Predictions of Ultra-High Energy Neutrino Fluxes

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Abstract

Recent discovery of the cutoff in the spectrum of Ultra-High Energy Cosmic Rays (UHECR) point to the extragalactic astrophysical origin of those cosmic rays. The only neutrino flux expected at highest energy come from the energy losses of protons and nuclei during propagation from sources to the Earth. Here we discuss uncertainties of this flux and possibilities of future experiments to discover it. We also briefly review possible Galactic and extragalactic point sources of neutrinos.

Key words: UHECR, neutrino

1. Introduction

Existence of cutoff in the Ultra-High Energy Cosmic Ray (UHECR) spectrum was subject of debates since it was predicted by K. Greisen, G. T. Zatsepin and V. A. Kuzmin in 1966 and called the GZK cutoff [1].

UHECR protons with energies above the threshold

$$E_{th} = \frac{2M_N m_\pi + m_\pi^2}{4\epsilon_{CMB}} \approx 4 \times 10^{19} \text{ eV} \qquad (1)$$

lose energy in the interactions with Cosmic Microwave Background photons and produce pions due to reactions:

$$P + \gamma_{CMB} \to P + \pi^0 + \sum_i \pi_i$$
$$P + \gamma_{CMB} \to N + \pi^+ + \sum_i \pi_i \qquad (2)$$

They also lose energy in the pair production reaction:

$$P + \gamma_{CMB} \to P + e^+ + e^- \qquad (3)$$

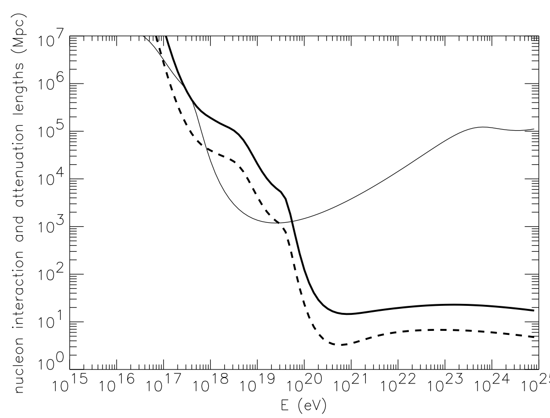

Fig. 1. Attenuation of protons as function of energy from review [2]. Dashed line is proton interaction length for pion production Eq. (2). Thick solid line is corresponding attenuation length. This solid line is for the e^+e^- pair production process, Eq. (3).

This process dominates at the energies below the pion production threshold, Eq. (1).

From Fig. 1 one can see that protons with energies above $E > 10^{20}$ eV can come only from nearby objects, $R < 100$ Mpc. Protons produced at the larger distance would lose energy and arrive at detector with $E < 10^{20}$ eV. Due to the fact that total

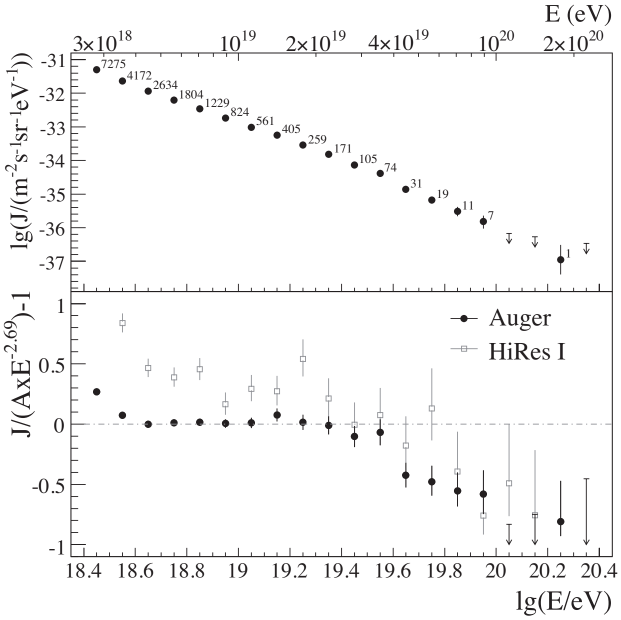

Fig. 2. Spectrum of UHECR measured by AUGER (tot) and comparison between AUGER and HiRes (bottom) from ref. [4]. Both experiments see cutoff in the spectrum with more then 5σ significance.

