Search for Dark Matter Signatures with ANTARES and KM3NeT

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Abstract

Extraterrestrial messengers can be used as trackers to probe the presence of dark matter particles in our Galaxy. Sizable fluxes of high-energy neutrinos, measurable with neutrino telescopes, are expected from pair annihilation and decay of dark matter in regions where it accumulates to a high density. This is the case for massive celestial bodies such as the Sun and the very large dark matter reservoir at the Galactic Center, which are inside the field of view of neutrino telescopes installed in the Mediterranean Sea. ANTARES was operated for 16 years and was recently decommissioned, and KM3NeT is currently taking its first data with its first detection lines. A search for signatures of Weakly Interacting Massive Particles (WIMPs) has been performed in 14 years of all-flavor neutrino data, yielding competitive upper limits on the strength of WIMP annihilation when targeting the Galactic Center. Limits on the WIMP-nucleon cross section have been set considering the nonobservation of dark-matter-induced neutrinos from the direction of the Sun. Other non-WIMP landscapes, such as the model predicting heavy dark matter candidates, have been tested with dedicated searches in ANTARES data. The current results with the first installed KM3NeT subdetectors are also discussed.

Keywords: neutrinos, dark matter, indirect searches
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1. INTRODUCTION

Dark matter makes up to 27% of the Universe's mass-energy budget, and it is an option to picture it as a new particle, fitting it in an extension of the Standard Model [1]. Based on macroscopic observations of dark matter, the candidate particle must be neutral, stable on cosmological scales, fitting the observation of its relic abundance, and not conflicting with Big Bang nucleosynthesis. However, left apart these basic properties, the particle mass and interaction strengths are unconstrained over a wide range of values. The main candidate for neutrino-based searches are weakly interacting massive particles (WIMPs), which naturally display an interaction strength of the same order of the known electroweak interaction, resulting in, therefore, a target for neutrino telescopes. For this kind of *indirect* searches, fluxes of WIMP pair annihilations or decays into neutrino final states, for the specific dark matter scenario considered, are needed as an input. Indirect searches target accumulation points in astrophysical ambient where to find the highest density of dark matter, gravitationally bound, point-like (as the Sun), or considerably more extended than classical astrophysical accumulation points (as the Galactic Center). The amount of dark matter inside a source is characterized using the J-factor $J = \int_{\Omega} d\Omega \int_{l} \rho^2(r(\theta,\phi))dl$, expressing the dark matter density integrated over a given viewing angle Ω and along the line of sight l, at the celestial coordinates θ and ϕ. The shape of the dark matter halo for extended sources is described with models built around astrophysical data, or taking input from N-body simulations, such as Navarro-Frenk-White (NFW) [2], used as a benchmark for the analyses presented here. In the searches presented here, there is no prior assumption on the dark matter candidate mass, which is considered to span values up to $100\,\mathrm{TeV/c^2}$ for classical WIMPs and is extended up to $6\,\mathrm{PeV/c^2}$ in some particular scenarios illustrated later. A lower bound on the WIMP mass tested is instead due to the energy threshold proper of the geometry and spacing of the detector, as detailed in the next sections. This threshold is about 50 GeV for ANTARES, a few GeV for KM3NeT/ORCA, and 100 GeV/c for KM3NeT/ARCA. It is to be stressed that indirect searches are largely affected by systematic uncertainties mostly coming from the parametrization of the dark matter halo profile, which makes the triangulation between search methods (direct, indirect, production) compelling in case of a signal appearance. However, neutrino telescopes are able to place competitive limits. All microscopic searches for a fundamental dark matter particle have until now come up empty-handed.

2. INSTRUMENTS

ANTARES was a very large volume Cherenkov neutrino detector located underwater in the Mediterranean Sea 40 km offshore from Toulon (France). It was composed of 12 detection lines each with a length of 450 meters, anchored to the seabed at a depth of 2500 meters. The lines hosted photomultiplier tubes enclosed in 885 optical modules, which instrumented about $0.1\,\mathrm{km}^2$ of water. ANTARES was cabled to shore and served by the shore station and control room at La Seyne (France); for a detailed technical description, see [4]. The spacing between optical modules determines a minimum energy threshold for an event to trigger a signal. The ANTARES telescope was initially designed for neutrino astronomy; its layout was optimized to detect energies between a few tens of GeV and $10^8\,\mathrm{GeV/c}$. This energy window is exploited for dark matter searches in its lower to middle range. From its geographical position at $42°48'$N, $6°10'$E, this instrument has a coverage of the Galactic Center, where the highest content of dark matter is located, for about 70% of the time. ANTARES was switched off in February 2022 and entirely removed from the waters. The technology expertise that leads to the stable and long-term operation of ANTARES has flown into conceiving the KM3NeT infrastructure.

