



GeV to TeV astrophysical tau neutrinos

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Abstract

Neutrinos with energy greater than GeV are copiously produced in the $p(A, p)$ interactions occurring in several astrophysical sites such as (i) the Earth atmosphere, (ii) our galactic plane as well as in (iii) the galaxy clusters. A comparison of the tau and mu neutrino flux in the presence of neutrino oscillations from these three representative astrophysical sites is presented. It is pointed out that the non-atmospheric tau neutrino flux starts dominating over the downward going atmospheric tau neutrino flux for neutrino energy E as low as ~ 10 GeV. This energy value is much lower than the energy value, $E \geq 5 \times 10^4$ GeV, estimated for the dominance of the non-atmospheric mu neutrino flux, in the presence of neutrino oscillations. Future prospects for possible observations of non-atmospheric tau neutrino flux are briefly mentioned.

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1. Introduction

A present day main motivation for the extra-terrestrial neutrino astronomy is to obtain the first evidence of tau neutrinos from the cosmos around us above the relatively well-known atmospheric neutrino background [1]. The tau neutrinos are essentially an unavoidable consequence of almost maximal neutrino flavor mixing between ν_μ and ν_τ as suggested by the atmospheric mu neutrino data analysis of the high statistics Super-Kamiokande detector (SKK) [2].

A recent SKK analysis of the L/E distribution of the atmospheric mu neutrino data imply the following range of neutrino mixing parameters [3]

$$1.9 \times 10^{-3} < \Delta m^2 < 3.0 \times 10^{-3} \text{ eV}^2, \\ \sin^2 2\theta > 0.9. \quad (1)$$

This is a 90% C.L. range with the best fit values approximately given by $\Delta m^2 = 2.4 \times 10^{-3} \text{ eV}^2$ and $\sin^2 2\theta = 1$, respectively. This range of neutrino mixing parameters results in purely two flavor oscillation explanation of the L/E distribution of the atmospheric mu neutrino flux disappearance. The tau neutrinos as a result of these $\nu_\mu \rightarrow \nu_\tau$ oscillations

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are so far identified on statistical basis (rather than on event by event basis).¹ The total number of observed atmospheric non-tau neutrinos, on the other hand, are by now greater than 10^4 from various detectors ranging in energy between $\sim 10^{-1}$ to $\sim 10^3$ GeV [4]. Given the recent detector developments, it is of some interest to estimate the tau neutrino flux from the Earth atmosphere as well as from the nearby astrophysical sites in order to provide a more complete basis for the hypothesis of $\nu_\mu \rightarrow \nu_\tau$ oscillations.

The expectations for high energy astrophysical mu neutrino flux with $E \geq 10^3$ GeV without neutrino oscillation effects are summarized in [5]. A purpose of this Letter is to point out through examples that the GeV to TeV (1 TeV = 10^3 GeV) tau neutrino astronomy can be quite *different* as compared to the below TeV mu neutrino astronomy which is essentially dominated by the study of atmospheric neutrinos only. The recently discovered neutrino flavor oscillations does not bring any significant changes as far as the below TeV extra-terrestrial mu neutrino search/astronomy is concerned. Considering a different neutrino flavor in the above energy range may change the situation somewhat by opening a *new* window to study cosmos. In this context, we shall distinguish between the possibilities offered by the different neutrino flavor astronomy through some examples. For a summary of above TeV astrophysical tau neutrino fluxes, see [6]. In this Letter, we shall focus on the tau neutrinos and estimate the total tau neutrino flux from the three different astrophysical sites in order to illustrate that the GeV to TeV tau neutrino astronomy may be quite different from the GeV to TeV mu neutrino astronomy.

The neutrino oscillation probability in the two neutrino flavor approximation is [7]

$$P(\nu_\mu \rightarrow \nu_\tau) = \sin^2 2\theta \sin^2 \left(1.27 \frac{\Delta m^2 (\text{eV}^2) L (\text{km})}{E (\text{GeV})} \right). \quad (2)$$

Here L , is the neutrino flight length. In the Earth atmosphere, it can be estimated using

$$L = \sqrt{(h^2 + 2R_\oplus h) + (R_\oplus \cos \xi)^2} - R_\oplus \cos \xi. \quad (3)$$

The L is essentially the distance between the detector and the height at which the atmospheric mu neutrinos

are produced. The $R_\oplus \simeq 6.4 \times 10^3$ km is the Earth radius, and $h = 15$ km is the mean altitude at which the atmospheric mu neutrinos are produced. In general, h is not only a function of the zenith angle ξ , the neutrino flavor but also the neutrino energy [8].

