Searches for Dark Matter Annihilations in the Sun with IceCube and DeepCore in the 79-string configuration

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

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, where dark matter could be gravitationally trapped. The recent commissioning of the full DeepCore sub-array, a low-energy extension of the IceCube neutrino observatory, offers exciting opportunities for neutrino physics in the energy region of 10 GeV to 1 TeV. DeepCore's improved energy reach will, in particular, provide sensitivity to neutrinos from attractive WIMP candidates, like the neutralino or the lightest Kaluza-Klein particle (LKP), down to WIMP masses in the region of about 50 GeV. This will lead to stringent upper limits on the flux of muons from dark matter annihilations in the Sun and constraints on WIMP-proton cross-sections. We report on the search for dark matter annihilations in the Sun with the IceCube neutrino detector in the 79-string configuration, which includes the full DeepCore sub-array. Furthermore, we review the impacts of IceCube observations of the Sun upon supersymmetric (SUSY) dark matter models.

Corresponding authors: M. Danninger[2] (*danning@fysik.su.se*) and E. Strahler[3] (*erik.strahler@vub.ac.be*)
[2]*Department of Physics, Stockholm University, AlbaNova, S-10691 Stockholm, Sweden*
[3]*Vrije Universiteit Brussel, Dienst ELEM, B-1050 Brussels, Belgium*

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1 Introduction

While the presence of dark matter in the universe has been inferred through its gravitational interactions, it has yet to be directly or indirectly observed. One of the most promising and experimentally accessible candidates for dark matter are so-called Weakly Interacting Massive Particles (WIMPs). In theories of the Minimal Supersymmetric Standard Model (MSSM), the WIMP can take the form of the lightest neutralino, χ [1], while in the framework of universal extra dimensions (UED) [2] it would be the lightest Kaluza-Klein (KK) particle (LKP). Here, we consider the first excitation of the KK photon, $\gamma^{(1)}$, to be the LKP. In current models, WIMPs are predicted to have a mass in the range of a few 10's of GeV to a few TeV. Whatever their underlying physics, these WIMPs may be swept up by the Sun on its transit through the galactic halo and become gravitationally bound by scattering weakly on solar nucleons. Over time, this leads to an accumulation of dark matter in the center of the Sun, exceeding the mean galactic density. Self-annihilation to standard model particles may result in a flux of high energy neutrinos that will be spectrally dependent on the annihilation channel and WIMP mass, and which can be searched for as a point-like source with neutrino telescopes such as IceCube. Several analyses [3, 4, 5] performed on the data from the IceCube detectors have already set stringent limits on the WIMP induced muon flux from the Sun and the spin-dependent WIMP-proton scattering cross section comparable to or better than those of direct detection experiments.

1.1 The IceCube Telescope

The IceCube Neutrino Telescope [6] records Cherenkov light in the ice from relativistic charged particles created in neutrino interactions in the vicinity of the detector. By recording the arrival times and intensities of these photons with optical sensors, the direction and energy of the muon and parent neutrino may be reconstructed. IceCube instruments 1 km^3 of glacial ice at the South Pole with 5160 Digital Optical Modules (DOMs) on 86 strings deployed between depths of 1450m-2450m. Eight more densely instrumented strings optimized for low energies plus the 12 adjacent standard strings at the center of the detector geometry make up the DeepCore subarray, which increases the sensitivity at low energies and substantially lowers the energy threshold. In addition, by using the surrounding IceCube strings as a veto, DeepCore will enable searches at low energies in the southern hemisphere, transforming IceCube into a full sky observatory. The current analysis of data uses the 79 string configuration of the detector, including 6 DeepCore strings, marked with squares in Figure 1.

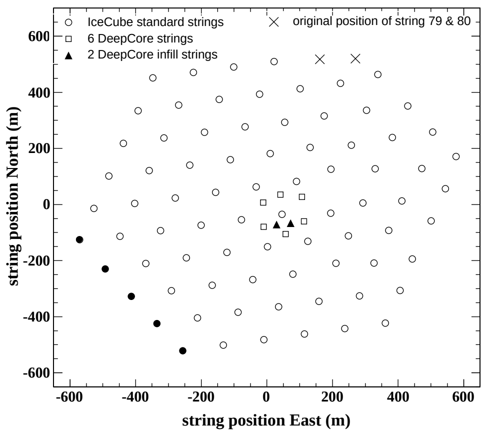

Figure 1: Top view of the final deployed IceCube-86 detector configuration. Standard IceCube strings are shown in circles, initial DeepCore strings in squares, 'in-fill'-strings in DeepCore in triangles and their original design position with crosses. All strings without solid markers make up the 79 string configuration.

