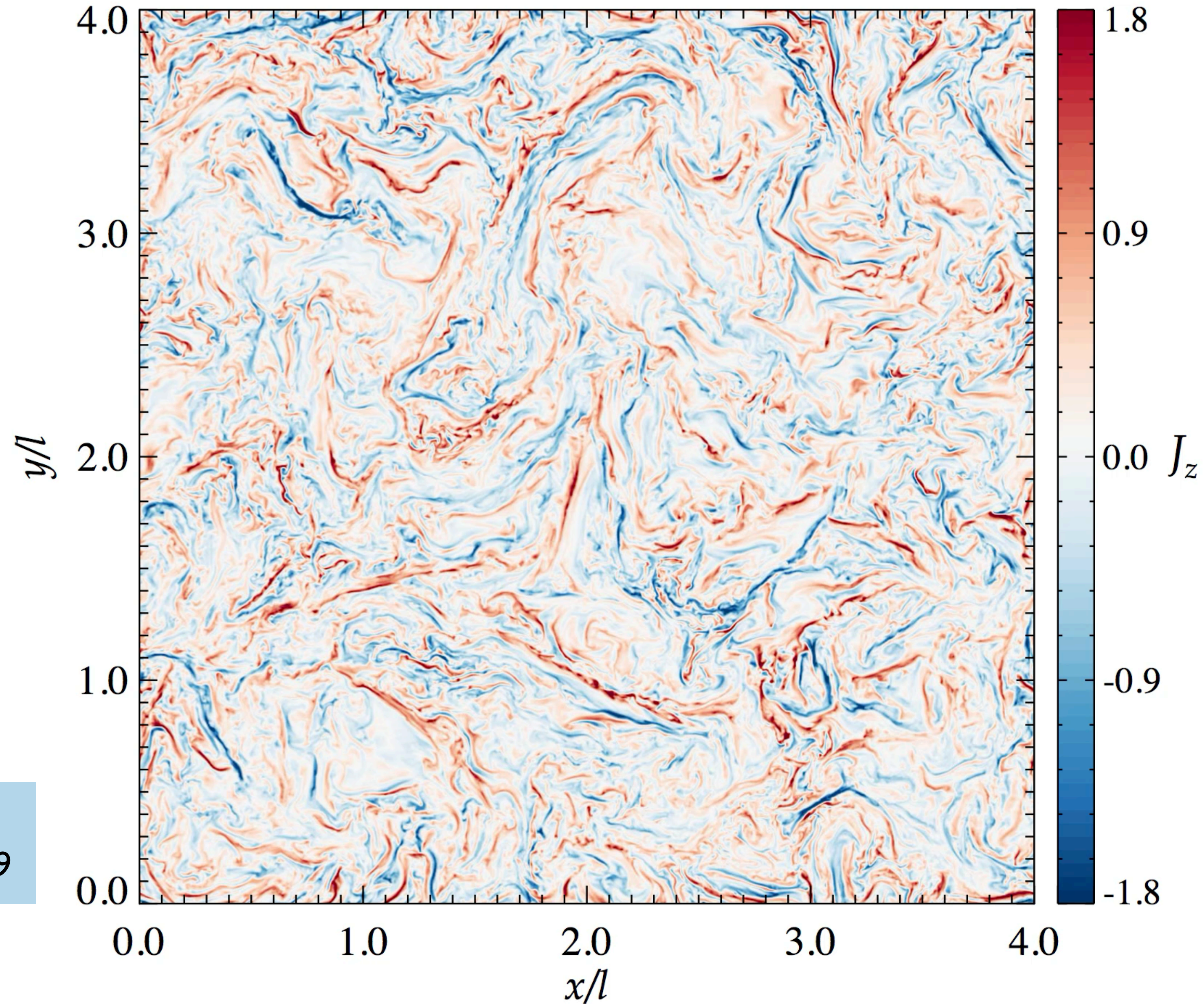
$$\rho = \sum_s q_s \int_{\mathbb{R}^3} f_s d\mathbf{p}, \quad \mathbf{J} = \sum_s \frac{q_s}{m_s} \int_{\mathbb{R}^3} f_s \frac{\mathbf{p}}{\gamma_s} d\mathbf{p}.$$

- ▶ Solution via particle-in-cell method



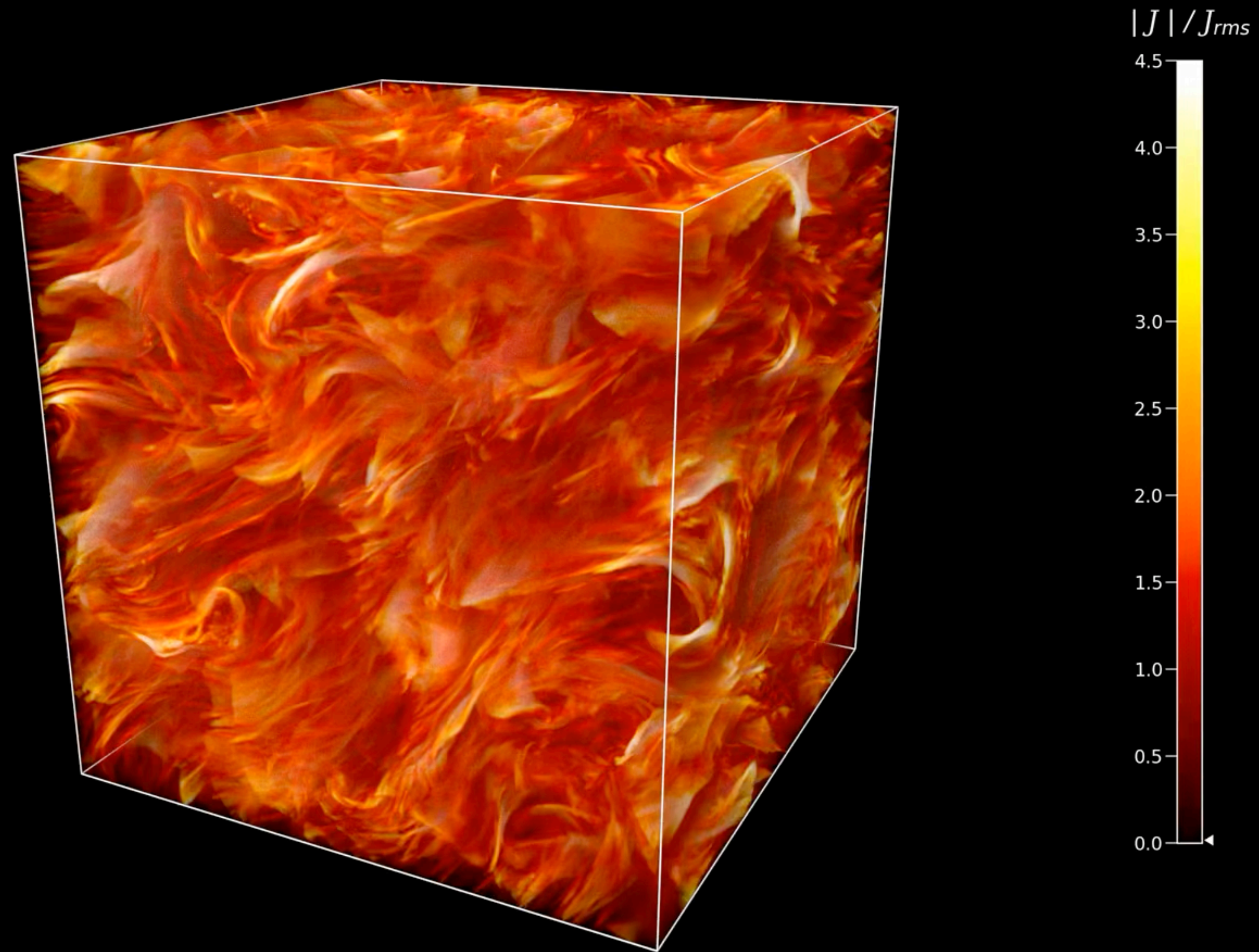
PIC code: TRISTAN-MP
(Spitkovsky 2005)

