ФИЗИКА ЭЛЕМЕНТАРНЫХ ЧАСТИЦ И АТОМНОГО ЯДРА
2016. Т. 47. ВЫП. 6

NEUTRINO SIGNAL AT THE BAIKAL FROM DARK MATTER IN THE GALACTIC CENTER

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We discuss neutrinos originating from Dark Matter in the Galactic Center and present the sensitivity of the Baikal Gigaton Volume Detector to this signal.

PACS: 95.35.+d; 95.85.Ry

INTRODUCTION

Dark Matter (DM) is nowadays a great mystery. There is a lot of evidence in favor of its existence [1]. Behavior of galaxy rotation curves proves that the gravitating mass of galaxies extends well beyond its visible mass. Weak gravitational lensing of distant objects like galaxy clusters indicates that there is a lot of unaccounted mass on the way of the light from them to the Earth. Observations of hot gas in galaxy clusters like Coma Cluster require existence of a deep potential well, which in turn requires an additional mass. Dark Matter also has great influence on the evolution of the Universe which gives evidence for its existence from the Big Bang Theory: measuring of cosmic microwave background anisotropy, structure formation and nucleosynthesis — all that tells us that the Dark Matter compounds about 25% of the total energy density of the Universe. There are a lot of Dark Matter models which have been proposed to explain observations and solve other experimental and theoretical problems of the Standard Model (SM). Among the particle DM candidates are neutralinos or gravitinos in supersymmetric theories, Kaluza–Klein states in theories with extra dimensions, axions, sterile neutrinos, etc.

Different DM candidates require different production mechanisms in the Early Universe. One of the most popular DM paradigms which unifies several classes of DM models is weakly interacting massive particles or WIMPs (see, e.g., [2]). In this scenario, DM particles are supposed to be in thermal equilibrium with plasma in the Early Universe and they can annihilate into the Standard Model (SM) particles:

$$\chi_{\text{DM}}\bar{\chi}_{\text{DM}} \leftrightarrow X_{\text{SM}}\bar{X}_{\text{SM}}.$$

In the equilibrium, the annihilations and corresponding inverse processes proceed with equal rates. But as the Universe expands and cools down, the rate of the annihilation decreases and number density of Dark Matter particles freezes out at some value. Observed abundance of the DM particles is related to annihilation cross section at the moment of freeze-out as follows:

$$\Omega_{\text{DM}}h^2 \sim \frac{3\cdot 10^{-27}\text{cm}^3\cdot\text{s}^{-1}}{\langle\sigma_A v\rangle_{\text{freeze-out}}} \sim 0.1.$$

To obtain correct value for the present DM density, this annihilation cross section should be of the order of $\langle\sigma_A v\rangle_{\text{freeze-out}} \sim 3\cdot 10^{-26}\ \text{cm}^3\cdot\text{s}^{-1}$. In WIMP models, this value appears quite naturally. The other possible types of DM candidates are based on nonthermal production; among them are sterile neutrinos, asymmetric dark matter, etc.

One of the approaches to look for the Dark Matter signal is based on the assumption that the DM particles can annihilate like WIMPs into SM particles. Among the products of these annihilations can be particles that traverse cosmological distances, like charged electrons, positrons, protons/antiprotons, photons or neutrinos, which can be detected in experiments. Searching for neutrino signal from DM is one of the goals of several neutrino experiments: ANTARES [3], Baksan [4], Baikal [5], IceCube [7], and Super-Kamiokande [8]. Below we will concentrate on neutrino signal from DM annihilations in the Galactic Center (GC) [9, 10] and on prospects of its observation at the Baikal-GVD experiment [11].

