Predictions of Ultra-High Energy Neutrino Fluxes

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Abstract

The recent discovery of the cutoff in the spectrum of Ultra-High Energy Cosmic Rays points to an extragalactic astrophysical origin of these cosmic rays. The neutrino flux at the highest energy is expected to come only from energy losses of protons and nuclei during propagation from their sources to the Earth. In this paper we discuss the uncertainties on this flux together with the possibilities of future experiments to discover it. We also briefly review possible Galactic and extragalactic point sources of neutrinos.

1. Introduction

The existence of a cutoff (the GZK cutoff) in the Ultra-High Energy Cosmic Ray (UHECR) spectrum has been the subject of debate since it was predicted by K. Greisen, G. T. Zatsepin and V. A. Kuzmin in 1966 [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 interactions with Cosmic Microwave Background (CMB) photons and produce pions due to the reactions:

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

They also lose energy in the pair production reactions:

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

This process dominates at the energies below the pion production threshold of 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 larger distances would lose energy and arrive at the detector with $E < 10^{20}$ eV. Due to the fact that the total Universe size is $R_U = 5000$ Mpc, one expects a strong cutoff in the UHECR spectrum above the threshold of Eq. (1).

The cutoff in the UHECR spectrum was discovered by the HiRes experiment with 5σ significance [3] and was recently independently confirmed by the AUGER experiment with 6σ significance [4]. Experimental data for the UHECR spectrum at the highest energies are shown in Fig. 1. The upper panel shows the flux measured by the Pierre Auger Observatory during its construction period. The lower panel shows both fluxes measured by the HiRes and the AUGER experiments multiplied by

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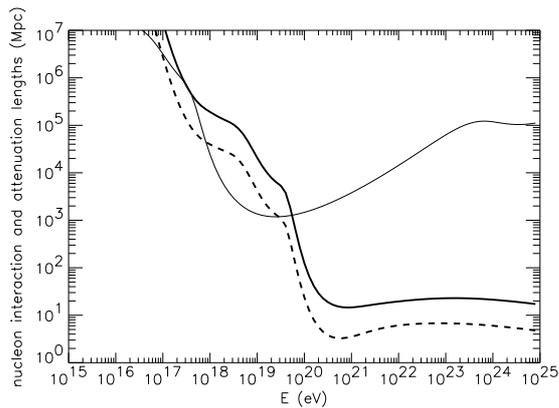`Tel: +33157276070, Fax: +33157276071` (Dmitri Semikoz).

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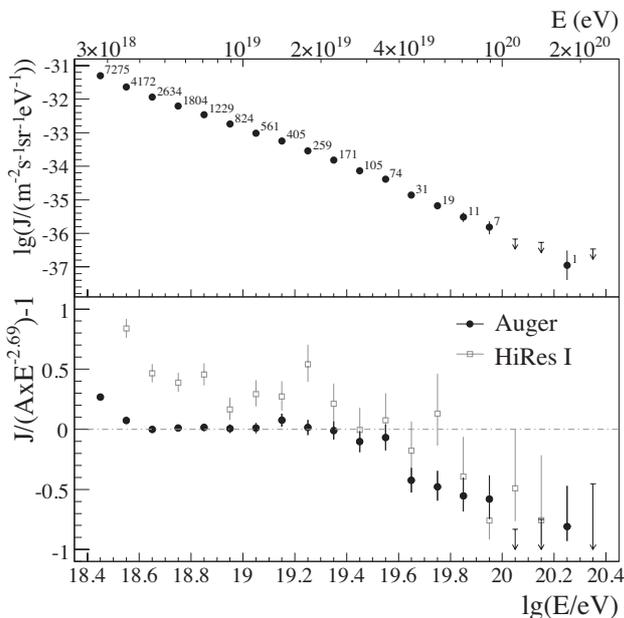

Fig. 2. The UHECR spectrum measured by AUGER (top) and a comparison between AUGER and HiRes spectra (bottom) from ref. [4]. Both experiments see a cutoff in the spectrum with more then 5σ significance.

$E^{2.6}$. It can be clearly seen from this figure that at $E > 4 \times 10^{19}$ eV (19.6 in log scale) the UHECR flux is well below horizontal dash-dotted line $\sim 1/E^{2.6}$.