Flying Through Turbulence Along the Mean Magnetic Field Direction

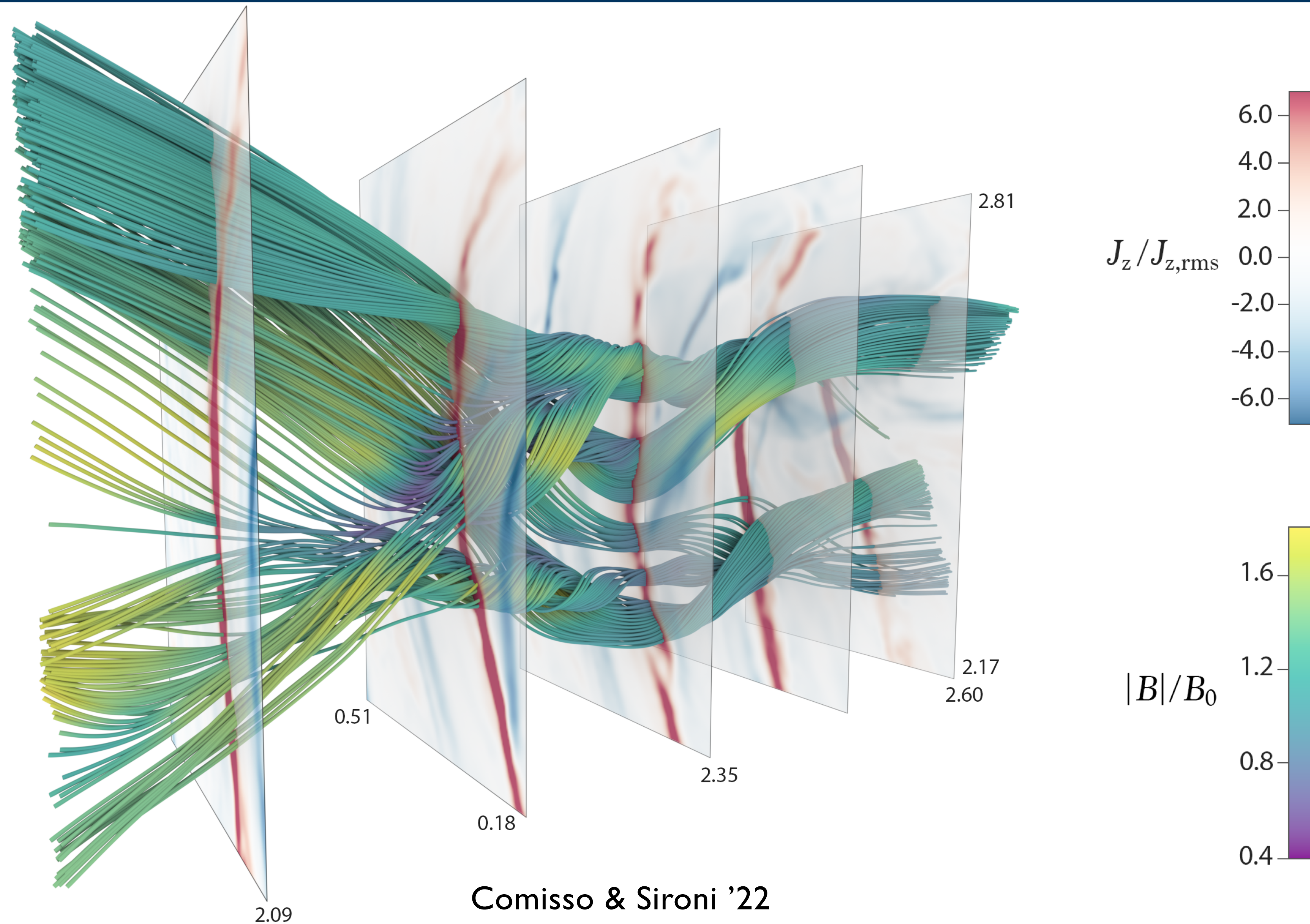


PIC Turbulence from
Comisso & Sironi '18, '19

3D Rendering of the Turbulent Domain

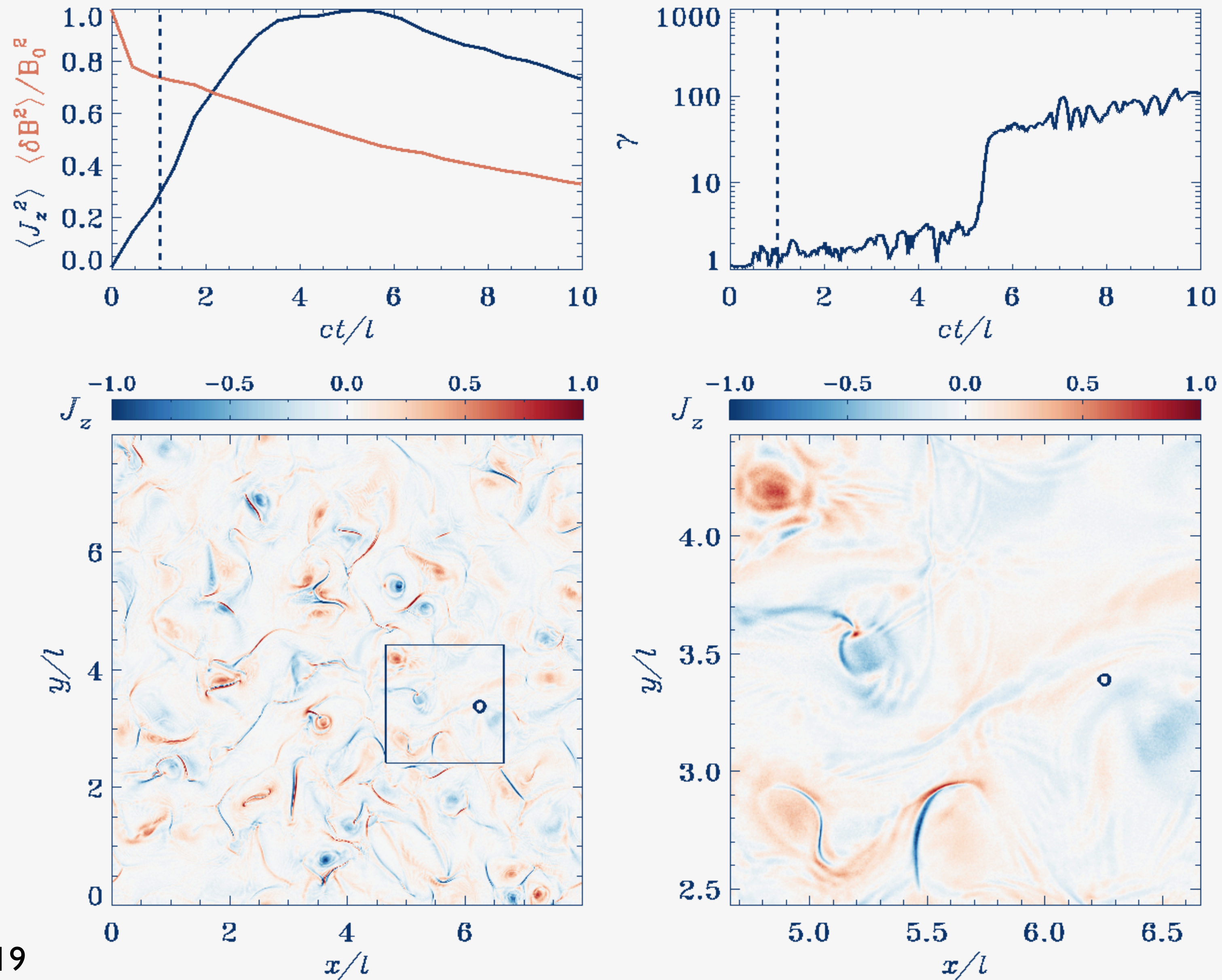


Magnetic Reconnection Within the Turbulent Cascade

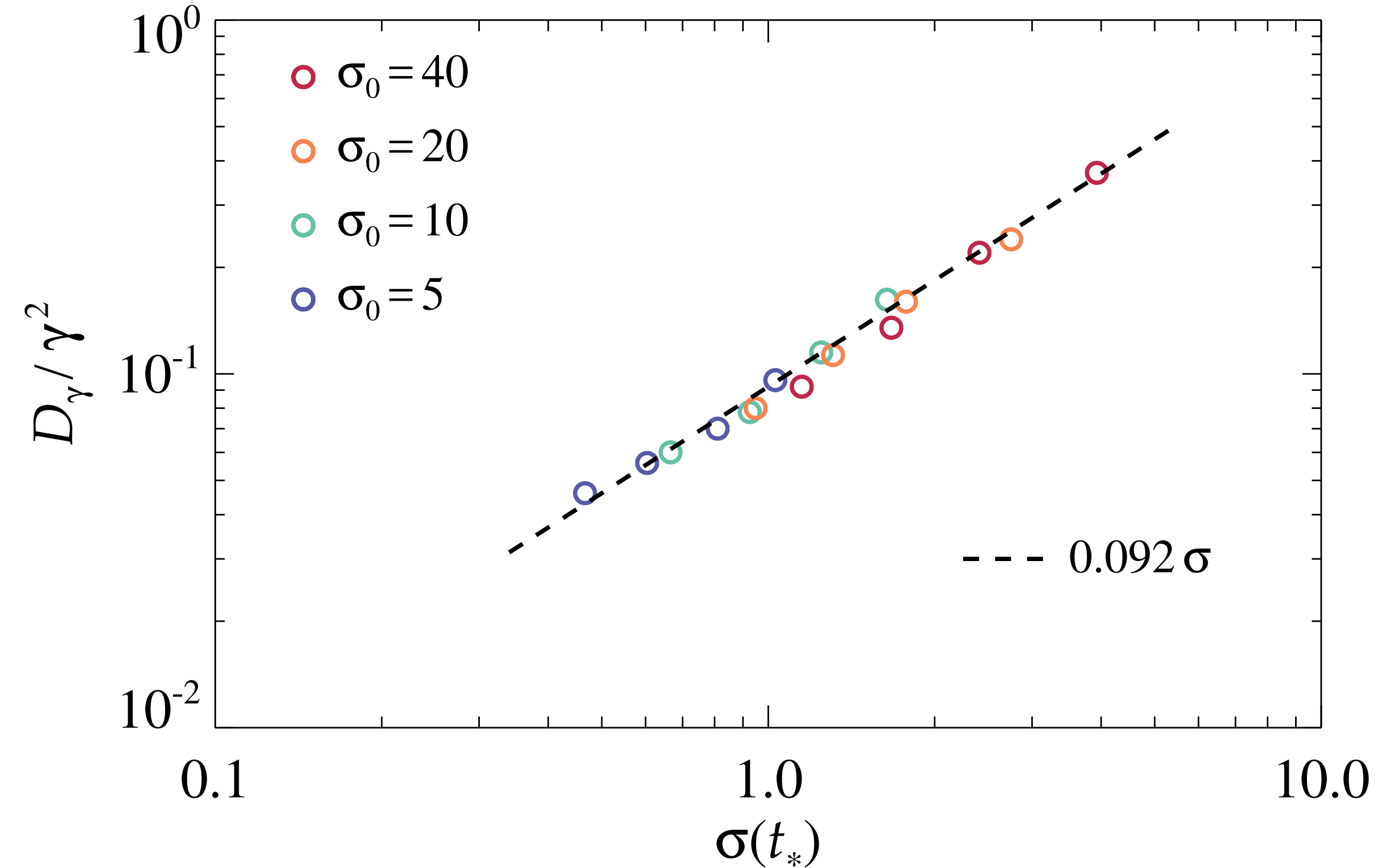
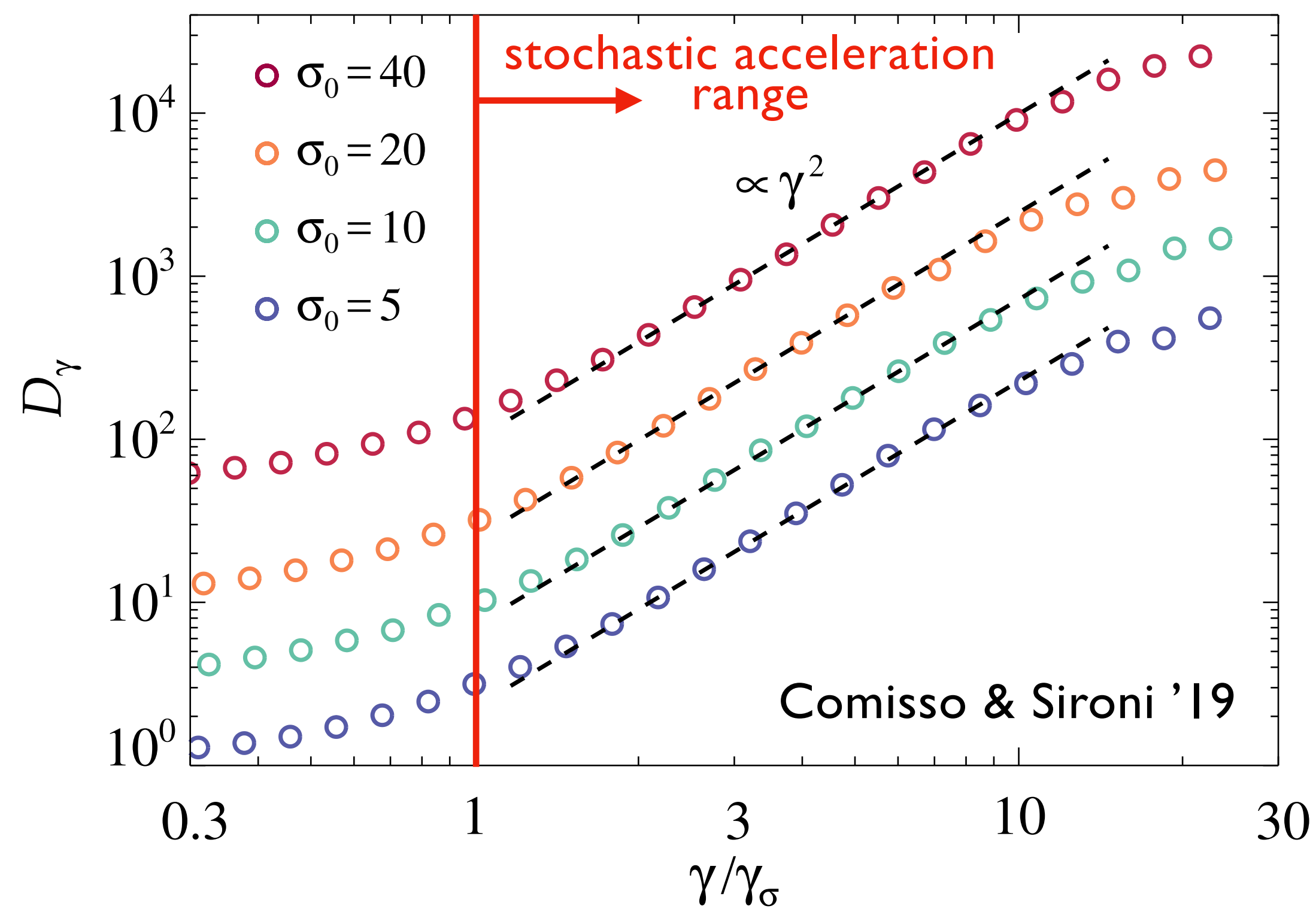


Formation of flux ropes within the turbulent domain (fully kinetic PIC turbulence)

