Indirect WIMP search for the Sun and Galactic center in Super-Kamiokande

Takayuki Tanaka* **for the Super-Kamiokande collaboration**

Solar-Terrestrial Environment Laboratory, Nagoya University, Japan

Abstract**. We present the result of indirect search for Weakly Interacting Massive Particles(WIMPs) using upward-going muon(upmu) events at the Super-Kamiokande detector.**
This search aims to detect the neutrino signals from the WIMP annihilation in the center of the Sun or Galactic Center(GC). Data set from SKI-SKIII(3142.9 days) were used for the analysis. We looked for the excess of neutrino signal from the Sun and GC as compared with the expected atmospheric neutrino background. No significant excess was observed.
DARKSUSY simulator was used for our analysis.
For the WIMP search of the Sun, the flux limit of WIMP induced upmu signal and the cross section limit of WIMP-proton spin-dependent interaction were calculated. For that of GC, the WIMP induced upmu flux was simulated and the boost factor which is needed to detect the WIMP induced upmu signal in Super-K is discussed.

Keywords**: dark matter, neutrino, SUSY theory**

I. Introduction

From the recent observation, WIMPs is considered as the favorite candidate of the cold dark matter. From the viewpoint of supersymmetric extensions of the standard model,lightest supersymmetric particle(LSP) can be WIMPs in the universe.
A candidate of the LSP which is theoretically well studied is the neutralino($\widetilde{\chi}$). The neutralino is a linear combination of the supersymmetric particles that mixes after the electroweak-symmetry breaking:

$$\widetilde{\chi} = N_1\widetilde{B} + N_2\widetilde{W} + N_3\widetilde{H}_1 + N_4\widetilde{H}_2, \qquad (1)$$

where $\widetilde{B}$ and $\widetilde{W}$ are the supersymmetric partners of gauge bosons called as gaugino. $\widetilde{H}_1$ and $\widetilde{W}_2$ are the supersymmetric partners of the Higgs bosons, which are called as Higgsino. N_{1-4} are the fraction of each component. From the SUSY breaking mechanism, the constraint by the accelerator experiment and the astronomical observations, expected neutralino mass range is from several tens of GeV to 10 TeV. This neutralino mass depends on the SUSY parameters.
There are two methods to search for the signal from the WIMPs, the direct search and the indirect search. In the direct search, people try to observe the signal from the WIMP scattering in a detector. In the indirect search, people try to detect the signal from the WIMP annihilation occurred near the center of gravitational potential in the universe.
In this paper, we performed an indirect search using upward going muons(upmu) in the Super-Kamiokande(SK) detector. High energy neutrinos which are categorized as upmu events coming from the Sun and the Galactic center(GC) was searched. The excess of neutrino flux comparing with the atmospheric neutrino background is searched for the upmu events.
To simulate the WIMP induced upmu flux from the Sun and the GC, we used DARKSUSY[1] simulator in our analysis. Using DARKSUSY, we can estimate the WIMP induced upmu flux for many combinations of SUSY parameter, many halo models, certain annihilation branches and so on.

II. Indirect WIMP search in the Super-Kamiokande

To perform the indirect search, WIMP needs to be trapped in the center of gravitational potential such as center of the celestial body or GC. WIMPs have a small but finite probability of elastic scattering with a nucleus. When WIMPs pass near the center of gravitational field, sometimes they are scattered. There are two types of scattering: spin-dependent(SD) and spin-independent(SI) scattering. In the former, WIMPs couple to the spin of the target nucleus, and in the latter WIMPs couple to the mass of the target nucleus. If their final velocity after the scattering is less than the escape velocity, they are trapped gravitationally and eventually accumulated into the center of the gravitational potential. WIMPs can annihilate in pairs, and produce primarily τ leptons, b, c and t quarks, gauge bosons, and Higgs bosons depending upon their masses and compositions. At the final, they produce many kind of particles (neutrinos,positrons,antiprotons,antideutrons...) via their decay. Our search aims to detect this neutrino signal from the Sun and GC using the SK detector. The detector is a 50000 ton water Cherenkov detector located at the Kamioka mine in Japan. Since SK started the operation in 1996, there are four experiment phases so far: SKI(Apr,1996-Jul,2001), SKII(Oct,2002-Oct,2005), SKIII(Jul,2006 - Aug,2008), SKIV(Sep,2008-). We used the dataset from SKI to SKIII(3142.9days) for this analysis.
The upmu events which are categorized as the most energetic events in SK were used. For the upmu events, muon neutrinos interact in the rock around the detector via charged current interaction and produce muons. If the energy of the incoming neutrino is high, energy becomes

