PROCEEDINGS OF SCIENCE

Latest Results and Lessons Learned from the ANTARES Neutrino Telescope

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The ANTARES neutrino telescope operated in the Mediterranean Sea from 2006 to 2022. The detector array, consisting of photomultipliers encompassing a volume of 0.01 km^3, was designed to detect high-energy neutrinos covering energies from a few hundred 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, including hints of cosmic neutrino signals. This proceeding will provide an overview of those results and the lessons learned from the operation of the detector.

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1. The ANTARES Neutrino Telescope

The ANTARES detector [1] was an underwater neutrino telescope active from 2006 to 2022, located off the French coast near Toulon. It was located at a depth of 2450 m and consisted of an array of 885 PMTs. A neutrino interacting with the medium near or inside the instrumented volume produces a relativistic lepton that induces Cherenkov light collected by the array of PMTs. By combining time and charge information with the positions of the PMTs one could estimate the energy and infer the direction of the primary neutrino.

The main scientific goal of the ANTARES collaboration was to detect high-energy neutrinos of cosmic origin. Even if no significant detection was claimed, several interesting results were produced during the operation of the experiment.

2. Latest Results

The ANTARES detector was decommissioned in 2022. The collaboration is currently actively working on producing the final results which will constitute the legacy of the experiment. These results are anticipated to be published throughout 2024. In this section, we will highlight some of the most relevant outcomes achieved by the ANTARES collaboration to date.

One of the breakthroughs in field of neutrino astronomy was the discovery of the existence of a cosmic neutrino flux in 2013 by the IceCube collaboration [2]. A 1.8σ mild excess was also observed using 9 years of ANTARES data [3]. This analysis will soon add 3.5 years to the dataset and will include some analysis improvements in its final version.

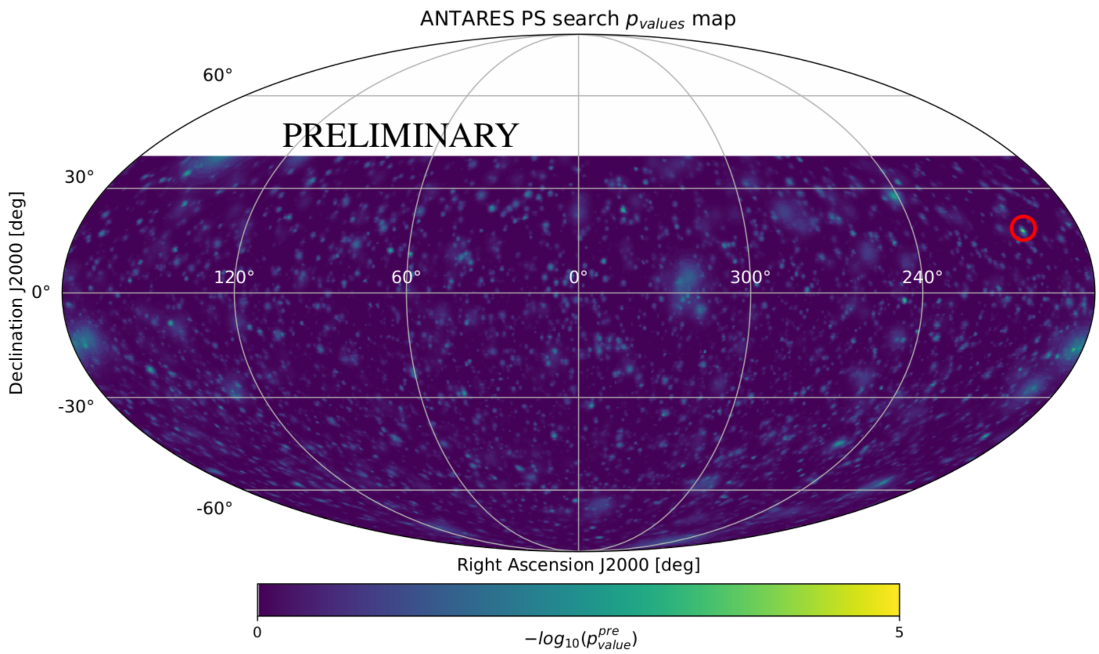

Figure 1: Skymap in equatorial coordinates including the complete ANTARES dataset. The color code refers to the p-value in each pixel. The most significant spot in the map in highlighted with a red circle.

From this cosmic diffuse flux, one would expect sources to emerge above the background of neutrinos produced by cosmic ray interacting with the Earth atmosphere. In this regard, searches for sources have been performed. First with an all-sky survey, which revealed no significant excess (see Fig.1). Then a targeted search, using a predefined list of potential neutrino sources was also carried out [4]. Among these sources, MG3 J225517+2409 and 3C403 showed the highest pre-trial significance, both at 3.4σ, which decreased to 1.7σ post-trial. It is worth noting that TXS 0506+056, for which IceCube has provided compelling evidence as a neutrino source [5], stood out as one of the top five sources with a pre-trial significance of 2.4σ.

