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Prospects of dark matter detection in IceCube

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Abstract: The IceCube neutrino telescope, under construction at the South Pole, currently consists of 22 IceCube strings and 19 AMANDA strings. Combining the two arrays leads to a large instrumented volume with AMANDA as a dense core, an ideal situation for indirect detection of WIMP dark matter annihilations in the Sun. From simulations we calculate the current detector's sensitivity for solar WIMP neutrinos and find that it improves considerably compared to AMANDA-II. The improvement is due to a combination of reduced trigger thresholds and larger detector volume which permits the use of veto against muonic background.

Introduction

We investigated the possibilities of detecting a neutrino signal from neutralino WIMP dark matter annihilations in the Sun. The studied neutralino masses were m_χ = 50, 100, 250, 500 and 1000 GeV and the annihilation channels were W^+W^- (*hard channel*) and $b\overline{b}$ (*soft channel*). For $m_\chi = 50$ GeV the $\tau^+\tau^-$ channel is defined as the hard channel. Neutrinos produced in the Sun from the decay and interactions of the neutralino annihilation products can reach the detector and produce muons in CC reactions $\nu_\mu(\overline{\nu}_\mu) + N \rightarrow \mu^-(\mu^+) + X$. These signal muons traversing the ice sheet produce Cherenkov light, detectable by the Optical Modules (OM) of the IceCube detector. The WIMP neutrino zenith angle will follow the Sun's position over the year, $\theta_\odot \in [67°, 113°]$, and the mean muon energy will be around $\langle E_\mu \rangle \sim m_\chi/3$ for hard channels and $\langle E_\mu \rangle \sim m_\chi/6$ for soft channels.

Muons produced in cosmic ray interactions in the atmosphere have a zenith angle range of $\theta_\mu \in [0°, 90°]$ since muons cannot traverse the whole Earth. These *atmospheric* μ constitute the main background. Another background is that of muon neutrinos produced in the atmosphere, *atmospheric* ν_μ, which have a near-isotropic angular distribution.

The 2007 IceCube detector [1] consists of 41 strings of which 19 constitute AMANDA [2]. The two arrays have separate trigger and data aquisition systems (DAQs) which record events autonomously. However, a trigger in AMANDA will force a readout of the IceCube strings, even if IceCube did not have a trigger.

To reject atmospheric μ background we searched for contained events, i.e. neutrino events with the CC vertex inside a fiducial volume, as defined in figure 1. We demanded the events to either have no OMs hit in the veto region or that the first OM hit in the veto region came later than the OM hits in the fiducial region. This aimed at ensuring that the muon was created inside the detector, and did not come from the atmosphere. To reduce the number of atmospheric μ events leaking in between veto strings, we also demand that the average downwards motion of hits should be less than 50 m. Events that did not fulfill these conditions were still accepted provided that they had track reconstructions with $\theta_{rec} \geq 70°$ and more than 10 hit OMs. These conditions together constitute the low-level filtering that will run at South Pole.

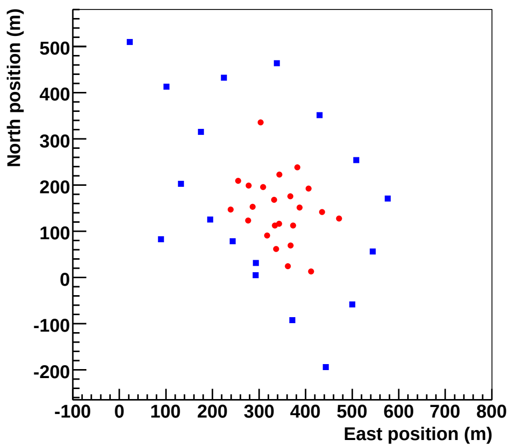

Figure 1: Top view of the 2007 IceCube detector consisting of 41 strings. The inner strings (dots) define the fiducial region, surrounded by veto strings (squares). Uppermost OMs of the fiducial strings belong to the veto region.

Simulations

A sample of atmospheric μ background events corresponding to $\sim$ 1 hour of detector livetime ($2.3 \cdot 10^6$ events triggering) was simulated using `CORSIKA` [3] with the Hörandel CR composition model [4]. For the atmospheric ν_μ background, a sample corresponding to ~ 0.5 years of detector livetime ($4.2 \cdot 10^4$ events triggering) was generated according to the Bartol spectrum [5].

The solar WIMP signals were simulated with `WimpSim` [6], which uses `DarkSUSY` [7] and `PYTHIA` [8] to calculate annihilation rates and neutrino production. The neutrinos were propagated through the Sun and to the Earth with standard full flavour oscillations [9]. A charged lepton and a hadronic shower were then generated in the ice. For this analysis only simulated muon events with the Sun under the horizon, $\theta_\odot \in [90°, 113°]$, were used.

Muon propagation through the ice was simulated with `MMC` [10]. Cherenkov light propagation through the ice to the OMs, taking into account the ice properties [11], was done with `Photonics` [12]. The detector response was simulated with the IceCube simulation package `icesim`.

