

Sensitivity of Baikal-GVD neutrino telescope to neutrino emission toward the center of Galactic dark matter halo

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We analyse sensitivity of the gigaton volume telescope Baikal-GVD for detection of neutrino signal from dark matter annihilations or decays in the Galactic Center. Expected bounds on dark matter annihilation cross section and its lifetime are found for several annihilation/decay channels.

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There is a lot of evidence on existence of dark matter (DM). Cosmological observations indicate that DM contributes about 27% in total energy density within Λ CDM model. Weakly Interacting Massive Particles (WIMP) are among the most interesting candidates for the dark matter. Currently, tremendous efforts are put in the searches for DM at colliders, in direct detection experiments and, finally, in indirect searches for a signal in products of WIMP annihilations/decays in astrophysical observations. The Galactic Center (GC) is a very promising region to look for such a signal. Recent analysis of gamma telescope FERMI-LAT dataset performed by few groups for several years of observation indicates on the existence of a diffuse gamma-ray excess from the center of our Galaxy at energies 10–20 GeV and a gamma-line feature about 133 GeV with a significance about 3σ [1]. There are many systematic uncertainties here due to gamma-ray background from galactic diffuse emission and from close around local astrophysical

sources like pulsars or supernova remnants. Another attractive possibility is to look for neutrino signal from DM and it has been put forward by neutrino telescope collaborations. Recently the IceCube collaboration announced four dozen candidates [2] for neutrinos of astrophysical origin with energies above hundreds TeV. However there is no any significant clustering of events in any direction.

New Baikal-GVD project aimed on installation of gigaton volume detector in lake Baikal [3–5] is now in progress. The main goal of GVD telescope is a search for neutrinos of astrophysical origin. Here, we estimate one year sensitivity to look for possible neutrino signal from dark matter in the center of our galaxy for the GVD telescope in planned configuration of 12 clusters composed by 2304 photodetectors per 96 strings. The telescope GVD is building in a place of previous telescope NT200 [6] in the south basin of the Lake Baikal, at a distance 3.5 km off the shore. Local coordinates are 51.83° N and 104.33° E. Position provides average visibility for the GC almost 75% per day.

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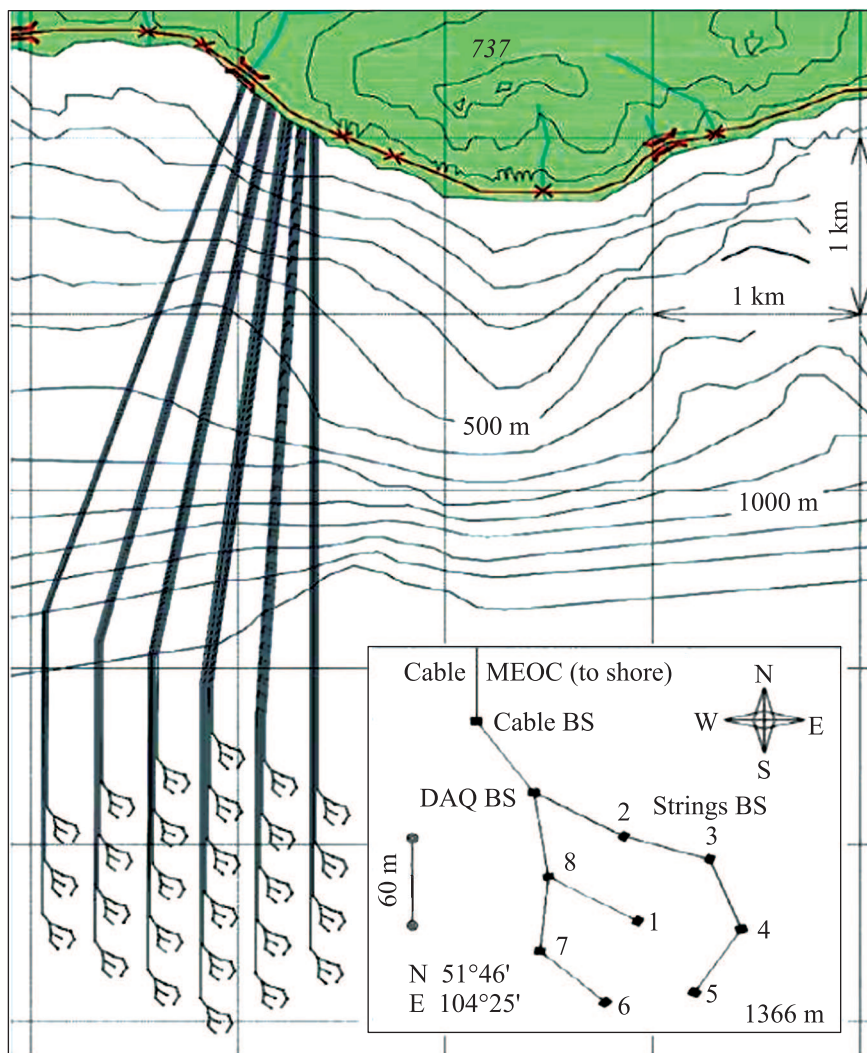


