Search for Dark Matter WIMPs using Upward-Going Muons in Super–Kamiokande

S. Desai, for the Super–Kamiokande Collaboration

Dept. of Physics, Boston University, MA 02215, USA

Abstract. We present the results of indirect searches for Weakly Interacting Massive Particles (WIMPs) with the Super-Kamiokande detector using neutrino-induced upward through-going muons. The search is done by looking for a statistically significant excess of upward muons from the Sun, the core of the Earth, and the Galactic Center as compared to the number expected from the atmospheric neutrino background. No such excess was seen; therefore we calculate flux limits in various angular cones around each of the above celestial objects. These flux limits are then compared with previous estimates by other detectors. For the Sun and the Earth these flux limits are calculated as a function of WIMP masses.

1 Introduction

The "dark-matter problem" is one of the most outstanding unsolved problems in modern astrophysics [1]. Dark matter does not emit or absorb electromagnetic radiation at any known wavelength; however its effect is manifested gravitationally at all scales in the universe [2,3]. Flat rotation curves of spiral galaxies imply that the enclosed mass within these systems increases with radius and is much more than that of visible matter. Dispersion velocities of clusters of galaxies and effects due to gravitational lensing also indicate the presence of large amounts of dark matter at larger length scales.

There is growing evidence indicating that non-baryonic cold dark matter constitutes a major component of the total dark matter [4]. A dark matter candidate is called "cold" if it is moving at non-relativistic velocities when it decouples from the rest of the matter and radiation. Current best-fit models [5,6] of the Universe suggest that cold dark matter accounts for $(35 \pm 10)\%$ of the closure density of the universe.

Weakly Interacting Massive Particles (WIMPs) and axions are some of the most promising cold dark matter candidates [7]. WIMPs are proposed to be stable particles which arise in extensions of the standard model. WIMPs have weak-scale interactions with matter and masses ranging from tens of GeV to a few TeV. The relic abundance of WIMPs, which is governed by electroweak scale interactions is remarkably close to the inferred density of dark matter in the universe [8]. The lightest supersymmetric particle (LSP) of supersymmetric theories is the most well motivated and theoretically developed WIMP candidate [7]. If R-parity is conserved 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 the LSP is the neutralino [9].

The neutralino $\tilde{\chi}$ is a linear combination of the supersymmetric partners of the photon, Z^o and neutral Higgs bosons which 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; $\tilde{H_1}$ and $\tilde{H_2}$ are Higgsino states which are supersymmetric partners of the Higgs bosons. The phenomenology of neutralinos within the Minimal Super Symmetric Standard Model (MSSM) is governed by about 63 free parameters [7,10]. Accelerator searches impose some constraints on SUSY parameter space. Current LEP data and cosmological constraints impose a lower limit of about 50 GeV and an upper limit of 600 GeV on the neutralino mass [11].

In this paper we describe an indirect method to look for high energy neutrinos from WIMP annihilation in the Earth, the Sun, and the Galactic Center with the Super–Kamiokande detector. Their signature would be an excess of neutrino-induced events coming from the direction of these objects over the background expected from atmospheric neutrinos. This is in contrast to direct detection experiments which look for signatures of 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.

2 Indirect WIMP Searches using Neutrino-Induced Muons

There is a tremendous amount of literature to address how neutrino detectors could be used for indirect detection of dark matter WIMPs from the Sun and the Earth [12–20]. A brief summary of the physics is given below.

If neutralinos and other WIMPs are the dark matter in our halo they will accumulate in the Sun and Earth. 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 get gravitationally trapped and eventually settle into the core of the body. WIMPs which have accumulated in this way annihilate primarily into τ leptons, b, c and t quarks, gauge bosons and Higgs bosons depending upon their masses and composition. As the WIMP density increases in the core of the body, their annihilation rate increases until equilibrium is achieved between capture and annihilation and the annihilation rate becomes half the capture rate. High energy muon neutrinos are produced by 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 ($\sim$ 300 km s^{-1}), the WIMP local density ($\rho_{\chi} \sim 0.3 - 0.6$ GeV cm^{-3}), the WIMP-nucleon scattering cross-section; and the mass and escape velocity of the celestial body. WIMPs undergo two kinds of interaction 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. Axial vector interactions are dominant in the Sun due to the large abundance of hydrogen. For the Earth, WIMPs undergo only scalar interactions due to the large abundance of even-mass number nuclei such as oxygen, silicon, magnesium and iron.

