Unparticle Decay of Neutrinos and its Possible Signatures at a km^2 Detector for (3+1) Flavour Framework

Madhurima Pandey
Astroparticle Physics and Cosmology Division
Saha Institute of Nuclear Physics, Kolkata, India

arXiv: 1804.07241

Introduction

- Almost a decade back Georgi proposed the probable existence of a scale invariant sector.
- At a very high energy scale this scale invariance sector and the Standard Model (SM) sector may coexist and the fields of these two sectors can interact via a mediator messenger field of mass scale $M_{\mathcal{U}}$.
- At low energies, the scale invariance of SM is manifestly broken (SM particles have masses).
- The interactions between this scale invariance sector and SM are suppressed (inverse power of $M_{\mathcal{U}}$).
- Georgi observed at low energies scale invariance sector manifests itself by **non-integral number ($d_{\mathcal{U}}$) of massless invisible particles (scaling dimension of scale invariance sector) → Unparticles.**

Introduction

- A prototype model of such scale invariant sector can be obtained from Banks-Zaks theory, where the scale invariance sets in at energy scale $\Lambda_{\mathcal{U}}$.

- We have taken a scalar unparticle operator and scalar interactions with neutrinos that enables a heavy neutrino decay to a lighter neutrino and another unparticle.

- We consider unparticle decay of ultrahigh energy (UHE) neutrinos for four flavour scenario, where an extra sterile neutrino is introduced to the three families of active neutrinos, from a distant extragalactic sources such as Gamma-Ray Bursts (GRBs) and estimate the detection yield of these neutrinos at a kilometre square detector like IceCube.

Formalism

Unparticle decay of GRB neutrinos

- We consider a decay phenomenon, where neutrino having mass eigenstate ν_j decays to the invisible unparticle $(\mathcal{U})$ and another light neutrino with mass eigenstate ν_i.

$$\nu_j \rightarrow \mathcal{U} + \nu_i \quad ....1)$$

- The effective Lagrangian for the above mentioned process takes the following form in the low energy regime

$$L_s = \frac{\lambda_\nu^{\alpha\beta}}{\Lambda_{\mathcal{U}}^{d_{\mathcal{U}}-1}} \bar{\nu}_\alpha \nu_\beta \mathcal{O}_{\mathcal{U}} \quad ....2)$$

- The most relevant quantity for the decay process is the total decay rate Γ_j or equivalently the lifetime of neutrino $\tau_{\mathcal{U}} = 1/\Gamma_j$. The lifetime $\tau_{\mathcal{U}}$ can be expressed as

$$\frac{\tau_{\mathcal{U}}}{m_j} = \frac{16\pi^2 d_{\mathcal{U}}(d_{\mathcal{U}}^2 - 1)}{A_d|\lambda_\nu^{ij}|^2} \left(\frac{\Lambda_{\mathcal{U}}^2}{m_j^2}\right)^{d_{\mathcal{U}}-1} \frac{1}{m_j^2} \quad .... 3)$$

where m_j is the mass of the decaying neutrino.

Formalism (Contd.)

- The normalization constant in Eq. (3) is defined as

$$A_d = \frac{16\pi^{5/2}}{(2\pi)^{2d_{\mathcal{U}}}} \frac{\Gamma(d_{\mathcal{U}}+1/2)}{\Gamma(d_{\mathcal{U}}-1)\Gamma(2d_{\mathcal{U}})} \quad ....4)$$

- The flux for a neutrino $|\nu_\alpha\rangle$ of flavour α on reaching the Earth from GRB after undergoing the unparticle decay along the baseline length (L) is given as

$$\phi_{\nu_\alpha}(E) = \sum_i \sum_\beta \phi^s_{\nu_\beta} |U_{\beta i}|^2 |U_{\alpha i}|^2 exp(-4\pi L/(\lambda_d)_i) \ . \quad ....5)$$

$U_{\alpha i}$, $U_{\beta i}$ - PMNS matrix elements, $(\lambda_d)_i$ - the decay length

