Exploring Neutrino-Dark Matter interaction via Astrophysical Neutrinos at IceCube

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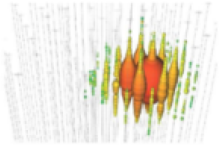
Neutrinos and Dark Matter (NDM-2020)
January 14, 2020

Motivation

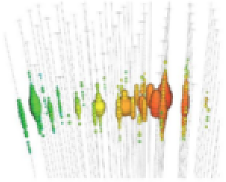
- Neutrinos interact weakly → travel unhindered through matter.
- Give us information about the regions inaccessible by photon astronomy.
- Astrophysical neutrinos have high energy → Probe new physics at high energy.
- Neutrino travels through large cloud of dark matter before reaching the Earth.
- Dark Matter (DM) may scatter neutrinos → Flux suppression + changed Flavour Ratio
- IceCube can observe these changes → probe neutrino-dark matter interaction.

IceCube : High energy neutrino detection

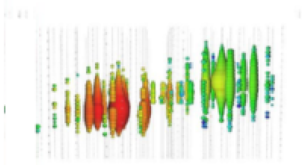
Neutrinos → interact with the ice → electrically charged secondary particles → emit Cherenkov light→ The IceCube sensors collect thislight→ digitized and time stamped→ reveal the direction and energy of neutrinos



