PRINCETON UNIVERSITY

Toward a Self-Consistent Contribution of Supermassive Black Hole X-ray Coronae to the Diffuse Extragalactic Neutrino Background

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Spitzer Fellow

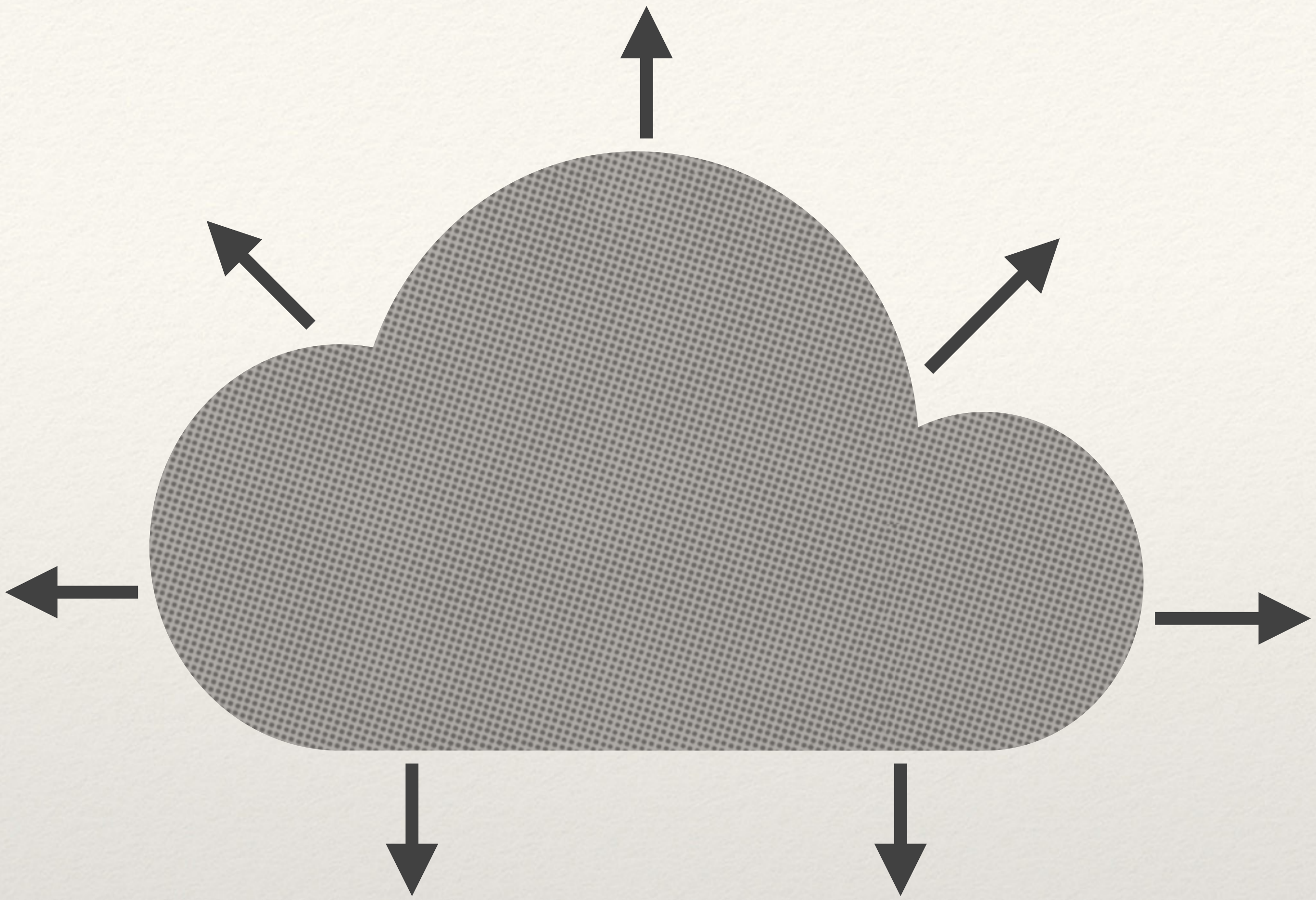
Simulation work in collaboration with:
Alexander Chernoglazov, Daniel Grošelj, Alexander Philippov

Outline

1- Stochastic Acceleration: a turbulent story
2- Connecting turbulent kinetic simulations to neutrino astronomy
3- Implications for the diffuse neutrino signal

Stochastic Acceleration: a turbulent story

Some Definitions



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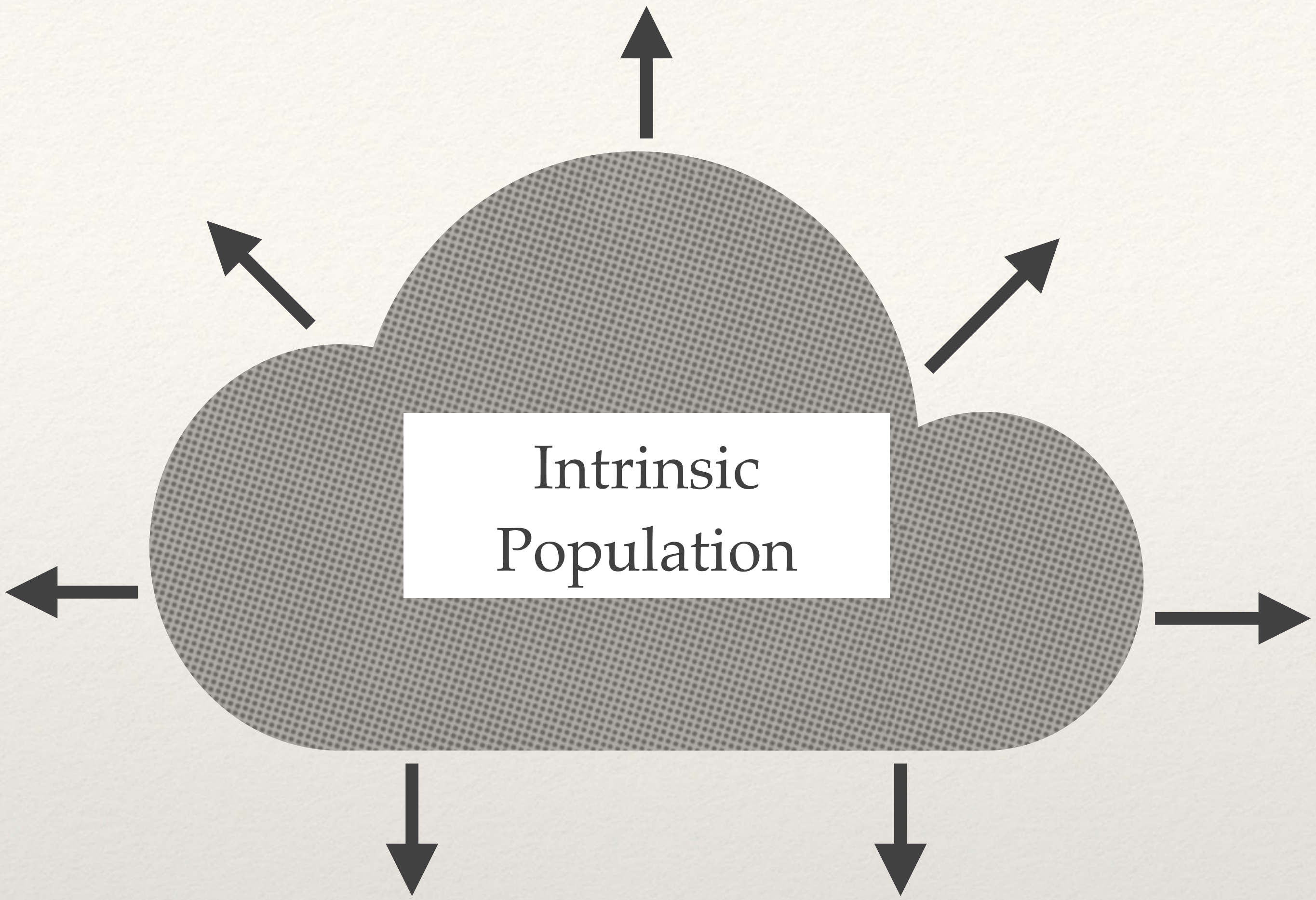

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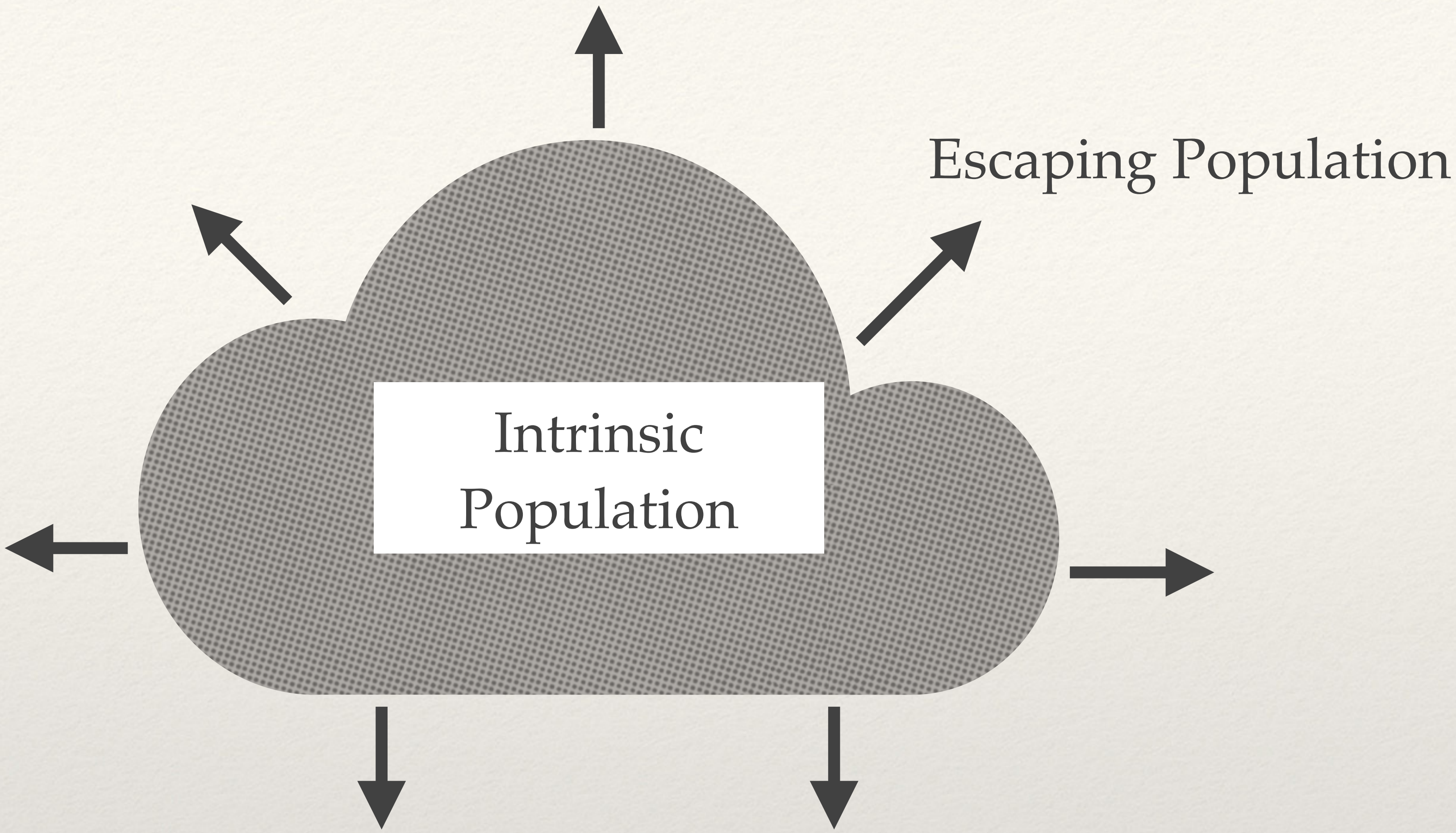

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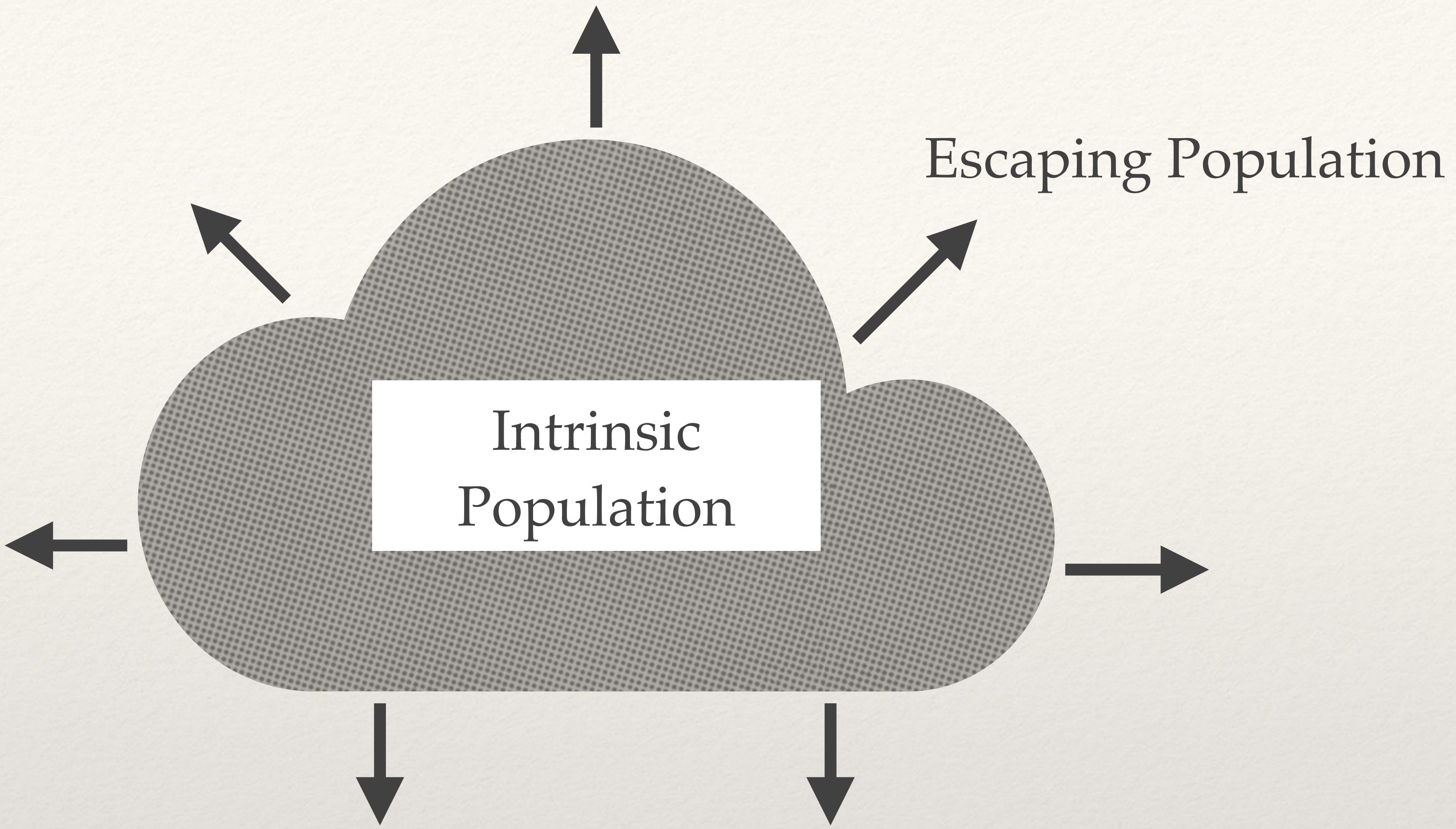

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ℓ_c: coherence length of the magnetic field

$$d_e = \sqrt{\frac{m_e c^2}{4\pi \bar{n}_e e^2}}$$: skin depth of the plasma

$$\sigma = B^2/(4\pi n m c^2)$$

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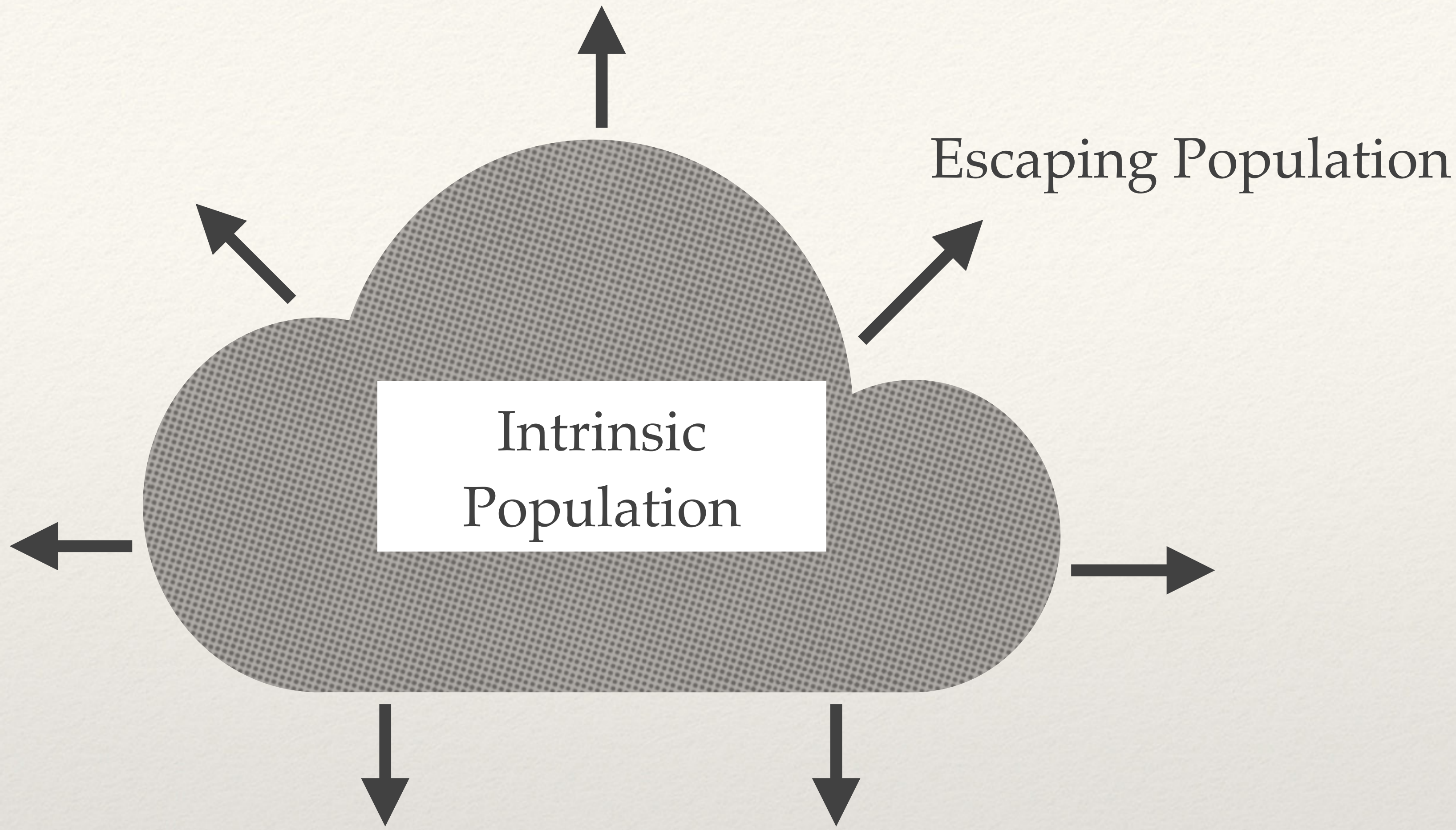

