Hunting Dark Matter through High-Energy Cosmic Neutrinos

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과학기술정보통신부

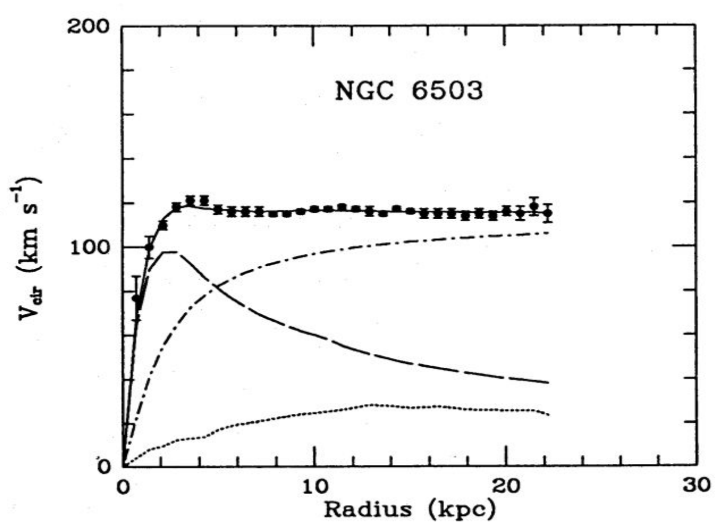
Tentative Talk Plan

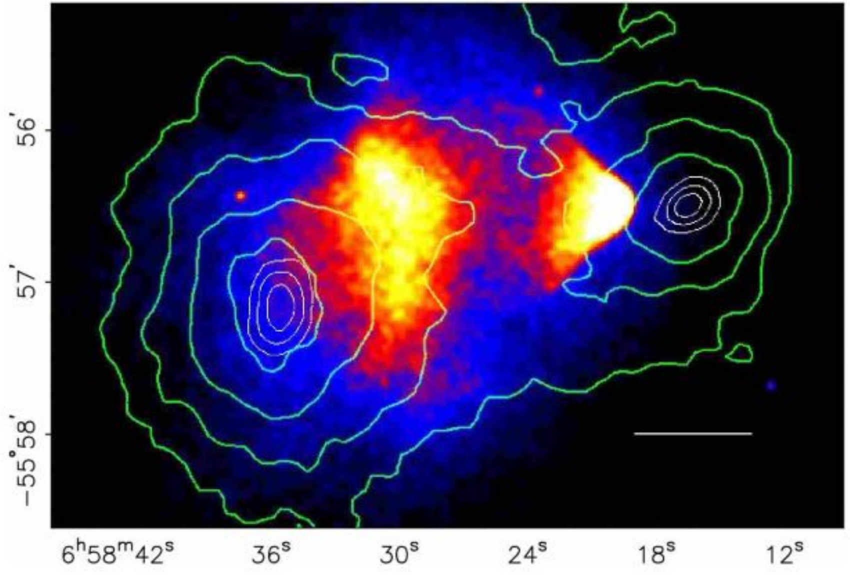
- Motivation for Dark Matter Study
- Description of KM3NeT signal
- Relevant studies on KM3NeT
- Our contributions
- Conclusion

❖ Motivation for Dark Matter Study

Bullet cluster and Velocity curve

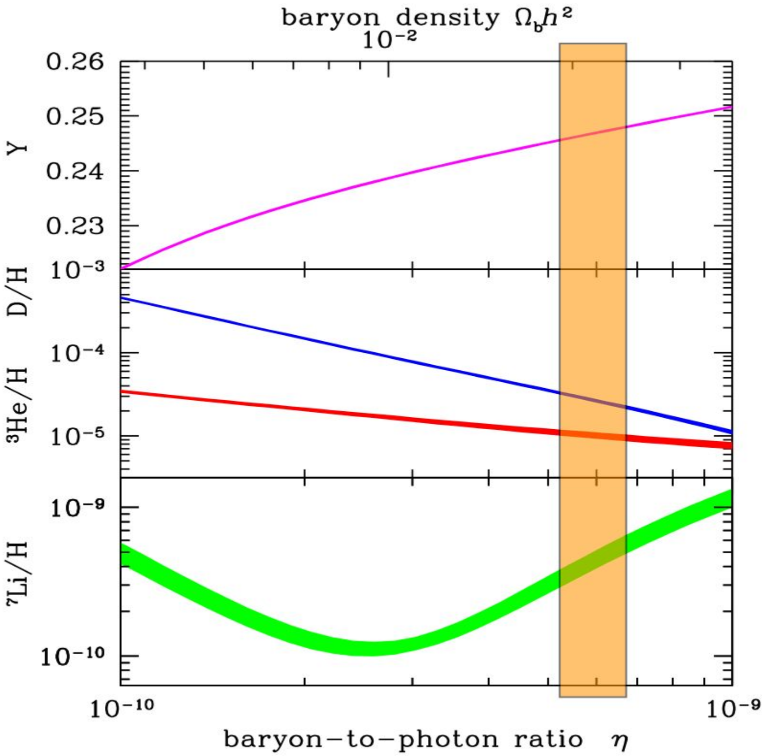
Astrophys. J. 648, L109 (2006)

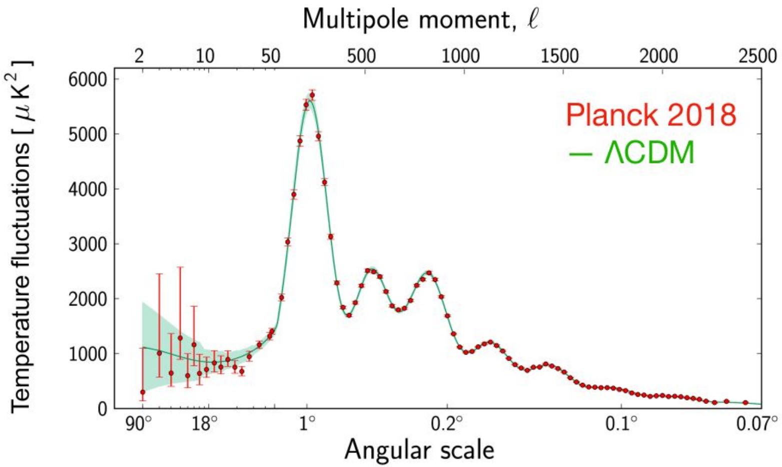




- ➢ Bullet cluster is a recent merging of galaxy clusters.
- ➢ The gravitational potential is not produced by baryons, but by DM.
- ➢ Hot gas is collisional and loses energy, so lags behind DM.
- ➢ DM clusters are collisionless and passed through each other

BBN and CMB





Parameter	Plik best fit	Plik [1]	CamSpec [2]	([2] − [1])/σ_1	Combined
$\Omega_b h^2$	0.022383	0.02237 ± 0.00015	0.02229 ± 0.00015	−0.5	0.02233 ± 0.00015
$\Omega_c h^2$	0.12011	0.1200 ± 0.0012	0.1197 ± 0.0012	−0.3	0.1198 ± 0.0012
$100\theta_{MC}$	1.040909	1.04092 ± 0.00031	1.04087 ± 0.00031	−0.2	1.04089 ± 0.00031
τ	0.0543	0.0544 ± 0.0073	$0.0536^{+0.0069}_{-0.0077}$	−0.1	0.0540 ± 0.0074
$\ln(10^{10} A_s)$	3.0448	3.044 ± 0.014	3.041 ± 0.015	−0.3	3.043 ± 0.014
n_s	0.96605	0.9649 ± 0.0042	0.9656 ± 0.0042	+0.2	0.9652 ± 0.0042
$\Omega_m h^2$	0.14314	0.1430 ± 0.0011	0.1426 ± 0.0011	−0.3	0.1428 ± 0.0011
H_0 [km s^{-1}Mpc^{-1}] . . .	67.32	67.36 ± 0.54	67.39 ± 0.54	+0.1	67.37 ± 0.54
Ω_m	0.3158	0.3153 ± 0.0073	0.3142 ± 0.0074	−0.2	0.3147 ± 0.0074
Age [Gyr]	13.7971	13.797 ± 0.023	13.805 ± 0.023	+0.4	13.801 ± 0.024
σ_8	0.8120	0.8111 ± 0.0060	0.8091 ± 0.0060	−0.3	0.8101 ± 0.0061
$S_8 \equiv \sigma_8(\Omega_m/0.3)^{0.5}$ . .	0.8331	0.832 ± 0.013	0.828 ± 0.013	−0.3	0.830 ± 0.013
z_{re}	7.68	7.67 ± 0.73	7.61 ± 0.75	−0.1	7.64 ± 0.74
$100\theta_*$	1.041085	1.04110 ± 0.00031	1.04106 ± 0.00031	−0.1	1.04108 ± 0.00031
r_{drag} [Mpc]	147.049	147.09 ± 0.26	147.26 ± 0.28	+0.6	147.18 ± 0.29

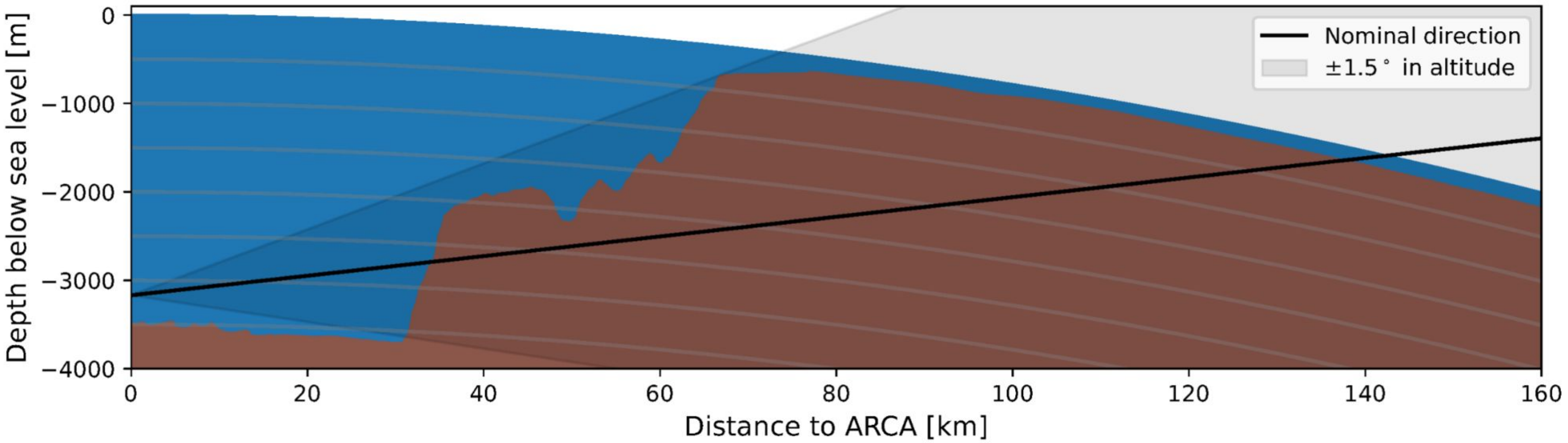
- ➢ LSS suggests without DM, density perturbations would start to grow only after recombination, so today there would not be structures.

