PROCEEDINGS OF SCIENCE

Indirect Search for Dark Matter with the KM3NeT Neutrino Telescope

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Neutrino telescopes aim to detect dark matter indirectly by observing the neutrinos produced by pair-annihilations or decays of weakly interacting massive particles (WIMPs). A signal excess of neutrinos resulting from the pair-annihilation of WIMPs can be detected in regions where large amounts of dark matter might accumulate. One possible source is the Sun, where WIMPs are expected to accumulate due to their scatterings in the dense core of the star. The dark matter halo of the Milky Way is another possible close dark matter container. The KM3NeT observatory is composed of two undersea Cherenkov neutrino telescopes (ORCA and ARCA) located in two sites in the Mediterranean Sea, offshore of France and Italy. The two detector configurations are optimised for the detection of neutrinos of different energies, which allows the search for WIMPs in a wide mass range, from the GeV to the TeV scale. In this contribution, searches for WIMP annihilations in the Galactic Centre and the Sun are presented. An unbinned likelihood method is used to discriminate the signal from the background in a 300-day livetime sample of the ARCA detector, and a 543-day sample of the ORCA detector. The limits on the velocity-averaged pair-annihilation cross section of WIMPs are computed for five different primary annihilation channels. For the ORCA analysis, the limits on the spin-dependent and spin-independent scattering cross sections are given for three annihilation channels.

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1. Introduction

Astrophysical observations have proven that a majority of the matter budget in the Universe is composed of a cold, non-baryonic form of matter, the nature of which is unknown. Direct and indirect detection experiments assume a particle nature of dark matter, aiming to determine its properties by observing its interactions with the Standard Model particles. In the case of indirect detection, searches for the products of dark matter annihilation are performed in regions where dark matter is thought to accumulate: one such place is the Galactic Centre, as galaxy formation theory predicts the existence of galactic dark matter halos with very high densities at the centre of the object [1]. A second possible source is the Sun, where dark matter particles of the Galactic halo scatter off nuclei composing the Solar medium, causing them to be trapped in the gravitational potential of the Sun and accumulate in the centre of the object.

The neutrino flux expected at the Earth surface due to the annihilation of dark matter particles into secondary products can be formulated as:

$$\frac{d\Phi}{dE} = \frac{\Gamma}{4\pi d^2}\frac{dN}{dE}. \tag{1}$$

The parameter Γ is the annihilation rate of WIMP particles, d represents the distance to the source centre, and $\frac{dN}{dE}$ represents the number of neutrinos per unit energy emitted in one annihilation event. In order to obtain the neutrino spectra, the dark matter particle is assumed to be a weakly interacting massive particle (WIMP). A model-independent search is performed, where neutrino yields are computed for a range of WIMP masses and up to five annihilation channels:

$$\text{WIMP} + \text{WIMP} \rightarrow \mu^-\mu^+, \tau^-\tau^+, b\bar{b}, W^-W^+, \nu\bar{\nu} \rightarrow \nu\bar{\nu}.$$

The neutrino yields from the subsequent decays and emissions of the annihilation products are described using PYTHIA, and are implemented in the form of tables in the PPPC4 framework [2].

In the case of the Galactic Centre, the annihilation rate, Γ, depends on two parameters: the spatial distribution of dark matter in the target object, and the parameter we are trying to measure or constrain: the thermally-averaged cross section of WIMP annihilation, $<\sigma v>$. The spatial distribution of WIMPs is expressed in terms of a Galactic density profile, obtained with the CLUMPY program [3]. The Navaro-Frenk-White profile is used to obtain limits in this analysis [4]. This density profile is integrated along the line of sight ,l.o.s, and through the solid angle that the object subtends in the sky, $\Delta\Omega$. The equation then reads:

$$\frac{d\Phi}{dE} = \frac{1}{4\pi}\frac{<\sigma v>}{2m^2_{\text{WIMP}}}\int_{\Delta\Omega}\int_{\text{l.o.s.}}\rho^2(\theta, l)dl\,d\Omega. \tag{2}$$

In the case of the Sun, an equilibrium between capture and annihilation is assumed, which implies $\Gamma = 1/2\,C_r$, C_r being the capture rate of dark matter in the Sun. The latter is related to the WIMP-nucleon scattering cross section, which can be spin-dependent or spin-independent. Therefore, a relationship between the WIMP-nucleon cross section and the flux of neutrinos can be established:

$$\sigma^{\text{SD,SI}} = K^{\text{SD,SI}}\Phi_{\nu+\bar{\nu}}, \tag{3}$$

where $\sigma^{\mathrm{SD,SI}}$ represents the spin-dependent/spin-independent cross section, and K represents the so-called conversion factor, which is computed using the software package DarkSUSY [9]. The conversion factor contains information about the WIMP-WIMP annihilation channel, the mass of the WIMP, and the density and velocity distribution of halo WIMPs surrounding the Sun.

