Dark matter searches with the KM3NeT telescope

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Abstract. KM3NeT is a neutrino telescope under construction in the Mediterranean sea, consisting of a GeV-TeV sensitive detector, ORCA, and a TeV-PeV one, ARCA. Indirect detection of dark matter particles could be possible through the observation of their annihilation products in the form of neutrinos. In this contribution we report the potential of the complete ARCA telescope on searches for WIMP dark matter annihilations in the Galactic Center. In addition, searches in the Sun and Galactic Center for partial detector configurations (ARCA8-19-21 and ORCA6) are presented. No significant excess over the expected background is observed, leading to limits on the WIMP dark matter thermally averaged annihilation cross section and the WIMP-nucleon scattering cross section.

1 Introduction

KM3NeT is an underwater neutrino telescope located at two sites in the Mediterranean sea. Neutrinos are indirectly detected from the products of their interactions, of which relativistic charged particles produce Cherenkov radiation [1]. The ORCA detector, off the coast of Toulon, is designed to measure atmospheric neutrino oscillations [2], and the ARCA detector, off the coast of Sicily, is designed to search for neutrinos from astrophysical sources [3]. In tandem with the primary scientific goals of both detectors, observations also allow to address other major questions, like the indirect search for dark matter (DM) [4].

Different cosmological observations require the introduction of DM as the dominant matter component of the Universe, while loosely constraining its nature. WIMPs (Weakly Interacting Massive Particles) constitute one of the possible particle DM theories. They not only emerge naturally in many extensions of the Standard Model and have the correct cosmological properties, but they also have many and diverse implications for observable phenomena. The main observable for neutrino telescopes is the neutrino flux created either directly by the annihilation of DM particles, or by the decay or interaction of the products of their annihilation.

This work presents the capability of the KM3NeT neutrino telescope to contribute to the long-standing question of the nature of DM. The search focuses on annihilation signals coming from the Galactic Centre and the Sun, where an over-density of DM is believed to be present. The DM masses explored range from 1 GeV to 100 TeV, limited by the detector capabilities and cosmological constraints, respectively. Because the limits for the Sun and Galactic Center searches have already been reported in the cited publications [4, 5], this contribution will focus on the potential for DM searches from the Galactic Center for the complete ARCA detector. The data set, source modelling and analysis method will be introduced

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first. Finally, sensitivities to the WIMP DM thermally-averaged annihilation cross-section with the complete ARCA detector will be presented and compared to the previous results using partial ARCA and ORCA detector configurations.

2 Dataset and event selection

The complete ARCA detector consists of 230 vertical structures attached to the sea bed, referred to as detection units. The detection units hold the digital optical modules detecting the Cherenkov light by means of photo-multiplier tubes (PMT). A Monte Carlo simulation for the complete ARCA detector, from the neutrino interactions in water and the atmospheric muon flux to the light propagation, the optical background and PMT response, has been employed to simulate the dataset [3].

In this work only events with a track signature have been selected. Track events are created by muons traversing the detector volume, which originate either from muon (anti-)neutrinos undergoing a charged current interaction or from atmospheric muons created by cosmic rays interacting in the atmosphere. In order to select neutrino track events, a set of cuts have been performed. Events that have a reconstructed direction traversing the Earth or a large part of the atmosphere (zenith angle $> 80\,\mathrm{deg}$[1]), referred to as up-going or horizontal, are selected reducing drastically the atmospheric muon background. Moreover, a set of cuts on the reconstructed variables (likelihood and number of hits of the event) are applied to remove badly re-constructed events. The last selection step is the training and evaluation of a boosted decision tree (BDT), with the aim of distinguishing well reconstructed tracks from atmospheric muons miss-reconstructed as up-going or horizontal. The reached muon contamination is approximately 42%[2]. The true and reconstructed MC information is used to characterise the detector response in terms of an effective area and resolution on energy and angle.

3 Source modelling and analysis method

The neutrino flux $d\Phi^c_\alpha/dEdt$ created by DM annihilations in the Galactic Center can be expressed as a function of the annihilation cross-section averaged over the relative velocity between DM particles $<\sigma v>$, the energy spectrum of neutrinos created in the process and the number density of each DM particle participating in the annihilation, ρ/m_{DM}, integrated over the region of interest:

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

where the superscript c refers to the annihilation channel and the subscript α to the neutrino flavour. A 1/2 term appears due to the assumption that WIMPs are their own antiparticles. The spectra are simulated with the χaroν [6] software, while the DM density distribution $\rho(\theta, l)$ is simulated with the CLUMPY software [7], using the Navarro-Frenk-White profile. A set of DM masses ranging from 300 GeV to 100 TeV are considered for five different annihilation channels: $\nu\bar{\nu}, \mu^+\mu^-, \tau^+\tau^-, W^+W^-, b\bar{b}$, for which in each case a 100% branching fraction is considered.

