Particle Acceleration in Highly Magnetized Turbulent Plasmas

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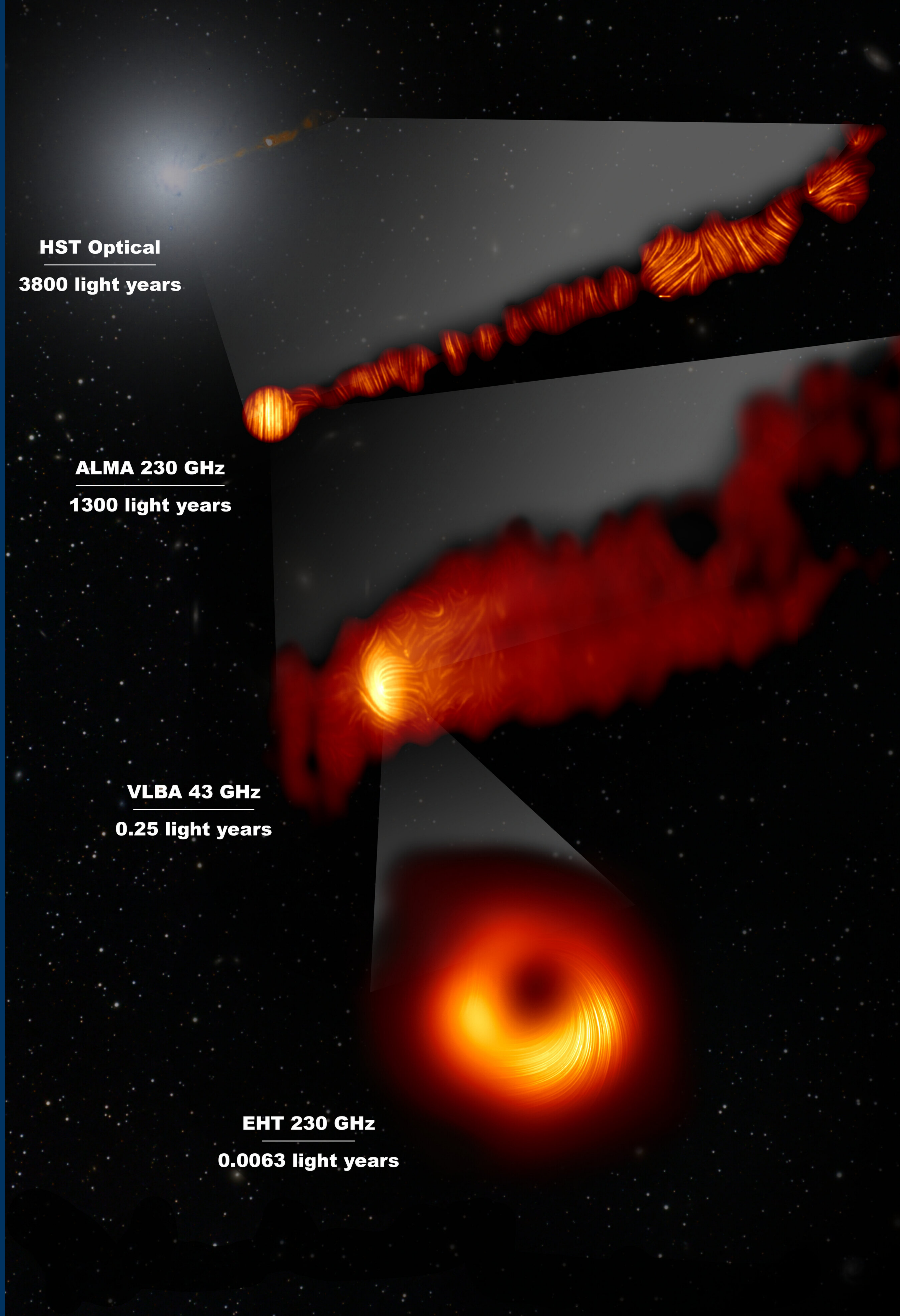
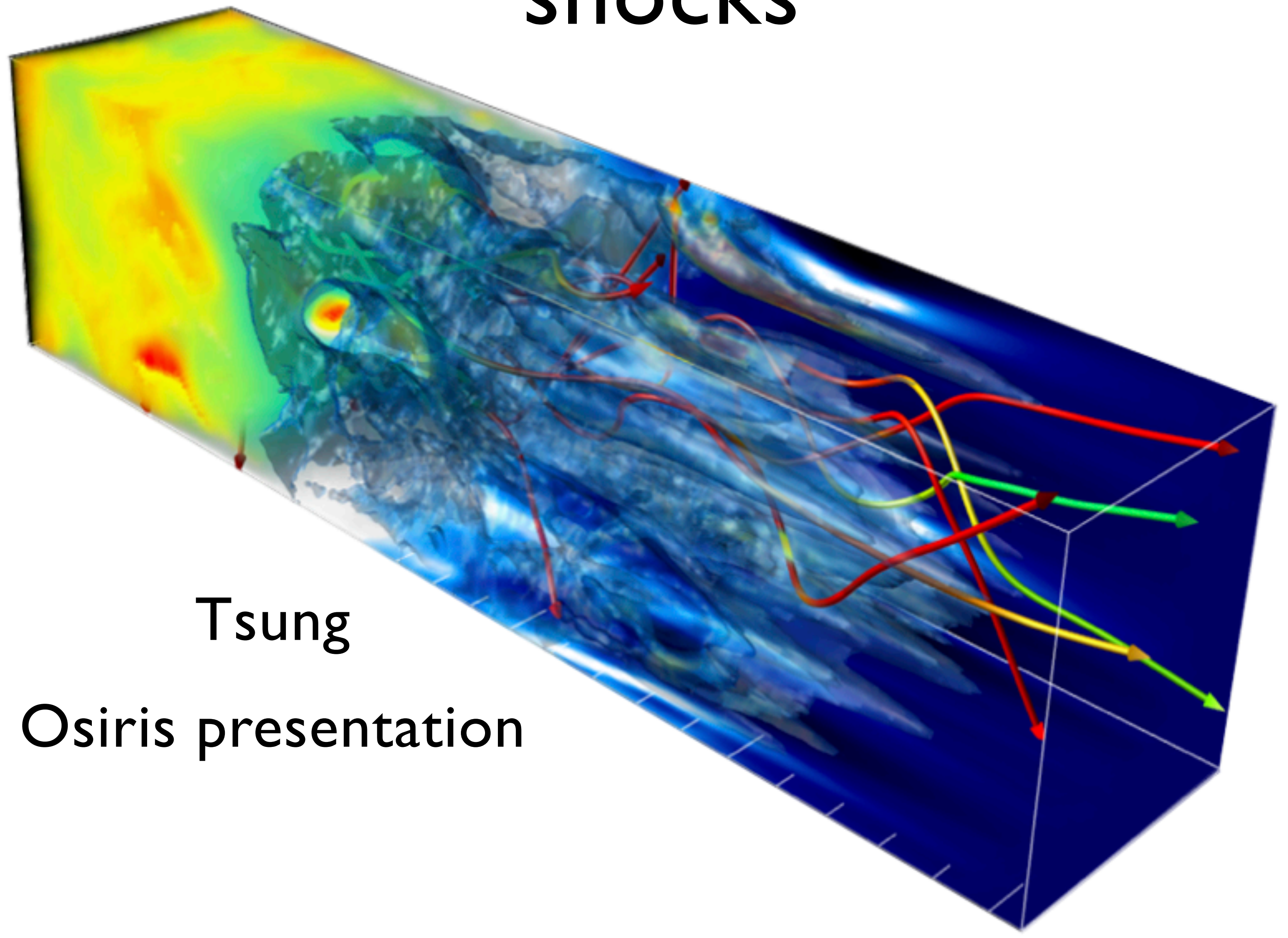
Cosmic Rays in the Multi-Messenger Era
APC Laboratory - Paris
December, 2024



What physical processes drive particle acceleration?

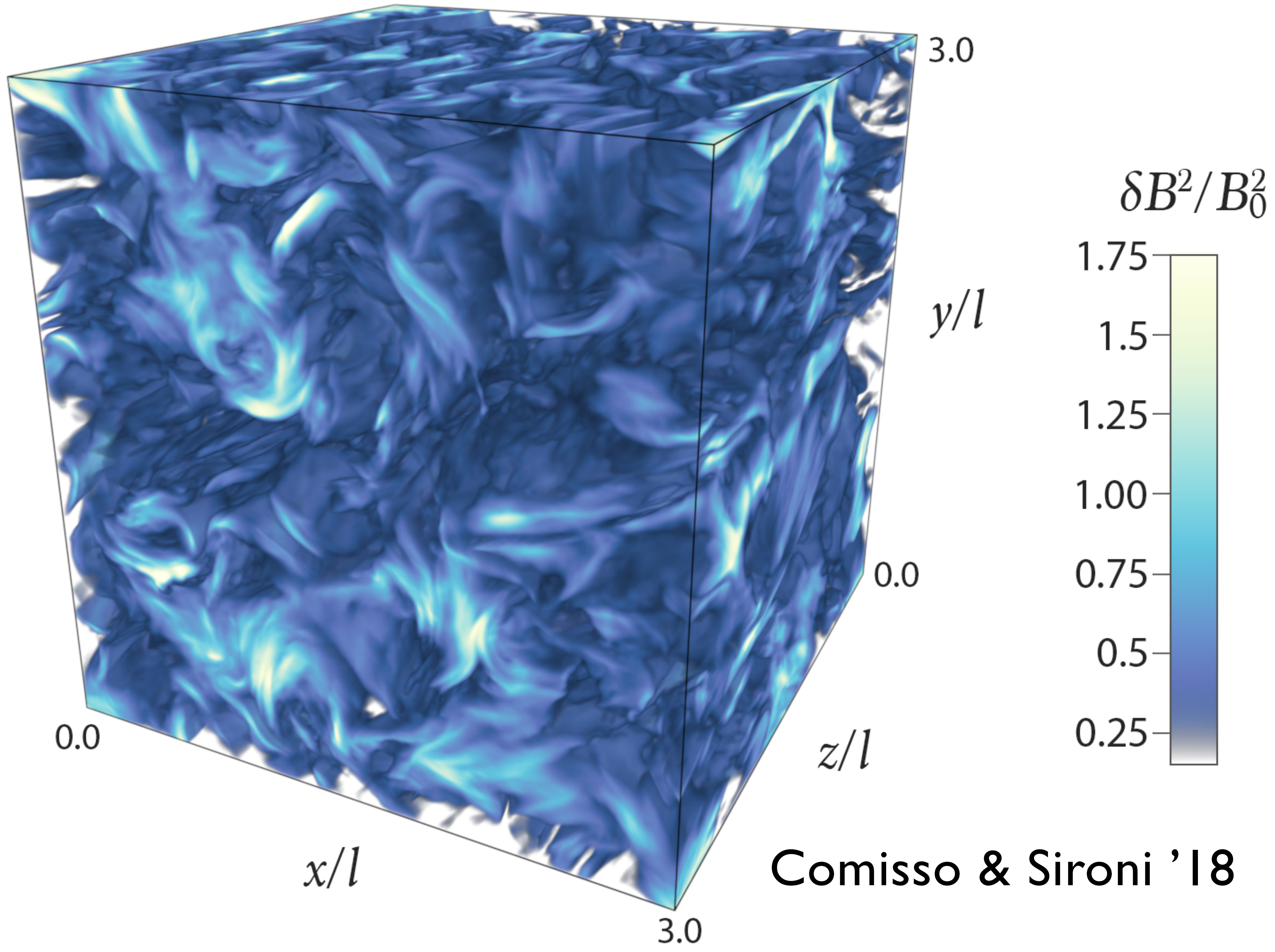
shocks



Tsung

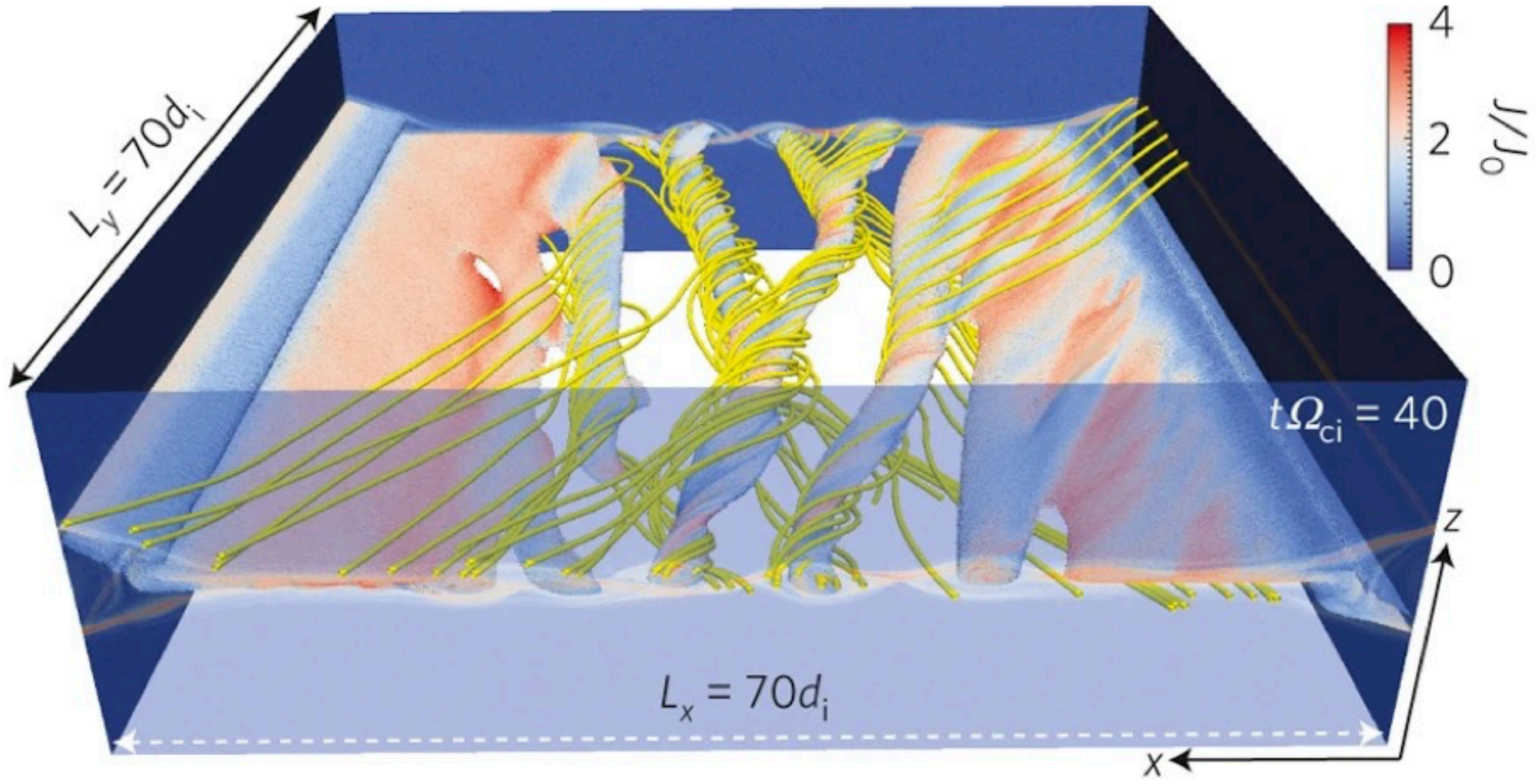
Osiris presentation

magnetized turbulence



Comisso & Sironi '18

magnetic reconnection



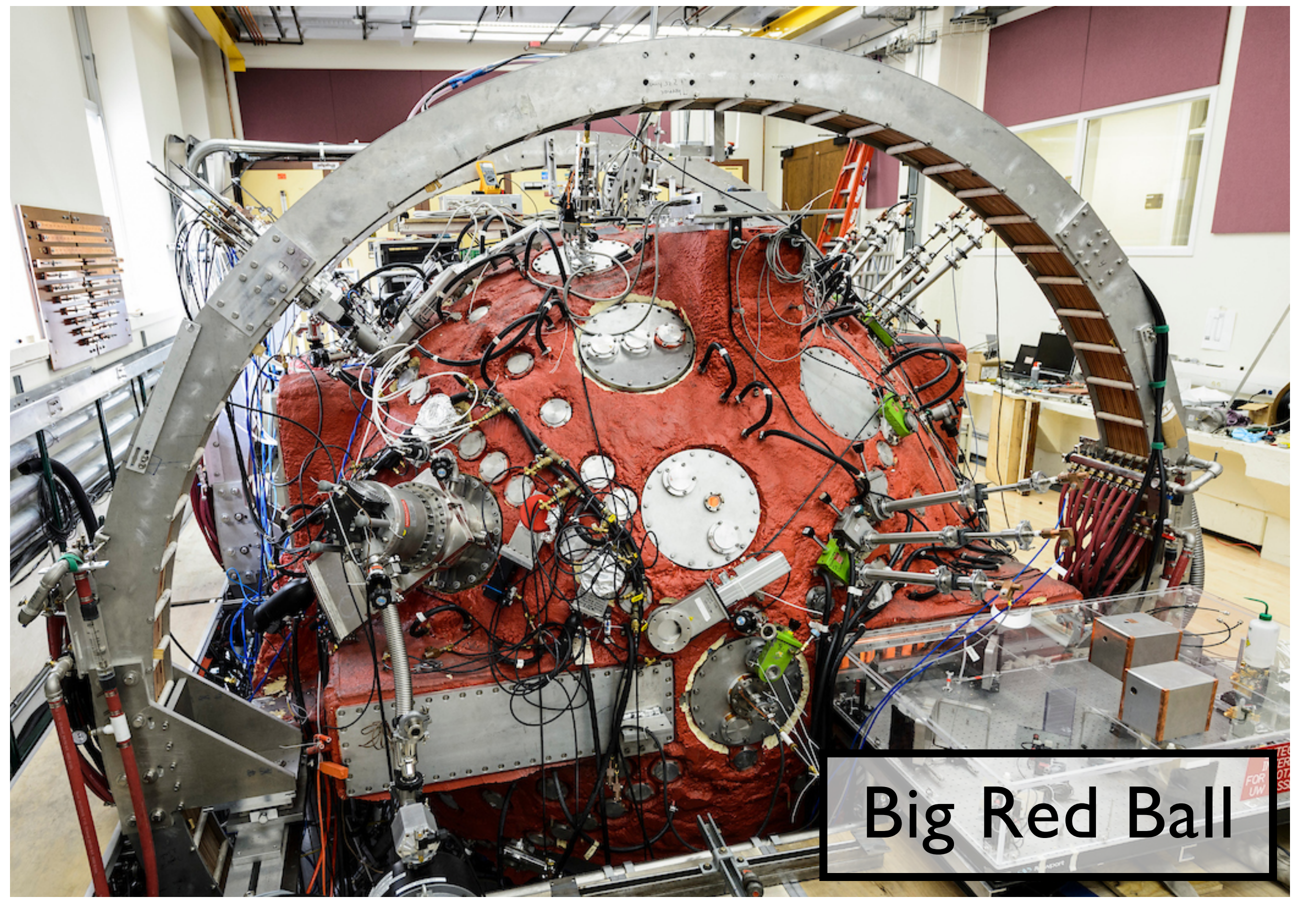
Daughton et al. '14

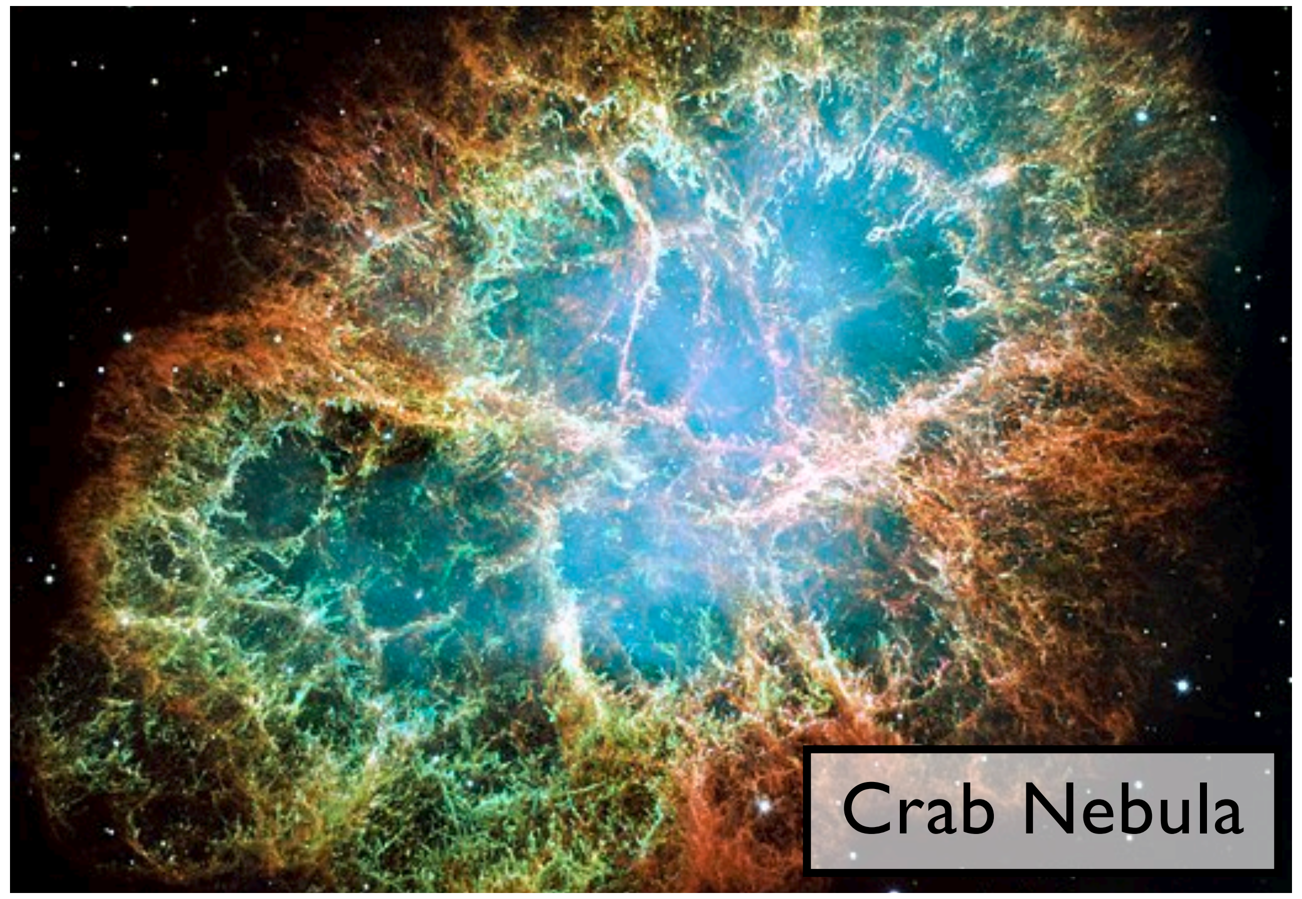
- sheared velocity flows
- magnetospheric gaps
- magnetized rotators

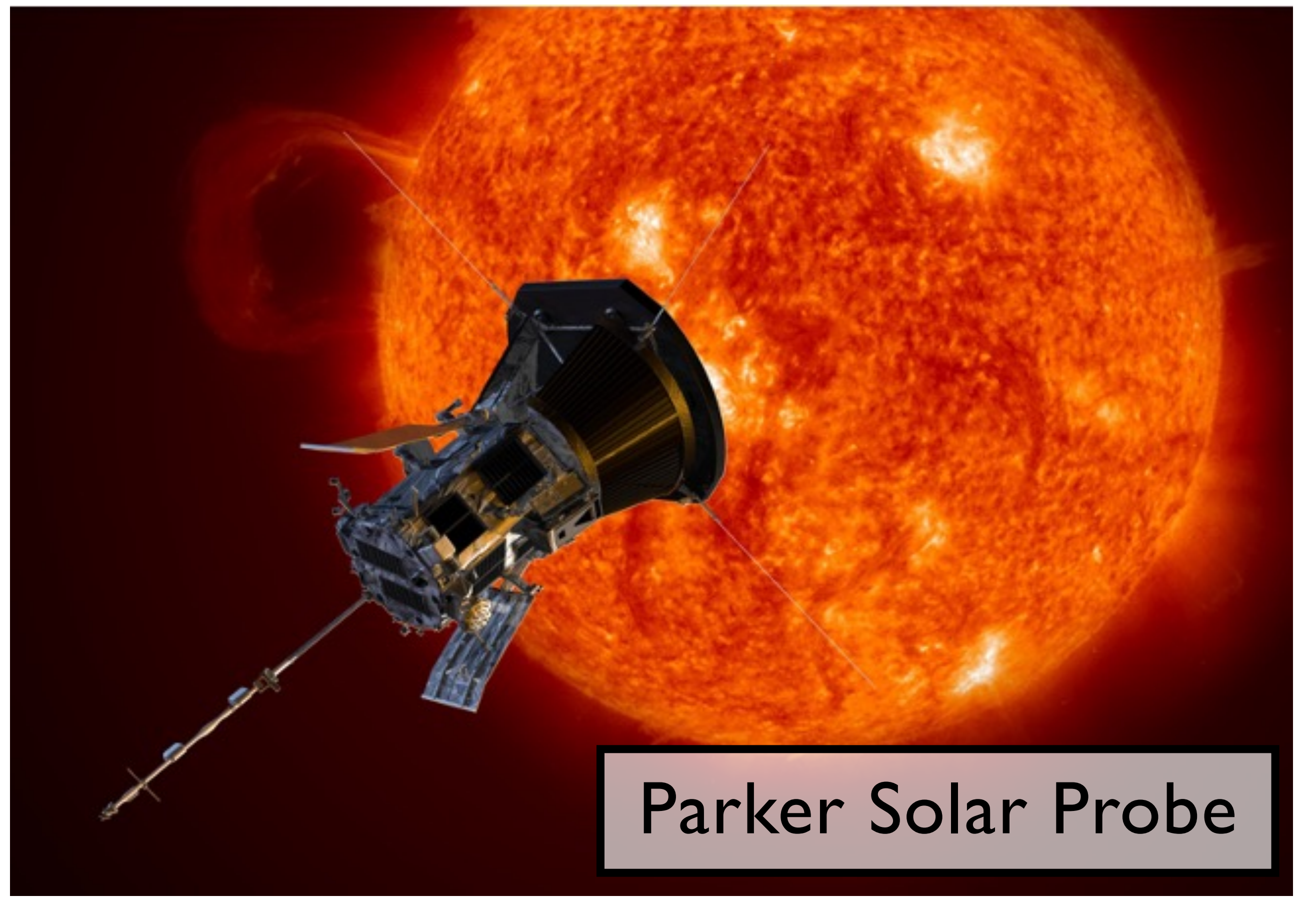
and others…

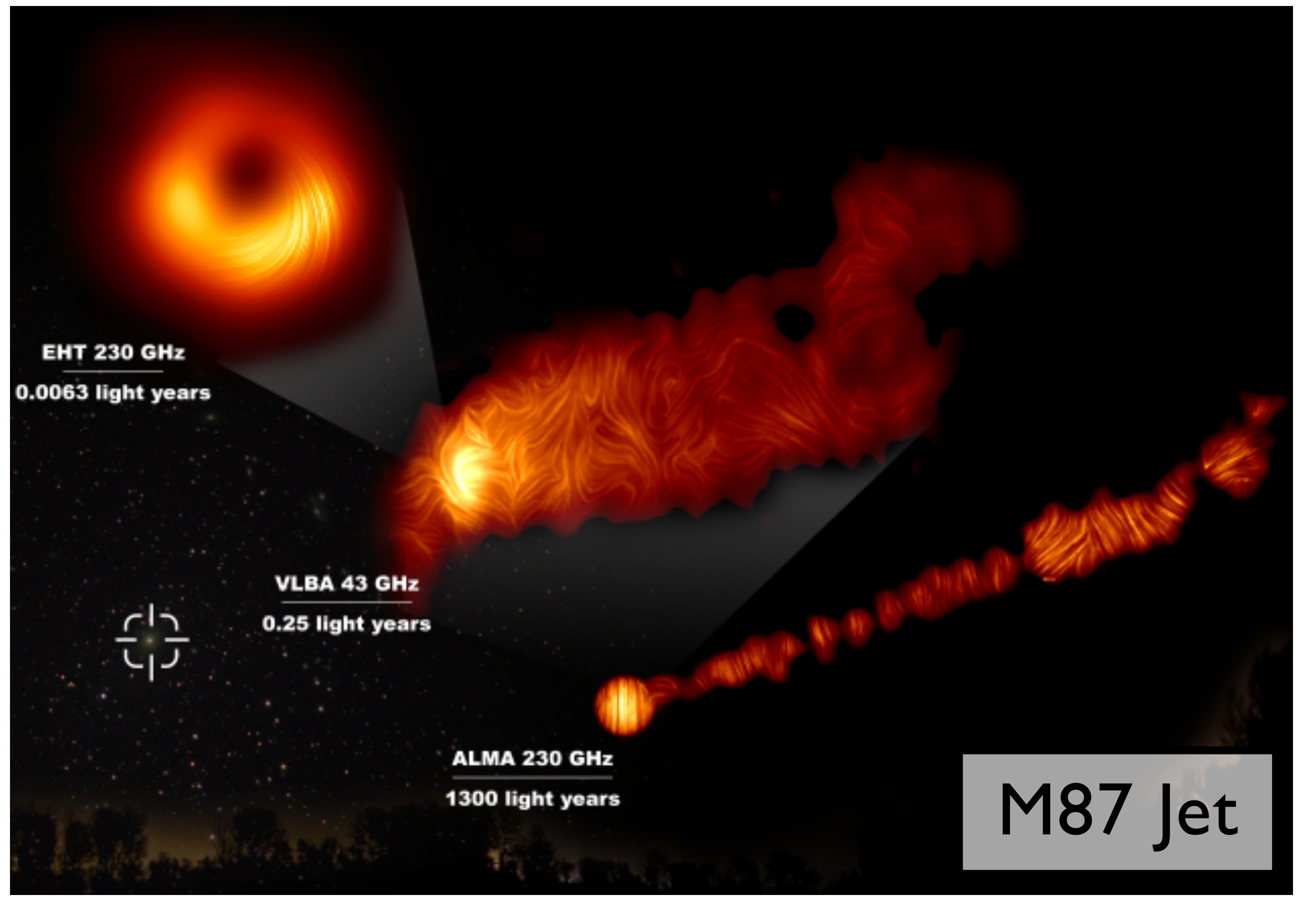
Magnetized environments (nonrelativistic *vs.* relativistic regimes: $\frac{v_A}{c} = \sqrt{\frac{\sigma}{1+\sigma}}$)