KM3NeT is a modular network of detectors as of now being deployed in the Mediterranean Sea with a phased installation scheme. The configuration currently in construction hosts one cubic kilometer detector, KM3NeT/ARCA (Astroparticle Research with Cosmics in the Abyss), conceived to catch low astrophysical fluxes, and one dense detector of smaller size, KM3NeT/ORCA (Oscillation Research with Cosmics in the Abyss), to study the properties of atmospheric neutrinos with unprecedented statistics [5]. Although the main goals of these instruments are the identification of neutrino sources (large volume, excellent angular resolution) and the precision measurement of neutrino mass ordering and oscillation parameters (very high statistics), both detectors are potentially suited to perform dark matter searches. From the Mediterranean Sea, as well as ANTARES, both KM3NeT detectors ensure a good visibility of the Galactic Center. All the KM3NeT detectors have the same technology and layout. Their geometry foresees 115 lines, with different spacing: 36 m between optical modules and 90 m interline spacing for KM3NeT/ARCA (that hosts two such blocks); 9 m between optical modules and 20 m inter-line spacing for KM3NeT/ORCA. KM3NeT/ARCA is connected to the shore station of Capo Passero (Italy) while KM3NeT/ORCA uses the same facilities serving the ANTARES supply and DAQ.

3. DATA

In ANTARES and KM3NeT, one data event appears as a pattern of light signals caused by the Cherenkov photons radiated by a lepton which crosses the detector. If the lepton comes from the direction of the Earth, this must have been produced in a weak process by a neutrino interacting on a nucleon in the vicinity of the instrumented volume. The position and time of each light signal are recorded. Both e and μ are currently being seen in these detectors, leaving spherically shaped and track-shaped signatures, respectively. Through the reconstruction of the arrival direction and topology of the daughter lepton track, and the amount of deposited light, it is possible to backtrack the neutrino variables (coordinates, flavor, and energy). The latest data set analyzed by ANTARES in search for dark matter was recorded with ANTARES between January 2007 and February 2020, for an effective lifetime of 3845 days, and contains 11174 tracks and 225 showers. A smaller data sample, covering from 2007 to 2015, was searched looking for heavy secluded dark matter. The sample used for the annihilation of dark matter in the Sun goes instead from 2007 to 2019 including tracks only. Those differences only arise from the logistic organization of the analyses and analysis agreements. KM3NeT/ARCA has taken data for a short period of 106 days in its 6-line configuration; the sensitivity reached with this data set when searching for dark matter from the direction of the Galactic Center is shown here. Similarly, searches for dark matter annihilation in the Sun are being carried out with a 6-line configuration of KM3NeT/ORCA, over a period of about two years.

All dark matter searches rely on Monte Carlo simulations for shaping the signal that would appear in ANTARES. Sets of simulated data have been produced in correspondence with the environmental and trigger conditions of each run of the ANTARES and KM3NeT data acquisition. This Monte Carlo simulation is used to reproduce the dark matter signals specific for each search through appropriate weights that account for energy and space distribution.

