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# The high-energy galactic tau neutrino flux and its atmospheric background

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**Abstract.** We compare the tau neutrino flux arising from the galaxy and the earth atmosphere for $10^3 \leq E/\mathrm{GeV} \leq 10^{11}$. The intrinsic and oscillated tau neutrino fluxes from both sources are considered. We find that, for $E \geq 10^3$ GeV, the oscillated $\nu_\tau$ flux along the galactic plane dominates over the maximal intrinsic atmospheric $\nu_\tau$ flux, i.e., the flux along the horizontal direction. We also briefly comment on the prospects for observing these high-energy tau neutrinos.

**PACS.** 95.85.Ry Neutrino, muon, pion, and other elementary particles; cosmic rays – 13.85.Tp Cosmic-ray interactions

## 1 Introduction

The Milky way is one of the nearby astrophysical sources producing high energy neutrinos, besides the familiar earth atmosphere [1]. Measurements of galactic neutrino and photon fluxes could provide information about the distribution of matter and cosmic rays in the galaxy. Furthermore, the above flux is also a background for the search of more distant high energy neutrino sources such as the AGNs and the GRBs. In this talk, we shall focus on the flux of $\nu_\tau$. It is clear that the observation of astrophysical $\nu_\tau$, with a flux comparable to the flux of $\nu_e$ and $\nu_\mu$, directly confirms the neutrino oscillations. In order to observe galactic $\nu_\tau$ flux, it is essential to study the atmospheric background. We shall focus on the energy range $E_\nu \geq 10^3$ GeV.

We first discuss the distinction between intrinsic and oscillated neutrino fluxes arising from the Milky way and the earth atmosphere. We then present results for galactic and atmospheric tau neutrino fluxes. Finally we comment on the prospects for observing galactic tau neutrinos.

## 2 Intrinsic and oscillated neutrino fluxes

It is well known that the relative flavor ratio for astrophysical neutrinos at the source is approximately $\phi^0_{\nu_e} : \phi^0_{\nu_\mu} : \phi^0_{\nu_\tau} = 1 : 2 : 0$. The commonly accepted astrophysical processes for producing electron and muon neutrinos are $(\gamma, p) + p \to \pi^\pm + X$ where pion further decays into electron and muon neutrinos with the ratio $\phi^0_{\nu_e} : \phi^0_{\nu_\mu} = 1 : 2$. On the other hand, the production mechanism for the tau neutrino is $(\gamma, p) + p \to D_s + X$ where $D_s$ further decays into tau neutrinos. The production cross section for $D_s$ meson is much smaller than that for $\pi^\pm$ for center-of-mass energy $\sqrt{s} \sim$ (1-10) GeV. Hence $\phi^0_{\nu_\tau}$ is suppressed compared to $\phi^0_{\nu_e}$ and $\phi^0_{\nu_\mu}$.

Although $\nu_\tau$ flux is rather suppressed at the source, it is not negligible at the detector. As neutrinos propagate to the earth, the oscillation effect takes place and the relative neutrino flavor ratio changes as a result. Let us denote the neutrino flux reaching the earth as $\phi_{\nu_\alpha}$. Then [2]

$$\phi_{\nu_\alpha} = \sum_\beta P_{\alpha\beta} \phi^0_{\nu_\beta}, \tag{1}$$

where $P_{\alpha\beta}$ is a function of neutrino mixing matrix $U_{\alpha i}$ which connects the neutrino mass eigenstate to the flavor eigenstate. The $\alpha, \beta$ run over $e, \mu$ and $\tau$. Assuming a bi-maximal mixing for $U_{\alpha i}$, one obtains for vanishing $\delta$ and $\theta_{13}$ [3]

$$P_{\alpha\beta} = \begin{pmatrix} 1/2 & 1/4 & 1/4 \\ 1/4 & 3/8 & 3/8 \\ 1/4 & 3/8 & 3/8 \end{pmatrix}. \tag{2}$$

