Search for Dark Matter in the Milky Way with IceCube

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

Abstract: We present results of the search for WIMP dark matter accumulated in the galactic halo and the galactic center, using two different configurations of the IceCube neutrino telescope. Limits on the dark matter self-annihilation cross-section at the level of $10^{-22}\,\mathrm{cm^3 s^{-1}}$ – $10^{-23}\,\mathrm{cm^3 s^{-1}}$ are achieved, depending on WIMP mass and the assumed annihilation channel. The status of on-going investigations and future prospects are also discussed.

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1 Introduction

The existence of a cold, non-baryonic dark matter component of the Universe is implied by a variety of astronomical observations. The velocity distribution of galaxy clusters suggests a mass content significantly higher than what should be expected from observation of the luminous mass. On smaller scales, the rotation profiles of galaxies show discrepancies, which hint at the existence of a dark matter halo reaching out far beyond the baryonic disc and bulge. Based on e.g. the anisotropy in the cosmic microwave background observed by WMAP [1], a determination of cosmological parameters is possible, which yields the concordance model of cosmology, with a dark matter content of about 22%. Large scale structure formation and N-body simulation of cosmic evolution require the existence of cold dark matter, which is expected to consist of massive non-relativistic particles. Weakly Interacting Massive Particles (WIMPs) form a class of promising dark matter candidates, that are expected to have masses from a few GeV up to several 100 TeV [2, 3]. Assumed to be relics from the Big Bang they would naturally yield correct cosmic relic abundances. A promising WIMP candidate is the neutralino, the lightest stable particle introduced by the hypothetical minimal super-symmetric extension to the Standard Model.

WIMPs, if assumed to be Majorana particles, can self-annihilate and produce a variety of Standard Model particles in the final state. The dark matter annihilation in the Milky Way would hence yield an excess flux of neutral messenger particles (γ, ν) from the direction of the Galactic Center, where the dark matter density is expected to peak. Further, it would also lead to a large-scale anisotropy over the sky. Such a flux of annihilation products can be detected by earth-based, air-borne or satellite experiments, or the absence of such a flux can be interpreted in terms of upper limits on the velocity-averaged self-annihilation cross-section, $\langle\sigma_A \mathrm{v}\rangle$, of dark matter particles in the considered model. In this paper we present two approaches to the search for dark matter with IceCube; an analysis of a possible large-scale anisotropy and a search for an excess flux from the direction of the Galactic Center.

2 Neutrino Flux from Dark Matter Annihilation in the Galactic Halo

Dark matter density profiles based on observations of dark matter dominated galaxies tend to have a rather flat density distribution in the central region, while profiles based on N-body simulations show a steep, often divergent increase of density towards the Galactic Center [4, 5]. An often-used parametrization of (spherically symmetric) dark matter profiles is

$$\rho_{\mathrm{DM}}(r) = \frac{\rho_0}{\left(\frac{r}{r_s}\right)^{\gamma} \cdot \left(1 + \left(\frac{r}{r_s}\right)^{\alpha}\right)^{(\beta-\gamma)/\alpha}} \quad (1)$$

where, r is the distance from the Galactic Center and r_s is the scaling radius. The commonly used NFW-profile is then defined by the parameters: $r_s = 20\,\mathrm{kpc}$, $(\alpha, \beta, \gamma) = (1, 3, 1)$ [6]. ρ_0 is chosen so that the locally (at radius

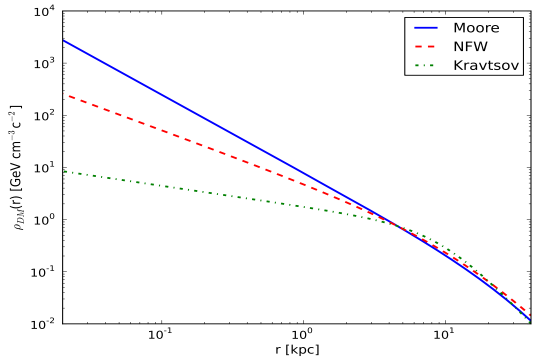

Figure 1: The NFW, Kravtsov, and Moore halo profiles are compared.