Energization History for a Typical Particle



Stochastic Particle Acceleration and Effective Diffusion in Energy Space

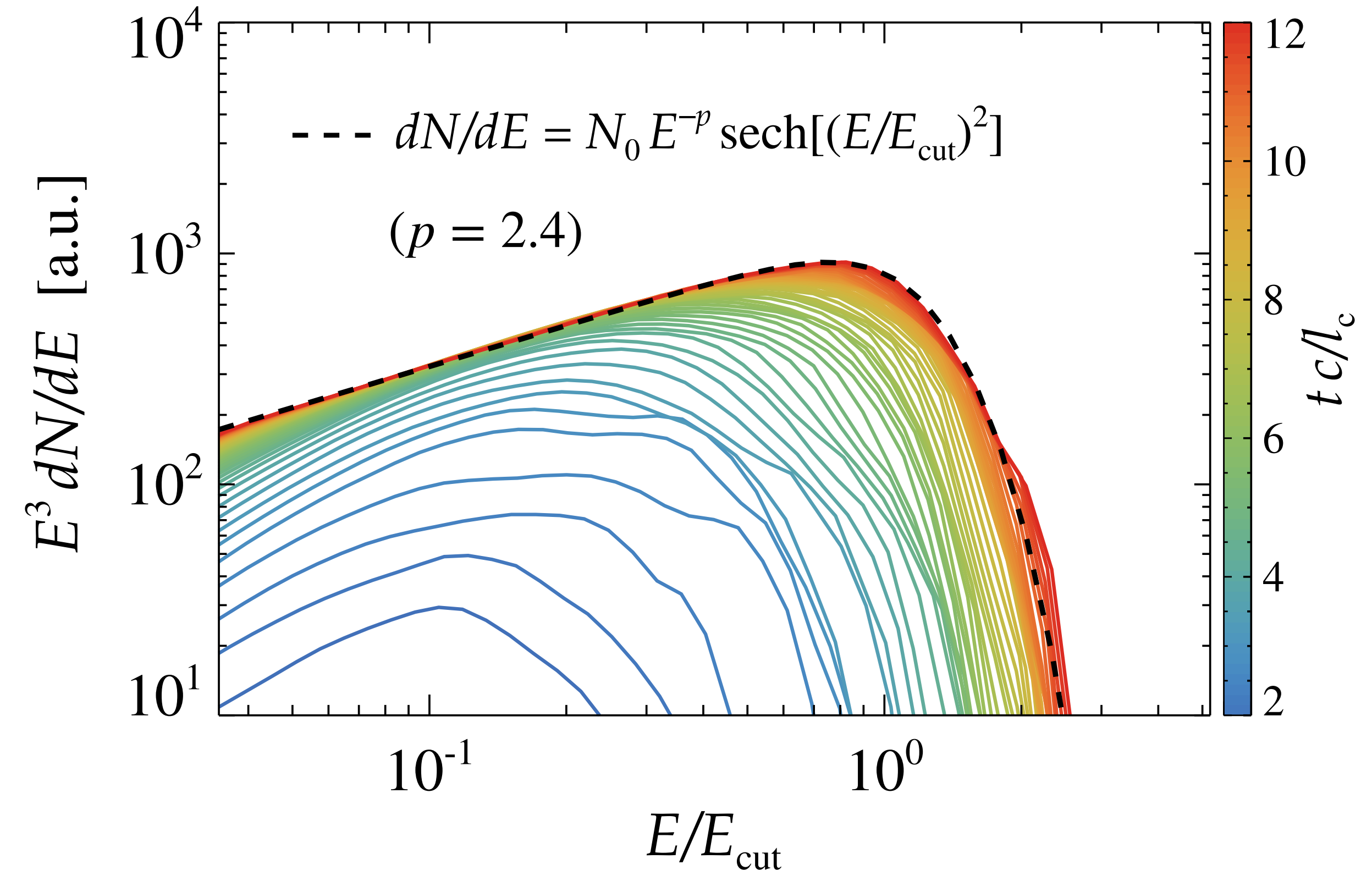
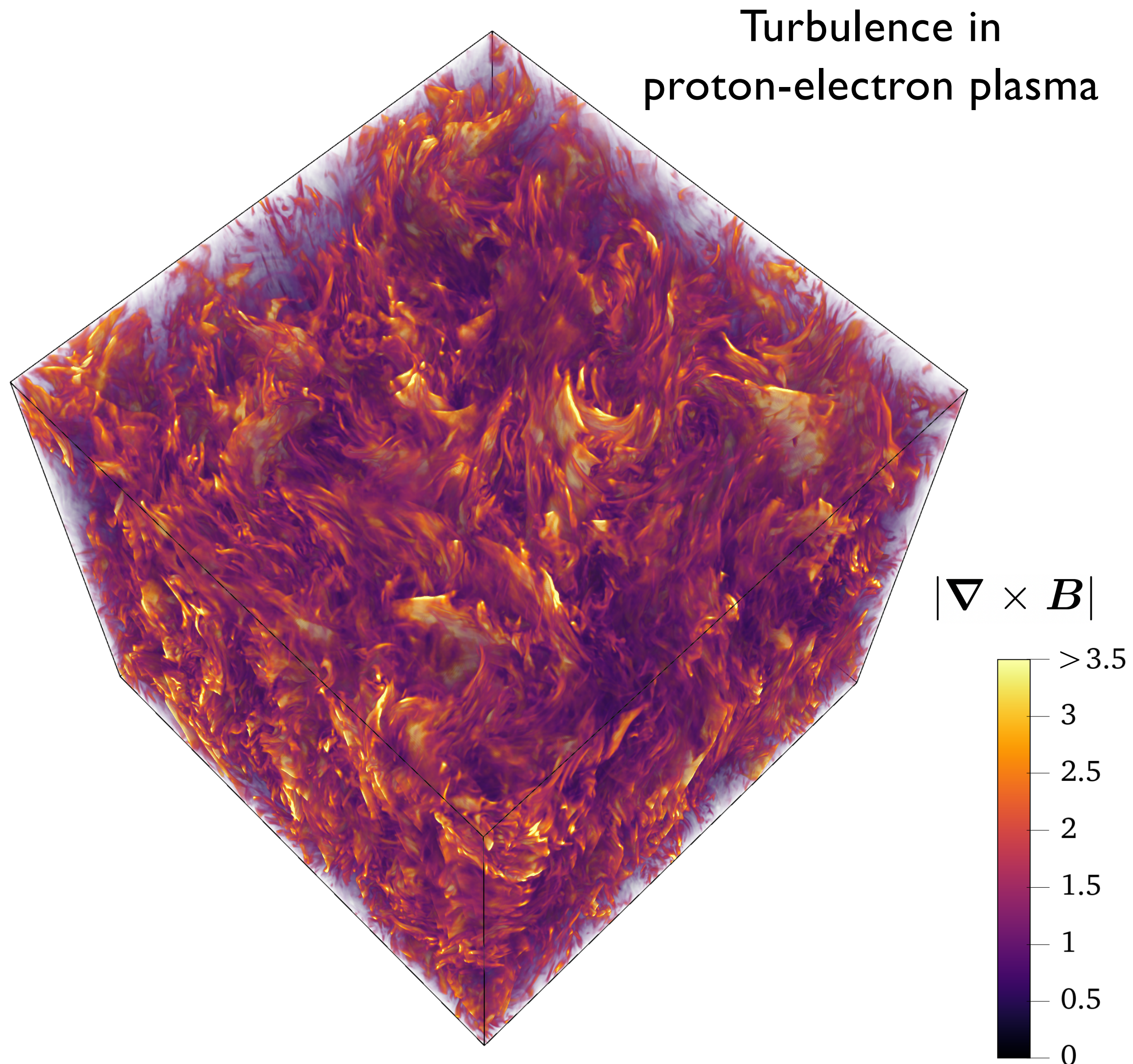


► Mean rate of change of γ due to stochastic acceleration: $\frac{d\langle\gamma\rangle}{dt} = \frac{1}{\gamma^2} \frac{\partial}{\partial \gamma} \left(\gamma^2 D_\gamma \right)$

► Acceleration timescale: $t_{\text{acc}} = \frac{\gamma^2}{4D_\gamma} \simeq \frac{1}{4\kappa_{\text{acc}} \delta u^2} \frac{B_{\text{rms}}^2 l_c}{\delta B_{\text{rms}}^2 c}$

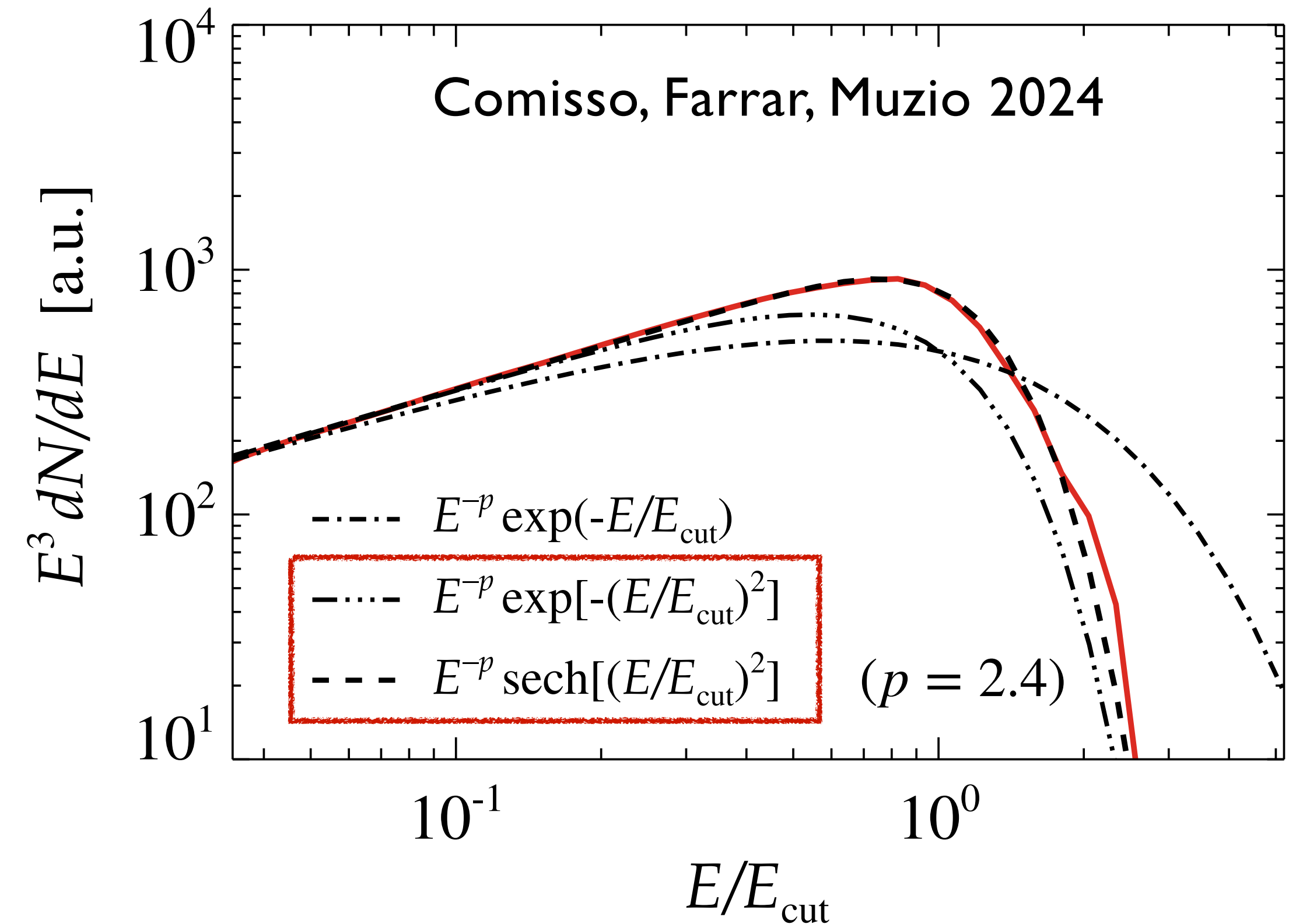
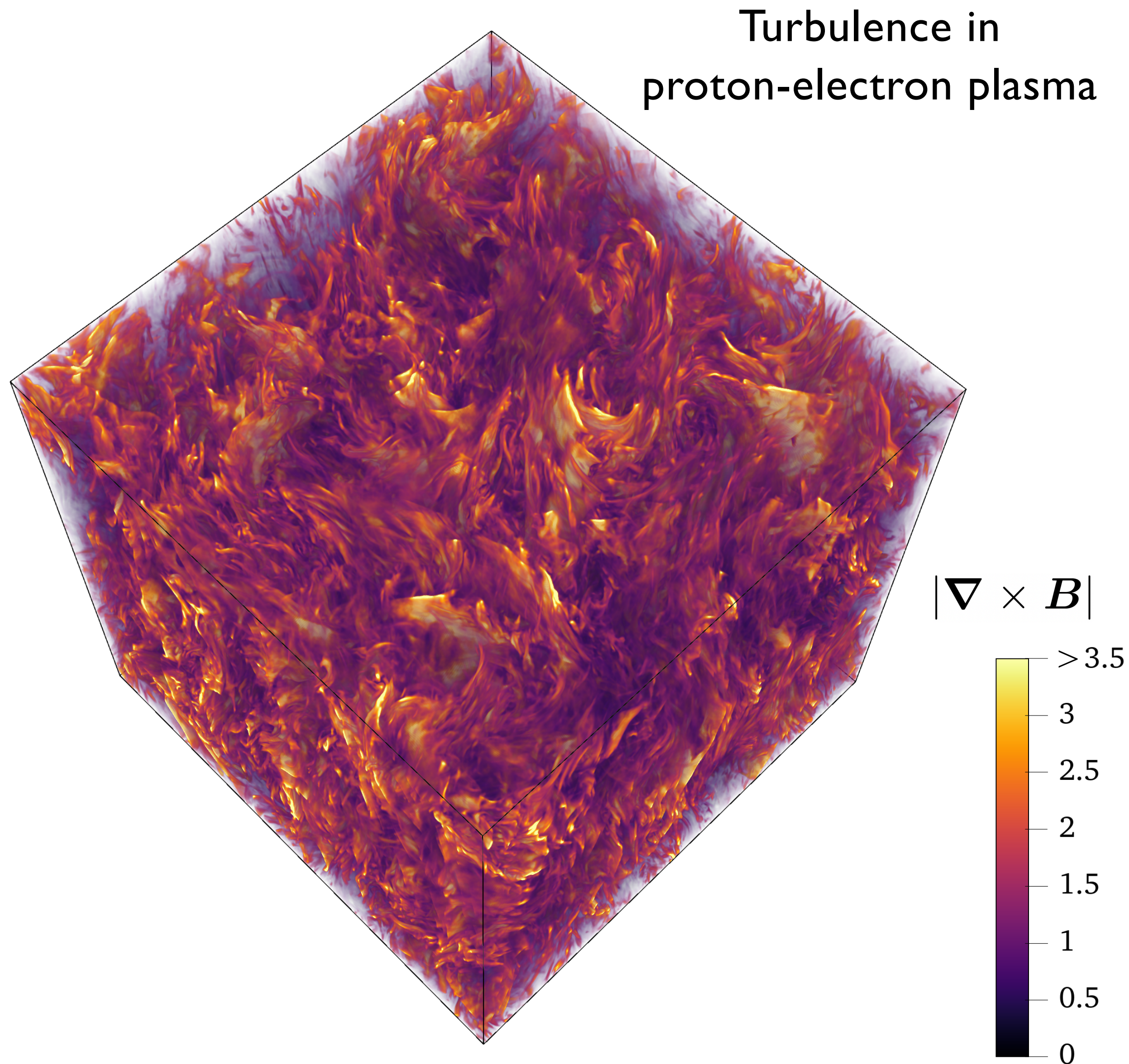
$\kappa_{\text{acc}} \simeq 0.1$ from PIC data measurements

