Ultrahigh-energy neutrino flux as a probe of large extra dimensions

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Abstract. A suppression in the spectrum of ultrahigh-energy (UHE, $\gtrsim 10^{18}$ eV) neutrinos will be present in extra-dimensional scenarios, due to enhanced neutrino–anti-neutrino annihilation processes with the supernova relic neutrinos. In the $n > 4$ scenario, $n$ being the number of extra dimensions, neutrinos cannot be responsible for the highest energy events observed in the UHE cosmic ray spectrum. A direct implication of these extra-dimensional interactions would be the absence of UHE neutrinos in ongoing and future neutrino telescopes.

Keywords: ultra high energy photons and neutrinos, supernova neutrinos

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1. Introduction

Experimental high-energy neutrino astronomy is developing very rapidly. There exist a number of experiments (AMANDA II [1], RICE [2], ANITA [3], Icecube [4], ANTARES [5]) that are currently analyzing or starting to take data. In the future there are planned projects (ARIANNA [6], AURA, NEMO, ACORNE) that will benefit from improved detection techniques and larger effective detection volumes.

A guaranteed source of UHE neutrino fluxes is the so-called cosmogenic GZK neutrinos, which are originated by the interactions of extragalactic UHE cosmic ray (CR) protons with CMB photons dominantly via $\Delta^+$ processes and subsequent charged pion decays. Cosmogenic neutrinos are typically characterized by a spectrum peaking in the $10^{17−19}$ eV energy range, depending on the redshift of the CR sources. Ongoing and future experiments expect to detect a few GZK neutrino events; the precise number depends on the full exposure of the instruments as well as on the production model. Direct emission of UHE neutrinos from the CR sources is expected but uncertain. Decays of topological defects or supermassive particles, leftover fossils from the GUT era, are speculative. Nevertheless, both mechanisms would produce neutrino fluxes with energies comparable to or higher than those associated to the GZK fluxes. These neutrinos could interact with 1.95 K CMB neutrinos ($C_\nu B$) via the standard model (SM) reaction $\nu\bar{\nu} \rightarrow Z^0$, provided that they are extremely energetic ($10^{22−25}$ eV) [7]–[10]. We do not explore these speculative neutrino fluxes in the present study.

In this study, we focus on the depletion of the GZK cosmogenic neutrino fluxes via strongly interacting annihilation processes with other neutrino relics that also permeate the universe: the diffuse supernova relic neutrinos (DSN$\nu$), that represent the flux of neutrinos from all supernova explosions that occurred during the universe’s history. The DSN$\nu$ direct detection is still elusive. The most stringent experimental current limit to the DSN relic $\bar{\nu}_e$ flux is $1.2 \text{ cm}^{-2} \text{s}^{-1}$ at 90% CL, from the SuperKamiokande experiment [11].

The presence of strongly interacting processes, such as the exchange of massive spin-2 particles in theories of large extra dimensions [12]–[14], can modify the $\nu\bar{\nu}$ annihilation cross section. This effect would take place at high values of the squared center-of-mass energy $s$, yielding a $\nu\bar{\nu}$ annihilation cross section that is larger than the cross section for
the SM process $\nu\bar{\nu}^{SM} \rightarrow Z^0$. In principle, the UHE cosmogenic neutrinos can annihilate with both the CMB [15] and DSN$\nu$ via extra-dimensional enhanced cross sections, which we discuss next.

2. Neutrino annihilation in extra-dimensional models

We consider the following annihilation cross sections for $n$ extra dimensions [14, 15]:

$$\sigma_{\nu\bar{\nu} \rightarrow g_{\text{KK}}} = \frac{(\pi^2/s)(s/M_{S}^2)^{n/2+1}}{s},$$

$$\sigma_{\nu\bar{\nu} \rightarrow f\bar{f}} = \frac{(\pi/60s)(s/M_{S}^2)^{n+2}F^2}{s},$$

$$\sigma_{\nu\bar{\nu} \rightarrow \gamma\gamma} = 3\sigma_{\nu\bar{\nu} \rightarrow f\bar{f}},$$

