PROCEEDINGS OF SCIENCE

Cosmic-Ray Boosted Relic Neutrinos

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The cosmic neutrino background is a prediction of standard cosmology but remains undetected due to the extremely low energies involved. By elastic scattering on cosmic-ray nuclei, these relic neutrinos can be upscattered to ultra-high energies observable by current neutrino telescopes such as the IceCube Neutrino Observatory and the Pierre Auger Observatory. Earlier calculations only took into account the elastic scattering on the proton component and ignored the effect of coherent elastic neutrino-nucleus scattering on heavier nuclei. In this contribution, we study the flux of cosmic-ray-boosted relic neutrinos, including coherent scattering on nuclei, and use the current upper limits to constrain the cosmic neutrino background density.

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1. Introduction

The standard cosmological model (ΛCDM) predicts a cosmic relic neutrino background (CνB), analogous to the cosmic microwave background [1–3]. The relic neutrinos are predicted to have an average number density of $56\,\mathrm{cm}^{-3}$ per flavor and spin degree of freedom with a temperature of 1.95 K. Despite being predicted as the most numerous population of neutrinos in the universe, due to their extremely low energies they have not been detected so far. In non-standard cosmologies, the neutrino number density can be significantly enhanced, e. g. in the presence of new Yukawa interactions of neutrinos or dark matter decay into neutrinos [4–7]. The strongest experimental constraints on the local CνB overdensity η were determined by the KATRIN collaboration as $\eta < 9.7 \times 10^{10}$ [8].

A novel approach to probe the existence of the CνB is the ultra-high-energy cosmic rays (UHECRs) scattering of relic neutrinos, thus boosting the neutrinos to ultra-high energies. While the first studies go back to Hara and Sato in the 1980s [9, 10], this concept has recently been investigated to constrain the CνB in various contexts to set stronger constraints on the overdensity of the CνB. Under the assumption of a pure proton composition of UHECRS, [11] determine an upper limit of $\eta \lesssim 10^4$; however, data from air shower elements indicate a composition dominated by heavy elements with less than 10% proton above cosmic ray energies of 10 EeV [12]. In addition, earlier studies took into account only elastic and deep-inelastic scattering on protons, while for low-energy neutrinos interacting with heavy nuclei, coherent enhancement through interaction with all nucleons collectively significantly increases the cross-section [13, 14].

In this study, we calculate the flux of boosted relic neutrinos taking into account both a mixed composition of UHECRs and coherent elastic neutrino-nucleon scattering and determine upper limits on the CνB overdensity by comparing against limits from ultra-high energy neutrino searches by the IceCube Neutrino Observatory [15, 16] and the Pierre Auger Observatory [17]. This flux is predicted for the same energy region as cosmogenic neutrinos from UHECR propagation; therefore, we cannot unambiguously detect the CνB when measuring ultra-high-energy neutrino events, but determine upper limits.

2. Cross-sections

The cross-section for elastic neutrino-nucleus scattering can be written as the sum of a coherent and an incoherent contribution $d\sigma^{\nu N}/dE_\nu = d\sigma_{\mathrm{coh}}/dE_\nu + d\sigma_{\mathrm{incoh}}/dE_\nu$. The coherent contribution, corresponding to small momentum transfer and collective interaction with the whole nucleus, can be written differential in the final state neutrino energy as

$$\frac{d\sigma_{\mathrm{coh}}}{dE_\nu} = \frac{2G_F^2 m_\nu}{\pi} Q_W^2 \left(1 - \frac{E_\nu}{E_N} - \frac{m_N^2 E_\nu}{2m_\nu E_N^2}\right) F^2(q^2), \tag{1}$$

where m_N, E_N are the mass and energy of the nucleus, m_ν, E_ν the rest mass and final state energy of the neutrino, $q^2 = 2m_\nu E_\nu$ the momentum transfer, $F(q^2)$ the nuclear formfactor, and $Q_W = Zg_p + (A - Z)g_V$ the nuclear weak charge, which is dominated by the neutron content of the nucleus (see [18] for a detailed derivation). The incoherent cross-section can be expressed in terms of the elastic neutrino-nucleon scattering cross-section as