Fig. 1. Layout of the GVD. In inner box the one cluster is shown

Actual position of the center of Galaxy to be used is taken with right ascension $\approx 266.42^\circ$ and declination $\approx -29.01^\circ$.

The Baikal water optical properties have been studied for a long time and are characterized by absorption length 20–24 m at 480 nm and a scattering length 30–70 m depending on season. The total trigger rate is expected to be approximately 100 Hz, dominated by downgoing atmospheric muons. The detection of relativistic particles crossing effective volume of a deep underwater telescope implies collection of their Cherenkov radiation by optical modules (OMs) synchronized in time and calibrated in pulses. Events arriving from down hemisphere are considered as candidates on those originated from neutrino scatterings off nucleons in surrounding water or rock. The main challenge is to suppress atmospheric muon background from upper hemi-

sphere exceeding upward going neutrino flux by factor 10^6 .

Stages of the GVD telescope design, its commissioning and deployment of the first prototypes are successfully completed. Presently there are five strings of the first demonstration cluster operating since April 2014 [7, 8]. The first cluster with eight strings will be fully deployed next April 2015. The Baikal-GVD is designed as 3D arrays of photomultiplier tubes (PMTs) each enclosed in an optical module. Each optical module consists of a pressure-resistant glass sphere with 43.2 cm diameter which holds OM electronics and PMT surrounded by a high permittivity alloy cage for shielding it against the Earth's magnetic field. Large photomultiplier tube Hamamatsu R7081-100 is selected as light sensor of OM. The tube gain adjusted to about 10^7 and factor 10 by the first channel of the preamplifier results

in a spectrometric channel linearity range up to about 100 photoelectrons (see [7] for details). The OMs are arranged on vertical load-carrying cables to form strings. Clusters of strings form functionally independent sub-arrays connected to shore by individual electro-optical cables as shown in Fig. 1. Each cluster has a central string identical to seven others distant at radius of 60 meters. The OMs are spaced by 15 m along each string and are faced downward. They are combined in sections on each string. In current design there are two sections on cluster. The distance between the central strings of neighboring clusters is 300 m. Details of data acquisition, basic controls, methods of calibrations, hard- and soft-ware triggers can be found in [4, 5, 7]. For the present study we apply a muon trigger formed by requirements to select events with at least 6 fired OMs on at least 3 strings within 500 ns. Here we make a conservative estimate and suppose the worse situation with angular resolution 4.5° for track events. The neutrino effective area at trigger level selection (3/6) as a function of energy for one cluster for neutrinos from GC is presented in Fig. 2 by black line.