Proton Acceleration: Energy Spectrum and Cutoff Shape



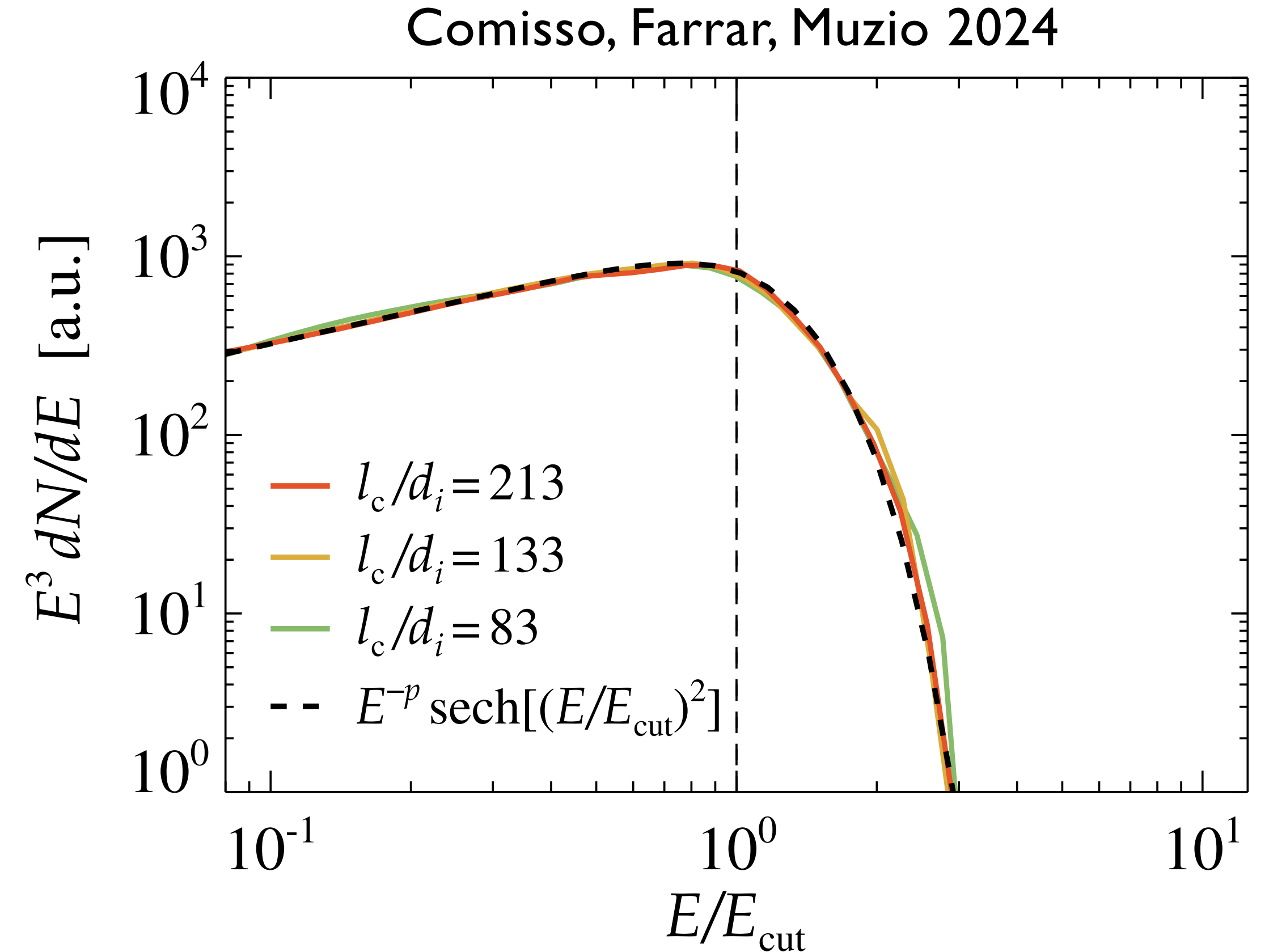
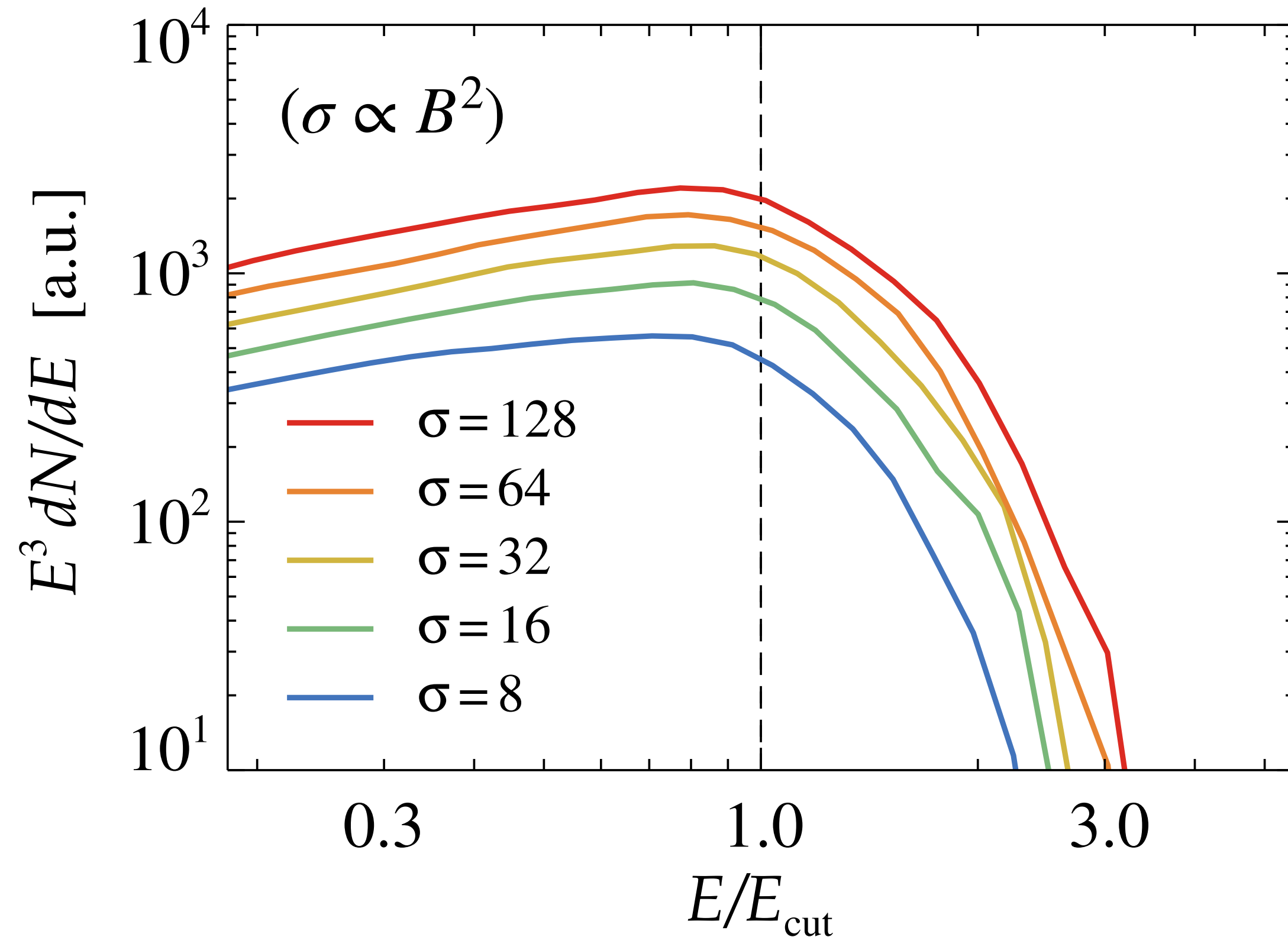
- Magnetized turbulence accelerates particles into a spectrum of the form
$$E^{-p} \text{sech}\left[\left(E/E_{\text{cut}}\right)^2\right] \sim E^{-p} \exp\left[-\left(E/E_{\text{cut}}\right)^2\right]$$

Proton Acceleration: Energy Spectrum and Cutoff Shape



- Magnetized turbulence accelerates particles into a spectrum of the form $E^{-p} \text{sech}\left[(E/E_{\text{cut}})^2\right] \sim E^{-p} \exp\left[-(E/E_{\text{cut}})^2\right]$

Proton Acceleration to the Highest Energies



- 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 $l_c = R_{\text{size}}$

Proton Escape from the Acceleration Region

- 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

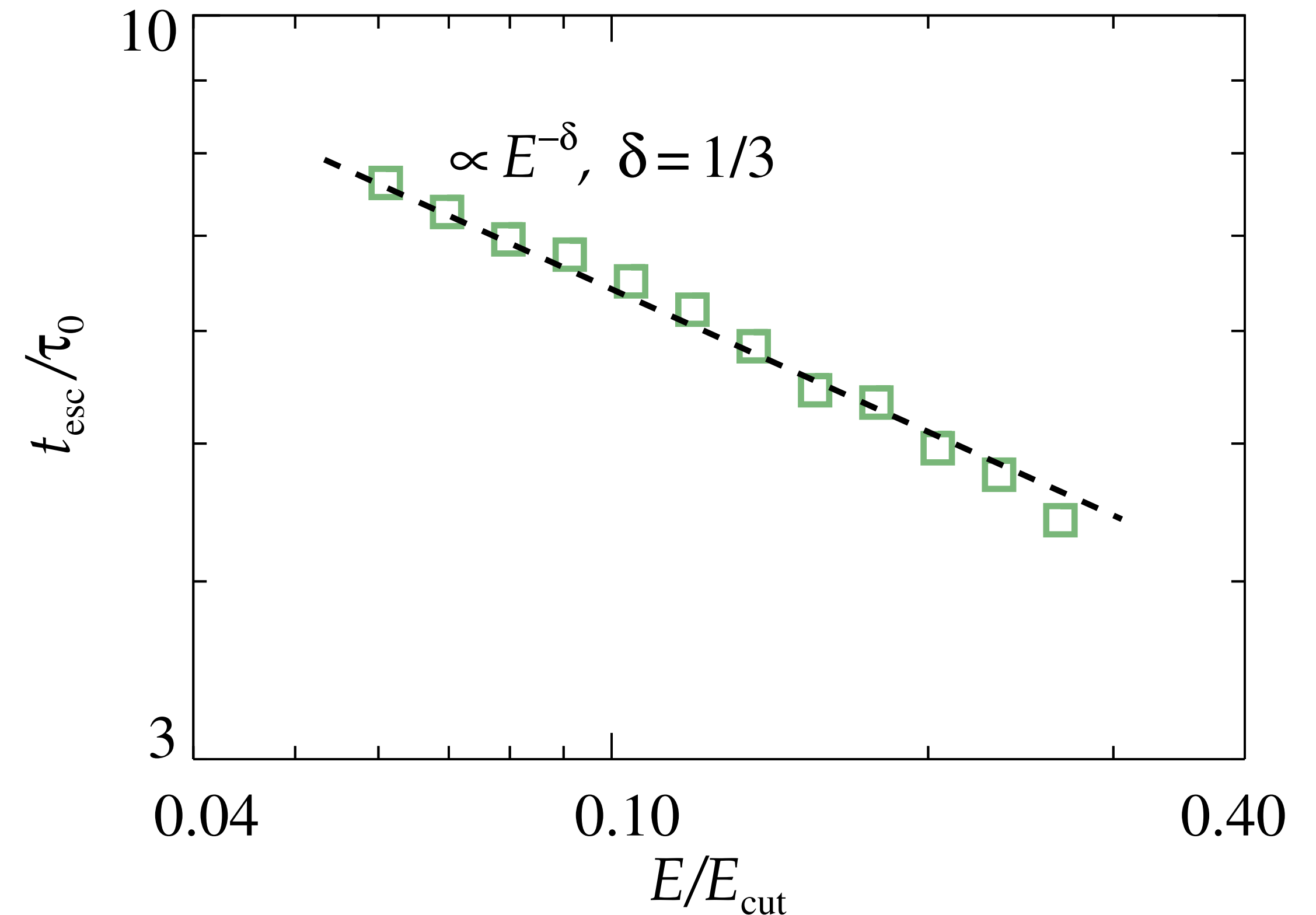
$$\phi(E) = \frac{dN}{dEdt} = \frac{1}{t_{\text{esc}}} \frac{dN}{dE} \propto E^{-s} \text{sech} \left[\left(E/E_{\text{cut}} \right)^2 \right]$$

