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EXTRA DIMENSIONS IN INTERACTIONS OF COSMIC NEUTRINOS

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Theories with extra spacial dimensions are reviewed. A significance of high energy cosmic neutrinos for a detection of effects coming from extra dimensions is underlined. Neutrino telescopes and their sensitivity to a diffuse neutrino flux are describes.

1 Cosmic rays and high energy neutrinos

One of the main problems in astroparticle physics is the origin and nature of extragalactic cosmic rays (CRs). While the spectrum of the CRs can be measured up to very high energies (see Fig. 1), their origin remains unclear.

The protons (nuclei) and photons cannot provide full information on astrophysical "accelerators". The protons and nuclei with energies up to 10^{20} eV are deflected by the galactic magnetic fields, while the photons with energies higher than 1 TeV are absorbed when interacting with the cosmic gamma-ray background. The neutrino is a unique cosmic messenger, since it is a neutral weakly interacting particle. The astrophysical neutrinos point back to their source and travel long distances without interaction.

The expected fluxes of high energy cosmic neutrinos is low, as well as the flux of high energy cosmic rays. In what follows, we will be interested in cosmic particles with energies above 10^{14} eV.

Ultra-high energy protons interact with the cosmic microwave background (CMB) via resonance photo-production,

$$p + \gamma_{\mathrm{CMB}} \rightarrow \Delta^+ \rightarrow p\,\pi^0,\ n\pi^+ \,. \tag{1}$$

The threshold energy of the process is equal to $6 \cdot 10^{19}$ eV. This effect, known as the Greisen-Zatsepin-Kuzmin (GZK) cutoff [1], limits the origin of high energy protons to a distance of the order of 100 Mpc. Recent data from HiRes collaboration [2] and Auger collaborations [3] say in favor of the GZK cutoff.

It is assumed that accelerated protons produce charged pions when interacting with matter or radiation:

$$p + p \rightarrow NN + \mathrm{pions}, \quad p + \gamma \rightarrow n + \pi^+ \,, \tag{2}$$

either in their source (actice galactic nuclei, gamma-ray bursts) or in their travel to the Earth. Then the neutrinos are produced via decays:

$$\pi^+ \rightarrow \mu^+ + \nu_\mu, \quad \mu^+ \rightarrow e^+ + \nu_{\mathrm{e}} + \bar{\nu}_\mu \,. \tag{3}$$

The following flavor ratio results from (3): $\nu_{\mathrm{e}} : \nu_\mu : \nu_\tau = 1 : 2 : 0$. However, due to neutrino oscillations, the neutrino flux near the Earth will have equal fraction of all flavors: $\nu_{\mathrm{e}} : \nu_\mu : \nu_\tau = 1 : 1 : 1$.

Upper bound on diffuse neutrino flux $\Phi_\nu(E_\nu)$ was derived in [4]:

$$E_\nu\, \Phi_\nu(E_\nu) < 4 \cdot 10^{-8}\, \mathrm{GeV\, cm^{-1} c^{-1} sr^{-1}} \,. \tag{4}$$

Given GZK cutoff, there should exist so-called guaranteed (or GZK) neutrino flux [24]. As a result of pion decays (3) the neutrinos are produced. The predictions for the GZK flux vary from rather low neutrino flux to most optimistic one [6] which is close to the Waxman–Bahcall bound (4).

In contrast to"cosmic accelerators", in top-down models [7] the CRs are produced as a result of a decay of massive objects (topological defects, cosmic string, X-particles with masses $> 10^{22}$ eV). All these models predict the photon dominance in the CR spectrum. They are strongly constrained by the recent data on the photon fraction in CRs [8].

2 Theories with extra spacial dimensions

The consideration of the space-time with extra spacial dimensions is motivated by the string theory. The string theory is self-consistent only if $D = 10$, where D means the total number of dimensions. Since our world has (1+3) dimensions, six extra dimensions should be compactified.

