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Results from the ANTARES neutrino telescope

Agustín Sánchez Losa[1,a] on behalf of the ANTARES Collaboration

[1] *INFN - Sezione di Bari, Via Edoardo Orabona 4, 70125 Bari, Italy*

Abstract. The ANTARES detector is an underwater neutrino telescope, the largest in the Northern Hemisphere and the first one ever built under the sea, located in the Mediterranean Sea 40 km off the Southern coast of France, at a depth of 2.5 km. It comprises 885 photomultiplier tubes distributed along twelve detection lines. The signal due to neutrinos is searched by reconstructing the tracks of secondary particles produced in the surroundings of the detector. The detector is in data taking with its final configuration since 2008. It is aimed at identifying the sources, either steady or flaring, of cosmic neutrinos, and is also suitable for detection of dark matter within the Sun and/or Galactic Centre. ANTARES can contribute in the confirmation of the cosmic neutrino flux observed by IceCube, being particularly competitive for the Galactic Centre, and in general for galactic sources, due its latitude and at lower energies and softer spectra due its configuration. Several multi-messenger analyses have been also attempted, including the search of coincidence signals of neutrinos with gravitational-waves. Additional topics include neutrino oscillations or the search of exotic particles, like nuclearites and magnetic monopoles. Results from the latest analyses are presented.

1 Introduction

ANTARES [1] is the largest underwater neutrino telescope on the Northern Hemisphere. It has been taking data smoothly in its final configuration since 2008 and is placed on the seabed at 40 km off the coast of Toulon (France) with an instrumental volume of approximately 0.01 km^3 distributed between 2.5 and 2.0 km depth on the Mediterranean Sea. It consists of 885 10″ photomultipliers distributed in a three-dimensional matrix in such volume that primarily reconstructs the muon tracks that cross its volume, in some occasions the result of a charged-current interaction of a ν_μ in the vicinity of the detector. Its main purpose is to discover the origin of high energy cosmic neutrinos while at the same time give an answer to other mysteries like the dark matter nature and other phenomena.

In the following, the latest highlighted ANTARES analysis are reported, which are point source, diffuse flux, multi-messenger (section 2 to 4 respectively) and dark matter analyses (see contribution [2] in this conference). Some analyses are explained in detail when not covered in other contributions of the conference, providing the latest upper limits of ANTARES.

2 Point sources

Point source searches is one of the main neutrino telescope analyses. They could resolve the source or sources responsible of the excess observed by IceCube [4].

[a] e-mail: agustin.sanchez@ba.infn.it

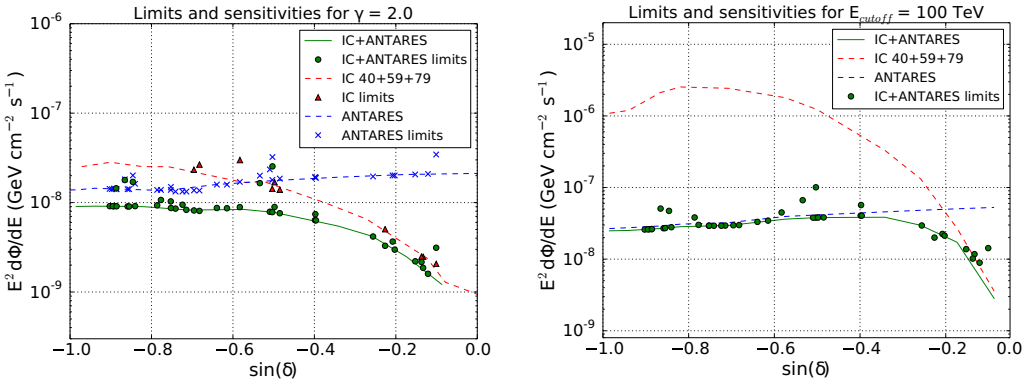

Figure 1. Combined upper limits for E^{-2} (left) and $E^{-2}\exp^{-\sqrt{E/100\text{TeV}}}$ (right) for the first combined IceCube-ANTARES point source analysis [3].