Such a probability matrix implies $\phi_{\nu_e} : \phi_{\nu_\mu} : \phi_{\nu_\tau} = 1 : 1 : 1$. This flavor ratio is applicable to galactic neutrinos since these neutrinos propagate through a distance much greater than the neutrino oscillation length. On the other hand, this ratio is not applicable to the atmospheric neutrinos for $E_\nu \geq 10^3$ GeV considered here. At this energy, the oscillation length for the atmospheric neutrino is of the order $10^{10}$ cm, which is much greater than even the earth diameter. Hence the atmospheric $\nu_\tau$ flux for $E_\nu \geq 10^3$ GeV must be dominantly an *intrinsic* one.

## 3 The galactic and atmospheric tau neutrino fluxes

The total galactic tau neutrino flux consists of intrinsic and oscillated components. Both components follow from the collisions of primary cosmic-ray proton with interstellar medium proton. The density of interstellar medium proton is taken to be $n_p = 1\,\mathrm{cm}^{-3}$ along the galactic plane, while the primary cosmic ray spectrum, $\phi_p(E_p)$, is taken to be [4]

$$\phi_p(E_p) = \begin{cases} 1.7\,(E_p/\mathrm{GeV})^{-2.7} & \text{for } E_p < E_0, \\ 174\,(E_p/\mathrm{GeV})^{-3} & \text{for } E_p \geq E_0, \end{cases} \quad (3)$$

where $E_0 = 5 \cdot 10^6$ GeV and $\phi_p(E_p)$ is in units of cm$^{-2}$ s$^{-1}$ sr$^{-1}$ GeV$^{-1}$. We assume directional isotropy in $\phi_p(E_p)$ for the above energy range. A more recent measurement of cosmic-ray flux spectrum between $2 \cdot 10^5$ GeV and $10^6$ GeV agrees with the $\phi_p(E_p)$ given by (3) within a factor of $\sim 2$ in this energy range [5]. The intrinsic galactic tau neutrinos are produced by $p + p \to D_s + X$, with the $D_s$ meson decays into a $\tau$ lepton and a $\nu_\tau$, while the $\tau$ lepton further decays into the second $\nu_\tau$ with other particles. We calculate the $D_s$ production cross section by the following two approaches: (i) the perturbative QCD (PQCD) and (ii) the quark-gluon string model (QGSM) [6]. In the PQCD approach, we use the CTEQ5 parton distribution functions [7] and apply a $K$ factor, $K = 2$, to account for the NLO corrections [8]. With the $D_s$ production cross section determined, one can calculate the $\nu_\tau$ flux using

$$\phi^0_{\nu_\tau} = \int_E^\infty \mathrm{d}E_p\, \phi_p(E_p)\, f(E_p)\, \frac{1}{\sigma_{pp}(E_p)}\, \frac{\mathrm{d}\sigma_{pp\to\nu_\tau+Y}}{\mathrm{d}E}, \quad (4)$$

where $f(E_p) = R/\lambda_{pp}(E_p)$ with $\lambda_{pp}(E_p)$ the $pp$ interaction length and $R$ a representative distance in the galaxy along the galactic plane. We take $R$ to be $\sim 10$ kpc, where 1 pc $\simeq 3{\cdot}10^{18}$ cm. We have focused on the intrinsic tau neutrino flux along the galactic plane just to obtain the maximal expected tau neutrino flux. The matter density decreases exponentially in the direction orthogonal to the galactic plane, therefore the amount of intrinsic tau neutrino flux decreases by approximately two orders of magnitude for the energy range of our interest. Another component of galactic tau neutrinos comes from the oscillation of galactic muon neutrinos. The flux of the latter can also be calculated by (4) with $\nu_\tau$ replaced by $\nu_\mu$ [9]. In this case, $\pi^\pm$ and $K^\pm$ are the dominant intermediate states that decay into muon neutrinos. Since $\phi^0_{\nu_\mu}$ is few orders of magnitude greater than $\phi^0_{\nu_\tau}$ while $\phi^0_{\nu_e}$ is approximately one half of $\phi^0_{\nu_\mu}$, we recover the flavor ratio $\phi^0_{\nu_e} : \phi^0_{\nu_\mu} : \phi^0_{\nu_\tau} = 1 : 2 : 0$ for the galactic neutrinos at the source. From the previous section, we have $\phi_{\nu_\tau} = \phi^0_{\nu_\mu}/2$. The flux $\phi_{\nu_\tau}$ can be parameterized as