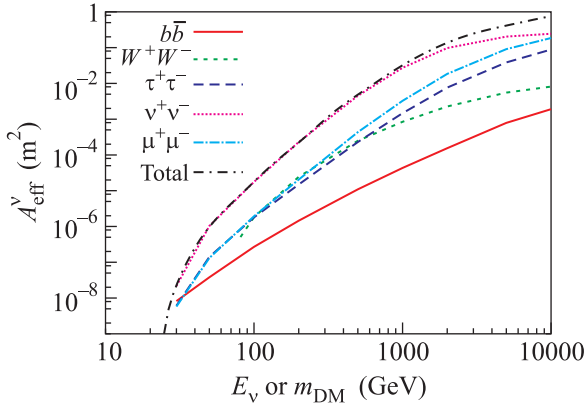


Fig. 2. Neutrino effective area of single Baikal-GVD cluster (black) and averaged over neutrino spectra effective areas for different annihilation channels (color)

Expected neutrino flux from DM annihilations in the Galaxy has the following form

$$\frac{d\phi_\nu}{dE} = \frac{\langle\sigma_{Av}\rangle}{2} J_2(\psi) \frac{R_0 \rho_{\text{local}}^2}{4\pi m_{\text{DM}}^2} \frac{dN_\nu}{dE}. \quad (1)$$

Here, $\langle\sigma_{Av}\rangle$ is annihilation cross section averaged over DM velocity distribution, dN_ν/dE is neutrino (and antineutrino) spectrum per act of annihilation. The dimensionless quantity $J_2(\psi)$ is the square of the DM density in MW, $\rho^2(r)$, integrated along the line of sight and

rescaled by the distance from GC to the Solar system R_0 and by the local DM density ρ_{local} as follows

$$J_2(\psi) = \int_0^{l_{\text{max}}} \frac{dl}{R_0} \frac{\rho^2 \left(\sqrt{R_0^2 - 2rR_0 \cos \psi + r^2} \right)}{\rho_{\text{local}}^2}, \quad (2)$$

where ψ is the angular distance from GC to the direction of observation and the integration in (2) goes to l_{max} which is much larger than the size of the Galaxy. There are several models for the DM density profile in the galaxies and, in particular, in the Milky Way²⁾. Here we consider Navarro–Frenk–White (NFW) [10, 11], the Kravtsov et al. [12], the Moore et al. [13], and Burkert [14] profiles. The last model is currently favored by the observational data [15]. The profiles can be parametrized by

$$\rho(r) = \frac{\rho_0}{(\delta + r/r_s)^\gamma [1 + (r/r_s)^\alpha]^{(\beta-\gamma)/\alpha}}, \quad (3)$$

where numerical quantities are presented in Table.

Parameters of DM density profiles

Model	α	β	γ	δ	r_s , kpc	ρ_0 , GeV/cm ³
NFW	1	3	1	0	20	0.3
Kravtsov	2	3	0.4	0	10	0.37
Moore	1.5	3	1.5	0	28	0.27
Burkert	2	3	1	1	9.26	1.88

In the case of dark matter decay in the Galaxy expected neutrino flux is

$$\frac{d\phi_\nu}{dE} = \frac{1}{\tau_{\text{DM}}} J_1(\psi) \frac{R_0 \rho_{\text{local}}}{4\pi m_{\text{DM}}} \frac{dN_\nu}{dE}, \quad (4)$$

where τ_{DM} is DM particle lifetime and $J_1(\psi)$ is the following integral

$$J_1(\psi) = \int_0^{l_{\text{max}}} \frac{dl}{R_0} \frac{\rho \left(\sqrt{R_0^2 - 2rR_0 \cos \psi + r^2} \right)}{\rho_{\text{local}}}. \quad (5)$$

Neutrino spectra from dark matter annihilation/decay have been taken from [16]. We consider $b\bar{b}$, $\tau^+\tau^-$, $\mu^+\mu^-$, W^+W^- , and $\nu\bar{\nu}$ channels, where in the latter case we assume flavor symmetric annihilation. Note that the authors of [16] artificially modified the neutrino spectra for $\nu\bar{\nu}$ to be able to solve their evolution equations which resulted to a large smearing of the monochromatic line. We change these spectra back to their physical width conserving the absolute

