Bound on a flux of ultra-high energy neutrinos in a scenario with extra dimensions

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Abstract. Assuming that a single-flavor diffuse neutrino flux dN_ν/dE_ν is equal to kE_ν^{-2} in the energy range 10^{17} eV – 2.5×10^{19} eV, an upper bound on k is calculated in the ADD model as a function of the number of extra dimensions n and gravity scale M_D. An expected number of neutrino induced events at the Surface Detector array of the Pierre Auger Observatory is estimated.

1 Introduction

High energy cosmic neutrinos may help us
– to discover cosmic rays (CRs) point sources;
– to define their position, in particular, to constrain a position of the gravity wave (GW) sources;
– to understand a mechanisms of CR acceleration;
– to define an energy boundary between galactic and extragalactic parts of CR spectrum;
– to give information on a nature of CR composition;
– to measure a cosmic neutrino flux, flavor ratio and high energy neutrino-nucleon cross section.

The first observation of high-energy astrophysical neutrinos was done by the IceCube neutrino detector [1]. The single-flavor diffuse neutrino flux was measured in the energy region 25 TeV $< E_\nu <$ 1.4 PeV to be [2]

$$\frac{dN}{dE_\nu} = 2.06 \times 10^{-18} \left(\frac{E_0}{E_\nu}\right)^{\gamma} \mathrm{GeV}^{-1}\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}, \tag{1}$$

where $E_0 = 10^5$ GeV, $\gamma = 2.46$. Later on, it was found that the neutrino-nucleon cross section agrees with SM predictions in the range 6.3 TeV – 980 TeV [3].

Ultra-high energy (UHE) neutrinos (with energies above 10^{17} eV) are of particular interest. They may probe a new physics if the latter gives us a significant enhancement of neutrino-nucleon cross sections. To detect UHE neutrinos, powerful CR detectors, such as the Pierre Auger Observatory (PAO) [4] or Telescope Array [5], are needed. Recently, the PAO Collaboration reported on searches both for downward-going (DG) and Earth-skimming (ES) neutrinos [6]. The DG air showers [7] are initiated by cosmic neutrinos moving with large zenith angle which interact in the atmosphere near the Surface Detector (SD) array of

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the PAO. The ES air showers [8] are induced by tau neutrinos coming at small negative angles with respect to the horizon which interact in the Earth producing tau leptons. In their turn, the tau leptons escape the Earth and initiate showers close to the SD. The zenith angles of $60° - 75°$ and $75° - 90°$ for the DG air showers, and zenith angles of $90° - 95°$ for the ES air showers were analyzed. The data were collected for a period which is equivalent of 6.4 years of a complete PAO SD working continuously [6].

No neutrino candidates were found. Assuming the diffuse flux of UHE neutrinos to be

$$\frac{dN}{dE_\nu} = k\,E_\nu^{-2} \tag{2}$$

in the energy range 1.0×10^{17} eV – 2.5×10^{19} eV, the single-flavor upper limit to the diffuse flux of UHE neutrinos was obtained by the PAO Collaboration [6]

$$k < 6.4 \times 10^{-9}\ \text{GeV cm}^{-2}\ \text{s}^{-1}\ \text{sr}^{-1}. \tag{3}$$

This bound is approximately four times less than the benchmark Waxman-Bachall bound on cosmic neutrino production in optically thin sources [9]. Note that the IceCube flux (1), if extrapolated to 1 EeV, would give

$$k = 0.3 \times 10^{-9}\ \text{GeV cm}^{-2}\ \text{s}^{-1}\ \text{sr}^{-1}. \tag{4}$$

Recently, from the nonobservation of neutrino candidates from the GW sources [10] the following upper limit was derived [11], [12]

$$E_\nu^2 \frac{dN}{dE_\nu} = (1.5 - 6.9) \times 10^{-8}\ \text{GeV cm}^{-2}\ \text{s}^{-1}\ \text{sr}^{-1}. \tag{5}$$

The bound (3) has was obtained under assumption that neutrino-nucleon collisions in the atmosphere are described by the CC and NC interactions. The goal of the present paper is to calculate the single-flavor upper bound on the diffuse flux of UHE cosmic neutrinos in the ADD model [13] as a function of the number of extra dimensions n and D-dimensional Planck scale M_D ($D = 4 + n$).