$$E\phi_{\nu_\tau}(E) = \begin{cases} 1.5 \cdot 10^{-5}\,(E/\mathrm{GeV})^{-2.63} & \text{for } E < E_1, \\ 9.5 \cdot 10^{-4}\,(E/\mathrm{GeV})^{-2.95} & \text{for } E \geq E_1, \end{cases} \quad (5)$$

where $E_1 = 4.7 \cdot 10^5$ GeV. The $E\phi_{\nu_\tau}(E)$ is in units of cm$^{-2}$ s$^{-1}$ sr$^{-1}$.

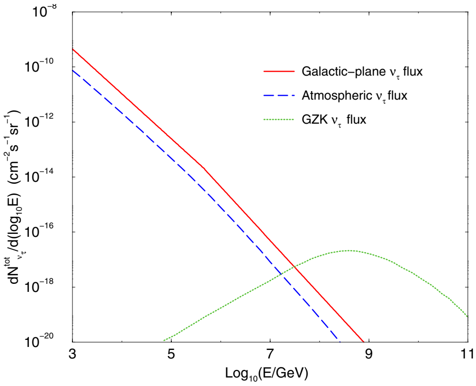

**Fig. 1.** Galactic-plane, horizontal atmospheric and GZK tau neutrino fluxes under the assumption of neutrino flavor oscillations

Having discussed the calculation of galactic tau neutrinos, we now turn to the atmospheric tau neutrinos. As said before, for $E_\nu \geq 10^3$ GeV, atmospheric $\nu_\tau$ flux has only the intrinsic component. We have used the nonperturbative QCD approach mentioned earlier to model the production of $D_s$ mesons in the $pA$ interactions. We have used the $\phi_p(E_p)$ given by (3) and the $Z$-moment description for the calculation of intrinsic tau neutrino flux [10]. We obtain the atmospheric tau neutrino flux by solving a set of cascade equations [11,12]

The results for galactic and atmospheric tau neutrino fluxes, along with the GZK [13] oscillated tau neutrino flux [14], are presented Fig. 1, where we have used the notation $\phi_{\nu_\tau} \equiv \mathrm{d}N_{\nu_\tau}/\mathrm{d}(\log_{10} E)$ . From the figure, we note that the galactic plane oscillated $\nu_\tau$ flux *dominates* over the intrinsic atmospheric $\nu_\tau$ flux for $E \leq 5 \cdot 10^7$ GeV, whereas the GZK oscillated tau neutrino flux dominates for $E \geq 5 \cdot 10^7$ GeV. Quantitatively, the atmospheric $\nu_\tau$ flux in the horizontal direction is $\sim 5$ times smaller than the galactic-plane $\nu_\tau$ flux. Furthermore, the downward atmospheric $\nu_\tau$ flux is factor of $\sim 8$ smaller than its horizontal counterpart. Let us recall here that particle physics aspects of intrinsic tau neutrino flux calculation presented here are empirically supported only up to $\sqrt{s} \sim$ TeV, which corresponds to $E_p \sim 10^6$ GeV.

Before we move on, it is instructive to compare the atmospheric $\nu_\tau$ and $\nu_\mu$ fluxes. We plot these two fluxes for $E_\nu \geq 10^3$ GeV in Fig. 2. The atmospheric $\nu_\mu$ flux is taken from [15]. The atmospheric $\nu_\mu$ flux has two components: conventional and prompt components. The former component is due to decays of $\pi^\pm$ and $K^\pm$, while the latter component is due to decays of charm hadrons. Although produced more copiously than charm hadrons, $\pi$ or $K$ meson does not decay efficiently in the air at sufficiently high energy. This effect disfavors the resulting neutrino flux.