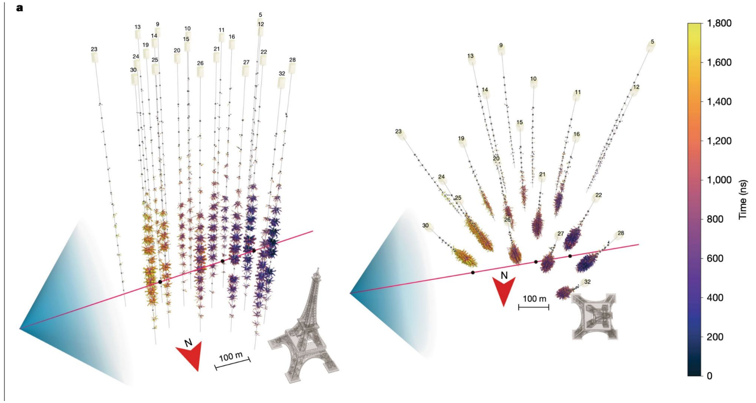
So far, there has been no direct detection of dark matter, only indirect hints. Searches continue, and today's discussion focuses on the possible dark matter origin of the **KM3NeT** observation.

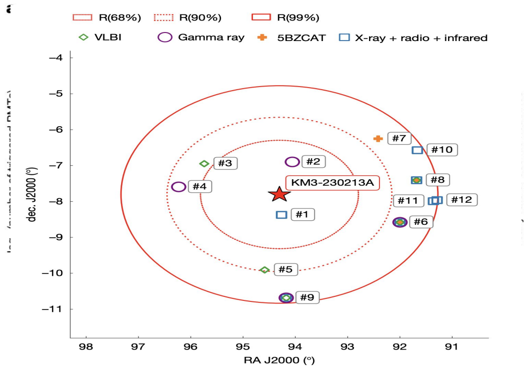
- Description of KM3NeT signal

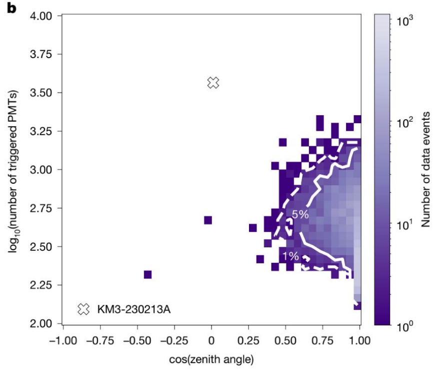
The neutrino event KM3-230213A

KM3NeT, Nature 376−382 (2025)



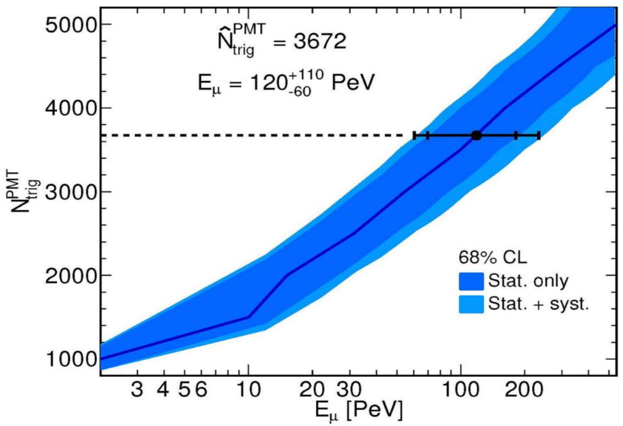


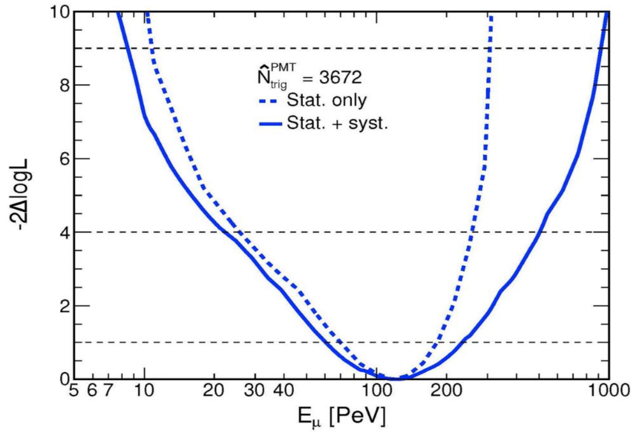


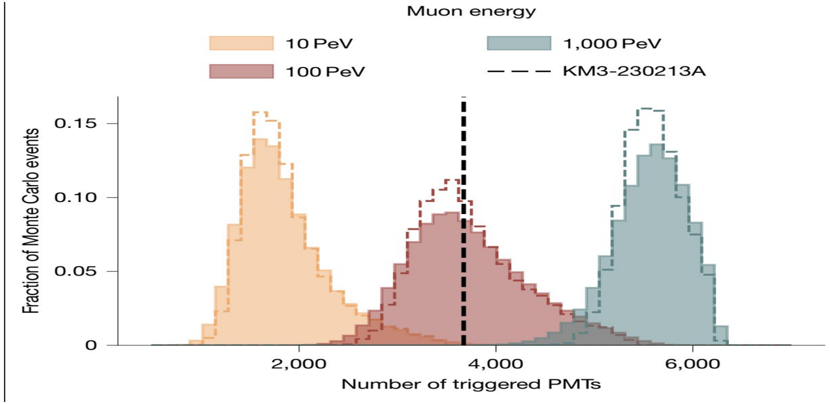


Energy estimation of muon

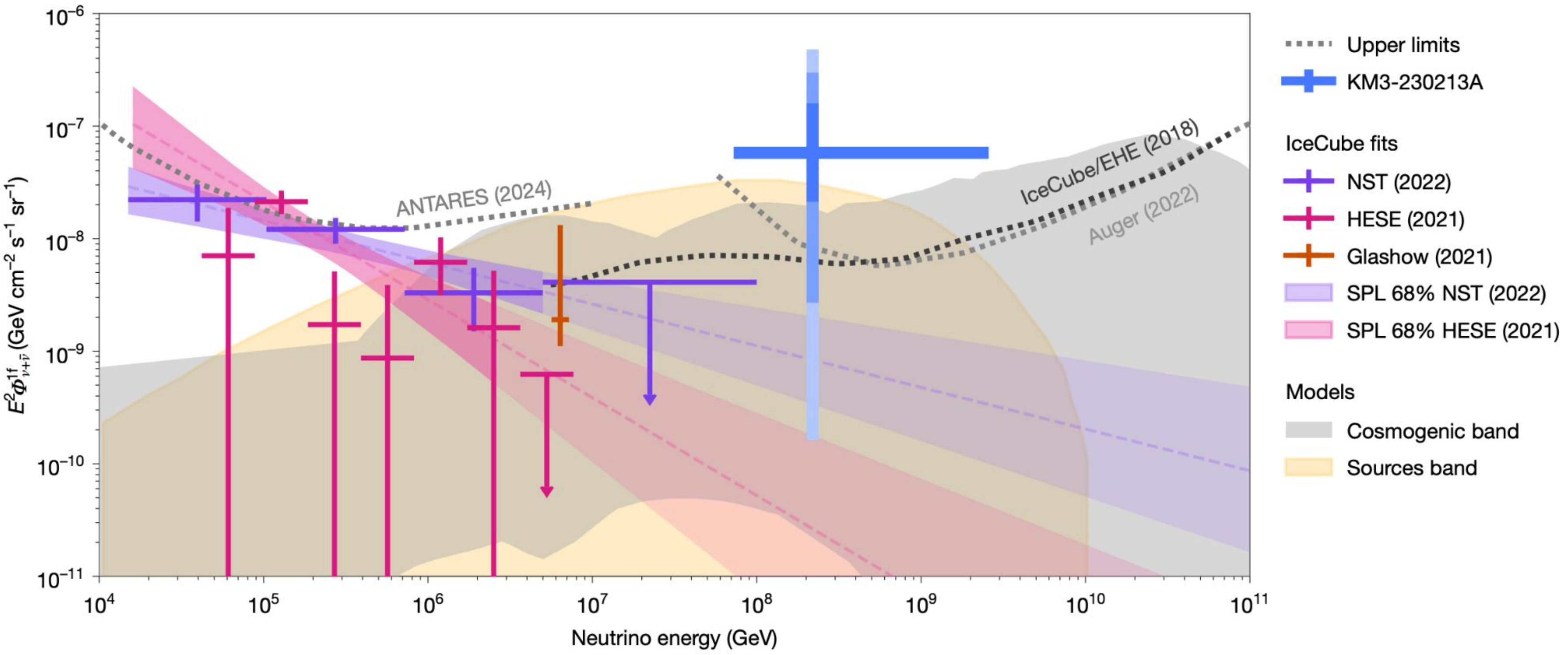
KM3NeT, Nature 376−382 (2025)