2 Neutrino-nucleon cross sections

Consider energy region $E_\nu > 10^{17}$ eV. At UHEs the neutrino interacts essentially with the the partons (quarks, antiquarks and gluons) inside the nucleon. If the impact parameter of the incoming neutrino b is much larger than a D-dimensional Schwarzschild radius R_S [14],

$$R_S(\hat{s}) = \frac{1}{\sqrt{\pi}} \frac{1}{M_D} \left[\frac{8\Gamma\left(\frac{n+3}{2}\right)}{n+2} \frac{\sqrt{\hat{s}}}{M_D} \right]^{\frac{1}{n+1}}, \tag{6}$$

the eikonal approximation for the scattering amplitude [15] is valid. Here $\sqrt{\hat{s}}$ is an invariant energy of the partonic subprocess. Then we are in so-called transplanckian regime [16] which corresponds to the conditions

$$\sqrt{\hat{s}} \gg M_D\,, \quad \theta \sim \left[\frac{R_S(\hat{s})}{b} \right]^{n+1} \ll 1, \tag{7}$$

were θ is a scattering angle.

In the eikonal approximation the leading part of the scattering amplitude is obtained by summation of all ladder diagrams with graviton exchange in the t-channel. The tree-level exchanges of the D-dimensional graviton gives the eikonal formula

$$A_{\text{eik}}(s,t) = -2is \int d^2b\, e^{iqb} \left[e^{i\chi(b)} - 1 \right], \tag{8}$$

with the eikonal phase [16] -[17]

$$\chi(b) = \left(\frac{b_c}{b} \right)^n , \quad \text{where} \ \ b_c = \left[\frac{(4\pi)^{n/2-1}\, \hat{s}\Gamma(n/2)}{2M_D^{n+2}} \right]^{1/n} . \tag{9}$$

If the impact parameter of the incoming neutrino is less than R_S, the neutrino and the parton form a black hole. In such a case, the cross section can be estimated as [18]-[19]

$$\sigma_{\nu N \to \text{BH}}(s) = \pi \sum_i \int\limits_{(M_{\text{bh}}^{\text{min}})^2/s}^{1} dx f_i(x, \hat{s})\, R_S^2(\hat{s}) \ , \tag{10}$$

where $f_i(x, \hat{s})$ is the parton distribution function (PDF) of the parton i with the momentum fraction x inside the nucleon ($i = q, \bar{q}, g$), and $\hat{s} = xs$. We use the CT14 set of the PDFs [20]. For chosen value of n we take M_D to be equal to a lower limit on M_D obtained by CMS Collaboration (see fig. 11 in [21]). For given values of n and M_D, we fix $M_{\text{bh}}^{\text{min}}$ to be equal to a corresponding lower limit on $M_{\text{bh}}^{\text{min}}$ from ref. [22].

As for the SM cross section for the UHE neutrino-nucleon scattering off the nucleon, we adopt a formula from [23], which was used by the PAO Collaboration to obtain the upper limit on the neutrino flux (3). The total cross sections as a function of M_D and fixed n are shown in figs. 1. The eikonal and black hole contributions to the total cross section are also shown for $n = 4$, $M_D = 2.3$ TeV.

