Search for Dark Matter from the Galactic Halo with IceCube

Carsten Rott (on behalf of the IceCube Collaboration†)

Center for Cosmology and AstroParticle Physics (CCAPP), The Ohio State University, Columbus, OH 43210, USA
carott@mps.ohio-state.edu
†http://www.icecube.wisc.edu

Abstract. Neutrinos produced in dark matter self-annihilations in the Galactic halo might be detectable by IceCube. We present a search for such a signal using the IceCube detector in the 22-string configuration. We first evaluate the sensitivity before presenting the result based on the collected data. We find that even with the partially instrumented detector and a small dataset, we are able to meaningfully constrain the dark matter self-annihilation cross-section. Future analyses, based on data sets from a larger detector and the inclusion of the Galactic center, are expected to considerably improve these results.

Keywords: IceCube, Dark Matter, Halo WIMPs
PACS: 95.35.+d,98.35.Gi,95.85.Ry

INTRODUCTION

There is overwhelming observational evidence for the existence of dark matter, however its nature remains unknown. A variety of models predict suitable particle candidates [1], which typically have the properties of a weakly interacting massive particle (WIMP). Neutrino telescopes are powerful tools in the search for WIMPs and their properties. They can be used to test the WIMP-nucleon scattering cross-section similar to direct detection experiments looking for nuclear recoils. To date, IceCube has provided very stringent constraints on the spin-dependent WIMP nucleon scattering cross-section [2] for WIMPs with masses above 100 GeV by looking for neutrino signals from self-annihilating dark matter captured in the Sun. Complementary to gamma-ray measurements, neutrino telescopes can test the dark matter self-annihilation cross-section \( \langle \sigma_A v \rangle \) (Throughout this document, we consider this product of cross-section and velocity averaged over the dark matter velocity distribution), which is the topic of these proceedings.

We discuss the search for dark matter self-annihilation signals from the Galactic dark matter halo. We first estimate the sensitivity for the detection of such signals using the IceCube detector in the 22-string configuration (active during 2007-2008), then present the result on data, and comment upon future prospects.

While the result will be model independent, we have in particular sensitivity to leptophilic dark matter in the TeV mass range, which is currently the most compatible with the lepton excess observed by Fermi [3], H.E.S.S. [4], and PAMELA [5] if interpreted as originating from dark matter self-annihilations [6].
HALO PROFILES AND SIGNAL EXPECTATIONS

The expected dark matter density distribution in the Milky Way can approximately be described by spherically symmetric functions, which are motivated by fits to large scale N-body cold dark matter simulations and observational evidence. Several different distribution functions and parameterizations exist. These halo models generally show very similar behavior for large distances from the Galactic center (GC), however they differ significantly in their predictions close to it. Figure 1 compares the dark matter density profiles $\rho(r)$, as function of the distance from the Galactic center. We use the Einasto [7] profile as benchmark model, while NFW [8], Moore [9], and Kravtsov [10] are used to estimate the uncertainty due to the halo model for this analysis.

The expected neutrino flux $\phi_\nu$ from dark matter self-annihilations is proportional to the square of the dark matter density $\rho^2$ integrated along the line of sight $J(\psi)$ for a given angular distance from the Galactic center $\psi$. The differential neutrino flux for a WIMP of mass $m_\chi$ is given by [11]:

$$\frac{d\phi_\nu}{dE} = \frac{<\sigma_A v>}{2} J(\psi) \frac{R_{sc} \rho_{sc}^2}{4\pi m_\chi^2} \frac{dN_\nu}{dE}. \quad (1)$$

Here $R_{sc}$ and $\rho_{sc}$ are scaling factors [11], and $\frac{dN_\nu}{dE}$ is the differential neutrino multiplicity per annihilation.

