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Indirect Dark Matter search towards the Sun with the ANTARES neutrino telescope

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Abstract. Dark Matter particles, such as Weakly Interactive Massive Particles (WIMPs) gravitationally captured in massive celestial objects, can be indirectly detected through their annihilation into Standard Model particles. The centres of those massive objects are, therefore, places where to look for a possible high energy neutrino flux excess from dark matter annihilations, using neutrino telescopes. The deep-sea neutrino telescope ANTARES, located in the Mediterranean Sea, has been shown to be very competitive in the quest for Dark Matter WIMPs produced in the Galactic Centre. A closer potential DM source is the Sun, where it is possible to have a very clean signal since the background from astrophysical origin is expected to be very low. In this work we show the expected sensitivity of a search for Dark Matter WIMPs from the Sun, using 13 years of data collected by ANTARES.

1. Introduction

The existence of dark matter was firstly inferred by Zwicky [1] in 1933, observing the velocity dispersion of the galaxies in the Coma cluster. Since that time many theories have been made about dark matter and different kinds of experiments are trying to prove them.
The most investigated class of dark matter candidates are WIMPs (Weakly Interacting Massive Particles)[6][7]. These particles must interact gravitationally, and potentially could annihilate into standard model particles via the weak interaction [8]. These standard model particles can decay in neutrinos[7].
For their characteristics, WIMP particles can accumulate into astrophysical objects and one of the closer object where it could be possible to search for dark matter is the Sun.
The analysis presented in this document describes the results obtained for the optimization of the sensitivities, considering the Sun as a neutrino source, from WIMP annihilation. Three WIMP annihilation channels are considered ($b\bar{b}$, $\tau^+\tau^-$, W^+W^-) as well as WIMP masses ranging from 50 to 3000 GeV/c^2 to compute the expected signal neutrino flux, using data collected by the ANTARES neutrino telescope from 2007 to the end of 2019.

2. ANTARES Detector

The ANTARES [2] detector is the first underwater neutrino telescope in the sea. It is located in the Mediterranean sea. ANTARES started to take data in 2007 and was completed in 2008. It is taking data until nowadays. The bases of the detector lines are anchored to the seabed at a depth of about 2500 m, 40 km from the French town of Toulon. It comprises a three-dimensional array of 885 optical modules (OMs) looking 45° downward and distributed along

12 vertical detection lines. An OM consists of a 10″ PMT housed in a pressure resistant glass sphere together with its base, a special gel for optical coupling and a μ-metal cage for magnetic shielding.
The OMs are grouped in 25 triplets (or storeys) on each line with a vertical spacing of 14.5 m between triplets. The total length of each line is 450 m; these are kept taut by buoyancy. The separation between the lines ranges from 60 to 75 m. Each line has been deployed by a ship and connected to a junction box by a remotely operated submarine vehicle. The junction box in turn is connected to shore via an electro-optical cable.
The detector also includes several calibration systems [9]. ANTARES is sensitive to energies above 100 GeV, even though, using particular analysis strategies, this can be lowered to few tens of GeV.

3. Search method

The strategy followed in the search for WIMP annihilation in the Sun presented here uses a binned method, based on minimisation of the sensitivity flux of ANTARES to such a signal.
Data have been selected in order to have upgoing events from the direction of the Sun.
The Model Rejection factor (MRF) is used to optimize the search window radius around the sources and the track quality cut parameters. A sensitivity for a given channel can be written as

$$\bar{\Phi}_{\nu_\mu+\bar{\nu}_\mu,90\%} = \frac{\bar{\mu}_{90\%}}{\bar{A}_{eff}(M_{WIMP}) \cdot T_{eff}}, \tag{1}$$

where $\bar{\mu}_{90\%}$ the averaged upper limit at 90% of confidence level, computed using a Poisson distribution in the Feldman-Cousins approach. At the denominator there is the total live-time T_{eff} of the detector and the acceptance for a given mass of Dark Matter particle M_{WIMP} and annihilation channel.
The acceptance (Figure 1) can be written as

$$Acc(M_{WIMP}) = \bar{A}_{eff}(M_{WIMP}) = \frac{\sum_{j=\nu,\bar{\nu}}(\int_0^{M_{WIMP}} A^j_{eff}(E_j)\frac{dN_j}{dE_j}dE_j)}{\int_0^{M_{WIMP}} \frac{dN_\nu}{dE_\nu}dE_\nu + \frac{dN_{\bar{\nu}}}{dE_{\bar{\nu}}}dE_{\bar{\nu}}}, \tag{2}$$