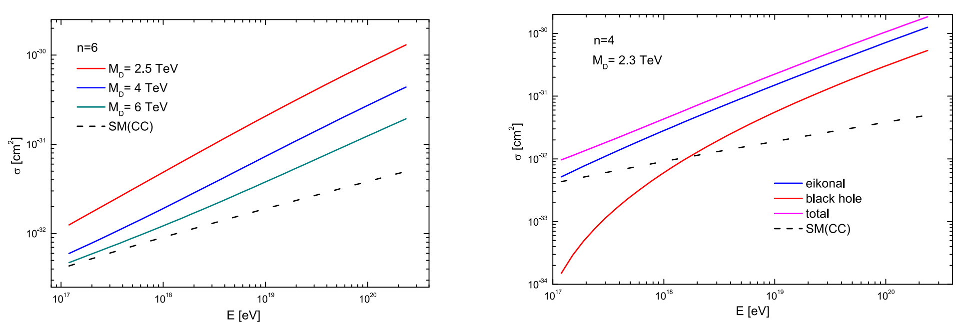

Figure 1. Left panel: the neutrino-nucleon total cross sections for $n = 6$ and $M_D = 2.5$ TeV, 4.0 TeV, 6.0 TeV for the neutrino energies above 10^{17} eV. Right panel: the eikonal and black hole contributions to the total cross section for $n = 4$.

In fig. 2 the neutrino-nucleon total cross section for the energy range 10^{13} eV – 10^{17} eV is show. As one can see, for the sensitivity region of the detector IceCube ($E_\nu \lesssim 2$ PeV) effects from the extra dimensions are negligible, in accordance with the cross section measurements by the IceCube Collaboration [3]. But they become important at $E_\nu > 10^{16}$ eV.

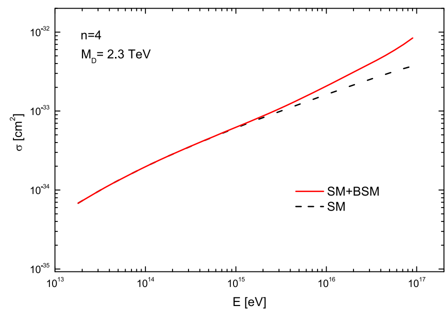

Figure 2. The neutrino-nucleon total cross section for $n = 4$, $M_D = 2.3$ TeV for the neutrino energies below 10^{17} eV in the ADD model (solid line). The SM prediction is shown by the dashed line.

The calculation of the cross sections is not an end of the story. It enables us to calculate exposures both for DG and ES neutrino events at the SD array of the PAO in the ADD model and thus to put an upper limit on the diffuse single-flavor flux of UHE neutrinos. It will be done in the next section.

3 Exposures and bounds on diffuse neutrino flux in the ADD model

The exposure of the DG neutrino events increases with the rise of the neutrino-nucleon cross section, that results in its dependence on the "new physics" cross section $\sigma_{\rm NP}$ [24]

$$\mathcal{E}^{\rm DG}_{\rm BSM}(E_\nu) = \mathcal{E}^{\rm DG}_{\rm SM}(E_\nu)\,\frac{\sigma^{\rm eff}_{\rm SM}(E_\nu) + \sigma_{\rm NP}(E_\nu)}{\sigma^{\rm eff}_{\rm SM}(E_\nu)}\ , \tag{11}$$

where $\mathcal{E}^{\rm DG}_{\rm BSM}$ ($\mathcal{E}^{\rm DG}_{\rm SM}$) is the exposure of the SD of the PAO with (without) account of the new interaction. The effective SM cross section $\sigma^{\rm eff}_{\rm SM}$ takes into account relative mass apertures for charged current (CC) and neutral current (NC) interactions of the DG neutrinos at the PAO (see [24] for details). In contrast to $\mathcal{E}^{\rm DG}_{\rm BSM}$, the exposure of the ES neutrino events decreases with the rise of the neutrino total cross section as [24]

$$\mathcal{E}^{\rm ES}_{\rm BSM}(E_\nu) = \mathcal{E}^{\rm ES}_{\rm SM}(E_\nu)\,\frac{\sigma^2_{\rm CC}(E_\nu)}{[\sigma_{\rm CC}(E_\nu) + \sigma_{\rm NP}(E_\nu)]^2}\ . \tag{12}$$

The formulas (11) and (12) allowed us to calculate exposures of the SD of the PAO for the period 1 January 2004 – 20 June 2013 expected in the ADD model. This period is equivalent of 6.4 years of a complete SD array working continuously. The PAO data on the exposures for the SM neutrino interactions in the region from $\log(E_\nu/\text{eV}) = 17$ to 20.5 were used [6]. The results of our calculations are presented in figs. 3.

