ФИЗИКА ЭЛЕМЕНТАРНЫХ ЧАСТИЦ И АТОМНОГО ЯДРА
2015. Т. 46. ВЫП. 2

INDIRECT SEARCHES FOR DARK MATTER AT BAKSAN AND BAIKAL

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We present our results of searches for neutrino signal from dark matter annihilations in the Sun at the Baksan Underground Scintillation Telescope and Baikal NT200 Deep-Underwater Neutrino Telescope. We obtain new upper limits at 90% CL on muon and neutrino fluxes, annihilation rate and on cross sections of dark matter elastic scattering off proton, and compare them with the limits obtained by other experiments.

PACS: 95.35.+d; 14.60.St; 29.40.Mc

INTRODUCTION

There is a strong evidence in favor of existence of new types of particles which comprise the dark matter (DM) [1]. Observation of the Sun is one of the possible indirect ways of searching for a signal from DM [2]. Namely, DM particles can scatter off nuclei, can be gravitationally trapped by the Sun and accumulate inside [3]. For this scenario to be viable the mass of dark matter particle should be larger than about 5 GeV. Otherwise, reverse process, namely, the evaporation of DM from the Sun is possible. If DM particles can annihilate into Standard Model (SM) particles among the final products of these annihilations can be high-energy neutrinos and only they can reach the surface of the Sun, can propagate towards the Earth and finally be observed at neutrino telescopes. Several neutrino telescopes are looking for such a signal. Among them are IceCube [4], Super-Kamiokande [5], ANTARES [6] and also two neutrino telescopes in the Russian Federation at the Baksan [7] and Baikal [8]. Here we will concentrate on the data provided by the last two telescopes and discuss the limits on characteristics of dark matter from this type of searches.

1. SIMULATIONS OF THE NEUTRINO SIGNAL

Let us describe the neutrino signal which could be expected if DM particles of mass $m_{\rm DM}$ annihilate in the Sun. A lot of physical processes are involved

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in this scenario and the size of possible signal depends on several characteristics of DM particles. First of all, dark matter should be captured by the Sun. This process crucially depends on the value of cross section of nonrelativistic elastic scattering of DM particles with nucleons, which has spin-dependent (SD) $\sigma_{\chi p}^{\rm SD}$ and spin-independent (SI) $\sigma_{\chi p}^{\rm SI}$ parts. Then the dark matter could annihilate into many different annihilation channels which depends on theoretical model. Instead of considering a particular model we work with several annihilation channels which are believed to capture many features of general picture. In the following analysis we will consider the following benchmark channels: $b\bar{b}$ with very soft energy spectrum of neutrinos and W^+W^- and $\tau^+\tau^-$ with more energetic spectra. Also, we include for comparison a possibility of annihilation into monochromatic neutrinos $\nu\bar{\nu}$. We will denote the neutrino energy spectra at production as $\dfrac{dN_{\nu_j}^{\rm prod}}{dE_{\nu_j}}$ for jth flavor of neutrino.

Produced neutrino propagates in the Sun, from the Sun to the Earth and in the Earth to a neutrino telescope, and here it is important to take into account oscillations of neutrino and their interactions with media. At the Baksan and Baikal neutrino telescopes only muon neutrinos are relevant for these searches. The expected muon neutrino flux (integrated from some threshold neutrino energy E_{ν_μ}) at the detector level can be put in the following form:

$$\Phi_{\nu_\mu} = \frac{\Gamma_A}{4\pi R^2} \sum_{\nu_j,\bar{\nu_j}} \int\limits_{E_{\rm th}}^{m_{\rm DM}} dE_{\nu_j} P_{\nu_\mu}(E_{\nu_j}, E_{\rm th}) \frac{dN_{\nu_j}^{\rm prod}}{dE_{\nu_j}}, \tag{1}$$

where Γ_A is dark matter annihilation rate; R is the distance to the Sun; the function $P_{\nu_\mu}(E_{\nu_j}, E_{\rm th})$ is the probability of obtaining muon neutrino from given neutrino or antineutrino at production which encodes all effects of neutrino propagation and interactions. To obtain muon flux, one should also include the probability to obtain muon from muon neutrino at the detector level.

