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Indirect Dark Matter Searches with the ANTARES and KM3NeT Neutrino Telescopes

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Neutrino telescopes perform an indirect search for dark matter (DM) through its annihilation into standard model channels yielding neutrinos, for a broad range of WIMP masses. The ANTARES detector, anchored to the Mediterranean seabed at a depth of about 2500 m, looks for a DM signal from two promising neutrino sources from WIMP annihilation: the Galactic Center and the Sun. We present the latest results on ANTARES indirect detection in a wide range of WIMP masses and decay channels, and give a future prospect on sensitivities of DM searches with the KM3NeT detector, the next-generation neutrino telescope, currently under deployment in the Mediterranean Sea. These experiments have specific advantages, complementary to other detection strategies, and can provide a smoking-gun signal. The geographical location of ANTARES and KM3NeT is particularly well suited for searches in the Galactic Center, allowing for the world-best sensitivity for WIMP annihilation.

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1. Introduction

Dark matter (DM) accounts for 26.4% of the critical density of the universe, but its nature remains unknown [1]. Among the diverse existing DM models, WIMPs (Weakly Interacting Massive Particles) are particularly interesting candidates. The hypothesis that WIMPs are unstable particles opens up the possibility to do indirect searches for WIMPs through the detection of Standard Model (SM) particles, like neutrinos, resulting from WIMP annihilation or decay. The cold and massive nature of WIMPs favors their accretion into celestial bodies, from which their signatures can be searched for. An alternative hypothesis for DM particles is called *Secluded Dark Matter*. This scenario is based on the idea that DM lives in the dark sector, and their annihilation to SM particles is only possible through a metastable mediator (ϕ), which afterwards decays to SM signatures [2–4]. The excellent pointing accuracy of the ANTARES and KM3NeT detectors (Fig. 1) makes them very well suited to perform these searches. Limits on the spin dependent (SD) and spin independent (SI) cross sections, for the solar searches, as well as on the thermally averaged cross sections [5], for the Galactic Center searches, are established.

This document is organized as follows. In section 2, the ANTARES and KM3NeT neutrino telescopes are briefly described. The ANTARES and KM3NeT WIMP searches towards the Sun and the Galactic Center are presented in section 3.1 and section 3.2, respectively. Section 4 ilustrates the results of the secluded DM scenario search.