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Maximum achievable power at each scale
(independently derived by *Boldyrev et al. (2026 ApJL)*):

$$E_l^2 \frac{dn_l}{dE_l} \simeq mc^2 \gamma_l n_l \simeq \frac{\bar{n} m}{2} \delta v_l^2 \simeq \frac{\delta B_l^2}{8\pi}$$

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So, we have:

$$\frac{\mathrm{d}n_l}{\mathrm{d}\gamma_l} \simeq \frac{\sigma \bar{n}}{2} \gamma_l^{-2 + \ln \mathcal{P} / \ln \mathcal{G}}$$

Slope of nonthermal intrinsic population in magnetized turbulence

The Acceleration Time:

$$t_{\rm acc} = \frac{\gamma^2}{D_{\gamma\gamma}} = \frac{2\gamma^2 \Delta t}{(\Delta\gamma)^2} \simeq \frac{2\gamma^2}{(\Delta\gamma)^2} \ell_c^{1-r} \mathcal{R}^r \simeq \frac{\pi}{2c} \left(\frac{h + \sigma_p}{\sigma_p} \right) \ell_c^{1-r} \mathcal{R}^r$$

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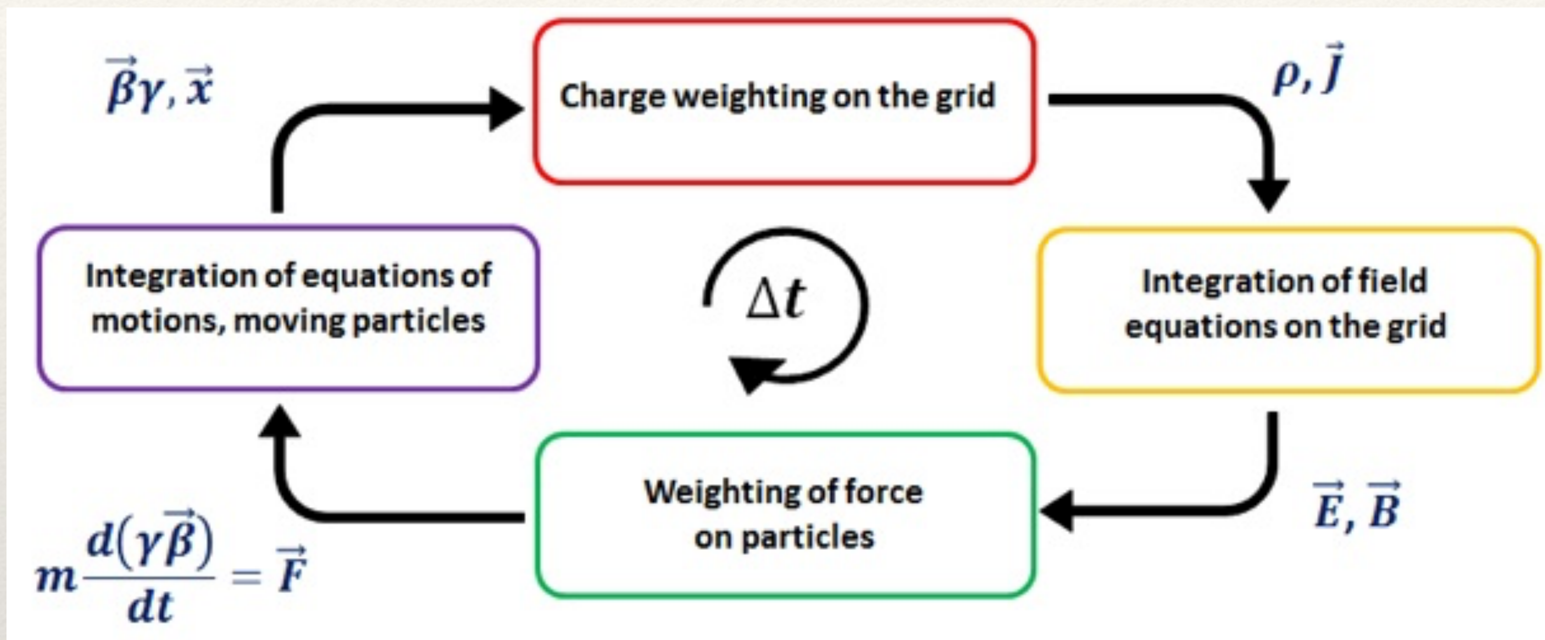
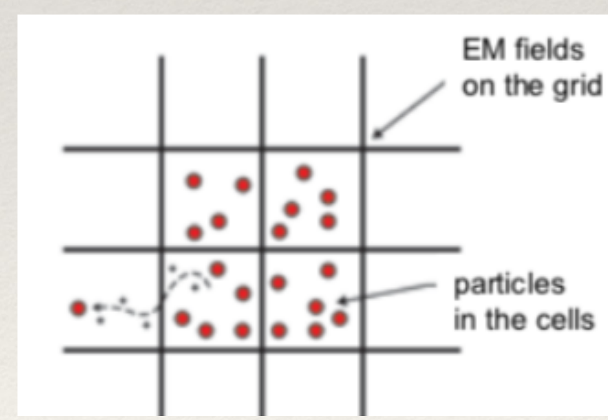
Does this work with Particle-In-Cell (PIC) simulations?

What is PIC? self-consistent simulation of plasma dynamics: systems where fields and particles influence each other dynamically



PIC simulations capture the interplay of charged particles and EM fields



Credit: Alberto Marocchino

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Extracting curvature distributions

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- Simulation Properties
  - 2D driven ion-electron turbulence with mass ratio $m_p/m_e = 5, d_e = 1.5$
  - $\delta B/B = 1$
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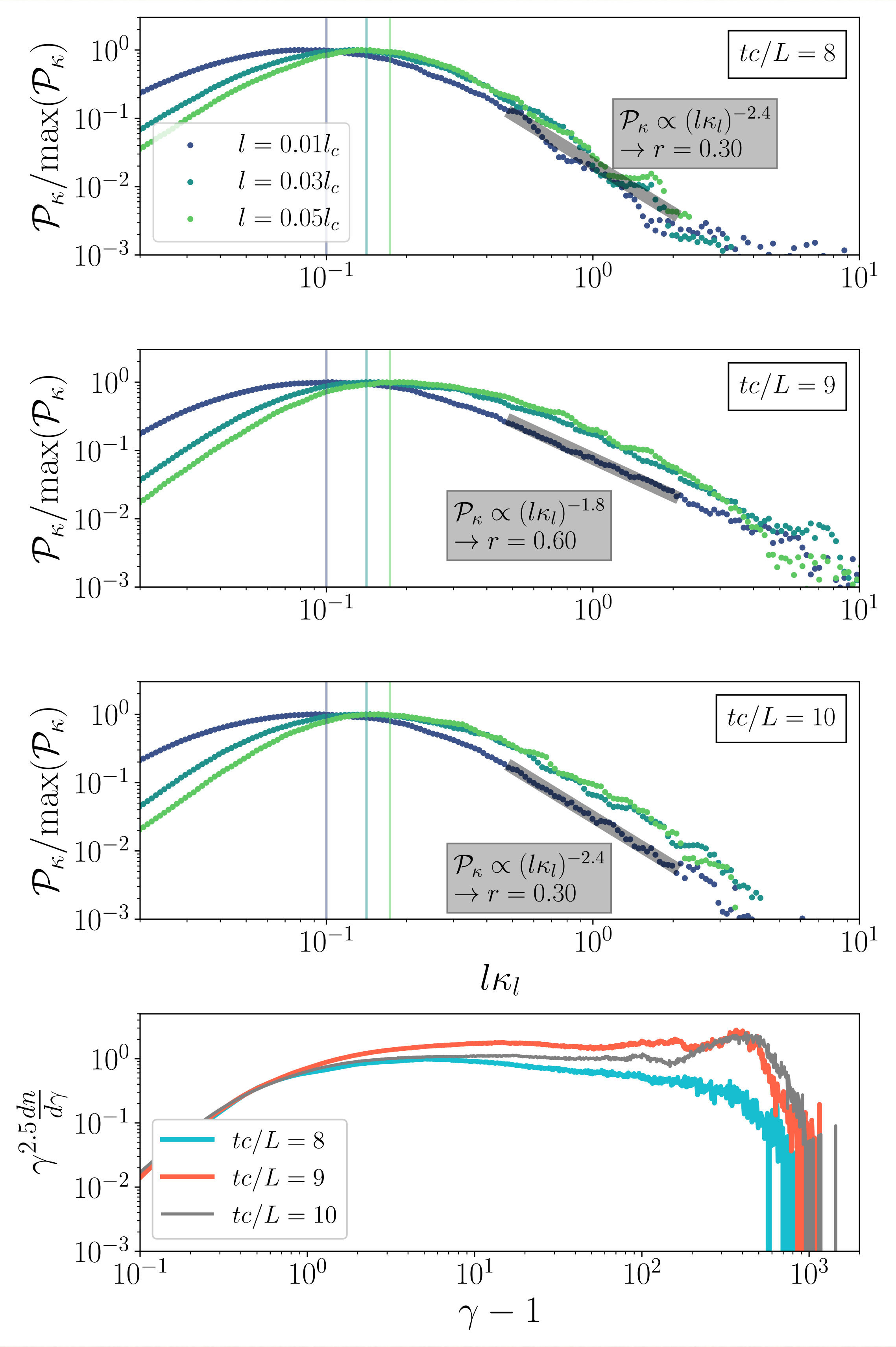

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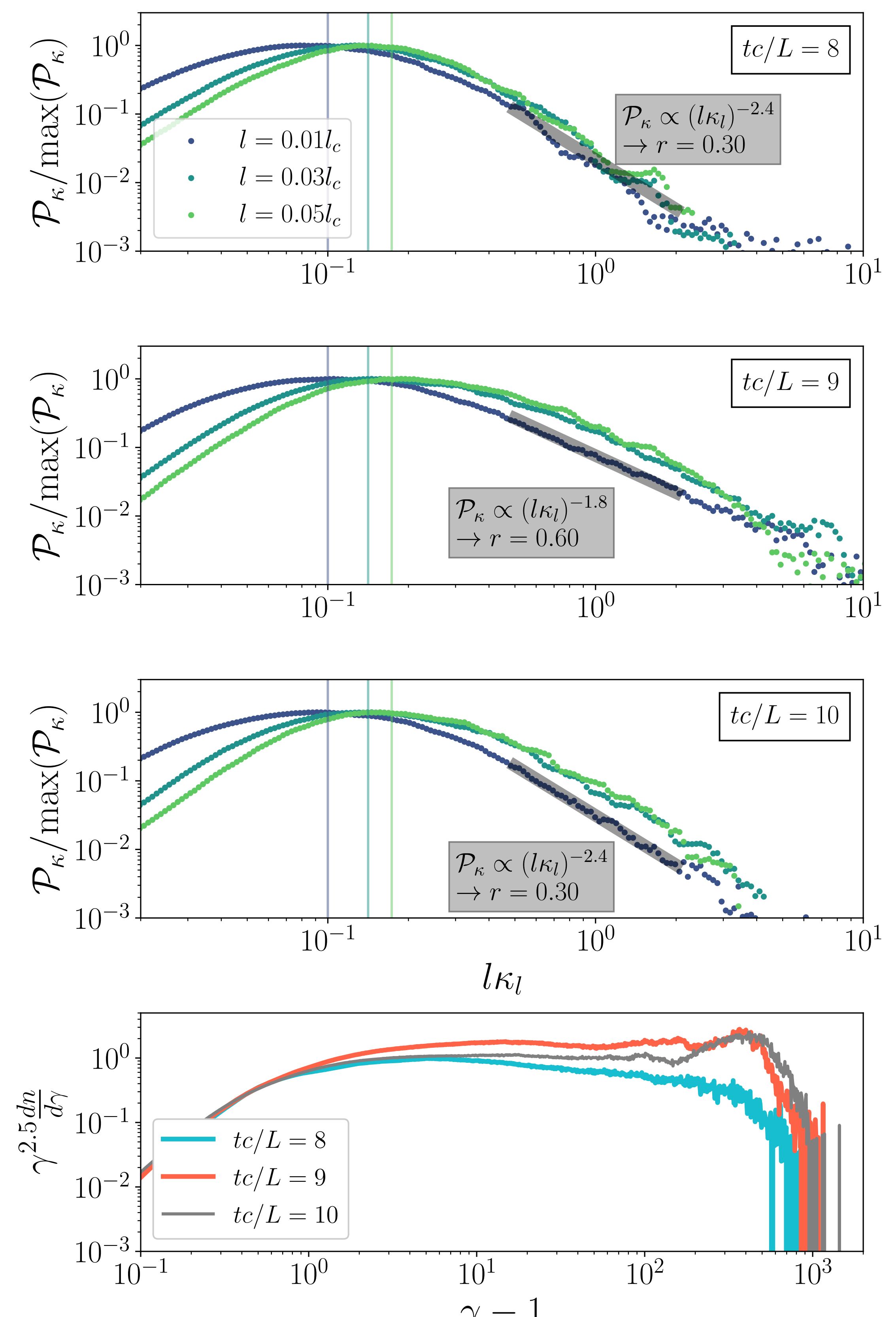

Mbarek et al. (2026 ApJL)

Does this work with PIC?

Extracting curvature distributions

- Simulation Properties
  - 2D driven ion-electron turbulence with mass ratio $m_p/m_e = 5, d_e = 1.5$
  - $\delta B/B = 1$
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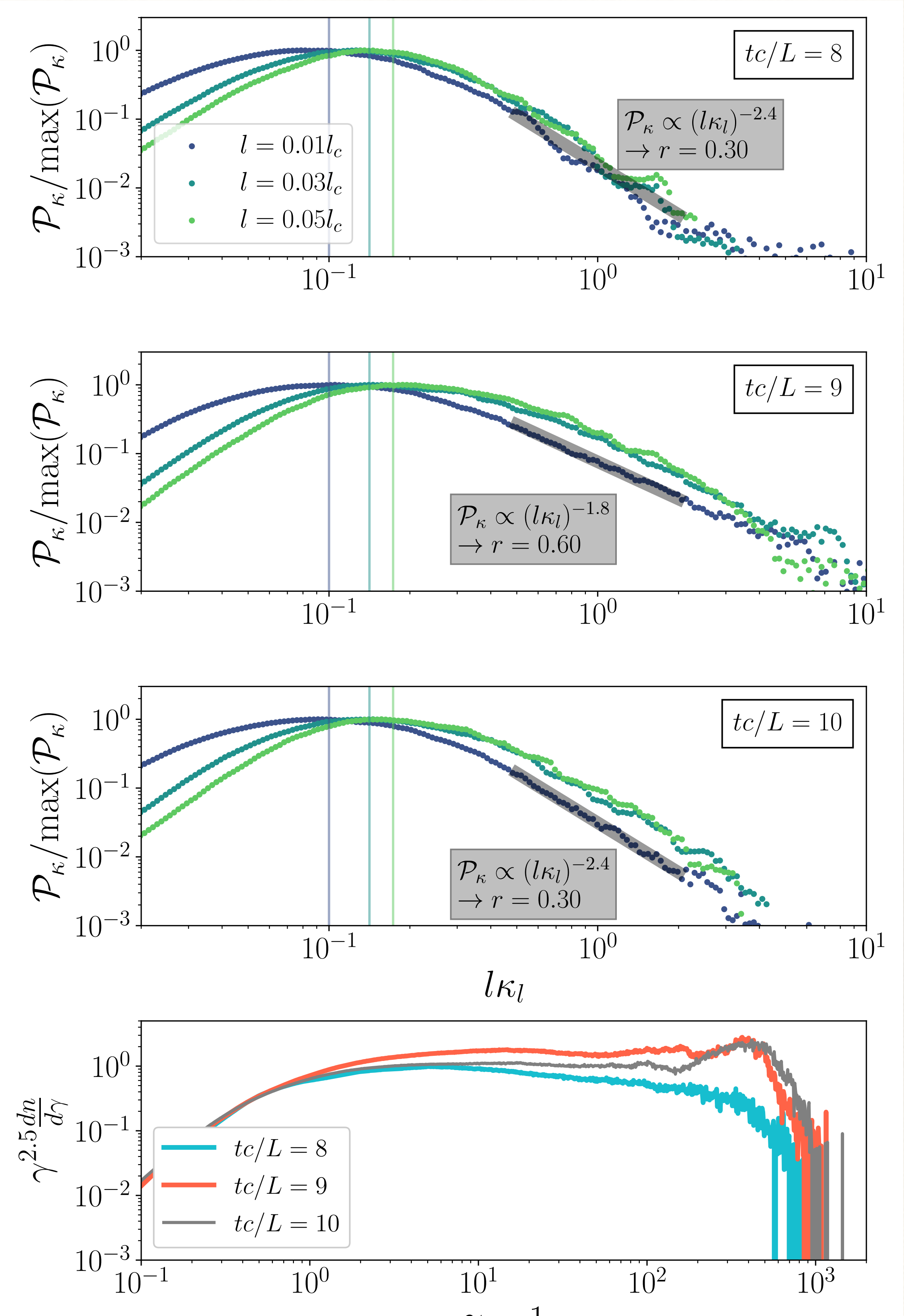

Mbarek et al. (2026 ApJL)

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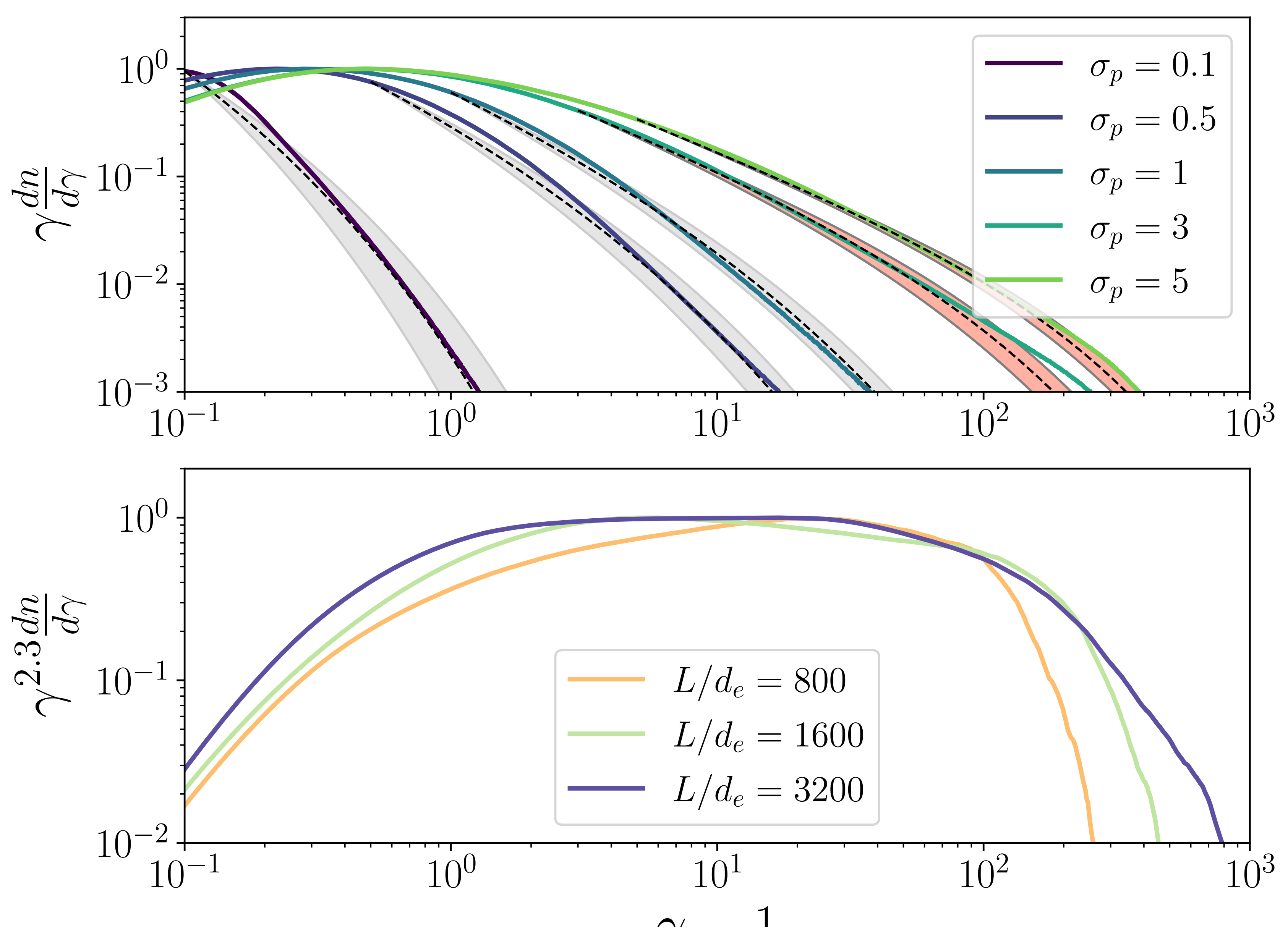