also high so that they can travel longer distances to reach the detector. These muons enter the detector from the bottom side with the upward direction. These events are tagged as upmu events. Upmu events are divided into three categories:stopping,nonshowering-through going and showering-through going. If upcoming muons are stopped in the detector, they are categorized as 'stopping'. Stopping upmus are the lowest energy portion of upmu. If upcoming muons penetrate the detector, they are classified as 'through going'. And if they accompanies the radiation due to their radiative energy loss, they are classified as 'showering-through going', and if not, they are classified as 'nonshowering-through going'. Showering-through going event are the highest energy portion of upmu. The detector angular resolution is 1° for stopping and nonshowering-through going and it is 1.4° for showering-through going. Effective area for the upmu events is $\approx 1200\text{m}^2$.

The main background source for this analysis is upmu events produced by atmospheric neutrinos. They are simulated by using the NEUT neutrino simulation package [2] and the GEANT-based detector simulator. The main uncertainty of the absolute number of upmu comes from the uncertainty of the cosmic ray flux($\approx$ 20%). The effect of the neutrino oscillation is also taken into account in the simulation.

Previous WIMP search in the SK has been already done using SKI through-going event only [3]. In this analysis, all categories of upmu in the updated sample(SKI-III) and DARKSUSY simulator was used for the analysis .

III. Result from the WIMP searches

A. *WIMP search from the Sun*

We searched a statistically significant excess of upmu events with half-angles from the Sun ranging from 5° to 30°. Almost all the upmu signal induced by WIMP annhilations is expected to be within 30° from the Sun direction for whatever SUSY parameters we choose. Here we divided upmu events into 3 categories as described in the previous section, and search the excess in each category. In the SK, the parent neutrino energy for each category is simulated as:

1) Stopping; 1.7 - 100 GeV
2) Non showering through going; 10 - 1000 GeV
3) Showering through going; 100 GeV -

The WIMP induced neutrino energy is related to WIMP mass. For instance, the high mass WIMP produces high energy neutrinos. We can roughly deduce the WIMP mass from the event category where an excess is observed. The result of excess search for each category is shown in Fig.1-3. No significant excess was observed here.

We calculated the upper limit of upmu flux respective to WIMP mass. We use the information from DARKSUSY simulation for the interpretation. We estimate the half angle of cone which contains more than 90% of

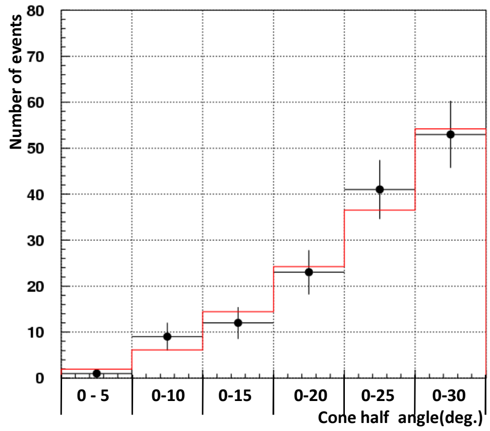

Fig. 1. Angular distribution of upmu-stopping events toward the Sun. Crosses indicate the data from SKI-III(2828.3 days) and the histogram indicates that of the atmospheric neutrino with normalization.

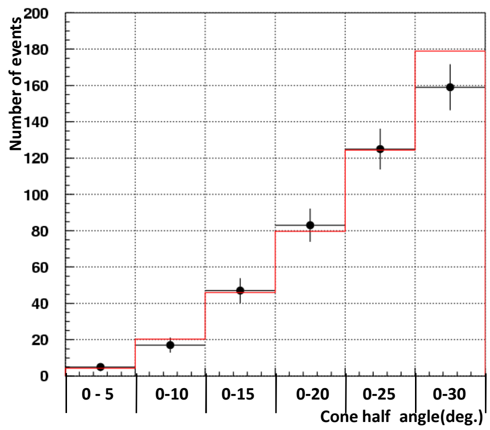

Fig. 2. Angular distribution of upmu-nonshowering events toward the Sun. All symbols are the same notation as Fig.1.

