# Effects of large extra dimensions on cosmogenic neutrino fluxes



2013 J. Phys. G: Nucl. Part. Phys. 40 055202

(http://iopscience.iop.org/0954-3899/40/5/055202)

J. Phys. G: Nucl. Part. Phys. **40** (2013) 079501 (1pp) doi:10.1088/0954-3899/40/7/079501

# Corrigendum: Effects of large extra dimensions on cosmogenic neutrino fluxes

2013 *J. Phys. G: Nucl. Part. Phys.* **40** 055202

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Received 23 April 2013
Published 16 May 2013
Online at stacks.iop.org/JPhysG/40/079501

An error was overlooked in the abstract of our paper: 'new generation acoustic detectors' in the final sentence should in fact read 'new generation radio detectors'. The rest of the paper is correct. We did not consider any other type of detector, although the acoustic detection technique is an interesting possibility, and is expected to help in detecting cosmogenic neutrinos [1].

In addition, ARA should be expanded to Askaryan Radio Array (ARA) in the first instance.

## Reference

[1] Abbasi R *et al* (IceCube Collaboration) 2012 *Astropart. Phys.* **35** 312

IOP PUBLISHING JOURNAL OF PHYSICS G: NUCLEAR AND PARTICLE PHYSICS

J. Phys. G: Nucl. Part. Phys. **40** (2013) 055202 (12pp) doi:10.1088/0954-3899/40/5/055202

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Received 12 September 2012
Published 15 April 2013
Online at stacks.iop.org/JPhysG/40/055202

**Abstract**

We study the consequences of theories with extra dimensions and a gravity scale of a few TeVs on the cosmogenic flux of neutrinos. Taking into account the most recent upper limits for the onset of the gravity effects given by the LHC, and the updated predictions for the cosmogenic neutrino flux consistent with Fermi-LAT data, we compute the expected number of shower events to be detected with new generation acoustic detectors such as ARA.

(Some figures may appear in colour only in the online journal)

## 1. Introduction

At present, the detection of high-energy neutrinos from cosmic accelerators is one of the most important aspects in the field of astroparticle physics. With the evidence of cosmic-ray acceleration up to $\sim 10^{11}$ GeV, a co-produced neutrino flux should be expected following the argument of Waxman and Bahcall [1]. A further mechanism for the generation of high-energy neutrinos is through cosmic-ray interactions with the cosmological background of microwave photons [2–4]. This so-called cosmogenic neutrino flux, relevant at ultra-high energies ($E_\nu > 10^7$ GeV), was often considered as *guaranteed*, although its intensity is highly dependent on the chemical composition of cosmic rays [5]. The fully operating neutrino telescope IceCube is accumulating data and constraining models, such as that of gamma-ray bursts as the origin of cosmic rays [6]. The detection principle relies primarily on the observation of Cherenkov radiation from secondary muons produced by $\nu N$ interactions. Although IceCube can be used to observe cosmogenic neutrinos [7], the radio detection technique is more efficient for the relevant high energies of these neutrinos. This technique has been successfully implemented in the detector RICE [8], and the upgrade ARA [9] is now under construction to achieve high sensitivity at the desired range for cosmogenic neutrinos.

The purpose of this work is to study the effects on the cosmogenic neutrino flux in the context of theories with extra dimensions with a Planck scale in the order of TeVs [10]. This, along with related issues, has been addressed in past studies [11–14]. In the present work, we carry out an updated study by taking into account predictions for the cosmogenic neutrino flux consistent with bounds from the gamma-ray detector Fermi-LAT [16]. We perform the analysis assuming different scales $M_D$ for the manifestation of the effects of gravity in extra dimensions which have not been excluded by LHC experiments, and we include values which cannot be probed with this machine.

This work is organized as follows. In section 2, we briefly describe the phenomenology for neutrino interactions within the models of large extra dimensions (LED). In section 3, we discuss the cosmogenic flux of neutrinos, their interaction with Earth matter, and their detectability with radio arrays such as ARA. In section 4, we present our results for the number of events expected under different assumptions of the incident cosmogenic flux and extra-dimension scenarios. Finally, we conclude with a discussion in section 5.

## 2. TeV scale gravity in large extra dimensions

Theories of extra dimensions have been proposed to solve the hierarchy problem, i.e. the fact that gravity is 32 orders of magnitude weaker than the electroweak interaction. The basic argument that solves this problem is that gravity is free to propagate in all of the $D$ dimensions, while the rest of the forces are confined to a 3-brane. This scenario can be realized in string theories of quantum gravity [17, 18].

Neutrinos of ultra-high energies interacting with nucleons can reach high values of center-of-mass energies, enough to suffer the effects of extra dimensions. We will concentrate on such effects in the case of LED which assume a $(4 + n)$-dimensional spacetime. The new phenomenology implied within these theories is the production of mini black holes (BHs), and the realization of interactions involving the exchange of virtual gravitons [19]. Micro BHs are expected to be generated in collisions of two particles if the impact parameter is smaller than the Schwarzchild radius of a BH of mass equal to the total center-of-mass energy divided by $c^2$. This is known as Thorne's hoop conjecture [20]. The mass of the produced BH is then

$$M(\hat{s}) = y_{\rm BH}\frac{\sqrt{\hat{s}}}{c}, \tag{1}$$

where the center of mass energy is $c\sqrt{\hat{s}}$ and $y_{\rm BH}$ is an inelasticity factor accounting for the fraction of energy lost in the process through gravitational waves. We take the value $y_{\rm BH} \approx 0.5$ considering the work by Yoshino *et al* [21], where also the basic cross section for BH production is given as

$$\hat{\sigma}_{\rm BH}(\hat{s}) = F\pi R^2_{\rm Sch}(\hat{s}). \tag{2}$$

Here, $F$ is a form factor that accounts for the maximal impact parameter for which collapse can occur. After [21], we adopt $F = 2.1$ for $n = 2$ and $F = 3.1$ for $n = 6$, the two representative cases we adopt in the present work. The Schwarzchild radius with $n$ extra spatial dimensions is

$$R_{\rm Sch}(\hat{s}) = \frac{\hbar}{cM_D}\left(\frac{M(\hat{s})}{M_D}\right)^{\frac{1}{n+1}}\left[\frac{2^n\pi^{\frac{n-3}{2}}\Gamma\left(\frac{n+3}{2}\right)}{n+2}\right]^{\frac{1}{n+1}}. \tag{3}$$