Mbarek et al. (2026 ApJL)

Hints of energy dependence in other PIC work

Diffusion coefficient in decaying turbulence in PIC

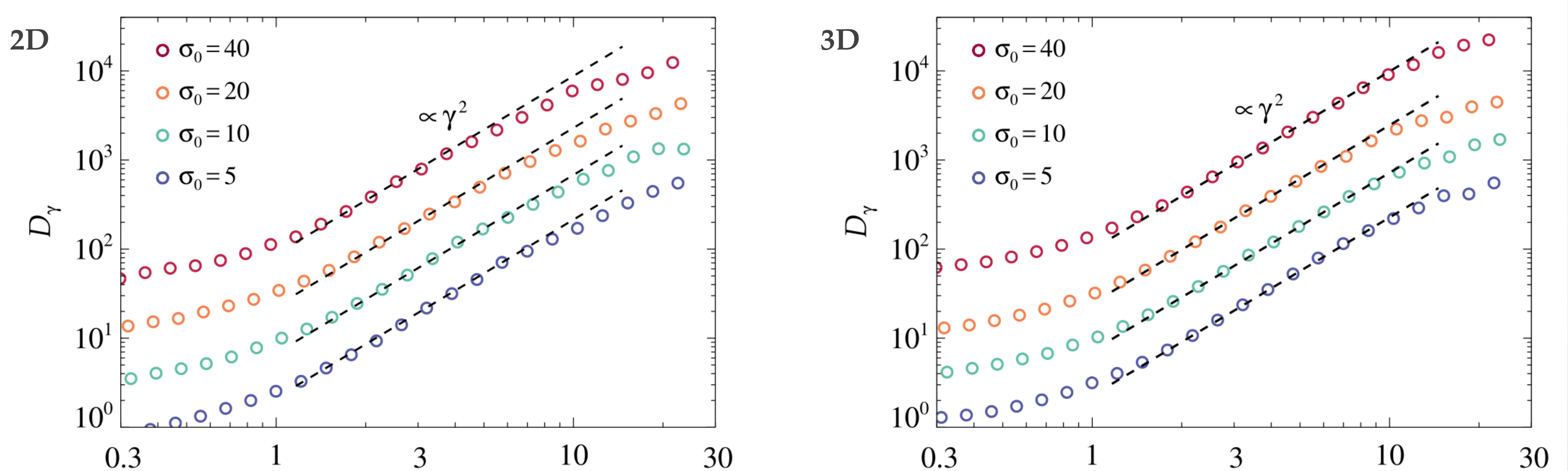


Fig. 25 in Comisso & Sironi (2019)

Diffusion coefficient in driven turbulence in PIC with no escape

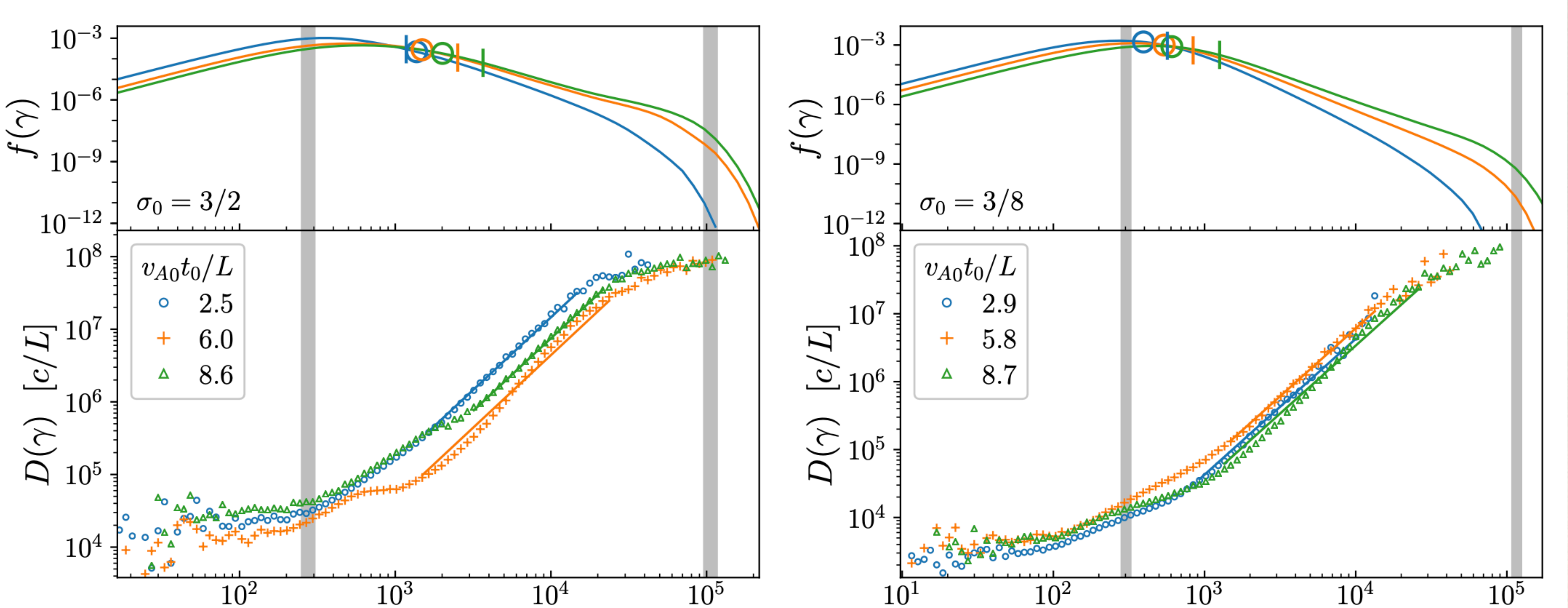
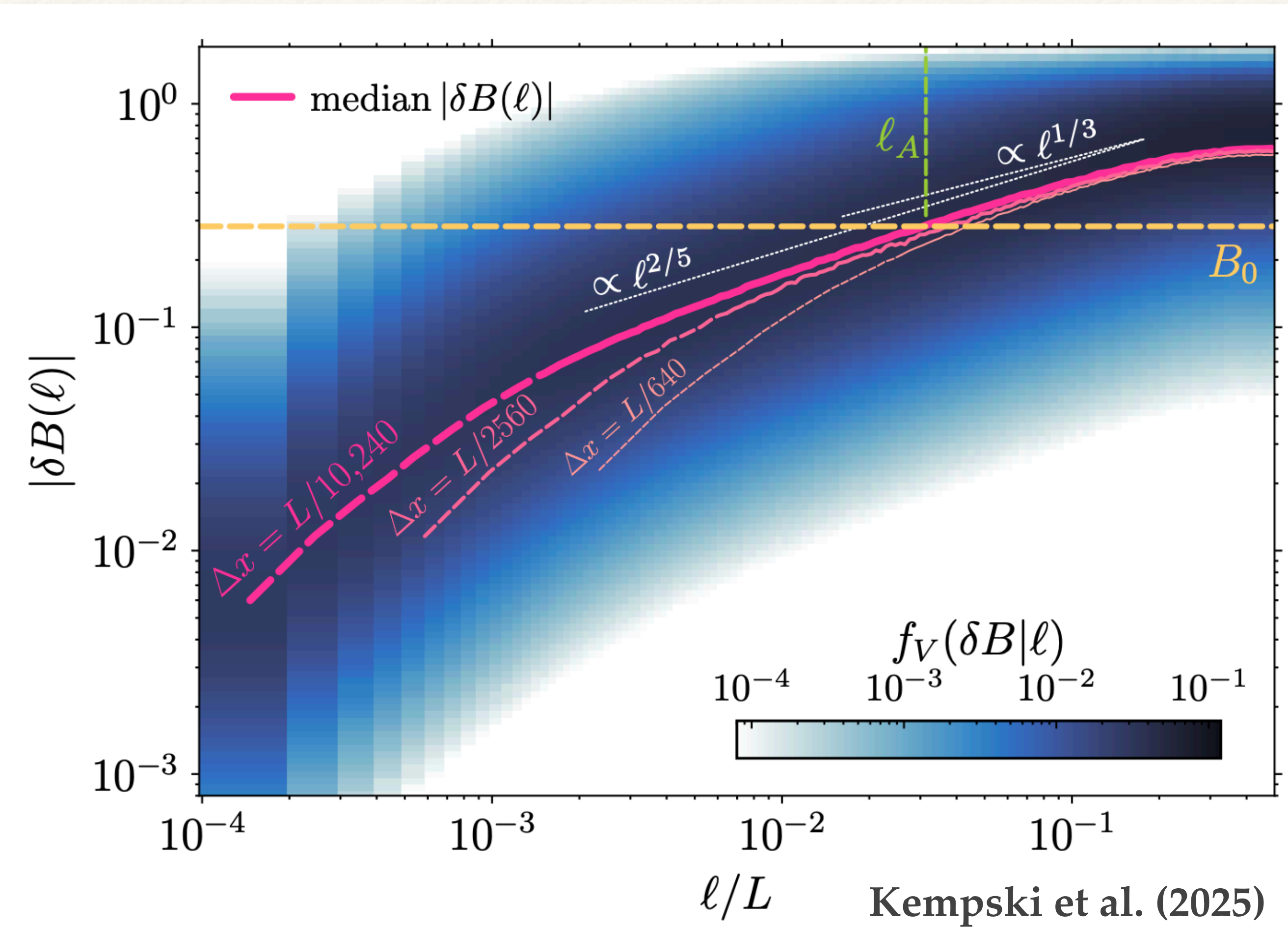
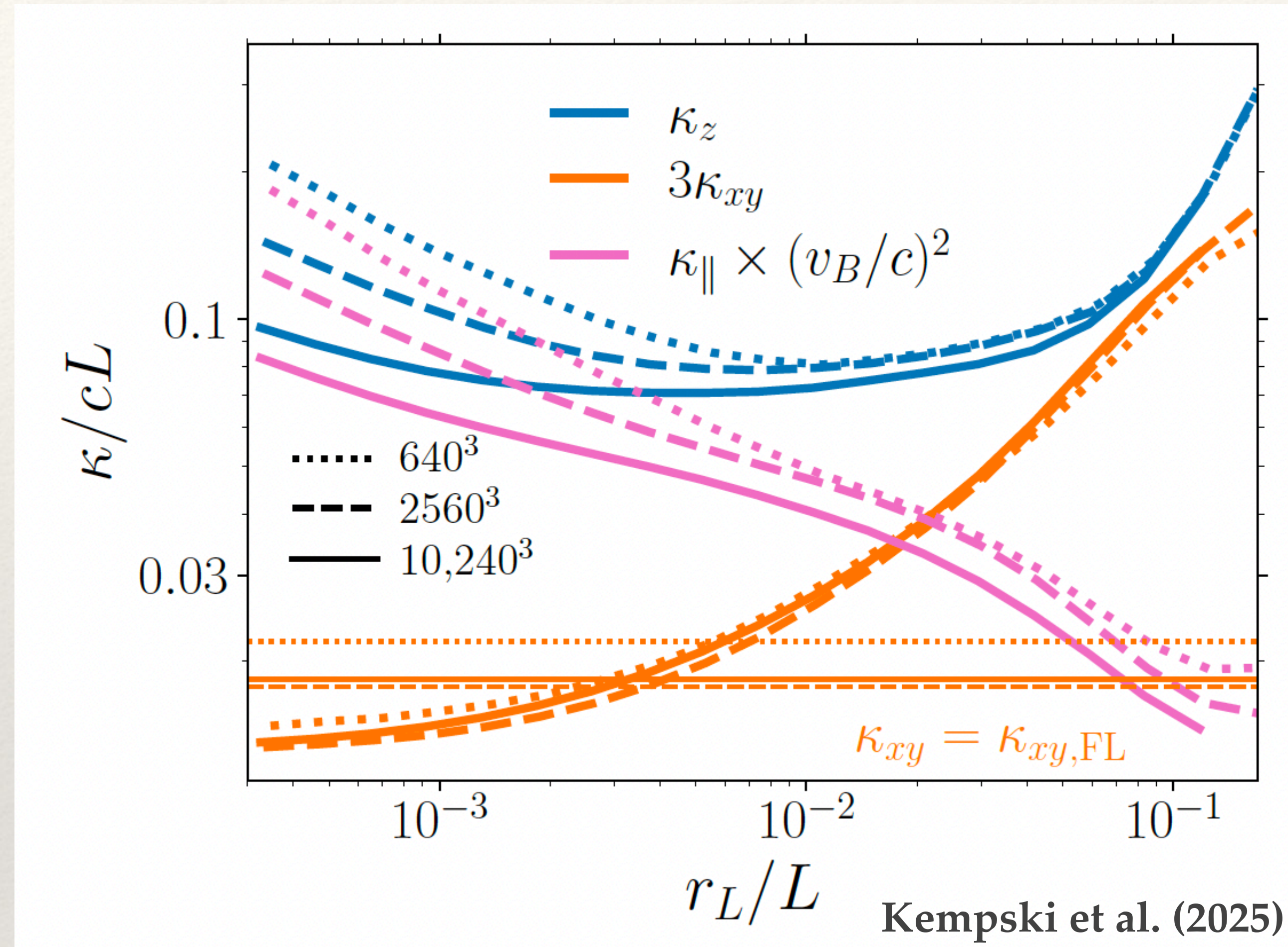


Fig. 14 in Comisso & Sironi (2019)

Hints of energy dependence in other MHD work

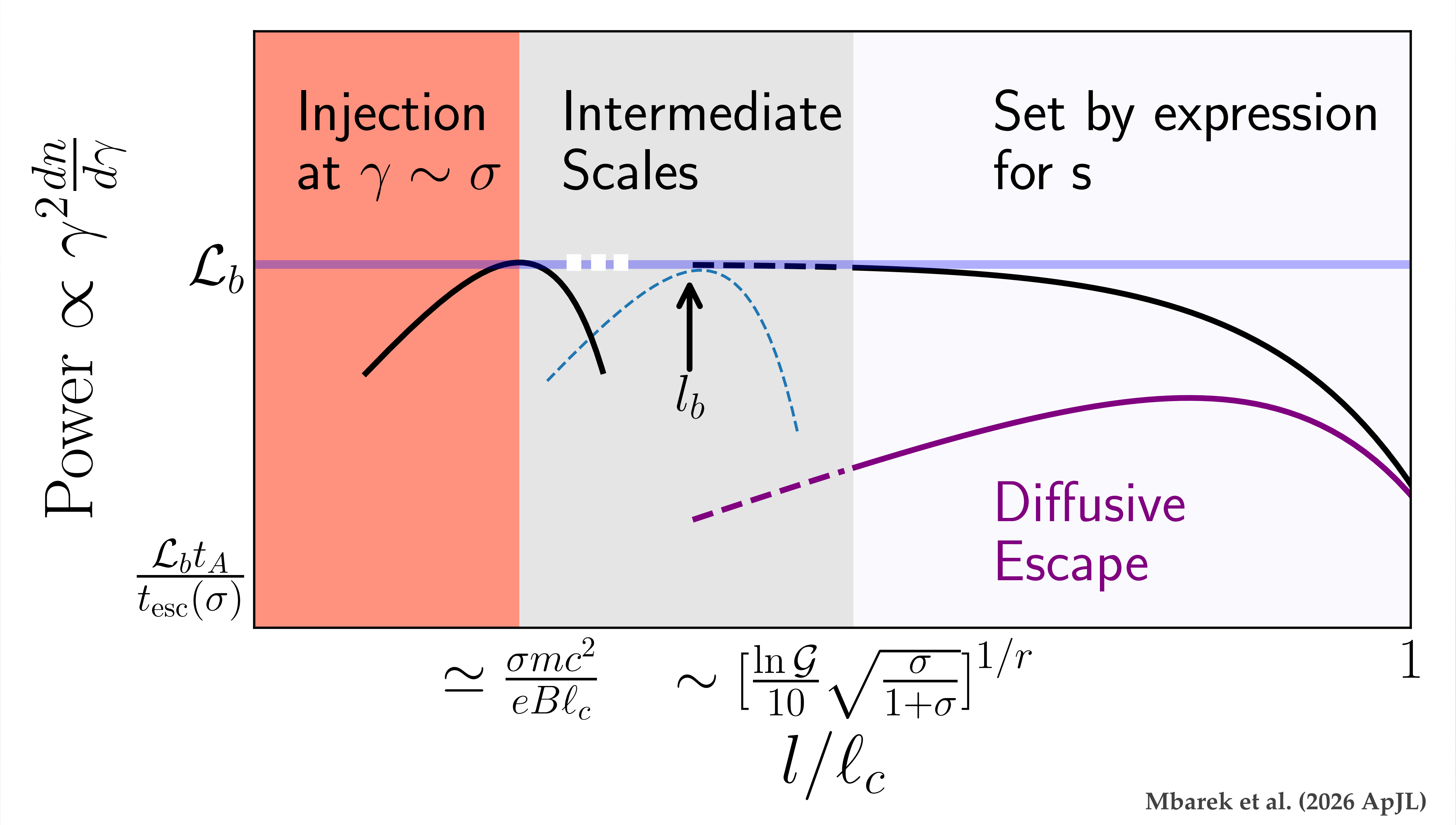




$\delta B/B \sim 1$ can be sustained on scales $\sim L/100$ in a turbulent box of size$L^3 = 10240^3$.

Parallel diffusion coefficient (relevant one is blue here). It shows an energy dependence a factor of 50 below the Hillas limit.