1. NEUTRINOS FROM DARK MATTER ANNIHILATION IN GC

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

$$\frac{d\phi_\nu}{dE\,d\Omega} = J_2(\psi)\,\frac{\langle\sigma_A v\rangle_0}{2}\,\frac{R_0\rho_0^2}{4\pi m_{\rm DM}^2}\,\frac{dN_\nu}{dE}. \tag{1}$$

Here $\langle\sigma_A v\rangle_0$ is annihilation cross section averaged over DM velocity distribution at present time; dN_ν/dE is neutrino (and antineutrino) spectrum per act of annihilation. These quantities are predicted within the given model of Dark Matter. The first factor is the square of the DM density in MW, $\rho^2(r)$, integrated along the line of sight and normalized on local DM density and the distance from the GC to the Solar System:

$$J_2(\psi) = \int\limits_0^{l_{\max}} \frac{dl}{R_0}\,\frac{\rho^2(l)}{\rho_0^2}.$$

Note that the annihilation cross section in (1) should be taken at present time and it can differ from that of at the time of freeze-out if we speak about WIMPs. Typically in supersymmetric or other models in which DM particles interact with ordinary matter via massive mediators the nonrelativistic thermally averaged cross section depends on the DM velocity as follows:

$$\langle\sigma_A v\rangle = a + b\bar{v}^2,$$

where the terms on the r.h.s. represent s- and p-wave contributions. If s-wave contribution is zero, which happens for several types of DM interactions, then the annihilation cross section at present epoch is smaller than at freeze-out. At the same time, in models with very light mediators the annihilation cross section gets Sommerfeld enhancement [12], which results in an increase of its values as compared to that of at the time of freeze-out.

In the case of DM decay in the Galaxy, expected neutrino flux is given by the similar expression

$$\frac{d\phi_\nu}{dE\,d\Omega} = J_1(\psi)\,\frac{1}{\tau_{\rm DM}}\,\frac{R_0\rho_0}{4\pi m_{\rm DM}}\,\frac{dN_\nu}{dE}.$$

The main difference is that the astrophysical J-factor is now proportional to the first power of DM density

$$J_1(\psi) = \int_0^{l_{\max}} \frac{dl}{R_0} \, \frac{\rho(l)}{\rho_0}.$$

There are several models for the DM density profile in the galaxies and, in particular, in the Milky Way. Numerical N-body simulations show that Dark Matter forms an almost spherical halo. Simulations without baryons predict cuspy profiles (see, e.g., [13]). However, inclusion of baryons can change these conclusions [14], and these simulations being limited in number of particles cannot resolve small area around the center of the Galaxy. At the same time, the signal from annihilations is proportional to the square of DM density. So, this part of astrophysical input is the main theoretical uncertainty for the signal from DM annihilation in the Galaxy. Direct observational data of the Milky Way cannot resolve this uncertainty, because the part of our Galaxy within the Solar System circle is dominated by baryons, so the influence of Dark Matter within this circle on motion of astrophysical objects is small. Even local DM density is known with quite a large uncertainty of 0.2–0.6 GeV. Moreover, one cannot exclude the possibility that Dark Matter can form clumps [15] in our Galaxy and then signal from a particular direction can be increased by the presence of a clump along line of sight. In Fig. 1, we show examples of the DM density profiles: Navarro–Frenk–White (NFW) [16, 17], Kravtsov et al. [18], Moore et al. [19] and Burkert [20]. We see that all profiles are in reasonably good agreement at distances larger than several kiloparsecs, while the central parts can differ considerably. In what follows we will use Navarro–Frenk–White profile as a default and comment on the influence of this uncertainty later.

The Dark Matter can annihilate over many different annihilation channels, which of course are model-dependent. Instead of considering a particular model we work with particular channels. In the following analysis we consider the following set of annihilation channels:

$$b\bar{b},\ W^+W^-,\ \tau^+\tau^-,\ \mu^+\mu^-, \quad \text{and} \quad \nu\bar{\nu} \equiv \frac{1}{3}(\nu_e\bar{\nu}_e + \nu_\mu\bar{\nu}_\mu + \nu_\tau\bar{\nu}_\tau).$$

Each annihilation channel provides a unique neutrino energy spectrum and, since the probability of neutrino detection crucially depends on its energy, different neutrino signals can be expected from different annihilation channels. For the present analysis we use neutrino energy spectra at production taking into account weak corrections which can change spectra for large DM masses [21]. During the propagation neutrino oscillates but after traversing cosmological distances the coherence between different flavor states gets lost, and actually neutrino comes to

