Indirect search for Solar dark matter with AMANDA and IceCube

THE ICECUBE COLLABORATION[1]
[1]*See special section in these proceedings*

DOI: 10.7529/ICRC2011/V05/0327

Abstract: It has been suggested that the Milky Way dark matter halo consists of Weakly Interactive Massive Particles (WIMPs) that scatter and accumulate in the center of gravitational wells like the Sun. In certain models this provides a source of high energy neutrinos originating in the centre of the Sun that may be detected by a neutrino detector on the Earth. We describe a search for Solar WIMP dark matter using AMANDA/IceCube data from 2008 with the 40-string IceCube detector configuration. We present combined limits using data acquired from 2001-2008 on the WIMP induced muon flux from the Sun for dark matter particle masses between 50 and 5000 GeV. We test WIMP model hypotheses of the lightest MSSM neutralino and the lightest Kaluza-Klein particle.

Corresponding author: Olle Engdegård (*olle@fysast.uu.se*)
Department of physics and astronomy, Uppsala University, S-75120 Uppsala, Sweden

Keywords: Dark matter; Indirect search for dark matter; WIMP; AMANDA; IceCube

1 Introduction

The intriguing question of why less than one fifth of the matter in our universe seems to be of the ordinary sort that emits electromagnetic radiation and the rest being invisible by all other means than gravitational inference, has been an outstanding problem in physics for almost 80 years. The most popular current hypotheses involve Weakly Interacting Massive Particles (WIMPs) that are distributed in and around galaxies as a halo. In several theories these particles will accumulate in massive objects, like the Sun, by scattering (weakly) multiple times. With each scatter momentum is lost and the particle becomes gravitationally trapped in the centre regions of the object. Should the WIMPs then be Majorana particles they will pair-wise annihilate and, in some channels, give rise to a neutrino signal that is detectable on Earth.

In this paper we present an explicit search for Solar WIMPs described by the Minimal Supersymmetric Standard Model (MSSM) [1], where the lightest supersymmetric particle $\tilde{\chi}_1^0$, henceforth denoted χ, is a promising dark matter candidate. The two most extreme annihilation channels are studied; $\chi \rightarrow b\bar{b}$ producing the softest possible neutrino spectrum, and $\chi \rightarrow W^+W^-$ producing the hardest possible spectrum. Note that for $m_\chi < m_W$ we consider instead the channel $\chi \rightarrow \tau^+\tau^-$.

The same event selection is also applied to search for another potential dark matter candidate, the Lightest Kaluza-Klein Particle (LKP), arising from theories of Universal Extra Dimensions (UED) [2]. The 5-dimensional model we considered here is described by the mass $m_\gamma^{(1)}$ of the LKP, the first photon excitation, and the mass splitting $\Delta_{q^{(1)}} = (m_{q^{(1)}} - m_{\gamma^{(1)}})/m_{\gamma^{(1)}}$, where $m_{q^{(1)}}$ is the mass of the first quark excitation. The Monte Carlo defining the signal here, with $\Delta_{q^{(1)}} = 0$, was taken from [3].

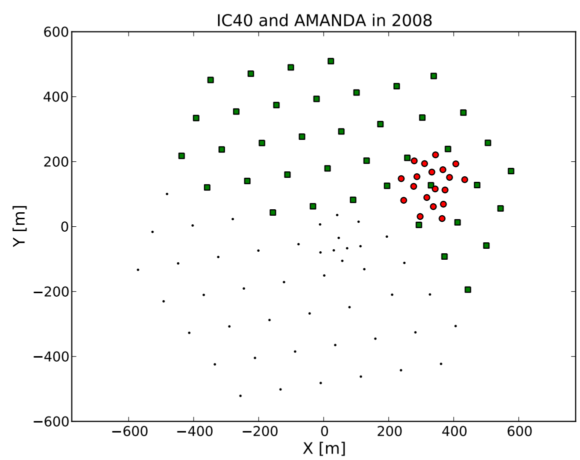


Figure 1: IceCube, depicted from above, in its 40-string configuration (squares) together with AMANDA (circles). The dots show the full 86-string IceCube detector in 2010.

The world's largest neutrino observatory, IceCube [4], was halfway to completion in 2008 with 40 strings, each containing 60 digital optical modules, deployed in the layout shown in figure 1. AMANDA, the predecessor detector to IceCube, underwent a low-energy trigger upgrade and integration of its Data Acquisition System (DAQ) with that of IceCube. As seen in Figure 1, AMANDA, with a markedly lower energy threshold than IceCube, was horizontally enclosed by the 2008 IceCube array. Data from this year thus provided a unique opportunity to use the two detectors as one. In particular, IceCube could be used as an efficient veto for horizontal atmospheric muons entering AMANDA. This opportunity was not missed, and we present here the result of a search for Solar dark matter using this data, and follow up by combining the result with previous AMANDA and IceCube limits.

