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Search for dark matter with the ANTARES and KM3NeT neutrino telescopes

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One of the most pressing tasks in physics today is the search for dark matter, whose nature is still unknown despite it makes the majority of the matter content in the Universe. If dark matter is made of particles, those are outside the Standard Model. In the last decades, several of their properties were learned, but they are still quite unbound. A multi-front attack to the problem is needed, as it is impossible to know in advance which is the best experimental strategy to look for dark matter. Neutrino telescopes have interesting advantages in this endeavour. It is expected that dark matter particles would accumulate in astrophysical bodies like the Sun or the Galactic Centre and their final annihilation/decay products would include neutrinos. In the case of the Sun, it would be a very clean signal, since no relevant astrophysical background is expected. In the case of the Galactic Centre, the results of the ANTARES neutrino telescope provide constraining limits for large masses of dark-matter candidates. In this talk, the most recent results obtained by ANTARES for the search of neutrinos due to dark-matter annihilation in different astrophysical objects are reviewed. The perspectives for its successor, KM3NeT, already in construction, are also shown.

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PoS(ICRC2019)552

1. Indirect dark-matter searches with neutrinos

The existence of cold, non-baryonic dark matter is well supported by astrophysical observations on macroscopic scale, encouraging searches for its fundamental particle constituents. Phenomenological details of a dark-matter theory are poorly constrained, apart from the request to accommodate the dark-matter relic density observed today, which can be obtained in a freeze-out scenario with a candidate whose interaction cross-section with Standard Model particles is of the order of the electro-weak scale. Searches concentrate then on Weakly Interacting Massive Particles (WIMPs) through their Standard Model products. Neutrino detectors operate in the 'indirect search' channel in astrophysical environment. These instruments can look at potential dark-matter sources for pair annihilation of WIMPs into neutrinos, either as a direct or a secondary product. In the search presented here, the channels with the highest neutrino yield were selected, each one independently with a 100% branching fraction. These channels are:

$$\text{WIMP WIMP} \rightarrow b\bar{b}, \tau^+\tau^-, W^+W^-, \mu^+\mu^-, \nu\bar{\nu} \tag{1.1}$$

In WIMP scenarios, the dark-matter candidate mass M_{WIMP} ranges from GeV/c^2 to TeV/c^2, and is kept as a free parameter in this analysis. The specific details concerning the model-building theory providing a WIMP candidate (SUSY neutralinos [1], axions [2], dark photons [3] just to cite some) are not directly relevant for this search.

The neutrino energy spectrum of each annihilation channel is taken from PPPC4 [4] and will be indicated as dN_ν/dE_ν from now on, representing the number of neutrinos emitted per energy and per WIMP annihilation. The spectra provided by PPPC4 refer to an isotropic emission of neutrinos at the source, and were modulated to account for flavour oscillation between source and detection point in the long baseline approximation.

In indirect searches, location and distribution of dark matter abundance is a necessary input. Observations indicate that galaxies are embedded in a halo of thermal relic density of dark matter with a high density at the centre, whose spatial profile is described by the J-factor function of the dark-matter density ρ integrated along the line of sight:

$$J = \int_\Omega d\Omega \int_{l.o.s.} \rho^2 ds. \tag{1.2}$$

The extension of the halo is such that the detector sits inside the source; the solid angle Ω identifies an appropriate search cone, representing the actual extension of the source. The parameter s is instead determined by the distance Earth-Galactic Centre. Different models for J were tested in this analysis: NFW [5], McMillan[6] and Burkert [7].

Predictions on neutrino fluxes deriving from dark-matter annihilation strongly rely on the parameterisation of the density ρ, which is affected by large uncertainties from astrophysical measurements of dark-matter distribution in the Galaxy. The relation between the observed flux and the annihilation rate, integral J-factor and WIMP annihilation spectra is given by

$$\frac{d\Phi(E_\nu)}{dE_\nu} = \frac{1}{4\pi M^2_{\text{WIMP}}} \frac{\langle\sigma v\rangle}{2} \frac{dN(E_\nu)}{dE_\nu} J. \tag{1.3}$$

Through this relation, a measurement of the integrated neutrino and antineutrino flux from the Centre of the Galaxy $\Phi_{\nu+\bar{\nu}} = \int dE_\nu\,(d\Phi_\nu/dE_\nu) + \int dE_{\bar{\nu}}\,(d\Phi_{\bar{\nu}}/dE_{\bar{\nu}})$ is converted into limits on the thermally averaged annihilation cross-section $\langle\sigma v\rangle$.