Since the annihilation products are highly model dependent, we take a practical approach by estimating the sensitivity for several different annihilation channels assuming a branching ratio of 100% for each of them in turn. $\frac{dN_\nu}{dE}$ was obtained with DarkSUSY [12] (see Figure 1). We considered the following annihilation channels:

- $\chi\chi \rightarrow b\bar{b}$ (results in a soft neutrino spectrum)
- $\chi\chi \rightarrow W^+W^-$ and $\chi\chi \rightarrow \mu\mu$ (both result in hard neutrino spectra)
In addition we also computed the sensitivity to a line spectrum ($\chi\chi \rightarrow \nu\nu$), which is of specific interest as it can be used to set a model independent limit on the total dark matter self-annihilation cross-section [13].

**Data Selection**

We use the same data sample and selection criteria as was used in the IceCube 22-string point source search [14], but contrary to the point source analysis, which was optimized to identify point sources with an $E^{-2}$ or $E^{-3}$ spectrum above atmospheric neutrino background, this analysis looks for a large scale anisotropy. Event selection criteria have been well established, which help minimize systematic effects. The dataset provides especially good sensitivity for annihilation signals from high mass WIMPs.

The dataset covers the northern sky with 5114 neutrino candidate events collected in 275.7 days of lifetime acquired during 2007-2008. It covers the region of $-5^\circ$ to $85^\circ$ in declination, which excludes the Galactic center, located on the southern hemisphere at $266^\circ$ RA and $-29^\circ$ DEC. From the Galactic center the expected neutrino flux from annihilations would be maximum as would the uncertainties due to halo models and other potential neutrino sources might be present (source contamination). The Galactic center is addressed in a separate analysis using down-going starting events [15].

**Background Estimation and Signal Optimization**

We have used a simulation sample scaled to the total number of observed neutrino candidate events to optimize the analysis. For the final data analysis we use the data itself to estimate the background, in an effort to reduce systematic uncertainties. We only have to rely on simulation to evaluate the signal acceptance.

A neutrino flux from dark matter self-annihilations in the Galactic dark matter halo would manifest itself on the northern hemisphere through a large scale anisotropy, with the largest excess neutrino flux at the horizon and centered around the same RA as the Galactic center. To test this we divided the northern hemisphere in an on-source and off-source region (see Figure 2). While the on-source region is centered around the same RA as the GC, the off-source region is rotated by $180^\circ$ in RA. This choice is motivated by the robustness and simplicity of the analysis. The track reconstruction efficiency is a function of the zenith angle, but typically averaged out in RA. We count the total events in each region, as this makes the analysis maximally independent of halo profiles. We optimized the size of the on-source region (as function of the angular distance from the Galactic center $\Theta_{GC}$) to maximize $S/\sqrt{B}$ (see Figure 2). Here $S$ is the expected number of signal events from annihilations in the Galactic halo and $B$ are atmospheric neutrino background events. The optimal $S/\sqrt{B}$ depends on the WIMP mass and annihilation channel, but flattens out at around $\Theta_{GC} = 80^\circ$, which is chosen for this analysis. The maximum size of the on-source region is also constrained by the caveat that it should not overlap with the off-source region. The remaining part of the observed sky (transition region), which is not classified as on or off-source region, does not have a
FIGURE 2. Left: Relative expected neutrino flux from dark matter self-annihilations in the Milky Way halo on the northern celestial hemisphere. The largest flux is expected at a RA closest to the Galactic center (\(\Delta RA = 0\)). Dashed lines indicate circles around the Galactic center, while the solid lines show the definition of on and off-source region on the northern hemisphere. The on-source region is centered around \(\Delta RA = 0\), while the off-source region is rotated by 180° in RA. Right: Optimization of the signal region as function of the distance from the Galactic center \(\Theta_{GC}\)

significant expected signal flux (compared to the on-source region) and can be used for cross-checks.