The existence of a cutoff in the UHECR spectrum points to the astrophysical origin of the UHE cosmic rays. At distance scales of $R < 100$ Mpc the Large Scale Structure (LSS) of the Universe is not uniform. Thus, in the case that extragalactic magnetic fields are not strong enough to randomize the
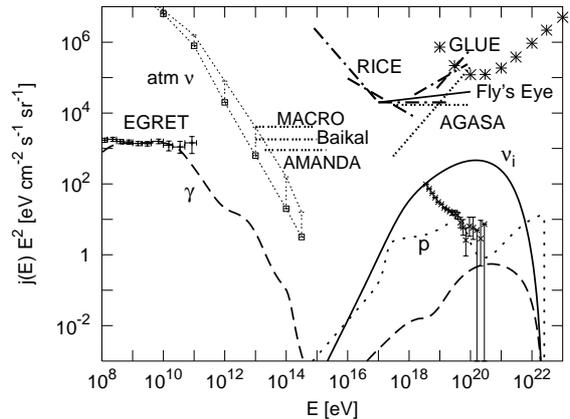

Fig. 3. Connection between UHECR proton flux, secondary photon and neutrino fluxes from ref. [9]. Part of the proton energy is converted through pion production processes to neutrinos and photons. The maximal photon flux saturates the EGRET measurement [10,11]

arrival directions of the cosmic rays, an anisotropy of the arrival directions should be seen, connected to existing large scale structure. Such anisotropy was first seen in the combined data of AGASA, HiRes and other experiments at $E >> 4 \times 10^{19} eV$ [5] with 3σ significance and also later was found in the first data of AUGER experiment [6].

Recently, in November 2007, AUGER published results of a blind test in which anisotropy was seen at $E > 57$ EeV in correlation with a preselected catalog of nearby AGN's with significance $\sim 10^{-3}$ [7]. This anisotropy clearly points to a UHECR origin in extragalactic sources. Nonetheless these results do not have enough statistical power to determine which exact class of the objects are the UHECR sources, since all of them correlate with the same LSS. This is a subject for future investigations.

The existence of the GZK cutoff guarantees a secondary neutrino flux coming from UHECR protons and nuclei. This flux is discussed in the following section. The discovery of a cutoff in the UHECR spectrum has, however, stopped wide discussion of exotic top-down models (for review see ref. [2]).

All protons produced at distances $R > 100$ Mpc should lose energy in pion production. In turn, neutral pions will produce gamma-rays via $\pi^0 \rightarrow 2\gamma$ and charged pions will produce positrons and neutrinos via $\pi^+ \rightarrow \nu_\mu + e^+ + \nu_\mu + \overline{\nu}_e$. Neutrinos will oscillate over the cosmological distance scale, and half of the muon neutrinos would be converted to tau neutrinos. At the detection point a similar flux of all neu-

trino flavors would be expected. $N_{\nu_e} : N_{\nu_\mu} : N_{\nu_\tau} = 1 : 1 : 1$. The existence of neutrinos from GZK mechanism was already under discussion in 1969 [8].

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

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

2. Predictions for diffuse flux neutrinos

In order to predict the diffuse neutrino flux at the highest energies we must specify the cosmic ray model. In this section we assume that most UHECRs at the highest energies are protons. In this case, the proton flux after propagation can be normalized to the measured cosmic ray flux.

Usually the proton flux of one source is parametrized as follows:

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

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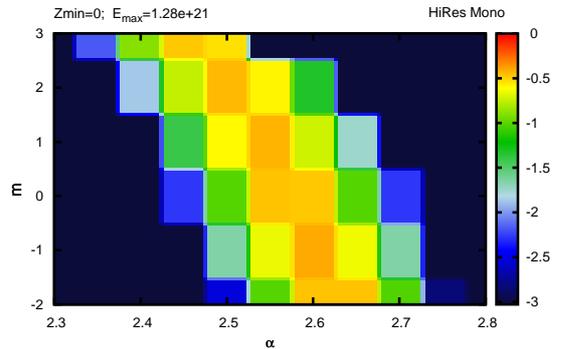

Fig. 4. The proton flux power law index and the evolution index are degenerated and their combination always perfectly fits total UHECR flux for $E > 2 \times 10^{18}$ eV [15]. Colours indicate the probability that a given model is consistent with HiRes data $P = 10^{-\gamma}$. Corresponding values of the power law index γ are shown on the right.

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

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

Finally the distribution of sources can be parametrized as follows:

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

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

Identical cosmic ray spectra can be reproduced with different combinations of the above parameters. In particular in Fig. 4 it is shown that the HiRes spectrum 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 the resulting extragalactic proton flux will be strongly affected by this [16].

