

Probing Dark Matter-Photon Interactions with High Energy Gamma-Ray Observations

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with

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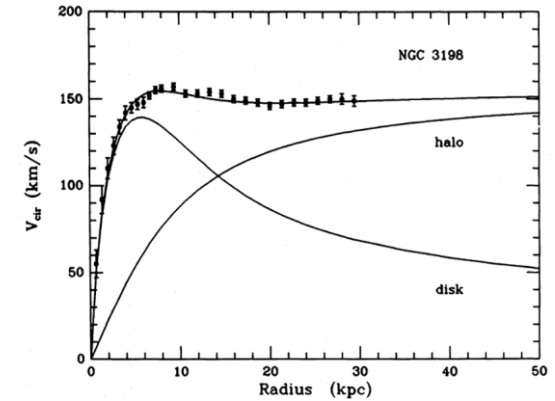
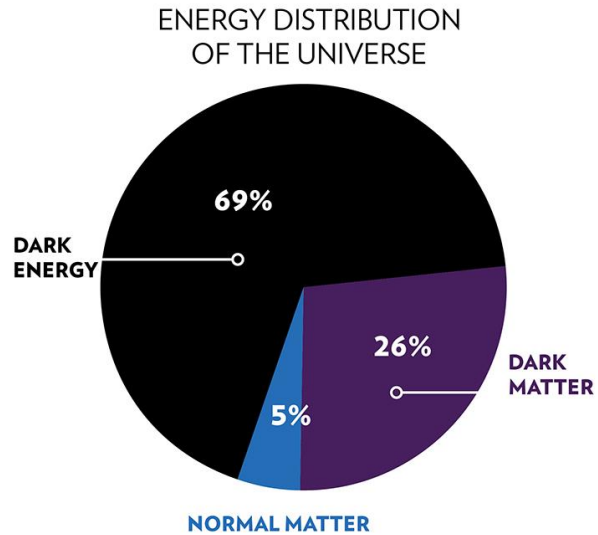
Nina Bavdaz, Gabrijela Zaharijas, Judit Perez (University of Nova Gorica, Slovenia)



