# Results and Prospects of Indirect Searches for Dark Matter with IceCube

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***Abstract*****. Dark matter could be indirectly detected through the observation of neutrinos produced as part of its self-annihilation process. Possible signatures are an excess neutrino flux from the Sun, the center of the Earth or from the galactic halo, where dark matter could be gravitationally trapped. We present a search for muon neutrinos from neutralino annihilations in the Sun performed on IceCube data collected with the 22-string configuration. No excess over the expected atmospheric background has been observed and upper limits at 90% confidence level have been obtained on the annihilation rate and converted to limits on WIMP-proton cross-sections, for neutralino masses in the range of 250 GeV to 5 TeV. Further prospects for the detection of dark matter from the Sun, the Earth, and the galactic halo will be discussed.**

***Keywords*****: Dark Matter, Neutrinos**

## I. INTRODUCTION

The existence of dark matter can be inferred from a number of observations, among them rotational profiles of galaxies, large scale structures, and WMAP's anisotropy measurement on the cosmic microwave background. Weakly Interacting Massive Particles (WIMPs), 'cold' thermal relics of the Big Bang, are leading dark matter candidates. Besides overwhelming observational evidence for its existence, the properties of dark matter can only be understood through detection of direct or indirect signals from its interactions or through the production at collider experiments. In the Minimal Supersymmetric Standard Model (MSSM) the neutralino is a promising WIMP particle. It is stable and can annihilate pair-wise into Standard Model particles [1]. Galactic WIMPs could be gravitationally captured in the Sun or the Earth and accumulated in their cores [2]. Among the secondary products from the WIMP annihilations we expect neutrinos, which could escape from the center of the Sun or Earth and be detected in neutrino telescopes. Neutrinos are also expected from annihilations in the galactic halo. In IceCube [3] we observe Cherenkov light from relativistic muons in ice. The data analysis is focused on selecting upward-going events in order to separate muons from neutrino interactions from background muons created in cosmic-ray air showers. In this paper we present a search for a neutralino annihilation signal from the Sun with the IceCube 22-string detector. Future sensitivities of IceCube to this signal are discussed, as well as the prospects of observing annihilation signals from the Earth or the galactic halo.

## II. THE ICECUBE NEUTRINO TELESCOPE

The IceCube Neutrino Telescope is a multipurpose detector under construction at the South Pole, which is currently about three quarter completed [3]. Upon completion in 2011, IceCube will instrument a volume of approximately one cubic kilometer of ice utilizing 86 strings, each instrumented with 60 Digital Optical Modules (DOMs). Eighty of these strings will be arranged in a hexagonal pattern with an inter-string spacing of about 125 m and with 17 m vertical separation between DOMs, at a depth between 1450 m and 2450 m. Complementing this 80 string baseline design will be a deep and dense sub-array named DeepCore [4] that will be formed out of seven regular IceCube strings in the center of the array together with six additional strings deployed in between them. In this way, the sub-array will achieve an interstring-spacing of 72 m. The six additional DeepCore strings will have a different distribution of their 60 DOMs, optimizing their design towards a lower energy threshold. The optical sensors will have a vertical spacing of 7 m, will be deployed in deep transparent ice [1] and will consist of high quantum efficiency photomultiplier tubes (HQE PMTs). This will enable us to study neutrinos at energies down to a few 10 GeV. DeepCore will be an extremely interesting detector for the study of WIMPs.

## III. ANALYSIS OF 22-STRING DATA

The 2007 dataset, consisting of 104.3 days livetime with the Sun below the horizon recorded with the IceCube 22-string detector, was searched for a neutrino signal from the Sun [5]. The event sample was reduced in steps from $4.8 \cdot 10^9$ to 6946 events at final level, which constitutes the expected sample of atmospheric

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[1] The deep ice is clearer, with a scattering length roughly twice that of the upper part of the IceCube detector. In addition, the deeper location (below 2000 m) provides an improved shielding of cosmic ray backgrounds.

