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

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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-antineutrino annihilation processes with the supernova relic neutrinos. In this scenario, neutrinos can not 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.

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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 are the so-called cosmogenic GZK neutrinos, which are originated by the interactions of extragalactic UHE cosmic ray (CR) protons with CMB photons dominantly via Δ^+ 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, is 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 via the standard model (SM) reaction $\nu\bar{\nu} \to Z^0$, provided that they are extremely energetic (10^{22-25} eV) [7, 8, 9, 10]. We do not explore these speculative neutrino fluxes in the present study.

In this *Letter*, 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 (DSNν), that represent the flux of neutrinos from all supernova explosions that occurred during the universe's history. The DSNν direct detection is still elusive. The most stringent experimental current limit to the DSN relic $\bar{\nu}_e$ flux is 1.2 cm^{-2}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, 13, 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 $\nu\bar{\nu}^{SM} \to Z^0$. In principle, the UHE cosmogenic neutrinos can annihilate with both the CMB [15] and DSNν via extra-dimensional enhanced cross sections, which we discuss next.

Neutrino annihilation in extra-dimensional models.— We consider the following annihilation cross sections for n extra dimensions [14, 15]

$$\begin{aligned} \sigma_{\nu\bar{\nu}\to g_{KK}} &= (\pi^2/s)(s/M_S^2)^{n/2+1} \\ \sigma_{\nu\bar{\nu}\to f\bar{f}} &= (\pi/60s)(s/M_S^2)^{n+2}\mathcal{F}^2 \\ \sigma_{\nu\bar{\nu}\to\gamma\gamma} &= 3\sigma_{\nu\bar{\nu}\to f\bar{f}}, \end{aligned} \quad (1)$$

respectively to produce KK gravitons, fermion- and γ-pairs, being n the number of extra dimensions and s the squared center-of-mass energy. Here $\mathcal{F}^2 = \pi^2 + 4I^2(M_S/\sqrt{s})$ and we use $I(M_S/\sqrt{s})$ as given in Ref. [14]. The "new physics" scale M_S is rather constrained from astrophysical considerations such as star cooling by graviton emission [12]. In particular, we use $M_S = 30$ TeV, 4 TeV and 1 TeV, respectively, for $n = 2$, 3 and 4 as derived to be the lowest values in each case from SN 1987A observations [16]. The neutrino interactions in Eqs. (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 corrections proportional to the squared mass splittings divided by s, which are negligible ($\mathcal{O}(10^{-27})$) [35].

A word of caution is needed here regarding the extra-dimensional scenario, which is an effective theory valid for $s \lesssim M_S^2$. At some energy scale $s \sim M_S^2$, this theory is supposed to match onto 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 $s \lesssim M_S^2$ energy regime, up to some cutoff Λ. The value of Λ is presumably somewhere between M_S and $E_{\rm max}$, where the latter is the scale at which perturbative unitarity would be violated [13]. For the models we consider $E_{\rm max}$ is always greater than $5.6 M_S$.

Within the context of extra-dimensional models, the νN cross sections will be enhanced as well [17, 18, 19, 20, 21, 22, 23], providing a possible explanation for the events above the GZK cut-off as explored in Refs. [15, 24, 25]. However, as we will discuss shortly, 10^{20} eV neutrinos would annihilate with DSNν on their flight to the Earth rather than producing an extended air shower in the atmosphere, via enhanced νN cross section, in the large extra-dimensional models. The advantage of exploring the $\nu\bar{\nu}$ annihilation channel is that extradimensional signatures would occur at lower energy, compared to the signatures in the commonly explored νN interaction.

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 Ref. [26] and references therein. Here we follow closely the derivation given in Ref. [27]. A fit to the neutrino spectra from numerical simulations of a SN is [28, 29]

$$\frac{dN_\nu^0}{dE_\nu} = \frac{(1+\beta_\nu)^{1+\beta_\nu} L_\nu}{\Gamma(1+\beta_\nu)\bar{E}_\nu^2} \left(\frac{E_\nu}{\bar{E}_\nu}\right)^{\beta_\nu} e^{-(1+\beta_\nu)E_\nu/\bar{E}_\nu}, \quad (2)$$