respectively to produce KK gravitons, fermion-pairs and $\gamma$-pairs. Here $F^2 = \pi^2 + 4f^2(M_S/s)$ and we use $I(M_S/s)$ as given in [14]. The ‘new physics’ scale $M_S$ is constrained from astrophysical considerations such as star cooling by graviton emission [12, 16] and from collider searches [17]. In particular, we use $M_S = 701$, 25.5 and 2.77 TeV for $n = 2$, 3 and 4, the most stringent current constraints from heating of neutron-stars [18]. For $n > 4$, the most stringent lower bounds are from the D0 collider experiment at the Tevatron, which sets the 95% CL limits for $n = 5$, 6 and 7 equal to 0.97, 0.9 and 0.85 TeV, respectively [17]. In the $n = 5$ scenario, the total $\nu\bar{\nu}$ annihilation cross section is $\simeq 4 \times 10^{-19}$ cm$^2$ at $\sqrt{s} \simeq 14$ TeV, which roughly corresponds to a $10^{19}$ eV GZK neutrino interacting with a 10 MeV DSN relic anti-neutrino. The cross section quoted above is therefore many orders of magnitude larger than the SM cross section $\sigma_{\nu\bar{\nu} \rightarrow \gamma\gamma (\text{SM})}$.

The neutrino interactions in equations (1) are independent of the neutrino flavor. Brane–bulk couplings are flavor blind, and consequently the exchange of the KK gravitons is unaffected by the electron, muon or tau nature of the DSN (anti-) neutrinos, except for corrections proportional to the squared mass splittings divided by $s$, which are negligible ($O(10^{-27}))$.

A word of caution is needed here regarding the extra-dimensional scenario, which is an effective theory valid for $s \sim M_{S}^2$. At some energy scale $s \sim M_{S}^2$, this theory is supposed to match a more fundamental theory of quantum gravity. It is not known how to do this matching. A phenomenological approach is to assume that the neutrino interaction cross sections in the $s \sim M_{S}^2$ energy range behave similarly to the cross sections in the $s \sim M_{S}^2$ energy regime, up to some cutoff $\Lambda$. The value of $\Lambda$ is presumably somewhere between $M_{S}$ and $E_{\text{max}}$, where the latter is the scale at which perturbative unitarity would be violated [13]. For the models we consider $E_{\text{max}}$ is always greater than $5.6M_{S}$.

Within the context of extra-dimensional models, the $\nu N$ cross sections will be enhanced as well [19]–[25], providing a possible explanation for the events above the GZK cutoff as explored in [26, 15, 27, 28]. However, as we will discuss shortly, $10^{20}$ eV neutrinos would annihilate with DSN$\nu$ on their flight to the Earth rather than producing an extended air shower in the atmosphere, via enhanced $\nu N$ cross section, in the large extra-dimensional models. The advantage of exploring the $\nu\bar{\nu}$ annihilation channel is that extra-dimensional signatures would occur at lower energy, compared to the signatures in the commonly explored $\nu N$ interaction.

This flavor blindness character of the extra-dimensional model presented here no longer holds if one or more of the neutrino species is in the bulk. Such a possibility is not considered through the present discussion.
3. Supernova relic neutrino density and UHE neutrino propagation

A number of authors have predicted the DSNν flux. For a recent appraisal of the theoretical and computational status, see [29] and references therein. Here we follow closely the derivation given in [30]. A fit to the neutrino spectra from numerical simulations of an SN is [31, 32]

\[ \frac{dN_{\nu}^0}{dE_{\nu}} = \frac{(1 + \beta_\nu)^{1+\beta_\nu} L_{\nu}}{\Gamma(1 + \beta_\nu) E_{\nu}^{\beta_\nu}} \left( \frac{E_{\nu}}{E_{\nu0}} \right)^{\beta_\nu} e^{-(1+\beta_\nu)E_{\nu}/E_{\nu0}}, \tag{2} \]

