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Recent results from the ANTARES deep sea neutrino telescope

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Abstract. The ANTARES deep sea neutrino telescope has been continuously taking data for more than ten years. Thanks to its excellent angular resolution in both the muon channel and the cascade channel, ANTARES offers unprecedented sensitivity for neutrino source searches in the Southern sky in the TeV-PeV energy range, so that already valuable constraints have been set on the origin of the cosmic neutrino flux discovered by the IceCube detector. This document highlights recent results obtained by ANTARES in the search for high energy cosmic neutrinos coming from point or extended sources, from multi-messenger analyses of transient sources, and from indirect searches for Dark Matter.

1. 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 better than 0.4° 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 allowing ANTARES to put interesting constraints on a possible galactic component of the IceCube high energy neutrino signal [2].

The construction of the ANTARES detector was conducted between 2006 and 2008. Being in operation for now 10 years, the experiment has detected about 11000 neutrino events with an energy larger than 10 GeV. The data acquisition of the detector implements a real time processing and an online reconstruction of the recorded events, allowing a real time generation of alerts [3] following the



identification of particularly interesting neutrino events with a delay of about 5 seconds for multi-messenger searches.

Several dedicated algorithms are used in offline analyses in order to reconstruct and select upgoing track events, mainly originating from charged-current interactions of ν_μ , and upgoing cascade events, coming from charged-current interactions of ν_e or ν_τ as well as neutral-current interactions of all flavour neutrinos. The track event topology offers a large detection volume thanks to the muon range, a small angular resolution as indicated above and a poor energy resolution of a factor ~ 3 on the neutrino energy. The contained cascade events lead to a small detection volume and an angular resolution of $\sim 3^\circ$ but an excellent energy resolution better than 10% for ν_e charged-current events.

The absolute pointing of the ANTARES detector has been checked exploiting the Moon shadow effect on primary cosmic rays. The measurement has also allowed an estimation of the detector angular resolution for the measurement of down-going atmospheric muons. The 2007-2015 ANTARES data sample shows a 3.5σ evidence of Moon shadow effect, and the corresponding estimation of the detector angular resolution for down-going muons is $0.73^\circ \pm 0.15^\circ$ [4]. The ANTARES pointing accuracy does not present any evident pointing shift. The Moon shadow results have been also confirmed by a surface array campaign with 15 scintillator units of 0.8 m^2 each performed in 2011 and 2012. The surface array analysis is consistent with a correct alignment of the detector.

2. Search for high energy neutrino diffuse flux

Astrophysical high energy neutrinos are probes to investigate the origin, the sources and the acceleration mechanisms of primary cosmic rays (CRs). A diffuse flux of cosmic neutrinos might originate from either the ensemble of unresolved individual sources, which are too faint to be detected individually, or from the interaction of primary CRs as they propagate in the Universe. The observation of a diffuse flux of cosmic neutrinos, i.e. the measurement of its spectrum and flavor composition, could provide valuable information on their production mechanism. Searches for a diffuse flux of cosmic neutrinos from the IceCube Collaboration have provided the observation of an excess of neutrinos over the expected background [2]. The measured flux can be modelled with a single power law with relatively soft spectral index $\Gamma > 2$. Assuming that the astrophysical neutrino flux is isotropic over the whole sky and consisting of equal flavours at Earth, the best fit spectral index is $\Gamma = 2.50 \pm 0.09$ and the normalization at 100 TeV is $\Phi_0 = 6.7_{-1.2}^{+1.1} \cdot 10^{-18} \text{ GeV}^{-1} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$ for an all-flavour flux [2]. The ANTARES detector can provide valuable information for the identification of this signal. This is especially true if part of it has a galactic origin.

