Which blazars are neutrino loud?

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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. 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. At the same time the smaller open angle reduces the number of possible neutrino-loud blazars compared to the number of γ-ray loud ones. We present a table of 15 blazars which are the most likely candidates for the detection by future neutrino telescopes.

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I. INTRODUCTION

Neutrino telescopes which already operate or are under construction will presumably be able to detect point sources of neutrinos with energies up to $\sim 10^{17}$ eV by looking for the showers and/or tracks from charged leptons produced by charged current reactions of neutrinos in ice, in the case of the Antarctic Moon and Neutrino Detector Array (AMANDA) [1,2] and its next generation version ICECUBE [3], and in water, in the case of BAIKAL [4,5], ANTARES [6], and NESTOR [7] (for recent reviews of neutrino telescopes see Ref. [8]).

From the other side, future ultrahigh energy cosmic ray (UHECR) experiments such as the Pierre Auger Observatory [9,10] will be able to detect neutrinos with energies above 10^{17} eV. At the highest energies above $\sim 10^{19}$ eV the telescope array [11,12] or space based observatories such as the Extreme Universe Space Explorer (EUSO) [13] and Orbiting Wide-Angle Light Collector (OWL) [14,15] will also measure the neutrino flux. The flux from pointlike sources at those energies can be a combination of the direct flux from a source and the secondary neutrino flux produced by ultrahigh energy (UHE) protons emitted by the source in interactions with cosmic microwave background radiation (CMBR) photons. If the neutrino flux at high energies $E > 10^{17}$ eV is large enough to give more than 1–3 events per km^2 per year, future km^2 neutrino telescopes like ICECUBE will be able to detect those neutrinos coming from above [16].

At the intermediate energies between $\sim 10^{15}$ eV and $\sim 10^{19}$ eV there are plans to construct telescopes to detect fluorescence and Čerenkov light from near-horizontal showers produced in mountain targets by neutrinos [17,18]. The alternative of detecting neutrinos by triggering onto the radio pulses from neutrino-induced air showers is also currently investigated [19]. Two implementations of this technique, RICE, a small array of radio antennas in the South pole ice [20], and the Goldstone Lunar Ultrahigh Energy Neutrino Experiment (GLUE) [21], have so far produced neutrino flux upper limits. Acoustic detection of neutrino induced interactions is also being considered [22].

The simplest way to produce neutrinos in astrophysical objects is to accelerate protons and then collide them with a soft photon background with energy above the photopion production threshold. The pions produced will decay into photons, electrons, positrons, and neutrinos. If protons are captured within the source, the estimate of neutrino flux from a given source can be obtained from the detected γ-ray flux, since the energy deposit in neutrinos in pion decays is of the same order as the energy in photons. If the sources are transparent for the primary protons then a limit on the diffuse neutrino flux from all possible sources can be obtained from the detected high energy proton flux. This idea was first suggested in [23]. For the particular case of the E^{-2} proton spectrum coming from active galactic nuclei (AGN's) the calculation was done in [24]. The same calculation for the E^{-1} proton flux was made in [25]. In [26] the dependence of the neutrino flux on the proton spectrum, cosmological parameters, and distribution of sources was investigated in detail. In particular it was shown that in many the cases neutrino flux can exceed the value calculated in [24] or even the value of [25], and the only bound on the diffuse neutrino flux comes from the Energetic Gamma Ray Experiment Telescope (EGRET) measurement.

The Universe is not transparent for photons with energies above 100 GeV. The highest energy photons from astrophysical objects (nearby TeV blazars) seen so far had energies $E \sim 10^{13}$ eV. No direct information about emission of $E > 10^{13}$ eV particles is available now. At the same time it is well established that photon emission from blazars (active galactic nuclei, which we see almost face on) in the MeV–TeV energy range is highly anisotropic. Typical estimates of the γ factors of the emitting plasma, $\gamma \sim 10$, imply that in the 10^6–10^{13} eV band almost all γ-ray flux is radiated in a cone with the opening angle $\theta \sim 1/\gamma \sim 5°$. Particles (photons, neutrinos) in the higher energy range $E > 10^{13}$ eV can be emitted