It was assumed that the astrophysical flux arrives isotropically from all directions, and neutrino flavor composition is $\nu_e : \nu_\mu : \nu_\tau = 1 : 1 : 1$. Following Pierre Auger Collaboration, we also adopted that the flux is described by a power law of the form (2). As one can see in fig. 1, in the ADD model the cross sections rise more rapidly with the neutrino energy than the SM cross sections. As a result, the exposure for the DG events, $\mathcal{E}^{\rm DG}_{\rm BSM}$ (11), rises, while the exposure for the ES events, $\mathcal{E}^{\rm ES}_{\rm BSM}$ (12), decreases as E_ν grows (see fig. 3).

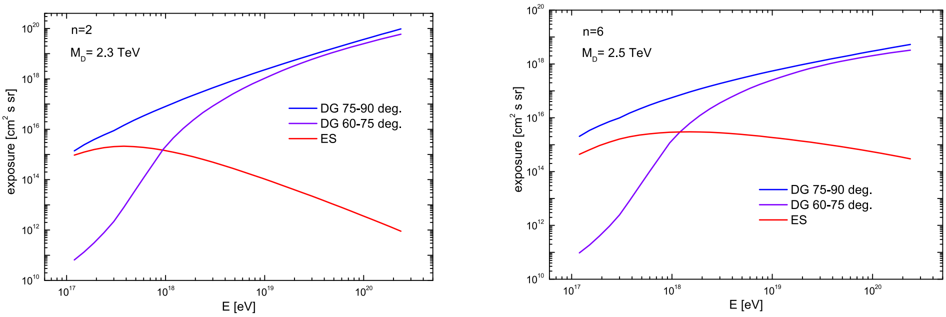

Figure 3. Left panel: the expected exposures of the SD array of the PAO for the DG and ES neutrinos in the ADD model for the period of 6.4 years. Right panel: the same as on the left panel, but for $n = 6$.

The upper limit on the value of k is defined as [6]

$$k = \frac{N_{\mathrm{up}}}{\int E_\nu^{-2} \mathcal{E}_{\mathrm{tot}}(E_\nu) dE_\nu} , \tag{13}$$

where $N_{\mathrm{up}} = 2.39$ is an actual value of the upper limit on the signal events, assuming a number of expected background events to be zero. The results of our calculations of the upper bound on the neutrino flux normalization k are shown in figs. 4, 5, in which the PAO upper bound on k is also shown.

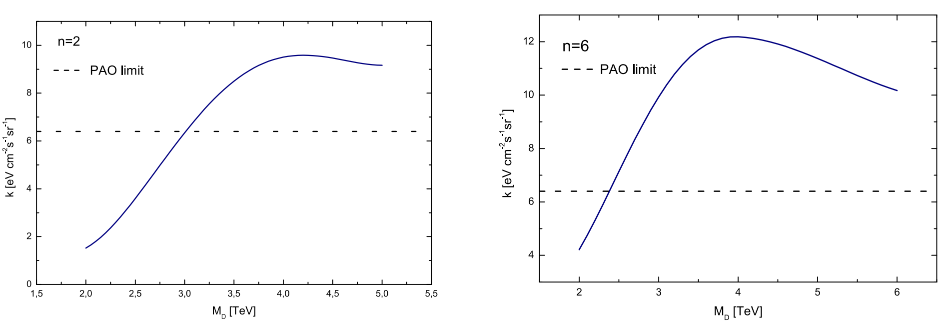

Figure 4. Left panel: the upper bound on the value of k as a function of D-dimensional Planck scale M_D for $n = 2$ in the ADD model. Right panel: the same as on the left panel, but for $n = 6$.

Finally, we have estimated the expected numbers of the neutrino events at the SD of the PAO for the period of 2×6.4 years. The calculations were done for the IceCube flux (1) extrapolated to the UHE region. The results are presented in fig. 6.

