Search strategies for Dark Matter in nearby Dwarf Spheroidal Galaxies with IceCube

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

DOI: 10.7529/ICRC2011/V05/1024

Abstract: Dwarf spheroidal galaxies are believed to contain a large fraction of dark matter due to their high mass-to-light ratio and are therefore promising targets for dark matter searches. They have been investigated by Imaging Air Cherenkov Telescopes and gamma-ray satellites, for which they are excellent targets due to a small field of view and uncomplicated backgrounds. Complementary to such searches, annihilations of WIMPs are also expected to result in neutrino signals that could be detected by the cubic kilometer scale neutrino telescope IceCube. The signal sensitivity can be increased by stacking known dwarf galaxies with the highest flux expectations. We discuss the prospects of the first analysis looking for dark matter in spheroidal galaxies in the northern sky with IceCube, using data taken during 2009 with the 59-string detector configuration.

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Keywords: IceCube, neutrino astronomy, WIMP annihilation, dwarf galaxies

1 Introduction

The observational evidence for the existence of dark matter, from galactic to cosmological scales, is strong. However, its underlying nature remains unknown. A variety of theories provide candidate particles for cold dark matter [1]. Supersymmetry and Extra Dimensions predict new particles with masses around the electro-weak scale, including a stable or long lived weakly interacting massive particle (WIMP) [1, 2]. Such WIMPs form ideal dark matter candidates, whose masses are predicted to be in a range between a few tens of GeV to several TeV.

A variety of standard model messenger particles (including high energy neutrinos) are expected to be produced as a result of the self-annihilation or decay of WIMPs. The neutrinos can be detected by high energy neutrino telescopes, while gamma-rays can be probed with ground based (e.g. H.E.S.S [3]) and space based (e.g. FERMI [4]) telescopes. Electron positron fluxes are sensitive to dark matter annihilations in the vicinity of the Sun (≤ 1 kpc) and have so far resulted in inconclusive results (e.g. PAMELA [5]). The dark matter self-annihilation cross section can be probed by looking for neutrino signals from the Galactic Center, Galactic halo [6] or dwarf galaxies.

In this paper we discuss the first IceCube search for neutrino signals produced by annihilating dark matter in dwarf galaxies surrounding the Milky Way. These objects are attractive targets for such searches because of their close proximity, relatively compact nature, and their large fraction of dark matter. The search will be used to probe the self-annihilation cross section by constraining the product of cross section and velocity averaged over the dark matter velocity distribution, $\langle\sigma v\rangle$, to probe the lifetime, τ, and to make comparison with recent measurements performed by the FERMI collaboration. Sensitivities will be given for a set of selected benchmark annihilation

2 Neutrino detection with IceCube

The IceCube Neutrino Observatory [7], located at the geographic South Pole, consists of the IceCube neutrino telescope and the IceTop air shower array. In the ice, a volume of one cubic kilometer of antarctic ice is instrumented with 5160 digital optical modules (DOMs) deployed at depths between 1450 m and 2450 m. The DOMs are distributed over 86 electrical cable bundles that handle power transmission and communication with electronics located on the surface. Each DOM consists of a 25 cm Hamamatsu R7081-02 photomultiplier tube connected to a waveform recording data acquisition circuit.

IceCube is sensitive to all flavors of neutrinos through Cherenkov light emission from secondary particles created when a neutrino interacts in the ice. Muon neutrinos are of particular interest since their extended track-like signature makes them relatively simple to identify and to reconstruct their direction with a few degrees precision at the detection