This Letter is organized as follows. In Section 2, the mu and tau neutrino flux originating from the Earth atmosphere, the galactic plane as well as from the galaxy clusters is briefly discussed. In Section 3, the neutrino oscillation effects are studied for these. In Section 4, the limited future prospects for possible observations of non-atmospheric tau neutrinos are mentioned, whereas in Section 5, conclusions are presented.

2. Some examples of GeV to TeV astrophysical tau neutrinos

In order to estimate the total tau neutrino flux from a given astrophysical site which is composed of intrinsic and oscillated ones, we need to first estimate the intrinsic mu and tau neutrino flux from that site. In this section, we briefly describe the general procedure used to estimate these.

Before doing that, let us remark here that the incident cosmic ray energy that we consider here ranges typically between $10 < E_p/\text{GeV} < 10^4$. The corresponding c.m. energy range in pp collisions is $1 < \sqrt{s_{pp}}/\text{GeV} < 10^2$ as $s_{pp} \sim 2m_p E_p$. The data from various collider experiments indicates that the tau neutrino parent hadron (D_S^\pm) production cross section here is suppressed relative to mu neutrino parent hadron (π^\pm) production cross section in pp collisions in the above $\sqrt{s_{pp}}$ range [9]. Therefore, any sizeable tau neutrino flux from the following sites should be verifying the neutrino flavor mixing.

2.1. Atmospheric

Briefly, the incoming cosmic rays interact with the air nuclei A , in the earth atmosphere and give rise to mu neutrino flux. For $1 \leq E/\text{GeV} \leq 10^3$, the π^\pm , K production and their direct and indirect decays are the main sources of mu neutrinos, both being in the region of conventional mu neutrino production [10]. The absolute normalization of the conventional atmospheric neutrino flux is presently known to be no better than (20–25)% [11].

¹ See, Y. Suzuki in Ref. [2].

For present estimates, the mu neutrino flux is taken from Ref. [12]. These are neutrino flux calculations in one dimension without geomagnetic field effects. The up down mu neutrino flux is taken to be the same, as the present discussion is independent of any specific detector. At higher energy, the prompt mu neutrino production from D 's dominates over the conventional one [13].

The atmospheric tau neutrino flux arises mainly from D_S^\pm and is calculated in Refs. [14,15]. The quark–gluon string model (QGSM) is used in Ref. [15] to model the pA interactions. The low energy atmospheric tau neutrino flux is essentially isotropic [14]. For $E \leq 10^3$ GeV, the atmospheric tau neutrino flux is obtained by following the procedure given in Refs. [14,15] and rescaling w.r.t. new cosmic ray flux spectrum, taking it to be dominantly the protons [17–19].

2.2. Galactic plane

The galactic plane mu neutrino flux is calculated in Refs. [20,21], whereas the galactic plane tau neutrino flux is calculated in Ref. [15]. These calculations consider pp interactions inside the galaxy with target proton number density $\sim 1/\text{cm}^3$ along the galactic plane, under the assumption that the cosmic ray flux spectrum in the Galaxy is constant at its locally observed value. The current Energetic Gamma Ray Experiment Telescope (EGRET) observations of the diffuse gamma-ray emission from the galactic plane seems to imply a slightly less (~ 0.62) target proton density along the galactic plane [16]. We have checked that taking into account this in our estimates makes only a minor difference.

Following Ref. [15], the galactic plane mu and tau neutrino flux for $E \leq 10^3$ GeV is obtained by rescaling w.r.t. new cosmic-ray flux spectrum. The tau neutrino production is rather suppressed in the galactic plane relative to mu neutrino production. The mu neutrino flux is larger than the tau neutrino flux for $E \leq 10^3$ GeV from the above two sites.

Fig. 1 gives the intrinsic mu and tau neutrino flux, $F_\nu(E) \equiv dN_\nu^0/d(\log_{10} E)$ in units of $\text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$, estimated using the above description. The figure also shows the cosmic-ray proton flux spectrum we have used.