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

$p \sim 2.4$

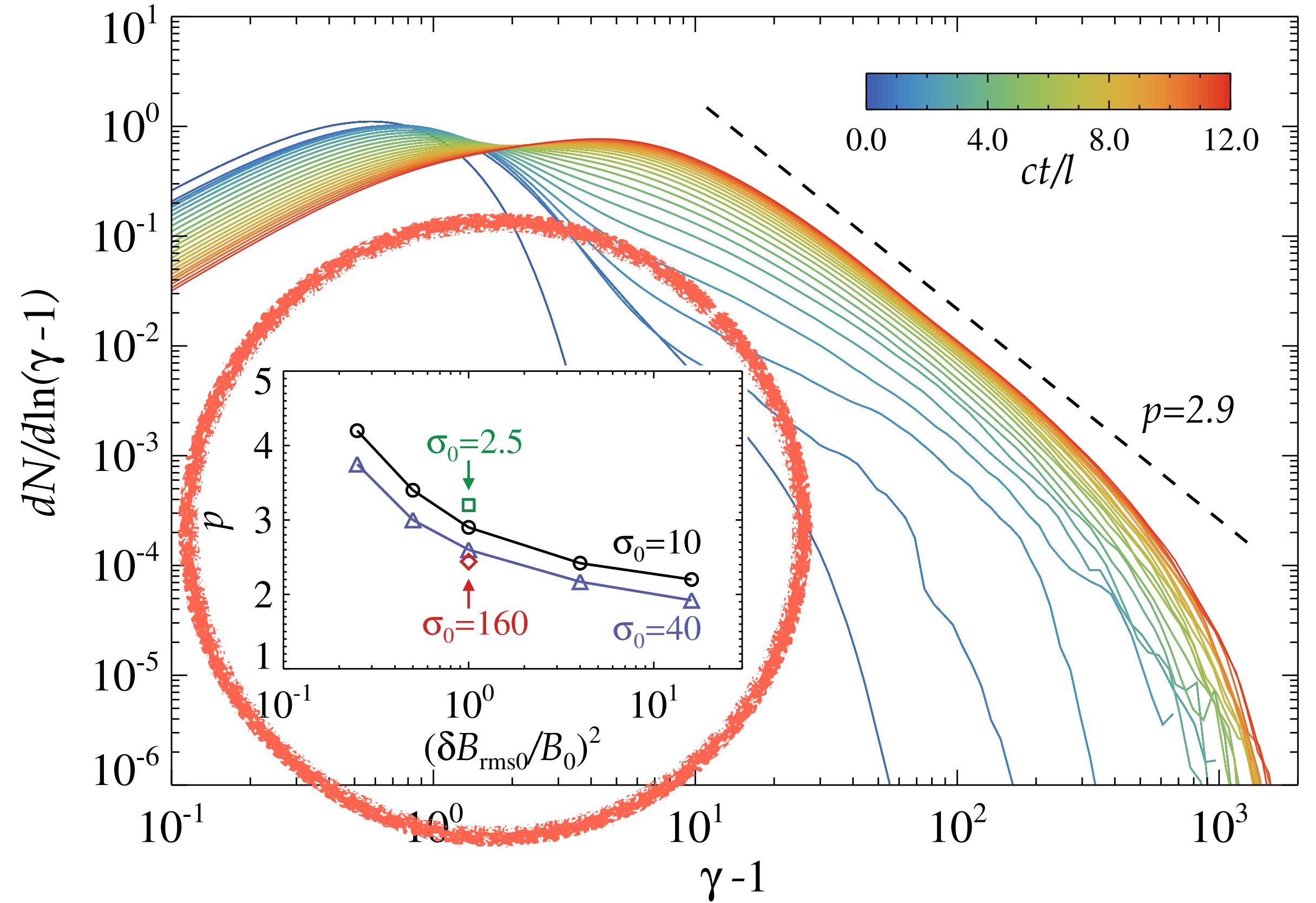
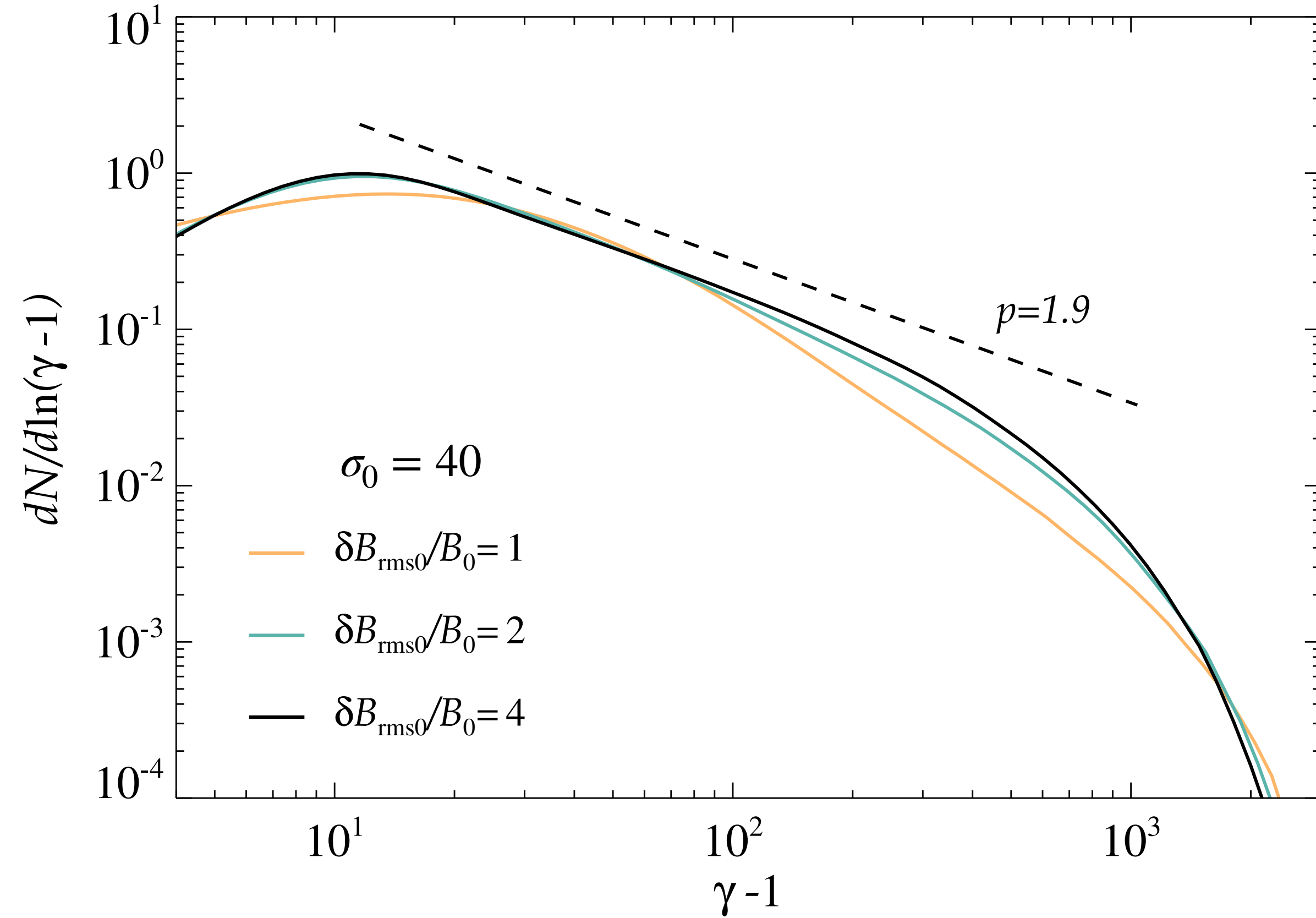
$\delta \sim 1/3$ from PIC simulations of highly magnetized ($\sigma \gg 1$) turbulence

Comisso, Farrar, Muzio 2024



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

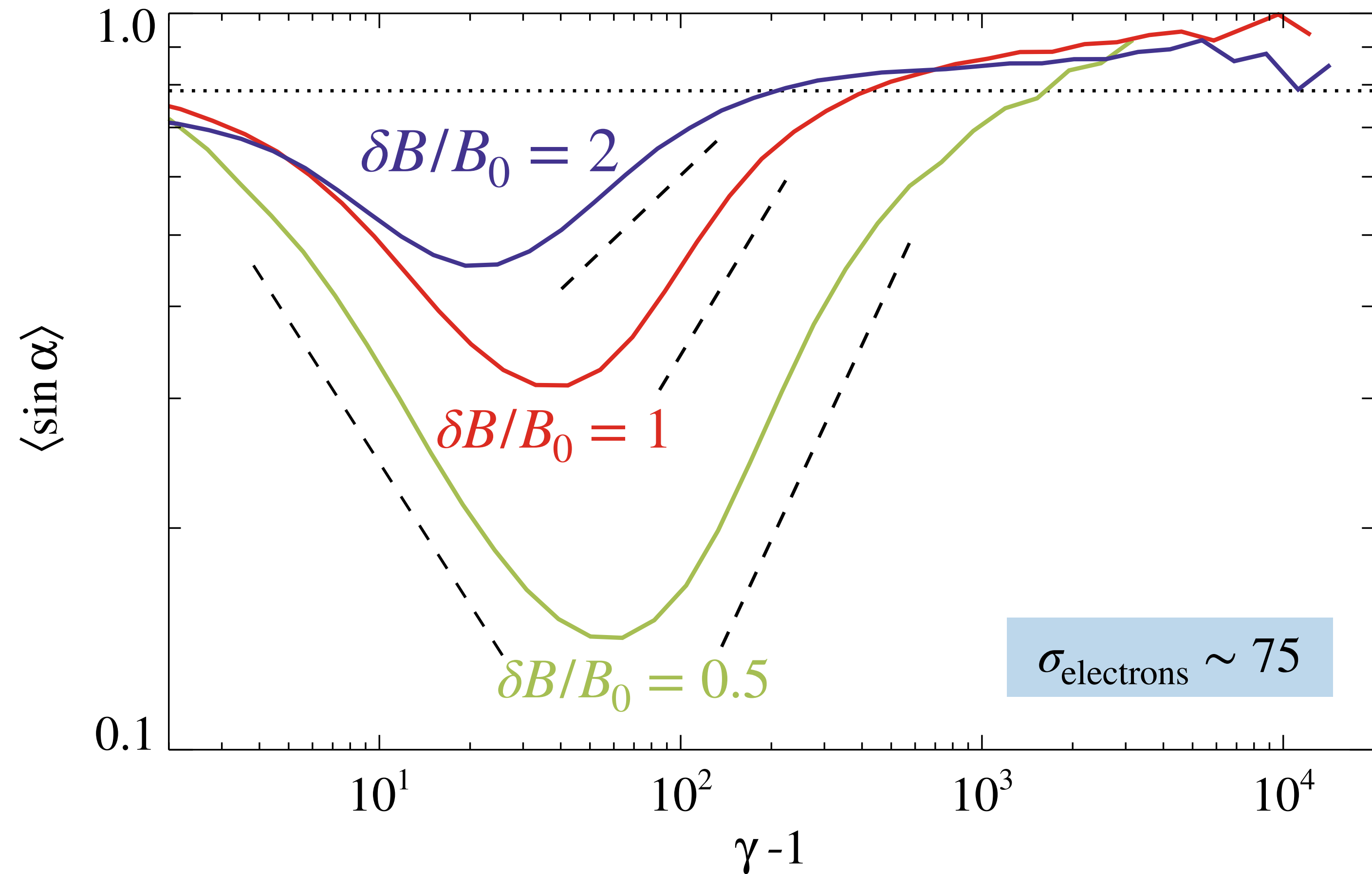
Spectral Hardness Depends on the Guide Field Strength and Magnetization