²⁾We do not take into account DM substructures which in general could modify the results [9].

norm³⁾. For calculation of muon-neutrino energy spectra at the Earth we use probabilities for long-baseline oscillations. As neutrino oscillation parameters we use [17] the following values: $\Delta m_{21}^2 = 7.6 \cdot 10^{-5} \text{ eV}^2$, $\Delta m_{31}^2 = 2.48 \cdot 10^{-3} \text{ eV}^2$, $\delta_{\text{CP}} = 0$, $\sin^2 \theta_{12} = 0.323$, $\sin^2 \theta_{23} = 0.567$, $\sin^2 \theta_{13} = 0.0234$. Neutrino spectra at the Earth level are presented in Fig. 3 for

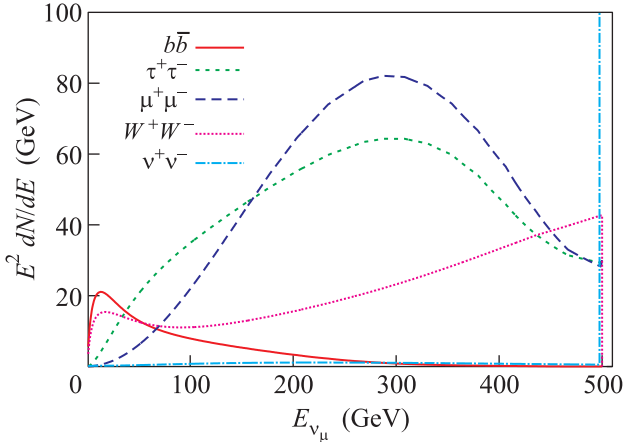


Fig. 3. Neutrino ν_μ energy spectra at the Earth for $m_{\text{DM}} = 500 \text{ GeV}$

$m_{\text{DM}} = 500 \text{ GeV}$. We simulate neutrino propagation through the Earth and obtain muon flux at the level of the detector as it was described in [18, 19].

To estimate the sensitivity of GVD to neutrinos from dark matter annihilations in GC we choose a search region as a cone around the direction towards the GC with half angle ψ_0 . The expected number of signal events in the search region for the livetime T is estimated as

$$N(\psi_0) = T \frac{\langle \sigma_{Av} \rangle R_0 \rho_{\text{local}}^2}{8\pi m_{\text{DM}}^2} J_{2,\Delta\Omega} \int dE S(E) \frac{dN_\nu}{dE}. \quad (6)$$

Here $S(E)$ is neutrino effective area of the telescope. In Fig. 2 along with effective area of one cluster (black) we show effective areas averaged over given neutrino spectrum dN_ν/dE for neutrinos coming from GC. The factor $J_{2,\Delta\Omega}$ is obtained by averaging of $J_2(\psi)$ over the search region

$$J_{2,\Delta\Omega} = \int d(\cos \psi) d\phi J_2(\psi) \epsilon(\psi, \phi), \quad (7)$$

where $\epsilon(\psi, \phi)$ is visibility of the corresponding point on the sky by the telescope.

The atmospheric neutrino background is estimated from MC simulations with trigger conditions described

³⁾We are grateful to Marco Cirelli for the correspondence on this issue.

above. The average total number of background events coming from low hemisphere for one year is expected to be 4300. Distribution of background events in angular distance from GC is shown in Fig. 4 in green. Angular