PoS(ICRC2019)552

2. Analysis setup

2.1 Sources

Target of observations are potential dark-matter accumulators as the Galactic Centre, the Sun or classes of non luminous galaxies. Among those, the Galactic Centre and the Sun are preferred for neutrino telescope analyses, which profit of their large J-factors. Dwarf Sphaeroidal Galaxies typically have smaller J-factors but are a good target for γ-ray telescopes because of their very low luminosity. From the point of view of visibility, the Galactic Centre is located in the Southern Hemisphere, observed from the latitude of ANTARES (42°48'N) from across the Earth. This allows 'standard' data acquisition using the Earth as screen for atmospheric muon background.

In these proceedings the latest results of ANTARES observations of the Galactic Centre are presented, together with sensitivity estimates with KM3NeT. An analysis of sensitivities reached for dark-matter annihilation in the Sun is presented in a parallel contribution [8].

2.2 Detectors

ANTARES is an underwater Cherenkov detector located in the Mediterreanean Sea 40 km offshore from Toulon, composed of 12 detection lines hosting photomultiplier cameras enclosed in optical modules. For a more detailed technical description see [9]. KM3NeT will consist of two detectors, ARCA (Astroparticle Research with Cosmics in the Abyss) and ORCA (Oscillation Research with Cosmics in the Abyss), both currently being deployed in the Mediterranean Sea [10]. KM3NeT will instrument a total of 1 km^3 of water, with 3 blocks of 115 lines each, in different geometries: 36 m between optical modules and 90 m inter-line spacing for ARCA, optimised for high energies; 9 m between optical modules and 20 m inter-line spacing for ORCA which is designed for conducting oscillation research with atmospheric neutrinos.

The potential of these new detectors towards dark-matter searches has been examined; not having a prior bound on the WIMP mass value, both ARCA and ORCA are suited for continuing the search after ANTARES. [8].

2.3 Data set

We have analysed 11 years of data taken with the ANTARES neutrino telescope between May 2007 and December 2017, updating upon prior searches conducted on a 9-year data set [11]. Signatures of dark-matter neutrinos are searched for in a data sample composed of reconstructed muon tracks originated by the charged current (CC) interaction of neutrinos in the vicinity of the detector volume. A set of pre-selection cuts has been applied to discriminate these ν_μ CC induced events from atmospheric muon background; this first discrimination is based on the zenith angle of provenience of the event and on the track-reconstruction quality. This sample is composed of 8976 tracks recorded over 3170 days of effective livetime; note that in the text that follows the term neutrinos stands for $\nu + \bar{\nu}$, as both are seen in our data indistinguishably. Tracks are reconstructed with a good angular resolution of less than 1 degree. Given its geometry and volume, the ANTARES telescope is not optimised for dark-matter searches, but rather for astrophysical high-energy searches, starting to trigger events with energies from about 20 GeV to PeV. The dark-matter analysis is, therefore, in the low-to-medium energy range. The energy of a neutrino-induced lepton track is proportional to the amount of Cherenkov photons radiated and consequently the number of hit OMs. A set of simulated data has been produced in ANTARES in correspondence with the environmental and trigger conditions of each data run, and has been adapted to the specific dark-matter analysis through the use of *weights* reproducing the energy distribution dN_ν/dE_ν of each WIMP annihilation channel. This search is optimised on right-ascension shuffled (*blind*) data, which are unblinded after having established the best selection criteria.

The sensitivity of KM3NeT-ARCA to dark-matter annihilations in the Galactic Centre is evaluated, both for a preliminary sub-block composed of 24 lines, and for the final configuration of 2 blocks of 115 lines each. Simulated data produced for two configurations of KM3NeT-ARCA were analysed; these simulations contain a sample of $\nu_\mu + \bar{\nu}_\mu$ CC events (tracks) corresponding to 1 year of livetime, for each of the two detector configuration.