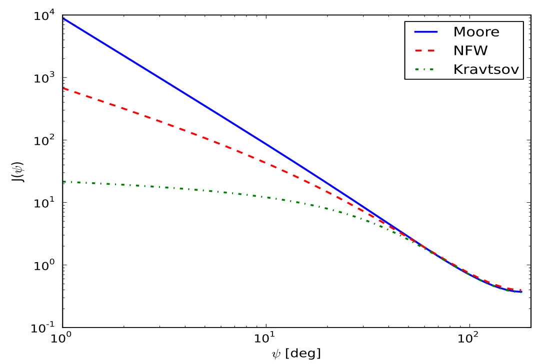

Figure 2: $J(\Psi)$ is shown for the NFW, Moore, and Kravtsov profile.

of the solar circle R_{SC}) assumed dark matter density is $0.3\ \text{GeV/c}^2\text{cm}^{-3}$. Figure 1 illustrates the NFW profile along with two other profiles with different scaling parameters; the flat Kravtsov profile [7] and the cuspy Moore profile [8].

Following [9], the expected neutrino flux from WIMP annihilation depends on the squared dark matter density integrated along the line of sight

$$J_a(\Psi) = \int_0^{l_{max}} \mathrm{d}l\ \frac{\rho^2_{\text{DM}}(\sqrt{R^2_{\text{SC}} - 2lR_{\text{SC}}\cos\Psi + l^2})}{R_{\text{SC}}\rho^2_{\text{SC}}} \quad (2)$$

where Ψ is the opening angle between the line of sight and the Galactic Center and R_{SC} and ρ^2_{SC} are used as scaling parameters, so that $J_a(\Psi)$ is dimensionless. The upper line-of-sight integration limit , l_{max}, is chosen to be approximately the Milky Way radius. Figure 2 shows the shape of $J_a(\Psi)$ for the above mentioned profiles. The differential flux can be written as:

$$\frac{d\phi_\nu}{dE} = \frac{\langle\sigma_A v\rangle}{2}\ J_a(\Psi)\ \frac{R_{\text{SC}}\rho^2_{\text{SC}}}{4\pi m^2_\chi}\ \frac{d\mathcal{N}}{dE}. \quad (3)$$

The factor $1/4\pi$ comes from isotropic emission, m_χ is the mass of the dark matter particle, and $\frac{d\mathcal{N}}{dE}$ is the energy spectrum of the final state neutrinos. For the presented analyzes, DarkSUSY [10] scans have been performed, for a variety of benchmark WIMP masses and annihilation channels.

3 IceCube Neutrino Observatory

IceCube is a km^3-size neutrino detector located at the geographic South Pole. Construction has been completed in December 2010. It consists of 86 strings instrumented with 60 Digital Optical Modules (DOMs) each, including a low energy sub-array DeepCore, that has an energy threshold of the order of 10 GeV. The DOMs are located at a depth ranging from 1.45 km to 2.45 km in the Antarctic glacier. The IceCube strings are arranged in a hexagonal symmetry, with an inter-string spacing of 125 m and a DOM distance of 17 m. Eight densely spaced DeepCore strings are deployed between regular IceCube strings and have a DOM spacing of 7 m and an inter-string spacing of 72 m. For the presented analyzes the 22– and 40–string configurations were used, which did not have any DeepCore strings.

4 Galactic Halo Analysis with IceCube–22

Between June 2007 and March 2008, the partially-deployed IceCube detector was operated in a configuration with 22 strings and acquired 275 days of live-time, that were searched for neutrino signals from WIMP annihilations in the outer Galactic halo (Northern hemisphere). The sample contained 5114 up-going muon neutrino candidate events, covering $-5°$ and $85°$ in reconstructed declination, with a purity of about 90% [11]. Despite the Galactic Center (RA 17h45m40.04s, Dec -29°00′28.1″) being located on the southern hemisphere and not accessible in this sample, we expect an anisotropy to be present on the northern hemisphere. The anisotropy is caused by the dark matter distribution in the Milky Way halo, which would result in a larger neutrino flux from the region closer to the Galactic Center compared to that further away from it. We have searched for a neutrino anisotropy by comparing fluxes from an on–source region centered around the same RA as the Galactic Center to that from an equally sized off–source shifted by 180° (see figure 3). The analysis was performed in an unbiased fashion, by only counting events in the regions after their size and the analysis procedure were optimized using simulations only.

We observed compatible numbers of events in the on– and off–source region: 1367 and 1389, respectively [12]. As we perform a relative comparison on data the uncertainties on the background estimate can be kept small. A systematic uncertainty of 0.3% due to any pre-existing anisotropy in the data caused by exposure and cosmic-ray anisotropy remains. The signal acceptance uncertainty is approximately 30% and is dominated by the incomplete modeling of ice properties and limitations in the detector simulation. Us-