where the average energy \( \bar{E}_{\nu} = 15.4 \) and 21.6 MeV respectively for \( \bar{\nu}_e \) and \( \nu_e \) corresponding to all other non-electron anti-neutrino and neutrino flavors. The spectral indices are \( \beta_{\bar{\nu}_e} = 3.8 \) and \( \beta_{\nu_e} = 1.8 \), while the total neutrino energies are \( L_{\bar{\nu}_e} \approx L_{\nu_e} = 5 \times 10^{52} \) erg. For \( \nu_e \), we use \( \bar{E}_{\nu_e} = 11 \) MeV [32], \( L_{\nu_e} \approx L_{\bar{\nu}_e} \) and \( \beta_{\nu_e} = \beta_{\bar{\nu}_e} \). Neutrino conversion inside the star mixes the different neutrino flavors and therefore the relic (anti-) neutrino flavor spectra at the stellar surface will differ from the original ones. The final flavor spectra will depend on the neutrino mass ordering (normal versus inverted) and the adiabaticity of the transitions in the resonances layer; see [33] for a complete description. As we will explain further below, the \( \nu \bar{\nu} \) interactions we explore here are flavor blind and therefore the GZK (anti-) neutrino will interact with the three (neutrino) anti-neutrino flavors. Therefore we do not need to account for conversion effects and the relevant quantity would be the total anti-neutrino (neutrino) SN relic neutrino spectra, given by

\[ \frac{dN_{\bar{\nu}(\nu)}^0}{dE_{\nu}} = \frac{dN_{\nu_e}^0}{dE_{\nu_e}} + 2 \frac{dN_{\bar{\nu}_e}^0}{dE_{\nu}}, \tag{3} \]

that is, the sum of the three flavor spectra.

The redshift-dependent SN rate is a fraction 0.0122\,M_{\odot}^{-1} of the star formation rate and is given, e.g. SF1 model in [34], by

\[ R_{\text{sn}}(z) = 0.0122 \times 0.32 h_{70} \exp(3.4z) \frac{\exp(3.8z)}{45} \left[ \Omega_m (1+z)^3 + \Omega_\Lambda \right]^{1/2}, \tag{4} \]

with a Hubble constant \( H_0 = 70 h_{70} \) km s\(^{-1}\) Mpc\(^{-1}\) and ΛCDM cosmology. The other parameters are \( \Omega_m = 0.3 \) and \( \Omega_\Lambda = 0.7 \). The differential number density of SN relic neutrinos at present from all past SNe up to a maximum redshift \( z_{\text{sn}, \text{max}} \) is then [30]

\[ \frac{dN_{\bar{\nu}(\nu)}^0}{dE_{\nu}} = \int_0^{z_{\text{sn}, \text{max}}} dz \frac{dt}{dz} (1+z) R_{\text{sn}}(z) \frac{dN_{\bar{\nu}(\nu)}^0}{dE_{\nu}'}, \tag{5} \]

Here \((dt/dz)^{-1} = -H_0 (1+z)[\Omega_m (1+z)^3 + \Omega_\Lambda]^{1/2} \) and \( E_{\nu}' = E_{\nu}/(1+z) \) is the redshift-corrected observed energy.

While the number density of the DSNν (\(10^{-9} \) cm\(^{-3}\) for the sum of the three (anti-) neutrino flavors) is orders of magnitude smaller than those for the CνB relics (56 cm\(^{-3}\) per (anti-) neutrino flavor), the average energy of the DSNν is tens of MeV, compared to the \(10^{-4}\) eV for CνB relics. Therefore, the UHE neutrino mean free path, \( \text{mfp} = 1/\sigma_{\nu\nu} n_{\nu} \), is many orders of magnitude smaller in the case of the less abundant, but more energetic DSNν compared to the CνB relics. If the strongly interacting processes deplete the UHE cosmogenic neutrino fluxes, the dominant attenuator will be the DSNν targets, which we discuss more quantitatively below.
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A UHE \( \nu \) of observed energy \( E_{\nu, \text{uhe}} \) may interact with a DSN\( \nu \) at redshift \( z' \) on its way via processes in equation (1) and annihilate. The corresponding \( s \approx 2E_{\nu, \text{uhe}}(1+z')E_{\nu, \text{sn}}(1+z) \), ignoring the \( \nu \) masses. We take the maximum SN \( \nu \) energy to be \( E_{\nu, \text{sn, max}}' = 60 \text{ MeV} \) in the SN rest frame. The inverse mfp for \( \nu \bar{\nu} \) annihilation is then