Summary Plot

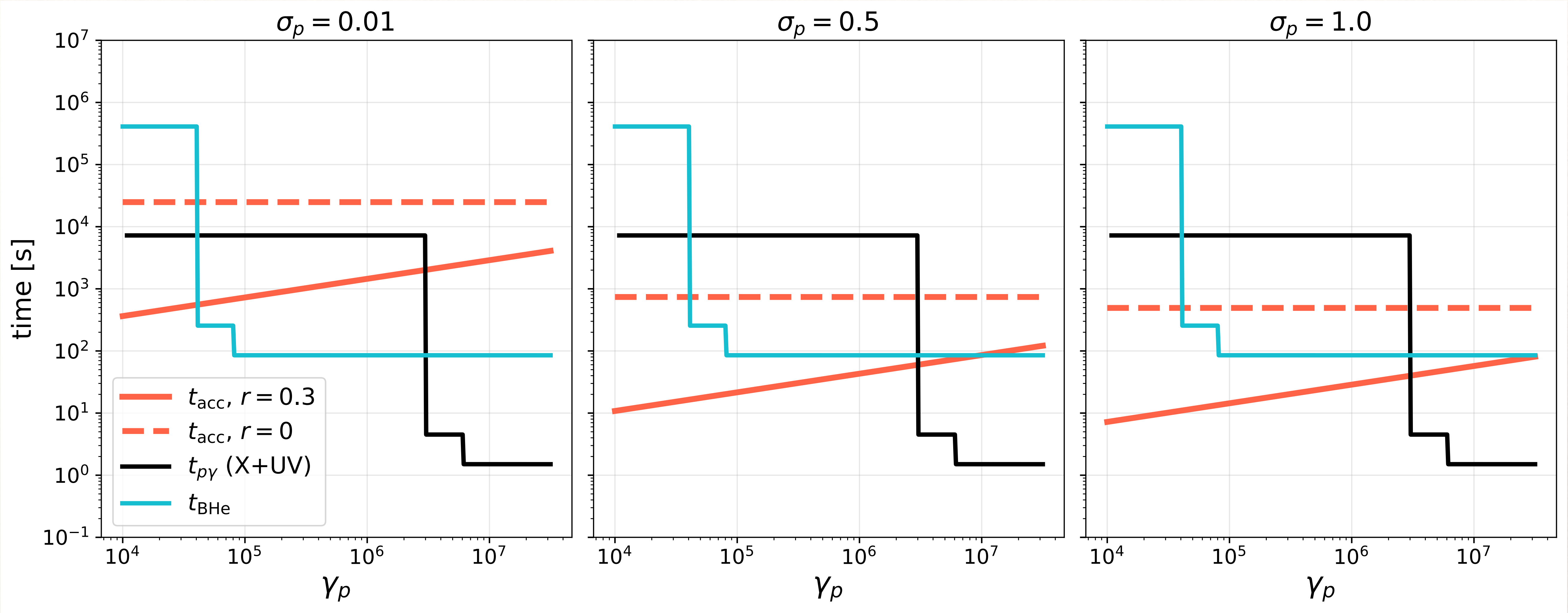


Mbarek et al. (2026 ApJL)

$$s \simeq 2 + \frac{\pi}{2}\sqrt{\frac{h+\sigma_p}{\sigma_p}}\left(\frac{\gamma \frac{m_p}{m_e} d_e}{\sqrt{\sigma_e}\ell_c}\right)^r \frac{1}{\ln \mathcal{G}}$$

Connecting particle acceleration to neutrino astronomy

The magnetization σ_p and energy dependence matter



Example of the impact of the energy dependence at the largest scales. For an X-ray luminosity $L_x = 10^{44}$ erg/s and $M_\bullet = 10^7 M_\odot$. The UV luminosity is obtained based on the α_{ox} relation

Astrophysical Implications: NGC 1068 corona

- The proton density in the corona above is

$$n_p(\gamma_p) \simeq \bar{n}_p \Big[\frac{\gamma_p}{\sigma_p}\Big]^{-s+1} \text{ with } \quad s \simeq 2 + \frac{\pi}{2}\sqrt{\frac{1+\sigma_p}{\sigma_p}} \Big[\frac{\gamma \frac{m_p}{m_e} d_e}{\sqrt{\sigma_e}\ell_c}\Big]^r \frac{1}{\ln \mathcal{G}}$$

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$\simeq 0.3 - 0.5$

$\sigma_p \sim 1$ (Mbarek et al. (2024))

$\ell_c \sim r_g$ (Mbarek et al. (2024))

$\mathcal{G} \simeq 3$ (Vega et al. (2024))

+ The skin depth is $d_e = \sqrt{\dfrac{m_e c^2}{4\pi \bar{n}_e e^2}}$; $\bar{n}_e \simeq \tau/(\sigma_T r_c)$; $\tau \sim 1$, and $r_c = 10 r_g$

+ $\bar{n}_p$ is such that $\bar{n}_p \sigma_p = \sigma_e \dfrac{m_e \bar{n}_e}{m_p} = \dfrac{2\ell}{\tau}\dfrac{U_\mathrm{B}}{U_\mathrm{x}}\dfrac{m_e \bar{n}_e}{m_p}$

+ If turbulence drives X-ray production with a moderate coronal optical depth $\tau \sim 1$, we expect $U_\mathrm{x} \sim 2U_B$ (Grošelj et al. 2024)

+ so basically, $\bar{n}_p \simeq U_\mathrm{x}/(m_p c^2)$

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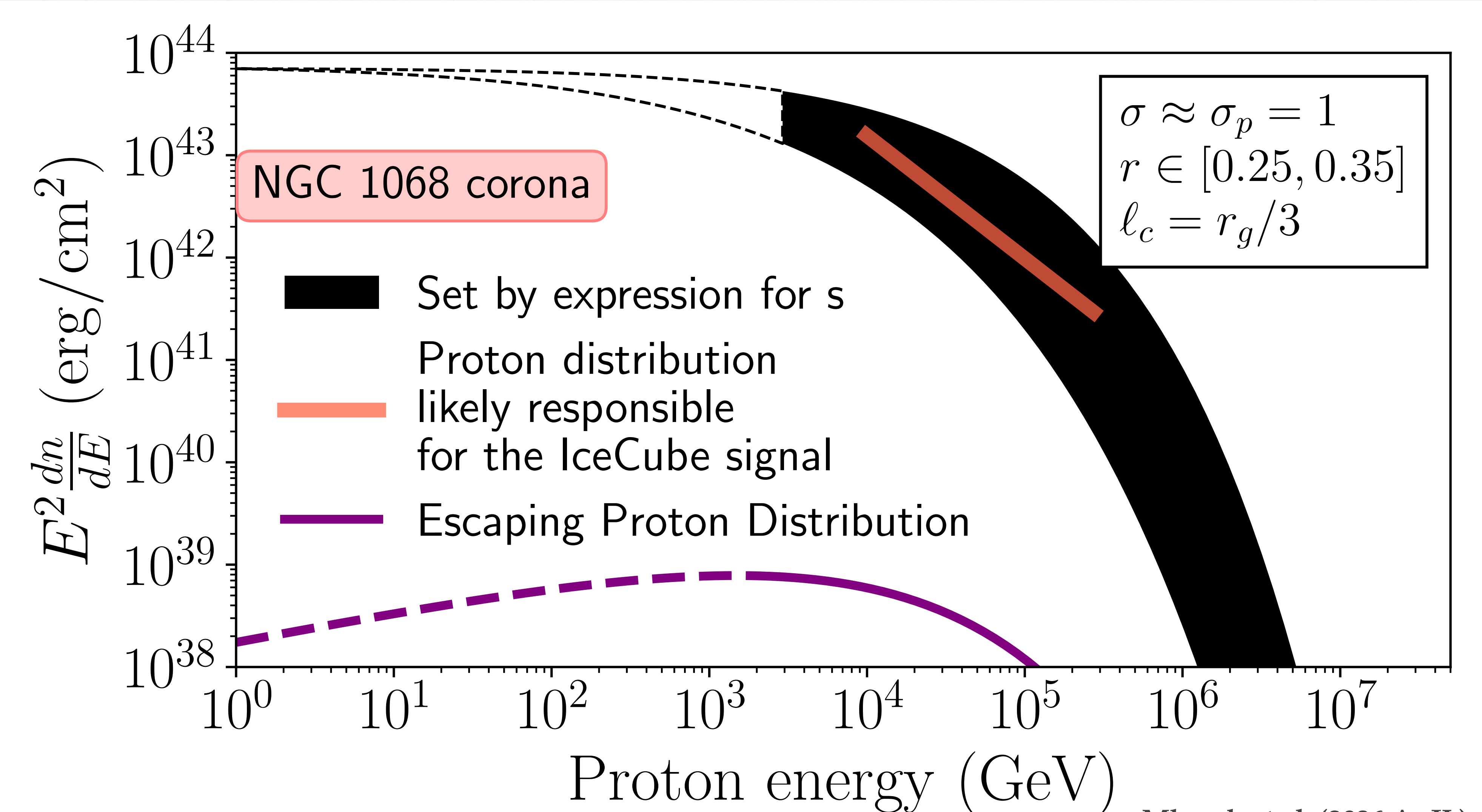

Mbarek et al. (2026 ApJL)

Implications for the diffuse neutrino signal

Obtain a galaxy-dependent Coronal Neutrino Luminosity

The Neutrino Luminosity: $L_\nu(\alpha E_p) \simeq \frac{3\pi}{2} c r_c^2 t_{\mathrm{diff}} t_{p\gamma}^{-1} E_p^2 \frac{dn_p}{dE_p}$

Put everything together:

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Mbarek (2026 PRD)

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Put everything together:

If $t_{\rm diff} t_{p\gamma}^{-1} < 1$:

Mbarek (2026 PRD)

$$L_\nu(\geq E_\nu^{\rm m}) \simeq \frac{C(r)}{\sigma_p^{1+r}\zeta^{1-r}} \left(\frac{10^7 M_\odot}{M_\bullet}\right) \left(\frac{L_{\rm x}}{10^{44}\,{\rm erg\,s^{-1}}}\right)^{1+r/2} \left(\frac{\gamma_p}{\sigma_p}\right)^{-s+2-r} \begin{cases} f_{\rm BHe}^{\rm x} \frac{L_{\rm x}}{\epsilon_0}, & \textbf{if } \frac{\bar\epsilon_{\rm th}}{2\epsilon_0} < \gamma_p < \frac{\bar\epsilon_{\rm th}}{2\epsilon_1} \\ f_{\rm BHe}^{\rm x+UV} \left[\frac{L_{\rm x}}{\epsilon_0} + \frac{L_{\rm UV}}{(r_{\rm UV}/r_c)^2 \epsilon_1}\right], & \textbf{if } \frac{\bar\epsilon_{\rm th}}{2\epsilon_1} < \gamma_p \end{cases}$$

$$\textbf{with } C(r) = \frac{\xi \sigma_{\rm eff} L_{x,0}}{8\pi c r_{g,0}} \left[\frac{e}{10 m_p}\sqrt{\frac{2L_{x,0}}{c^5}}\right]^r \approx (4\times 10^{-9})(3\times 10^9)^r \ \text{erg}$$

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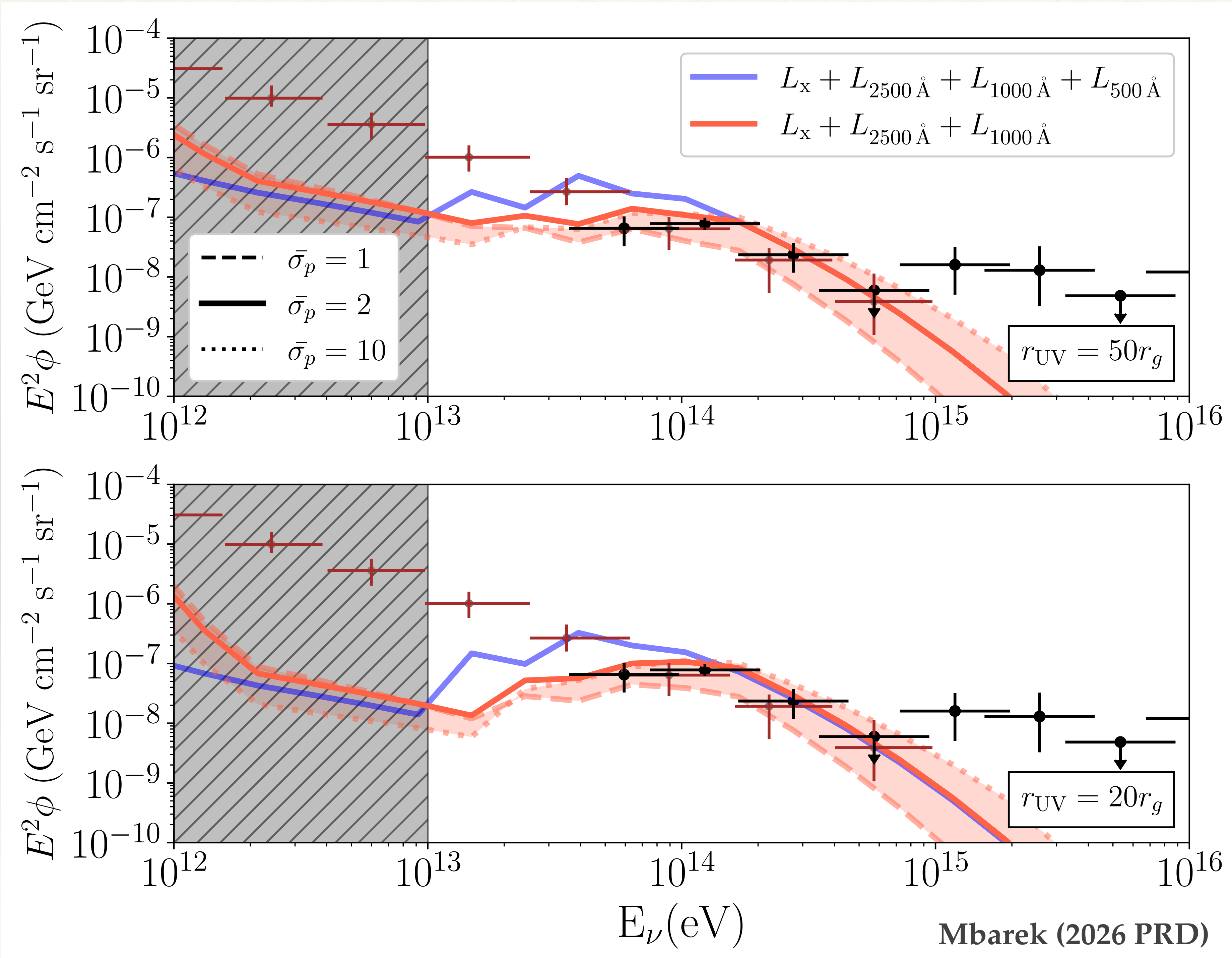
If $t_{\rm esc} t_{p\gamma}^{-1} = 1$:

$$L_\nu(E_\nu \geq E_\nu^{\rm m}) \simeq \frac{3L_{\rm x}}{4} \frac{f_{\rm BHe}}{\sigma_p} \left(\frac{\gamma_p}{\sigma_p}\right)^{-s+2} \simeq 8\times 10^{43} \frac{L_{\rm x}}{10^{44}{\rm erg/s}} \frac{f_{\rm BHe}}{\sigma_p} \left(\frac{\gamma_p}{\sigma_p}\right)^{-s+2}$$

Integrate cosmologically, and obtain the neutrino diffuse Flux

$$\mathscr{F}(E_\nu) = \frac{c}{4\pi}\int_0^{z_{\max}} \frac{dz}{H(z)} \int_{L_{\min}}^{L_{\max}} dL_{\mathrm{x}} \frac{d\rho}{dL_{\mathrm{x}}}(L_{\mathrm{x}}, z) \times L_\nu[\frac{(1+z)E_\nu}{\alpha m_p c^2}, L_{\mathrm{x}}, \bar{M}_\bullet(z)]$$



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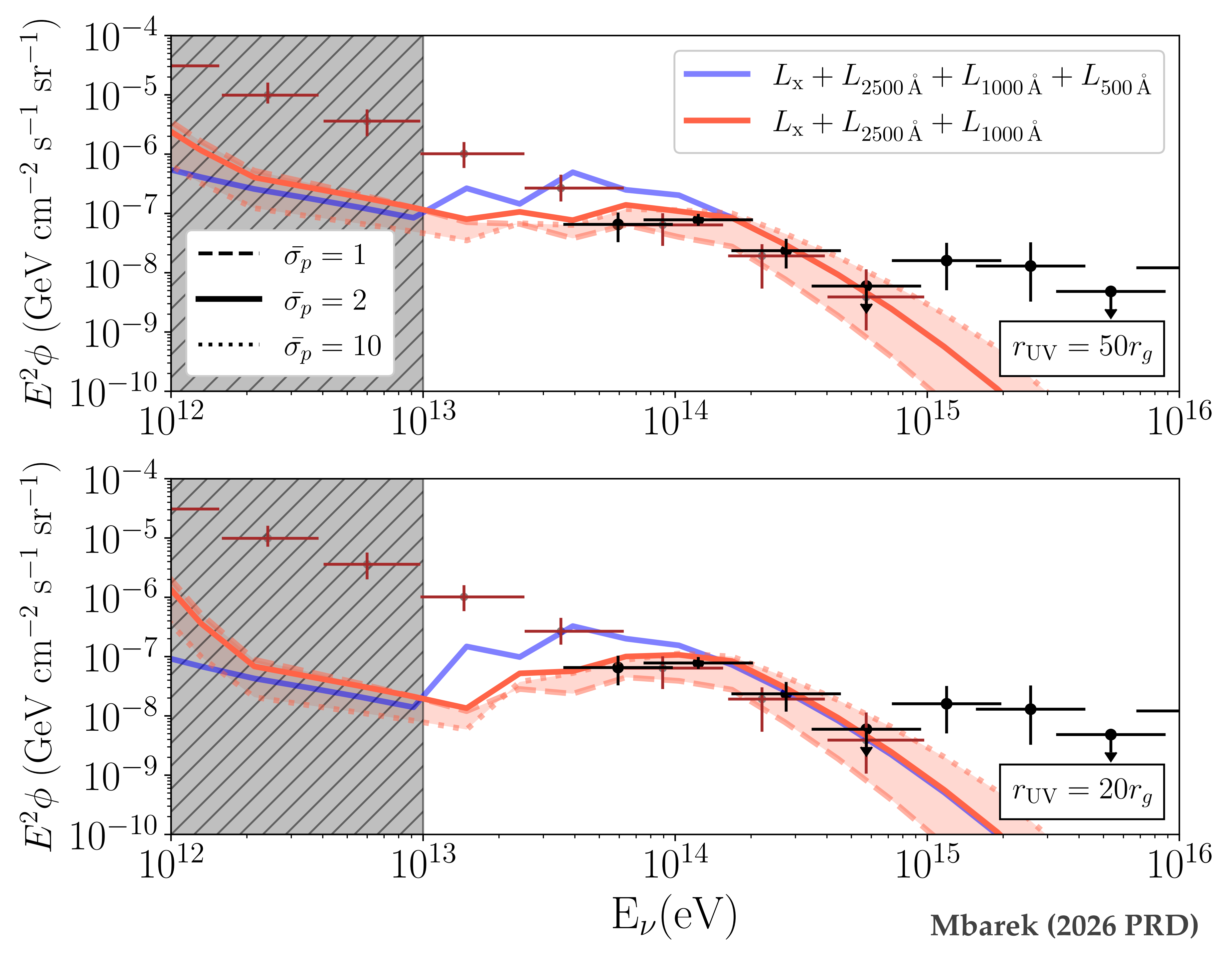
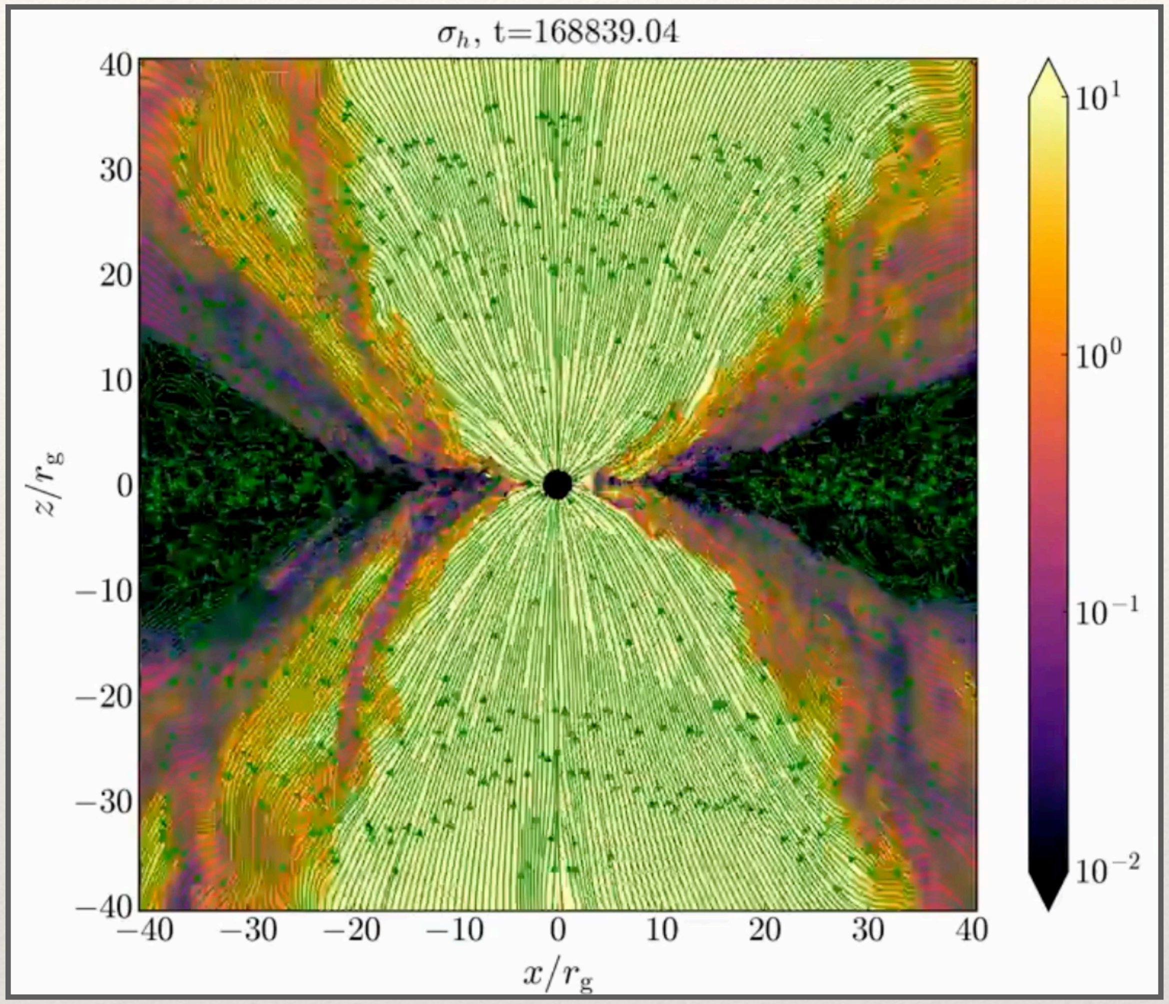


