Theoretical Predictions of Ultra-High Energy Neutrino Fluxes

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Abstract

Applying our recently developed propagation code we review extragalactic neutrino fluxes above 10^{14} eV in various scenarios. We specifically identify scenarios in which the cosmogenic neutrino flux, produced by pion production of ultra high energy cosmic rays outside their sources, is considerably higher than the ”Waxman-Bahcall bound”. We also compare this flux with neutrino fluxes in top-down models, the Z-burst model and a model of new hadrons. All these fluxes allow to detect ultra-high energy neutrinos with experiments currently under construction or in the proposal stage. We also discuss the possibility to detect point-like neutrino sources.

1. Cosmogenic neutrinos

The flux of ”cosmogenic” neutrinos created by primary protons above the GZK cutoff in interactions with CMB photons depends both on the primary proton spectrum and on the location of the sources. The cosmogenic neutrino flux is the only one that is guaranteed to exist just by the observations of ultra-high energy cosmic rays (UHECRs) and was studied soon after the discovery of the CMB [1]. Note, however, that there is no firm lower bound on the cosmogenic neutrino flux if the UHECR sources are much closer than the GZK distance.

Using our recently developed propagation code [3] we investigated in detail the dependence of the cosmogenic neutrino flux on unknown parameters including maximal source redshift $z_{\max}$, maximal injection energy $E_{\max}$, source redshift evolution index m, proton spectral power law index α, and cosmological parameters [5].

In any scenario involving pion production for the creation of $\gamma-$rays and neutrinos, the fluxes per flavor are approximately related by $F_\nu(E) \approx F_\gamma(E)/3$. Assuming smooth spectra and comparing with the EGRET $\gamma-$ray fluence, energy conservation implies $E^2 F_\nu(E) \leq 6 \times 10^2\,\mathrm{eV cm^{-2} s^{-1} sr^{-1}}$. This ultimate bound is shown in Fig. 1. as “γ-ray bound”. As we show in Fig. 1., it is easy to exceed

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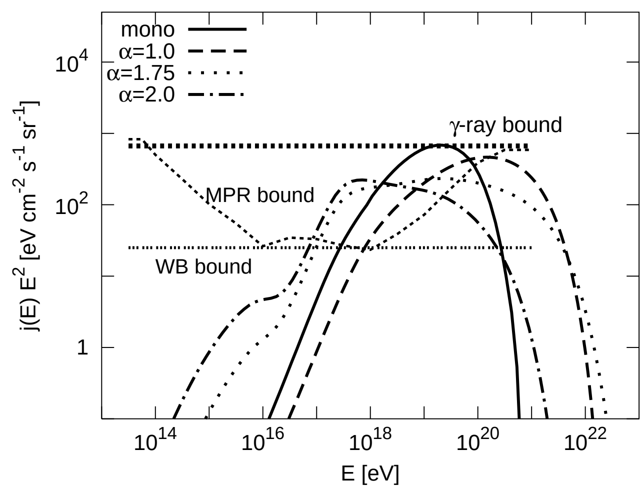

Fig. 1. Dependence of the average cosmogenic neutrino flux per flavor maximized over maximal injection energy $E_{\max}$, evolution index m, and normalization consistent with all cosmic and $\gamma-$ray data, on the injection spectrum power law index α. "mono" indicates mono-energetic proton injection at $E = 10^{21}$ eV.

the Waxman-Bahcall bound [8] and even the MPR [6] bound for injection spectra harder than about E^{-2}. This is because Waxman & Bahcall restricted themselves to nucleon injection spectra softer than E^{-2} and sources smaller than the nucleon interaction length [8]. Thus, their bound does not apply to the cosmogenic neutrino flux. In addition, in our opinion, their assumptions on the injection spectra are too narrow: possible scenarios with hard injection spectra and the redshift evolution of sources different from AGN allow to overcome these bounds [5] (see also Fig. 1.).

2. Ultra-high energy neutrinos in various UHECR models

Many theoretical models of UHECR predict significant neutrino flux at ultra high energies. Because these models are constructed to explain UHECR flux, measuring of UHECR flux along will not allow to distinguish between those models. In Fig. 2. we compare an optimistic scenario for the cosmogenic neutrino flux (GZK line) to the neutrino flux in various exotic UHECR models. Curve "top-down" correspond to scenarios where UHECRs and UHE neutrinos are the decay products of some super-massive "X" particles of mass $m_X \gg 10^{20}$ eV close to the grand unified scale, and have energies all the way up to $\sim m_X$, see details in [5]. In the Z-burst scenario UHECRs are produced by Z^0 bosons decaying within the distance relevant for the GZK effect. These Z^0 bosons are in turn produced by UHE neutrinos interacting with the relic neutrino background. The line "Z-burst" in Fig. 2. shows the huge initial neutrino flux required in this model