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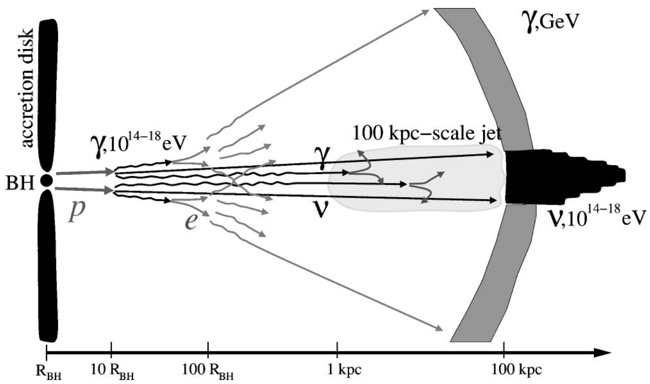

FIG. 1. Neutrino production in the AGN core.

in an even narrower cone. This fact favors blazars as promising neutrino sources.

Recent x-ray observations of large-scale jets in AGN's can shed some light on the issue of particle acceleration to energies much above TeV in the AGN cores. Indeed, in order to explain x-ray synchrotron emission on very large scales of the order of 100 kpc away from the AGN core one needs to suppose that multi-TeV electrons are continuously produced over the whole jet length. A model which naturally explains this continuous production of multi-TeV electrons was recently proposed in [27] (see Figs. 1 and 2 below). The idea is that γ rays with energies 10^{14}–10^{16} eV emitted from the AGN core produce e^+e^- pairs in interactions with the CMBR photons at the distance scale 10–100 kpc away from the core. Thus, within this model the fact that jets with the lengths about 10–100 kpc are commonly observed in AGN's enablesus to conclude that (1) particles with energies $E \geqslant 10^{14}$–10^{16} eV are produced in the AGN cores and (2) these particles are normally emitted in a cone with opening angle $\theta \sim 1°$. The diffuse neutrino flux in this model was calculated in [26]. In this paper we discuss which blazars will be the most promising neutrino sources if neutrinos are produced in the AGN cores, as in the model [27]. AGN's that can be significant point sources of neutrinos were analyzed

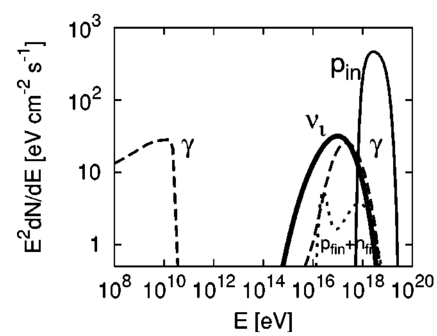

FIG. 2. Typical particle spectra of GeV-loud blazar in the model presented in Fig. 1. The thin solid line is the initial spectrum of accelerated protons. The dotted line is the final spectrum of protons and neutrons after interaction with UV photons. The thick solid line presents the spectrum of neutrinos averaged over flavor. Photons are shown by the dashed line. High energy photons will feed a kpc-scale jet and partly contribute to the GeV region. The spectra are normalized to the flux of a typical GeV-loud EGRET source.

in [28–30,23]. In particular, high neutrino fluxes were conjectured to come from brightest quasars like 3C 273 [28,29] or TeV blazars like Mkn 421 [23]. Enhancement of neutrino flux during the flaring activity in 3C 279 was considered in [30]. The predictions of the model [27] are quite different. In particular, none of the three blazars cited above enters our list of most probable neutrino sources.

In Sec. II we will discuss the mechanism of neutrino production and derive a bound on the magnitude and redshift of blazars which can be neutrino loud. In the third section we discuss the neutrino flux from TeV gamma-ray sources. In Sec. IV we derive the neutrino fluxes from 15 blazars which are the most promising neutrino sources. In Sec. V we will discuss the secondary neutrino fluxes from UHECR sources.

II. PRODUCTION OF NEUTRINOS IN BLAZARS

If an AGN is expected to be a bright neutrino source, physical conditions inside the AGN core must be favorable for intense production of neutrinos in photopion processes. This means that the density of soft photons in the core must be high enough for protons to interact at least once with the background photons while they traverse the core. Of course, the soft photon density in the core is expected to be highly anisotropic and the mean free path of protons depends essentially on the direction of propagation. The main contribution to the soft photon background in the direct vicinity of the central black hole is usually assumed to come from the optical or UV (or "blue bump") photons produced by the inner part of the accretion disk.

