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

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

> > arXiv: 1804.07241

Tuesday, September 4, 2018 Invisibles18 Workshop, 2018

# 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 Mu.
- 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  $M_{u}$ ).
- Georgi observed at low energies scale invariance sector manifests itself by non-integral number (*du*) 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  $\nu_j$  decays to the invisible unparticle ( $\mathcal{U}$ ) and another light neutrino with mass eigenstate  $\nu_i$ .

$$\nu_j \rightarrow \mathcal{U} + \nu_i \dots 1$$

- The effective Lagrangian for the above mentioned process takes the following form in the low energy regime  $L_s = \frac{\lambda_{\nu}^{\alpha\beta}}{\Lambda_{\mathcal{U}}^{d_{\mathcal{U}}-1}} \bar{\nu}_{\alpha} \nu_{\beta} \mathcal{O}_{\mathcal{U}}$ ......2)
- The most relevant quantity for the decay process is the total decay rate  $\Gamma_j$  or equivalently the lifetime of neutrino  $\tau_u = 1/\Gamma_j$ . The lifetime  $\tau_u$  can be expressed as

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

where  $m_j$  is the mass of the decaying neutrino.

## Formalism (Contd.)

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

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

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

$$\phi_{\nu_{\alpha}}(E) = \sum_{i} \sum_{\beta} \phi_{\nu_{\beta}}^{s} |U_{\beta i}|^{2} |U_{\alpha i}|^{2} exp(-4\pi L/(\lambda_{d})_{i}) . \dots 5)$$

 $U_{\alpha i}$ ,  $U_{\beta i}$  - PMNS matrix elements,  $(\lambda_d)_i$  - the decay length For a 4 flavour scenario the PMNS matrix can be written as