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

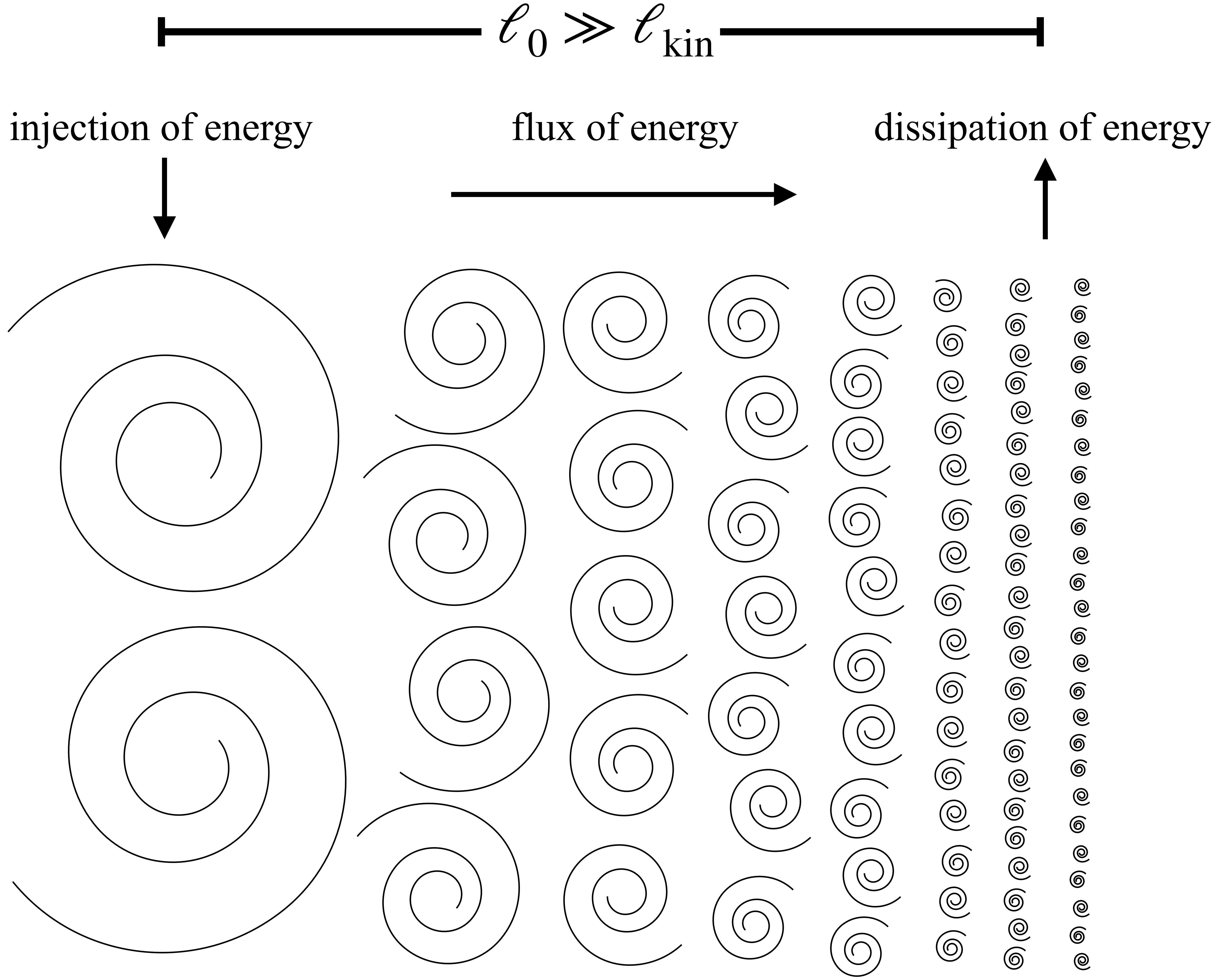




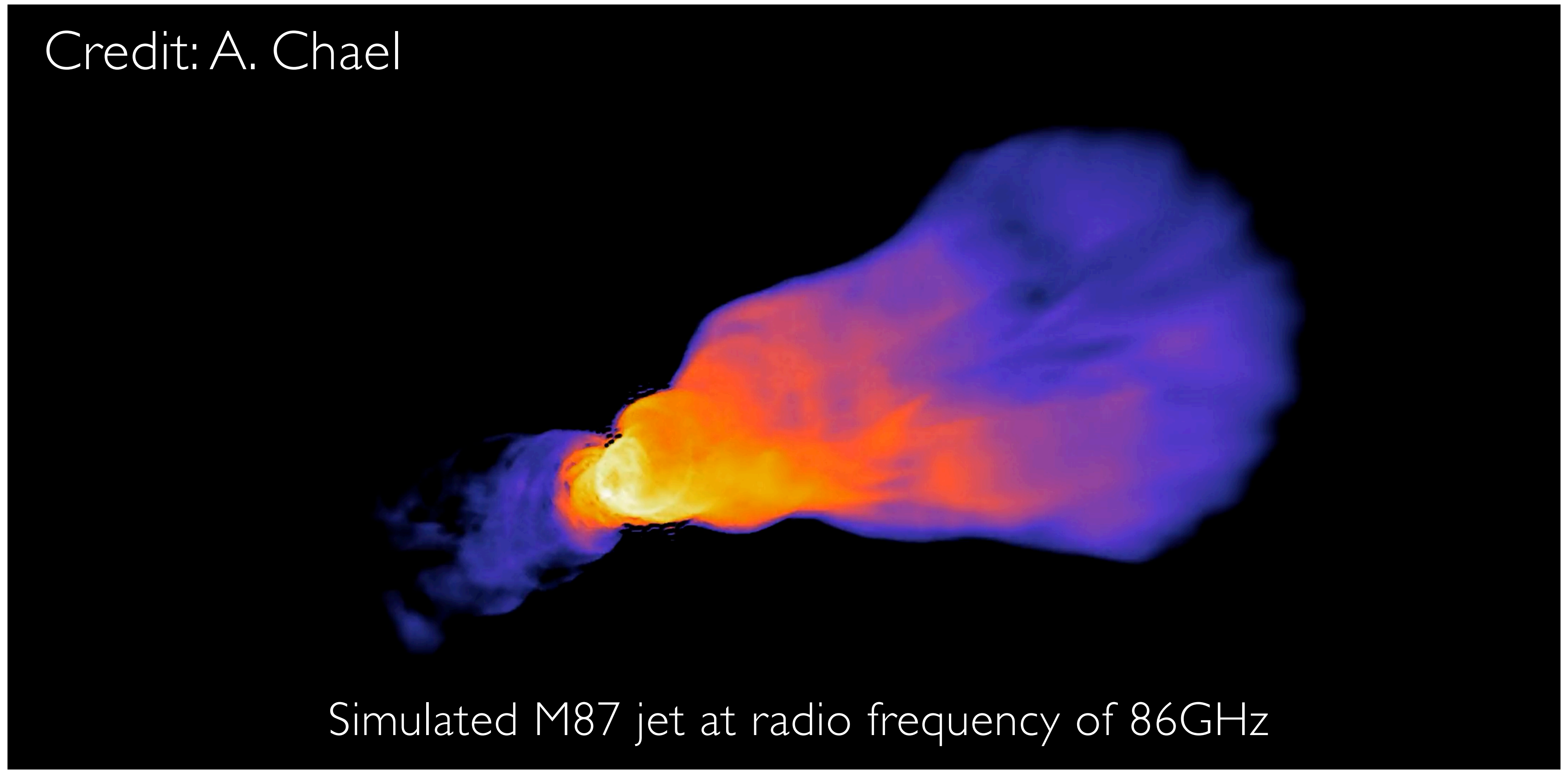




Expected turbulence in large-scale (astrophysical) systems



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



M87's Corona (with large uncertainties):

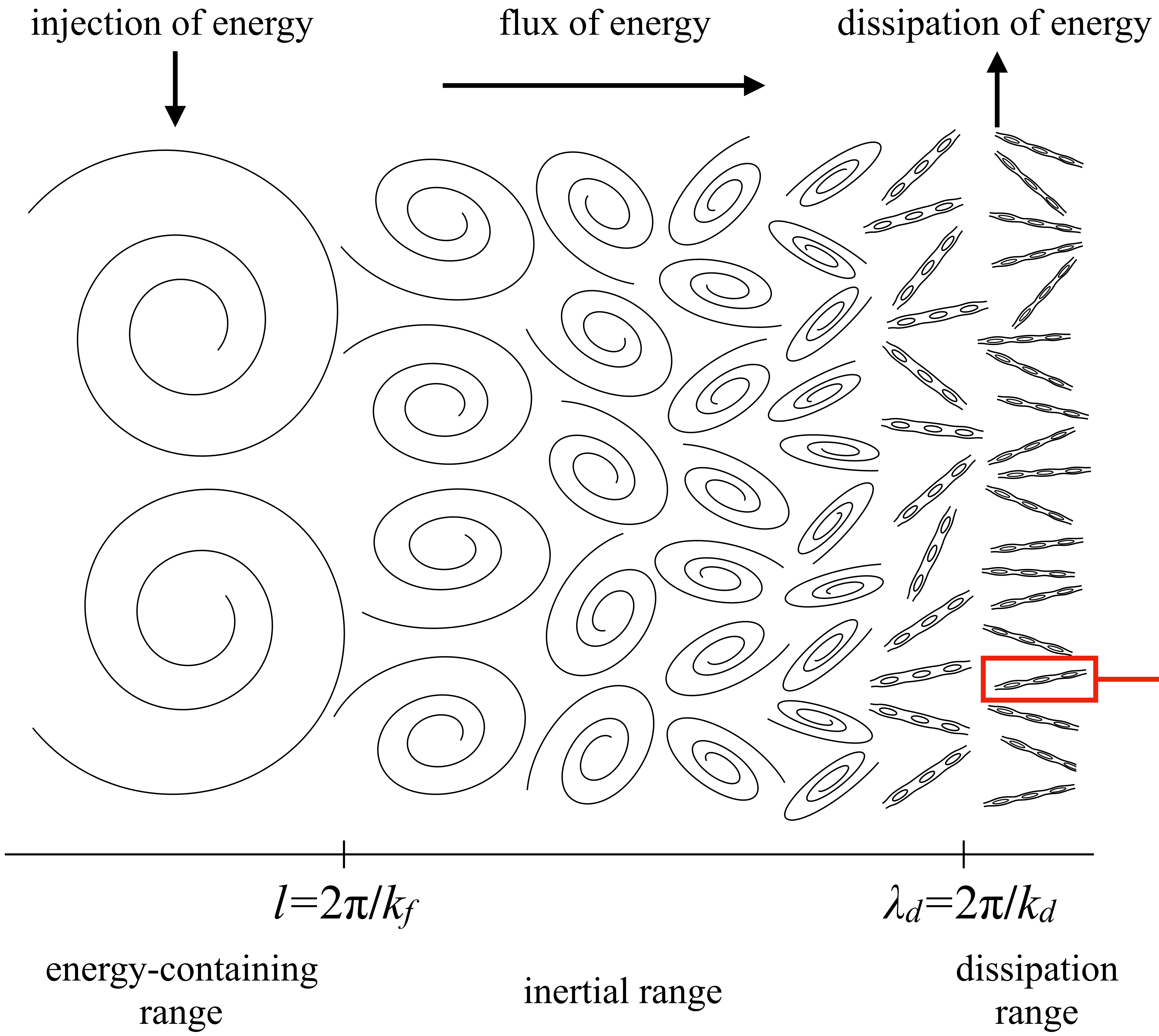
$$\ell_0 \gtrsim R_S = 2GM/c^2 \sim 2 \times 10^{12}\,\mathrm{m}$$

$$\ell_{\rm kin} \sim \rho_p \sim 5 \times 10^3\,\mathrm{m}$$

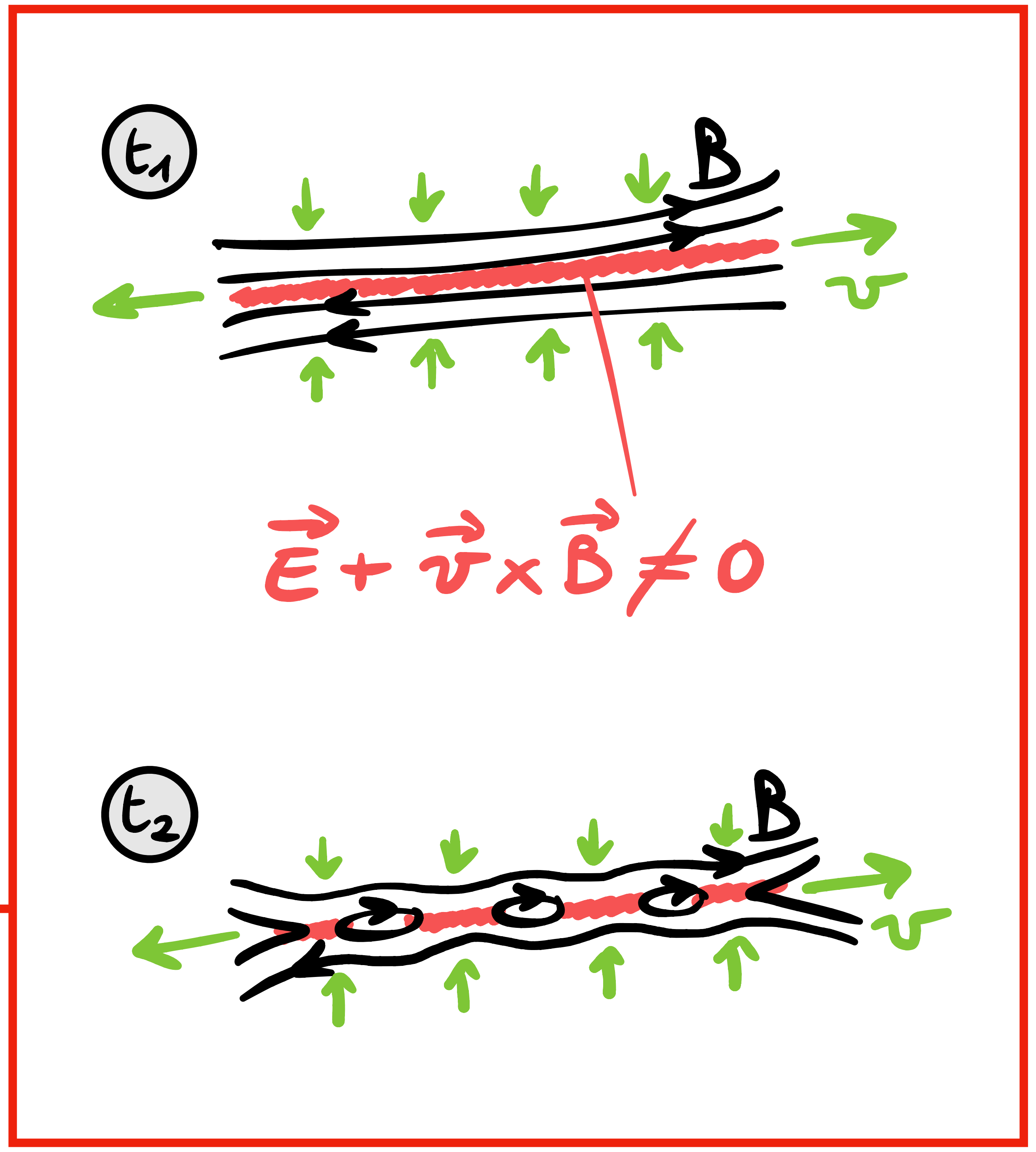
$$(\lambda_{\mathrm{mfp},p} \sim 10^{20}\,\mathrm{m})$$

Estimates from EHT Collaboration 2019

Turbulent energy cascade in large-scale magnetized systems



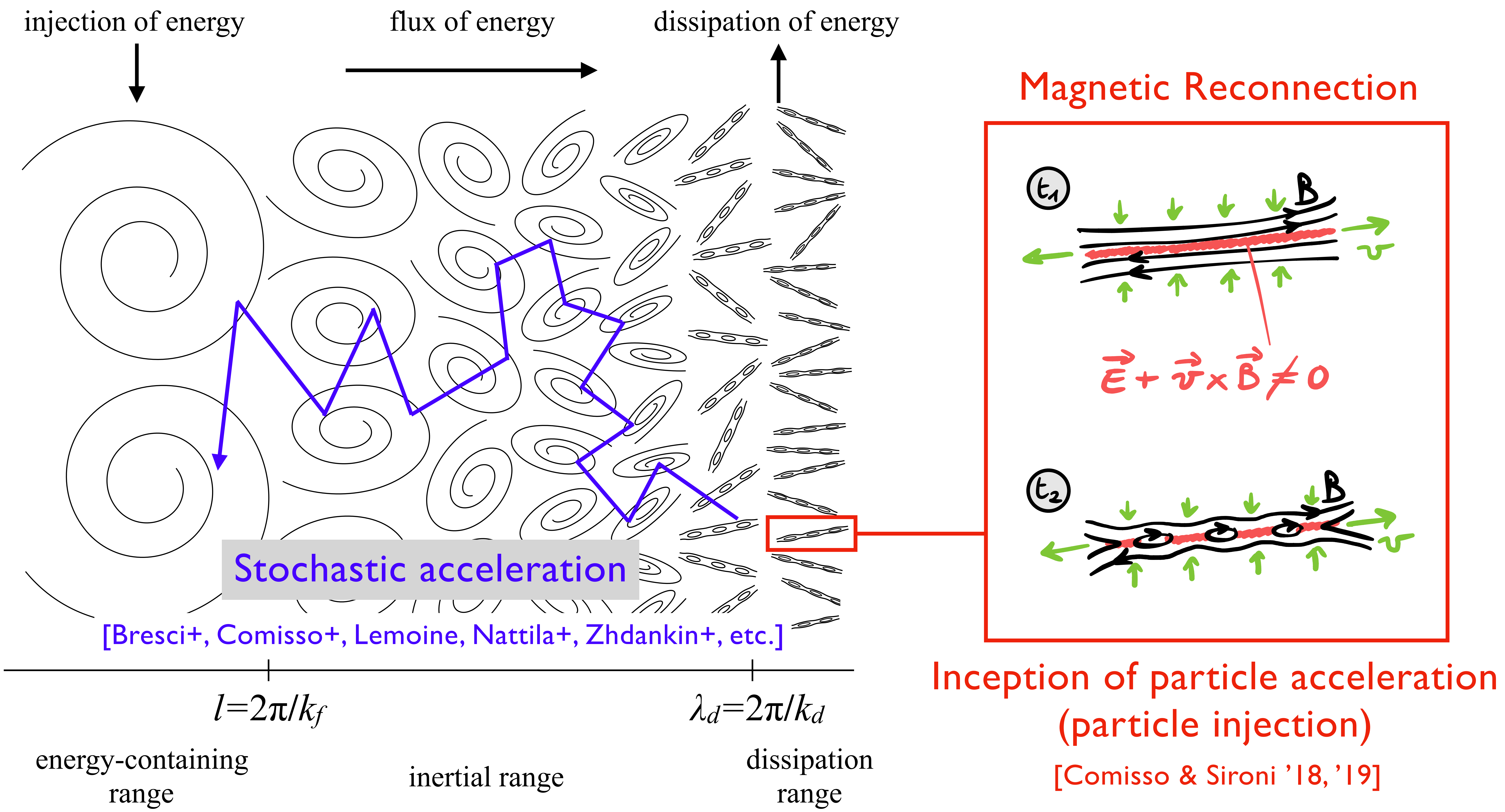
Magnetic Reconnection



Inception of particle acceleration (particle injection)

[Comisso & Sironi ’18, ’19]

Turbulent energy cascade in large-scale magnetized systems



Fully kinetic treatment of the plasma

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

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

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

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

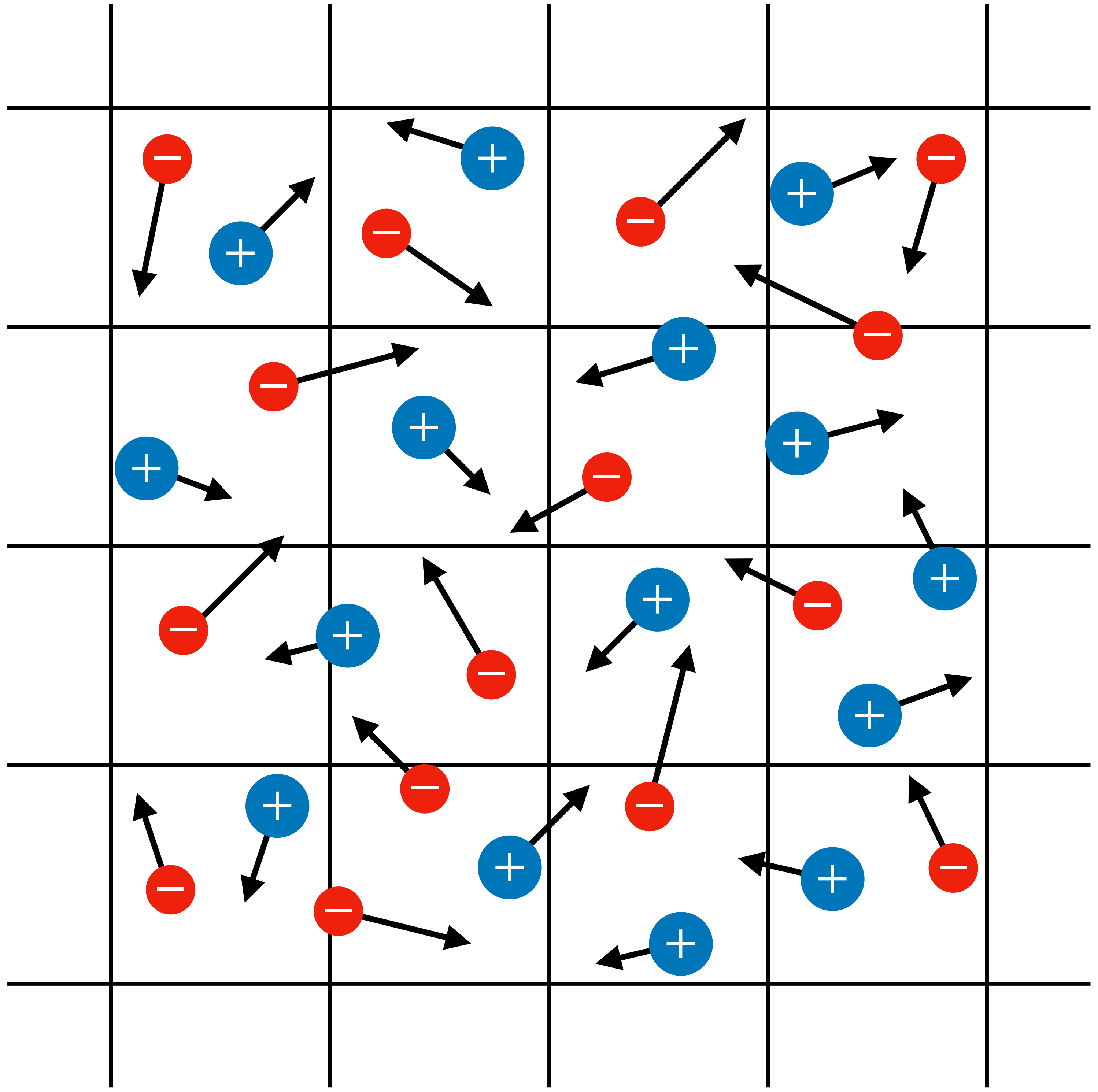
$$\frac{\partial \boldsymbol{E}}{\partial t} - c \, \mathrm{curl} \boldsymbol{B} = -4\pi \boldsymbol{J} \,, \qquad \mathrm{div} \boldsymbol{E} = 4\pi \rho \,,$$