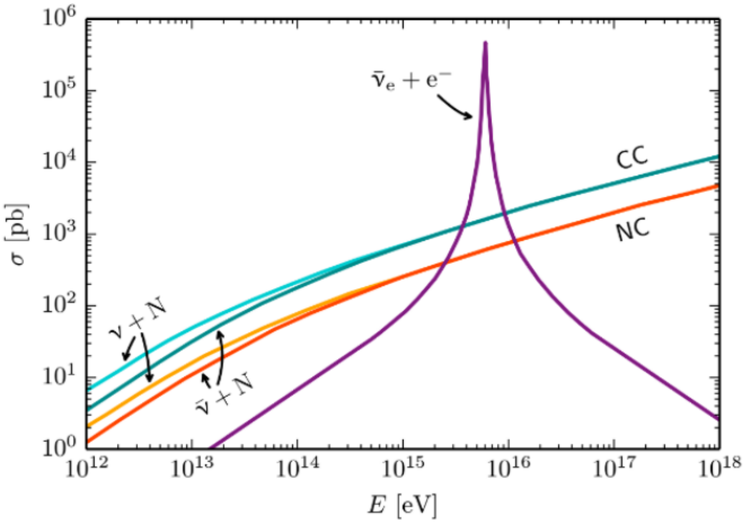
cascade signature



track signature

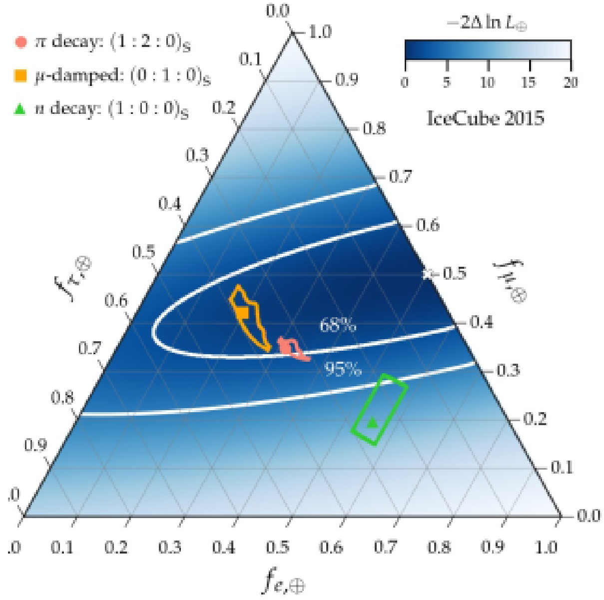


double bang signature



Flavour composition: now and in the future

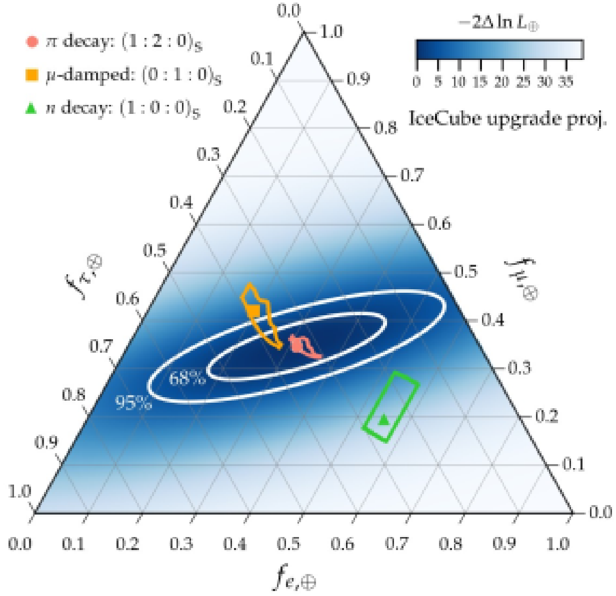
Today
IceCube



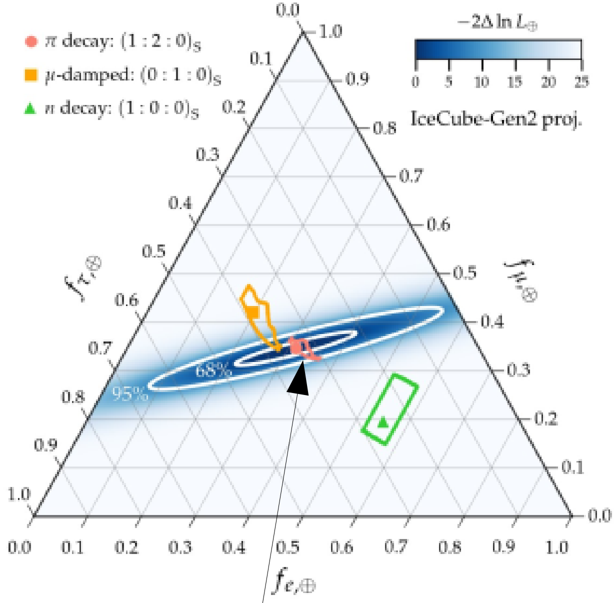
Best Fit : (1:1:0)

(6 year IC observation)

Near future (2022)
IceCube upgrade



In 10 years (2030s)
IceCube-Gen2

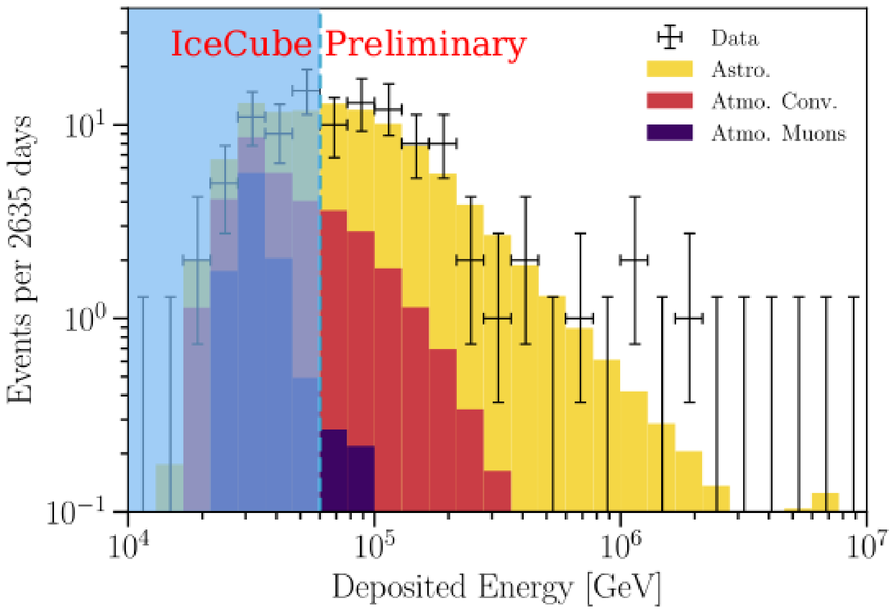


PAHEN 2019
[M Bustamante Talk]

Standard (1:1:1) can be probed

Assuming production by the full pion decay chain

IceCube Observations:



- No cosmogenic event.
- Paucity of events between 500 TeV to 1 PeV (dip?).
- No contained event after 2 PeV (cut-off?)
- No double bang event (Paucity of tau neutrinos?).
- No Glashow event in 7.5 years!
- Can neutrino-DM interaction lead to features in neutrino spectrum?

Flux suppression:

Generating a dip with a t-channel process!

$$\frac{\partial F(E,x)}{\partial x} = -n\sigma(E)F(E,x) + n\int_E^\infty dE' \frac{d\sigma(E,E')}{dE} F(E',x)$$

Attenuation term

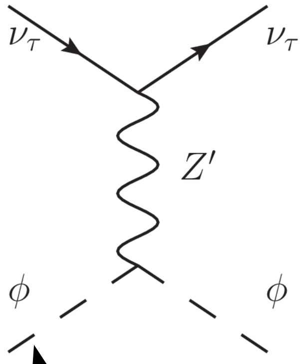
Regeneration term

$\sigma(E)$ — Neutrino-DM cross-section

n — DM number density

$F(E,x)$ — Flux at energy E, distance x

t-channel process



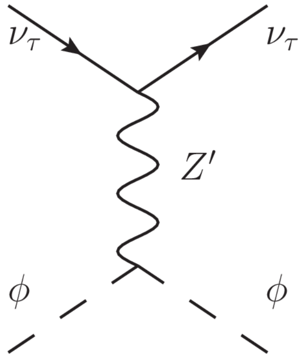
DM

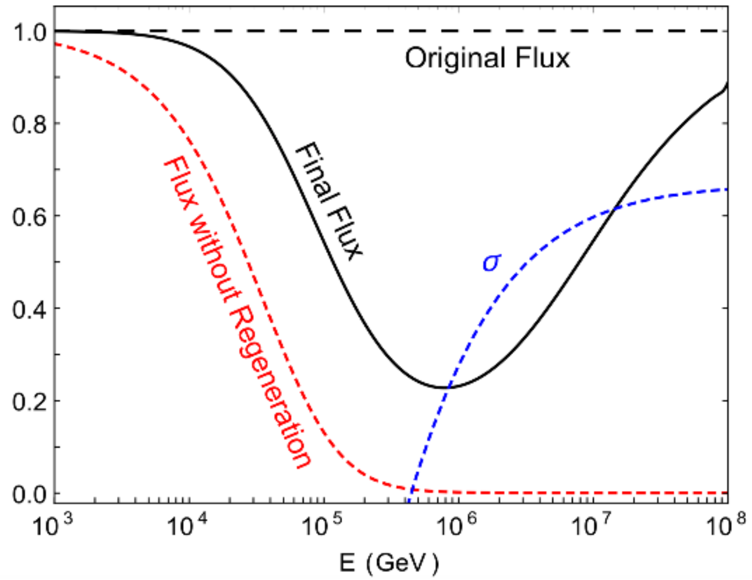
Flux suppression:

Generating a dip with a t-channel process!

$$\frac{\partial F(E,x)}{\partial x} = -n\sigma(E)F(E,x) + n\int_E^\infty dE' \frac{d\sigma(E,E')}{dE} F(E',x)$$

Neutrino regeneration





Fluxes: $E^2 F(E) \times 3.\ 10^9$
in units of GeV cm^{-2} s^{-1} str^{-1}

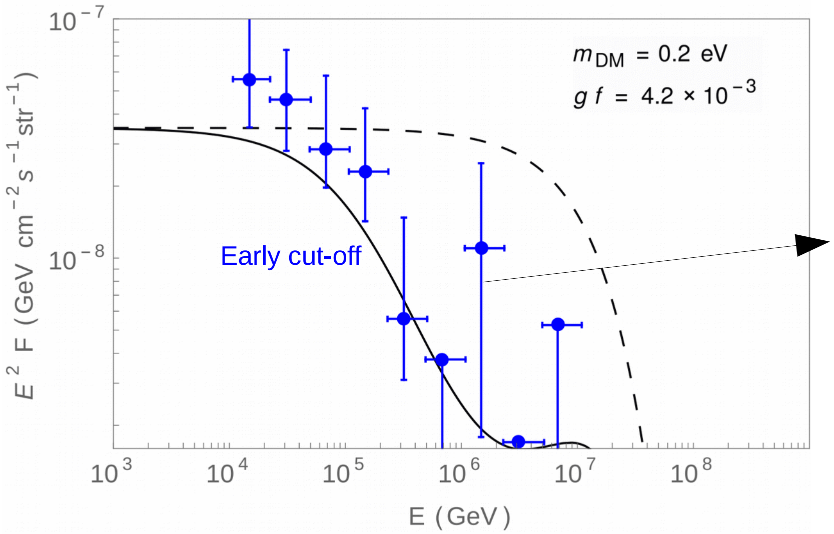
$\sigma : \sigma_{\nu-DM} \times 3.\ 10^{21}$
in units of eV^{-2}

Z'-mediated ν—DM interaction:
$m_{\rm DM} = 0.3$ eV, $gf = 7.\ 10^{-3}$
$m_{Z'} = 10$ MeV, $m_\nu = 0.1$ eV

$$\sigma = \begin{cases} \frac{g'^2 f^2}{2\pi} \frac{m_{\rm DM} E}{m_{Z'}^4} & \text{if } E < m_{Z'}^2/m_{DM} \\ \frac{g'^2 f^2}{4\pi} \frac{1}{m_{Z'}^2} & \text{if } E > m_{Z'}^2/m_{DM}. \end{cases}$$

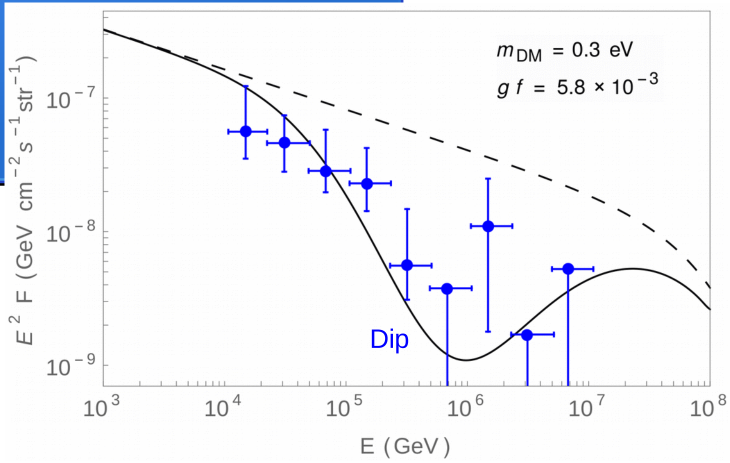
Density of the isotropic DM background: 1.2×10^{-6} GeV cm^{-3}

Features for different DM mass:



$$F(E) = 3.5 \times 10^{-8}\ E^{-2}\ \exp[-E/(1.2 \times 10^{7}\mathrm{GeV})]$$
$$\mathrm{GeV}^{-1}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}\ \mathrm{str}^{-1}$$

