PROCEEDINGS OF SCIENCE

Highlights from the ANTARES neutrino telescope

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The ANTARES detector was the first deep sea neutrino telescope, located offshore the French southern coast at about 2500 m under the sea level. Despite its (relative) small size, it has given an essential contribution to recent development of neutrino particle physics and astrophysics. ANTARES was operating in its full configuration from May 2008 to February 2022. After the stop of data tacking, the detector was decommissioned between May and June 2022. The large amount of high quality data and its scientific results has proven the reliability of underwater detection technique of high-energy neutrinos and has pushed the development of the new generation of seawater neutrino telescopes. Its detection principle is based on the collection of the Cherenkov photons emitted along the path of relativistic particles emerging from neutrino interactions in the vicinity of the telescope, using a lattice of almost 900 optical modules, each hosting a 10" photomultiplier, distributed along 12 flexible strings. All information on the signal - time, position and charge - are transmitted to the onshore control station where a computer farm processes the data stream using dedicated trigger algorithms. Potentially interesting events are then stored and finally treated with tracking programs that reconstruct the direction of parent neutrinos. Technical details on ANTARES can be found in [1]. In this contribution a short review of some recent results obtained with the ANTARES detector is given.

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1. Introduction

ANTARES (see Fig. 1) detected neutrinos at different energies, from the tens of GeV range (when atmospheric neutrino oscillations are still active), passing to the TeV-scale (relevant for indirect dark matter searches) up to the multi-TeV energies of cosmic neutrinos. The principal background for neutrino telescopes are atmospheric muons. The typical signature of an atmospheric muon (even a bundle of atmospheric muons) is a downgoing track which can be easily rejected during physics analysis with a directional cut on reconstructed events. The results of the ANTARES searches for neutrinos induced by dark matter candidates are presented elsewhere in this Conference [2]. In this document, we focus on oscillations studies and the search for cosmic neutrinos.

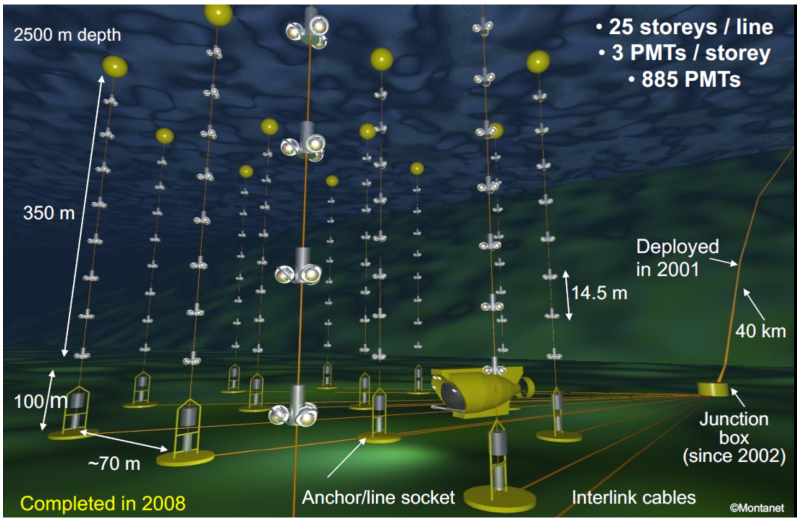

Figure 1: Illustrative view of the underwater detector, with 12 lines anchored at a depth of 2.5 km, 40 km off the cost of Toulon, South of France. ANTARES has been operational from 2008 to 2022.