Comisso & Sironi '18, '19, '21, '22, Comisso+ '20

Particle energy distribution depends on guide field strength and magnetization

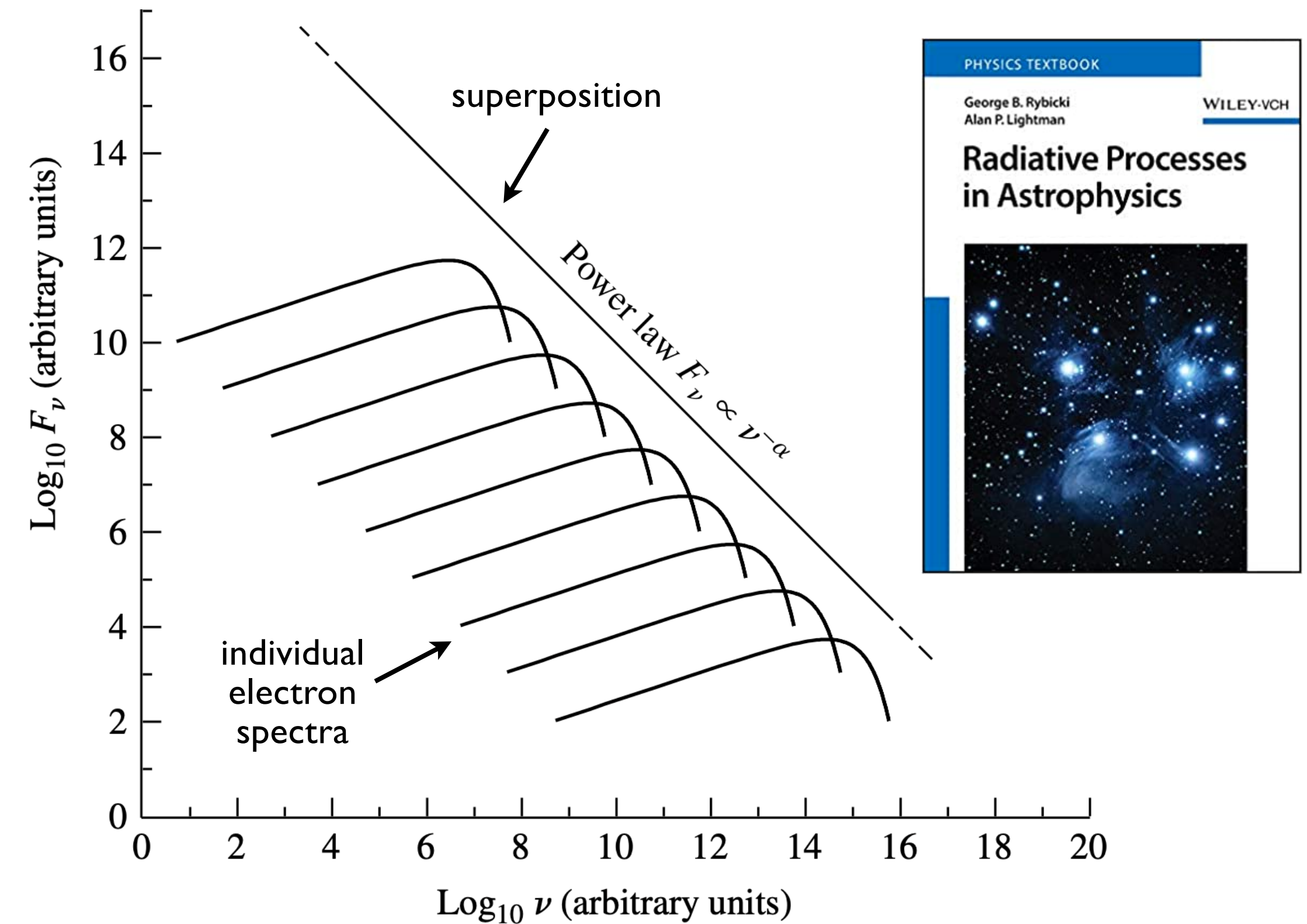
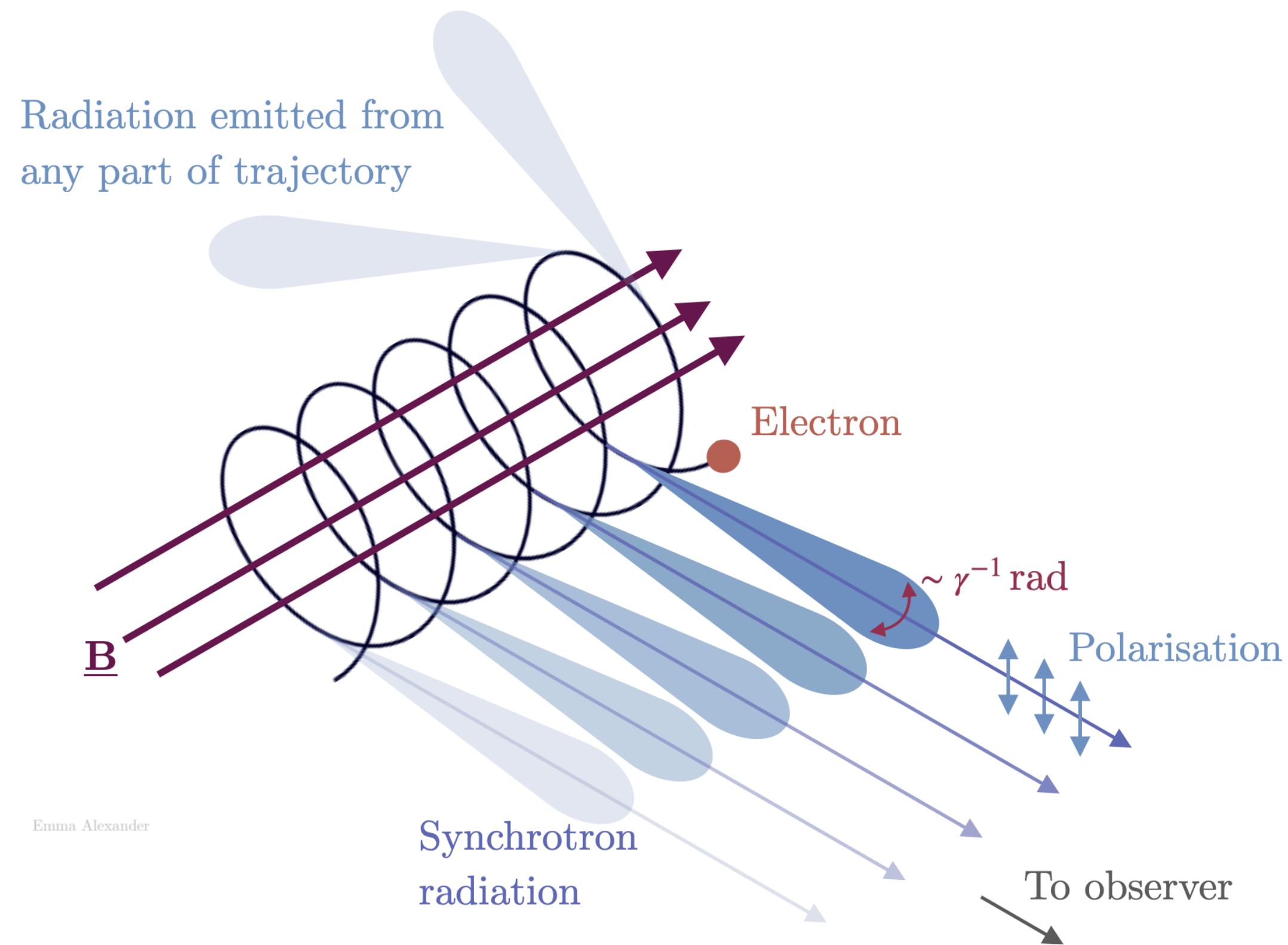
Pitch-Angle Anisotropy of Accelerated Electrons



Comisso & Sironi '19, Comisso+ '20

- Pitch-angle anisotropy depends on guide field strength and magnetization

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

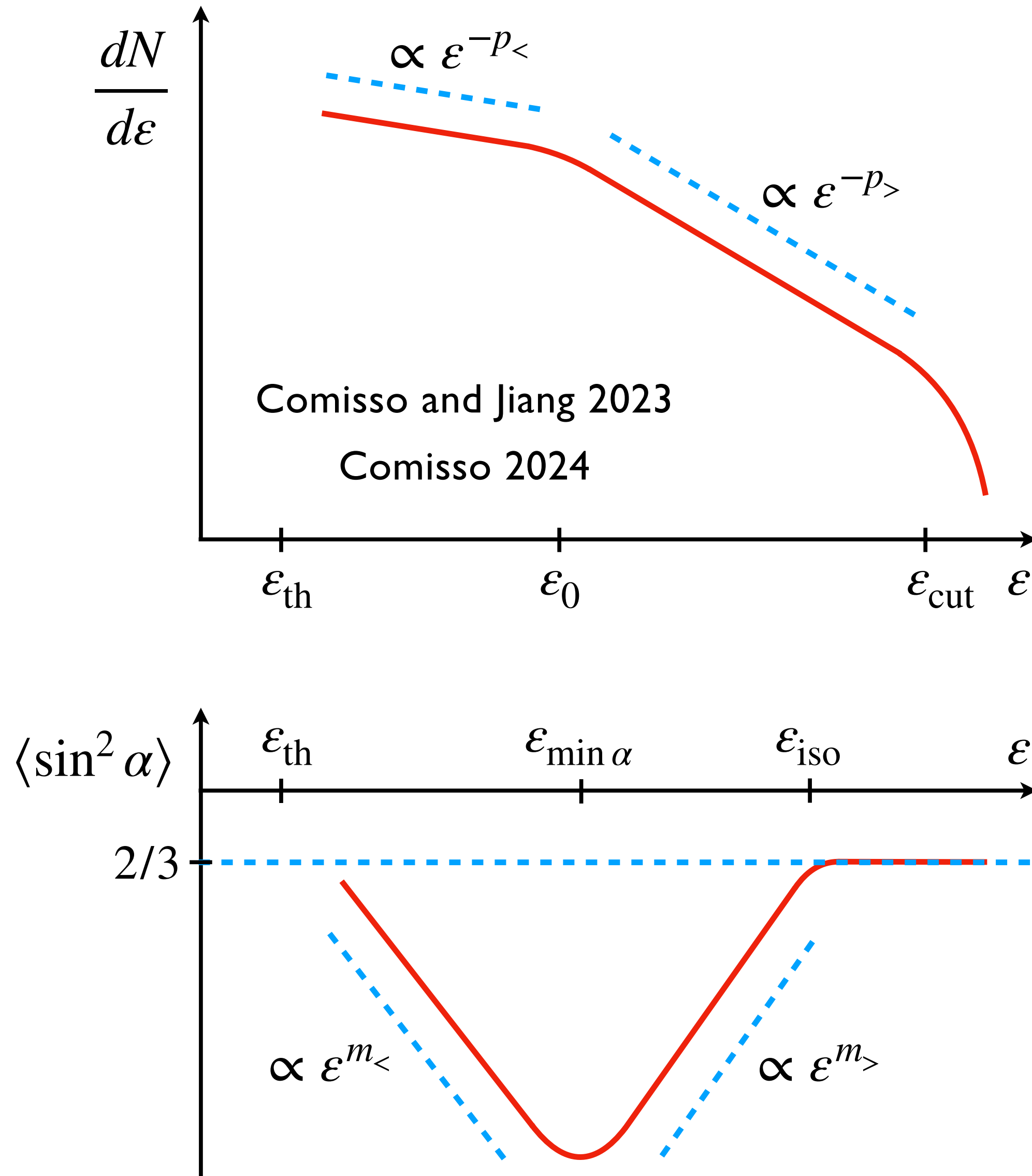
$$dN/d\gamma \propto \gamma^{-p}$$

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 ($\gamma \gg 1$):

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

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

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

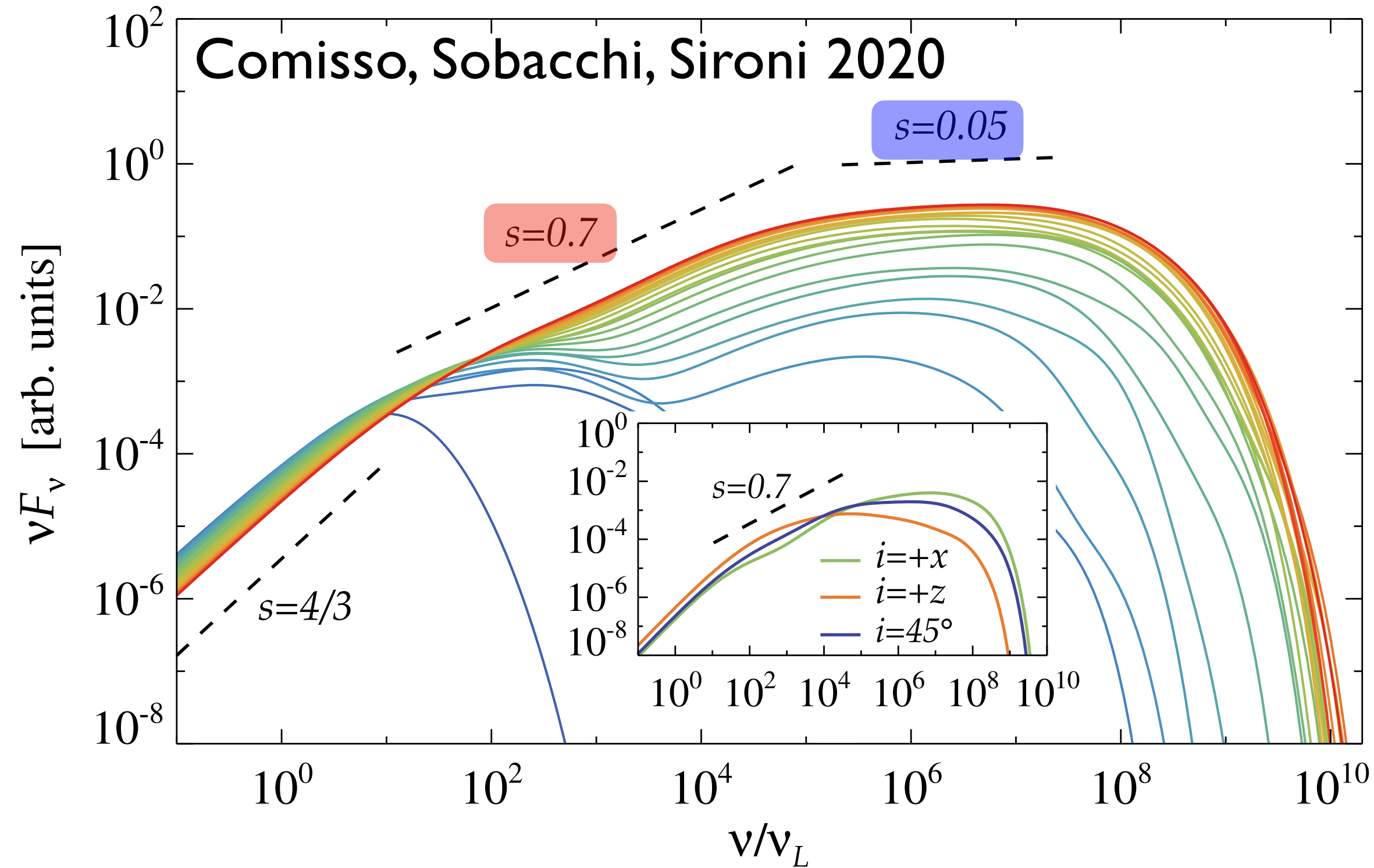
$$\nu \sim \gamma^2 \nu_L \sin \alpha \propto \gamma^{2+m/2} \quad (\nu_L = eB/2\pi m_e c)$$

