# Search for dark matter WIMPs using upward through-going muons in Super–Kamiokande

The Super-Kamiokande Collaboration

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We present the results of indirect searches for Weakly Interacting Massive Particles (WIMPs), with 1679.6 live days of data from the Super-Kamiokande detector using neutrino-induced upward through-going muons. The search is performed by looking for an excess of high energy muon neutrinos from WIMP annihilations in the Sun, the core of the Earth, and the Galactic Center, as compared to the number expected from the atmospheric neutrino background. No statistically significant excess was seen. We calculate the flux limits in various angular cones around each of the above celestial objects. We obtain conservative model-independent upper limits on the WIMP-nucleon cross-section as a function of WIMP mass, and compare these results with the corresponding results from direct dark matter detection experiments.

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## I. INTRODUCTION

There is growing evidence which indicates that the universe contains, at all length-scales, "dark matter" which does not emit or absorb electromagnetic radiation at any known wavelength, but manifests itself only through gravity [1]. Recent data from WMAP and other CMB experiments, large-scale structure surveys, Lyman-$\alpha$ forest, Type 1a supernovae etc. [2, 3, 4, 5, 6] point with increasing accuracy towards a standard cosmological model [7, 8], in which the universe is flat, with about 5% baryons, 25% non-baryonic dark matter, and about 70% dark energy. In this model, the non-baryonic dark matter consists of "Cold Dark Matter" particles, which decoupled from rest of the matter and radiation while moving at non-relativistic velocities [9, 10].

Weakly Interacting Massive Particles (WIMPs) are one of the plausible cold dark matter candidates [11, 12]. WIMPs are stable particles which are predicted to occur in extensions of the standard model, such as supersymmetry. WIMPs undergo only weak-scale interactions with matter, and could have masses in the GeV-TeV range. If WIMPs exist, their relic abundance (which is governed by electroweak scale interactions) is remarkably close to the inferred density of dark matter in the universe [13]. The lightest supersymmetric particle (LSP) of supersymmetric theories is the most theoretically well developed WIMP candidate [14, 15]. Most SUSY theories contain a multiplicatively conserved quantum number called R-parity, where R-parity is equal to 1 for ordinary standard model particles, and is equal to $-1$ for their supersymmetric partners [11]. If R-parity is conserved, superpartners can form and decay only in pairs. Thus, the LSP is stable and hence should be present in the Universe as a cosmological relic from the Big Bang. The most likely candidate for this LSP is the neutralino [15].

The neutralino $\tilde{\chi}$ is a linear combination of the supersymmetric particles that mix after electroweak-symmetry breaking:

$$\tilde{\chi} = a_1\tilde{\gamma} + a_2\tilde{Z} + a_3\tilde{H}_1 + a_4\tilde{H}_2, \tag{1}$$

where $\tilde{\gamma}$ and $\tilde{Z}$ are the supersymmetric partners of the photon and the $Z$ boson, and $\tilde{H}_1$ and $\tilde{H}_2$ are the supersymmetric partners of the Higgs bosons (Higgsino). The current lower limit on neutralino mass, without assuming anything about the SUSY breaking mechanism, and taking into account the results from LEP2 data, is about 18 GeV [16]. The upper limit on neutralino mass depends on the model assumed for SUSY breaking, and ranges from 500 GeV in some models [17] and up to 10 TeV in other models [18].

In this paper, we perform an indirect search for WIMP dark matter using the Super–Kamiokande detector, by looking for a high energy neutrino signal resulting from WIMP annihilation in the Earth, the Sun, and the Galactic Center. The signature would be an excess of neutrino-induced events coming from the direction of these objects over the background expected from atmospheric neutrinos. Such a search is complementary to direct detection experiments, which look for direct interaction of WIMPs with a nucleus in a low background detector. However, both direct and indirect detection experiments probe the coupling of WIMPs to nuclei. We then compare our results with those of direct detection of dark matter experiments.

## II. INDIRECT WIMP SEARCHES USING NEUTRINO-INDUCED MUONS

If WIMPs constitute the dark matter in our galactic halo, they will accumulate in the Sun [19] and the Earth [20, 21]. When their orbits pass though a celestial body, the WIMPs have a small but finite probability of elastically scattering with a nucleus of that body. If their final velocity after scattering is less than the escape velocity, they become gravitationally trapped and eventually settle into the center of that body. WIMPs which have accumulated this way annihilate in pairs, primarily into $\tau$ leptons, $b$, $c$ and $t$ quarks, gauge bosons, and Higgs bosons, depending upon their mass and composition. As the WIMP density increases in the core, the annihilation rate increases until equilibrium is achieved between capture and annihilation, making the annihilation (each of which involves two captured WIMPs) rate half of the capture rate. High energy muon neutrinos are produced by the decay of the annihilation products. The expected neutrino fluxes from the capture and annihilation of WIMPs in the Sun and the Earth depend upon several astrophysical parameters: the WIMP mean halo velocity ($v_\chi \sim 220$ km s$^{-1}$), the WIMP local density ($\rho_\chi \sim 0.3$ GeV cm$^{-3}$), the WIMP-nucleon scattering cross-section; and the mass and escape velocity of the celestial body. WIMPs undergo two kinds of interactions with the celestial bodies: axial vector interactions in which WIMPs couple to the spin of the nucleus; and scalar interactions in which WIMPs couple to the mass of the nucleus [22]. For the Earth, WIMPs mainly undergo scalar interactions, since the abundance of nuclei with odd mass number (which are needed for spin coupling) is extremely small [23]. In the Sun, WIMPs interact through both scalar as well as axial vector interactions (due to the large abundance of hydrogen). There are many calculations of the expected neutrino fluxes from WIMP capture and annihilation in the Sun and the Earth [20, 21, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33].

It has been also pointed out that cold dark matter near the Galactic Center can be accreted by the central black hole resulting in a dense spike in the density distribution [34]. WIMP annihilations in this spike would make it a compact source of high energy neutrinos. The flux of these neutrinos depends on the density profile of the inner dark matter halo. Halos with isothermal or finite cores produce a negligible flux of neutrinos, while halos with inner density cusps produce an appreciable flux of neutrinos [34].