For Monte Carlo simulation of propagation of neutrinos, we use our own program written in C (see detailed description in [7]) and compare the results of corresponding simulations with those obtained by using the well-known WimpSim package [9, 10] which is in use in the analysis of other neutrino telescopes. Let us briefly sketch the main ingredients of our program. First of all, calculation of initial neutrino spectra has been performed by several groups. We use two versions of spectra, one of them was presented in [11] and the other obtained by using WimpSim which use PYTHIA for this purpose. We found that the final neutrino spectra are very similar. We simulate annihilation point near the center of the Sun according to the following distribution [2]:

$$n(r) = n_0 \exp\left(-\frac{r^2}{R_{\rm DM}^2}\right), \tag{2}$$

where $R_{\rm DM} \sim 0.01 R_{\rm Sun}\sqrt{100\ {\rm GeV}/m_{\rm DM}}$. Then we simulate neutrino oscillation in 3×3 scheme including matter effects. We use neutrino oscillation parameters presented in [12]. Varying density of the Sun has been taken into account in the following way: we subdivide the neutrino path into sufficiently small pieces in which the electron density can be considered as a constant and then evolve neutrino wave function with exact evolution operator [13]. During the propagation we take into account charged current (CC) and neutral current (NC) neutrino–nucleon interactions. Corresponding inelastic cross sections have been calculated including tau-mass effects. NC interactions result in change of neutrino energy spectrum, while CC interactions in case of electron and muon neutrino result in neutrino disappearance from the flux*, while for tau-neutrino regeneration in CC interactions is possible. Namely, produced tau lepton τ can decay into tau neutrinos of lower energy and also into electron or muon antineutrinos. We take into account ν_τ regeneration. We compare the results of simulations performed with our program and by using WimpSim with the same initial neutrino energy spectra and find a good agreement [7]. Some details of propagation of neutrino from dark matter annihilations in the Sun have also been described in [14].

To obtain muon signal at the position of the neutrino telescopes, we propagate neutrinos in the Earth and simulate their CC interactions in the rock or water surrounding telescope. Muons which propagate to the detector loose their energies and these losses were taken into account in average in the following rather standard way:

$$\left\langle \frac{dE}{dx} \right\rangle = -\left(\alpha(E) + \beta(E)E\right)\rho, \qquad (3)$$

with coefficients which depend on energy. We take their numerical values from [15]. Also, because we are looking in the direction of the Sun, it is important at which angle muon deflects from the direction towards the Sun. The first source of this deflection arises at the neutrino CC interaction point and also the muon can deflect from its path by multiple Coulomb scattering which we also take into account.

2. DATA AND OBTAINED RESULTS

Now let us describe data obtained at the Baksan and Baikal neutrino telescopes which were used in the analysis. The detailed description and operation of the Baksan Underground Scintillation Telescope have been described elsewhere [16, 17]. The telescope has the form of four-storey building whose four

*Muons stop before decay thus producing only low-energy neutrinos.

horizontal and four vertical planes are entirely covered by liquid scintillator counters. It is able to detect through-going charged particles, and the time-of-flight method [18] is in operation to distinguish between upward- and downward-going muons. There are two triggers which help selecting high-energy upward-going muon events which are relevant for the search for dark matter signal. The main characteristics of the telescope related to this analysis were found from MC simulations with atmospheric neutrinos and the muon energy threshold is around 1 GeV [21] and angular resolution is around 1.5° [19,20]. In this analysis we use data of upward-going muons collected from December 1978 till November 2009, which corresponds to a lifetime of more than 24 y. During this lifetime, only 1255 of upward-going events are found and left for further analysis.

