PROCEEDINGS OF SCIENCE

Search for dark matter signatures in ANTARES neutrino data

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Extraterrestrial neutrinos can be used as messengers to probe the presence of dark matter particles in our Galaxy. Indeed, sizable fluxes of high-energy neutrinos are expected from pair annihilation and decay of dark matter in regions where it accumulates to a high density. Massive celestial bodies such as the Sun and a possible large dark matter reservoir like the centre of the Milky Way were inside the field of view of the ANTARES neutrino telescope, which was operated underwater in the Mediterranean Sea for 16 years (2007-2022) and was recently decommissioned. ANTARES could trace the arrival direction of neutrinos with a precision of half a degree. A search for signatures of Weakly Interacting Massive Particles (WIMPs) has been performed with 14 years of all-flavour neutrino data, yielding competitive upper limits on the strength of WIMP annihilation. Other non-WIMP landscapes, such as models predicting heavy dark matter candidates, have been tested with dedicated searches in ANTARES data. Indirect dark matter searches are being continued with the KM3NeT telescopes, currently in construction in the Mediterranean Sea.

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1. Introduction

Astrophysical messengers such as neutrinos and photons can be trackers of the annihilation of dark matter particles inside an astrophysical environment. Dark matter makes up to 27% of the Universe mass-energy budget and it comes natural to postulate it as a new particle, fitting it in an extension of the Standard Model [1]. Possible properties of the dark matter particle are inferred from current macroscopic observations: the candidate must be neutral, stable on cosmological scales, explaining the relic abundance observed nowadays, not conflicting with Big Bang nucleosynthesis. 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), that naturally display an interaction strength of the same order of the know electroweak interaction, resulting therefore a target for neutrino telescopes. For this kind of *indirect* searches, fluxes of WIMP pair annihilations or decays into neutrino final states are needed as input. Indirect searches target 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 overdensity regions (as the Galactic Centre). The amount of dark matter inside a source is characterised using the J-factor expressing the dark matter density integrated over a given viewing angle and along the line of sight. 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]. There is no prior assumption on the dark matter candidate mass, that is considered to span values up to 100 TeV/c^2 for classical WIMPs, and is extended up to 6 PeV in some particular scenarios illustrated later. A lower bound of about 50 GeV/c^2 is instead due to the energy threshold related to the geometry and spacing of the ANTARES detector, as detailed in the next sections. It is to be stressed that indirect searches are largely affected by systematic uncertainties mostly coming from the parametrisation of the dark matter halo profile, which makes the triangulation between search methods (direct, indirect, production) compelling in case of a signal appearance. Even though all microscopic searches for a fundamental dark matter particle have until now come up empty-handed, neutrino telescopes are able to place competitive limits.

2. Instruments

ANTARES was a very-large volume Cherenkov neutrino detector that used be located underwater in the Mediterranean Sea 40 km offshore from Toulon (France). It was composed of 12 detection lines with a length of 450 metres, anchored to the seabed at a depth of about 2500 metres. Those lines hosted photomultiplier tubes enclosed in 885 optical modules, which instrumented about 0.1 km^2 of sea water. ANTARES was cabled to shore and served by the shore station and control room at La Seyne (France); for a complete detailed technical description see [7]. 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 optimised to detect energies between a few tenths of GeV/c^2 and 10^8 GeV/c^2. This energy window is exploited for dark-matter searches in its lower to middle energy range. From its geographical position at 42°48'N, 6°10'E, this instrument has a good coverage of Galactic Centre (visible for about 70% of the time), where the highest content of dark matter is expected to be. ANTARES was switched off in February 2022 and entirely removed from the sea waters. The technology expertise that leads to the stable and long-term operation of ANTARES has flown into conceiving the KM3NeT infrastructure. Two detectors are part of the current design of KM3NeT: a dense detector targeting atmospheric neutrino studies (ORCA) and two detectors instrumenting a cubic kilometre for catching astrophysical neutrinos (ARCA). KM3NeT is currently being deployed in the Mediterranean Sea with a phased installation scheme, so that the connected lines are recording data and first results have been obtained with intermediate of the full detector. For details on the KM3NeT neutrino telescope see [8].

