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WIMP Dark Matter Searches from the Galactic Centre with KM3NeT

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Weakly Interacting Massive Particles (WIMP) are interesting dark matter (DM) candidates because they exhibit the usual DM properties (such as being non-relativistic and electrically neutral), while having the advantage of weakly interacting with Standard Model particles, which makes them detectable in principle. When DM decays or annihilates, neutrinos are produced. Therefore, an indirect detection of DM involves searching for an excess of neutrinos in astrophysical targets such as the Galactic Centre or the Sun, where large amounts of DM are believed to accumulate. Such an excess of neutrinos could then be observed by large-scale Cherenkov detectors such as KM3NeT, which is currently under construction in the abyss of the Mediterranean Sea, while taking data in partial detector configurations. KM3NeT is composed of two undersea Cherenkov neutrino detectors: KM3NeT/ORCA, a dense-geometry detector optimised for the measurement of low energy (GeV) neutrinos, and KM3NeT/ARCA, a cubic kilometer-sized detector, intended for the detection of high energy astrophysical neutrinos. In this contribution, we present a binned and unbinned likelihood analysis looking for WIMP-like DM annihilations occurring at the Galactic Centre, where we consider DM with masses ranging from approximately 10 GeV up to 100 TeV. We use data from various partial ORCA-detector configurations with 6, 10 and 11 lines to explore the low DM mass region. For the higher DM mass regions, we use data from the KM3NeT/ARCA detector with 19 and 21 lines and also the full configuration with 230 lines.

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1. Introduction

Substantial astrophysical evidence points to a missing component in the Universe: Dark Matter (DM). Observations of this component are confined to gravitational interactions, measured through its gravitational effects on visible matter [1]. Early proposals included celestial bodies and baryonic matter [2], while current research still considers possibilities like Primordial Black Holes [3]. Among particle candidates, Weakly Interacting Massive Particles (WIMPs) remain a leading proposal due to their theoretical appeal and detectable cross-sections. Today, the particle dark matter paradigm dominates experimental efforts, pursued through: indirect detection of annihilation products [4], direct detection of scattering events [5] and collider production at high energies[6]. According to cosmic structure formation Dark Matter is expected to accumulate at locations of high density [7], such as the Galactic Center (GC) or celestial bodies such as the Sun or the Earth. Due to the high density of DM particles in the GC we could expect DM annihilation to happen, with the subsequent production of Standard Model particles. In this analysis we focus on benchmark annihilation channels such as $\tau^+\tau^-$, $\mu^+\mu^-$, $b\bar{b}$, $\nu\bar{\nu}$, and W^+W^-, which lead to detectable neutrino final states. The chosen annihilation channels represent standard benchmarks motivated by particle physics models. Leptonic channels (τ, μ), well-constrained by gamma-ray telescopes, also produce neutrino signatures, while hadronic channels (b) dominate in Higgs-portal scenarios. Gauge boson final states (W) test high-mass thermal relics, and the ν channel probes neutrino couplings. Neutrino telescopes aim to observe the flux of neutrinos produced by pair-annihilation of WIMPs occurring in the Milky Way, given by the following equation:

$$\frac{d\phi}{dE_\nu} = \frac{1}{2} \cdot \frac{\langle \sigma v \rangle}{4\pi m_{DM}^2} \cdot \frac{dN}{dE_\nu} \cdot J. \tag{1}$$

The factor 1/2 arises from the fact that we consider Majorana DM fermions (identical particle and antiparticle), $\langle \sigma v \rangle$ is the thermally averaged cross section of the interaction, m_{DM} is the DM mass, $\frac{dN}{dE_\nu}$ is the spectrum of the interaction of neutrinos that arrive to the Earth from the production source (right panel, Fig. 1). The last term is the J-Factor (left panel, Fig. 1), which describes the distribution of Dark Matter around the GC, integrates DM density along lines of sight within cones of angle, α.