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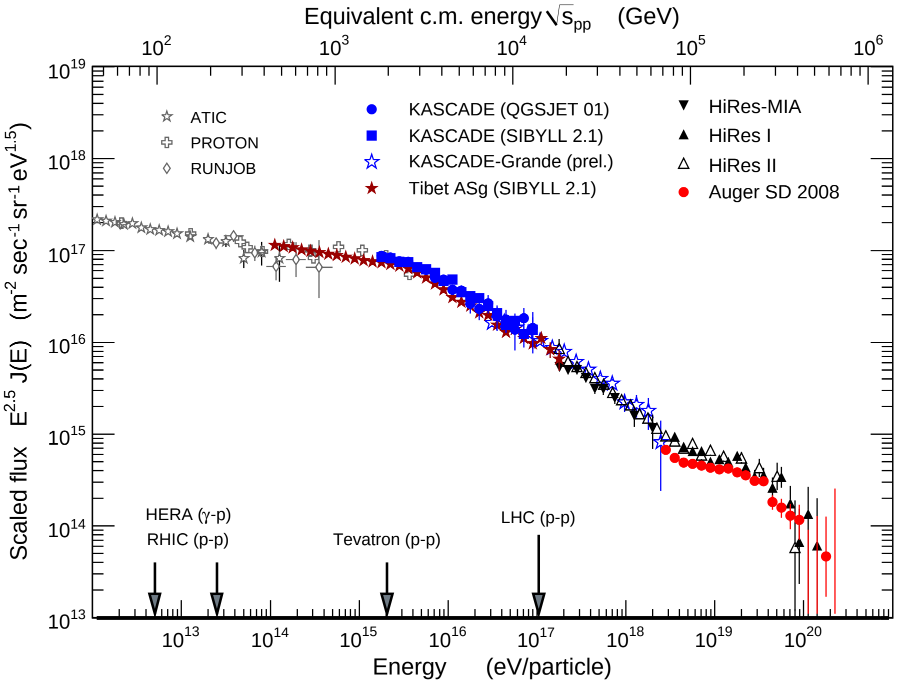

Figure 1. The CR spectrum.

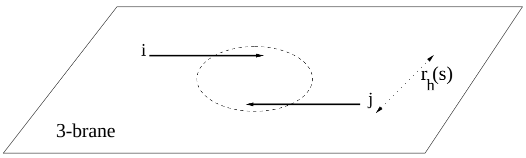

Figure 2. The black hole production.

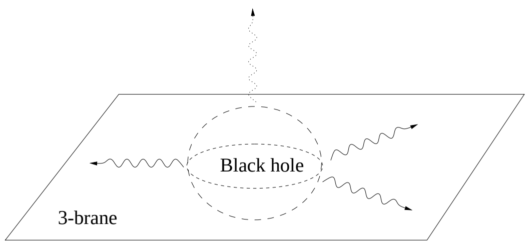

Figure 3. The black hole decay.

The large extra dimension scenario with the flat metric was proposed in [9] (ADD model). Background metric of the space-time looks like:

$$ds^2 = g_{\mu\nu}\, dx^\mu dx^\nu + \eta_{ab}\, dy^a dy^b \,, \tag{5}$$

where $\{x^\mu\}$ are the coordinates in four-dimensional space-time ($\mu = 0, 1, 2, 3$), and $\{y^a\}$ are the coordinate in $n = D - 4$ extra dimensions ($a, b = 1 \ldots n$).

Stating from D-dimensional action, one can derive the following hierarchy relation [9]:

$$\bar{M}_{\rm Pl}^2 = (2\pi R_c)^n \, \bar{M}_D^{2+n} \,. \tag{6}$$

Here $\bar{M}_{\rm Pl}$ is the (reduced) Planck mass, $\bar{M}_D$ is the (reduced) fundamental gravity scale, R_c is the size of extra dimensions. Given strong gravity in D dimensions, $\bar{M}_D \sim 1$ TeV, we get form (6) that $R_c = 10^{-3}$ cm, 10^{-7} cm, 10^{-12} cm, for $n = 2, 3, 6$, respectively. Note that $R_c = 10^8$ km for $n = 1$.

The Standard Model (SM) fields are assumed to be confined to a (1+3)-dimensional brane embedded into a $(4 + n)$-dimensional space-time (bulk) in which the gravity lives. From the point of view of 4-dimensional observer, D-dimensional massless graviton looks like an infinite set of Kaluza-Klein (KK) modes with the masses $m_k \sim k/R_c$ ($k = 0, 1, \ldots$). The coupling constant of both massless and massive gravitons with the SM fields is very small, $G_N = 1/M_D^2$. Nevertheless, cross sections for the production of KK gravitons appear to be proportional to $(\sqrt{s})^n/M_D^{2+n}$ where $\sqrt{s}$ is the invariant collision energy.

The gravitons in the ADD model are massive stable spin-2 particles. Experimental signature is an imbalance in missing mass of final states with a continuous mass distribution.