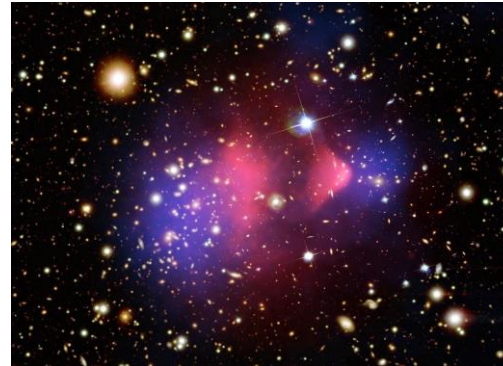
CAPP

Centre for Astro-Particle Physics

Dark Matter

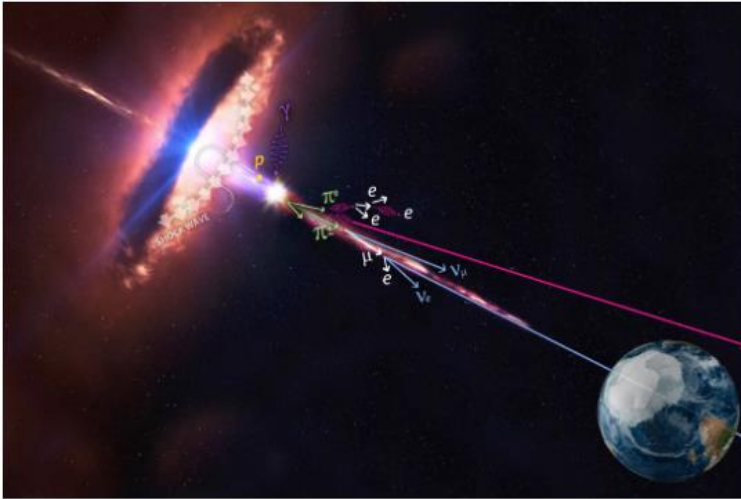


Rotational curves of galaxies

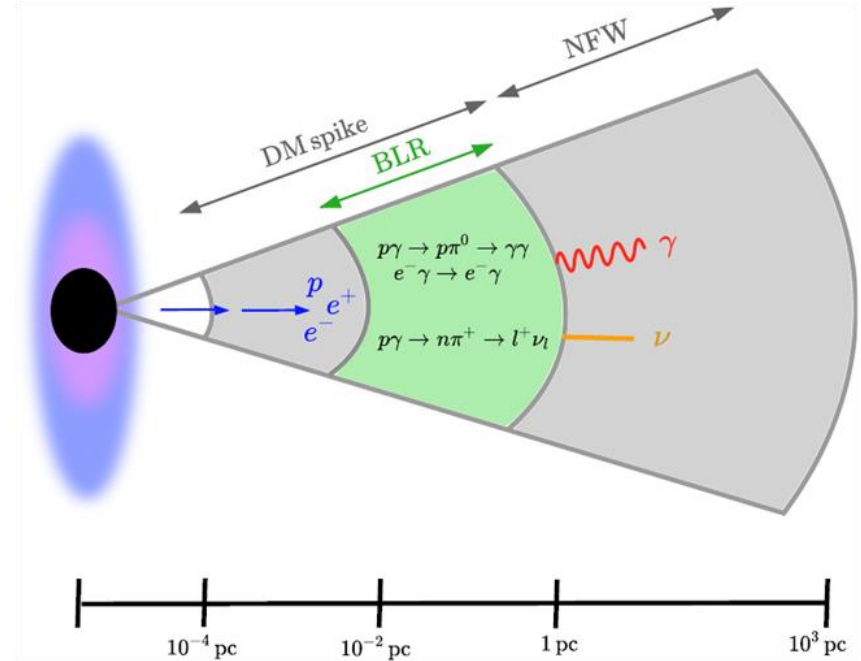


Weak lensing effect in Bullet Clusters

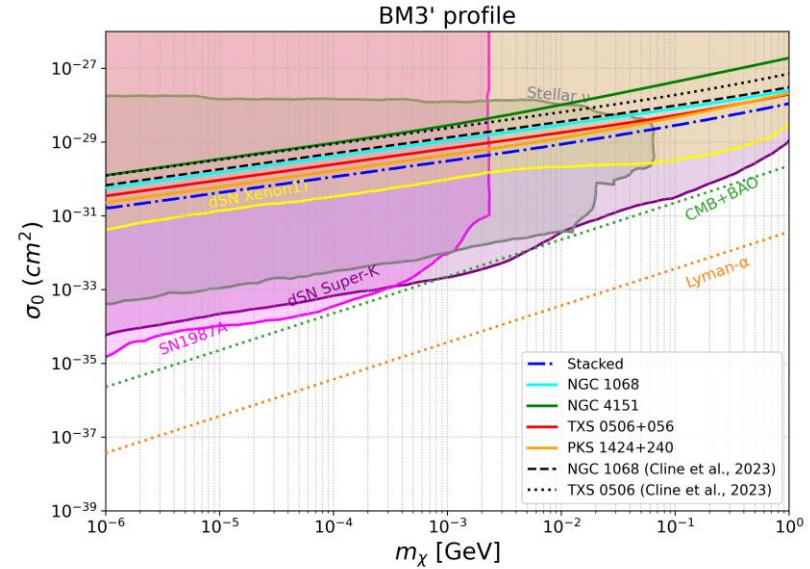
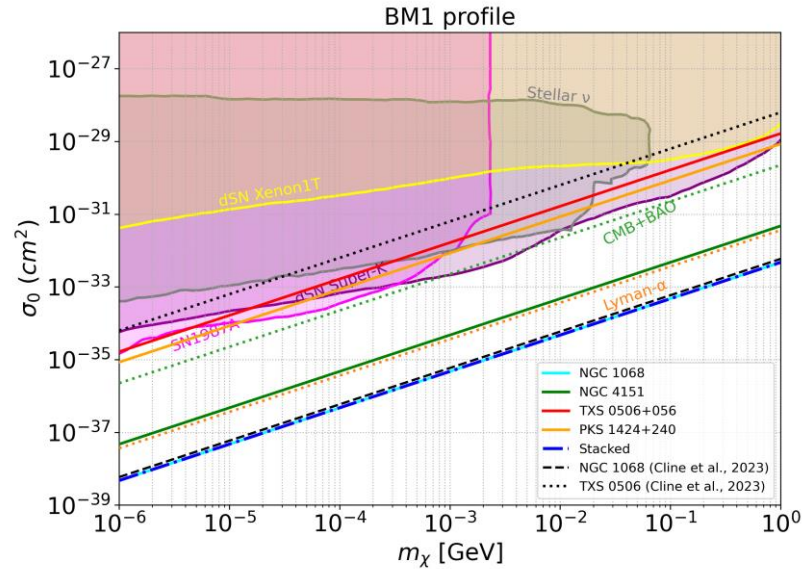
The dark matter profile in AGNs around blackhole



Credit: IceCube/NASA



Previous DM-neutrino scattering results



K.D., Mohlabeng, Razzaque, PRD 2026.

Bounds from “NGC 1068, TXS 0506+056, PKS 1424+240” (3.3σ CL), NGC 4151 (2.9σ CL) (IceCube, 22' 24')

Gamma ray photon counts at Fermi-LAT

4FGL-DR4 catalog: 14 years all-sky survey, Aug 2008 – Aug 2022; 50 MeV – 1 TeV catalog energy range

Source	Type	Spectral model	N_{pred}	Significance
NGC 1068	Seyfert 2 galaxy	Power law, $\Gamma = 2.35$	1416	19.7σ
NGC 4151*	Seyfert 1.5 galaxy	Power law, $\Gamma = 2.11$	227	6.0σ
TXS 0506+056	Blazar (BL Lac)	Log-parabola, $\alpha = 2.03$, $\beta = 0.053$	9906	118.6σ
PKS 1424+240	Blazar (BL Lac)	Log-parabola, $\alpha = 1.70$, $\beta = 0.057$	11083	171.1σ

NGC 4151 has no catalog association: we use 4FGL J1210.3+3928 (~5' away), attributed to NGC 4151 (Peretti et al., JCAP 2025)

(Abdollahi et al., ApJS 2022 [4FGL-DR3]; Ballet et al., arXiv:2307.12546 [4FGL-DR4])

Dark Matter Density Profile

- Adiabatic growth of black hole makes the DM density profile steeper in the inner halo
(Gondola & Silk, PRL 1999)
- **Gravitational scattering between DM and stars** can dynamically relax the slope of DM spike profile
(Gnedin & Primack, PRL 2004)
- If **DM annihilates**, the spike profile is **more cored**