2. KM3NeT Experiment

KM3NeT [12] is a large underwater neutrino telescope located in the Mediterranean Sea, succesor of the ANTARES experiment [13], which was shut down in 2022 after nearly two decades of data taking. KM3NeT is composed by two detectors that are currently being built and are already taking data: ARCA with 33 lines located in the south of Sicily (Italy) and ORCA with 28 lines close to Toulon (France). Both detectors provide complementary coverage over a wide range of energies: from GeV to TeV energies, ORCA is typically used to study matter properties using neutrino oscillations; while ARCA operates in the TeV - PeV energy range, searching for neutrinos coming from distant astrophysical sources such as supernovae, gamma ray bursts or colliding stars. Both detectors share the same technologies; they consist of arrays of detector Optical Modules (DOMs), each with 18 photomultipliers (PMTs), that, attached to the Mediterranean seabed, detect the faint

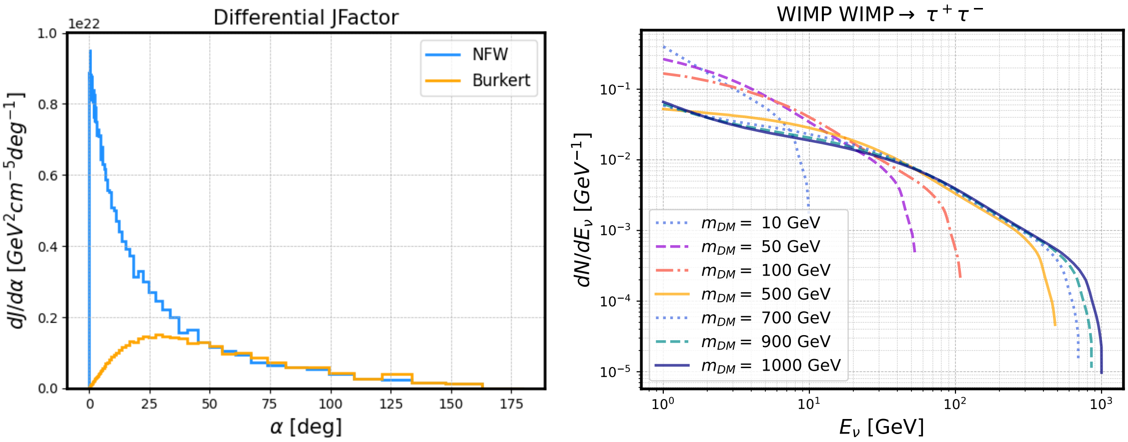

Figure 1: Left: Differential J-factor [11] obtained as a function of opening angle, α, for spherical dark matter halos, comparing Navarro-Frenk-and-White (NFW) and Burkert density profiles [8, 9]. Right: Energy distribution for product neutrinos coming from a WIMP pair annihilation into $\tau^+\tau^-$, followed by decay chains producing neutrinos [10].

flashes produced when neutrinos interact with water. Neutrinos can travel through the Universe unimpeded, arriving from distant sources with unaltered directions and energies. By detecting these particles, we can study the properties of neutrinos and investigate the extreme cosmic events that produce them. Additionally, these observations also provide a unique way to search for DM annihilations occurring in the Galactic Center.

The experiment measures light patterns; once the noise coming from natural environmental events such as bioluminescence or natural ^{40}K decays is rejected, the measurements are analyzed in search of typical signatures produced by the leptonic and hadronic products left by neutrinos in their charged and neutral interactions with matter. These products typically leave two kinds of signatures: track-like events are created by muon particles that cross the detectors, and shower-like events are left by electrons, tauons, or hadrons from neutral interactions.

The main background that the detector is subject to comes from atmospheric muons from the interactions of cosmic rays with the atmosphere; additionally, in DM searches atmospheric neutrinos are also a background. Even though the kilometers of sea act as a shield, we still receive a large amount of atmospheric muons, to discard them we usually apply cuts to only accept up-going particles that cross the Earth.