$$\frac{\partial \boldsymbol{B}}{\partial t} + c \, \mathrm{curl} \boldsymbol{E} = 0 \,, \qquad \mathrm{div} \boldsymbol{B} = 0 \,,$$

where the source terms are computed by

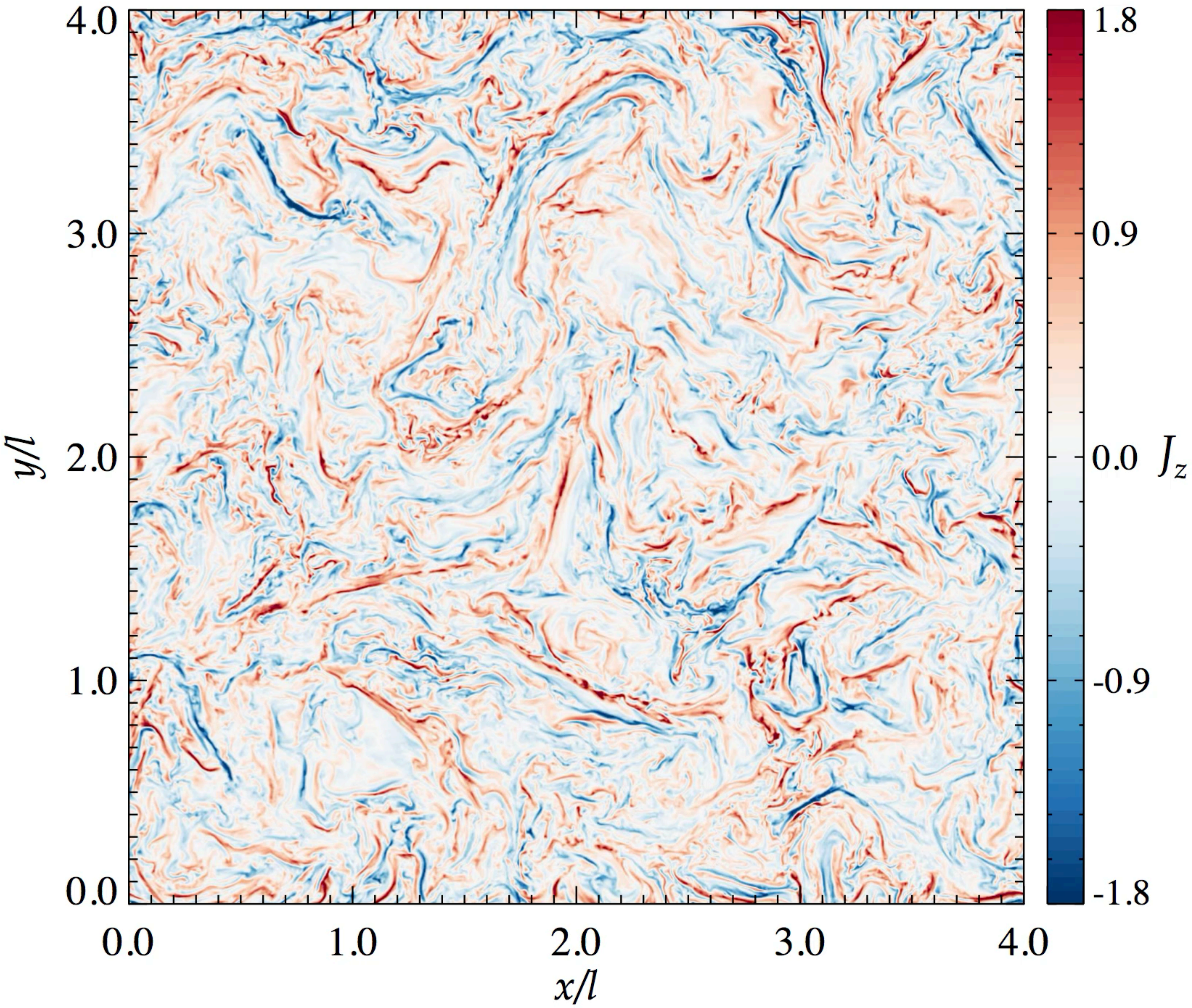
$$\rho = \sum_s q_s \int_{\mathbb{R}^3} f_s d\boldsymbol{p} \,, \qquad \boldsymbol{J} = \sum_s \frac{q_s}{m_s} \int_{\mathbb{R}^3} f_s \frac{\boldsymbol{p}}{\gamma_s} d\boldsymbol{p} \,.$$

- Solution via particle-in-cell method



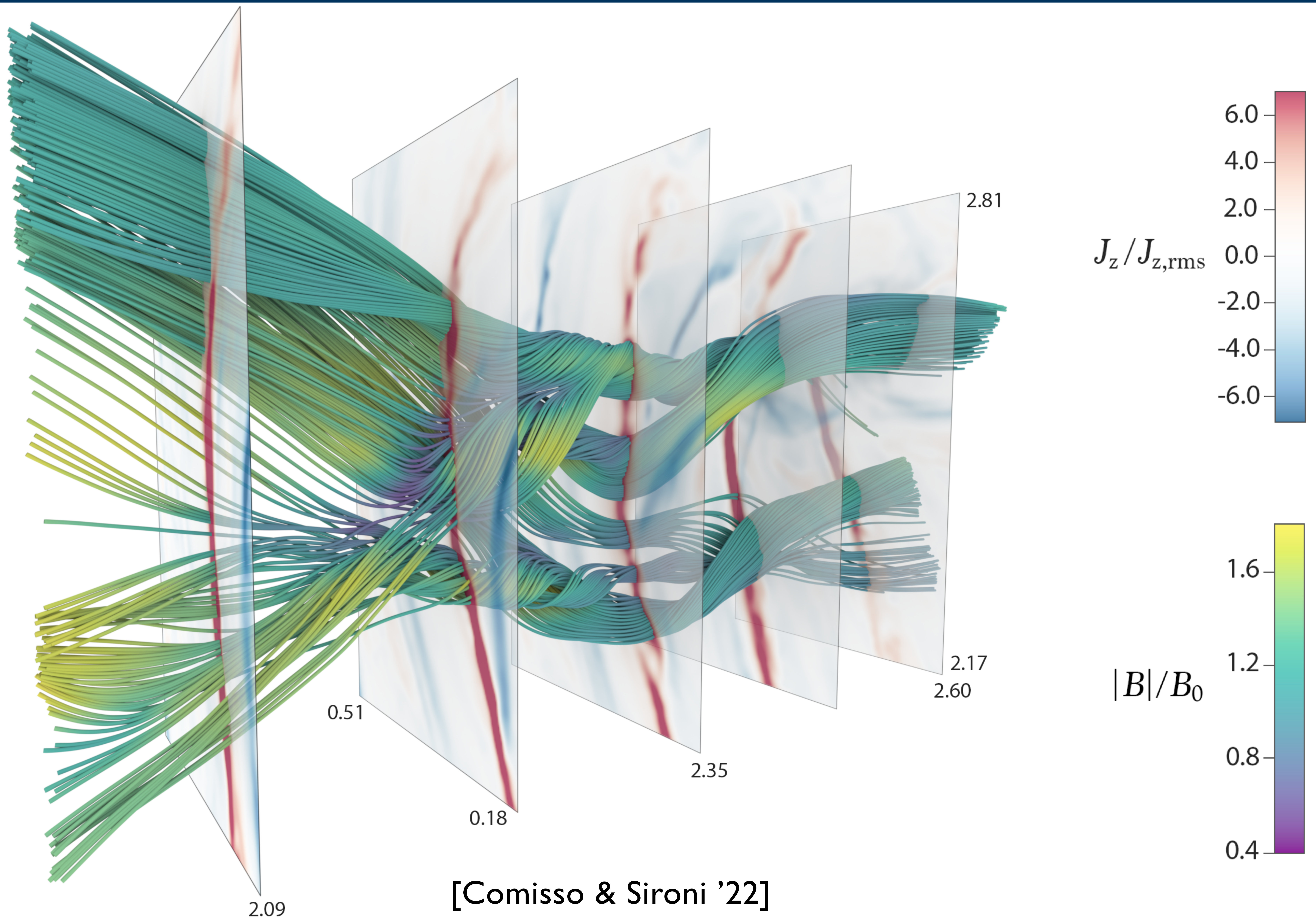
PIC code: TRISTAN-MP
(Spitkovsky 2005)

Flying through turbulence along the mean magnetic field direction



PIC Turbulence

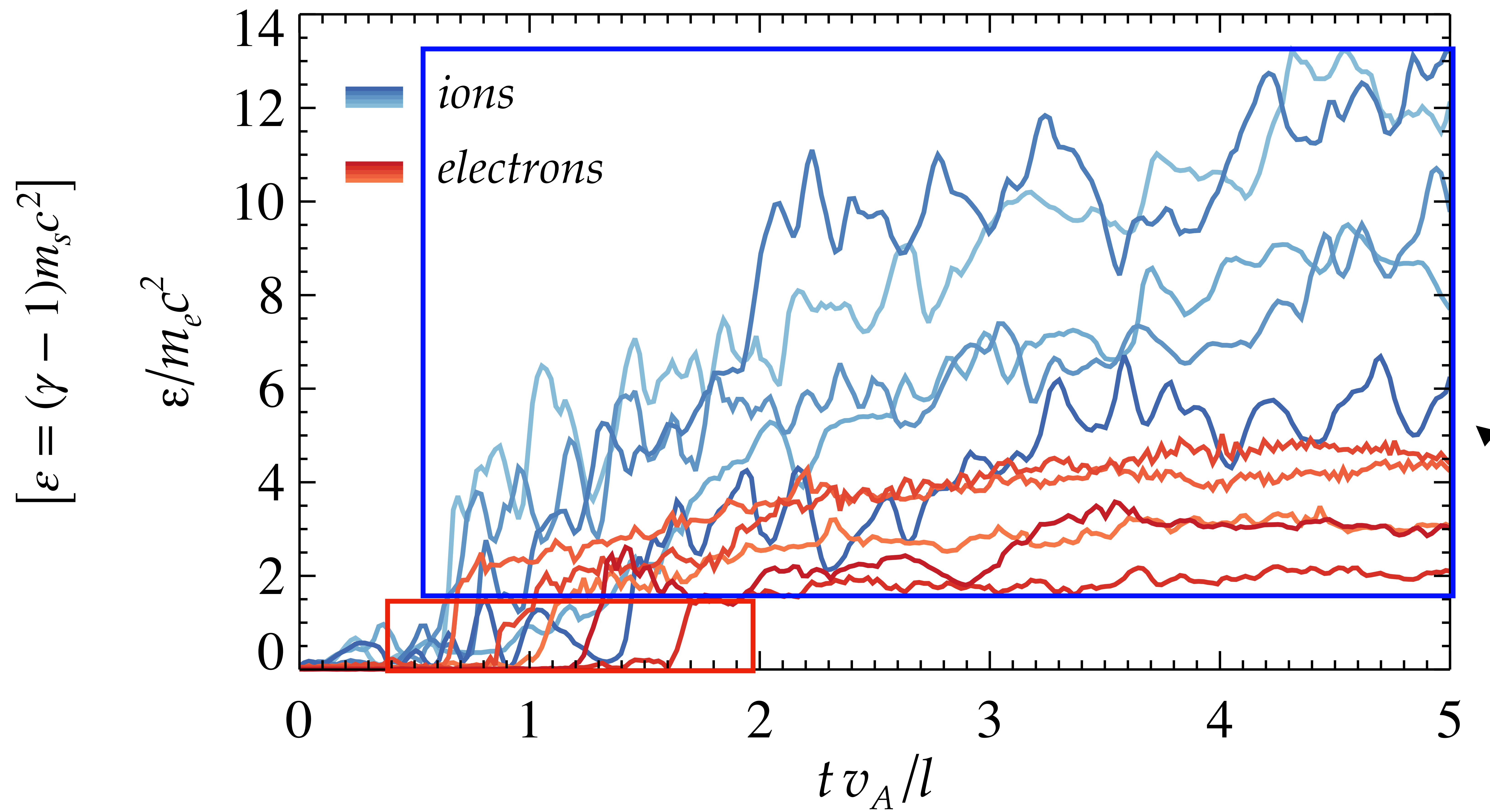
Magnetic reconnection occurring within the turbulent cascade



[Comisso & Sironi ’22]

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

Time evolution of the kinetic energy for some representative particles



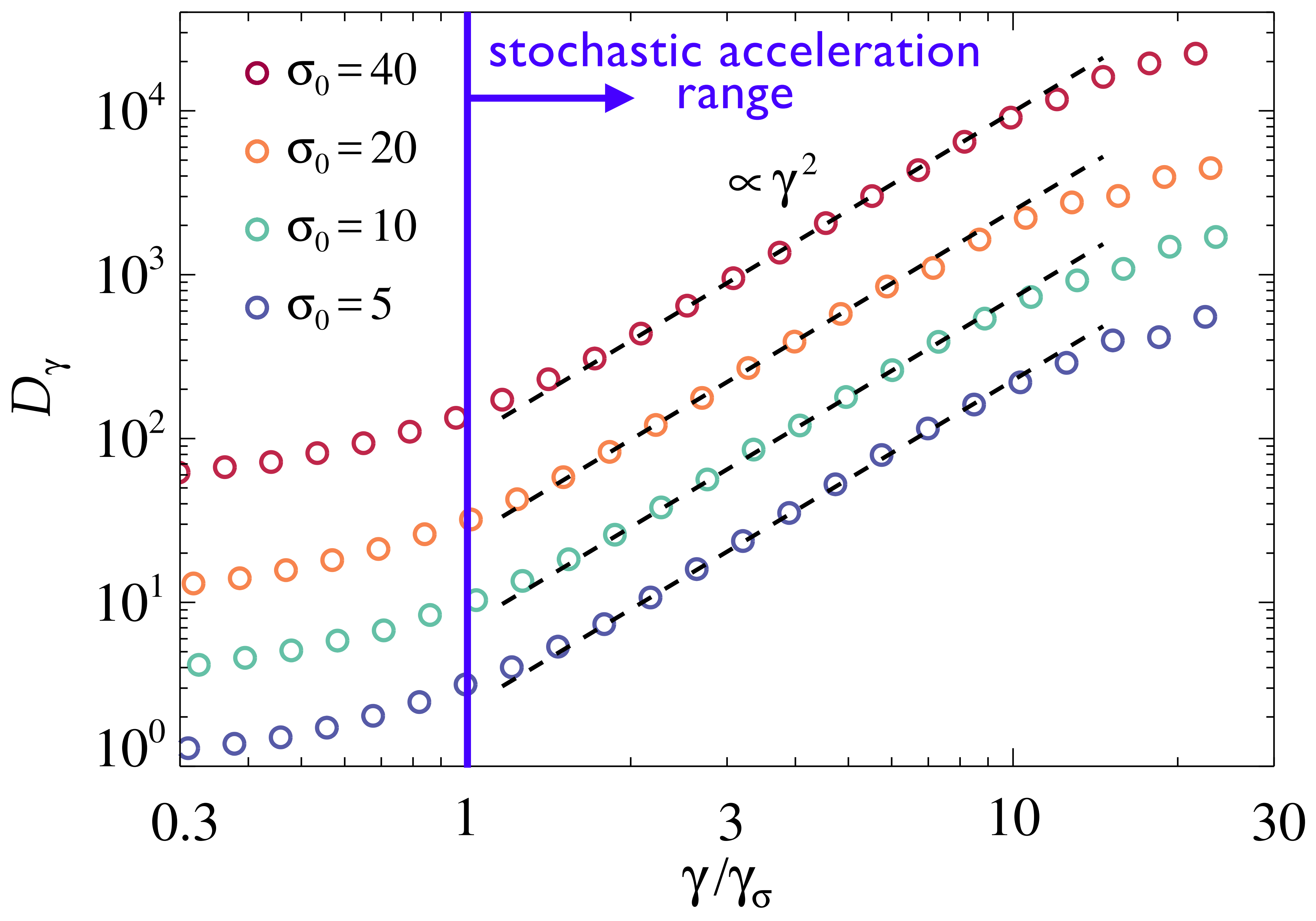
Results from non-relativistic ($\sigma \ll 1$) turbulence [Comisso & Sironi 2022]

- Two phases of the acceleration process:

  (1) particle injection

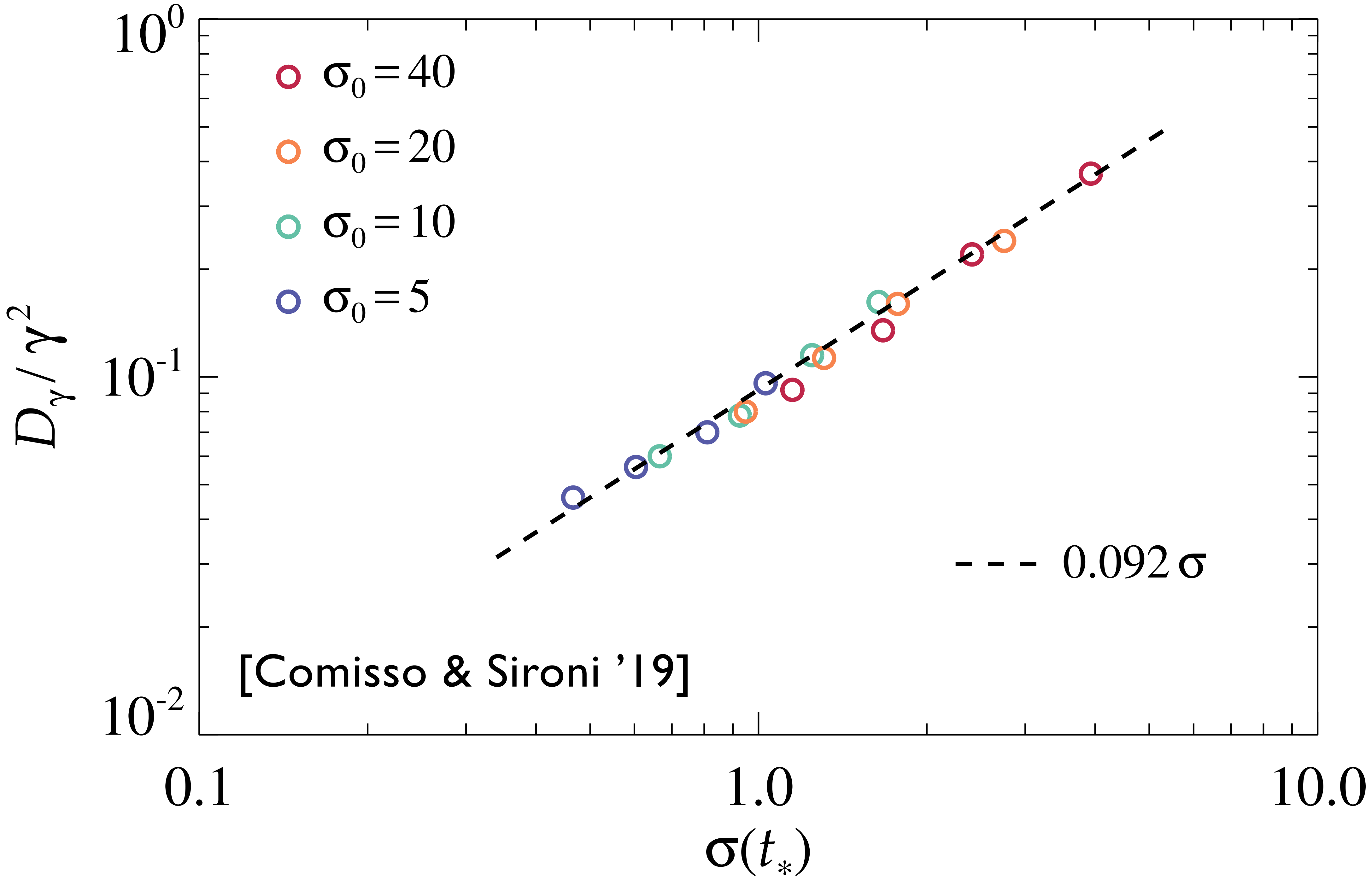
  (2) stochastic acceleration

Stochastic particle acceleration: energy and magnetization dependence



[Comisso & Sironi '19]

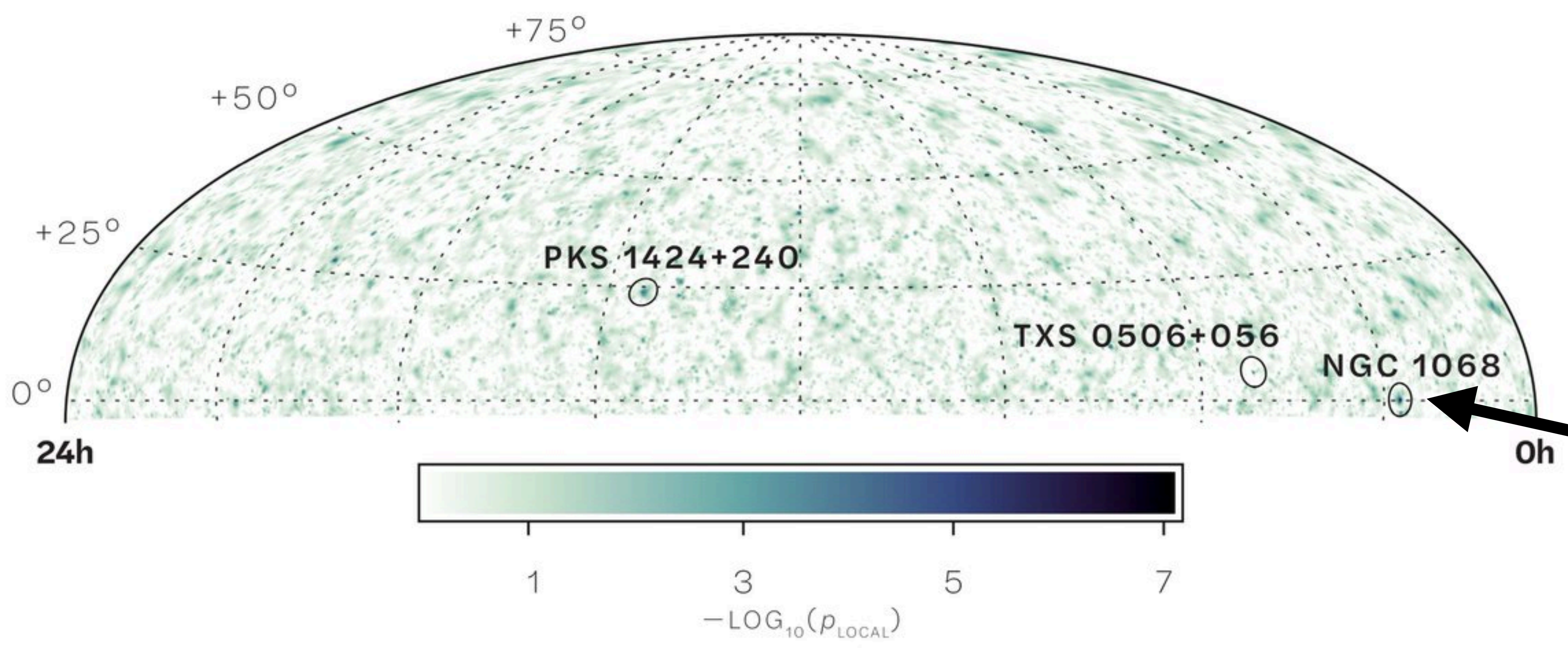
[see also Wong at al. '20 for γ dependence]