In the case of ultra-energetic neutrinos of energy $E_\nu$ deeply interacting with nucleons, we have a differential cross section for the production of a BH of mass $M$ given by

$$\frac{{\rm d}\sigma_{\nu N\to{\rm BH}}}{{\rm d}M^2}(s) = c^2\sum_i\int_\tau^1 {\rm d}x f_i(x,Q^2)\hat{\sigma}_{\rm BH}(xs)\delta\left(\hat{s} - \frac{M^2c^2}{y^2}\right), \tag{4}$$

where $f_i$ are the parton distribution functions, $s = 2\,m_pE_\nu$ is the total squared center-of-mass energy divided by $c^2$ in the $\nu N$ collision, and $x$ is the fraction of that which is involved in the interaction with the $i$th parton. For the momentum exchanged with the parton, we take $Q \approx \sqrt{\hat{s}}$, which in spite of being a naive choice, does not have a significant impact on the result as discussed in [11].

The integral in equation (4) can be performed to yield

$$\frac{d\sigma_{\nu N\to BH}}{dM^2}(s) = \frac{c^2}{s}\sum_i f_i(x, Q^2)\hat{\sigma}_{BH}\big(M^2c^2y_{BH}^{-2}\big). \tag{5}$$

The total BH cross section can be found by integration,

$$\sigma_{BH}(s) = \int_{3M_D} dM \frac{d\sigma_{\nu N\to BH}}{dM}(s), \tag{6}$$

where the lower limit in the BH mass is necessary for this semiclassical approach to work (e.g. [14]).

As for the exchange of Kaluza–Klein (KK) gravitons, this is viewed as an elastic process with a differential cross section (e.g. [19]):

$$\frac{d\sigma_{KK}}{dy}(s) = \int_0^1 \frac{dx}{16\pi xs}\sum_i f_i(x, \bar{q})|\mathcal{M}(x, y, \sqrt{s}/M_D)|^2, \tag{7}$$

where

$$y = \frac{E_\nu - E_y}{E_\nu} \equiv \frac{q^2}{xs},$$

and the amplitude is computed as

$$i\mathcal{M} = 4\pi s b_c^2 \int_0^\infty dx' x' J(x'qcb_c)(e^{ix^{-n}} - 1). \tag{8}$$

Here, $J$ is the Bessel function and

$$b_c^n = \frac{(4\pi)^{\frac{n}{2}-1}}{2}\Gamma\left(\frac{n}{2}\right)\frac{xsc^2}{(M_Dc^2)^{n+2}}. \tag{9}$$

As in Emparan *et al* [19], the momentum transferred to the parton is $\bar{q} = q$ if $q\,c < b_c^{-1}$, or otherwise,

$$c\bar{q} = b_c^{-1}\left(\frac{cqb_c}{n}\right)^{-\frac{1}{n+1}}.$$

In figure 1, we show the total cross section for the production of BHs (equation (6)) together with the cross section for graviton exchange interactions, obtained by integrating equation (7). For comparison, we also include the Standard Model (SM) cross section for $\nu N$ interactions.

## 3. Cosmogenic neutrinos and their interactions

The shape of the spectrum and the chemical composition of ultra-high energy cosmic rays are still issues of debate. The measurements by HiRes seem to indicate a pure proton composition, although more recent results by AUGER favor a content dominated by heavy nuclei. Yet, this conclusion is subject to uncertainties in models of hadronic interactions at the highest energies. In what follows, we assume a pure proton composition for the extragalactic cosmic rays, which leads to the strongest predictions for the flux of cosmogenic neutrinos. These are produced by cosmic-ray protons interacting with microwave photons via the channel

$$p + \gamma \to \pi_i + X, \tag{10}$$

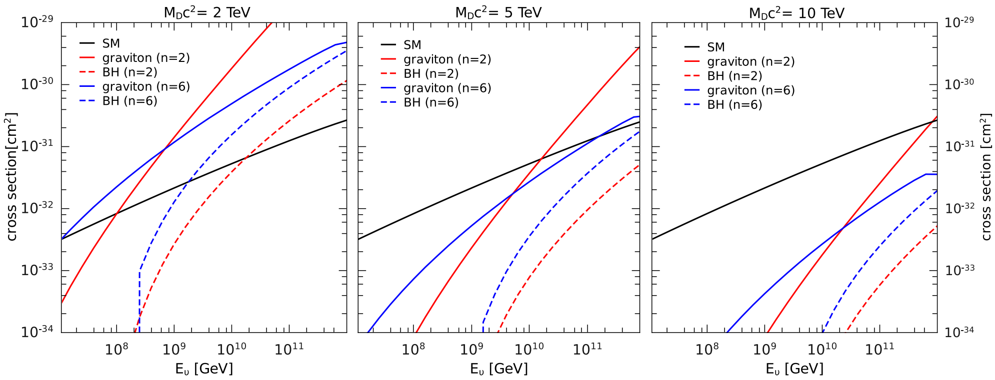


**Figure 1.** Cross sections for BH production (dashed lines) and graviton exchange interactions (solid lines) for $n = 2$ (red lines), and $n = 6$ (blue lines).