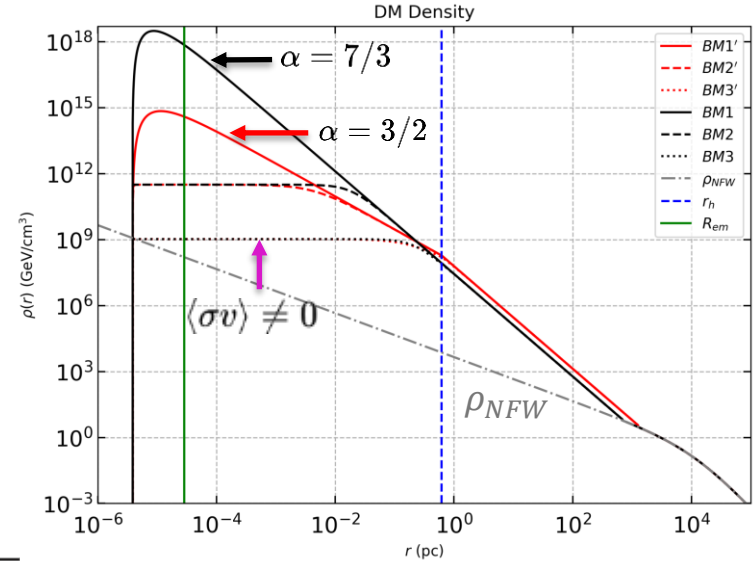
$$\rho \propto r^{-\gamma} \Rightarrow \rho'(r) \propto r^{-\alpha}, \quad \alpha = \frac{9-2\gamma}{4-\gamma}$$

$$\rho'(r) \propto r^{\alpha} \Rightarrow \rho_{DM} = \rho_{\chi} = \frac{\rho(r)\rho_{max}}{\rho(r)+\rho_{max}}, \quad \rho_{max} = \frac{m_{\chi}}{\langle\sigma v\rangle t_{BH}}$$

$m_{\chi} \rightarrow$ DM mass ;

$t_{BH} \rightarrow$ age of SMBH ;

$\langle\sigma v\rangle \rightarrow$ velocity average annihilation cross section ($10^{-26} \text{ cm}^3/\text{s}$)



Dark Matter Density Profile

- Normalization $\rho'(r)$ via $\int_{r_{min}}^{r_{max}} 4\pi\rho'(r)r^2dr \approx M_{BH}$

radius of the influence of the BH, $r_{max} = 10^5 R_S$
and $r_{min} = 4R_S$

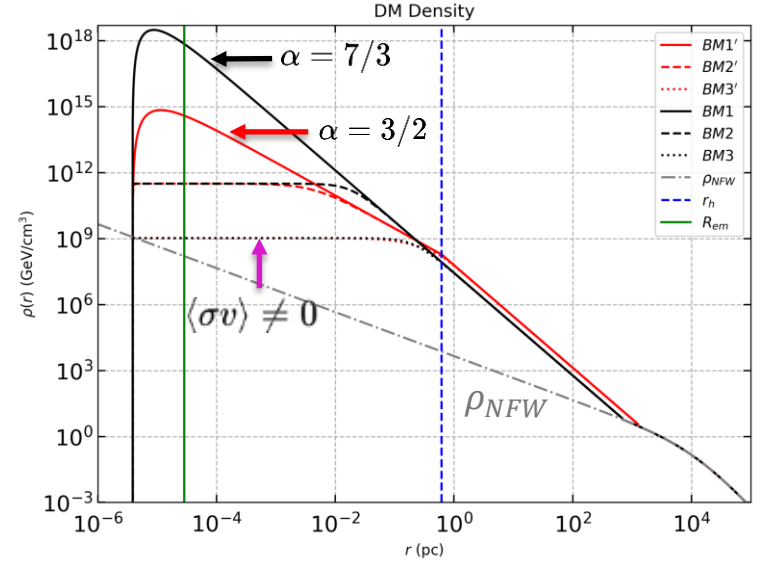
- Outside of the spike radius, NFW density profile (Navarro, Frenk & White, APJ 1996)

$$\rho_{DM}(r) = \rho_0(r/r_0)^{-\gamma}(1 + \frac{r}{r_0})^{\gamma-3} \quad \text{if } r \geq R_{sp}$$

- The attenuation of the photon fluxes produced at the distance R_{em} from the BH can be described by

$$\phi = \phi_0 e^{-\sigma_0 \Sigma_\chi / m_\chi}$$

- DM column density $\Sigma_\chi = \int_{R_{em}}^{\infty} dr \rho_\chi(r)$



$\langle\sigma_a v\rangle$	Model	α	Model	α
0	BM1	7/3	BM1'	3/2
0.01	BM2	7/3	BM2'	3/2
3	BM3	7/3	BM3'	3/2

Methodology

- We define a Poisson likelihood χ^2

$$\chi^2 = 2 \sum_i [N_i^{th} - N_i^{exp} + N_i^{exp} \ln(\frac{N_i^{exp}}{N_i^{th}})] + 2 \sum_j N_j^{th}$$

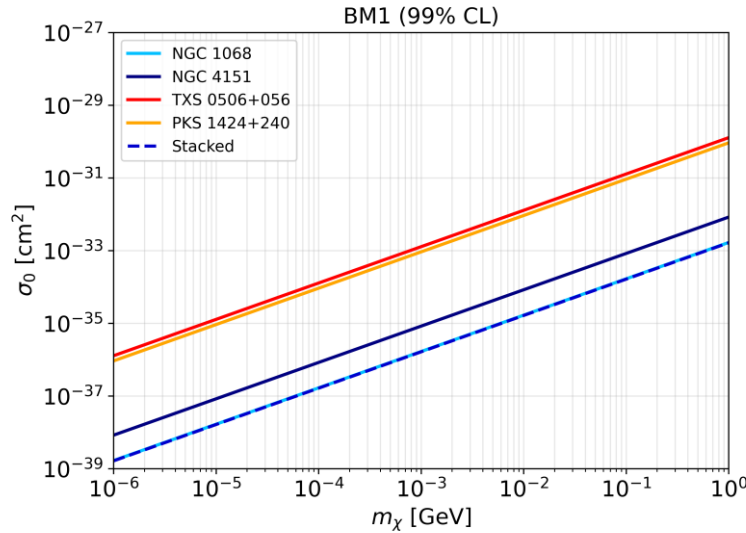
where $N_i^{exp} \equiv n_i^{SM}$ and $N_i^{th} \equiv n_i^{th}(\sigma_{\nu\chi})$, for $i, N_i^{exp} \neq 0$ and for $j, N_j^{exp} = 0$