Recently it has been pointed out that if cold dark matter is present at the Galactic Center it can be accreted by the central black hole into a dense spike in the density distribution [21]. WIMP annihilations in this spike 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. This is in contrast to halos with inner cusps which produce a huge flux of neutrinos. Thus neutrino telescopes could be used to constrain the density slope of the inner halo.

Gondolo has also compared the expected radio emission due to synchrotron radiation from electrons and positrons resulting from neutralino annihilation with the observed Sgr. A* spectrum [22]. He finds that the neutralino dark matter in the minimal supersymmetric standard model is incompatible with a dark matter cusp extending to the galactic center. Nevertheless, it is still important to look for signals of dark matter annihilation from the Galactic Center since the above calculation depends on the strength and structure of the magnetic field close to the Galactic Center which is quite uncertain. Moreover, with neutrinos we can probe the presence of a dark matter cusp independently of accretion models onto the black hole.

Energetic muon 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. These energetic muon neutrinos can undergo charged current interactions with the rock around the detector and produce muons. These neutrino-induced muons coming from the direction of the Sun, the Earth and the Galactic Center could provide a signature of non-baryonic cold dark matter.

3 WIMP Searches in Super–K

The Super–Kamiokande ("Super–K") detector is a 50,000 tonne water Cherenkov detector, located in the Kamioka-Mozumi mine in Japan with 1000 m rock overburden. It is divided by a lightproof barrier into an inner detector with 11,146 inward-facing 50-cm Hamamatsu PMTs and an outer detector equipped with 1,885 outward-facing 20-cm Hamamatsu PMTs which serves as a cosmic ray veto counter. More details about the detector can be found in Ref. [23]. The data used in this analysis was taken from April 1996 to February 1999 corresponding to 923 days of detector livetime.

Upward through-going muons in Super–K are produced by interactions of atmospheric ν_μ 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 calculated parent neutrino energy spectrum peaks at 100 GeV [24]. The downward going cosmic ray muon rate in Super–K is 3 Hz, so it is impossible to distinguish any neutrino-induced muons from this large background of downward going muons. Hence we restrict our analysis to upward going muons.

Event reconstruction of a muon is performed using the charge and timing information recorded by each hit PMT. The trigger efficiency of muons entering the detector with momentum greater than 200 MeV/c is $\sim$ 100 %. Muons are required to have ≥ 7 meters measured path length ($E_\mu > 1.6$ GeV) in the inner detector.The detector effective area for upward through-going muons with this path length cut is $\sim 1200\ \mathrm{m}^2$. For each event, we obtain the arrival direction and time. After a visual scan by two independent groups and a final handfit direction, 1028 upward through-going muon events have been observed. The handfits agree with each other to within 1.5°. More details of the data reduction procedures can be found in [23]. The above sample is contaminated by some downward going cosmic ray muons close to the horizon due to the tracking angular resolution of the detector and multiple Coulomb scattering in the rock. The total number of such non-ν background events has been estimated to be 7.4 ± 0.7, all contained in the $-0.1 < \cos\theta < 0$ bin, where θ is the zenith angle. The contamination from photoproduced upward going pions from downward going cosmic ray muons is estimated to be $< 1\%$ [25].

The expected background for a WIMP search, which is due to interactions of atmospheric ν's in the rock below the detector is evaluated with Monte Carlo simulations. These simulations use the Bartol atmospheric ν flux [27], the BEBC parton distribution function [28], and energy loss mechanisms of muons in rock from [29]. There is a 20% uncertainty in the prediction of absolute upward-going muon fluxes.

