Indirect Search for Dark Matter with the ANTARES Neutrino Telescope

V. Bertin

Indirect Search for Dark Matter with the ANTARES Neutrino Telescope

V. Bertin[1] on behalf of the ANTARES Collaboration

[1]CPPM, Aix-Marseille Université, CNRS/IN2P3,
163 avenue de Luminy – Case 902, 13288 Marseille cedex 9, France

E-mail : bertin@cppm.in2p3.fr

Abstract. Indirect search for Dark Matter trapped inside celestial bodies is one of the main physics goals of neutrino telescopes. The expected sensitivity of ANTARES with its data recorded in 2007 and 2008 to detect the flux of neutrinos originating from Dark Matter annihilations inside the Sun is presented. A comparison to current limits coming from direct detection experiments and other indirect detection experiments is shown with regards to the predictions of popular models such as the CMSSM and the Minimal Universal Dimension model.

1. Introduction

The most popular paradigm of modern cosmology considers the Dark Matter as a population of stable weakly interacting massive particles (WIMPs) relic from the Big Bang, although not yet discovered. Those particles would gravitationally accumulate in the core of massive celestial bodies such as stars or to a lesser extend planets as the Earth, where they could self-annihilate into ordinary matter and eventually produce significant high energy neutrino fluxes. Indirect search for Dark Matter looking at such neutrino fluxes coming from the core of the Sun, the Earth or the Galactic Centre is thus one of the main physics goals of the current and future neutrino telescopes.

2. The ANTARES neutrino telescope

The ANTARES detector [1] is the first undersea neutrino telescope and the largest one of the Northern hemisphere. It is composed of 12 mooring lines, each holding 75 photomultipliers distributed on 25 storeys (the titanium structure holding a triplet of photodetectors), installed at a depth of about 2500 metres off shore the Provençal coast of France, in order to form a 3D-matrix of ~900 photodetectors. The main goal of the experiment is to look for the Cherenkov light induced by high energy muons during their travel in the sea water throughout the detector. The trajectory of the muon track is reconstructed from the detection time of the Cherenkov photons as well as from the positions of the photodetectors. An indirect search for neutrinos can then be performed by selecting the upward-going muons produced by neutrinos which have passed through the entire planet and interacted in the vicinity of the detector. The direction of the incoming neutrino, being almost collinear with the secondary muon, can then be determined with an accuracy reaching 0.2° for high energy neutrinos above 10 TeV. Due to its size and the spacing of the photomultipliers, the ANTARES detector has a low energy threshold of ~20 GeV for reconstructed neutrinos and an effective area of $\sim 10^{-3}$ m² for neutrinos with an energy of 500 GeV. The effective area increases strongly with the neutrino energy and reaches ~1 m² for PeV energy neutrinos. Its location in the Northern hemisphere makes it complementary in sky coverage with the South Pole neutrino telescope IceCube. In addition, a large fraction of the full sky can be observed with ANTARES thanks to the rotation of the Earth, including the central part of the Galaxy which is believed to be the host of many high energy phenomena.

The building of the ANTARES detector started in 2006 with the installation and the operation of the first line, and was completed in May 2008. The current analysis presented here is based on the data recorded in 2007 with a 5-line detector and in 2008 with a 9-to-12-line detector. The event reconstruction is performed by a χ^2 fit of the photodetector hit times as a function of their positions assuming that the light originates from the Cherenkov cone of a muon track passing through the detector [2]. Although the photomultipliers point at 45° downwards, the vast majority of reconstructed events are due to down-going atmospheric muons. The neutrino candidates are obtained by looking for upward-going tracks selected by a set of quality cuts on the reconstruction parameters in order to reject the background of badly reconstructed down-going atmospheric muons. After selection, the event sample contains about 1000 neutrino candidates recorded in about 295 effective days of data taking.

3. Indirect search for Dark Matter annihilations in the Sun with ANTARES

A search for neutrinos produced by Dark Matter annihilations into the Sun has been carried out in the data sample collected by ANTARES in 2007 and 2008. The analysis is based on a binned search strategy looking for an excess of neutrino events in a cone centred towards the direction of the Sun over the background of atmospheric neutrinos. Although a good agreement in the number and the distribution of events between data and Monte Carlo simulation is observed after selection, the background coming from atmospheric muon and atmospheric neutrino events has been estimated by scrambling the time of the data events in order to generate a fake Sun. This allows to supress the systematic errors coming from the uncertainties on the fluxes of atmospheric muon and neutrino events.

The estimation of the neutrino signal induced by Dark Matter annihilations in the core of the Sun has been estimated by using the WIMPSIM package [3] which generates the neutrino spectrum originating from the annihilations in a model independent way. For a given WIMP mass, this Monte Carlo simulation program calculates the capture rate and the annihilation rate in the Sun at equilibrium and generates the neutrino spectrum resulting from all possible self-annihilation channels. The propagation of the neutrinos within the Sun and in vacuum up to the Earth is simulated taking into account neutrinos interactions and regeneration of the tau leptons in the Sun medium, as well as neutrino oscillations in a full three-flavour framework.