- For stacking analysis: $\chi_{total}^2 = \sum_s \chi_s^2$; $s = \text{NGC 1068, TXS 0506 + 056, PKS 1424 + 240, NGC 4151}$

Parameter	NGC 1068	NGC 4151	TXS 0506+056	PKS 1424+240
$M_{BH} (M_{\odot})$	1.0×10^7	2.0×10^7	3.09×10^8	1.0×10^9
R_S (pc)	9.5×10^{-7}	1.9×10^{-6}	2.9×10^{-5}	9.5×10^{-5}
t_{BH} (yr)	10^9	10^9	10^9	10^9
r_h	$6.5 \times 10^5 R_S$	$6.5 \times 10^5 R_S$	$10^5 R_S$	$10^5 R_S$
R_{em}	$30 R_S$	$30 R_S$	$2 \times 10^3 R_S$	$6.5 \times 10^2 R_S$

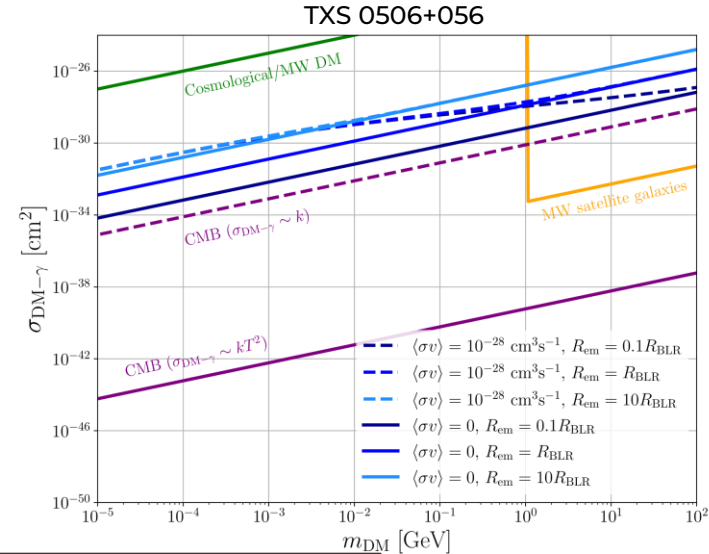
Constraint on DM-photon Cross-Section

Constant $\sigma_{\nu\chi}$: For benchmark models where $\langle\sigma v\rangle = 0 \rightarrow \Sigma_\chi(m_\chi) = \text{constant}$; **NGC 1068 dominates the stacking analysis.**



$$\sigma_0 \lesssim \sqrt{\frac{2 \cdot 2.71}{n_i^{SM}}} m_\chi / \Sigma_\chi$$

ρ_χ for SMBH with lighter mass, peaks at smaller distance with higher amplitude, hence larger Σ_χ (Gondolo & Silk 1999)



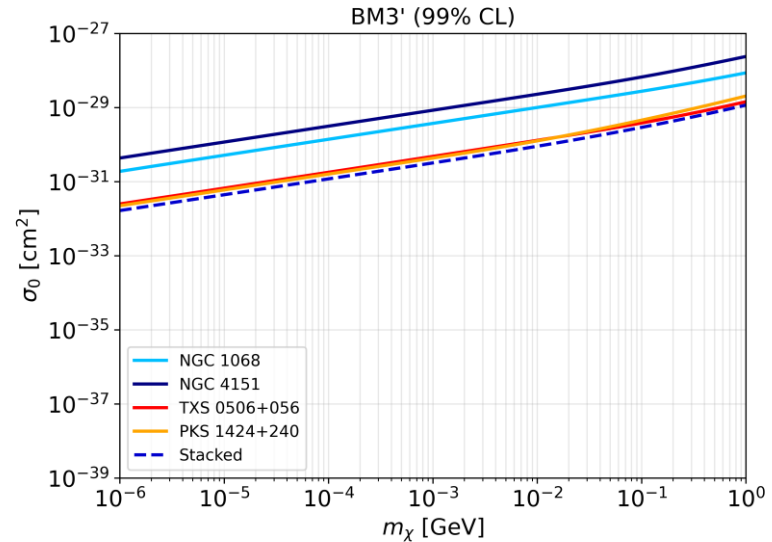
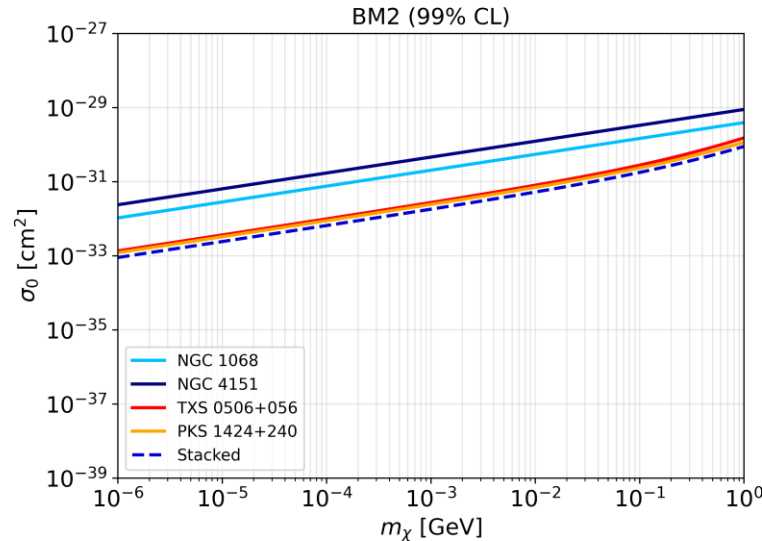
(Ferrer et al., 2023)

(Bavdaz, KD, Perez, Razzaque, Zaharijas in prep.)

