Probing Dark Matter Signatures in IceCube Astrophysical Neutrino Data

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with
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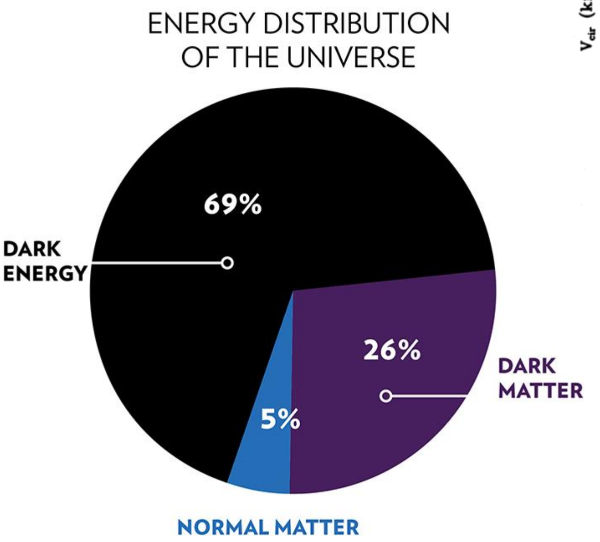
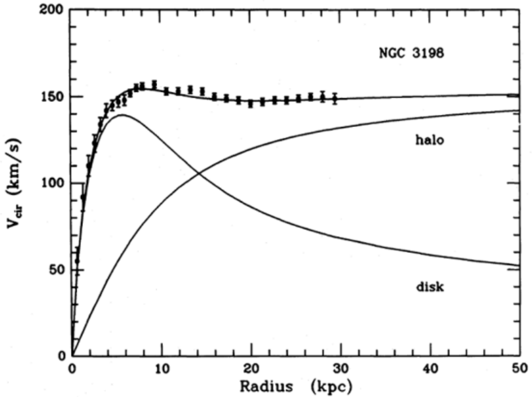
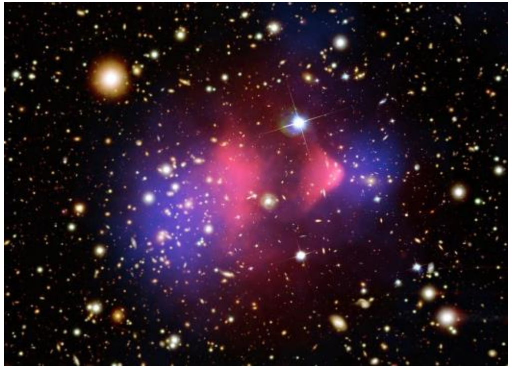
Dark Matter