In a previous analysis [5], ANTARES constrained the extension of a possible source responsible of the IceCube cosmic neutrino flux observed close to the Galactic Centre, in particular a source with a Gaussian-like extension smaller than 0.5° for declinations below −11° and smaller than 1° for $\delta \lesssim -33°$ for a E^{-2} spectrum. In a recent update [6], these limits have been extended to softer spectral indexes up to a $E^{-2.5}$ spectrum, disfavouring an origin of the IceCube signal for a point-like source with these spectra.

The TANAMI collaboration reported observations of 6 bright blazars locally compatible with the 2 first PeV IceCube events IC14 (Bert) and IC20 (Ernie). ANTARES realised a point source analysis of these 6 sources in collaboration with TANAMI [7] in order to discover or constrain them as possible source of the Ice Cube events, excluding at a 90% confidence level such possibility unless the neutrino spectrum is softer than −2.4.

2.1 IceCube-ANTARES combined analysis

For the first time, a combined IceCube-ANTARES analysis has been performed [3] on the Southern Sky by using muon tracks detected by both experiments from Jan 29, 2007 to Dec 31, 2012 for ANTARES and from Apr 5, 2008 to May 13, 2011 for IceCube, including its IC-40, IC-59 and IC-79 configurations. This joint analysis summed up the great statistics of IceCube with the privileged ANTARES sensitivity for the Southern Sky (including the Galactic Centre) and lower energies (i.e. soft spectra) and its good angular resolution.

From the IceCube data 146,018 Southern-sky track-like events were selected, while 4,136 tracks were selected from ANTARES. An unbinned maximum likelihood ratio estimation has been used to evaluate them in the search of a possible signal excess, weighting each detector contribution as a function of their acceptances.

A full Southern-sky search and a candidate list search of 40 Galactic and extra-Galactic sources have been carried out finding no statistically significant excess in both searches. The most significant cluster is located at equatorial coordinates $\alpha = 332.8°$, $\delta = -46.1°$ with a post-trial significance of 24%. From the candidate list, HESS J1741-302 shows the lowest p-value, with a 11% post-trial probability of being produced by the background. In figure 1 the combined upper limits are shown,

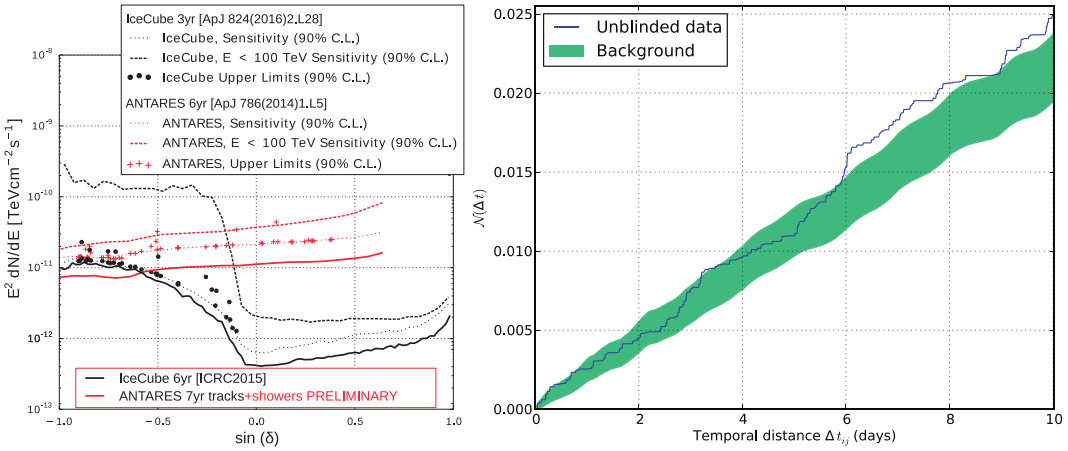

Figure 2. Left: ANTARES combined sensitivity for tracks and showers with data collected between 2007 and 2013. Right: Cumulative two-point distribution over 10 days for the time correlation analysis. The green area corresponds to the standard deviation of each bin of the cumulative distribution, in the background only hypothesis while the two-point cumulative distribution for the unblinded dataset is represented in blue.

where both detectors contributed to improve the limits that the respective datasets would have achieved separated.