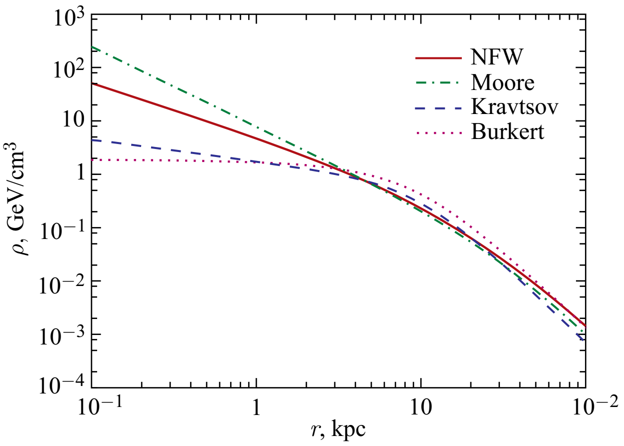

Fig. 1. Different DM density profiles for the Milky Way

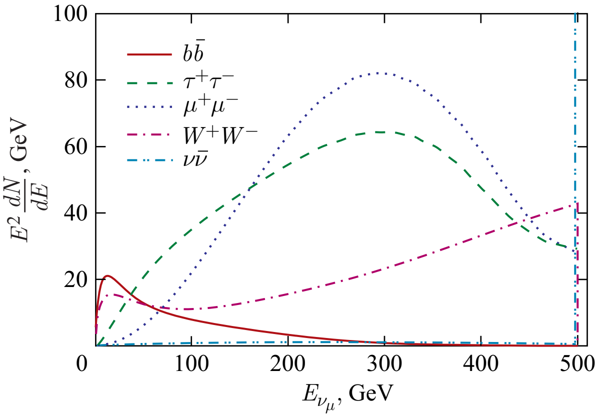

Fig. 2. Neutrino ν_μ energy spectra at the Earth for $m_{\rm DM} = 500$ GeV

the Earth as the mass states. We simulate also propagation in the Earth, but for the energies of neutrino below 10 TeV absorption and interactions of neutrinos with the Earth are small. Examples of muon neutrino energy spectra for different annihilation channels are presented in Fig. 2 for mass of Dark Matter particle of 500 GeV.

2. NEUTRINO SIGNAL AT THE BAIKAL-GVD EXPERIMENT

In what follows we will discuss the sensitivity of the Baikal-GVD experiment to the neutrino signal from DM annihilation and decays in the GC. The general scheme of operation of the Baikal-GVD was described elsewhere [6,22–25]. Here let us briefly summarize what is important for the present study. We assume basic configuration of the GVD telescope consisting of 12 clusters each composed by 192 optical modules on eight strings. For the present study, we consider only upward-going muon signal which is formed by requirements that there is a signal from at least six optical modules from at least three strings on a single cluster within 500-ns time window. The angular resolution of the GVD is expected to be 0.5–1 degrees for muons with energy more than 10 TeV. In our analysis, we are interested in much less energetic muons and conservatively take this resolution to be 4.5 degrees. Actually, because the signal region is not point-like but quite broad, the final result is expected to be not very sensitive to this value. We will be interested in the events from the region around the Galactic Center. The Baikal-GVD has a good view of the GC with visibility of about 75% per day.