Energetic neutrinos coming from WIMP annihilation in the Sun, the Earth, and the Galactic Center could be detected in neutrino detectors. The mean neutrino energy ranges from 1/3 to 1/2 the mass of the WIMP, i.e. from about 5 GeV to 5 TeV. In this energy range, neutrino-induced upward through-going muons from charged current interactions provide the most effective signatures in Super-Kamiokande.

## III. WIMP ANALYSIS WITH SUPER–K

The Super–Kamiokande ("Super–K") detector is a 50,000 ton water Cherenkov detector, located in the Kamioka-Mozumi mine in Japan with 1000 m rock overburden. For this analysis, Super-K consisted of an inner detector with 11,146 inward-facing 50 cm photomultiplier tubes (PMTs) and an outer detector equipped with 1885 outward-facing 20 cm PMTs, serving as a cosmic ray veto counter. More details about the detector can be found in Ref. [35]. The data used in this analysis was taken from April 1996 to July 2001, corresponding to 1679.6 days of detector livetime.

Upward through-going muons in Super–K are mainly produced by interactions of atmospheric $\nu_\mu$ in the rock around the detector and are energetic enough to cross the entire detector. The effective target volume extends outward for many tens of meters into the surrounding rock and increases with the energy of the incoming neutrino, as the high energy muons resulting from these interactions can travel longer distances to reach the detector. Thus, upward through-going muons represent the highest energy portion of the atmospheric neutrino spectrum observed by Super–K, and the corresponding parent neutrino energy spectrum peaks at $\sim 100$ GeV [36]. The downward-going cosmic ray muon rate in Super–K is 3 Hz, making it impossible to distinguish any downward-going neutrino-induced muons from this large background of downward-going cosmic ray muons. Hence we restrict our analysis to upward-going muons.

Reconstruction of a muon event is performed using the charge and timing information recorded by each hit PMT. Muons are required to have $\geq 7$ meters measured path length ($E_\mu > 1.6$ GeV) in the inner detector. The effective detector area for upward through-going muons with this path length cut is $\sim 1200$ m$^2$. For each event, we obtain the arrival direction and time. After a final precision fit and visual scan, 1892 upward through-going muon events have been observed. The detector angular resolution for upward through-going muons is about $1^\circ$. More details of the data reduction procedure for selecting upward going muons can be found in Ref. [37]. The sample described above is contaminated by some downward-going cosmic ray muons close to the horizon, which appear to be upward-going due to the tracking angular resolution of the detector and multiple Coulomb scattering in the rock. The total number of such non-$\nu$ background events has been estimated to be $14.4 \pm 9.4$, all contained in the $-0.1 < \cos\Theta < 0$ bin, where $\Theta$ is the zenith angle. With the 7 m path-length cut, the contamination from photoproduced upward going pions from nearby downward-going cosmic ray muons is estimated to be $< 1\%$ [38].

The expected background due to interactions of atmospheric $\nu$'s in the rock below the detector is evaluated with Monte Carlo simulations. These simulations, which were generated using the `Nuance` neutrino simulation package [39], use the Bartol atmospheric $\nu$ flux [40], the GRV-94 parton distribution function [41], energy loss mechanisms of muons in rock from Ref. [42], and a GEANT-based detector simulation. There is a 20% uncertainty in the prediction of absolute upward-going muon flux. Analysis of the most recent Super-K data [43, 44] of upward going muons and contained events is consistent with $\nu_\mu \to \nu_\tau$ oscillations with best fit values given by : $\sin^2 2\theta \simeq 1$ and $\Delta m^2 \simeq 2 \times 10^{-3} eV^2$. For evaluating our background, we suppress the atmospheric muon neutrino flux due to oscillations from $\nu_\mu$ to $\nu_\tau$ using these oscillation parameters.

The distribution of upward through-going muons with respect to the Earth is shown in Fig. 1. For the Sun, there is an additional background of high energy neutrinos resulting from cosmic ray interactions in the Sun, but this is negligible compared to the observed atmospheric $\nu$ flux and hence can be neglected [45, 46]. Normalization was done by constraining the total number of Monte Carlo events to be equal to the observed events, after taking oscillations into account. In order to compare the expected and observed distribution of upward through-going muon events with respect to the Sun and Galactic Center, each Monte Carlo event was assigned a time sampled from the observed upward through-going muon arrival time, in order to match the livetime distribution of the observed events. This procedure allows us to obtain the right ascension and declination for every Monte Carlo event, from which the angle between the upward muon and any celestial object can be estimated. The distribution of upward muons with respect to the Sun and the Galactic Center is shown in Figs. 2 and 3 respectively.

## IV. RESULTS FROM WIMP SEARCHES

We searched for a statistically significant excess of muons in cones about the potential source of neutrinos, with half angles ranging from 5 to 30 degrees. This en-

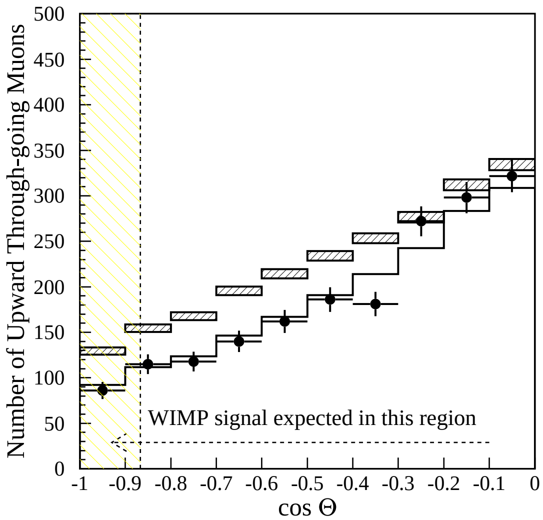


FIG. 1: Zenith angle distribution of upward through-going muons with respect to the center of the Earth along with comparison against the expected flux. The black circles indicate observed data along with statistical uncertainties. Hatched regions indicates the background from atmospheric neutrinos, the solid lines indicate the atmospheric neutrino background after taking into account neutrino oscillations with: $\sin^2 2\theta = 1.0$ and $\Delta m^2 = 2 \times 10^{-3} eV^2$. The hatched region in $-1.0 < cos(\Theta) < -0.866$ range indicates the angular region where WIMP searches were done.