The analysis reported in this proceeding is conducted on the ARCA detector in the configuration with 19, and 21 DUs, referred to as ARCA19/21, in operation from June 2022 to September 2023. We update on the full ARCA configuration with 230 lines, ARCA23O, where further data selection improvements have been made [14]. The ORCA data analysed in this proceeding was taken with the configuration with 6, 10 and 11 DUs, referred to as ORCA6/10/11, in operation from January 2020 to December 2022. The analysis is optimised on simulated events: for both detectors, the gSeaGen KM3NeT code [15] was used to simulate neutrino interactions in water and the resulting flux of neutrinos at the detectors, whereas the MUPAGE package [16] was used to simulate the atmospheric muon flux at the detectors. The simulation of the light propagation and detection and the event reconstruction is handled by a KM3NeT software package.

3. Methodology

In KM3NeT the detection method is based on the measurement of Cherenkov light left by charged leptons, with the detection of track and shower signatures. Both data sets are optimised for track events with the cuts showed in Table 1. Figure 2 (left) shows that the optimized cuts provide acceptable data-Monte Carlo agreement for ARCA. ORCA data samples have a muon contamination $< 0.22\%$, while ARCA data samples show a muon contamination of $< 15\%$.

ARCA19/21	pre-cuts: $\{E > 100$ GeV$\}$, direction: $\{$zen $> 90°\}$, anti-noise: $\{$lik> 50; Nhit> 20 $\}$, BDT > 0.998 (ARCA19) or 0.9999 (ARCA21)
ARCA230	cuts from [17] ; optimised BDT cuts: BDT > 0.99 (zen $< 90°$); 0.9 (zen $> 90°$)
ORCA6/10/11	pre-cuts: $\{ E \in [10, 1500]\ GeV$; cos (zen) > 0 $\}$; anti-background: $\{$ noise BDT $< 2 \times 10^{-5}$; muon BDT $< 1.5 \times 10^{-4}$ $\}$; track BDT > 0.56

Table 1: The cuts used to select upgoing neutrino events and reject the atmospheric muon background. For ARCA samples cuts are made on energy (E), track reconstruction likelihood (lik), zenith angle (zen), number of hits (Nhit) and boosted decision tree cut (BDT) to account for signal deficiencies. For ORCA, the angular resolution is optimized using an energy cut (E), noise/muon suppression cuts (via trained BDTs to separate upgoing atmospheric neutrinos from noise/downgoing muons), and a track-score cut (BDT-based signature) to select a high-purity track-like sample.

In this analysis we search for an excess of signal events in the Galactic Center region, distinguishing it from the atmospheric neutrino background. While the atmospheric neutrino flux is isotropic in zenith angle, it becomes declination-dependent in a neutrino telescope due to Earth's absorption and detector geometry (see bottom panel for ORCA background example, Figure 2). Pseudo-experiments (PEX) are created with a certain number of signal events with the objective to minimise the logarithmic likelihood, in order to measure the sensitivity of the detector to signal events. To determine the number of signal events in the PEX two approaches are followed: a binned likelihood analysis for ARCA and unbinned for ORCA.

$$\text{ARCA:} \qquad -\log\mathcal{L}(\mu) = -\sum_i^{N_{bin}} N_i \log\left(B_i + \mu \cdot S_i\right) - \left(B_i + \mu \cdot S_i\right) - \log\left(N_i!\right) \tag{2}$$

$$\text{ORCA:} \quad -\log\mathcal{L}(n_s) = -\sum_i^{N_{tot}} log\left[n_{sg} \cdot P_{sg}(\psi_i, E_i) + (N_{tot} - n_{sg})P_{bg}(\delta_i, E_i)\right] - N_{tot} \tag{3}$$

In ARCA, the logarithmic likelihood of the data set is minimised by varying the signal strength signal strength μ, obtained from the the probability of observing N_i events per bin. The probability density functions (PDFs) used in the likelihood are two-dimensional histograms in angular distance from the source centre, and the reconstructed energy. We loop over the number of bin N_{bin} for each PDF bin, a value for the expected signal rate S_i and background rate B_i are calculated. In ORCA, the above logarithmic likelihood function is minimized by varying the number of signal events, n_{sg}, ψ_i and E_i denote the event angular distance from the source and reconstructed energy. The parameters P_{sq} and P_{bg} denote the signal and background PDFs, and N_{tot} the total number of events.