The dependence of the diffuse neutrino flux on the key parameters α, m, E_{max} and z_{max} was studied in detail in [14]. The values of all these 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 depend only weakly on E_{max}. In
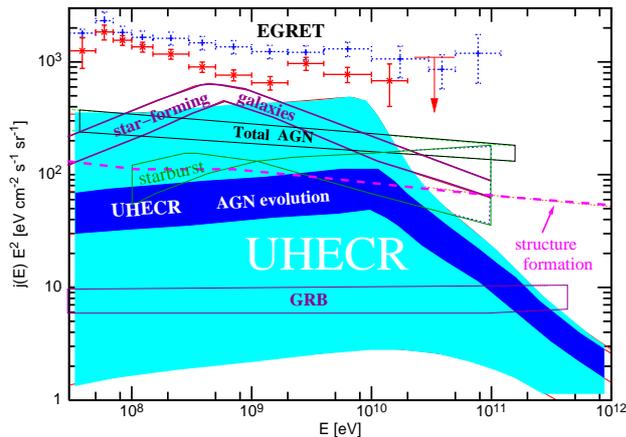
Fig. 5. The possible range of UHECR induced cascade fluxes (light shaded band) compared to estimated $\gamma-$ray fluxes by different mechanisms from ref. [17]. Total extragalactic $\gamma-$ray background was measured by EGRET[10,11] and will be revised soon by GLAST (Fermi) [12].

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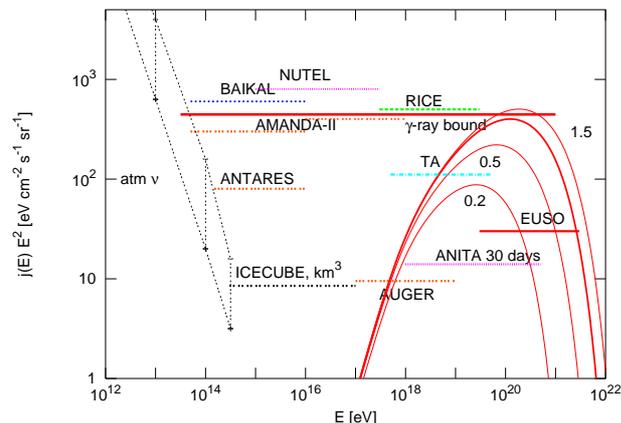

Fig. 6. Maximal neutrino flux as a function of energy and sensitivities of experiments from ref. [18].

Fig. 5 we plot the possible range of diffuse gamma-ray fluxes (light shaded band) allowed by fits to the cosmic ray flux at highest energies. The dark shaded band corresponds to the assumption that the luminosity of cosmic ray sources is similar to that of AGN's. One can see that prediction is more certain in this case, since it imposes a very tight connection between α, m and z_{max}. If most of the diffuse flux measured by EGRET comes from unresolved point sources, the real diffuse flux could be much smaller. The GLAST(Fermi) experiment in the near future should establish a new upper limit for the flux of gamma-rays coming from cosmic rays, and as result a new upper limit on the diffuse neutrino flux.
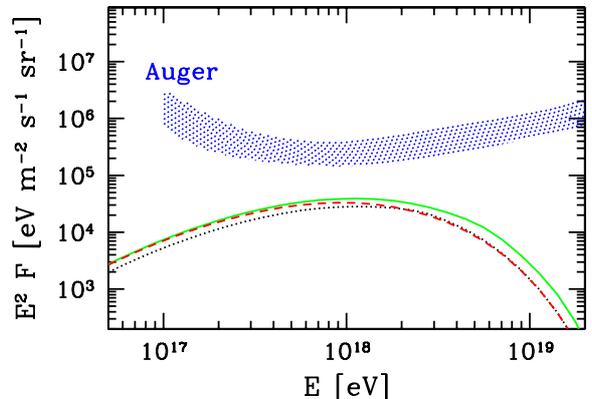
Another important parameter of the diffuse neutrino flux is the minimal energy of cosmic rays to which we choose to fit the UHECR spectrum, E_{min} in Eq. (4). The value of this parameter depends on whether the dip in the spectrum at $E \sim 3 \times 10^{18}$ eV is assumed due to pair production of protons due to a transition from galactic to extragalactic cosmic rays. For extragalactic cosmic rays, fits to only the highest part of the observed spectrum with very small values of $\alpha < 1.5$ yield a very high diffuse neutrino flux, as shown in Fig. 6 for different maximum energy. The line with index 0.2 corresponds to $E_{max} = 10^{21}$ eV.

