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 neutrino flux is highly beamed along the rotation axis of the central black hole. The enhancement of neutrino flux compared to GeV $\gamma$-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 $\gamma$-ray loud ones. We present the table of 15 blazars which are the most likely candidates for the detection by future neutrino telescopes.

I. INTRODUCTION

Neutrino telescopes which already operate or 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 AMANDA [1, 2] and its next generation version ICECUBE [3], 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 Ultra-High Energy Cosmic Ray (UHECR) experiments like the Pierre Auger Observatory [9, 10] will be able to detect neutrinos with energies above $10^{17}$ eV. If neutrino flux at high energies above $10^{17}$ eV the telescope array will also measure the neutrino flux. The flux from point-like sources at those energies can be a combination of the direct flux from a source and the secondary neutrino flux produced by Ultra-High Energy (UHE) protons emitted by the source in interactions with cosmic microwave background radiation (CMBR) photons. If neutrino flux at high energies $E > 10^{17}$ eV is large enough to give more then 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.

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 [11]. The alternative of detecting neutrinos by triggering onto the radio pulses from neutrino-induced air showers is also currently investigated [12]. Two implementations of this technique, RICE, a small array of radio antennas in the South pole ice [13], and the Goldstone Lunar Ultra-high energy neutrino Experiment (GLUE) [14], have so far produced neutrino flux upper limits. Acoustic detection of neutrino induced interactions is also being considered [15].

The simplest way to produce neutrinos in astrophysical objects is to accelerate protons and then collide them with soft photon background with energy above photo-pion production threshold. The produced pions will decay in photons, electrons, positrons and neutrinos. If protons are captured within the source, the estimate on neutrino flux from a given source can be obtained from the detected $\gamma$-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 than a limit on diffuse neutrino flux from all the possible sources can be obtained from the detected high-energy proton flux. This idea was first suggested in [16]. For a particular case of $E^{-2}$ proton spectrum coming from AGN’s the calculation was done in [17]. The same calculation for $E^{-1}$ proton flux was made in [18]. In [19] the dependence of neutrino flux from proton spectrum, cosmological parameters and distribution of sources was investigated in details. In particular it was shown that in many cases neutrino flux can exceed value calculated in [17] or even value of [18] and only bound on diffuse neutrino flux come from 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 (AGN), which we see almost face on) in the MeV-TeV energy range is highly anisotropic. Typical estimates of the $\gamma$ factors of the emitting plasma, $\gamma \sim 10$, imply that in the $10^{0-13}$ eV band almost all $\gamma$-ray flux is radiated in a cone with the opening angle $\theta \sim 1/\gamma \sim 5^\circ$. Particles (photons, neutrinos) in the higher energy range $E > 10^{13}$ eV can be emitted in an even narrower cone. This fact favors blazars as promising neutrino sources.

Recent X-ray observations of large-scale jets in AGN can shed some light on the issue of particle acceleration to the energies much above TeV in the AGN cores. Indeed, in order to explain X-ray synchrotron emission on very large scales of order of 100 kpc away from the AGN core one needs to suppose that multi-TeV electrons are con-
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 Fig. 1 and 2). The idea is that \(\gamma\)-rays with energies \(10^{14-18}\) 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 AGNs enables to conclude that (1) particles with energies \(E \geq 10^{14-18}\) eV are produced in the AGN cores and (2) these particles are normally emitted in a cone with opening angle \(\theta \sim 1^\circ\). The diffuse neutrino flux in this model was calculated in \[24\]. 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 which can be significant point sources of neutrinos were analyzed in \[23, 28, 29, 30\]. 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 \[30\]. Predictions of the model \[27\] are quite different. In particular, none of the three above cited blazars enters our list of most probable neutrino sources.

In Section II we will discuss a 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 Section IV we will derive the neutrino fluxes from 15 blazars which are the most promising neutrino sources. In Section 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 photo-pion process. 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/UV (or "blue bump") photons produced by the inner part of accretion disk.

As an example, the neutrino production mechanism in model \[27\] 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 horizon is converted in the core into a beam of secondary particles such as \(\gamma\)-quanta, neutrinos, electrons and positrons. The beam of high-energy \(\gamma\)-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 AGNs which are not seen in TeV range, no direct estimate of optical depth for protons in a given direction is possible because \(\gamma\)-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 assuming that the optical/UV background is isotropic and is produced inside the region of the size of order of \(R_{\text{core}} \sim 10^{16}\) cm as it is indicated by typical optical/UV variability of AGNs \[32\]. If the flux from the source is \(\nu F_{\nu}\), 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

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

(1)

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

$$R_p = \frac{1}{\sigma_T n_{soft}} = \frac{\epsilon R_{\text{core}}^2 \epsilon}{\sigma_T (\nu F_\nu) D_L^2}.$$

(2)

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

$$\frac{D_L^2 (\nu F_\nu) \nu_{13} \sigma_T}{\epsilon V R_{10}} \gg 1,$$

(3)

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

The luminosity distance depends on the cosmological model. For our calculations we choose the best motivated at present cosmological model. 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:

$$D_L = \frac{1 + z}{H_0 \sqrt{\Omega_M}} \int_1^{1+z} \frac{dx}{\sqrt{H_0^2 + x^3}}.$$

(4)

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

The bound Eq. (3) imposes a restriction on the blazar redshift and magnitude which is shown on Fig. 1 (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 photo-pion interaction a proton looses only a fraction (typically 20%) of its energy.