For each PEX the test statistic (TS) quantity is computed, defined as the ratio of the minimised logarithmic likelihoodand the likelihood for a pure background data set ($n_{inj} = 0$).

$$TS = \frac{\mathcal{L}(n_{inj,max})}{\mathcal{L}(n_{inj} = 0)} \tag{4}$$

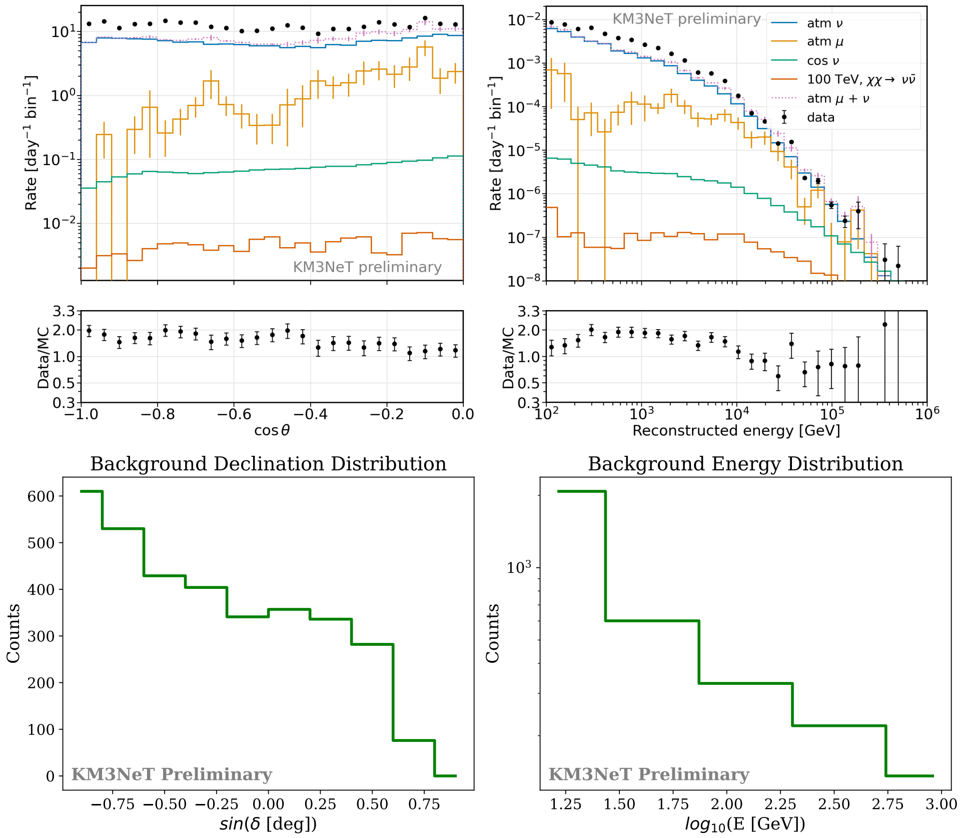

Figure 2: Top: Event rate distributions for ARCA19/21 energy and zenith variables, with optimized cuts for ARCA19/21 targeting a maximum of 15% muon contamination. The cosmic neutrino rate corresponds to a flux $\phi_\nu = 0.6 \times 10^{-4}\ E^{-2}$ and the DM rate is for a 100 TeV DM mass directly annihilating into neutrinos, assuming a $10^{-24}\ cm^3 s^{-1}$ thermally averaged annihilation cross-section. Bottom: Background event distribution for ORCA6/10/11 for declination and energy variables in representation of the total 3365 background events in the sample.