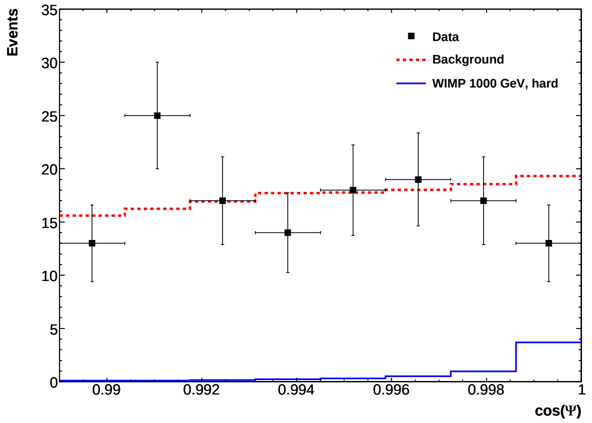

Fig. 1. Cosine of the angle to the Sun, $\Psi$, for data (squares) with one standard deviation error bars, and the atmospheric background expectation (dashed line). Also shown is a simulated signal ($m_{\tilde{\chi}_1^0}$ = 1000 GeV, hard spectrum) scaled to the found upper limit of $\mu_s = 6.8$ events.

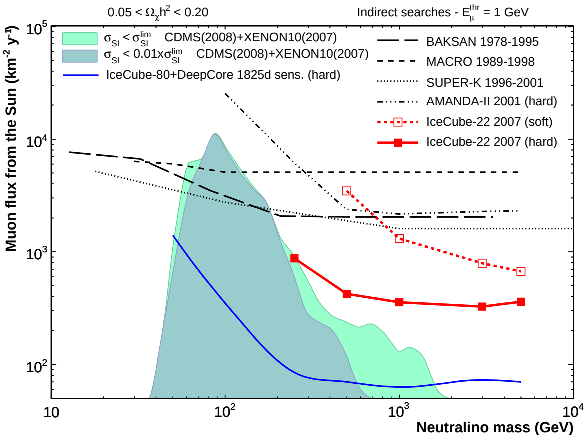

Fig. 2. Upper limits at the 90% confidence level on the muon flux from neutralino annihilations in the Sun for the soft ($b\bar{b}$) and hard ($W^+W^-$) annihilation channels, adjusted for systematic effects, as a function of neutralino mass [5]. For neutralino masses below $m_W$ $\tau^+\tau^-$ is used as the hard annihilation channel. The lighter [green] and darker [blue] shaded areas represent MSSM models not disfavored by direct searches [20], [21] based on $\sigma^{SI}$ and $100 \cdot \sigma^{SI}$, respectively. A muon energy threshold of 1 GeV was used when calculating the flux. Also shown are the limits from BAKSAN [15], MACRO [16], Super-K [17], and AMANDA [18], and the expected sensitivity of IceCube with DeepCore.

neutrinos with a contamination of atmospheric muons. Since the analysis is based on comparing the shape of the angular distribution of signal and background (see section III-B), there is no need to achieving a high purity atmospheric neutrino sample at final cut level. Filtering was based on log-likelihood muon track reconstructions, geometry, and time evolution of the hit pattern. Events were required to have a good quality track reconstruction with a zenith angle in the interval 90° to 120°. Multivariate training and selection was done with the help of Support Vector Machines [6]. At the final stages in the analysis, randomized real data were used to model the atmospheric background.

### A. *Simulations*

Five WIMP masses: 250, 500, 1000, 3000, and 5000 GeV were simulated using `WimpSim` [7] in two annihilation channels, $b\bar{b}$ (soft channel), and $W^+W^-$ (hard channel), representing the extremes of the neutrino energy distributions. Single and coincident shower atmospheric muon backgrounds were simulated using `CORSIKA` [8]. The atmospheric neutrino background was simulated [9] following the Bartol flux [10]. Charged particle propagation [11] and photon propagation [12], using ice measurements [13], were also simulated.

### B. *Results*

The final data sample was used to test the hypothesis that it contains a certain signal level, against the null hypothesis of no signal. The shape of the angular distribution of events with respect to the Sun was used as a test statistic (see Figure 1). The background-only p.d.f. was constructed from data with randomized azimuth angles, while the p.d.f.s for the different signal models tested were obtained from Monte Carlo. A limit was set on the relative strength of the signal p.d.f. using a Feldman-Cousins [14] confidence interval construction. These limits were transformed to a limit on the muon flux above 1 GeV, which is shown in Figure 2 together with previous limits [15], [16], [17], [18], MSSM models [19], and a conservative estimate of the full IceCube sensitivity including DeepCore. The models shown are those not excluded by CDMS [20] and XENON10 [21] based on the spin-independent WIMP-proton cross-section. Models in the darker region require a factor of 100 increase in sensitivity of direct detection experiments in order to be probed by them. Assuming that WIMPs are in equilibrium in the Sun, the limit on the muon flux can be converted to a limit on the spin-dependent WIMP-proton cross-section [22]. These limits are shown in Figure 3 together with previous limits [17], [20], [23], [24], MSSM models, and the IceCube sensitivity.