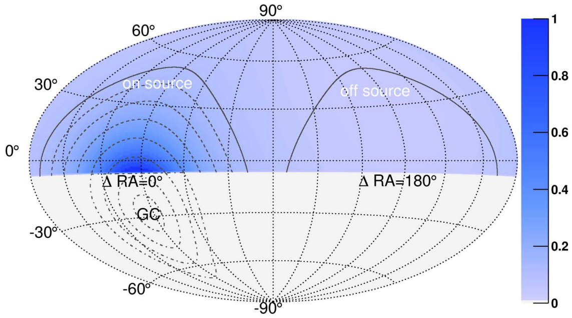

Figure 3: Relative expected neutrino flux in the northern hemisphere from self-annihilation in the Milky Way halo. The on–source region (solid line) is centered around largest the flux expectation at $\Delta\mathrm{RA} = 0$, while the off–source region is shifted by $180°$ in RA.

ing equations (2) and (3), a limit on the self-annihilation cross section has been calculated and is shown in figure 4 compared with the limits from the Galactic Center analysis, described in the next section. As the analysis uses the outer halo, the uncertainty on the choice of halo model is small as indicated by the error band on the limits.

5 Galactic Center Analysis with IceCube–40

The 40–string configuration of IceCube was taking data from April 2008 to May 2009, yielding a total detector livetime of 367 days.

The highest neutrino flux from WIMP annihilation is expected to come from a relatively wide region centered at the direction of the Galactic Center which, at the location of IceCube, is always about 30° above the horizon. Data from this direction is dominated by atmospheric muons, therefore this analysis is based on the identification of events with an interaction vertex inside the detector (atmospheric muons produce incoming tracks) and it relies on the on-source/off-source method; based on Monte Carlo simulations, the width of a declination band (centered at the location of the Galactic Center) is optimized to maximize $\mathrm{signal}/\sqrt{\mathrm{background}}$, assuming the NFW-profile. In this declination band, a window in right ascension is optimized. The optimum window sizes both in right ascension and declination were found to be $\pm 8°$. After correction for uneven exposure, as well as signal quality cuts, the uncertainty on the background prediction is reduced to the 0.1%-level. Based on the above mentioned background estimation, the expected number of background events in the signal region was 798819. The number of observed events was 798842. The difference of 23 events is compatible with the null-hypothesis, therefore a 90%C.L.-limit on the number of signal events has been calculated (1168), following the Feldman-Cousins approach [13]. Using equations (2) and (3), a limit on the self-annihilation cross-section has been calculated and is shown in figure 4 along with the limits from the previous analysis. Figure 5 shows the obtained limits for the τ channel, compared to the PAMELA/Fermi regions [14].

The IceCube–40 limits are preliminary, since they do not include signal acceptance systematic uncertainty due to optical ice properties.

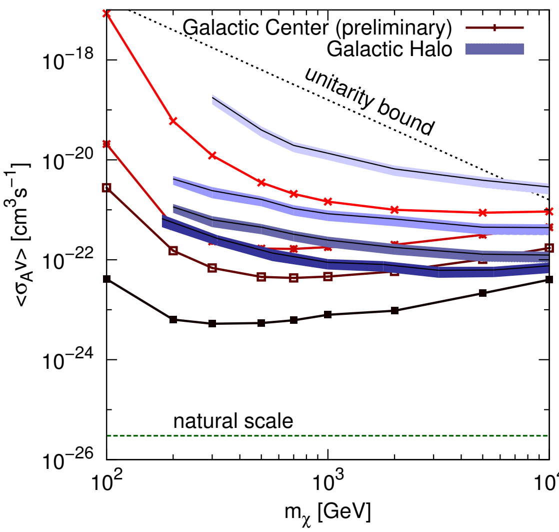

Figure 4: 90% C.L.-limits on the $\langle\sigma_A \mathrm{v}\rangle$ from the IceCube–22 halo analysis (blue-shaded lines) [12], and the limits obtained from the IceCube–40 Galactic Center analysis (simple lines). For both analyses the lines from top to bottom correspond to the $b\bar{b}$, $\mathrm{W}^+\mathrm{W}^-$, $\mu^+\mu^-$ and $\nu\bar{\nu}$ annihilation channels. The IceCube–40 limits are preliminary.

6 Outlook on the Galactic Center Analysis with IceCube–79

For IceCube–79, a dedicated Galactic Center data filter has been implemented and was taking data from June 2010 to May 2011. The filter consists of two parts. A so-called high energy part accepts all events with a reconstructed arrival direction within an angular window of $\pm 10°$ in declination and $\pm 40°$ in RA with respect to the direction of the Galactic Center and if their brightness exceeds a zenith-dependent threshold. The so-called low-energy part accepts events from a $15°$ wide zenith band around the Galactic Center, but applies a pre-scale factor of 3 on events from the zenith band, which have a distance of more than $20°$ to the Galactic Center in right ascension. Further restrictions for the low energy filter are a top veto defined by the upper 5 DOMs, in which no hits are allowed, and a side veto. The side veto consists of the outer layer of IceCube strings; the earliest pulse is not allowed in this veto region. These filter conditions allow for a preselection of tracks, which appear to start within IceCube. Figure 6 shows a comparison of the effective area at filter level for IceCube–40 and for