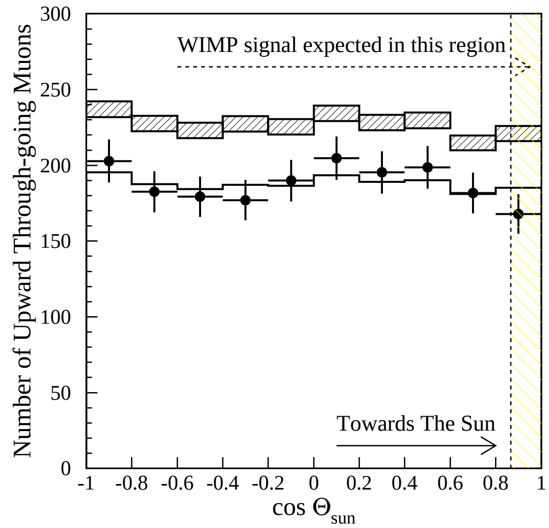


FIG. 2: Angular distribution of upward through-going muons with respect to the Sun. All symbols are same as in Fig. 1.

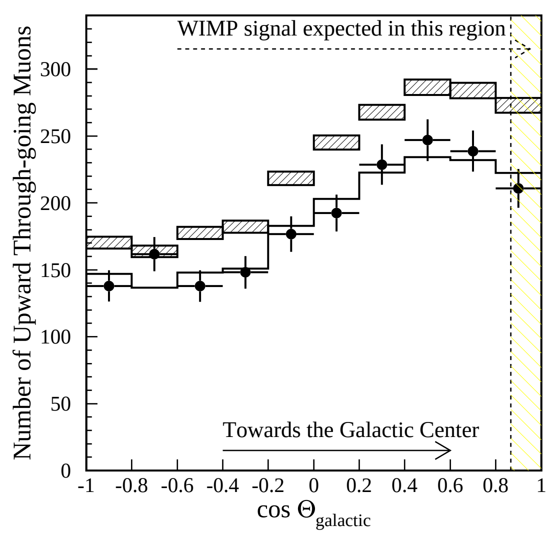


FIG. 3: Angular distribution of upward through-going muons with respect to the Galactic Center. All symbols are same as in Fig. 1.

sures that we catch 90% of the signal for a wide range of WIMP masses, as smaller masses produce a wider angular distribution of neutrinos. Searching in different cone angles allows us to optimize the signal to background ratio as a function of neutralino mass.

The distribution of data and Monte Carlo (both with and without oscillations) in different angular regions ranging from 5 to 30 degrees around the center of the Earth, the Sun and the Galactic Center is shown in Figs. 4, 5 and 6 respectively. There was no statistically significant excess that was seen in any half angle cones up to 30°. We calculate the flux limit of excess neutrino-induced muons in each of the cones. The flux limit is given by :

$$\Phi(90\% \, CL) = \frac{N_{90}}{E} \tag{2}$$

where $N_{90}$ is the upper Poissonian limit (90% CL) given the number of measured events and expected background [47] (due to atmospheric neutrinos after oscillations), and $E$ is the exposure given by equation:

$$E = \epsilon \times A \times T \tag{3}$$

where $A$ is the detector area in the direction of the expected signal ; $\epsilon$ is the detector efficiency which is $\approx 100\%$ for upward through-going muons; and $T$ is the experimental livetime.

The comparison of Super-K flux limits with searches by other experiments is shown in Figs. 7–9. All the other experiments have muon energy thresholds around 1 GeV. The upward muon flux limits for the Earth and the Sun by MACRO, Kamiokande, Baksan, and IMB are in Refs. [49, 50, 51, 52] respectively, and those for the Galactic Center by the above detectors are in Refs. [53, 54, 55, 56] respectively. We also find that varying the oscillation parameters and choosing values corresponding to the boundaries of the 90 % confidence level allowed region does not change the flux limits within

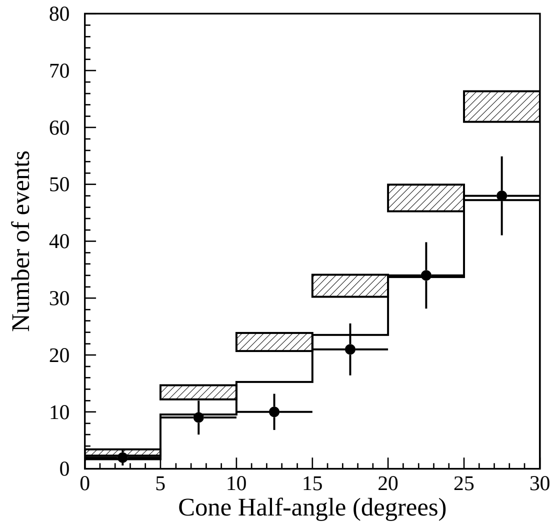


FIG. 4: The expanded view of the zenith angle distribution of upward through-going muons around the Earth's center (Fig. 1). All symbols are same as in Fig. 1.

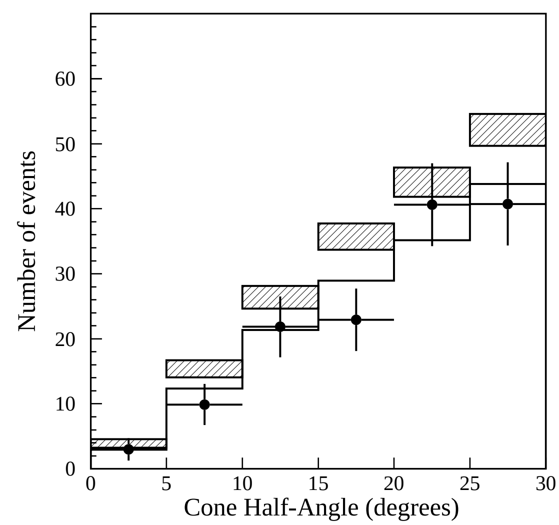


FIG. 6: The expanded view of the angular distribution of upward through-going muons around the Galactic Center (Fig. 3). All symbols are same as in Fig. 1.