Analysis of the most recent Super-K data [26] of upward going muons and contained events is consistent with $\nu_\mu \rightarrow \nu_\tau$ oscillations with $\sin^2 2\theta = 1$ and $\Delta m^2 = 3.5 \times 10^{-3} \mathrm{eV}^2$ being the best fit values. Therefore for evaluating our background we suppress the atmospheric muon neutrino flux due to oscillations from ν_μ to ν_τ. The distribution of upward through-going muons with respect to the Earth is shown in Figure 1. For the Sun, there is also a background of high energy neutrinos resulting from cosmic ray interactions in the Sun, which is about 3 orders of magnitude less than the observed atmospheric ν's and hence can be neglected [32]. Normalization for the Earth was done by constraining the total number of Monte Carlo events to be equal to the observed events, which is approximately the same normalization we used for oscillation analysis with upward through-going muons [33]. For the Sun and the Galactic Center we normalized the Monte Carlo by live time. In order to compare the expected and

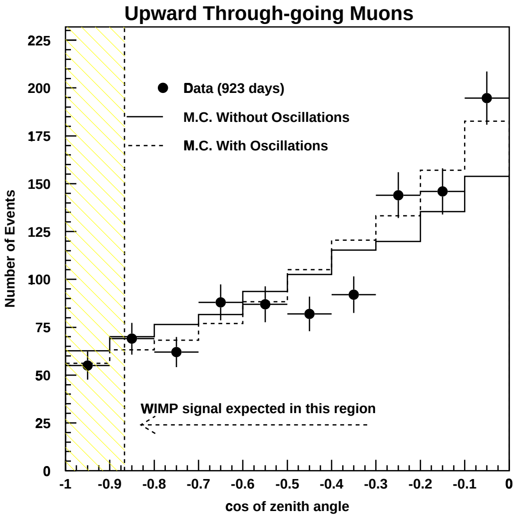

Fig. 1. Distribution of upward through-going muons with respect to the Earth. The oscillation parameters used for the atmospheric neutrino Monte-Carlo are: $\sin^2 2\theta = 1.0$ and $\Delta m^2 = 2.5 \times 10^{-3} eV^2$.

observed distribution of upward through-going muon events with respect to the Sun and Galactic Center each Monte Carlo event was assigned a random time based on the arrival times of the observed upward through-going muon events. This procedure allows us to obtain the angle between the upward muon and any celestial object for each Monte Carlo event. The distribution of upward muons with respect to the Sun and the Galactic Center is shown in Figures 2 and 3 respectively.

4 WIMP Analysis

We searched for a statistically significant excess of muons in cones with half angles ranging from 5 to 30 degrees. This ensures that we catch about 90% of the signal for a wide range of WIMP masses. Thus, searching in different cone angles allows us to optimize the signal to noise ratio for various neutralino masses.

No statistically significant excess was seen in any of the half angle cones. We calculate the flux limit of excess neutrino-induced muons in each of the cones. The flux limit is given by :

$$\Phi(90\%\,\mathrm{c.l.}) = \frac{\mathrm{N}_{\mathcal{P}}(90\%\,\mathrm{c.l.})}{\mathcal{E}} \tag{2}$$

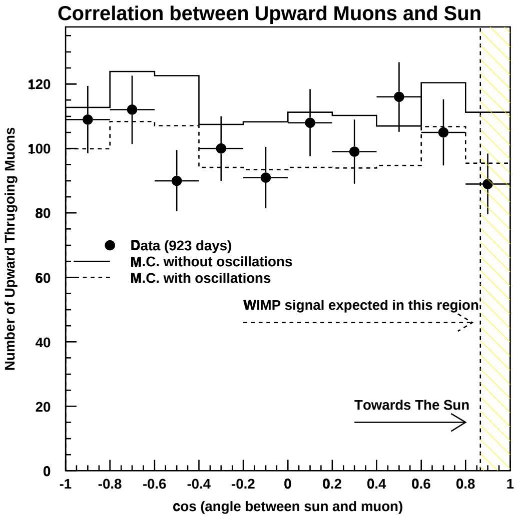

Fig. 2. Distribution of upward through-going muons with respect to the Sun The oscillation parameters used for the atmospheric neutrino Monte-Carlo are: $\sin^2 2\theta = 1.0$ and $\Delta m^2 = 2.5 \times 10^{-3} eV^2$.

where $N_{\mathcal{P}}$ is the upper Poissonian limit (90% c.l.) given the number of measured events and expected background [30] due to atmospheric neutrinos, taking into account oscillations, and $\mathcal{E}$ is the exposure given by equation:

$$\mathcal{E} = \varepsilon(t) \times A(\Omega) \times T \tag{3}$$

where $A(\Omega)$ is the detector area in the direction of the expected signal (Ω) ; ε is the detector efficiency which is ≈ 100% for upward through-going muons; and T is the experimental livetime.