4. RESULTS OF DARK MATTER SEARCHES

In these proceedings, three main results are shown: (1) search for WIMP annihilations in the Galactic Center using all-flavor neutrino data, (2) search for heavy dark matter in secluded scenarios, and (3) search for dark matter annihilation in the Sun. All these searches are structured as a hypothesis test, discriminating a signal of dark-matter-induced neutrino events around the source region from the null hypothesis, where all events are neutrinos originated in the Earth's atmosphere. A binned or unbinned maximum likelihood method is used. Sensitivity is obtained as the average upper limit from pseudo-experiments. The data set is initially blinded (i.e., randomized in the significant discriminating variables) to ensure an unbiased cut optimization. The specific signal that would appear in ANTARES is obtained by reweighting Monte Carlo simulated events to match the energy distribution of a WIMP pair collision. The corresponding energy distributions are obtained with PPPC4DMID [3] for the Galactic Center, with WIMPSim [9] for the Sun, and with dedicated spectra for the secluded case. In all these cases, a pair of WIMPs annihilate into intermediate states (primaries) that being in turn unstable yield secondaries such as neutrinos. Above an energy threshold of $\mathcal{O}(100)$ GeV, W and Z radiation initiates an electroweak cascade where secondaries can as well be emitted. The best source for ANTARES is the Galactic Center where dark matter is known to accumulate gravitationally bound. Being very dense and relatively close (therefore seen as extended), the Galactic Center turns out to have the largest J-factor among all dark matter sources. Firstly, ANTARES has searched for a WIMP annihilation signal in their 2007–2020 data set using both tracks and cascades, finding the test statistic of these data to be compatible with the background. Upper limits at 90% CL based on this nonobservation are shown in Figure 1. The same figure also shows sensitivities achieved with the existing subdetector ARCA6 (6 deployed lines) of KM3NeT, for a short lifetime of 106 days.

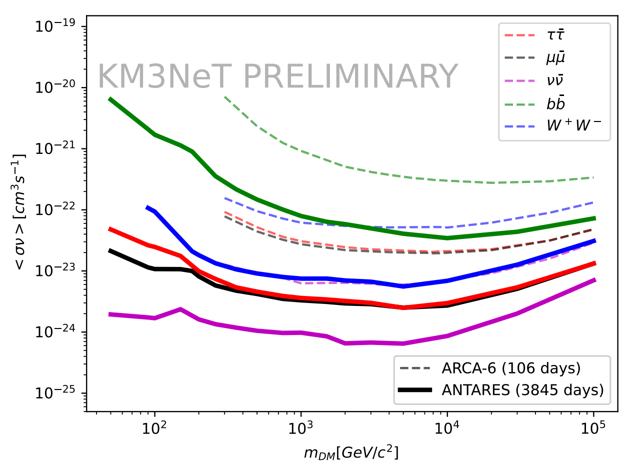

FIGURE 1: Upper limits at 90% CL on the thermally averaged cross section for WIMP pair annihilation as a function of the WIMP candidate mass set with 14 years of ANTARES data, shown for five independent annihilation channels (each with 100% branching ratio) and NFW halo model [2].

As mentioned earlier, systematic uncertainties largely affect these results, such as the dark matter halo model and the relative branching fractions of the different annihilation channels. In this analysis, each channel is considered independently with a 100% branching ratio. The data collected with ANTARES set

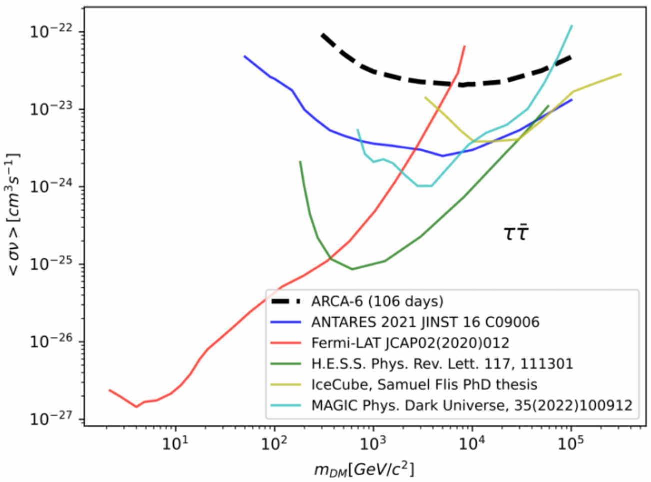

FIGURE 2: Upper limits at 90% CL on the thermally averaged cross section for WIMP pair annihilation obtained with different experiments.

particularly stringent limits on the channel where two WIMPs annihilate directly into neutrinos, more favorable for detection due to their spectra peaking toward high energies; additionally, this channel is exclusively visible with neutrino telescopes. For other channels, stringent limits come as well from nonobservations with γ-ray telescopes, as illustrated for the WIMP WIMP $\rightarrow \tau^+\tau^-$ case in Figure 2.