Mbarek (2026 PRD)

- Implications
  - The theoretical neutrino spectrum fits the diffuse one below PeV for fiducial plasma values
  - L_ν depends mostly on L_x and σ_p → the diffuse flux should statistically trace the extragalactic X-ray background
  - The dominant uncertainties are σ_p and ℓ_c: reducing these uncertainties is intrinsically a multi-community problem
  - Potentially: Probing Obscured far UV with neutrinos

Diffusive escape might not be enough, but!



credit: Musoke

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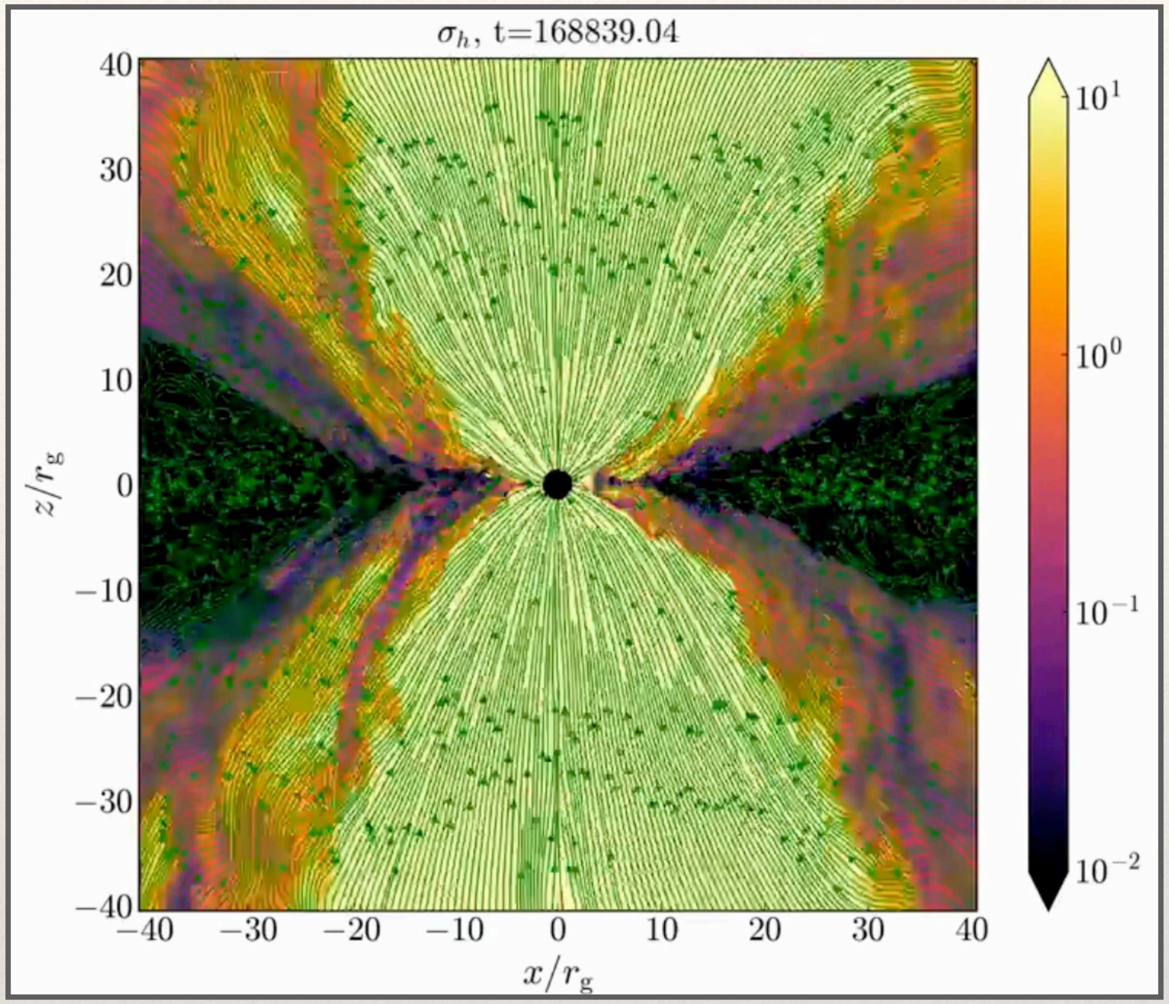

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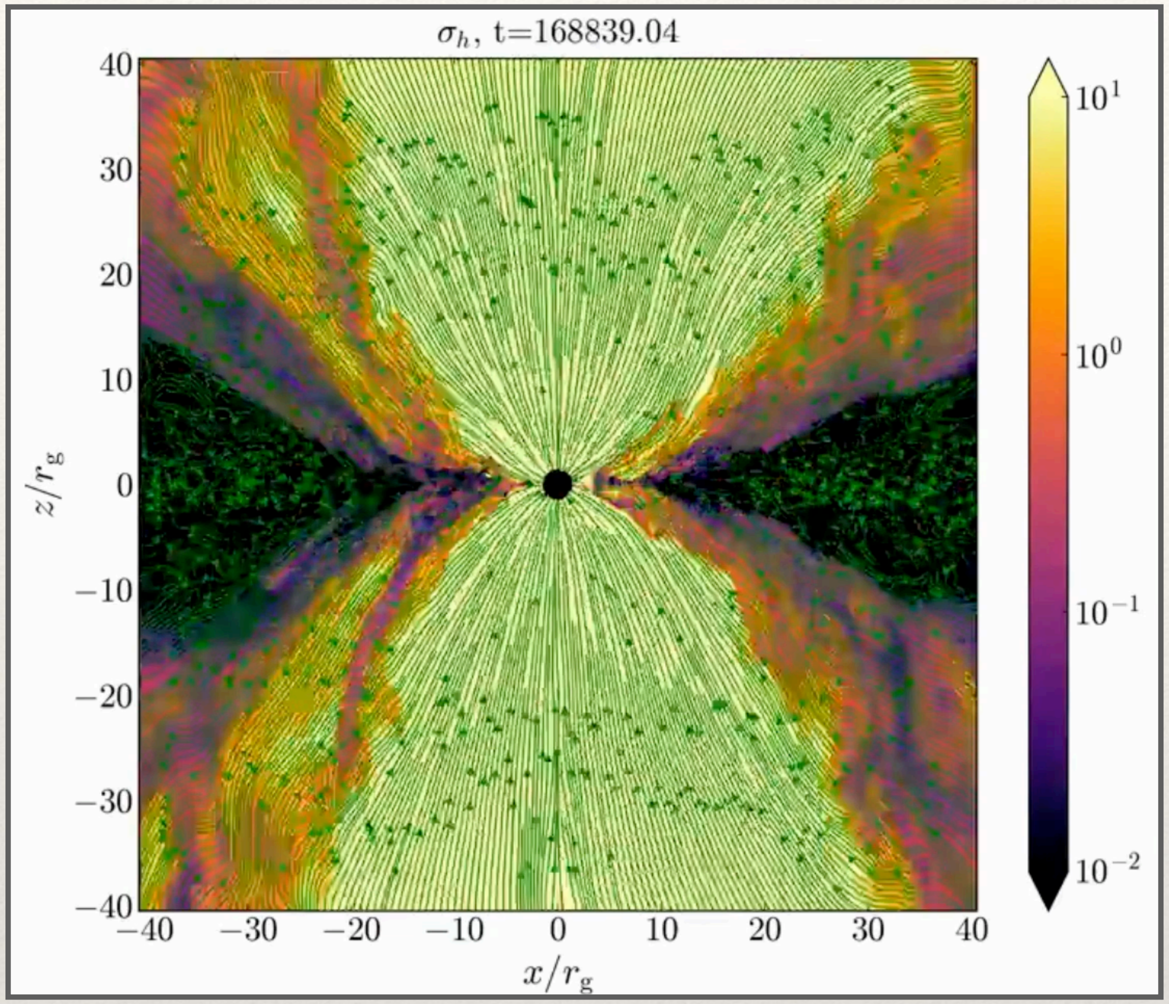

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GRMHD simulation of the inner black hole region (Whatever the corona is) favor a poloidal field-line structure

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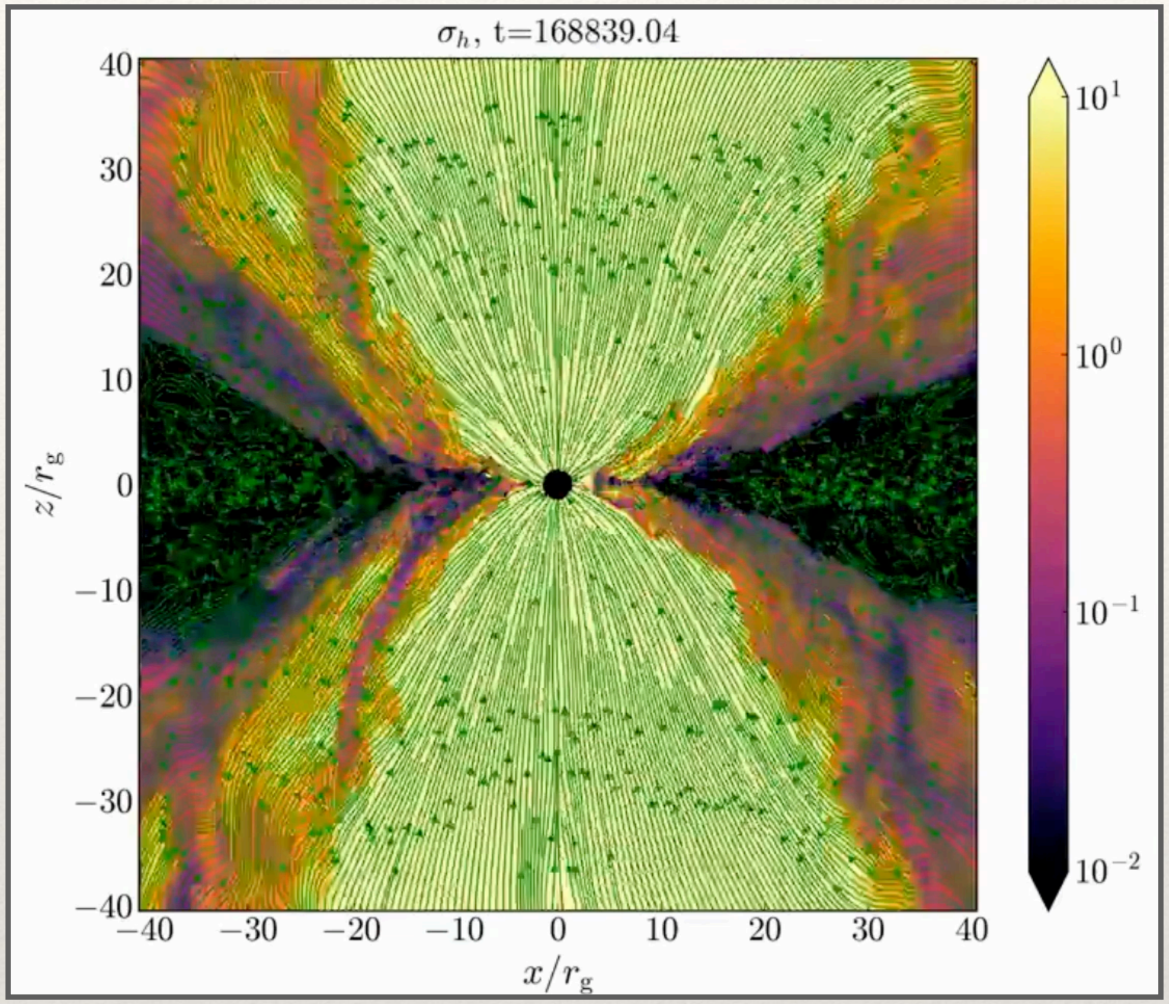

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If 1% of the protons streams non-diffusively or are advected out of the corona:
$L_{CR} \sim 10^{41}$erg/s (made out of ~10 TeV cosmic rays) in a galaxy similar to NGC 1068

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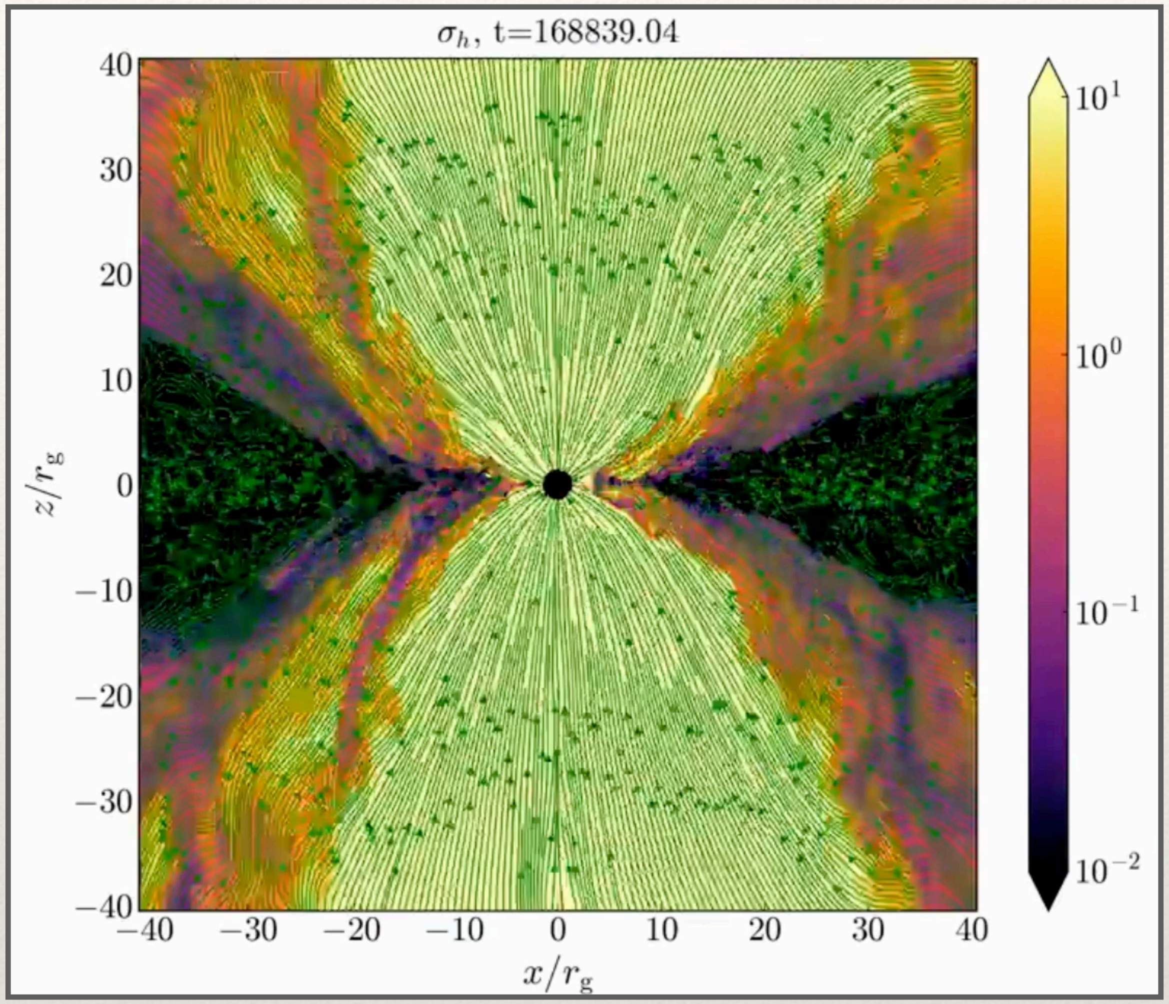