As an example, the neutrino production mechanism in the model of [27] is presented schematically in Fig. 1. A beam of high energy protons accelerated in a strong electromagnetic field in the direct vicinity of the black hole (BH) horizon is converted in the core into a beam of secondary particles such as γ quanta, neutrinos, electrons, and positrons. The beam of high energy γ quanta feeds the bright 100 kpc scale jet with high-energy electrons, while the beam of neutrinos just escapes the source. Typical particle spectra of GeV-loud blazar in this model are shown in Fig. 2. The spectra are calculated using the code developed in [31].

For AGN's which are not seen in TeV range, no direct estimate of the optical depth for protons in a given direction is possible because γ rays with energies below 100 GeV do not interact with the "blue bump" photons in the AGN core. In this case one can roughly estimate the conditions inside the AGN core by assuming that the optical or UV background is isotropic and is produced inside a region of size of the order of $R_{\rm core} \sim 10^{16}$ cm, as is indicated by the typical optical and UV variability of AGN's [32]. If the flux from the source is νF_ν, the luminosity is $L = 4\pi D_L^2(\nu F_\nu)$ where D_L is the luminosity distance. The number density of photons inside the core is

$$n_{\rm soft} = \frac{L}{4\pi R_{\rm core}^2 c\epsilon} = \frac{D_L^2(\nu F_\nu)}{R_{\rm core}^2 c\epsilon}, \tag{1}$$

where $\epsilon = \epsilon_V \times 2.26$ eV is the typical energy of soft photons in the V band. The mean free path of the proton is given by

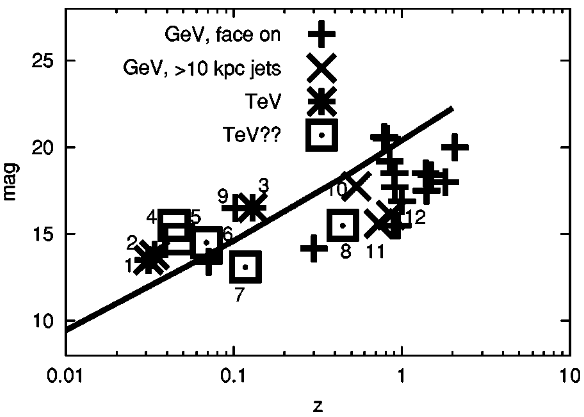

FIG. 3. Bound on the magnitude and redshift of blazars which can be neutrino loud, Eq. (3). Above the solid line only part of the proton energy is converted into photons and neutrinos. The energy of blue bump photons is taken to be 2.26 eV (V-band optical range). Cosmological parameters used for calculation of the luminosity distance are $H_0 = 70$ km/s/Mpc, $\Omega_V = 0.7$, $\Omega_M = 0.3$. Points show the V-band optical flux from the sources listed in Tables I, II, and III.

$$R_p = \frac{1}{\sigma_{p\gamma} n_{\rm soft}} = \frac{c R_{\rm core}^2 \epsilon}{\sigma^{p\gamma}(\nu F_\nu) D_L^2}. \tag{2}$$

The requirement that the proton mean free path is much smaller than $R_{\rm core}$ imposes the following restriction on the flux in the V band from blazars at a given redshift:

$$\frac{D_{L,100}^2 (\nu F_\nu)_{\rm V,13} \sigma_{28}^{p\gamma}}{\epsilon_V R_{16}} \gg 1, \tag{3}$$

where $D_{L,100}$ is the luminosity distance in units of 100 Mpc, the size of the core $R_{16} = R/(10^{16}\ {\rm cm})$, the normalized cross section $\sigma_{28}^{p\gamma} = \sigma^{p\gamma}/(10^{-28}\ {\rm cm}^2)$, and the flux normalized on magnitude $m_V = 13$ is $(\nu F_\nu)_{\rm V} = 1.26 \times 10^{-13} (\nu F_\nu)_{\rm V,13}$ W/m^2. Here $(\nu F_\nu)_{\rm V,13} = 10^{-0.4(m_V - 13)}$.

