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Highlights from the ANTARES neutrino telescope

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The ANTARES detector, located offshore the French southern coast at about 2500 m under the sea level, was the first deep sea neutrino telescope. Despite its (relative) small size, ANTARES has provided essential contributions to neutrino particle physics and astrophysics. ANTARES was operating in its full configuration from May 2008 to February 2022. After the stop of data taking, 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 (HE) 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 the data stream is processed using dedicated trigger algorithms. Technical details on ANTARES can be found in [1]. ANTARES detected neutrinos at different energy ranges, from the tens of GeV (when atmospheric neutrino oscillations can be measured), passing to the TeV-scale (relevant for indirect dark matter searches) up to the multi-TeV energies of cosmic neutrinos. The main background in neutrino telescopes comes from atmospheric muons, which can be easily rejected during physics analysis with a directional cut on reconstructed events. In this contribution a highlight of recent results obtained with the ANTARES detector is given.

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1. Neutrino oscillation studies

Atmospheric neutrinos (whose ν_μ and ν_e flux have been measured in [2]) arrive at the ANTARES detector with baseline distances L_ν ranging from $\sim$ 10 km of vertically down-going events to $\sim 10^4$ km of vertically up-going ones. The detector can trigger events if $E_{\nu_\mu} > 10 - 20$ GeV, allowing to study neutrino oscillations as a function of the E_ν/L_ν ratio through the ν_μ disappearance channel. The reconstructed zenith angle θ_{reco} corresponds to a given L_ν distance. If the muon stops inside the detector the ν_μ energy, E_{reco}, can be estimated through the determination of the muon range. By studying the distribution of $E_{\text{reco}}/\cos\theta_{\text{reco}}$ vs. Monte Carlo (MC) predictions, the non-oscillation hypothesis has been discarded with a significance of 4.6σ. The allowed values in the $(\sin^2\theta_{23}, \Delta m^2_{32})$ parameter space are consistent with world best-fit values [3]. 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 flavors, its presence would modify oscillation patterns through, e.g., mixing angles θ_{24} or θ_{34}. Comparing data and MC under these additional oscillation possibilities, exclusion contours are built. In Fig. 1 (left) the resulting 90% C.L. exclusion limits have been computed in the plane of the two oscillation matrix elements depending on mixing angles θ_{24} and θ_{34} [3]. Moreover, neutrino Non Standard-model Interactions (NSIs), quantified through dimensionless constants $\epsilon_{\alpha\beta}$ $(\alpha, \beta = e, \mu, \tau)$ can alter atmospheric ν propagation in Earth through matter effects. ANTARES [4], using a log-likelihood ratio test on $\epsilon_{\mu\tau}$ and $\epsilon_{\tau\tau} - \epsilon_{\mu\mu}$, has provided no evidence of NSIs. The constraint on $\epsilon_{\mu\tau}$ in the $\mu - \tau$ sector is among the most stringent to date for NSIs. These studies demonstrated the capability of undersea detectors which will be fully exploited by KM3NeT/ORCA [5].

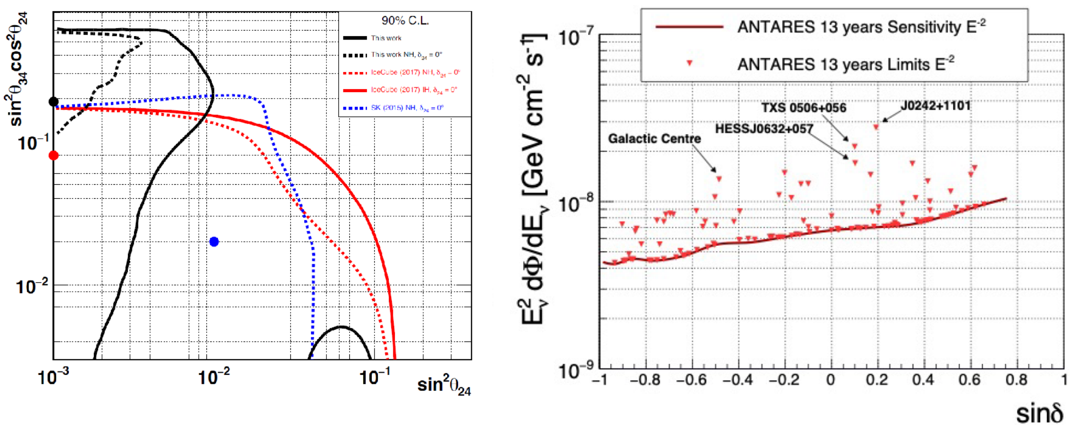

Figure 1: Left: 90% C.L. limits for the 3+1 neutrino model in the parameter plane of $|U_{\mu 4}|^2 \equiv \sin^2\theta_{24}$ and $|U_{\tau 4}|^2 \equiv \sin^2\theta_{34}\cos^2\theta_{24}$ [3]. Right: 90% C.L. upper limits on the one-flavour neutrino flux for the 121 potential sources vs. the declination. [12].