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

### Formalism (Contd.)

- The decay length  $((\lambda_d)_i)$  in the Eq. (5) can be expressed as  $(\lambda_d)_i = 2.5 \text{Km} \frac{E}{\text{GeV}} \frac{\text{ev}^2}{\alpha_i} \dots 7) [\alpha_i (= m_i/\tau)]$
- 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{split} \phi_{\nu_{e}}^{4} &= \left[ \left\| \tilde{U}_{e1} \right\|^{2} (1 + \left\| \tilde{U}_{\mu 1} \right\|^{2} - \left\| \tilde{U}_{\tau 1} \right\|^{2} - \left\| \tilde{U}_{s1} \right\|^{2} \right) \\ &+ \left\| \tilde{U}_{e2} \right\|^{2} (1 + \left\| \tilde{U}_{\mu 2} \right\|^{2} - \left\| \tilde{U}_{\tau 2} \right\|^{2} - \left\| \tilde{U}_{s2} \right\|^{2} \right) \exp(-4\pi L/(\lambda_{d})_{2}) \\ &+ \left\| \tilde{U}_{e3} \right\|^{2} (1 + \left\| \tilde{U}_{\mu 3} \right\|^{2} - \left\| \tilde{U}_{\tau 3} \right\|^{2} - \left\| \tilde{U}_{s3} \right\|^{2} \right) \exp(-4\pi L/(\lambda_{d})_{3}) \\ &+ \left\| \tilde{U}_{e4} \right\|^{2} (1 + \left\| \tilde{U}_{\mu 4} \right\|^{2} - \left\| \tilde{U}_{\tau 4} \right\|^{2} - \left\| \tilde{U}_{s1} \right\|^{2} \right) \exp(-4\pi L/(\lambda_{d})_{4}) \right] \phi_{\nu_{e}}^{s} , \\ \phi_{\nu_{\mu}}^{4} &= \left[ \left\| \tilde{U}_{\mu 1} \right\|^{2} (1 + \left\| \tilde{U}_{\mu 1} \right\|^{2} - \left\| \tilde{U}_{\tau 1} \right\|^{2} - \left\| \tilde{U}_{s1} \right\|^{2} \right) \\ &+ \left\| \tilde{U}_{\mu 2} \right\|^{2} (1 + \left\| \tilde{U}_{\mu 3} \right\|^{2} - \left\| \tilde{U}_{\tau 3} \right\|^{2} - \left\| \tilde{U}_{s3} \right\|^{2} \right) \exp(-4\pi L/(\lambda_{d})_{3}) \\ &+ \left\| \tilde{U}_{\mu 4} \right\|^{2} (1 + \left\| \tilde{U}_{\mu 4} \right\|^{2} - \left\| \tilde{U}_{\tau 1} \right\|^{2} - \left\| \tilde{U}_{s1} \right\|^{2} \right) \\ &+ \left\| \tilde{U}_{\tau 2} \right\|^{2} (1 + \left\| \tilde{U}_{\mu 3} \right\|^{2} - \left\| \tilde{U}_{\tau 2} \right\|^{2} - \left\| \tilde{U}_{s3} \right\|^{2} \right) \exp(-4\pi L/(\lambda_{d})_{3}) \\ &+ \left\| \tilde{U}_{\tau 2} \right\|^{2} (1 + \left\| \tilde{U}_{\mu 3} \right\|^{2} - \left\| \tilde{U}_{\tau 3} \right\|^{2} - \left\| \tilde{U}_{s3} \right\|^{2} \right) \exp(-4\pi L/(\lambda_{d})_{3}) \\ &+ \left\| \tilde{U}_{\tau 4} \right\|^{2} (1 + \left\| \tilde{U}_{\mu 4} \right\|^{2} - \left\| \tilde{U}_{\tau 1} \right\|^{2} - \left\| \tilde{U}_{s 1} \right\|^{2} \right) \\ &+ \left\| \tilde{U}_{s 2} \right\|^{2} (1 + \left\| \tilde{U}_{\mu 3} \right\|^{2} - \left\| \tilde{U}_{\tau 1} \right\|^{2} - \left\| \tilde{U}_{s 1} \right\|^{2} \right) \exp(-4\pi L/(\lambda_{d})_{4}) \right] \phi_{\nu_{e}}^{s} , \end{aligned} \right.$$

Tuesday, September 4, 2018

Invisibles18 Workshop, 2018

## **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  $\frac{dN_{\nu}^{\text{obs}}}{dN_{\nu}} = \frac{dN_{\nu}}{1}$ 

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

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

Now the neutrinos produced in the GRB process in the proportion

$$\nu_e: \nu_\mu: \nu_\tau: \nu_s = 1:2:0:0 \dots 10$$

Therefore

$$\phi_{\nu_e}^s = \frac{1}{6} \mathcal{F}(E_{\nu}) \ , \phi_{\nu_{\mu}}^s = \frac{2}{6} \mathcal{F}(E_{\nu}) = 2\phi_{\nu_e}^s \ , \phi_{\nu_{\tau}}^s = 0 \ , \phi_{\nu_s}^s = 0 \ , \ \dots \dots 11)$$

where  $\phi_{\nu_e}^s$ ,  $\phi_{\nu_{\mu}}^s$ ,  $\phi_{\nu_{\tau}}^s$  and  $\phi_{\nu_s}^s$  are the fluxes of  $\nu_e$ ,  $\nu_{\mu}$ ,  $\nu_{\tau}$  and  $\nu_s$  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  $E_{\text{thr}}$  is given by  $S = \int_{-}^{E_{\nu \text{max}}^{\text{obs}}} dE_{\nu}^{\text{obs}} \frac{dN_{\nu}^{\text{obs}}}{dE_{\nu}^{\text{obs}}} P_{\text{surv}}(E_{\nu}^{\text{obs}}, \theta_z) P_{\mu}(E_{\nu}^{\text{obs}}, E_{\text{thr}}),$ 

$$P_{\text{surv}}(E_{\nu}^{\text{obs}}, \theta_z)$$
 - Probability that a neutrino reaches the detector travelling through Earth matter  
 $P_{\text{surv}}(E_{\nu}^{\text{obs}}, \theta_z) = \exp[-X(\theta_z)/L_{\text{int}}]$  ..... 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  $P_{\mu}(E_{\nu}^{\text{obs}}, E_{\text{thr}}) = N_A \sigma^{\text{CC}} \langle R(E_{\nu}^{\text{obs}}; E_{\text{thr}}) \rangle$ ....15)