3. Data

One data event appears in ANTARES as a pattern of light signals with timing information, caused by a lepton embedded in its Cherenkov cone crossing the detector, or by Cherenkov light related to a particle shower, in turn produced in a weak process by a neutrino interacting on a nucleon in the vicinity of the instrumented volume. Through reconstruction of arrival direction of the daughter lepton, energy and topology of the event it is possible to backtrack the neutrino variables. The latest data set analysed by ANTARES in search for dark matter was recorded with ANTARES between January 2007 and February 2020, for an effective livetime 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 annihilation of dark matter in the Sun goes instead from 2007 to 2019 including tracks only. Those differences only arise from logistic organization of the analyses and analysis agreements. All dark matter search strategies 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 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 of dark matter overdensity regions.

4. Results of dark matter searches

In these proceedings, three main results are shown: (1) search for WIMP annihilations in the Galactic Centre using all-flavour 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 tests, 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. randomised 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 WIMP pair collisions. The corresponding energy distributions are obtained with PPPC4DMID [4] for the Galactic Centre, with WIMPSim [6] for the Sun, and with dedicated spectra for the secluded case. The best candidate for ANTARES is the Galactic Centre where dark matter is expected to accumulate gravitationally bound. Being very dense and relatively

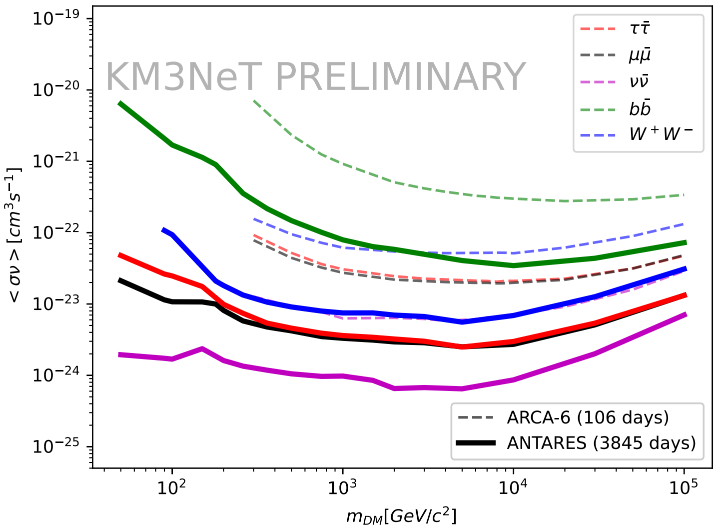

Figure 1: Upper limits at 90% C.L. on the thermally averaged cross-section for WIMP pair annihilation as a function of the WIMP candidate mass set with 14 years of ANTARES data, shown for five independent annihilation channels (each with 100% branching ratio) and NFW halo model [2].

close (therefore seen as extended), the Galactic Centre turns out to have the largest J-factor [2] 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 background. Upper limits at 90% C.L. based on this non-observation of signal from dark matter annihilations are shown in Fig. 1. The same figure also shows sensitivities achieved with the existing sub-detector ARCA6 (6 deployed lines) of KM3NeT, for a short livetime of 106 days. WIMPs are searched in the 50 GeV to 100 TeV mass range, assuming a freeze-out mechanism granting their relic abundance; but there are extensions to classical WIMP cosmological evolution. A search for a heavy dark matter candidate in a secluded scenario has been carried out in ANTARES data from 2007 to 2015 [10]. In this model, the dark matter particles pair-annihilate into a mediator V with example masses of 50 GeV, 1 TeV and 10 TeV, subsequently decaying into Standard Model particles yielding neutrinos. The presence of this mediator modifies the freeze-out point allowing for the dark matter candidate to be heavier; freeze-out happens at an earlier time with respect to WIMP cosmology, and the dark matter particles are later more diluted. Also this search results empty-handed, and upper limits at 90% C.L. are displayed in Fig. 2. What is distinctive for the model tested here is that the mass range investigated ranges up to 6 PeV/c^2. Despite limits for heavy secluded dark matter are not stringent in the high mass region, this represents the first search for a dark matter up to the PeV with a neutrino telescope. In all analyses targeting the Galactic Centre the full process leading to neutrino final states happens inside the region, implying that the energy distributions of neutrinos are not distorted by the passage through matter and are only flavour-oscillated on the distance Galactic Centre to Earth. The Sun can also be an accumulation point for dark matter targeted with neutrino telescopes. WIMPs can have two types of interactions with ordinary matter: spin-dependent, coupling to the spin of the target nucleon, and spin-independent,