To perform the analysis, a binned method is employed. The detector response functions are used to create the expected signal distributions (neutrinos from DM annihilations) and background distributions (atmospheric muons and neutrinos), binned as a function of

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[1] A zenith angle of 0 deg corresponds to vertical down-going events.

[2] Defined as the fraction of atmospheric muons in the total background sample, at the final selection level.

the reconstructed energy and the angle from the Galactic Center. Based on this, pseudo-experiments using Poisson statistics are generated, while varying the signal strength ζ ($\zeta = 0$ for background-only hypothesis). The potential to discriminate signal from background is studied by a log-likelihood ratio test-statistic λ,

$$\lambda = \log L(\zeta = \hat{\zeta}) - \log L(\zeta = 0) \ , \quad \log L = \sum_{ij \in bins} N_{ij} \log\left(B_{ij} + \zeta S_{ij}\right) \ , \tag{2}$$

where the estimated signal strength $\hat{\zeta}$ of the dataset is obtained by maximising the likelihood. The sensitivity is defined as the expected 90% confidence level limit on the neutrino flux from DM annihilations, expressed as a limit on the thermally averaged annihilation cross-section, and is derived from the test-statistic distributions following the Neyman approach.

4 Results

The complete ARCA potential to limit the WIMP annihilation cross-section from annihilations in the Galactic Center is presented in Figure 1, for 1 yr of observation time. The best sensitivities are obtained for the $\nu\bar{\nu}$ annihilation channel, for which the energy distribution of the annihilation process to neutrinos is the hardest. The sensitivity curves are determined by the interplay of a larger neutrino flux at smaller DM masses and the spectra of the annihilation channel, the better reconstruction of higher energy events and the better signal-background discrimination at higher energies.

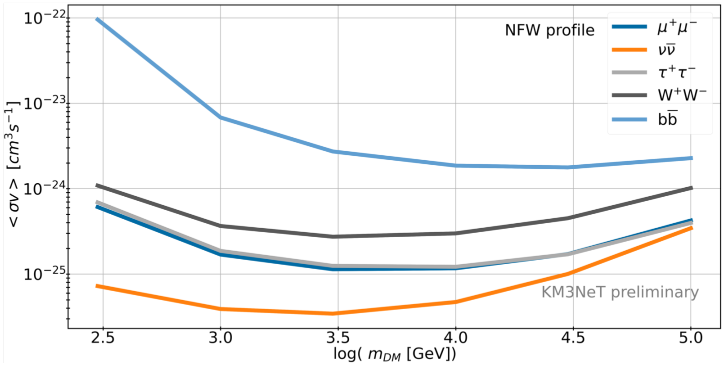

Figure 1. 90% CL sensitivities for the complete ARCA detector for 1 yr of observation time, on the thermally-averaged WIMP annihilation cross section as a function of the DM mass for each of the five annihilation channels.

In Figure 2, the results are compared to the DM searches using data from the ARCA detector configurations with 8, 19, and 21 detection units, for a total livetime of 331 days [4]. No excess from the expected background is found in these datasets, setting limits on the DM annihilation cross-section. The comparison to other neutrino and gamma-ray experiments is also included.

In conclusion, the ARCA detector is already competitive with the IceCube neutrino telescope at large DM masses, while the ORCA detector is still approaching the limits from the ANTARES and IceCube telescopes [5]. The results improve much further with the complete ARCA detector configuration, approaching the thermal relic annihilation cross-section $\sim 10^{-26} cm^3 s^{-1}$.

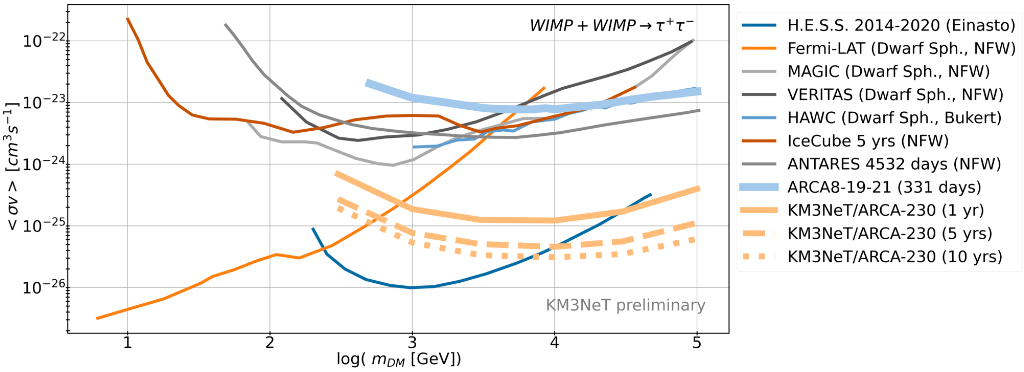

Figure 2. 90% CL sensitivities (complete ARCA and ORCA 6) and upper limits (ARCA8-19-21), on the thermally-averaged WIMP annihilation cross section as a function of the DM mass for the $\tau^+\tau^-$ annihilation channel. The results are compared to other experiments [8–14].

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