The hierarchy problem, i.e. unnaturally large ratio of the gravity scale ($\sim 10^{19}$ GeV) to the electroweak scale ($\sim 10^2$ GeV) is one of the most important problem of the modern physics. This problem is solved in the ADD scenario by introducing the new large scale R_c (6). The model which does solve the hierarchy problem most economically is the Randall-Sundrum (RS) model with a single extra dimensions and warped background metric [10]:

$$ds^2 = e^{2\kappa(\pi r - |y|)}\,\eta_{\mu\nu}\,dx^\mu dx^\nu + dy^2\,. \tag{7}$$

Here $y = r\,\theta$ $(-\pi \leq \theta \leq \pi)$, r is the radius of the extra dimension. The parameter κ defines the scalar curvature in five dimensions. Note that the points (x^μ, y) and $(x^\mu, -y)$ are identified, and the periodicity condition, $(x^\mu, y) = (x_\mu, y + 2\pi r_c)$, is imposed. The tensor $\eta_{\mu\nu}$ is the Minkowski metric.

It is assumed that there are two 3-dimensional branes with equal and opposite tensions located at the points $y = 0$ (called the Plank brane) and $y = \pi r_c$ (referred to as the TeV brane). All SM fields are confined to the TeV brane, while the gravity propagates in five dimensions. The following relation between the 4-dimensional (reduced) Planck mass and (reduced) gravity scale in five dimensions can be derived:

$$\bar{M}_{\mathrm{Pl}}^2 = \frac{\bar{M}_5^3}{\kappa}\left(e^{2\pi\kappa r} - 1\right)\,. \tag{8}$$

The masses of the Kaluza-Klein (KK) graviton excitations are proportional to the curvature parameter κ: $m_k = x_k \kappa$ $(k = 1, 2 \ldots)$ where x_k are zeros of the Bessel function $J_1(x)$. The coupling of the massive graviton to the SM fields is proportional to TeV^{-1}.

Effects related with the extra dimension were searched for at the Tevatron collider in the processes:

$$p + \bar{p} \to \mathrm{jet} + \not{E}_\perp\,, \qquad p + \bar{p} \to \gamma + \not{E}_\perp. \tag{9}$$

No deviation from the SM were seen, and the region $\bar{M}_D < 1$ TeV is now excluded by the data. The RS model with the small curvature was checked by DELPHI collaboration. The lower limit obtained is $\bar{M}_5 > 0.92$ TeV.

3 Production of multidimensional black holes

When the impact parameter of colliding particles becomes smaller than the Schwarzschild radius [12],

$$R_{\mathrm{S}}(\sqrt{s}) = \bar{M}_D^{-1}\,(\sqrt{s}/\bar{M}_D)^{1/(n+1)}\,, \tag{10}$$

the black hole (BH) should be produced (see Fig. 2). The cross section of the BH production is given by the geometric formula [13]:

$$\sigma(\sqrt{s}) \simeq \pi\, R_{\mathrm{S}}^2(\sqrt{s})\,. \tag{11}$$

It is assumed that $R_{\mathrm{S}}(M_{\mathrm{BH}}) \ll R_c$, where M_{BH} is the mass of the BH. The semiclassical description of the BH production is valid provided $M_{\mathrm{BH}} > M_D$.

The cross section for the neutrino-nucleon scattering is given by more complicated formula:

$$\sigma_{\nu N \to \mathrm{BH}}(\sqrt{s}) = \sum_{a=q,\bar{q},g} \int_{x_{\min}}^{1} dx_a\, f_a(x_a)\, \sigma_{\nu a \to \mathrm{BH}}(x_a\sqrt{s})\,, \tag{12}$$

where $f_a(x_a)$ is the distribution function of the parton of the type a, and $x_{\min} = M_{\mathrm{BH}}/\sqrt{s}$.

The lifetime of the BH is $\sim 10^{-26}$ c. There are several stages of the BH decay, the most important one is the Schwarzschild stage. At this stage the BH emits particles as a black body with the Hawking temperature $T_{\mathrm{H}} = (n+1)/(4\pi R_{\mathrm{S}})$ [14]. Note that the BH decays predominantly into the SM particles [15] (see Fig. 3).

The experimental signatures of BH decay are very distinct: the large multiplicity, flavor blindness, direct leptons and photons with energies ~ 100 GeV. The expected ratio of the hadronic decay mode to leptonic mode is $5:1$.

4 Neutrino telescopes

The neutrino astronomy require the huge size to record a sufficient number of neutrino events. The detection technique is the observation of the Cherenkov light induced by interactions of cosmic neutrinos when traversing natural media such the ice of the South Pole or the water of deep oceans or lakes.

