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Secluded Dark Matter search in the Sun with the ANTARES neutrino telescope

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Abstract. Models where Dark Matter (DM) is secluded from the Standard Model (SM) via a mediator have increased their presence during the last decade to explain some experimental observations. This is a special scenario where DM, which would gravitationally accumulate in sources like the Sun, the Earth or the Galactic Centre, is annihilated into a pair of non-standard Model mediators which subsequently decay into SM particles, two co-linear muons for example. As the lifetime of the mediator could be large enough, its decay may occur in the vicinity of the Earth and the resulting SM particles could be detected. In this work we will describe the analysis for Secluded Dark Matter (SDM) annihilation from the Sun with ANTARES in three different cases: a) detection of di-muons that result of the mediator decay, or neutrino detection from: b) mediator that decays into di-muon and, in turn, into neutrinos, and c) mediator that directly decays into neutrinos. The ANTARES limits for these kinds of SDM case will be presented.

1. Introduction

The possibilities of DM detection have been motivated by its gravitational capture, in massive objects like the Sun, and subsequent annihilation. If as expected DM self-annihilates, the capture is balanced by the annihilation of DM particles. The intensity of the annihilation signal would be a probe of the DM scattering cross-section on nucleons. Neutrinos could be produced in the annihilations, also SM particles which interact strongly with the interior of the Sun being largely absorbed but, during this process, producing high-energy neutrinos which could scape and can be potentially seen by neutrino detectors as ANTARES. Limits from ANTARES on WIMP DM annihilation in the Sun have been reported in [1], also from Baksan [2], Super-Kamiokande [3] and IceCube [4]. Another popular explanation is based in the idea that DM annihilates first into metastable mediators (ϕ), which subsequently decay into SM states, [5–9]. In all of these models, the thermal relic WIMP DM scenario is considered as usual while there is also the potential to explain some astrophysical observations as the positron excess observed by PAMELA [10] or FERMI [11]. In the Secluded Dark Matter scenario, the presence of a mediator, as a communication way between DM and SM, can dramatically change the annihilation signature of DM captured in the Sun. If the mediators are long-lived enough to escape the Sun before decaying, they can produce detectable charged-particle or γ-ray fluxes [12, 13] and also neutrinos that could reach the Earth and be detected. In many of the secluded dark matter models, ϕ can decay into leptons near the Earth. Some differences appear in the leptons created by the neutrino interaction

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and the leptons arising from ϕ decays. In the latter case, for kinematics, as the DM mass is greater than the ϕ mass the leptons may be boosted and parallel. If these leptons are muons the signature in the vicinity of the detector would be two muon tracks almost parallel. The di-muon signature could be interpreted as a single muon and it could be discriminated (or at least the selection could be optimized for these cases) from the atmospheric neutrino signal by their energy deposition topology. Even being short-lived and decaying inside the Sun energetic neutrinos would remain the only signature. Also in these situations the neutrino signal could be enhanced compared to the standard scenario where high energy neutrinos can interact with nuclei and be absorbed before escaping the Sun. The fact that the solar density decreases exponentially with radius facilitates that the neutrinos injected by ϕ at larger radii propagate out of the Sun because they are subjected to much less absorption. In this work an indirect search for SDM using the 2007–2012 data recorded by the ANTARES neutrino telescope is reported by looking at the different mediator decay products: a) di-muons (a good discrimination between di-muons and single muon is not the priority, but to obtain the best efficiency to detect di-muons from secluded dark matter in the Sun), b) di-muons which in turn, decay into neutrinos and c) neutrinos.

1.1 The ANTARES Neutrino Telescope

The ANTARES [14] neutrino detector was completed in 2008 and is presently the largest neutrino telescope in the northern hemisphere. Its scientific scope is very broad, but the two main goals are the observation of astrophysical sources and the indirect detection of dark matter. The latter is possible through neutrinos produced after the annihilation of WIMPs, which would accumulate in sources like the Sun, the Earth or the Galactic Centre. The operation principle is as follows: when a high energy neutrino interacts via charged current inside the detector or close to it, it produces a relativistic muon which, in the water, induces Cherenkov light observable by the photomultipliers (PMTs). The information of the time, position and amplitude of the photon signals in the PMTs is used in order to reconstruct the muon track and therefore the direction of the original neutrino. The muon track is reconstructed with the BBFit algorithm [15], which provides an angular resolution of about two degrees at energies of tens of GeVs for the selected tracks (less than two degrees for higher energies).

