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# A search for neutrino signal from dark matter annihilation in the center of the Milky Way with Baikal NT200

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ABSTRACT

We reanalyze the dataset collected during the years 1998–2003 by the deep underwater neutrino telescope NT200 in the lake Baikal with the low energy threshold (10 GeV) in searches for neutrino signal from dark matter annihilations near the center of the Milky Way. Two different approaches are used in the present analysis: counting events in the cones around the direction towards the Galactic Center and the maximum likelihood method. We assume that the dark matter particles annihilate dominantly over one of the annihilation channels $b\bar{b}$, $W^+W^-$, $\tau^+\tau^-$, $\mu^+\mu^-$ or $\nu\bar{\nu}$. No significant excess of events towards the Galactic Center over expected neutrino background of atmospheric origin is found and we derive 90% CL upper limits on the annihilation cross section of dark matter.



## 1. Introduction

Today all cosmological and astrophysical observations are successfully explained within a paradigm of the standard cosmological model ($\Lambda$CDM) stating that the most of the energy density of the Universe is stored in the dark energy or cosmological constant ($\Lambda$, about 68%) and non-baryonic cold dark matter (CDM, about 27%). Unambiguous presence of the latter component is confirmed by measurements of galaxy rotation curves [1], weak gravitational lensing of distant objects like galaxy clusters [2], measurements of properties of cosmic microwave background [3–5], analysis of structure formation [6] and nucleosynthesis [7] (see also Ref. [8] for a review).

One of the most favorable ideas for explaining dark matter (DM) phenomena is Weakly Interacting Massive Particles or WIMPs [9]. In this scenario predicted by several classes of models of new physics [10,11], these particles are supposed to be in thermal equilibrium in the early Universe and can annihilate into Standard Model particles. But as the Universe was expanding and cooling down, the annihilation processes ceased out and number density of the dark matter particles became frozen out at some

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value which is determined by their annihilation cross section. Thus, at least in the WIMP scenario one can expect some signal from the dark matter annihilations towards the directions of local overpopulation of these particles. The Galactic Center (GC) of the Milky Way is one such direction.

Two types of messengers from DM annihilation signal in the Galactic Center, i.e. gamma rays and neutrinos, are expected to be detected by the telescopes. They both originate in the same energy ranges (GeV–TeV for WIMPs) in decays of particles produced in kinematically allowed dark matter annihilation channels. Several analyses of diffuse gamma-rays from the FERMI-LAT dataset (pass 7) point out on an evidence for central and spatially extended excess toward the Galactic Center (GCE). Large astrophysical uncertainties to the background of diffuse gamma-radiation in the Galaxy generate ambiguous interpretations of the GCE. Among the scenarios explaining the GCE there have been discussed possibilities of unresolved conventional astrophysical gamma-ray sources, e.g. millisecond pulsars [12] as well as different extensions of the Standard Model with dark matter particles annihilating in the MW halo [13] (for a review see e.g. Ref. [14]). The analysis performed in Ref. [13] which uses filtered emissions from individual point sources like globular clusters and millisecond pulsars detected by the FERMI-LAT, supports a DM signal from annihilations either into $b\bar{b}$ channel with dark matter particle of the mass about 30–60 GeV or into $\tau^+\tau^-$ channel for the masses in 5–15 GeV range. The annihilation cross section is found to be about $10^{-26}\,\mathrm{cm}^3/\mathrm{s}$ which is close to the value predicted in the scenario of WIMPs annihilation in the early Universe. The latest analysis of the FERMI-LAT dataset (pass 8) [15] shows some tension in consistency with the dark matter interpretations of the GCE, related to the dark matter density profile and the value of local dark matter density.

The operating neutrino telescopes have not yet observed a signal from the dark matter annihilations in the GC over expected atmospheric neutrino background, see recent analyses from the ANTARES [16], IceCube [17] and Super-Kamiokande [18] collaborations. In this paper we analyze the dataset of upward going muons produced by neutrinos in the lake Baikal and measured with the NT200 telescope for a period between April of 1998 and February of 2003 in search for an excess in the directions near the GC. We focus on the dark matter particles with masses from 30 GeV to 10 TeV annihilating dominantly into one of the following benchmark annihilation channels: $b\bar{b}$, $W^+W^-$, $\tau^+\tau^-$, $\mu^+\mu^-$ and also flavor-symmetric neutrino channel $\nu\bar{\nu}$. Two independent analyses of the data are performed and consistent results are found. Finally, we obtain upper limits on the dark matter annihilation cross section for these annihilation channels. Also we discuss influence of systematic uncertainties on the obtained results.