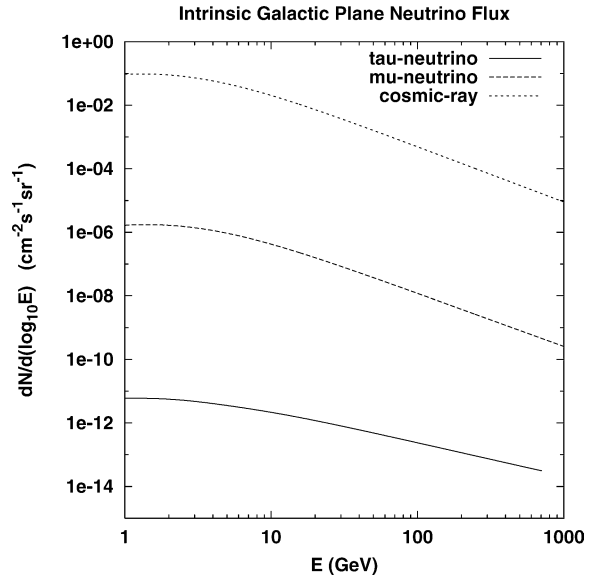


Fig. 1. The intrinsic galactic plane mu and tau neutrino fluxes. The cosmic-ray flux spectrum used in the estimates is also shown.

2.3. Clusters of galaxies

Clusters of galaxies are presently considered to be an interesting laboratory to investigate various stages of structure formation via the study of diffuse gamma-rays (and cosmic-rays) from these [22,23].

The mu and tau neutrino fluxes are produced here in pp interactions (of cosmic-rays with the intra cluster gas), under the main assumption that a large fraction of the cosmologically produced baryons is inside these galaxy clusters. The intrinsic tau neutrino flux estimate here is rather similar to the galactic plane situation.

The maximum mu neutrino flux from clusters of galaxies is estimated by correlating it with the corresponding gamma-ray flux in pp collisions. This estimate is under the assumption that diffuse gamma-ray flux observed in the energy range $10 \leq E/\text{GeV} \leq 50$ by EGRET is dominantly from clusters of galaxies. We shall use this upper limit as an another example of an astrophysical site that may produce tau neutrino flux in the GeV to TeV energy range.

The detailed model dependent calculations indicate that the actual contribution of the galaxy clusters towards the recently observed extra-galactic diffuse gamma-ray flux is approximately two orders of magnitude small [24].

Before studying the effects of neutrino oscillations on these intrinsic neutrino fluxes, let us here emphasize that the non-atmospheric mu and tau neutrino fluxes can only be considered as upper limits on these fluxes in light of the existing inherent uncertainties in estimating these.

3. Effects of neutrino oscillations

We shall perform here the two neutrino flavor oscillation analysis. In the context of two neutrino flavor oscillations, there are only two neutrino mixing parameters. The mixing angle θ and the $\Delta m^2 (\equiv m_2^2 - m_1^2)$. There are no matter effects for these two flavors.

In the two flavor approximation, the *total* tau neutrino flux from an astrophysical site is given by

$$F_{\nu_\tau}(E) = P_{\mu\tau}(E) \cdot F_{\nu_\mu}^0(E) + P_{\mu\mu}(E) \cdot F_{\nu_\mu}^0(E), \quad (4)$$

where $P_{\mu\tau}(E) \equiv P(\nu_\mu \rightarrow \nu_\tau)$ is given by Eq. (2) and $P(\nu_\mu \rightarrow \nu_\mu) = 1 - P(\nu_\mu \rightarrow \nu_\tau)$. The $F_\nu^0(E)$ is the intrinsic neutrino flux in units of $\text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$ and is taken according to discussion in Section 2.

Three general directions in the Earth atmosphere are considered as representative examples to compare the atmospheric tau neutrino flux with the non-atmospheric one in the *presence* of neutrino oscillations. These are the downward, the horizontal and the upward directions. Fig. 2 depicts the L_{osc} given by Eq. (2) for the range of Δm^2 given by Eq. (1) with maximal mixing. The three distances are taken from Eq. (3), with, for instance, the downward distance is obtained by setting $\xi = 0$. The horizontal distance is obtained by setting $\xi = \pi/2$.