Filtering

Events were first selected based on a log-likelihood (LLH) reconstruction, by demanding $\theta_{LLH} \in [90°, 120°]$. Half of the atmospheric μ and the WIMP events passing this cut were then used to train and half to test a neural network (NN) using two hidden layers and eight event observables based on hit topology as well as the LLH reconstructed track parameters. A cut was made on the NN output value, the hit multiplicity and the reconstruction quality. This cut removed all simulated atmospheric μ background, and only WIMP events and atmospheric ν_μ background remained.

Among the remaining events we selected the neutrino candidates originating from the Sun's direction within a cone with half opening angle varying between 3° and 10° depending on m_χ and annihilation channel. At this final analysis stage V_{eff} for the observation of WIMP signals were calculated as

$$V_{eff} = \frac{N_{det} \cdot V_{gen}}{N_{gen}}, \tag{1}$$

where N_{gen} is the number of generated CC interactions, V_{gen} is the generation volume, and N_{det} is the number of WIMP events in the search cone. Results are given in figure 2 (squares).

Sensitivity

From the expected number of surviving atmospheric ν_μ events μ_b we calculated the mean expected Feldman-Cousins $\mu_s^{90\%}(n_{obs}, \mu_b)$ [13] signal upper limit from all possible outcomes n_{obs} as the Poisson weighted sum

$$\bar{\mu}_s^{90\%} = \sum_{n_{obs}=0}^{\infty} \mu_s^{90\%}(n_{obs}, \mu_b) \frac{(\mu_b)^{n_{obs}}}{n_{obs}!} e^{-\mu_b}. \tag{2}$$

From the WIMP V_{eff} and $\bar{\mu}_s^{90\%}$ we then calculated the mean expected upper limit on the neutrino to muon conversion rate

$$\bar{\Gamma}_{\nu\to\mu}^{90\%} = \frac{\bar{\mu}_s^{90\%}}{V_{eff} \cdot t}, \tag{3}$$

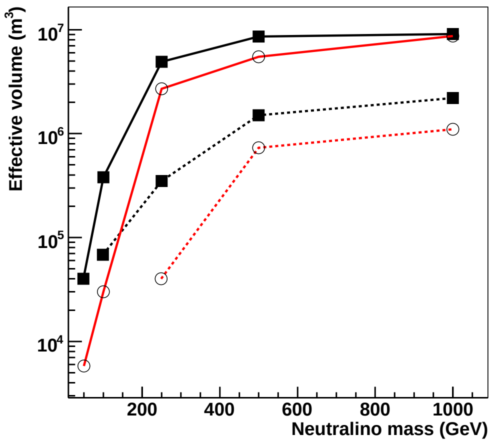

Figure 2: WIMP effective volume as a function of neutralino mass for hard (solid) and soft (dashed) annihilation channel, for analysis done on IceCube-22 + AMANDA (squares) and IceCube-22 only (circles).

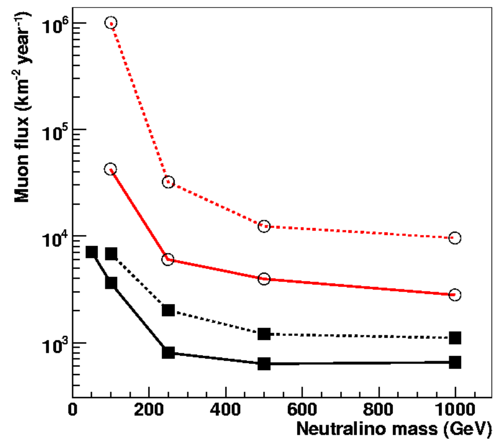

Figure 3: Expected sensitivity to muon flux from neutralino annihilations in the Sun as a function of neutralino mass for hard (solid) and soft (dashed) annihilation channel for this analysis using IceCube-22 and AMANDA (squares), compared to the 2001 AMANDA analysis [16, 17] (circles). Systematic uncertainties are not included.

where t is the analysis livetime, which here is 0.5 years. These values (one for each WIMP signal) were then used to calculate the mean expected upper limit on the muon flux from neutralino annihilations in the Sun, $\bar{\Phi}_\mu^{90\%}$ [14, 15], which is a measure of the detector's WIMP sensitivity. Comparing these values with the mean expected values from an earlier analysis with AMANDA-II [16, 17], we see improvements of an order of magnitude for lower WIMP masses, see figure 3.

Repeating the analysis with only the IceCube-22 array, we found that AMANDA stands for the major contribution to the sensitivity at lower m_χ and that the IceCube strings dominates for $m_\chi \geq 500$ GeV (see figure 2). The increase in sensitivity for the AMANDA array is due to lowered trigger multiplicity thresholds thanks to the new TWR-DAQ [18], whereas for higher m_χ the increased sensitivity comes from the increased detector volume in IceCube compared to AMANDA. The forced readout of IceCube when AMANDA has a trigger makes it much easier to distinguish a neutrino event from an atmospheric μ event.

Outlook

This sensitivity estimation demonstrates the feasibility of a WIMP analysis on experimental data from 2007 using the combined IceCube-22 and AMANDA detector.

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