The sensitivity is the upper limit on detectable signal events, calculated at a 90% confidence level, assuming the data behaves like the average background. We obtain the sensitivity by comparing TS distributions from signal-injected data to the median TS of pure background data [18]. The thermal cross-section is then obtained from the sensitivity to the number of signal events, μ_{90}:

$$\langle \sigma v \rangle = \frac{\mu_{90}}{Acc \cdot T} \cdot \frac{8\pi m_{DM}^2}{J}. \tag{5}$$

with the period of data taking T, the dark matter mass m_{DM}, the J-Factor and the acceptance Acc, a measure of the detector efficiency to a certain energy spectrum. The acceptance is computed convolving the effective area with the predicted DM signal spectrum:

$$Acc = \sum_{\nu}^{\nu_e,\nu_\mu,\nu_\tau} \int_{E_{\text{threshold}}}^{m_{DM}} A_{eff,\nu} \cdot \left(\frac{dN}{dE}\right)_\nu \cdot dE_\nu \tag{6}$$

The effective area of the detector, A_{eff} is computed with detector simulations from the ratio of detected neutrino events and the generated neutrino flux.

4. Results

The data set taken with the ARCA19/21, ARCA230 and ORCA6/10/11 configurations was analyzed in search of a WIMP annihilation signal, for WIMP masses in the range 50 GeV/c^2 – 100 TeV/c^2. The sparse configuration of ARCA and the dense configuration of ORCA allow us to probe a wide range of WIMP masses, covering both high- and low-energy regimes. Figure 3 compares the sensitivities obtained for the different ARCA configurations for the optimized cuts in Table 1. The results for the optimized ORCA6/10/11, ARCA19/21 and ARCA230 sensitivities are placed in context to other indirect searches upper limits in the field in Figure 4.

KM3NeT's location in the Northern Hemisphere allows it to observe the Galactic Center at high elevations near 50°, enhancing its exposure to neutrino events from this region compared to detectors at the Southern Hemisphere. Combined with KM3NeT's angular resolution of $< 1°$ at 100 GeV and $< 0.1°$ above 1000 TeV for track-like events, the detector can reconstruct Galactic Center neutrinos with high precision. This precision will be improved as the detector's full configuration is completed.

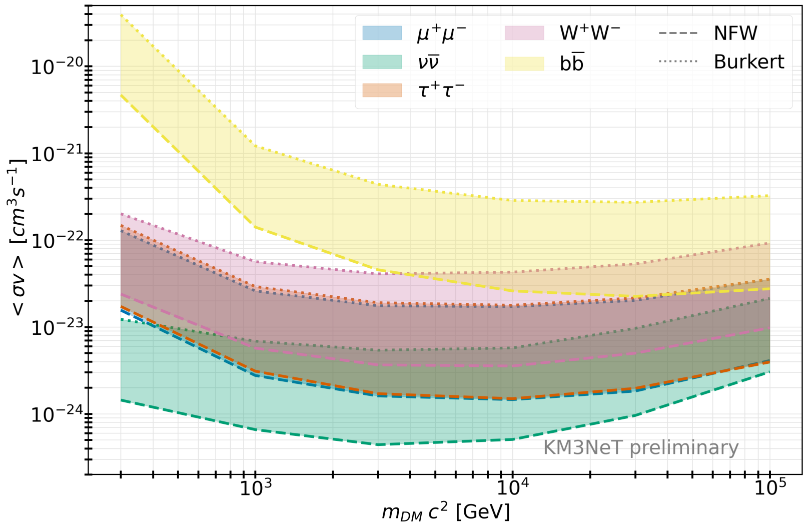

Figure 3: Sensitivity to the thermally averaged DM annihilation cross-section for the NFW and Burkert profiles using ARCA19-21 configuration. The selection has been optimised to have a maximum of 15% muon contamination.