2 Data and simulation

Data

An analysis was undertaken on the 2008 IceCube-AMANDA dataset amounting to a total livetime of 149 days. The livetime considers the period when the sun was below the horizon (March to September). A triggered sample of 1.7×10^{10} events exists in this dataset, the vast majority of which are atmospheric muons.

The chosen event-sample was to be reduced by a factor of $\sim10^{-7}$ using variable cuts and a machine learning algorithm in an effort to maximise the separation of signal and background. When optimising the event selection, described further in section 3, data from November 2008 was used and then discarded.

Simulation

The signal Monte Carlo was generated with DarkSUSY [5], simulating WIMPs and LKPs for a range of different particle masses. As mentioned in section 1, we generated two MC samples for each MSSM mass corresponding to soft and hard neutrino spectra.

The atmospheric muon background was simulated with CORSIKA [6] using the Hörandel [7] model for the cosmic ray spectrum and composition. The background of atmospheric ν_μ was generated with the Honda et al.[8] conventional flux model and the Enberg et al.[9] prompt flux model. After simulating charged particle propagation with MMC [10] and light propagation in the ice with PHOTONICS [11], the detector response was finally simulated using the IceCube simulation software IceSim.

3 Event selection

This analysis divided the data into two data streams: One stream used IceCube as the main detector searching for high WIMP masses, using as a signal template the 1000 GeV WIMP model with the hard spectrum. The second stream used AMANDA as the main fiducial volume and

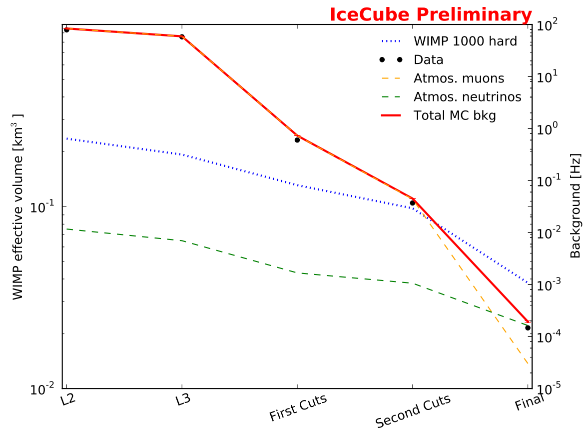


Figure 2: Effective volume for a 1000 GeV WIMP signal on the left y-axis and background rates on the right y-axis, as functions of the accumulated data reduction cuts in the IceCube-stream. In the steep step to the final level a cut was applied on SVM output values.

IceCube as a sophisticated veto, with the 100 GeV soft-spectrum WIMP as a signal template.

In each stream a series of linear cuts were applied to data and MC, optimised individually using the signal templates and data from November 2008 as the estimate for the background. In the AMANDA-stream no more than 4 hits were allowed in IceCube, effectively favouring low-energy events. In both streams we made log-likelihood reconstructions of the particle tracks, requiring them to be upward-going and good fits to the hit information. The progression of data reduction is visualised in figure 2.

After applying the linear cuts a Support Vector Machine (SVM) [12] was trained to separate signal from background. A separate signal MC sample and November data as background were again used, the both of which were discarded after the training. When applying a trained SVM on a set of events, a single number $Q \in [0, 1]$ is obtained for each event that characterises it as signal-like or data-like, which can be used as a powerful multivariate cut parameter.

Starting with a set of about 20 variables, an iterative method was used to eliminate variables that did not contribute significantly to the overall separation. In this way, 12 and 10 variables were chosen for the SVMs in the AMANDA- and IceCube-stream respectively, covering a large part of the available phase-space and showing modest internal correlations.

The final cut on Q was set at 0.1, which optimised the *sensitivity* of the dark matter search, i.e., the median 90% upper limit in a large set of random samples drawn from a background distribution without any signal content. It is noted that the neutrino spectra from the Kaluza-Klein signal are very similar to the hard MSSM spectra once convoluted in the propagation through the Sun and processed as IceCube triggers. For this reason, no separate optimisation was necessary to study this potential signal.

Uncertainties

A number of systematic effects were studied which impact the effective volume of the signal. Uncertainties in the neutrino oscillation parameters, neutrino-nucleon cross-section, muon propagation through ice and calibration of detector time and geometry, all change $V_{\rm eff}$ less than 5% when individually shifted 1σ from their nominal values. The uncertainty in light propagation through the ice and the absolute sensitivity of the PMTs remain the dominant systematic effect. This was estimated from dedicated Monte Carlo studies. The total systematic uncertainty, the squared sum of all effects, was calculated for 3 template energy regions: The AMANDA-region, the combined region and the IceCube-region were given the uncertainties 26%, 25% and 15% respectively.