We choose a search region as a cone around the direction towards the GC with half angle ψ. The expected number of signal events in the search region $N(\psi)$ for the lifetime T is estimated by integrating expected neutrino flux (1) with visibility of point in the sky $\epsilon(\psi, \phi)$ and the effective area $S(E)$ of the telescope for events coming from the direction towards the GC as follows:

$$N(\psi) = T\frac{\langle\sigma_A v\rangle R_0 \rho^2_{\mathrm{local}}}{8\pi m^2_{\mathrm{DM}}} J_{2,\Delta\Omega} \int dE\, S(E) \frac{dN_\nu}{dE}, \qquad (2)$$

where $J_{2,\Delta\Omega} = \int d(\cos\psi)\, d\phi\, J_2(\psi)\, \epsilon(\psi, \phi)$. In Fig. 3, we present the effective area at trigger level of one cluster of the GVD telescope in black dashed-dotted line. Also, in this figure we present effective areas for different annihilation channels which were obtained by averaging the effective area with corresponding neutrino energy spectrum. One can see that the effective area crucially depends

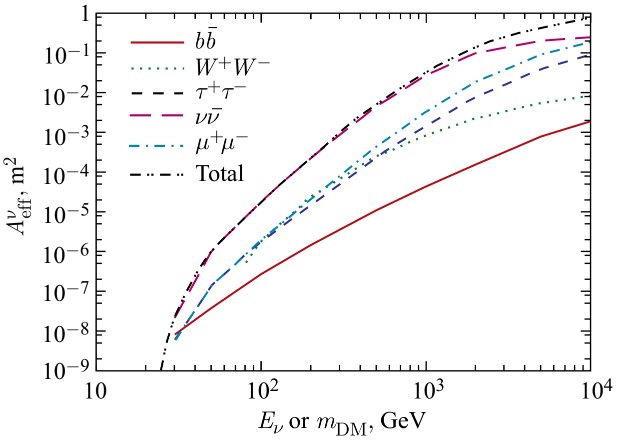

Fig. 3. Effective areas of the Baikal-GVD for monochromatic neutrinos as well as for different annihilation channels

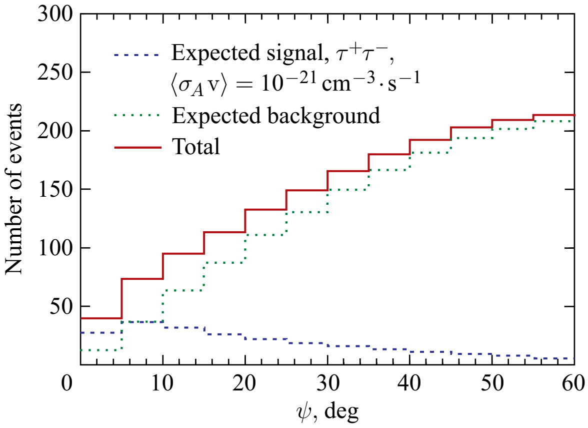

Fig. 4. Expected distribution of background and signal events in angular distance from the GC

on annihilation channel and it is small for $b\bar{b}$ annihilation channel and almost coincides with the maximal one for $\nu\bar{\nu}$ channel. For the present analysis, we estimated the effective area for full GVD telescopes as factor 12, which is the number of clusters times the effective area for one cluster.

Expected angular distributions of signal and background were obtained with MC simulation. The average total number of background events coming from down hemisphere for one year is expected to be about 4300. Signal angular distribution with respect to the direction of GC were simulated assuming Navarro–Frenk–White DM density distribution. Angular resolution gives an additional spread to this distribution. In Fig. 4, we show as an example of the distribution of signal events for one year of lifetime for $\tau^+\tau^-$ annihilation channel with annihilation cross section fixed to a particular value. The horizontal axis corresponds to the angular distance of event from the GC.

The next step of the analysis is the choice of optimal value of the cone around the GC with which expected upper limits will be optimal. Optimization has been performed using obvious difference between angular distributions of background and signal events. We construct the quantity $\frac{\bar{N}^{90}}{\sqrt{N_B}}(\psi)$, in which the numerator $\bar{N}^{90}$ is the upper limit on the number of additional events inside a given cone half-angle averaged over the number of observed events with the Poisson distribution with average number taken from the background and N_B is the number of background events inside this cone. We maximize this quantity with respect to ψ. The values of optimal angles vary from 9 degrees for very hard W^+W^- and large masses of DM to 20 degrees for soft channels like $b\bar{b}$ and small dark matter masses.