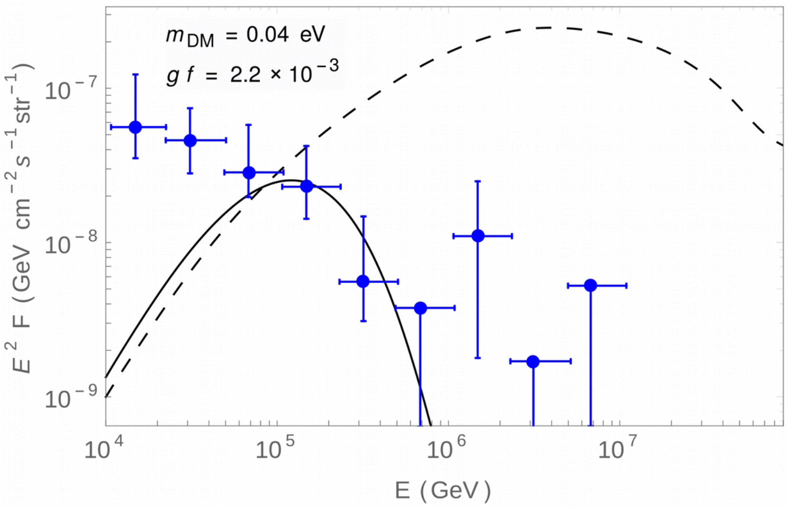
A. Karle, Talk presented at La Palma 2018



$F(E) \propto E^{-2.3}$
with an exp cut-off at 100PeV

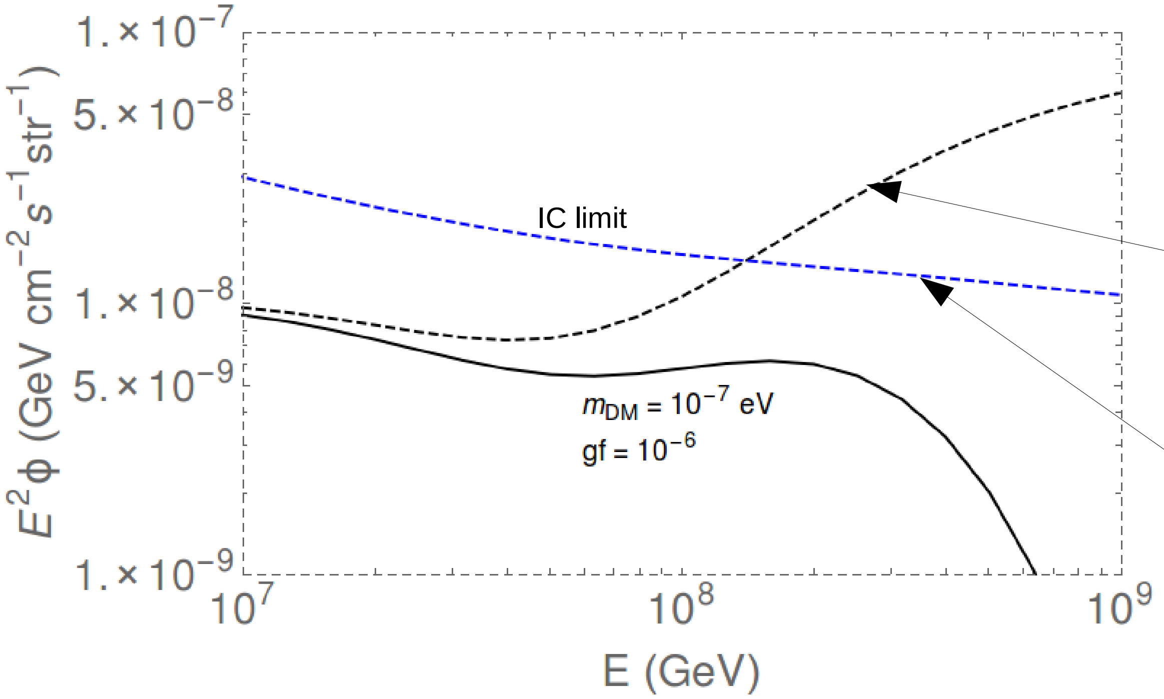
Shifting high energy neutrinos to lower energy

AGN core model S05



S. Karmakar, S. Pandey, S. Rakshit, arXiv: 1810.04192

Cosmogenic Neutrinos:



$$p + \gamma_{bg} \rightarrow n + \pi^+$$

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

$$\mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e$$

KoteraFRII

PRL 117, 241101 (2016)

Neutrino-DM interactions for flux suppression: Effective + Renormalisable

Flux suppression can only happen when: $n\sigma L \sim \mathcal{O}(1)$

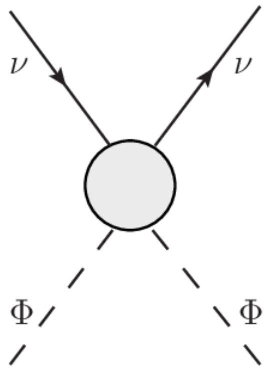
Keeping L = 200 Mpc ... Whether extragalactic DM could lead to 1% flux suppression ?

Thermal cold dark matter, due to relic density and N_{eff} constraints, does not lead to flux suppression

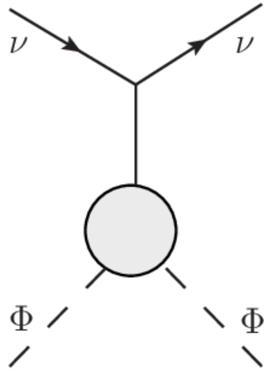
Ultralight BEC DM are very interesting because of large n!