- For a 4 flavour scenario the PMNS matrix can be written as

$$\tilde{U}_{(4\times4)} = \begin{pmatrix} c_{14}U_{e1} & c_{14}U_{e2} & c_{14}U_{e3} & s_{14} \\ -s_{14}s_{24}U_{e1}+c_{24}U_{\mu1} & -s_{14}s_{24}U_{e2}+c_{24}U_{\mu2} & -s_{14}s_{24}U_{e3}+c_{24}U_{\mu3} & c_{14}s_{24} \\ \begin{matrix} -c_{24}s_{14}s_{34}U_{e1} \\ -s24s34U_{\mu1} \\ +c_{34}U_{\tau1} \end{matrix} & \begin{matrix} -c_{24}s_{14}s_{34}U_{e2} \\ -s24s34U_{\mu2} \\ +c_{34}U_{\tau2} \end{matrix} & \begin{matrix} -c_{24}s_{14}s_{34}U_{e3} \\ -s24s34U_{\mu3} \\ +c_{34}U_{\tau3} \end{matrix} & c_{14}c_{24}s_{34} \\ \begin{matrix} -c_{24}c_{34}s_{14}U_{e1} \\ -s_{24}c_{34}U_{\mu1} \\ -s_{34}U_{\tau1} \end{matrix} & \begin{matrix} -c_{24}c_{34}s_{14}U_{e2} \\ -s_{24}c_{34}U_{\mu2} \\ -s_{34}U_{\tau2} \end{matrix} & \begin{matrix} -c_{24}c_{34}s_{14}U_{e3} \\ -s_{24}c_{34}U_{\mu3} \\ -s_{34}U_{\tau3} \end{matrix} & c_{14}c_{24}c_{34} \end{pmatrix} \quad ......6)$$

Formalism (Contd.)

- The decay length $((\lambda_d)_i)$ in the Eq. (5) can be expressed as $(\lambda_d)_i = 2.5\text{Km}\frac{E}{\text{GeV}}\frac{\text{ev}^2}{\alpha_i}$ ...7) [$\alpha_i(= m_i/\tau)$]
- Applying the equation Eq. (5) and by considering the condition that the lightest mass state $|\nu_1\rangle$ is stable we can write the flux of neutrino flavours for 4 flavour cases on reaching the Earth as