The sensitivity study we present for the full 86 string detector uses the initially proposed DeepCore geometry consisting of the same 6 additional strings, as present in the 79 string detector.

2 86 String Sensitivity Study

In order to gauge the dark matter physics potential of IceCube as well as the impact of the DeepCore subarray, we have performed a detailed study to determine the sensitivity of the 86 string detector to signals originating from dark matter annihilations in the center of the Sun. (note, DeepCore infill strings, as indicated in Fig. 1, are assumed at their original design position within this study.) Contrary to previous estimates, this study was performed as a full analysis in all details, including detailed data processing and event selection, while making conservative choices where possible. This gives us a realistic expectation of the capabilities of IceCube to observe dark matter induced signals, given the state of data extraction, reconstruction, and signal discrimination techniques available at the time of the study, conducted prior to the start of 79 string data taking.

2.1 Data Sample

High statistics atmospheric muon and neutrino background samples are simulated including both single events as well as multiple muon coincidences within the detector. The propagation of muons and photons in the ice is simulated [7, 8] taking measured ice properties into account [9]. All signal simulations use `DarkSUSY` [10] and `WimpSim` [11].

The primary WIMP annihilation spectrum is extremely different between χ and $\gamma^{(1)}$. For the LKP, branching ratios are fixed from theory, and therefore a 'true' spectrum can be simulated, whereas every MSSM model will result in a different set of branching ratios. To cover the full range, we assume 100% branching into the two end points of the spectrum, i.e the 'soft' $b\bar{b}$ and 'hard' W^+W^- ($\tau^+\tau^-$ below 80.2 GeV) channels. WIMP signals are generated for 7 different WIMP masses with the 'hard', 'soft' and 'LKP' spectra. The selected masses for the Neutralino models range from 50 GeV to 5000 GeV and for the LKP models between 300 GeV to 1500 GeV. Three different algorithms are used to trigger the detector; the standard IceCube simple majority trigger 'SMT' with multiplicity threshold 8, a string trigger (5 hit DOMs within 7 adjacent DOMs on the same string within 1000 ns) and a lower threshold SMT trigger for the fiducial DeepCore volume optimized for low energies.

2.2 Event Selection

After performing likelihood-based reconstructions to achieve the best possible estimate of the muon direction, a series of increasingly stringent event selections are applied to remove the cosmic-ray induced backgrounds. Events are selected which appear to originate from the direction of the Sun and which exhibit low energy signatures. These cuts are not optimized for each model individually, but rather are chosen to provide good general signal retention, ranging from 25% to 70%, while rejecting as much background as possible ($\sim 4 \times 10^{-3}$). The remaining signal and background is separated through the use of multivariate training algorithms. In order to determine the best possible approach, multiple algorithms were tested, including support vector machines (SVM), neural networks (NN), and boosted decision trees (BDT). It was found that the best sensitivity could be achieved through the combined use of a BDT and a NN applied on independent sets of observables with low correlation and high discrimination power. In order to further maximize the sensitivity across all models, and taking into account the fact that observables are often strikingly different in different energy regimes, these machines were trained for 2 classes of models, 'high energy' and 'low energy', depending on the resulting muon spectrum after dark matter annihilation and neutrino interaction in the ice. A selection was made on the product of the outputs of the machines to maximize the Model Rejection Factor (MRF) [12] of the analysis. This selection was then tightened in order to achieve a conservative result in light of the fact that the study is limited by statistics on the background simulation. With respect to the straight cuts level, the background reduction is 1×10^{-5} with signal efficiencies ranging within 20% to 30%.

From the two final 'low energy' and 'high energy' event selections of the signal simulation, we derive the effective area for muon neutrinos from the direction of the Sun as a function of neutrino energy, see Fig. 2. Also shown in

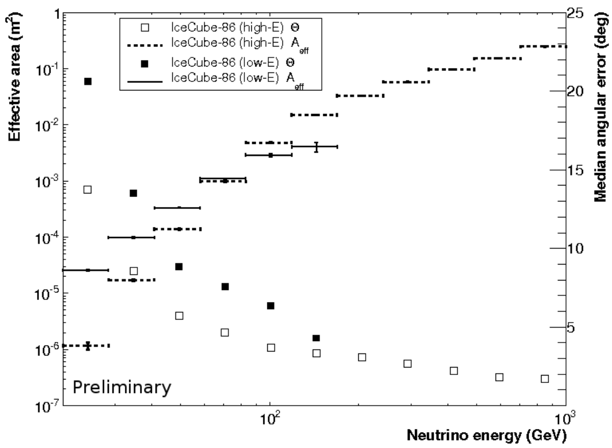

Figure 2: Effective area and median angular error for the final event selection as a function of neutrino energy in the range $20-1000$ GeV, for muon neutrinos from the direction of the Sun for the low and high energy cut selection. The result is an average over the austral winter.

the figure is the median angular error between the reconstructed muon and the neutrino directions, Θ. The result is an average over the austral winter, during which the Sun is below the horizon.