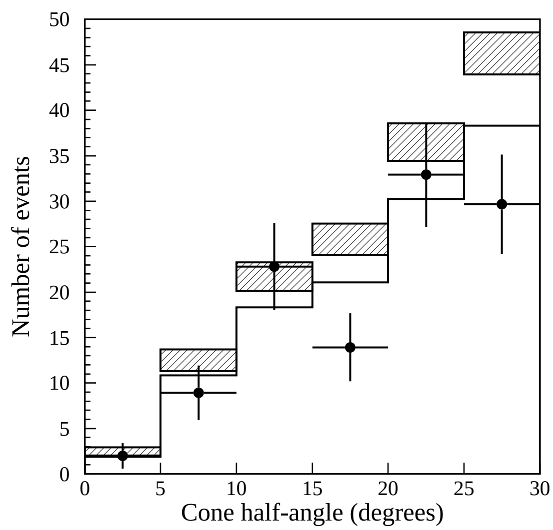


FIG. 5: The expanded view of the angular distribution of upward through-going muons around the Sun (Fig. 2). All symbols are same as in Fig. 1.

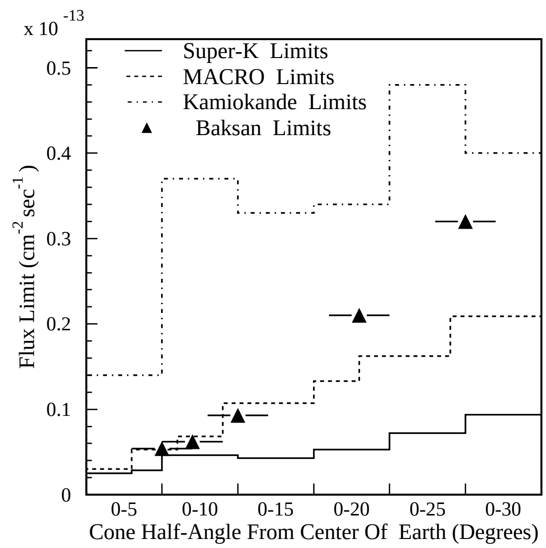


FIG. 7: Comparison of Super-K 90 % CL excess neutrino-induced upward muon flux limits from the Earth in cone half-angles ranging from 5° to 30° along with those from other experiments.

the first 20 degrees from the celestial object. Only in the largest half angle cones (half angle 30 degrees) does the flux limit vary by as much as ±10 %. In this paper all results are reported with the above best-fit oscillation parameters.

Once WIMPs are captured in the Sun and the Earth they settle to the core with an isothermal distribution equal to the core temperature of the Sun or of the Earth [48]. While the Sun is effectively a point source of energetic neutrinos resulting from WIMP annihilations, the Earth is not a point source for WIMPs with mass less than 50 GeV. For the Earth, the angular shape of the annihilation region has been estimated to be : [28, 48]

$$G(\Theta) \simeq 4m_\chi \beta e^{-2m_\chi \beta \sin^2 \Theta} \quad (4)$$

where $\Theta$ is the nadir angle, $\beta$ is a parameter depending on the central temperature, the central density and radius of the Earth. In addition, muons deviate from the in-

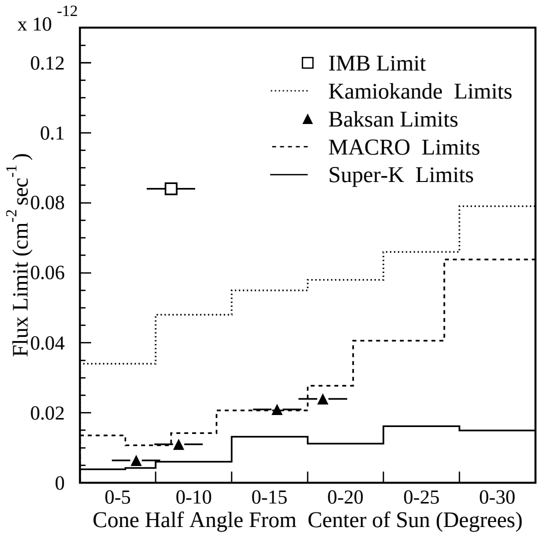


FIG. 8: Comparison of Super-K 90 % CL excess neutrino-induced upward muon flux limits from the Sun in cone half-angles ranging from 5° to 30° along with those from other experiments.

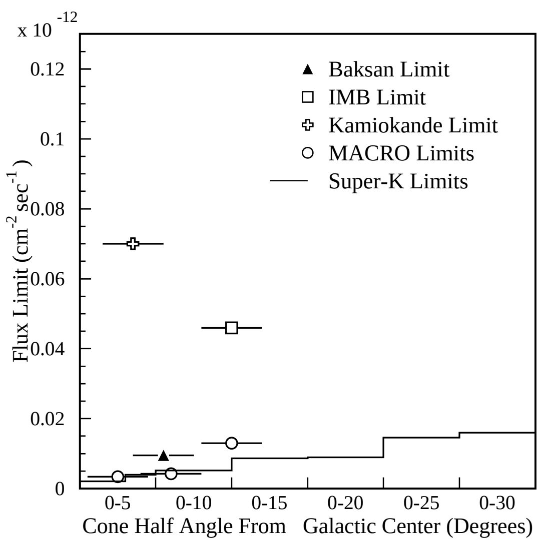


FIG. 9: Comparison of Super-K 90 % CL excess neutrino-induced upward muon flux limits from the Galactic Center in cone half-angles ranging from 5° to 30° along with those from other experiments.

coming direction of their parent neutrino due to multiple coulomb scattering of the muon.

We used the Monte Carlo simulations done in Ref. [50] to calculate the angular windows for the Sun and the Earth, which contain 90% of the signal for various neutralino masses, taking into account the spread because of neutrino physics as well as the finite angular size of the WIMP annihilation region for the Earth. The simulations assumed that 80% of the annihilation products are from $b\bar{b}$, 10% from $c\bar{c}$ and 10% from $\tau^+\tau^-$. However the neutrino-muon scattering angle is mainly dependent on the neutralino mass, and does not change much with different branching ratios [49]. For the case of the Earth, cones of half-angle 2° and 22° contain 90% of the signal from WIMPs with masses of 10 TeV and 18 GeV respectively. The corresponding numbers for the Sun are 1.5° and 19° for WIMPs with masses of 10 TeV and 18 GeV respectively. The corresponding cone half-angle for other intermediate masses can be found in Ref. [50].