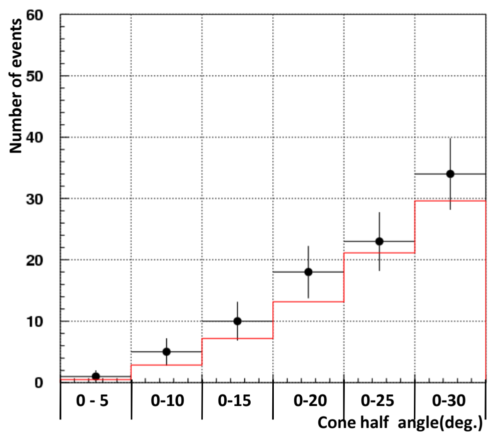

Fig. 3. Angular distribution of upmu-showering events toward the Sun. All symbols are the same notation as Fig.1.

upmu signals expected from neutralino annihilations in the Sun. Here we consider three cases of annihilation channel:1),annihilations into only $b\bar{b}$ 2),annihilations into only $t\bar{t}$ 3), annihilations into all channels . For case 1) and 2), we used the output of WIMPsim which is the one of the package in the DARKSUSY. WIMPsim

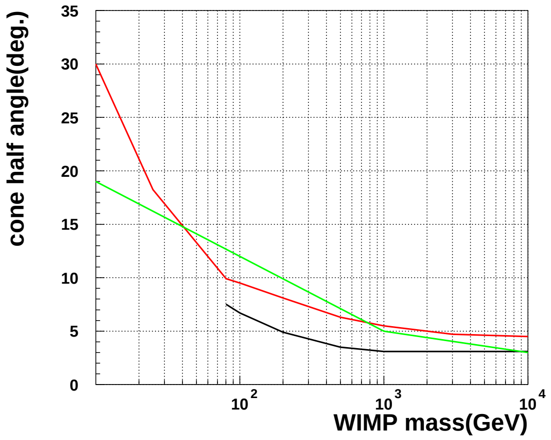

Fig. 4. Cone half angle which contain more than 90% of the signal from the WIMP annihilation is shown as a function of the WIMP mass [4]. Red line indicates the case 1), black one indicates the case 2) and green one indicates the case 3)

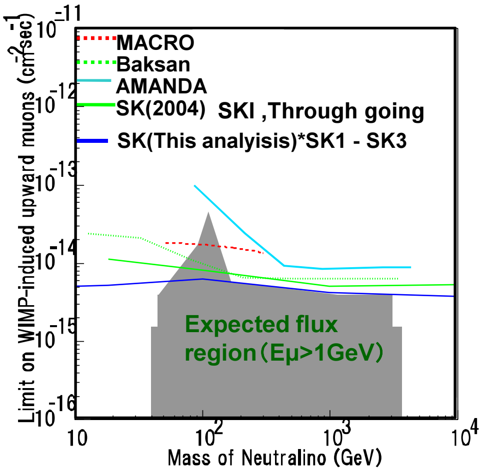

Fig. 5. Upmu flux limit for the WIMP mass from MACRO [5], Baksan [7], AMANDA [6], ,SK(published) [3] and this analysis. The shaded region is the expected flux region from DARKSUSY.

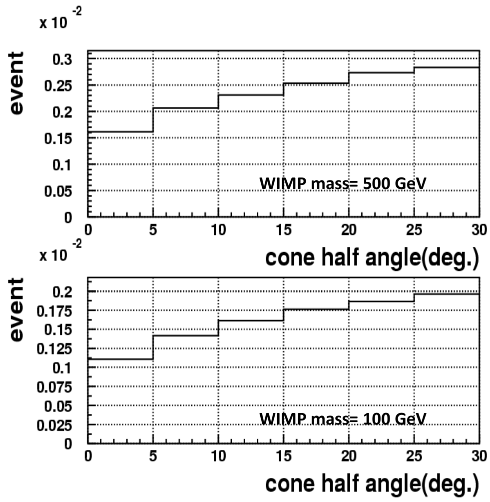

Fig. 6. Expected number of upmu event in 1679.6days' exposure for the two SUSY parameters(M_χ=500,100GeV).

simulates WIMP annihilations, propagation of neutrinos from the WIMP annihilations and propagation of muons from the neutrino interactions. For case 3), we simulate the annihilation for many SUSY parameters and choose the average half angle of cone. The result for case 1),2) and the half angle of cone which was used in the former analysis [3] are shown in Fig.5.