For effective interactions we consider 3 broad topologies:

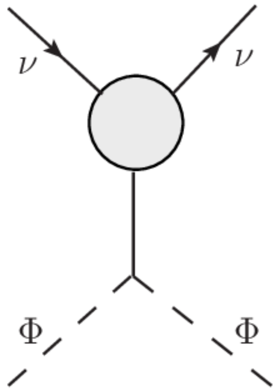
S. Pandey, S. Karmakar and S. Rakshit, JHEP 1901(2019) 095



Topology I



Topology II



Topology III

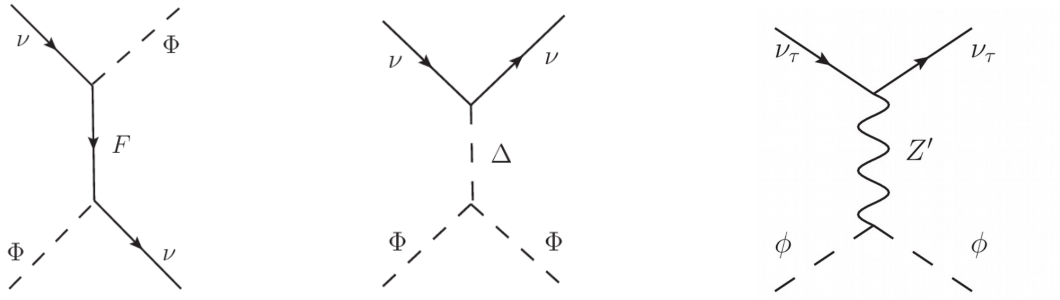
Topology	Interaction	Constraints	Remarks
I 1	$\frac{c_l^{(1)}}{\Lambda^2}(\bar{\nu} i \partial\!\!\!/ \nu)(\Phi^*\Phi)$	$c_l^{(1)}/\Lambda^2 \lesssim 8.8\times10^{-3}\,\text{GeV}^{-2}$, $c_e^{(1)}/\Lambda^2 \lesssim 1.0\times10^{-4}\,\text{GeV}^{-2}$, $c_\mu^{(1)}/\Lambda^2 \lesssim 6.0\times10^{-3}\,\text{GeV}^{-2}$, $c_\tau^{(1)}/\Lambda^2 \lesssim 6.2\times10^{-3}\,\text{GeV}^{-2}$	disfavoured
I 2	$\frac{c_l^{(2)}}{\Lambda^2}(\bar{\nu}\gamma^\mu\nu)(\Phi^*\partial_\mu\Phi - \Phi\partial_\mu\Phi^*)$	$c_l^{(2)}/\Lambda^2 \lesssim 1.8\times10^{-2}\,\text{GeV}^{-2}$, $c_e^{(2)}/\Lambda^2 \lesssim 2.6\times10^{-5}\,\text{GeV}^{-2}$, $c_\mu^{(1)}/\Lambda^2 \lesssim 1.2\times10^{-2}\,\text{GeV}^{-2}$, $c_\tau^{(1)}/\Lambda^2 \lesssim 1.3\times10^{-3}\,\text{GeV}^{-2}$	disfavoured
I 3	$\frac{c_l^{(3)}}{\Lambda}\bar{\nu^c}\nu\,\Phi^\star\Phi$	$c_l^{(3)}/\Lambda \leq 0.5\,\text{GeV}^{-1}$	favoured[a]
I 4	$\frac{c_l^{(4)}}{\Lambda^3}(\bar{\nu^c}\sigma^{\mu\nu}\nu)(\partial_\mu\Phi^*\partial_\nu\Phi - \partial_\nu\Phi^*\partial_\mu\Phi)$	$c_l^{(4)}/\Lambda^3 \lesssim 2.0\times10^{-3}\,\text{GeV}^{-3}$	disfavoured
I 5	$\frac{c_l^{(5)}}{\Lambda^3}\partial^\mu(\bar{\nu^c}\nu)\partial_\mu(\Phi^*\Phi)$	$c_l^{(5)}/\Lambda^3 \lesssim 7.5\times10^{-4}\,\text{GeV}^{-3}$	disfavoured
I 6	$\frac{c_l^{(6)}}{\Lambda^4}(\bar{\nu}\partial^\mu\gamma^\nu\nu)(\partial_\mu\Phi^*\partial_\nu\Phi - \partial_\nu\Phi^*\partial_\mu\Phi)$	$c_l^{(6)}/\Lambda^4 \lesssim 2.5\times10^{-5}\,\text{GeV}^{-4}$, $c_e^{(6)}/\Lambda^4 \lesssim 1.2\times10^{-6}\,\text{GeV}^{-4}$, $c_\mu^{(6)}/\Lambda^4 \sim c_\tau^{(6)}/\Lambda^4 \lesssim 10^{-5}\,\text{GeV}^{-4}$	disfavoured
II 1	$\frac{c_l^{(7)}}{\Lambda^2}(\partial^\mu\Phi^*\partial^\nu\Phi - \partial^\nu\Phi^*\partial^\mu\Phi)Z'_{\mu\nu} + f_i\bar{\nu}_i\gamma^\mu P_L\nu_i Z'_\mu$	$f_l c_l^{(7)}/\Lambda^2 \lesssim 4.2\times10^{-2}\,\text{GeV}^{-2}$, $f_e c_e^{(7)}/\Lambda^2 \lesssim 1.9\times10^{-5}\,\text{GeV}^{-2}$, $f_\mu c_\mu^{(7)}/\Lambda^2 \sim f_\tau c_\tau^{(7)}/\Lambda^2 \lesssim 8.1\times10^{-3}\,\text{GeV}^{-2}$, $[f_e, f_\mu, f_\tau] \lesssim [10^{-5}, 10^{-6}, 0.02]$ for $m_{Z'} \sim 10\,\text{MeV}$	disfavoured
II 2	$\frac{c_l^{(8)}}{\Lambda}\partial^\mu\|\Phi\|^2\partial_\mu\Delta + f_l\bar{\nu^c}\nu\Delta$	$m_\nu \sim f_l v_\Delta \lesssim 0.1\,\text{eV}$, $m_\Delta \gtrsim 150\,\text{GeV}$	disfavoured
III	$C_1(\Phi^*\partial_\mu\Phi - \Phi\partial_\mu\Phi^*)Z'^\mu + \frac{c_l^{(9)}}{\Lambda}(\bar{\nu^c}\sigma_{\mu\nu}P_L\nu)Z'^{\mu\nu}$	$c_l^{(9)}/\Lambda \lesssim 3.8\times10^{-3}\,\text{GeV}^{-1}$ for $m_{Z'} \sim 10\,\text{MeV}$	favoured[b]