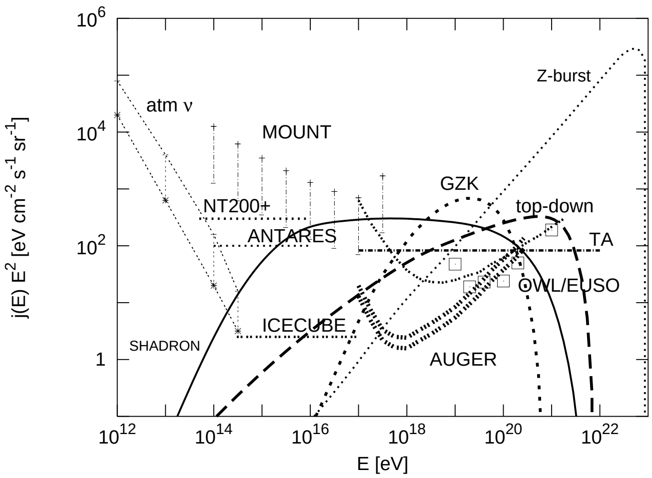

Fig. 2. The neutrino flux for one flavor and sensitivities of the currently being constructed experiments. Cosmogenic neutrino flux compared to fluxes in top-down models, Z-burst model, and model with new hadrons. Theoretical fluxes compared to experimental sensitivities.

(see details in [4]). Astrophysical sources also can produce exotic hadrons (for example, containing SUSY particles) which are responsible for UHECR. In this model UHE neutrino are unavoidably produced in astrophysical sources [2].

In Fig. 2. we compare predicted neutrino fluxes with sensitivity of the future neutrino telescopes including NT200+ at Lake Baikal, ANTARES in the Mediterranean, (AMANDA-II at South Pole will be similar), and ICECUBE, and air shower detectors including the Auger project, the Japanese telescope array, the fluorescence/Čerenkov detector MOUNT, and the space based EUSO and OWL experiments. For the references to all experiments see Ref.[5].

3. Neutrinos flux from astrophysical sources

Protons accelerated in the cores of active galactic nuclei can effectively produce neutrinos only if the soft radiation background in the core is sufficiently high. We find restrictions on the spectral properties and luminosity of blazars under which they can be strong neutrino sources [7]. We analyze the possibility that the neutrino flux is highly beamed along the rotation axis of the central black hole. The enhancement of the neutrino flux compared to the GeV γ-ray flux from a given source makes the detection of neutrino point sources more probable. In Fig. 3. we show typical neutrino fluxes in such a model. The solid line shows neutrino flux similar in power to photon flux in GeV region, while the dashed line show neutrino flux enhanced by beaming. At the same time the smaller open angle reduces the number of possible neutrino-loud blazars compared to

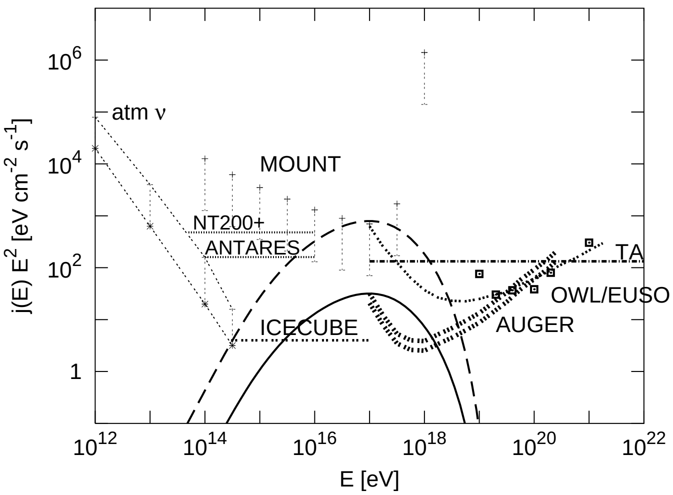

Fig. 3. Neutrino flux from typical GeV-loud blazar from list in [7] (thick solid line) compared with expected sensitivities to electron/muon and tau-neutrinos in same detectors as in Fig. 2.. All not published experimental sensitivities are scaled from corresponding diffuse sensitivities with the same factor as ICECUBE. The dashed line is for an opening angle for neutrino 5 times smaller than the opening angle for GeV photons.

the number of γ-ray loud ones. We listed 14 blasars which are most favorite candidates for detection by future neutrino telescopes in Ref. [7].

Comparing theoretical predictions of neutrino fluxes with sensitivities of future experiments in Figs.2.-3. we conclude that UHECR detectors and neutrino telescopes are close to the theoretically interesting region at the moment and have good chances to detect high energy neutrinos and distinguish between different models in the near future.

4. References

1. V. S. Beresinsky and G. T. Zatsepin, Phys. Lett. B **28**, 423 (1969); Sov. J. Nucl. Phys. 11 (1970) 111 [Yad. Fiz. 11 (1970) 200].
2.M. Kachelriess, D. V. Semikoz and M. A. Tortola, hep-ph/0302161.
3. O. E. Kalashev, V. A. Kuzmin and D. V. Semikoz, astro-ph/9911035; Mod. Phys. Lett. A **16**, 2505 (2001) [astro-ph/0006349].
4. O. Kalashev *et al*, Phys. Rev. D **65**, 103003 (2002) [hep-ph/0112351].
5. O. Kalashev *et al*, Phys. Rev. D **66**, 063004 (2002) [hep-ph/0205050].
6. K. Mannheim, R. Protheroe and J. Rachen, Phys. Rev. D **63**, 023003 (2001)
7. A. Neronov and D. Semikoz, Phys. Rev. D **66**, 123003 (2002) [hep-ph/0208248].
8. E. Waxman and J. N. Bahcall, Phys. Rev. D **59**, 023002 (1999) [hep-ph/9807282]