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Dark Matter Searches 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 2016. The results of the search for WIMP-induced neutrinos from the Sun, the Earth's core and the Milky Way are discussed. We looked for an excess of neutrinos related to a given source 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 & Earth 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 energy density 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 arise within supersymmetric models and belong to a collective group referred to as WIMPs (Weakly Interacting Massive Particles, often denoted as χ 's) [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 or even inside the Earth's core. The scattering off χ 's on the nuclei present in the Sun/Earth leads to the capture of the relic particles in the presence of heavy gravitational potential. The equilibrium is then expected to be set between their capture and annihilation rate. Neutrinos, as one of the annihilation products, can escape the dense matter region of the 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].



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Detection of neutrino interactions is based on observation of charged particles, primarly leptons, which may produce Cherenkov radiation while moving faster than the speed of light 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 μ -like rings).

In the energy range expected for WIMP-induced neutrinos (GeV-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 ~ 1 GeV up to 10 GeV. Neutrinos of the higher energies are seen mostly as through-going (showering or non-showering) or through-going stopping muons. They are produced in ν_{μ} 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 traveling in upward direction (UPMU) must be neutrino induced. The FC, PC and UPMU event classes can be divided into more specific subcatagories described elsewhere [5].

The discussed search for DM-induced ν 's from the Sun is based on atmospheric neutrino data collected with SK detector in years 1996-2012, corresponding in total to 3902.7 live-days for FC/PC and 4206.7 live-days for UPMU events. The searches regarding the DM-induced ν 's from the Earth's core and the Milky Way are extended with data collected until 2016, which in total corresponds to 5325.8 live-days for FC/PC and 5629.1 live-days for UPMU events.

3. Analysis

In all of presented 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 obtained using a fit method. Both, the signal and background predictions are based on the Monte Carlo (MC) simulations. The signal contribution is governed by the normalization parameter and is varied in the fit. The background, normalization and shape, is fitted by varying 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 with 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 well as to the real data. In order to simulate the WIMP-induced neutrinos, 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 ν '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 figure 1.



Figure 1. Comparison of angular distributions of the fully-contained Multi-GeV μ -like events for the Galactic (a), Earth (b) and Solar (c) DM-induced neutrino searches. Plots show SKI-IV data (black points with errors), atmospheric ν background MC (normalized to data live-time, solid red) and WIMP-induced neutrino signal before fit (filled blue histogram) for 5-6 GeV WIMPs annihilating into $b\bar{b}$. Only one data sample out of 19 (18 in case of Solar search) used in a fit is shown in this example.

4. Results of Solar WIMP Search

No excess of DM-induced neutrinos has been found in a fit based on the 1996-2012 data collected with the SK detector. 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 (see [8]). This result 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/cm³, 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 figure 2 for SD/SI case along with results from other neutrino experiments. Limits are compared also to those from direct detection experiments. Detailed description can be found in [8].

5. Results of Earth WIMP Search

Dark matter could be captured in the Earth's core. The scattering off χ particles is the most effective when occurs on the nuclei with the mass closest to M_{χ} . Therefore, for the certain χ masses corresponding for example to masses of ¹⁶O, ²⁴Mg, ²⁸Si, ⁵⁶Fe (and their isotopes) the resonant feature of the capture spectrum is expected. This would be also reflected in the intensity of the annihilation products for selected M_{χ} 's. The SK data collected between 1996-2016 is searched for the presence of DM-induced neutrinos related to the annihilation of χ 's in the Earth's core assuming realistic angular and momentum characteristics of the signal events for various M_{χ} hypotheses. The result of the fit is consistent with null WIMP contribution and it can be translated into the limit for WIMP-nucleon scattering cross section based on the assumption of equilibrium between χ capture and annihilation rates. Limits obtained in this analysis for SI WIMP-nucleon cross section are presented in figure 3. They are the most stringent among neutrino experiments for $M_{\chi} < 100$ GeV up to date.



Figure 2. 90% CL upper limits on SD (SI) WIMP-nucleon cross section are shown as thick solid lines for the $b\bar{b}$, W^+W^- and $\tau^+\tau^-$ channels [8]. Also shown are limits from other experiments, along with annual modulation signal reported by DAMA/LIBRA (black hatched regions). SK result corresponds to 3902.7 live-days for FC/PC and 4206.7 live-days for UPMU events (1996-2012).

6. Results of 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 ranging from 1 GeV up to 10 TeV. No significant signal contribution of DM-induced neutrinos from the Milky Way is allowed by the data collected with the SK detector between 1996-2016. Based on this result the 90% CL upper limit on the thermally averaged annihilation cross section $\langle \sigma_A V \rangle$ is derived as shown in figure 4 and compared with the results from other neutrino telescopes [12, 13]. Obtained limit yields the most stringent constrains among neutrino experiments below 20 - 100 GeV (depending on the ann. mode). It reflects the characteristics of the SK data which in this range relay on numerous fully-contained samples providing precise information on interacting neutrino energy.

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Figure 3. 90% CL upper limit on the spin-indpendent WIMP-nucleon cross section assuming χ annihilation in the Earth's core and equilibirum state between the capture and annihilation rate of the relic particles. The latest SK result for $b\bar{b}$ and $\tau^+\tau^-$ channels is the strongest among neutrino experiments for the M_{χ} ranging from 10 up to 100 GeV. Limits from ANTARES [9] and IceCube [10] neutrino experiments are also shown, along with best fit contours from DAMA/LIBRA [11].



Figure 4. 90% CL upper limits on DM selfannihilation cross section $\langle \sigma_A V \rangle$ (region above the lines is excluded) for $\nu\nu$ (dark yellow), $b\bar{b}$ (blue), W^+W^- (maroon) and $\mu^+\mu^-$ (dark orchid) annihilation modes. Limits are based on expected signal intensity (DM squared density) from NFW halo profile [14]. SK result corresponds to 5325.8 live-days for FC/PC and 5629.1 live-days for UPMU events (1996-2016).

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