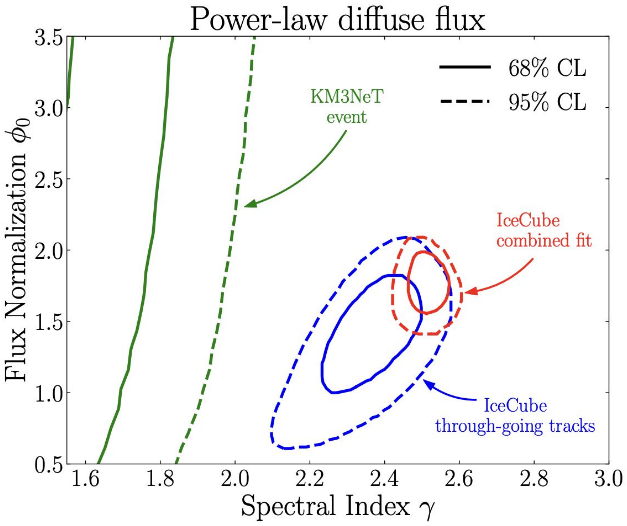


KM3NeT Signal flux

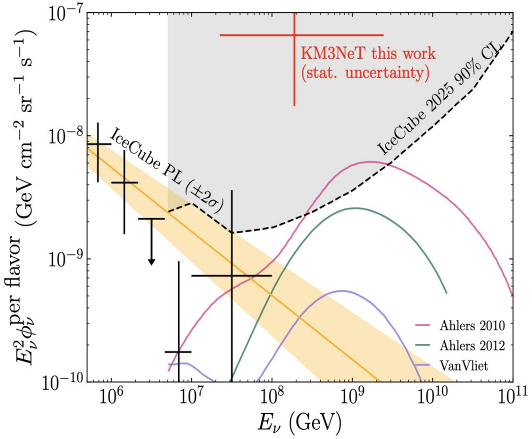


❖ Relevant studies on KM3NeT

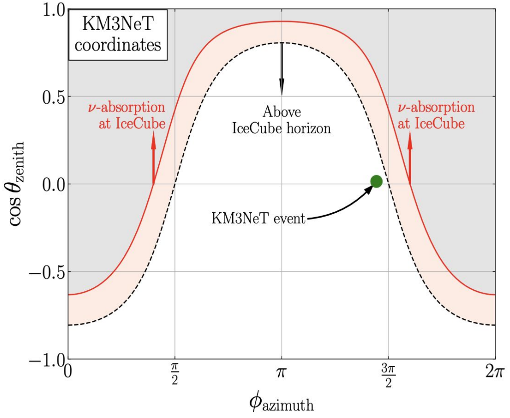
❖ The tension between the KM3NeT event and the absence of similar high-energy events in IceCube leads 3.5 sigma (1.9 sigma by KM3NeT, due to flay neutrino energy prob. and non-observation of events outside the 90% CL energy interval) when assuming the neutrino is from the diffuse isotropic neutrino flux reduces for steady or transient point source



$$\frac{d\phi}{dE_\nu} = \phi_0 \left(\frac{E_\nu}{100\,\mathrm{TeV}}\right)^{-\gamma} \times 10^{-18}/\mathrm{GeV/cm^2/s/sr}\,,$$

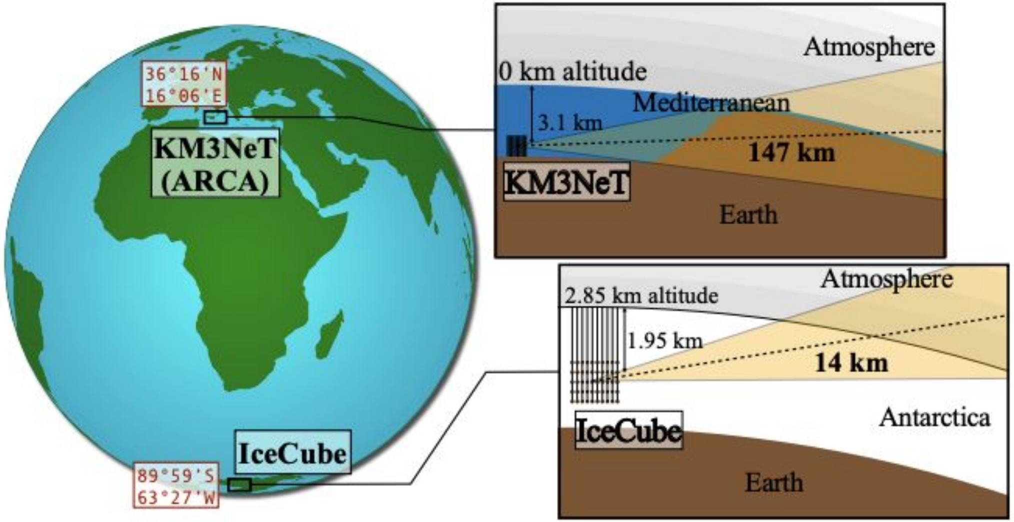


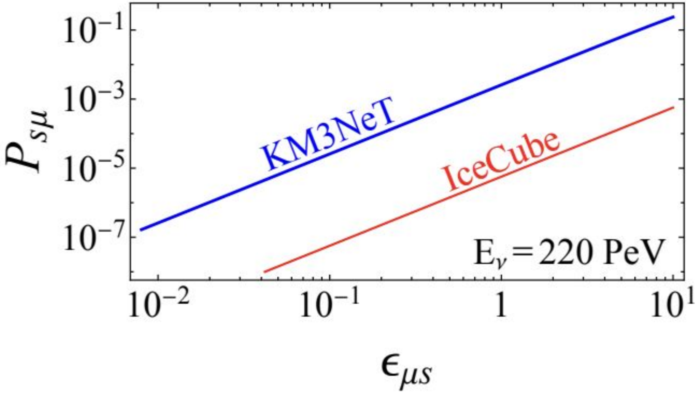
Cosmogenic flux



Point Sources

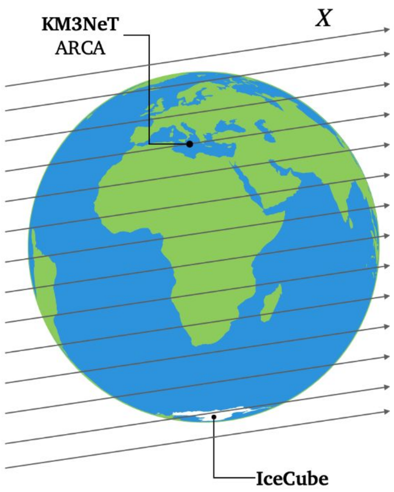
❖ Neutrino detected at KM3NeT has traversed 147 km of rock and sea, whereas neutrinos arriving from the same location would have only traveled through about 14 km of ice before reaching IceCube. We use this difference in propagation distance to address the tension between KM3NeT and IceCube through the PeV sterile neutrino oscillation to active neutrino.

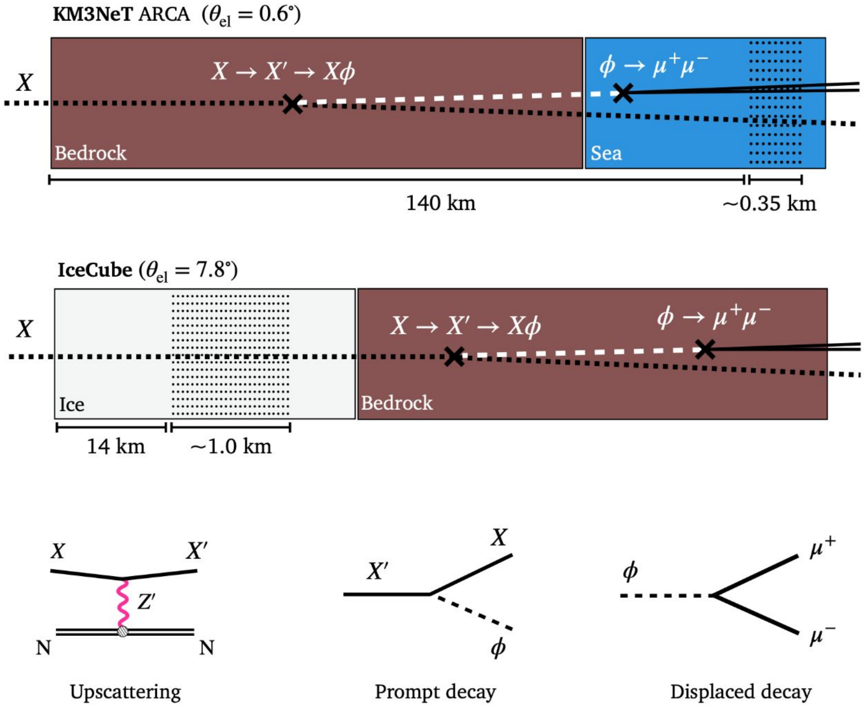




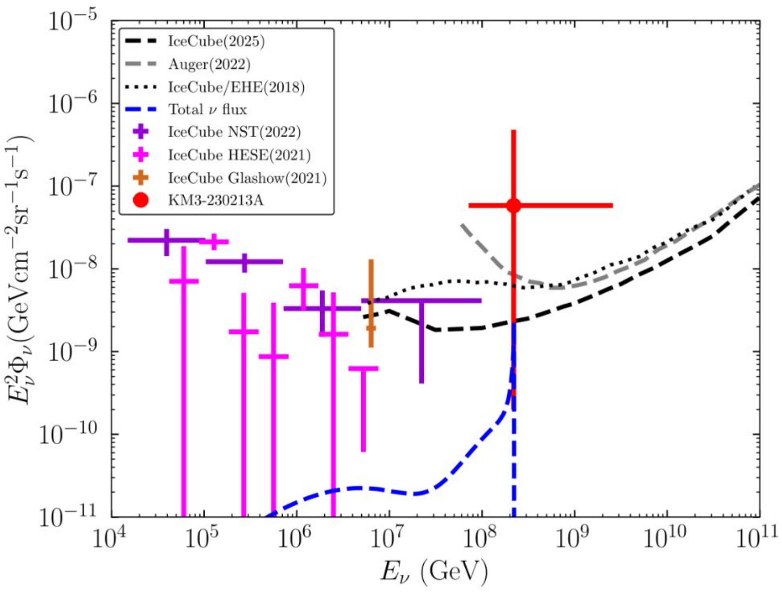
Farzan, Hostert (2505.22711);
Dev, Dutta, Karthikeyan, Maitra, Strigari, Verma (2505.22754)

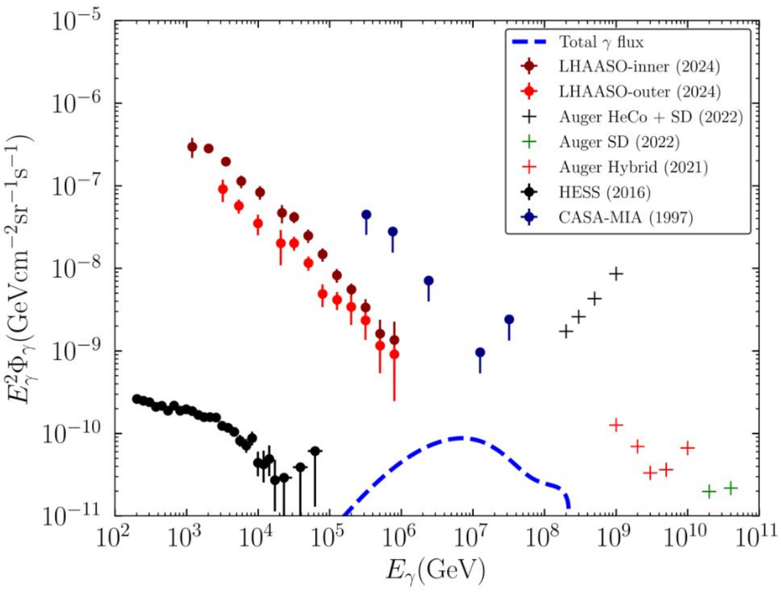
❖ Transient astrophysical sources can produce a flux of dark particles that induce ultra-high-energy signatures at neutrino telescopes such as IceCube and KM3NeT. Authors consider upscattering of a new particle X onto new metastable particles that decay to dimuons with decay lengths of O(100) km.