[a] Disfavoured if realised with a $SU(2)_L$ triplet scalar.

[b] Favoured if $0.08\,\text{eV} \lesssim m_{\text{DM}} \lesssim 0.5\,\text{eV}$ for $m_{Z'} \sim 10\,\text{MeV}$ and $E_\nu \sim 1$ PeV.

$Z \to inv$, LEP monophoton+$\not{E}_T$, $Z \to \mu^+\mu^-$, $Z \to \tau^+\tau^-$ and $(g-2)_{e,\mu}$

Renormalisable interaction:



Mediator	Interaction	Constraints	Remarks
Fermion	$(C_L \bar{L} F_R + C_R \bar{l}_R F_L)\Phi + h.c.$	$m_F \gtrsim 100\,\text{GeV},\ m_{\text{DM}} \gtrsim 10^{-21}\,\text{eV},$ $C_L C_R \lesssim \{2.5, 0.5\} \times 10^{-5}$ for e and μ	disfavoured
Scalar	$f_l \bar{L}^c L \Delta + g_\Delta \Phi^* \Phi \lvert\Delta\rvert^2$	$m_\nu \sim f_l v_\Delta \lesssim 0.1\,\text{eV},\ g_\Delta \sim v_\Delta^2 / m_{\text{DM}}^2$	disfavoured
Vector	$f_l' \bar{L} \gamma^\mu P_L L Z'_\mu + i g' (\Phi^* \partial^\mu \Phi$ $- \Phi \partial^\mu \Phi^*) Z'_\mu$	$[f_e, f_\mu, f_\tau] \lesssim [10^{-5}, 10^{-6}, 0.02]$ for $m_{Z'} \sim 10\,\text{MeV}$	favoured only for ν_τ

Flavour Ratio and Flavour Conversion

Flavour ratio (FR) is the ratio of electron: muon : tauon neutrinos in the flux.

$$(f_{e,S}, f_{\mu,S}, f_{\tau,S}) \equiv (N_{e,S}, N_{\mu,S}, N_{\tau,S})/N_{tot}$$

FR at Earth $(\alpha = e, \mu, \tau)$:

$$f_{\alpha,\oplus} = \sum_{\beta=e,\mu,\tau} P_{\nu_\beta \to \nu_\alpha} f_{\beta,S}$$

FR at source

Probability changes due to new interactions

$$P_{\alpha\to\beta} = |U^S_{\alpha i}|^2 |U^D_{\beta i}|^2 - P^c_{ij}(|U^S_{\alpha i}|^2 - |U^S_{\alpha j}|^2)(|U^D_{\beta i}|^2 - |U^D_{\beta j}|^2)$$

Probability of jumping from one mass state to another

Adiabacity parameter

$$\gamma_R = \frac{\Delta m^2 \sin^2 2\theta}{2E\cos 2\theta |\mathrm{d}\ln n_\phi/\mathrm{d}x|_R}$$

Neutrino-dark matter interaction

In the presence of Dark Matter interacting with only tau neutrino the effective Hamiltonian is given by:

$$H_{\rm eff} = \frac{1}{2E(1+z)} U \begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta m_{12}^2 & 0 \\ 0 & 0 & \Delta m_{23}^2 \end{pmatrix} U^\dagger + \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & V_{\tau\tau}(r)(1+z)^3 \end{pmatrix}$$

