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Combined Search for Neutrinos from Dark Matter Annihilation in the Galactic Center using IceCube and ANTARES

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Neutrino telescopes have searched for self-annihilating dark matter in the Galactic Halo and placed stern limits on the dark matter self-annihilation cross section $\langle \sigma v \rangle$ for dark matter particle masses above 30 TeV. To date, the most stringent limit were obtained by the ANTARES neutrino telescope looking at the Galactic Center region for masses > 100 GeV/c^2 and is closely followed by the limits of the IceCube experiment at lower masses. In this contribution, we present the sensitivities of a future combined search for dark matter in the Milky Way using data from both experiments. From the IceCube experiment, data from 2012 to 2015 with the complete 86-strings detector were selected, while from ANTARES the data sample collected from 2007 to 2015 have been used. The analysis considered dark matter with particle masses ranging from 50 to 1000 GeV/c^2. We used the annihilation into $\tau\bar{\tau}$ as a benchmark to explore the potential gain by combining the two experiments using a common likelihood framework.

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1. Introduction

Astrophysical observations provide strong evidence for the existence of dark matter in the Universe, however its nature remains unknown. One of the most popular hypotheses for dark matter is that it is made up of non-baryonic particles called WIMP that are non-relativistic, electromagnetically neutral and interacting only via a weak interaction. According to observational evidence, the galaxies are embedded in a halo of thermal relic density of dark matter from the early Universe. The high density of dark matter particles at the center of galaxies, for example in our Milky Way, can contribute to the annihilation of WIMPs producing secondary particles such as high energy neutrinos.

Limits on WIMP dark matter annihilation cross-section have already been set by neutrino detectors such as IceCube [1] and ANTARES [2]. The purpose of this analysis is to combine the data of the two neutrino detectors in the form of probability density function of the two neutrino detectors for the search of neutrinos from dark matter annihilation in the Galactic Center (GC). Another goal of this work is to understand the differences in the approaches taken by Antares and IceCube for this kind of analysis.

2. The IceCube and ANTARES neutrino telescopes

Deep under-water/ice neutrino telescopes follow a similar detection principle. Given the low interaction cross-section of neutrinos, a large volume of target material is required which is achieved by placing a sparse array of photodetectors in deep, dark, and transparent environments such as the sea or the Antarctic ice. The photodetectors will record the Cherenkov emission induced by the secondary particles produced in the deep-inelastic scattering (DIS) interaction of a neutrino with a nucleon of the surrounding medium. The main objective of neutrino telescopes is the detection of astrophysical neutrinos produced close to the cosmic ray sources. However, given the versatility of these experiments they can be used to search for dark matter signatures in an indirect fashion.

The main background contribution of neutrino telescopes comes from atmospheric muons and atmospheric neutrinos. These particles are produced by the interaction of cosmic rays with the higher layers of our atmosphere. Atmospheric muons trigger the detectors more than 6 orders of magnitude more often than atmospheric neutrinos. For up-going directions, the Earth acts as a shield against atmospheric muons. As a consequence, declination corresponding to angles between $0^\circ - 90^\circ$ are less background dominated in the IceCube detector. For ANTARES, declination below -47° are less background dominated since they are always below the horizon of the detector. Declination between -47° and 47° are below the horizon for part of the sidereal day.

2.1 IceCube

IceCube is a cubic-kilometer neutrino observatory located at the South Pole [3] between depths of 1,450 m and 2,450 m and was completed in 2010. The IceCube observatory consists of an array of 5,160 digital optical modules (DOMs) attached to vertical strings placed in 86 boreholes. The reconstruction of the direction, energy and flavor of the neutrinos relies on the optical detection of Cherenkov radiation emitted by charged particles produced in the interactions of neutrinos in the surrounding ice or the nearby bedrock. In the center of the detector, eight strings are deployed in a more compact way, forming the DeepCore subdetector. This denser configuration extends the detection of neutrinos to energies below 100 GeV.