3. Search method

The dark-matter annihilation signal is expected to appear as a cluster of events around the position of the Galactic Centre, whose energy distribution mimics the dN_ν/dE_ν WIMP annihilation spectra and with morphology given by the J-factor. A cluster of dark-matter induced events would superimpose to the atmospheric neutrino background uniformly distributed in right ascension. Discriminating variables are therefore the coordinates α_i of the neutrino events and the energy proxy N_{HITS}. The signal is described by a space and energy distribution $\mathscr{S}$ of variables from simulated data weighted with dark-matter spectra. Analogously, a background distribution $\mathscr{B}$ is built from blind data, representing atmospheric neutrinos, being any possible cluster washed away by randomly shuffling of their space coordinates. Both distributions, $\mathscr{S}$ and $\mathscr{B}$, are normalised to 1 to be used as probability density functions (PDFs) for signal and background respectively. A large number of toy skymaps (pseudo-experiments) is generated injecting an arbitrary number of signal events n_s, according to the $\mathscr{S}$ PDF, over a total set of $n_s + n_{bg}$ events. The number of background events is obtained from the total number of tracks in the data sample. The algorithm used for cluster search is based on an unbinned likelihood function $\mathscr{L}$ associated with each skymap

$$\log \mathscr{L}(n_s) = \sum_{i=1}^{N} \log \left[n_s \mathscr{S}(\psi_i, N^i_{\text{HITS}}, q_i) + n_{bg} \mathscr{B}(\delta_i, N^i_{\text{HITS}}, q_i) \right] - n_{bg} - n_s. \tag{3.1}$$

Likelihood maximisation returns the number of events n_s^* found to belong to a cluster around the fixed coordinates of the Galactic Centre (α, δ) = (266°,−29°). The significance of a cluster is established by the test statistics TS, function of the ratio between maximum likelihood and pure background likelihood

$$TS = -\log \frac{\mathscr{L}(n_s^*)}{\mathscr{L}(n_s = 0)}. \tag{3.2}$$

The number of events in each set of pseudo-experiments is subject to fluctuations following a Poisson distribution. To include this effect, a transformation through a Poisson function $\mathscr{P}$ is performed, returning the TS as a function of the Poissonian mean μ

$$P(TS(\mu)) = P(TS(n_s^*)) \times \mathscr{P}(n_s, \mu). \tag{3.3}$$

Finally, a 15% systematics on the number of detected events is expected with ANTARES [12]. This effect is included folding the above equation with a Gaussian smearing of 15% width.

4. Sensitivity estimation

Following Neyman's prescription [13], an average upper limit on the number of signal events is firstly computed from the background median test statistics $\overline{TS}_0$, compared with each distribution $P(TS)$ for each pseudo-experiment set. The sensitivity is defined as the 90% C.L. upper limit for a measurement coinciding with the median of the background TS distribution. Limits are set equal to the sensitivity in case a value smaller than the background median is observed in the data.

5. Acceptances

In this analysis, a measurement (limit) on the total number of signal events in the data is converted into an integrated flux $\Phi_{\nu+\bar{\nu}}$ through the acceptance $\mathscr{A}$ and the livetime t as

$$\Phi_{\nu+\bar{\nu}} = \frac{\mu_{90}}{\mathscr{A}t}, \tag{5.1}$$

where the acceptance is defined as the integral effective area modulated through each annihilation mode spectrum dN_ν/dE_ν:

$$\mathscr{A}(M) = \int_0^M A^{\nu}_{eff}(E_\nu)\frac{dN_\nu(E_\nu)}{dE_\nu}dE_\nu + A^{\bar{\nu}}_{eff}(E_{\bar{\nu}})\frac{dN_{\bar{\nu}}(E_{\bar{\nu}})}{dE_{\bar{\nu}}}dE_{\bar{\nu}}. \tag{5.2}$$

The detector effective area increases with energy due to the raise with energy of the ν_μ CC cross section [14], combined with the better track definition (improved reconstruction quality) of high energy events, and with an increase in the effective volume, as partially contained tracks can still be measured. This calculation relies on spectra provided by PPPC4 [4].

The integrated flux of Eq. 5.1 is converted into a measurement (limit) on the cross-section for WIMP annihilation rate using Eq. 1.3.