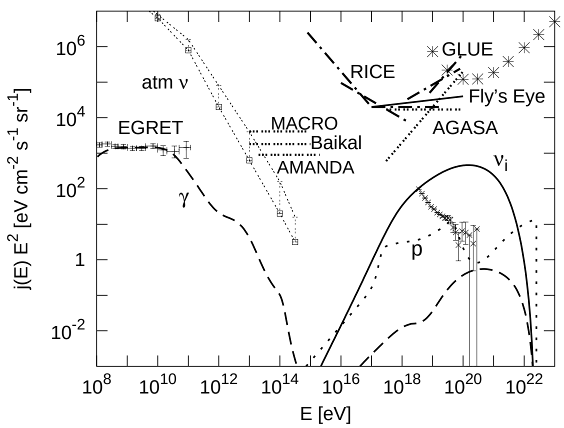

Fig. 3. Connection between UHECR proton flux, secondary photon and neutrino fluxes from ref. [9]. Part of proton energy converted through pion production processes to neutrinos and photons. Maximal photon flux saturates EGRET measurement [10,11]

Universe size is $R_U = 5000$ Mpc, one expect strong cutoff in the spectrum of UHECR above threshold Eq. (1).

Cutoff in the UHECR spectrum was discovered by HiRes experiment with 5σ significance [3] and was recently independently confirmed by AUGER experiment with 6σ significance [4]. Experimental data for the UHECR spectrum at highest energies are shown in the Fig. 1. Upper panel show flux measured by the Pierre Auger Observatory during construction period. Lower panel show both fluxes measured by the HiRes and the AUGER experiments multiplied by $E^{2.6}$. One can clearly see from this figure that at $E > 4 \times 10^{19}$ eV (19.6 in log scale) UHECR flux is well below horizontal dash-dotted line $\sim 1/E^{2.6}$.

Existence of cutoff in the UHECR spectrum points to the astrophysical origin of the UHE cosmic rays. At the scales $R < 100$ Mpc the Large Scale Structure (LSS) of the Universe is not uniform. Thus, in the case extragalactic magnetic fields are not strong enough to randomize arrival directions of the cosmic rays one should see anisotropy of the arrival directions connected to existing large scale structure. Such anisotropy was first seen in the combined data of AGASA, HiRes and other experiments at $E >> 4 \times 10^{19}$ [5] with 3σ significance and also later was found in the first data of AUGER experiment [6].

Finally, in November 2007 AUGER published results of blind test in which anisotropy was seen at $E > 57$ EeV in correlation with preselected catalog of nearby AGN's with significance $\sim 10^{-3}$ [7]. This anisotropy clearly points to origin of UHECR in extragalactic sources. From other side above results do not have enough statistical power to figure out exact class of the objects – sources of the UHECR, because all off them correlate with the same Large Scale Structures. This is the subject of the future investigation.

Existence of the GZK cutoff guarantee secondary neutrino flux coming from the UHECR protons and nuclei. This flux we will discuss in the next section. From other side discovery of cutoff in the UHECR spectrum stopped wide discussion of exotic top-down models (for review see ref. [2]). For high energy neutrino physics this mean absence of very high neutrino fluxes and additional experimental challenge.

All protons produced at distances $R > 100$ Mpc would lose energy in pion production. In turn neutral pions will produce gamma-rays $\pi^0 \to 2\gamma$ and charged pions will produce positrons and neutrinos: $\pi^+ \to \nu_\mu + e^+ + \nu_\mu + \overline{\nu}_e$. Neutrinos would oscillate on cosmological distance and half of muon neutrinos will be converted to tau neutrinos. Finally, one expect similar flux of all neutrino flavors. $N_{\nu_e} : N_{\nu_\mu} : N_{\nu_\tau} = 1 : 1 : 1$. Existence of neutrinos from GZK

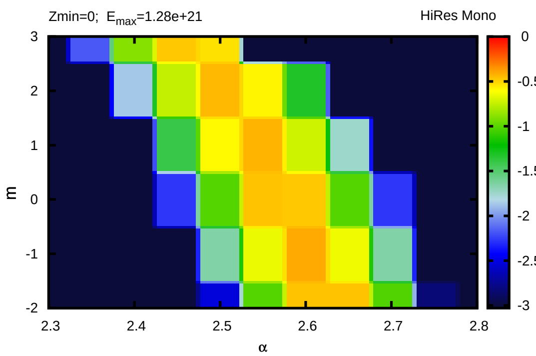

Fig. 4. The proton flux power law index and the evolution index are degenerated and their combination always perfectly fits total UHECR flux for $E > 2 \times 10^{18}$ eV [15].

mechanism was already discussed in 1969 in refs. [8].