An all-sky and all-flavour neutrino search has been performed looking for an excess of cosmic neutrinos over the atmospheric backgrounds in the data recorded by ANTARES between 2007 and 2015, corresponding to an equivalent livetime of 2450 days. Both samples selected by the track events and cascade topology reconstruction algorithms have been considered in this analysis. The high energy neutrino candidates have been selected above a given threshold on an energy estimator distribution for each sample. The unblinding of the two samples yielded an observation of 33 high energy events overall while the expectation from simulations of the backgrounds is 24 ± 7 events [5]. This result can be translated into a 68% confidence interval and a 90% confidence level upper limit on the cosmic neutrino flux as presented in figure 1. The p-value of the observed excess is 0.15. It should be noted that, though not significant, the observation is fully compatible with the expectation from an IceCube-like cosmic contribution in addition to the atmospheric backgrounds.

The interaction of galactic CRs with interstellar matter in the region of the galactic plane can lead to an enhanced neutrino production, thus leading to anisotropies in the cosmic neutrino signal as measured by IceCube. The expected diffuse galactic neutrino emission can be obtained linking a model of generation and propagation of CRs with the morphology of the gas distribution in the Milky Way. A dedicated analysis applying a likelihood ratio test on nine years of ANTARES data, collected from 2007 to 2015, has been performed looking for a possible galactic contribution to the IceCube cosmic neutrino signal. This analysis assumes as reference the newly introduced so-called “KRA γ ” model which relies on radially-dependent CR diffusion and reproduces the diffuse galactic gamma-ray emission measured

by Fermi-LAT, H.E.S.S. and Milagro experiments [7]. No excess of events has been observed and an upper limit on the neutrino flux is set at 1.1 (1.2) times the prediction of the “KRA γ ” model assuming the primary CR cutoff at 5 (50) PeV, as presented in figure 2 [8].

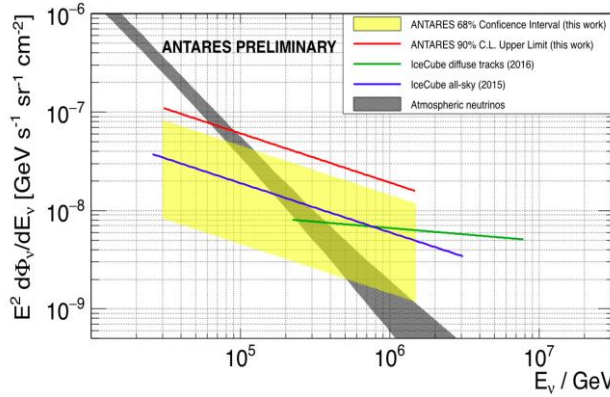


Figure 1. Result on the all sky and all flavour cosmic neutrino search obtained with the 2007-2015 data sample of ANTARES, compared with the measurement from IceCube for the Northern sky flux with tracks (green) [6] and the all-sky flux assuming a signal spectrum proportional to $E^{-2.5}$ (blue) [2].

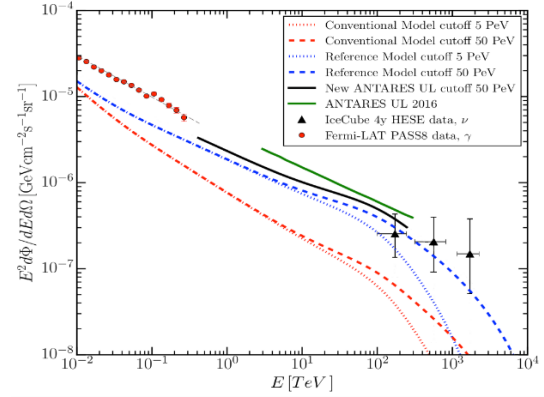


Figure 2. Upper limit on the galactic diffuse neutrino flux obtained by ANTARES with the 2007-2015 data sample compared to the prediction of the “KRA γ ” model.