Constraint on DM-photon Cross-Section

Constant σ_{ν_χ} :

For benchmark profiles with $\langle\sigma v\rangle \neq 0$, $\Sigma_\chi(m_\chi)$ varying with m_χ , **PKS 1424+240 dominates the stacking analysis.**



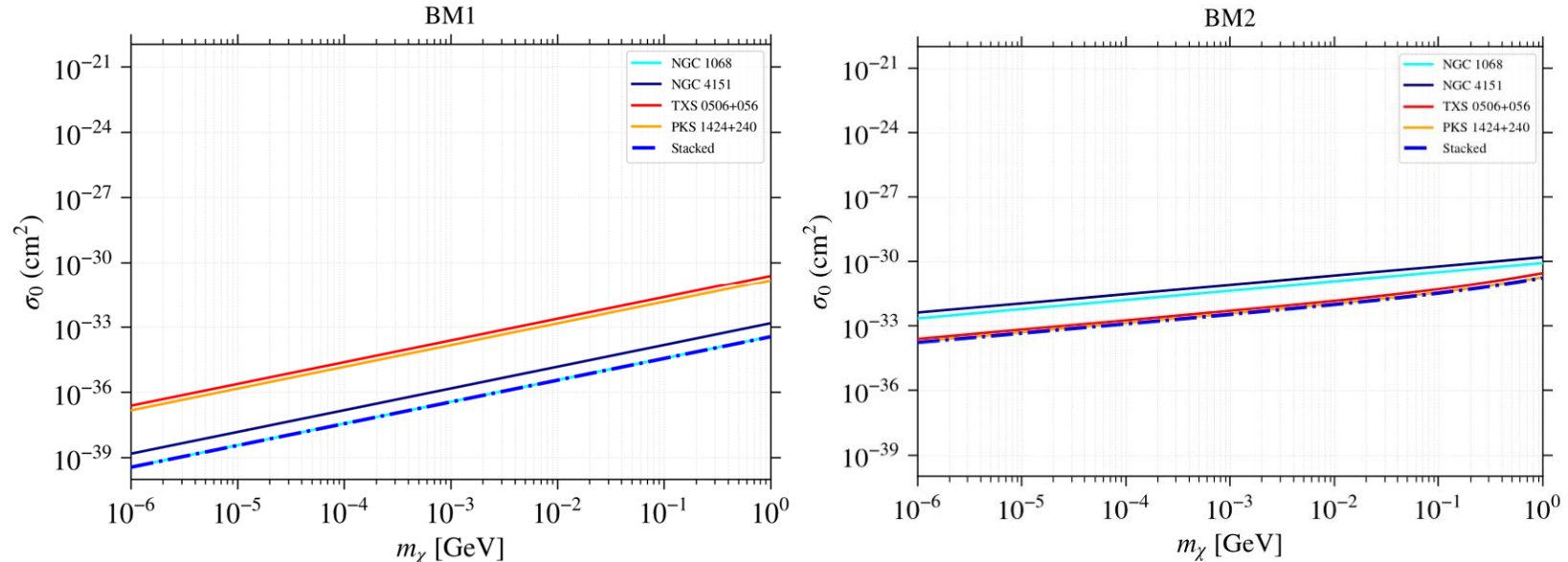
The denser the dark matter spike, the stronger the depletion due to self-annihilations, the weaker the constraints.

(Bavdaz, KD, Perez, Razzaque, Zaharijas in prep.)

Constraint on DM-photon Cross-Section

Energy dependent $\sigma_{\nu\chi} \propto E$:

$$\frac{d\phi}{d\tau} = -\sigma_{\nu\chi}\phi + \int_{E_\nu}^{\infty} dE'_\nu \frac{d\sigma_{\nu\chi}}{dE_\nu}(E'_\nu \rightarrow E_\nu)\phi(E'_\nu)$$



Similar qualitative features to the constant-cross-section case, but with stronger constraints.

(Bavdaz, KD, Perez, Razzaque, Zaharijas in prep.)

Possible model interpretation

- Millicharged DM $\mathcal{L} \supset \epsilon e \bar{\chi} \gamma^\mu \chi A_\mu$ $\gamma + \chi \rightarrow \gamma + \chi$
for the low-energy photon–DM scattering reducing to the Thomson limit ([Kouvaris, PRD 2013](#);
[Bélanger, EPJC 2021](#))

$$\sigma_{\gamma\chi} \simeq \frac{8\pi}{3} \frac{\alpha^2 \epsilon^4}{m_\chi^2}, \quad E_\gamma \ll m_\chi$$

- Scalar Rayleigh dark matter $\mathcal{L}_{\text{int}} = \frac{c_\phi}{4\Lambda^2} \phi^2 F_{\mu\nu} F^{\mu\nu}$ $\gamma + \phi \rightarrow \gamma + \phi$
In relativistic regime

$$\sigma_{\gamma\phi} \simeq \frac{c_\phi^2}{24\pi} \frac{m_\phi E_\gamma}{\Lambda^4} \quad E_\gamma \gg m_\chi \quad (\text{Barducci et al., JHEP 2025})$$

For low energy $\sigma \propto E_\gamma^4/(\Lambda^4 m_\phi^2)$

Summary

- The observation of gamma-rays from AGNs and Blazars can be used to constrain the dark matter scattering cross section with photons, since these need to traverse the dark matter spike around the black hole and the halo of the host galaxy.
- We obtained the bounds one order of magnitude stronger than the previous analysis done without a proper statistical analysis. EBL inclusion in future for energy dependent DM-photon scattering.
- The constraints are subject to uncertainties from the flux modelling, the emitting region of neutrinos and gamma-rays, and from the dark matter profile.
- Future Fermi-LAT or MAGIC observations can improve results in this line.