Ultra-high energy photons would also interact with CMB photons and other backgrounds and cascade down to multi-GeV energies, where Universe is transparent to photons. Due to the pion symmetry total amount of energy deposited in the neutrinos expected to be of the same order as the total amount of energy in the GeV photons. This together with normalization of the proton flux to one measured by UHECR experiments give connection between cosmic ray, neutrino and photon fluxes. In the Fig. 3 we show this connection as result of numerical calculation of propagation of protons and production of secondary photons and neutrinos from ref. [9]. Maximal photon flux restricted by EGRET measurement of diffuse gamma-ray flux in GeV region. Same measurement restrict diffuse neutrino flux from above. This is very important upper bound which will be revised soon by GLAST experiment, which has two orders of magnitude better sensitivity [12].

Connection between cosmic ray, neutrino and gamma-ray fluxes allows us to predict UHE neutrino flux using existing data for cosmic ray and gamma-ray fluxes. In the next Section we will discuss diffuse flux of neutrinos and in Section 3 flux from point sources.

2. Predictions for diffuse flux neutrinos

In order to predict diffuse neutrino flux at the highest energies we have to specify the cosmic ray model. In this section we will assume that most of

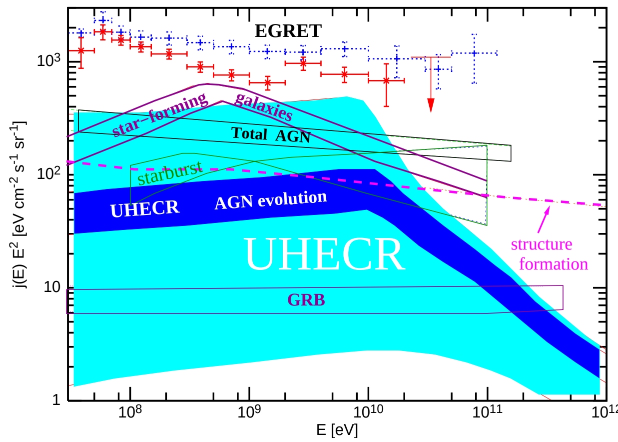

Fig. 5. The possible range of UHECR induced cascade fluxes (light shaded band) compared to estimated $\gamma-$ray fluxes by different mechanisms from ref. [17]. Total extragalactic $\gamma-$ray background was measured by EGRET[10,11] and will be revised soon by GLAST [12].

UHECR at the highest energies are protons. In this case proton flux after propagation can be normalized on the measured cosmic ray flux.

Usually proton flux of one source parametrized as the following:

$$F(E) = \frac{A}{E^{\alpha}} \qquad E_{min} < E < E_{max} \ , \tag{4}$$

where α is universal power law constant, typically $\alpha = 2-2.2$ in shock acceleration. A is normalization and $E_{min} < E < E_{max}$ is energy range. In most of cases maximum energy assumed to be constant. However if sources are not identical, it should vary from source to source and it's distribution is:

$$F(E_{max}) = \frac{B}{E_{max}^{\beta}} \qquad \beta = \alpha_0 - \alpha + 1 \ . \tag{5}$$

Here α_0 is universal constant connected to observed cosmic ray flux. So one can define β for given α and α_0 . Fortunately, for the study of total diffuse neutrino flux one can integrate out Eq. (6) and use only Eq.(4) with effective $\alpha = \alpha_0$ [13]. Below for diffuse sources we will always take $\alpha = \alpha_0$.

Finally distribution of sources can be parametrized as following:

$$N = N_0(1+z)^{3+m} \qquad z_{min} < z < z_{max} \ . \tag{6}$$

Here $m = 0$ corresponds to uniform distribution if sources with equal luminosity.

