WIMP ANNIHILATIONS IN THE SUN : A SEARCH BASED ON THE FIRST YEAR OF DATA FROM THE COMPLETED ICECUBE NEUTRINO TELESCOPE.

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Weakly Interacting Massive Particles, which are favored candidates for Dark Matter, may be captured gravitationally in the Sun and pair-annihilate to produce standard model particles, including neutrinos. The resulting neutrino flux from the Sun might be detected by terrestrial neutrino telescopes such as IceCube. In these proceedings we present the preliminary results from the analysis of 341 days of operation of IceCube-DeepCore, between May 2011 and May 2012, in the completed 86 string configuration. In addition to the standard analysis using upward going neutrino-induced events during austral winter, improved veto techniques have been used to reduce the atmospheric muon background and improve sensitivity during the austral summer. Overall sensitivity has also benefited from better analysis methods and reconstructions and improved with respect to all previous analyses.

1 Introduction

Astrophysical observations provide strong hints about Dark Matter(DM). However the nature of it is entirely unknown. An exciting and experimentally accessible candidate is the so called 'Weakly Interacting Massive Particle (WIMP)'(see [1] for a comprehensive review). If the DM content of the universe consists of WIMPs, they can scatter off nuclei in massive bodies such as the Sun and be captured gravitationally[2], where they may pair-annihilate into standard model particles, including neutrinos at an enhanced rate. Given enough time, the capture and annihilation processes would reach equilibrium[3] and on average only as many WIMPs annihilate as are captured in any unit time. This DM-induced neutrino flux may be detected at terrestrial neutrino detectors such as IceCube. As the region at the centre of the Sun where most of the annihilations will occur is very small, the search is equivalent to looking for a point-like source of neutrinos. However, neutrinos above 1 TeV have interaction lengths significantly smaller than the radius of the Sun, and as a result all the signal is expected in the range of a few GeVs to ∼1 TeV, making this a very low energy point-source search by the standards of IceCube.

2 The Detector and Event Selection

IceCube is a cubic-kilometer-sized detector embedded in the ice at the geographic South Pole[6]. A more detailed description of the detector is presented in[7]. Neutrino flux predictions at Earth from WIMP annihilations in the Sun have been widely studied, for example in Ref[4]. We use the flux predictions from DarkSuSy and WimpSim[4] to simulate signals for the IceCube detector according to specific annihilation scenarios.

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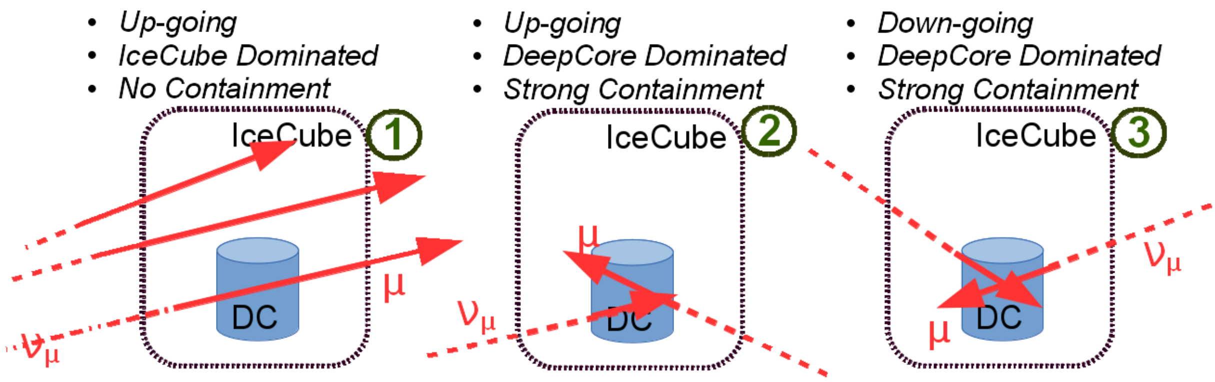

Figure 1 – The three event selection strategies for the solar WIMP analysis. Most of the sensitivity for neutrino signals below 100 GeV comes from the DeepCore (DC) dominated low energy samples. During the austral summer (when the Sun is a source of downgoing neutrinos), the overwhelming muon background forces us to use the outer detector as a Veto (see Fig. 2) and consequently there is only a DeepCore dominated - low energy sample.