$$\frac{d\sigma_{\text{incoh}}}{dE_\nu} = \left(Z \frac{d\sigma^{\nu p}_{ES}}{dE_\nu} + (A - Z) \frac{d\sigma^{\nu n}_{\text{EH}}}{dE_\nu} \right) (1 - F^2(q^2)), \tag{2}$$

with the elastic scattering cross-section from [19].

3. Boosted CνB flux

The differential flux of boosted CνB neutrinos at Earth can be written as

$$\begin{aligned} \frac{d\phi_\nu}{dE_\nu} = \sum_{i,j} \int_{z_{\min}}^{z_{\max}} dz \, \frac{c}{H_0 \sqrt{\Omega_\Lambda + (1+z)^3 \Omega_m}} f(z) \eta n_{\nu_j} (1+z)^3 \\ \times \int_0^\infty dE_N \frac{d\sigma^{\nu N}}{dE_\nu} \frac{d\phi_{N,i}}{dE_N} \Theta(E_\nu^{\max} - E_\nu(1+z)), \end{aligned} \tag{3}$$

where the sum goes over nuclear species i and neutrino flavors j, $d\phi_{N,i}/dE_N$ denotes the UHECR flux and $f(z)$ denotes the scaling of the UHECR source density with redshift z. The range of redshifts integrated over is $z_{\min} = 0 < z < z_{\max} = 6$.

For this study, we use the spectrum and composition parametrization of the cosmic-ray flux by [20] above a primary energy of 5×10^8 GeV, scaled by the source density evolution, as the cosmic-ray flux. The study of the effects of UHECR propagation will be subject of future investigations. The sources of UHECRs are so far unknown, therefore we use several well-motivated source density evolutions, all normalized to $f(z = 0) = 1$:

- the star formation rate by [21] for our baseline prediction,
- the quasar redshift distribution by [22], and
- the gamma-ray burst redshift distribution by [23].

We take into account the mass differences between the three mass eigenstates determined from oscillation [24] and vary the lowest mass m_1, assuming normal neutrino mass ordering.

The flux of boosted relic neutrinos is shown in Fig. 1 for $m_1 = 0.1$ eV and source density scaling with the star formation rate. While elastic scattering on protons dominates above $E_\nu \gtrsim 10^7$ GeV with a significant contribution from incoherent scattering on nuclei, at lower energies, coherent scattering on heavier nuclei clearly dominates the flux of boosted neutrinos.

Changing the lightest neutrino mass mostly changes the normalization of the flux with higher flux for higher neutrino masses, and in addition shifts the peak of the spectrum somewhat to lower energies for higher neutrino masses (cf. Fig. 2).

4. Constraints on the CνB overdensity

With this flux prediction, we can determine neutrino-mass-dependent limits on the CνB overdensity by using data collected for extremely-high energy neutrino searches published by the IceCube Neutrino Observatory [15, 16] and the Pierre Auger Observatory [17]. Using the effective