2. The KM3NeT neutrino telescope

The KM3NeT detector is an underwater Cherenkov detector positioned at two sites in the Mediterranean Sea [5]. The KM3NeT/ ORCA (Oscillation Research with Cosmics in the Abyss) detector, situated off the coast of Toulon, France, performs neutrino oscillation studies by detecting atmospheric neutrinos at GeV energies, whereas the KM3NeT/ARCA (Astroparticle Research with Cosmics in the Abyss) detector, placed off-shore of Sicily, Italy, attempts to detect astrophysical neutrinos at higher energies, although both detectors are well-suited for dark matter searches.

The detection principle relies on the detection of the Cherenkov light emitted by ultra-relativistic leptons that are produced when neutrinos interact in the vicinity of the detector. The light is detected by 3D arrays of Digital Optical Modules (DOMs), which are grouped in vertical Detection Units (DUs), with each DU consisting of 18 DOMs [6]. Each DOMs in itself is composed of 31 photomultiplier tubes (PMTs), along with sensors that determine the position and orientation of each DOM. The ARCA detector is currently consisting of 21 DUs. The analysis reported in this proceeding was conducted on the ARCA detector in the configuration with 6 and 8 DUs, referred to as ARCA6/8, in operation between May 2021 and June 2022. The ORCA detector currently consists of 18 DUs. The data analysed in this proceeding was taken with the configuration with 6 DUs, referred to as ORCA6, in operation between January 2020 and November 2021. The analysis was optimised on simulated events: for both detectors, the gSeaGen KM3NeT code was used to simulate neutrino interactions in water and the resulting flux of neutrinos at the detectors [7], whereas the MUPAGE package was used to simulate the atmospheric muon flux at the detectors [8]. The simulation of the light propagation and detection and the event reconstruction is handled by a custom KM3NeT software package.

3. Methods

Muon neutrinos interacting via the charge-current interaction produce muons that traverse the detector whilst inducing the emission of a cone of Cherenkov light. These events are referred to as track-like events. The muon produces a large amount of light while traversing through the entirety of the detector volume, which is why this event topology offers the best angular resolution. Neutral-current interactions of neutrinos produce hadronic showers which dissipate their energy in short distances, likewise for leptonic showers induced by electrons and tau leptons produced from charged-current interactions of their associated neutrino. This class of events is referred to as shower-like events. The analyses reported in this proceeding are conducted on track-like events. The largest source of background for this event topology are downgoing atmospheric muons. In order to reject them, only upgoing events, which enter the atmosphere and traverse through the Earth before arriving at the detector, are considered. Furthermore, additional selection cuts are

ARCA6/8	track likelihood > 50, $n_{\text{hits}} > 20$, cos(zen) > 0, E(GeV) > 10, track length > x, β < y.
ORCA6	ICRC_V2 cuts, β < a, n_{hits} > b, track likelihood > c.

Table 1: The cuts used to select upgoing neutrino events and reject the atmospheric muon background. Two variables were used in the optimisation procedure for the ARCA6/8 sample, the length of the reconstructed track ($x \in 100-200$ m), and the reconstruction angular error estimate, β ($y \in 0.5^{\circ}-1^{\circ}$). For the ORCA6 sample, the ICRC_V2 set of cuts is used in order to ensure the compatibility among data and simulations. Additionally, cuts in β ($a \in 0.9^{\circ}-1^{\circ}$), the number of hits ($b \in 20-40$) and the track likelihood ($c \in 60-120$) are used to optimise the limits on the neutrino flux.

applied to remove noise, and to remove muons that are mis-reconstructed as upgoing. A summary of the cuts applied to the data can be found in Table 1.