An estimate (but not an upper limit, see below Section IV) of the neutrino flux from sources which satisfy the constraint Eq. (3) can be obtained from the detected $\gamma$-ray flux. The GeV $\gamma$-rays can be produced in the AGN core through a variety of mechanisms: inverse Compton scattering of soft background photons like in synchrotron-self Compton model [3], synchrotron radiation of very-high energy protons in extreme proton synchrotron model [4], development of electromagnetic cascade initiated by photo-pion production in proton blazar models [5]. Neutrinos can be produced only in the last case. In the following we will suppose that photo-pion 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 the high energy neutrinos are produced together with the high energy photons in photo-pion reaction, the presence of high energy photons in the spectrum of a given source can serve as an indicator for a possible neutrino flux from this source. However, produced high energy photons still can interact with the background photons both in the source and on the way to the Earth, cascading down to the 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. Thus, 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 (8 sources) presented in the Table 1. TeV gamma-rays from the first three sources in this table are confirmed by several experiments with high significance, while the last 5 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 GeV region. Thus, the total number of sources in our analysis is 27. We used NED [40] and Simbad [41] databases to find 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

| NAME      | z     | V mag | Type     | Telescopes       |
|-----------|-------|-------|----------|------------------|
| 1 Mkn 421 | 0.031 | 13.5  | HBL      | CAT, HEGRA, WHIPPLE [33] |
| 2 Mkn 501 | 0.0337| 13.8  | HBL      | CAT, HEGRA, WHIPPLE [33] |
| 3 1ES 1426-428 | 0.129 | 16.5  | HBL      | CAT, HEGRA, WHIPPLE [33] |
| 4 1ES 2344+514 | 0.044 | 15.5  | HBL      | WHIPPLE [40] |
| 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 [43] |

**TABLE 1:** TeV loud blazars. Number in the first column same as in Fig. 1. Second column is the name of the object. Third is redshift. Forth is magnitude in V range (eV range). Fifth is BL Lac type, and the last is experiment name and reference.
The energy of blue bump photons is taken to be $2.26\text{ eV}$.

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,

$$R_\gamma = \frac{1}{\sigma_{\gamma\gamma} n_{soft}}, \quad (5)$$

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

$$R_\gamma > R_{core}. \quad (6)$$

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

$$R_p \geq 10^3 R_{core}, \quad (7)$$

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

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

Among the possible TeV sources 4-8 in Table II only the first three do not obey the restriction Eq. (3) and thus their neutrino flux is suppressed as compared to the photon flux. So, 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,

$$R_\gamma = \frac{1}{\sigma_{\gamma\gamma} n_{soft}}, \quad (5)$$

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

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

Among the possible TeV sources 4-8 in Table II 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 neither 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 the detailed analysis both in the synchrotron-self-Compton model and in the proton blazar model [18].

### IV. Most Favorite Neutrino Sources.

If the photon emission in the $10^{14}-16\text{ eV}$ 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 the protons accelerated in the AGN core. The assumption about an anisotropic character of the neutrino emission can change dramatically predictions about possible detection of neutrino point sources in neutrino telescopes. For example, some γ-ray loud blazars, like 3C 273 or 3C 279 which were conjectured to be strong neutrino emitters [49], would not be

### TABLE II: GeV loud blazars, which have large scale jets.

| N  | 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     |
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 on synchrotron radiation rather than on inverse Compton scattering of ambient photons. In this case the power contained in the photon beam will mostly go into synchrotron photons with the energies below MeV rather than to GeV-TeV ranges. Finally, several sources which have jets seen face-on can be very bright neutrino

| NAME          | Longitude | Latitude | z    | V mag | $F_{\text{GeV}}$ | 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     | 16.39    | 0.940 | 15.5  | 5.3 ± 1.2        | LBL  |
| QSO 0440+603 | 70.55     | -0.55    | 0.844 | 19.2  | 1.4 ± 0.5        | HPQ  |
| QSO 0525+134 | 82.74     | 13.38    | 2.060 | 20.0  | 3.0 ± 0.5        | LPQ  |
| QSO 0537+714 | 85.02     | -44.05   | 0.894 | 15.5  | 2.3 ± 0.7        | LBL  |
| QSO 0616+714 | 110.47    | 71.34    | 0.3   | 14.17 | 1.9 ± 0.5        | LBL  |
| QSO 0954+156 | 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 1633-392 | 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  | 1.9 ± 5.5        | HBL  |

The AGN luminosity satisfies the bound Eq. (3). A large scale jet is either not observed or its length is less than 1 kpc.