WIMPs are searched in the 50 GeV/c^2 to 100 TeV/c^2 mass range, assuming a freeze-out mechanism granting their relic abundance, but there are extensions to classical WIMP cosmology. A search for a heavy dark matter candidate in a secluded scenario has been carried out in ANTARES data from 2007 to 2015 [8]. In this model, the dark matter particles pair-annihilate into a mediator V, subsequently decaying into Standard Model particles yielding neutrinos. The coupling of V to Standard Model particles can be tuned as small as necessary not to conflict with the nonobservation of dark matter production at colliders. In a secluded dark matter annihilation, a pair of mediators V is thermally produced on-shell and originates 4 Standard Model particles. The presence of this mediator modifies the freeze-out point allowing for the dark matter candidate to be heavier than in classical WIMP cosmology: freeze-out happens at an earlier time and the dark matter particles are later more diluted. Also for this search, the test statistics of ANTARES data is compatible with the null hypothesis, and upper limits at 90% CL are displayed in Figure 3. What is distinctive about the model tested here is that the investigated mass range for the dark matter particle ranges up to 6 PeV/c^2. Although limits for heavy secluded dark matter are not stringent in the large mass region, this represents the first search for a dark matter up to PeV energies with neutrino telescopes.

In all analyses targeting the Galactic Center the full process leading to neutrino final states happens inside the source, implying that the energy distributions of neutrinos are not distorted by the passage through matter and are only flavor-oscillated on the distance Galactic Center to Earth.

The Sun is also an accumulation point for dark matter targeted with neutrino telescopes. WIMPs can have two types of interactions with ordinary matter: spin-dependent, coupling to

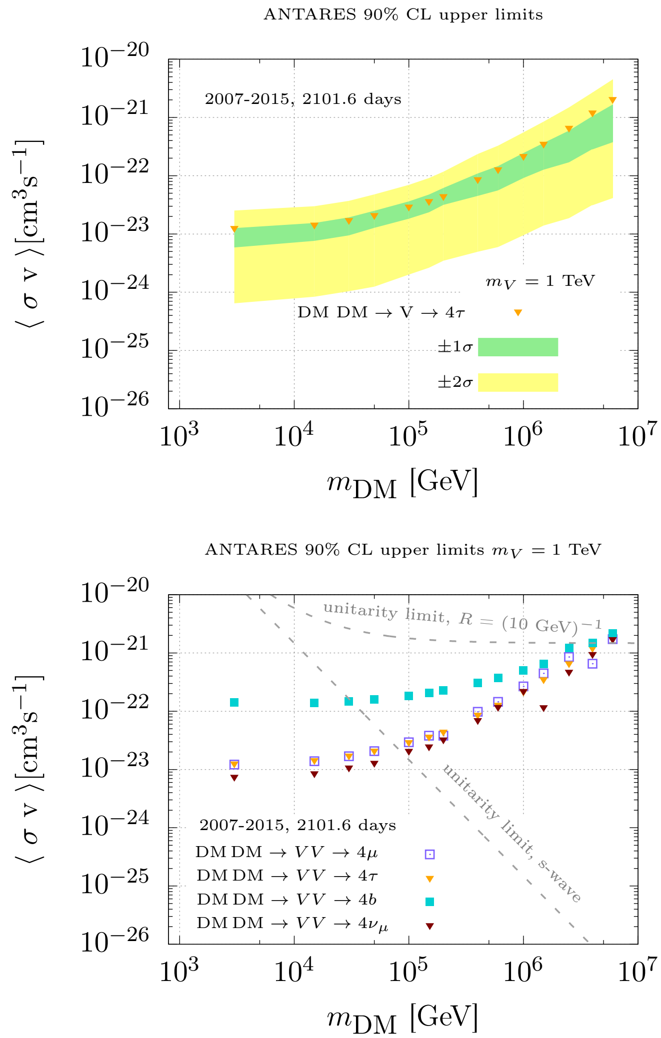

FIGURE 3: Upper limits at 90% CL on the thermally averaged cross section for pair annihilation of dark matter in a secluded scenario, with 1σ and 2σ containment bands, shown here for example values of mediator mass mV = 1 TeV and 4τ final states (upper panel) and for the mediator decay channels 4μ, 4τ, $4b$, $4\nu_\mu$ (lower panel); see [8] for complete details.