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

We can now compare the above theoretical predictions with present day experimental limits. In Fig. 8 the AUGER limit on the diffuse flux of tau neutrinos is shown with a thick solid line, [20]. Assuming an E_ν^{-2} differential energy spectrum, the limit is set at the 90 % C.L. is $E_\nu^2 dN_{\nu_\tau}/dE_\nu < 130$ eV cm^{-2} s^{-1} sr^{-1} in the energy range 2×10^{17}eV $< E_\nu < 2 \times 10^{19}$ eV [20]. This limit is comparable to present limits from the AMANDA-II experiment at the highest energies. In Fig. 8 the theoretical predictions for the GZK neutrino flux lie between the
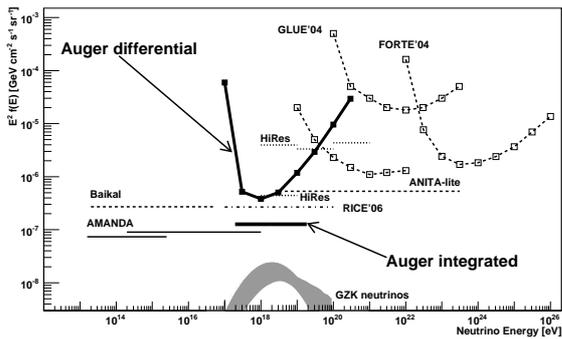
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Fig. 8. Recent limits on the diffuse flux of neutrinos from ref. [20].

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

minimal flux from Fig. 7 and the maximal flux from Fig. 6. The 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 an interesting region of theoretical expectations for diffuse neutrino fluxes. Also ANITA and other radio experiments will have the possibility to measure the diffuse neutrino flux.

Finally, we note two important points concerning searches of the diffuse neutrino flux at the highest energies.

Firstly, the minimal diffuse neutrino flux shown in Fig. 7 is 'minimal' under the assumption that all UHECRs are protons. In the event that some UHECRs are nuclei, this flux can be reduced since nuclei usually are photo-disintegrated before they produce significant numbers of pions. Also since models with nuclei have many more free parameters, we cannot tightly predict the diffuse neutrino flux in this case. However, we might expect a flux even lower than that of Fig. 7.

Secondly, good energy resolution is likely to be more important than good angular resolution for the measurement of the diffuse neutrino flux, and should help to distinguish between different models. The detection of "cascades" could be the best method for measuring the diffuse neutrino flux at km^3 underwater or under-ice detectors.

3. Neutrinos from point sources

Neutrinos can be created at astrophysical sources both during acceleration and propagation of protons and nuclei inside these sources, in $p + \gamma$ or $p + p$ collisions. In both cases the pions produced will decay into neutrinos and photons, and the resulting total energy in neutrinos can be estimated from the total energy in the high energy photons.
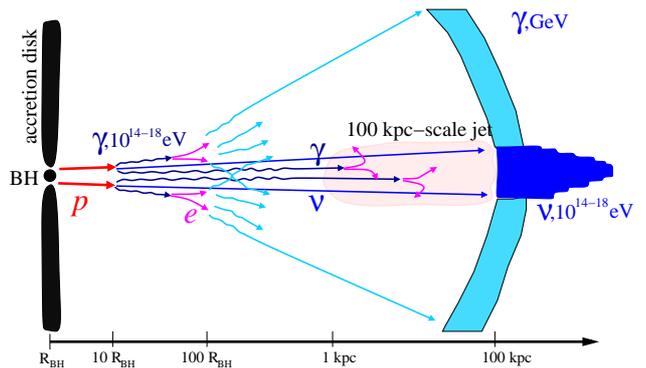
Usually it is assumed that TeV gamma-ray sources are good candidates for neutrino sources with similar flux. In the case of $p + \gamma$ it is usually not so. Indeed, protons would produce pions in the gamma-ray background with density n_γ and size of the region R if:

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

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

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

We may restrict ourselves to a comparison of the cross sections of the two processes;
$\sigma_{P\gamma} = 6 \times 10^{-28} cm^2$
while $\sigma_{\gamma_{TeV}\gamma} = 6.7 \times 10^{-25} log(s)/s \ \ cm^2$,
where $s = (p_1 + p_2)_\mu (p_1 + p_2)^\mu$ is s-invariant.

In order that neutrinos are produced and TeV gamma-rays can escape from the same region $\sigma_{P\gamma} > \sigma_{\gamma_{TeV}\gamma}$ is required. This can happen only in the Klein-Nishina limit, $s > 10^3$, i.e. when the background is X-ray, which is extremely unlikely in most models. For more usual optical and infrared photon backgrounds, TeV gamma-rays would not be expected to escape from the neutrino production region.

