Searches for Dark Matter with the IceCube Detector

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Abstract. Construction of the IceCube neutrino observatory was recently completed, including the full DeepCore sub-array, a low-energy extension of the IceCube detector. We present recent results from the searches of dark matter candidates with IceCube, performed with the 22- and 40-string configurations using the Sun and the Galactic Center and Halo as possible dark matter sources. We also report on the search for dark matter annihilations with the IceCube neutrino detector in the 79-string configuration. Furthermore, a formalism for quickly and directly comparing event-level IceCube data with arbitrary annihilation spectra in detailed model scans is presented. We show an application of this formalism to both model exclusion and parameter estimation in models of supersymmetry.

1. Introduction

While the presence of dark matter (DM) 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 DM are so-called Weakly Interacting Massive Particles (WIMPs). In current models, WIMPs are predicted to have a mass in the range of a few tens of GeV to a few TeV. Neutrino telescopes, such as IceCube, can be used in the search for WIMPs and their underlying fundamental properties. IceCube searches for decaying or self-annihilating DM in the halo of galaxies and thereby can probe its livetime, or self-annihilation cross section [1]. Additionally, IceCube can directly test the WIMP-nucleon scattering cross section by looking for neutrino signals from self-annihilating DM captured in large celestial bodies [2], like the Sun or the Earth.

Here recent results are presented from the searches for DM candidates with AMANDA-II and IceCube in its 22- and 40-string configurations. First, we focus on the latest limits on \( \langle \sigma_A v \rangle \) from the Galactic Center and Halo. Then, we discuss a multi-year search for DM annihilations in the Sun with the AMANDA-II and IceCube detectors. We conclude with a brief discussion on a new formalism for quickly and directly comparing event-level IceCube data with arbitrary annihilation spectra in detailed model scans and comments on prospects for the full IceCube 86-string detector.

For IceCube search strategies for self-annihilating DM in dwarf galaxies surrounding the Milky Way, the reader is referred to reference [3].

The IceCube detector

The IceCube Neutrino Telescope [4] 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 1450 m and 2450 m. Eight more densely instrumented strings optimized for low energies plus the 12 adjacent standard strings 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. IceCube’s predecessor, AMANDA-II, was operational until May 2009. It consisted of an array of 677 optical modules deployed on 19 strings at depths between 1500 m and 2000 m.

2. Galactic Dark Matter searches with IceCube

The expected DM density distribution in the Milky Way can be approximated by a spherically symmetric function. Such a distribution is strongly motivated by observational evidence e.g., galaxy rotation curves, but also by large scale N-body simulations. While halos are relatively well understood in the outer regions, the inner structure currently cannot be directly measured or resolved in simulations. Therefore, halo models generally show good agreement in the outer halo, and differ significantly for the Galactic center (GC). The analyses discussed here uses the Navarro-Frenk-White, NFW, profile \cite{5} as a benchmark model, while other profiles are used to estimate the impact on the results from the choice of halo model. The expected neutrino flux from DM self-annihilations is proportional to $\rho_{DM}^2$ integrated along the line of sight, $J(\Psi)$, for a given angular distance to the GC, where $\rho_{DM}$ is the local DM density, which is normalized to 0.3 GeV/cm$^3$ at a distance of 8.5 kpc from the GC.

The differential neutrino multiplicity per annihilation is highly model dependent. Therefore, various possible annihilation channels are investigated, assuming a branching ratio of 100% for each of them.

The highest neutrino flux from WIMP annihilation is expected to come from a relatively wide region, centered in the direction of the GC that is at the location of IceCube about 30$^\circ$ above the horizon. Data from this direction are dominated by atmospheric muons. Therefore, this analysis is based on the identification of events with an interaction vertex inside the detector, to distinguish signal from atmospheric muons that produce incoming tracks. The optimum on-source region both in right ascension and declination were found to be $\pm 8^\circ$. This analysis is performed on IceCube 40-string data taken in 2008 and 2009.

In the Galactic halo analysis we search for a neutrino anisotropy by comparing fluxes from an on-source region centered around the same right ascension as the GC, to that from an equally sized off-source region shifted by 180$^\circ$ at the same declination. This analysis is performed on IceCube 22-string data taken during 2007 and 2008. Here, the final event selection is dominated by upwards going neutrino-induced muon events.

![Figure 1. 90% C.L. upper limits for $\tau$ channel, compared to preferred phenomenological annihilation channels if PAMELA excess and Fermi $e^-$ are interpreted as DM. IceCube 40-string limits are preliminary, since they do not include signal acceptance systematic uncertainties.](image-url)
Observations in both analyses were consistent with background-only expectations. Upper limits on $\langle \sigma_A v \rangle$ are computed at the 90% confidence level as a function of WIMP mass and annihilation channel. Figure 1 shows the obtained limits for the $\tau$ channel, compared to preferred phenomenological annihilation channels if the PAMELA excess and Fermi electrons are interpreted as DM [6]. Details on both analyses can be found in Ref. [7] and [8].