For this analysis, we use the IceCube data selection developed in the course of the Galactic Center WIMP search analysis [4]. This data sample consists of 1007 days of track-like events compatible with ν_μ signatures taken with the 86-strings configuration from the 15th of May 2012 to 18th of May 2015. Being located at the South Pole, IceCube observes the Galactic Center in the Southern Hemisphere where the background is dominated by atmospheric muons. The selection uses a veto-technique to reduce the level of atmospheric muons by seven orders of magnitude. Details of the event selection can be found in [4]. The total number of events in our sample is 22,553 events.

2.2 ANTARES

The ANTARES telescope is an underwater Cherenkov detector located in the Mediterranean sea, about 40 km from Toulon at depth of roughly 2500 m [5]. ANTARES is a smaller array consisting of 885 optical modules (OM) placed along 12 lines of 350 meters each, spread over a surface of 0.1 km^2 on the seabed and kept vertical by buoys located at their top. In this work, we consider a data sample corresponding to a total lifetime of 2101.6 days, which corresponds to the actual ANTARES uptime from 2007 to 2015 [6]. The ANTARES detector uses two different reconstruction algorithms depending on the deposited energy of the events: a single line reconstruction for events below 100 GeV and multi-line reconstruction for energies over 100 GeV. The total number of events in this sample is 595 events. Despite its smaller scale compared to IceCube, ANTARES has a privileged view of the Galactic Center as it can use the Earth to block the main contribution of the atmospheric background and therefore no veto is necessary.

3. Dark Matter Annihilation Flux

The expected neutrino flux to be observed in neutrino telescopes from dark matter annihilation is given by [7]

$$\frac{\mathrm{d}\phi_\nu(\Psi)}{\mathrm{d}A\,\mathrm{d}\Omega\,\mathrm{d}t\,\mathrm{d}E} = \frac{\langle\sigma_A v\rangle}{2}\,\frac{J_a(\Psi)}{4\pi m_\chi^2}\,\frac{\mathrm{d}N_\nu}{\mathrm{d}E}\ , \tag{3.1}$$

where m_χ is the mass of the WIMP, $\langle\sigma_A v\rangle$ is the WIMPs thermally-averaged annihilation cross-section and $\mathrm{d}N_\nu/\mathrm{d}E$ is the neutrino energy spectrum per annihilating WIMP pair. $J_a(\Psi)$ is the integrated J-factor defined as the integral of the squared dark matter density along the line-of-sight

$$J_a(\Psi) = \int_0^{l_{max}} \rho_\chi^2\left(\sqrt{R_{sc}^2 - 2\,l\,R_{sc}\,cos(\Psi) + l^2}\right)\mathrm{d}l\ , \tag{3.2}$$

where Ψ denotes the opening angle to the Galactic Center, R_{sc} is the radius of the solar circle ($R_s \simeq 8.5$ kpc), and ρ_χ is the dark matter density profile. The quantity l is the distance along the line-of-sight and the upper integration limit l_{max} is a quantity which depends on the radius of the Galactic Halo R_{halo} and can be expressed as

$$l_{max} = \sqrt{R_{halo}^2 - sin^2\Psi R_{sc}^2} + R_{sc}\, cos\Psi \ . \tag{3.3}$$

The radius of the Galactic Halo is chosen to be the radius of the Milky Way $R_{halo} = 50$ kpc and Ψ is the angular distance from the Galactic Center. For this analysis, we used the Navarro-Frenk-White (NFW) dark matter profile

$$\rho_\chi(r) = \frac{\rho_0}{\frac{r}{r_s}(1+\frac{r}{r_s})^2} \ , \tag{3.4}$$

where the parameters to model the matter distribution in the Milky Way are defined in [8], with r_s being the scale radius and ρ_0 the characteristic dark matter density. From these ingredients, it is possible to derive the astrophysical J-factor as a function of Ψ, which is shown in fig. 1 (left).