6. Results, discussion and future

Upper limits have been obtained with 11 years of ANTARES data. The unblinding procedure consists in computing the test statistics of the data after having re-assigned the real coordinates to each event. Upon unblinding, no TS compatible with signal has been observed in the data. This measurement sets limits on the cross-section for WIMP-pair annihilation, shown in Figure 1 and computed according to equation 1.3. The total amount of dark matter within a 30° angle around the Galactic Centre is computed, which corresponds to the solid angle Ω in Eq. 1.2. Best limits are obtained for the direct $\nu\bar{\nu}$ channel, which has the highest acceptance and lowest number of resolvable events, due to the peak of events around the WIMP candidate mass. Channels with steeply falling spectra as $b\bar{b}$ give the least stringent limits.

Limits from dark-matter annihilation strongly rely on the J-factor model. A set of 10^5 toy skymaps has been generated for each mass and for each of three halo models NFW [5], Burkert [7], McMillan [6], delivering considerable differences in the minimum number of events resolved μ_{90}. The limits on the WIMP pair-annihilation cross section for these three halo models are reported in Figure 2.

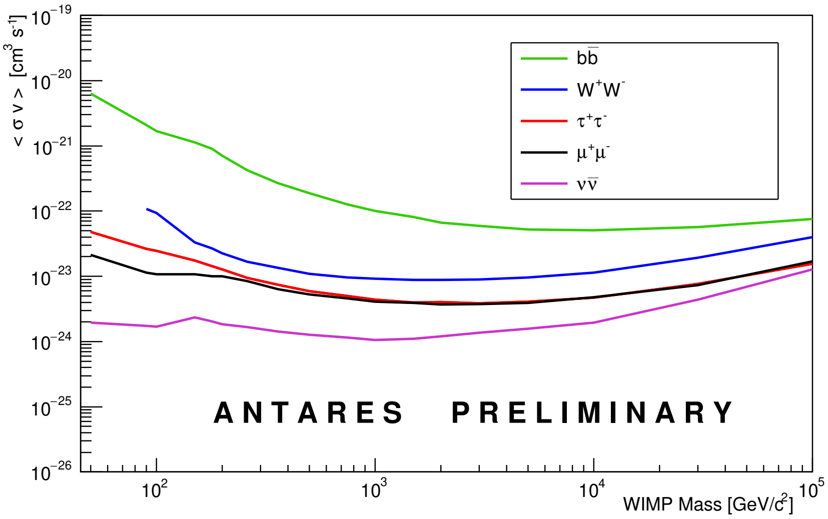

Figure 1: Upper limits at 90% C.L. on the thermally averaged cross-section for WIMP pair annihilation as a function of the WIMP candidate mass set with 11 years of ANTARES data, shown for five independent annihilation channels (each with 100% branching ratio) and NFW halo model [5].

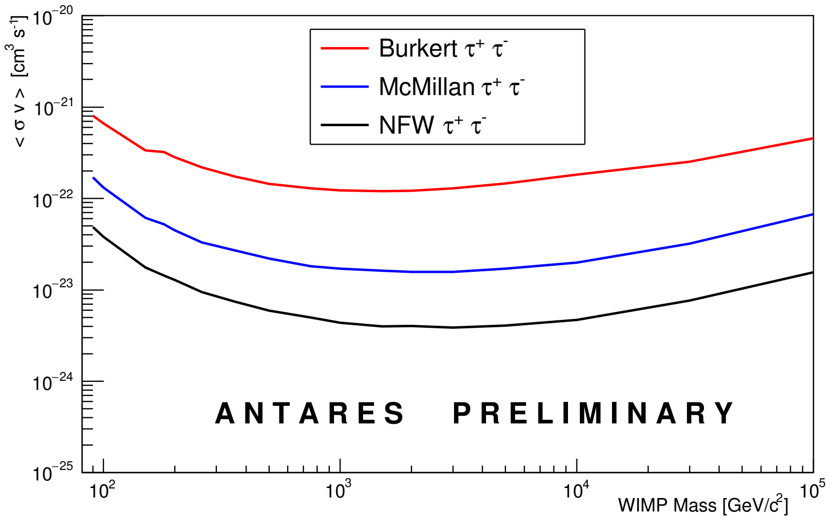

Figure 2: Upper limits at 90% C.L. on the thermally averaged cross-section for WIMP pair annihilation as a function of the WIMP candidate mass set with 11 years of ANTARES data for three different halo models. Here the $\tau^+\tau^-$ channel is shown.