2. Signal and background simulation

Two main sources of background are present in ANTARES: 1) Down-going atmospheric muons resulting from the interaction of cosmic rays in the atmosphere. Almost all of this is reduced by the deep sea location and by the reconstruction algorithms that are tuned to up-going events. Cuts on the quality of the tracks are also applied to reject down-going muons wrongly reconstructed as up-going. 2) Atmospheric neutrinos produced by cosmic rays. These neutrinos can traverse the Earth, so they can be detected as upgoing tracks. This is an irreducible background. For background estimation scrambled data (randomizing the time) during the period under study has been used. This allows to reduce the effect of systematic uncertainties (efficiency of the detector, assumed flux, etc.). The data used correspond to the period from 2007–2012. During almost all 2007 only 5 lines were installed. The number of operative lines was increasing until arriving to 12 in 2008. In order to test the SDM model, a new tool for Di-Muon signal generation (DiMugen) has been developed. DiMugen generates and propagates di-muons coming from decay of mediators resulting of dark matter annihilation. For this analysis, the mediator arrives from Sun direction following the zenith and azimuth info about the Sun position during the period under study with respect to the

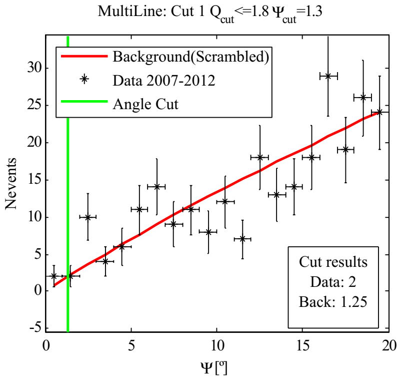

Figure 1. Differential distribution of the angular separation of the even tracks with respect to the Sun's direction for the expected background (red line) compared to the data (black).

ANTARES position. Different DM masses in the range between 30 GeV to 10 TeV have been simulated and a typical ϕ mass of 1 GeV. Di-muon flux sensitivity would be given by Eq. (1). For the cases where the neutrino is the final decay product that arrives to the Earth we have used the ANTARES effective areas for neutrinos in this energy range. In b) neutrino spectra have been obtained by Michel's spectra [16] taking into account the boost. For c) long lifetime mediators have been considered, for these cases the neutrino spectra is almost flat in the energy region under study [17]. Neutrino flux sensitivity would be given by Eq. (2). We have considered the more conservative assumption that after oscillations all neutrino flavours arrive to the Earth with the same ratio 1:1:1.

$$\Phi_{di-\mu} = \frac{\left(\frac{N_{sim}}{T_{live}}\right)\frac{\bar{\mu}_{90}}{n_s}}{\left(\left(\frac{4}{3}\right)\pi R_{sph}^{3}\right)^{2/3}} \qquad (1) \qquad\qquad \Phi_{\upsilon+\bar{\upsilon}} + \frac{\bar{\mu}_{90}/Aeff_{\upsilon+\bar{\upsilon}}}{T_{live}}\,. \qquad (2)$$

3. Optimization of the event selection criteria

In this analysis a blinding policy in order to avoid biases in the event selection has been followed. The values of the cuts have been chosen before looking at the region where the signal is expected. Best sensitivities for di-muon flux and cross-sections are extracted with the Model Rejection factor (MRF) method [18]. It consists of finding the set of cuts which provide, in average, the best flux upper limit. MRF is used to optimize the half-con angle around the sun and the track quality cut parameters (Q).

4. Results and discussion

After a detailed study of three different SDM scenarios the cut optimization procedure provided a pair of optimised values Q and ψ for each DM mass and for each SDM scenario. Finally it was decided, for the unblinding, selecting a total of 6 cuts (on quality parameter (Q_{cut}) and angular distance to the source (ψ_{cut}) for all considered masses and scenarios.