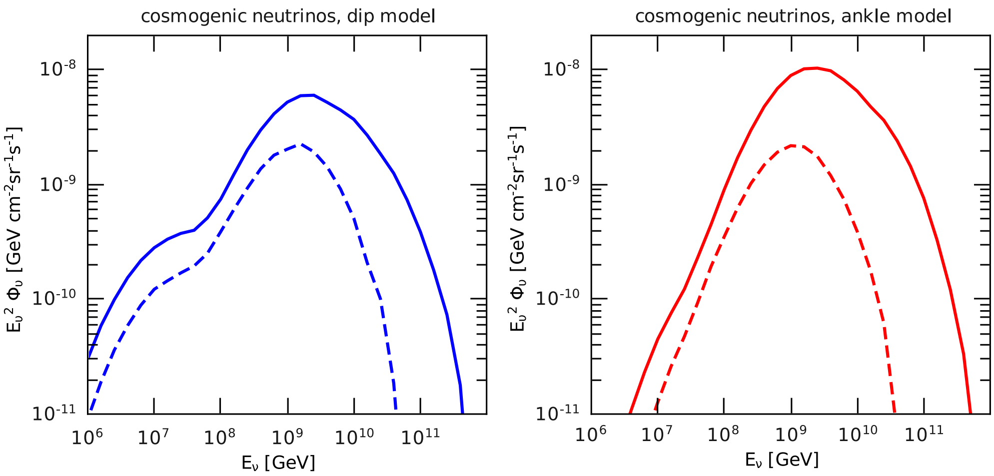


**Figure 2.** Cosmogenic neutrino fluxes expected in the dip model (left panel) and in the ankle model (right panel).

where $\pi_i = \{\pi^-, \pi^+, \pi^0\}$. These interactions are believed to be the cause of the suppression observed in the cosmic-ray spectrum above energies $\sim 4 \times 10^{11}$ GeV, which is normally known as the GZK cutoff or suppression [22]. The charged pions decay giving neutrinos, while the neutral pions give gamma-rays that can be observed with telescopes such as EGRET in the past, and now Fermi-LAT. Taking this into account, we adopt two different models for the UHE cosmic ray spectrum: the so called 'dip' model and the 'ankle' model. In the dip model [23], the spectrum above $10^9$ GeV is fitted to the HiRes data, and a dip feature is present due to $e^+e^-$ production of cosmic ray interactions with microwave photon background. In the case of the ankle model [24, 25], the HiRes data is fixed starting from a higher energy, $10^{10}$ GeV. For these two models, we follow the recent work by Gelmini *et al* [16] and consider the maximum and minimum predictions for the cosmogenic neutrino flux shown in figure 2 obtained by varying the maximum energy of the cosmic rays. The fluxes arise using a source evolution corresponding to the star formation rate, which is not excluded by Fermi-LAT data as mentioned in [16, 26].

We consider the interactions of cosmogenic neutrinos with nucleons of Earth and study the modification of the flux for different inclinations of the neutrino path: from 20° below the horizon (corresponding to an angle from the nadir $\theta = 70°$) to downward-going neutrinos ($\theta = 180°$). The column density at different angles is

$$X(E_\nu, \theta) = \int_0^{2R_\otimes \cos\theta} \mathrm{d}l\, \rho_\otimes(r(l)) + \int_{l_{\rm atm}} \mathrm{d}l\, \rho_{\rm atm}, \tag{11}$$

where the Earth and atmospheric densities $\rho_\otimes$ and $\rho_{\rm atm}$ are taken from the Preliminary Earth Model given in [27] and [28], respectively.

The flux of muon neutrinos and anti-neutrinos, $\nu_\mu + \bar{\nu}_\mu$, is defined as

$$\Phi_\nu \equiv \frac{\mathrm{d}\mathcal{N}_\nu}{\mathrm{d}E_\nu\, \mathrm{d}\Omega\, \mathrm{d}A\, \mathrm{d}t}, \tag{12}$$

where $\mathcal{N}_\nu$ is the total number of these neutrinos. The transport equation useful for describing the flux evolution along a dense medium such as the Earth is given by

$$\frac{\mathrm{d}\Phi_\nu(E_\nu, X)}{\mathrm{d}X} = -\frac{\Phi_\nu(E_\nu, X)}{\lambda_\nu(E_\nu, X)} + S_{\rm BH\to\nu}(E_\nu, X) + \int_0^1 \frac{\mathrm{d}y}{1-y}\left[\frac{\mathrm{d}\sigma_{\rm NC}(E_\nu, y)}{\mathrm{d}y} + \frac{\mathrm{d}\sigma_{\rm KK}(E_\nu, y)}{\mathrm{d}y}\right]\frac{\Phi_\nu(E_y, X)}{\sigma_{\rm tot}(E_y)\lambda_\nu(E_\nu)}, \tag{13}$$

where $y = (E_y - E_\nu)/E_y$, the mean free path is $\lambda_\nu(E_\nu) = N_{\rm Av}\, \sigma_{\rm tot}$, and the total neutrino cross section is

$$\sigma_{\rm tot}(E_\nu) = \sigma_{\rm CC}(E_\nu) + \sigma_{\rm NC}(E_\nu) + \sigma_{\rm BH}(E_\nu) + \sigma_{\rm KK}(E_\nu). \tag{14}$$

Here, the usual contributions from the SM are the charged and neutral current cross sections, $\sigma_{\rm CC} + \sigma_{\rm CC} = \sigma_{\rm SM}$.