The luminosity distance depends on the cosmological model. For our calculations we choose the cosmological model best motivated at present; namely, a flat Universe, filled with matter $\Omega_M = \rho_M / \rho_c$ and vacuum energy densities $\Omega_V = \rho_V / \rho_c$ whose sum equals the critical energy density, $\Omega_V + \Omega_M = 1$. The critical energy density $\rho_c = 3H_0^2/(8\pi G_N)$ is defined through the Hubble parameter H_0. The luminosity distance in this model has the following form:

$$D_L = \frac{1+z}{H_0 \sqrt{\Omega_M}} \int_1^{1+z} \frac{dx}{\sqrt{\Omega_V/\Omega_M + x^3}}. \tag{4}$$

In our calculations we used the values $H_0 = 70$ km/s/Mpc, $\Omega_V = 0.7$, and $\Omega_M = 0.3$.

The bound Eq. (3) imposes a restriction on the blazar redshift and magnitude which is shown on Fig. 3 [the solid line corresponds to the case when the left-hand side of Eq. (3) equals 5]. Such a choice is motivated by the fact that in one photopion interaction a proton loses only a fraction (typically 20%) of its energy.

TABLE I. TeV-loud blazars. The number in the first column is the same as in Fig. 3. The second column is the name of the object. The third is the redshift. The forth is the magnitude in the V range (eV range). The fifth is the BL Lac type, and the last is the name and reference for the experiment. We use the following abbreviations for the object types in Tables I–III: HBL and LBL for high- and low-energy cut-off BL Lacertae, HPQ aand LPQ for high- and low-polarization quasars and FSRQ for flat spectrum radio quasars.

No.	Name	z	V mag	Type	Telescopes
1	Mkn 421	0.031	13.5	HBL	CAT, HEGRA, WHIPPLE [38]
2	Mkn 501	0.0337	13.8	HBL	CAT, HEGRA, WHIPPLE [39]
3	1ES 1426+428	0.129	16.5	HBL	CAT, HEGRA, WHIPPLE [40]
4	1ES 2344+514	0.044	15.5	HBL	WHIPPLE [41]
5	1ES 1959+650	0.047	14.7	HBL	Utah Tel. Array [42]
6	BL Lac	0.0686	14.5	LBL	Crimean Obs. [43]
7	PKS 2155-304	0.117	13.1	HBL	Durham Mark 6 [44]
8	3C 66A	0.444	15.5	LBL	Crimean Obs. [45]

An estimate (but not an upper limit; see Sec. IV) of the neutrino flux from sources which satisfy the constraint Eq. (3) can be obtained from the detected γ-ray flux. GeV γ rays can be produced in the AGN core through a variety of mechanisms: inverse Compton scattering of soft background photons as in the synchrotron–self-Compton model [33], synchrotron radiation of very high energy protons in the extreme proton synchrotron model [34], development of an electromagnetic cascade initiated by photopion production in proton blazar models [35]. Neutrinos can be produced only in the last case. In the following we will suppose that photopion production gives a significant contribution to the observed GeV photon flux, allowing us to estimate the resulting neutrino flux.

III. CAN TeV-LOUD BLAZARS BE NEUTRINO SOURCES?

Since high energy neutrinos are produced together with high energy photons in photopion reactions, the presence of high energy photons in the spectrum of a given source can serve as an indicator of a possible neutrino flux from this source. However, the high energy photons produced can still interact with the background photons both in the source and on the way to the Earth, cascading down to energies below the pair production threshold. The typical energy of the blue-bump photons in the source (1–10 eV) is similar to the energy of infrared background photons. Thus, the high energy photon spectrum should end in the 10 GeV–TeV region, depending on the source properties and the distance to the Earth. That is, promising neutrino sources should be GeV or TeV loud.

For our analysis we have taken the catalog of blazars which are detected by EGRET [36] (51 objects), singled out the ones which are listed as GeV sources [37] (21 sources), and added all known TeV gamma-ray sources (eight sources) presented in Table I. TeV gamma rays from the first three sources in this table are confirmed by several experiments with high significance, while the last five sources have been seen only by one experiment and require confirmation in the future. Two of the sources, Mkn 421 and 3C 66A, were also seen by EGRET with significant flux in the GeV region. Thus, the total number of sources in our analysis is 27. We used NED [46] and Simbad [47] databases to find the V magnitudes and redshifts of the objects.