The potential of KM3NeT-ARCA to detect neutrinos from dark-matter annihilations in the Galactic Centre has also been evaluated. With one year of the ARCA-24 lines configuration, the sensitivity reaches approximately the limits currently set by ANTARES, as shown in Figure 3 (top). The different shape of the sensitivity curve depends on the different geometry of the two detectors, the sparser configuration of KM3NeT-ARCA being designed for optimising high-energy searches. An evaluation of sensitivities reached with 1 year of the complete KM3NeT-ARCA detector is shown in Figure 3 (bottom, dashed lines).

Some of the channels considered for this search also yield $\gamma\gamma$ pairs as a final product. For this case, ANTARES limits are set in context with existing limits from γ-ray telescopes (Figure 4). In particular, the HESS Galactic Centre survey [15] has strong constraints due to the good visibility of this source from their location and to the prolongued observation campaign performed on this target. Note that both MAGIC and VERITAS are located in the Northern Hemisphere and therefore they obtain their limits from a campaign of observation of Dwarf Spheroidal Galaxies [16, 17]. The results shown for IceCube are obtained with Deep Core data, configuration where the whole IceCube detector acts as a veto for atmospheric muons, because of the Galactic Centre visibility, and are therefore limited to masses up to 1 TeV/c^2. The sensitivitiy estimated for one year of KM3NeT-ARCA is shown as a dashed line. In Figure 4, the $\tau^+\tau^-$ channel has been chosen as a benchmark.

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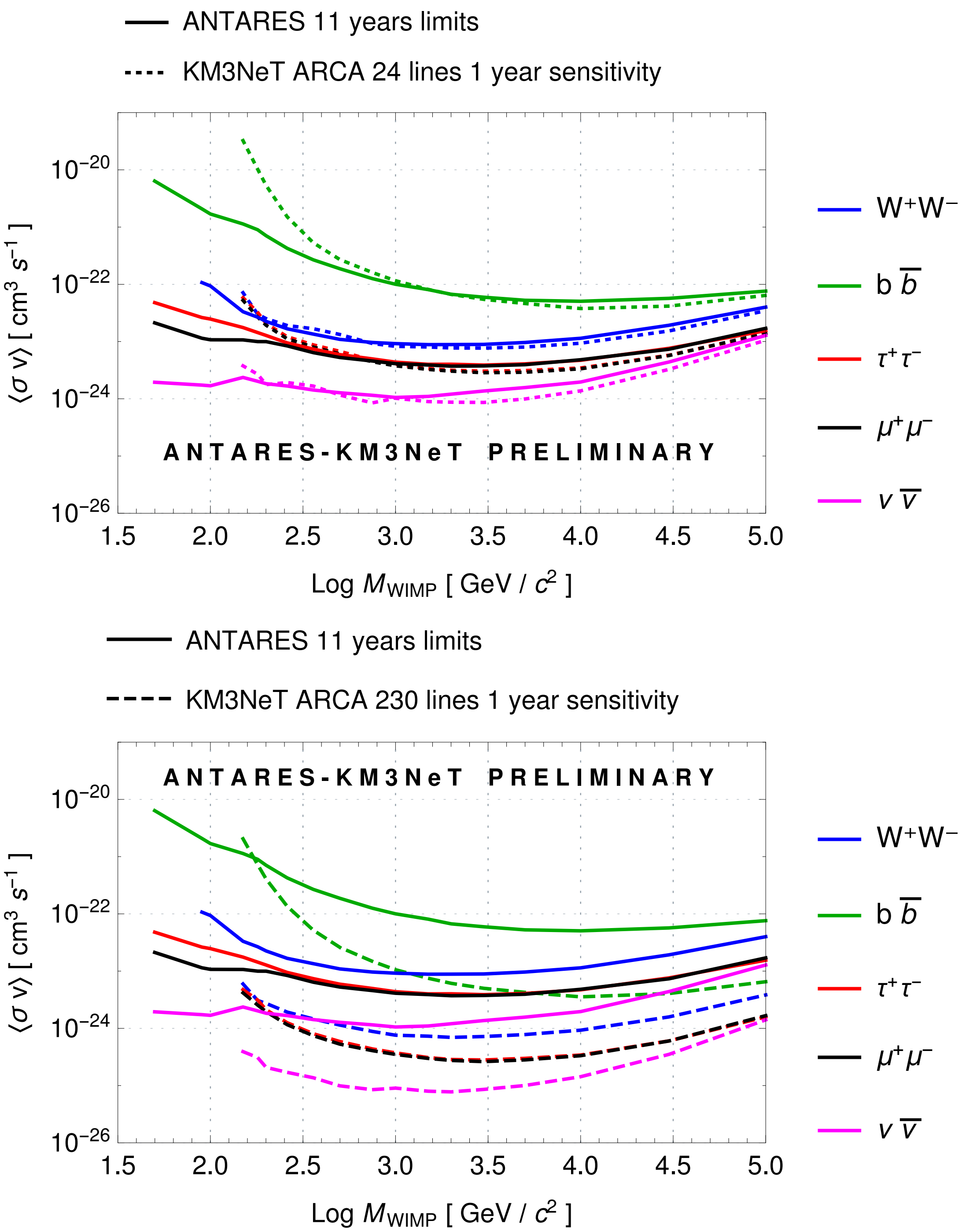