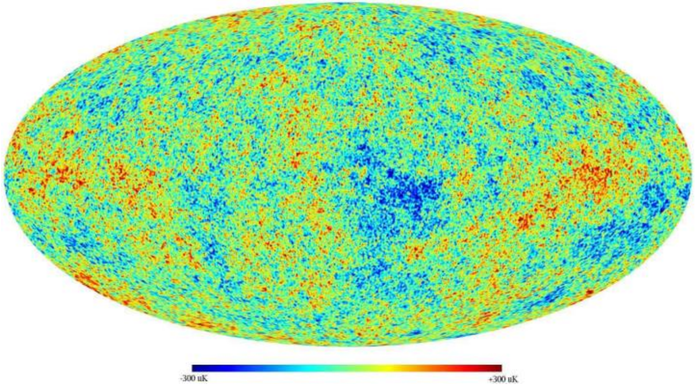




Rotational curves of galaxies

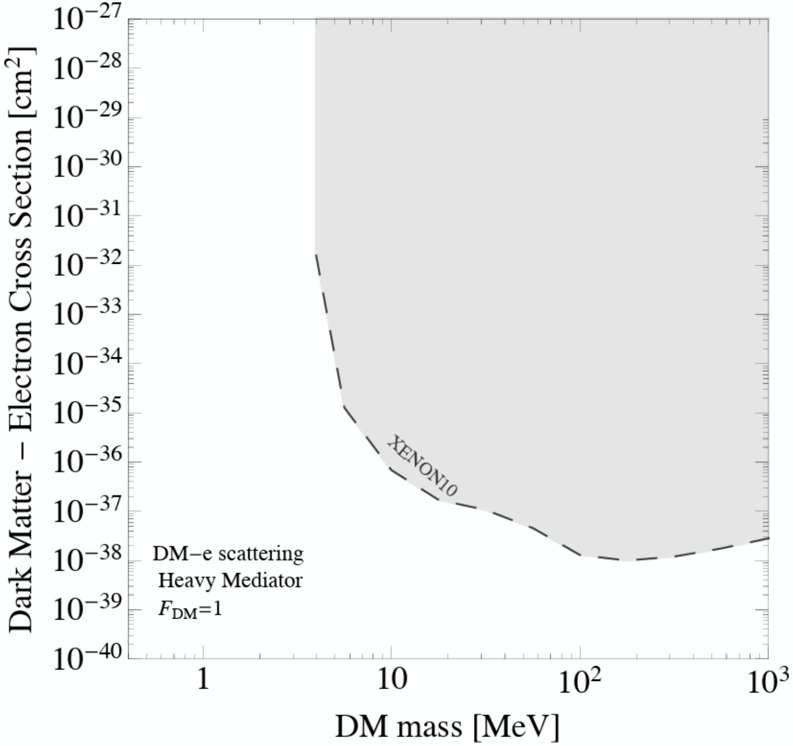


Weak lensing effect in Bullet Clusters



Anisotropies in CMB

Earlier Dark Matter Searches



Essig et al., PRL 2012

Bounds on neutrino-DM interaction

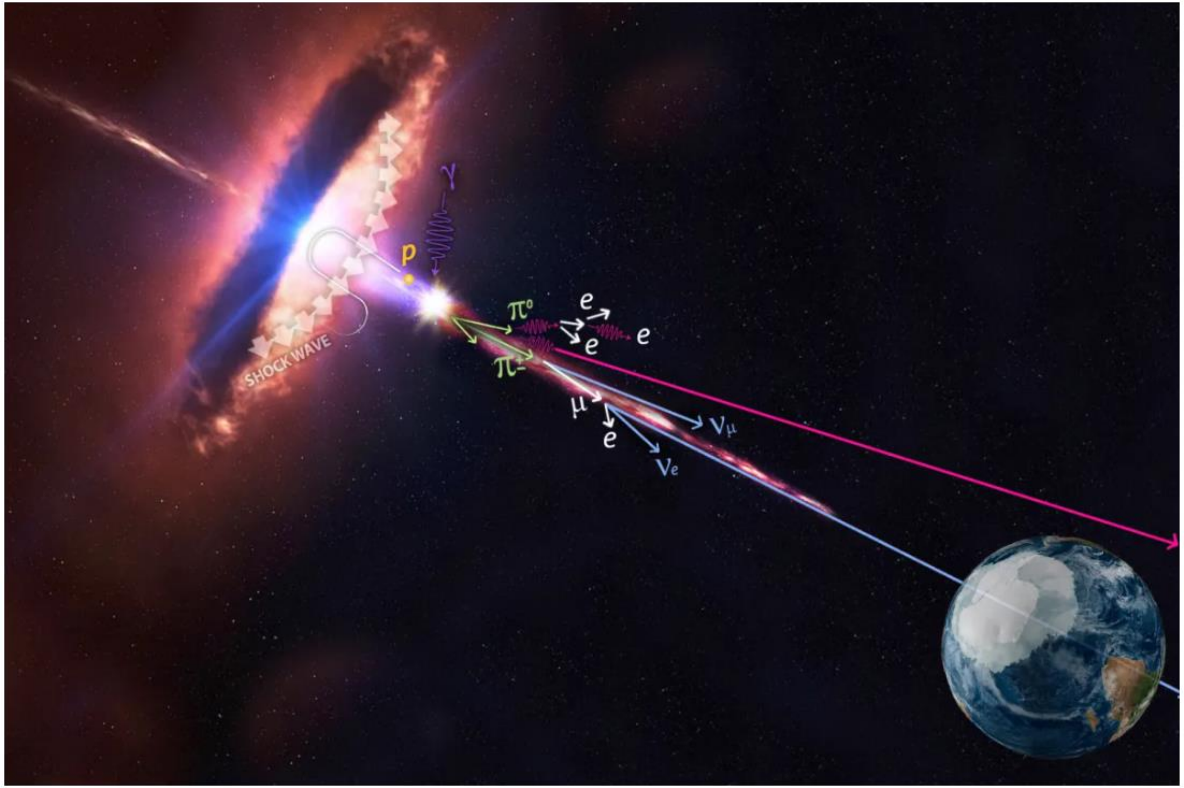
How can we put model independent bounds on neutrino-dark matter interactions?