❖ The simplest possibility that KM3NeT event originates from the decay of a super-heavy dark matter (SHDM). The signal sets stringent constraint on the DM mass ranging from 1.5E8 GeV to 5.2E9 GeV with lifetime in the range: 1.42E30 s to 5.4E29 s. The SHDM scenario alleviate the tension between the KM3NeT observation and the non observation of this event by IceCube and Auger can be reduced to below 1.2σ.





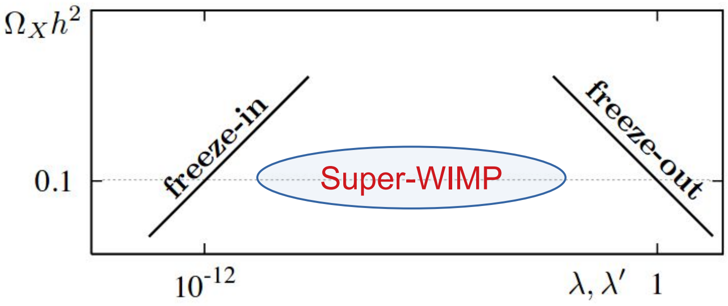
Fang,Halzen, Hooper (AJL 25);Kohri,Paul,Sahu PRD 25;Borah,Das,Okada,Sarmah (PRD 25);Jiang, Huang(JCAP 25);Jho,Park,Shin(2503.18737);Barman,Das,Sarmah (PRD 25),Murase,Narita,Yin (2504.15272);Mondol,Bouri,Saha,Laha(2506.19910);Aloisio,Ambrosone,Evoli(2508.08779);Dubey,Saha(2509.08039);Boehm,Laha,Maity(2509.07982);

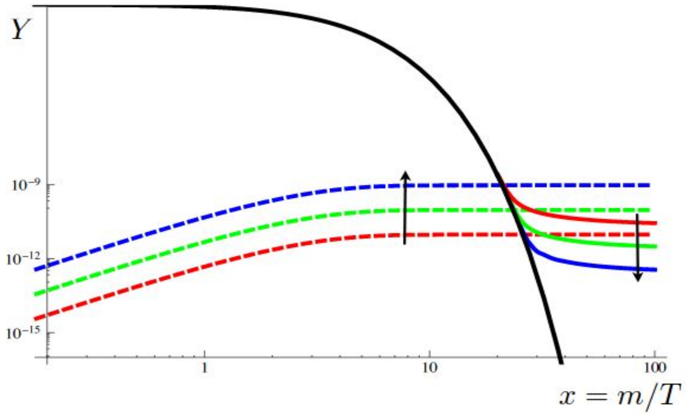
❖ Our contributions

Part I: Using Vector dark matter and kinetic mixing

DM Production Mechanisms

Hall et al' 09





- WIMP DM is easy to detect but no signal puts bound on its parameter space.
- FIMP DM is difficult to probe in different experiments due to its feeble interaction.
- In this work, we focus on production via freeze-in/out with the UV physics dependences.

- We first discuss the drawbacks of heavy DM in the freeze-in/out mechanisms.
- As remedy, we produce DM with the entropy dilution and UV freeze-in.

Abelian Vector dark matter

S. Khan, J. Kim and H. M. Lee (2509.17129)

Gauge	Baryon Fields			Lepton Fields		Scalar Field	
Group	$Q_L^i=(u_L^i,d_L^i)^T$	u_R^i	d_R^i	$L_L^i=(\nu_L^i,e_L^i)^T$	e_R^i	H	ϕ_D
$\mathrm{SU(2)_L}$	2	1	1	2	1	2	1
$\mathrm{U(1)_Y}$	1/6	2/3	−1/3	−1/2	−1	1/2	0
$\mathrm{U(1)_D}$	0	0	0	0	0	0	1

$$\mathcal{L}=\mathcal{L}_{\rm SM}+\left(D_\mu^\dagger\phi_D D^\mu\phi_D\right)-\mathcal{L}_{Kinetic}^{gauge}-\mathcal{V}(\phi_D,H),$$

$$\frac{dY_{W_D}}{dx}=-\frac{s(x)\langle\sigma v\rangle}{xH(x)}\left[Y_{W_D}^2-\left(Y_{W_D}^{\rm eq}\right)^2\right],$$

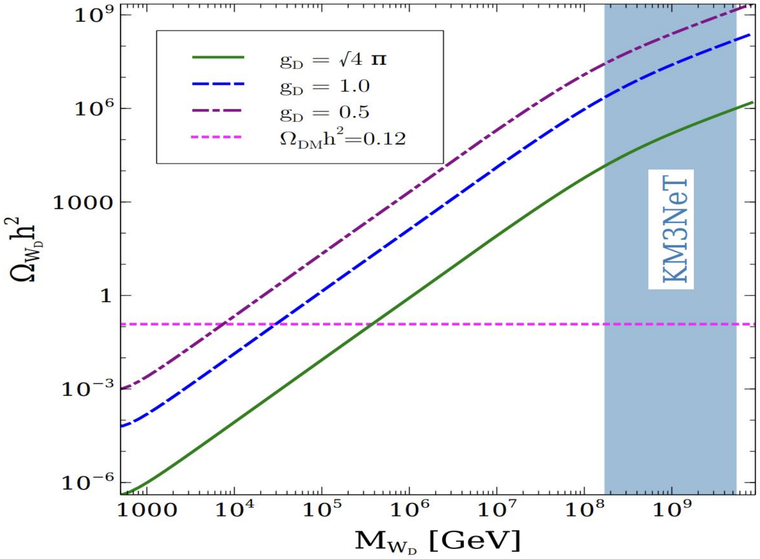
$$\Downarrow$$

$$Y_{W_D}^0=Y_{W_D}^f\left[1+\frac{2\pi^2}{45}\sqrt{\frac{90}{\pi^2}}M_{\rm P}m_iY_{W_D}^f\frac{g_s(x^f)}{\sqrt{g(x^f)}}\frac{\langle\sigma v\rangle_{W_DW_D\to h_2h_2}}{x_f}\right]^{-1},$$

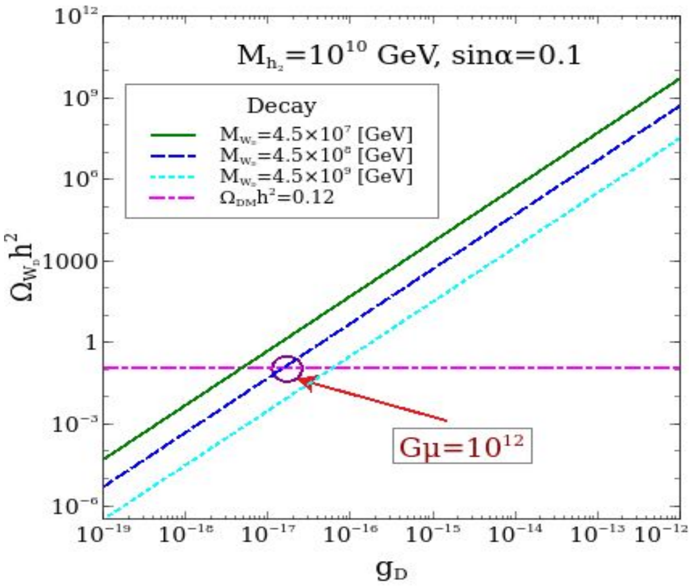
$$\Downarrow$$

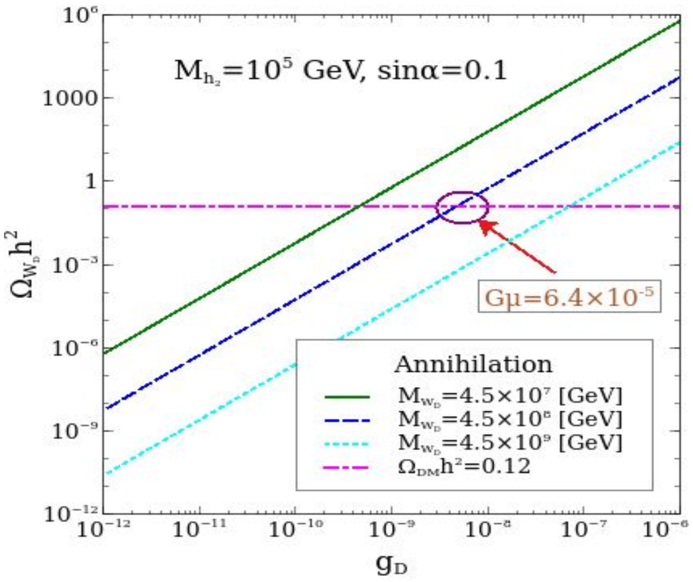
$$\Omega_{W_D}h^2=2.755\times10^8\,Y_{W_D}\left(\frac{M_{W_D}}{\rm GeV}\right)$$

Drawback of Freeze-out Mechanism



Drawback of Freeze-In Mechanism





Solutions

- ➔ Low reheating for FO/FI
- ➔ UV Freeze-in

- ❖ For decay processes, the dark symmetry breaks at scales above the Planck scale, unlike in the annihilation case.
- ❖ Symmetry breaking in both cases leads to large cosmic string tension (G\mu) that are excluded by EPTA and CMB observations.