$$
\begin{aligned}
\phi^4_{\nu_e} &= [|\tilde{U}_{e1}|^2(1+|\tilde{U}_{\mu 1}|^2-|\tilde{U}_{\tau 1}|^2-|\tilde{U}_{s1}|^2) \\
&+|\tilde{U}_{e2}|^2(1+|\tilde{U}_{\mu 2}|^2-|\tilde{U}_{\tau 2}|^2-|\tilde{U}_{s2}|^2)\exp(-4\pi L/(\lambda_d)_2) \\
&+|\tilde{U}_{e3}|^2(1+|\tilde{U}_{\mu 3}|^2-|\tilde{U}_{\tau 3}|^2-|\tilde{U}_{s3}|^2)\exp(-4\pi L/(\lambda_d)_3) \\
&+|\tilde{U}_{e4}|^2(1+|\tilde{U}_{\mu 4}|^2-|\tilde{U}_{\tau 4}|^2-|\tilde{U}_{s4}|^2)\exp(-4\pi L/(\lambda_d)_4)]\phi^s_{\nu_e}\ , \\
\phi^4_{\nu_\mu} &= [|\tilde{U}_{\mu 1}|^2(1+|\tilde{U}_{\mu 1}|^2-|\tilde{U}_{\tau 1}|^2-|\tilde{U}_{s1}|^2) \\
&+|\tilde{U}_{\mu 2}|^2(1+|\tilde{U}_{\mu 2}|^2-|\tilde{U}_{\tau 2}|^2-|\tilde{U}_{s2}|^2)\exp(-4\pi L/(\lambda_d)_2) \\
&+|\tilde{U}_{\mu 3}|^2(1+|\tilde{U}_{\mu 3}|^2-|\tilde{U}_{\tau 3}|^2-|\tilde{U}_{s3}|^2)\exp(-4\pi L/(\lambda_d)_3) \\
&+|\tilde{U}_{\mu 4}|^2(1+|\tilde{U}_{\mu 4}|^2-|\tilde{U}_{\tau 4}|^2-|\tilde{U}_{s4}|^2)\exp(-4\pi L/(\lambda_d)_4)]\phi^s_{\nu_e}\ , \\
\phi^4_{\nu_\tau} &= [|\tilde{U}_{\tau 1}|^2(1+|\tilde{U}_{\mu 1}|^2-|\tilde{U}_{\tau 1}|^2-|\tilde{U}_{s1}|^2) \\
&+|\tilde{U}_{\tau 2}|^2(1+|\tilde{U}_{\mu 2}|^2-|\tilde{U}_{\tau 2}|^2-|\tilde{U}_{s2}|^2)\exp(-4\pi L/(\lambda_d)_2) \\
&+|\tilde{U}_{\tau 3}|^2(1+|\tilde{U}_{\mu 3}|^2-|\tilde{U}_{\tau 3}|^2-|\tilde{U}_{s3}|^2)\exp(-4\pi L/(\lambda_d)_3) \\
&+|\tilde{U}_{\tau 4}|^2(1+|\tilde{U}_{\mu 4}|^2-|\tilde{U}_{\tau 4}|^2-|\tilde{U}_{s4}|^2)\exp(-4\pi L/(\lambda_d)_4)]\phi^s_{\nu_e}\ , \\
\phi^4_{\nu_s} &= [|\tilde{U}_{s1}|^2(1+|\tilde{U}_{\mu 1}|^2-|\tilde{U}_{\tau 1}|^2-|\tilde{U}_{s1}|^2) \\
&+|\tilde{U}_{s2}|^2(1+|\tilde{U}_{\mu 2}|^2-|\tilde{U}_{\tau 2}|^2-|\tilde{U}_{s2}|^2)\exp(-4\pi L/(\lambda_d)_2) \\
&+|\tilde{U}_{s3}|^2(1+|\tilde{U}_{\mu 3}|^2-|\tilde{U}_{\tau 3}|^2-|\tilde{U}_{s3}|^2)\exp(-4\pi L/(\lambda_d)_3) \\
&+|\tilde{U}_{s4}|^2(1+|\tilde{U}_{\mu 4}|^2-|\tilde{U}_{\tau 4}|^2-|\tilde{U}_{s4}|^2)\exp(-4\pi L/(\lambda_d)_4)]\phi^s_{\nu_e}\ .
\end{aligned}
$$

.....8)

GRB neutrino flux

In the absence of decay or oscillation the neutrino spectrum on reaching the Earth from a GRB at redshift z takes the form

$$\frac{dN_\nu^{\rm obs}}{dE_\nu^{\rm obs}} = \frac{dN_\nu}{dE_\nu}\frac{1}{4\pi r^2(z)}(1+z) \quad ...9)$$

In the absence of CP violation $\mathcal{F}(E_\nu) = \frac{dN_\nu^{\rm obs}}{dE_\nu^{\rm obs}} = \frac{dN_{\nu+\bar\nu}^{\rm obs}}{dE_\nu^{\rm obs}}$. The spectra for neutrinos will be $0.5\mathcal{F}(E_\nu)$.

Now the neutrinos produced in the GRB process in the proportion

$$\nu_e : \nu_\mu : \nu_\tau : \nu_s = 1:2:0:0 \quad ....10)$$

Therefore

$$\phi^s_{\nu_e} = \frac{1}{6}\mathcal{F}(E_\nu)\ ,\phi^s_{\nu_\mu} = \frac{2}{6}\mathcal{F}(E_\nu) = 2\phi^s_{\nu_e}\ ,\phi^s_{\nu_\tau} = 0\ ,\phi^s_{\nu_s} = 0\ , \quad .....11)$$

where $\phi^s_{\nu_e}$, $\phi^s_{\nu_\mu}$, $\phi^s_{\nu_\tau}$ and $\phi^s_{\nu_s}$ are the fluxes of ν_e, ν_μ, ν_τ and ν_s at source respectively.