Figure 3: Sensitivities of a first sub-block of KM3NeT-ARCA with 24 lines (top panel, dotted lines) and of the full KM3NeT-ARCA with 2 blocks of 115 lines (bottom panel, dashed lines) to the thermally averaged cross-section for WIMP pair-annihilation, for NFW profile [5], with 1 year of effective livetime. ANTARES limits are shown with solid lines.

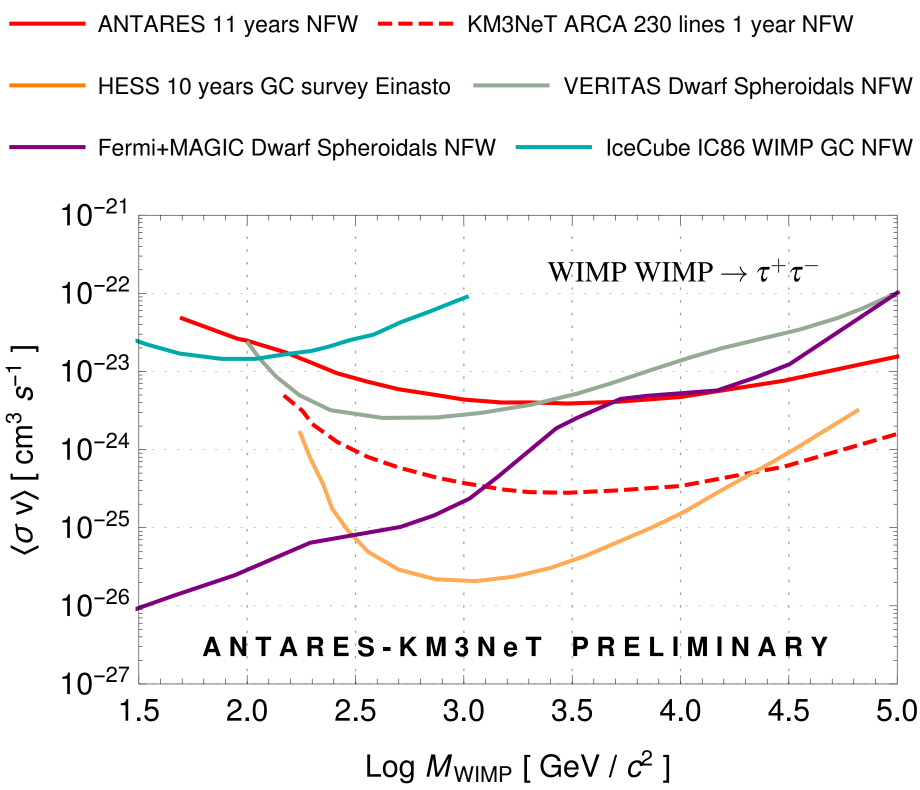

Figure 4: Limits on the thermally averaged cross-section for WIMP pair-annihilation set with 11 years of ANTARES data, compared with current similar searches from IceCube [18] and from γ-ray telescopes HESS [15], VERITAS [17] and Fermi-MAGIC [19]. The sensitivity for 1 year of KM3NeT-ARCA 230 lines and NFW profile [5] is shown as a dashed line. All curves are for the $\tau^+\tau^-$ benchmark channel.

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