A hint that a fraction of the diffuse neutrino flux has a Galactic origin has been first observed by ANTARES [6] and later confirmed with a higher significance by IceCube [7]. The ANTARES results are summarized in Fig. 2. However, disentangling possible individual source contributions from the pure diffuse Galactic emission has proven elusive so far, leaving it as a goal for upcoming detectors like KM3NeT which will be more sensitive to the inner Galactic plane.

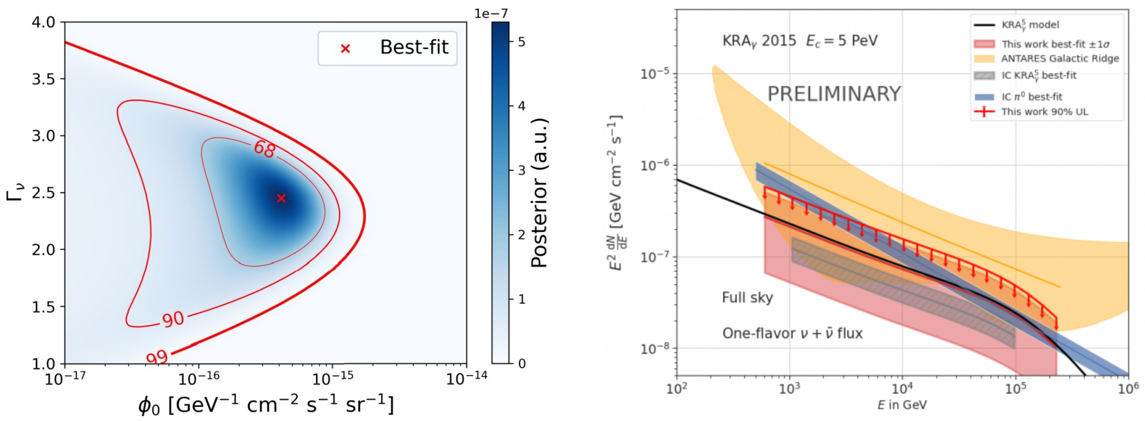

Figure 2: Left: The best fit parameters (flux normalization and spectral index) obtained by ANTARES using a on/off counting method as explained in [6]. Right: The flux estimation comparing different signal hypotheses and IceCube results as presented in [8].

ANTARES has also produced interesting results regarding the potential identification of radio-bright blazars as neutrino sources. A possible hint (1.6σ) was reported in [9]. A subsequent search was done using a refined selection of candidate sources, focusing on the brightest ones and incorporating more data into the sample [10]. In this updated analysis, not only did the overall correlation increase to 2.2σ, but the time-dependent search for individual sources revealed 18 candidates with potential neutrino flares (3σ pre-trial excess). The probability of background fluctuations producing as many sources with such significance was only 1.4% (equivalent to 2.5σ). One particularly remarkable case involved multiple coincident observations in different messenger channels, including a neutrino flare detected by ANTARES, a gamma-ray flare detected by Fermi-LAT, a radio flare observed by OVRO, and a high-energy neutrino detected by IceCube. The likelihood of this coincidence happening by chance was as low as 0.5%. However, it is important to note that this coincidence was identified *a posteriori*, making it impossible to determine a reliable post-trial significance.

Finally, while ANTARES was primarily designed for neutrino astronomy, the results obtained covered a broad scientific scope including searches for dark matter, particle physics, neutrino oscillations and interactions, among others. Additionally, due to its unique location, ANTARES contributed to environmental research in Earth and sea sciences. A comprehensive list of publications by the collaboration can be found at the ANTARES website [11].

3. Lessons Learned

There are several lessons that we have learned after the ANTARES lifespan of more than 15 years. One of them is that, despite the challenges faced, it is possible to reliably operate a neutrino telescope in the hostile environment of the deep sea.

We also found out that the volume of ANTARES was not enough to have a significant detection. Nevertheless, as it was showed, we were able to collect thousands of neutrino candidates with some interesting hints of different cosmic signals. If these upper fluctuations are indeed neutrinos from astrophysical origin, the next generation telescope KM3NeT [12], with more than one order of magnitude greater sensitivity, should clearly unveil them reaching a 5σ discovery level.

Another important lesson is that we need more large-scale neutrino telescopes in operation in order to have a complete coverage of the sky in neutrinos, to enable cross-checks within the overlapping fields of view, and minimize the statistical penalization required to account for the 'look-elsewhere' effect in all-sky searches.

An additional way to overcome the limited signal statistics collected by neutrino telescopes is to focus on events of astrophysical relevance provided by other observatories. This approach can significantly reduce the expected background and therefore enhance the discovery potential. In this context, collaborative multi-messenger efforts with other observatories are essential and represent the path forward for future experiments.

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