The energy range of the expected signal (a few TeV at maximum) and the properties of IceCube at these energies dictate the event selection strategies. While the principal IceCube array has an energy threshold of $\sim$100 GeV, the more densely instrumented DeepCore infill array has an energy threshold of $\sim$10 GeV. This means that for WIMP masses $<$ 200 GeV, which produce signal neutrinos mostly with energies below the IceCube threshold, only DeepCore[5] will contribute significantly towards the effective volume. However, for higher WIMP masses where a significant fraction of the resultant neutrinos are above the IceCube threshold, the full effective volume of IceCube comes into play. For optimizing the event selections for the analysis and setting upper limits, we consider two scenarios: WIMPs annihilating completely into W^+W^-, a 'hard' channel with emission peaked at neutrino energies close to the WIMP mass, and WIMPs annihilating completely into $b\bar{b}$, a 'soft' channel with emission peaked at neutrino energies of a few GeV. Since IceCube acceptance is very energy dependent, cuts have to be optimized for the spectral composition of the expected signal flux. For WIMP masses below 80.4 GeV, we also consider a WIMP annihilating into $\tau\bar{\tau}$, since annihilations to W^+W^- are no longer kinematically allowed.

Within IceCube, a standard set of filters are used to pre-select signal-like muon events and reduce the rate of the dominant atmospheric background. This analysis starts with a stream of data from three of these filters, a low-energy DeepCore filter and two filters selecting muon-like events that point upwards. After these filters the data rate is $\sim$ 100 Hz. From this point onwards, data are treated differently depending upon whether they fall in the austral winter or summer.

During the austral winter, when the Sun is below the horizon, the signal consists of upgoing neutrinos. The background is dominantly made up of downgoing atmospheric muons falsely reconstructed as upgoing. Reconstructed event properties quantifying topology, track length, reconstruction quality etc are used to reject background such as very high energy events or vertical events which obviously cannot come from the Sun and reduce the data to $\sim$ 2 Hz. At this point, a likelihood reconstruction with a prior based on the zenith distribution, which takes into account that the majority of the tracks are downgoing atmospheric muons, is performed to identify and remove falsely reconstructed downgoing events. Depending upon the location of the majority of detected Cherenkov photons (whether within IceCube (1) or within DeepCore (2)), events are split into two streams (see Fig 1). Subsequently, separate instances of a multivariate classification algorithm, known as Boosted Decision Tree (BDT), are used to select signal-like events from both these streams. The BDT of the IceCube dominated sample (1) is optimized for events from a 1 TeV WIMP annihilating into the hard W^+W^- channel while the DeepCore dominated sample (2) is optimized for events from 100 GeV and 50 GeV Wimps annihilating