Basic idea: Infer ν-DM scattering properties by studying how the neutrino flux from a source gets attenuated along its journey (Choi et al., PRD 2019)

We need:

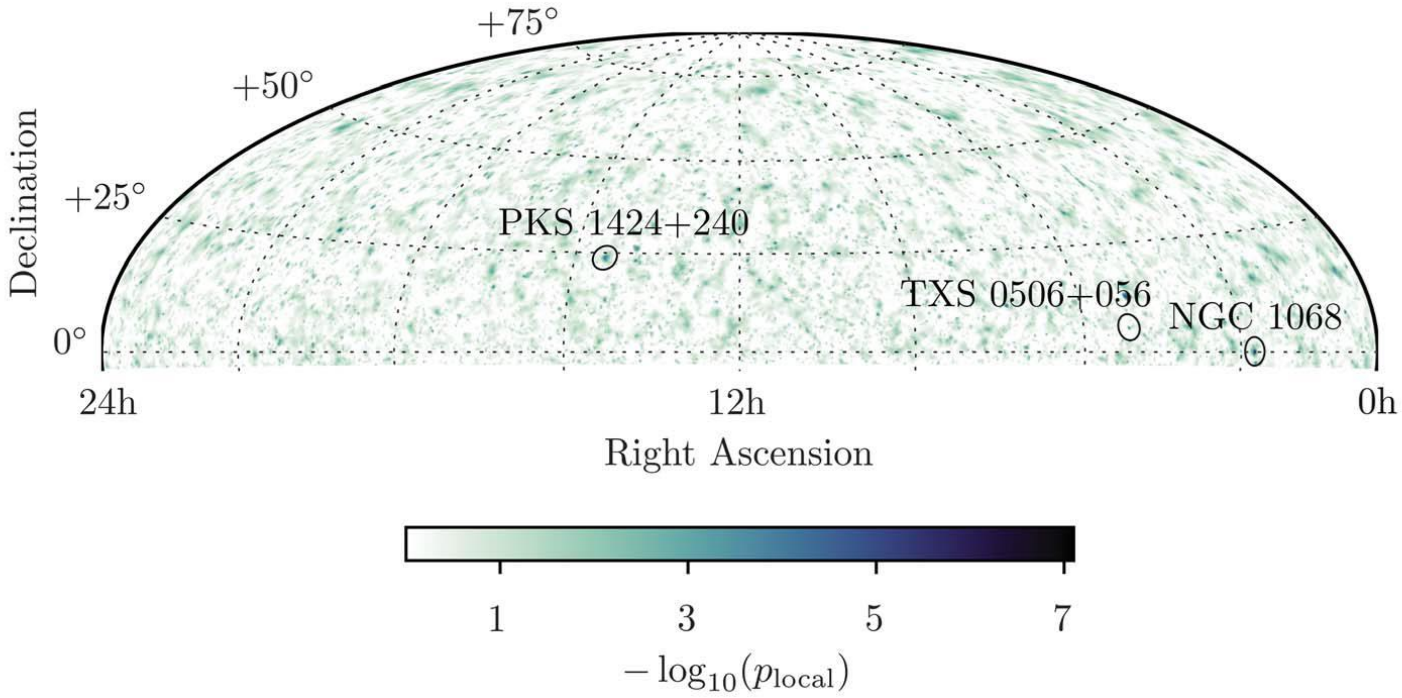
- High energy neutrino sources, whose neutrinos are already detected
- Theoretical understanding of the initial ν-spectrum at the source
- Knowledge of the possible DM distribution along the path of neutrino journey

Astrophysical neutrinos



Credit:
IceCube/NASA

Searches for Point-like Neutrino Sources at IceCube



IceCube Collaboration, 2022

High Energy Astrophysical Neutrino Data from IceCube

➔ IceCube has performed several all-sky searches for point-like neutrino sources using track-like events induced by ν_μ and $\bar{\nu}_\mu$.

➔ PSTracks event selection : IceCube public data from its IC86 configuration

- Designed for point-source studies with the good angular resolution of tracks $(< 1^o)$
- Can tolerate larger atmospheric background contributions compared to diffuse neutrino analyses.

➔ Cumulative excess of events has been observed, mostly determined by four sources with significance of 3.3σ (Abbasi, et al., 2021)

Point sources detected by IceCube with high significance

Name	RA (Deg)	Dec (Deg)	Redshift	Distance (Mpc)
NGC 1068	40.669629	−0.013281	0.00379	16.3
TXS 0506+056	77.358185	5.693148	0.3365	1339.3
PKS 1424+240	216.751632	23.8	0.604	2244.2
GB6 J1542+6129	235.737265	61.498707	0.34-1.76	1352.0-4896.5

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Also included NGC 4151, 2.9σ significance (Abbasi et al., 2024)

Source Flux and Event Distributions

- Typical pion-decay neutrino flux from astrophysical sources: $\Phi^0_{\nu_\mu} \approx \Phi^0_{\bar{\nu}_\mu} \approx \Phi^0_{\nu_e} = \phi^0 \left(\frac{E_\nu}{1\ \mathrm{TeV}}\right)^{-\gamma}$
- Source flux at the detector: $\Phi^{\mathrm{src}}_{\nu_\mu} = \Phi^0_{\nu_\mu} P_{\mu\mu} + \Phi^0_{\nu_e} P_{e\mu} = x P_{ee} \Phi^0_{\nu_e} + (1-x) P_{e\mu} \phi^0_{\nu_\mu}$

$$(x = 1/3 \text{ for } \pi - \text{decay})$$

- Events from the source:

$$n_s = T \int d\Omega \int_{E_1}^{E_2} dE_\nu \, A^{\mathrm{eff}}_\nu(E_\nu, \Omega) \, \Phi^{\mathrm{src}}_{\nu_\mu}(E_\nu; \delta m_i^2, \phi^0, \gamma) + \text{antineutrinos}$$