where $dN_{\nu,\bar{\nu}}/dE_{\nu,\bar{\nu}}$ is the energy spectrum of the (anti-)neutrinos at the surface of Earth, simulated using WimpSim [4] and the the channels $b\bar{b}$, $\tau^+\tau^-$, W^+W^- are considered. A_{eff} is the effective area of ANTARES as function of the (anti-)neutrinos energy for tracks coming from the direction of the Sun below the horizon [3]. Due to their different cross-sections, the effective areas for neutrinos and anti-neutrinos are slightly different and therefore are considered separately.
Another necessary ingredient is the amount of background passing the selection cuts in order to calculate $\mu_{90\%}$. The background is computed from scrambled data as a function of the angular separation between tracks and the Sun's direction and the track quality cut parameters (Figure 2).
To perform a better estimation of number of events of the background for different selections it is necessary to compute the cumulative distribution of the background. Then a fit of the distribution is performed to estimate the number of event for a specific cone angle selecting a range of ψ, where ψ is the angular separation computed by doing the scalar product of vectors of the reconstructed track and Sun's directions.

4. Results

The sensitivity to the neutrino flux (Figure 3) is obtained by considering upgoing events ($\theta_{zenith} > 90°$) and the best track quality cut parameters.

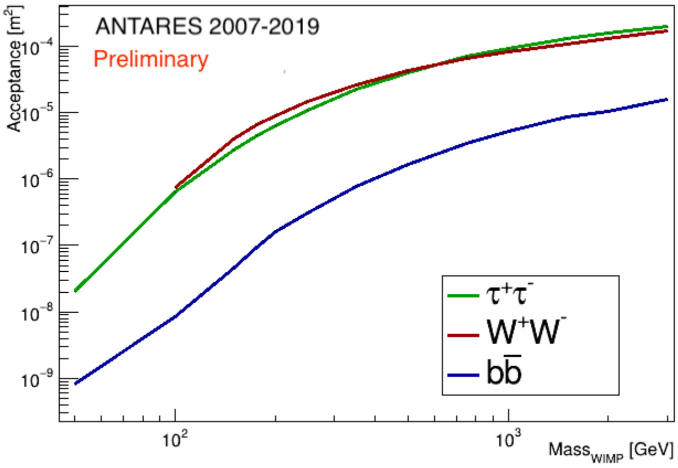

Figure 1. Acceptance as a function of the WIMP mass for neutrino flux coming from WIMP annihilations in the Sun for the three annihilation channels, $b\bar{b}$, $\tau^+\tau^-$, W^+W^-.

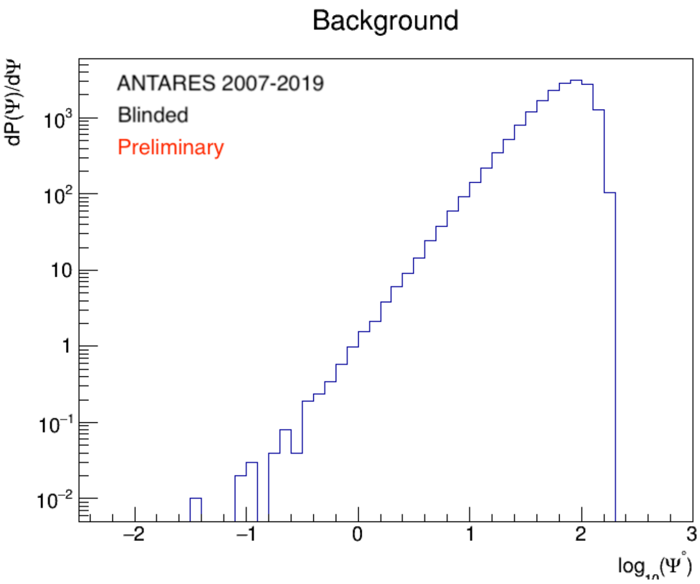

Figure 2. Background distribution as a function of the half-opening angle of the selection cone around the Sun position, obtained with scrambled data.

Assuming equilibrium between the WIMP capture rate in the Sun and their annihilation rate, the sensitivity is then translated in to WIMP-nucleon cross-section for the two cases: spin dependent cross section (Figure 4) and spin independent cross section (Figure 5).