## IV. EARTH WIMPS

Dark matter could also be gravitationally trapped at the center of the Earth. Such scenarios are generally not favored due to its less efficient capture of dark matter. However, from an experimental point of view, the searches from dark matter from the center of the Earth are still of interest due to the many unknowns that plague the relic, capture and annihilation processes that enter into the calculation of the expected fluxes. In order to search for an indirect signal from dark matter annihilation from the Earth, IceCube uses muon neutrinos $\nu_\mu$ that interact in or below the IceCube detector. They produce vertically up-going track-like events, that point back to the center of Earth. We have designed a string trigger [25] for IceCube that is specifically optimized for

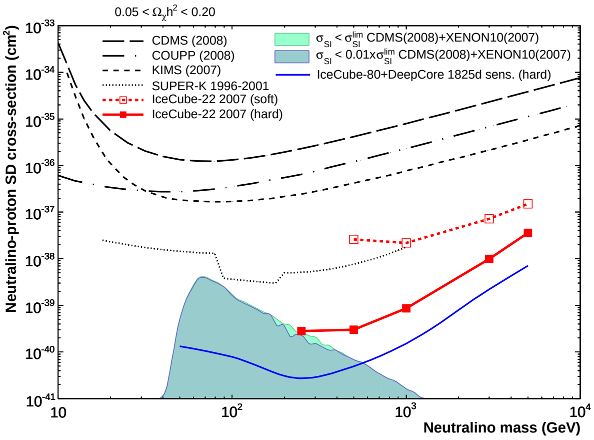

Fig. 3. Upper limits at the 90% confidence level on the spin-dependent neutralino-proton cross-section $\sigma^{SD}$ for the soft ($b\bar{b}$) and hard ($W^+W^-$) annihilation channels, adjusted for systematic effects, as a function of neutralino mass [5]. The lighter [green] and darker [blue] shaded areas represents MSSM models not disfavored by direct searches [20], [21] based on $\sigma^{SI}$ and $100 \cdot \sigma^{SI}$, respectively. Also shown are the limits from CDMS [20], COUPP [24], KIMS [23] and Super-K [17], and the expected sensitivity of IceCube with DeepCore.

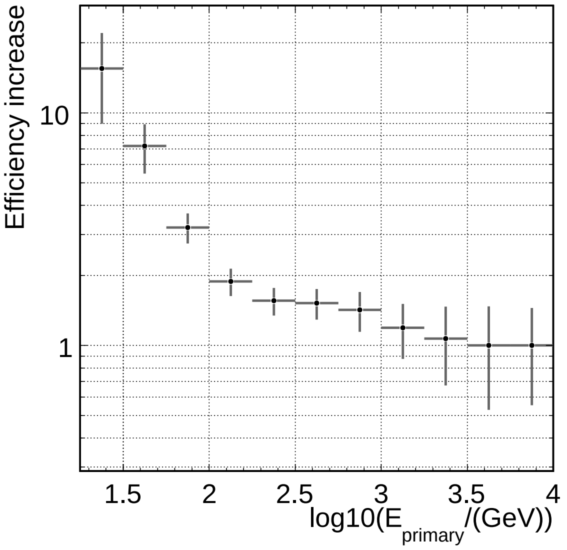

Fig. 4. Impact of the string trigger for the detection of vertically up-going muon neutrinos as function of their energy. The efficiency increase is shown compared to IceCube's multiplicity eight DOM trigger.

this class of events. A similar trigger has also been active in AMANDA. The IceCube string trigger, which selects events with a cluster of hits on a single string, has been active since spring 2008. It requires 5 DOMs to be above threshold in a series of 7 consecutive DOMs, within a time window of 1.5 $\mu$s. Due to the low noise environment and this special trigger, IceCube has an energy threshold for these vertical events that can reach below 100 GeV. The increase in efficiency to these events, over the default DOM multiplicity trigger condition, is shown in Figure 4. Based on selection criteria optimized for these vertically up-going events [30], we will derive a sensitivity for the detection of a possible additional muon flux. These results will be shown at the time of the conference.