The second term in the right member of equation (13) is a source term accounting for the neutrinos from the decay of BHs:

$$S_{\rm BH\to\nu}(E_\nu, X) = \int_{3M_D c^2} \mathrm{d}M \int_{E_{\rm BH}^{\rm (min)}}^{E_{\rm BH}^{\rm (max)}} \mathrm{d}E_{\rm BH} \frac{\Phi_{\rm BH}(M, E_{\rm BH}, X)}{\lambda_{\rm BH}^{\rm (dec)}(M, E_{\rm BH})} \frac{1}{\Gamma_{\rm BH}} \frac{\mathrm{d}N_\nu}{\mathrm{d}E_\nu\, \mathrm{d}t}, \tag{15}$$

where the differential flux of BHs is,

$$\Phi_{\rm BH}(M, E_{\rm BH}, X) = \frac{\mathrm{d}\mathcal{N}_{\rm BH}}{\mathrm{d}M\, \mathrm{d}E_{\rm BH}\, \mathrm{d}A\, \mathrm{d}\Omega\, \mathrm{d}t}, \tag{16}$$

and the BH mean free path is

$$\lambda_{\rm BH}^{\rm (dec)}(M, E_{\rm BH}) \simeq \gamma_{\rm BH}\tau_{\rm BH}(M) c \bar{\rho}(\theta), \tag{17}$$

with $\bar{\rho}(\theta)$ as the average density along the neutrino path, and the decay timescale for a BH of mass $M$ as

$$\tau_{\rm BH}(M) = \frac{\hbar}{M_D c^2}\left[\frac{M}{M_D}\right]^{\left(\frac{n+3}{n+1}\right)}. \tag{18}$$

In the laboratory frame, $\Gamma_{\rm BH}^{-1} = \gamma_{\rm BH}\tau_{\rm BH}(M)$ is the decay rate. The spectrum of neutrinos is given by (e.g. [29])

$$\frac{\mathrm{d}N_\nu}{\mathrm{d}E_\nu\, \mathrm{d}t} = \frac{c_\nu}{4\pi^2\hbar}\left[\frac{\sigma_{\rm GB}(M, E'_\nu)}{\exp\left(\frac{E'_\nu}{kT_{\rm BH}}\right) + 1}\right], \tag{19}$$

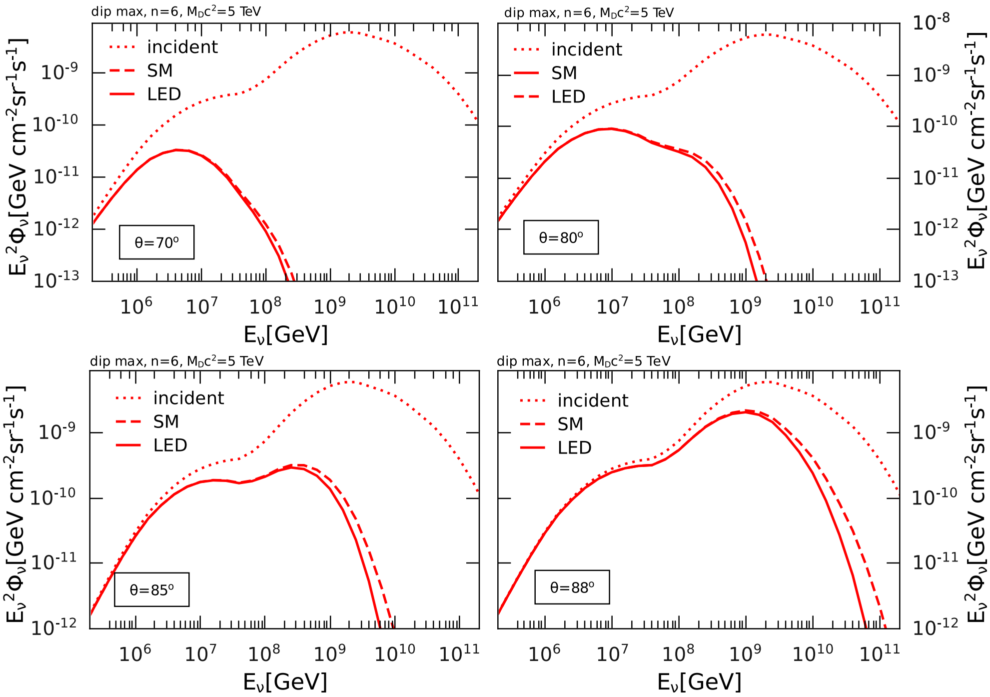


**Figure 3.** Surviving cosmogenic neutrino fluxes expected in the maximal dip model at different angles. The incident flux (dotted line) is compared to the predictions within the Standard Model (SM, dashed line) and large extra dimensions with $n = 6$ (LED, solid line).

where the neutrino energy in the BH frame is $E'_\nu = E_\nu \gamma_{\rm BH}(1 - \beta_{\rm BH})$, $c_\nu = 4$ is the number of degrees of freedom for $\nu_\mu + \bar{\nu}_\mu$, $\sigma_{\rm GB}$ is the graybody factor for spin-1/2 particles [30], and the BH temperature is

$$T_{\rm BH} = \frac{n+1}{4\pi k} \frac{\hbar c}{R_{\rm Sch}(M^2 c^2)}. \tag{20}$$

For the BH flux, a transport equation can be written as

$$\frac{{\rm d}\Phi_{\rm BH}(M, E_{\rm BH}, X)}{{\rm d}X} = -\frac{\Phi_{\rm BH}(M, E_{\rm BH}, X)}{\lambda^{(\rm dec)}_{\rm BH}(M, E_{\rm BH})} + S_{\nu\to{\rm BH}}(M, E_{\rm BH}, X), \tag{21}$$

where the source term for BH production is

$$S_{\nu\to{\rm BH}}(M, E_{\rm BH}, X) = 3\frac{\Phi_\nu(E_{\rm BH}/y_{\rm BH}, X)}{\lambda_{\rm TOT}(E_{\rm BH}/y_{\rm BH})}\left(\frac{1}{\sigma_{\rm TOT}}\frac{{\rm d}\sigma_{\nu N\to{\rm BH}}}{{\rm d}M}\right). \tag{22}$$