Blazars loud in the TeV energy range are often named as good candidate sources of neutrinos, because the existence of TeV gamma rays favors the possibility of proton acceleration up to high energies. However, in order to produce neutrinos the acceleration of protons to energies above the pion production threshold is required, but not enough. A second important condition is the large optical depth for protons, Eq. (3). Blazars from Table I are shown by stars (confirmed TeV sources) and by squares (possible TeV sources) in Fig. 3. All of them are marked with the same numbers 1–8 as in Table I. One can see that sources 1–6 do not obey the restriction Eq. (3) and thus their neutrino flux is suppressed as compared to the photon flux.

Of course, the bound Eq. (3) is only an order of magnitude argument. In order to estimate correctly the neutrino flux from a given source one needs to present a detailed model for this source, explaining all experimental data. However, we can significantly improve the bound on the neutrino flux if we take into account the fact that the source emits TeV gamma rays. Let us make a simplest estimate of the optical depth in the direction from the center of the core toward the Earth for TeV blazars. The fact that TeV γ rays produced in the vicinity of the central black hole are able to escape from the core and reach the Earth means that the mean free path of TeV photons with respect to pair production on background photons,

$$R_\gamma = \frac{1}{\sigma_{\gamma\gamma} n_{\rm soft}} \tag{5}$$

($\sigma_{\gamma\gamma} \sim \sigma_T = 6.6\times 10^{-25}$ cm^2 is the cross section of pair production for center-of-mass energies close to the pair production threshold; $n_{\rm soft}$ is the angle-dependent number density of the soft photons) is larger than the core size in the direction toward the Earth,

$$R_\gamma > R_{\rm core}. \tag{6}$$

The cross section $\sigma_{p\gamma} \sim 10^{-28}$ cm^2 of interactions of protons with the same soft photons is more than three orders of magnitude smaller than $\sigma_{\gamma\gamma}$. Thus, the mean free path for protons must be at least

$$R_p \geqslant 10^3 R_{\rm core}, \tag{7}$$

which means that just a negligible fraction of protons propagating in the direction of interest interacts with the soft photons in the core. Thus, AGN's which are the sources of TeV γ rays, like Mkn421, Mkn 501 or 1ES1426+428, cannot be strong neutrino sources, since the proton energy cannot be effectively converted into the energy of neutrinos. This, of course, does not mean that protons cannot be accelerated in TeV blazars to ultrahigh energies. The observed TeV gamma ray can be a result of synchrotron radiation from ultrahigh energy protons [34].

Of course, one can try to construct a model in which the ''hidden luminosity'' in protons exceeds the observed TeV flux by three orders of magnitude. This would cause a problem in explaining the enormous energy balance of the source.

Among the possible TeV sources 4–8 in Table I only the first three do not obey the restriction Eq. (3) and thus are similar to the confirmed TeV sources. However, PKS 2155-304 and 3C 66A obey the bound Eq. (3) and can be sources of neutrinos (if they are not real TeV sources). Let us also note, that the HBL Lac W Comae (1219+285) marked by number 9 in Fig. 3 also cannot can be a neutrino source according to Eq. (3). It is interesting to note that this source was recently suggested as a possible candidate for future TeV detection after a detailed analysis both in the synchrotron–self-Compton model and in the proton blazar model [48].

IV. MOST FAVORED NEUTRINO SOURCES

If the photon emission in the 10^{14}–10^{16} eV range is highly beamed, one would expect that the neutrino emission in the same energy range is also highly beamed since both photons and neutrinos are presumably produced through the photo pion process by protons accelerated in the AGN core. The assumption about the anisotropic character of the neutrino emission can dramatically change predictions about the possible detection of neutrino point sources in neutrino telescopes. For example, some γ-ray loud blazars, such as 3C 273 or 3C 279 which were conjectured to be strong neutrino emitters [49] would not be detected by neutrino telescopes because their jets are not oriented along the line of sight (the jet in 3C 273 has a projected size about 39 kpc, while the one in 3C 279 is 14 kpc long [50]). Moreover, blazar 3C 273 was not even included in our list of sources, because its γ-ray flux in the GeV energy range is small.

The above argumentation enables one to work out simple selection criteria for possible neutrino sources. (1) The AGN is γ-ray loud in GeV range; (2) the AGN luminosity satisfies the bound Eq. (3); (3) a large scale jet is either not observed or its length is less than 1 kpc. (The last condition roughly ensures that the AGN is seen at a viewing angle $\theta \leqslant 1°$ if we suppose that the typical length of the large scale jet is 100 kpc.)