Same cosmic ray spectrum can be reproduced with different combinations of above parameters. In particular in Fig. 4 it is shown that HiRes spectrum

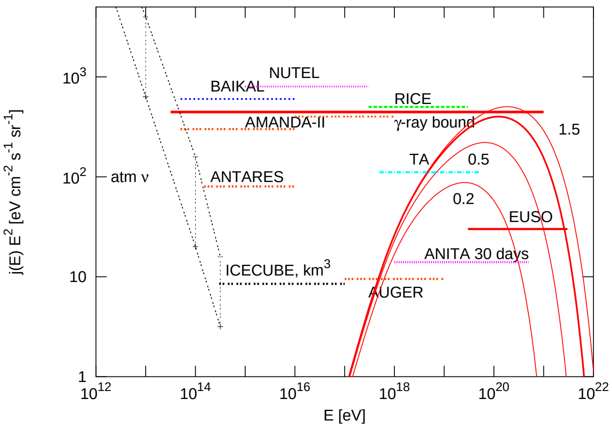

Fig. 6. Maximal neutrino flux as function of energy and sensitivities of experiments from ref. [18].

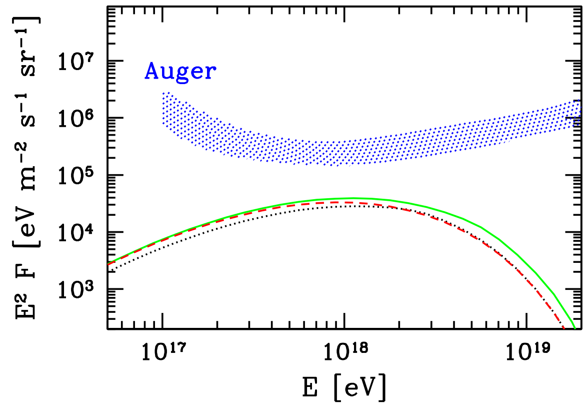

Fig. 7. Minimal neutrino flux as function of energy from ref. [19].

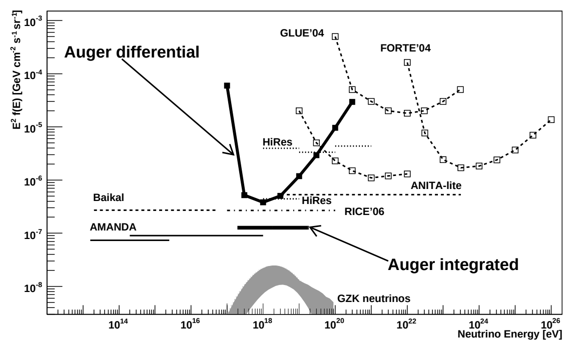

Fig. 8. Recent limits on the diffuse flux of neutrinos from ref. [20].

can be fitted with different combinations of m and α for all energies $E > 2 \times 10^{18}$ eV. Note that at the lower energies $E < 10^{18}$ eV cosmic rays diffuse in the extragalactic and galactic magnetic fields and resulting extragalactic proton flux will be strongly affected by this [16].

Dependence of the diffused neutrino flux from the key parameters α, m, E_{max} and z_{max} was studied in details in ref. [14]. All of those parameters are very important for the final value of diffused neutrino and GeV photon fluxes. Parameter E_{max} is very important if $\alpha \leq 2$. For $\alpha \sim 2.5$ results weakly depends on E_{max}. In Fig. 5 we with light shaded band we plot possible range of diffused gamma-ray fluxes allowed by fit to cosmic ray flux at highest energies. Dark shaded band corresponds to assumption that luminosity of cosmic ray sources similar to one of AGN's. One can see that prediction is more certain in this case, because it give very strict connection between α, m and z_{max}. If most of diffuse flux measured by EGRET come from unresolved point sources, real diffused flux can be much smaller. GLAST experiment in near future can establish new upper limit for flux of gamma-rays coming from cosmic rays, and as result new upper limit on the diffuse neutrino flux.

Another important parameter of diffuse neutrino flux is minimal energy of cosmic rays at which one want to fit UHECR spectrum, E_{min} in Eq. (4). Value of this parameter depends on the assumption if dip in the spectrum at $E \sim 3 \times 10^{18}$ eV is due to pair production of protons of due to change from galactic to extragalactic cosmic rays. In last case one can still fit only highest part of observed spectrum with very small values of $\alpha < 1.5$ and get very high diffuse neutrino flux, which is shown at Fig. 6 for different maximum energy. Line with note 0.2 will correspond to $E_{max} = 10^{21}$ eV.

Contrary, fit of UHECR spectrum with extragalactic protons up to energies $E_{min} = 10^{18}$ eV leads to larger values of α and smaller m, see Fig. 4. As result diffuse neutrino flux can be orders of magnitude smaller, see Fig. 7.