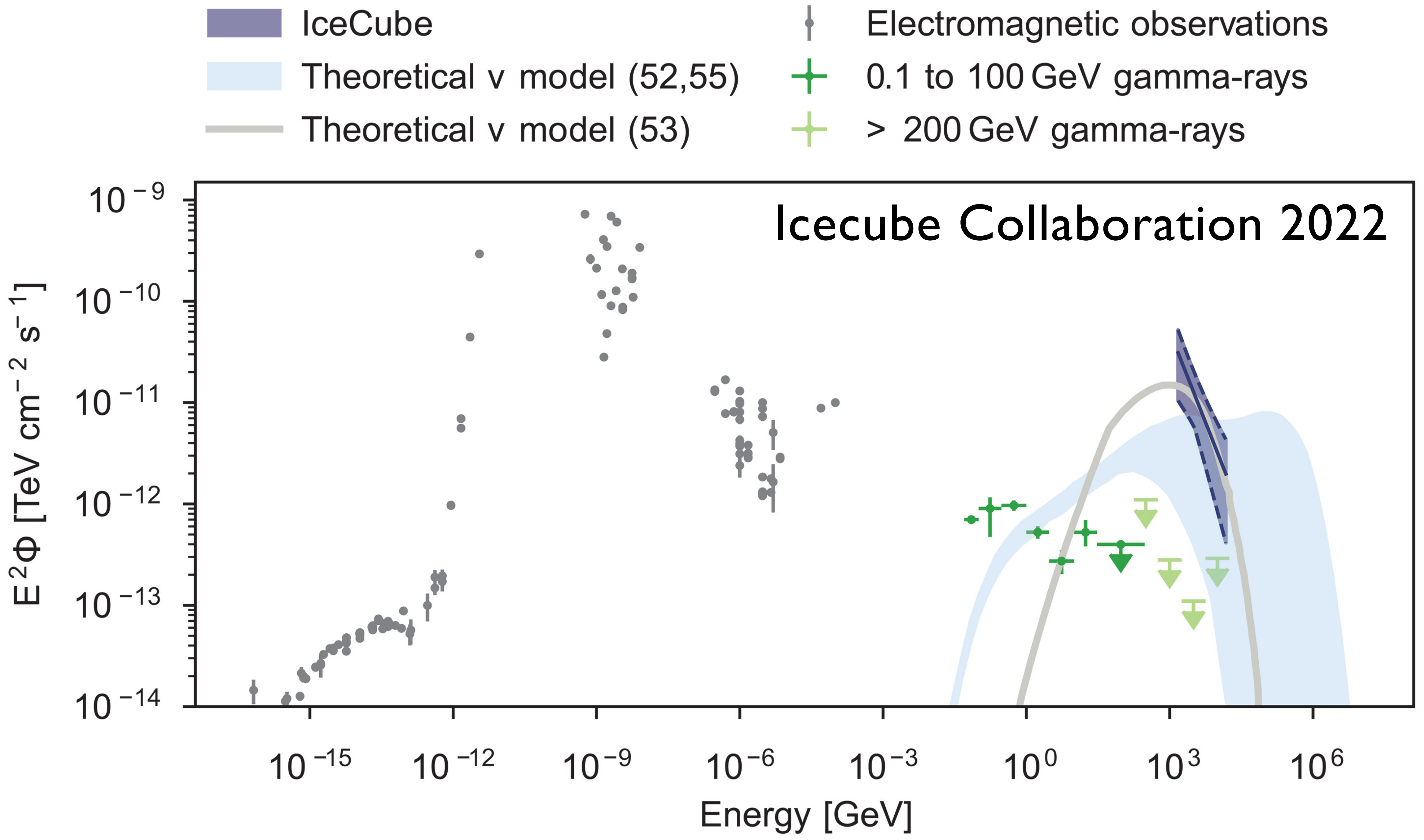


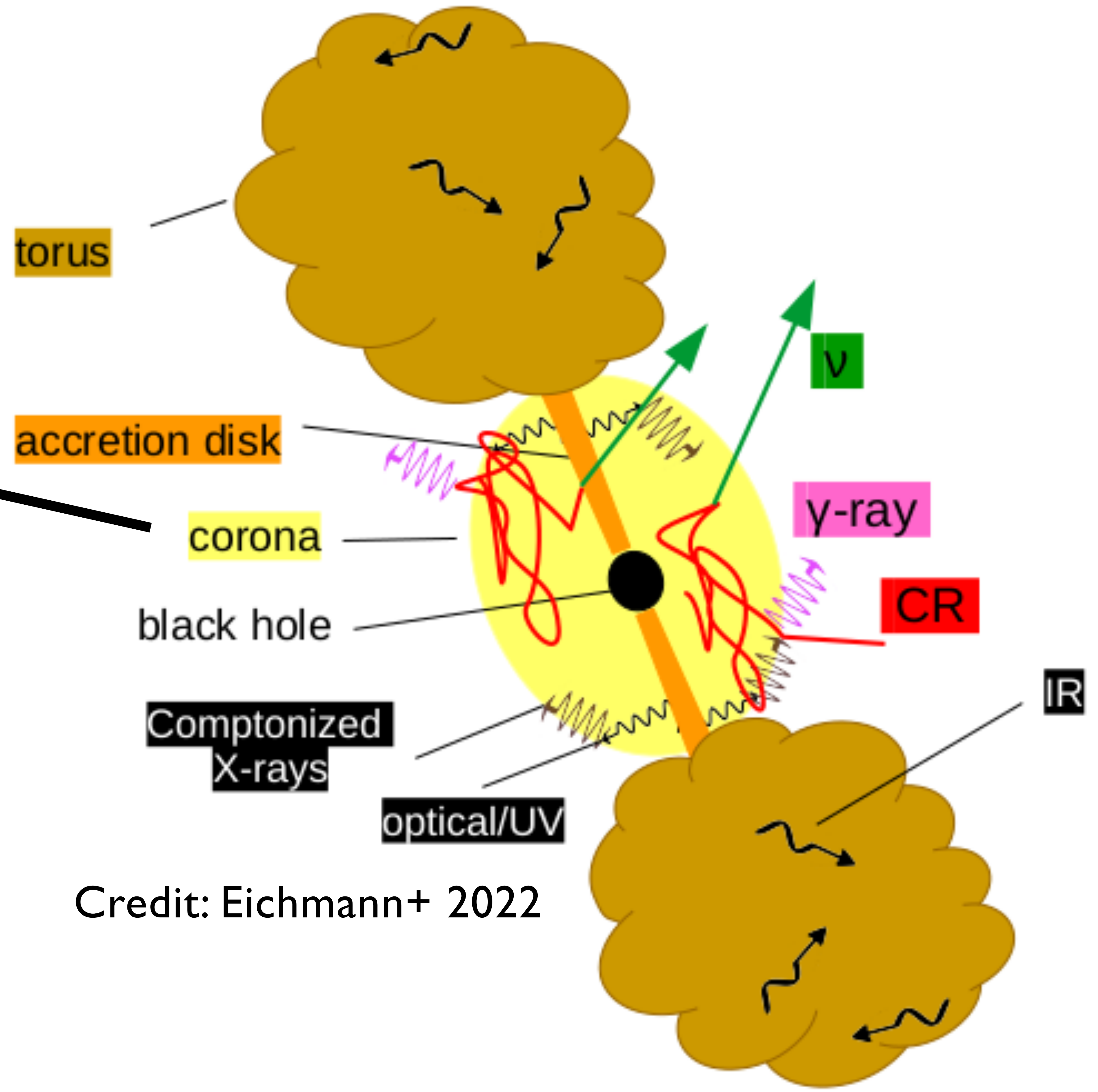
- Mean rate of change of γ due to stochastic acceleration: $$\frac{d\langle\gamma\rangle}{dt} = \frac{1}{\gamma^2}\frac{\partial}{\partial\gamma}\left(\gamma^2 D_\gamma\right)$$
- PIC simulations give: $D_\gamma \sim 0.1\sigma_{\rm tur}\left(\frac{c}{\ell_c}\right)\gamma^2 \longrightarrow t_{\rm acc}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

Nonresonant rather than gyro-resonant interactions (see also Lemoine '21, '22, Bresci+ '22)

Localized high-energy neutrinos from the nearby active galaxy NGC 1068



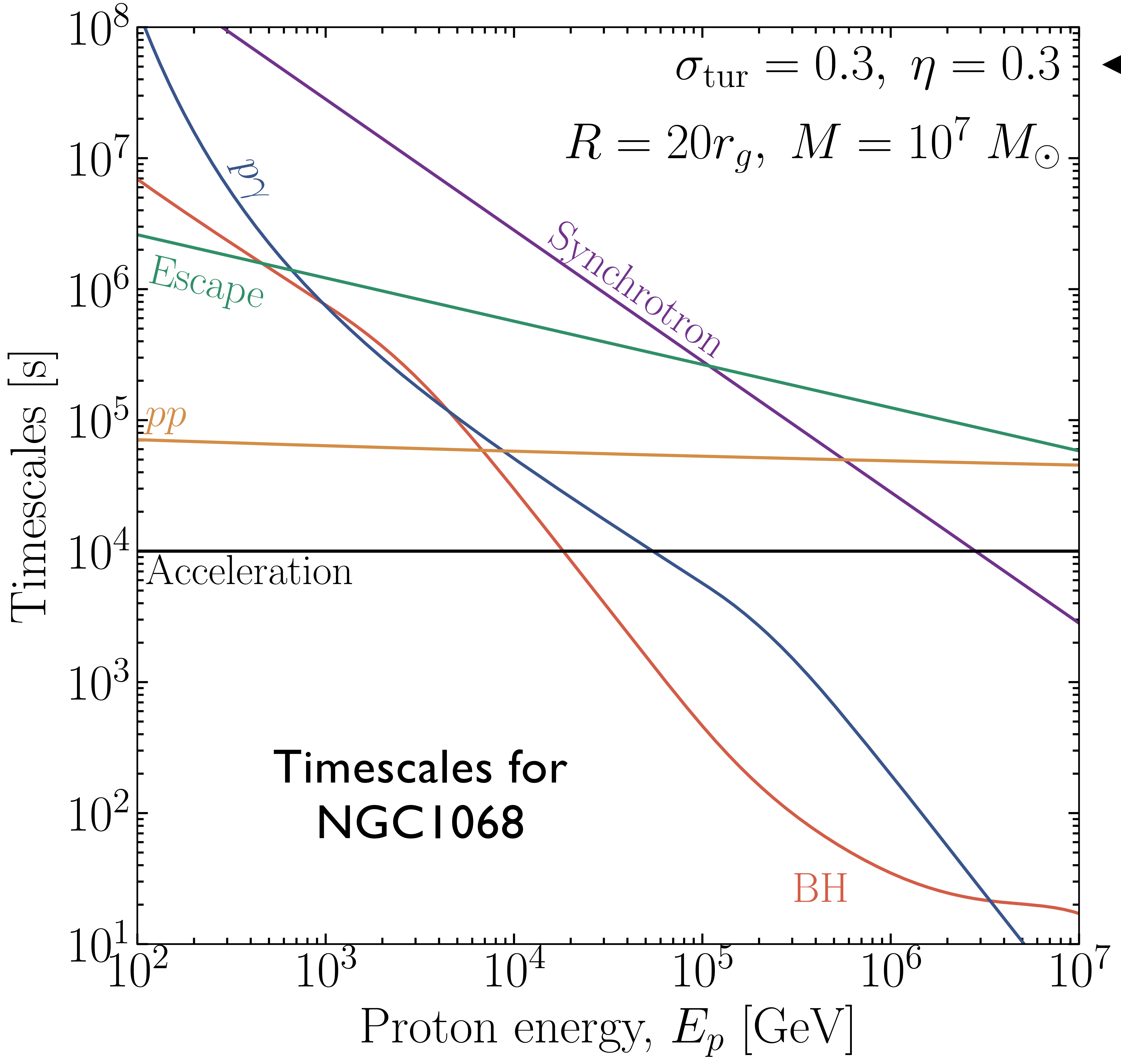




Credit: Eichmann+ 2022

- Magnetized turbulence in the BH corona may drive cosmic ray acceleration linked to neutrino emission [Dermer+'96, Murase+'20, Eichmann+'22, Fiorillo+'24, Mbarek+'24Lemoine+'24, etc.]

Stochastic proton acceleration with cooling in the active galaxy NGC 1068



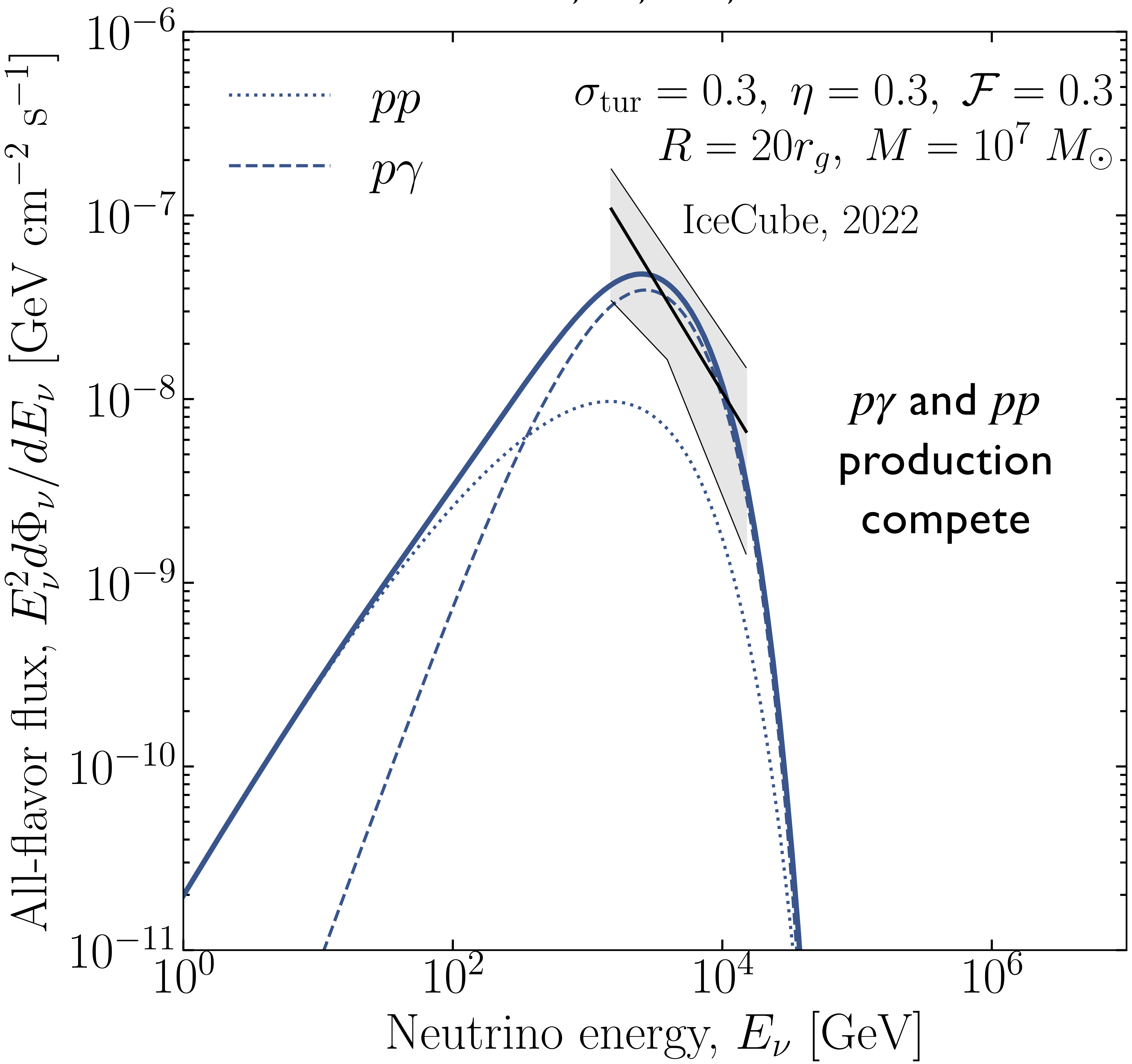
$$\sigma_{\rm tur} = \frac{\delta B^2}{4\pi n_p m_p c^2}\ , \quad \eta = \frac{\ell_c}{R}$$

- $t_{\rm acc} = \frac{\gamma^2}{D_\gamma}$ with $D_\gamma \sim 0.1\sigma_{\rm tur}\left(\frac{c}{\ell_c}\right)\gamma^2$
- electron-proton corona: $n_e/n_p \sim 1$
- Bethe-Heitler cooling limits proton energy to 20 TeV (needs sufficiently compact corona)

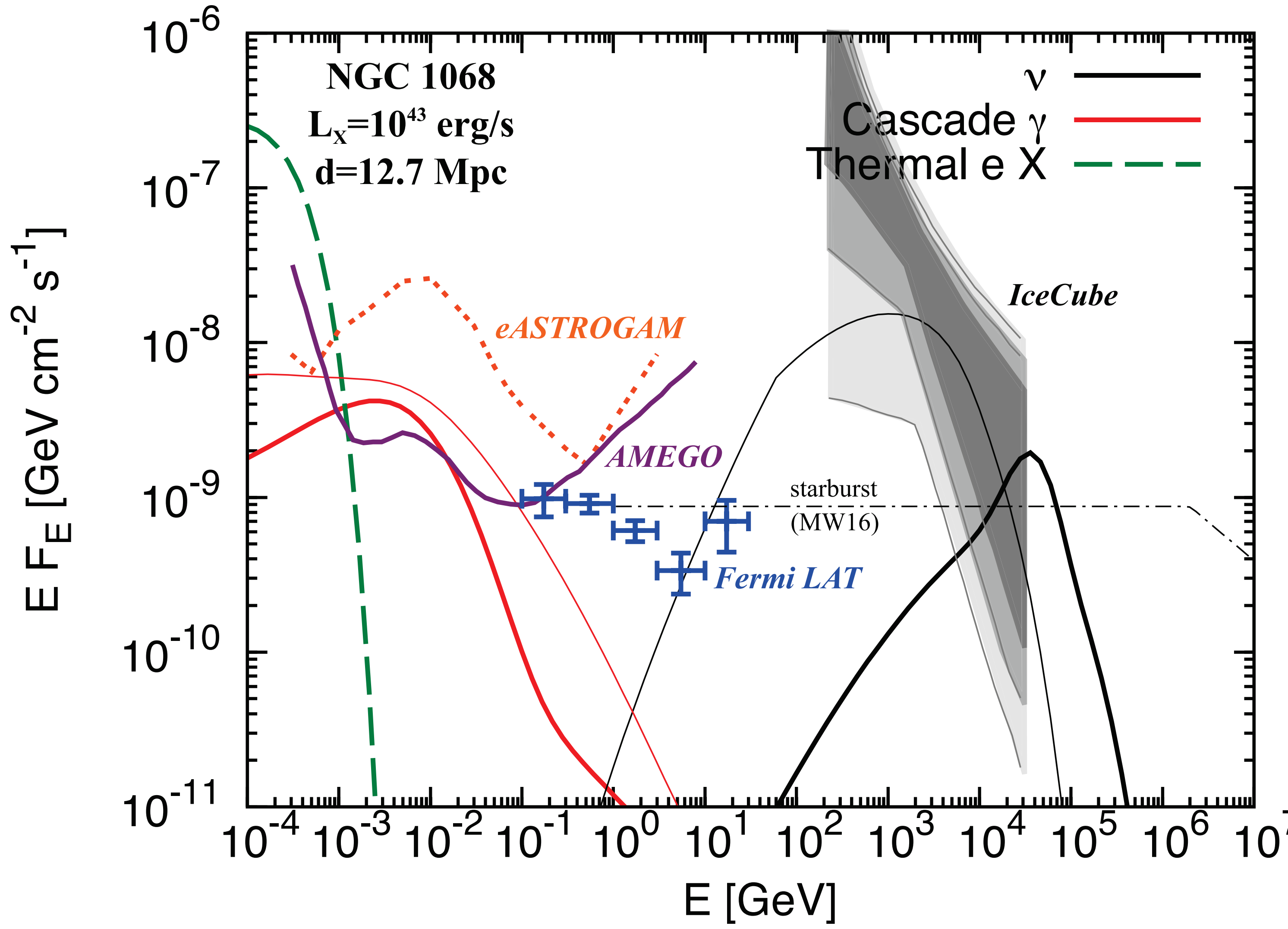
See also earlier model by Murase et al. ’20

Predicted neutrino spectrum for the active galaxy NGC 1068

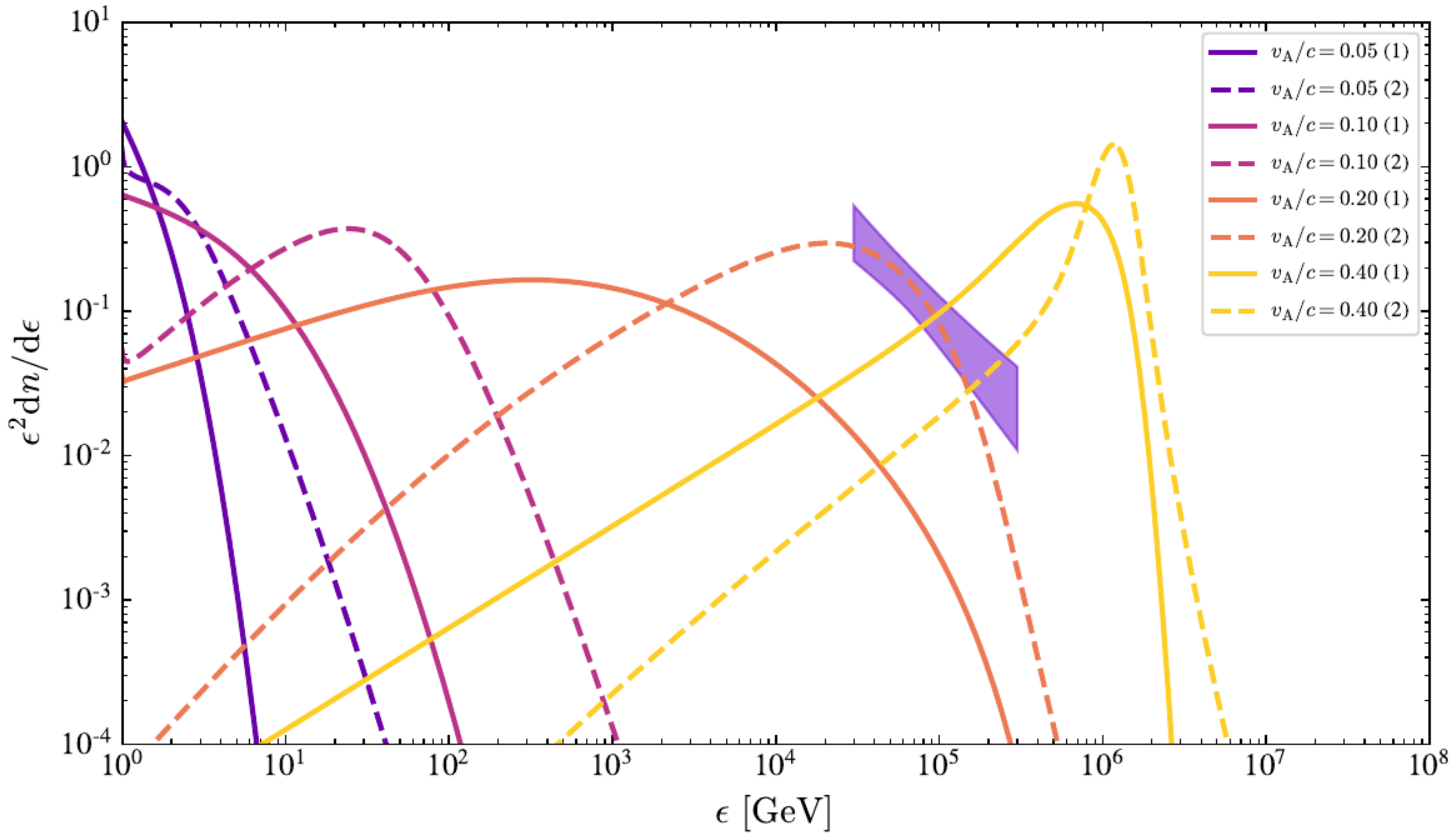
Fiorillo, LC, et al, 2024



See also earlier model by Murase+ '20

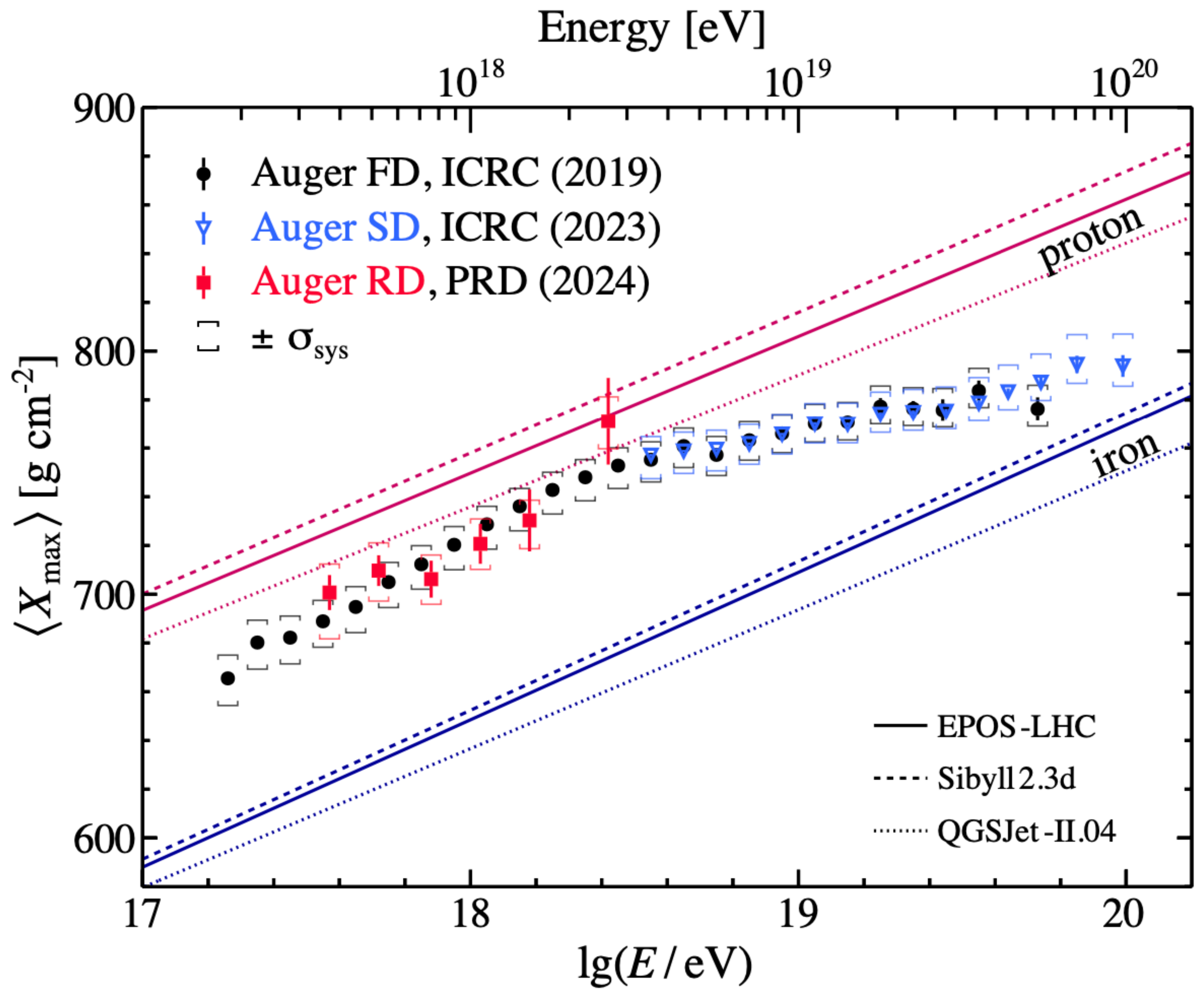


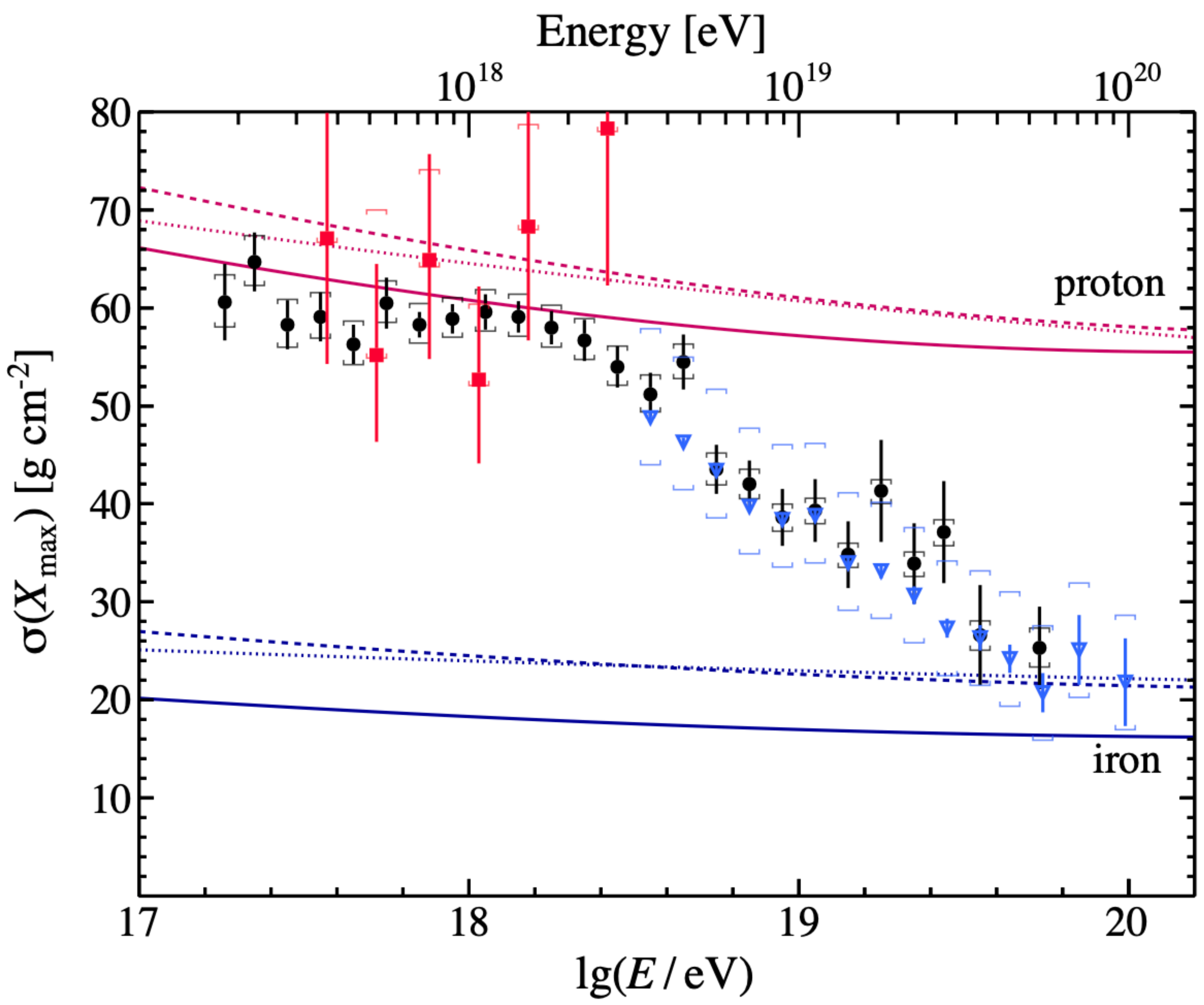
Relying solely on an energy diffusion coefficient might be over-simplistic [Lemoine & Rieger '24]