From our list of sources (27 objects), which obey the condition 1, we exclude nine which do not obey the bound Eq. (3). Then we separated three objects in which large scale (with length more than 1 kpc) jets are detected using the catalog of extragalactic jets [50]. Those objects are listed in Table II and presented in Fig. 3 with the numbers 10–12. The 15 sources left after the selection procedure are listed in Table III.

Assuming that the GeV γ-ray flux from these sources comes mostly from the cascaded photons produced in the photopion process, we can estimate the neutrino flux from each source, using the fact that the energy deposit in photons is of the same order as the energy deposit in neutrinos in photopion production processes.

TABLE II. GeV loud blazars, which have large scale jets. Number in the first column same as in Fig. 3. Second column is the name of the object. Third is redshift. Forth is magnitude in V range (eV range). Fifth is object type, six is GeV flux in units of 10^{-8} s^{-1} cm^{-2} and the last is jet length in kpc.

No.	Name	z	V mag	Type	F_{GeV}	Jet length
10	3C 279	0.536	17.75	HPQ	6.9 ± 0.7	14 kpc
11	4C 29.45	0.729	15.60	HPQ	1.9 ± 0.5	16 kpc
12	3C 454.3	0.859	16.10	HPQ	3.5 ± 0.8	21 kpc

However, it is important to note that the γ-ray flux from a given source can be even lower than the neutrino flux for avariety of reasons. First of all, if the proton optical depth is not too high, say $\tau_p \sim 10$, very high energy (VHE) γ rays with energies $E_\gamma > 10^{17}$ eV partially escape from the AGN core and dissipate their energy in the large scale jet. Thus, the power carried by the photon beam is transmitted to the 100 kpc scale jet [27]. Next, if there is a strong (disordered) magnetic field inside the core, pairs produced by VHE photons can lose their energy mostly in synchrotron radiation rather than in inverse Compton scattering of ambient photons. In this case the power contained in the photon beam will mostly go into synchrotron photons with energies below MeV rather than to the GeV–TeV range. Finally, several sources which have jets seen face on can be very bright neutrino sources with the neutrino flux much larger then the observed GeV flux. Indeed, in the photopion process the total energy emitted in 10^{14}–10^{17} eV photons and neutrinos is of the same order. But the neutrino flux remains collimated within 1° over the whole propagation distance to the Earth, while the γ-ray flux loses its collimation during the development of electromagnetic cascades in the soft radiation background in the AGN core and in the intergalactic medium. The cascade ends in the GeV energy range and the GeV γ-ray flux from a blazar is emitted into a cone with larger opening angle, as shown in Fig. 1.

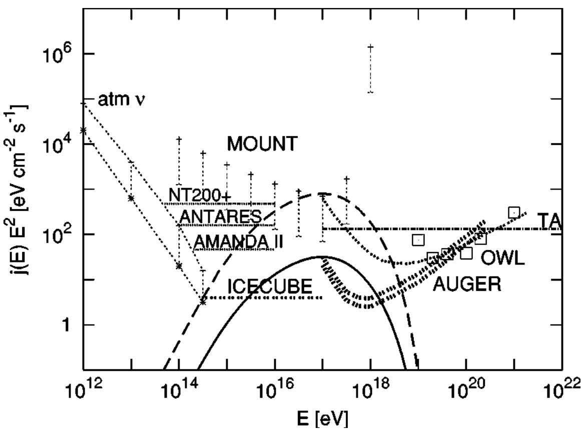

FIG. 4. Neutrino flux from typical GeV-loud blazar from Table III (thick solid line) compared with expected sensitivities to electron or muon and tau neutrinos in detectors AMANDA II [2], Auger [10], and the planned projects Telescope Array (TA) [12] (dash-dotted line), the fluorescence/Čerenkov detector MOUNT [18], the space based OWL [15] (indicated by squares) (we take the latter as representative also for EUSO), the water-based NT200+ [5], ANTARES [6] (the NESTOR [7] sensitivity would be similar to ANTARES according to Ref. [8]), and the ice-based ICECUBE [3], as indicated. All not published experimental sensitivities are scaled from the corresponding diffuse sensitivities with the same factor as ICECUBE. The dashed line is for an opening angle for neutrinos five times smaller than the opening angle for GeV photons.