Detection of UHE neutrinos from a single GRB

The secondary muon yields from the GRB neutrinos can be detected in a detector of unit area above a threshold energy $E_{\rm thr}$ is given by

$$S = \int_{E_{\rm thr}}^{E_{\nu \max}^{\rm obs}} dE_\nu^{\rm obs} \frac{dN_\nu^{\rm obs}}{dE_\nu^{\rm obs}} P_{\rm surv}(E_\nu^{\rm obs}, \theta_z) P_\mu(E_\nu^{\rm obs}, E_{\rm thr}), \quad .....12)$$

$P_{\rm surv}(E_\nu^{\rm obs}, \theta_z)$ - Probability that a neutrino reaches the detector travelling through Earth matter

$$P_{\rm surv}(E_\nu^{\rm obs}, \theta_z) = \exp[-X(\theta_z)/L_{\rm int}] \quad ..... 13)$$

The effective path length $X(\theta_z) = \int \rho(r(\theta_z, l)) dl$ . ..... 14)

Probability of neutrino induced muon to reach the detector $P_\mu(E_\nu^{\rm obs}, E_{\rm thr}) = N_A \sigma^{\rm CC} \langle R(E_\nu^{\rm obs}; E_{\rm thr}) \rangle$ . ...15)

where the average muon range in the rock $\langle R(E_\nu^{\rm obs}; E_{\rm thr}) \rangle$ is given by

$$\langle R(E_\nu^{\rm obs}; E_{\rm thr}) \rangle = \frac{1}{\sigma^{\rm CC}} \int_0^{1 - E_{\rm thr}/E_\nu} dy R(E_\nu^{\rm obs}(1-y), E_{\rm thr}) \frac{d\sigma^{\rm CC}(E_\nu^{\rm obs}, y)}{dy} \quad .... 16)$$

$$R(E_\mu, E_{\rm thr}) = \int_{E_{\rm thr}}^{E_\mu} \frac{dE_\mu}{\langle dE_\mu/dX \rangle} \simeq \frac{1}{\beta} \ln\left(\frac{\alpha + \beta E_\mu}{\alpha + \beta E_{\rm thr}}.\right) \quad ......17)$$

The average energy loss of muon with energy E_μ is given as

$$\left\langle \frac{dE_\mu}{dX} \right\rangle = -\alpha - \beta E_\mu \; . \quad .... 18)$$

$$\begin{aligned} \alpha &= 2.033 + 0.077 \ln[E_\mu({\rm GeV})] \times 10^3 \ {\rm GeV\ cm^2\ gm^{-1}} \ , \\ \beta &= 2.033 + 0.077 \ln[E_\mu({\rm GeV})] \times 10^{-6} \ {\rm GeV\ cm^2\ gm^{-1}} \ , \end{aligned} \quad ... 19)$$

for $E_\mu \lesssim 10^6$ GeV and otherwise

$$\begin{aligned} \alpha &= 2.033 \times 10^{-3} \ {\rm GeV\ cm^2\ gm^{-1}} \\ \beta &= 3.9 \times 10^{-6} \ {\rm GeV\ cm^2\ gm^{-1}} \ . \end{aligned} \quad .... 20)$$

$\frac{dN_\nu^{\rm obs}}{dE_\nu^{\rm obs}}$ in Eq. (12) is replaced by $\phi_{\nu_\mu}^4$ in Eq. (8).

Calculations and Results

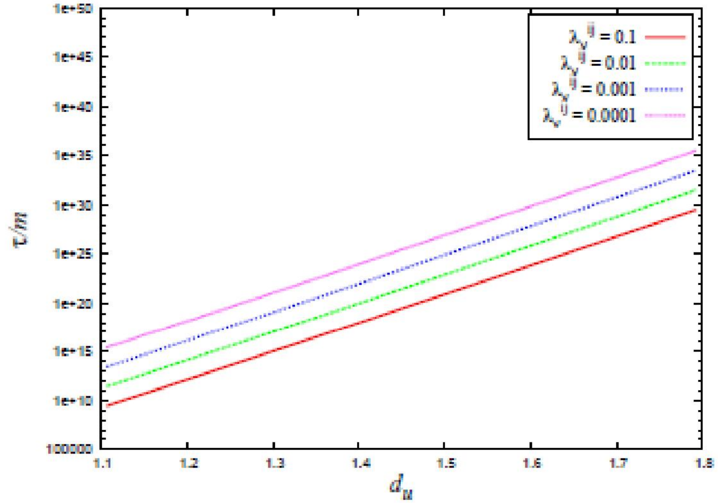


Figure 1: The Variations of the neutrino decay life time (τ/m) with the unparticle dimension $(d_{\mathcal{U}})$ are shown for four different values (0.1, 0.01, 0.001, 0.0001) of couplings λ_ν^{ij}.