Entropy Production from Inflation decay

$$V(\phi) = \lambda_\phi M_{pl}^2 \phi^2.$$

$$\frac{d\rho_\phi}{dt} + 3H\rho_\phi = -\Gamma_\phi \rho_\phi,$$
$$\frac{ds}{dt} + 3Hs = \frac{\Gamma_\phi \rho_\phi}{T}$$

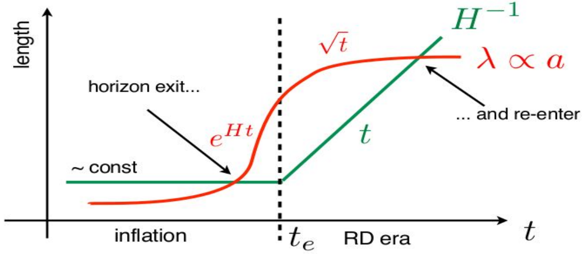
$$H^2 = \frac{8\pi}{3} \frac{\rho_\phi + \rho_R}{M_{pl}^2}$$

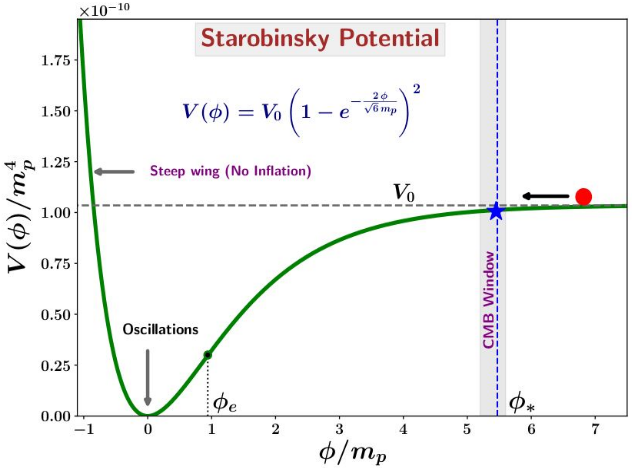
$$T_{reh}^2 = \frac{3}{2\pi}\sqrt{\frac{5}{\pi g_{eff}(T_{reh})}} M_{pl}\Gamma_\phi$$

$$T_{max}^4 = \frac{15}{2\pi^3 g_{eff}(T_{max})}\left(\frac{3}{8}\right)^{8/5} M_{pl}^2 \Gamma_\phi H_I$$

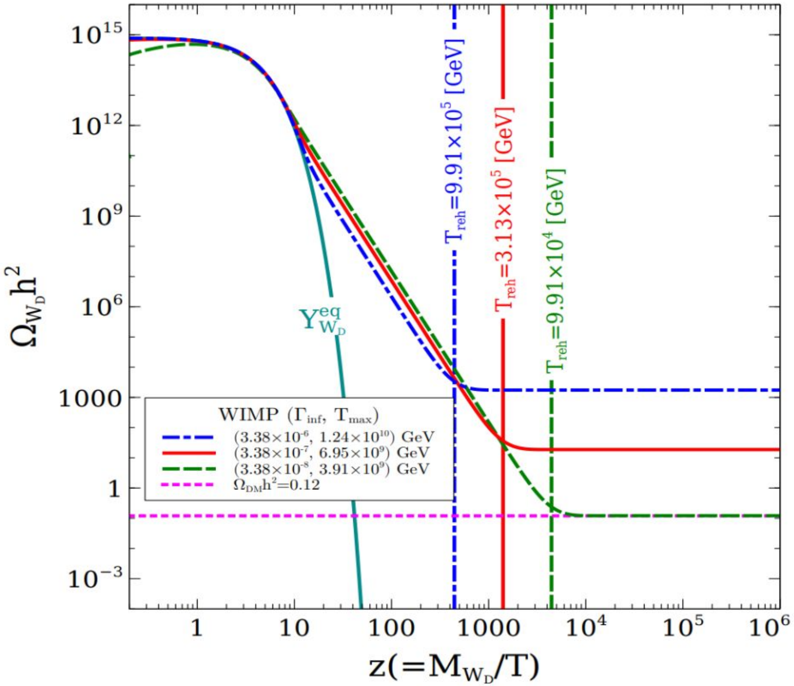
$$\delta z_{W_D} = -\frac{d\log(\bar{z}_{W_D})}{da}\frac{Ha^4}{2\langle\sigma v\rangle}, \quad \delta a = \frac{1}{\bar{z}_{W_D}}\frac{Ha^4}{2\langle\sigma v\rangle}.$$

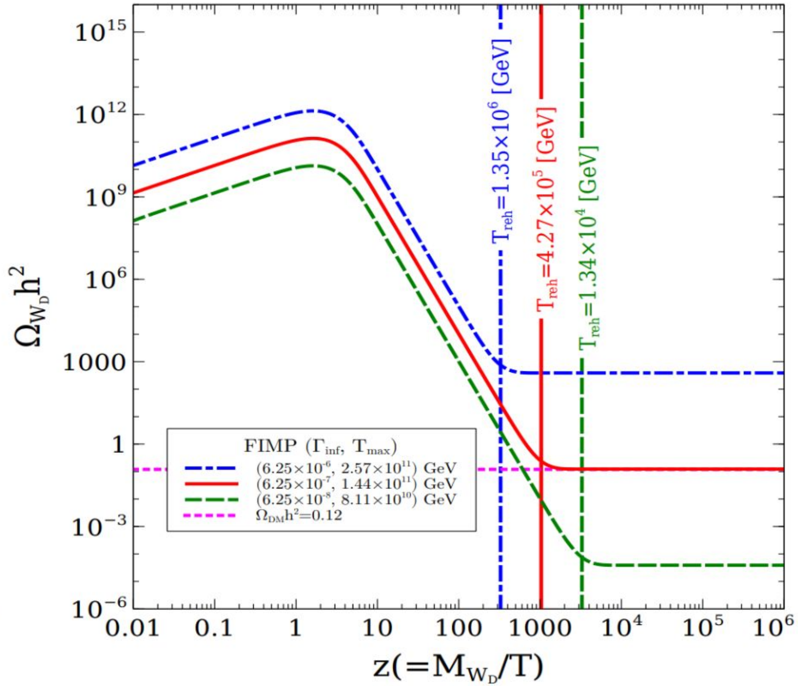
$$\frac{\delta z_{W_D}}{\bar{z}_{W_D}} < 10^{-2} \text{ and } \frac{\delta a}{a} < 10^{-3}$$
$$\Downarrow$$
$$\text{Thermal DM}$$