Using these windows, 90% confidence level flux limits can be calculated as a function of neutralino mass, using cones which collect 90% of expected signal for any given mass and after correcting for the collection efficiency of the cones. These flux limits as a function of neutralino mass are shown in Figs. 10 and 11 for the Earth and the Sun respectively, along with similar limits from AMANDA [57], BAKSAN [55], MACRO [49]. The Super-K limits have been plotted from 18 GeV up to 10 TeV. The lower limit of 18 GeV is the minimum WIMP mass for which at least 90% of the upgoing muon signal would be through-going, rather than stopping upward muons. These limits can be compared with theoretical expectations from SUSY models.

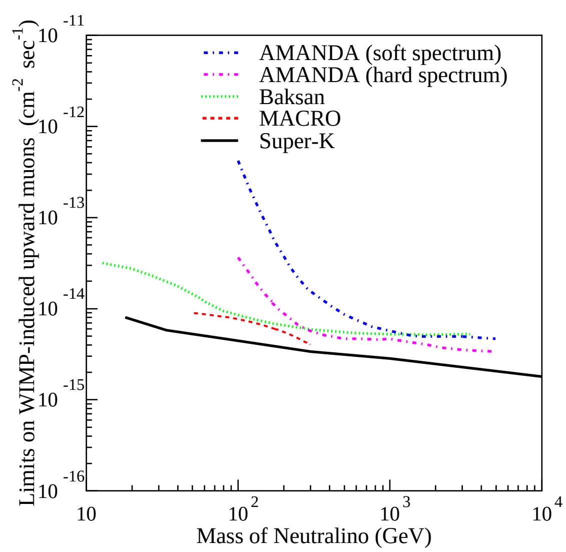


FIG. 10: Super-K WIMP-induced upward muon flux limits from Earth as a function of WIMP mass along with those from other detectors.

For the case of the galactic center, the apparent size of the annihilation region is less than 0.05° [34]. Hence the Galactic Center can be considered a point source for WIMP annihilation, and the angular point spread function is same as that for the Sun. These flux limits, as a function of neutralino mass for the Galactic Center (which also have been plotted from 18 GeV up to 10 TeV), are shown in Fig. 12.

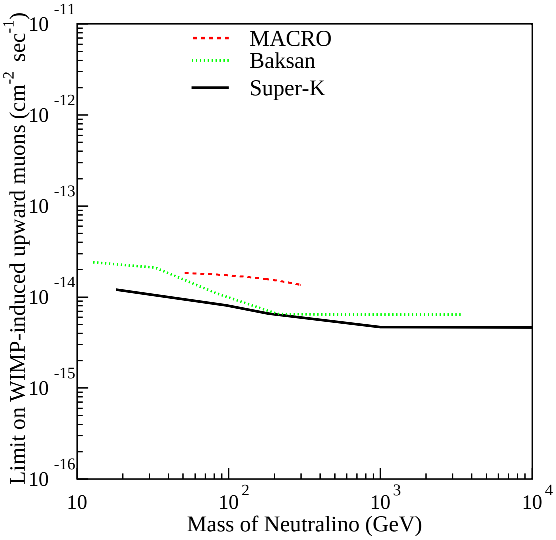


FIG. 11: Super-K WIMP-induced upward muon flux limits from Sun as a function of WIMP mass along with comparison with other detectors.

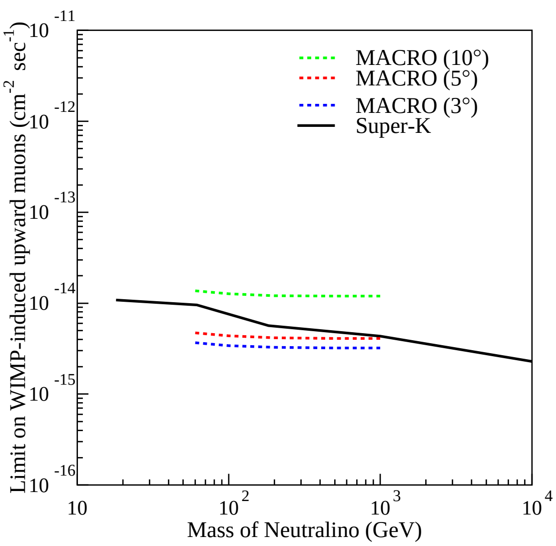


FIG. 12: Super-K WIMP-induced upward muon flux limits from Galactic Center as a function of neutralino mass along with corresponding limit from MACRO.

## V. COMPARISON WITH DIRECT DETECTION EXPERIMENTS

Direct detection experiments seek to observe the keV energy recoil in a low-background detector, when a WIMP elastically scatters from a nucleus therein. On the other hand, indirect detection experiments involve a search for energetic neutrinos produced by annihilation of WIMPs, which have been trapped in the center of the Sun and the Earth. Rates for both techniques depend primarily upon the WIMP-nucleon cross-section and mass. It is possible to compare direct and indirect experiments by making realistic assumptions about some of the model-dependencies [58]. We sketch some of the details and outline how we obtain limits on WIMP-nucleon cross-section using these results.