- Events from atmospheric and astrophysical backgrounds:

$$n_b = T \int d\Omega \int_{E_1}^{E_2} dE_\nu \, A^{\mathrm{eff}}_\nu(E_\nu, \Omega) \left[\phi^{\mathrm{atm}}_{\nu_\mu}(E_\nu, \Omega) + \phi^{\mathrm{ast}}_{\nu_\mu}(E_\nu, \Omega)\right] + \text{antineutrinos}$$

$\phi^{atm}_{\nu_\mu}$ → Conventional & prompt atmospheric background (Honda et al., 2015; Reno and Enberg, 2008)
$\phi^{ast}_{\nu_\mu}$ → Diffuse astrophysical background (IceCube collaboration, 2020)

Statistical Analysis

- Probability density for a neutrino with energy E_j from an astrophysical point source with flux $\Phi^{\rm src}$ and corresponding signal events $n_{s,k}$ is

$$P(E_j|\phi^{\rm src}) = \frac{\sum_k M(E_j,E_k^*)n_{s,k}}{\sum_k n_{s,k}}$$;

$M(E_j, E_k)$ ⟶ energy migration matrix provided by the IceCube Collaboration

- Source probability density for the j-th ν event drawn from a Gaussian profile

$$\mathcal{S}_j(\vec{x}_j, \vec{x}_s, E_j, \phi^{\rm src}) = \frac{1}{2\pi\sigma_j^2} e^{-\frac{|\vec{x}_j - \vec{x}_s|^2}{2\sigma_j^2}} P(E_j|\phi^{\rm src})$$

- Background probability density for the j-th ν event $\mathcal{B}_j = \frac{P(E_j|\phi^{\rm atm}+\phi^{\rm ast})}{\Delta\Omega_s}$

- Likelihood function $\mathcal{L}(\vec{x};\hat{\theta}) = \Pi_{j=1}^{N}\left[\frac{n_s}{N}\mathcal{S}_j + \left(1-\frac{n_s}{N}\right)\mathcal{B}_j\right], \hat{\theta} = \{\phi^0, \gamma\}$

- Test Statistic $TS = -2\left[\log\mathcal{L}(\vec{x}_s;\hat{\theta}_0) - \log\mathcal{L}(\vec{x}_s;\hat{\theta})\right]$ (Braun et al. 2008)

Statistical Analysis

Best-fit values with corresponding 1σ intervals of number of events and the spectral index

Source	$\hat{\gamma}_{\rm SM} \pm 1\sigma$	$\hat{n}_s \pm 1\sigma$
NGC 1068	$2.9^{+0.2}_{-0.3}$	76^{+16}_{-15}
TXS 0506+056	$2.3^{+0.2}_{-0.3}$	28^{+13}_{-11}
PKS 1424+240	$3.3^{+1.2}_{-0.6}$	44^{+16}_{-14}
NGC 4151	$2.4^{+0.4}_{-0.3}$	30^{+13}_{-10}

(K.D., Miranda, Razzaque, 2024)

Dark Matter Density Profile

- Adiabatic growth of black hole makes the DM density profile steeper in the inner halo (Gondola & Silk, PRL 1999)

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

where, $\gamma = 1 \Rightarrow \alpha = 7/3$

- Gravitational scattering between DM and stars can dynamically relax the slope of DM spike profile to $\alpha = 3/2$ (Gnedin & Primack, PRL 2004)

- We can normalize $\rho'(r)$ via (Ullio et al., PRD 2001)

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

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

Dark Matter Density Profile

- Outside of the spike radius, the density of DM halo continues to be determined by the pre-existing NFW density profile (Navarro, Frenk & White, APJ 1996)

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

- If DM annihilation occurs, the spike profile becomes more cored

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

where, $\langle\sigma v\rangle$ is the velocity averaged annihilation cross section ($10^{-26}\ cm^3/s$) and t_{BH} is the age of SMBH

$\langle\sigma_a v\rangle$	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

Column Density

- The probability for neutrinos to scatter from DM in the spike depends on the DM column density, defined as