Source	Right asc.	Declination	Distance (kpc)	Mass ($10^7 M_\odot$)	$J(10^{19} GeV^2/cm^5)$
Segue 1	10 07 04	+16 04 55	25	1.58	$1.26^{+3.75}_{-0.94}$
Ursa Major II	08 51 30.0	+63 07 48	32	1.09	$0.58^{+0.91}_{-0.35}$
Willman 1	10 49 22.3	+51 03 04	38	0.77	
Coma Berenices	12 26 59	+23 55 09	44	0.72	$0.16^{+0.22}_{-0.08}$
Ursa Minor	15 09 08.5	+67 13 21	66	1.79	$0.64^{+0.25}_{-0.18}$
Draco	17 20 12.4	+57 54 55	80	1.87	$1.2^{+0.31}_{-0.25}$
Ursa Major I	10 34 52.8	+51 55 12	106	1.1	
Hercules	16 31 02	+12 47 30	138	0.72	
Canes Venatici II	12 57 10	+34 19 15	151	0.7	
Leo II	11 13 29.2	+22 09 17	205	1.43	
Canes Venatici I	13 28 03.5	+33 33 21	224	1.4	
Leo I	10 08 27.4	+12 18 27	250	1.45	
Leo T	09 34 53.4	+17 03 50	417	1.3	

Table 1: List of dwarf spheroidal galaxies ordered by distance from the Earth [14]. J values from [8] and for Segue 1 from [15]. The integral in Eq. 2 is performed over a circle of $0.25°$ radius for Segue 1 and $0.5°$ for the other sources.

threshold of 50 GeV. This analysis is based on data taken from May 2009 to May 2010 with an intermediate construction stage of the in-ice detector with 3540 DOMs on 59 strings monitoring $\sim 2/3$ of a Gton of antarctic ice. The trigger rate in this configuration is between ~ 1600 Hz and ~ 1900 Hz and reflects the seasonal modulation of muons produced in cosmic air showers. In future analyses, the denser low energy extension DeepCore, finalized in 2010, will considerably improve the detection of muons with energies below a few hundred GeV. It will also provide sensitivity to celestial objects in the South by employing the veto capacity of the surrounding IceCube strings.

The primary background in the search for neutrinos originates from cosmic ray hadronic air showers produced in the Earth's upper atmosphere. The decay of pions and kaons results in a continuous stream of neutrinos and muons. High energy muons are capable of travelling long distances through matter before they eventually decay, resulting in a down-going muon flux at the IceCube detector. We therefore restrict ourselves to dwarf galaxies in the northern hemisphere, using the Earth as a shield.

This paper discusses a sensitivity study of WIMP annihilation in dwarf galaxies. One of the appeals of this analysis is the ability to perform a direct comparison with the search for photons originating in a similar set of dwarf galaxies. We therefore follow the procedures outlined in a recent publication by the FERMI collaboration which set flux limits on several dwarf galaxies [8] and presented a preliminary stacking analysis [9].

3 Dwarf galaxies target selection

The number of identified dwarf galaxies has risen in recent years due to a systematic search by the SLOAN Digital Sky Survey (SDSS) [10, 11]. Table 1 lists galaxies in the Northern hemisphere that are accessible to IceCube in the up-going neutrino event sample. The expected neutrino flux from annihilating dark matter is [12]

$$\frac{d\Phi(\Delta\Omega, E)}{dE} = \frac{\langle\sigma v\rangle}{8\pi m_\chi^2}\frac{dN}{dE}J(\Delta\Omega), \qquad (1)$$

where m_χ denotes the WIMP mass and $\frac{dN}{dE}$ the energy spectrum of the produced neutrinos per annihilation. The "J factor" is the line-of-sight integral of the squared dark matter density:

$$J(\Delta\Omega) = \int_{\Delta\Omega} d\Omega \int_{l.o.s.} \rho_\chi^2(s)ds. \qquad (2)$$

Note that this factor is highly dependent on the assumed dark matter distribution as the annihilation is proportional to the square of the dark matter density ρ_χ. For this paper we assume the commonly used Navarro-Frenk-White (NFW) [13] profile to describe the dark matter density distribution.