Let us compare above theoretical predictions with present day experimental limits. In the Fig. 8 AUGER limit on the diffuse flux of tau neutrinos is shown with thick solid line, ref. [20]. Assuming an E_ν^{-2} differential energy spectrum the limit set at 90 % C.L. is $E_\nu^2 \mathrm{d}N_{\nu_\tau}/\mathrm{d}E_\nu < 130$ eV cm^{-2} s^{-1} sr^{-1} in the energy range 2×10^{17}eV $< E_\nu < 2 \times 10^{19}$

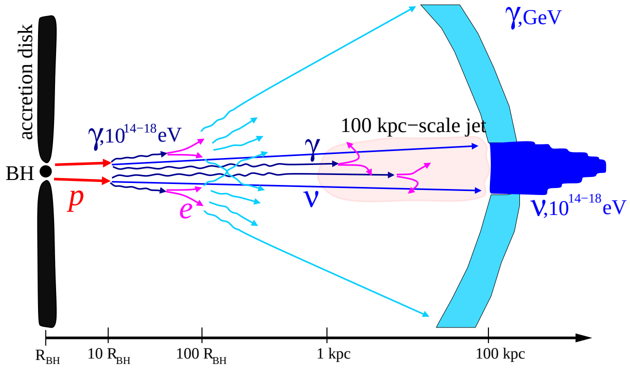

Fig. 9. Possibility of enhanced neutrino flux due to small opening angle from ref. [22].

eV [20]. This limit is comparable to present limits from AMANDA-II experiment at highest energies. In this figure theoretical predictions for GZK neutrino flux lie in between of minimal flux from Fig. 7 and maximal flux from Fig. 6. Maximal neutrino flux from Fig. 6 is very close to present experimental upper limits. Thus future measurements both by AUGER and ICECUBE will start to probe interesting region of theoretical expectations for diffuse neutrino fluxes. Also ANITA and other radio experiments have possibility to measure diffuse neutrinos flux.

Finally, let us note two important points concerning searches of the diffuse neutrino flux at the highest energies. First, minimal diffuse neutrino flux shown in the Fig. 7 is minimal under assumption that all UHECR are protons. In case some of UHECR are nuclei this flux can be reduced because nuclei usually photo-disintegrated before they produce significant amount of pions. Also due to the fact that models with nuclei have much more free parameters, one can not strictly predict diffuse neutrino flux in this case. In any case one can expect flux even lower then in the Fig. 7.

Second, one does not need at all in angular resolution to measure diffuse neutrino flux. Contrary as good as possible energy resolution will help to distinguish between different models. Thus measuring of "cascades" at km^3 detectors would be the method for measuring diffuse neutrino flux underwater of under ice.

3. Neutrinos from point sources

Neutrinos can be created in the astrophysical sources both during acceleration and propagation of protons and nuclei inside of those sources in $p+\gamma$ or $p+p$ collisions. In both cases produced pions will decay on neutrinos and photons and resulting total energy in neutrinos can be estimated from total energy in high energy photons.

Usually it is assumed that TeV gamma-ray sources are good candidates for neutrino sources with similar flux. In case of $p+\gamma$ it is usually not so. Indeed, protons would produce pions in the gamma-ray background with density n_γ and size of the reason R if:

$$\sigma_{P\gamma} n_{back} R > 1 \ . \tag{7}$$

At the same time TeV gamma-rays would escape from the same region if

$$\sigma_{\gamma_{TeV}\gamma} n_{back} R < 1 \ . \tag{8}$$

Thus one just need to compare cross sections of both processes. $\sigma_{P\gamma} = 6\times 10^{-28}\mathrm{cm}^2$ while $\sigma_{\gamma_{TeV}\gamma} = 6.7\times 10^{-25} log(s)/s \ \mathrm{cm}^2$, where $s=(p_1+p_2)_\mu(p_1+p_2)^\mu$ is s-invariant.. In order neutrinos produced and TeV gamma-rays escape from the same region one need $\sigma_{P\gamma} > \sigma_{\gamma_{TeV}\gamma}$. This can happen only in Klein-Nishina limit, $s > 10^3$, i.e. when background is x-rays, which is rare and rather impossible in most of cases. For usual optical and infrared background photons TeV gamma-rays would not escape from neutrino production region.