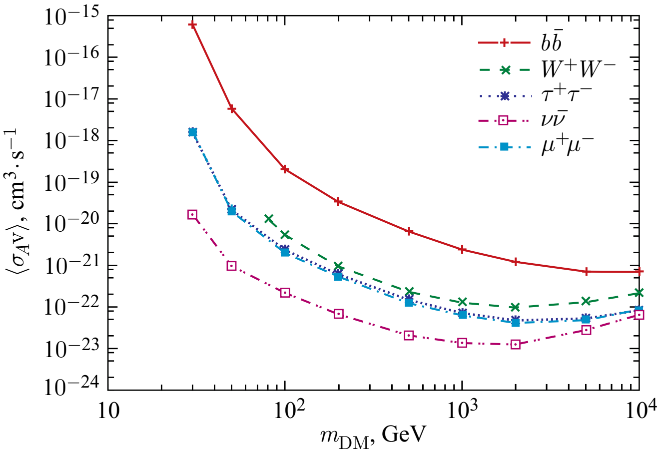

Fig. 5. Sensitivity of GVD to $\langle\sigma v\rangle$ for one year for different annihilation channels

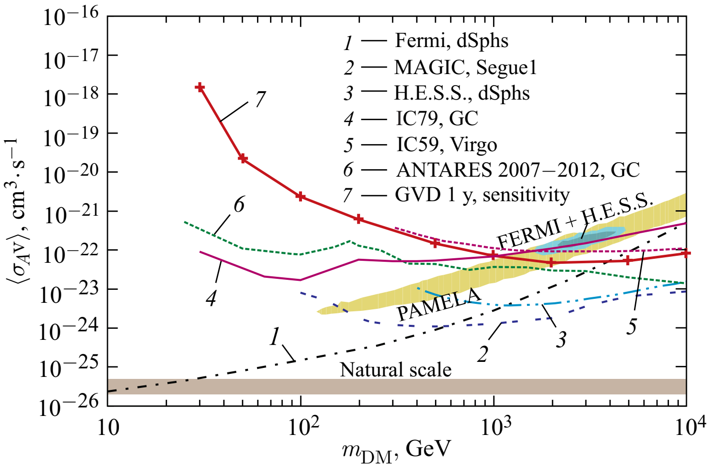

Fig. 6. Sensitivity of GVD to $\langle\sigma v\rangle$ in comparison with other experiments

Using the optimal values for cone half angles, we obtain one-year sensitivity of 12 clusters of the Baikal GVD to neutrino signal from DM annihilation in the Galactic Center, see Fig. 5. Limits reach values of 10^{-23} cm^3/s which corresponds to the boost factor of the order of several hundreds. In obtaining this limit we inverted the formula for the number of expected events, replaced this number with average upper limit. Also, in obtaining this sensitivity we take into account the expected efficiency of 0.6 and experimental systematic uncertainty of 50%.

In Fig. 6, we show the comparison of one-year Baikal-GVD sensitivity to DM annihilation cross section with results from other neutrino telescopes for $\tau^+\tau^-$