2. Neutrino oscillation and NSI studies

Atmospheric neutrinos are produced through the interaction of cosmic rays with nuclei in the atmosphere. Their flux spans many orders of magnitude in E_ν, from GeV to hundreds of TeV, and their baseline distances L_ν range from ~ 10 km of neutrinos arriving in the detector vertically down-going to $\sim 10^4$ km of those vertically up-going. The ANTARES detector has a trigger energy threshold for ν_μ at 10-20 GeV, allowing to study neutrino oscillations (which depend on the E_ν/L_ν ratio) through the ν_μ disappearance channel. Once the trajectory of an upgoing track (which must come from a ν_μ, not from an atmospheric muon) has been reconstructed, its zenith angle θ_{reco} corresponds to a given L_ν distance. If the muon stops inside the detector, it can be considered a m.i.p. and the neutrino energy, E_{reco}, can be estimated through the determination of the muon range. Fig. 2 (left) shows the distribution of data vs. Monte Carlo (MC) predictions as a function of $E_{reco}/\cos\theta_{reco}$. The non-oscillation hypothesis has been discarded with a signficance of 4.6σ, and the allowed values in the $(\sin^2\theta_{23}, \Delta m^2_{32})$ parameter space are consistent with world best-fit values. In a similar way, constraints on the 3+1 neutrino model, which foresees the existence of one sterile neutrino, can be inferred. Even though a sterile neutrino does not interact as the active

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flavors, its presence would modify the standard oscillation patterns, due to the fact that the ν mass eigenstates (e.g, that of eigenvalues m_2 or m_3) could oscillate into an additional forth sterile state through mixing angles θ_{24} or θ_{34}. Comparing data and MC under these additional oscillation possibilities, exclusion contours are built. In Fig. 2 (right) the resulting 90% CL exclusion limits have been computed on a 2D grid in the plane of the two oscillation matrix elements depending on mixing angles θ_{24} and θ_{34}. Further details in [3].

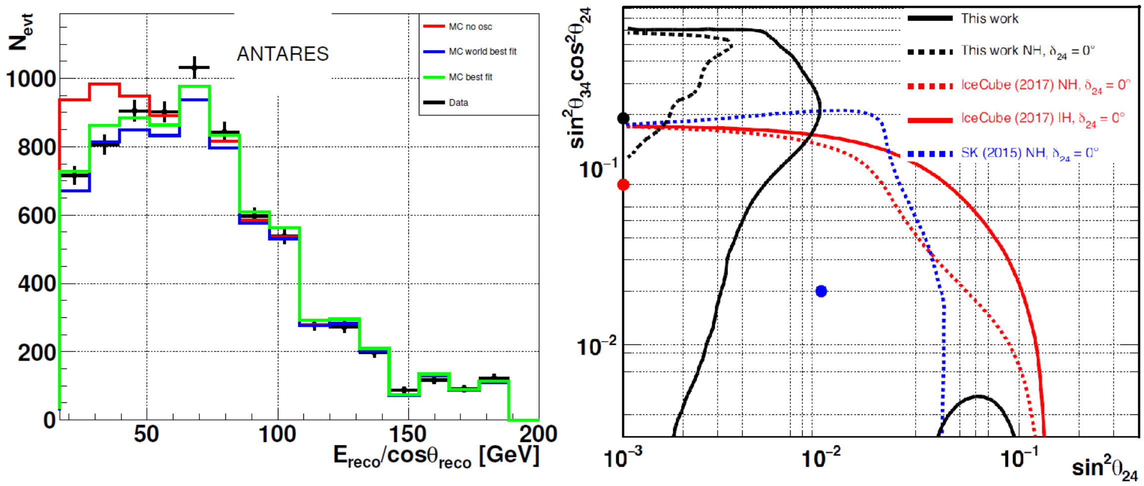

Figure 2: Left: distribution for data (black), MC without oscillation (red), MC assuming the world best-fit values (blue) and MC assuming best-fit values of this analysis (green). Right: 90% CL limits for the 3+1 neutrino model in the parameter plane of $|U_{\mu 4}|^2 \equiv \sin^2\theta_{24}$ and $|U_{\tau 4}|^2 \equiv \sin^2\theta_{34}\cos^2\theta_{24}$. See [3]