4 Analysis procedure

In order to cover a large range of possible WIMP signatures, we study WIMP masses in the 0.3–10.0 TeV range and assume a few selected benchmark annihilation channels: $\chi\chi \rightarrow \mu^+\mu^-$, $\tau^+\tau^-$, W^+W^-, $b\bar{b}$, and $\nu\bar{\nu}$. Neutrinos will have undergone extensive mixing through vacuum oscillations over the distances travelled from the dwarf galaxies to the Earth. We determine neutrino flavor oscillations in the long baseline limit. The Monte Carlo results and selection efficiencies are obtained by reweighting the Monte Carlo sample with the expected muon energy distributions for the WIMP masses and annihilation channels studied.

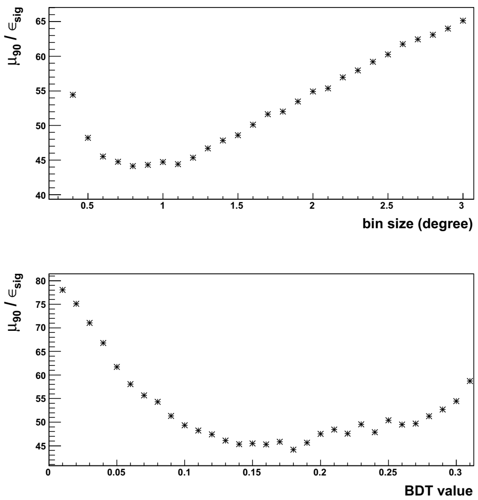

Figure 1: Optimization of selection parameter for Segue 1 and 1 TeV WIMPs annihilating to $\tau^+\tau^-$. Upper plot: Signal mean upper limit (μ_{90}) divided by signal efficiency ($\epsilon_{\rm sig}$) versus bin size at an optimal cut value of 0.18. Lower plot: Signal mean upper limit divided by signal efficiency versus cut value at an optimal bin size of 0.8°.

5 Event selection and sensitivity determination for individual sources

A pre-selection at the South Pole for up-going reconstructed muon tracks and two further likelihood reconstruction and filtering steps reduces the data rate to ~ 2 Hz. We select events with reconstructed arrival direction 9 degrees below the horizon, as the lowest dwarf galaxy in the North is Leo I at a declination of $12°18'27''$. At this selection cut level the data samples are still dominated by atmospheric muons that are misreconstructed. The sample is then separated into one branch for each WIMP mass and annihilation channel. The event selection is optimized for the expected muon neutrino fluxes obtained with DarkSUSY [16]. Using the Multivariate Analysis package of ROOT (TMVA) several Boosted Decision Trees (BDTs) are trained on simulated signal and background samples, where the signal is weighted to the according energy spectrum for each Tree. The input variables include the likelihood of the track reconstruction, the angular difference between different reconstruction methods, an estimator for the individual angular resolution and the likelihood difference to a reconstruction that is forced to be down-going.

Given the ~ 1 degree angular resolution of IceCube, the dwarf galaxies can be considered point-like. For each WIMP annihilation channel and dwarf galaxy, the event variable cuts and the circular area around the source location are optimized for the most stringent mean upper limit assuming no signal divided by the signal efficiency with respect to the pre-selection. Figure 1 shows the optimization

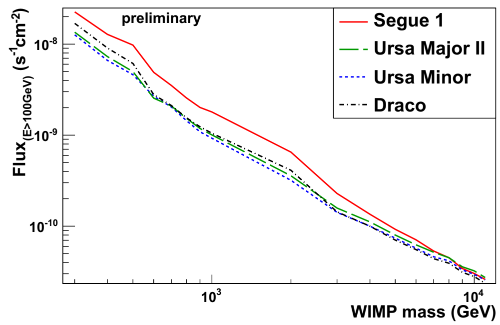

Figure 2: Expected mean upper limit on the neutrino flux versus WIMP mass for different dwarf spheroidals. Values for the $\tau^+\tau^-$ annihilation channel are shown.