2.3 Sensitivity

After final event selection, the atmospheric muon background reduction is $< 5.2 \cdot 10^{-8}$, which implies that surviving events in the background sample are dominated by atmospheric neutrinos. We search for an excess of neutrino events over this expected background from the direction of the Sun in a specifically determined search cone, the angular size of which is determined by maximizing the MRF= $\bar{\mu}_s^{90\%}/n_s$, where n_s is the number of simulated signal events remaining in the search cone, and $\overline{\mu}_s^{90\%}$ is the average Feldman-Cousins 90% confidence level upper limit on the signal given an expected background $n_{\rm bg}$ and no true signal content. [13] We derive this 90% C.L. average upper limit, or sensitivity, for the 86 string detector configuration assuming a livetime of 180 days, and from this calculate the limit on the neutrino to muon conversion rate $\Gamma_{\nu\to\mu}$. Using the signal simulation, we can convert this rate to a limit on the WIMP annihilation rate in the Sun, $\Gamma_{\rm A}$.

Assuming equilibrium between WIMP capture and annihilation in the Sun, the capture rate is then directly proportional to the WIMP-proton scattering cross sections σ_{SI} and σ_{SD}. By assuming that the capture is dominated either by spin-independent or spin-dependent scattering, it is possible to derive sensitivities for σ_{SI} and σ_{SD} [14]. Results on σ_{SD} are shown in Figure 3 for the case of the LKP and the neutralino, and compared to other experimental limits.

3 79 String Data Analysis

Data taking with the 79 string configuration of IceCube (including 6 DeepCore strings) took place between May of 2010 and May of 2011, and analysis of this dataset is underway. Several improvements have been realized since the completion of the study detailed above and we describe their potential impact on the sensitivity of the analysis here. While this work is ongoing, it is anticipated that results will be seen in the coming months.

• The low energy trigger in actual data taking was reduced from the planned 4 required hit DOMs within the DeepCore fiducial volume to a less stringent 3 hit DOMs. This further extends the acceptance of the lowest energy events, and boosts the sensitivity for low mass WIMPs.

• In previous datasets, hit information was recorded only for those DOMs which had a timing coincidence with their vertical neighbors. This virtually eliminates random noise hits, but at the same time removes a not insubstantial fraction of real physics hits. Beginning in 2009, this condition is relaxed, and limited hit information is read out for all DOMs which see light in a triggered event. Noise cleaning algorithms have been developed to clean this expanded dataset of unwanted noise while retaining physics information vital for low energy analysis.

• Rather than considering only those events in a search cone around the angular position of the Sun, it is possible to conduct the search utilizing a more sophisticated likelihood technique. Probability distribution functions (PDFs) for WIMP signal and ν_{atm} background can be constructed relative to the solar position. The signal PDF, $f_s(\Psi)$, is well known for each model from simulation, while the background PDF, $f_{bg}(\Psi)$, can be found by randomizing the azimuth angle in the final event sample. The likelihood that an event belongs to either of the PDFs can be evaluated, and the most likely signal contribution in the final event sample determined. This method is superior to a search cone in that all events are considered, while still penalizing those that lie further away from the Sun's location.

• Extending searches to the southern hemisphere opens up the entire period when the Sun would otherwise be above the horizon, or the austral summer. This doubles the potential livetime of the experiment, though the challenges in reducing the downgoing atmopsheric muon backgrounds are immense. Much of this background can be removed by considering DeepCore and its surrounding strings as a fiducial volume and using the surrounding IceCube strings as an active veto. Furthermore, techniques have been developed to determine the likelihood that a reconstructed muon originates within the detector volume, a sign that it was the result of a neutrino interacting in the ice.