Non-standard interactions (NSIs) of ν's arise in many BSM theories: they can alter atmospheric ν propagation in Earth through matter effects. NSIs are quantified through dimensionless constants $\epsilon_{\alpha\beta}$ $(\alpha, \beta = e, \mu, \tau)$ that appear in the four-fermion Lagrangian containing new interaction terms. ANTARES [4] has used a log-likelihood ratio test on $\epsilon_{\mu\tau}$ and $\epsilon_{\tau\tau} - \epsilon_{\mu\mu}$, which provides no evidence of deviations from standard interactions. The constraint on $\epsilon_{\mu\tau}$ in the $\mu - \tau$ sector is among the most stringent to date for NSIs. These ANTARES studies demonstrated the capability of the undersea detectors which will be fully exploited by the growing KM3NeT-ORCA [5].

3. High-energy cosmic neutrino studies

Neutrino astronomy is a branch of astroparticle physics and has proven its ability to explore the far universe thanks to the IceCube finding of a diffuse flux of cosmic neutrinos [6] and the first compelling evidences of neutrinos associated to sources [7]. The latter is an example of the multi-messenger approach, when coincidences are looked for between events detected within limited space-time intervals by different observatories. Thanks to the shielding action of the Earth, only neutrinos produce upward going events. The search for a cosmic neutrino signal is performed on statistical basis exploiting different strategies. They rely on:

i) the detection of an excess of high-energy events above the background of atmospheric ν's [8];

ii) the identification of a directional excess of events in a given sky direction [9];

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iii) search for a stacked space/time coincidences between ν's and existing catalogues [10];
iv) observation of a single neutrino candidate almost coincident with a transient event observed with electromagnetic emissions, cosmic rays, gravitational waves, in a multi-messenger context [12].
ANTARES used both event topologies identified in neutrino telescope, i.e., track like events (induced mainly by ν_μ CC interaction) and cascades (induced by ν_e CC interaction and NC of all flavors). Tracks allow an angular precision on the neutrino direction better than 0.4° for $E_\nu > 10$ TeV [9]. Cascade events have poorer angular resolution but allow a better determination of E_ν.

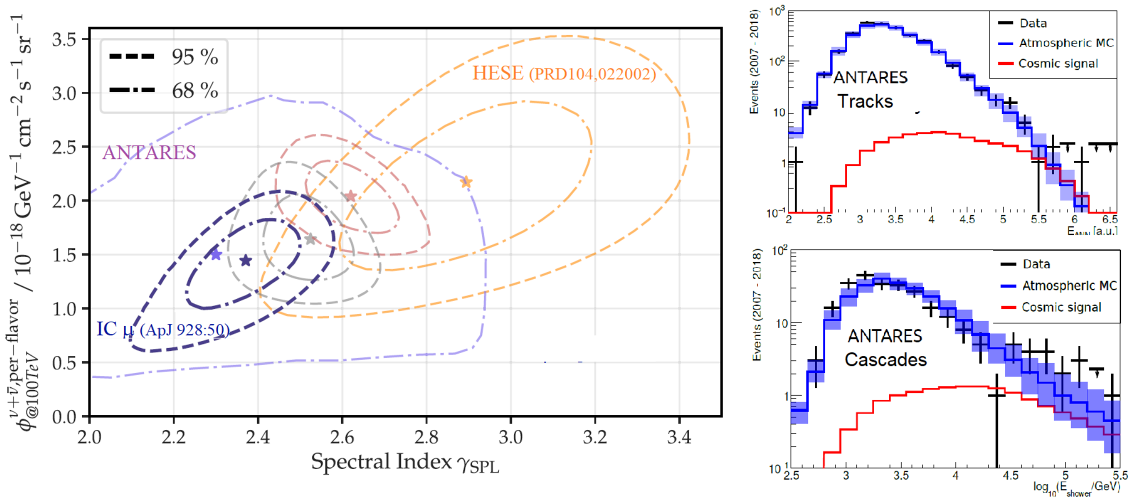

Figure 3: Summary of diffuse cosmic ν's measurements. Left: best-fit parameters and uncertainty contours, using a power-law, are drawn for different IceCube samples [11]. Right: ANTARES observes a mild excess over the expected atmospheric backgrounds above E_T both for tracks and cascades [8].