where the average energy $\bar{E}_\nu = 15.4$ MeV and 21.6 MeV respectively for $\bar{\nu}_e$ and ν_x corresponding to all other non-electron anti-neutrino and neutrino flavors. The spectral indices are $\beta_{\bar{\nu}_e} = 3.8$ and $\beta_{\nu_x} = 1.8$ while the total neutrino energies are $L_{\bar{\nu}_e} \simeq L_{\nu_x} = 5 \times 10^{52}$ erg. For ν_e, we use $\bar{E}_{\nu_e} = 11$ MeV [29], $L_{\nu_e} \simeq L_{\bar{\nu}_e}$ 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 resonance layers. There are two such resonances, one of them at higher densities, associated to the atmospheric mass splitting Δm^2_{atmos}, and another at lower densities, associated to the solar mass splitting Δm^2_{solar}. The adiabaticity of the higher resonance transition is governed by the size of the mixing $|U_{e3}|^2$, so the precise composition of the final flavor eigenstates at the stellar surface will depend on the value of the mixing angle θ_{13}, see Ref. [30] 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) antineutrino flavors. Therefore we do not need to account for conversion effects and the relevant quantity would be the total antineutrino (neutrino) SN relic neutrino spectra, given by:

$$\frac{dN_{\bar{\nu}(\nu)}}{dE_\nu} = \frac{dN^0_{\bar{\nu}_e(\nu_e)}}{dE_\nu} + 2\frac{dN^0_{\nu_x}}{dE_\nu}, \quad (3)$$

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 Ref. [31], by

$$R_{sn}(z) = 0.0122 \times 0.32 h_{70} \frac{\exp(3.4z)}{\exp(3.8z)+45} \times \left[\frac{\Omega_m(1+z)^3 + \Omega_\Lambda}{(1+z)^3}\right]^{1/2} \ {\rm yr}^{-1}\ {\rm Mpc}^{-3} \quad (4)$$

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 $z_{\rm sn,max}$ is then [27]

$$\frac{dn_{\bar{\nu}(\nu)}}{dE_\nu} = \int_0^{z_{\rm sn,max}} dz \frac{dt}{dz}(1+z) R_{sn}(z) \frac{dN_{\bar{\nu}(\nu)}}{dE'_\nu}. \quad (5)$$

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 is orders of magnitude smaller than those for the CMB relic neutrinos (56 cm^{-3} per each (anti) neutrino flavor), the average energy of the DSNν is tens of MeV, compared to the 10^{-4} eV for CMB neutrinos. Therefore, the UHE neutrino mean-free-path, $mfp = 1/\sigma_{\nu\bar{\nu}} n_\nu$ is many orders of magnitude smaller in the case of the less abundant, but more energetic DSNν compared to the 1.95 °K CMB neutrinos. If these strongly interacting processes deplete the UHE cosmogenic neutrino fluxes, the dominant attenuator will be the DSNν targets, which we discuss more quantitatively below.

An UHE ν of observed energy $E_{\nu,\rm uhe}$ may interact with a DSNν at redshift z' on its way via processes in Eq. (1) and annihilate. The corresponding $s \simeq 2E_{\nu,\rm uhe}(1+z')E_{\nu,\rm sn}(1+z)$, ignoring the ν masses. We use the maximum SN ν energy to be $E'_{\nu,\rm sn,max} = 60$ MeV in the SN rest frame. The *mfp* for $\nu\bar{\nu}$ annihilation is then

$$\mathcal{L}^{-1}(E_{\nu,\rm uhe}, z') = \int_{z'}^{z_{\rm sn,max}} dz \frac{dt}{dz}(1+z) R_{sn}(z) \times \int_0^{E'_{\nu,\rm sn,max}} dE'_{\nu,\rm sn} \frac{dN_{\bar{\nu},\rm sn}}{dE_{\nu,\rm sn}} \sigma_{\nu\bar{\nu}}(s). \quad (6)$$

The *mfp* for a 10^{19} eV neutrino, in case of $n = 4$ extra-dimensional model, is ~ 37 Mpc in our local universe ($z' \sim 0$), which is comparable to the GZK radius. At higher energy the *mfp* is substantially smaller. To explain GZK CR data with UHE neutrinos through enhanced νN cross section requires $n \geq 4$. Thus UHE neutrinos propagating from outside the GZK radius can not be the candidates for GZK CR events, since they would be absorbed by DSNν.