HALO SENSITIVITY

The sensitivity for \(\langle \sigma_A v \rangle\) was determined. Our atmospheric neutrino simulations predicted a Poisson distributed 1255 background events in the equal shaped on and off-source regions. The expected difference in events between the regions for the 'background-only' hypothesis is \(\langle \Delta N \rangle = \langle N_{on} \rangle - \langle N_{off} \rangle = 0\) with an error given by \(\sigma_{\Delta N} = \sqrt{2 \langle N_{off} \rangle}\). The expected limit (at 90% C.L.) on the difference in number of events is \(\Delta N_{90} = 65\). To convert \(\Delta N_{90}\) into an expected self-annihilation cross-section limit requires accounting for the possible presence of signal in the off-source region.

\[
\Delta N = N_{on} - N_{off} = (N_{on}(bkg) + (N_{on}(sig)) - (N_{off}(bkg) + (N_{off}(sig))) \tag{2}
\]

The amount of signal events in each direction depends directly on \(J(\psi)\), which would cause the difference between on and off-source regions.

The signal expectation in both regions scales with \(\langle \sigma_A v \rangle\). The difference in the expected number of neutrino events between the on and off source region is given by \(\Delta N_{sig} = N_{on}(sig) - N_{off}(sig)\). For a given cross-section \(\langle \sigma_A v \rangle_0\) it is determined from simulations. For all other cross-sections the expected number is then given by:

\[
\Delta N_{sig}(\langle \sigma_A v \rangle) = \frac{\langle \sigma_A v \rangle}{\langle \sigma_A v \rangle_0}(N_{on,sig}(\langle \sigma_A v \rangle_0) - N_{off,sig}(\langle \sigma_A v \rangle_0)) \tag{3}
\]
FIGURE 3. IceCube’s sensitivity to the self-annihilation cross-section \( \langle \sigma_A v \rangle \) as function of the WIMP mass \( m_\chi \), compared to theoretical and derived limits. The red areas labeled “Milky Way Halo Angular”, “Average”, “Isotropic”, respectively, are derived constraints [11] from the observed atmospheric neutrino energy spectrum (SuperK, Frejus, AMANDA) assuming the WIMP annihilates into neutrinos with a 100% branching ratio. The green region (“Natural scale”) is for dark matter candidates consistent with being a thermal relic. The white solid lines are the unitarity bound (right) and the cross-section for which annihilation flattens the cusps of the halo (left). The yellow dashed line is an estimate for a limit from cosmic neutrino observations [13]. The blue broad lines are the IceCube expected average upper limits for 22-string detector data for different annihilation channels. The central black line is for the Einasto profile (NFW is almost identical), while the width is given by the results for the Moore and Kravtsov profile.

Therefore the cross-section sensitivity at 90% C.L. is given by \( \langle \sigma_A v \rangle_{90} = \Delta N_{90} \times \frac{\langle \sigma_A v \rangle}{\Delta N_{sig}(\langle \sigma_A v \rangle)} \). Under the background only assumption we obtain IceCube’s sensitivity for \( \langle \sigma_A v \rangle \) as shown in Figure 3 as function of the WIMP mass and annihilation channel.

SYSTEMATIC UNCERTAINTIES

We have performed a preliminary study of the systematic uncertainties associated with the background estimation and signal acceptance. By design, the comparison of events in the on and off-source regions enables the determination of the background from the data itself, which allows for most systematic effects associated with understanding the detector to cancel out. The remaining systematic uncertainties on the background are due to a possible large scale anisotropy of the measured data. This could be caused by variations in the exposure for different right ascensions, or by an existing anisotropy in the cosmic ray flux, which translates into the atmospheric muon neutrino flux. These two effects are expected to dominate the systematic uncertainty on the background estimation.

The TIBET air shower array has observed an anisotropy in the cosmic ray flux in the northern hemisphere [16], which is also present on the southern hemisphere, as observed by IceCube in the down-going muon flux [17]. For cosmic ray energies of about 50 TeV,
which are most relevant in contributing to the background atmospheric muon neutrino flux of this analysis, the scale of the overall anisotropy is about 0.2%. In the worst case if the anisotropy is aligned so that it peaks in one region and is minimal in the other one, this effect could contribute a difference of three events between on and off-source regions. The effect on the sensitivity is estimated to be less than 4%.