3. Solar Dark Matter searches with IceCube

In theories of the Minimal Supersymmetric Standard Model [9], the WIMP can take the form of the lightest neutralino, $\chi$, while in the framework of universal extra dimensions [10] it would be the lightest Kaluza-Klein particle (LKP). Whatever their underlying physics, 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 DM at 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 can be searched for as a point-like source in AMANDA-II and IceCube.

In this analysis, the two most extreme annihilation channels are studied; the softest ($\chi\chi \rightarrow b\overline{b}$) and hardest ($\chi\chi \rightarrow W^+W^-$) possible neutrino spectrum. The same event selection is also applied to search for the LKP. The dominant background for this search comes from downwards going muons created by cosmic ray interactions in the atmosphere. By restricting the search to the Austral winter period, when the Sun is below the horizon, the muon background can be significantly reduced. Background is further eliminated by a series of quality cuts, resulting in a final event selection that is dominated by neutrino-induced muon events. The analysis is performed in a blind manner such that the azimuth of the Sun is not revealed until the selection cuts are finalized. This analysis combines data from previous work on AMANDA-II and IceCube 22-string with the latest IceCube 40-string analysis (AMANDA-II is embedded within IceCube 40-string array and was used as a low energy extension to IceCube). As all three data samples are independent, we can combine them in a statistically suitable way in one likelihood analysis with a total livetime of 1065 days. Here, we use the shape of the space angle distribution of the final samples with respect to the Sun’s position, to build a confidence interval for the number of signal events compatible with the observed data at the 90% C.L.. The full study is detailed in Ref. [11].

From the upper limit on the number of signal events, a limit on the annihilation rate in the Sun can be derived, which in turn can be used to set a limit on the WIMP capture rate in the Sun. Assuming equilibrium between WIMP capture and annihilation in the Sun, the capture rate is then directly proportional to the WIMP-proton scattering cross sections $\sigma_{SI}$ and $\sigma_{SD}$. By assuming that the capture is dominated by spin-dependent scattering, it is possible to derive the limit on $\sigma_{SD}$ at the 90% C.L. for this multi-year analysis (Fig. 2). Also shown in Fig. 2 is a projected sensitivity for the full IceCube and DeepCore detector and current experimental limits from direct searches. Corresponding limits on the LKP are discussed in Ref. [11] and [12].

4. Global SUSY analysis with IceCube

We will perform two specialized analyses of the impacts of IceCube observations of the Sun upon (SUSY) DM models. The primary difference between these analyses and the existing IceCube upper limits is that the new analyses would be based on explicit exploration of theoretical SUSY parameter spaces, including a model-by-model comparison of fluxes with the IceCube observations. This approach would also allow models to be tested against a range of complementary data, including accelerator constraints, the relic density of DM, limits on rare processes from $B$-physics and the anomalous magnetic moment of the muon.
Figure 2. Limits on $\chi p$ spin-dependent cross-section at 90% C.L. vs. $m_\chi$ (black markers). Also shown is a projected 86-string sensitivity (red line), and limits from other experiments (soft models in dashed lines, hard in solid lines). The model space represents a scan over the allowed MSSM parameter space, accounting for all current experimental constraints.

The first analysis is model exclusion. Here individual SUSY models are tested for consistency (at some set C.L.) with IceCube data and other existing constraints, and identified as allowed or excluded by IceCube. The second analysis constitutes a parameter estimation exercise within a given SUSY framework. This analysis involves a global fit to all existing constraints, with the inclusion of IceCube data. In this analysis, the full likelihood of each experimental result, including IceCube, is combined to give confidence intervals and Bayesian credible intervals on SUSY parameters. A detailed description of the methods used and the obtained results of both analyses will be discussed in detail in future publications.

Prospects for DM searches with the full IceCube and DeepCore

With the completion of the IceCube telescope in December of 2010, a sensitive platform for the discovery of DM candidates in the energy range of 50 GeV to 5 TeV was created. DeepCore lowers the energy threshold of the detector into the 10 GeV regime and gives the possibility to extend searches to the southern hemisphere. For solar DM searches, this effectively doubles the experimental livetime while greatly improving the sensitivity for low mass WIMP models.

Further, all analyses presented here are aiming to extend the search to include the cascade channels. This is feasible owing to the excellent atmospheric muon veto capabilities with IceCube/DeepCore, and even more rewarding as the atmospheric neutrino background in this channel is much lower. These advantages outweigh the drawbacks of a poor angular resolution of cascade events, and will allow further improvement in sensitivity.

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