4 Conclusions

Using the exposure of the PAO for the period equivalent of 6.4 years of the complete PAO SD array working continuously, we have estimated the PAO exposures for the neutrino induced events expected in the ADD model with n extra dimensions and gravity scale M_D. Both downward-going and Earth-skimming UHE cosmic neutrinos were considered. As a result,

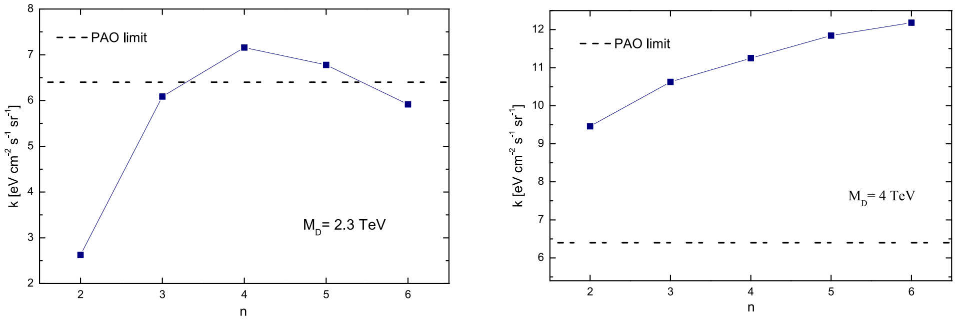

Figure 5. Left panel: the upper bound on the value of k as a function of number of extra dimensions n for $M_D = 2.3$ TeV. Right panel: the same as on the left panel, but for $M_D = 4.0$ TeV.

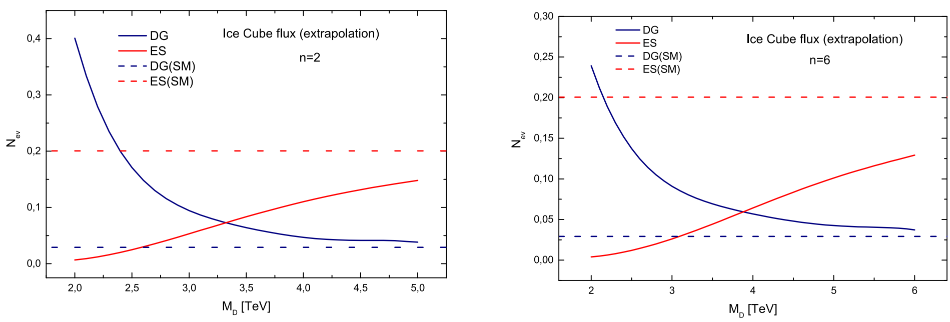

Figure 6. Left panel: the expected number of events at the SD array of the PAO for the period of 2×6.4 years for the IceCube neutrino flux extrapolated to EeV energy region. Right panel: the same as on the left panel, but for $n = 6$.

we have calculated the single-flavor upper limit on the diffuse neutrino flux in the presence of the massive graviton interactions in the ADD model. We assumed that the flux of UHE neutrinos has the power form (2).

It appeared that in the ADD model the upper bound on the diffuse neutrino flux can be more stringent that the PAO bound (3), depending on two parameters of the ADD model. As one can see in fig. 4, it takes place for $M_D < 3.01$ TeV (2.38 TeV), if $n = 2$ (6). For $M_D = 2.3$ TeV it is true for $n \leqslant 3$ and $n \geqslant 6$ (see the left panel of fig. 5). However, with the increase of M_D our bound becomes weaker than the PAO bound for all n, and it tends to it from above as M_D grows (see, for instance, the right panels of figs. 4, 5). All these results are explained by different dependence of the DG and ES exposures on the neutrino-nucleon cross section (see formulas (11), (12)).

In the ADD model the expected numbers of the neutrino events N_{ev} at the SD of the PAO are calculated for the period of 2×6.4 years for the IceCube flux (1) extrapolated to the UHE region (see fig. 6). These numbers tend to the SM predictions, as M_D grows. For the ES events, the SM value is achieved for very large values of M_D.

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