Tables 1, 2, and 3 show the number of detected events observed (with and without oscillations) and corresponding excess muon flux limits for the cones around the Sun, Earth and Galactic Center. We also found that varying the oscillation parameters and other normalization schemes hardly changes the flux limits close to the celestial objects. It is only in the cone with half angle 30° that the flux limits vary within 10% for different oscillation parameters.

The comparison of Super-K flux limits with previous estimates by other experiments is shown in Figures 4, 5, and 6 respectively. All the other experiments have muon energy thresholds around 1 GeV. The WIMP flux limits for the Earth and the Sun by MACRO, Kamiokande, Baksan, and IMB are in [34–37] respectively, and the WIMP flux limits for the Galactic Center by the above detectors are in [38–41] respectively.

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 the

Table 1. Expected background (with and without neutrino oscillations) and flux limits of excess ν_μ-induced μ's in various half angle cones around the earth

Cone	Data	Background (No Osc.)	Background (Osc.)	Flux Limit ($cm^{-2}s^{-1}$)
5°	1	1.61	1.01	4.71×10^{-15}
10°	4	8.71	7.71	5.03×10^{-15}
15°	13	20.45	18.38	6.94×10^{-15}
20°	28	34.84	31.32	1.05×10^{-14}
25°	47	58.57	51.13	1.28×10^{-14}
30°	76	85.75	76.5	1.81×10^{-14}

Table 2. Expected background (with and without neutrino oscillations) and flux limits of excess ν_μ-induced μ's in various half angle cones around the Sun

Cone	Data	Background (No Osc.)	Background (Osc.)	Flux Limit ($cm^{-2}s^{-1}$)
5°	0	2.02	0.99	5.17×10^{-15}
10°	6	9.85	7.53	1.01×10^{-14}
15°	17	18.96	17.97	1.89×10^{-14}
20°	22	35.40	30.7	1.32×10^{-14}
25°	41	53.1	50.91	1.98×10^{-14}
30°	54	74.85	74.89	1.90×10^{-14}

Table 3. Expected background (with and without neutrino oscillations) and flux limits of excess ν_μ-induced μ's in various half angle cones around the Galactic Center

Cone	Data	Background (No Osc.)	Background (Osc.)	Flux Limit ($cm^{-2}s^{-1}$)
3°	0	2.02	0.99	4.19×10^{-15}
5°	4	1.77	1.62	1.16×10^{-14}
10°	10	9.36	7.74	1.47×10^{-14}
15°	23	23.51	19.73	2.08×10^{-14}
20°	38	35.40	30.7	2.26×10^{-14}
25°	57	61.44	52.35	3.07×10^{-14}
30°	82	88	75.92	3.70×10^{-14}

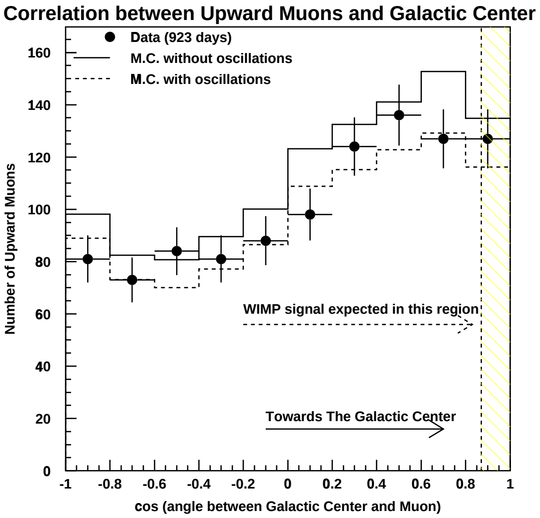

Fig. 3. Distribution of Upward Through-going Muons with respect to the Galactic Center. Coordinates of Galactic Center are: Right Ascension = 17h 42.4 m and Declination $=-28°55'$. The oscillation parameters used for the atmospheric neutrino Monte-Carlo are: $\sin^2 2\theta = 1.0$ and $\Delta m^2 = 2.5 \times 10^{-3}\mathrm{eV}^2$.