2.2 Point source update

The first ANTARES point source analysis including the shower channel has been performed [8] with data between 2007 and 2013, comprising 1690 days of live-time. 6490 tracks and 172 showers with a median angular resolution of 0.3° and 3° respectively, have been selected for a full sky and candidate list search. It has been estimated a ∼10% contamination of atmospheric muons for the shower channel. The candidate list included 54 Galactic and extra-Galactic sources, the Galactic Centre and 8 IceCube muon tracks [4].

The most significant cluster found is at equatorial coordinates $\alpha = 311.7°$, $\delta = -48.3°$ with a post-trial 1.3σ significance and the source with the largest excess was HESS J0632+057 with a 0.75σ post-trial significance. In the absence of a signal excess, upper limits on the neutrino fluxes have been set (see figure 2 left).

3 Diffuse fluxes

Diffuse flux searches look for cosmic neutrino fluxes that do not presume a point source origin, but an extensive region or even no location dependence at all. Therefore, they suffer of a larger background than the point source searches but are not constrained to any source origin.

For the first time, a search for an cosmic neutrino diffuse flux using both muon tracks and shower events in ANTARES has been carried out, using data between 2007 and 2015, where 7 events have been observed with 5 events expected from background and 2 from an IceCube flux. Results and used methods are covered in contribution [9] in this conference. Also there, an update is presented for a dedicated analysis of neutrinos coming from the Fermi bubbles [10], with ANTARES muon

tracks reconstructed in the period 2007−2015 and a 1σ excess, and the search of a neutrino diffuse flux coming from the Galactic Ridge [11] with 2007−2013 data, where 2 events were observed with 3.7 expected from background.

3.1 Time correlation with IceCube HESE

A search of ANTARES neutrinos in temporal coincidence with IceCube High-Energy Starting Events (HESE) and space compatible has been carried out. The analysis [12] uses ANTARES tracks occurred between May 2010 and November 2012 for $E^{-2.5}$ to E^{-2} spectra in coincidence with the 8 IceCube HESE [4] that are within 45° from the Galactic Centre during that period. This is done by a two-point time-spatial correlation function without need of a prior on the burst timing structure nor on the electromagnetic emission, providing an effective way to acquire information on the possible origin of the IceCube astrophysical signal from a transient source.

The ANTARES event selection criteria have been optimized through Monte-Carlo simulations to reach a constant neutrino candidate rate over time. This has been done with a Model Discovery Potential optimization on the cut on the track quality parameter for each of the five sub-samples of optical module mean counting rates chosen for the analysis. The signal model used has been the IceCube flux as reported in [13]. These sub-samples reflect different data taking conditions regarding its data quality. The selection of data this way lead to a final sample consisting of 4337 events.

ANTARES results show a fluctuation with at least a 35% probability of being of background origin. Thus, no significant correlation has been found. Comparison between data and background (see figure 2 right) shows that the largest deviation between the two-point distributions corresponds to a time scale of 6.1 days, being this the most likely time scale of a possible transient signal responsible of the selected IceCube events.

4 Multi-messenger

The search for neutrinos in coincidence with other astronomical messengers allows to reduce the amount of signal required for a discovery under the assumption of a correlation in both messenger productions.

With the discovery of the first gravitational-wave, GW150914 [14], possible high energy neutrino events in coincidence have been searched in a joint analysis of ANTARES with the IceCube collaboration [15]. The neutrino follow-up of this gravitational-wave and of two IceCube HESE event alerts are described in detail in contribution [16] in this conference.

