Indirect dark matter search with the ANTARES neutrino telescope

G Lambard, J P Gómez González, on behalf of the ANTARES collaboration
IFIC - Instituto de Física Corpuscular - Edificio Institutos de Investigación,
Apartado de Correos 22085 E-46071 Valencia, Spain
E-mail:lambard@ific.uv.es

Abstract. Using the ANTARES neutrino telescope, the largest neutrino telescope in the Northern hemisphere, from its first configuration with 5 lines of photodetectors to the actual nominal one corresponding to a total of 12 lines, we have studied our ability to search indirectly an evidence of Dark Matter annihilations in heavy astrophysical objects as the Sun. First limits have been obtained using the data recorded by ANTARES in 2007 and 2008, and compared with neutrino fluxes predicted within a minimal supersymmetric extension of the Standard Model with supersymmetry-breaking scalar and gaugino masses constrained to be universal at the GUT scale, the CMSSM, as well as a minimal Universal Extra-Dimensions scenario with one extra compact dimension where all the Standard Model fields propagate into the bulk, the mUED. The current limits over the neutrino/muon fluxes coming from the dark matter self-annihilations, as well as the spin-dependent and spin-independent cross-sections, are presented.

1. Introduction

As the very old problem about the unseen planets, measuring a deviation from the known laws of gravitation and the theory of general relativity in large astrophysical systems, we assume the existence of a huge amount of unseen matter, the dark matter [1], which represents 83 % of the matter in the Universe. Massive and weakly interacting with the matter, the WIMPs (Weakly Interacting Massive Particles), defining the dark matter nature whatever the framework in Particle Physics, can be elastically scattered in a medium to be decelerated, and gravitationally attracted in heavy objects as the galactic center, or the stars like our Sun which is the point source of the present analysis. It’s through the self-annihilation of WIMPs in the Sun’s core, that muon neutrinos (independently of electron, and tau neutrinos) can be produced in an energy range reachable to a neutrino telescope as ANTARES.

Since the 29th of May 2008, the neutrino telescope ANTARES has been completed at 40 km offshore from Toulon at 2475 m depth, making it the largest neutrino telescope in the northern hemisphere, and the first to operate in the deep sea [2]. It is made up of
12 mooring detection lines holding ten-inch photomultiplier tubes, distributed into 25 storeys on each line, designed for the measurement of neutrino induced charged particles based on the detection of Čerenkov light emitted in water. With a low energy threshold of about 20 GeV for well reconstructed muons, and an angular resolution of about $1^\circ$ at low energy ($E_\nu < 1$ TeV), ANTARES has a great potential to detect neutrinos induced by the self-annihilation of WIMPs in the Sun’s core.

2. Dark Matter signal, and efficiency of ANTARES

Model-independently, the differential spectrum of neutrinos at the surface of the Earth, as a function of the mass of the WIMP $M_{\text{WIMP}}$, have been computed using the software package WIMPSIM [3] for all possible self-annihilation channels which can be reached in the Sun’s core ($q\bar{q}$, $\bar{t}t$, Higgs doublet, $\nu\bar{\nu}$) in the two common frameworks studied: CMSSM, and mUED. All of the physical contributions have been taken into account as the three-flavors oscillations, or the $\tau$ lepton regeneration through the Sun medium. An averaged effective area $A_{\nu+\bar{\nu}}^{\text{eff}}(M_{\text{WIMP}})$ for the ANTARES telescope, with the Sun as a point source, is defined as a function of the WIMP mass, a track fit quality cut $Q$ based on a fast reconstruction algorithm [4], and a half-cone angle $\Psi$ around the source, over the neutrino energy range $E_\nu \in [10 \text{ GeV}; M_{\text{WIMP}}]$, weighted by the normalized differential amount of neutrinos for the $W^+W^-$, $b\bar{b}$, $\tau\bar{\tau}$ channels, and for the mUED merged channels. These $A_{\nu+\bar{\nu}}^{\text{eff}}(M_{\text{WIMP}})$ have been computed for each ($Q, \Psi$), and for a set of thirteen different WIMP masses chosen in a range $[10 \text{ GeV}, 10 \text{ TeV}]$ (see [5] for details).

3. Results and discussions

Following the Model Rejection Factor (MRF) technique [6] to optimize the $(Q, \Psi)$ cuts couple in the Sun direction, the limit in neutrinos $\phi_{\nu+\bar{\nu}}$ of ANTARES must be maximized for each value of WIMP mass, and each considered channel in the dark matter self-annihilation. For this, $\phi_{\nu+\bar{\nu}}$ can be expressed as:

$$\phi_{\nu+\bar{\nu}} = \frac{\mu^{90}}{A_{\nu+\bar{\nu}}^{\text{eff}}(M_{\text{WIMP}}) \times T_{\text{eff}}}, \quad (1)$$