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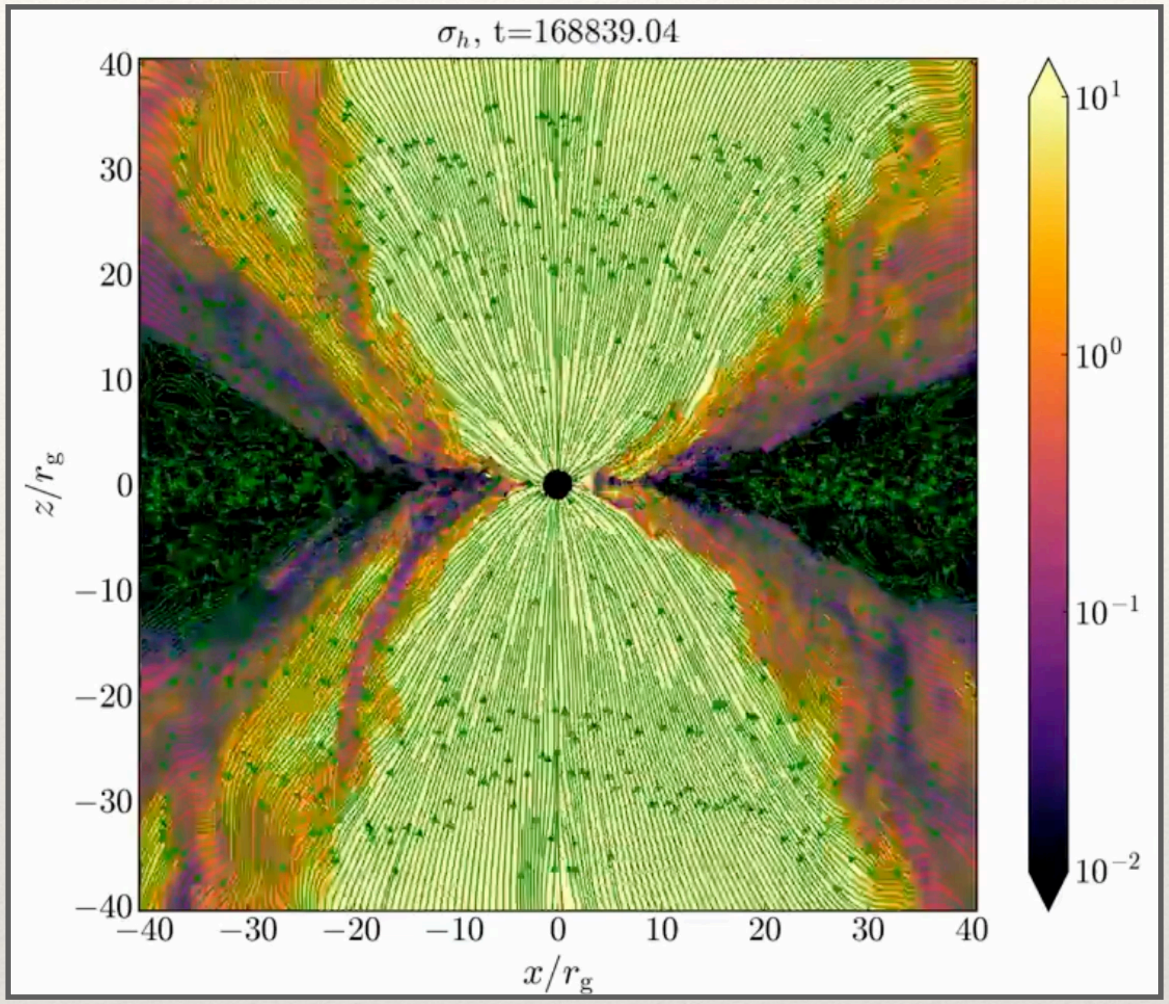

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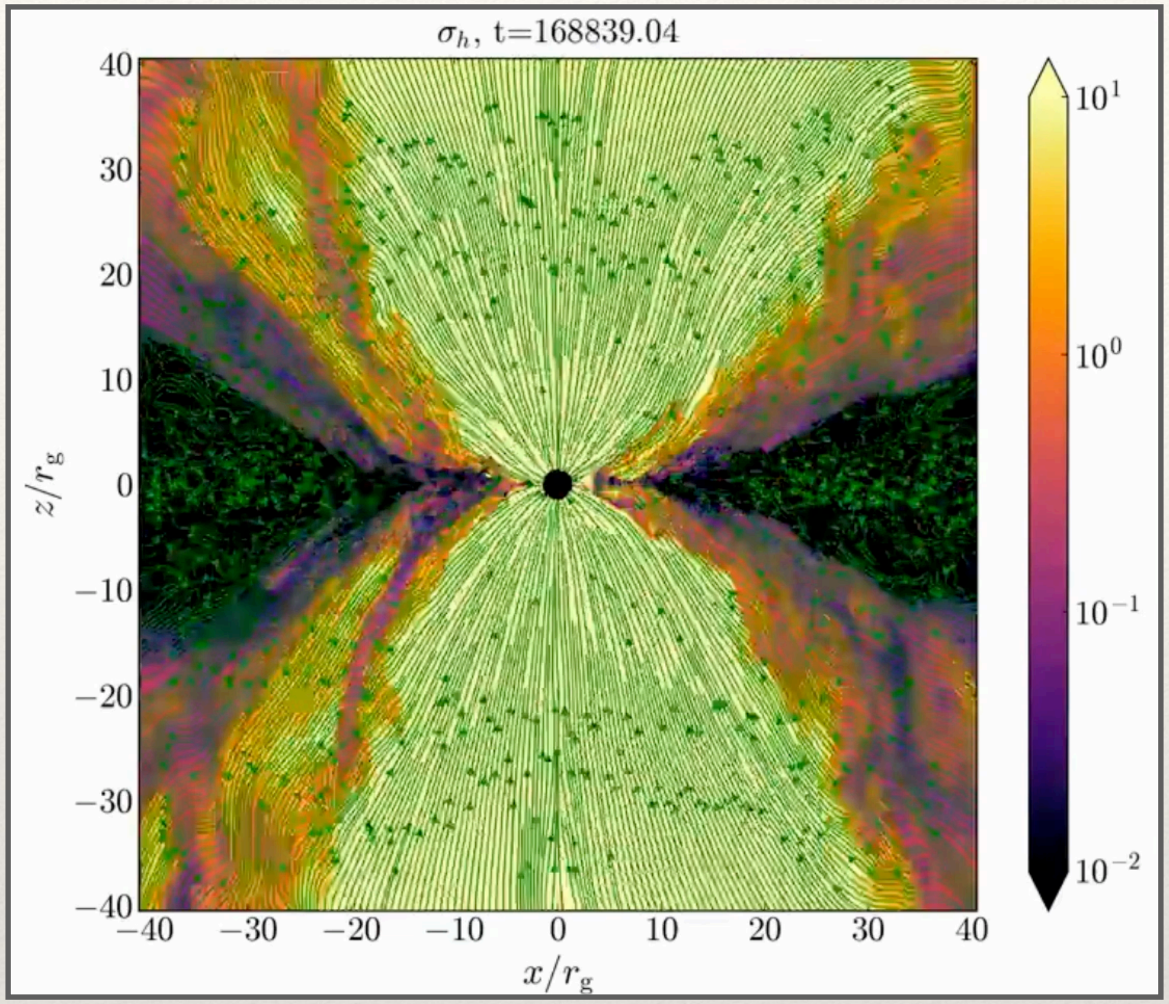

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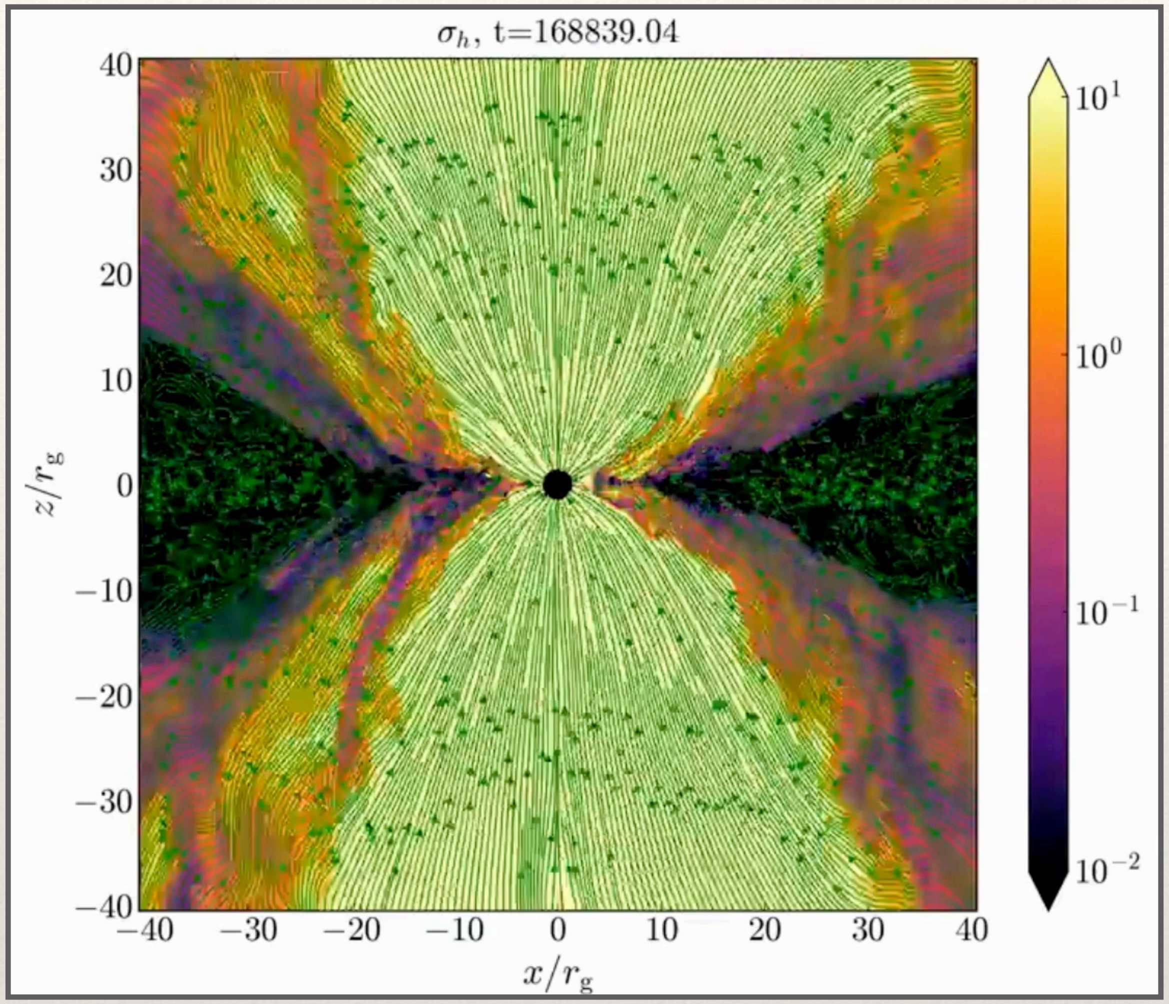

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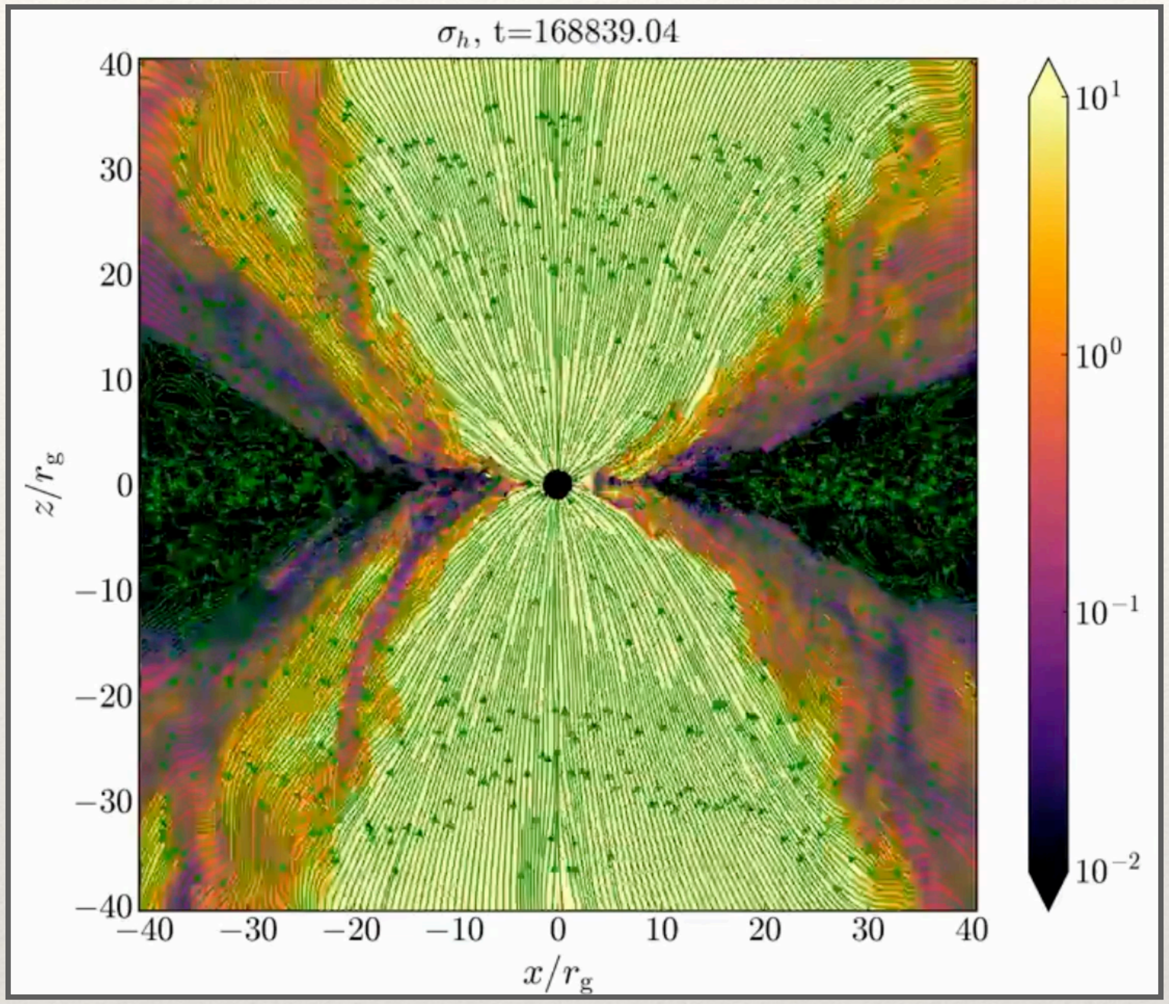

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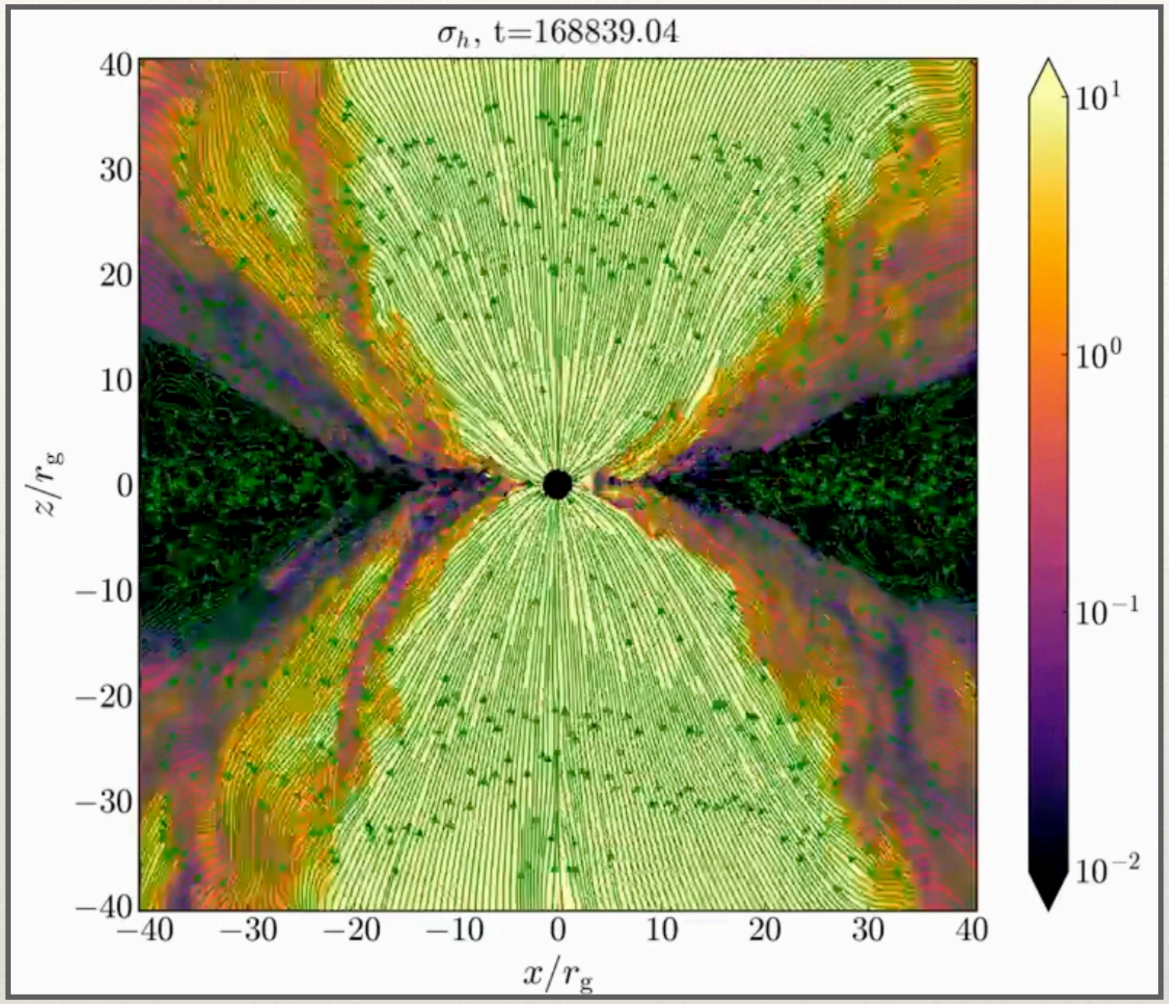

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To Conclude

- Robust AGN-corona predictions require a better understanding of particle acceleration across scales
- PIC and MHD simulations suggest energy-dependent acceleration at the largest scales
- Energy dependence of $t_{\rm acc}$ leads to source-specific neutrino luminosities and diffuse-flux contributions
- X-ray-luminous AGN coronae can explain the diffuse neutrino flux below PeV energies

Backup Slides

Generally dealt with using a Fokker-Planck formalism

$$\frac{\delta f_0}{\delta t} - \nabla_i D_{ij} \nabla_j f_0 + (\vec{u} \cdot \nabla) f_0 - \frac{\nabla \cdot \vec{u}}{3} p \frac{\delta f_0}{\delta p} = \frac{1}{p^2} \frac{\delta}{\delta p} p^2 D_{pp} \frac{\delta f_0}{\delta p}$$