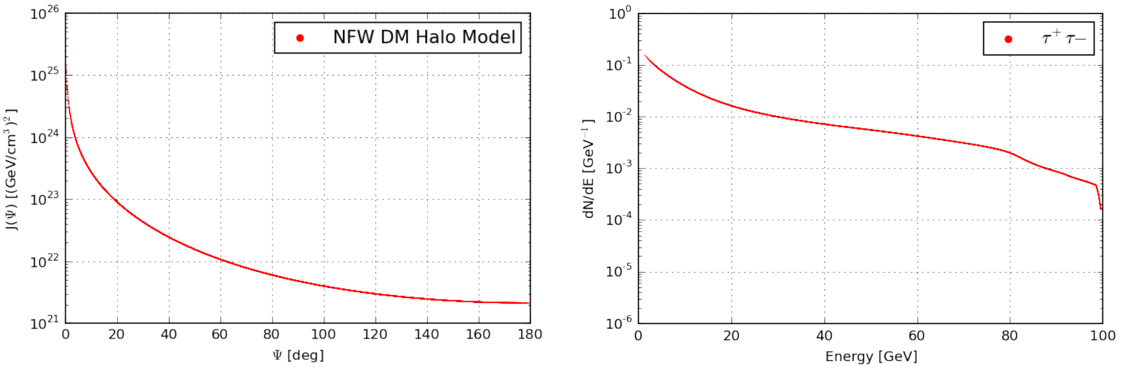

Figure 1: Left: J-factor as a function of the opening angle Ψ calculated for the NFW halo model with the parametrisation found in [8]. **Right :** Neutrino energy spectrum at Earth for the annihilation of WIMP particle of 100 GeV/c^2 mass with ν_μ in the final state through the $\tau\bar{\tau}$ annihilation channels.

In the following paragraphs, we will focus on the decay of WIMP particles via the $\tau\bar{\tau}$ annihilation channel as a benchmark of the analysis for WIMP masses ranging from 50 GeV/c^2 to 1000 GeV/c^2 where the sensitivity of both experiments is comparable. At higher masses, the ANTARES telescope dominates since the effective volume scales with the range of the resulting muon, while the veto-technique of IceCube is beneficial at lower masses. A 100% branching ratio into the $\tau^+\tau^-$ decay channel is assumed. The average neutrino spectra per annihilation process (dN/dE) for these masses and $\tau^+\tau^-$ decay channel were computed using PYTHIA simulation package [9] and are shown in Fig.1 (right).

4. Analysis Method

A binned maximum likelihood method with the two-component mixture model is performed for all annihilation channels assuming WIMP masses ranging from 50 to 1000 GeV/c^2. The first step is to determine the probability density functions (PDFs) of the signal as well as of the background for each experiment. For IceCube, the PDFs used consist of 2-dimensional distributions in right ascension and declination. IceCube PDFs use 12 bins for a band covering [-2, 2] radians in declination and 10 bins in the full range of right ascension [-2π, 2π] (see Fig.2). As already mentioned, at low masses ANTARES only reconstructs events using single-line events where the azimuth estimate is not possible. For WIMP masses between 500 and 1000 GeV/c^2, the multiline reconstruction was used. In both case, PDFs are 1-dimensional distributions of the opening angle Ψ with respect to the Galactic Center (see Fig. 3). The idea of the likelihood analysis is to compare the data to the shapes of the expected signal and the background.