The AMANDA telescope, deployed in the ice of the South Pole [16] (Fig. 4), has been taking data since more than a decade. Its successor, IceCube telescope [17] (Fig. 4), is operating and it will be completed in the end of 2011. The ice act as a shield for down-going muons. On the other hand, it is transparent to the Cherenkov light emitted by the shower or up-going muons. The latter come from neutrinos traversing the Earth.

The IceCube is optimized for detection of the muons induced by muonic neutrinos:

$$\nu_\mu + N \to \mu + X\,. \tag{13}$$

The number of the neutrino events for the period T is given by

$$N_{\mathrm{ev}} = 2\pi\, A_{\mathrm{eff}}\, T \int dE_\nu \int d\cos\theta_z \Phi_\nu(E_\nu)\, P_{\nu\to\mu}(E_\nu, \cos\theta_z)\,, \tag{14}$$

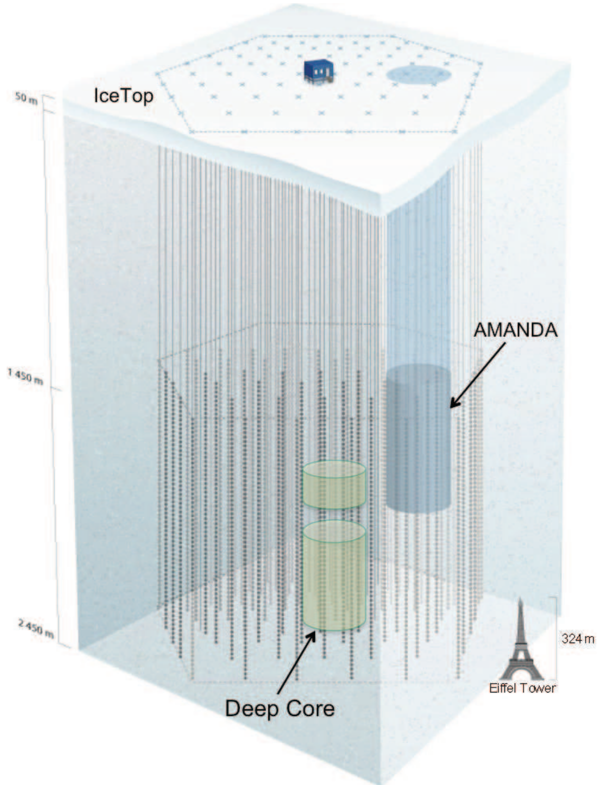

Figure 4. The IceCube neutrino telescope.

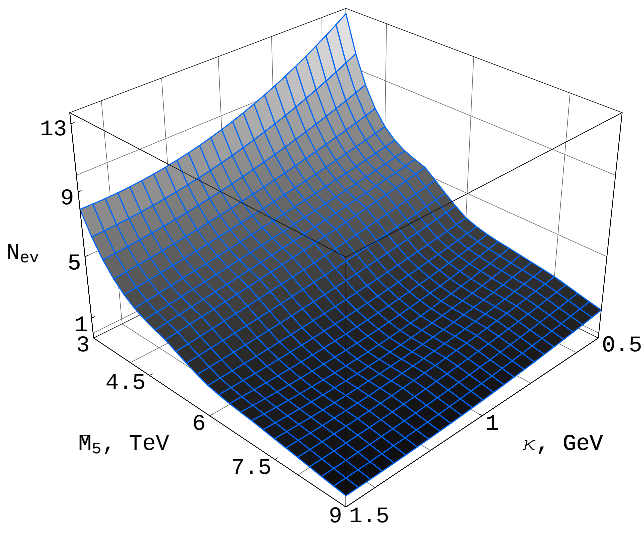

Figure 5. The number of inclined events at the Auger detector (RS scenario with the small curvature).

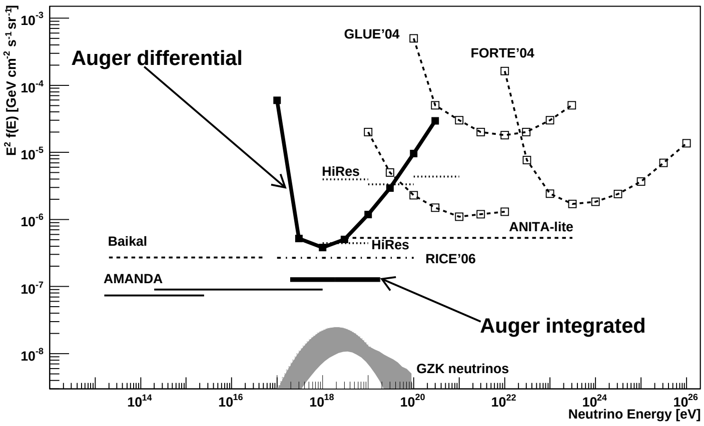

Figure 6. The experimental limits on the diffuse neutrino flux (converted to a single flavor).

where $A_{eff} = 1$ km^2 is the effective area of the detector, θ_z is zenith angle, $P_{\nu\to\mu}$ describes detection probability.