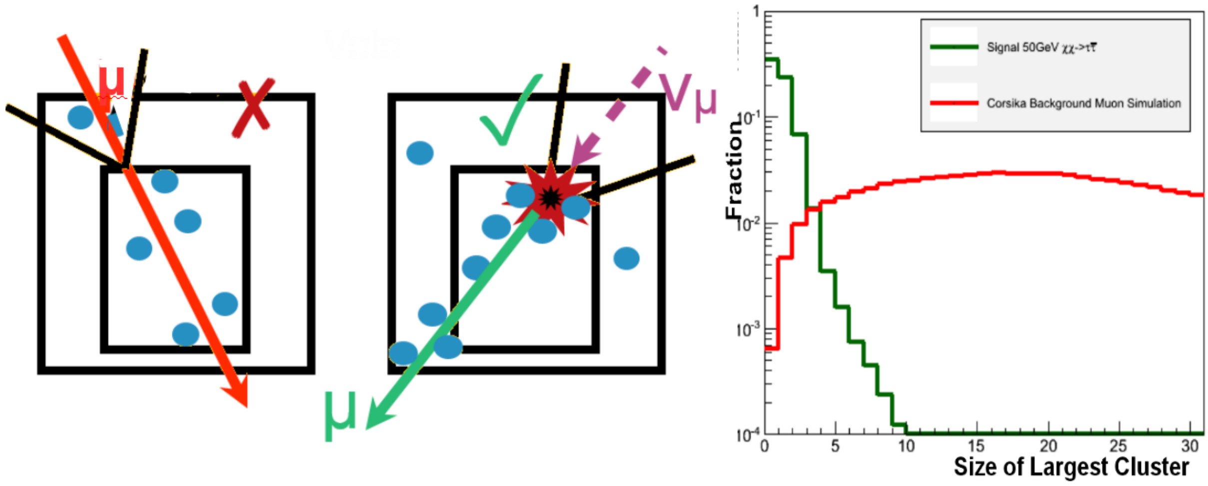

Figure 2 – On the left and center: A schematic representation of the veto concept to reject atmospheric muon background and retain neutrinos during austral summer. Only events with their reconstructed vertex near Deep-Core are selected. Subsequently, the number of hits within a cone of 40° half-angle at the vertex and aligned along the muon track that are within a specific 'Radius + Time (RT)' radius of each other are counted. The size of the largest of these clusters of hits is reported. On the right: size of this cluster for signal (green) and background (red). Selecting events with cluster sizes ≤ 3 will keep more than 90% of signal while rejecting more than 90% of background of atmospheric muons.

into W^+W^-, $b\bar{b}$ and $\tau^+\tau^-$ channels. After the selection based on the BDT classifier, event rates of the two samples are ~ 2.9 and ~ 0.34 mHz, respectively, consistent with expectations from a background that is dominated by atmospheric neutrinos.

During the austral summer (23rd September 2011 to 16th March 2012), the signal (down-going) is overwhelmed by a background of downgoing atmospheric muons ($\sim 10^6$ times higher in rate) in addition to the atmospheric neutrinos. A sample of DeepCore dominated downgoing tracks (3) can be isolated by using the outer laters of IceCube as a veto (see Fig. 2). This sample is again optimized using a BDT algorithm to select events expected from 100 GeV and 50 GeV Wimps annihilating into W^+W^-, $b\bar{b}$ and $\tau^+\tau^-$ channels. After the BDT-based event selection the even rate is ~ 0.24 mHz, consistent with the expected residual atmospheric neutrino and muon background.

Fig. 3 summarizes final effective areas and angular resolutions of the two samples.

3 Analysis method

The significance of a cluster of events in the direction of the Sun can be estimated using a modified version of the unbinned maximum likelihood ratio method described in Ref. [8]. Due to the very large point spread function of IceCube at these low neutrino energies, we model the spatial signal p.d.f of Ref. [8] as a Fisher-Bingham distribution from directional statistics [9].

For the fully contained events of the DeepCore dominated samples (2) and (3), the energy of the neutrino can be estimated by summing the energy of the muon (obtained by reconstructing the starting and stopping vertex of the muon) and the hadronic cascade from the charged current interaction. Signal and background p.d.f.s are constructed from the signal simulation and datasets randomized in azimuth respectively. Energy weighting is added to the likelihood to enhance sensitivity. Thus the signal p.d.f. is given by:

$$S_i(|\vec{x}_i - \vec{x}_{sun}(t_i)|, E_i, m_\chi, c_{ann}) = \mathcal{K}(|\vec{x}_i - \vec{x}_{sun}(t_i)|, \sigma_i) \times \mathcal{E}_{m_\chi, c_{ann}}(E_i), \tag{1}$$

where $\mathcal{K}$ stands for the spatial and $\mathcal{E}$ for the spectral parts of the p.d.f. and m_χ and c_{ann} stand for the mass and annihilation channel of the WIMP respectively. The best estimate for the number of signal events in the sample is obtained by maximizing the likelihood ratio as defined