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

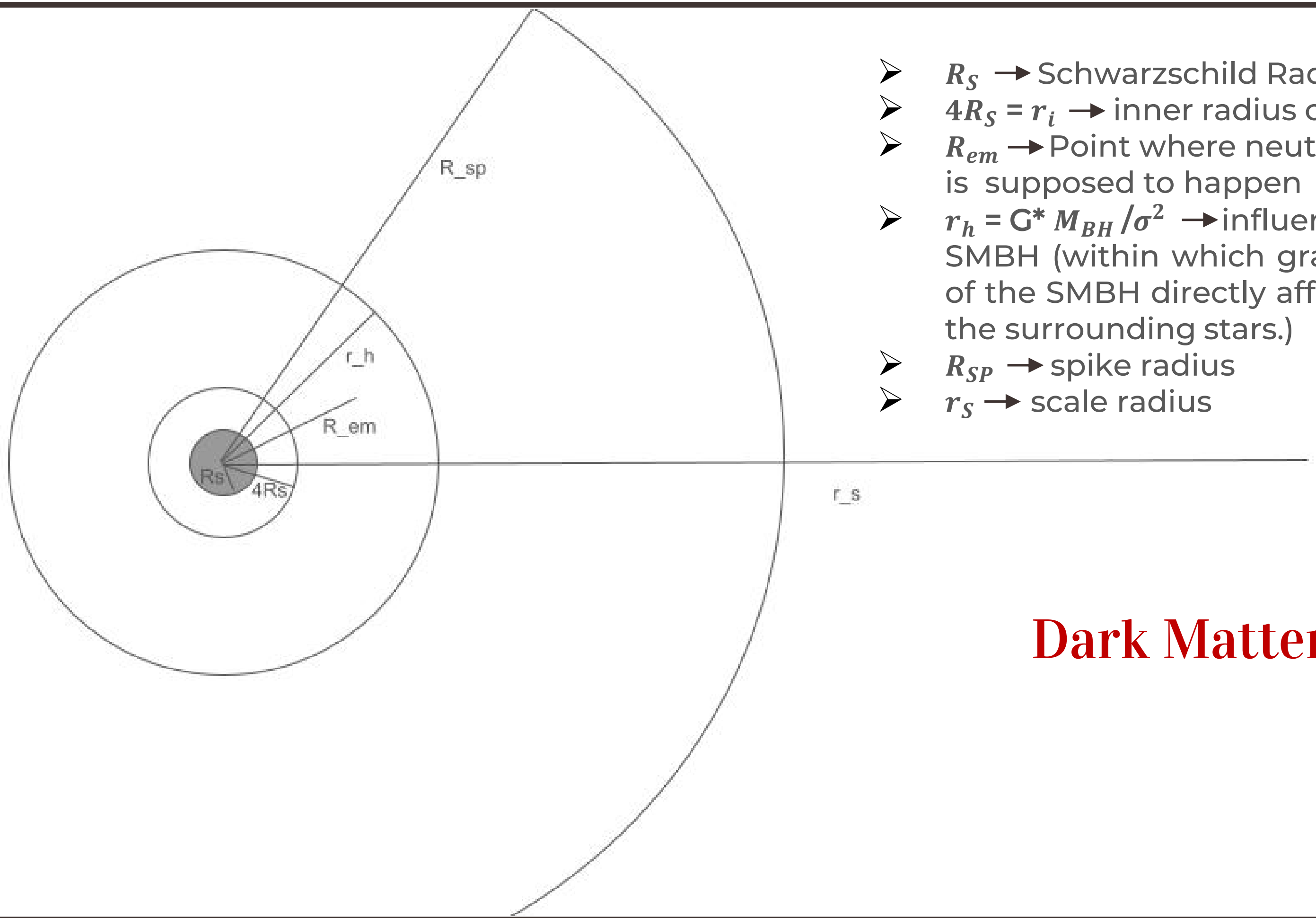
- The cosmological and Milky-Way galactic contributions to σ_{DM} are negligible compared to the DM spike.

- The neutrino flux attenuation due to the scatter with DM along their journey to the detector can be described by (Arguelles et al., PRL 2017)

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

where, $\tau = \Sigma(r)/m_{DM}$ is the accumulated column density.

For constant $\sigma_{DM} = \sigma_0 \Rightarrow \phi_0 e^{-\sigma_0 \Sigma/m_{DM}}$
In the high-energy regime of a model with a mediator of mass $m_{Z'} << \sqrt(E_\nu m_\chi)$, the second term can be neglected (Cline et al., PRL 2023)



- R_S → Schwarzschild Radius
- $4R_S = r_i$ → inner radius of spike
- R_{em} → Point where neutrino emission is supposed to happen
- $r_h = G^* M_{BH} / \sigma^2$ → influence radius of SMBH (within which gravitational effects of the SMBH directly affect the motion of the surrounding stars.)
- R_{SP} → spike radius
- r_S → scale radius