For the each cone half angle which corresponds certain WIMP mass for each annihilation case,we calculate the upper limit for upmu flux.

$$\phi(90\%C.L.) = \frac{N_{90}}{\epsilon \times A \times T}, \quad (2)$$

where N_{90} is the upper Poissonian limit(90 % C.L)given the number of measured events and expected background; A is the detector area in the direction of the expected signal; ϵ is the detector efficiency which is $\approx$ 100 % for upmu; and T is the experimental livetime.

Table. I is the summary of numbers used to calculate the flux limit for example. All categories of the upmu events were combined considering their efficiency at each neutrino energy.

The result of the upmu flux limit comparing other experiments is shown in Fig.5. We have obtained the good limit for especially lower mass WIMP.

B. WIMP search from the galactic center

From the full sky observation of PAMELA [8] and ATIC [9] experiment, they found the event excess of positron fraction. This excess can be explained by some way; existence of some unknown pulsars in the galaxy, WIMP annihilation and so on. However WIMP annihilation scenario requires so large boost factor($10^3 - 10^5$). In order to check possible signal in neutrinos with such a large boost factor, we investigated the number of upmu events and expected atmospheric neutrino background for vatious cone half angles as same as analysis for the Sun. The result is shown in Fig.6 in [3] .

Next, the expected upmu flux from the WIMP annihilation around the Galactic center was simulated by DARKSUSY. Here the result much depends on the density profile of galactic halo model. The NFW profile, the iso-thermal clumpy profile and the iso-thermal smooth profile were assumed here. The many SUSY parameters which are not excluded by the constraint from theory and accelerator experiments were used for input of the DARKSUSY. Also the model which relic density was expected in the region $0.094 < \Omega_{DM}h^2 < 0.135$ was used [10]. For the two SUSY models which have relatively large cross section, we estimated the expected upmu event as the cone half angle. The result is shown in Fig.6.

χ mass (GeV)	cone (deg.)	A.stopping		B.nonshowering		C,showering		Efficiency (A:B:C)	N90	Flux limit($\times 10^{-16}$) ($cm^{-2}sec^{-1}$)
		data	MC	data	MC	data	MC			
10	19	19	22.1	71	73.1	15	11.7	94:5:1	7.51	4.95
10^2	12	9	9.4	23	27.9	8	4.4	17:75:8	9.27	6.11
10^3	5	1	1.9	5	4.3	1	0.5	4:80:16	6.31	4.16
10^4	3	0	0.6	2	1	1	0.2	1:54:45	5.56	3.64

TABLE I

EVENT SUMMARY FOR THE CALCULATION OF UPMU FLUX LIMIT IN THE CASE 3 (HERE, I SHOW THE RESULT USING OLD CONE HALF ANGLE DEFINED IN [4], AND USING DATASET OF 2828.3 DAYS)

Roughly speaking, comparing the most optimistic scenario as shown in Fig.6 with our result shown in [3], signal from WIMP annhilation occurring around the GC can be observed in SK if boost factor is $\approx 10^3$, .

IV. CONCLUSION

We performed the indirect search using the Super-Kamiokande.Dataset of SKI-III(3142.9 days) was used for the analysis. WIMP(neutralino) induced neutrino signal was searched for the direction of the Sun and the Galactic Center.

In the search of the direction toward the Sun, no significant excess was seen. To calculate the upmu flux limit, we introduced the new method with aid of the DARKSUSY simulator. Here, cone half angle which contain more than 90% signal for each WIMP mass was simulated for various kinds of SUSY parameters. We have obtained much improved upper limit than existing.

In the search toward the direction of the GC, we compared the expected event from the WIMP annihilation from the DARKSUSY with the observed event for various cone half angles. If we choose some optimistic models, we find the signal can be detected in the SK if boost factor is $\approx 10^3$.

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