$$V_{\tau\tau} = 4g' f n_\phi / m_{Z'}^2$$

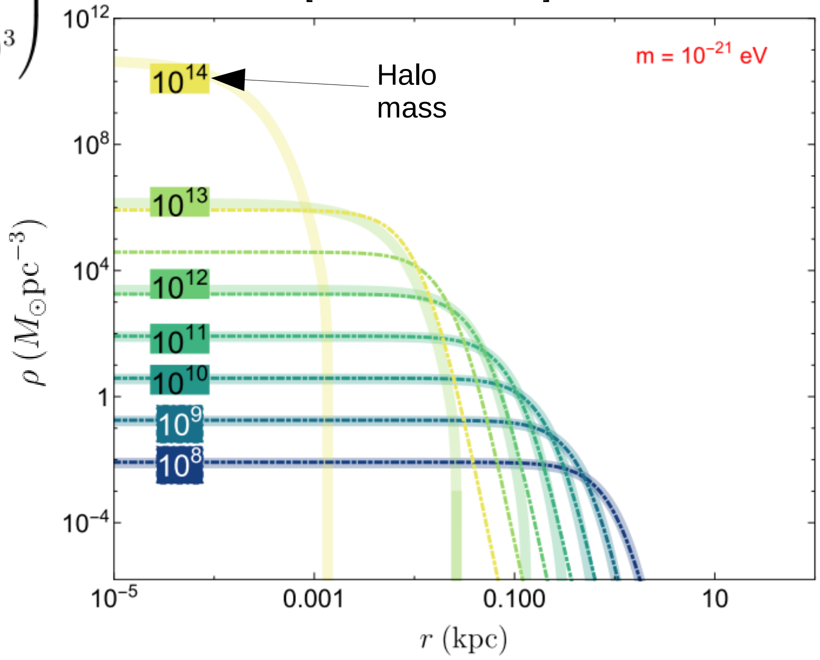
For antineutrinos: $U \longrightarrow U^*, \qquad V \longrightarrow -V.$

Local DM density is 0.4 GeV/cc.

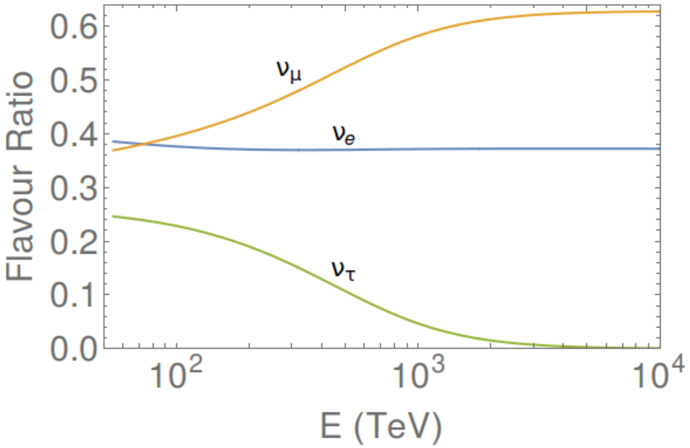
AGN is considered as the neutrino source.

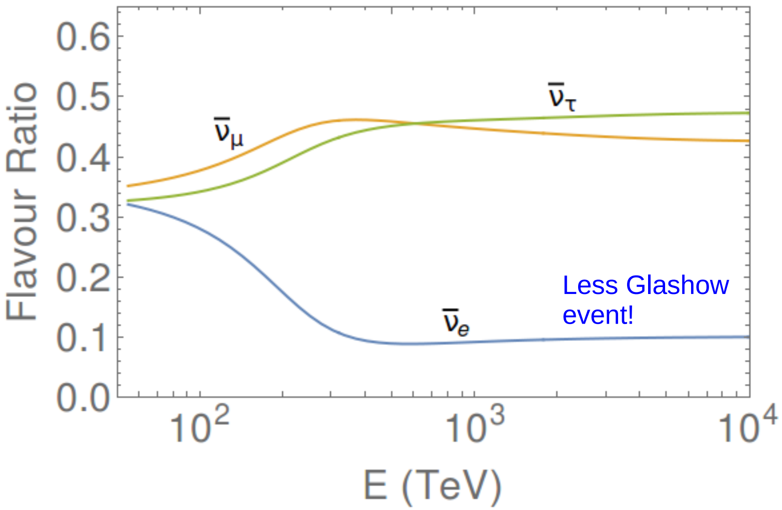
DM density near the center depends on DM mass and the mass of SMBH.

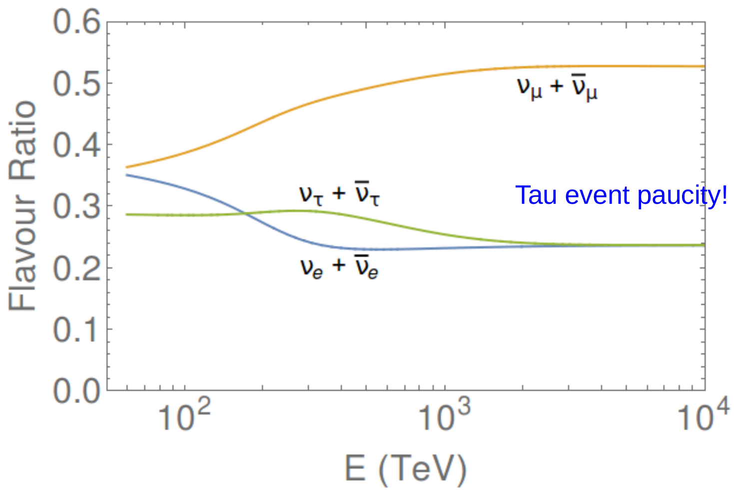
Density at source
[arXiv:1908.04790]



Flavour Ratio at Earth:







$f_{\beta,\mathrm{S}}$ = (1:2:0)

$$G'_F = 2.5 \times 10^{-26}\ \mathrm{eV}^{-2},\ m_{\mathrm{DM}} = 8 \times 10^{-15}\ \mathrm{eV},$$
$$M_{\mathrm{BH}} = 10^5 M_\odot \text{ and } \rho = 3.2 \times 10^9\ \exp(-\tfrac{x}{0.0001\ \mathrm{pc}})\ \mathrm{GeV\ cm}^{-3}$$