In Fig. 2, *a* the distribution of events in cosine of measured angle with respect to the direction towards the Sun is shown. The dashed line is a mean number of events per bin. The direction towards the Sun corresponds to the $\cos\Psi = 1$. If we drop all upward-going muon events with arrival time corresponding to the situation when the Sun is above the horizon, the distribution will look as in Fig. 2, *b* shown in red crosses. One can see that the number of events in the directions nearby the direction towards the Sun does not change because all events here are obtained when the Sun is below the horizon. The histogram on this plot represents an estimation for the background which was taken directly from data in the following way. The real position of the Sun was shifted along its track on the sky and the background was obtained by averaging of muon angular distributions with respect to shifted Sun positions and fitted with isotropic distribution. Now let us look close to the real Sun direction and in Fig. 2 we plot number of signal and expected background events inside the corresponding cone half-angle: data in red crosses while green line is the expected integrated background. We do not see any significant deviation from the background, so we can set an upper limit on number of signal events.

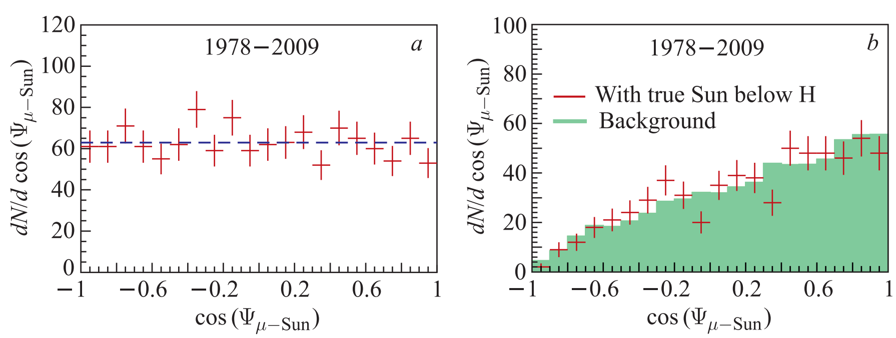

Fig. 1 (color online). Angular distribution (red points) with respect to the Sun position for all events (*a*) and for events when the Sun is below the horizon (*b*). The histogram on the plot *b* is an estimation of the background (see the main text)

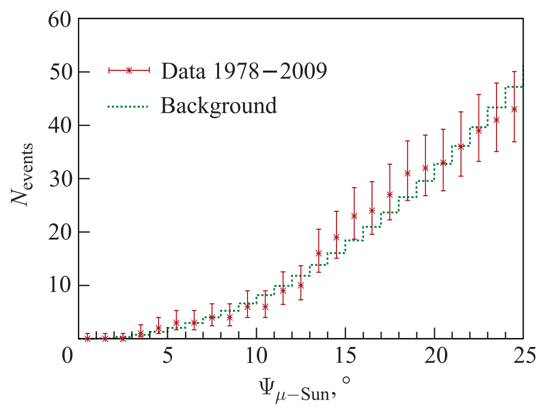

Fig. 2. Number of signal and background events inside a cone half-angle $\Psi_{\mu-\text{Sun}}$

The final step is the choice of value of cone half-angle corresponding to the cone around the Sun direction in which we collect the signal events. Here we use obvious difference between background and signal events. While muons from atmospheric neutrino are distributed isotropically over the sky, the distribution of signal muons is correlated with the direction towards the Sun. In the previous analysis made by Baksan group [21], the method of looking for muon signal from dark matter annihilations in the Sun consisted in searching for events inside such a cone in which 90% of signal is expected. In our present analysis we optimize the search with respect to the value of this angle. For this purpose we use the method discussed in the following paper [22] which consists in minimization of mean expected limit on muon flux with respect to the value of chosen cone half-angle γ. Namely, we construct the following quantity:

$$\text{sensitivity}(\gamma) = \frac{\bar{N}^{90}(\gamma)}{x(\gamma)A_{\text{eff}}(\gamma)T}, \tag{4}$$

where $\bar{N}^{90}(\gamma)$ is 90% CL limit on number of signal events inside given cone averaged over number of observed events with Poisson distribution; $x(\gamma)$ is fraction of signal events inside this cone and $A_{\text{eff}}(\gamma)$ is effective area which is constructed by converting the geometrical area of the telescope for muons with given energy and given arriving angle with the efficiency and expected energy and angular distribution of signal events. The optimization has been performed for all chosen channels depending on the mass of dark matter particle, and the corresponding values of the cone half-angle are presented in Fig. 3. The values of this angle are similar for W^+W^- and $\tau^+\tau^-$ channels, while for $b\bar{b}$ channel they are larger because of softer neutrino energy spectrum. Then we can obtain a 90% confidence level upper limit for number of events inside given cone half-angle

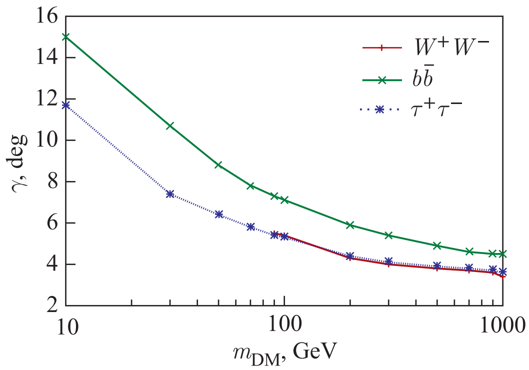

Fig. 3. Optimal values of the cone half-angles for different annihilation channels

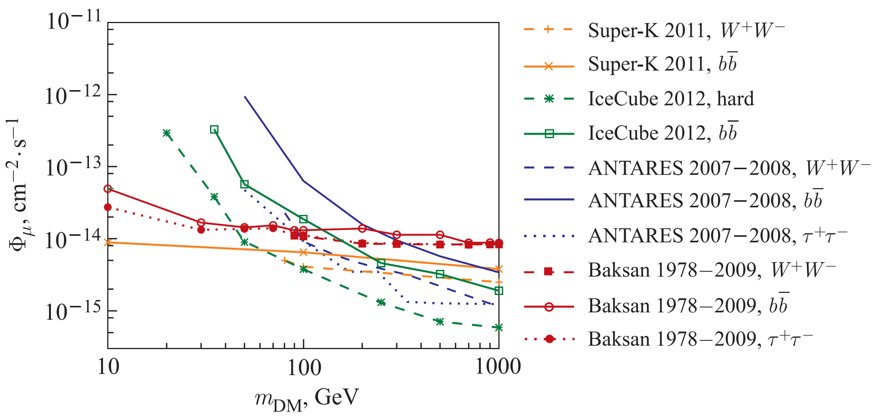

Fig. 4. Baksan upper limits on muon flux in comparison with the results of other neutrino experiments

according to mass and annihilation channel. And the upper limit on muon flux with muon threshold energy 1 GeV is obtained by Eq. (4) in which we insert optimal value for γ and use real upper limit. In Fig. 4 we present the Baksan limits on muon flux in comparison with results of other experiments: SuperK [5], IceCube [4], ANTARES [6]. Baksan results are comparable with those presented by Super-Kamiokande. In the small mass range they are more stringent for $\tau^+\tau^-$ than those of large volume telescopes. However, their sensitivities for larger DM masses are bounded by their small areas.