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

$$\langle R(E_{\nu}^{\text{obs}}; E_{\text{thr}}) \rangle = \frac{1}{\sigma^{\text{CC}}} \int_{0}^{1-E_{\text{thr}}/E_{\nu}} dy R(E_{\nu}^{\text{obs}}(1-y), E_{\text{thr}}) \frac{d\sigma^{\text{CC}}(E_{\nu}^{\text{obs}}, y)}{dy} \dots 16)$$

#### Tuesday, September 4, 2018 Invisibles18 Workshop, 2018

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

The average energy loss of muon with energy  $E_{\mu}$  is given as

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

$$\alpha = 2.033 + 0.077 \ln[E_{\mu}(\text{GeV})] \times 10^3 \text{ GeV } \text{cm}^2 \text{ gm}^{-1},$$

$$\beta = 2.033 + 0.077 \ln[E_{\mu}(\text{GeV})] \times 10^{-6} \text{ GeV cm}^2 \text{ gm}^{-1}, \dots 19$$

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

$$\alpha = 2.033 \times 10^{-3} \text{ GeV cm}^2 \text{ gm}^{-1}$$
  
$$\beta = 3.9 \times 10^{-6} \text{ GeV cm}^2 \text{ gm}^{-1}. \dots 20$$

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

# **Calculations and Results**

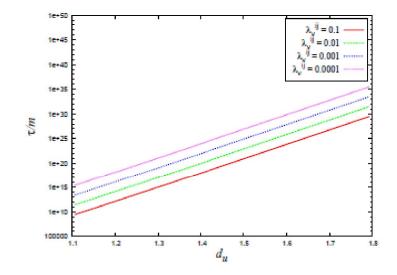


Figure 1: The Variations of the neutrino decay life time  $(\tau/m)$  with the unparticle dimension  $(d_{\mathcal{U}})$  are shown for four different values (0.1, 0.01, 0.001, 0.0001) of couplings  $\lambda_{\nu}^{ij}$ .

# **Calculations and Results**

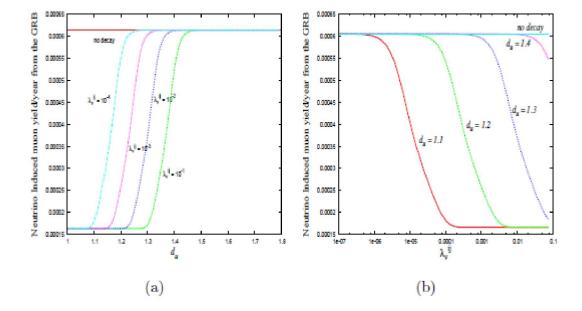


Figure 2: The variations of the neutrino induced upward going muons per year from the GRB with (a) different values of  $d_{\mathcal{U}}$  for four different fixed values of  $\lambda_{\nu}^{ij}$  as well as for the mass flavour case (no decay case), (b) different values of  $\lambda_{\nu}^{ij}$  for 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<sup>2</sup> detector such as IceCube for a four flavour scenario.
- We also investigate the effect of fractional unparticle dimension d<sub>u</sub> as also the coupling λ<sup>ij</sup><sub>ν</sub> on the muon yield and compare them with the case where only flavour suppression (without an unparticle decay) is considered.