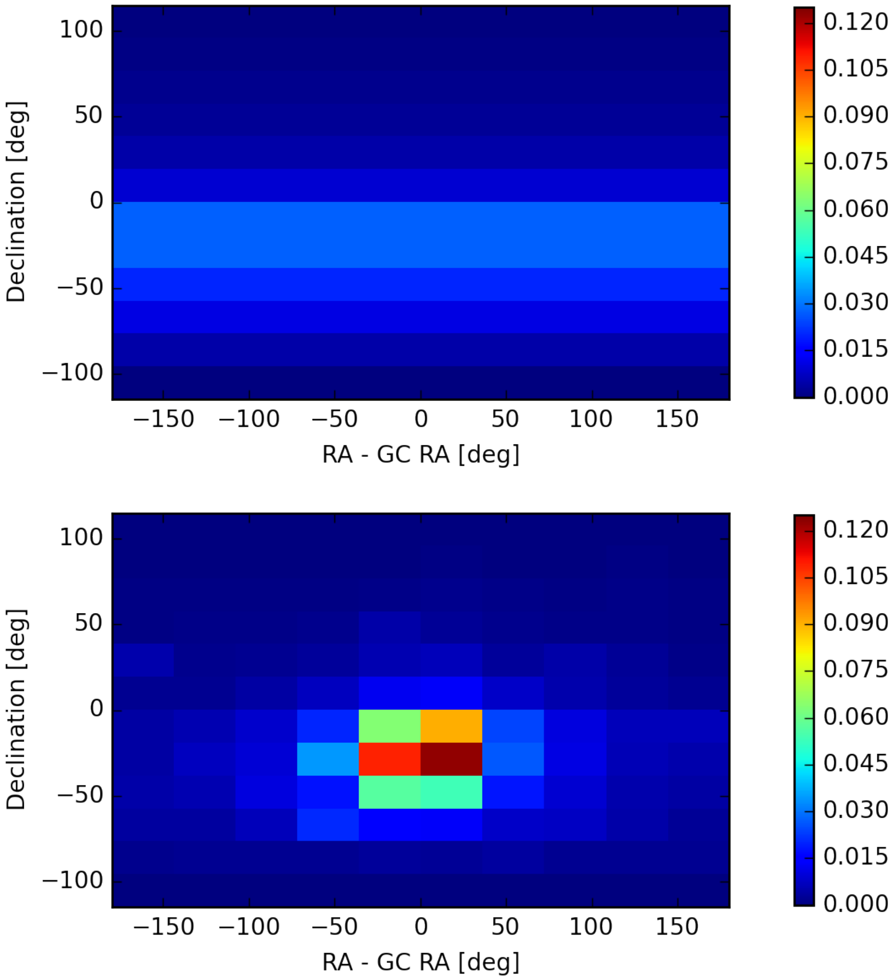

Figure 2: Top: Normalized background PDF of the IceCube sample. Bottom: Normalized signal PDF for the annihilation of 100 GeV/c^2 WIMP particle into the $\tau^+\tau^-$ channel.

The binned likelihood method used in this analysis is defined as

$$\mathscr{L}(\mu) = \prod_{bin_i=bin_{min}}^{bin_{max}} \text{Poisson}\left(n_{obs}(bin_i)|n_{obs}^{tot} f(bin_i|\mu)\right) , \tag{4.1}$$

where the parameter to minimize, μ, is the ratio of the number of signal events over the total number of background events in the sample n_{obs}^{tot}. The method compares the observed number of events in a given bin i, $n_{obs}(bin_i)$, with the expectations, n_{obs}^{tot}, $f(bin_i|\mu)$, where

$$f(bin_i|\mu) = \mu\, f_s(bin_i) + (1-\mu)\, f_{bg}\ , \tag{4.2}$$

is the fraction of events in the bin i, with f_s and f_{bg} being the signal and the background density distributions shown in Fig. 2 and Fig. 3. In the case of a combined analysis, two likelihoods are combined in a single $\mathscr{L}_{comb}(\mu)$ defined as

$$\mathscr{L}_{comb}(\mu) = \prod_{k=0}^{2} \mathscr{L}_k(\mu_k)\ , \tag{4.3}$$

where $k = 0$ represents the ANTARES likelihood and $k = 1$ the IceCube likelihood. Each detector has a signal to background ratio given by $\mu_k = w_k\mu$ where the weight w_k is calculated by taking into account the relative expected number of signal events in each detector, and the relative number of background events in each sample.