4 Search for a Solar excess

At the final cut level, the 2008 data sample contains a total of 3012 events. We examine the properties of the space angles (ψ_i) between the reconstructed track and the Sun. The angular resolution, measured as the median space angle for neutrinos in the signal MC sample, is 2.2° for the 1000 GeV hard-spectrum signal and 9.0° for the 100 GeV soft-spectrum signal. The distribution of IceCube data in the direction of the Sun is shown in figure 3 together with the expected background. This background probability density function (PDF) is constructed from actual data using the reconstructed zenith-angles and random, oversampled, azimuth angles.

Since the AMANDA- and IceCube-streams have completely non-overlapping event samples, we will treat them as separate sets of observations, denoted A08 and IC08, that can be combined using techniques described below. In addition to these samples, we also include a sample from an earlier analysis of AMANDA data from 2001-2006 [13] (A01-06, around 2000 events) and the sample from the 22-string IceCube data of 2007 [14] (IC07, 6946 events) to prepare a final analysis that incorporates up to four independent event samples. For all WIMP channels we compare the individual sensitivities and exclude, for computational efficiency, samples yielding a sensitivity 10 times weaker than the strongest. In the results for the Kaluza-Klein models, e.g., A08 did not contribute significantly and was dropped in favour of IC07 and IC08.

The two older samples were both obtained in a similar manner to what is described in this paper. In A01-06 a Boosted Decision Tree (BDT) was trained and optimised for each WIMP channel using 21 variables, in this way performing several parallel searches in a detector livetime of 812 days. The optimal BDT cut was chosen to minimise the number of events needed to have 90% probability of a 5σ discovery.

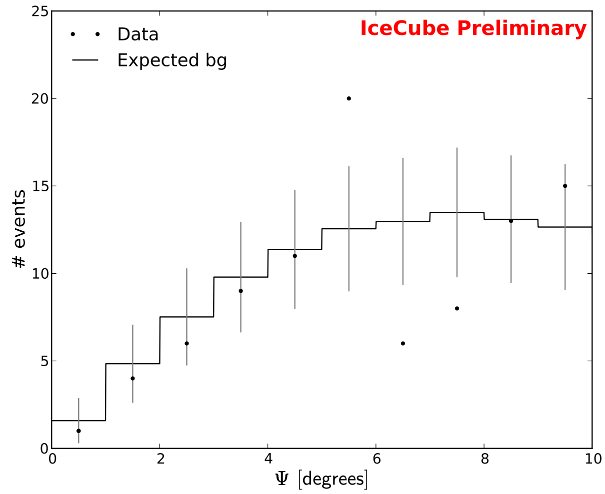


Figure 3: The distribution of space angles between the reconstructed event track and the Sun, for IceCube data at the final cut level and the expected background, in the region near the Sun. The error bars on the background are 1σ Poisson standard deviations.

The IC07 sample resulted from a combination of straight cuts and two SVMs. Each SVM was trained with 6 different uncorrelated variables, and the optimised cut was made on the product of the two output values.

The goal here is to obtain a confidence interval on the number of signal events, μ, in the total data set. We use the same procedure and profile-likelihood method as outlined in [15], but adapt it for the more general case of N independent experiments. The total likelihood of having μ signal events in the data set becomes

$$\mathcal{L}(\mu) = \sum_j^N \mathcal{L}_j(\mu_j) = \sum_j^N \prod_i^{n_j^{\rm obs}} f_j(\psi_i^j|\mu_j), \qquad (1)$$

where each μ_j is weighted with the livetime and effective volume of the individual experiment using

$$\mu_j = \mu \frac{t_j^{\rm live} V_j^{\rm eff}}{\sum_k^N t_k^{\rm live} V_k^{\rm eff}}, \qquad (2)$$

so that $\sum_j \mu_j = \mu$. In equation 1, $f(\psi|\mu)$ is the total PDF of expected background plus a signal content of size μ.

Table 1 shows the upper limit, at 90% confidence level, for μ (or the entire confidence interval if the lower bound is not zero) together with the sensitivity as defined in section 3, the best fit of μ to data and the probability of observing at least the current deviation from the sensitivity. This was consistent with $\mu = 0$, and the upper edge of the interval was converted to an upper limit, following [15], on the muon flux from the Sun.