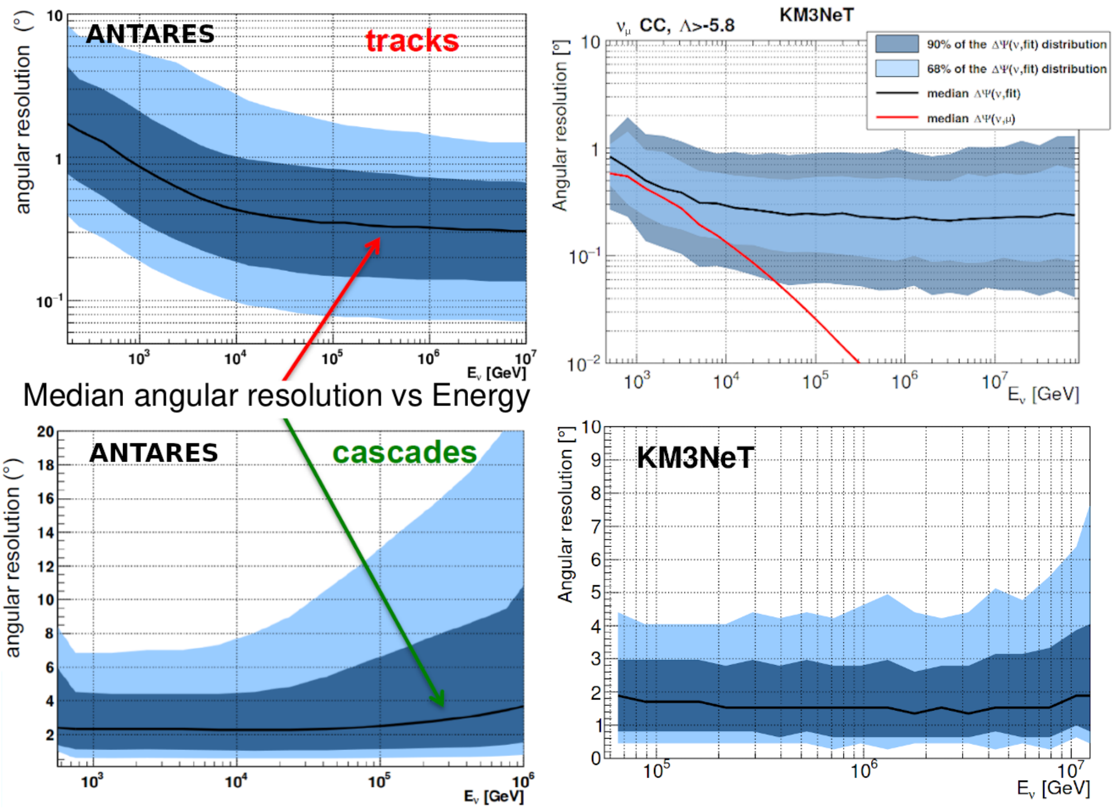

Figure 1: Median angular resolution in ANTARES (left) and KM3NeT (right) for reconstructed track (top) and shower (bottom) events.

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2. The ANTARES and KM3NeT Neutrino Telescopes

The ANTARES detector, anchored on the Mediterranean seabed 40 km offshore of Toulon, France, is the first undersea neutrino telescope [6]. The ANTARES full configuration, completed in 2008, comprises 12 detection lines separated 60-75 m and distributed in an octogonal layout. ANTARES has 295 storeys in total, distributed within the 12 detection lines and with a vertical spacing of about 14 m. The 12^{th} line has 20 storeys and is completed with acoustic detection devices. Each storey contains a triad of optical modules (OMs) [7], housing a photomultiplier tube (PMT). The PMTs are pointing 45° downward in order to optimize the detection of upgoing light from charged particles.

The KM3NeT detector (under deployment) [8] is the next generation undersea neutrino telescope. This infrastructure will consist of two main topologies of 115 strings[1], each string holds 18 digital optical modules (DOMs) and each DOM houses 31 3-inch PMTs. One of the configurations is referred to as ARCA (Astroparticle Research with Cosmics in the Abyss). The other one, more densely configured, is referred to as ORCA (Oscillation Research with Cosmics in the Abyss). ORCA is being installed offshore of Toulon, close to the actual site of ANTARES, while ARCA is being installed at Capo Passero, Italy.

Photons impinging in the sensitive area of the PMTs can induce a signal, called *hit* [9]. Each hit has associated a position, time and collected charge which are used to reconstruct the direction and energy of each event. The influence of the environmental noise (mainly by ^{40}K and bioluminiscence) is reduced by different trigger algorithms [6].

The hard environmental conditions to which an undersea neutrino telescope is exposed may affect the trigger and data acquisition. Therefore, to correctly reproduce the response of the detector under these conditions, a Monte Carlo (MC) *run-by-run* strategy [10] is followed.