The electronic neutrino initiates an electromagnetic cascade via the process $\nu_{\rm e} + N \to {\rm e} + X$. The high energy tau neutrinos can produce so-called double-bang events [18].

In its full set-up, the IceCube telescope will be sensitive to the following diffuse neutrino flux ($2 \cdot 10^{14}$ eV $<$ $E_\nu < 10^{18}$ eV):

$$E_\nu\, \Phi_\nu(E_\nu) < 1.5 \cdot 10^{-8}\, \mathrm{GeV\, cm^{-1} c^{-1} sr^{-1}}\,. \tag{15}$$

The Baikal neutrino telescope [19] operates since 1993 at the depth 1 km. The modern detector Baikal NT200+ has the effective volume $\sim 10^7$ m^3. There are plans to enlarge it up to 0.4 km^3 - 1.0 km^3. In the Mediterranean Sea, the ANTARES telescope [20] is taking data since 2008 in its full configuration. The first project in the Mediterranean Sea was the NESTOR detector [21] that started in 1989. It is located close to Pylos at the depth 4000 km. The NEMO projects [22] stated in 1998 is closed to Capo Passero with the depth of 3500 km. However, the low expected fluxes of the cosmic neutrinos call for a km^3-scale detector under the see. Such a telescope, KM3Net [23], was initiated in 2008. Its construction is expected to start by 2011.

5 Inclined air showers at the Auger Observatory

In order to discriminate neutrino induced events from events initiated by protons, nuclei or photons, it was suggested to search for quasi-horizontal (inclined) events with $\theta_z > 70^\circ$ [24] (see also [25]).

High energy cosmic particles produce extensive air showers (EASs) in the atmosphere. For the inclined events induced by the protons, only muonic component of the shower reaches the ground detector, that enable to select high energy neutrino events at the Auger Observatory [26]. The number of inclined events which can be detected by the Auger ground array is given by

$$\frac{dN_{\rm ev}}{dt} = \int_{E_{\rm th}}^{E_{\rm max}} dE_\nu \int_0^1 dy\, \theta(E_{\rm sh} - E_{\rm th})\, \frac{d\sigma(E_\nu)}{dy}\, \Phi(E_\nu)\, A_{\rm eff}(E_{\rm sh}, E_\nu)\;, \tag{16}$$

where $E_{\rm sh} = yE_\nu$ is the shower energy. Effective aperture of the detector, $A_{\rm eff}(E_{\rm sh})$, is defined by its geometrical size, neutrino attenuation factor and detector efficiency. As one can see from (16), the number of EASs rises with the increase of neutrino-nucleon cross section $\sigma_{\nu N}(E_\nu)$ and neutrino flux $\Phi(E_\nu)$.

In Fig. 5 the expected number of the neutrino events in the RS scenario with the small curvature is presented [27]. The other predictions for the inclined event rate at the Auger detector can be found in [28].

There exist interesting events induced by so-called Earth-skimming tau neutrinos [29]. The up-going tau neutrinos turn into tau leptons in the Earth's crust. Then these tau leptons with energy $> 10^{19}$ eV can cross the crust and produce a shower in the atmosphere at altitude of 0-2500 m.

In contrary to the inclined events, the number of EASs initiated by Earth-skimming tau neutrinos decreases with the increase of $\sigma_{\nu N}(E_\nu)$. Thus, the simultaneously determining the cosmic neutrino flux and high energy neutrino cross section is possible by comparing the inclined and Earth-skimming events.

The EAS can be also induced by decay products of the BH. The estimates show that the BH production cross sections dominate SM neutrino-nucleon cross section at neutrino energy $> 10^{15}$ eV (10^{16} eV) [30].

Up to now, no signals from cosmic neutrinos were seen, but only upper limits on the diffuse neutrino flux were obtained by different collaborations [31] (see Fig. 6). Nevertheless, the expectation is that future 1 km^3-size IceCube and KM3Net telescopes, as well as Auger Observatory will be able to detect the cosmic neutrinos in a few years.

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