Indirect searches for dark matter particles at Super-Kamiokande

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Abstract. This work presents indirect searches for dark matter (DM) as WIMPs (Weakly Interacting Massive Particles) using neutrino data collected with the Super-Kamiokande detector from 1996 until 2014. The results of the search for WIMP-induced neutrinos from the Sun and the Milky Way are discussed. We looked for an excess of neutrinos from the Sun/Galactic Center direction as compared to the expected atmospheric neutrino background. No excess of the WIMP-induced neutrinos is observed in any of the analyses. Limits on the WIMP-nucleon spin-dependent/independent cross sections (solar analysis) and on the WIMP self-annihilation cross section $\langle \sigma A V \rangle$ (galactic analysis) are derived assuming various annihilation modes and masses of the relic particles.

1. Introduction
There is a compelling evidence that ordinary baryonic matter composes only $\sim 5\%$ of the total mass-energy of the Universe which is dominated by dark energy ($68\%$) and dark matter ($27\%$) components of the unknown nature [1]. Some well motivated candidates for the DM particle arises within supersymmetric models and belong to a collective group referred to as WIMPs (Weakly Interacting Massive Particles) [2]. Observation of WIMPs present in the Milky Way may be attempted directly via elastic scattering of DM particles on nuclei in the detectors or indirectly through detection of the products of their annihilations, including neutrinos. WIMP-induced neutrinos are expected to arrive mostly from the direction of the Galactic Center (GC) as density of the relic particles inside this region should be greatly enhanced according to predictions of halo models [3]. Such neutrinos can provide a very good directional information on their origin and on primary energy spectra while traversing unaffected throughout galactic scales.

Moreover, WIMPs are believed to be accumulated inside heavy celestial objects like the Sun and could effectively annihilate there. Neutrinos, as one of the annihilation products, can escape the dense matter region of the star’s core and could be detected using neutrino telescopes.

2. Data Samples
The sample of neutrino interactions in which we search for WIMP-induced neutrinos consists of the atmospheric neutrino events collected with the Super-Kamiokande detector located in the Kamioka Observatory of the Institute for Cosmic Ray Research, University of Tokyo [4]. Detection of neutrino interactions is based on observation of charged particle, primarily lepton, which may produce Cherenkov radiation while moving faster than $c$ in water. The Cherenkov
light projected onto the walls of the tank and recorded by photomultiplier tubes, allows to
reconstruct energy, direction and flavour of produced lepton (e-like or \(\mu\)-like rings).

In the energy range expected for WIMP-induced neutrinos (MeV-TeV scale) only atmospheric
neutrinos contribute as background. Based on the topology and energy of the detected events,
they can be assigned to three main event categories: fully-contained (FC), partially-contained
(PC), and upward-going muons (UPMU). The FC events have reconstructed neutrino interaction
vertex inside the fiducial volume of 22.5 kton mass and particles produced in the parent neutrino
interaction stop inside the inner part of the detector. The PC events have some tracks recorded
also in the outer part of the detector (veto region). The true neutrino energy of events classified
as FC is in the range from hundreds of MeV up to several GeV. The average energy of neutrinos
producing a lepton which is partially-contained in the detector is higher, from \(\sim 1\) GeV up to
10 GeV. Neutrinos of the higher energies are seen as through-going or through-going stopping
muons and are produced in \(\nu_\mu\) interactions in the surrounding rock or in the veto region.
Downward-going muons produced in interactions of neutrinos cannot be distinguished from
the constant flux of cosmic ray muons. However, muons travelling in upward direction (UPMU)
must be neutrino induced. The FC, PC and UPMU event classes can be divided into more
specific subcategories described elsewhere [5].

The discussed search for DM-induced \(\nu\)'s from the Sun is based on atmospheric neutrino
data collected with SK detector in years 1996-2012 (SK-I,-II,-III and -IV data taking periods),
corresponding in total to 3902.7 live-days for FC/PC and 4206.7 live-days for UPMU events.
The second analysis regarding the Milky Way is extended with data collected in 2013 and 2014,
which in total corresponds to 4223.3 live-days for FC/PC and 4527.0 live-days for UPMU events.

3. Analysis
In the conducted analyses it is assumed that atmospheric neutrino data collected with the Super-
Kamiokande detector could be described by two components: WIMP-induced neutrinos (signal)
and atmospheric neutrinos (background). The best combination of signal and background that
would fully explain the data is tried to find using a fit method. Both, the signal and background
prediction are based on the Monte Carlo (MC) simulations. The signal contribution is govern by
the normalization parameter and is varied in the fit. The background normalization and shape
are fitted throughout the values of the atmospheric neutrino oscillation parameters and through
the values of systematic uncertainty terms.