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

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

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

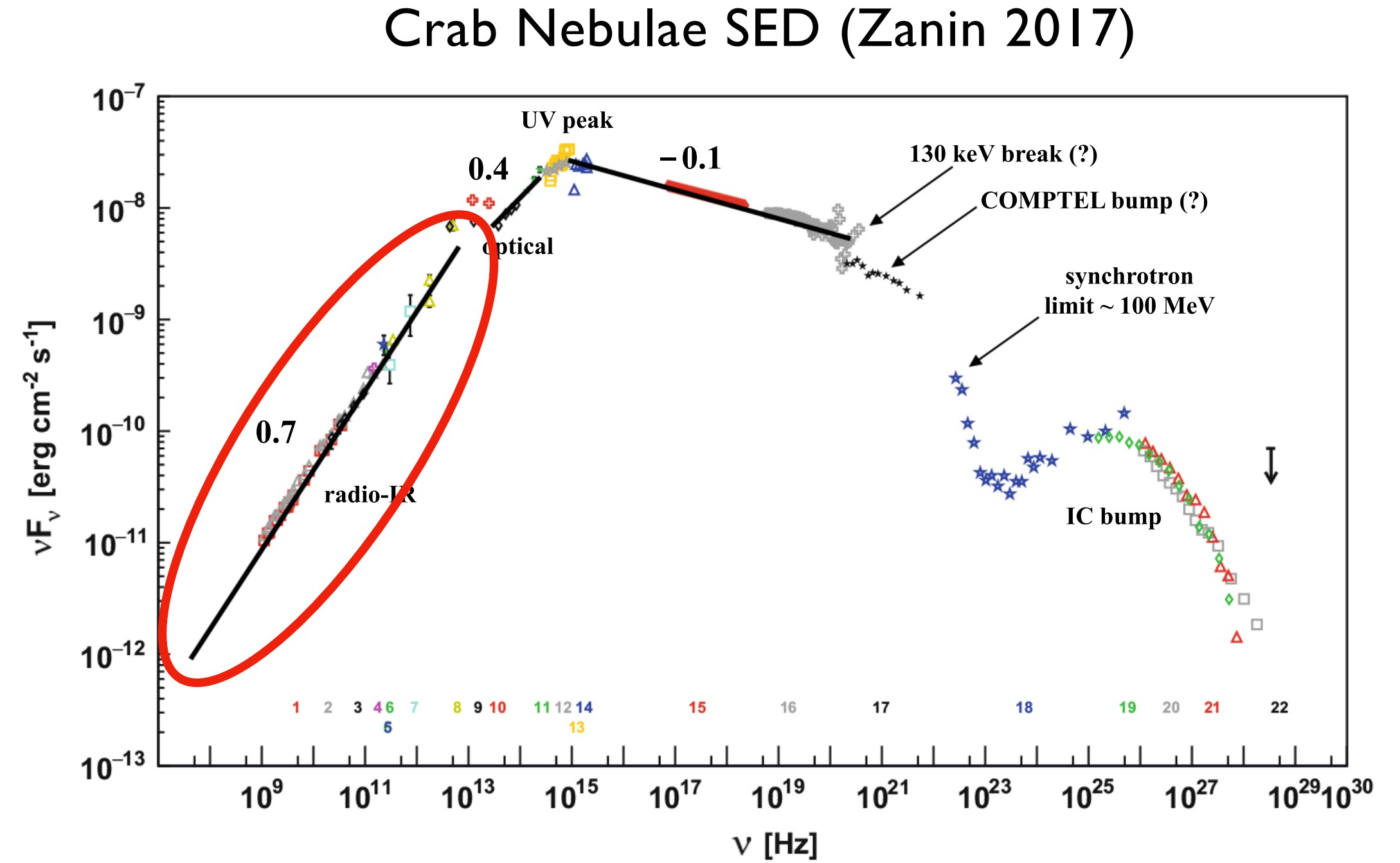
Modification of the Spectral Energy Distribution: Confirmation in PLC simulations



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

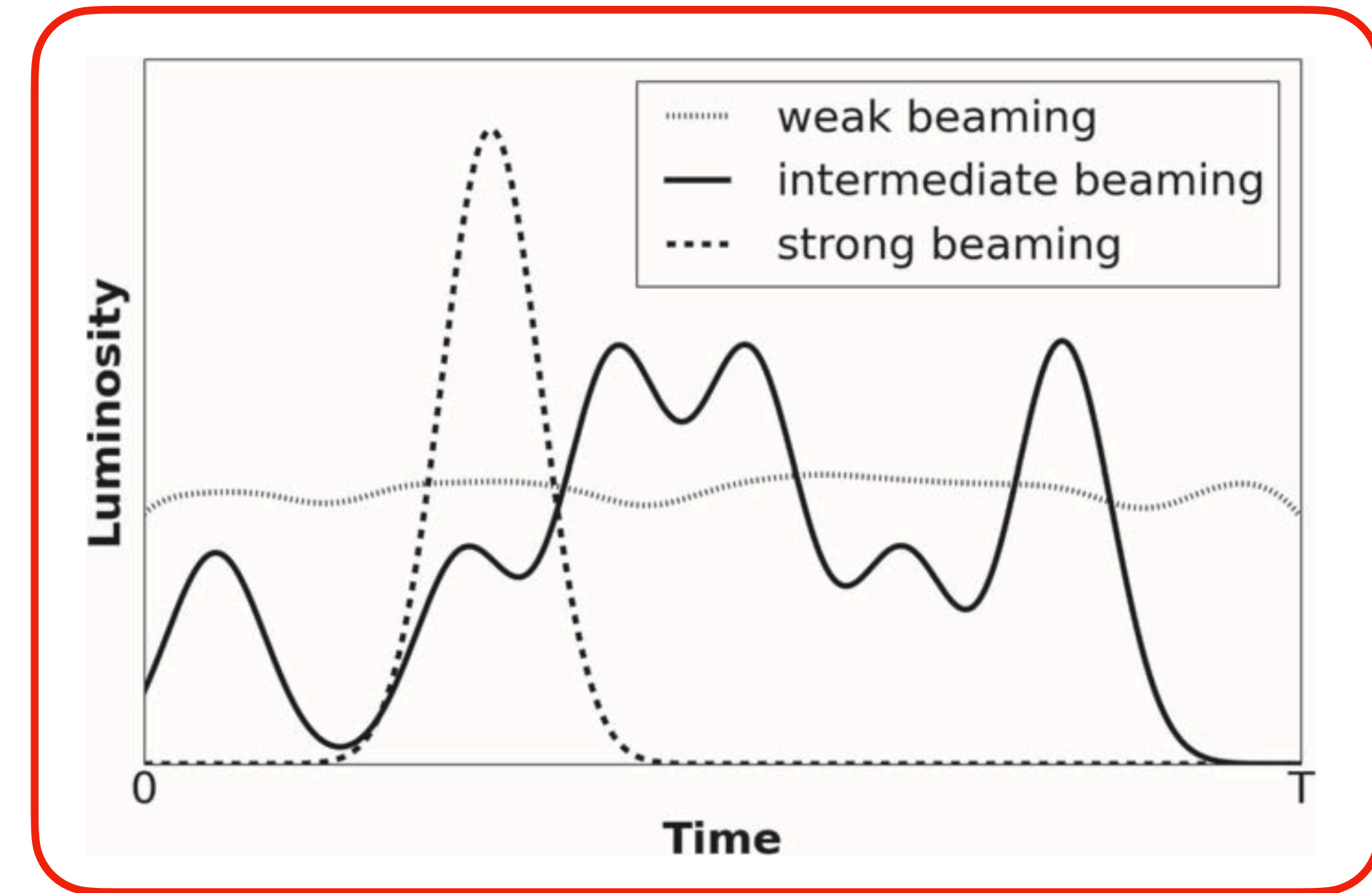
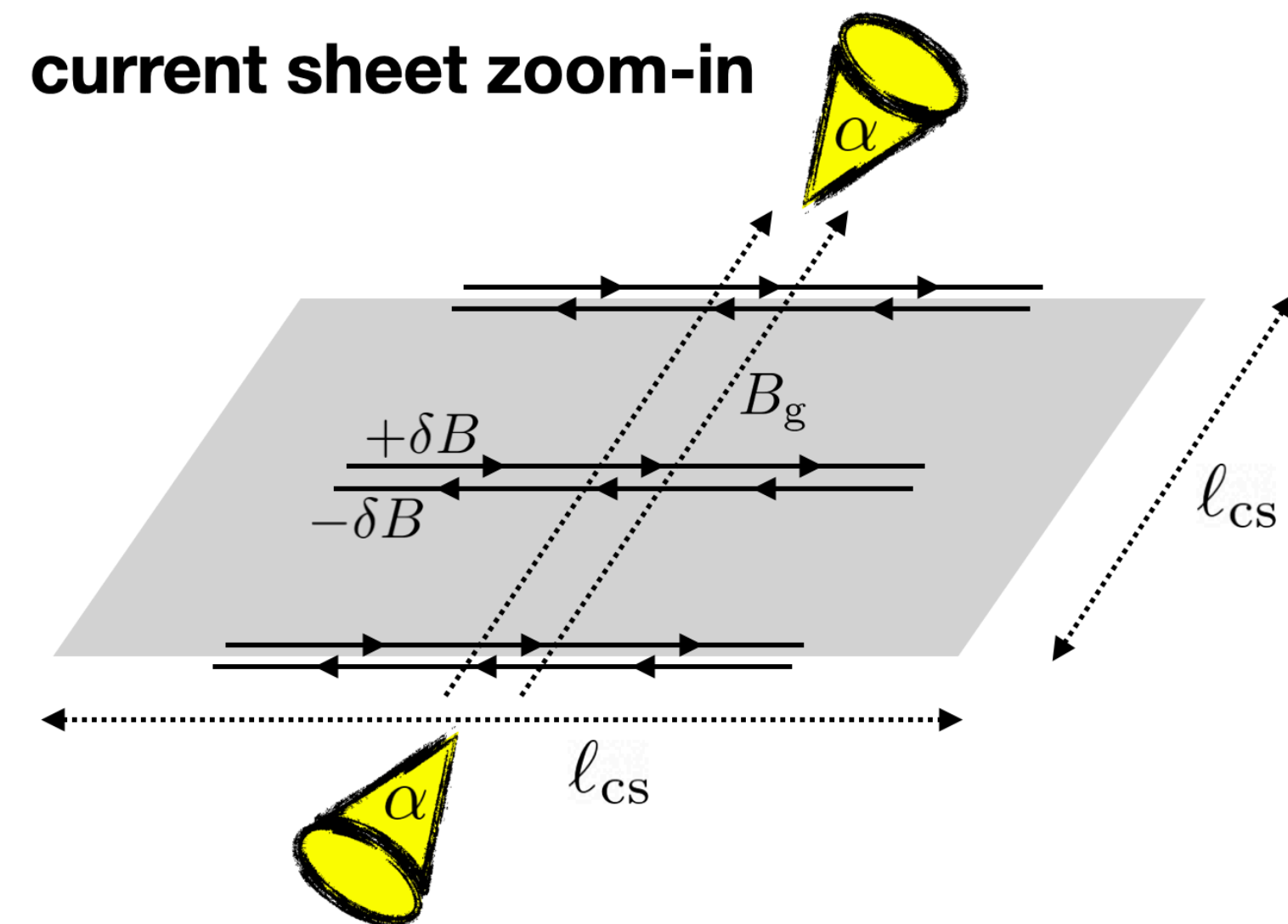
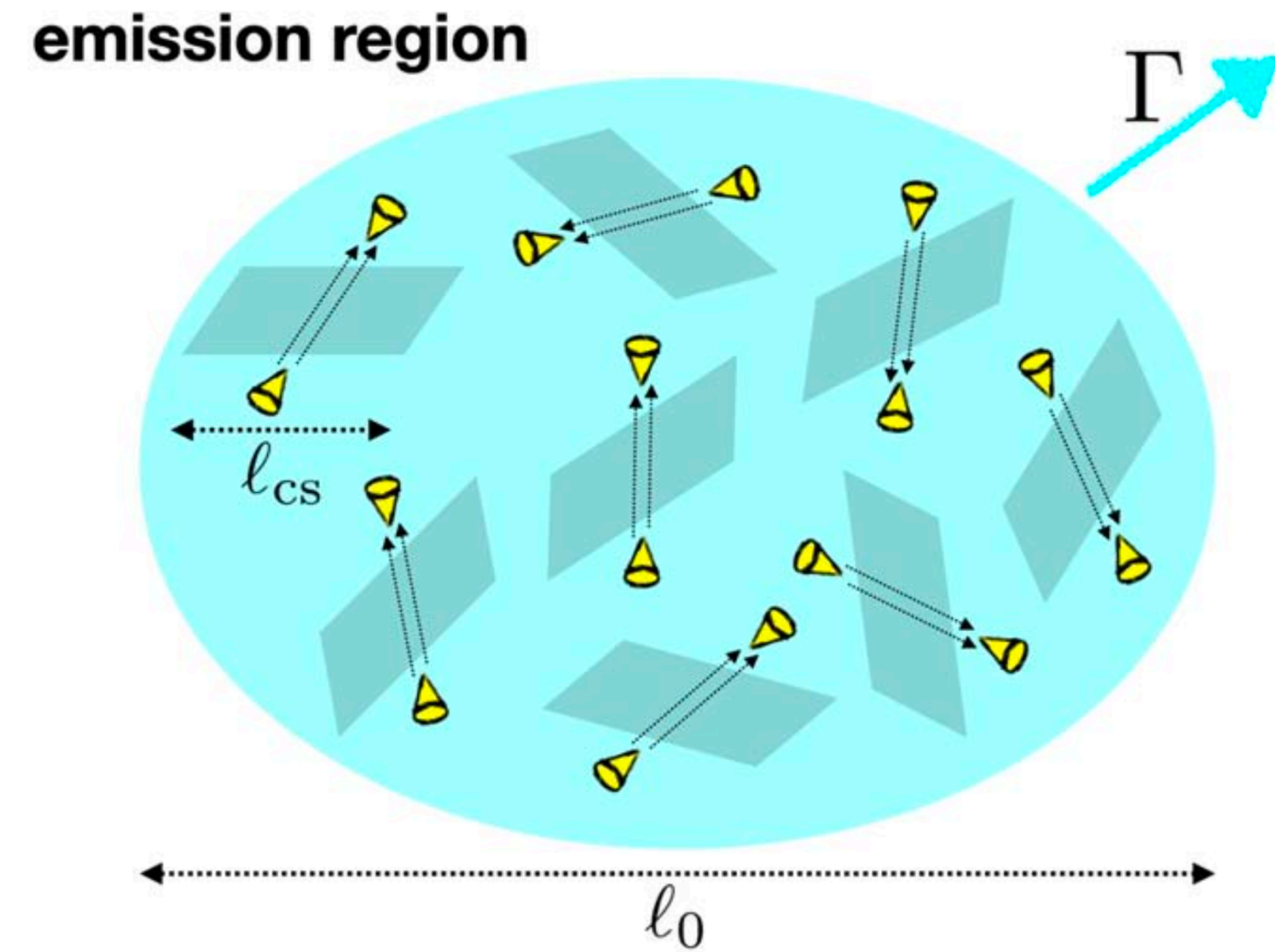
$$\nu F_\nu \propto \nu^{(3-p+m)/(2+m/2)} \quad \text{for } \nu_{\min \alpha} < \nu < \nu_{\text{iso}} \sim \gamma_{\text{iso}}^2 \nu_L$$