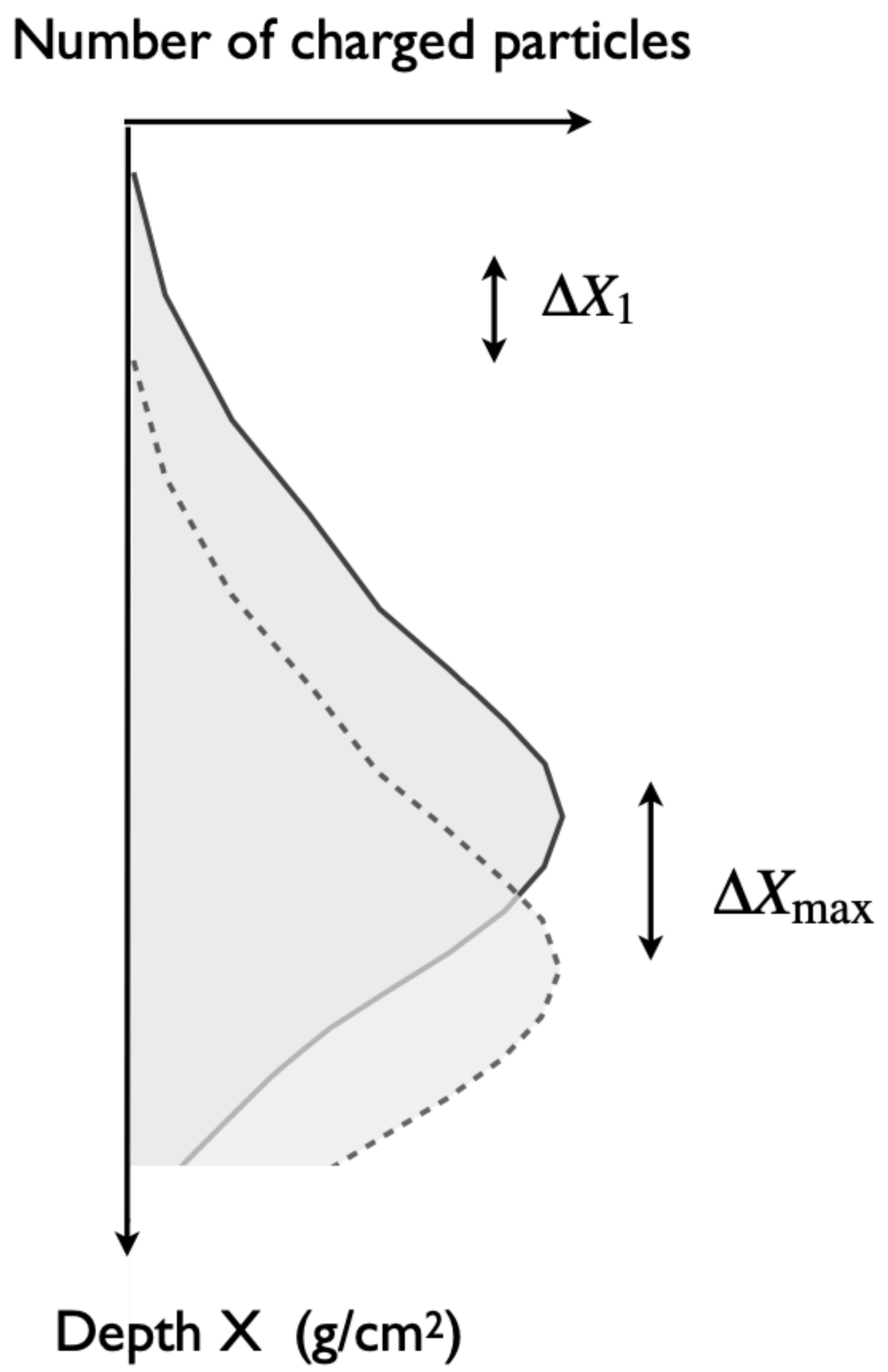


Magnetized turbulence as the mechanism for UHECR acceleration?

Mass composition results of Auger Observatory: [Slide credit: Engel, 2024 (This Conference)]







(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)

Shock-informed cutoffs require exceptionally hard power laws

- The source energy cutoff is generally modeled (inspired by shock acceleration theory) as:

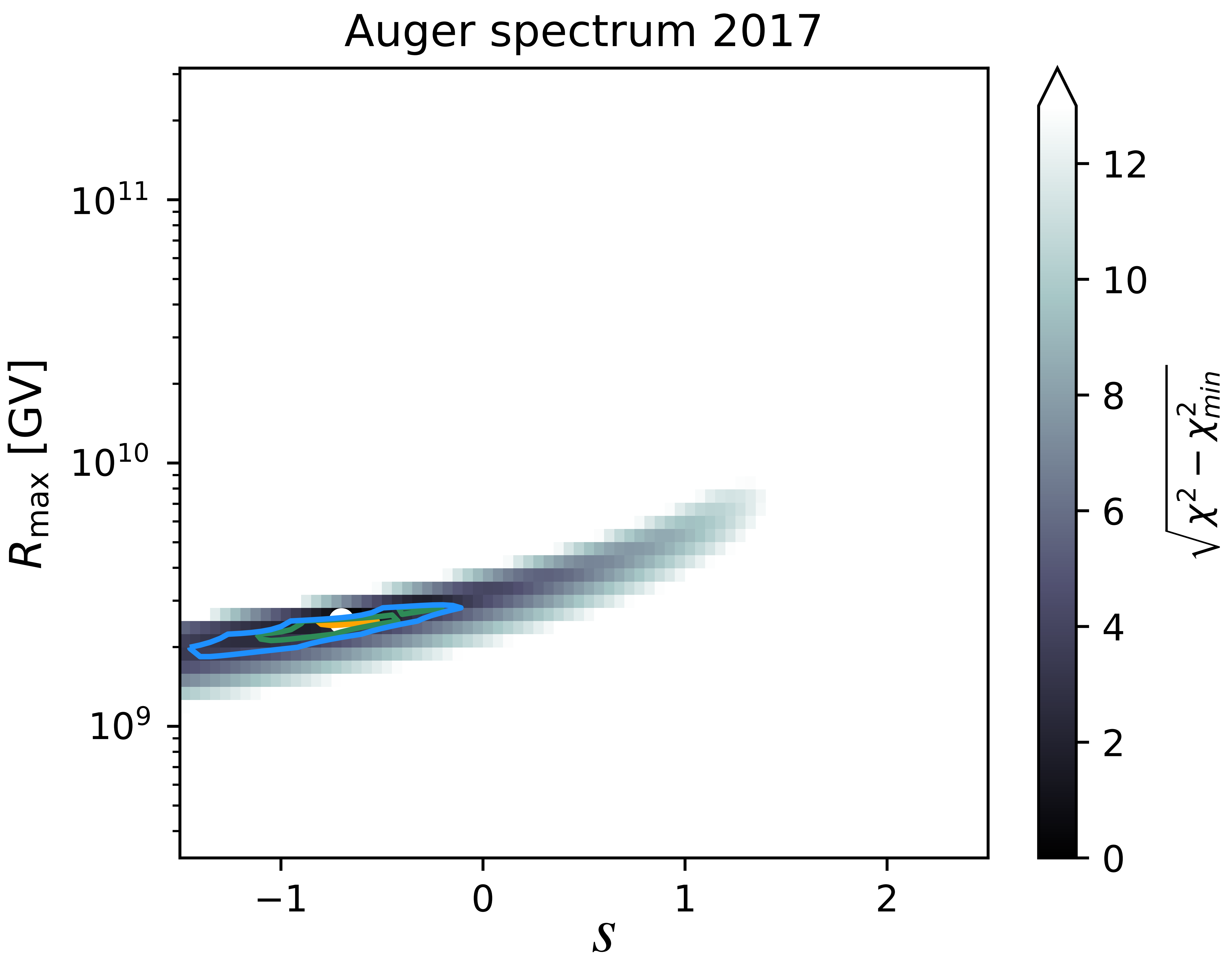
$$\phi(E) \propto E^{-s} \exp\left[\left(-E/E_{\text{cut}}\right)\right], \text{ with } s \geq 2$$

[e.g., Protheroe & Stanev 1999]

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

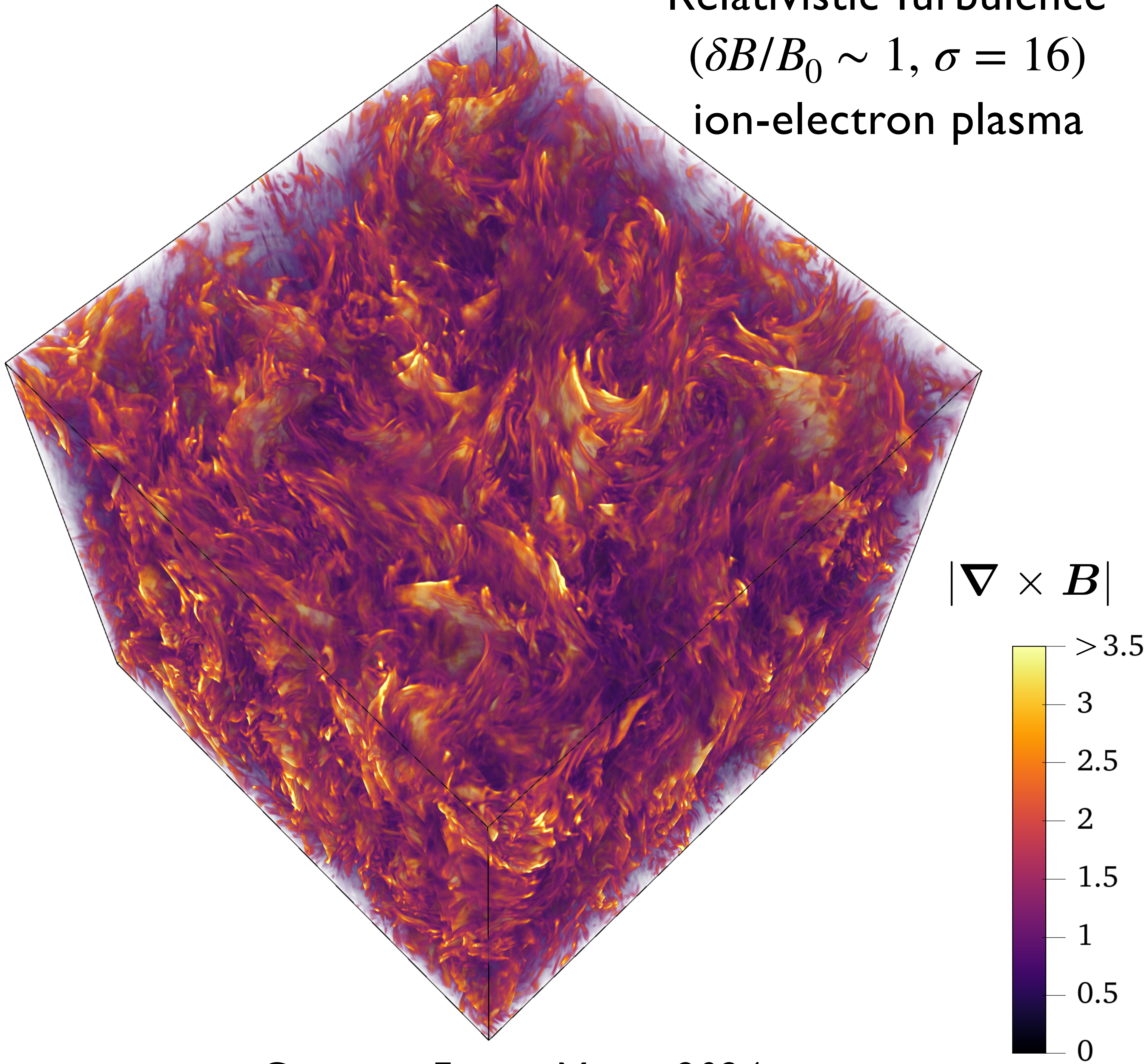
$$\phi(E) \propto E^{-s} \times \begin{cases} 1 & , E \leq E_{\text{cut}} \\ \exp\left[\left(-E/E_{\text{cut}}\right)\right] & , E > E_{\text{cut}} \end{cases}$$

- Fit to UHECR spectrum and composition data return $s \lesssim 1$ (at odds with shocks)

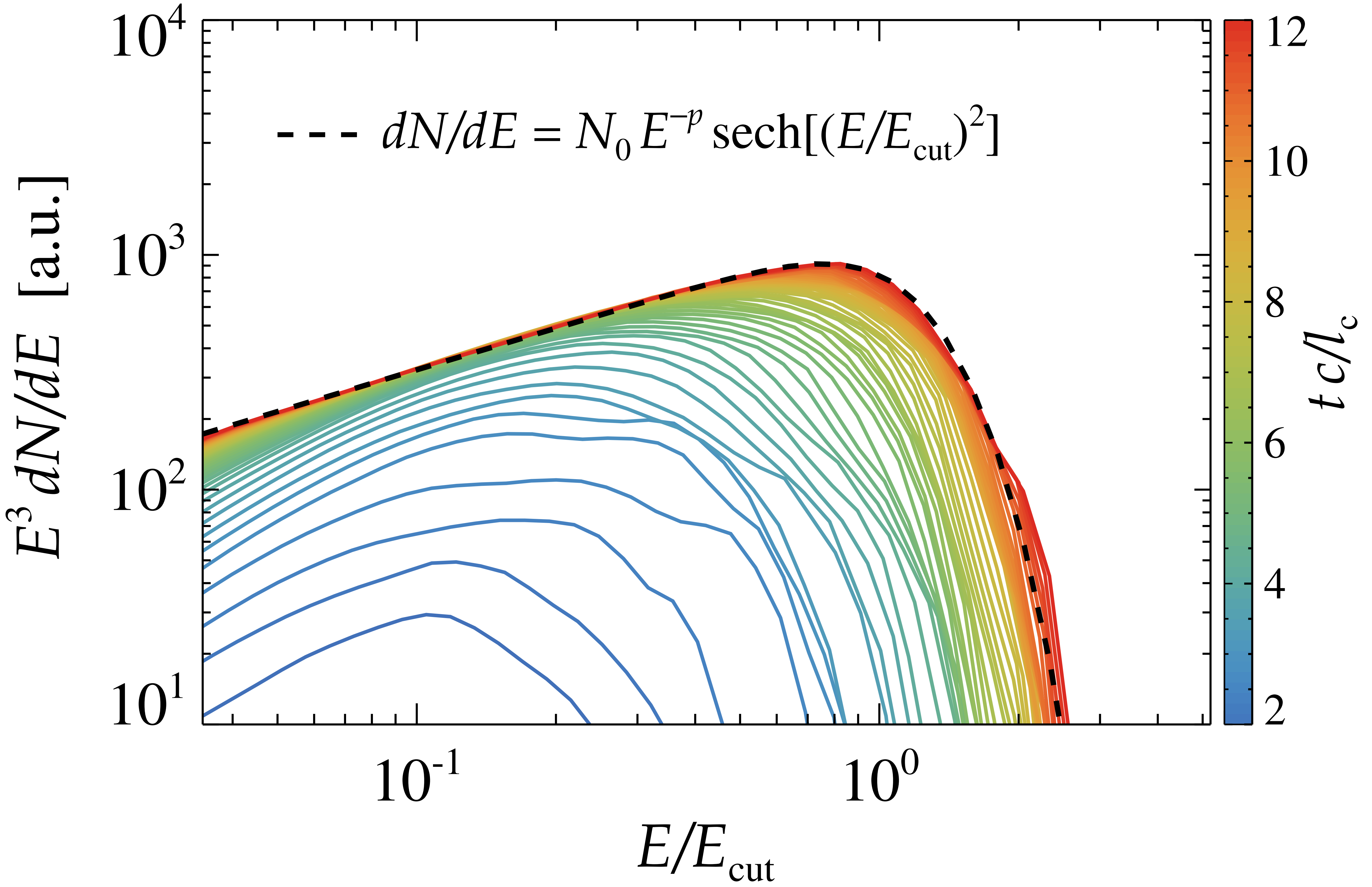


Heinze et al. 2019

Particle acceleration via magnetized turbulence: sharp energy cutoff



Comisso, Farrar, Muzio 2024

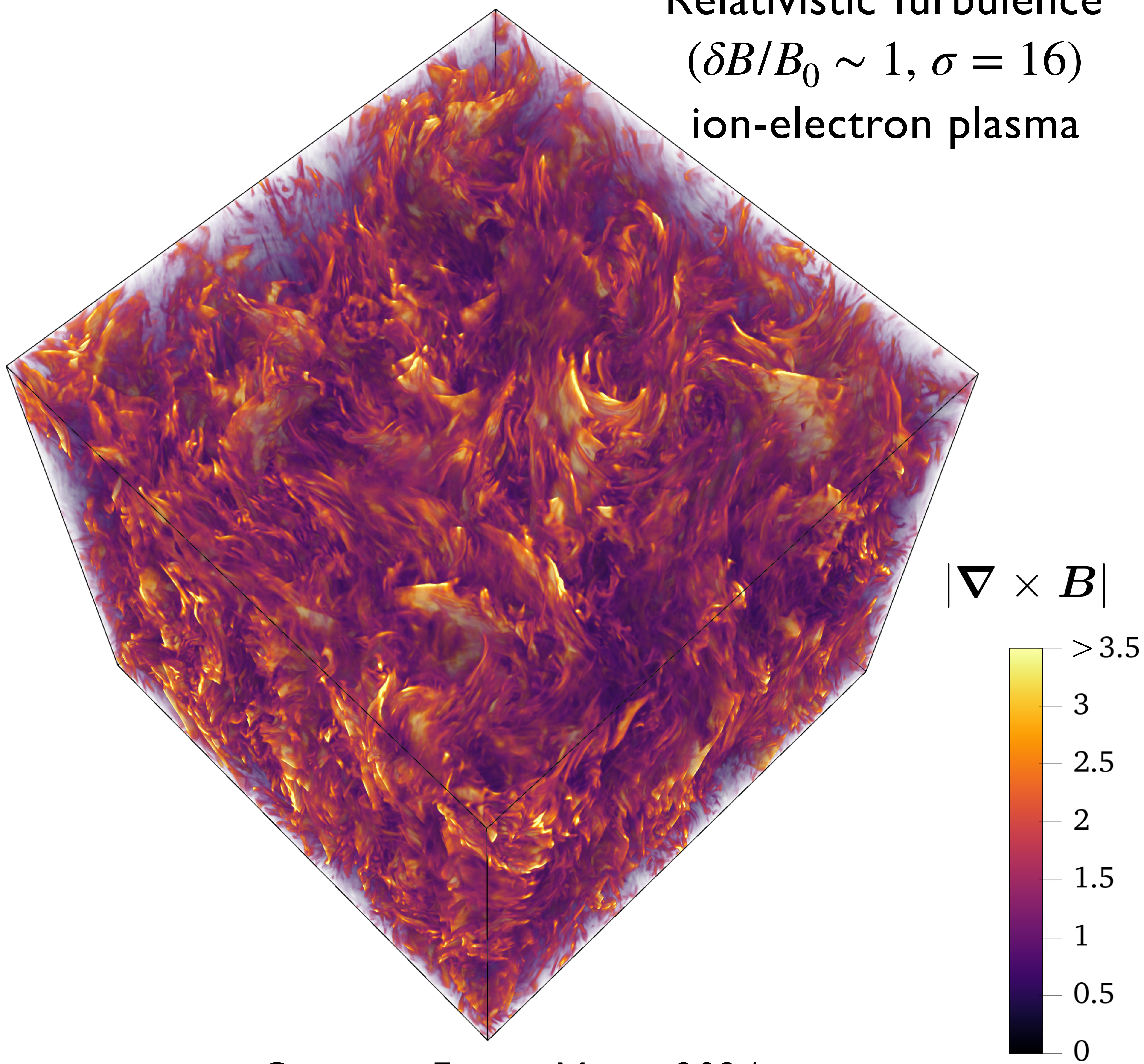


- Magnetized turbulence accelerates particles into a spectrum of the form:

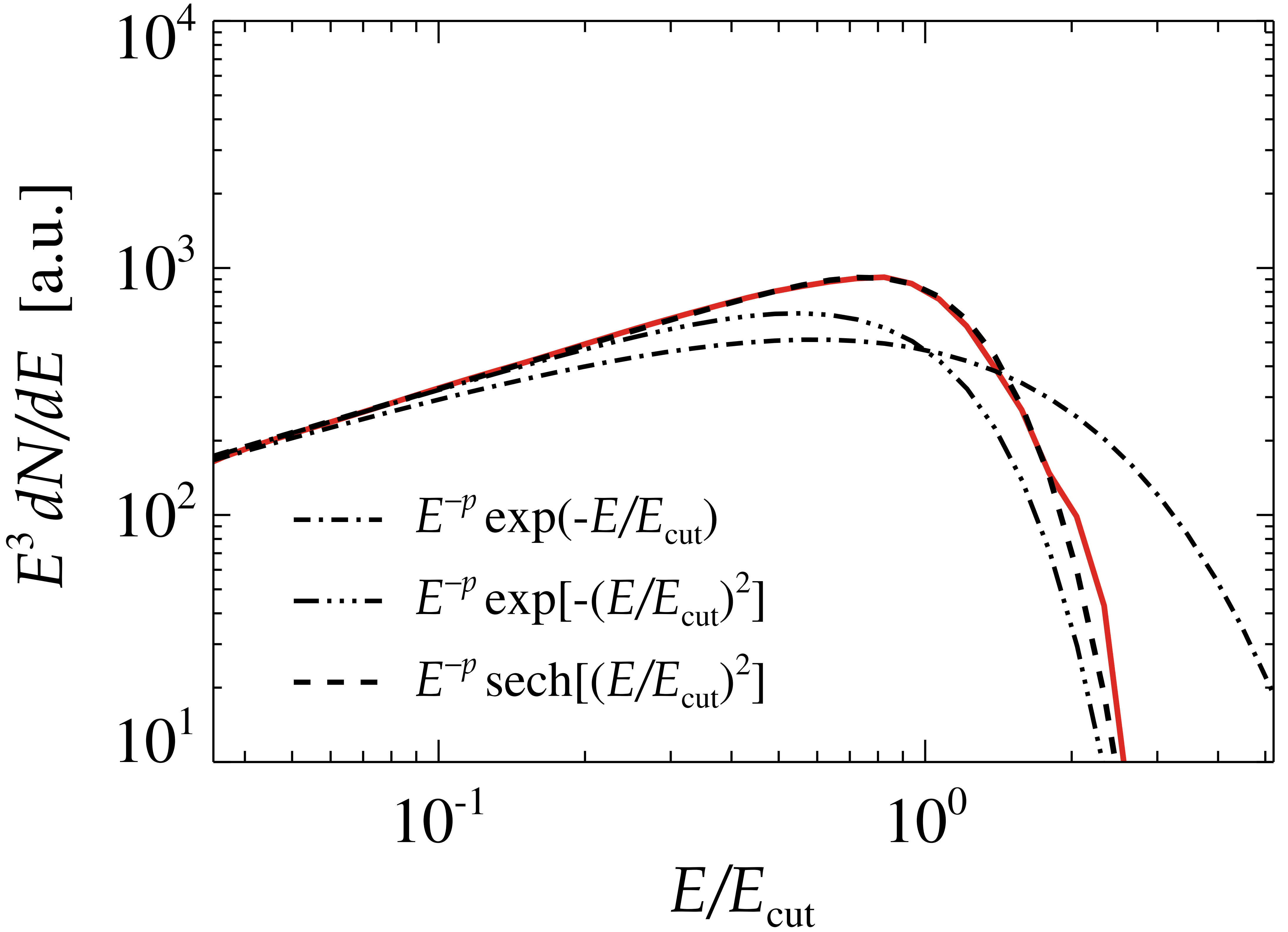
$$\frac{dN}{dE} = N_0\, E^{-p}\, \mathrm{sech}\left[\left(E/E_{\rm cut}\right)^2\right]$$

Particle acceleration via magnetized turbulence: sharp energy cutoff

Relativistic Turbulence
$(\delta B/B_0 \sim 1,\ \sigma = 16)$
ion-electron plasma



Comisso, Farrar, Muzio 2024

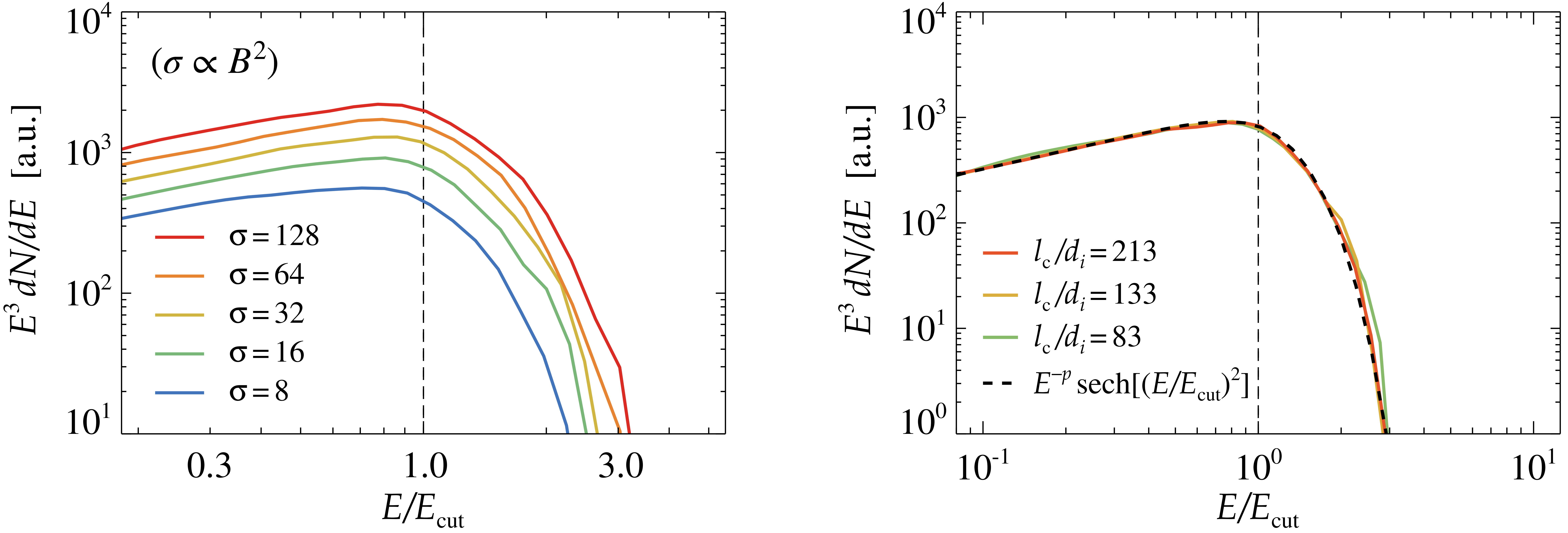


- Magnetized turbulence accelerates particles into a spectrum of the form:

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

Particle acceleration via magnetized turbulence: rigidity-dependent energy cutoff

Comisso, Farrar, Muzio 2024



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

Particle acceleration via magnetized turbulence: particle escape timescale

- residence time within the accelerator:

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

- flux of particles escaping the accelerator is given by

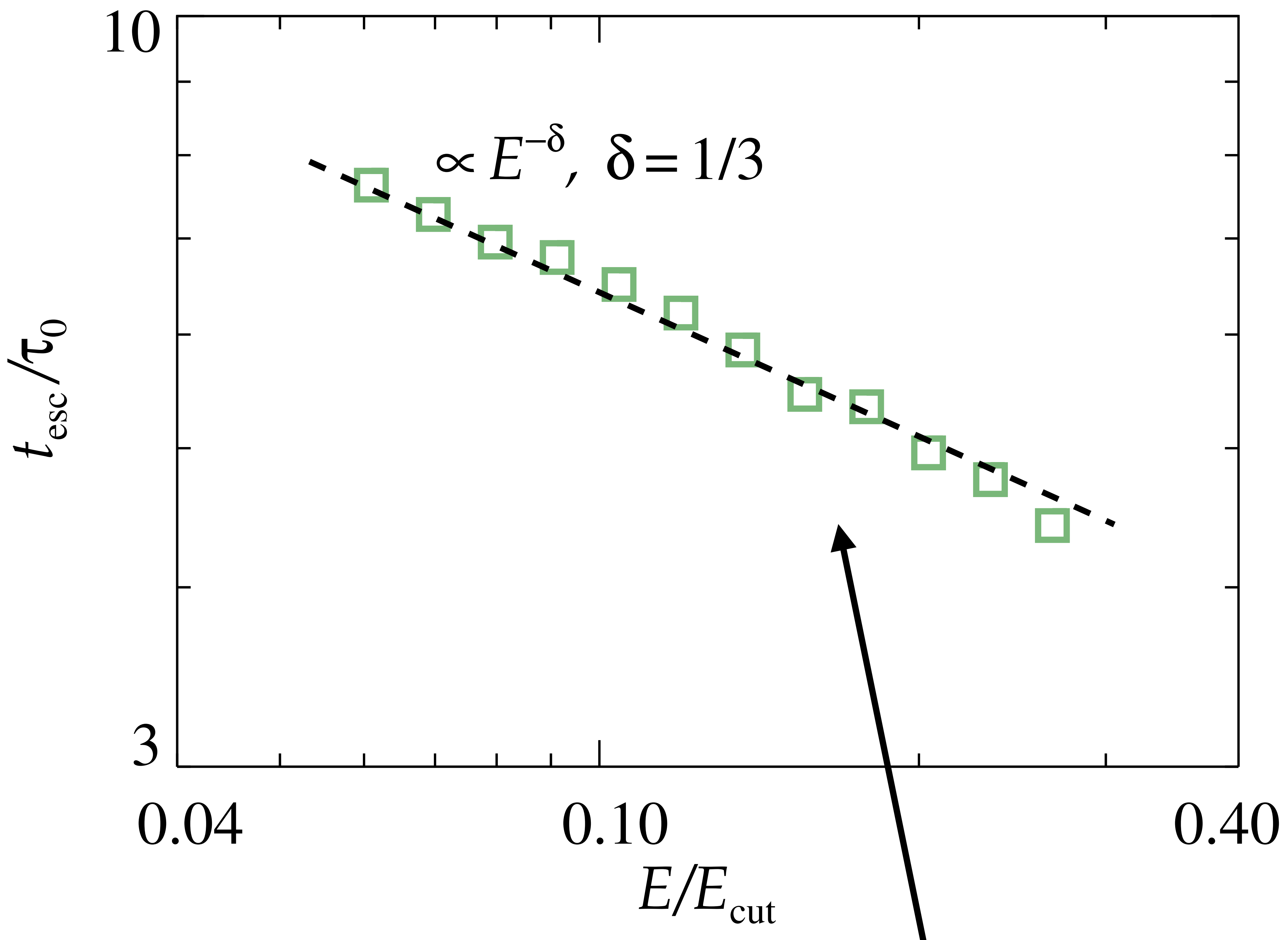
$$\phi(E) = \frac{dN}{dEdt} = \frac{1}{t_{\rm esc}}\frac{dN}{dE} \propto E^{-s}\,{\rm sech}\left[\left(E/E_{\rm cut}\right)^2\right]$$

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

$p \sim 2.4$

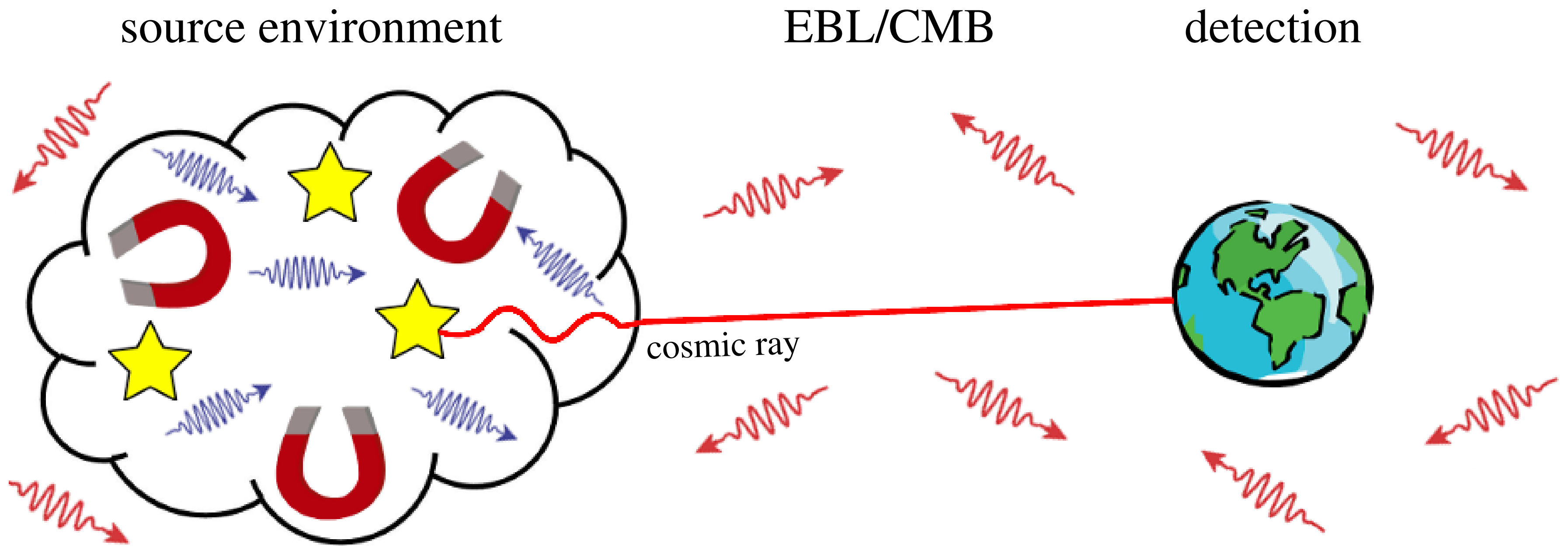
$\delta \sim 1/3$ from PIC simulations of highly magnetized ($\sigma \gg 1$) turbulence

Comisso, Farrar, Muzio 2024

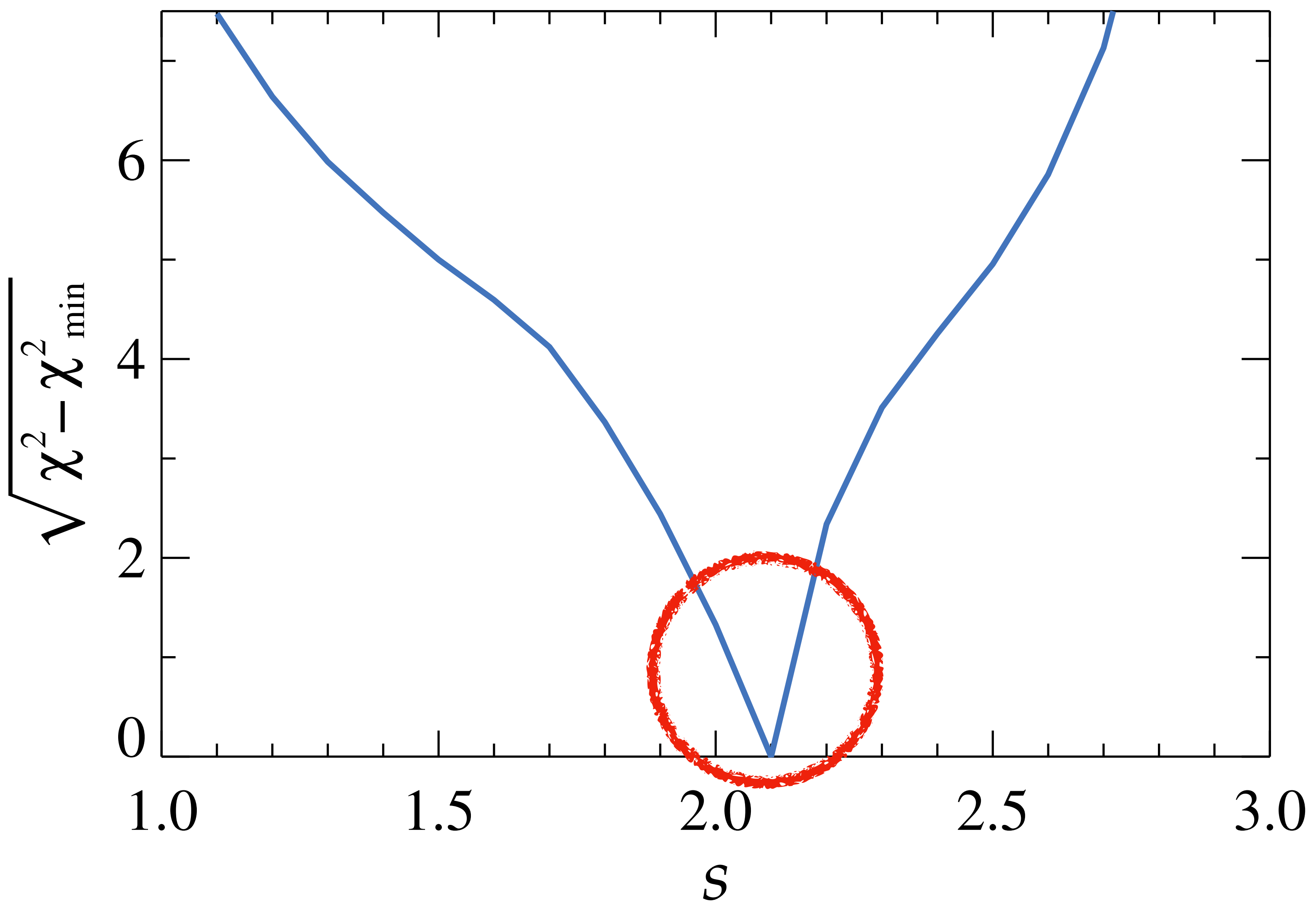


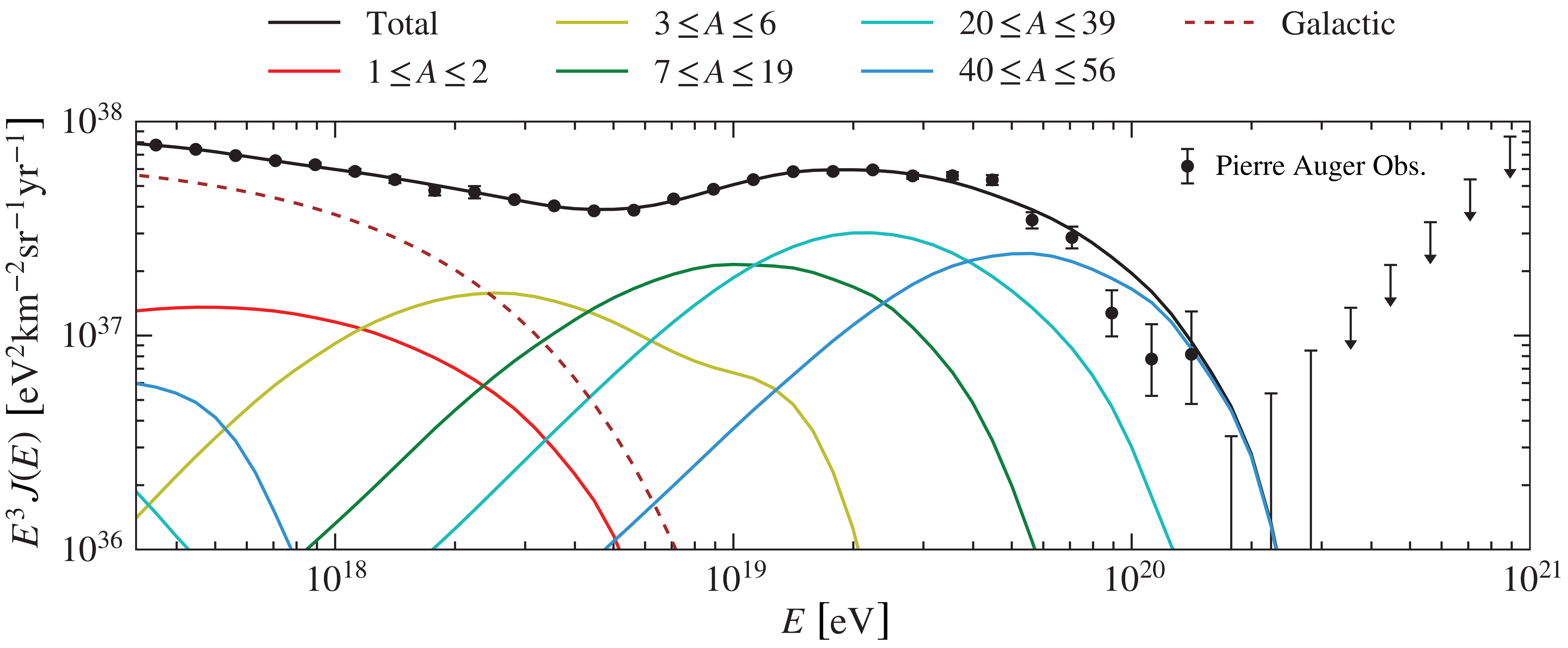
[similar scaling in test particle simulations of large amplitude turbulence: see Lemoine 2024]

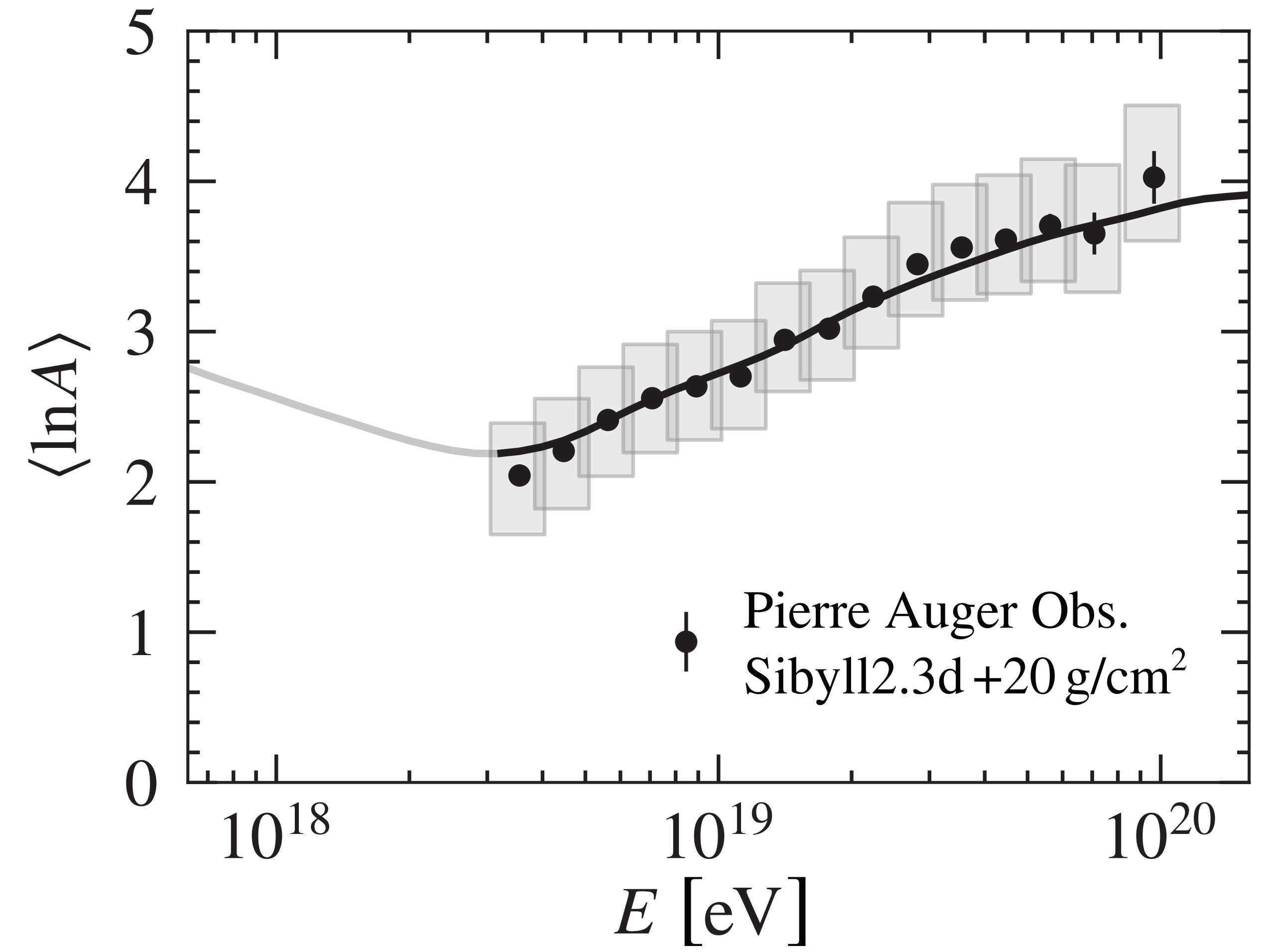
Particle acceleration via magnetized turbulence: fitting to UHECR data

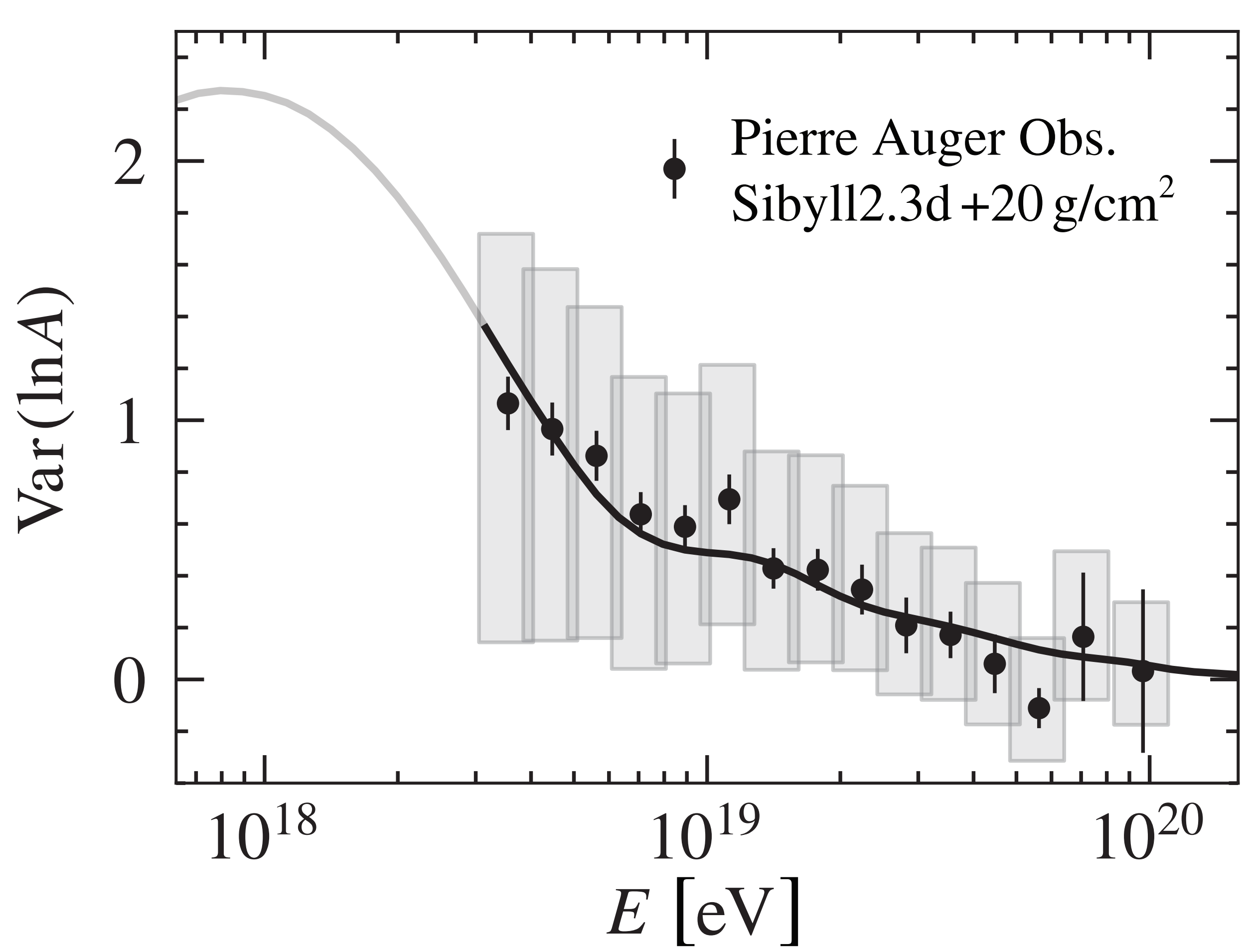


Particle interaction and propagation according to Unger, Farrar, Anchordoqui 2015 (see also Muzio and Farrar 2023)