Taking these and other improvements into account, we expect to be able to substantially improve the sensitivity of the analysis over the baseline described in the study above, most notably at the lowest energies, where background dis-

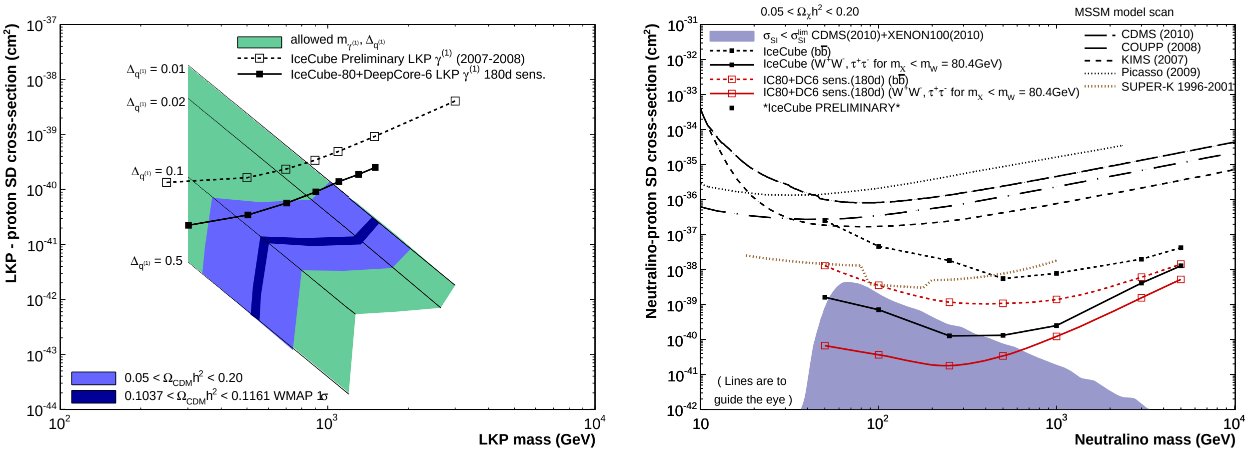

Figure 3: (left plot) Limits on the LKP-proton SD scattering cross-section from IceCube [3] (dashed line) and the final sensitivity for IceCube-86 (solid line) compared to the theoretically allowed region of $m_{\gamma^{(1)}}$ and $\Delta_{q^{(1)}}$. The region below $m_{\gamma^{(1)}} = 300$ GeV is excluded by collider experiments [15]. The upper bound on $m_{\gamma^{(1)}}$ corresponds to the over-closure limit for each individual LKP model [16]. The darker regions (blue in on-line version) indicate the overlap with two different $\Omega_{\rm CDM}h^2$ intervals [17]. (right plot) Sensitivity to χ on proton spin-dependent cross section at 90% confidence level with respect to χ mass. IceCube current best limits [3] are shown in solid markers, IceCube-86 sensitivity is shown in non-filled markers and compared to other experiments. Soft WIMP models are indicated by the dashed lines, whereas hard models are shown in solid lines. The indicated model space represents a scan over the allowed MSSM parameter space, accounting for all current experimental constraints.

crimination is difficult and well reconstructed signal event rates are low.

4 Outlook

Construction of the IceCube telescope was completed in December of 2010, creating a sensitive platform for the discovery of Dark Matter candidates in the energy range of 50 GeV to 1 TeV. The co-located DeepCore subarray pushes the energy threshold of IceCube into the 10 GeV regime and allows for the possibility to extend searches to the southern hemisphere. For searches of dark matter annihilation in the center of the Sun, this effectively doubles the experimental livetime while greatly improving the sensitivity for low mass WIMP models where the bulk of the neutrinos and daughter muons are at these very low energies.

We have conducted a detailed simulation-based sensitivity study utilizing the full 86 string detector geometry to better understand the possible physics reach of the detector and have shown that with only 180 days of livetime, we will improve the limits on the spin-dependent WIMP-nucleon scattering cross section by an order of magnitude. In addition, this study shows that the inclusion of the DeepCore detector significantly improves the reach at low WIMP mass, allowing IceCube to probe the full range allowed by current models.

Data-taking with the 79 string configuration of the detector has concluded in May of 2011 and analysis of this dataset has begun. Many improvements in the detector configuration, extraction of useful information from the data, and in analysis techniques for maximizing the WIMP signal lead us to believe that we can substantially improve upon the predictions described in the above sensitivity study. With these improvements in mind, in the coming months we will be able to set the most stringent limits to date on the WIMP-proton spin-dependent scattering cross section, rule out individual models, or potentially detect an excess neutrino flux from the Sun, strongly indicating the capture and annihilation of dark matter in its core.

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