(The last condition roughly insures that the AGN is seen at a viewing angle $\theta \lesssim 1^\circ$ if we suppose that the typical length of the the large scale jet is 100 kpc.)

From our list of sources (27 objects), which obey the condition 1, we exclude 9 which do not obey the bound Eq. (3). Then we have separated 3 objects in which the large scale (with length more than 1 kpc) jets are detected using the catalog of extragalactic jets [4]. Those objects are listed in Table I and presented in Fig. 3 with the numbers 10-12. The 15 sources left after the selection procedure are listed in the Table II.

Assuming that the GeV $\gamma$-ray flux from these sources comes mostly from the cascaded photons produced in the photo-pion 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 photo-pion production process.

However, it is important to note that the $\gamma$-ray flux from a given source can be even lower than the neutrino flux due to a variety of reasons. First of all, if the proton optical depth is not too high, say $\tau_p \sim 10$, VHE $\gamma$-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

FIG. 4: Neutrino flux from typical GeV-loud blazar from Table I (thick solid line) compared with expected sensitivities to electron/µon and tau-neutrinos in detectors AMANDA II [3], Auger [10], and the planned projects: Telescope Array (TA) [12] (dashed-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 according to Ref. [8], and the numbers 10-12. The 15 sources left after the selection procedure are listed in the Table II.
sources with the neutrino flux much larger then the observed GeV flux. Indeed, in the photo-pion process the total energy emitted in $10^{14} - 10^{17}$ eV photons and neutrinos are of the same order. But the neutrino flux remains collimated within 1° all over the propagation distance to the Earth, while the $\gamma$-ray flux looses its collimation during the development of electromagnetic cascades on the soft radiation background in the AGN core and in the intergalactic medium. The cascade ends in the GeV energy range and the GeV $\gamma$-ray flux from a blazar is emitted into a cone with larger opening angle, as it is shown in Fig. [1].

In Fig. [1] we presented neutrino flux from GeV-loud blazar in two cases: when the neutrino flux is similar to photon flux, and when neutrino flux is collimated in small angle (1 degree instead of 5 degree for GeV photons). In first case only ICECUBE and Pierre Auger Observatory will be able to detect neutrino fluxes from point-like sources. In the last case many other experiments will be able to see the neutrino flux from the sources in the Table [11]. However, the smaller opening angle for neutrino flux will reduce the number of neutrino sources.

V. ULTRA-HIGH ENERGY NEUTRINOS FROM BLAZARS.

In the previous Section we have considered the case when protons are accelerated up to the energies $10^{18} - 10^{19}$ eV. However, UHECR with energies up to $3 \times 10^{20}$ eV were observed. This means that in principle the sources of UHECR can accelerate protons at least up to energies $E \sim 10^{21}$ eV. Let us note here, that the recent disagreement in results between AGASA [52] and HiRes [53] experiments does not raise the question of the existence or non-existence 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. (1) on the magnitude-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 ultra-high energy protons and photons are able to leave the core of AGN the optical depth for them must be extremally low. In this respect we note that the set of EGRET blazars presented in Table [11] is ”anti-correlated” with the selection of EGRET blazars whose positions coincide with the arrival directions of UHECR presented in [2].

However, blazars with large optical depth 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 presented both spectra in Fig. [3]. 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 [52], are not applicable to blazars, which produce neutrinos in the AGN cores.

As it is argued at the end of Section IV, the detected $\gamma$-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 flux of UHE neutrinos. Blazars in which the neutrino flux is peaked at high energies as in Fig. [5] and is collimated in 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 (GZK) effect [58]. 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. [28]. The spectrum presented in Fig. [3] can serve as a prototype for the spectrum from a ”pure neutrino source”. However, in Z-burst model the protons should be accelerated even to higher energies $E > 10^{23}$ eV and the UHECRs with highest energies $E > 10^{20}$ eV should come from few strong neutrino sources. The last condition is required to overcome bound on diffuse neutrino flux [20], which come from diffuse gamma-ray flux, measured by EGRET [11].

VI. CONCLUSIONS

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

An estimate of the neutrino flux from a given object can be obtained from the observed $\gamma$-ray flux if we assume that the main contribution to the GeV-TeV luminosity of a blazar comes from the electromagnetic cascade initiated by $10^{14-16}$ eV photons which are produced together with neutrinos in photo-pion reactions. It is important to note that the neutrino flux from a given source can be much higher than the $\gamma$-ray flux detected by EGRET or other $\gamma$-ray telescopes due to the variety of reasons listed in Section 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 not 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 have 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 a smaller opening angle for neutrinos as compared to GeV gamma-rays.

We have 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. 3.

We conclude that the next generation of neutrino telescopes and UHECR detectors will have a good chance to see point-like neutrino sources.

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