Now we discuss the data obtained with the Baikal Deep Underwater Neutrino Telescope and what we used in this analysis [8]. Relativistic particles crossing the effective volume of a deep underwater telescope are detected via their Cherenkov radiation. This radiation is recorded by optical modules (OMs) which are timesynchronized and energy-calibrated by artificial light pulses. The general scheme and details of functional systems of the Baikal telescope have been described elsewhere [23, 24]. For the present analysis we use data sample of NT200 telescope configuration (consisting of 8 strings with 192 OMs) for operated time from April 1998 to February 2003. The expected number of muons generated by neutrino is related to the effective area $A(E_\nu, E_{\rm th})$ of the telescope as follows:

$$N_\mu = \int\limits_{E_{\rm th}}^{M_{\rm DM}} dE_\nu\, d\Omega\, A^\nu_{\rm eff}(E_\nu, \Omega) \frac{d^2 N_\nu}{dE_\nu\, d\Omega}. \tag{5}$$

The effective area of the telescope has been obtained from MC simulation of the detector response and further application of all found reconstruction cuts [23]. It is shown in Fig. 5 for all neutrinos and those whose incoming direction is correlated with the direction towards the Sun.

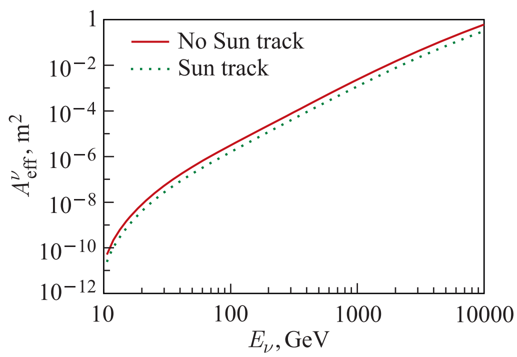

Fig. 5. The effective area of NT200 for muon neutrinos

Optimization of the analysis with respect to the size of the cone around the direction towards the Sun has been performed in a similar way as for data of the Baksan Scintillation Telescope. The difference is that we minimized the expected limit on muon neutrino flux instead of muon flux, i.e.,

$$\frac{\bar{N}^{90}(\gamma)}{A^\nu_{\rm eff}(\gamma) T}, \tag{6}$$

where the effective area for neutrino has the form

$$A^\nu_{\rm eff}(\gamma) = \frac{\int\limits_{E_{\rm th}}^{m_{\rm DM}} dE_\nu A(E_\nu, E_{\rm th}) P_\mu(E_\nu, \theta) \dfrac{dN_\nu(E_\nu)}{dE_\nu}}{\int\limits_{E_{\rm th}}^{m_{\rm DM}} dE_\nu P_\mu(E_\nu, \theta) \dfrac{dN_\nu(E_\nu)}{dE_\nu}}, \tag{7}$$