We can now calculate the survival probability for an UHE ν created at redshift $z_{\rm uhe}$ to reach Earth as

$$P(E_{\nu,{\rm uhe}}; z_{\rm uhe}) = \exp\left[-c\int_0^{z_{\rm uhe}} dz' \frac{dt}{dz'}\mathcal{L}(E_{\nu,{\rm uhe}}, z')\right]$$

$$= \exp\left[-\mathcal{K}\frac{c}{H_0^2}\int_0^{z_{\rm uhe}} \frac{dz'}{(1+z')\sqrt{\Omega_m(1+z')^3+\Omega_\Lambda}}\right.$$

$$\times \int_{z'}^{z_{\rm sn,max}} \frac{dz}{(1+z)^{3/2}}\frac{\exp(3.4z)}{\exp(3.8z)+45}$$

$$\left.\times \int_0^{E'_{\nu,{\rm sn,max}}} dE_{\nu,{\rm sn}}\frac{dN_{\bar\nu,{\rm sn}}}{dE_{\nu,{\rm sn}}}\sigma_{\nu\bar\nu}(s)\right], \quad (7)$$

where $\mathcal{K}c/H_0^2 \approx 2.45\times 10^{-38} h_{70}^{-1}$ cm^{-2} and the differential SN ν spectrum is $dN_{\bar\nu,{\rm sn}}/dE_{\nu,{\rm sn}} \approx 10^{49}$ MeV^{-1}. Large $\nu\bar\nu$ cross section then suppresses UHE neutrinos. We discuss UHE ν fluxes that will be attenuated by $\nu\bar\nu$ annihilation next.

Ultrahigh-energy neutrino flux.— The CR energy generation rate per unit volume in our local universe in the energy range 10^{19-21} eV is $P_{\rm CR} \approx 5\times 10^{44}$ erg Mpc^{-3} yr^{-1} [32]. Assuming an injection spectrum for CR protons $dN_p/dE_p^0 \propto E_p^{-2}$, as typically expected, we define a convenient conversion formula

$$\mathcal{N}_{\rm CR} = \frac{c}{4\pi H_0}\frac{P_{\rm CR}}{\ln(10^{21}/10^{19})}$$

$$\approx 7.1\times 10^{-8} h_{70}^{-1}\ {\rm GeV\ cm^{-2}\ s^{-1}\ sr^{-1}}, \quad (8)$$

which is proportional to the CR flux $E_p^2 J_p$ above 10^{19} eV. We will use Eq. (8) to fix the normalization of UHE ν 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 $z > 2.7$ [32].

The Waxman-Bahcall (WB) bound on UHE ν flux [32] is based on CRs that interact at their sources and lose all their energy equally to charged and neutral pions. The resulting ν_μ flux is given by

$$E_\nu^2 J_{\nu,{\rm WB}} = \frac{\mathcal{N}_{\rm CR}}{8}\int_0^{z_{\rm max}} dz_{\rm uhe}\frac{S(z_{\rm uhe})P(E_\nu; z_{\rm uhe})}{\sqrt{\Omega_m(1+z_{\rm uhe})^3+\Omega_\Lambda}} \quad (9)$$

after integrating over CR source evolution and $\nu\bar\nu$ annihilation probability in Eq. (7).

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

$$E_\nu J_\nu(z\sim 0) \propto \mathcal{N}_{\rm CR}\int dE_p^0 \frac{dN_p}{dE_p^0} Y(E_p^0, E_\nu, z\sim 0) \quad (10)$$

Here Y is called the neutrino yield function as in Ref. [33] and is the number of secondary neutrinos generated per unit energy interval by a CR proton of energy E_p^0. We use a fit to $Y(E_p^0, E_\nu, z\sim 0)$ corresponding to ν_μ and $\bar\nu_\mu$ from a CR proton propagating 200 Mpc as generated by the SOPHIA Monte Carlo code as reported in Ref. [33]. The GZK ν 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 νN interactions of UHE CRs with DSNν in $n = 4$ large extra-dimensional model. Hence we can calculate the effect of $\nu\bar\nu$ annihilation assuming that a fully evolved GZK ν flux exist at a given redshift of interaction.