This analysis tries to distinguish a cluster of signal events around the source centre (the signal hypothesis, H_1) from the null hypothesis (H_0), where all the events originate from the atmospheric background. Pseudo-experiments are generated with the number of signal events injected varied between 0 and 50, and an unbinned likelihood analysis is performed in order to determine the most likely number of signal events on a sky map. The probability density functions (PDFs) used in the likelihood are two-dimensional histograms in angular distance from the source centre, and the reconstructed energy. The likelihood function used is an extended log likelihood:

$$\mathcal{L} = \Sigma_{N_{\text{tot}}} \log(n_{\text{sg}} P_{\text{sg}}(\alpha, E) + (N_{\text{tot}} - n_{\text{sg}}) P_{\text{bg}}(\alpha, E)) - N_{\text{tot}}. \quad (4)$$

The variables α and E denote the event angular distance from the source and event reconstructed energy, the parameters P_{sg} and P_{bg} denote the signal and background PDFs, and N_{tot} and n_{sg} denote the total number of events and the number of signal events. For each mock sky map generated, the number of signal events is varied in order to maximise the likelihood, and the test statistic (TS) is calculated:

$$TS = \frac{\mathcal{L}(n_{\text{sg,max}})}{\mathcal{L}(n_{\text{sg}} = 0)}. \quad (5)$$

The parameter $\mathcal{L}(n_{\text{sg,max}})$ denotes the maximised likelihood, and the parameter $\mathcal{L}(n_{\text{sg}} = 0)$ denotes the likelihood of the sky map consisting of only background events. The number of events in each pseudo-experiment is subject to Poisson fluctuations, which are accounted for by applying a transformation of the TS distribution through a Poisson function, $\mathcal{P}$ with mean μ, as follows:

$$P(\text{TS}(\mu)) = \Sigma_{n_{\text{sg}}} P(\text{TS}(n_{\text{sg,max}})) \times \mathcal{P}(n_{\text{sg}}, \mu). \quad (6)$$

In order to take into account the systematic uncertainty in the number of detected signal events, a Gaussian smearing is applied with a value of 30% (15% for ORCA6): this value was obtained by simulating events in KM3NeT with a modified absorption length of photons in water, the uncertainty in this parameter exerted the largest influence on the number of detected events. The Neyman approach is followed to obtain an averaged upper limit on the number of signal events [11]:

the median of the background TS distribution is compared with each TS distribution with injected signal events. The sensitivity in the number of events, n_{90}, is obtained as the 90% confidence level upper limit for a measurement that coincides with the median of the background TS distribution. The flux sensitivity is then obtained from the number of events sensitivity, n_{90}, with the following equation:

$$\Phi^{90}_{\nu+\bar{\nu}} = \frac{n_{90}}{Acc \times T}. \tag{7}$$

The quantity T is the livetime of the analysed dataset, whereas the parameter Acc is the detector acceptance to signal events, obtained as a convolution of the detector effective area, A_{eff} and the WIMP annihilation spectrum:

$$Acc = \int_{E_{\text{th}}}^{M_{\text{WIMP}}} A_{\text{eff}}(E_\nu)\frac{dN}{dE}dE_\nu. \tag{8}$$

The effective area is defined as the area of an ideal, one hundred percent efficient detector, which is computed with detector simulations from the ratio of generated and detected neutrino events. The acceptance is integrated from the minimum threshold energy of the detector, E_{th}, up to the WIMP mass. Equations 2 and 3 are then used to convert the flux sensitivities into cross section sensitivities in the case of the Galactic Centre and the Sun.

4. Results: searches in the Galactic Centre

The data set taken with the ARCA6/8 configurations was analysed in search of a WIMP annihilation signal, for WIMP masses in the range 500 GeV$/c^2$ – 100 TeV$/c^2$. The event selection applied to the data was varied for each annihilation channel / WIMP mass combination, with the selected cut mask attaining the best sensitivities for that mass / channel combination. The TS of the unblinded dataset is compatible with the background hypothesis, for all combinations of WIMP masses and annihilation channels, and the limit on the thermally-averaged WIMP annihilation cross section was placed following Equation 2. The upper limits are compared to the limits obtained with the complete ANTARES dataset [10], the predecessor of the KM3NeT neutrino telescope, in Figure 1. An improvement on the ANTARES results is expected with the upcoming datasets of the expanded ARCA detector. The results are placed in context to other indirect searches in the field in Figure 2.