## 2. Experiment and data sample

The NT200 is a deep underwater neutrino telescope in lake Baikal which began data taking in 1993. This detector was the first that proved the method of study of high energy muons, which come from top or bottom hemisphere across a large volume of natural water, by recording their Cherenkov radiation [19]. Lake Baikal deep water is characterized by the absorption length of $L_{abs}(480\,\mathrm{nm}) = 20$–$24$ m, scattering length of $L_{sc}$ =30–70 m and strongly anisotropic scattering function with the mean cosine of the scattering angle of 0.85–0.9. The Cherenkov light of relativistic particles is recorded at appropriate wavelengths by an array of optical modules (OMs) which are time-synchronized and energy-calibrated by artificial light pulses. At 1 km water depth, the muon flux from cosmic ray interactions in the upper atmosphere is about one million times higher than the flux of upward going muons initiated by neutrino interactions in the water and rock below the array. Selection of clean neutrino event sample of true upward going muons is a major challenge which requires highly efficient rejection of misreconstructed downward moving muons. The NT200 instrumentation volume encloses 100 Ktons placed in the southern basin of the lake Baikal, at the distance of 3.5 km off the shore and at the depth of 1.1 km. In Fig. 1 (on left), the visibility over declinations for the NT200 site located at 51.83° of Northern latitude is shown. Here we account for its dead time when the detector had to be upgraded in the winter expeditions [20]. Note that in April 2015 there has been deployed a new larger detector [21] operating now at this place as a demonstration cluster of about 2 Mton size for a future Gigaton volume detector [22]. Sensitivity of the future experiment to the DM annihilation signal from the GC has been discussed in Ref. [23]. The NT200 configurations, functional systems, calibration methods and software for muon track reconstruction have been described elsewhere [20,24–28]. The detector consists of 192 optical modules arranged pairwise on 8 strings of 68.75 m length: seven peripheral strings and a central one. The distance between the nearest strings is 21.5 m. Each OM contains hybrid photodetector QUASAR-370, a photo multiplier tube (PMT) with 37-cm diameter. To suppress background from dark noise, two PMTs of a pair are switched in coincidence within the time window of 15 ns. Present analysis is based on the data collected between April of 1998 and February of 2003, with in total 2.76 live years, and taken with the muon trigger. The trigger requires $N_{hit} \geq n$ within 500 ns, where hit refers to a pair of fired OMs coupled in a *channel*. Typically the value of $n$ is set to 3 or 4. We use the same dataset and Monte Carlo (MC) sample as in Ref. [29]. The detector response to the atmospheric muons and neutrinos has been obtained with MC simulations based on standard codes `CORSIKA` [30] and `MUM`[31] using the Bartol atmospheric $\nu$ flux [32]. To distinguish upward and downward going muons on one-per-million mis-assignment level, a filter with several levels of quality cuts was developed for the atmospheric neutrino ($\nu_{atm}$) analysis [33]. The atmospheric muons which have been mis-reconstructed as upward-going particles are the main source of the background in the search for neutrino induced upward-going muons. The offline filter which requires at least 6 hits on at least 3 strings ("6/3") selects about 40% of all triggered events. At this level the r.m.s. mismatch angle $\psi_{reco}$ between the direction of incoming muon and its reconstructed value is about 14.1° for the $\nu_{atm}$-sample. To get the best possible estimator for the direction, we use multiple start guesses for the $\chi^2$ minimization [28]. For the final choice of the local minimum of $\chi^2$, we use quality parameters which are not related to the time information. The quality cuts are applied to variables like the number of hit channels, $\chi^2/d.o.f.$, the probability of fired channels to have been hit or not and the actual position of the track with respect to the detector center. To improve the signal-to-background ratio we use only events with the reconstructed zenith angle $\Theta > 100°$. All the cuts provide rejection factor for the atmospheric muons of about $10^{-7}$, resulting in the neutrino energy threshold of about 10 GeV, dispersion of 4.5° for the distribution of mismatch angles and the median value 2.5° as it is seen in Fig. 1 (right) (for more details see Refs. [28,33]). In Fig. 2 we show the arrival directions of reconstructed muons in galactic coordinates and cones around the GC with opening angles 20°, 5° and 2.5° containing 31, 2 and 2 observed events, respectively. In the next section, we discuss expected signal from the dark matter annihilations in our Galaxy and background from the atmospheric neutrinos.

## 3. Signal and background

Neutrino flux at the Earth from the dark matter annihilations in the Galactic Center from a particular direction has the following