Calculations and Results

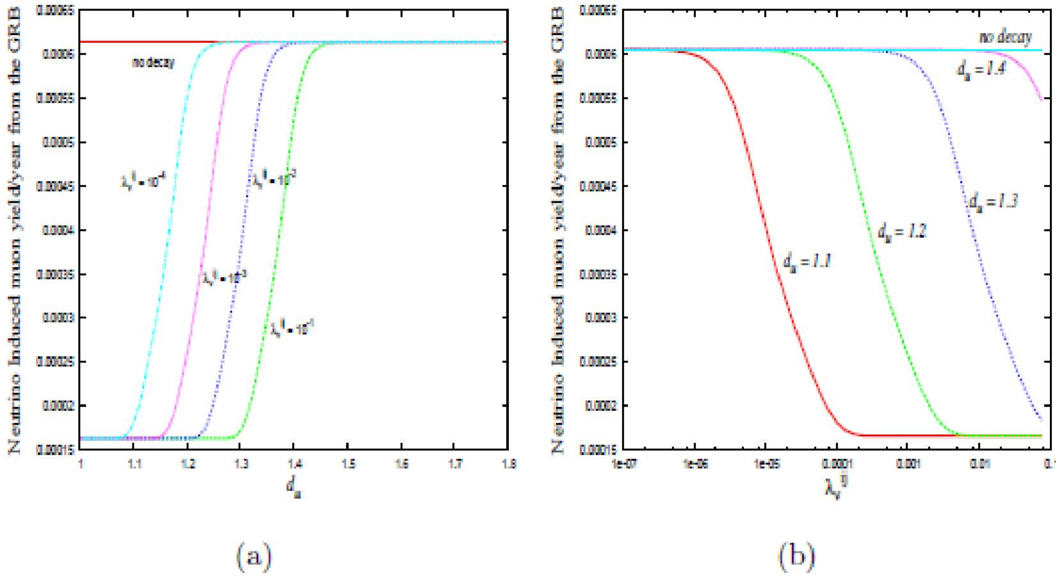
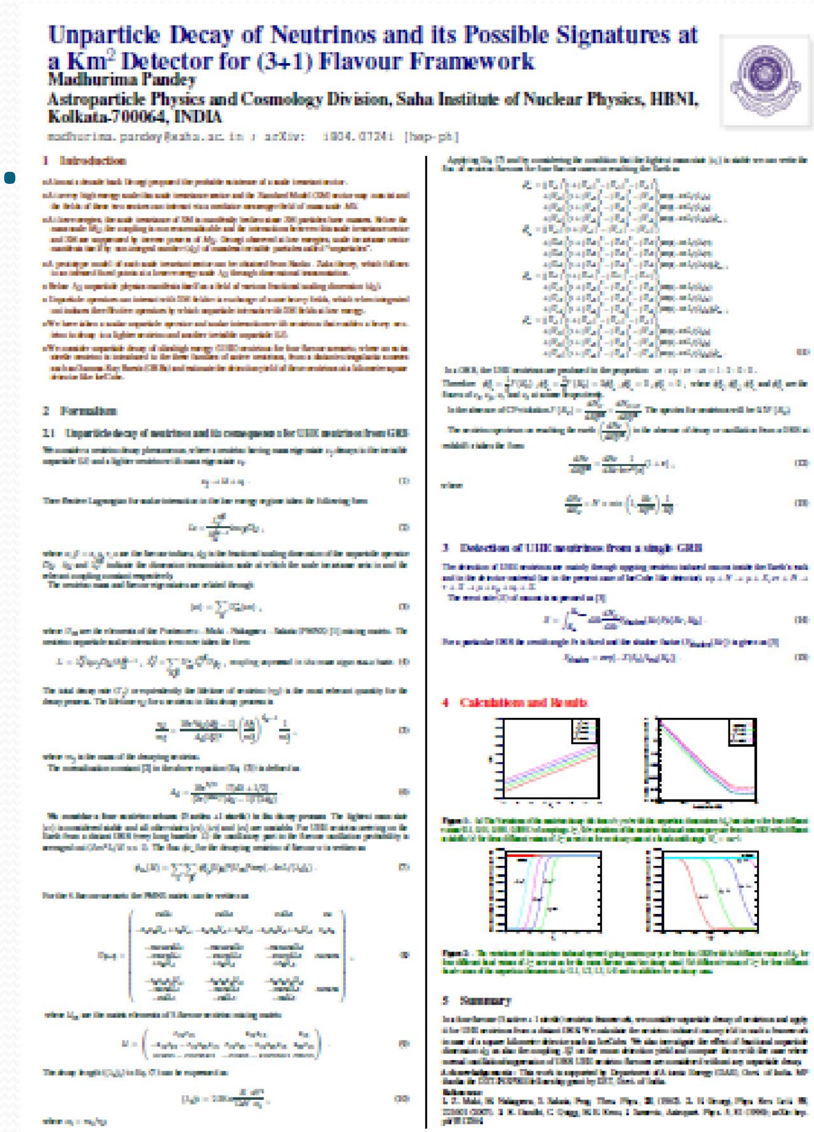