5. Results: searches in the Sun

The ORCA6 dataset has been analysed in search of dark matter in the Sun, considering WIMP masses in the range 10 GeV$/c^2$ – 10 TeV$/c^2$. As in the ARCA6+8 sample, the TS obtained for this dataset is compatible with the background hypothesis for all combinations of WIMP masses and annihilation channels. In particular, the TS of the dataset is found to be below the median of the background-only TS distribution for every test case. Consequently, the limit on the neutrino flux is set to be equal to the sensitivity. Limits to the spin-dependent and the spin-independent cross sections are obtained through Equation 3. Figures 3 and 4 show such limits.

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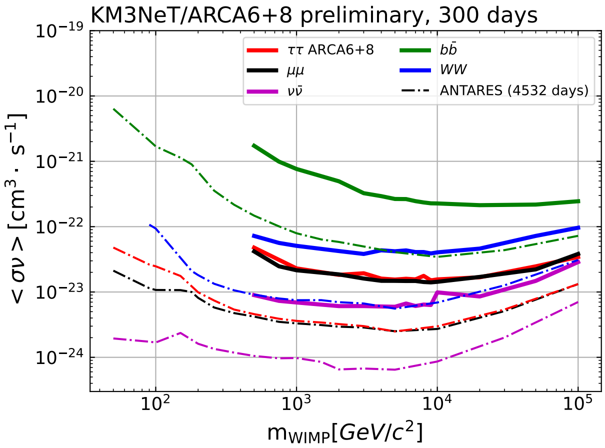

Figure 1: The 90% CL upper limits on the thermally-averaged WIMP annihilation cross section as a function of the WIMP mass for each of the five annihilation channels. The full lines show the results obtained in this analysis, whereas the dashed lines show the upper limits obtained with the complete ANTARES dataset [10].

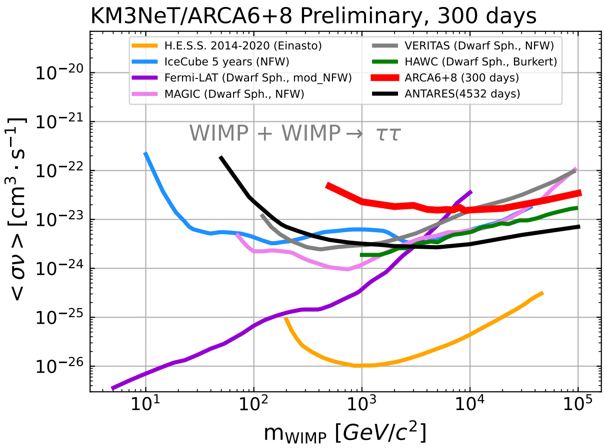

Figure 2: The 90% CL upper limits on the thermally-averaged WIMP annihilation cross section as a function of the WIMP mass for each of the five annihilation channels, shown along with results obtained by other experiments in the field [12–17].

6. Discussion

The first results on searches for dark matter annihilation signatures with the KM3NeT neutrino telescope have been presented in this contribution. Thanks to their different detector configurations, the ARCA and ORCA detectors can cover a wide range of the allowed parameter space of the WIMP mass. By searching for dark matter signatures towards the Sun and Galactic Centre, the two detectors are already providing competitive results in the field in their initial construction phase, surpassing its predecessor in certain regions of the parameter space. Follow-up searches with currently deployed and future larger detector configurations will push the boundary of dark matter searches with neutrino telescopes.

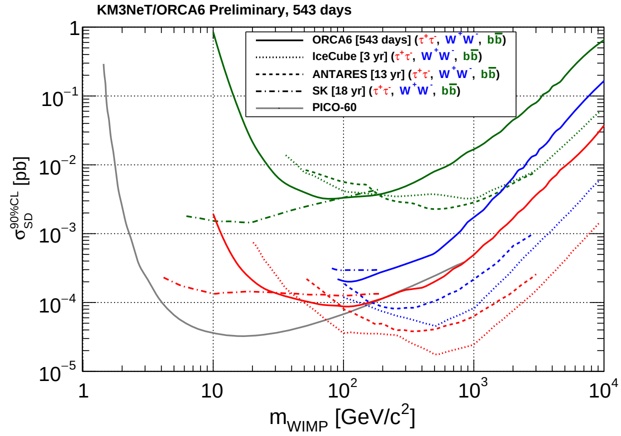

Figure 3: The 90% CL upper limits on the spin-dependent WIMP-nucleon cross section as a function of the WIMP mass for each of the three annihilation channels. The full lines show the results obtained in this analysis, whereas the other lines show the upper limits obtained by IceCube [18], ANTARES [19], Super-Kamiokande [20] and PICO-60 [21] (shown as a full line).