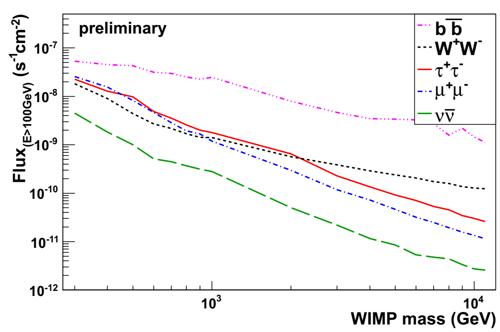

Figure 3: Expected mean upper limit on the neutrino flux versus WIMP mass for different annihilation channels. Values for Segue 1 are shown.

for WIMPs of 1 TeV and assuming self-annihilations into $\tau^+\tau^-$. The background is estimated from a zenith band of $\pm 2.5°$ around the source position. A Feldman-Cousins confidence interval construction [17] is used for the determination of the upper limit. From the corresponding flux a sensitivity for the WIMP annihilation cross section can be derived by using Eq. 1. The average upper limit on the cross section is shown in figure 4.

Figure 2 and 3 show the expected average upper limit on the neutrino flux as function of WIMP mass for different dwarf galaxies and annihilation channels, respectivly. The limits are based on an integrated lifetime of 334.5 days of data-taking with the 59-string detector configuration of IceCube.

6 Source stacking

The sensitivity can be improved by analyzing multiple sources simultaneously, a method called source stacking. A prerequisite of this technique is that the flux from all targets

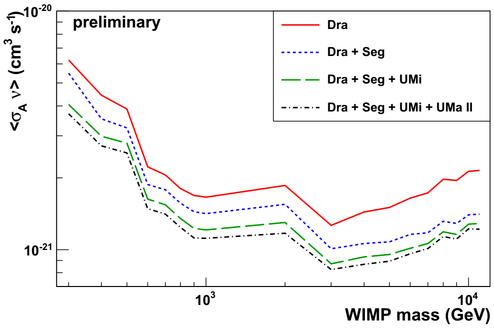

Figure 4: IceCube sensitivities for different number of stacked sources for one year of data in the $\tau^+\tau^-$ channel as function of the WIMP mass.

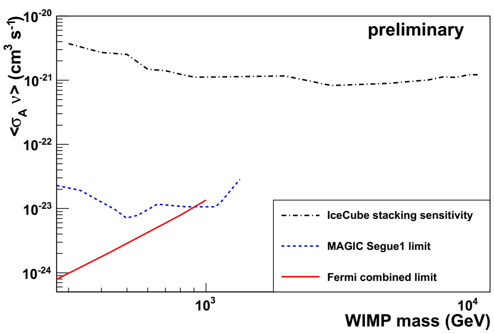

Figure 5: IceCube sensitivity (expected mean upper limit) for one year of data in the $\tau^+\tau^-$ channel as function of the WIMP mass. The sensitivity of the stacking analysis (Draco, Segue, Ursa Minor and Ursa Major II) is compared to results from MAGIC [18] and a preliminary combined limit from Fermi observations of 10 Dwarf Galaxies [9]

differs only in normalization. This is clearly the case for the WIMP annihilation signal of dwarf galaxies. Adding more sources to the analysis lets the signal grow linearly while the background grows proportionally to $\sqrt{N}$. Figure 4 shows how the sensitivity on the annihilation cross section in the $\tau^+\tau^-$ channel improves while increasing the number of stacked sources. In Figure 5 we compare the IceCube sensitivity for four stacked sources assuming dark matter annihilation into $\tau^+\tau^-$, compared to results from MAGIC [18] and a preliminary combined limit from Fermi observations of 10 dwarf galaxies [9].

7 Conclusion

We have presented sensitivities for IceCube in the 59-string configuration for the observation of neutrino signals from self-annihilating dark matter in dwarf spheroidal galaxies on the northern hemisphere. Sensitivities for the dark matter self-annihilation cross section are better than $10^{-20}\text{cm}^3\text{s}^{-1}$, for WIMP masses in a range of 300 GeV to several TeV. Searches are complementary to γ-ray observation in most channels, but have the advantage that IceCube data of these sources is collected continuously and extend to higher WIMP masses. The now operational full IceCube detector will be able to improve the sensitivity to dwarf speroidals further.

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