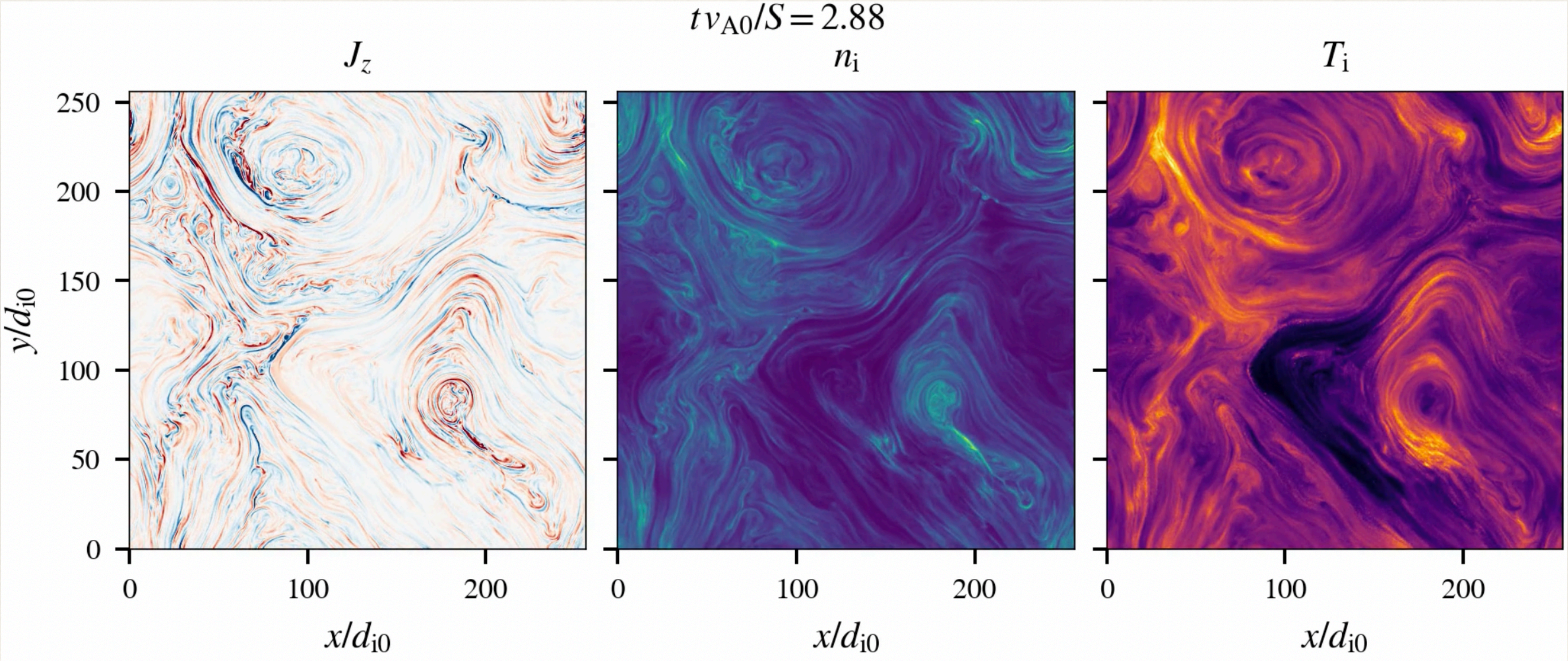
spatial diffusion

momentum diffusion

However: The validity and appropriate form of the Fokker–Planck equation for turbulence is not yet known (e.g. Zhdankin et al. (2020), Isliker et al. (2020))

Does this work with PIC?

- Simulation Properties
  - 2D driven ion-electron turbulence with mass ratio $m_p/m_e = 5$, $d_e = 1.5$
  - $\delta B/B = 1$
  - $t_{\rm esc} = L/4c$: particles are taken out when their displacement reaches L/4



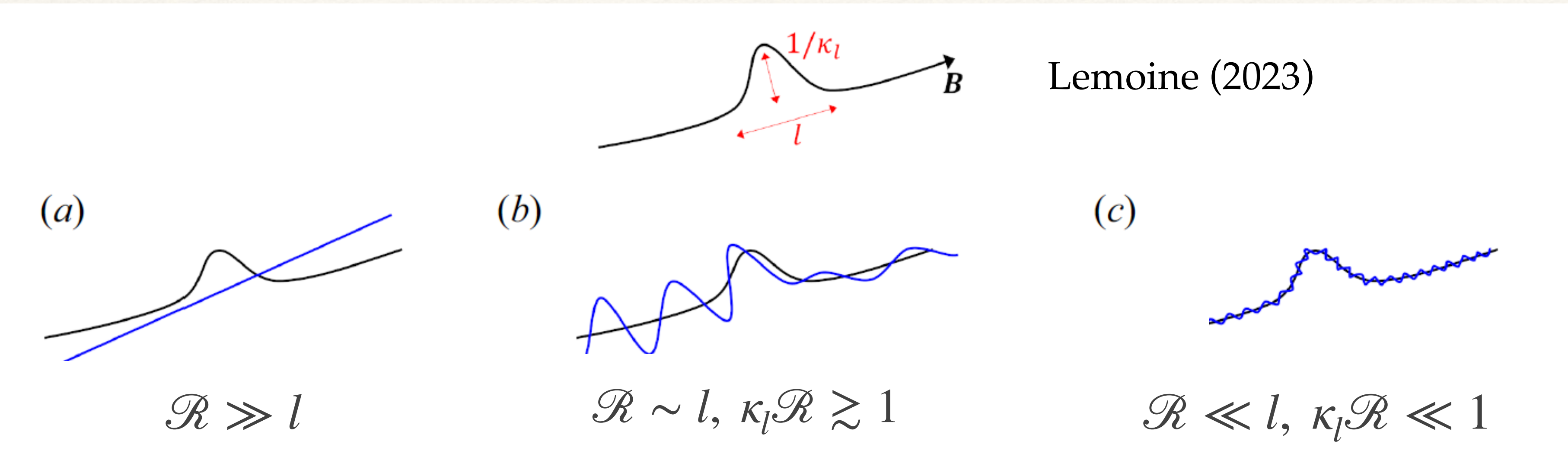
Interlude: The scattering time

$$ct_{\rm sc} \simeq \ell_c^{1-r}\mathscr{R}^r$$

Lemoine (2023); Kempski et al. (2023)

Coefficient r dependent on properties of system

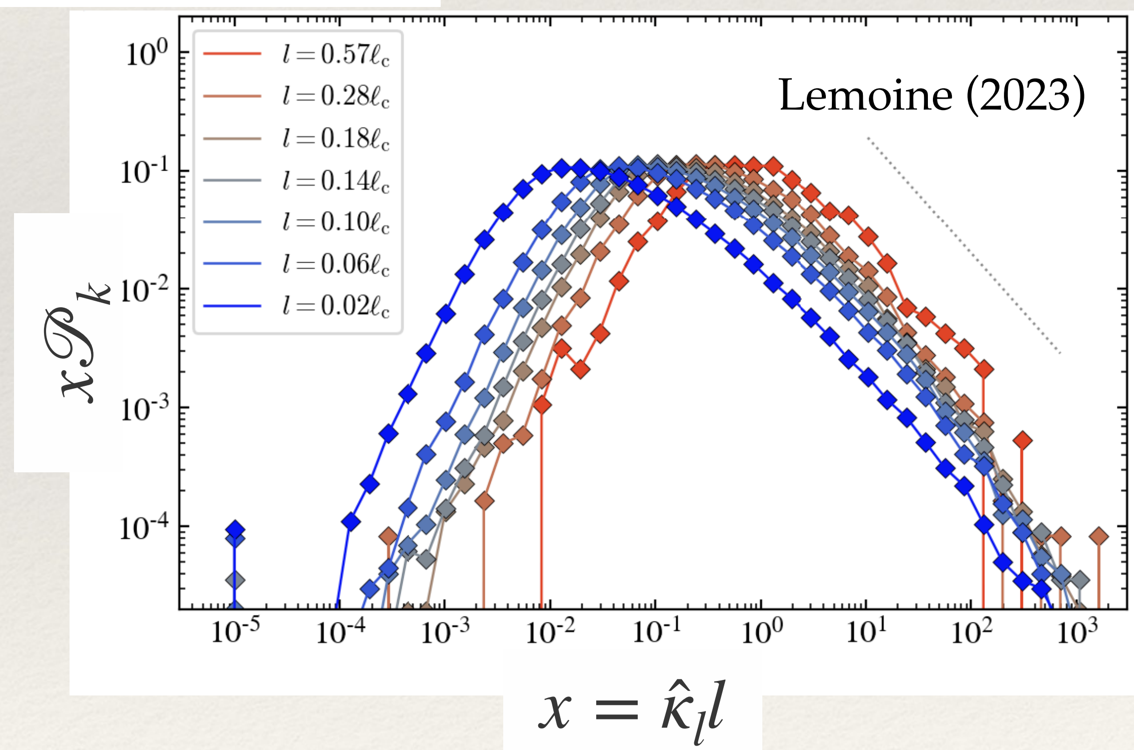
Larmor radius



- Probability of interaction depends on filling factor at each scale:

$$ct_{\rm sc} \simeq \frac{l}{\int_1^\infty dx\mathscr{P}_k(x)} \text{ for } l \sim \mathscr{R}$$

- The slope α sets the probability distribution with $\mathscr{P}_\kappa \propto (\hat{\kappa}_l l)^{-\alpha}$ for $l\hat{\kappa}_l \gtrsim 1$



Probability distribution of the magnetic field curvature $\mathscr{P}_\kappa$ in the system

Confined Population: Energy Gain $\mathscr{G}$

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$$\boxed{\frac{dn}{d\gamma} \propto \gamma^{-2-\frac{(t_{\rm acc}/t_A)}{\ln \mathscr{G}}}}$$

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θ is the pitch angle of the particles

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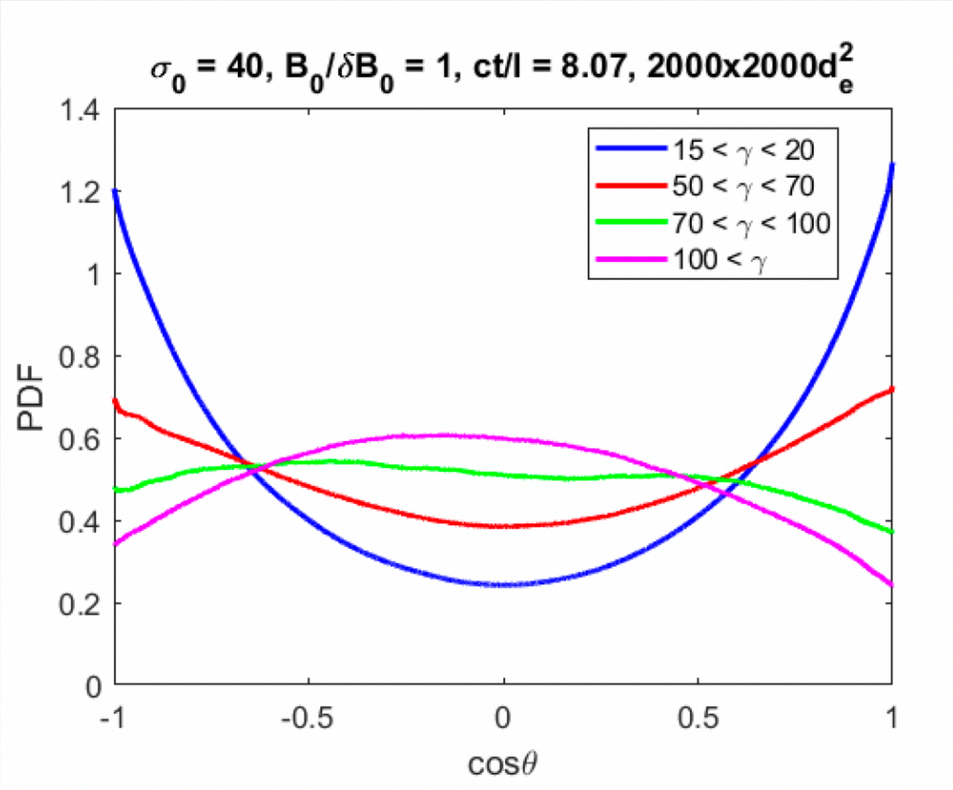

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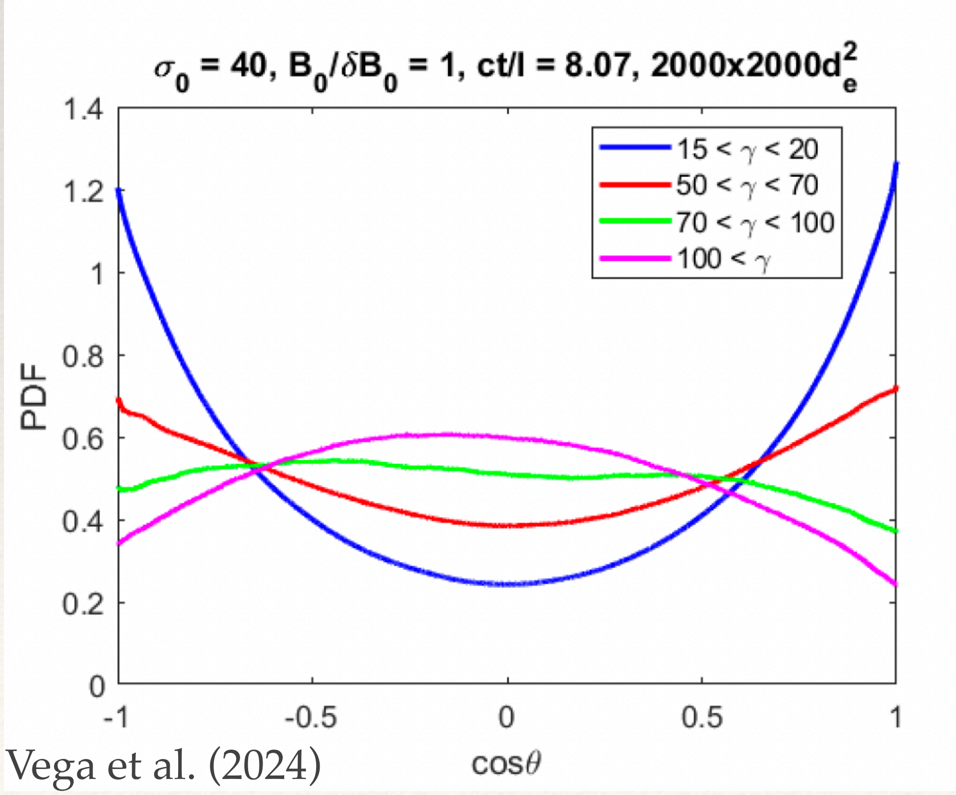

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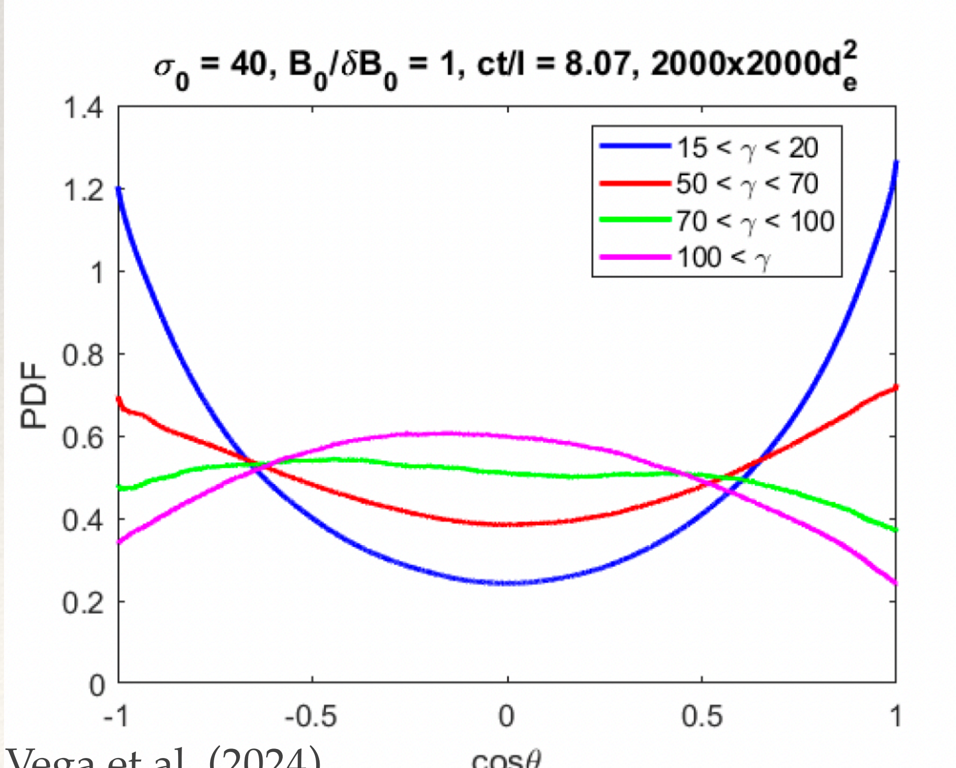
Vega et al. (2024) pointed out:

$$\Delta\gamma/\gamma \simeq 2\beta_b \cos\theta$$

θ is the pitch angle of the particles



Vega et al. (2024)

Confined Population: Energy Gain $\mathcal{G}$

$$\boxed{\frac{dn}{d\gamma} \propto \gamma^{-2-\frac{(t_{\rm acc}/t_A)}{\ln \mathcal{G}}}}$$

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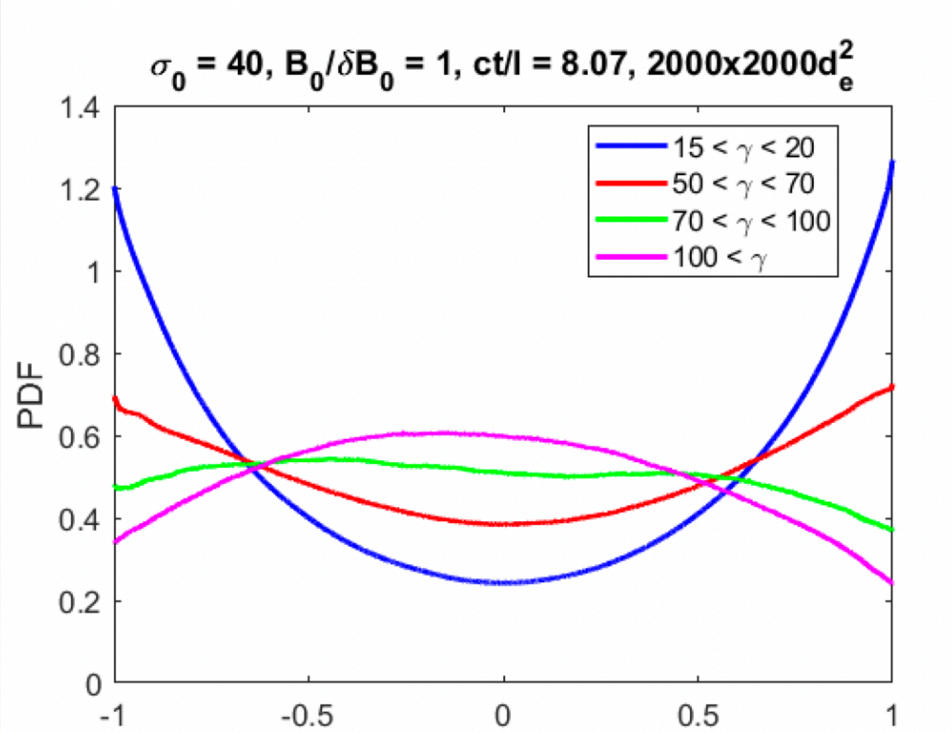