On a different approach, the Telescopes-ANTARES as Target of Opportunity [17, 18] (TAToO) multi-wavelength follow-up program has studied more than 200 high energy neutrino alerts with optical follow-ups (with the optical robotic telescopes TAROT, ROTSE and MASTER) since mid-2009 and 12 alerts with X-ray follow-ups with the Swift-XRT instrument since mid-2013. The results of these analyses are presented in contribution [16] in this conference, with a recent update of the Murchinson Widefield Array (MWA) radio follow-up of two neutrino alerts.

A new analysis evaluating two promising GRB neutrino emission models, internal shock [19] and photospheric [20] ones, has been carried out. On this analysis, neutrinos were searched for coincidence with four of the brightest GRBs visible by ANTARES between 2008 and 2013: GRB080916C, GRB110918A, GRB130427A and GRB130505A. The details of this analysis are extended in contributions [21] and [22] of this conference.

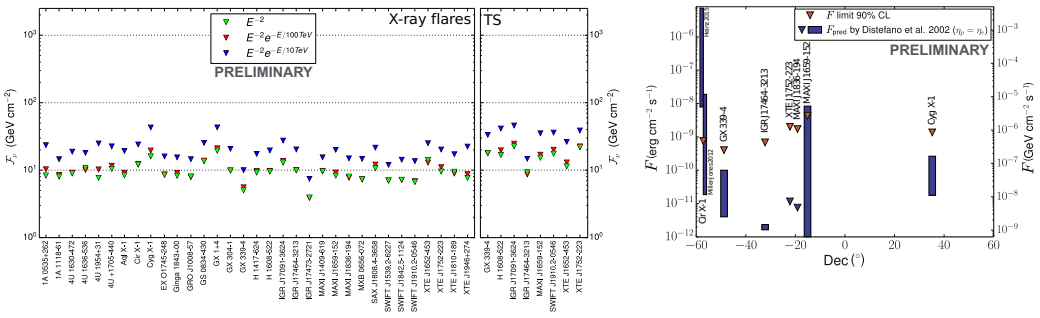

Figure 3. Upper limits at 90% C.L. on (left) the neutrino fluence for the 33 X-ray binary candidates and 8 hardness transition state sources and (right) on the neutrino energy flux for the microquasars studied considering a $E^{-2}\exp^{-\sqrt{E/100\,\mathrm{TeV}}}$ spectra, compared with the expectations from [23].

4.1 X-ray binaries

A time-dependent search looking for possible Galactic high energy neutrino sources has been performed, testing X-ray binaries as possible candidates, using ANTARES muon tracks reconstructed from 2008 to 2012 [24]. This analysis completes one carried out for blazars as extra-Galactic transient neutrino source candidates [25] with similar methodology and updates one precedent where six microquasars were studied [26].

The search for cosmic neutrinos has been carried out during flaring periods deduced with Bayesian block time-series analysis methods [27] from X-ray emission light curves measured on 33 X-ray binary candidates by the Swift/BAT [1] telescope, completed with data from RXTE/ASM [2] and MAXI [3] instruments. Additionally, hardness transition states on 8 X-ray binaries have been considered. The tested spectra are E^{-2} and $E^{-2}\exp^{-\sqrt{E/cut-off}}$ with 10 TeV and 100 TeV cut-offs. ANTARES data selection is based on a Model Discovery Potential optimization. The devised maximum likelihood ratio analysis considered also a possible lag between the neutrino and the electromagnetic signals.

The data unblinding provided no significant excess, with the most significant fluctuation corresponding to GX1+4 with a 74% post-trial probability of being produced by the background. Upper limits have been computed on the neutrino fluence and on different neutrino flux model parameters found in the literature (see figure 3).

5 Conclusions

The latest ANTARES analyses have provided numerous constrains to the possible origin of the IceCube signal, from Galactic to extra-Galactic candidates, point sources or extended ones, and even limits on a possible transient nature. Not to mention the latest dark matter analysis, which proved to be very competitive on the exclusion of certain dark matter candidate parameters. In the future, KM3NeT will take over of its contribution to the neutrino astronomy, as it has been presented on contribution [28] in this conference.

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