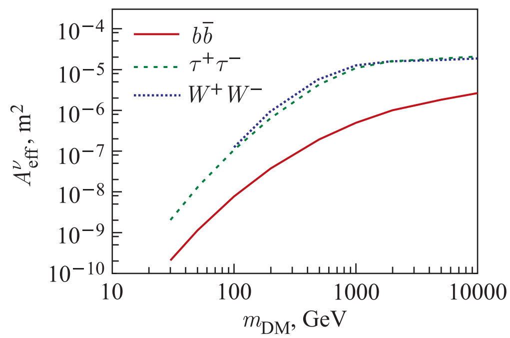

Fig. 6. Effective area of NT200 for different annihilation channels

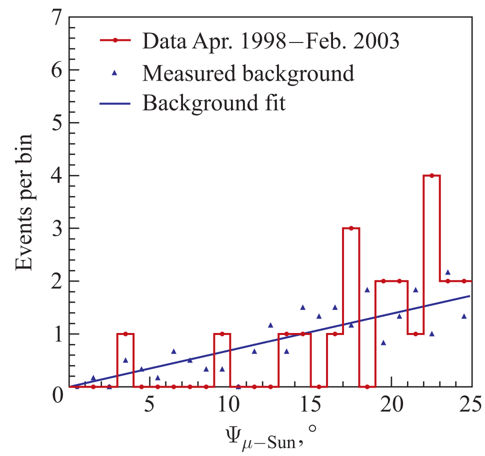

Fig. 7. Distribution of signal and background events obtained at NT200

and $P(E_\nu, \theta)$ is the probability to obtain muon from this neutrino inside a cone of given size. By this procedure we obtain optimal values of cone half-angles γ and we use them to put the upper limits on neutrino fluxes. Also, in Fig. 6 we present the effective area for given annihilation channel depending on the mass of dark matter particles. One can see that it is an order of magnitude higher for hard annihilation channel. The procedure of selecting the data is completely the same as for the case of the Baksan Underground Scintillation Telescope: we should choose upward-going events in the direction towards the Sun. In Fig. 7 we show the signal and background events. The estimation of the background has been obtained by averaging over the position of the Sun. In Fig. 8 we show the results on the limits on muon neutrino fluxes from dark matter annihilation

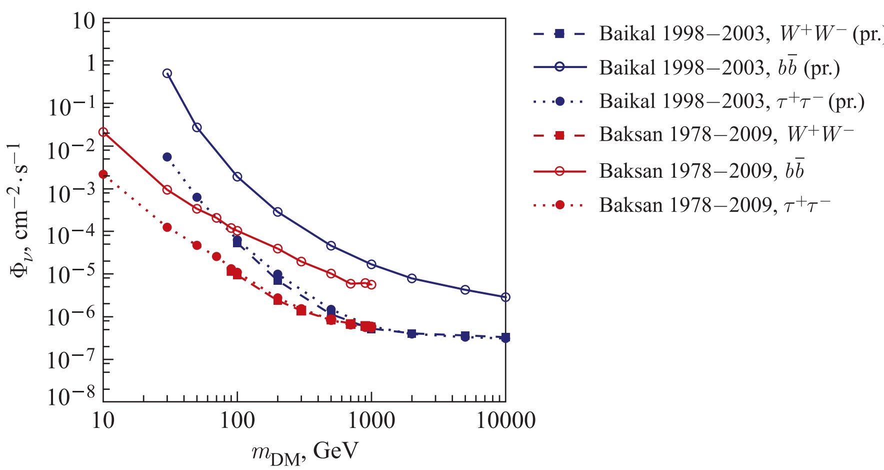

Fig. 8. Baksan and Baikal NT200 upper limits at 90% C.L. on muon neutrino fluxes for three conventional channels

in the Sun in comparison with the Baksan results. The Baikal results have been recalculated to the energy threshold of 1 GeV, while the NT200 neutrino energy threshold is about 10 GeV.

The limits on muon fluxes can be recalculated to the limits on other quantities which are closer to DM physics, namely, to annihilation rate of dark matter in the Sun and finally to elastic cross section of DM particle scattering by proton [25,26]. Using formulas for muon or neutrino flux, one can recalculate to the upper limit on annihilation rate. Further, if the processes of capture and annihilation of DM in the Sun are in equilibrium, then the annihilation rate equals one half of the capture rate. And in this way the annihilation rate becomes directly related to SD and SI parts of elastic cross section of DM on proton (see [8] for details). In particular, strong limits are obtained on SD cross sections because of high hydrogen content of the Sun. In Fig. 2 we show the limits on SD cross section obtained by Baksan and Baikal in comparison with the results from other neutrino experiments: IceCube, Super-K and ANTARES. The most stringent limits are obtained for harder annihilation channels. We note that hard spectrum for IceCube means W^+W^- channel for masses larger than 80 GeV and $\tau^+\tau^-$ for smaller masses of DM. It is seen that for small masses of dark matter the Baksan limits are very competitive due to its low energy threshold. Dependence of SD cross section limits on hardness of neutrino spectra are shown in Fig. 10 with Baikal NT200 results for six annihilation channels including monochromatic neutrinos. One can see that so-called leptophilic dark matter models have more stringent constraints from this type of searches as compared to the others and