2. Intermediate energies and indirect Dark Matter searches

A well-motivated hypothesis for dark matter (DM) is the existence of weakly interacting massive particles (WIMPs) that form halos in which galaxies are embedded. WIMPs, accumulated in celestial objects, can annihilate into pairs of standard model particles. Neutrinos, in particular, are the final product of a large variety of decay processes. One of the possible target is the Galactic

Centre. The search for a ν excess due to DM has been performed combining both ANTARES and IceCube data [6] and no significant signal has been observed. Consequently, upper limits on the thermally-averaged annihilation cross section of WIMPs have been set. ANTARES has searched also for *secluded* DM signals. Secluded scenarios contain a natural way around the unitarity bound on the DM mass, via the early matter domination induced by the mediator of its interactions with Standard Model particles. Upper limits on the secluded DM annihilation cross section for masses up to 6 PeV are reported in [8]. Another target for such indirect searches is the Sun, where WIMPs could accumulate via scattering with nuclei and where equilibrium between capture and annihilation is expected. The dominant presence of H nuclei in the Sun allows to test the mechanism of spin-dependent interaction of WIMPs with matter that is difficult to verify with terrestrial experiments. The non-observation of neutrinos with $E_\nu > 50$ GeV from the Sun direction allows to set the most stringent upper limits on the spin-dependent WIMP cross section in a wide region of masses [7].

3. High-energy cosmic neutrino studies

ANTARES used both event topologies identified in neutrino telescope, i.e., track like events (induced mainly by ν_μ CC interactions) and cascades (induced mainly by ν_e CC and all-flavour NC). Track events allow an angular precision on the neutrino direction better than 0.4° for $E_\nu > 10$ TeV [12]. Cascade events have poorer angular resolution but allow a better determination of E_ν. The search for a cosmic neutrino signal is performed on statistical basis exploiting different strategies.
i) Diffuse flux, i.e., detection of an excess of HE events above the background of atmospheric ν's [11]. The diffuse flux of cosmic ν's discovered by IceCube is, so far, compatible with an equal flavour equipartition and can be described by single-power-law, i.e., $d\Phi/dE = \Phi_0(E/E_0)^{-\gamma}$. Some tension exists between the results obtained by IceCube using different samples [13], which can be solved, e.g., with a multi-component origin or a contribution from our Galaxy. ANTARES searched for an excess of HE ν's above a given threshold of reconstructed energy, E_T that is optimized blindly. The analysis yield 19 track-events with $E > E_T$, when 13.5 are expected; the cascade-like sample has 14 events vs. 10.5 expected. The significance of the excesses is estimated to be $\sim$1.6 σ and the null-cosmic hypothesis rejected at 85% C.L. A fraction of ANTARES data (alone [9] or combined with IceCube [10]) have been used to search for a diffuse neutrino flux from the inner Galaxy. The encouraging results testing CR propagation models are waiting for the full ANTARES data set.
ii) Point sources. ANTARES provides competitive results on the searches for point sources of cosmic ν's in the Southern sky. The analysis has applied a likelihood function to evaluate the significance of a possible excess of events over the atmospheric background [12]. Two different strategies are pursued. In the first one, the visible sky is explored looking for an excess of signal events scanning regions of $1^\circ \times 1^\circ$ size. Deviations from the null hypothesis are tested with pre-trial p-values. The cluster with the smallest p-value is 6.8×10^{-6}: its position is close to a known radio-bright blazar, J0242+1101. However, due to the large number of trials, its post-trial p-value is 0.48. The second significant cluster is close to the blazar (of unknown redshift) MG3 J225517+2409, which has also a HE IceCube ν_μ event $\sim 1.1^\circ$ away. In the second study, 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 located at an angular distance of 1° from the most significant cluster of the full-sky strategy. Fig. 1 (right) shows the upper limits on

the one-flavour neutrino flux for the 121 objects assuming a $E^{-2.0}$ 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 [14] is used to search for an excess of upgoing ν_μ in correlation with different catalogs: (a) a sub-sample of the blazars in the Fermi 3LAC (with 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. None of the tested sources shows a significant 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 $2.8(1.6)\sigma$ 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, a close IceCube HE muon track is present, and a dedicated analysis yields a posteriori significance of 2.4σ for the combination of ANTARES and IceCube data.

iv) Multi Messenger. ANTARES was deeply involved since 2009 in many multimessenger alert programs [15]. 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 [16] 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 [17]. By requiring temporal coincidence, this approach increases the sensitivity and the significance of a potential discovery. 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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