Using Eq. (4), the total *downward* going atmospheric tau neutrino flux is estimated. It is then compared with the total galactic plane and total upper limit galaxy clusters tau neutrino flux in Fig. 3 for the whole range of Δm^2 with maximal mixing. The distance L for galactic plane neutrinos is taken as ~ 5 kpc, where $1 \text{ pc} \sim 3 \times 10^{13} \text{ km}$. For galaxy clusters, its representative value is taken as 1 Mpc. Since $L_{\text{osc}} \ll L$, the galactic plane and galaxy cluster mu neutrinos oscillate before reaching the Earth. Also, note that this flux is averaged out for the whole range of Δm^2 in the entire considered energy range. The effect of different Δm^2 values diminishes for $E \geq 50 \text{ GeV}$ for total atmospheric tau neutrino flux. From the figure, it can be

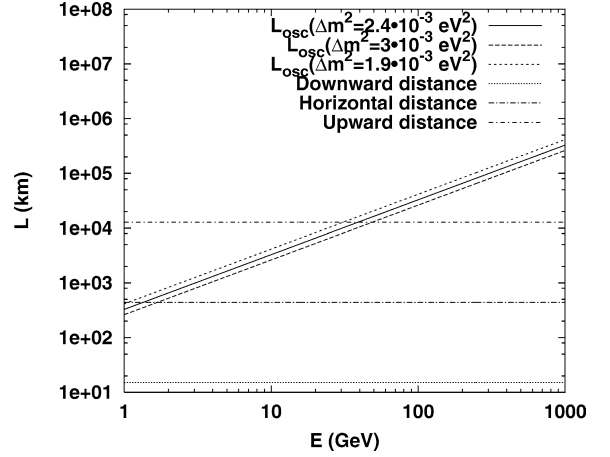


Fig. 2. The $\nu_\mu \rightarrow \nu_\tau$ oscillation length $L_{\text{osc}} [\equiv 0.787 \text{ km } E(\text{GeV}) / \Delta m^2(\text{eV}^2)]$ in km as a function of neutrino energy in GeV. The three general distances traversed by mu neutrinos in the Earth atmosphere are also shown (the horizontal lines). More details are given in the text.

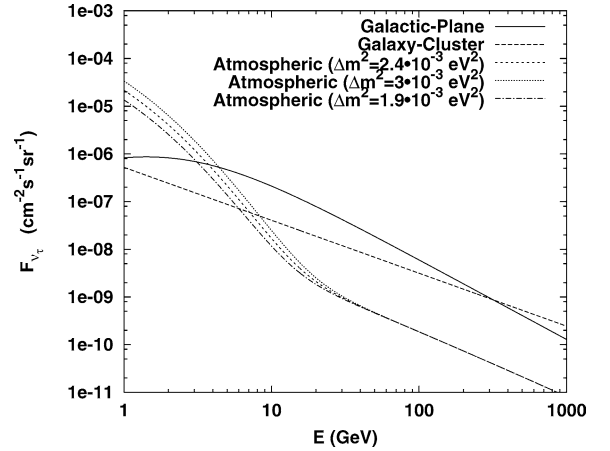


Fig. 3. An illustrative comparison of the galactic plane, the maximum galaxy clusters and the downward going atmospheric tau neutrino flux in the presence of neutrino oscillations as a function of neutrino energy.

seen that the galactic plane/non-atmospheric tau neutrino flux starts *dominating* over the downward going atmospheric tau neutrino flux even for E as low as 10 GeV in the presence of neutrino oscillations. This is a very specific feature of *tau neutrinos*, and is absent for mu neutrinos. This specific behavior has to do with the *neutrino oscillations*. The galactic plane tau neutrino flux for $1 \leq E/\text{GeV} \leq 10^3$ in the presence of

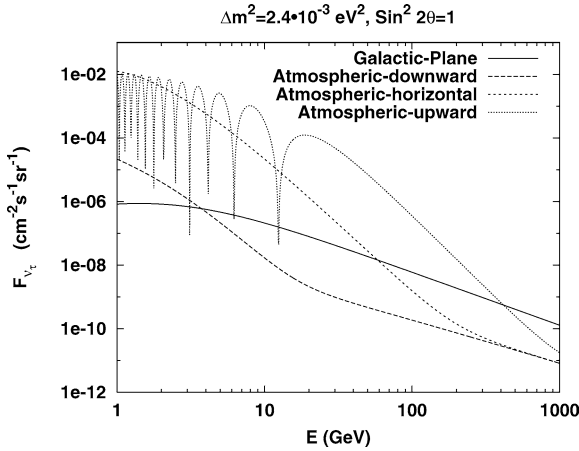


Fig. 4. The galactic plane and the atmospheric tau neutrino flux in the presence of neutrino oscillations for the three general directions in the Earth atmosphere as a function of neutrino energy. The neutrino mixing parameter values used here are the approximate best fit values, i.e., $\Delta m^2 = 2.4 \times 10^{-3} \text{ eV}^2$ and $\sin^2 2\theta = 1$.