Thank you for attention!
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Constraint on DM-neutrino Cross-Section

Energy-dependent σ_{ν_χ} :

Linear energy dependence, i.e., $\sigma_{\nu_\chi} = \sigma_0 \frac{E_\nu}{E_0}$

$$\frac{d\phi}{d\tau} = -\sigma_{\nu_\chi} \phi + \int_{E_\nu}^{\infty} dE'_\nu \frac{d\sigma_{\nu_\chi}}{dE_\nu}(E'_\nu \rightarrow E_\nu) \phi(E'_\nu)$$


$$\frac{d\Phi_i}{dy} = A \left(-\hat{E}_i \Phi_i + \Delta x \ln 10 \sum_{j=i}^N \hat{E}_j \Phi_j \right),$$

where, $A = \frac{\Sigma_\chi}{m_\chi} \frac{\sigma_0}{\hat{E}_0}$, $\hat{E}_i = 10^{x_i}$ and, $E_0 = 10 \text{ TeV}$

$$\sigma(E') = \sigma_0 \frac{E'}{E_0}, \quad \frac{d\sigma(E' \rightarrow E)}{dE} \simeq \frac{\sigma(E')}{E'} = \frac{\sigma_0}{E_0}$$

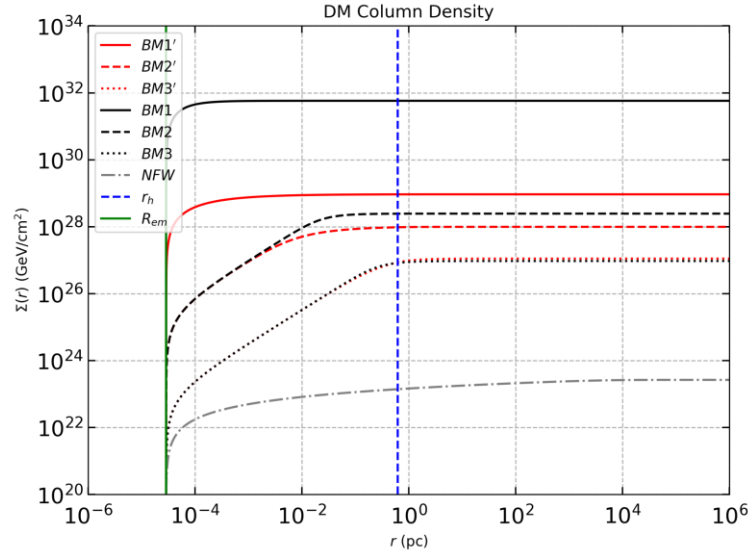
Assuming approximately isotropic centre-of-mass scattering and $E_\nu \gg m_\chi$

K.D., Mohlabeng, Razzaque, PRD 2026.

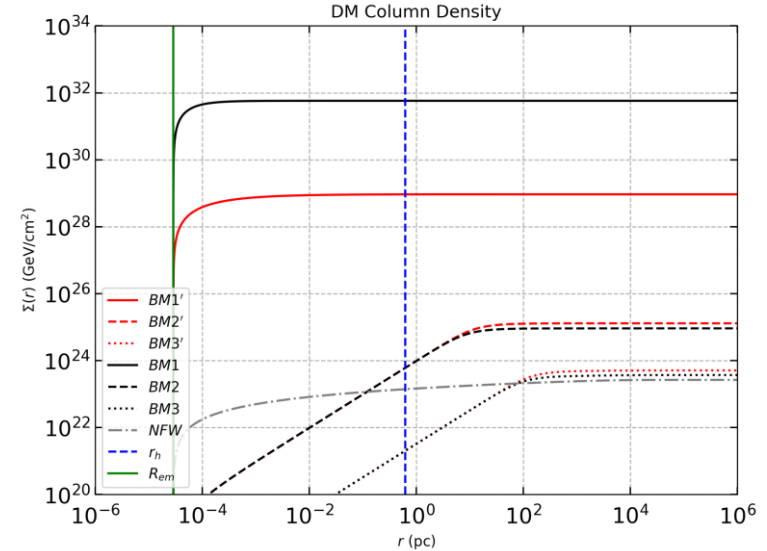
BACKUP: Dark Matter Column Density Profile