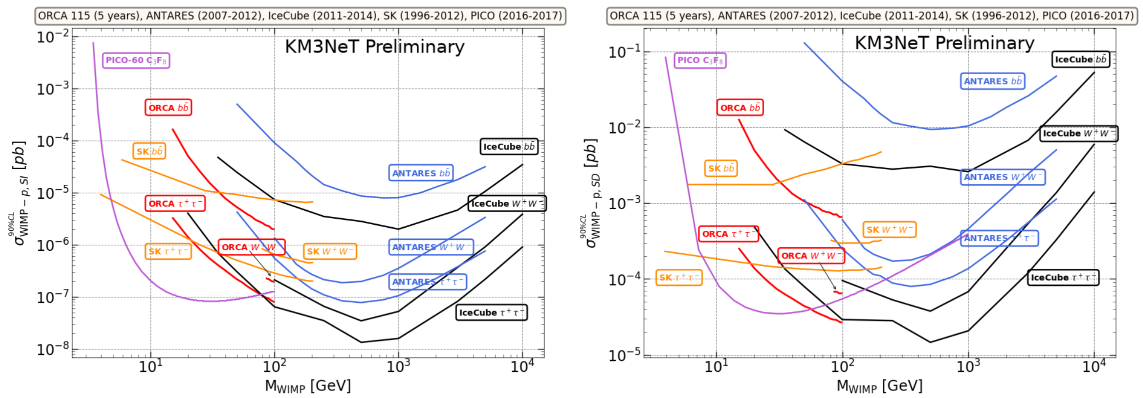

Figure 2: Sensitivities for Spin Independent (left) and Spin Dependent (right) WIMP-proton cross section derived from WIMP annihilation in the Sun, as function of the WIMP mass. The ANTARES limits (blue lines) [11] and the KM3NeT sensitivites (red lines) [12] are shown alongside the results of 3 years of IceCube data (black lines) [13], 1 year of PICO-60 C_3F_8 data (purple line) [14] and 16 years of Super Kamiokande data (orange lines) [15], for comparison.

[1]The word string and detection lines are interchangeable throughout the text.

3. WIMP Dark Matter

3.1 Solar WIMP Dark Matter

The Sun is a privileged place for searching for DM signatures given its proximity to the Earth. The dominant background on searches for DM in the Sun comes from atmospheric muons, atmospheric neutrinos and solar atmospheric neutrinos [20]. The ANTARES sensitivity to this last source of contamination has been studied for 11 years of ANTARES data and presented at the ICRC conference [21].

In 2016 ANTARES published an indirect search for solar WIMP DM particles with 5 years of data (2007-2012) [11], through three main annihilation channels (WIMP-WIMP $\rightarrow b\bar{b}$, W^+W^- and $\tau^+\tau^-$). A new analysis with the full ANTARES data set is in progress. In 2019, KM3NeT performed a preliminary analysis on the potential of the full ORCA detector (115 detection lines) searching for neutrinos yielded by solar WIMP DM annihilations for 5 years of data taking [12]. In Fig. 2 these results from ANTARES and KM3NeT are shown. Equilibrium between annihilation and capture rates is assumed. ORCA improves the sensitivity to solar WIMP DM with respect to ANTARES by almost two orders of magnitude,being highly competitive with other experiments like IceCube within a similar data taking period.

3.2 WIMP Dark Matter in the Galactic Center

ANTARES and KM3NeT, being located in the northern hemisphere, have a privileged position to look to the galactic center (GC). Dark matter accumulated in the GC is distributed in halos, with a higher density of DM at the center. The spatial profile of the halo is described by the so called J-factor, which is function of the dark matter density ρ integrated along the line of sight. In the analysis reported here, three different models for the J-factor have been tested: NFW [22], McMillan [23] and Burkert [24].

In 2020 the ANTARES search for DM in the GC using 11 years of data was published [25]. In the same year, a combined analysis using 9 years of ANTARES data and 3 years of IceCube data

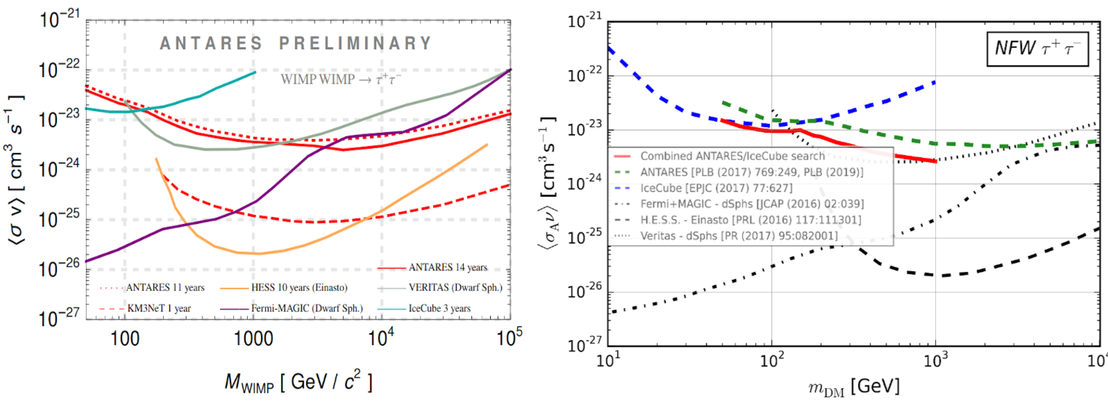

Figure 3: Upper limits at 90% C.L. on the thermally averaged cross-section for WIMP pair annihilation in the GC as a function of the WIMP mass for 14 years of ANTARES data, in comparison with IceCube [16], HESS [17], Veritas [18], Fermi-LAT+MAGIC [19] (left), and for the ANTARES-IceCube combined analysis (right).