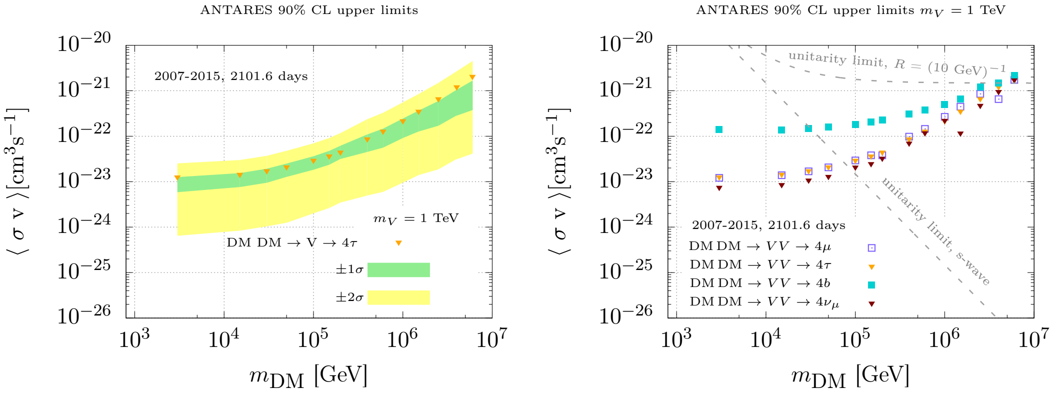

Figure 2: Upper limits at 90% C.L. on the thermally averaged cross section for pair annihilation of dark matter in a secluded scenario, with 1σ and 2σ containment bands, shown here for example values of mediator mass mV = 1 TeV and 4τ final states (left panel) and for the mediator decay channels 4μ, 4τ , $4b$, $4\nu_\mu$ (right panel). See [10] for complete model and analysis details.

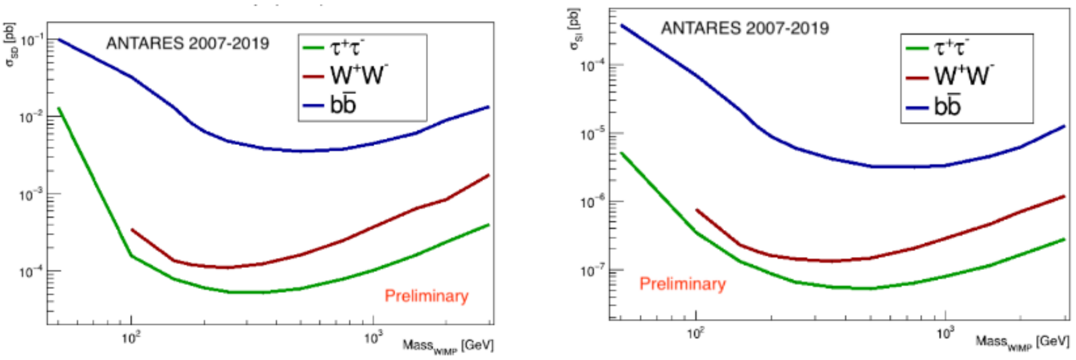

Figure 3: Upper limits at 90% C.L. on WIMP-nucleon interactions in the Sun, for spin-dependent cross section (left panel) and spin-independent cross section (right panel). Three different annihilation channels are displayed. The data set searched includes tracks from 2007 to 2019.

coupling to its mass [5] (SD and SI, respectively, in Fig. 3). 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 capture rate equals the rate of their 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 [6]. ANTARES have 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 both for SD and SI interactions, as displayed in the two panels of Fig. 3. For searches in the Sun, a special source of background from cosmic-ray interactions in the Sun, known as solar atmospheric neutrinos, has been thoroughly searched for [11]; upper limits to this contribution are shown in Fig. 4.

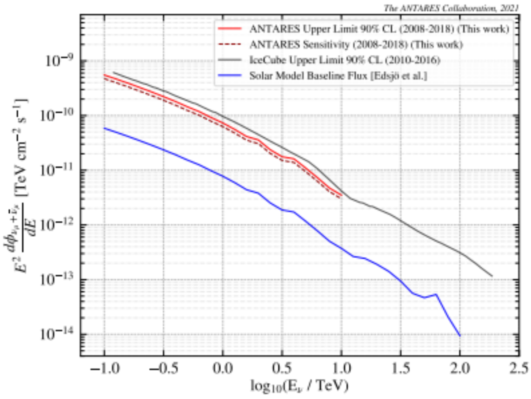

Figure 4: ANTARES upper limit on solar atmospheric neutrinos (solid red line) for 11 years of data, assuming the Sun as point like source. Details are described in [11].

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