When one calculates the ratio of direct detection rates to the flux of upward-going muons from WIMP annihilation, the main model-dependent term which cannot be canceled and depends on details of the SUSY spectrum is in the quantity defined in Ref. [58] as $\xi(m_\chi)$; this is the second moment of the neutrino energy spectrum from a given annihilation channel, scaled by the branching ratio of WIMP to that annihilation channel:

$$\begin{aligned}\xi(m_\chi) = \textstyle\sum_F B_F[3.47 < Nz^2 >_{F,\nu} (m_\chi) \\ +2.08 < Nz^2 >_{F,\overline{\nu}} (m_\chi)].\end{aligned} \quad (5)$$

Here, the sum is over all annihilation channels, F, available to any specific neutralino candidate, $B_F$ is the branching ratio for annihilation, and $< Nz^2 >$ is the scaled second moment of the neutrino energy spectrum from final state F for a given neutralino mass. All other terms are functions of only the neutralino mass and the elastic scattering cross-section. As argued in Ref. [11], an upper and lower bound can be estimated for $\xi(m_\chi)$ depending on the neutralino mass. For a WIMP heavier than the top quark, the lower limit comes from annihilation to gauge bosons. For WIMPs lighter than the $W$ boson, the lower limit comes from annihilation to $b\bar{b}$, and for intermediate mass WIMPs the lower limit comes from annihilation to $\tau\bar{\tau}$ pairs. Using these assumptions, maximum values of the ratio of direct to indirect fluxes have been calculated for WIMPs with pure scalar couplings, and for WIMPs with pure axial vector coupling. These ratios have been plotted in Figure (2) of Ref [58]. In comparing direct and indirect searches for scalar-coupled WIMPs, the sum of WIMP-induced upward muon flux from the Sun and the Earth has been taken into account, whereas for WIMPs with axial vector couplings only the WIMP-induced upward muon flux from the Sun has been considered. To get a rough idea of the sensitivities of the direct and indirect searches, the event rate in a 1 kg Germanium detector is equivalent to the event rate in $10^4 - 10^6$ $m^2$ of upward muon detector for a WIMP with scalar couplings, and the event rate in a 50-gm hydrogen detector is roughly same as that in a $10 - 500$ $m^2$ muon detector. Using the maximum inferred ratios of direct to indirect detection rates, we can compare our results with those from direct detection experiments as we shall describe below. Before that we shall briefly describe results from some of the direct dark matter detection experiments.

The DAMA experiment at Gran Sasso has claimed that their data, collected over 7 annual cycles corresponding to 107731 kg.day exposure, contain an annual modulation which is consistent with the possible presence of scalar-coupled WIMPs [59, 60], with the best fit values being : $M_w = 52$ GeV and $\sigma_p = 7.2 \times 10^{-6}$ pb using standard astrophysical assumptions [59]. The CDMS [61, 62, 63, 64] and EDELWEISS [65] experiments, which employ Ge and Si detectors, and the ZEPLIN [66] experiment, which uses liquid Xe, do not see any WIMP signal. They rule out most or all of the DAMA allowed region at more than 99% CL.

Using the maximum inferred ratio of the direct-to-indirect detection rates, we get conservative model independent limits on neutralino-nucleon spin-independent as well as spin-dependent cross-sections (on protons) from the Super-K flux limits, and compare them with the results of direct-detection experiments, since we have obtained 90% CL upper flux limit.

To get limits on the WIMP-nucleon cross-section for a WIMP with scalar coupling, we first calculate the combined WIMP flux limits from the Sun and the Earth as a function of WIMP mass and solve the following equation to calculate the upper limit on WIMP-nucleon cross-section:

$$\text{Max Ratio (M)} = \frac{\text{Direct Detection Rate ( M, } \sigma \text{ )}}{\text{Super-K limit (M)}} \quad (6)$$

where the quantity on the left is the maximum calculated ratio of direct to indirect detection rates for a WIMP with scalar coupling, and the numerator on the right hand side indicates the event rate in a direct detection experiment as a function of WIMP mass and cross-section. The denominator on the right hand side is the combined Super-K limit from the Sun and the Earth as a function of WIMP mass. To obtain the combined flux limit, we first calculate the total number of observed events for each WIMP mass. This is done by adding the observed number of events in the corresponding cone which contains 90% of the flux for a given mass from the Sun and the Earth, after scaling for their different exposures. The same procedure is used to obtain the total expected background. Using this, we obtain the 90% CL flux limit, which is then scaled by the cone collection efficiency. We then evaluate the direct detection rate at a given value of WIMP mass and cross-section, using an exponential form factor [67], and using values for the WIMP halo density and mean velocity from Ref. [61]. Thus, for each value of WIMP mass, using the combined Super-K flux limit, the direct detection rate, and the maximum expected ratio for the direct to indirect detection rate, Eqn. 6 is solved for $\sigma$ to get the 90 % upper limit on the WIMP-nucleon cross-section. These Super-K upper limits on WIMP-nucleon scalar cross-section are shown in Fig.13 along with CDMS [64], EDELWEISS [65], ZEPLIN [66] upper limits, and DAMA [59] best fit region. The dip around a WIMP mass of 56 GeV occurs because of an enhancement in the WIMP capture rates in the Earth caused by a resonance due to WIMP mass matching that of iron [48], whose abundance in the Earth is about 30% [23]. There are two discontinuities in the Super-K limits on WIMP-nucleon cross-section in Fig. 13. The first discontinuity occurs at around 80 GeV and the other occurs at around 174 GeV. The reason for this is that these limits have been calculated assuming a lower limit for $\xi(M)$, where $\xi$ is defined in Eqn. 5. For WIMPs more massive than the top quark (with mass of around 174 GeV), the lower limit is given by WIMP annihilation to gauge bosons, and for WIMPs less massive than the top quark, the lower limit is given by WIMP annihilation to tau leptons. This continues until the WIMP mass is less than the W boson mass at around 80 GeV, below which the lower limit comes from WIMP annihilation to $b\bar{b}$ pairs. The Super-K limits rule out a significant portion of the WIMP parameter space favored by the DAMA experiment with a very different technique.

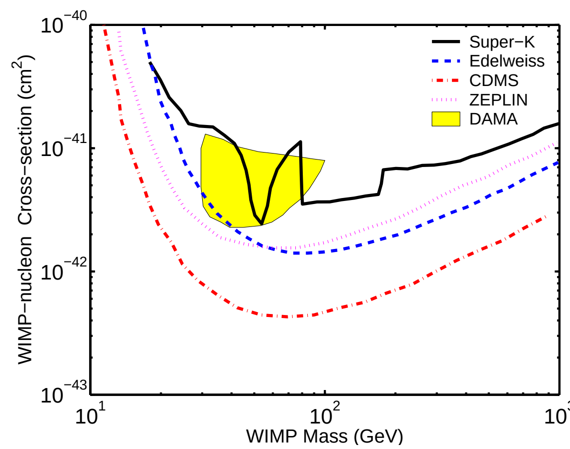


FIG. 13: Super-K 90 % CL exclusion region in WIMP parameter space (solid line) for a WIMP with scalar coupling obtained using limits on WIMP-induced muons from the Sun and the Earth. Also shown are the DAMA $3\sigma$ allowed region (filled), 90 % CL exclusion region from CDMS (dot-dashed), EDELWEISS (dashed), and ZEPLIN (dotted).

