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Legacy Results of the ANTARES Neutrino Telescope

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The ANTARES neutrino telescope was operational in the Mediterranean Sea from 2006 to 2022. The detector array, consisting of 12 vertical string-like structures hosting a total of 885 optical modules, was designed to detect high-energy neutrinos covering energies from a few tens of GeV up to the PeV range. Despite the relatively small size of the detector, the results obtained are relevant in the field of neutrino astronomy, due to the view of the Southern sky and the good angular resolution of the telescope. This document will give an overview of the legacy results of ANTARES, including searches for point sources, neutrinos from the Galactic Ridge, from dark matter annihilation, and from transients, as well as limits on new physics.

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1. Introduction

The ANTARES neutrino telescope [1] took data between 2006 and 2022, and was located some 40 km offshore of Toulon, France, in the Mediterranean Sea at a depth of 2475 m. After its completion in 2008, it consisted of 12 strings, with 885 optical modules in total, each consisting of a single 10-inch photomultiplier tube (PMT), pointing downwards under an angle of 45°; the PMTs were grouped in storeys of 3 optical modules each. Its northern-hemisphere location of 42°50′ N 6°10′ E gave a view of the sky complementary to that of IceCube, with in particular a good view of the Galactic Centre. The goals of ANTARES were to study neutrino oscillations ($E_\nu > 10$ GeV), search for dark matter and new physics, and search for cosmic neutrinos at high energies ($E_\nu > 1$ TeV). The decay of the potassium isotope ^{40}K in seawater provided a signal that was used to calibrate the detector [2]. By regular tuning of the PMT high voltages, the loss of efficiency could be kept to no more than 20% over 16 years of data taking; also detector timing was shown to remain stable. The detector strings moved with the water current, and their position was calibrated with acoustic triangulation; the absolute direction calibration was verified by looking for the cosmic ray shadow of the Sun and the Moon [3]. The detector was shut off in February 2022, and dismantled.

2. Atmospheric neutrinos

Collisions of cosmic rays in the Earth atmosphere are a copious source of GeV-range neutrinos. Neutrinos from all directions can reach ANTARES, their angle of incidence in the detector is an unambiguous indication of their production point. After propagating from the production point, they can be detected in a different flavour-state, a phenomenon known as neutrino oscillations. Matter effects in the Earth must be taken into account in the formalism.

ANTARES measured the (unfolded) atmospheric neutrino energy spectrum between 100 GeV and 50 TeV [4], measured neutrino oscillation parameters [5], and set limits on sterile neutrinos [5] as well as Non-Standard Interactions (NSI) [6]. Limits on the NSI parameters $\varepsilon_{\tau\tau} - \varepsilon_{\mu\mu}$ and $\varepsilon_{\mu\tau}$ obtained by ANTARES are shown in Fig. 1, these limits are comparable to those of other experiments.

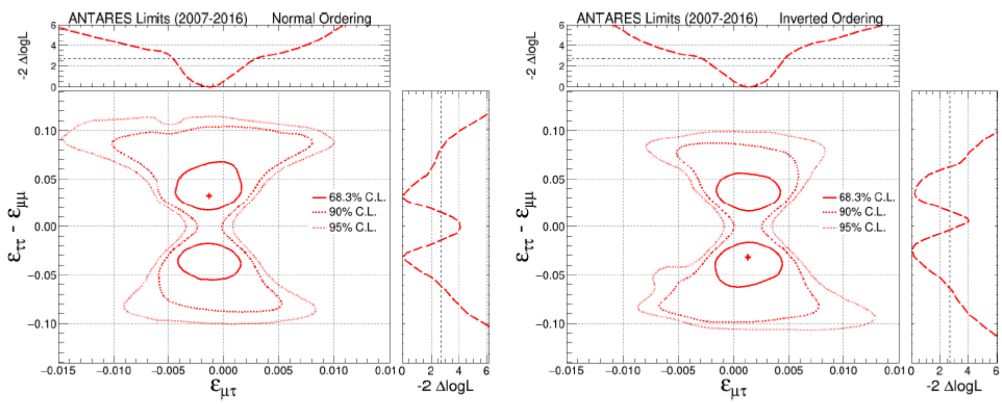

Figure 1: Limits on the NSI parameters $\varepsilon_{\tau\tau} - \varepsilon_{\mu\mu}$ and $\varepsilon_{\mu\tau}$ obtained by ANTARES, left for normal mass ordering, right for inverted mass ordering.