The track reconstruction efficiency varies as function of the azimuth angle. This variation in detector coordinates is typically averaged out in RA, however the usage of a geo-synchronous satellite for communication with the South Pole introduces a slight bias in the sidereal time when maintenance runs are performed. The choice of symmetric on and off-source regions rotated by 180° in RA, reduces this effect significantly as the track reconstruction efficiency is almost identical to the case where the detector is rotated by $\pi$. The total expected variation in events is comparable to the cosmic ray anisotropy effect. A correction for this effect is possible, however was not used as one would still end up with a comparable uncertainty on an azimuth angle dependent scale factor.

The systematic uncertainty on the signal acceptance is dominated by the DOM efficiency, ice properties, and a discrepancy between simulations and data for nearly horizontal events, which was observed in the point source analysis. This discrepancy could be related to the DOM efficiency and ice properties and is under further investigation.

RESULT ON DATA

After the described signal optimization and sensitivity study on simulation, we have performed the analysis on data collected during 2007-2008 with the IceCube 22-string configuration. This was done in a blind manner, meaning that we only looked at the data once the selection criteria and analysis procedure were finalized.

![Figure 4](image)

FIGURE 4. The distribution of the neutrino candidate events in the on (red) and off (black) source region. We have rotated the on-source region in 60° steps to be centered at $\Delta RA + \delta$, to check that there is no systematic effect present. Note that bins 4-6 are the inverse of bins 1-3.

1 The track reconstruction efficiency variation is present in the partially instrumented 22-string detector. It becomes more uniform for the full IceCube detector.
FIGURE 5. Left: Confidence belt for a background expectation of 1389 events. Based on an observation of 1367 events $\Delta N_{90}$ is determined to be 46. Right: Preliminary 90% C.L. exclusion limit (no systematics included). Shown are theoretical bounds and the bound derived from this analysis for a given annihilation channel: soft, hard, line (in order top to bottom). The central black line is for the Einasto profile, while the width is given by the results for the Moore and Kravtsov profile.

In data we observed 1367 events in the on-source region, while the off-source region contains $N_{\text{off}} = 1389$. Figure 4 shows the distribution of these neutrino candidate events. The number of observed events are consistent with each other and we have computed a 90% C.L. limit, by constructing the confidence interval through Monte Carlo. The number of observed events in the off-source region is our best guess on the background. We scan a wide range of possible outcomes and calculate the intervals that would contain the signal with 90% C.L. Figure 5 shows the confidence interval and the preliminary exclusion limit obtained.

To check for any possible systematic effect in the analysis, we have rotated the on and off-source region in 60° steps. For all the bins, no effect was observed, i.e. the ratio of $N_{\text{on}}/N_{\text{off}}$ is consistent with one (see Figure 4).

CONCLUSIONS AND DISCUSSIONS

We have evaluated IceCube’s sensitivity towards the detection of neutrinos from dark matter self-annihilations in the Galactic dark matter halo by searching for a large scale anisotropy on the northern hemisphere. Using data collected during 2007-2008 with IceCube in the 22-string configuration, we have not observed any such anisotropy. With the performed analysis we were able to place relevant constraints on the dark matter self-annihilation cross-section $\langle \sigma_A v \rangle$ at 90% C.L. for WIMPs in the mass the range from a few hundred GeV to several TeV. Such an analysis has previously not been performed with AMANDA or IceCube and $\langle \sigma_A v \rangle$ has only been constrained through theory or theoretical derived limits.
IceCube’s reach can be significantly improved by looking at the Galactic center, which will be possible beginning with the IceCube 40-string dataset, by using neutrinos interacting inside the detector volume. While such an analysis will be able to put significantly better constraints, a large scale anisotropy would provide a more distinct discovery signal.