the spin of the target nucleon, and spin-independent, coupling to its mass [7] (SD and SI, respectively, in Figure 4). The two of them can take place inside the Sun that contains both light elements with an odd number of nucleons, like hydrogen, and relatively heavy elements, like Helium and Oxygen. Through either process, WIMPs are captured inside the Sun where their density raises until equilibrium, when the capture rate equals the rate of annihilation into Standard Model particles, making the Sun a source of a continuous neutrino flux from WIMP annihilation. The final states, energy spectra undergo further distortions due to the amount of dense matter to cross before leaving the Sun's surface and are computed using WIMPSim [9]. ANTARES has searched their 2007–2019 data set using tracks coming from the direction of the Sun and placed upper limits on the presence of dark-matter-induced events for both SD and SI interactions, as displayed in the two panels of Figure 4. For searches in the Sun, a special source of background from cosmic

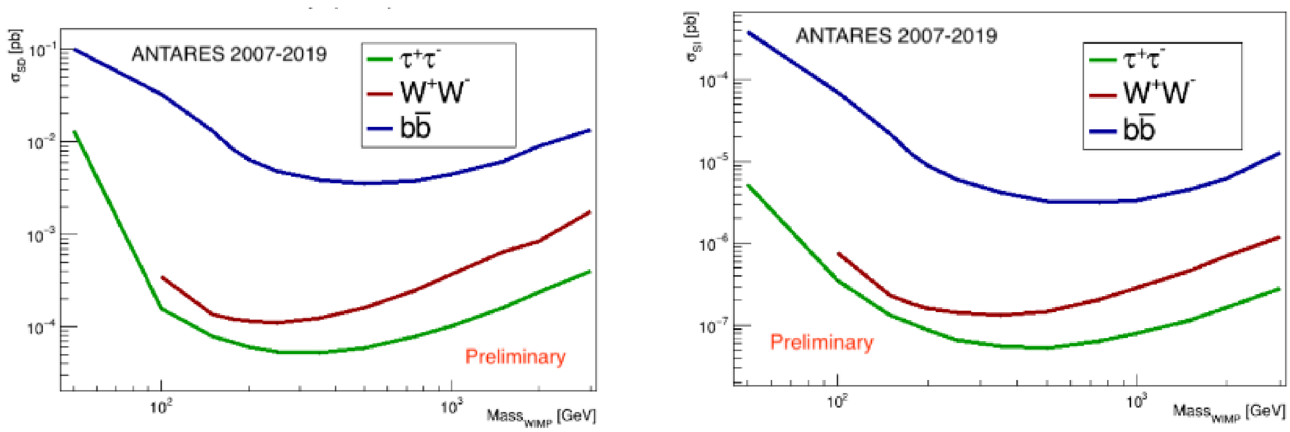

FIGURE 4: Upper limits at 90% CL on WIMP-nucleon interactions in the Sun, for spin-dependent cross section (left panel) and spin-independent cross section (right panel). Three different annihilation channels are displayed. The data set searched includes tracks from 2007 to 2019.

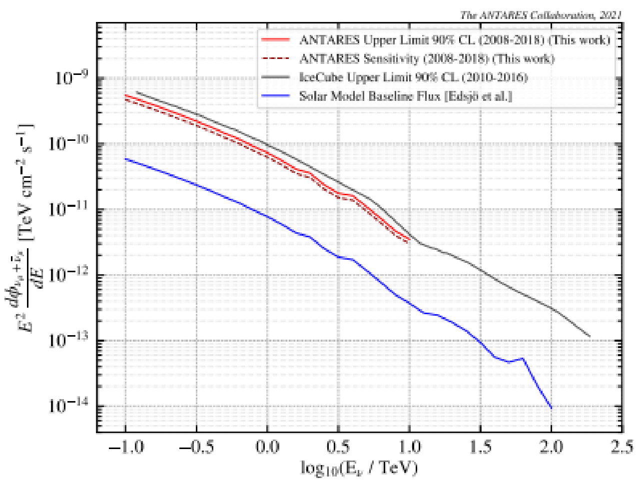

FIGURE 5: ANTARES upper limit on solar atmospheric neutrinos (solid red line) for 11 years of data, assuming the Sun as point-like source. Details are described in [10].

ray interactions in the Sun, known as solar atmospheric neutrinos, has been thoroughly searched for [10]; upper limits to this contribution are shown in Figure 5.

CONFLICTS OF INTEREST

The author declares that there are no conflicts of interest regarding the publication of this paper.

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