For the atmospheric neutrino interactions, the MC simulation of the detector response is
available in large statistics corresponding to 500 years of livetime separately for each of the four
running periods of the detector (2000 years of livetime in total). Oscillations of neutrinos are
taken into account in those predictions. The simulations assume realistic fluxes of neutrinos,
their interactions in the detector or in the surrounding rock. The detector response is taken into
account and the same set of reduction and classification cuts is applied to simulated events as
to the real data. In order to simulate the WIMP-induced neutrinos coming from the Milky Way
and the Sun, DarkSUSY [6] and WimpSim [7] packages are used. Given the expected signal
characteristics at the production point, neutrino propagation under the assumption of three-
flavour oscillations is applied. As a next step, neutrino interactions in/around the detector and
its response are obtained for each signal event. Therefore, the final signal simulation set reflects
the characteristics expected from WIMP-induced \(\nu\)'s: reconstructed angular distributions of
neutrino directions are peaked from the direction of the source and their energy spectra
expected for various WIMP annihilation channels are reproduced and take into account detector
acceptance and resolution. Each analysis is performed in the coordinate system in which
the expected signal can be distinguished the most effectively from the atmospheric neutrino
background as illustrated in Fig. 1.
4. Results

4.1. Solar WIMP search
No excess of DM-induced neutrinos has been found in a fit. Based on the null contribution, the 90% CL upper limit on the DM-induced muon neutrino flux is derived assuming \( \tau^+ \tau^- \), \( b\bar{b} \), \( W^+W^- \) WIMP annihilations in the Sun and masses of relic particles in a range 4 – 200 GeV (Fig. 2). This limit is converted into the upper limit on WIMP-nucleon cross-section using DarkSUSY 5.0.6 [6]. Only a single type of WIMP interaction with a nucleus, either an axial vector interaction in which WIMPs couple to the nuclear spin (spin dependent, SD) or a scalar interaction in which WIMPs couple to the nucleus mass (spin independent, SI) is assumed. Standard DM halo with local density 0.3 GeV/cm\(^3\), a Maxwellian velocity distribution with a RMS velocity of 270 km/s and a solar rotation speed of 220 km/s are considered. Obtained limits are shown in Fig. 3(4) for SD(SI) case along with results from other experiments. The uncertainties related to the WIMP capture process are indicated by the shadowed regions (detailed description can be found in [8]).

4.2. Galactic WIMP search
The global fit of atmospheric neutrino background and WIMP-induced signal for \( \mu^+\mu^- \), \( b\bar{b} \), \( W^+W^- \), \( \nu\bar{\nu} \) annihilation channels is performed assuming WIMP masses from 1 GeV up to 10 TeV. No significant signal contribution of DM-induced neutrinos from the Milky Way is allowed by the data (Fig. 5).

This result can be translated into the 90% CL upper limit on DM-induced diffuse neutrino flux. From the latter, the 90% CL upper limit on the DM self-annihilation cross \( \langle \sigma_A V \rangle \) can be derived (Fig. 6, indicated as global fit) [9, 10].

Independently, the second analysis is conducted for the search of WIMP-induced neutrinos from the Milky Way. It is based on a concept of equally sized ON- & OFF-source regions defined in right ascension (RA) and declination (DEC) plane. The signal is expected only in ON-source region centered around the GC while the OFF-source region is offset in RA but having the same DEC (the level of background should be the same in both regions). Therefore, the difference in number of neutrino events between ON- and OFF-source regions should correspond only to the
Figure 3. 90% CL upper limits on SD WIMP-proton cross section calculated with DarkSUSY [6] default are shown in red solid with uncertainty bands to take account uncertainties in the capture rate for the $b\bar{b}$, $W^+W^-$ and $\tau^+\tau^-$ channels from top to the bottom. Also shown are limits from other experiments (for references see [8]).

Figure 4. 90% CL upper limits on the SI WIMP-nucleon cross section. Also shown are event excesses or annual modulation signals reported by other experiments: DAMA/LIBRA (black regions, $3\sigma$ CL), CoGeNT (magenta diagonally cross-hatched region, 90% CL), CRESST-II (violet horizontally-shaded regions, $2\sigma$ CL), CDMS II Si (blue vertically-shaded region, 90% CL), and limits from other experiments (for references see [8]).

Figure 5. Fitted number of WIMP-induced $\nu$'s of all flavors from WIMP annihilation into $b\bar{b}$, $\mu^+\mu^-$, $W^+W^-$ and $\nu\bar{\nu}$ as a function of mass of the relic particles. The gray band corresponds to $3\sigma$ sensitivity with null WIMP hypothesis. Points shown in this figure are not independent as the same set of data is used to test each WIMP mass hypothesis.

difference in signal events and is directly proportional to the $\langle \sigma_A V \rangle$. In this way the potential signal contribution can be estimated directly from the data. This method is independent on atmospheric MC simulations and related systematic uncertainties as they should equally affect ON- and OFF-source regions and cancel out in the subtraction of recorded number of events.
Figure 6. 90% CL upper limits on DM self-annihilation cross section $\langle \sigma v \rangle$ (region above the lines is excluded) from global fit (solid) and ON-OFF source (dotted) searches. Limits for $\nu\nu$ (black circles), $b\bar{b}$ (blue crosses), $W^+W^-$ (red squares) and $\mu^+\mu^-$ (green triangles) annihilation modes are based on expected signal intensity (DM squared density) from NFW halo profile [11].

The limits derived in this approach are also shown in Fig. 6 (indicated as ON-OFF source).

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