i) Diffuse flux. The diffuse flux of high-energy cosmic neutrinos coming from unresolved sources discovered by IceCube [6] can be originated by faint sources and/or by interactions during hadron propagation. This cosmic neutrino flux is, so far, compatible with an equal equipartition between the three flavours and can be described by unbroken single-power-law, i.e., $d\Phi/dE = \Phi_0(E/E_0)^{-\gamma}$, where Φ_0 is the normalization at energy E_0 (usually, 100 TeV). Some tension exists between the results obtained by IceCube using different samples [11]. A spectral index $\gamma \simeq 2.9$ results as best-fit for the sample mostly containing cascades from all sky directions, while the analysis of upward-going muons from the Northern Sky obtains $\gamma \simeq 2.3$. Also the normalization Φ_0 is different (see Fig. 3). A multiple-component origin can explain this tension, including a possible contribution from our Galaxy. ANTARES has so far analyzed data from 2007 and 2018. As atmospheric ν's are topologically indistinguishable from cosmic neutrinos (the only difference between background and signal is given by the energy spectra), an excess of HE neutrinos is searched for above a given threshold for the reconstructed energy, E_T. The value of the threshold energy is optimized blindly, using Monte Carlo events only and it is different for track and cascade samples. The track-like events yield 19 events with $E > E_T$, when 13.5 are expected; the cascade-like sample has 14 events vs. 10.5 expected (see Fig. 3, right). The significance of the excesses is estimated to be ~1.6σ and the null-cosmic hypothesis rejected at 85% C.L. The ANTARES best fit point and the 68% C.L. allowed region in the $(\gamma; \Phi_0)$ space are shown together with the IceCube results in Fig. 3 left.

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ii) Point sources. IceCube can monitor, with up-going tracks, the Northern sky hemisphere. On the contrary, the geographical location of ANTARES offers a privileged point of view of the Galactic plane and its centre. In addition, the optical properties of sea water w.r.t. ice guarantee a better angular resolution. For this reason, ANTARES provides competitive results on the searches for point-sources of cosmic neutrinos in the Southern sky. The analysis has used data from 2007 to 2020, for a livetime of 3845 days, and has applied a likelihood function to evaluate the significance of a possible excess of events over the atmospheric background, as described in [9]. Two different strategies are pursued:

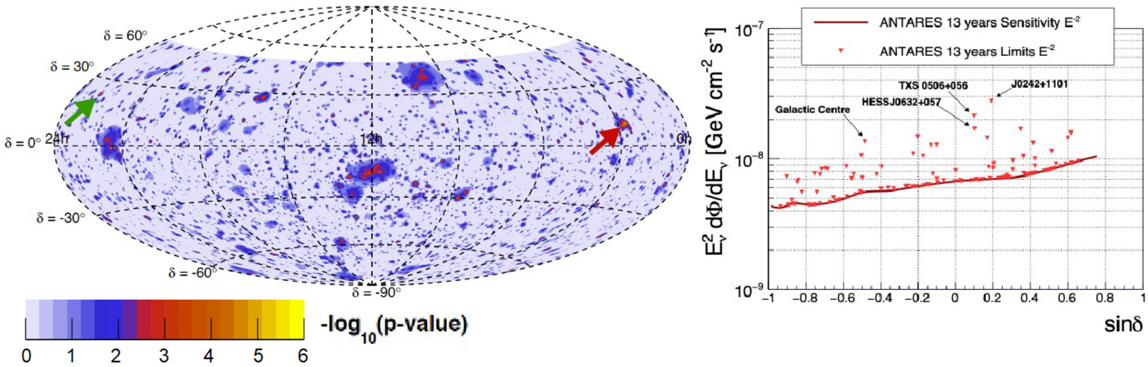

Figure 4: Left: Sky map in equatorial coordinates of pre-trial p-values of the ANTARES visible sky. Right: 90% C.L. upper limits on the one-flavour neutrino flux for the 121 potential sources vs. the declination. [9].