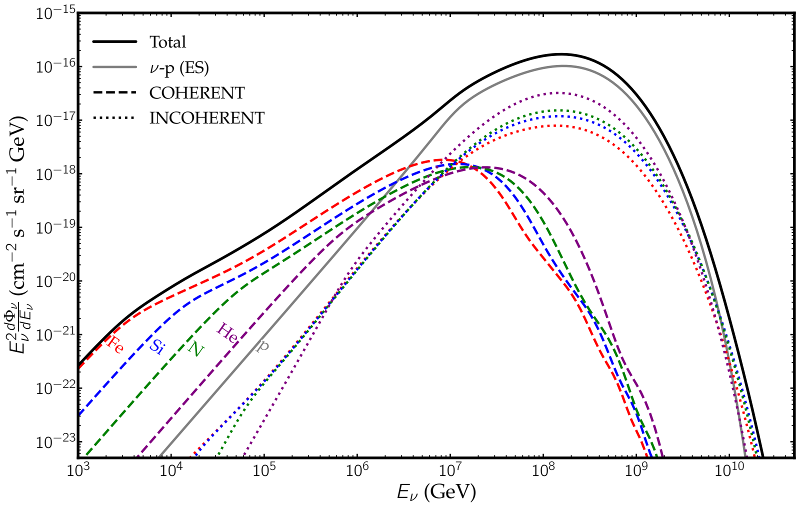

Figure 1: Boosted CνB flux as a function of neutrino energy E_ν for lowest neutrino mass $m_1 = 0.1$ eV, assuming a scaling of the UHECR source density with the star formation rate. The colors denote the various nuclear species, while dashed and dotted lines denote the coherent and incoherent contributions to the neutrino-nucleus scattering cross-section.

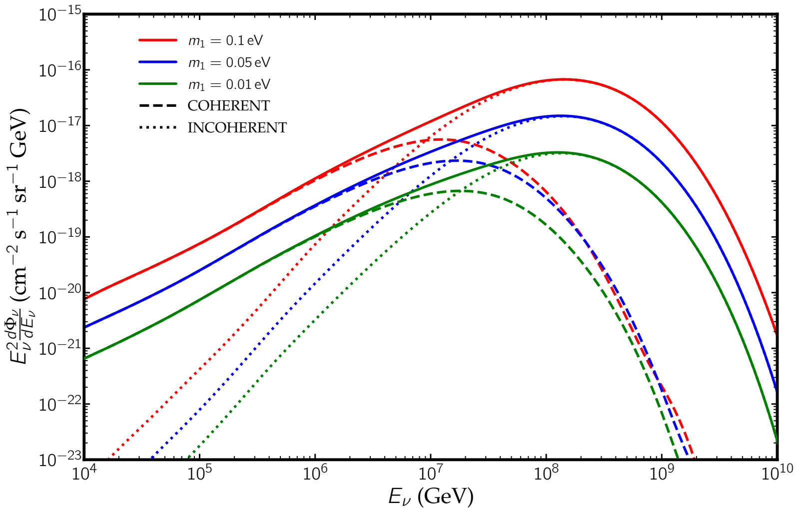

Figure 2: Impact of changing the lightest neutrino mass on the boosted relic neutrino mass. The total flux from all nuclei except protons is shown with solid lines, while dashed and dotted lines denote the coherent and incoherent contributions for the different neutrino masses denoted by different colors.

areas and uptime from these analyses and the number of observed events, we obtain the 90% CL Feldman-Cousins upper limits in Fig. 3. In the context of our model, both IceCube and the Pierre Auger Observatory set a stronger limit than the model-independent measurement by KATRIN for each of the investigated source density scalings. The strongest limit for all masses is for the case of the GRB scaling, while it is the weakest for scaling according to the quasar rate. For $m_1 = 0.01$ eV, the limits become flat because the dominant contributions arise from the mass eigenstates m_2, m_3.

In addition, the recent observation by the KM3Net collaboration of a neutrino event with