To get limits on WIMP-proton spin-dependent cross-section, we carried out the same exercise as above, this time using only the limits from the Sun in the denominator of Eqn. 6, and using the maximum inferred ratio for direct-to-indirect detection rates with axial-vector couplings on the left hand side of Eqn. 6. The Super-K limits on WIMP-proton cross-section are shown in Fig. 14 along with limits from other direct experiments like UKDMC [70] and ELEGANT-V [71] experiments. The reason for the jumps around 80 GeV and 174 GeV is the same as that for the limits on WIMP-nucleon scalar cross-section. The Super-K limits on WIMP-proton cross-section are about 100 times more sensitive than those from direct detection experiments. Also a limit on WIMP-proton spin-dependent cross-section using earlier Super-K limits from the Sun [68] has been done in Ref. [69], which showed that the annual modulation seen in DAMA cannot be because of a WIMP with axial vector coupling to a proton, since this is ruled out by null searches for WIMP-induced annihilations in the Sun from Super-K and other upward muon detectors.

It must be cautioned that these limits on WIMP-nucleon cross-section depend on the maximum expected

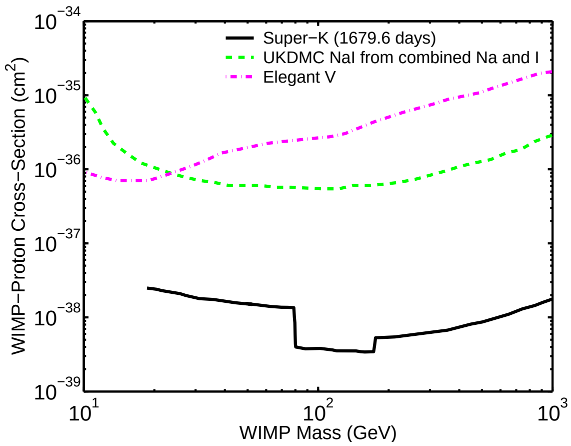


FIG. 14: Super-K 90 % CL exclusion region in WIMP parameter space for a WIMP with spin-dependent coupling along with corresponding 90 % CL exclusion limits from UKDMC (dashed) and ELEGANT (dot-dashed).

ratio of direct-to-indirect detection rates evaluated in Ref. [58]. These calculations give a rough idea of expected sensitivities of upward muon detectors as compared to direct detection experiments. For WIMPs with significant annihilation branching ratio to pure Higgs bosons or gluons, the ratio could fall outside the indicated range [58]. Also, in the comparison of direct and indirect detection rates, oscillations of neutrinos produced from WIMPs is not taken into account [72, 73]. Furthermore, the ratio does not include contribution from the proposed bound solar system population of WIMPs [74, 75]. All these effects could change the limits from what we have evaluated. However, by using the maximum expected value for the estimated ratio of direct to indirect detection rates in Ref. [58] we have obtained conservative limits on WIMP-nucleon cross-section.

## VI. CONCLUSIONS

We have looked for indirect signatures of dark matter using 1892 neutrino-induced upward through-going muon events by looking for an excess in the direction of the Sun, the Earth, and the Galactic Center. We looked for an excess of upward muons over atmospheric neutrino background close to the centers of the above bodies. No statistically significant excess was seen.

Flux limits were obtained for various cone angles around these potential sources, and compared with previous estimates by other detectors. These flux limits were calculated as a function of the WIMP mass.

Then, using model-independent comparison of fluxes of direct to indirect detection rates obtained in Ref. [58], we obtained limits on WIMP-nucleon cross-section for a WIMP with both scalar as well as axial-vector couplings.

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[1] V. Trimble, Annu. Rev. Astron. Astrophys. **25**, 425 (1987).
[2] D.N. Spergel *et al.*, Astrophys. J. Suppl. **148**, 175 (2003).
[3] M. Tegmark *et al.*, Phys. Rev. D **69**, 103501 (2004)
[4] S. Perlmutter *et al.*, Astrophys. J **517**, 565 (1999).
[5] A. Riess *et al.*, Astron. J **116**, 1009 (1998).
[6] J.L. Tonry *et al.*, Astrophys. J **594**, 1 (2003).
[7] W.L. Freedman and M.S. Turner, Rev. of Mod. Phys. **75**, 1433 (2003).
[8] A. Melchiorri and J. Silk, Phys. Rev. D **66**, 041301 (2002).
[9] P.J.E. Peebles, Astrophys. J **263**, L1 (1982).
[10] G.R. Blumenthal *et al.*, Nature **311**, 517 (1984).
[11] G. Jungman, M. Kamionkowski, and K. Griest, Phys. Rep. **267**, 195 (1996).
[12] L. Bergström, Rept. Prog. Phys. **63**, 793 (2000).
[13] B.W. Lee and S. Weinberg, Phys. Rev. Lett. **39**, 165 (1977).
[14] H. Goldberg, Phys. Rev. Lett. **50**, 1419 (1983).
[15] J. Ellis *et al.*, Nucl. Phys. B **238**, 453 (1984).
[16] D. Hooper and T. Plehn, Phys. Lett. B **562**, 18 (2003).
[17] J. Ellis *et al.*, Phys. Lett. B **565**, 176 (2003).
[18] J. Edsjö and P. Gondolo, Phys. Rev. D **56**, 1879 (1997).
[19] W.H. Press and D.N. Spergel, Astrophys. J, **296**, 679 (1985).
[20] K. Freese, Phys. Lett. B **167**, 295 (1986).
[21] L.M. Krauss, M. Srednicki, and F. Wilczek, Phys. Rev. D **33**, 2079 (1986).
[22] M. Goodman and E. Witten, Phys. Rev. D **31**, 3059 (1985).
[23] D.L. Anderson, *Theory of the Earth* (Blackwell Scientific Publications), Boston, (1989).
[24] J. Silk, K. Olive, and M. Srednicki, Phys. Rev. Lett. **55**, 257 (1985).
[25] T.K. Gaisser, G. Steigman, and S. Tilav, Phys. Rev. D **34**, 2206 (1986).
[26] S. Ritz and D. Seckel, Nucl. Phys. B. **304**, 877 (1988).
[27] G. Jungman and M. Kamionkowski, Phys. Rev. D **51**, 328 (1995).
[28] A. Bottino *et al.*, Astropart. Phys. **3**, 65 (1995).
[29] V. Berezinsky *et al.*, Astropart. Phys. **5**, 333 (1996).
[30] L. Bergström, J. Edsjö, and P. Gondolo, Phys. Rev. D