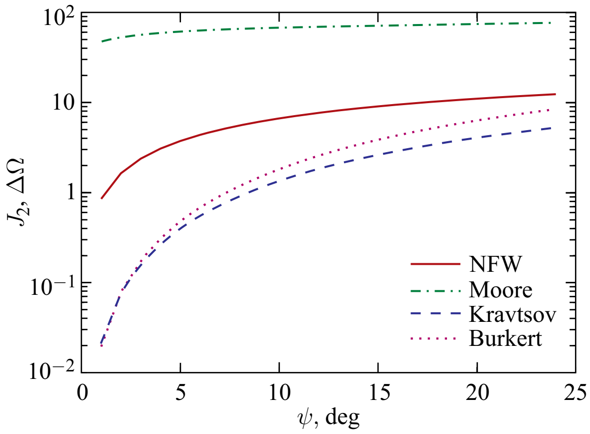

Fig. 7. J_2-factors for different models of DM density profile

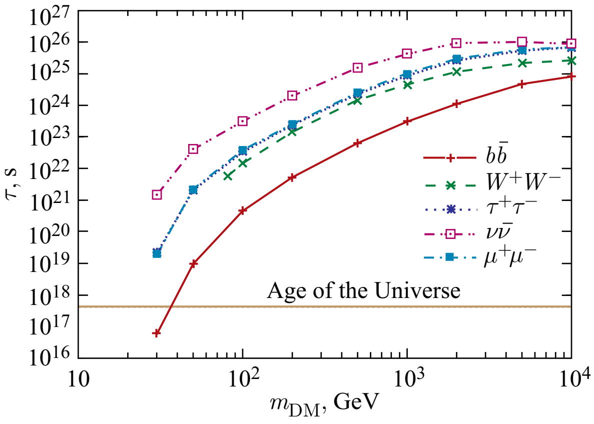

Fig. 8. GVD-Baikal sensitivity to τ_{DM} for $T = 1$ yr

annihilation channel with selected results from other experiments and some of the expected sensitivities: FERMI [26], MAGIC [27], H.E.S.S. [28], IceCube [7,29], ANTARES [3], and with the results of DM interpretation of positron excess [30].

Now let us briefly describe the main theoretical uncertainties. Among them are the uncertainties in the parameters of neutrino oscillations and neutrino–nucleon cross sections which in total can give up to 10%. The main uncertainty lies in poorly known DM density profile of the Galactic Halo which enters in number of expected events via J-factor integrated over a cone around the Galactic Center. In Fig. 7, we demonstrate this by calculating integrated J-factors depending on cone sizes for different DM density profiles. We see that for values of

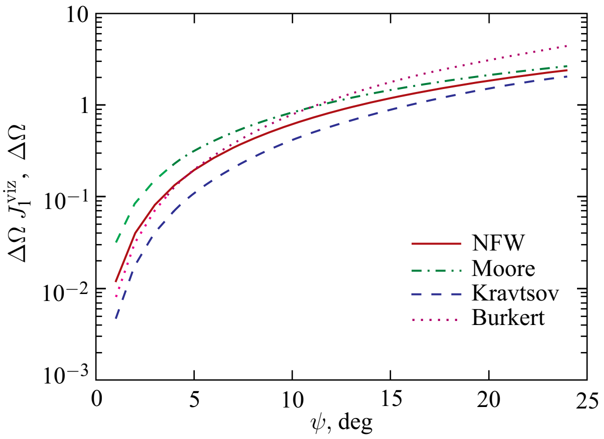

Fig. 9. J_1-factors for different models of DM density profile

half-cone angle from 9 to 20 degrees this can give about two orders of magnitude in the uncertainty.

To get the Baikal-GVD sensitivity for the DM lifetime, we use the same search regions obtained before and the same optimal cone angles. We plot one-year sensitivity to DM lifetime for a NFW profile for a chosen set of decay channels in Fig. 8. Note that the angular distribution of signal events in the case of DM decay is different from the case of its annihilation. We performed new optimization with respect to the search region for decaying DM and the optimal values of psi are obtained to be about 70 degrees which is well beyond the neighborhood of the GC. From this analysis we expect an improvement by a factor of 2–3 in the bounds on the DM lifetime with searches in the whole Galactic Halo. Here we note that the signal from DM decay is proportional to the first power of DM density and thus less sensitive to uncertainty in density profiles. This is illustrated in Fig. 9 where we show integrated J-factor for DM decay case for different profiles.

CONCLUSIONS

To summarize, we studied the sensitivity of the Baikal-GVD experiment to DM annihilations and decays in the GC for one year of lifetime at trigger selection level for planned configuration of 12 clusters. We are going to work on improvements which in particular include new selection criteria for the whole Baikal-GVD and discrimination between high- and low-energy regions. Also, we plan to estimate the sensitivity of this Baikal-GVD to neutrino signal from DM annihilations and decays in the Halo of our Galaxy and Dwarf Galaxies.

Acknowledgements. The work of S. V. Demidov and O. V. Suvorova was supported by the RSCF grant No.14-12-01430.

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