There are two ways out of this dilemma. Firstly, multi-GeV gamma-rays might be produced - though generally forbidden by reaction Eq.(8) as being below threshold. Secondly, very high energy gamma-rays with $s > 10^3$ might be produced which would then in turn produce secondary gamma-rays in a spatially-different region. Such possibilities are discussed in the model of kpc-scale jet [21]. Production of neutrinos in this model was studied in ref. [22]. In this model protons are accelerated to high energies near supermassive a black hole in an active galaxy,
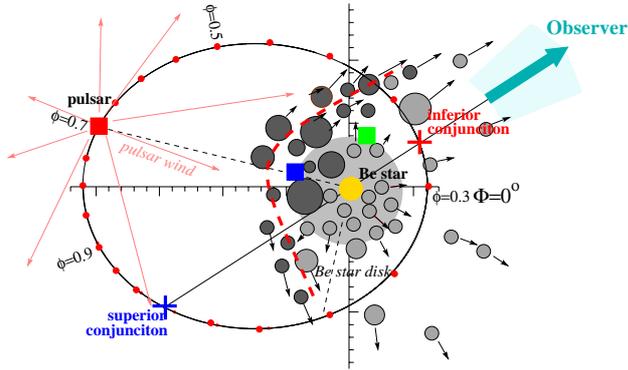
Fig. 10. Production of gamma-rays in binary system LS I+61 303 from ref. [23].

(Fig. 9). The protons produce both neutrinos and photons in interactions with optical photons from the hot accretion disk. Neutrinos escape in the forward direction in a compact jet of degree size, while secondary GeV gamma-rays are redistributed over a 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 Fig. 9 neutrino sources can be much more compact than gamma-ray sources. As result, one would see fewer neutrino sources compared to gamma-ray sources, but those sources would be much brighter! In the near future, the GLAST(Fermi) experiment is expected discover thousands of GeV sources, the most powerful of which might be good candidates for point neutrino sources.

A completely different mechanism for simultaneous neutrino and TeV gamma-ray production comes 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 a relatively rare phenomenon.

Binary systems might represent a possibile environment for efficient proton-proton collisions. Specifically, TeV gamma-rays have been detected from binary LS I+61 303, which consists of a pulsar and a nearby accompanying Be star (Fig. 10). Although most astrophysical TeV gamma-rays are produced by electrons, as in the model of ref. [23], TeV radiation can also be produced by proton-

proton collisions. In the latter case, if the neutrino flux is of the same order as the TeV photon flux, we could expect 0.3 neutrino events per year in the ICECUBE experiment [24].

We may also consider future Galactic Supernovae at distances around 10 kpc. In these cases, the high energy neutrino flux can be produced at an early stage after the shocks exit the star [25], with an expectation between 100 and 1000 events per km^3 of detector volume during the first year following the explosion [26]. Also these high energy neutrinos will allow a SN to be visible - even from the 'wrong' (atmospheric) side of detector - due to the high signal-to-background ratio [27].

Finally, we can comment that the angular resolution of experiments is the most important parameter in searches for point sources. The main problem of such searches is expected to be the low statistics, as in the case of the binary LS I+61 303, even for km^3 scale detectors. It is very important, therefore, to reduce background through as good an angular resolution as possible. On the theoretical side, the uncertainties in astrophysical parameters do not allow the shape of the neutrino flux from point sources to be predicted with high precision, meaning that precise experimental measurements of the neutrino energy will generally be subordinate to high precision angular resolution measurements in the search for point neutrino sources.

4. Conclusions

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

Recent observations of the GZK cutoff in the spectrum of UHECRs, together with their anisotropy have indicated that UHECRs come from extragalactic astrophysical sources. These observations disfavour exotic top-down models. For measurement of the diffuse neutrino fluxes this means one can expect only a secondary diffuse neutrino flux from UHECR protons. This flux is guaranteed, but its level strongly depends on unknown parameters, such as the acceleration spectrum, luminosity of UHECR sources and the fraction of protons in the total UHECR flux. In Section 2 we have discussed the above uncertainties and given examples of possible high and low GZK neutrino fluxes. In Section 3 we have considered several examples of Galactic neutrino sources and indicated the large uncertain-

ties in predictions of neutrino fluxes due to the many unknown parameters. Some of these parameters should be constrained in the near future by the GLAST(Fermi) satellite and other ongoing cosmic ray experiments.

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