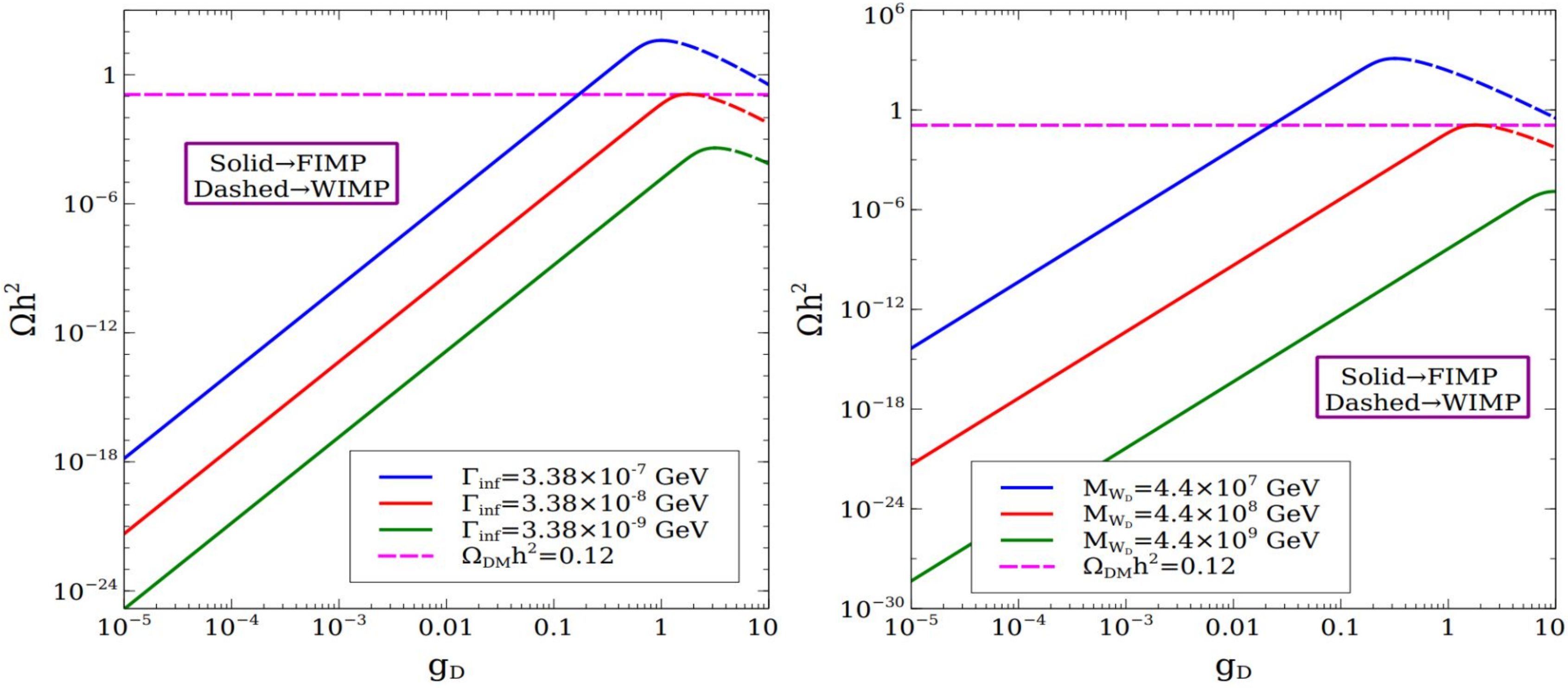


Freeze-out/in with entropy dilution

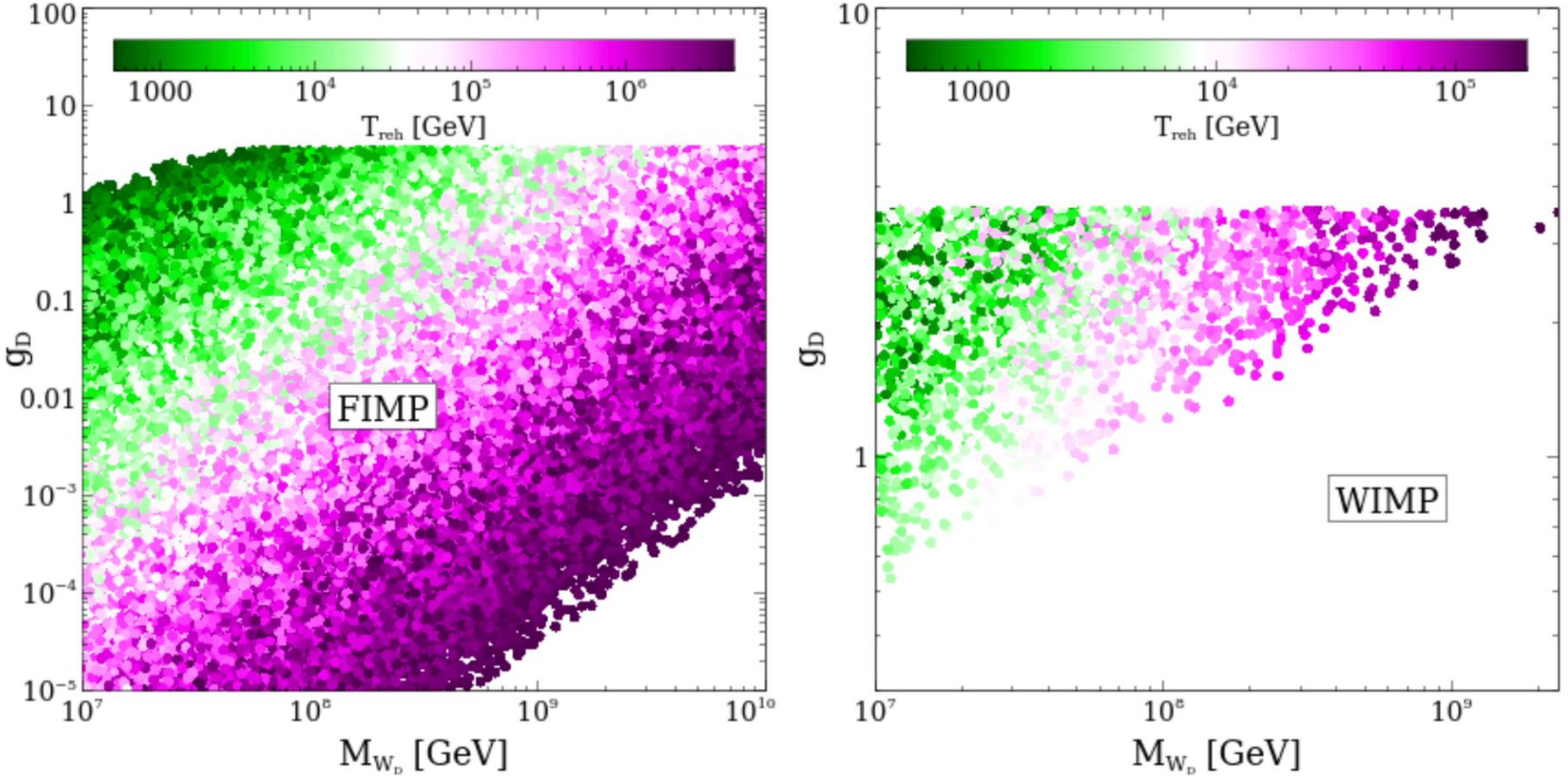




WIMP-FIMP Transitions



Viable regions



Kinetic mixing term

$$\mathcal{L}_{Kinetic} = -\frac{1}{4}\hat{B}_{\mu\nu}\hat{B}^{\mu\nu} - \frac{1}{4}\hat{W^a}_{\mu\nu}\hat{W^a}^{\mu\nu} - \frac{1}{4}\hat{W}_{D\mu\nu}\hat{W_D}^{\mu\nu} - \frac{\alpha}{2}\hat{B}_{\mu\nu}\hat{W_D}^{\mu\nu}$$
$$+\frac{1}{2}\hat{M}^2_{\hat{Z}}\hat{Z}_\mu\hat{Z}^\mu + \frac{1}{2}\hat{M}^2_{W_D}\hat{W}_{D\mu}\hat{W_D}^\mu.$$

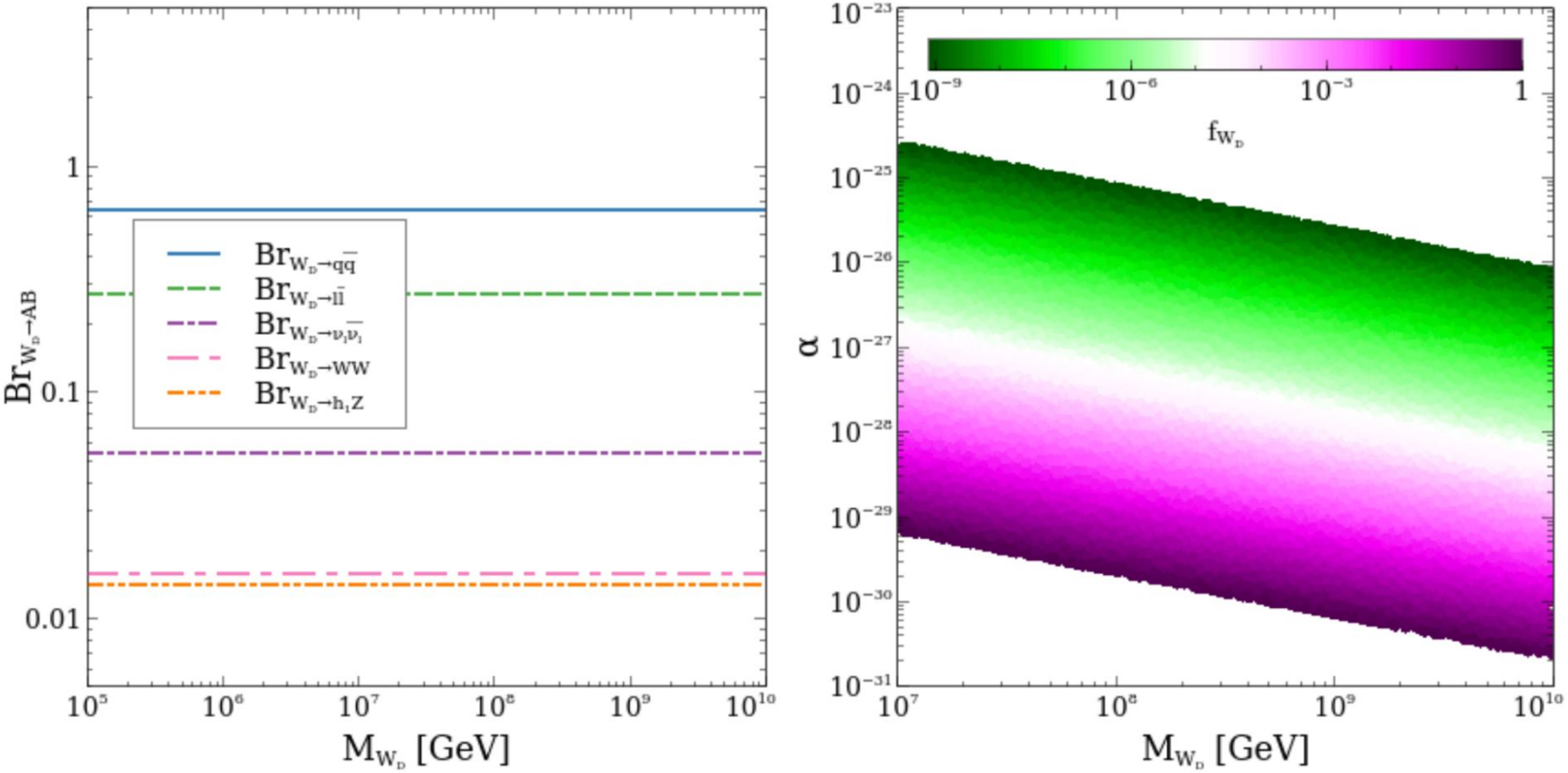
$$\begin{pmatrix}\hat{A}\\ \hat{Z}\\ \hat{W}_D\end{pmatrix} \simeq \begin{pmatrix}1 & 0 & -\hat{c}_w\alpha \\ 0 & 1 & \frac{\hat{s}_w\alpha\hat{M}^2_{W_D}}{\hat{M}^2_{W_D}-\hat{M}^2_Z} \\ 0 & -\frac{\hat{s}_w\alpha\hat{M}^2_Z}{\hat{M}^2_{W_D}-\hat{M}^2_Z} & 1\end{pmatrix}\begin{pmatrix}A\\ Z\\ W_D\end{pmatrix}$$

- $W_D \to WW$: The decay width takes the following form,

$$\Gamma_{W_D\to WW} = \frac{e^2c_w^4M^5_{W_D}}{192\pi M_w^4}\left(1-\frac{4M_W^2}{M^2_{W_D}}\right)^{3/2}\left(1+\frac{20M_W^2}{M^2_{W_D}}+\frac{12M_W^4}{M^4_{W_D}}\right)\left(\alpha-\frac{\alpha\hat{M}^2_{W_D}}{\hat{M}^2_{W_D}-\hat{M}^2_Z}\right)^2$$

(B1)

DM decay branchings and allowed regions



Galactic neutrino flux

$$\left.\frac{d\Phi_\nu^G}{dE_\nu d\Omega}\right|_{E_\nu=E} = \frac{D_g}{4\pi M_\chi}\sum_i \Gamma_i \left.\frac{dN_\nu^i}{dE_\nu}\right|_{E_\nu=E}, \qquad D_g = \frac{1}{\Delta\Omega}\int_{\Delta\Omega} d\Omega \int_0^{r_{\max}} dr' \rho(r'),$$