Mass (GeV)	μ_{90} 90% CI	$\overline{\mu}_{90}$ Sens.	μ Best fit	P(obs)
Soft				
50	26.0	29.2	0.0	0.43
100	23.7	20.3	2.8	0.37
250	[0.6, 27.1]	13.7	10.8	0.08
500	12.7	17.3	0.0	0.34
1000	14.0	17.1	0.0	0.38
3000	9.9	17.1	0.0	0.21
5000	9.4	17.1	0.0	0.20
Hard				
50	20.6	16.2	3.0	0.33
100	19.4	12.2	4.7	0.20
250	15.3	16.8	0.0	0.43
500	10.9	16.8	0.0	0.26
1000	6.8	15.9	0.0	0.13
3000	9.3	16.4	0.0	0.22
5000	8.7	15.8	0.0	0.22

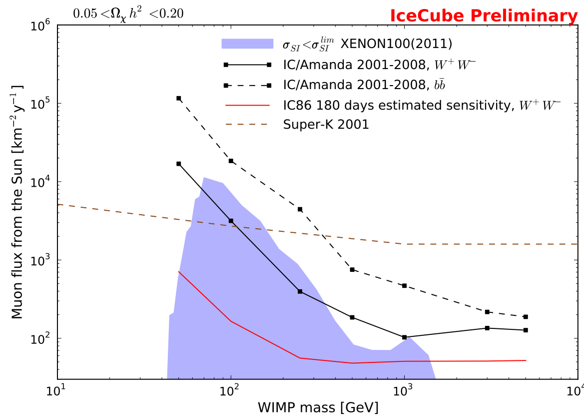
Table 1: With μ as the number of signal events in the final combined sample, the columns show the 90% CI or upper limit, the sensitivity, the best fit to data and the probability to observe at least this deviation from the sensitivity

5 Results

Taking into consideration the uncertainties discussed in section , figure 4 shows the 90% CL upper limits on the muon flux from the Sun by self-annihilating dark matter modelled by MSSM and Kaluza-Klein. In the MSSM plot we outline the MSSM model space not yet excluded by the direct detection experiments CDMS [16] and XENON [17], generated by an extensive parameter scan. The lower figure indicates the available Kaluza-Klein model space for considered values of $\Delta_{q^{(1)}}$. We refer the reader to [3] for a more detailed account of probing the Kaluza-Klein space with IceCube.

6 Discussion

We have presented an indirect search for Solar WIMP dark matter using data taken with the integrated AMANDA/IceCube detector in 2008. Combining this data with two other event samples from AMANDA and IceCube from 2001-2007 we establish the strongest current upper limit on the muon flux from WIMP dark matter annihilation in the Sun. The completed IceCube detector has now started to take data and, together with the DeepCore low-energy extension, the expected sensitivity will probe substantial regions of the previously untested WIMP parameter space.



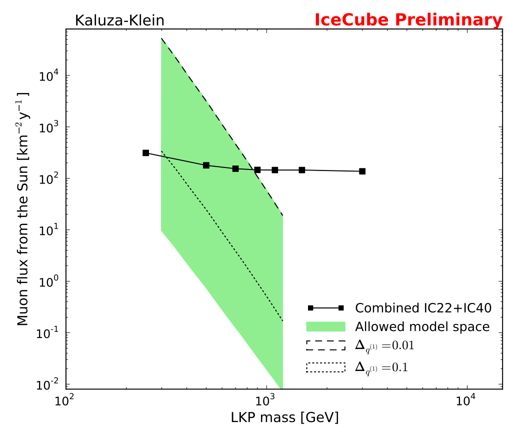


Figure 4: Limits on the WIMP induced muon flux from the Sun modelled by MSSM (above) and Kaluza-Klein (below). In the MSSM limit labeled W^+W^-, the channel $\tau^+\tau^-$ was used for $m_\chi < m_W$.

References

[1] G. Jungman, K. Kamionkowski and K. Griest, Phys. Rep **267**, 195 (1996)
[2] D. Hooper and S. Profumo, Phys. Rep **453** (2007)
[3] R. Abbasi et al., Phys. Rev. D **81**, 057101 (2010)
[4] H. Kolanoski, IceCube summary talk, these proceedings
[5] P. Gondolo et al., JCAP **07**, 008 (2004)
[6] D. Heck et al., FZKA Report 6019 (1998)
[7] J. Hörandel, Astropart. Phys. **19**, 193 (2003)
[8] M. Honda et al., Phys. Rev. D **75**, 043006 (2007)
[9] R. Enberg et al., Phys. Rev. D **78**, 043005 (2008)
[10] D. Chirkin and W. Rhode, hep-ph/0407075v2 (2008)
[11] J. Lundberg et al., Nuclear Instrumentation and Methods **A581**, 619 (2007)
[12] C. J. C. Burges, Data Mining and Knowledge Discovery **2**, 121 (1998)
[13] A. Rizzo, PhD thesis, Vrije Universiteit Brussel (2010)
[14] R. Abbasi, Phys. Rev. Lett. **102**, 201302 (2009)
[15] T. Burgess, PhD thesis, Stockholm University (2008)
[16] Z. Ahmed et al., Science **327**, 1619 (2010)
[17] E. Aprile et al., hep-ex/1104.2549v2 (2011)