The sensitivity to Dark Matter signal has been estimated firstly in a model independent way by considering an extreme "soft" neutrino spectrum corresponding to self-annihilations into b-quarks and a "hard" neutrino spectrum corresponding to self-annihilations into W/Z boson pairs or tau-leptons. These channels are well representative of a WIMP in the form of neutralinos in the framework of Minimal Supersymmetric extensions of the Standard Model. The specific case of the minimal Universal Extra Dimension model (mUED) in which the WIMP is the first excitation of the hypercharge gauge boson $B^{(1)}$ and thus the lightest Kaluza-Klein (LKP) particle [4] has also been studied explicitly. This model provides a highly predictive phenomenology with mainly two free parameters: the LKP mass M_B^1 and the relative mass splitting between the LKP and the first quark excitation $\Delta = (M_Q^1 - M_B^1)/M_B^1$. In particular, the branching ratios of LKP annihilations into the different final states are fixed in the model and dominated by annihilations into $\tau^+\tau^-$. In all cases, a full sensitivity study has been performed for twelve different values of the WIMP mass ranging from 10 GeV to 1 TeV.

For a WIMP with a given mass and a given neutrino annihilation spectrum, the number of signal events is obtained by convoluting the neutrino flux with the detector efficiency, the so-called effective area, determined for a given set of the selection parameters, mainly the values of the track fit quality parameter and of the half-opening angle of the cone around the Sun. The sensitivity to a given WIMP model is thus derived as the ratio between the average upper limit on the number of background events estimated from the scrambled data, considering a Poisson statistics in the Feldman-Cousins approach [5], and the number of signal events predicted for the corresponding WIMP mass and decay channel spectrum, and for the lifetime of the data taking. Following the Model Rejection Factor (MRF) technique [6], the values of the cuts on the track fit quality parameter and on the half-cone angle are optimized for each considered model in order to minimize the sensitivity. The optimization leads to a selection cone around the Sun of 3°-5° of half-opening angle for the various models corresponding to about 1-3 events of background inside the cone.

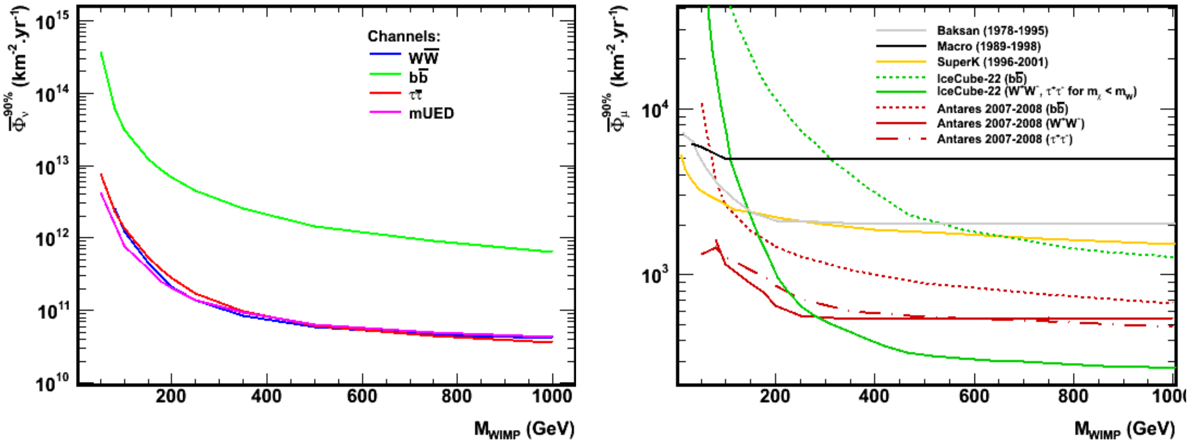

Figure 1. Sensitivity of ANTARES using the data recorded in 2007-2008 to the flux of neutrinos (left) and neutrino-induced muons (right) originating from Dark Matter annihilations inside the Sun as function of the WIMP mass for various decay channels and for the mUED model.

4. Results and perspectives

Figure 1 (left) shows the expected sensitivity of ANTARES with the data collected in 2007-2008 to the flux of neutrinos produced by annihilations of Dark Matter particles in the core of the Sun as function of the mass of the WIMP for various decay channels. In this calculation, a minimal threshold of 10 GeV has been considered for the energy of the neutrinos. As expected, the fluxes of neutrinos coming from Dark Matter annihilations into W^+W^- or $\tau^+\tau^-$ are much better constraint than annihilations into b-quarks which give a much softer neutrino spectrum. A high sensitivity is also observed for the specific case of the mUED model for which the theoretical branching ratios are taken into account for the calculation of the neutrino spectrum.

In order to compare our sensitivity to current limits set by other experiments, it is more convenient to present it in terms of neutrino-induced muon flux into the detector taking into account the interaction rate of neutrinos into the Earth, the muon mean range in matter and the nucleon density in the vicinity of the detector. Figure 1 (right) presents the expected sensitivity of ANTARES with the data collected in 2007-2008 to the flux of neutrino-induced muons produced by annihilations of Dark Matter inside the Sun integrated above a muon energy of 1 GeV. One can see that although the size of the ANTARES detector is limited compared to IceCube, its capability to detect neutrinos as low in energy as about 10 GeV leads to a very promising probability to detect a signal of Dark Matter annihilations inside the Sun in the WIMP mass range between 50 and 300 GeV.