Figure 2: The variations of the neutrino induced upward going muons per year from the GRB with (a) different values of $d_{\mathcal{U}}$ for four different fixed values of λ_ν^{ij} as well as for the mass flavour case (no decay case), (b) different values of λ_ν^{ij} for four different fixed values of the unparticle dimension $d_{\mathcal{U}}$ (1.1, 1.2, 1.3, 1.4) and in addition for no decay case.

Summary and Discussions

- In this work we have explored the possibility of unparticle decay of Ultrahigh Energy (UHE) neutrinos from a distant single GRB and its consequences on the neutrino induced muon yields at a kilometre square detector.
- In order to explore the unparticle decay process we have considered the UHE neutrino signatures obtained from GRB events for a 3+1 neutrino framework.
- We estimate how the effect of an unparticle decay of neutrinos in addition to the mass-flavour oscillations can change the secondary muon yields from GRB neutrinos at a 1 Km^2 detector such as IceCube for a four flavour scenario.
- We also investigate the effect of fractional unparticle dimension $d_{\mathcal{U}}$ as also the coupling λ_ν^{ij} on the muon yield and compare them with the case where only flavour suppression (without an unparticle decay) is considered.

See you soon here…..



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Madhurima Pandey
Astroparticle Physics and Cosmology Division, Saha Institute of Nuclear Physics, HBNI, Kolkata-700064, INDIA
madhurima.pandey@saha.ac.in ; arXiv: 1804.07241 [hep-ph]

1 Introduction

2 Formalism

3 Detection of UHE neutrinos from a single GRB

4 Calculations and Results

5 Summary

THANK YOU

BACKUP SLIDES

Formalism

- **Unparticle decay of GRB neutrinos**
- We consider a decay phenomenon, where neutrino having mass eigenstate ν_j decays to the invisible unparticle $(\mathcal{U})$ and another light neutrino with mass eigenstate ν_i.

$$\nu_j \to \mathcal{U} + \nu_i \quad ....4)$$

- The effective lagrangian for the above mentioned process takes the following form in the low energy regime

$$L_s = \frac{\lambda_\nu^{\alpha\beta}}{\Lambda_\mathcal{U}^{d_\mathcal{U}-1}} \bar{\nu}_\alpha \nu_\beta \mathcal{O}_\mathcal{U} \quad ....5)$$

where $\alpha, \beta = e, \mu, \tau, s$ - flavour indices, $d_\mathcal{U}$ - the scaling dimension of the scalar unparticle operator $\mathcal{O}_\mathcal{U}$ $\Lambda_\mathcal{U}$ - the dimension transmutation scale at which the scale invariance sets in, $\lambda_\nu^{\alpha\beta}$ - the relevant coupling constant.