In Fig. 4 we present the neutrino flux from a GeV-loud blazar in two cases: when the neutrino flux is similar to the photon flux, and when the neutrino flux is collimated in a small angle (1° degree instead of 5° for GeV photons). In the first case only ICECUBE and the Pierre Auger Observatory will be able to detect neutrino fluxes from pointlike

TABLE III. Blazars which satisfy the selection criteria 1–3. Coordinates are in the Equatorial J2000 system. GeV flux in units of 10^{-8} s^{-1} cm^{-2}.

Name	Longitude	Latitude	z	V mag	F_{GeV}	Type
QSO 0208-512	32.58	−50.93	1.003	16.9	8.5 ± 1.2	HPQ
QSO 0219+428	35.70	42.90	0.444	15.5	2.8 ± 0.7	LBL
QSO 0235+164	39.36	16.59	0.940	15.5	5.5 ± 1.2	LBL
QSO 0440-003	70.55	−0.55	0.844	19.2	1.4 ± 0.5	HPQ
QSO 0528+134	82.74	13.38	2.060	20.0	3.0 ± 0.5	LPQ
QSO 0537-441	85.02	−44.05	0.894	15.5	2.3 ± 0.7	LBL
QSO 0716+714	110.47	71.34	0.3	14.17	1.9 ± 0.5	LBL
QSO 0954+556	148.01	55.02	0.901	17.7	1.4 ± 0.4	HPQ
QSO 1406-076	212.42	−7.75	1.494	18.4	2.0 ± 0.6	LPQ
QSO 1611+343	243.54	34.40	1.401	17.5	2.3 ± 0.8	LPQ
QSO 1633+382	248.92	38.22	1.814	18.0	4.8 ± 1.1	LPQ
QSO 1730-130	263.46	−13.23	0.902	18.5	2.4 ± 0.6	FSRQ
QSO 2005-489	302.4	−48.8	0.071	13.4	2.2 ± 0.8	FSRQ
QSO 2022-077	306.36	−7.75	1.388	18.5	2.5 ± 0.8	FSRQ
QSO 2155-304	329.0	−30.5	0.116	13.1	<1.5	HBL

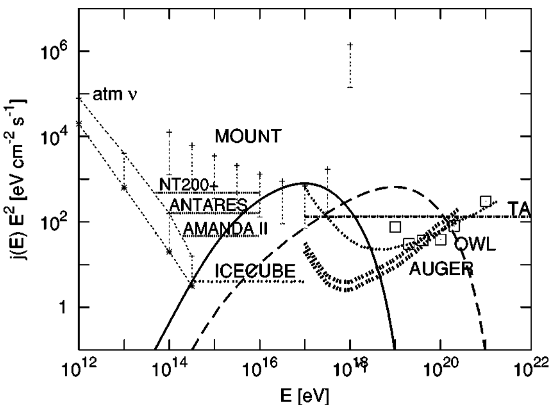

FIG. 5. Same neutrino flux as in Fig. 4 for 1° opening angle in the case $E_p \sim 10^{19}$ eV (solid line) and neutrino flux from the same source in the case $E_p \sim 10^{21}$ eV (dashed line). Fluxes are compared to the sensitivities of future detectors. Line keys for experiments are the same as in Fig. 4.

sources. In the second case many other experiments will be able to see the neutrino flux from the sources in Table III. However, the smaller opening angle for the neutrino flux will reduce the number of neutrino sources.

V. ULTRAHIGH ENERGY NEUTRINOS FROM BLAZARS

In the previous section we considered the case when protons are accelerated up to energies 10^{18}–10^{19} eV. However, UHECR's with energies up to 3×10^{20} eV [51] were observed. This means that in principle the sources of UHECR can accelerate protons at least up to energies $E\sim10^{21}$ eV. Let us note here that the recent disagreement in results between the AGASA [52] and HiRes [53] experiments does not raise a question of the existence or nonexistence of events with energy $E>10^{20}$ eV. Both experiments detect events at those energies and there is disagreement only in the number of such events.