Dark Matter Profile

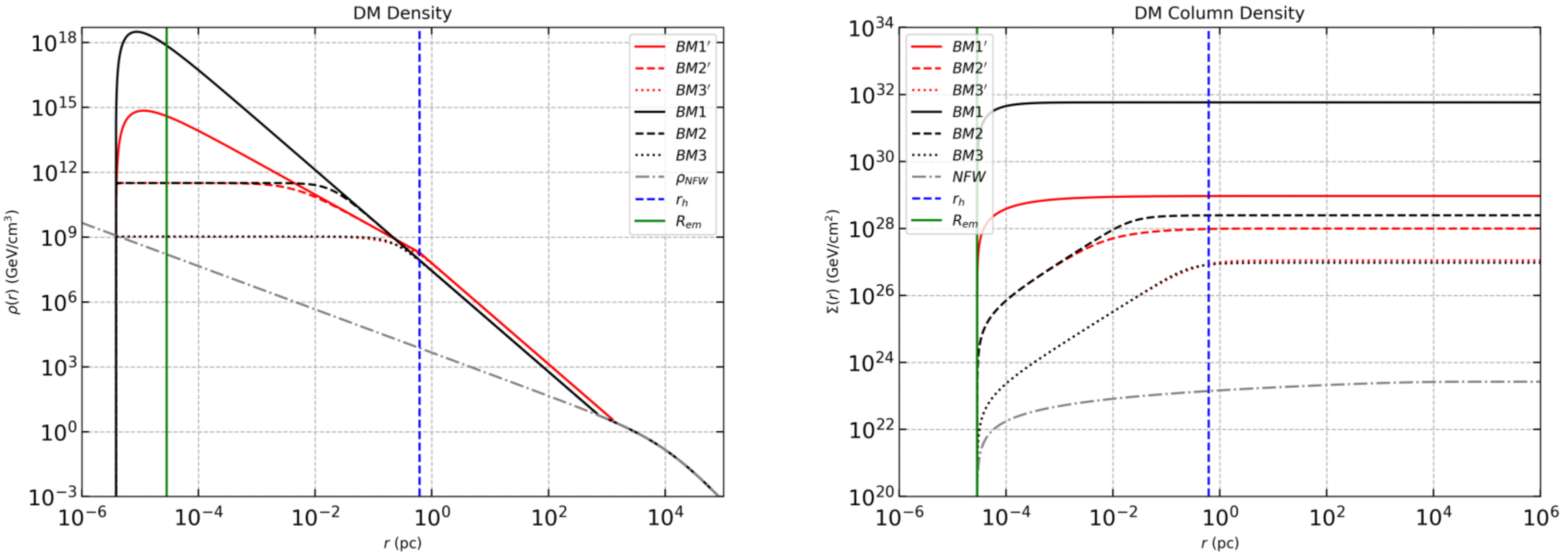
Dark Matter Density Profile

Parameter	NGC 1068	TXS 0506+056	PKS 1424+240	NGC 4151
M_{BH} ($M_{\odot}$)	1.0×10^{7}	3.09×10^{8}	$1.0x10^{9}$	2.0×10^{7}
R_S (pc)	9.6×10^{-7}	3.0×10^{-5}	9.5×10^{-5}	2.0×10^{-6}
t_{BH} (yr)	10^{9}	10^{9}	10^{9}	10^{9}
r_h	$6.5x10^{5}\ R_S$	$10^{5}\ R_S$	$10^{5}\ R_S$	$6.5x10^{5}\ R_S$
R_{em}	$10R_S$	$2x10^{3}R_S$	$100\ R_S$	$10R_S$

K.D., Mohlabeng, Razzaque, in prep.