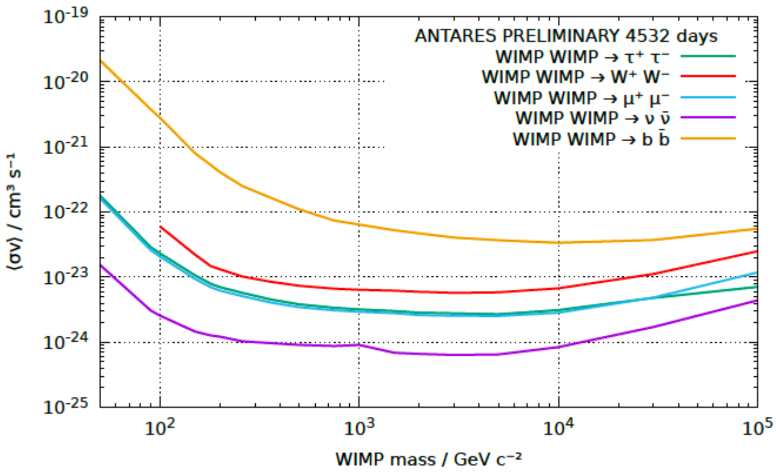

Figure 2: Upper limits at 90% CL on the thermally averaged cross section for pair annihilation of WIMPs in the Galactic Centre, resulting in neutrinos via various annihilation channels.

3. Dark matter

Neutrinos from extra-terrestrial origin could originate from the self- or co-annihilation of dark matter particles. A common assumption is that dark matter consists of weakly interacting massive particles (WIMPs) that are embedded in galaxies. ANTARES has recently analysed the full 2007-2022 data sample for signs of dark matter annihilation in the Galactic Centre, found no evidence for a signal and put limits on the thermally averaged WIMP annihilation cross section, as shown in Fig. 2 [7]. Other recent ANTARES analyses include a search for secluded dark matter [8] and a combination of Galactic Centre dark matter limits with IceCube [9].

4. Cosmic neutrinos

At high energy, the neutrino flux in ANTARES is expected to be dominated by neutrinos from cosmic origin. ANTARES has performed several searches for cosmic neutrinos.

4.1 Diffuse flux

A first hint of a diffuse cosmic neutrino flux was reported by IceCube ten years ago [10], and was confirmed in several other IceCube analyses. ANTARES has also searched for evidence for a diffuse cosmic flux [11]; in an exposure of 3330 days (2007-2018) ANTARES finds an excess with respect to the hypothesis of the absence of such a flux corresponding to 1.8σ. This is not sufficient to claim an observation, but the best fitted flux, $\Phi_{100\text{TeV}} = (1.5 \pm 1.0) \times 10^{-18}$ GeV^{-1} cm^{-2} s^{-1} sr^{-1}, and spectral index, $\gamma = 2.3 \pm 0.4$, are consistent with those from IceCube data.

4.2 Galactic Ridge and Plane

The densest regions of our Galaxy (the Galactic Plane and the Galactic Ridge) are likely sources of a diffuse neutrino flux from the decay of pions and kaons originating from collisions of cosmic rays with matter in dust- and gas clouds. ANTARES has analysed the Galactic Ridge region around

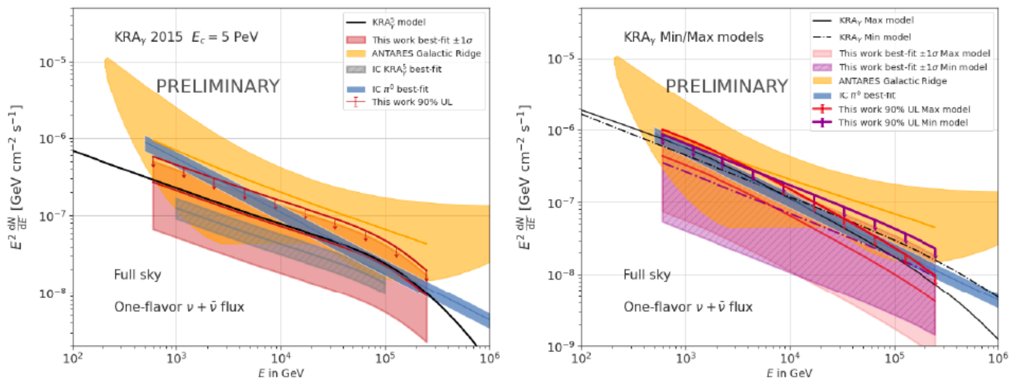

Figure 3: One-flavour $\nu + \bar{\nu}$ flux from the Galactic Plane, normalised to the full sky, as a function of neutrino energy. Left for the KRA$_\gamma^5$ model, right for KRA$_\gamma^{\min}$ and KRA$_\gamma^{\max}$ models. The ANTARES Galactic Plane results are shown in red, the Galactic Ridge analysis results are shown in orange. The IceCube results are also shown.

the Galactic Centre with an on/off-target method for background estimation, and found a global excess of neutrinos corresponding to approximately 2σ [12]. IceCube recently presented evidence for Galactic neutrinos using a template method based on γ-ray flux observations [13]. ANTARES has applied a similar method to its full data set (4541 days exposure) using the KRA$_\gamma^5$ [14] and the KRA$_\gamma^{\min}$ and KRA$_\gamma^{\max}$ [15] templates, and finds an excess corresponding to 1.7σ, and a flux consistent with the one reported by IceCube, as shown in Fig. 3 [16].