It is interesting to note that the bound Eq. (3) on the magnitude of the redshift of blazars which can be neutrino loud can be converted into a bound on UHECR-loud sources, if we just turn $\gg$ into $\ll$. Indeed, if we suppose that ultrahigh energy protons and photons are able to leave the core of AGN's the optical depth for them must be extremely low. In this respect we note that the set of EGRET blazars presented in Table III is "anticorrelated" with the selection of EGRET blazars whose positions coincide with the arrival directions of UHECR's presented in [54].

However, blazars with large optical depths for protons still could be significant sources of UHE neutrinos if we assume that protons are accelerated in the source up to energies 10^{20}–10^{21} eV. The resulting neutrino spectrum will be very different from the one discussed in the previous section. We present both spectra in Fig. 5. The neutrino flux from blazars accelerating protons up to the highest energies will be peaked in the region 10^{19} eV or above and will be seen by future UHECR experiments, while neutrino flux from "moderate accelerators" of protons will be peaked at the energies 10^{16}–10^{17} eV and can be detected by future neutrino telescopes. Let us note that constraints on neutrino sources, discussed recently in [55], are not applicable to blazars, which produce neutrinos in the AGN cores.

As is argued at the end of Sec. IV, the detected γ-ray flux from a given blazar can serve only as a "hint," not as the upper limit on the neutrino flux. By the same arguments this is also true for the case of the flux of UHE neutrinos. Blazars in which the neutrino flux is peaked at high energies as in Fig. 5 and is collimated in a smaller opening angle as compared to the photon flux can serve as "pure neutrino sources," which are required for the so-called Z-burst model. In the Z-burst scenario the UHECRs are produced by Z bosons decaying within the distance relevant for the Greisen-Zatsepin-Kuzmin effect [56]. These Z bosons are in turn produced by UHE neutrinos interacting with the relic neutrino background [57] (for recent detailed numerical simulations see [58,59]). The flux of photons from astrophysical sources in this model should be significantly suppressed in comparison to the neutrino flux, otherwise the Z-burst model would be ruled out, as demonstrated in Ref. [58]. The spectrum presented in Fig. 5 can serve as a prototype for the spectrum from a "pure neutrino source." However, in the Z-burst model the protons should be accelerated to even higher energies $E>10^{23}$ eV and the UHECR's with highest energies $E>10^{20}$ eV should come from a few strong neutrino sources. The last condition is required to overcome the bound on the diffuse neutrino flux [26], which comes from the diffuse gamma-ray flux measured by EGRET [60].

VI. CONCLUSIONS

In this work we considered conditions under which γ-ray loud blazars can be significant neutrino sources. High energy neutrinos are produced in the photopion interactions of protons accelerated in AGN cores with a soft photon background. We derived the bound Eq. (3) on the redshift and V magnitude of the candidate neutrino-loud blazars. From 27 GeV–TeV γ-ray loud blazars we selected the 15 most favored candidates which satisfy the criteria 1–3 listed in Sec. IV.

An estimate of the neutrino flux from a given object can be obtained from the observed γ-ray flux if we assume that the main contribution to the GeV–TeV luminosity of a blazar comes from the electromagnetic cascade initiated by 10^{14}–10^{16} eV photons which are produced together with neutrinos in photopion reactions. It is important to note that the neutrino flux from a given source can be much higher than the γ-ray flux detected by EGRET or other γ-ray telescopes for the variety of reasons listed in Sec. IV.

Because the optical depth for TeV photons in the AGN core is three orders of magnitude smaller than the optical depth for protons in the same photon background we conclude that confirmed TeV-loud blazars cannot be sources of significant neutrino flux. (At the same time, this argument does not exclude the possibility that these objects can be neutrino sources from UHECR protons which produce neutrinos in interactions with CMBR photons.)

We considered the model in which the neutrino flux is highly beamed in the directions of the large scale jets emitted by the AGN. This model has several experimentally testable predictions. First, GeV-loud sources in which the large scale jets are not seen face on (like 3C 279) cannot be neutrino sources. Next, the neutrino flux from a given source can be much larger than the observed gamma-ray flux due to the smaller opening angle for neutrinos as compared to GeV gamma rays.

We also found that if the optical depth for protons is large enough and protons are accelerated up to the highest energies 10^{20}–10^{21} eV, the same sources from Table III can be seen both by future UHECR detectors and by neutrino telescopes (see Fig. 5).

We conclude that the next generation of neutrino telescopes and UHECR detectors will have a good chance of seeing pointlike neutrino sources.

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