## See you soon here.

#### Unparticle Decay of Neutrinos and its Possible Signatures at a Km<sup>2</sup> Detector for (3+1) Flavour Framework Madhurima Pandey

Astroparticle Physics and Cosmology Division, Saha Institute of Nuclear Physics, HBNI, Kolkata-700064, INDIA

machurina, pandey (saha, ar. in / arXiv: 1904.07241 [hep-ph]

#### 1 Introduction

#### ed lands a detaile back. Design proposed the period de minister of a social transition of an All are reliable workers and the and investment and in Namley Madel CMI worker are not to and the fields of these two modern contractions are contracted and seen and a SAS. edition region de cost investeur el 56 in conditaily inderent en 56 particles los manos. Nelse de mana sub-183, de conpling in une encensitable col de interaction ference initiale investoremente. and 200 an approach is increasion of My. Chargi charved a line energies, and in advance on in-manifest in Fig. and singula moder (Ag) of manifest invited particles with Computation".

ed. pertury provide at an invariant sector and a sector and the Markov Needer. Take theory, which full need is an infrared listed paints of a least rearrange scale. Ag through the sector is invariant. a linker Ag sequences physics considers in the a field of various fractional scaling descenter (Ag). Deputities operation are interest with DM index is reaching of some invery fields, which when hings and indexes live Fluider operators by which superiods interests with DM index is rearge.

We have taken a made sequencies aprecia and made interactions with a minimum that walking a longy area. inter to them too lighter projector and earlier to table security 1.5. eWe consider comparish droug of clinicity energy (CHE) emotions for from the same of the set of the

on hard another they have a (20 h) and relevant to a source sections, there is all inter-respirate in terms of the lattice of

#### 2 Formalism

2.1 Unparticle decay of neutrinos and its consequence a for UER matrices from GRB We could be available they please on a first a stable laring our signals to describ the initiality the full and a lighter series iner ill care right in the sy sy all say (D)

ter Beite Legengie for autorisiensite in finite range opier idea in following fore

where  $a_i f = a_{i,k} a_i$  are the law architer,  $a_i$  is the functional scaling discretion of the separate spin-term  $D_{ij}$ ,  $b_{ij}$  and  $\frac{1}{2^2}$  induce for discretion incompletion and of which for each involvem with its call for effected coupling consists requester by The residue case and forces that makes are related from the

 $|\mathbf{u}| = \sum_{i=1}^{n} |\mathbf{u}_{i}|_{i=1}^{n}$  .

vice Up on it chooses of its Parissons. Main . Natagers . Main (PSPR) [1] mixing mains. The resident approach and a interaction income takes the large

 $L = \sqrt{2} q_{0} \rho_{0} Q_{0} Q_{0}^{0} - \gamma_{0}^{0} Q_{0}^{0} - \sum_{ijj} Q_{ij}^{0} Q_{jj}^{0} + major q a partial in the matrix sign matrix last. (6)$ 

The total determine (T-2) or reachables for lifetime of evolution (real to the most external quantity for the ny para. To librar sy he caratta is disibut prava is

> $\frac{\pi_{0}}{\pi_{0}} = \frac{2h^{2}\theta_{0}(d_{0}^{2}-1)}{A_{0}(d_{0}^{2})^{2}} \left(\frac{A_{0}^{2}}{\pi_{0}^{2}}\right)^{\frac{1}{2}\mu-1};$

vice of a lite same of the description of sizing To consider the second of [2] is the above reputites (2a) (2b) is defined as

```
A_{ij} = \frac{31\pi^{3/2}}{(2\pi)^{10} \Gamma(A_{ij}^{-1} - 1)^2 \Gamma(A_{ij}^{-1})}
```

```
\theta_{m}(R) = \sum_{i} \sum_{j} \theta_{ij} P_{jk} P_{jk} P_{ik} P_{ik
```