4.3 Source searches

ANTARES has performed an all-sky point source search with the full 2007-2022 data set [17]. A total of 11029 track-like and 239 shower-like neutrino candidates were selected. The most significant source was found to be located at (declination, right ascension) = (17.74°, 200.46°), with pre-trial significance of 4.0σ, and a post-trial significance of 1.2σ, which is insufficient to claim a discovery.

In the same full data set, ANTARES has also searched for evidence of neutrinos originating from sources in a list of 163 celestial objects that are considered promising neutrino sources [17]. Eight sources are found to have a pre-trial significance exceeding 2.0σ, including the Galactic Centre, and the flaring blazar TXS0506+056, as shown in Fig. 4. The most significant source found by ANTARES is the blazar MG3 J225517+2409, with a pre-trial (post-trial) significance of 3.4σ (1.7σ). The IceCube hotspot NGC1068 is not significantly visible in the ANTARES data, as expected.

VLBI (radio) blazars have been suggested as promising neutrino sources [18]. ANTARES analysed 3845 days of 2007-2020 data to search for neutrinos from VLBI blazars [19]. Fig. 5 shows a distribution derived from the angle between pairs of observed neutrinos and known VLBI sources; the excess of pairs over random background is plotted as a function of the angular distance, expressed in units of the assigned neutrino angular uncertainty. An excess is visible with a post-trial significance of 2.2σ, at an angular distance corresponding to 0.81 times the assigned uncertainty. The excess is confirmed at the same significance with a time-integrated likelihood analysis [19].

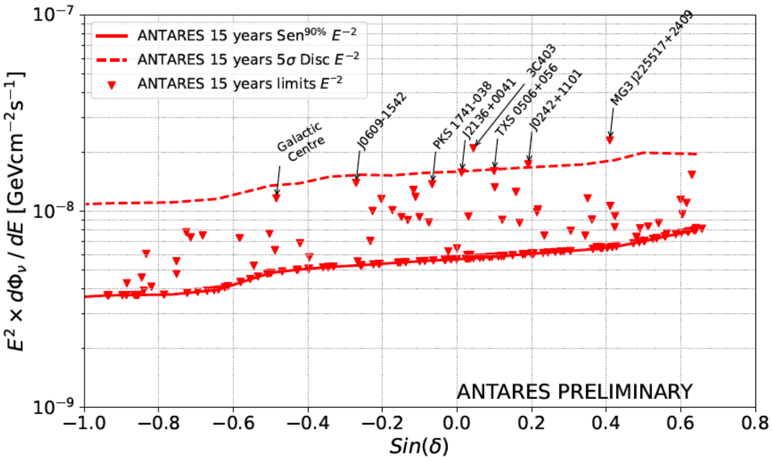

Figure 4: Upper limits at 90% CL on the one-flavour neutrino flux from 163 possible sources considered.

Analyses have also been carried out focusing on known flaring periods of potential sources [19]. A total of 36 flaring sources were considered, selected from a list of 110 possible neutrino flares compiled by IceCube [20]. Overall no significant correlations were found, but four sources were found to have a non-zero signal contribution in the fit [19].

4.4 Multimessenger programme

ANTARES had an active multimessenger programme, both in terms of following up on external alerts and in terms of sending alerts to other telescopes for possible follow-up [21]. Between 2009 and 2021 ANTARES sent some 350 alerts to robotic optical telescopes and X-ray obervatories, 20 alerts to MWA (radio) and 2 alerts to HESS (γ-rays).

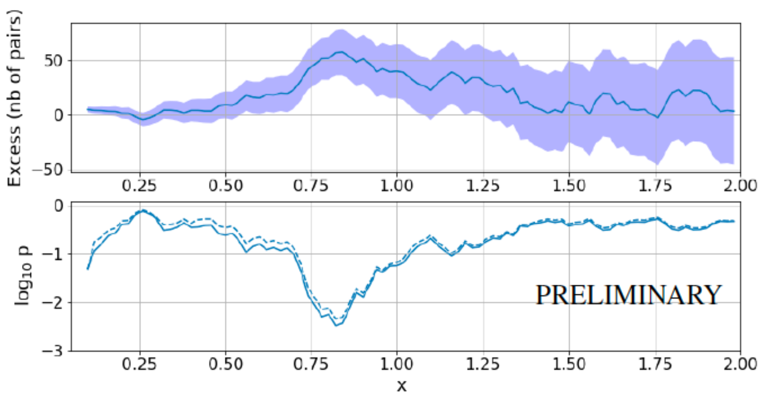

Figure 5: Excess over random background of pairs of observed neutrinos in ANTARES and known VLBI (radio) blazars, as a function of their angular distance, expressed in units of the assigned neutrino angular uncertainty.

5. Conclusion

ANTARES has successfully taken data during 16 years in the Mediterranean Sea, reaching design performance, and paving the way for future sea-based neutrino telescopes. ANTARES results complement and agree with those of IceCube, but also indicate the need for a telescope with a larger instrumented volume in the Northern Hemisphere. In the Mediterranean Sea, the torch has now been passed to KM3NeT [22].

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