5. Discussion

In this analysis we have obtained the sensitivity for Dark Matter particles with masses in between 50 GeV/c^2 – 100 TeV/c^2 annihilating in the Galactic Center. The Galactic Center analysis performed for the first time with ORCA demonstrates the experiment's capability to achieve meaningful results even with its compact detector design. The experiment successfully achieves competitive sensitivities to dark matter annihilation events in the Galactic Center, comparable to other detectors that can reach low-energy ranges. While our current ORCA6/10/11 configurations can probe dark matter masses down to ~50 GeV, larger detector arrays will extend coverage to lower masses where

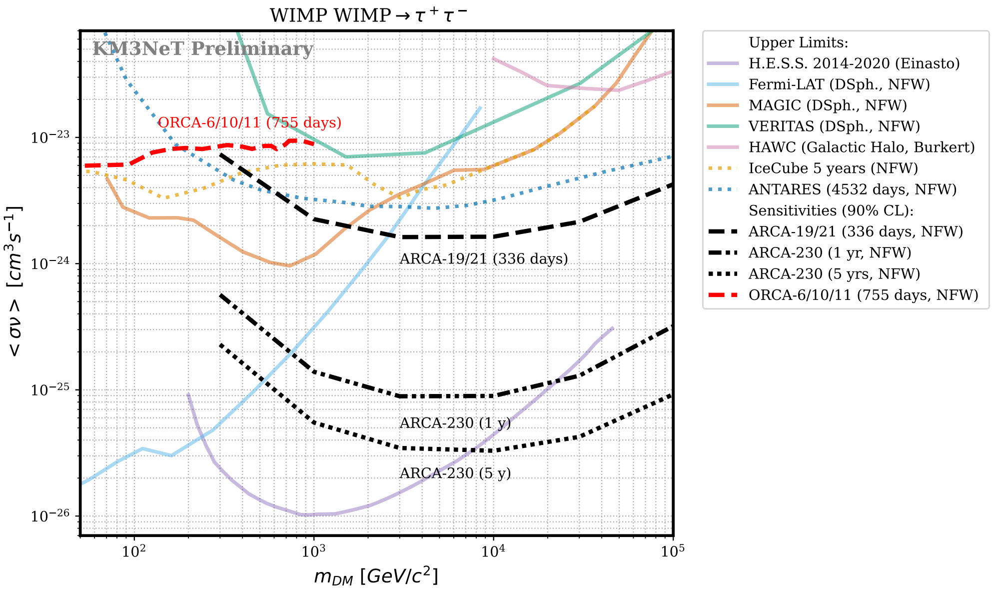

Figure 4: 90% CL sensitivities for ARCA19/21, ARCA230, and ORCA6/10/11 to thermally averaged DM annihilation cross-section for the $\tau^+\tau^-$ annihilation channel, compared to upper limits for other experiments.

signal-background discrimination becomes challenging. Future detector updates, with an improved angular resolution, will provide enhanced sensitivities for a robust detection of lighter dark matter particles. Currently, ARCA19/21 sample provides the very constraining sensitivities for neutrino telescopes. The full ARCA detector configuration result, shows that within a year of data taking it could be leading above 10 TeV DM masses.

A critical consideration in dark matter searches is that $\langle \sigma v \rangle$ exhibits a strong dependence on systematic factors, particularly on the assumed dark matter spectrum and the choice of a J-factor halo characterization for a realistic Milky Way target. Future studies should explore diverse halo scenarios and conduct in-depth analyses of systematic uncertainties. However, establishing a unified model that accurately describes the Milky Way's dynamical behavior remains a crucial goal for the astroparticle physics community.

These results highlight KM3NeT's growing potential in the search for dark matter, particularly as full detector deployment progresses. To this day, ARCA and ORCA detectors already are providing competitive sensitivities in dark matter searches targeting the Galactic Center; surpassing other leading detectors in the same field. Follow-up searches with currently deployed and future larger detector configurations will push the boundary of dark matter searches with neutrino telescopes.

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