**55**, 1765 (1997).
[31] L. Bergström, J. Edsjö, and P. Gondolo, Phys. Rev. D **58**, 103519 (1998).
[32] J.L. Feng, K.T. Matchev, and F. Wilczek, Phys. Rev. D **63**, 045024 (2001).
[33] V. Barger *et al.*, Phys. Rev. D **65**, 075022 (2002).
[34] P. Gondolo and J. Silk, Phys. Rev. Lett. **83**, 1719 (1999).
[35] Super-Kamiokande Collaboration, S. Fukuda *et al.*, Nucl. Instruments and Methods A **501**, 418 (2003).
[36] Super-Kamiokande Collaboration, Y. Fukuda *et al.*, Phys. Lett. B **467**, 185 (1999).
[37] Super-Kamiokande Collaboration, Y. Fukuda *et al.*, Phys. Rev. Lett. **82**, 2644 (1999).
[38] MACRO Collaboration, M. Ambrosio *et al.*, Astropart. Phys. **9**, 105 (1998).
[39] D. Casper, Nucl. Phys. Proc. Suppl. **112**, 161 (2002).
[40] V. Agrawal, T. K. Gaisser, P. Lipari, and T. Stanev, Phys. Rev. D **53**, 1314 (1996).
[41] M. Glück, E. Reya, and A. Vogt, Z. Phys C **67**, 433 (1995).
[42] P. Lipari and T. Stanev, Phys. Rev. D **44**, 3543 (1991).
[43] Super-Kamiokande Collaboration, Y. Fukuda *et al.*, Phys. Rev. Lett. **81**, 1562 (1998).
[44] A. Habig, for the Super-Kamiokande Collaboration, ICRC 2003 Proceedings, (2003).
[45] D. Seckel, T. Stanev, and T.K. Gaisser, Astrophys. J. **382**, 652 (1991).
[46] G. Ingelman and M. Thunman, Phys. Rev. D **54**, 4385 (1996).
[47] C. Caso *et al.*, Review of Particle Physics, Eur. Phys. J. C **3**, 1 (1998).
[48] A. Gould, Astrophys. J. **321**, 571 (1987).
[49] MACRO Collaboration, M. Ambrosio *et al.*, Phys. Rev. D **60**, 082002 (1999).
[50] Kamiokande Collaboration, M. Mori *et al.*, Phys. Rev. D **48**, 5505 (1993).
[51] O. Suvorova, hep-ph/9911415 in Proc. of the 2nd Int. Conf. on Physics beyond the Standard Model, edited by I.V. Krivosheina and H.V. Klapdor-Kleingrothaus (2000).
[52] IMB Collaboration, J.M. LoSecco *et al.*, Phys. Lett. B **188**, 388 (1987).
[53] MACRO Collaboration, M. Ambrosio *et al.*, Proc. 26th ICRC, hep-ex/9905020 (1999) .
[54] Kamiokande Collaboration, Y. Oyama *et al.*, Phys. Rev. D **39**, 1481 (1989).
[55] Baksan Collaboration, M.M. Boliev *et al.*, Proc. 24th ICRC (Rome) **1**, 722 (1995).
[56] IMB Collaboration, R. Svoboda *et al.*, Astrophys. J. **315**, 420 (1987).
[57] AMANDA Collaboration, J. Ahrens *et al.*, Phys. Rev. D **66**, 032006 (2002).
[58] M. Kamionkowski *et al.*, Phys. Rev. Lett. **74**, 5174, (1995).
[59] DAMA Collaboration, R. Bernabei *et al.*, Phys. Lett. B. **480**, 23 (2000).
[60] DAMA collaboration, R. Bernabei *et al.*, Riv. Nuovo Cim. **26**, 1 (2003).
[61] CDMS collaboration, R. Abusaidi *et al.*, Phys. Rev. Lett. **84**, 5699, (2000).
[62] CDMS collaboration, R. Abusaidi *et al.*, Phys. Rev. D **66**, 122003 (2002).
[63] CDMS Collaboration, R. Abusaidi *et al.*, Phys. Rev. D **68**, 082002 (2003).
[64] CDMS Collaboration, D.S. Akerib *et al.*, astro-ph/0405033, Submitted to Phys. Rev. Lett. (2004)
[65] EDELWEISS collaboration, A. Benoit *et al.*, Phys. Lett. B. **545**, 43 (2002).
[66] ZEPLIN Collaboration, D. Cline *et al.*, Proc. of 4th International Workshop on the Identification of Dark Matter, edited by N.J.C. Spooner and V. Kudryavtsev (2003).
[67] K. Freese, J. Frieman, and A. Gould, Phys. Rev. D **37**, 3388 (1988).
[68] A. Okada, for the Super-Kamiokande Collaboration. Contributed paper to 30th International Conference on High Energy Physics, astro-ph/0007003 (2000).
[69] P. Ullio, M. Kamionkowski, and P. Vogel, JHEP **0107**, 044 (2001).
[70] UK Dark Matter Collaboration, T.J. Sumner *et al.*, Nucl. Phys. B (Proc Suppl) **70**, 74 (1999).
[71] S. Yoshida *et al.*, Spin 2000 Proceedings, AIP Conf Proc. **570**, 343 (2001).
[72] M. Kowalski, Phys. Lett. B. **511**, 119 (2001).
[73] N. Fornengo, hep-ph/0011030 (2000).
[74] L.M. Krauss and T. Damour, Phys. Rev. Lett. **81**, 5726, (1998).
[75] L.M. Krauss and T. Damour, Phys. Rev. D **59**, 063509, (1999).