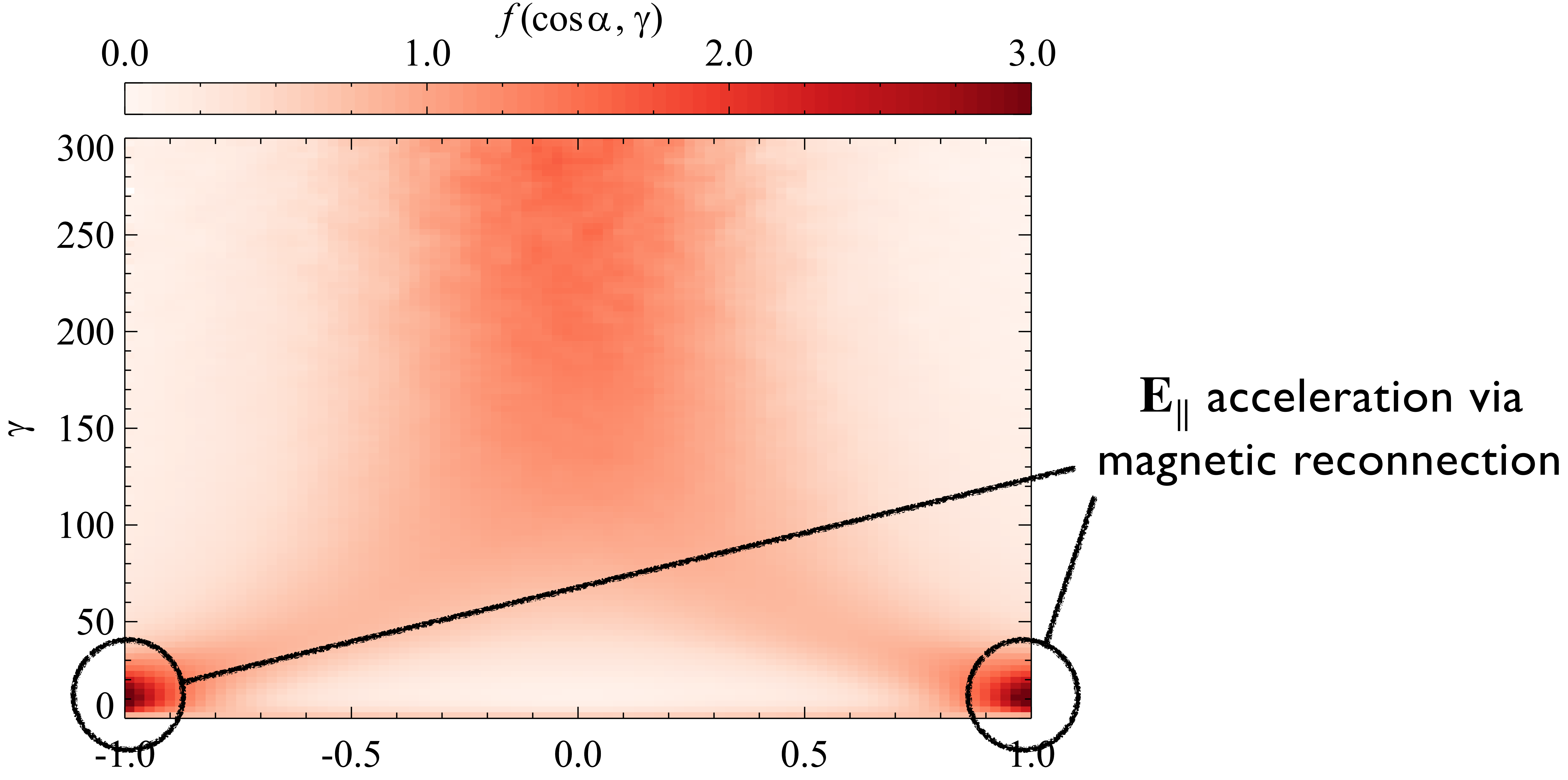






Comisso, Farrar, Muzio 2024

Particle acceleration via magnetized turbulence: back to the injection stage

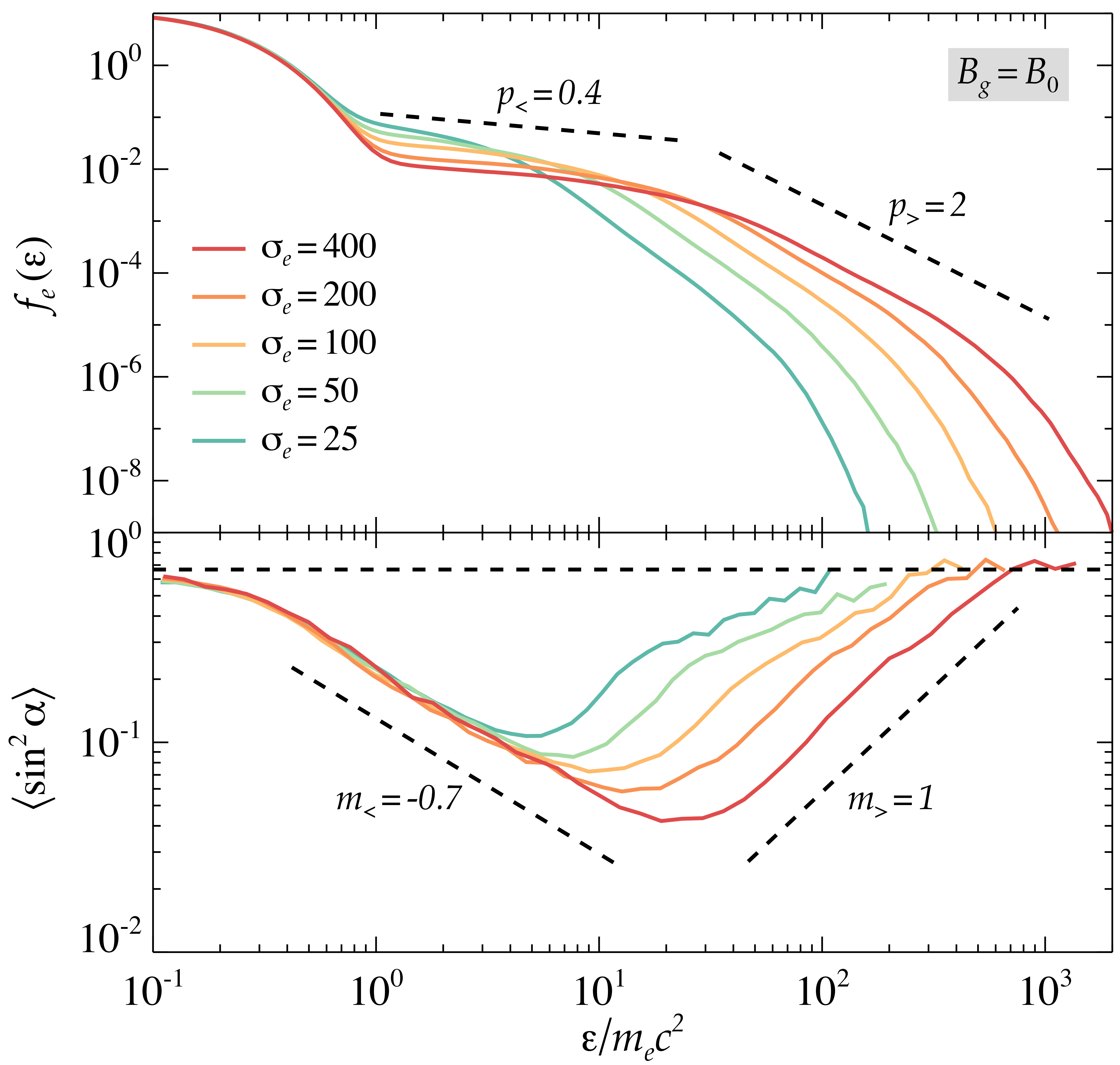


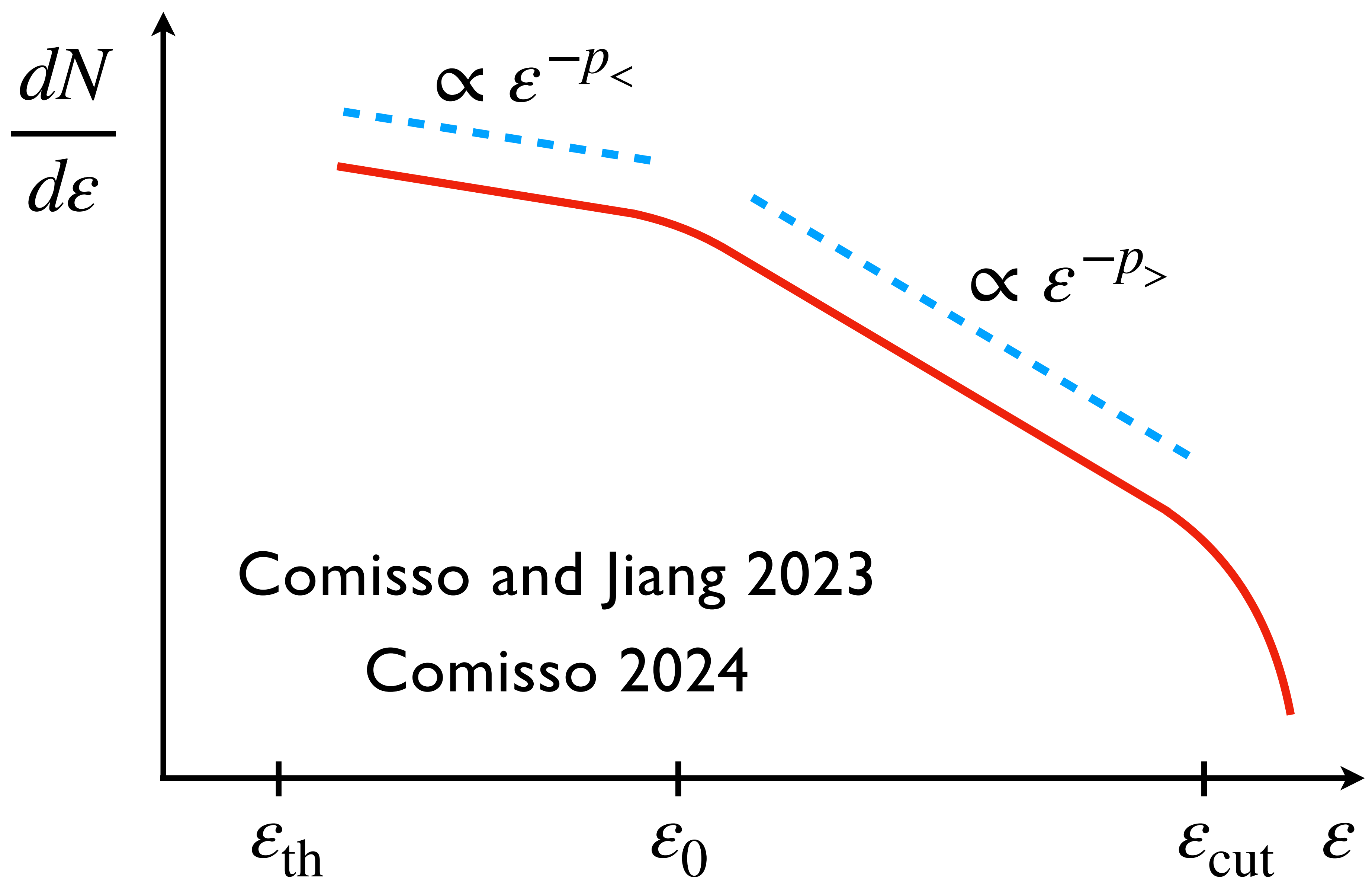
$$\cos\alpha = \frac{\mathbf{v} \cdot \mathbf{B}}{|\mathbf{v}||\mathbf{B}|}$$

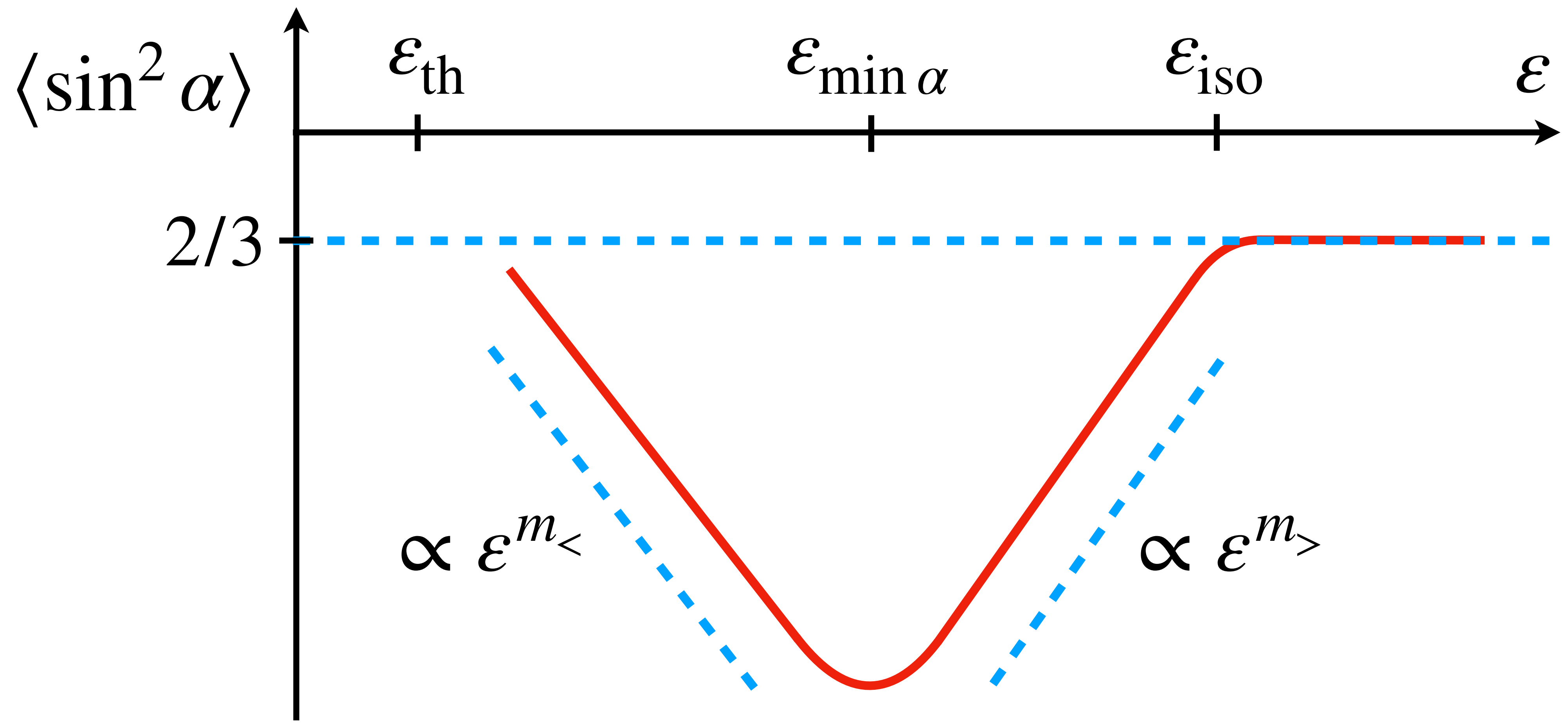
Comisso and Sironi '19, Comisso et al '20

Anisotropic pitch angle distributions develop in highly magnetized turbulence

Concurrent particle acceleration and pitch-angle anisotropy from reconnection

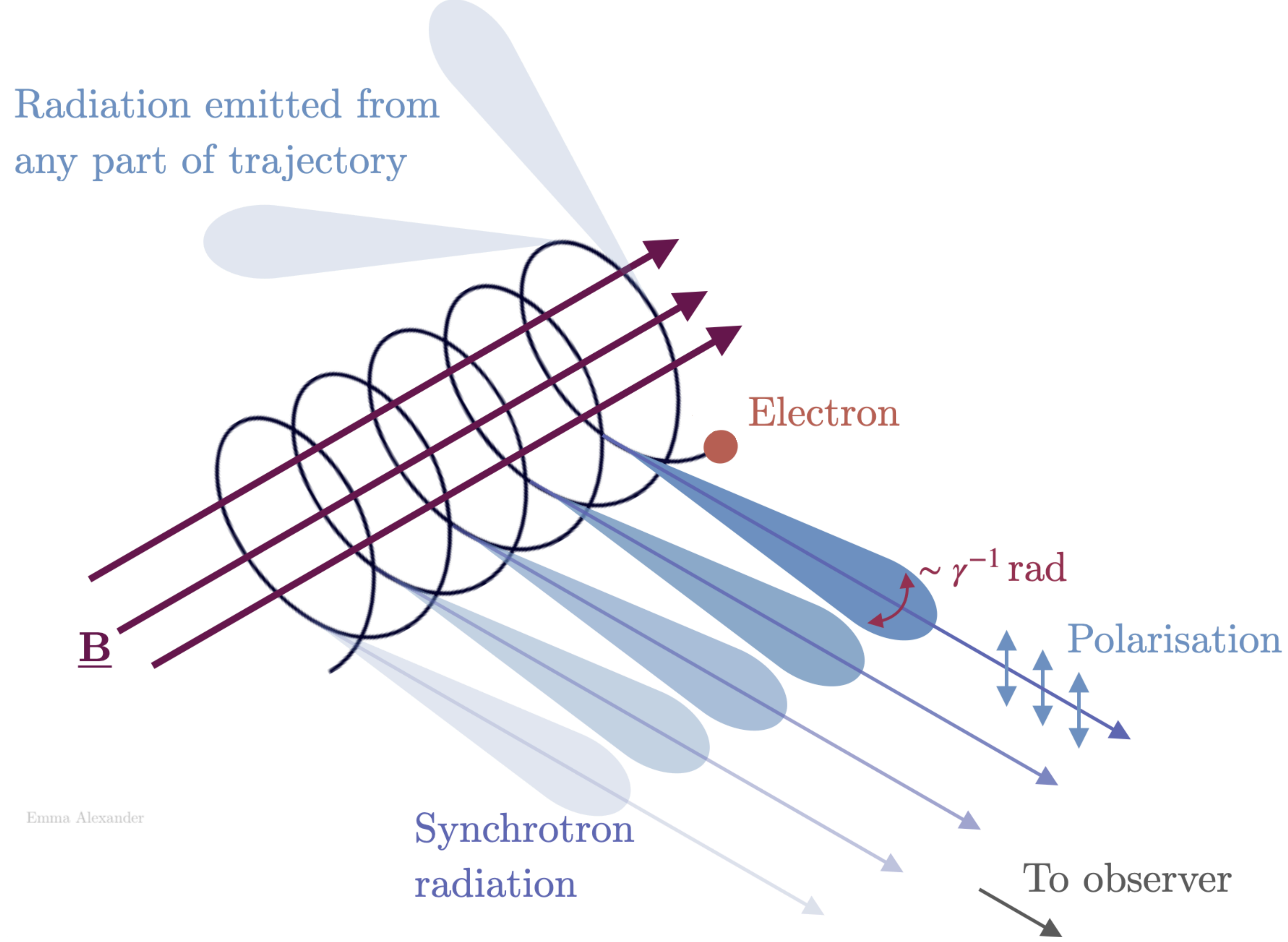


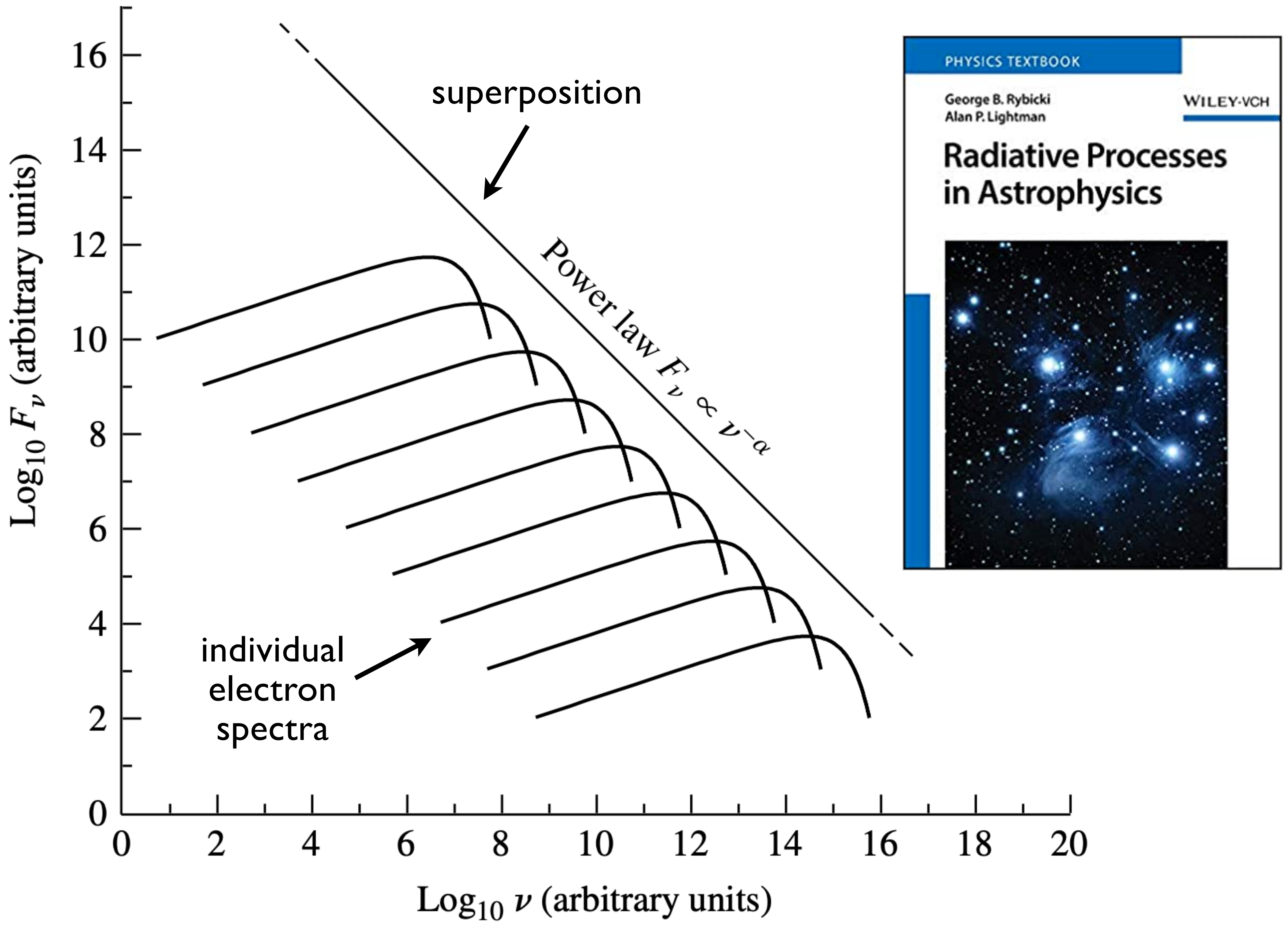




Broken power laws from reconnection (in both energy spectrum and pitch angle anisotropy)

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

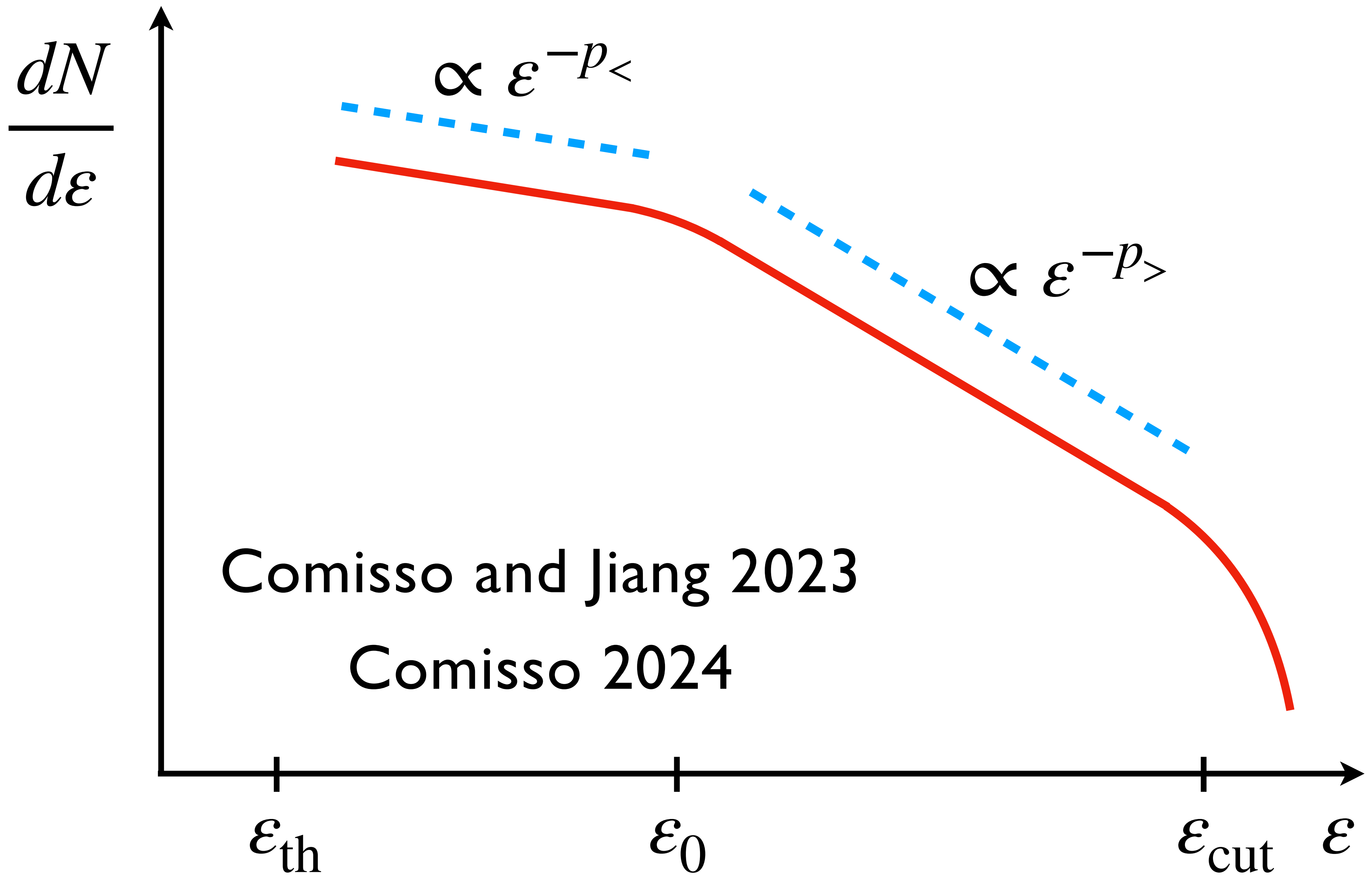
$$dN/d\gamma \propto \gamma^{-p}$$

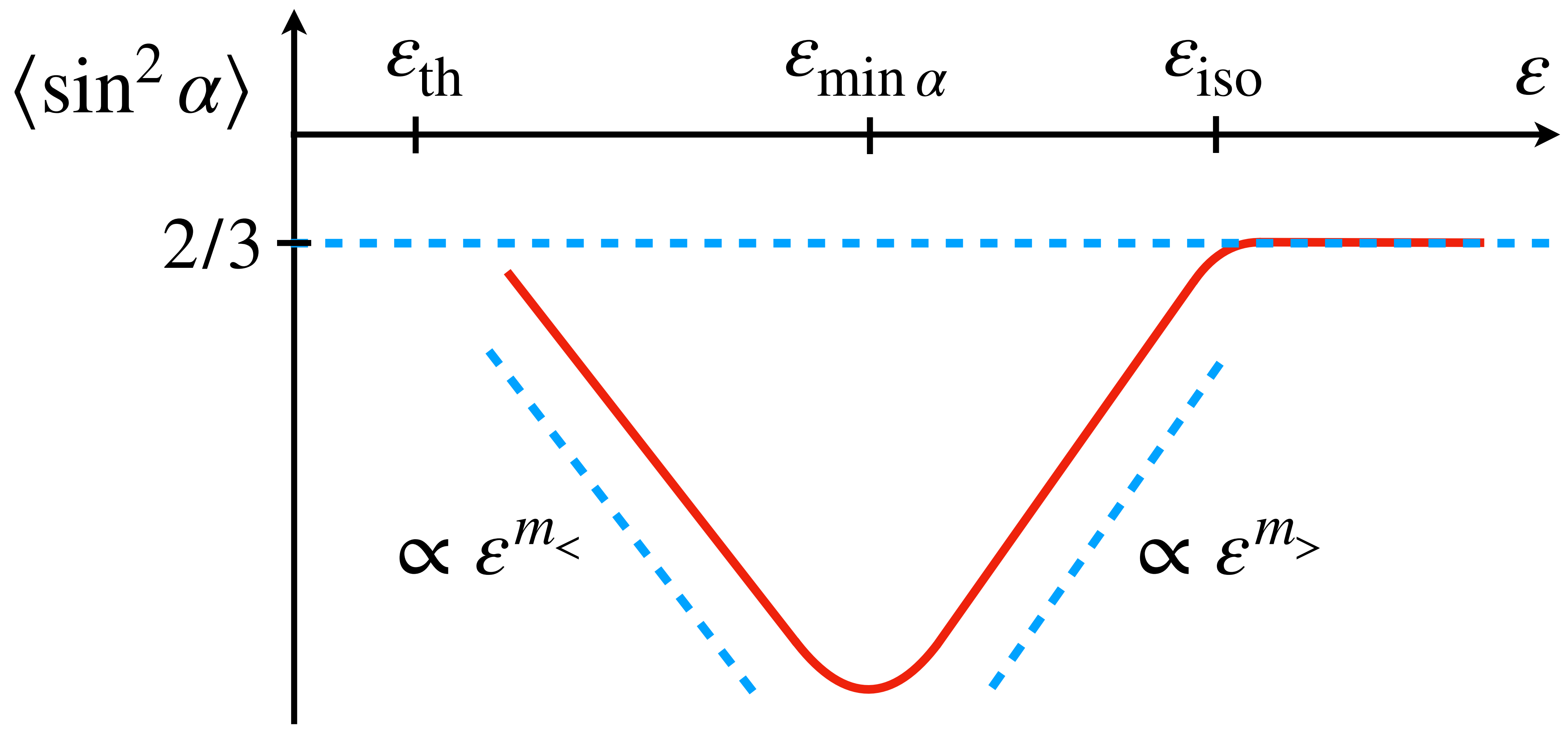
lead to synchrotron energy flux

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

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

Consequences for the Spectral Energy Distribution





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

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

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

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

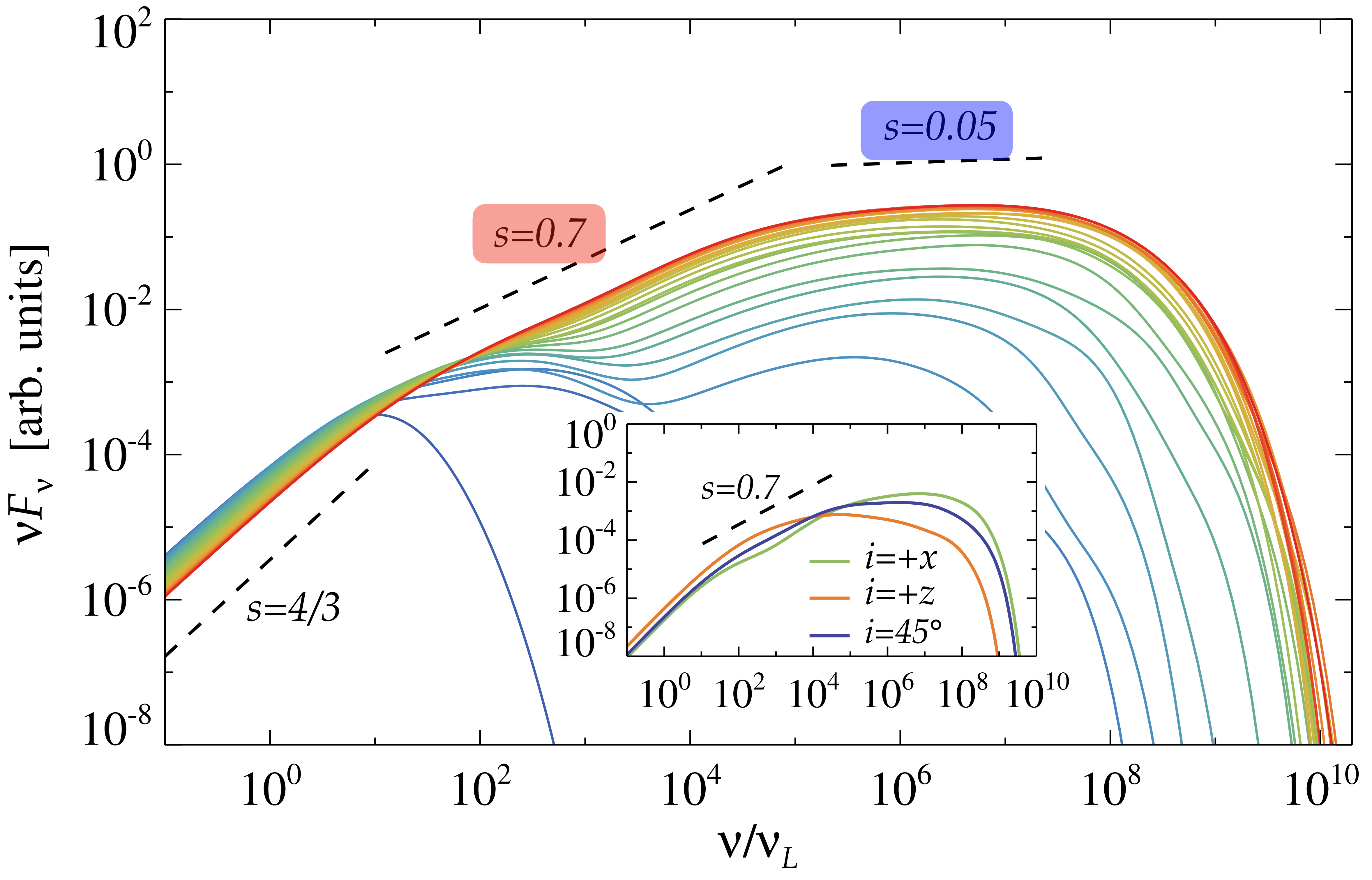
$$\nu \sim \gamma^2 \nu_L \sin\alpha \propto \gamma^{2+m/2} \qquad (\nu_L = eB/2\pi m_e c)$$