neutrino oscillations can be parameterized as

$$F_{\nu_\tau}(E) = (1.31 \times 10^{-5}) E^{1.07} \times [E + 2.15 \exp(-0.21\sqrt{E})]^{-2.74}, \quad (5)$$

where F_{ν_τ} is in units of $\text{cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$ and on r.h.s. E is in units of GeV.

In Fig. 4, the galactic plane tau neutrino flux is compared with the atmospheric tau neutrino flux, using Eq. (4) for the three general directions for the atmospheric tau neutrino flux reaching the detector. Here the best fit values of the neutrino mixing parameters are used. The oscillatory nature of the upward going tau neutrino flux can be seen from Eq. (2). The cross over for the galactic tau neutrinos relative to the horizontal atmospheric tau neutrinos occurs at $\sim 50 \text{ GeV}$, whereas the same occurs for the upward direction at $\sim 400 \text{ GeV}$. The total atmospheric tau neutrino flux is maximum in the upward direction. It is *minimum* in downward direction, relative to the galactic plane tau neutrino flux in the presence of neutrino oscillations, owing to the behavior of L/L_{osc} ratio as a function of neutrino energy. Fig. 4 indicates that zenith angle dependence of the total tau neutrino flux can at least in principle help to distinguish between atmospheric and non-atmospheric tau neutrino flux. The galactic tau neutrino flux transverse to the galac-

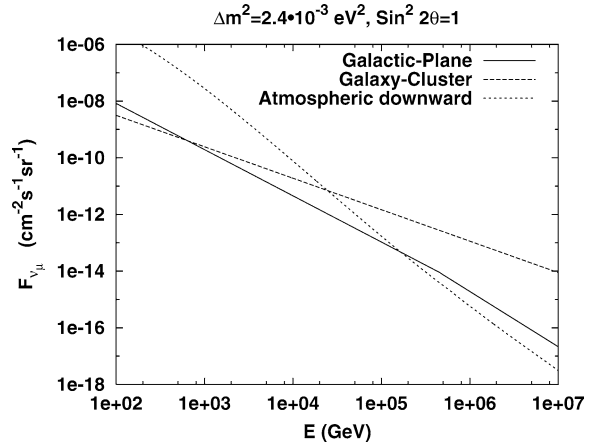


Fig. 5. Comparison of the downward going atmospheric mu neutrino flux, the galactic plane mu neutrino flux and the maximum galaxy cluster mu neutrino flux in the presence of neutrino oscillations. The non-atmospheric mu neutrino flux starts dominating over the atmospheric one only for $E \geq 5 \times 10^4 \text{ GeV}$.

tic plane is three to four orders of magnitude smaller than the galactic plane one [15].

Fig. 5 gives a comparison of the downward going atmospheric and the galactic plane mu neutrino flux in the presence of neutrino oscillations. For this comparison, mu neutrino flux is taken from Ref. [25] without rescaling for $E \leq 10^3 \text{ GeV}$. This mu neutrino flux includes contribution from the D 's for $E \geq 6.3 \times 10^5 \text{ GeV}$. The total mu neutrino flux is estimated according to Eq. (4) with appropriate modifications for the best fit values of the two neutrino mixing parameters. In contrast to the possibility of seeing the galactic plane with multi GeV tau neutrinos, note here that with mu neutrinos, it can occur only for $E \geq 10^5 \text{ GeV}$.

A relevant remark is that for the best fit values of the neutrino mixing parameters, the $P(\nu_\mu \rightarrow \nu_\tau)$ is relatively large along the horizontal and upward directions in the Earth atmosphere (see Eq. (2) and Fig. 1) for $1 \leq E/\text{GeV} \leq 10$. So essentially the atmospheric mu neutrino flux in the absence of neutrino oscillations alone determine the total atmospheric tau neutrino flux in comparison with the total galactic tau neutrino flux.