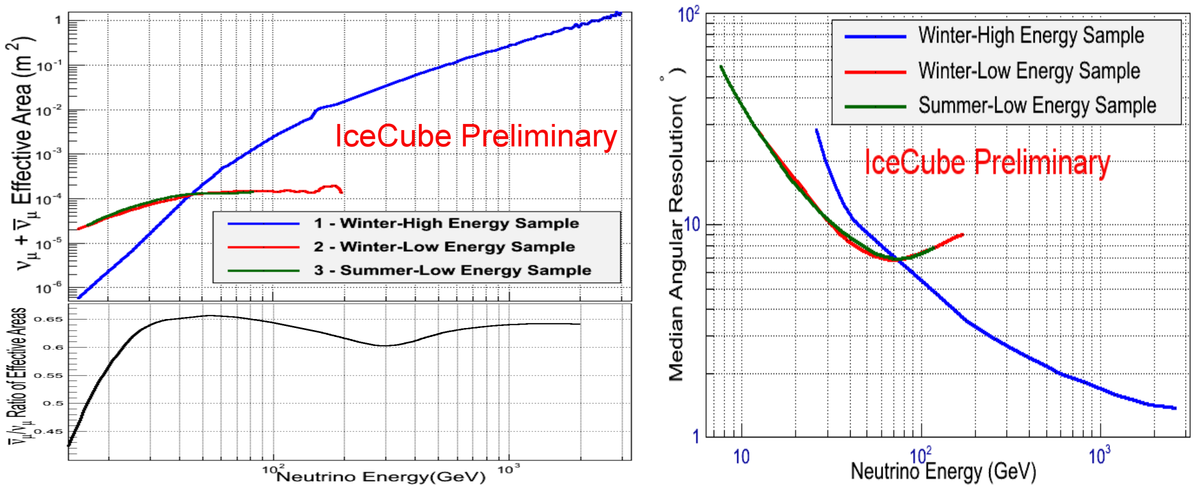

Figure 3 – Top Left: $\nu_\mu + \bar{\nu}_\mu$ effective areas for the three different event selections. Bottom Left : Ratio of the $\bar{\nu}_\mu$ and ν_μ effective areas. Right: The angular resolutions of the three samples at different energies, defined as the median of the angular separation between the incoming neutrino and the reconstructed muon.

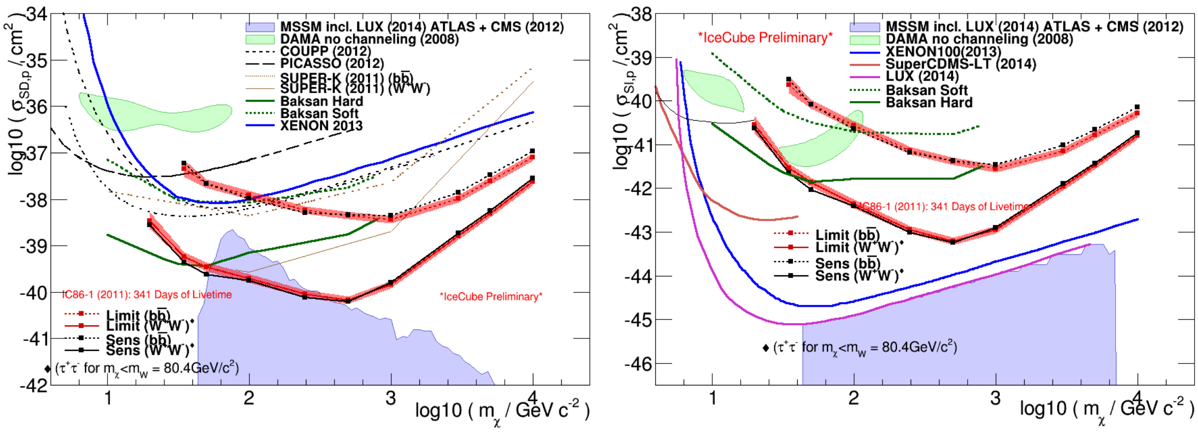

Figure 4 – Limits on the spin dependent (left) and spin independent (right) WIMP-Nucleon scattering cross section as a function of the WIMP mass, derived from this analysis and compared to other experiments' limits from [12,13,14,16,15,17,18,19] . The assumed local DM density is 0.3 GeV/cm^3 and a standard Maxwellian halo velocity distribution.

in Ref. [8]. The significance of the observation can be estimated without depending on Monte Carlo simulations by repeating the process on datasets scrambled in right ascension. As the three separate event selections have no events in common, they can be combined statistically using the method described in [10]. Confidence intervals on the number of signal events present within the sample are constructed using the method of Feldman and Cousins[11].

4 Results and discussion

No significant excess was found in the direction of the Sun, allowing us to set stringent limits on the neutrino flux from the Sun in the GeV-TeV range. This limit can also be interpreted as a limit on the WIMP-nucleon scattering cross section. For the spin dependent case, IceCube limits are the most competitive in the region above $\sim$ 20 GeV (Fig. 4). Limits have improved by a factor of $\sim$30% to 60% w.r.t. the previous IceCube analysis.

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