NGC 1068

$m_\chi = 1 \text{ GeV}$

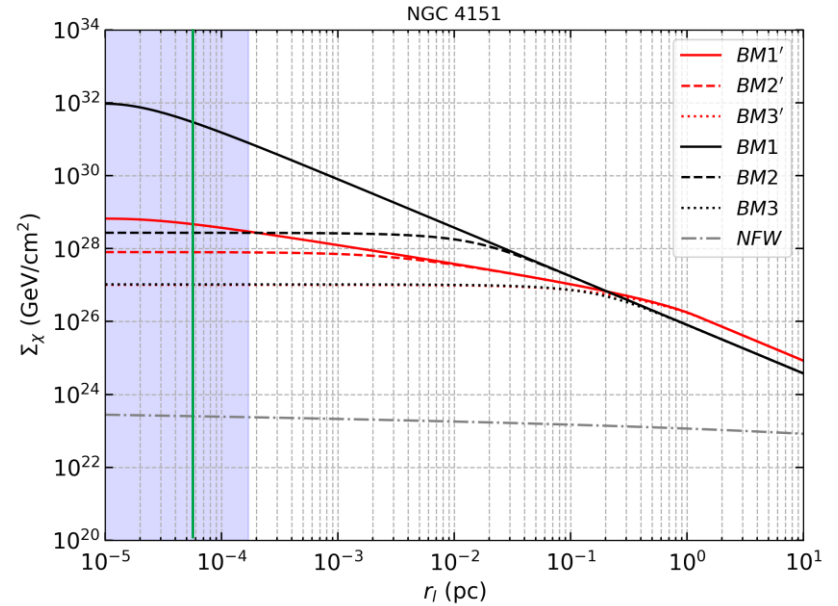
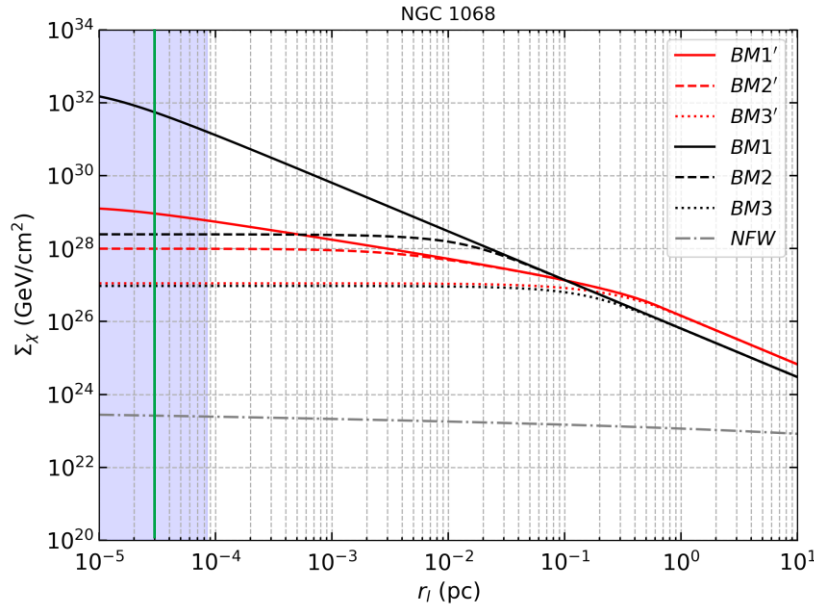


$m_\chi = 0.001 \text{ MeV}$



K.D., Mohlabeng, Razzaque, PRD 2026.

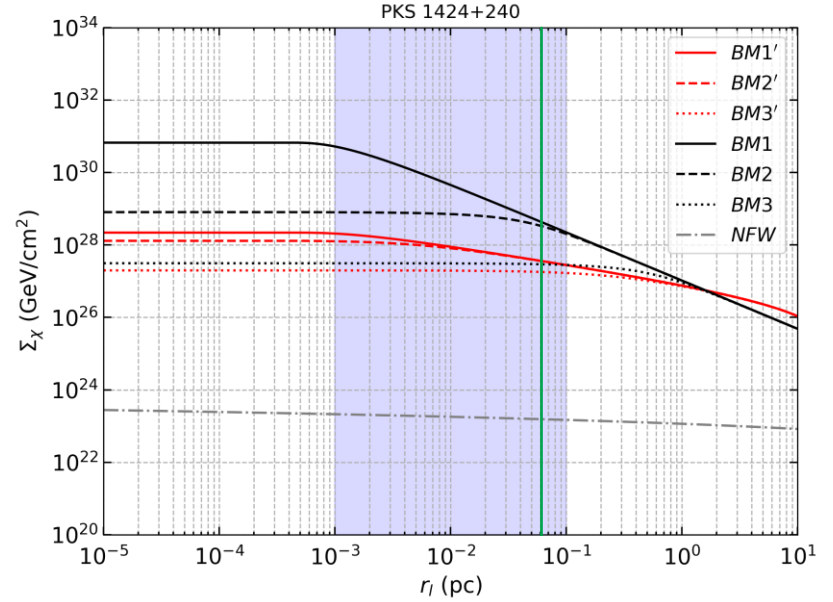
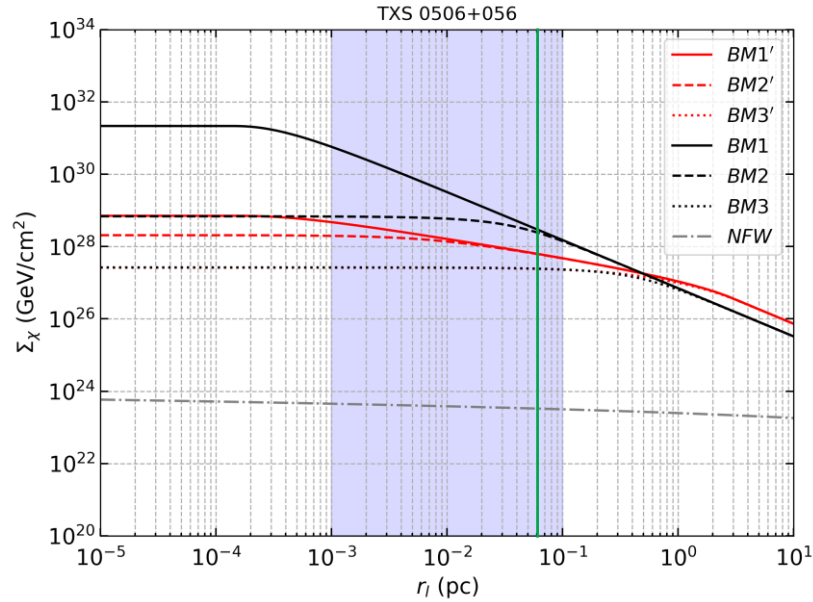
BACKUP: Astrophysical Uncertainty



- ❑ There is large uncertainty on the neutrino emission point R_{em} .
- ❑ For AGNs like NGC 1068 and NGC 4151, the constraint may be weakened by a factor of 4 (2) for non-annihilating DM models BM1 (BM1').