Dark Matter Density Profile

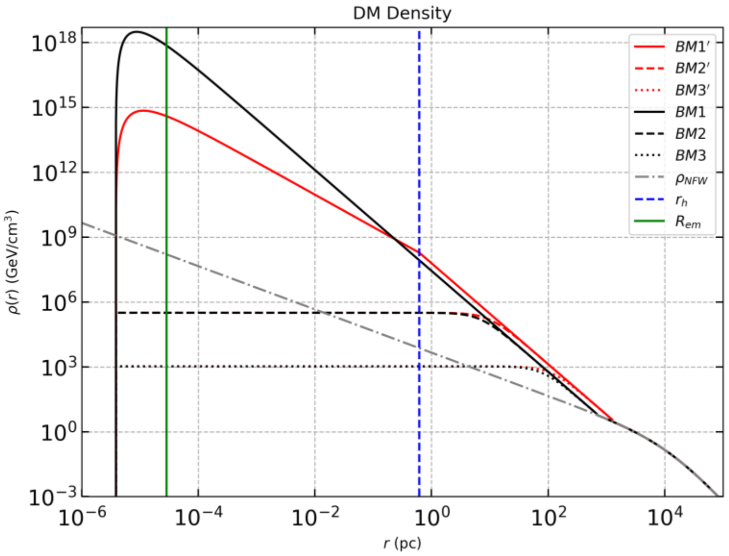
NGC 1068 $(m_\chi = 1\ GeV)$

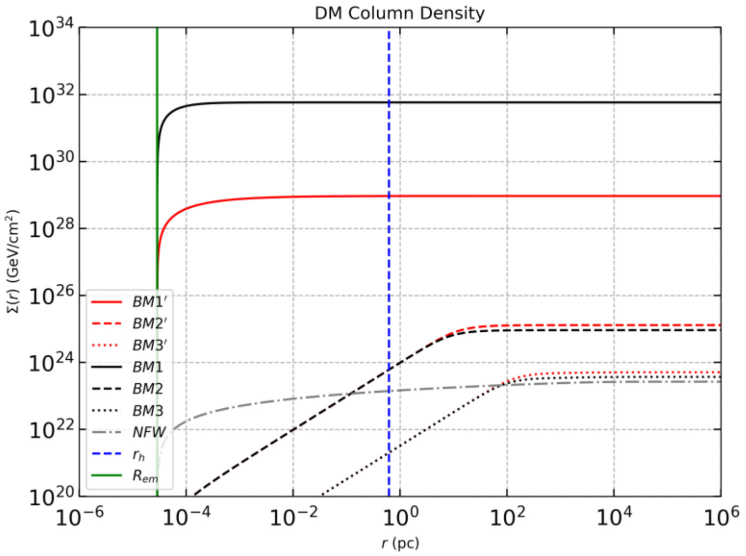


K.D., Mohlabeng, Razzaque, in prep.

Dark Matter Density Profile

NGC 1068 $(m_\chi = 0.001\ MeV)$





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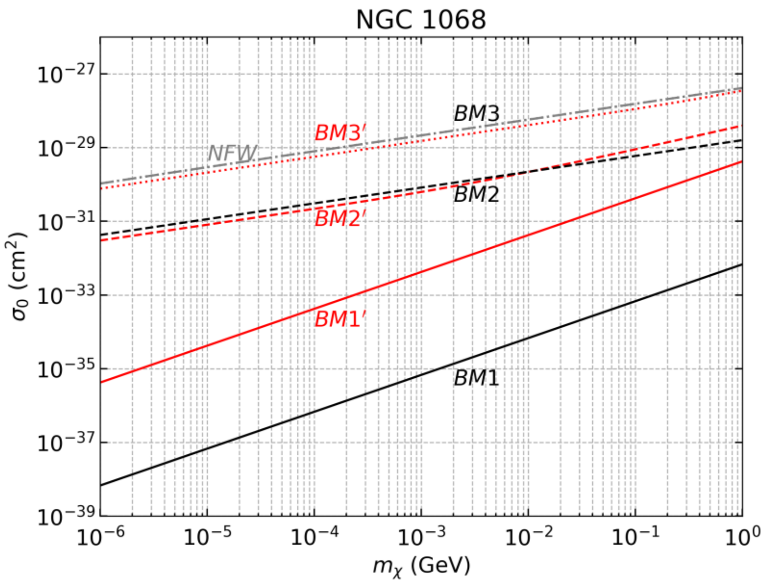
Methodology

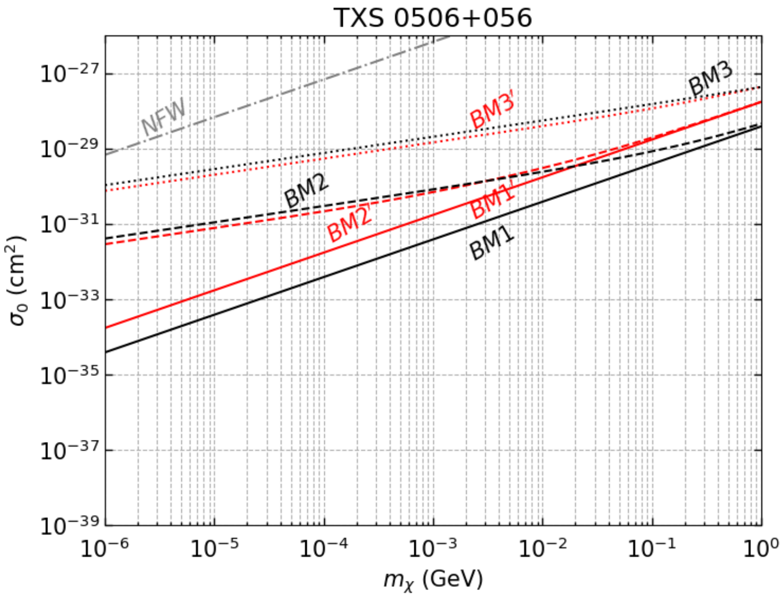
- Neutrino flux gets attenuated due to interaction with dark matter.
- We calculate the total number of observed events in IceCube for individual sources with lower limit on these number of events with 90% CL.
- The attenuation is allowed to be within the 90% CL lower limit on number of events, and that puts the constraint/upper bound on the cross section of this scattering.

$$\sigma_0 < \frac{n_s^{90\% CL_{lower}}}{n_s^{best\ fit}} \frac{m_\chi}{\Sigma_\chi}$$

K.D., Mohlabeng, Razzaque, in prep.