ACKNOWLEDGMENTS

We thank John Beacom, Shunsaku Horiuchi, and Matt Kistler for valuable discussions. We acknowledge the support from the following agencies: U.S. National Science Foundation-Office of Polar Program, U.S. National Science Foundation-Physics Division, University of Wisconsin Alumni Research Foundation, U.S. Department of Energy, and National Energy Research Scientific Computing Center, the Louisiana Optical Network Initiative (LONI) grid computing resources; Swedish Research Council, Swedish Polar Research Secretariat, and Knut and Alice Wallenberg Foundation, Sweden; German Ministry for Education and Research and Education (DFG), Deutsche Forschungsgemeinschaft (DFG), Research Department of Plasmas with Complex Interactions (Bochum), Germany; Fund for Scientific Research (FNRS-FWO), FWO Odysseus programme, Flanders Institute to encourage scientific and technological research in industry (IWT), Belgian Federal Science Policy Office (Belspo); Marsden Fund, New Zealand.

REFERENCES

1. G. Bertone, D. Hooper, and J. Silk, *Phys. Rept.* **405**, 279–390 (2005), [hep-ph/0404175](https://arxiv.org/abs/hep-ph/0404175).
2. R. Abbasi, et al., *Phys. Rev. Lett.* **102**, 201302 (2009), [arXiv:0902.2460](https://arxiv.org/abs/0902.2460).
3. A. A. Abdo, et al., *Phys. Rev. Lett.* **102**, 181101 (2009), [arXiv:0905.0025](https://arxiv.org/abs/0905.0025).
4. H. E. S. C. F. Aharonyan (2009), [arXiv:0905.0105](https://arxiv.org/abs/0905.0105).
5. O. Adriani, et al., *Nature* **458**, 607–609 (2009), [arXiv:0810.4995](https://arxiv.org/abs/0810.4995).
6. P. Meade, M. Papucci, A. Strumia, and T. Volansky (2009), [arXiv:0905.0480](https://arxiv.org/abs/0905.0480).
7. J. Einasto, *Trudy Inst. Astrofiz.* Alma-Ata **5**, 87 (1965).
8. J. F. Navarro, C. S. Frenk, and S. D. M. White, *Astrophys. J.* **462**, 563–575 (1996), [astro-ph/9508025](https://arxiv.org/abs/astro-ph/9508025).
9. B. Moore, T. R. Quinn, F. Governato, J. Stadel, and G. Lake, *Mon. Not. Roy. Astron. Soc.* **310**, 1147–1152 (1999), [astro-ph/9903164](https://arxiv.org/abs/astro-ph/9903164).
10. A. V. Kravtsov, A. A. Klypin, J. S. Bullock, and J. R. Primack, *Astrophys. J.* **502**, 48 (1998), [astro-ph/9708176](https://arxiv.org/abs/astro-ph/9708176).
11. H. Yuksel, S. Horiuchi, J. F. Beacom, and S. Ando, *Phys. Rev.* **D76**, 123506 (2007), [arXiv:0707.0196](https://arxiv.org/abs/0707.0196).
12. P. Gondolo, et al., *JCAP* **0407**, 008 (2004), [astro-ph/0406204](https://arxiv.org/abs/astro-ph/0406204).
13. G. D. Mack, T. D. Jacques, J. F. Beacom, N. F. Bell, and H. Yuksel, *Phys. Rev.* **D78**, 063542 (2008), [arXiv:0805.0167](https://arxiv.org/abs/0805.0167).
14. R. Abbasi, et al., *Astrophys. J.* **701**, L47–L51 (2009), [arXiv:0905.2253](https://arxiv.org/abs/0905.2253).
15. S. Euler, D. Grant, and O. Schulz, *Proc. 31st ICRC OG2.5* (2009).
16. M. Amenomori, *Science* **314**, 439–443 (2006), [astro-ph/0610671](https://arxiv.org/abs/astro-ph/0610671).
17. R. Abbasi, *these proceedings* (2009).