K.D., Mohlabeng, Razzaque, PRD 2026.

BACKUP: Astrophysical Uncertainty



- ❑ For blazars TXS 0506+056 and PKS 1424+240, the emission region is likely to be farther from the central BH.
- ❑ The constraint may get weakened by a factor of 2 for $BM1$, $BM1'$, $BM2$ and $BM2'$.

K.D., Mohlabeng, Razzaque, PRD 2026.

BACKUP: Previous analyses

$$\frac{\Phi_{\text{obs}}}{\Phi_{\text{em}}} = \exp(-\mu_i)$$
$$\mu_i|_{DM} \propto \frac{\sigma_{DM-i}}{m_{DM}} \Sigma_{DM}$$
$$\frac{\sigma_{DM-i}}{m_{DM}} \lesssim \begin{cases} \frac{2.3}{\Sigma_{DM}}, & i = \nu \\ \frac{4.6}{\Sigma_{DM}}, & i = \gamma \end{cases}$$

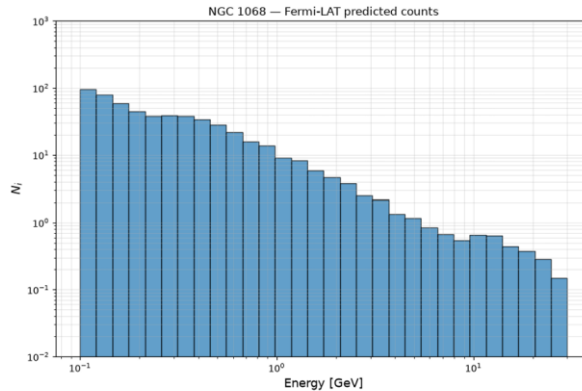
(Ferrer et al., 2023)

$$\begin{aligned} \mu_{\text{TXS } 0506+056} &= 0.0345894 \\ \mu_{\text{NGC } 1068} &= 0.0967699 \\ \mu_{\text{NGC } 4151} &= 0.24169 \\ \mu_{\text{PKS } 1424+240} &= 0.0365866 \end{aligned}$$

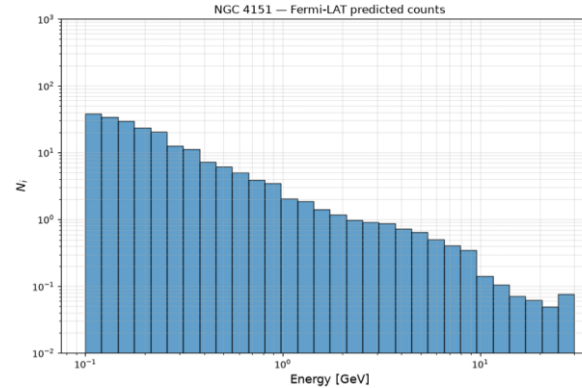
Source	Survival [%]	Attenuation [%]
TXS 0506+056	96.60	3.40
NGC 1068	90.78	9.22
NGC 4151	78.53	21.47
PKS 1424+240	96.41	3.59

K.D., Mohlabeng, Razzaque, PRD 2026.

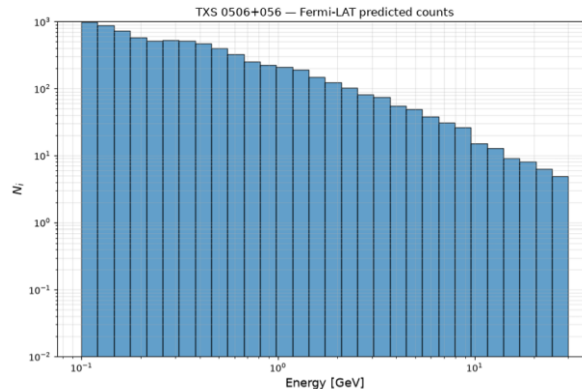
BACKUP: Predicted counts by Fermi-LAT



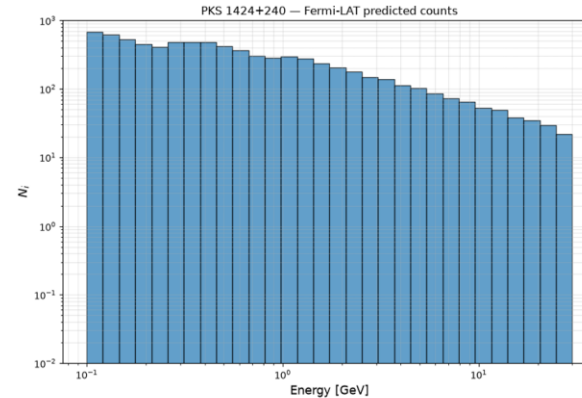
NGC 1068: total counts = 549.91



NGC 4151: total counts = 287.25



TXS 0506+056: total counts = 7588.28



PKS 1424+240: total counts = 7642.67