Here, the factor 3 accounts for the fact that cosmogenic neutrinos from all flavors can produce BHs, and the implicit approximation is that $\Phi_\nu \approx \Phi_{\nu_e+\bar{\nu}_e} \approx \Phi_{\nu_\tau+\bar{\nu}_\tau}$. This is indeed a conservative approximation, since the tau-neutrino flux could be greater due to the effect of tau regeneration. However, since this effect is most important for Earth-skimming neutrinos [31], our results will not be significantly affected. We can solve equation (21) through the integral:

$$\Phi_{\rm BH}(M, E_{\rm BH}, X) = \int_0^X {\rm d}X' S_{\nu\to{\rm BH}}(M, E_{\rm BH}, X') \exp\left[-\frac{X - X'}{\lambda^{(\rm dec)}_{\rm BH}(M, E_{\rm BH})}\right], \tag{23}$$

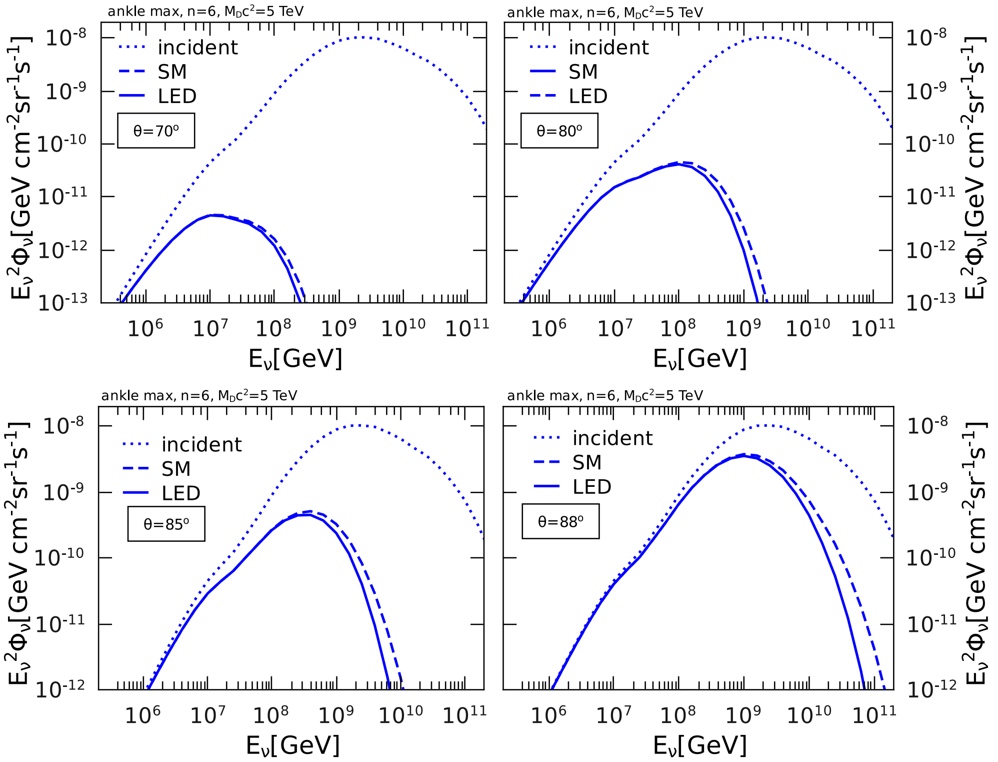


**Figure 4.** Surviving cosmogenic neutrino fluxes expected in the maximal ankle model at different angles. The incident flux (dotted line) is compared to the predictions within the Standard Model (SM, dashed line) and large extra dimensions with $n = 6$ (LED, solid line).

and given the short mean free path, the integrand is significant only for $X' \approx X$, which yields

$$\Phi_{\rm BH}(M, E_{\rm BH}, X) \approx \lambda_{\rm BH}^{(\rm dec)}(M, E_{\rm BH}) S_{\nu\to {\rm BH}}(M, E_{\rm BH}, X). \tag{24}$$

We solve the neutrino transport equation equation (13) using the iterative method of [32]. The first approximation. taken as the solution corresponding to just the absorption term, is

$$\Phi_\nu^{(0)}(E_\nu, X) = \Phi_\nu^{(\rm inc)} \exp\left(-\frac{X}{\lambda_{\rm TOT}(E_\nu)}\right), \tag{25}$$

and this solution is used to work out the second approximation $\Phi_\nu^{(1)}(E_\nu, X)$, which is the one we retain. As discussed in [32], this solution is accurate enough in the case of fast decreasing neutrino fluxes, as in the present case.

## 4. Results

In figures 3 and 4, we show the surviving fluxes for different angles through the Earth when the incident cosmogenic flux is the maximum possible prediction with the dip and in the ankle model, respectively. In these plots, we compare the SM prediction to the one obtained in an LED scenario with $n = 6$ and $M_D = 5$ TeV. Due to the effects of absorption, the surviving flux becomes too weak for large amounts of matter to be traversed (i.e. for $\theta < 85°$), and hence for illustration we will show the surviving fluxes for $\theta = 88°$ under different assumptions.