There are two ways out of this problem. First, one can produce multi-GeV gamma-rays for which reaction Eq.(8) forbidden below threshold. Second, one can produce first very high energy gamma-rays with $s > 10^3$ and then they would produce secondary gamma-rays in spatially different region. Such possibilities discussed in the model of kpc-scale jet [21]. Production of neutrinos in this model was studied in the ref. [22]. In this model protons are accelerated to high energies near supermassive black hole in the active galaxy, see Fig. 9. Then protons produce both neutrinos and photons in the interactions with optical photons from hot accretion disk. Neutrinos escape in the forward direction with compact jet of the degree size, while secondary GeV gamma-rays can be redistributed with much wider region due to deflections of secondary electrons and positrons in the electromagnetic cascade. At the same time 10^{17} eV gamma-rays escape in the forward direction and produce large kpc-scale jets.

As shown in the Fig. 9 neutrino source can be much more compact as compared to gamma-ray source. As result one would see fewer neutrino sources compared to gamma-ray sources, but those

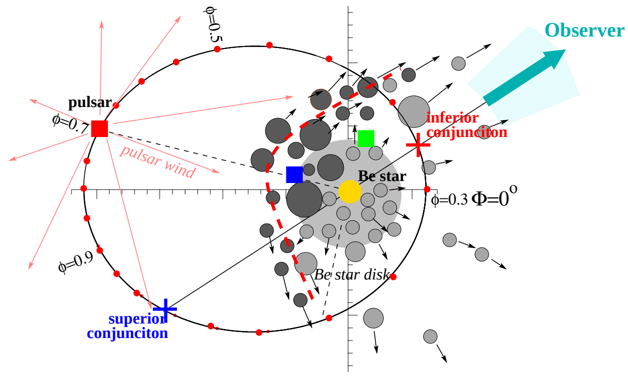

Fig. 10. Production of gamma-rays in binary system LS I+61 303 from ref. [23].

sources would be much brighter! Also in near future GLAST experiments can discover thousands of Gev sources, most powerful of which can be good candidates for point neutrino sources.

Completely different possibility to produce neutrinos and TeV gamma-rays at the same time come from proton-proton collisions. In this case both cross sections are of the same order of magnitude and TeV gamma-rays can escape from the neutrino production region. The only problem is that large proton background is relatively rare phenomenon.

One possibility to have efficient proton-proton collisions give binary systems. In particular TeV gamma-rays was registered from binary LS I+61 303, which consist from pulsar and accompanying nearby Be star, see Fig. 10. In most of astrophysical TeV gamma-rays usually produced by electrons, as in the model of ref. [23]. However, either part or all TeV radiation can be produced by proton-proton collisions as well. In last case if the neutrino flux is of the same order as the TeV photon flux one expect 0.3 neutrino events per year in the ICECUBE experiment [24].

Now let us consider future Galactic Super Novae at 10 kpc distance. In this case high energy neutrino flux can be produced at early stages after shock came out of the star [25] with amount 100 events per km^3 detector and during first year after explosion with amount 1000 events per km^3 detector [26]. Also those high energy neutrinos will allow to see SN even from wrong side of detector due to high signal over background ratio [27].

Finally, let us mention that angular resolution of experiments is most important parameter for all searches of point sources. The main problem of such searches is expected low statistics as in the case of the binary LS I+61 303 even for the km^3 size detectors. So it is very important to reduce background due to as good as possible angular resolution. From other side uncertainties in the unknown astrophysical parameters don't allow to predict exact shape of the neutrino flux from point sources, which mean that one does not need in the exact knowledge of the neutrino energy. Thus standard measurements of muon neutrinos with as good as possible angular resolution would serve to study point neutrino sources.

4. Conclusions

In this paper we reviewed theoretical predictions of diffuse Ultra-High Energy neutrino fluxes and fluxes of point sources.

Recent observation of GZK cutoff in the spectrum of UHECR and their anisotropy indicate that they come from extragalactic astrophysical sources. This fact disfavor exotic top-down models. For measurement of the diffuse neutrino fluxes this mean one can expect only secondary diffuse neutrino flux from UHECR protons. This flux is guaranteed, but its level strongly depends on unknown parameters, such as acceleration spectrum, luminosity of UHECR sources and fraction of protons in the total UHECR flux. Some of those parameter can be constrained in near future by GLAST satellite and the cosmic ray experiments.

In the Section 2 we discussed above uncertainties and gave examples of possible high and now GZK neutrino fluxes. In the Section 3 we considered several examples of Galactic neutrino sources and indicate large uncertainties in predictions of neutrino fluxes coming from many unknown parameters.

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