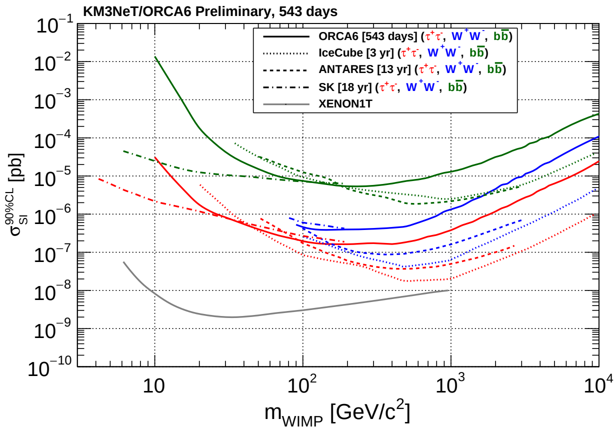

Figure 4: The 90% CL upper limits on the spin-independent WIMP-nucleon cross section as a function of the WIMP mass for each of the three annihilation channels. The full lines show the results obtained in this analysis, whereas the other lines show the upper limits obtained by IceCube [18], ANTARES [19], Super-Kamiokande [20] and XENON1T [22] (shown as a full line).

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References

[1] G. Bertone, D. Hooper and J. Silk, *Phys. Rept.* **405** (2005): 279.

[2] M.Cirelli et al. *Journal of Cosmology and Astroparticle Physics* **1103** (2011): 051.

[3] A.Charbonnier, C.Céline, and D.Maurin, *Computer Physics Communications* **183.3** (2012): 656-668.

[4] J.F.Navarro, C.S.Frenk and S.D.M.White, *The Astrophysical Journal* **462** (1996): 563-575.

[5] KM3NeT Collaboration, *Journal of Physics G: Nuclear and Particle Physics* **43.8** (2016): 084001.

[6] KM3NeT Collaboration, *J. Phys.: Conf. Ser.* **1056** (2018): 012031.

[7] KM3NeT Collaboration, *Computer Physics Communications* **256** (2020): 107477.

[8] Carminati, G., et al. *arXiv* preprint [arXiv:0907.5563] (2009).

[9] T. Bringmann, J. Edsjö, P. Gondolo, P. Ullio and L. Bergström, *Journal of Cosmology and Astroparticle Physics* **1807** (2018): 033.

[10] ANTARES Collaboration, S.R. Gozzini, *PoS*(ICRC2023) 1375 (these proceedings).

[11] J. Neyman, *Philosophical Transactions of the Royal Society of London. Series A, Mathematical and Physical Sciences* **236** (1937): 333–380.

[12] H.E.S.S. Collaboration, *Phys. Rev. Lett.* **129.11** (2022): 111101.

[13] IceCube Collaboration, arXiv preprint arXiv:2303.13663 (2023).

[14] M. Di Mauro, M. Stref, and F. Calore, *Physical Review D* **106** (2022): 123032.

[15] MAGIC Collaboration *Phys. Dark Universe* **35** (2022): 100912.

[16] VERITAS Collaboration, *Physical Review D* **95** (2017): 082001.

[17] HAWC Collaboration, *The Astrophysical Journal* **945** (2023): 25.

[18] IceCube Collaboration, *Eur. Phys. J. C* **77** (2017): 146 [erratum: *Eur. Phys. J. C* **79** (2019): 214].

[19] C. Poirè, doi:10.4995/Thesis/10251/188750

[20] Super-Kamiokande Collaboration, *Phys. Rev. Lett.* **114** (2015): 141301.

[21] PICO Collaboration, *Phys. Rev. D* **100** (2019) no.2, 022001.

[22] XENON Collaboration, *Phys. Rev. Lett.* **121** (2018): 111302.

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