- The neutrino and flavour eigenstates are related through $|\nu_i\rangle = \sum_\alpha U_{\alpha i}^* |\nu_\alpha\rangle$ ....6)
  $U_{\alpha i}$ - elements of the PMNS mixing matrix.
- In the mass basis the interaction between neutrinos and the unparticles can be written as $\lambda_\nu^{ij} \bar{\nu}_i \nu_j \mathcal{O}_\mathcal{U} / \Lambda_\mathcal{U}^{d_\mathcal{U}-1}$, where λ_ν^{ij} is the coupling constant in the mass eigenstate i, j.

λ_ν^{ij} can be expressed as

$$\lambda_\nu^{ij} = \sum_{\alpha,\beta} U_{\alpha i}^* \lambda_\nu^{\alpha\beta} U_{\beta j} \quad ....7)$$

Calculations and Results

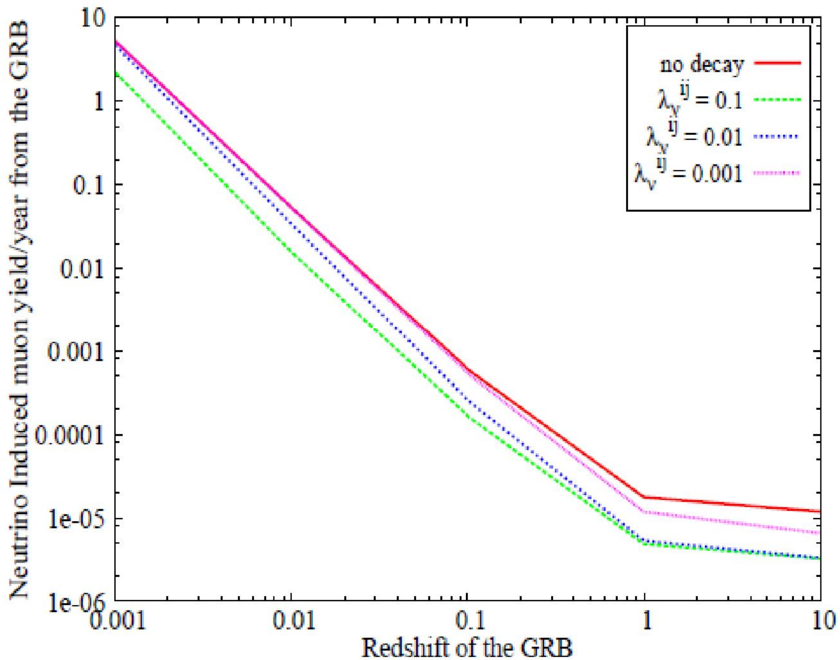

Figure 3: Variations of the neutrino induced muons per year from the GRB with different redshifts (z) for three different values of λ_ν^{ij} as well as for no decay case at a fixed zenith angle ($\theta_z = 160°$) .

Paper Published in Journals

1. A.D. Banik, M. Pandey, D. Majumdar and A. Biswas, " Two component WIMP-FImP dark matter model with singlet fermion, scalar and pseudo scalar, Eur. Phys. J. C **77**, 657 (2017).
2. M. Pandey, D. Majumdar and A.D. Banik, "Probing a four flavor vis-a-vis three flavor neutrino mixing for ultrahigh energy neutrino signals at 1 km^2 detector", Phys. Rev. D. **97**, 103015 (2018).

Paper Accepted for Publication

M. Pandey, D. Majumdar and K P. Modak, "Two Component Feebly Interacting massive Particle (FIMP) Dark Matter, [arXiv:1709.05955[hep-ph]] (accepted for the publication in the journal JCAP).

Paper Submitted for Publication

M. Pandey, "Unparticle Decay of Neutrinos and the Possible signatures at a 1km^2 Detector", [arXiv: 1804.07241 [hep-ph]] (under review for the publication in the journal JHEP).

Papers in Preparation

S. Jana, D. Majumdar and M. Pandey, "Neutrino Masses from Effective Dimension-7 Operator and Two Component FIMP Dark Matter" (this work also is in the stage of manuscript preparations which will be archived soon).