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



- ▶ 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

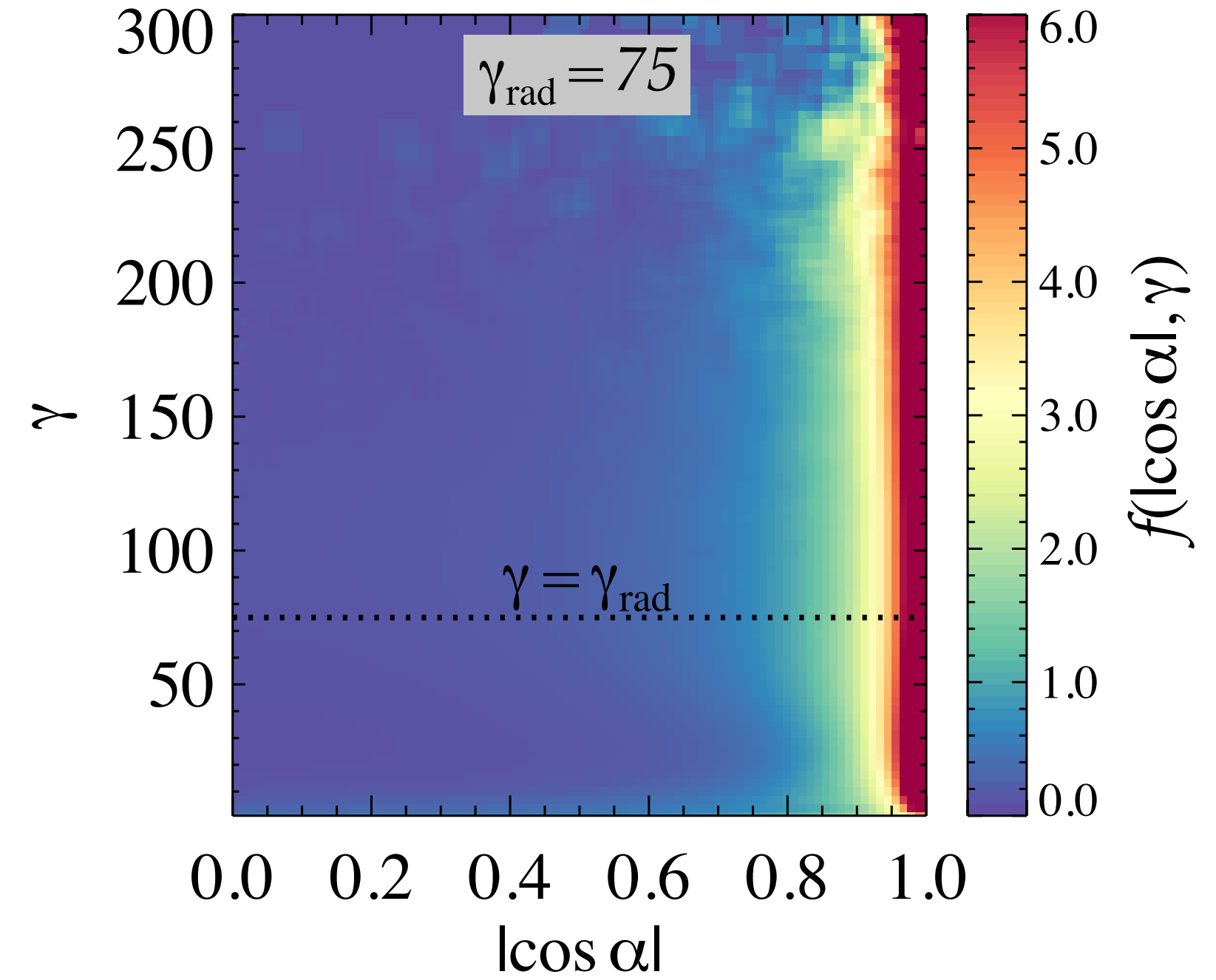
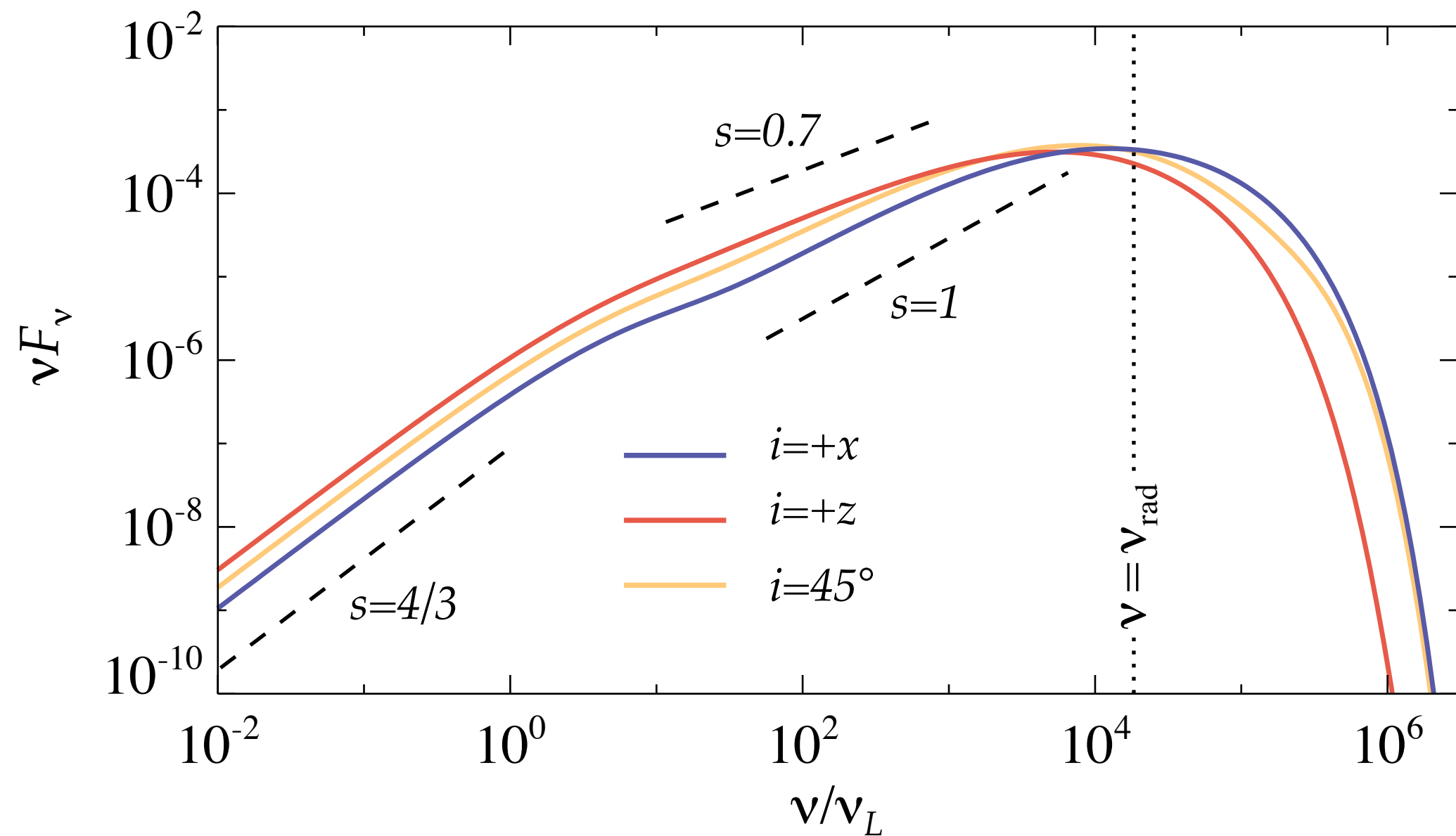
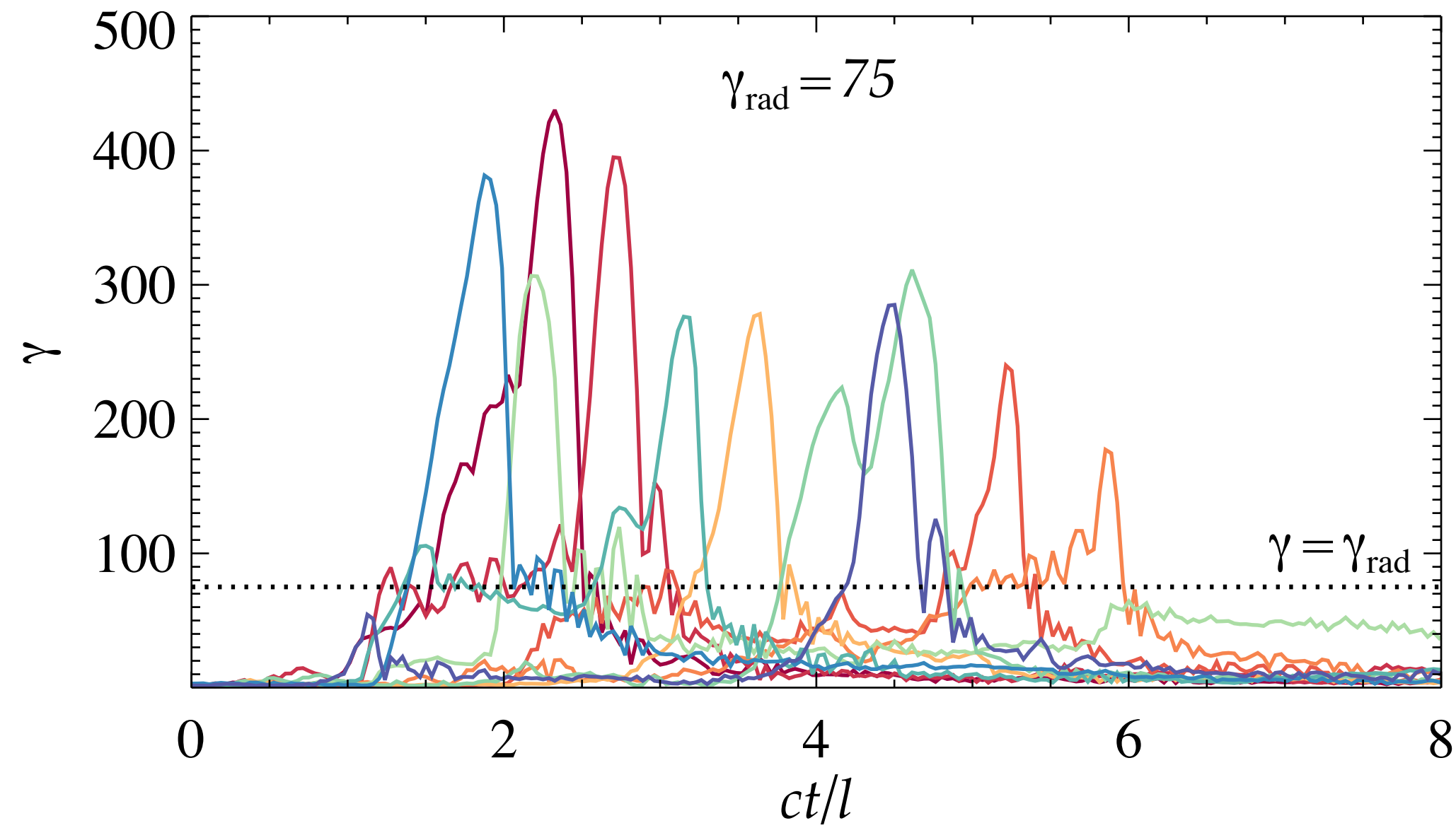
Beamed Radiation and Frequency-Dependent Variability



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)

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)

A Few Key Takeaways

1. Magnetized turbulence and magnetic reconnection co-occur
2. Large-amplitude magnetized turbulence produces power-law energy distributions with a sharp cutoff [$\sim \text{sech}(E^2) \sim \exp(-E^2)$]
3. Turbulence can accelerate particles up to the “Hillas limit”
 $E_{\text{cut}} = ZeR_{\text{cut}} = Ze(B_{\text{rms}}\kappa l_c)$ (if not limited by cooling)
4. Electrons can develop significant pitch-angle anisotropy, depending on the magnetization and the guide-field strength relative to fluctuations)
5. The SED, variability, and maximum electron energy are all influenced by pitch-angle anisotropy.