S. Pandey, S. Rakshit

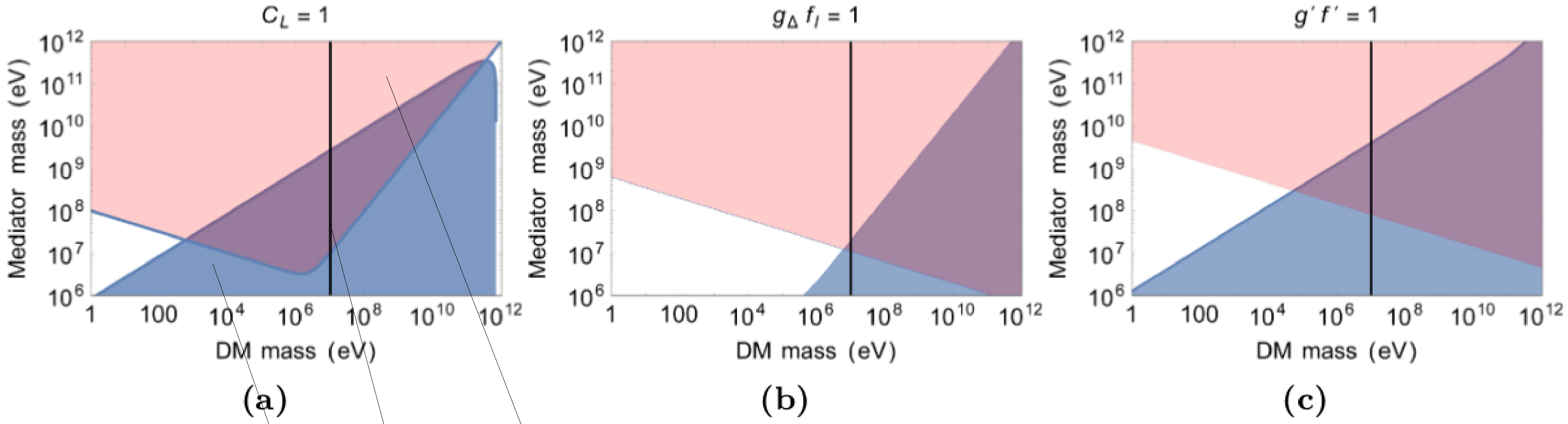
To be communicated soon.

Conclusion

- Neutrino-DM interaction can lead to flux suppression which can lead to various features at IceCube. With greater statistics these can be probed.
- Neutrino-dark matter interaction can lead to flavour changes which can be probed at IceCube.
- Even the interactions with lower cross-section, that does not lead to flux suppression of astrophysical neutrinos can be probed via flavour changes.
- Such interactions can explain various features at IceCube.

Thank you!

Backup slides: Thermal DM



Scalar mediated

Vector mediated

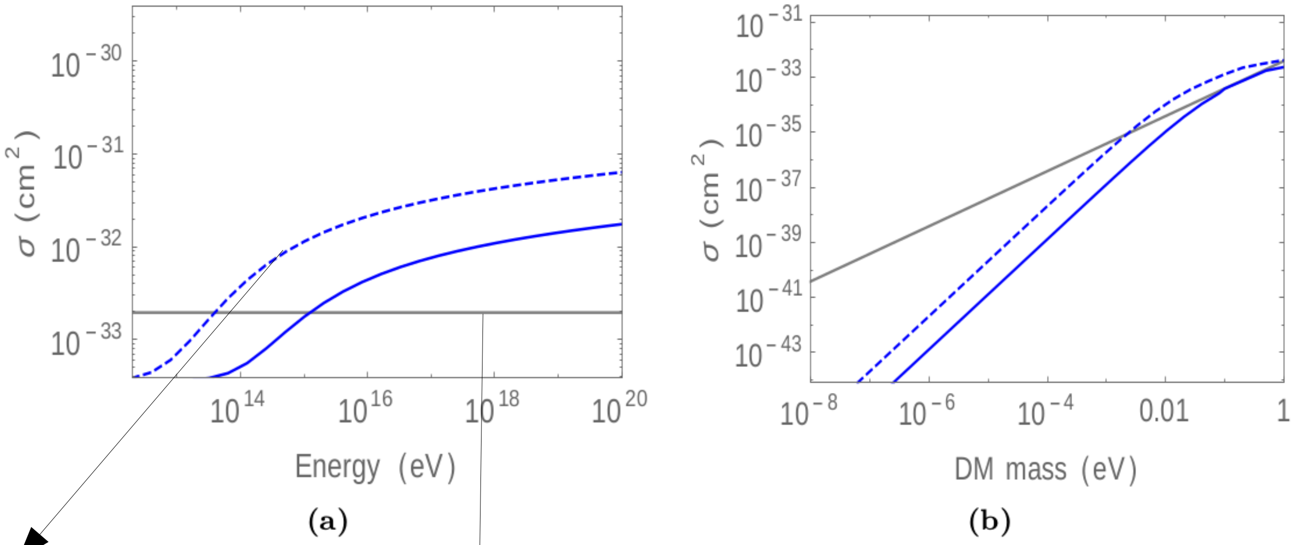
N_{eff}

Collisional damping

Relic density

Fermion mediated

Topology III



$M_{Z'}$= 5 GeV, m_{DM}=0.5 eV

E= 1 PeV

Required cross-section