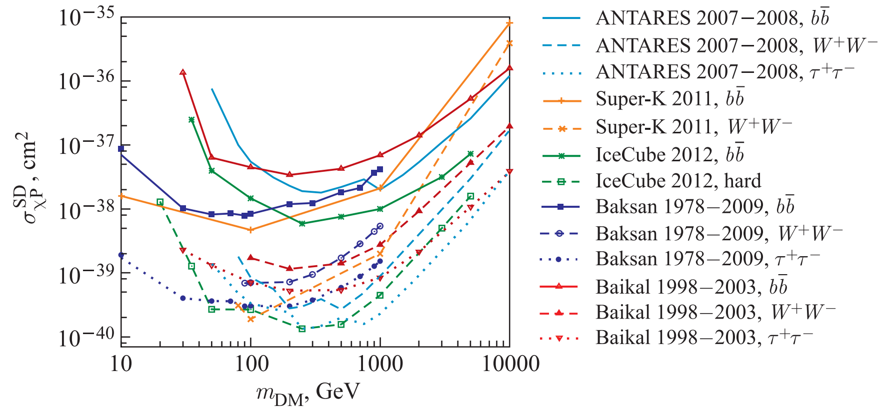

Fig. 9 (color online). Upper limits at 90% C.L. on SD elastic cross section of dark matter particles on proton for three conventional channels obtained by the Baikal NT200 (red lines) and Baksan (blue) experiments in comparison with the results of other indirect searches

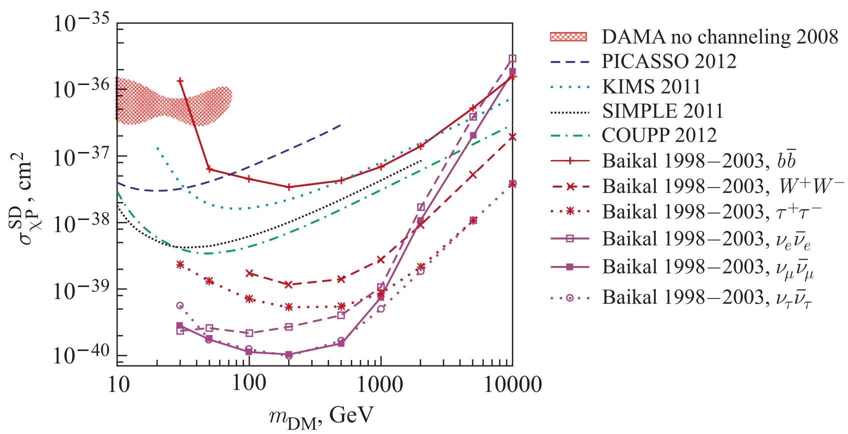

Fig. 10. Baikal NT200 upper limits at 90% C.L. on SD elastic cross section of dark matter particles on proton for six channels in comparison with the results of direct searches

compared to limits of direct DM search experiments, where selected ones are PICASSO [27], KIMS [28], SIMPLE [29], DAMA [30, 31] and COUPP [32].

CONCLUSIONS

Let us summarize that we performed simulation of neutrino signal from dark matter annihilations in the Sun assuming several different annihilation channels. We performed analysis of upward-going muon data collected for more than 24 y of lifetime at the Baksan Underground Scintillation Telescope and more than 1000 days of lifetime for the Baikal NT200 deep-underwater telescope. No significant excess has been found in both data samples, and new limits on muon flux, annihilation rate and SD elastic cross sections have been obtained. These limits are competitive with those obtained by other neutrino telescopes especially in the case of the Baksan Scintillation Telescope for low masses of dark matter particles. Finally, we found that indirect searches with neutrino telescopes are more sensitive to leptophilic dark matter models than to others.

Acknowledgements. The research was supported in part by RFBR grants 13-02-12221, 14-02-00972, 13-02-01127 (S. D.), and by grant of the President of the Russian Federation NS-2835.2014.2 (S. D.).

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