was also published [26]. In 2021, ANTARES and KM3NeT performed an analysis of DM in the GC [27], and compared the thermally averaged cross-section for WIMP annihilations between 14 years of ANTARES data (2007–2020) and the potential sensitivity of 1 year of full ARCA (221 lines), with the results of the same measurement from IceCube, HESS, Veritas and Fermi-LAT+MAGIC. The comparison between the 14 years of ANTARES data and the potential of 1 year of ARCA is presented on the left panel of Fig. 3. The great improvement on the sensitivity on the thermally averaged cross-section for WIMP pair annihilation of ARCA with respect to ANTARES is shown. Moreover, ARCA shows to be potentially competitive for DM searches in the GC. On the right side of Fig. 3, the ANTARES-IceCube combined search is plotted. This combined analysis shows an improvement with respect to searches carried out by each experiment independently.

4. Secluded Dark Matter

4.1 Secluded Dark Matter in the Sun

In secluded models, DM particles decay into SM particles through an unstable mediator. The first result on the search for secluded DM from the Sun with the ANTARES detector using 6 years of data (2007 – 2012) was published in 2016 [28] and is shown in Fig. 4. In this analysis, three different scenarios for a typical mediator mass of 1 GeV were tested: (a) direct detection of dimuons produced by the decay of a long-lived mediator, (b) neutrino detection from the decaying dimuons produced by mediators that decayed before reaching the Earth, and (c) the detection of neutrinos decaying directly from mediators, for a mediator lifetime long enough to escape the solar medium.

The lifetime for the dimuon case has to be long enough to ensure that the mediator reaches the vicinity of the Earth. In contrast, for both neutrino cases, the lifetime of the mediator has to be long enough to escape the solar medium, but not so long that it decays before reaching the Earth's vicinity.

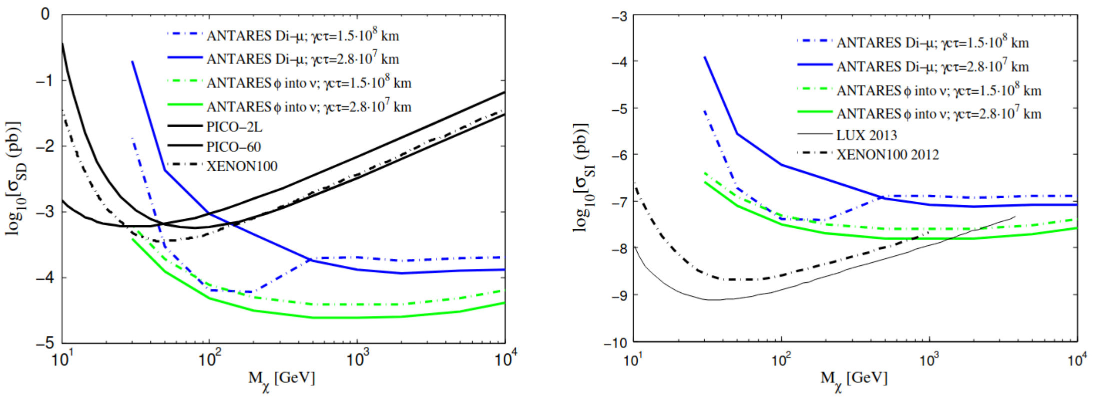

Figure 4: ANTARES upper limits at 90% C.L. on WIMP-nucleon cross section, for the solar secluded DM scenario, as function of DM mass for SD (left) and SI (right) WIMP interactions. Two favourable mediator lifetimes are considered. $\gamma c\tau$ stands for the decay length of the mediator. The bounds from PICO [29–31], LUX [32] and XENON [33, 34] are also shown.