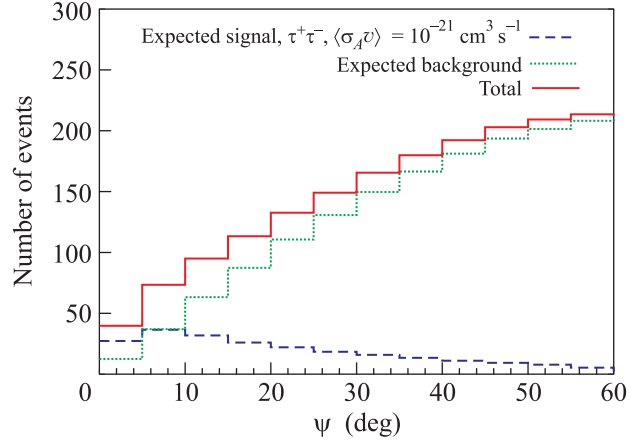


Fig. 4. Distribution of background and signal events in angular distance from GC

distribution of signal events for $\tau^+\tau^-$ annihilation channel with $m_{\text{DM}} = 200 \text{ GeV}$ and $\langle \sigma_{Av} \rangle = 10^{-21} \text{ cm}^3 \text{ s}^{-1}$ is also shown in this Figure in blue. Using the differences in their angular distributions we optimize the size of the search region with respect to cone half-angle in the following standard way. Assuming absence of the signal we construct the ratio $\bar{N}^{90}(\psi_0)/\sqrt{N_B}$ where $\bar{N}^{90}(\psi_0)$ is 90% CL upper limit on number of events in the given cone averaged over number of observed events with Poisson distribution and N_B is expected number of background events. We maximize it with respect to ψ_0 and obtain optimized values of cone half angles vary from 9° for hard ($\nu\bar{\nu}$) channels and large DM masses to 21° for soft channels ($b\bar{b}$) and small values of m_{DM} .

The expected upper bounds on dark matter annihilation cross section have been obtained from (6) where $N(\psi_0)$ were replaced by $\bar{N}^{90}(\psi_0)$. Further, we include realistic estimates for detection efficiency $\epsilon = 0.6$ and systematic uncertainties $\eta = 50\%$, into the bounds as $\bar{N}^{90}(\psi_0)/[\epsilon(1-\eta)]$. The sensitivity to DM annihilation cross sections for NFW density profile is shown in Figs. 5 and 6 in comparison with the results/sensitivities of other experiments FERMI [20], MAGIC [21], H.E.S.S. [22], IceCube [23, 24], ANTARES [25] and with the results of DM interpretation of positron excess [26]. Also our estimates show possible improvement in the bounds for better angular resolution of 1° up to 8–10%.

To get expected low bound on the DM lifetime τ_{DM} we use the search regions obtained before and apply

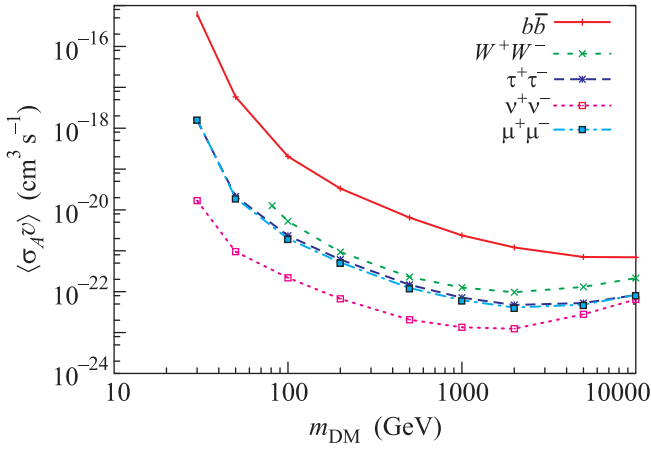


Fig. 5. Sensitivity of GVD to $\langle\sigma v\rangle$ for one year for different annihilation channels