\[
\mathcal{L}^{-1}(E_{\nu, \text{uhe}; z'}) = \int_{z'}^{z_{\text{uhe}}} \frac{dz'}{dz'} (1+z') R_{\text{sn}}(z) \int_0^{E_{\nu, \text{sn, max}}'} \frac{dE_{\nu, \text{sn}}}{dE_{\nu, \text{sn}}'} \sigma_{\nu\bar{\nu}}(s) \, dz'.
\]

The mfp for a \( 10^{19} \text{ eV} \) neutrino to annihilate with a DSN\( \nu \) via the SM process \( t_{\nu\bar{\nu}}^{\text{SM}} \rightarrow \) all is \( 10^{18} \text{ Mpc} \), which exceeds the Hubble distance. Within the \( n = 5 \) extra-dimensional model, the annihilation cross section is greatly enhanced at high energies, and the mfp for a \( 10^{19} \text{ eV} \) neutrino is \( \sim 12 \text{ Mpc} \) in our local universe \((z' \sim 0)\), which is less than the GZK radius. Even for the \( n = 4 \) extra-dimensional model, the mfp for the highest energy CR, \( 3 \times 10^{20} \text{ eV} \), is \( \sim 127 \text{ Mpc} \) which is comparable to the GZK radius. To explain GZK CR data with UHE neutrinos through enhanced \( \nu N \) cross section requires \( n > 4 \). Thus UHE neutrinos propagating from outside the GZK radius cannot be the candidates for GZK CR events, since they would be absorbed by DSN\( \nu \).

We can now calculate the survival probability for a UHE \( \nu \) created at redshift \( z_{\text{uhe}} \) to reach Earth as

\[
P(E_{\nu, \text{uhe}}; z_{\text{uhe}}) = \exp \left[ -c \int_0^{z_{\text{uhe}}} \frac{dz'}{dz'} \mathcal{L}^{-1}(E_{\nu, \text{uhe}; z'}) \right] = \exp \left[ -KcH_0^2 \int_0^{z_{\text{uhe}}} \frac{dz'}{(1+z')(1+3z')} \Omega_m(1+z')^3 + \Omega_\Lambda \right. \]

\[
\times \left. \int_{z'}^{E_{\nu, \text{sn, max}}'} \frac{dE_{\nu, \text{sn}}}{dE_{\nu, \text{sn}}'} \sigma_{\nu\bar{\nu}}(s) \right] \approx 2.45 \times 10^{-38}h_{70}^4 \text{ cm}^{-2} \text{ and the differential SN } \nu \text{ spectrum is } \frac{dN_{\nu, \text{sn}}}{dE_{\nu, \text{sn}}} \approx 10^{49} \text{ MeV}^{-1}. \text{ Large } \nu\bar{\nu} \text{ cross section then suppresses UHE neutrinos. We discuss UHE } \nu \text{ fluxes that will be attenuated by } \nu\bar{\nu} \text{ annihilation next.}
\]

4. Ultrahigh-energy neutrino flux

The CR energy generation rate per unit volume in our local universe in the energy range \( 10^{19}-21 \text{ eV} \) is \( P_{\text{CR}} \approx 5 \times 10^{44} \text{ erg Mpc}^{-3} \text{ yr}^{-1} \) [35]. Assuming an injection spectrum for CR protons \( dN_p/dE_p^{-1} \propto E_p^{-2} \), as typically expected, we define a convenient conversion formula

\[
N_{\text{CR}} = \frac{c}{4\pi H_0} \frac{P_{\text{CR}}}{\ln(10^{21}/10^{19})} \approx 7.1 \times 10^{-8}h_{70}^{-1} \text{ GeV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1},
\]

which is proportional to the CR flux \( E_p^2J_p \) above \( 10^{19} \text{ eV} \). We will use equation (8) to fix the normalization of UHE \( \nu \) fluxes. The CR sources may also evolve with redshift.
as \(S(z) = (1 + z)^3\) for \(z < 1.9\), \((1 + 1.9)^3\) for \(1.9 < z < 2.7\) and \(\exp((2.7 - z)/2.7)\) for \(z > 2.7\) [35].