HDMSpectra

$$\rho_\chi(r) = \frac{\rho_0}{r/r_c\,(1+r/r_c)^2},$$

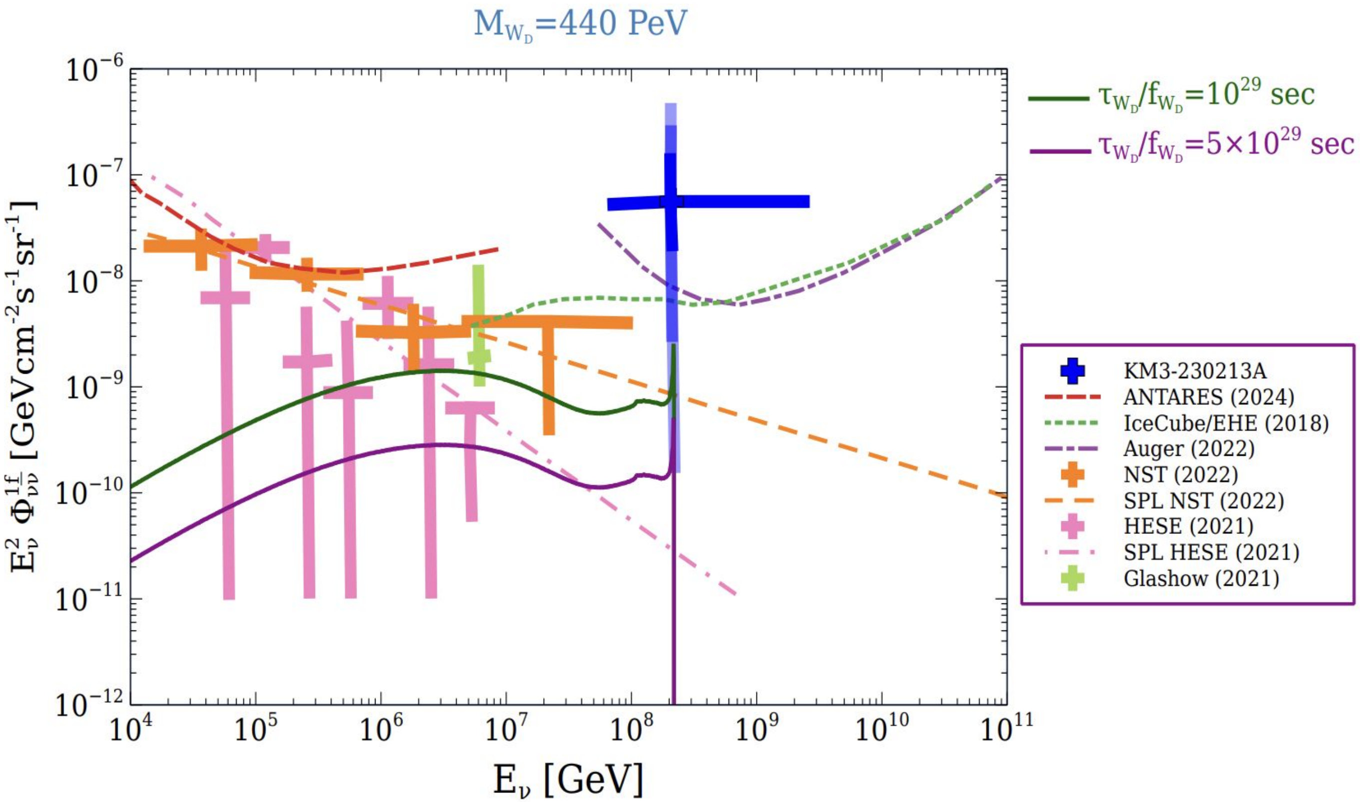
Extra Galactic neutrino flux

$$\frac{d\Phi_\nu^{EG}}{dE_\nu d\Omega} = \int_{z_0}^{\infty} dz \frac{1}{\mathcal{H}(z)(1+z)}\left(\frac{1+z_0}{1+z}\right)^3 \frac{\bar{\rho}_\chi(z)}{m_\chi}\sum \Gamma_i \left.\frac{dN_\nu^i}{dE'_\nu}\right|_{E'_\nu=(1+z)E} e^{-s_\nu(E_\nu,z)},$$

$$\mathcal{H}(z) = \mathcal{H}_0\sqrt{\Omega_\Lambda + \Omega_\mathrm{m}(1+z)^3 + \Omega_r(1+z)^4},$$

$$D_\mathrm{eg} = \frac{\Omega_\chi \rho_c}{4\pi M_\chi \tau_\chi \mathcal{H}_0} = 1.6\times 10^{-16}\left(\frac{100\mathrm{PeV}}{M_\chi}\right)\left(\frac{10^{29}\mathrm{s}}{\tau_\chi}\right)\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1},$$

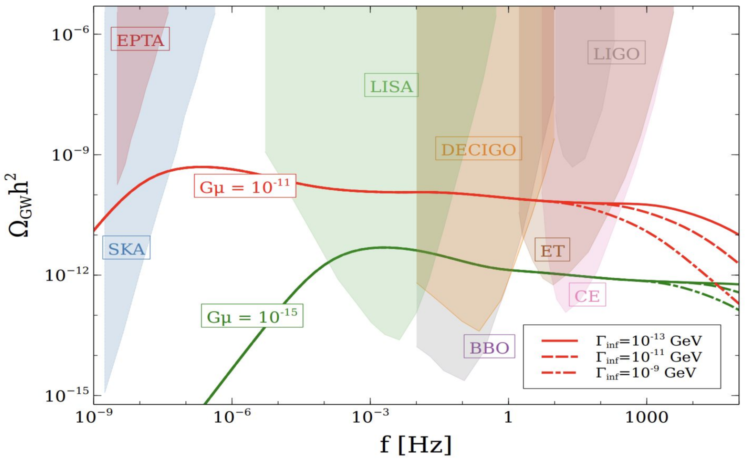
KM3NeT Signal



Gravitational Waves production from cosmic strings

$$\frac{dE}{dt} = -\Gamma G\mu^2 \Longrightarrow l(t) = \alpha t_i - \Gamma G\mu(t - t_i).$$

$$\Omega_{GW}^{(k)} = \frac{1}{\rho_c}\frac{2k}{f}\frac{F_\alpha \Gamma^{(k)} G\mu^2}{\alpha(\alpha+\Gamma G\mu)}\int_{t_F}^{t_0} d\tilde{t}\,\frac{C_{eff}(t_i^{(k)})}{(t_i^{(k)})^4}\left[\frac{a(\tilde{t})}{a(t_0)}\right]^5\left[\frac{a(t_i^{(k)})}{a(\tilde{t})}\right]^3\theta(t_i^{(k)} - t_F).$$



$$t_i^{(k)}(\tilde{t}, f) = \frac{1}{\alpha+\Gamma G\mu}\left[\frac{2k}{f}\frac{a(\tilde{t})}{a(t_0)} + \Gamma G\mu\tilde{t}\right].$$

Part II: Using Fermion dark matter with effective operator

Lagrangian with U(1) and charged fermion

S. Khan, J. Kim and P. Ko [JCAP 11(2025)033]

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{1}{2}\bar{N} i\partial\!\!\!/ N - \left(\frac{1}{2} m_N \bar{N}^c N + y\bar{L}\widetilde{H}N + \text{h.c.}\right) - \frac{1}{4}X_{\mu\nu}X^{\mu\nu} - \frac{1}{2}\sin\epsilon X_{\mu\nu}F_Y^{\mu\nu}$$
$$+ D_\mu\Phi^\dagger D^\mu\Phi - V(\Phi, H) + \bar{\chi}\left(iD\!\!\!/ - m_\chi\right)\chi - \left(\kappa\bar{\chi}\Phi N + \text{h.c.}\right),$$

$M_N \gg M_\chi$ $\Rightarrow$ $\frac{y\kappa}{m_N}\bar{\chi}\Phi H^\dagger L + h.c.$

$$\theta \simeq \frac{y\kappa}{2}\frac{v_\phi v_H}{m_N m_\chi}.$$

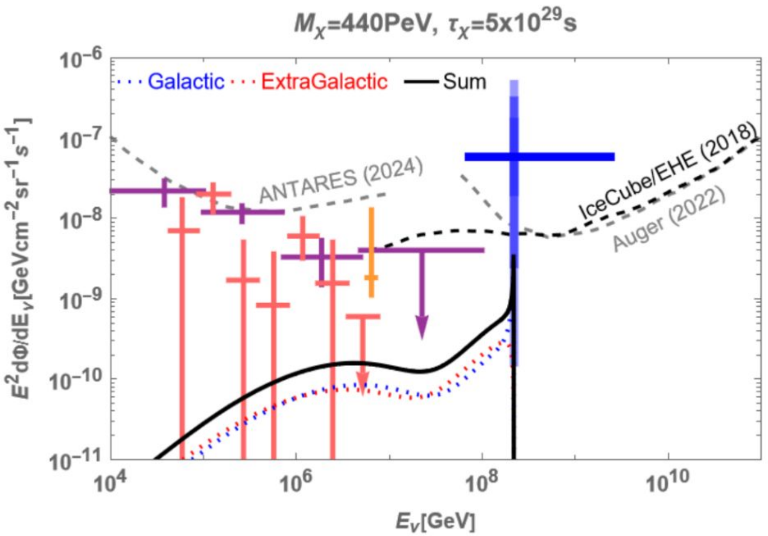
χ and ν mixing

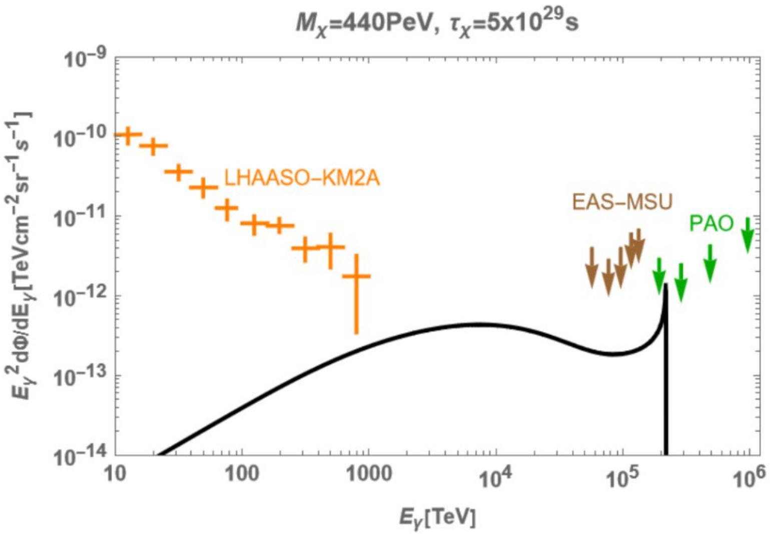
$$\frac{y\kappa}{2}\frac{v_\phi v_H}{m_N}\bar{\chi}\nu, \quad \frac{y\kappa}{2}\frac{v_\phi}{m_N}\bar{\chi}h\nu, \quad \frac{y\kappa}{2}\frac{v_H}{m_N}\bar{\chi}\phi\nu, \quad \frac{y\kappa}{2}\frac{1}{m_N}\bar{\chi}\phi h\nu.$$

$$\chi \to Z'\nu, Z\nu, W^\mp l^\pm, \quad \Rightarrow \quad \sim v_H^2 : v_\phi^2 : 2v_\phi^2.$$

$$\chi \to h\nu, \phi\nu, \quad \chi \to \phi/Z' + h + \nu,\ \phi/Z' + Z + \nu,\ \phi/Z' + W^\pm + l^\mp, \quad \Rightarrow \quad \frac{\Gamma_2\left(\chi \to h\nu, \phi\nu\right)}{\Gamma_3\left(\chi \to \phi h\nu\right)} \simeq 16\pi^2\frac{v_\phi^2 + v_H^2}{m_\chi^2}.$$