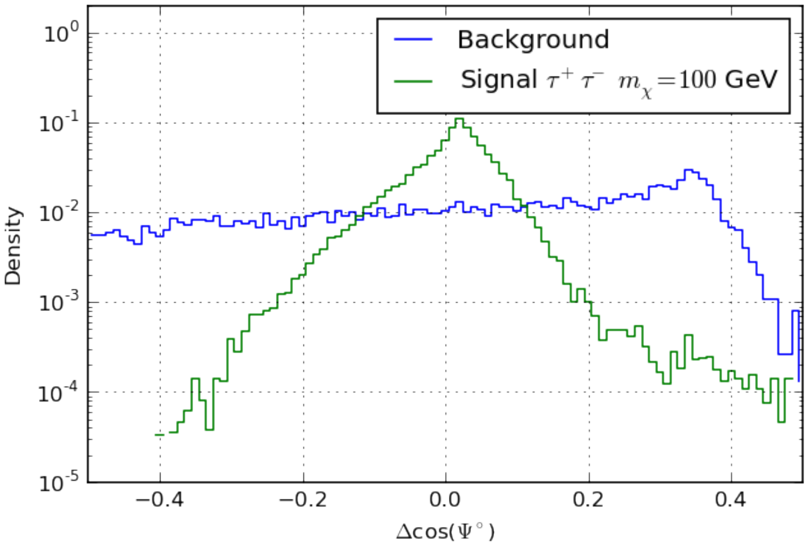

Figure 3: The blue line shows the normalised background PDF of the ANTARES sample, while the green line is the normalised signal PDF for WIMP particles of 100 GeV/c^2 mass that annihilate into via the $\tau^+\tau^-$ channel.

The best estimate of the signal fraction is obtained by minimizing $-\log\mathscr{L}_{comb}(\mu)$. If this value is consistent with zero, the upper limit on the signal fraction, $\mu_{90\%}$, is estimated by determining the 90% confidence interval using the Feldman-Cousins approach [10]. The signal fraction can be linked to $\langle\sigma_A v\rangle$ using the estimated number of signal events for the specific dark matter signal (mass, channel and halo profile). The upper limit on $\langle\sigma_A v\rangle$ for background events only is then calculated by generating a pseudo-experiments sample of 100,000 events and by determining the p-value for the value μ found in the data. We chose to quote the sensitivity as the median value of the 90% upper limits obtained.

5. Results and discussion

The sensitivity to $\langle\sigma_A v\rangle$ for the combined analysis of IceCube and ANTARES is shown in Fig.4. The results show an improvement of the sensitivity in the energy range of 65 to 1000 GeV/c^2 when compared to the individual results of both IceCube and ANTARES. This analysis opens the possibility to explore additional channels ($b\bar{b}$, W^+W^-, $\nu_\mu\nu_\mu$, $\mu\bar{\mu}$ and $\tau\bar{\tau}$) and halo profiles in order to set the best limits for a combination of results from all neutrino telescopes.

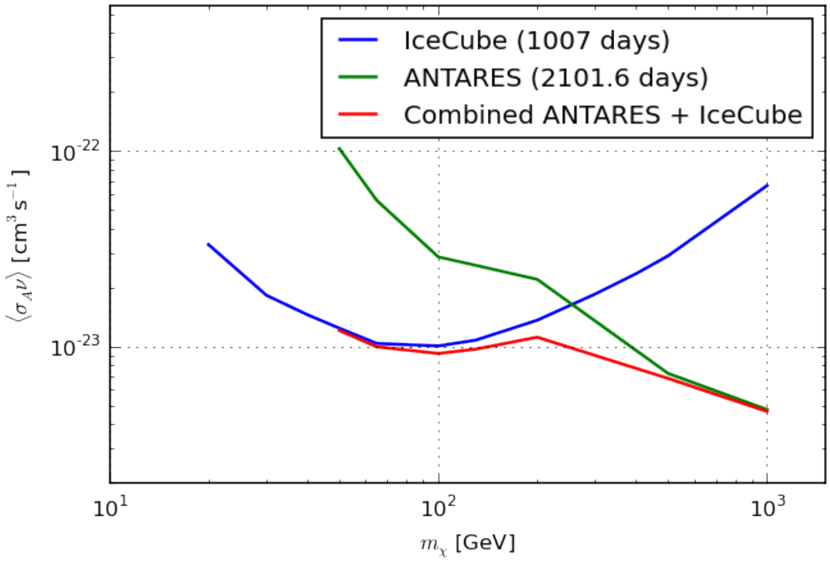

Figure 4: Preliminary plot of the sensitivities obtained for 2101.6 days of ANTARES data (green), 1007 days of IceCube data (blue) and the combination of both experiment (red).

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