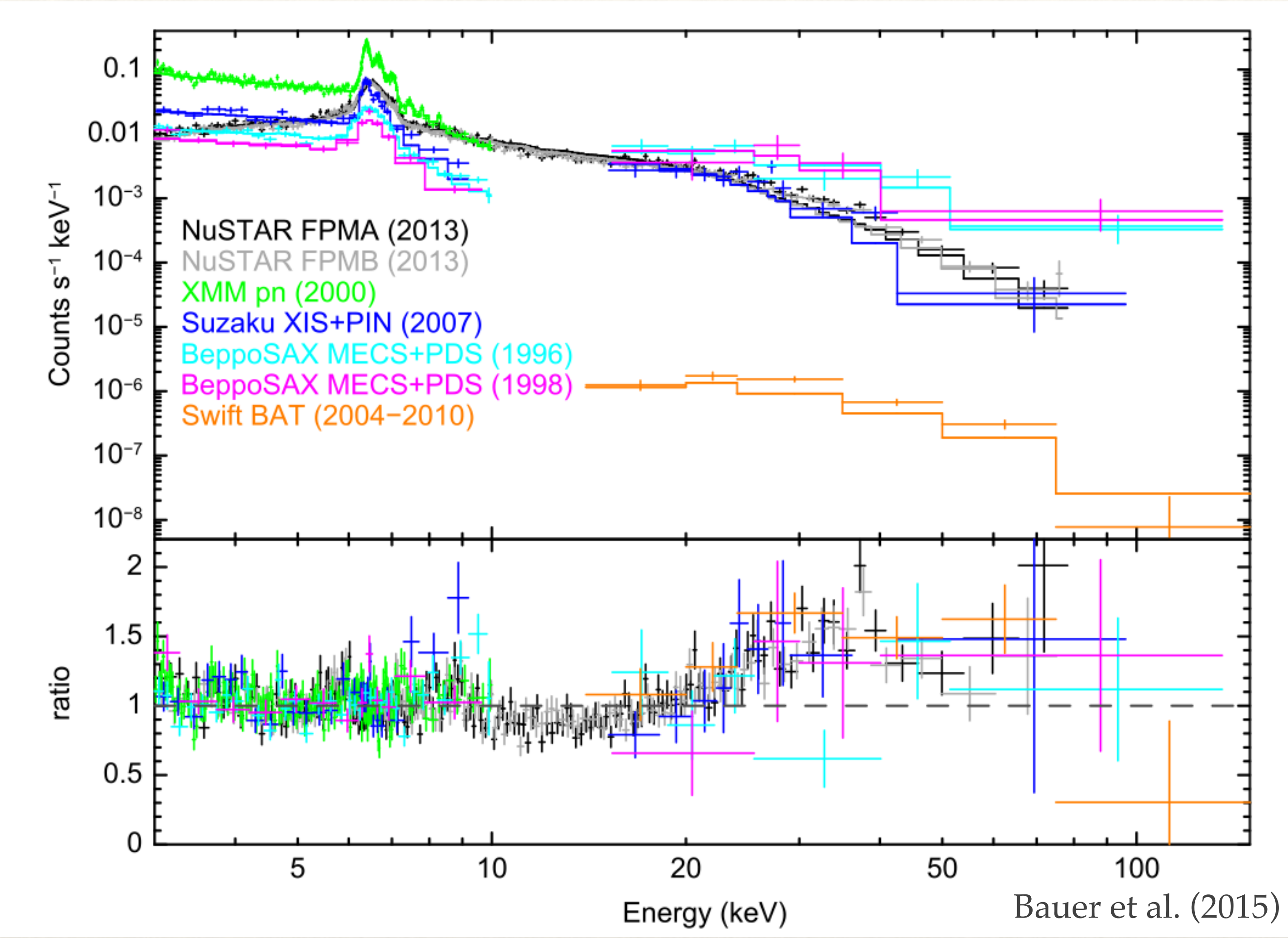
Vega et al. (2024)

Distribution is rather uniform with $\langle \cos\theta \rangle \simeq 2/\pi$

$$\mathcal{G} \simeq 1 + \frac{4}{\pi}\sqrt{\sigma_p/(1+\sigma_p)}$$

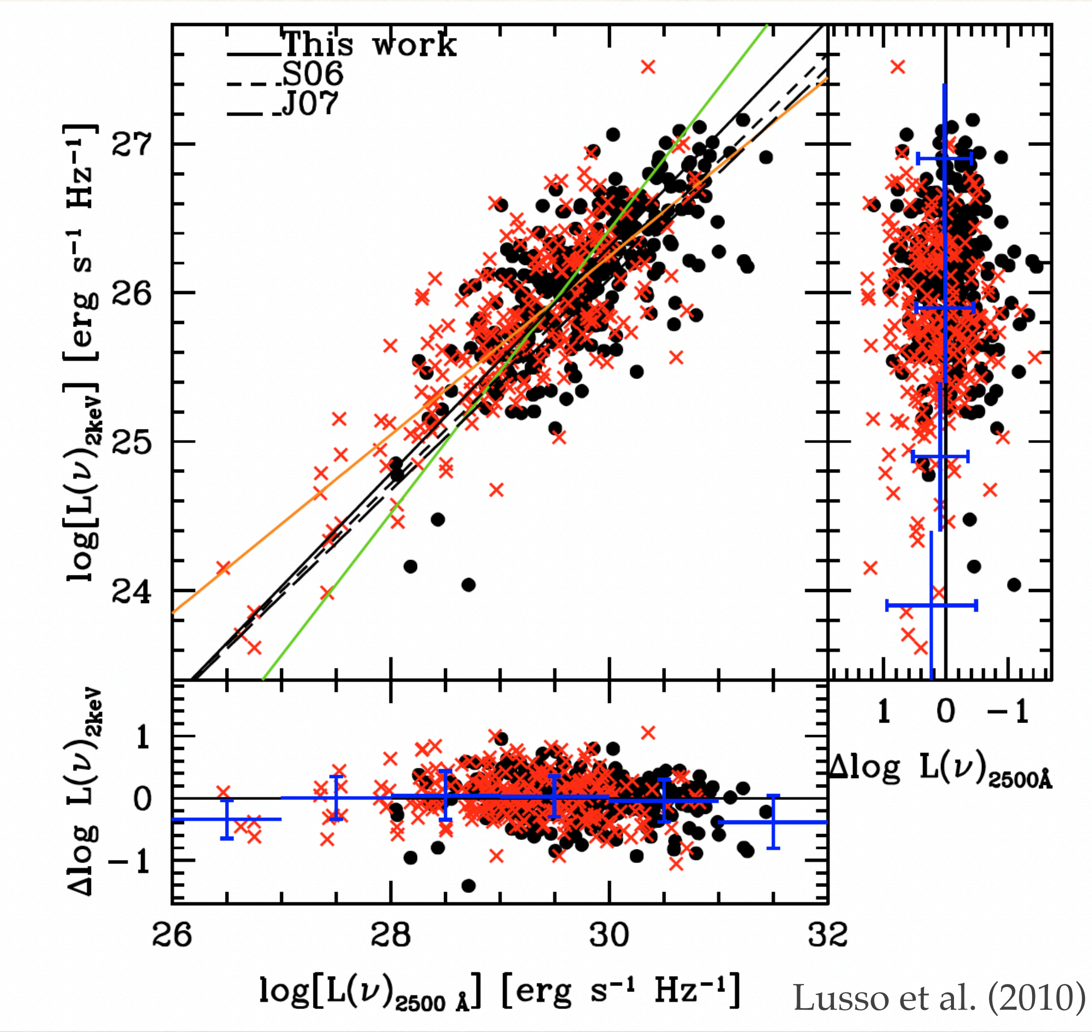
Observables: Photon Fields

X-ray emission from NGC 1068



Bauer et al. (2015)

$\alpha_{\rm ox}$ relation in Seyfert galaxies



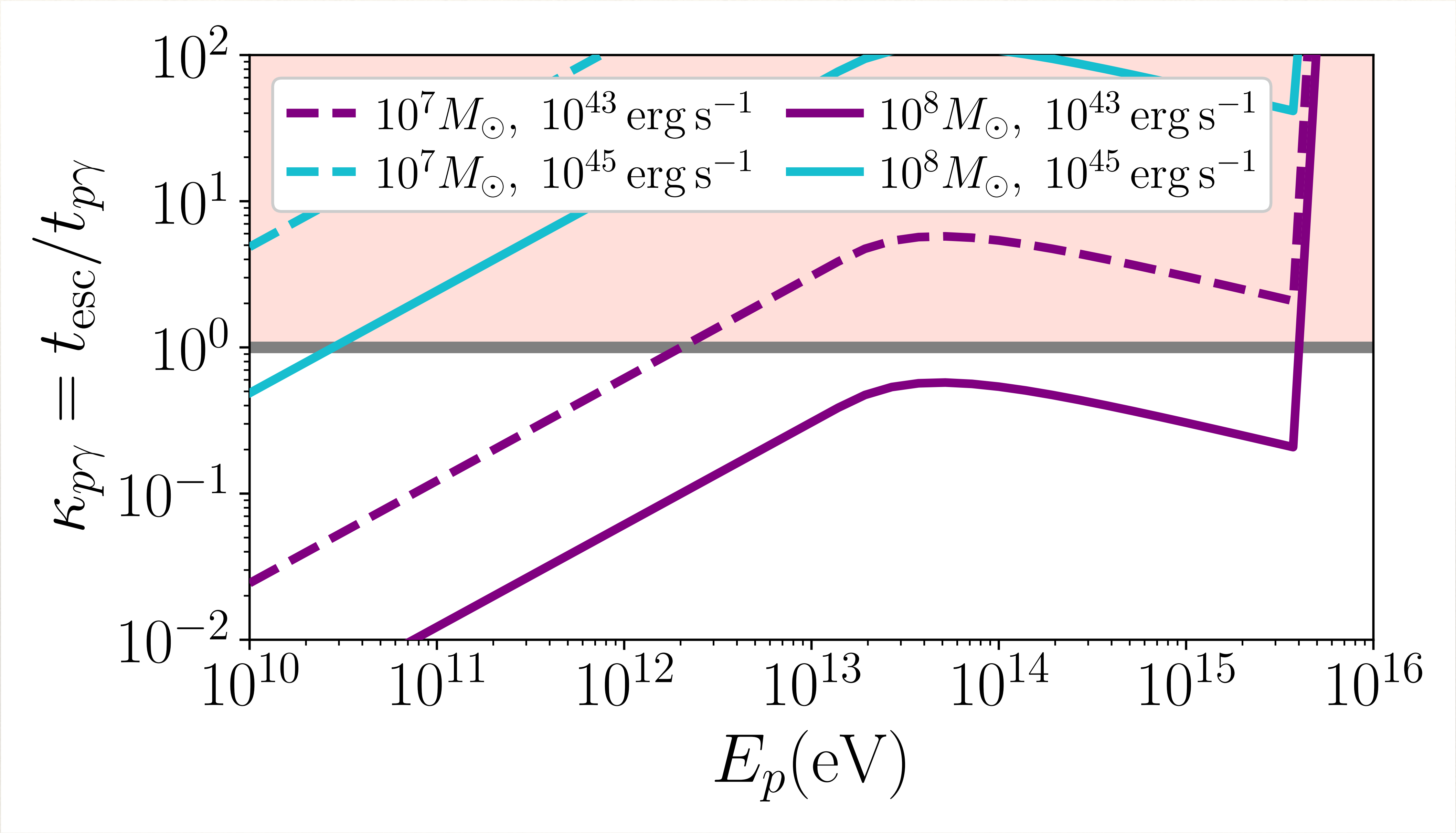
Lusso et al. (2010)

Can extract properties of X-ray spectrum from observations

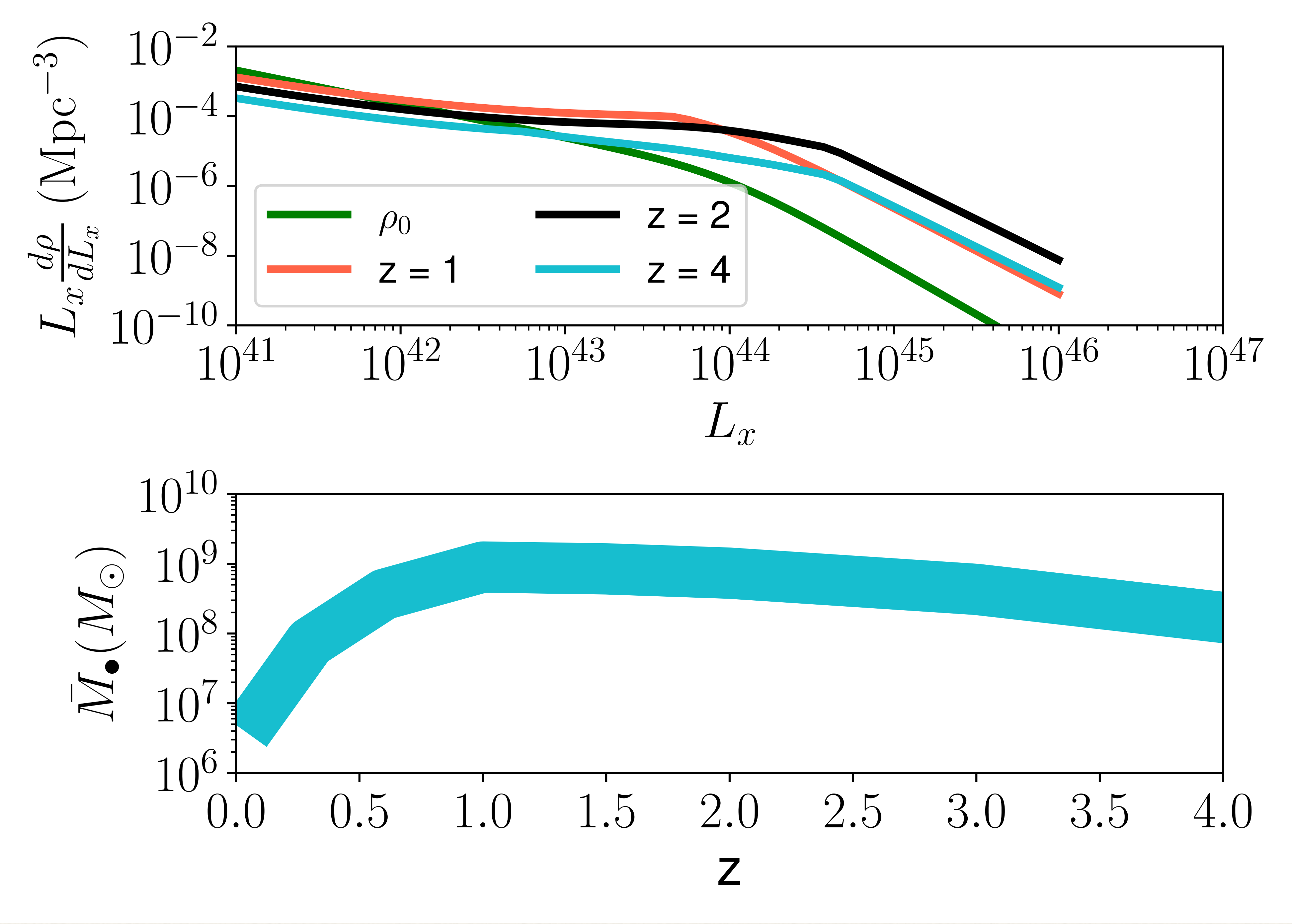
A tight relation between the Optical-UV and X-rays in AGNs, set by:

$$\alpha_{\rm ox} = -\frac{\log(L_{\rm 2keV}/L_{\rm 2500A})}{2.605}$$

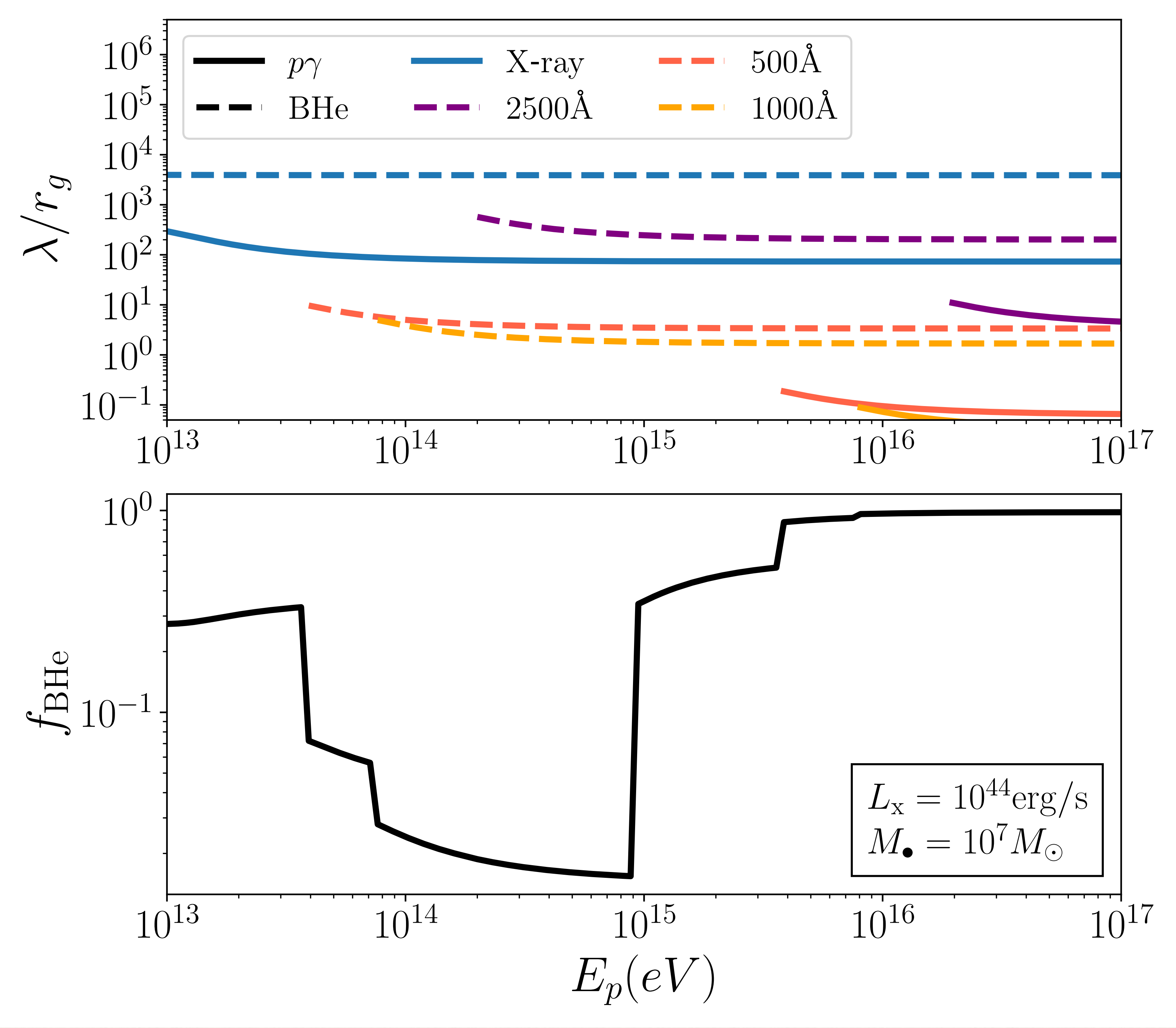
The neutrino production efficiency κ



The black hole mass distribution vs. redshift



Impact of Bethe-Heitler



γ-ray suppression

Upper Panel: Optical depth of $\gamma\gamma$ interactions for produced γ-ray depending on the target photons.

Lower Panel: γ-ray spectrum suppression based on X-ray and Optical-UV.