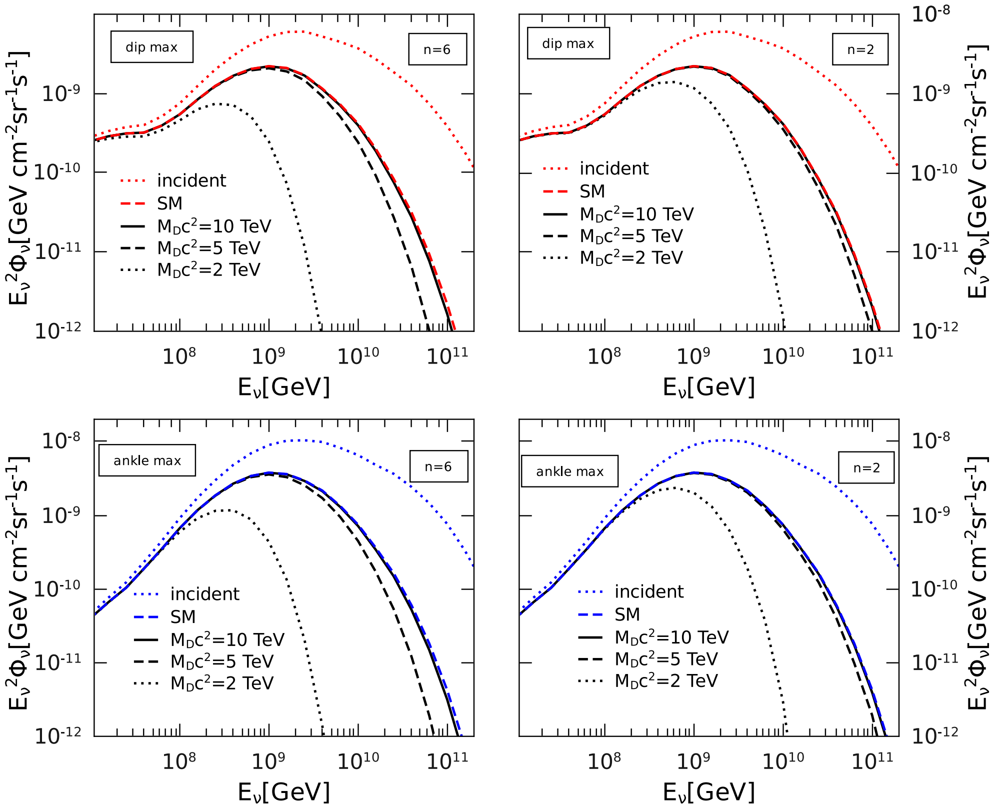


**Figure 5.** Surviving cosmogenic neutrino fluxes at $\theta = 88^{\circ}$ expected in the maximal dip and ankle models in the upper and lower panels, respectively. The incident fluxes (red and blue dotted lines) are compared to the predictions within the SM (red and blue dashed lines) and LED with $n = 6$ and $n = 2$ in the left and right panels, respectively. The predictions with different values of $M_D$ are shown by black lines.

In figure 5 we show the surviving fluxes for a nadir angle $\theta = 88^{\circ}$, for incoming fluxes corresponding to the maximal dip and angle models. We compare the results obtained for different mass scales $M_D = 2, 5,$ and 10 TeV with the SM prediction. As can be seen from these plots, the surviving flux for $M_D = 10$ TeV is almost identical to the SM one.

We now turn to the calculation of the number of shower events in a radio detector such as RICE [8] or the future ARA [9]. We pay some attention to the effective area, which is the area corresponding to an ideal detector and is normally worked out from simulations describing the detector response and the efficiency of signal detection. As, for example, in [33], a rough parametrization of the neutrino effective area in IceCube is

$$A_{\nu}^{\rm eff}(E_{\nu}, \theta) \approx A_{\rm geom} P_{\mu}(E_{\nu}, \theta), \tag{26}$$

where $A_{\rm geom}$ is the geometric area of the detector, and $P_{\mu}(E_{\nu}) \propto \sigma_{\rm CC}(E_{\nu})$ is the probablity of muon production, which is detectable by IceCube. In the case of radio detectors, the probability of shower production depends on the total neutrino cross section $\sigma_{\rm tot}$, rather than just $\sigma_{\rm CC}$,

$$P_{\rm sh}(E_{\nu}, \theta) = L_{\rm det}(\theta) N_{\rm Av} \rho_{\rm ice} \sigma_{\rm tot}(E_{\nu}), \tag{27}$$

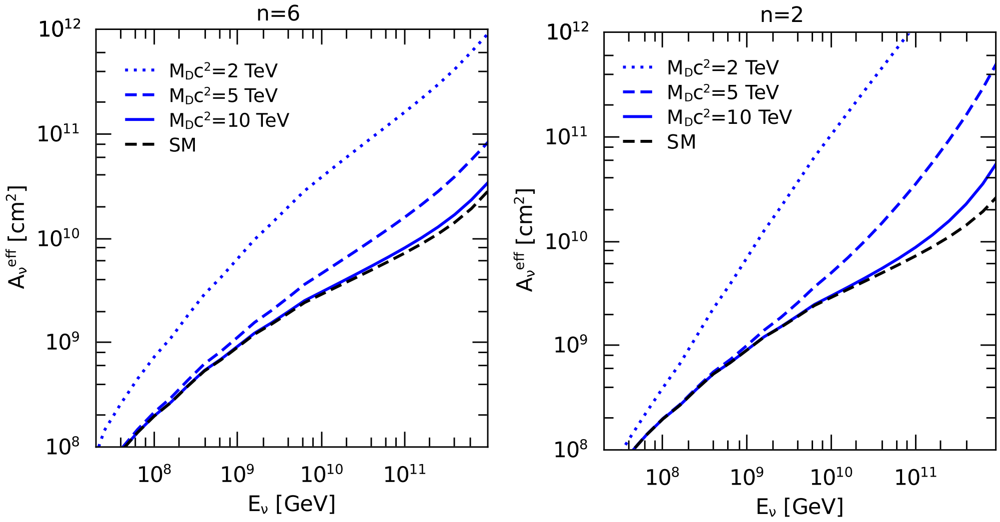


**Figure 6.** Neutrino effective areas estimated for the SM and for LED scenarios with $n = 6$ and $n = 2$ in the left and right panel, respectively.