5. Conclusions

In this document the first preliminary sensitivities for a Dark Matter search towards the Sun using 13 years of data collected by ANTARES between 2007 and 2019 are presented.
The results are compared with previous results obtained by ANTARES with a smaller data

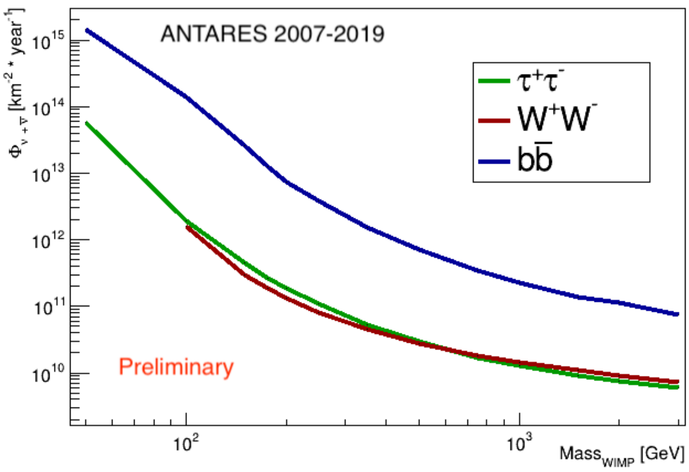

Figure 3. Sensitivity to the neutrino flux originating from WIMP annihilations in the Sun.

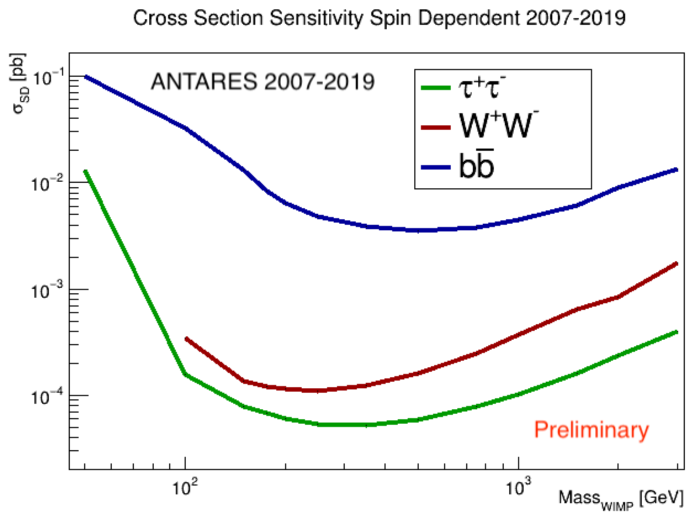

Figure 4. Sensitivity to the WIMP-nucleon spin dependent cross-section.

sample ([5],[10]) and similar analyses and these results are compatible with what is expected with the increase in livetime of a factor larger than 2.

The next steps foreseen for this work are to improve the analysis by including further low-energy neutrino events with a more efficient event reconstruction strategy; and to unblind data.

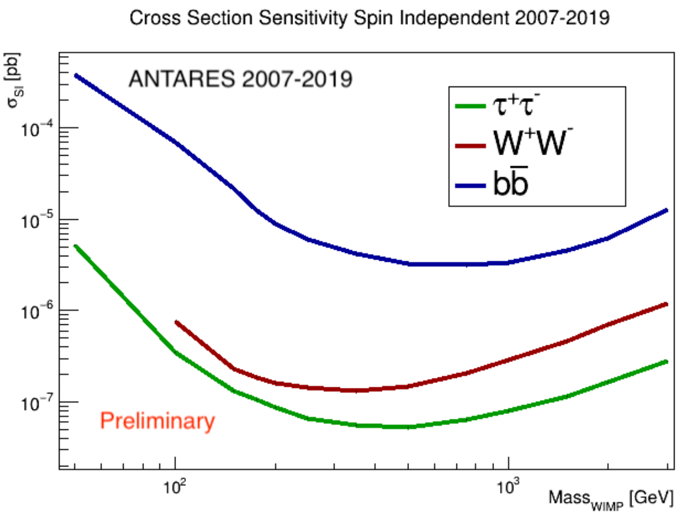

Figure 5. Sensitivity to the WIMP-nucleon spin independent cross-section.

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