Earth [7]. Although the Sun is effectively a point source of energetic neutrinos resulting from WIMP annihilations, the Earth is not. For the Earth the angular size of the annihilation region has been estimated by [20,31] to be:

$$G(\theta) \simeq 4m_\chi \alpha e^{-2m_\chi \alpha \sin^2\theta} \tag{4}$$

where θ is the nadir angle; α is a parameter depending on the central temperature (T = 6000 K), the central density (ρ = 13 g cm^{-3}) and radius of the Earth (α = 1.76 GeV^{-1}). In addition muons scatter from the incoming direction of their parent neutrino due to multiple coulomb scattering and charged current interactions in the rock below the detector.

The Kamiokande collaboration [35] has calculated the angular windows for Sun and Earth which contain 90% of the signal for various neutralino masses. These angular windows agree quite well with those obtained by the MACRO collaboration [34] for masses down to 20 GeV. 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. These flux limits as a function of neutralino mass are shown in Figures 7 for Earth and Sun .

Contrary to the Sun and Earth, the annihilation profile for the Galactic Center does not depend on the neutralino mass, because collisionless particle dark matter does not come into thermal equilibrium near the Galactic Center [21]. However the apparent size of the annihilation region is less than 0.05°. Hence

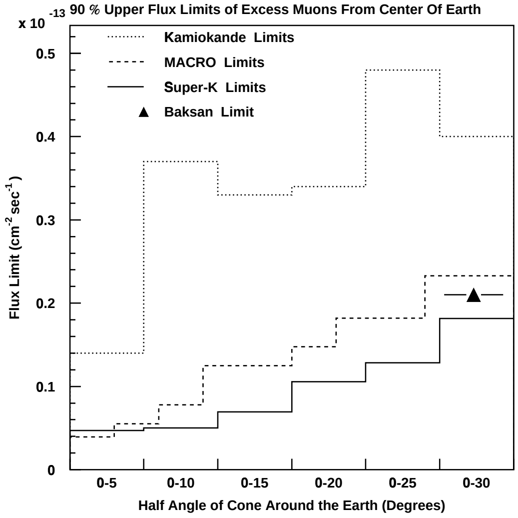

Fig. 4. Comparison of Super-K excess neutrino-induced upward muon flux limits from the Earth with those from other experiments.

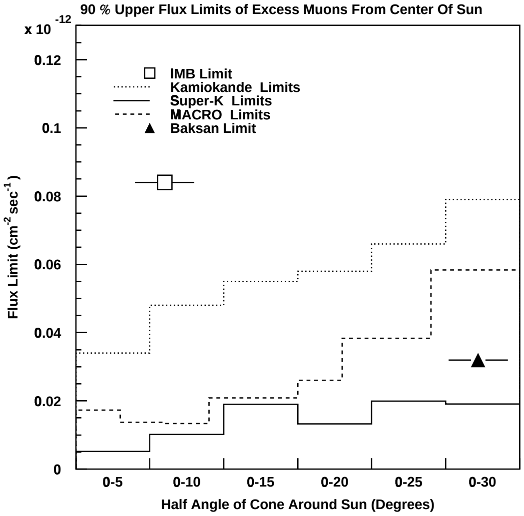

Fig. 5. Comparison of Super-K excess neutrino-induced upward muon flux limits from the Sun with those from other experiments.

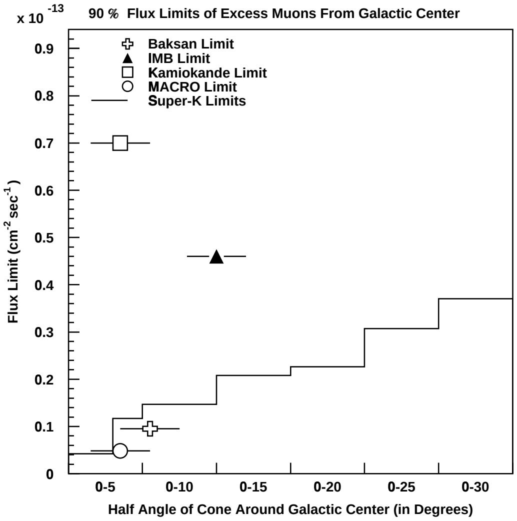

Fig. 6. Comparison of Super-K excess neutrino-induced upward muon flux limits from the Galactic Center with those from other experiments.