where the density of ice is $\rho_{\rm ice} \approx 0.9\,{\rm g\,cm^{-3}}$ and $L_{\rm det}(\theta)$ is the length of the neutrino path through the detector, taken to be a cylinder with a 10 km radius and 2 km height as planned for ARA. Hence, we write the neutrino effective area as the following factorization:

$$A_\nu^{\rm eff}(E_\nu, \theta) = \varepsilon(E_\nu) A_{\rm geom}(L_{\rm det}(\theta) N_{\rm Av} \rho_{\rm ice} \sigma_{\rm tot}(E_\nu)), \tag{28}$$

where the function $\varepsilon(E_\nu)$ accounts for the detector response, and is here fixed using the effective area computed for ARA in [9]. Now, in an scenario with new physics such as LED, $\varepsilon(E_\nu)$ remains unchanged, but since the total neutrino cross section changes, the neutrino effective area will be affected. In figure 6, we plot the different effective areas averaged over $\theta$, obtained for different realizations of LED scenarios. The number of shower events per unit time per solid angle units, for the three neutrino flavors, is computed as

$$\frac{{\rm d}N_{\rm sh}(\theta)}{{\rm d}\Omega\,{\rm d}t} \simeq 3 \int_{E_{\rm min}} {\rm d}E_\nu \Phi_\nu(E_\nu, \theta) A_\nu^{\rm eff}(E_\nu, \theta). \tag{29}$$

For illustration, we plot this event number above $E_{\rm min} = 10^7$ GeV for the case of the dip model in figure 7, and a similar plot can be obtained in the case of the ankle model.

We can integrate the total number of shower events within different LED cases to better appreciate the difference with respect to the SM case. In figure 8 we show the total number of events expected for an incident cosmogenic flux given by the dip model, comparing the SM results to those obtained within LED scenarios with $n = 6$ and $n = 2$. The same, but for the ankle model incident flux, is shown in figure 9. In both figures, we chose the scale $M_D c^2 = 5$ TeV, for which the non-standard effects are visible only after 5–6 years of observation taking into account the corresponding statistical errors assuming Poisson-distributed events.

## 5. Discussion

We have studied the effects of LED on different predictions for the cosmogenic neutrino flux that would be incident on Earth under the assumption that the UHECR composition is

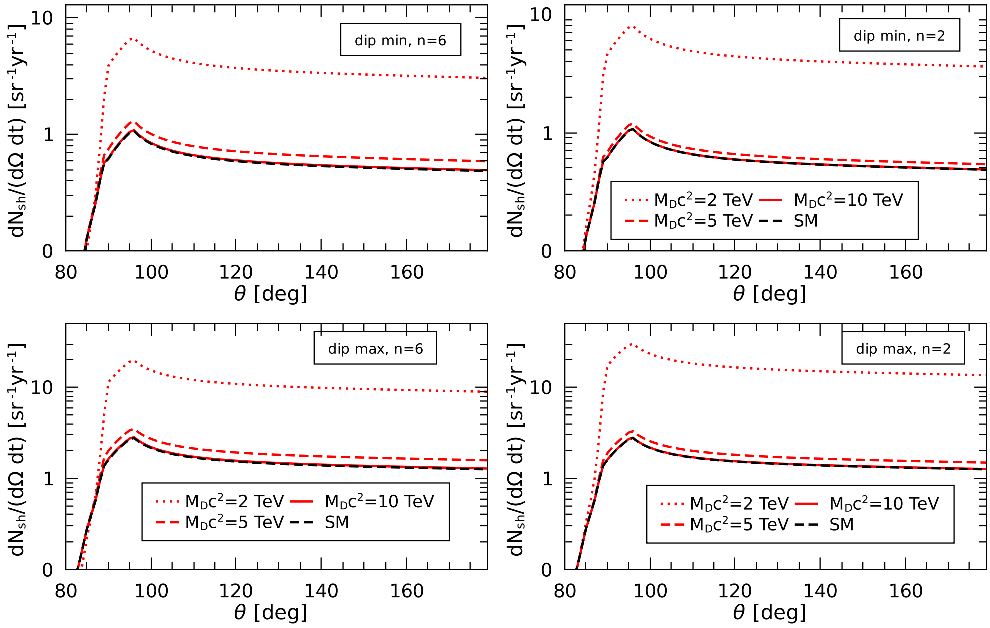


**Figure 7.** Neutrino shower events per year per solid angle units predicted for ARA using an incident cosmogenic flux given by the dip model, for the SM and for LED scenarios with $n = 6$ and $n = 2$ in the left and right panel, respectively.