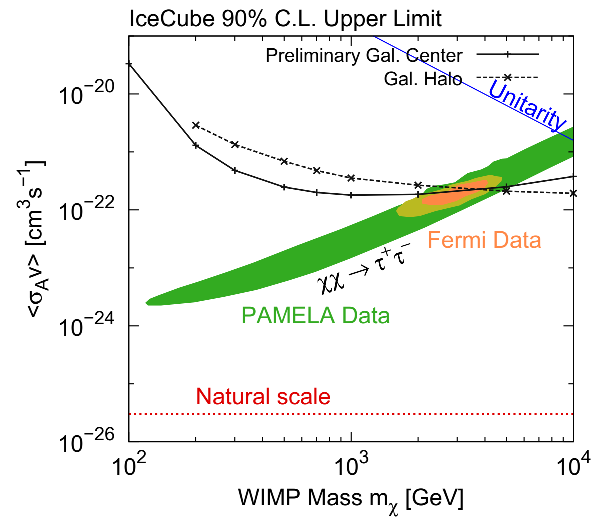

Figure 5: IceCube 90% C.L. upper limits on the $\langle\sigma_A \mathrm{v}\rangle$ from the Galactic halo with the 22–string and the Galactic Center with the 40–string array compared to the preferred regions for PAMELA data, and the region including Fermi data for annihilation to $\tau^+\tau^-$ [14].

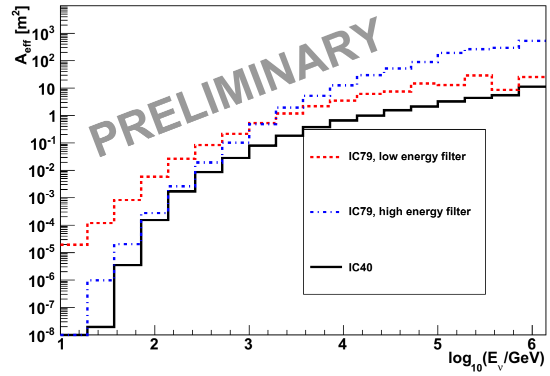

Figure 6: Effective area for IceCube–40, and the two parts of the Galactic Center filter for IceCube–79 at online filter level.

the low and high-energy filter of IceCube–79. Especially in the low energy region below 100 GeV, more events are accepted. This improvement can be attributed to the DeepCore array. If these events can be retained throughout the analysis cuts, considerable improvement is to be expected for exclusion limits on the self-annihilation cross-section in the low energy region.

7 Conclusion

Data collected with the partially instrumented IceCube neutrino detector has been searched for dark matter self-annihilation signals. Two independent analyses, targeting the Galactic halo and Galactic Center, have been performed and resulted in observations consistent with background expectations. Based on these results the dark matter self-annihilation cross section was constrained to $\sim 10^{-22}\mathrm{cm}^3\mathrm{s}^{-1}$ for WIMP masses between 200 GeV and 10 TeV for annihilation into $\tau^+\tau^-$ and $\mu^+\mu^-$. For a neutrino line spectrum $\chi\chi \rightarrow \nu\bar{\nu}$, annihilation cross sections larger than $\sim 10^{-23}\mathrm{cm}^3\mathrm{s}^{-1}$ can be excluded, assuming the NFW-profile for the Galactic Center analysis. Limits from the halo analysis are less halo-profile dependent, since the different models show similar behavior for larger distances from the Galactic Center. Despite the small dataset and less than half of the full IceCube detector, the limits already probe a region of interest. A new dedicated filter stream for neutrinos from the Galactic Center has been implemented, that led to an increase in neutrino effective area at filter level of about two orders of magnitude at energies below 100 GeV. With the IceCube detector completed and a dataset available that is already more than three times larger than the ones used for the presented analyzes, we expect to probe dark matter self-annihilation cross sections below $\sim 10^{-24}\mathrm{cm}^3\mathrm{s}^{-1}$. Further, the Galactic halo analysis is currently pursued using the DeepCore detector and the cascade channel (ν_e, ν_τ). It utilizes the excellent atmospheric muon veto capabilities with IceCube/DeepCore and lower atmospheric neutrino background in this channel. As the analysis targets a large scale anisotropy, the poor angular resolution of cascade events does not effect this analysis in a strong manner, and will allow for a further improvement in sensitivity.

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