DM neutrino flux matches KM3NeT data





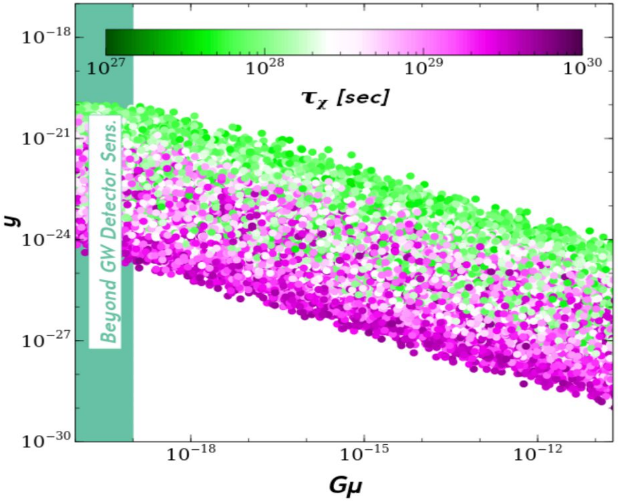
From DM decay we can easily explain the signal by suitable choice of DM mass, lifetime and fraction of DM abundance

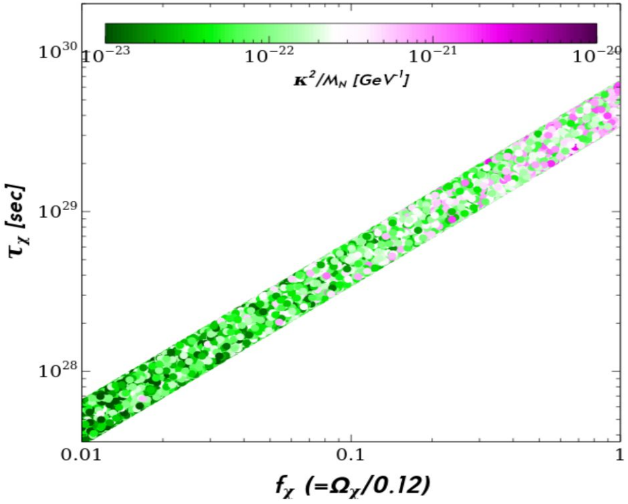
DM Production

$$\frac{dY_\chi}{dz} = \frac{2M_{sc}s(T)}{z^2\mathcal{H}(T)T}\left[\langle\sigma v\rangle_{\phi\phi\to\bar{\chi}\chi}Y_\phi^2 - \langle\sigma v\rangle_{\bar{\chi}\chi\to\phi\phi}Y_\chi^2\right],$$

$$\sigma_{\phi\phi\to\chi\bar{\chi}} = \frac{1}{8\pi s}\left(\frac{2\kappa^2}{M_N}\right)^2\left[\frac{s-4M_\chi^2}{s-4M_\phi^2}\right]^{1/2}(s-4M_\chi^2)$$

$$Y_\chi \simeq \frac{3.6M_{\rm pl}(T_R-T_0)}{\pi^7 g_s\sqrt{g_\rho}}\left(\frac{2\kappa^2}{M_N}\right)^2, \quad \Longrightarrow \quad \Omega_\chi h^2 = 2.755\times10^{14}\left(\frac{M_\chi}{\rm PeV}\right)Y_\chi.$$

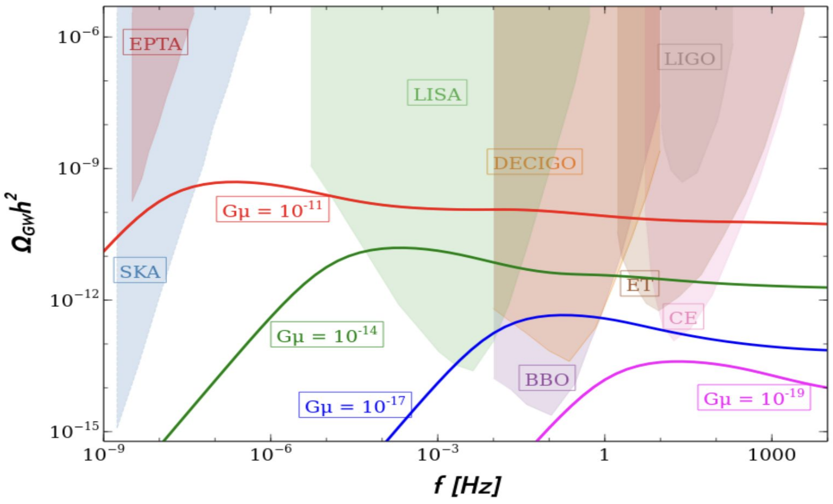




Gravitational Waves production from cosmic strings

$$\frac{dE}{dt} = -\Gamma G\mu^2 \Longrightarrow l(t) = \alpha t_i - \Gamma G\mu(t - t_i).$$

$$\Omega_{GW}^{(k)} = \frac{1}{\rho_c}\frac{2k}{f}\frac{F_\alpha \Gamma^{(k)} G\mu^2}{\alpha(\alpha+\Gamma G\mu)}\int_{t_F}^{t_0} d\tilde{t}\,\frac{C_{eff}(t_i^{(k)})}{(t_i^{(k)})^4}\left[\frac{a(\tilde{t})}{a(t_0)}\right]^5\left[\frac{a(t_i^{(k)})}{a(\tilde{t})}\right]^3\theta(t_i^{(k)} - t_F).$$



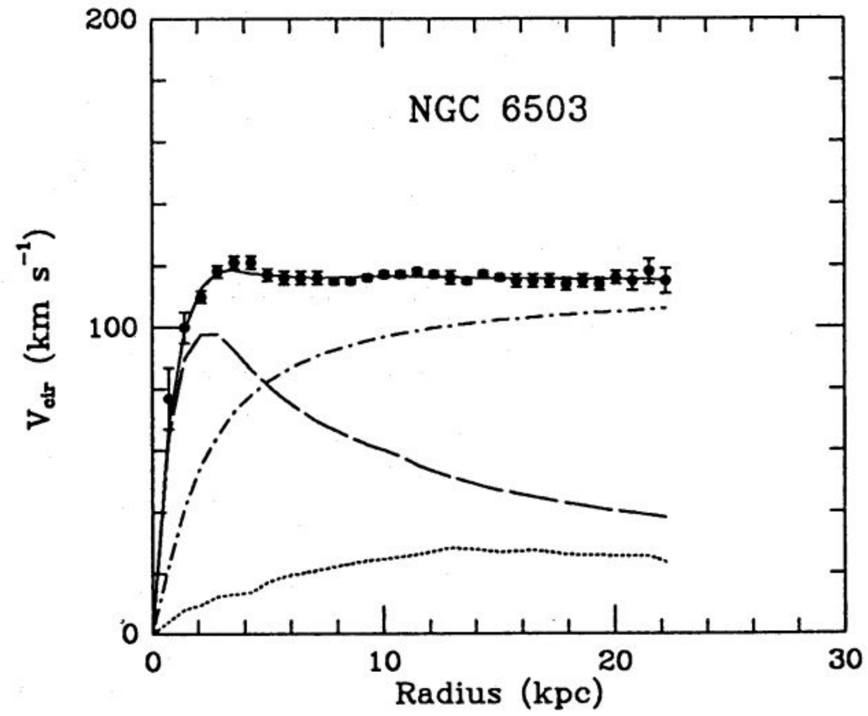
$$t_i^{(k)}(\tilde{t}, f) = \frac{1}{\alpha+\Gamma G\mu}\left[\frac{2k}{f}\frac{a(\tilde{t})}{a(t_0)} + \Gamma G\mu\tilde{t}\right].$$

❖ Conclusion

- We have explained the KM3NeT signal from the decay of vector and fermionic DM.
- By suitably choosing mass, fraction and lifetime of the DM, we can explain KM3NeT signal.
- With SHDM, we can predict the flux below the IceCube limit while satisfying the KM3NeT data.
- SHDM is difficult to produce in Planck limit, we produce them through the UV freeze-in mechanism and entropy dilution.
- Suitably choosing reheat temperature, desired DM abundance can be achieved for both vector and fermion type DM.
- In both cases due to high scale dark symmetry breaking, we find that the present model can be accessed at the proposed GW detectors.
- The present formulations of SHDM we have developed can be used in future for any new potential high energy neutrino signals by adjusting DM parameters.

Thank You

Rotation curve of galaxy NGC 6503



The velocity v(R) of stars in the galaxy is given by the Newton's law (assuming circular motion)

$$v(R) = \sqrt{\frac{G_N M(R)}{R}}, \qquad M(R) = 4\pi \int_0^R \rho(r) r^2 \mathrm{d}r\,,$$

Only Luminous matter would lead to $v(r) \propto r^{-\frac{1}{2}}$

We see observationally v(R) ≃ Constant

This demand a halo distribution M(R) ∝ R

Linear increment in mass with distance demand $\rho(r) \propto r^{-2}$

Galactic neutrino flux

$$\left.\frac{d\Phi_\nu^G}{dE_\nu d\Omega}\right|_{E_\nu=E} = \frac{D_g}{4\pi M_\chi}\sum_i \Gamma_i \left.\frac{dN_\nu^i}{dE_\nu}\right|_{E_\nu=E}, \qquad D_g = \frac{1}{\Delta\Omega}\int_{\Delta\Omega} d\Omega \int_0^{r_{\max}} dr'\rho(r'),$$

$$\rho_\chi(r) = \frac{\rho_0}{r/r_c\,(1+r/r_c)^2},$$

HDMSpectra

Extra Galactic neutrino flux

$$\frac{d\Phi_\nu^{EG}}{dE_\nu d\Omega} = \int_{z_0}^{\infty} dz \frac{1}{\mathcal{H}(z)(1+z)}\left(\frac{1+z_0}{1+z}\right)^3 \frac{\bar\rho_\chi(z)}{m_\chi}\sum \Gamma_i \left.\frac{dN_\nu^i}{dE'_\nu}\right|_{E'_\nu=(1+z)E} e^{-s_\nu(E_\nu,z)},$$

$$\mathcal{H}(z) = \mathcal{H}_0\sqrt{\Omega_\Lambda + \Omega_{\mathrm{m}}(1+z)^3 + \Omega_r(1+z)^4},$$

$$D_{\mathrm{eg}} = \frac{\Omega_\chi\rho_c}{4\pi M_\chi\tau_\chi\mathcal{H}_0} = 1.6\times10^{-16}\left(\frac{100\mathrm{PeV}}{M_\chi}\right)\left(\frac{10^{29}\mathrm{s}}{\tau_\chi}\right)\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1},$$