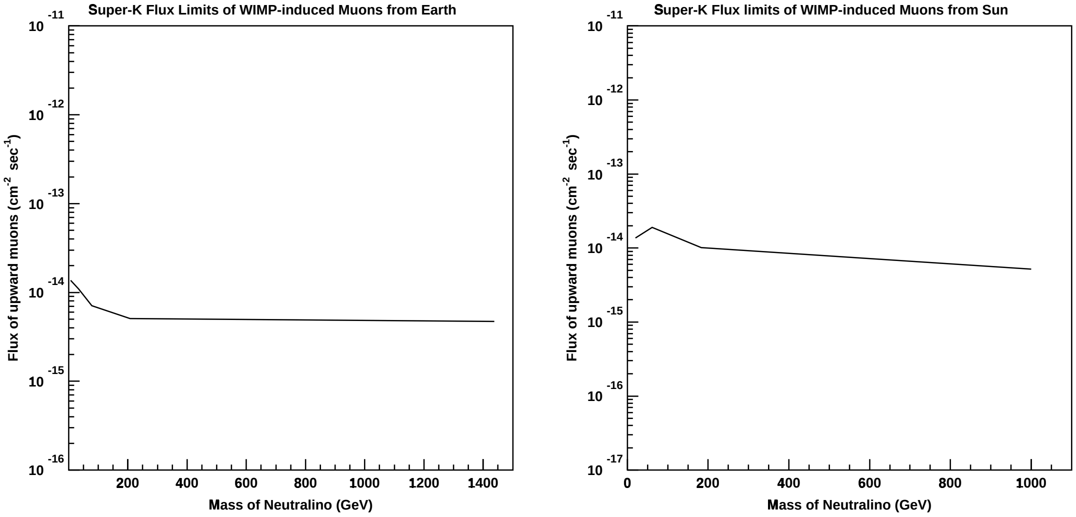

Fig. 7. Super-K WIMP-induced upward-throughgoing muon flux limits from (a) Earth and (b) Sun as a function of neutralino mass.

the Galactic Center can be considered a point source for WIMP annihilation. Thus, similar to the Sun, one can exploit the angular dependence of the charged current interaction and multiple coulomb scattering on neutrino energy to obtain the flux limits for the Galactic Center as a function of mass. This calculation shall be addressed in a future publication.

These flux limits can be compared with predictions from MSSM models. Recently, the DAMA/NaI experiment for direct detection of dark matter reported an annual modulation effect at 4σ confidence level which they claim is caused by WIMP scattering in their detector [42]. Their data is consistent with a relic neutralino forming a major dark matter component of the Galactic Halo [43]. The Super–K flux limits could be used to rule out some regions of the SUSY parameter space implied by the DAMA results.

5 Conclusions

An indirect search for dark matter was done using 1028 neutrino induced upward through-going muon events corresponding to 923 days of livetime. High energy neutrino induced muons can be produced from WIMP annihilation in 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. For the Sun and the Earth these flux limits were calculated as a function of the WIMP mass.

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References

1. P. J. E. Peebles: *Principles of Physical Cosmology.* (Princeton University Press 1993)
2. V. Trimble: Ann. Rev. Astron. Astrophys. **25**, 425 (1987)
3. M.S. Turner: To be published in *The Third Stromlo Symposium: The Galactic Halo*, eds. B.K. Gibson, T.S. Axelrod, M.E. Putnam (Astron. Soc. Pac. Conf. Series, Vol. 666, 1999), astro-ph/9811454
4. D.N. Spergel: 'Particle Dark Matter'. In *Unsolved Problems in Astrophysics*, ed. by J.N. Bahcall, J.P. Ostriker (Princeton University Press 1997), p. 97
5. M.S. Turner, J.A. Tyson: Rev. Mod. Phys. **71**, S145 (1999)
6. M. Roos, S.M. Harun-or-Rashid: astro-ph/9901234