3. Search for neutrino point sources

Thanks to the development of a novel reconstruction algorithm for cascade events [9], ANTARES was able to perform a search for neutrino point sources considering all neutrino flavor interactions, unlike previous analyses where only information from track-like events were exploited. The cascade events contribute about 23% of all signal events for an E^{-2} energy spectrum. In order to find the clusters of neutrinos from point-like sources over the randomly distributed atmospheric background events, a maximum likelihood ratio approach has been followed. The search for astrophysical sources is performed with four strategies. In the full-sky search, the whole visible sky of ANTARES is scanned to find the most significant cluster of events. In the second approach, the directions of a pre-defined list of 106 gamma sources and 13 muon tracks from the IceCube high energy sample events, which are potential neutrino emitters, are investigated. The third search is similar to the full-sky search but restricted to the region around the Galactic Centre (GC). Finally, the fourth approach tests the location of Sagittarius A* as an extended source assuming a Gaussian emission profile of various widths. The analysis selected a total of 7629 track-like events and 180 cascade-like events in the data set recorded by ANTARES between 2007 and 2015, corresponding to an equivalent livetime of 2424 days. No significant evidence of neutrino source is found [10]. The most significant cluster in the full-sky search is located at $(\alpha, \delta) = (348.8^\circ, 23.5^\circ)$ with a significance of 1.9σ . Upper limits on the total neutrino flux from the investigated astrophysical candidate sources are set between 0.60×10^{-8} and 2.1×10^{-8} $\text{GeV cm}^{-2} \text{s}^{-1}$. These searches provide the most sensitive limits for a large fraction of the Southern sky, especially at neutrino energies below 100 TeV [10], as presented in figure 3. A future joint analysis of the ANTARES events with data from the IceCube detector could significantly improve the sensitivity of the point-like source search in the Southern sky, as already shown in the past [11].

4. Multi-messenger analyses of transient sources

High energy neutrinos could be produced in the interaction of charged CRs with matter or radiation surrounding astrophysical sources. Transient phenomena, such as gamma-ray bursts, core-collapse supernovae or active galactic nuclei are promising candidates to emit high energy neutrinos. To search for coincidence between a transient event and a neutrino emission, a follow-up program of neutrino

alerts is in operation in ANTARES since 2009 [3]. This program triggers a network of robotic optical telescopes with a delay of ~ 5 s after the observation of a selected neutrino event, with a precision on the direction better than 0.4° , and schedules several observations in the following weeks. The most interesting neutrino candidates are also followed by the Swift XRT telescope, the Murchison Wide field Array radio telescope and the H.E.S.S. very high energy gamma-ray telescope. By combining the information provided by the ANTARES neutrino telescope with information coming from other observatories, the probability of detecting a source is enhanced, allowing the possibility of identifying a neutrino progenitor from a single detected event. More than 250 alerts have been sent by ANTARES since 2009, no significant counterpart associated with a neutrino emission has been identified so far by image analyses [12].

ANTARES is also developing an important multi-messenger offline analysis program in order to look for neutrino events in spatial and temporal coincidence with flares of transient sources, such as blazars, Active Galactic Nuclei, X-ray binaries, Gamma-Ray Bursts, Fast Radio Bursts, ..., detected by other observatories in radio, X-rays, Gamma-rays, neutrinos, ultra-high energy CRs or Gravitational Waves (GW). In particular, ANTARES has searched for neutrinos detected in coincidence with the 3 GW events (GW150914, GW151226 and LVT151012) detected during the Observation Run O1 of Advanced LIGO in 2015-2016 [13]. These three events correspond to the coalescence of stellar-mass Black Hole binary systems at distances ranging from 400 Mpc to about 900 Mpc. While an electromagnetic counterpart (presumably associated with a neutrino emission) is generally expected from a Neutron Star/Black Hole or Neutron Star/Neutron Star merger, current consensus is that Black Hole/Black Hole merger does not produce electromagnetic or neutrino counterpart. However, in a dense enough hadronic environment, an accretion disk might form, and relativistic outflow connected to the accretion could be released. Energy dissipation in this outflow would consequently lead to a Gamma-ray emission with a potential high energy neutrino (of energy $\gg$ GeV) counterpart. The detection of such high energy neutrino would then allow to pinpoint the localization of the GW source with a precision better than 1° , facilitating the search for electromagnetic counterparts. The ANTARES and IceCube Collaborations looked for high energy neutrino events during a ± 500 s time window around each of the GW events. Few neutrino candidates were detected, consistent with the expected background rate, but none of those neutrino candidates are found to be directionally coincident with the GW detection [13]. This non-observation constraints the potential energy released in neutrino emission to be smaller than 10% of the total energy of the GW event.