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

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

(standard "textbook case" when $m = 0$)

Consequences for the Spectral Energy Distribution

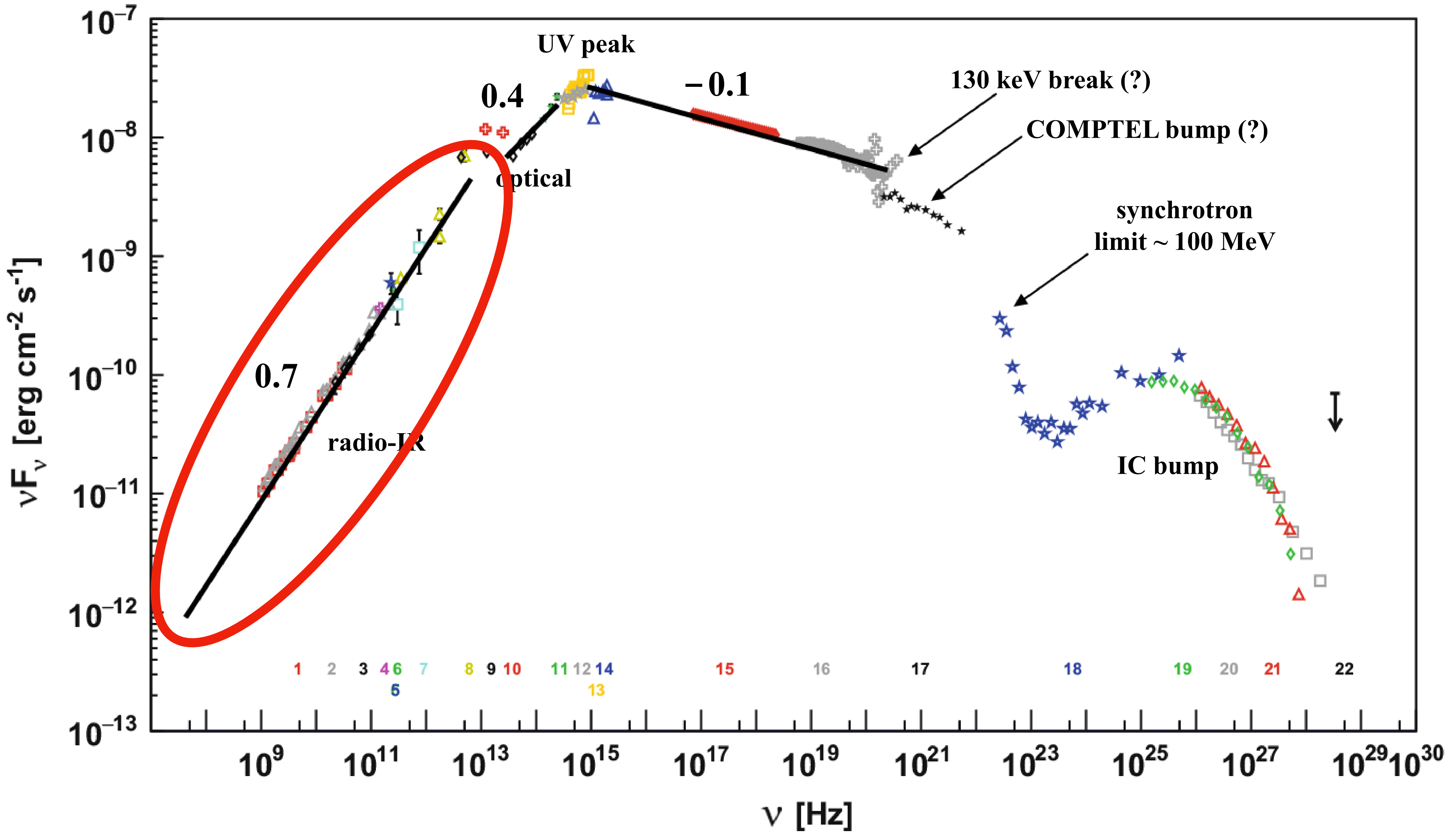


$$\nu \sim \gamma^2 \nu_L \sin\alpha \propto \gamma^{2+m/2} \qquad (\nu_L = eB/2\pi m_e c)$$

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

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

Crab Nebulae SED (Zanin 2017)



- Relativistic turbulence ($\sigma \gg 1$) produces radio spectra with $s \sim 0.7$ for an extended fluctuation range
- Radio spectra with $s \sim 0.7$ are typical of PWNe (not just the Crab Nebula)

A few key takeaways

1. Turbulence and magnetic reconnection commonly act in tandem

2. Particle acceleration from the thermal pool is effectively a two-stage process

3. Turbulence might account for neutrino production in AGN corona

4. Turbulence acceleration gives rise to $dN/dE \propto E^{-p}\,\mathrm{sech}[(E/ZeR_{\mathrm{cut}})^2]$ with $R_{\mathrm{cut}} \sim B_{\mathrm{rms}} l_c$ and $s \sim [2 - 2.2]$ for $\sigma \gg 1$ (matches nicely UHECR data)

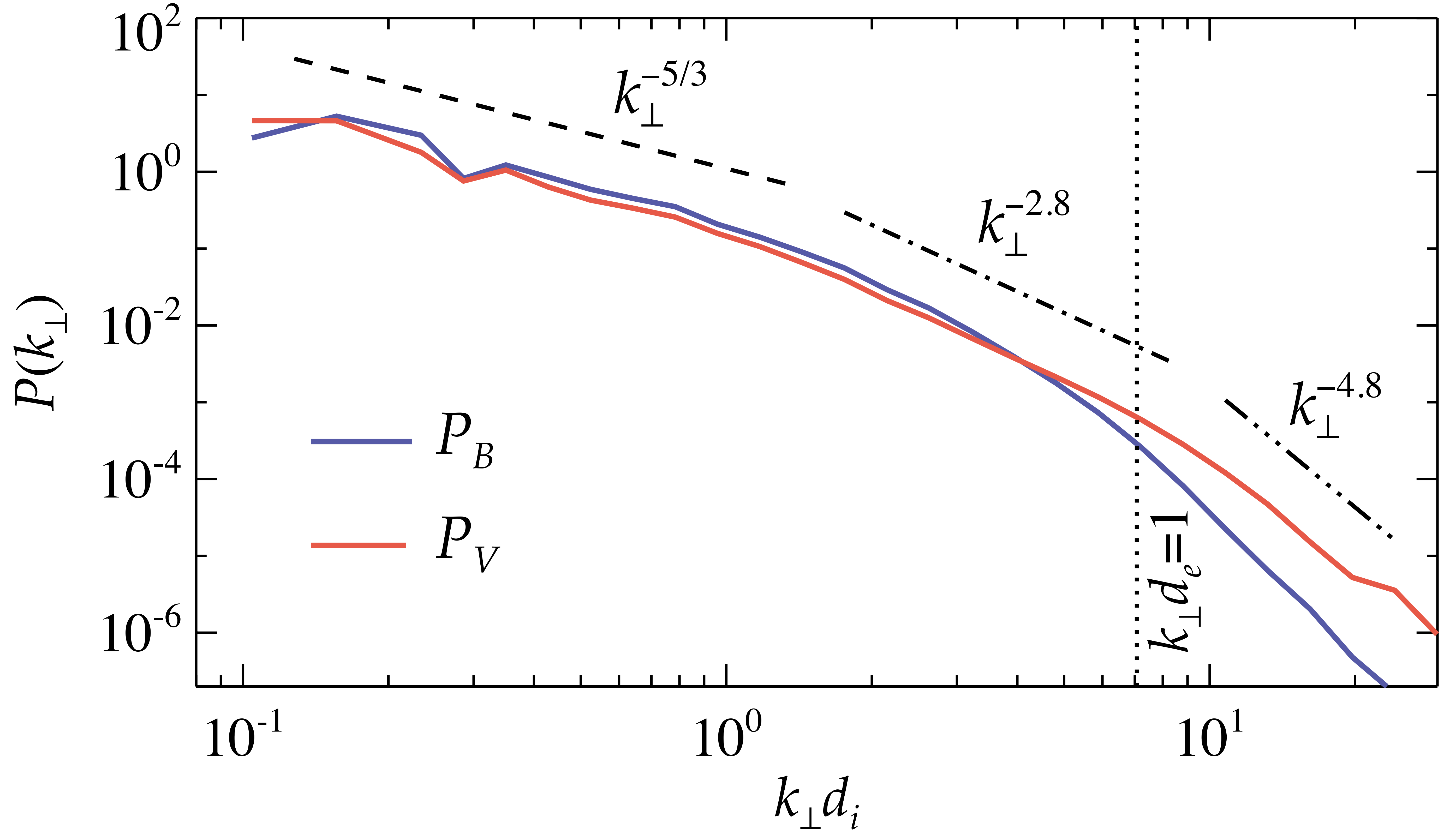
5. In magnetically dominated collisionless plasmas, pitch angle anisotropy is anticipated as the norm rather than the exception

6. Knowledge of both particle energy spectrum and pitch-angle anisotropy is needed to understand the radiation signatures emitted by energized particles

Power spectrum in collisionless plasma turbulence

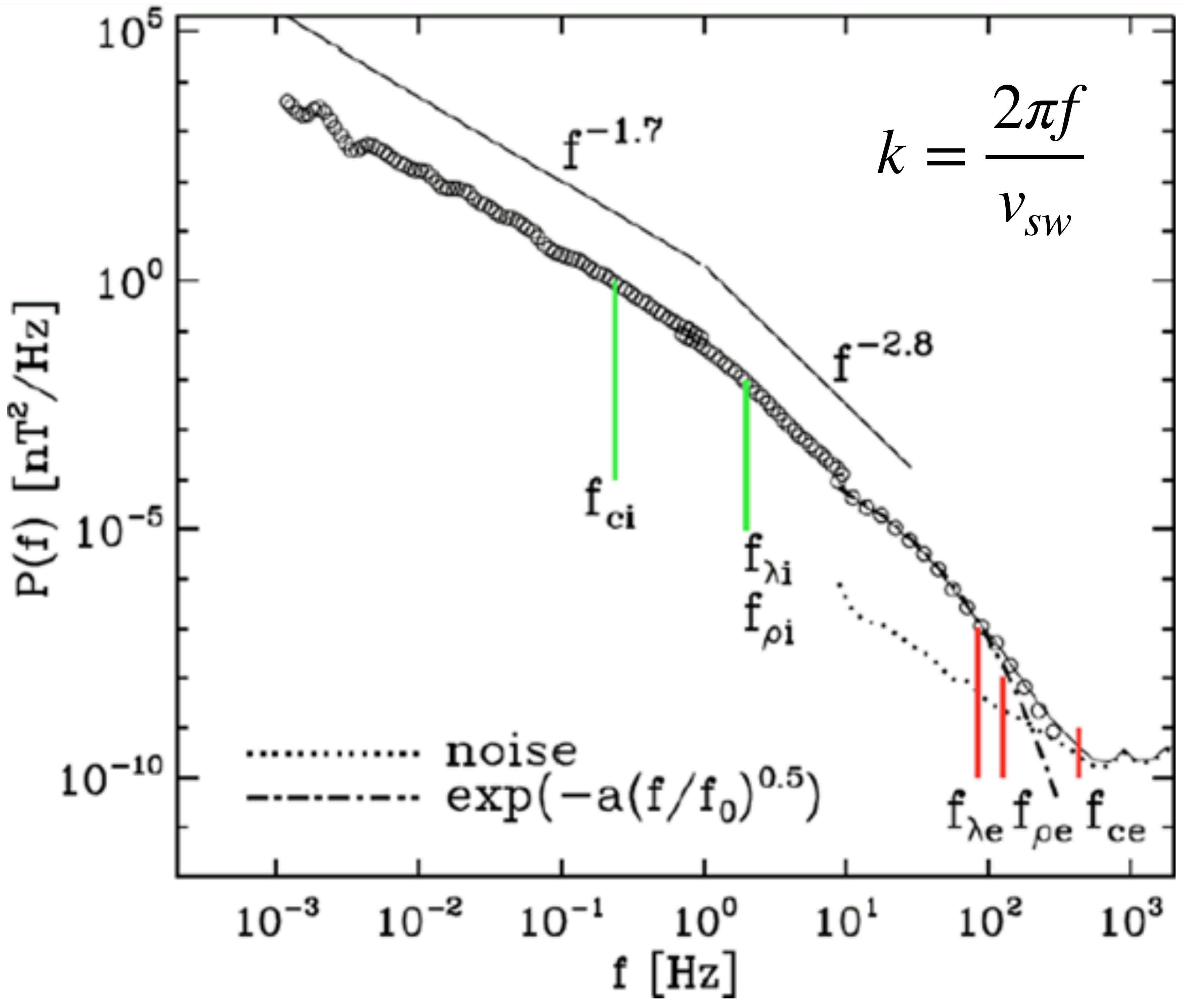
Transition from MHD to kinetic scales:

Power spectra from PIC simulation



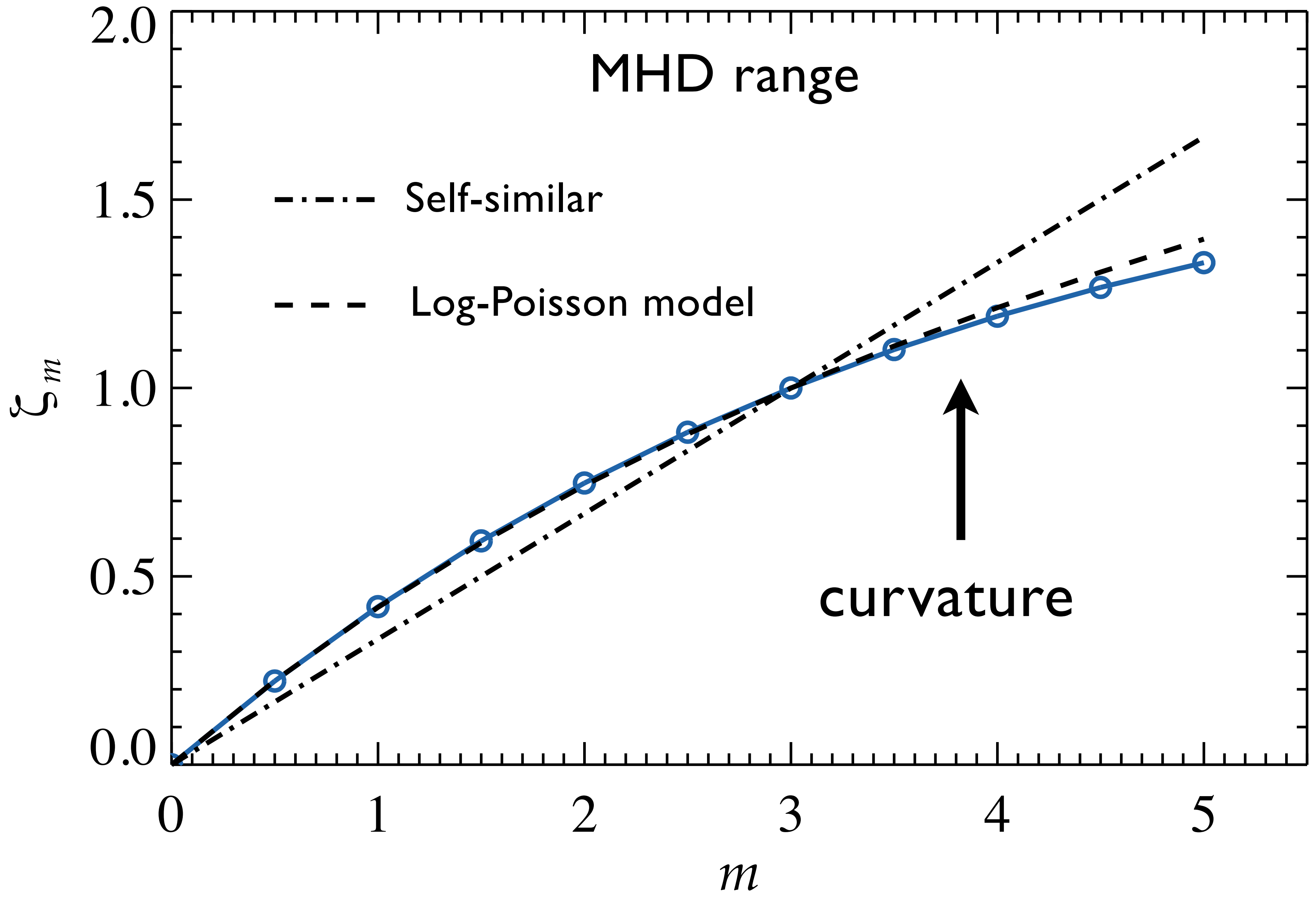
Comisso and Sironi 2022

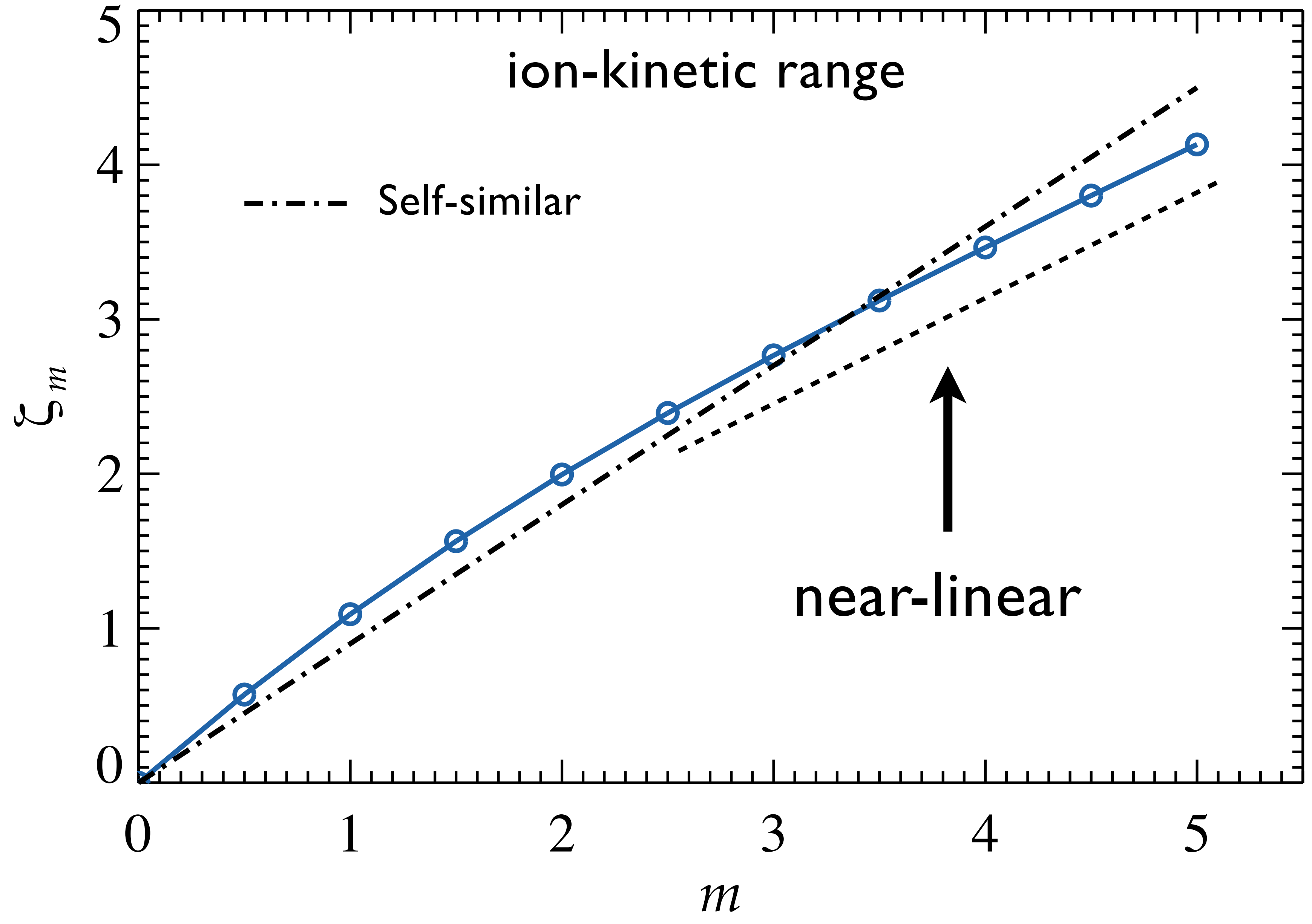
Magnetic power spectrum of solar wind



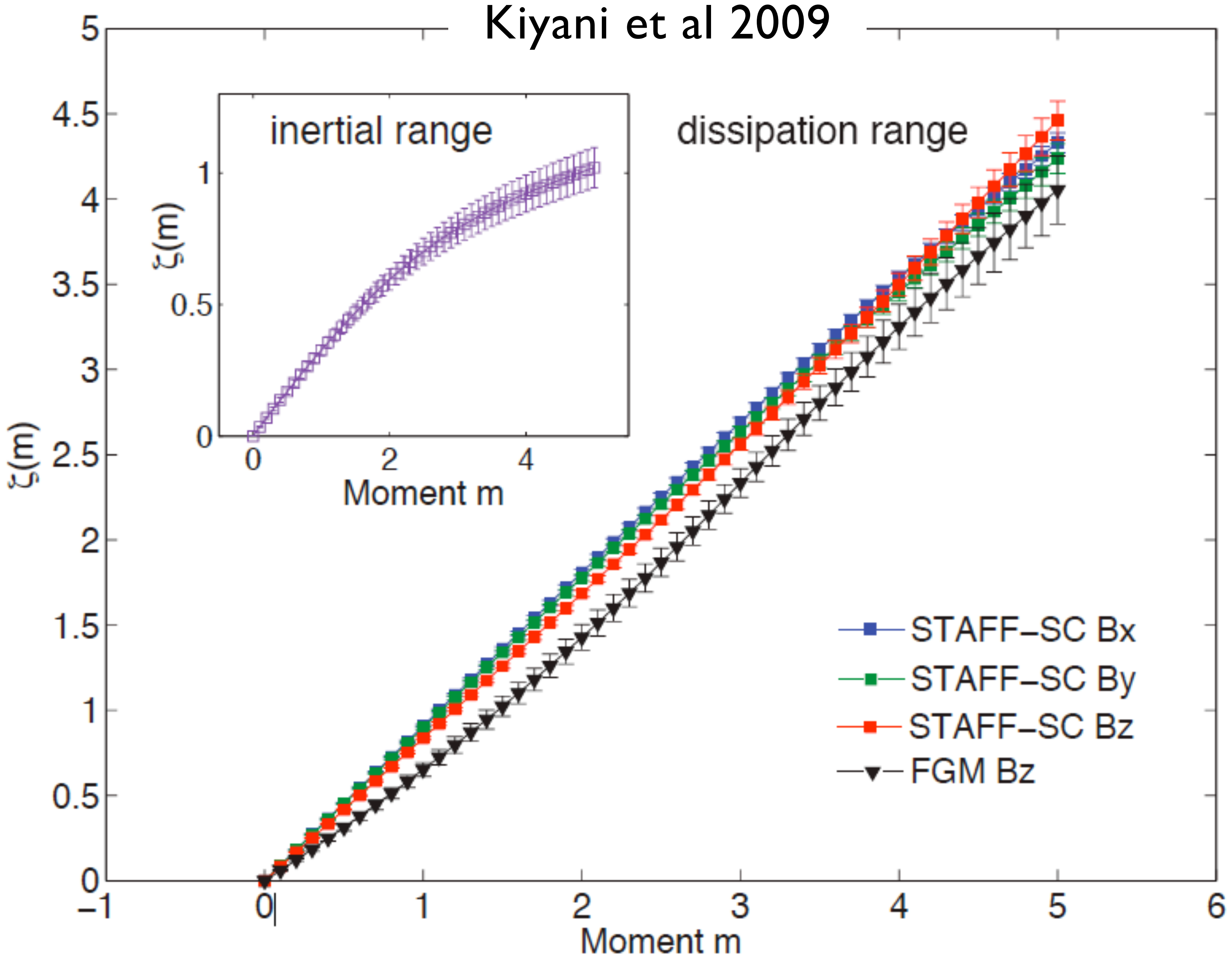
Alexandrova et al. 2013

Intermittency at MHD and kinetic scales





Scaling exponents from the solar wind



From the measure of the scaling exponents

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

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