7. G. Jungman, M. Kamionkowski, K. Griest: Phys. Rep. **267**, 195 (1996)
8. M. Kamionkowski: Lectures given at the 1997 ICTP Summer School on High Energy Physics and Cosmology, Trieste, hep-ph/9710467
9. J. Ellis, J.S. Hagelin, D.V. Nanopoulos, K.A. Olive, M. Srednicki: Nucl. Phys. B**238**, 453 (1984)
10. J. Edsjö: Aspects of Neutrino Detection of Neutralino Dark Matter. PhD Thesis, Uppsala University, Sweden (1997), hep-ph/9704384
11. J. Ellis: Talk presented at COSMO 98, Asilomar, California, astro-ph/9903003
12. W.H. Press, D.N Spergel: Astrophys. J, **296**, 1001 (1985)
13. K. Freese: Phys. Lett. B **167**, 295 (1986)
14. J. Silk, K. Olive, M. Srednicki: Phys. Rev. Lett. **55**, 257 (1985)
15. L.M. Krauss, M. Srednicki, F. Wilczek: Phys. Rev. D. **33**, 2079 (1986)
16. T. Gaisser, G. Steigman, S. Tilav: Phys. Rev. D. **34**, 2206 (1986)
17. L.M. Krauss, K. Freese, D.N. Spergel, W.H. Press: Astrophys. J. **299**, 1001 (1985)
18. M. Kamionkowski: Phys. Rev. D **44**, 3021 (1991)
19. L. Bergström, J. Edsjö, P. Gondolo: Phys. Rev. D **55**, 1765 (1997)
20. A. Bottino, N. Fornengo, G. Mignola, L. Moscoso: Astropart. Phys. **3**, 65 (1995)
21. P. Gondolo, J. Silk: Phys. Rev. Lett. **83**, 1719 (1999)
22. P. Gondolo: hep-ph/0002226. See also P. Gondolo this volume
23. Super-Kamiokande Collaboration, Y. Fukuda et. al.: Phys. Lett. B **433**, 9 (1998)
24. Super-Kamiokande Collaboration, Y. Fukuda et. al.: Phys. Lett. B **467**, 185 (1999)
25. MACRO Collaboration, M. Ambrosio et al.: Astropart. Phys. **9**, 105 (1998)
26. Y. Totsuka, Nucl. Phys. A **663-664 (1-4)**, 218 (2000)
27. V. Agrawal, T. K. Gaisser, P. Lipari, T. Stanev: Phys. Rev. D **53**, 1314 (1996)
28. BEBC WA 59 Collaboration, K. Varnell et al.: Z. Phys. **C36**, 1 (1987)
29. P. Lipari, T. Stanev: Phys. Rev. D **44**, 3543 (1991)
30. C. Caso et al.: Review of Particle Physics, Eur. Phys. J. C **3**, 1 (1998)
31. A. Gould: Astrophys. J. **321**, 571 (1987)
32. D. Seckel, T. Stanev, T.K. Gaisser: Astrophys. J. **382**, 652 (1991)
33. Super-Kamiokande Collaboration, Y. Fukuda et. al.: Phys. Rev. Lett. **82**, 2644 (1999)
34. MACRO Collaboration, M. Ambrosio et al.: Phys. Rev. D **60**, 082002 (1999). For updated MACRO flux limits, see D.G. Michael, this volume
35. Kamiokande Collaboration, M. Mori et al.: Phys. Rev. D **48**, 5505 (1993)
36. Baksan Collaboration, M.M. Boliev et al.: Nucl. Phys. B (Proc. Suppl) **48**, 83 (1996)
37. IMB Collaboration, J.M. LoSecco et al.: Phys. Lett. B **188**, 388 (1987)
38. MACRO Collaboration M. Ambrosio et al.: Proc. 26th ICRC, hep-ex/9905020
39. Kamiokande Collaboration, Y. Oyama et al.: Phys. Rev. D **39**, 1481 (1989)
40. Baksan Collaboration, M.M. Boliev et al.: Proc. 24th ICRC (Rome) **1**, 722 (1995)
41. IMB Collaboration, R. Svoboda et al.: Astrophys. J. **315**, 420 (1987)
42. R. Bernabei et al.: University of Rome Report No.2F/2000/01 and INFN/AE-00/01
43. A. Bottino, N. Fornengo, F. Donato, S. Scopel: Report No. DFTT 1/2000, IFIC/00-12, FTUV/00-11, LAPTH-779/2000, hep-ph/0001309