4. Prospects for possible future observations

In this section, we shall estimate the galactic plane tau neutrino induced shower event rate for a megaton

Table 1

Galactic plane tau neutrino induced shower event rate for a megaton class of detectors in eight logarithmically equal energy bins. Details are given in the text

Energy bin (GeV)	Event rate (Mtyr 2π sr) ⁻¹	Energy bin (GeV)	Event rate (Mtyr 2π sr) ⁻¹
10–17.78	0.22	100–177.83	0.16
17.78–31.62	0.30	177.83–316.23	0.12
31.62–56.23	0.26	316.23–562.34	0.10
56.23–100	0.22	562.34–1000	0.07

class of detectors to indicate the limited prospects offered by GeV to TeV tau neutrino astronomy to search for extra atmospheric astrophysical neutrino sources in this energy range.

Let us add a remark here that, at present, the dedicated large high energy neutrino detectors such as the Antarctic Muon and Neutrino Detector Array (AMANDA) are also sensitive to all neutrino flavors, however, with energy $\simeq 50$ TeV [26].

For $10 \leq E/\text{GeV} \leq 10^3$, a signature for the tau neutrinos is to measure the energy spectrum of the tau lepton induced electromagnetic and hadronic showers produced in tau neutrino nucleon interactions occurring inside a densely instrumented Cherenkov radiation detector [27]. Though, it is a challenging task to distinguish between tau and non-tau neutrinos for the present generation of detectors in the above energy range [28], however certain shower signatures remain distinctive for tau neutrinos [27].

The galactic tau neutrino induced shower production rate can be approximately estimated by convolving the total galactic tau neutrino flux in the presence of neutrino oscillations, given by Eq. (5) with the $\sigma_{\nu_\tau N}^{\text{CC}}(E)$. The $\sigma_{\nu_\tau N}^{\text{CC}}(E)$ for $10 \leq E/\text{GeV} \leq 10^3$ is parameterized as

$$\sigma_{\nu_\tau N}^{\text{CC}}(E) = -4.43 + 0.52E + (3.58 \times 10^{-4})E^2. \quad (6)$$

The $\sigma_{\nu_\tau N}^{\text{CC}}$ is in units of 10^{-38} cm^2 and E is in units of GeV. The CTEQ6 parton distribution functions [29] were used to estimate the cross section.

For recent detailed evaluations of $\sigma_{\nu_\tau N}^{\text{CC}}$, see Ref. [30]. The possible tau lepton polarization effects [31] are not taken into account in the event rate estimates presented here.

Table 1 gives the galactic tau neutrino induced shower event rate for a one megaton detector, in units of (Mtyr)⁻¹ in 2π steradians of upper hemisphere in eight logarithmically equally spaced energy bins. The

table indicates that the per year event rate is about 1.5. With a 3 to 5 year data collection time for a one megaton detector, the galactic tau neutrino induced shower event rate can thus be in the range of $\sim \mathcal{O}(10)$ for $E \geq 10$ GeV. This detector faces only the downward going atmospheric tau neutrino flux as background to the dominant galactic plane tau neutrino flux in the presence of neutrino oscillations.

5. Conclusions

(1) The effects of neutrino oscillations on low energy ($1 \text{ GeV} \leq E \leq 10^3 \text{ GeV}$) tau neutrino flux produced in the Earth atmosphere, in our galactic plane and in galaxy clusters are presented in two neutrino flavor approximation.

(2) The galactic plane should be observable with tau neutrinos with energy ≥ 10 GeV, depending on the orientation of the concerned detector w.r.t. galactic center/plane at the time of observation. The observation of galactic plane with multi GeV *tau neutrinos* is in sharp contrast to the case of mu neutrinos with which the galactic plane is observable only with energy $\geq 10^5$ GeV for the same orientation of the detector.

(3) Transverse to the galactic plane, the maximum galaxy clusters tau neutrino flux is also above the atmospheric one, providing another example of a new window to study cosmos in the above energy range.

(4) This observation may also have some relevance for the long baseline experiments searching for the tau neutrinos in $\nu_\mu \rightarrow \nu_\tau$ oscillations [32].

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