The Waxman–Bahcall (WB) bound on UHE \(\nu\) flux [35] is based on CRs that interact at their sources and lose all their energy equally to charged and neutral pions. The resulting \(\nu\) flux is given by

\[
E_\nu^2 J_{\nu,WB} = \frac{N_{\text{CR}}}{8} \int_0^{z_{\text{max}}} dz_{\text{uhe}} \frac{S(z_{\text{uhe}}) P(E_\nu; z_{\text{uhe}})}{\sqrt{\Omega_m (1 + z_{\text{uhe}})^3 + \Omega_\Lambda}}
\]

(9)

after integrating over CR source evolution and \(\nu\bar{\nu}\) annihilation probability in equation (7).

If UHE CRs interact with CMB photons in the local universe then the resulting GZK neutrino flux would be

\[
E_\nu J_{\nu}(z \sim 0) \propto N_{\text{CR}} \int dE_p^0 dN_p \frac{dY(E_p^0, E_\nu, z \sim 0)}{dE_p^0}.
\]

(10)

Here \(Y\) is called the neutrino yield function as in [36], and is the number of secondary neutrinos generated per unit energy interval by a CR proton of energy \(E_{\text{uhe}}^0\). We use a fit to \(Y(E_p^0, E_\nu, z \sim 0)\) corresponding to \(\nu\) and \(\bar{\nu}\) from a CR proton propagating 200 Mpc as generated by the SOPHIA Monte Carlo code as reported in [36]. The GZK \(\nu\) spectra are fully evolved by 200 Mpc in our local universe and over smaller distance at higher redshift. Our calculation shows that this distance is much shorter than the mfp for \(\nu N\) interactions of UHE CRs with DSN\(\nu\) in \(n \geq 4\) large extra-dimensional models. Thus we calculate the effect of \(\nu\bar{\nu}\) annihilation assuming that a fully evolved GZK \(\nu\) flux exists at a given redshift of interaction.

The GZK \(\nu\) flux integrated over all CR sources, after taking into account the redshift evolution of the neutrino yield function \(Y(E_p^0, E_\nu, z) = Y(E_p^0(1 + z), E_\nu(1 + z)^2, z \sim 0)\) [36], the source evolution \(S(z)\) and finally the survival probability \(P(E_\nu; z_{\text{uhe}})\) in equation (7), is given by

\[
E_\nu J_{\nu,\text{GZK}} = N_{\text{CR}} \int_0^{z_{\text{max}}} dz_{\text{uhe}} \frac{S(z_{\text{uhe}}) P(E_\nu; z_{\text{uhe}})}{\sqrt{\Omega_m (1 + z_{\text{uhe}})^3 + \Omega_\Lambda}} \frac{dE_p^s}{dE_p^s} Y(E_p^s, E_\nu, z_{\text{uhe}}).
\]

(11)

In case of no \(\nu\bar{\nu}\) annihilation, \(P(E_\nu; z_{\text{uhe}}) = 1\) and the flux is the same as in [36].