Interpreting a possible muon flux (induced from muon neutrino interactions in or below the IceCube detector) from WIMP annihilation in the Earth is somewhat more complicated compared to the solar WIMP searches. The escape velocity is relatively small ($v \simeq 15$ km/s at the center) and capture is only possible for low speed WIMPs unless its mass is nearly identical to that of one of the nuclear species in the Earth. WIMPs are typically only expected to be captured after they are bound to the solar system due to previous scattering in the Sun; such capture mechanisms are described in [26], [27], [28]. Contrarily to the Sun, capture and annihilation of WIMPs are generally not in equilibrium in the Earth. Hence, the expected flux of neutrinos from dark matter annihilations strongly depends on how much dark matter was previously accumulated. Models that enhance the collection of dark matter by the Earth therefore also significantly boost expected signals. One such example is an expected boost due to lower velocity WIMPs in the galactic halo from previous dwarf mergers. Such scenarios could boost fluxes at neutrino telescopes by a few orders of magnitude [29].

Such examples show that big uncertainties remain in the overall flux predictions for neutrinos from the center of the Earth. IceCube, with the combination of DeepCore, is an ideal instrument to look for such signals.

## V. HALO WIMPS

Besides searches for indirect signals from dark matter annihilation in the center of the Sun and Earth, another promising way is to look directly at the galactic halo. Such a signal could be seen in neutrinos as a large scale flux anisotropy that peaks towards the Galactic Center. IceCube has in the past not performed a dedicated search for such signals. However, theoretical predictions indicate that such a search can provide stringent limits [31], [32] on the dark matter self-annihilation cross-section. They are complementary to Solar WIMP searches, as they probe the dark matter self-annihilation cross-section directly.

The analysis for a neutrino flux anisotropy is still ongoing on the IceCube dataset. We perform this analysis on data collected with the IceCube 40-string configuration. Neutrino-induced muon events are being used to search for a neutrino flux anisotropy towards the direction of the Galactic Center. In its current configuration, IceCube can only access up-going muon neutrinos for the energy range of interest (around and below a TeV) with sufficient background rejection. The region closest towards the Galactic Center, accessible in IceCube with up-going events, is therefore near the horizon. It covers, in part, a distance of about 30° towards the Galactic Center. Using a declination band simplifies the background estimation, as an on and off-source comparison can be performed. Second order effects need to be taken into account; these include uneven detector exposure-times, as the reconstruction efficiency is a function of the azimuth angle for the tracks in the same declination band. We plan to present the sensitivity using this method at the time of the conference for different signal distributions within the declination bands [33].

For the future, DeepCore is especially promising for the halo WIMP searches, as it lowers the neutrino energy threshold, holds promises for cascade reconstruction and will allow observation of the entire sky. The lower energy threshold will increase expected signal rates, especially to WIMPs with masses of a few hundred GeV and scale with the increase in neutrino effective area. Leading dark matter candidates have masses in the sub-TeV range, so the expected neutrino energy spectrum is at the low energy end of IceCube's sensitivity. The detection of low energy cascades caused by $\nu_\tau$, $\nu_e$ charged current interactions or neutral current of all neutrino flavors is especially interesting, as the atmospheric neutrino background to this signal is much lower than the muon neutrino background. Even a very limited angular resolution for these cascades, which IceCube might be able to achieve, would benefit the analysis, as it is looking for a large scale anisotropy. The usage of surrounding IceCube strings as veto against down-going muons in DeepCore is expected to give large reductions in this background and enable us to study the entire sky. Simple veto methods have achieved background reductions of four orders of magnitude with excellent signal retention and have potential for greater than 6 orders of magnitude rejection utilizing reconstruction veto methods [34]. Since the Galactic Center, for which the largest flux from dark matter annihilation is expected, is located in the southern hemisphere, this will benefit the analysis in particular.

Expected neutrino fluxes from dark matter self-annihilations in the galactic halo are generally small. Results from PAMELA [35] and Fermi [36] might indicate larger than usual self-annihilation cross-sections of the halo dark matter, this could either be due to unusually large boost factors (clumpiness) well above expectations from dark matter halo simulations, or due to an enhancement in the self-annihilation cross-section (for example Sommerfeld enhancement). Lepton results could also be entirely explainable by astronomical sources (for example pulsars [37]). Regardless of what the source of the recent excess is, it only shows there remains a large uncertainty in any flux predictions for neutrinos from dark matter annihilations or decays in the galactic halo. This, it will be important to check for any such signals with neutrinos.

## VI. SUMMARY

IceCube has set the best limits to date on WIMP annihilation in the Sun using 22-string data from 2007. Using data from the completed 86-string detector, which will include the DeepCore low-energy extension, improvements of an order of magnitude are expected. Searches for signals from the Earth and the galactic halo are also expected to give interesting results.

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