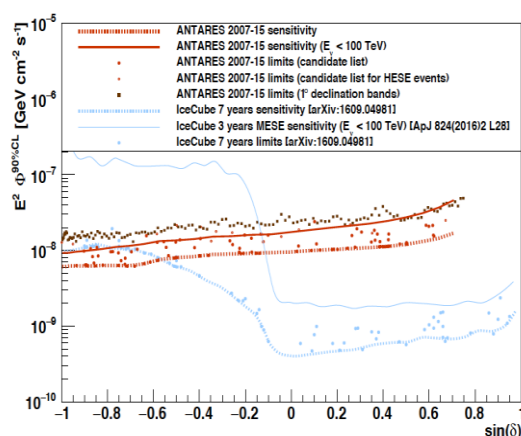


Figure 3. Upper limits on the total signal neutrino flux of the investigated candidate sources assuming an E^{-2} energy spectrum obtained by ANTARES on the point source analysis of the data recorded between 2007 and 2015.

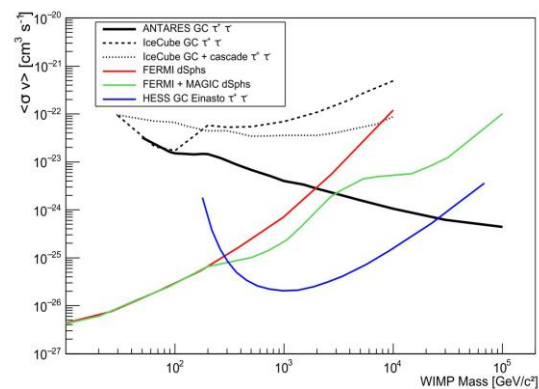


Figure 4. Limit on the thermally averaged annihilation cross-section of WIMPs obtained by ANTARES with the data recorded between 2007 and 2015, assuming a Dark Matter galactic halo with a NFW profile.

5. Indirect searches for Dark Matter

Neutrino telescopes such as ANTARES are also powerful detector to perform indirect searches for Dark Matter. ANTARES has developed several analyses looking for high energy neutrinos produced by annihilations of WIMPs in the direction of the centre of the Earth, the Sun and the Galactic Centre [14]. Figure 4 shows in particular the limit on the thermally averaged annihilation cross-section of WIMPs obtained by ANTARES while looking for neutrinos produced by Dark Matter annihilations in the direction of the Galactic Centre and the Galactic Halo. This result assumes a galactic WIMP distribution following a NFW profile. The limit obtained by ANTARES is the most stringent of all indirect detection experiments for WIMP masses above 30 TeV.

6. Conclusions and perspectives

The ANTARES experiment, the largest neutrino telescope in the Northern hemisphere, is celebrating more than ten years of continuous data taking. In addition to track-like events, the cascade-like events have been included in most of the analyses with an angular resolution better than 3° allowing all-flavour neutrino searches of high energy neutrino signal coming from point or extended sources and from diffuse flux. ANTARES provides the strongest limits for galactic point sources located in the Southern hemisphere especially at neutrino energies below 100 TeV, and derives interesting constraint on the origin of the IceCube cosmic neutrino signal. ANTARES observes a small excess of high energy neutrinos in its diffuse flux analysis, which is, although not significant, of magnitude expected from the IceCube signal. ANTARES is also performing a very intensive multi-messenger analysis program looking for neutrino potentially produced by cosmic transient sources. Finally, ANTARES offers very competitive results in the indirect searches for Dark Matter. The nice results obtained by ANTARES for the last ten years demonstrate the great potential of deep sea neutrino telescopes, and in particular of the next generation KM3NeT detector currently under construction in the Mediterranean Sea [15].

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