Constraint on DM-neutrino Cross-Section



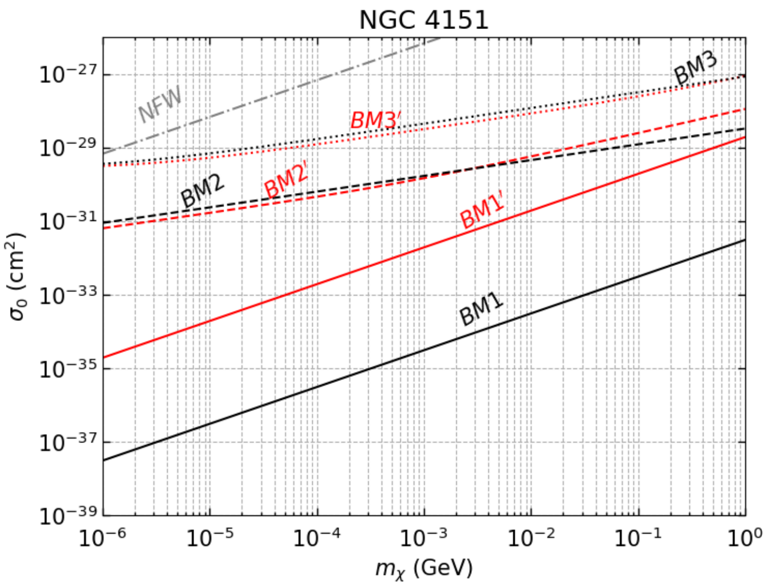


$\sigma_0 < 0.39 \frac{m_\chi}{\Sigma_\chi}$ NGC 1068

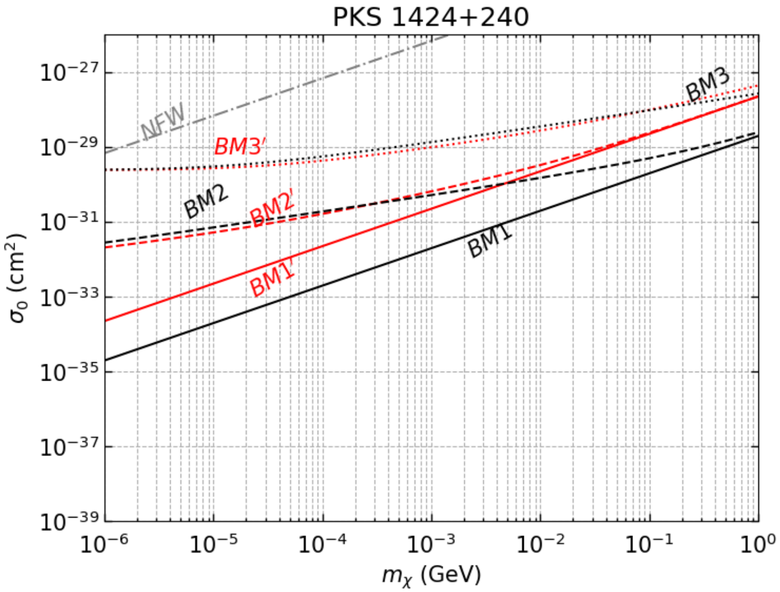
$\sigma_0 < 1.03 \frac{m_\chi}{\Sigma_\chi}$ TXS 0506 + 056

K.D., Mohlabeng, Razzaque, in prep.

Constraint on DM-neutrino Cross-Section



$$\sigma_0 < 0.88 \frac{m_\chi}{\Sigma_\chi} \quad \text{NGC 4151}$$



$$\sigma_0 < 0.77 \frac{m_\chi}{\Sigma_\chi} \quad \text{PKS 1424+240}$$

K.D., Mohlabeng, Razzaque, in prep.

Summary

- Astrophysical neutrinos provide an enormous platform to probe dark matter.
- IceCube has provided its data publicly and allows to put significant constraints on neutrino-dark matter interaction
- We obtain bound on the DM-ν cross-section from recently observed four neutrino point sources
- Future experiments viz, KM3Net, IceCube Gen-2, P-ONE and so on can improve results in this line.

Future direction: Constraining energy dependent cross-section of dark matter-neutrino interaction; performing stacking analysis.

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Thank you for attention!