We have numerically evaluated the GZK flux, both without and with \(\nu\bar{\nu}\) annihilation, using \(z_{\text{max}} = z_{\text{uhe}} = z_{\text{sn,max}} = 5\) and in the energy range \(10^{19} < E_{\text{uhe}}^0 < 10^{22}\) eV with an exponential cutoff of the \(\propto E_{\text{uhe}}^{-2}\) spectrum at \(3 \times 10^{21}\) eV as in [36]. The results for the GZK cosmogenic \(\nu\) flux are depicted in figure 1, assuming an \(n = 5\) extra-dimensional scenario. The dotted curves labeled 1 and 2 correspond to \(\Lambda = \infty\) and 20 TeV respectively; allowing the cross sections in equation (1) to grow below \(\sqrt{s} = \Lambda\) and become flat above. Also shown is the WB flux without and with \(\nu\bar{\nu}\) annihilation. Notice that the \(n = 5\) extra-dimensional scenario leaves a clear imprint on the GZK cosmogenic neutrino fluxes, which would be abruptly truncated above \(E > 10^{17}\) eV. This characteristic feature in the GZK cosmogenic fluxes could be recognized by the presence of a dip in the neutrino spectra, provided the detection technique has a low enough energy threshold. For ongoing and future UHE neutrino experiments with higher energy thresholds \((E > 10^{17}\) eV), such as ANITA and ARIANNA shown in figure 1, there would be an absence of neutrino induced events caused by strongly interacting, KK-mode mediated \(\nu\bar{\nu}\) processes. For the \(n < 5\) extra-dimensional models, the UHE neutrino flux suppression would occur at UHE
neutrino energies $E \gtrsim 10^{19-20}$ eV, where the cosmogenic neutrino fluxes are smaller, and consequently also the statistics expected in ongoing and future UHE neutrino observatories would be reduced.

Figure 2 depicts the GZK cosmogenic $\nu_\mu$ flux with and without extra-dimensional suppression for the case that nature has $n = 4, 5, 6$ and 7 extra dimensions. For $n < 4$, the UHE neutrino flux suppression is subtle and therefore it would be highly challenging and difficult to detect experimentally. Figure 3 illustrates the WB flux without and with $\nu\bar{\nu}$ annihilation. If $n < 5$, tracking the extra-dimensional induced suppression dip would be more difficult in general. Note that an increase of $\nu N$ cross section, expected in this scenario, does not significantly increase the detector sensitivity because of a steeply falling $\nu$ flux and a decreasing angular acceptance with increasing energy (see, e.g., [2]).

5. Summary and conclusions

We have shown that UHE neutrinos will be absorbed, in theoretical models that predict fast-rising cross sections such as large extra-dimensional models, by a diffuse background
of 10 MeV neutrinos provided by all core-collapse SNe in the history of the universe. Detection of neutrinos from the SN 1987A proves the existence of such neutrinos, and upcoming megaton detectors will measure the diffuse flux to a good accuracy.

If there exist $n \geq 5$ large extra dimensions in nature, and the DSN\nu flux is detected at the level of the current theoretical models, then UHE neutrinos cannot be the primaries of the super GZK events, since the UHE neutrino fluxes will suffer a cutoff in their energy spectra in the $10^{16-18}$ eV energy range. On the other hand, a detection of GZK neutrinos at energies $E \gtrsim 10^{18}$ eV could imply the absence of $n \geq 5$ large extra dimensions in nature, and therefore eliminate such models. For $n < 5$ extra dimensions, neutrinos could be the UHE CR primaries if the $\nu N$ cross section is sufficiently enhanced to mimic the hadronic cross section.

In the case when the DSN\nu flux is detected at a much lower level, then the dip in the UHE neutrino spectrum, due to absorption by DSN\nu, would be shifted to higher energy. Note that $\nu \bar{\nu}$ annihilation by UHE neutrinos would not produce $\gamma$-rays over the EGRET limit, since the primary UHE CR interactions with CMB and infrared photons cannot account for the observed diffuse $\gamma$-ray flux [37]. Also the GZK CRs are not affected due to large $\nu N$ cross section, since they are expected to be produced within $\sim 50$ Mpc, a radius smaller than the $\nu N$ mfp with enhanced cross section.
Measuring an enhancement of UHE neutrino cross sections at ongoing or future neutrino observatories will be therefore extremely difficult, since in these scenarios the GZK cosmogenic neutrino fluxes would be depleted in their way to the Earth via annihilation with the DSN$\nu$ background.

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