where $\mu^{90}$ is the upper limit using a Poisson statistics in the Feldman-Cousins approach [7] which has been computed considering the $(Q, \Psi)$ couple of cuts optimized from a scrambled data set extracted from the 2007-2008 data taking period of ANTARES equivalent to the effective time $T_{\text{eff}} \simeq 292.9$ days. Finally, $A_{\nu+\bar{\nu}}^{\text{eff}}(M_{\text{WIMP}})$ is the efficiency defined in section 2. In order to compare properly the limits in neutrino flux from ANTARES 2007-2008 data to the other experiments, their translations in muon flux $\phi_\mu$ must be produced, using the cross section of neutrinos with the Earth medium, the averaged muon range, the nucleon density in the vicinity of the detector, and the neutrino transmission probability through the Earth, all derived from the atmospheric
Figure 1. On the top left, the limit for the spin-dependent cross-section \( \sigma_{H,SD} \) as a function of the WIMP mass, in the range \( M_{WIMP} \in [10 \text{ GeV}; 10 \text{ TeV}] \) and from the 2007-2008 data, for the CMSSM framework, with a comparison to the present direct detection experiments as KIMS 2007 [13] (dash-dotted black line), COUPP 2011 [14] (dashed black line), and the indirect experiments like IceCube-40/AMANDA-II 2001 – 2008 [15] (dotted green line for \( b\bar{b} \), solid green line for \( W^+W^- \)), and SuperKamiokande 1996 – 2008 [16] (dotted blue line for \( b\bar{b} \), solid blue line for \( W^+W^- \)). The ANTARES 2007 – 2008 contributions appear for the \( b\bar{b} \) channel (dotted red line), for the \( W^+W^- \) channel (solid red line), and for the \( \tau\bar{\tau} \) channel (dashed red line). On the top right, the limit for the spin-independent cross-section \( \sigma_{H,SI} \) as a function of the WIMP mass using exactly the same style and color code than mentioned before for the plotted experiments, with CDMS 2010 [11] (dot-dashed black line) and XENON100 2011 [12] (dashed black line) as the most stringent contraints from the direct detection. For both of these plots, concerning the theoretical grey area, please refer to the text. On the bottom part, the limit \( \phi_\mu \) as a function of the WIMP mass, in the range \( M_{WIMP} \in [10 \text{ GeV}; 1 \text{ TeV}] \), for the CMSSM framework, with Macro 1989 – 1998 (solid black line), Baksan 1978 – 1995 (solid cyan line), SuperKamiokande 1996 – 2008 (dotted blue line for \( b\bar{b} \), solid blue line for \( W^+W^- \)), IceCube-40/AMANDA-II 2001 – 2008 for the \( b\bar{b} \) channel(dotted green line for \( b\bar{b} \), solid green line for \( W^+W^- \)), and ANTARES 2007 – 2008 for the \( b\bar{b} \) channel (dotted red line), for the \( W^+W^- \) channel (solid red line), and for the \( \tau\bar{\tau} \) channel (dashed red line). (anti-)neutrinos Monte-Carlo. The figure 1 (bottom row) shows it for the CMSSM framework as an example. The sensitivities for the mUED framework can be found in [5].

All of the muon flux limits \( \phi_\mu \) can be compared to the theoretical parameter space allowed by the experimental constraints, and derived from the SuperBayes simulation.
for the CMSSM framework [8] (grey area in figure 1, top row), for mUED [9]. For this purpose, the spin-dependent $\sigma_{H,\text{SD}}$ and spin-independent $\sigma_{H,\text{SI}}$ WIMP-proton cross-sections are developed using the method described in [10], as it appears in figure 1 (on the top row), for CMSSM. More the theoretical parameter space has a deep color more this one is allowed by the actual experimental contraints [8], with a comparison to the present indirect and direct detection experiments. These curves show a $b\bar{b}$ channel limit from ANTARES which is competitive with SuperKamiokande for a mass $M_{\text{wimp}} > 1$ TeV, and slightly similar to IceCube-40/AMANDA-II for the same channel at the masses $M_{\text{WIMP}} \leq 300$ GeV. For the $W^+_W^-W^-$ channel, ANTARES stays very closed to IceCube-40/AMANDA-II for $M_{\text{WIMP}} < 200$ GeV despite of the larger effective volume of this last one, thanks to the low energy threshold ($E_\nu \sim 20$ GeV) and the Sun visibility of ANTARES. For the same reason, as the $\tau\bar{\tau}$ channel is harder than $W^+_W^-$ in the $(\sigma_{H,\text{SD,SI}},M_{\text{WIMP}})$ plan, the ANTARES limit dedicated to it becomes competitive with the IceCube-40/AMANDA-II harder one (no $\tau\bar{\tau}$ limit has been published yet) for a mass range $M_{\text{WIMP}} < 300$ GeV.

To conclude, the indirect experiments as ANTARES are very complementary to the direct ones in the way that they can constrain more roughly a spin-dependent cross-section, when the second ones can reach better results for a spin-independent cross-section. Thanks to the direct and indirect experiments, the theoretical parameter spaces, like the CMSSM one, began to be constrained, approching the probability to confirm the being of the dark matter or at least to put very strict parameters on its nature.

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