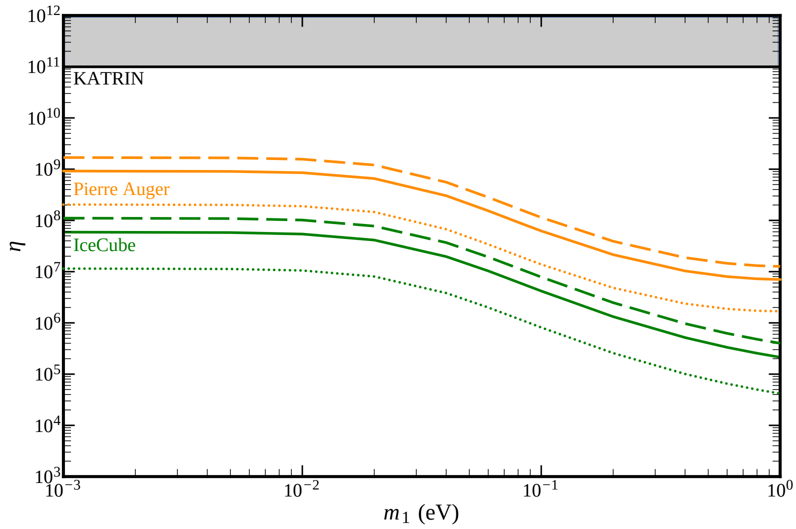

Figure 3: Upper limits on the CνB overdensity, determined from the results of extremely-high-energy neutrino searches by IceCube (green) [16] and the Pierre Auger Observatory (orange) [17]. The source density scaling is indicated by the line style: star formation rate – solid, quasar rate – dashed, gamma-ray burst rate – dotted. For comparison, the direct limit from KATRIN [8] is shown.

reconstructed energy of 220^{+570}_{-110} PeV [25] and the agreement of this energy with the peak of the boosted relic neutrino flux invite to speculate about a possible connection. It must, however, be kept in mind that interpreting this event in terms of a time-independent flux leads to strong tensions with the upper limits determined by IceCube and Auger. We show the prediction of our model for an overdensity of $\eta = 10^8$ together with neutrino flux measurements by IceCube [26–28] and upper limits from IceCube, ANTARES, and the Pierre Auger Observatory [16, 17, 29] in Fig. 4, together with predictions of cosmogenic flux models [30–32].

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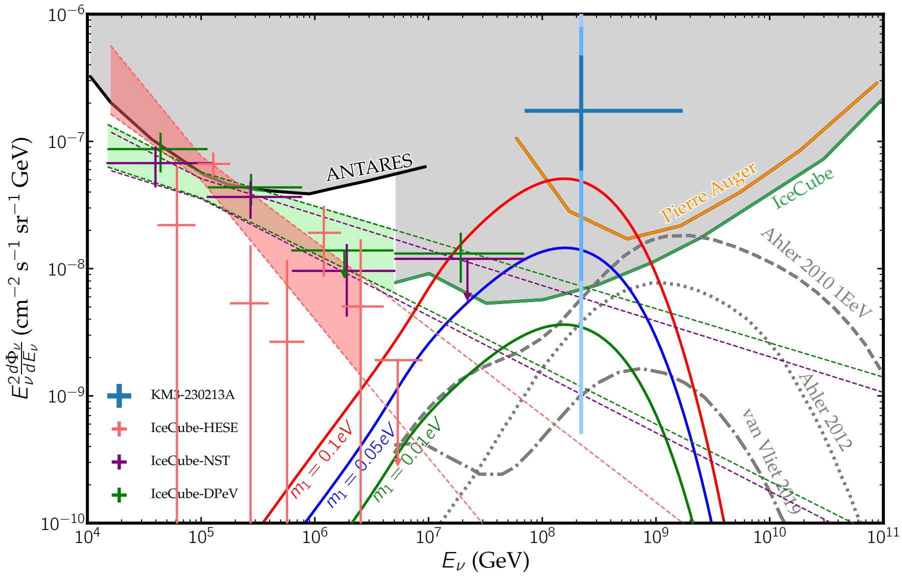

Figure 4: Predicted boosted relic neutrino flux for an overdensity of $\eta = 10^8$ compared to upper limits on the ultra-high energy neutrino flux from IceCube, ANTARES, and the Pierre Auger Observatory [16, 17, 29], astrophysical flux measurements at lower energies from IceCube [26–28]. The KM3Net event is shown with the different shades of blue corresponding to 1, 2, and 3σ ranges [25]. Various cosmogenic neutrino flux models [30–32] are shown for comparison.

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