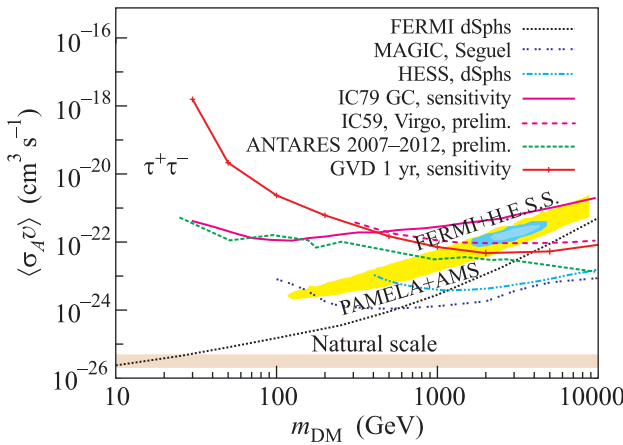


Fig. 6. Sensitivity of GVD to $\langle\sigma v\rangle$ in comparison with other experiments

Eq. (5). We plot GVD sensitivity to DM decays for NFW profile in Fig. 7

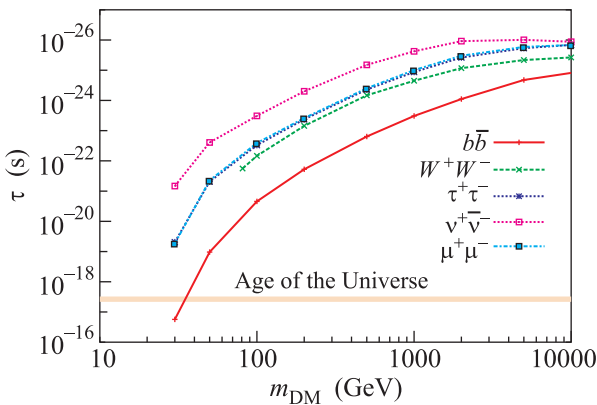


Fig. 7. GVD-Baikal sensitivity to τ_{DM} for $T = 1$ yr

for chosen set of decay channels. We note that the angular distribution of signal events in the case of DM decay is different from the case of its annihilation. We perform new optimization with respect to the search region for decaying DM and the optimal values of ψ_0 are obtained to be about 70° which is well beyond the neighbourhood of GC. From this analysis we expect an improvement by factor 2–3 in the bounds on τ_{DM} with searches in the whole Galactic halo.

There are several theoretical uncertainties in the number of signal events related to neutrino oscillation parameters, neutrino-nucleon cross section etc. However, the most important of them is the uncertainty related to our lack of knowledge of DM density profile near GC. To illustrate this issue in Fig. 8 we plot J_2 -factors

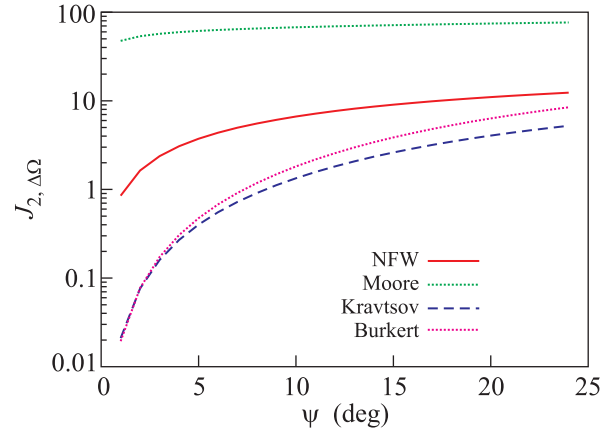


Fig. 8. J_2 -factors for different models of dark matter density profile

for different models of DM distribution. We see that the difference can reach several orders of magnitude. Note that the factor J_1 is less model dependent.

To summarize, we studied the GVD sensitivity to DM annihilations/decays in GC for 1 year of livetime at trigger selection level. The expected bounds for realistic efficiency and systematic uncertainties reach values about 10^{-23} cm³ s⁻¹ for dark matter annihilation cross section and 10^{26} s for DM lifetime in the most energetic $\nu\bar{\nu}$ channel. Improved sensitivity is expected for heavy DM particles with km³-square upgrade of Baikal-GVD.

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