The total UHE ν flux integrated over all CR sources, after taking into account the redshift evolution of the neutrino yield function $Y(E_p^0, E_\nu, z) = Y(E_p^0(1+z), E_\nu(1+z)^2, z\sim 0)$ [33], the source evolution $S(z)$ and finally the survival probability $P(E_\nu; z_{\rm uhe})$ in Eq. (7), is given by

$$E_\nu J_{\nu,{\rm GZK}} = \mathcal{N}_{\rm CR}\int_0^{z_{\rm max}} dz_{\rm uhe}\frac{S(z_{\rm uhe})P(E_\nu; z_{\rm uhe})}{\sqrt{\Omega_m(1+z_{\rm uhe})^3+\Omega_\Lambda}}$$

$$\times \int dE_p^s \frac{dN_p}{dE_p^s} Y(E_p^s, E_\nu, z_{\rm uhe}). \quad (11)$$

In case of no $\nu\bar\nu$ annihilation, $P(E_\nu; z_{\rm uhe}) = 1$ and the flux is the same as in Ref. [33].

We have numerically evaluated the GZK flux, both without and with $\nu\bar\nu$ annihilation, using $z_{\rm max} = z_{\rm uhe} = z_{\rm sn,max} = 5$ and in the energy range 10^{19} eV $< E_p^0 < 10^{22}$ eV with an exponential cutoff of the $\propto E_p^{-2}$ spectrum at 3×10^{21} eV as in Ref. [33]. The results for the GKZ cosmogenic ν_μ flux are depicted in Fig. 1, assuming a $n = 4$ extra-dimensional scenario. Also shown is the WB flux without and with $\nu\bar\nu$ annihilation. Notice that the extra-dimensional scenario leaves a clear imprint on the GZK cosmogenic neutrino fluxes, which would be abruptly truncated above $E \gtrsim 10^{17}$ 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 ($E \gtrsim 10^{17}$ eV), such as ANITA and ARIANNA shown in Fig. 1, there would be an absence of neutrino induced events caused by strongly interacting, KK-modes mediated $\nu\bar\nu$ processes. For the $n = 2$ and $n = 3$ extradimensional 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. In this latter case, tracking the extra-dimensional induced suppression *dip* would be more difficult in general.

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 his-

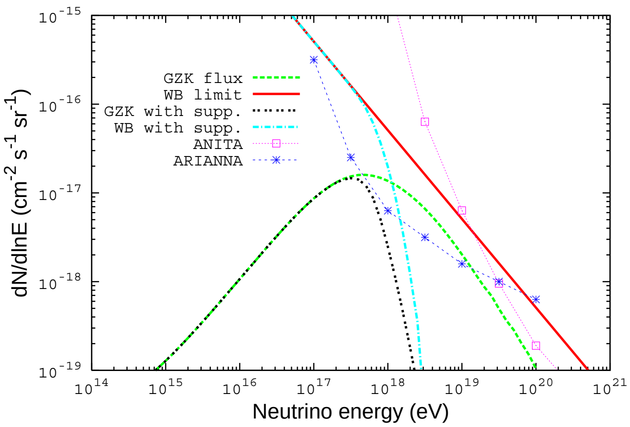

FIG. 1: Ultrahigh-energy ν fluxes from the cosmic ray protons interacting at the source (WB) and in CMB (GZK). If $\nu\bar{\nu}$ annihilation is important, as in large extra-dimensional models (shown here for $n = 4$ case), then UHE ν fluxes would be suppressed. Also shown are the projected sensitivities for the ANITA (50 days) and the proposed ARIANNA (6 months) UHE neutrino experiments at the South Pole.

tory 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 $n = 4$ large extra-dimensions in nature, and the DSNν flux is detected at the level of the current theoretical models, then UHE neutrinos can not be the primaries of the super GZK events. In case the DSNν flux is detected at a much lower level, then the *dip* in the UHE neutrino spectrum, due to absorption by DSNν, would be shifted to higher energy. Note that $\nu\bar{\nu}$ annihilation by UHE neutrinos would not produce γ-rays over the EGRET limit, since the primary UHE CR interactions with CMB and infrared photons can not account for the observed diffuse γ-ray flux [34]. Also the GZK CRs are not affected due to large νN cross section, since they are expected to be produced within ~ 50 Mpc, a radius smaller than the νN *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 DSNν background.

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