• A full sky search: the visible sky is explored looking for an excess of signal events, regardless of any hypothesis on the position of the source, scanning regions of $1^\circ \times 1^\circ$ size. Fig. 4a shows the ANTARES sky map with the indication of pre-trial p-values. A p-value close to 1 is compatible with the background hypothesis. The smallest one is 6.8×10^{-6}: its position is reported as a red arrow in Fig. 4a. This direction is close to a known radio-bright blazar, J0242+1101. However, due to the larger numbers of trials, its post trial p-value is 0.48. The second significant cluster (green arrow) is close to the blazar (of unknown redshift) MG3 J225517+2409. A high energy IceCube ν_μ event (ID=3), $\sim 1.1^\circ$ away from the object, was recorded when the blazar was in a flaring state.

• A search over a predefined list of 121 potential sources uses their coordinates in the likelihood maximization. The most interesting cluster, with a post-trial significance of 2.4σ, is at an angular distance of 1° from the full sky hot spot (red arrow in Fig. 4a). Fig. 4b) shows the upper limits on the one-flavour neutrino flux for the 121 objects assuming a E^{-2} spectrum. The sources indicated with an arrow in the plot have a pre-trial significance larger than 2σ. The solid line indicates the 90% C.L. median sensitivity.

iii) Stacked analysis. A likelihood stacking method is used to search for a global excess of upgoing ν_μ in correlation with catalogs [10]. Different catalogs are considered: (a) a sub-sample of the blazars in the Fermi 3LAC (containing 1420 objects observed between 1-100 GeV by LAT); (b) a catalog, still from LAT, with 64 star-forming galaxies; (c) a sample of hard X-ray with the brightest and most accretion-efficient radio galaxies in the local sky, clearly identified with a double lobed radio morphology; (d) a population of 15 AGNs with jet obscured by dust; and (e) the public sample of 56 VHE track events from the IceCube experiment. None of the tested sources shows a significant

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association with the ANTARES sample. The smallest p-value is obtained for the catalog of radio galaxies, with a pre(post)-trial p-value equivalent to a 2.8(1.6)σ excess. The most significant excess from the catalog (a) of LAT-blazars is MG3 J225517+2409 (five ANTARES tracks located less than 1° from the source). As mentioned, also an IceCube HE muon track close to the source is present. A dedicated analysis is done for this blazar. An a posteriori significance of 2.4σ for the combination of ANTARES and IceCube data with that blazar is estimated.

iv) Multi Messenger. ANTARES was deeply involved since 2009 in many multimessenger alert programs [12]. A dedicated real-time pipeline was developed to look for ν candidates in both time and space coincidences with transient events announced by public alerts distributed through the Gamma-ray Coordinates Network [13] or by private alerts. Activities include searches for neutrino candidates coincident with gamma-ray bursts detected by the Swift and Fermi satellites, HE events registered by IceCube, transient events from blazars monitored by HAWC, photon-neutrino coincidences by AMON notices and gravitational wave candidates observed by LIGO/Virgo. By requiring temporal coincidence, this approach increases the sensitivity and the significance of a potential discovery. Thanks to the good angular accuracy of ANTARES events, a coincident detection also improves the localisation area of non-well localised triggers such as the gravitational waves [14]. This online analysis framework also hosted a neutrino alert sending program. This program, named TAToO, has triggered robotic ground based optical telescopes (MASTER, TAROT, ROTSE, ZADKO and the SVOM) immediately after the detection of any relevant neutrino candidate. A subset of events with highest probabilities of being of cosmic origin has also been followed by the Swift and the INTEGRAL satellites, the Murchison Widefield Array radio telescope and the H.E.S.S. gamma-ray telescope. The results of twelve years of observations are reported in a paper in preparation. No optical counterpart has been significantly associated with an ANTARES neutrino signal during image analysis. Constraints on transient neutrino emission have been set.

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