For the 6 far service and the PADC sales, such revision as

Spect -	-meaning -meaning steps	- manufacture -	- manufactoria	10.000
	- Martin	- Martin	1000	1015.0



where up a maybe





#### 3 Detection of UHE neutrinos from a single GRB

The detection of DEE evolutions are mainly decayly applying residue induced masses inside the Deck's walk and its detection inside (for in the present same of in Cale in the detection) equily  $N \rightarrow p + X_{c} p + N \rightarrow p + X_{c} p + X_{c} p + N \rightarrow p$ The ment and Chail and a long point of [2].

$$T = \int_{-\infty}^{\infty} dM \frac{dN_{\mu}}{dM} Q_{harlow}(M) P_{h}(M_{\mu}, M_{\mu}), \qquad (10)$$
  
Sindse (103) is continuede it is the formal for datation ( $N_{harlow}(M_{\mu})$  is given as  $[1]$ 

$$S_{\text{that in }} = \exp[-T(t_{a})/t_{\text{rel}}(t_{a})]$$
 (20)

4 Calculations and Results

wine,

Berge

120

10

(1)

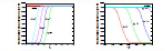
-

100

12



Figure 1. - Collins Technologies - Constanting Collins (Collins) - Collins (Collins) (Collins) A 144 and the lot of the lot of allow of the second Colorentes (\* 188 mains d Lange (\* 1996) and a state and a locality



#### 5 Summary

In a line factor (Lation 1 and Constant Source), we could empetite data of entries and apply the USE matrice from a data (USE We address for matrix index) many (Clinearies for source) is one of a super-bilicenter interior and as locality. We disc increasingly the effect of functional superbilit formations by an data for complex of a first interior problem interpret theorem the over the most combination agreement of 1983–1987 and the formation of combined with the properties of the pro-120 Ashenevinigenessis: The work is expected by Department of A lands Harry (DAD) Clevi of India MP inside the DAT MCDERIC Cleving gravity DAT, Clevi, of India. References L. Z. Mais, M. Maingers, S. Main, Pop. Time, Phys. 21, 1993; L. R. Grangi, Phys. Rev. Lett. 49, 0.0

[2010] (2017). 2 K. Bando, C. Quag, K.K. Kong, J. Sawain, Astropat. Phys. Rev. Lett. 98, 1971 (2017).





## THANK YOU

Tuesday, September 4, 2018 Invisibles18 Workshop, 2018

\_\_\_\_\_

## BACKUP SLIDES

Tuesday, September 4, 2018 Invisibles18 Workshop, 2018

\_\_\_\_\_

# Formalism

## Unparticle decay of GRB neutrinos

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

$$\nu_j \rightarrow \mathcal{U} + \nu_i \dots 4$$
)

• The effective lagrangian for the above mentioned process takes the following form in the low energy regime  $\lambda_{\nu}^{\alpha\beta}$  is a 0

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  $|\nu_i\rangle = \sum_{\alpha} U^*_{\alpha i} |\nu_{\alpha}\rangle \dots 6$  $U_{\alpha i}$  - 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  $\lambda_{\nu}^{ij}$  is the coupling constant in the mass eigenstate i, j.

# **Calculations and Results**

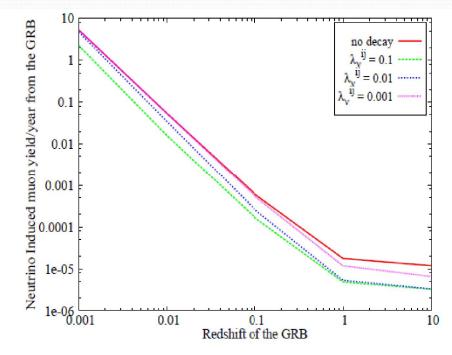


Figure 3: Variations of the neutrino induced muons per year from the GRB with different redshifts (z) for three different values of  $\lambda_{\nu}^{ij}$  as well as for no decay case at a fixed zenith angle ( $\theta_z = 160^\circ$ ).

### Paper Published in Journals

 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<sup>2</sup> 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<sup>2</sup> 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).