4.2 Secluded Dark Matter from the Galactic Center

The Galactic Center is also suitable for secluded DM searches. Mediator particles decay in the Galactic Center producing SM particles that yield neutrinos via decays or showering. In 2020 ANTARES performed a search in the GC using 9 years of data (2007 – 2015) [35]. Mediator masses considered for the analysis were 50 GeV, 250 GeV and 1 TeV, and four final states SM particles: $\mu^+\mu^-$, $\tau^+\tau^-$, $b\bar{b}$ and $\nu\bar{\nu}$. No signal evidence was found. Limits on the thermally averaged annihilation cross section were established (Fig. 5).

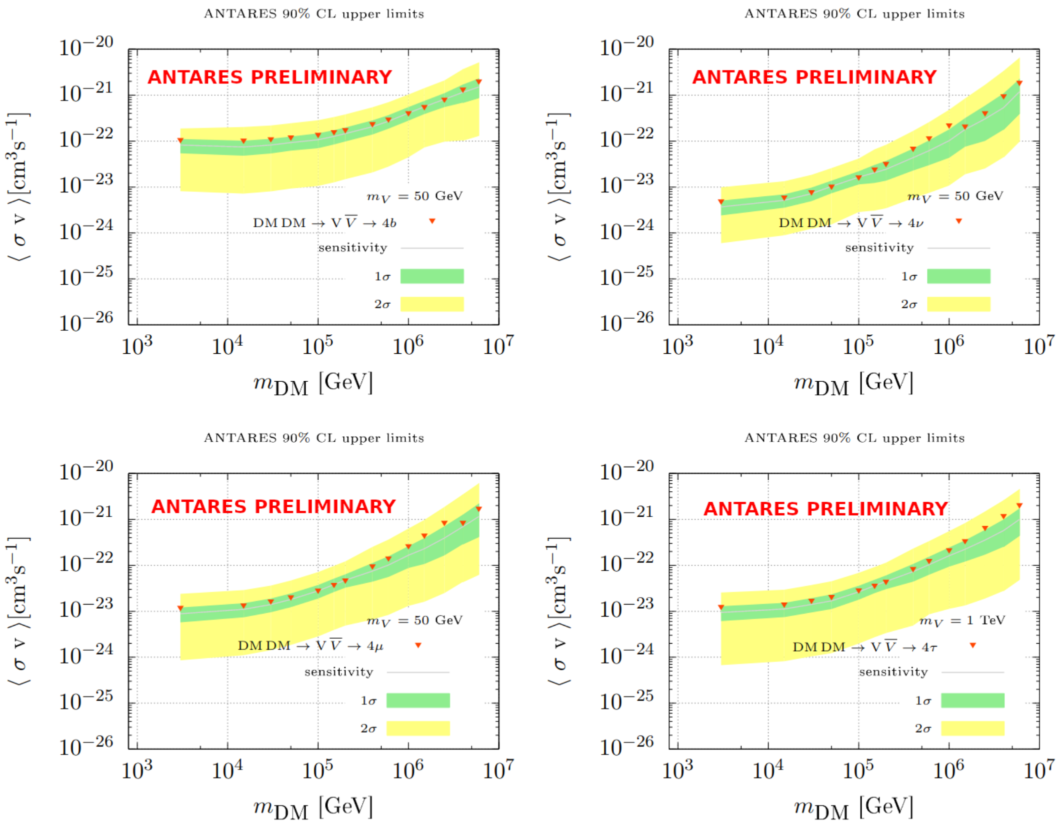

Figure 5: Upper limits at 90% C.L. on the thermally averaged annihilation cross section $\langle\sigma v\rangle$ for a mediator mass m_V = 50 GeV, with 1σ and 2σ containment bands, for four different final states [35] for secluded DM in the Galactic Center searches.

5. Summary

ANTARES and KM3NeT neutrino telescopes have been performing indirect dark matter searches for two different scenarios: WIMP, and Secluded dark matter particles. The Sun and the Galactic Center as sources for dark matter particles accretion have been explored. An unbinned (binned for the combined analysis) likelihood method seeking for dark matter signatures has been employed. No dark matter signal evidence has been found. Upper limits on the thermally averaged annihilation cross section, in the case of the GC, and on the WIMP-proton scattering cross section, for solar searches, have been established. KM3NeT has shown to be potentially competitive in both solar and galactic center DM searches scenarios, overcoming the actual ANTARES sensitivities.

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