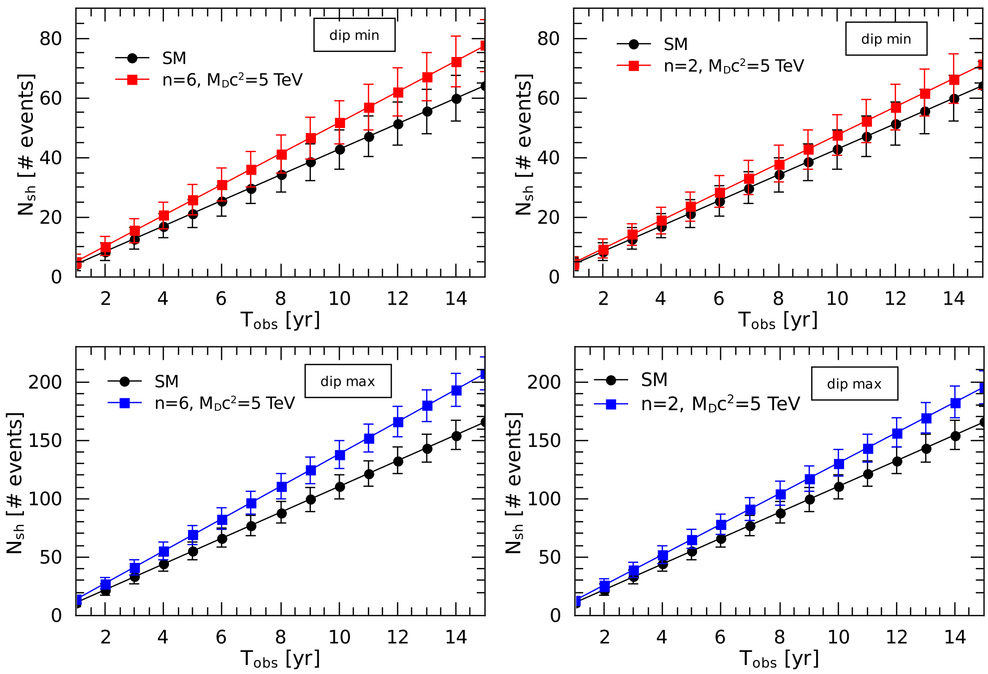


**Figure 8.** Neutrino shower events predicted for ARA using an incident cosmogenic flux given by the dip model. The SM results are compared to those obtained within LED scenarios with $n = 6$ and $n = 2$ in the left and right panel, respectively.

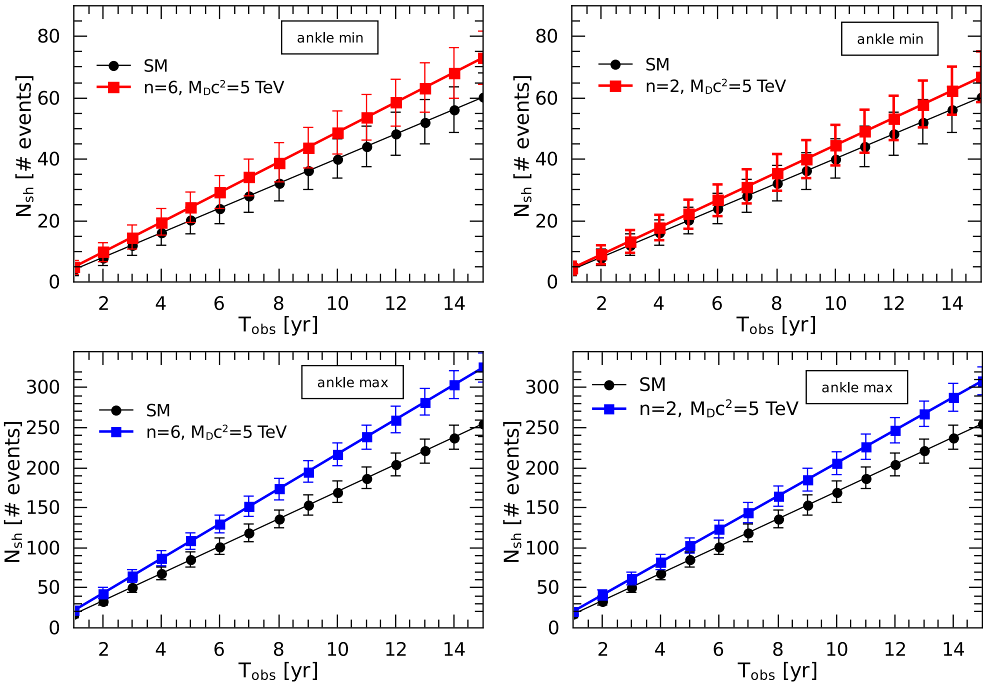


**Figure 9.** Neutrino shower events predicted for ARA using an incident cosmogenic flux given by the ankle model. The SM results are compared to those obtained within LED scenarios with $n = 6$ and $n = 2$ in the left and right panel, respectively.

dominated by protons. The main effect of LED models on the neutrino flux as they propagate through Earth comes from the exchange of virtual KK gravitons. This is a neutral current interaction that regenerates neutrinos by degrading their energy. Yet, this process can be responsible for a significant increase in the cross section, especially for $M_D c^2 \simeq 5$ TeV, and this is found to lead to an increased neutrino effective area in radio detectors such as ARA, since more showers are expected to be produced in comparison to the standard expectation. Taking this into account, we computed the number of shower events that would be expected in such a detector, and found that the effects of extra dimensions would result in an increased number of events as compared to what would be expected within the SM. For instance, for scale $M_D c^2 = 5$ TeV, these effects would be observable if the incoming cosmogenic flux were close to the maximum prediction in either of the two cases studied (the dip and the ankle model) after 5–6 years of observation. We note that in this case, the search for BH with $Mc^2 > 15$ TeV would be beyond the reach of the LHC, while at present the upper limit for the BH mass obtained by the CMS Collaboration is $Mc^2 < 3.8$–$5.3$ TeV [34].

It is important to note that an increased number of events in ARA as a result of LED effects would not be accompanied by an equally increased number of muon events produced by charged current interactions, and observable with IceCube. This is because the muon producing cross section is unchanged (e.g. equation (26)), since the greater effect would come from graviton exchange, which would generate showers as pointed out earlier [13]. Taking this into account, in the case that ARA detects a given event number corresponding to cosmogenic neutrinos, a corresponding measure of muon events in detectors such as IceCube and KM3NeT could help to distinguish an excess of shower events that could then be due to LED. The observation of the specific signatures corresponding to such events could be very useful at this point, in order to identify the occurrence of the non-standard interactions [14, 15]. Clearly, these effects would be significant for $M_D c^2 \lesssim 5$ TeV, while for higher values, LED effects would gradually become negligible on an ultrahigh energy neutrino flux arriving on Earth.

## Acknowledgments

We thank UNMdP (Argentina) and CONICET (Argentina) for their financial support through grants EXA 524/10 and PIP 100587, respectively.

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