The flux of neutrinos can also be related to the annihilation rate of Dark Matter into the Sun and then to the capture rate of the WIMP by elastic scattering, and thus to the spin-dependent cross section of the WIMP on protons, with the reasonable hypothesis of equilibrium between the annihilation rate and the capture rate. Figure 2 presents the sensitivity of ANTARES with the data collected in 2007-2008 to the spin-dependent cross section of the WIMP to protons as function to the WIMP mass compared to predictions of allowed regions of the parameter space of the CMSSM (left) and mUED (right)

models. In both cases, the scans of the model parameter spaces have been performed by using the SuperBayes program [7] taking into account the experimental constraints coming from the determination of the relic density or from collider observables. This demonstrates the complementary as well as the great sensitivity of neutrino telescopes with respect to direct detection experiments in the hunting quest of the Dark Matter of the Universe. In particular, ANTARES and IceCube are now starting to probe interesting regions of the parameter space in the case of SUSY models such as the CMSSM, while their sensitivity is still one to two orders of magnitudes above the predicted domain for the mUED model.
Thanks to the data taking performed in 2009 and 2010 with a complete detector, ANTARES has now accumulated more than 3000 neutrino candidates corresponding to about three times the statistic used in the analysis presented here. In addition, other potential Dark Matter sources such as the Earth, the Galactic Centre and Dwarf Spheroidal galaxies are being studied by dedicated analyses. The hunt for Dark Matter with ANTARES is therefore only starting and the near future will certainly be exciting.

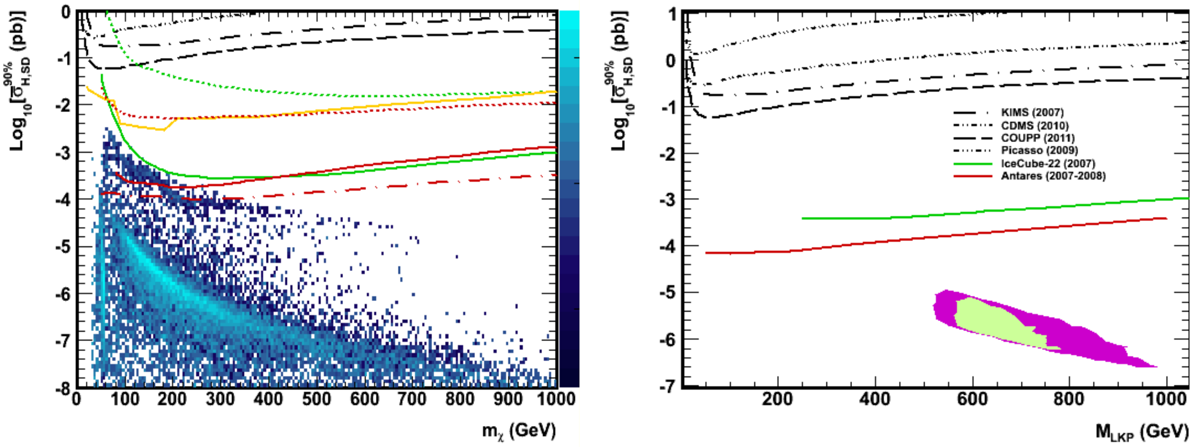

Figure 2. Sensitivity of ANTARES using the data recorded in 2007-2008 to the spin-dependent cross section of WIMP to proton as function of the WIMP mass compared to the predictions obtained for the CMSSM (left) and for the mUED model (right). In the left plot, the sensitivity of ANTARES in the "hard" channel (red line) and in the "soft" channel (red dashed dotted line) is compared to existing limits of direct detection experiments (black curves, see the legend details in the right plot) and of Super-Kamiokande (yellow) and IceCube-22 (green line for the "hard" channel and green dotted line for the "soft" channel). In the right plot, the light green region corresponds to models satisfying the observables input in the SuperBayes scan within one sigma while the purple zone highlights the two sigma region of the mUED parameter space.

References

[1] M. Ageron et al., ANTARES Collaboration, *Nucl. Inst. Meth. A* **656,** 11 (2011).
[2] J.A. Aguilar et al., ANTARES Collaboration, *Astropart. Phys.* **34**, 652 (2011).
[3] M. Blennow, J. Edsjo, T. Ohlsson, *JCAP* **0801**, 021 (2008).
[4] G. Servant and T.M.P. Tait, *Nucl. Phys. B* **650**, 391 (2003).
[5] G.L. Feldman and R.D. Cousins, *Phys. Rev. D* **57**, 3873 (1998).
[6] G.C. Hill and K. Rawlins, *Astropart. Phys.* **19**, 393 (2003).
[7] R. Trotta et al., *JHEP* 0812:024 (2008).