Figure 1 shows the distribution of the angular separation between the events and the Sun's direction obtained after applying the selection criteria on the zenith angle, the minimum number of hits and lines, and a Q_{cut} =1.8. No statistically significant excess has been

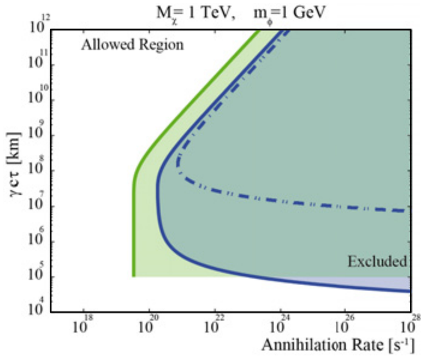

Figure 2. ANTARES exclusion limits for the three SDM scenarios (products of DM annihilation in the Sun through mediators decaying into: dimuons (dash-dotted blue), neutrinos from dimuons (solid blue), directly into neutrinos (green)) as a function of the annihilation rate and the decay length.

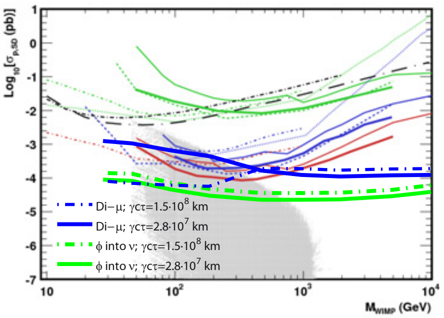

Figure 3. Sensitivities collection of different experiments of search for dark matter in the Sun. ANTARES 2007–2008 (thin solid lines: W^+W^-(blue), $\tau^+\tau^-$(red), $b\bar{b}$ (green)), ANTARES 2007–2012 for the three annihilation channels (thick solid lines) [1], IceCube-79 (dashed lines) [4], SuperKamiokande (colored dash-dotted lines) [3], SIMPLE (black short dash-dotted line) [22], COUPP (black long dash-dotted line) [23], SDM ANTARES limits (super-thick lines. For colour identification see legend).

observed above the expected background in the Sun's direction in neither of the cuts. It has been proceed to put limits for this model. Taking into account the number of events observed and the expected background, the upper limit for di-muon or neutrino flux can be obtained as the 90% confidence interval in the Feldman-Cousins approach [19]. Considering this, limits for the annihilation rates [20] have been obtained for each scenario. Figure 2 shows the ANTARES exclusion limits for the three Secluded DM scenarios for DM mass of 1 TeV and the typical ϕ mass of 1 GeV. Assuming that the annihilation balances the DM capture in the Sun,$\Gamma_{ann} = C_\odot/2$, the capture is approximately [21]:

$$C_\odot \simeq 10^{20}\mathrm{s}^{-1}\left(\frac{1TeV}{M_\chi}\right)^2 \frac{2.77\sigma_{SD} + 4.27\cdot 10^3\sigma_{SI}}{10^{-40}\mathrm{cm}^2} \tag{3}$$

where, σ_{sc} and σ_{SI} are the spin-dependent (SD) and spin-independent (SI) cross sections respectively. The limits on the SD and SI WIMP-proton scattering cross-sections are derived for the case in which one or the other is dominant. Sensitivity in terms of the annihilation rates depends on the lifetime of the ϕ. For cross-section evaluation it will be necessary fixing its lifetime. To see the maximum potential for these models, lifetime values for which the sensitivities are the best have been assumed. For the dimuon case, the lifetime has to be long enough to assure that the mediator reach the vicinity of the Earth. Following this, the best sensitivity would be obtained for mediators with decay length about Sun-Earth distance. In both neutrino cases the lifetime of the mediator for best sensitivity has to be long enough to ensure that the mediator escapes of the solar dense core, but not too long so that it decays before reaching the Earth. The lifetime of the mediator for the best sensitivity must be enough to travel an approximately distance of forty times the solar radius (value obtained by minimization of the decay probability equation). To finalize the cross section limits are presented and compared with other experiments. Figure 3 shows Antares proton-WIMP cross-section limits for SDM scenario (products of DM annihilation in the Sun through mediators decaying into: di-muons (blue) and directly into neutrinos (green)) for favourable mediator life time values.

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