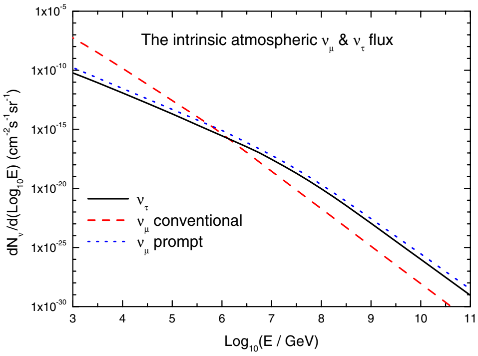

**Fig. 2.** The comparison of downward atmospheric $\nu_\mu$ and $\nu_\tau$ fluxes

Indeed, in Fig. 2, the two components of $\nu_\mu$ flux cross roughly at $E_\nu = 10^6$ GeV [15]. We also observe that the atmospheric $\nu_\mu$ and $\nu_\tau$ fluxes are comparable for $E_\nu > 10^6$ GeV, since both fluxes are due to charm production in this energy range.

## 4 The prospects of observations

For downward going or near horizontal high-energy tau neutrinos, the deep inelastic neutrino nucleon scattering, occurring near or inside the detector, produces two showers [16]. The first shower is due to a charged current neutrino nucleon deep inelastic scattering, whereas the second shower is due to the (hadronic) decay of the associated $\tau$ lepton produced in the first shower. It might be possible for the proposed large neutrino telescopes such as the IceCube to constrain the two showers simultaneously for $10^6 \leq E/\text{GeV} \leq 10^7$, depending on the achievable shower separation capabilities [17]. Here, the two showers develop mainly in ice. With such a detection strategy, we estimate the event rate for observing the galactic tau neutrinos. In the above energy range for the tau neutrinos, the event rate in 1 km$^3$ water/ice Cherenkov detector is rather small, about $\sim 5 \cdot 10^{-3}\,\text{yr}^{-1}\,\text{sr}^{-1}$. Such a low event rate implies that one can only search for galactic tau neutrinos in the lower energy. Alternatively, one should consider other detection strategies. Since Fig. 1 shows that galactic tau neutrino flux dominates over its atmospheric counterpart for $E_\nu \geq 10^3$ GeV, it is desirable to develop strategies for identifying tau neutrinos at TeV energies or even lower because of relatively large absolute $\nu_\tau$ flux. The present AMANDA search for all flavor neutrino-induced cascades is not tight enough to constrain/observe our predicted $\phi_{\nu_\tau}$ [18].

We point out that the persistent dominance of galactic tau neutrino flux over its atmospheric background is a unique phenomenon among all neutrino flavors. Such a dominance does not occur for $\nu_e$ and $\nu_\mu$. For example, the result in Sect. 2 tells us that $\phi_{\nu_\mu} = \phi_{\nu_\tau}$ for the galactic neutrinos. On the other hand, the atmospheric $\nu_\mu$ flux is much greater than the atmospheric $\nu_\tau$ flux for $E_\nu < 10^5$ GeV, as can be seen from Fig. 2. Hence the galactic $\nu_\mu$ flux no longer dominates over the atmospheric $\nu_\mu$ flux for $E_\nu < 10^5$ GeV.

In conclusion, we have presented our calculations of both the galactic and atmospheric tau neutrino fluxes for $E_\nu \geq 10^3$ GeV. The former flux is shown to dominate over the latter. Such a dominance is unique to *tau neutrinos*. The event rate for galactic tau neutrinos by observing the double showers (with $10^6 \leq E_\nu/\text{GeV} \leq 10^7$) is rather suppressed. Therefore, to observe the galactic tau neutrinos, it is desirable to develop techniques for identifying tau neutrinos at lower energies.

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