PROCEEDINGS OF SCIENCE

The ANTARES neutrino telescope

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ANTARES is the first deep sea neutrino telescope. It is in data taking since 2007 and the large amount of high quality data has proven the reliability of this detection technique and has given a strong impulse to the development of the new generation of seawater neutrino telescopes. In this contribution a short review of some recent results obtained with the ANTARES detector is given.

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1. Introduction

Neutrino astronomy is a recent branch of astroparticle physics and has proven its ability to explore the far universe. Particularly interesting is the multi-messenger approach, when coincidences are looked for between events detected within limited space-time intervals by different observatories. In this scientific framework, the ANTARES detector, an underwater telescope located offshore the French southern coast, at about 2500 m under the sea level, has given an essential contribution to recent development of neutrino astronomy, despite its small size. ANTARES has been operating since 2008 in its complete configuration. 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 ("all-data-to-shore" approach, [1]) 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 ref. [2]. The major background when searching for cosmic neutrinos with a submarine telescope like ANTARES is represented by atmospheric muons and atmospheric neutrinos, which are the relics of extensive air showers due to high energy cosmic rays impinging with the Earth atmosphere. 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. Thanks to the shielding action of the Earth, the only particles producing upward going tracks are neutrinos. On average ANTARES detects about one thousand neutrinos per year, the large majority being atmospheric. The search for a cosmic signal is performed on statistical basis exploiting different strategies:

- detection of an excess of very high-energy events coming from unresolved sources;
- identification of a directional excess of events over the expected background of atmospheric neutrinos;
- search for space/time coincidences between neutrino events and other probes, like electromagnetic emissions, cosmic rays or gravitational waves, in a multi-messenger context.

This contribution presents some recent results obtained with the ANTARES detector. The complete list of the papers published by the ANTARES collaboration is available at https://antares.in2p3.fr

2. Diffuse flux search and neutrino energy spectra

A diffuse flux of high-energy cosmic neutrinos coming from unresolved sources is considered to be present in the cosmic radiation reaching the Earth. It can be originated by faint sources or in neutrino interactions along their propagation. Previous studies already published indicates the presence of such a diffuse flux in the data sample collected between 2007 and 2018 [3]. Two different topologies of events can be identified in a neutrino telescope:

- track-like events, characterized by the presence of a long track, a muon, and due to charged current interactions of muon neutrinos. A pure sample is obtained applying quality cuts on

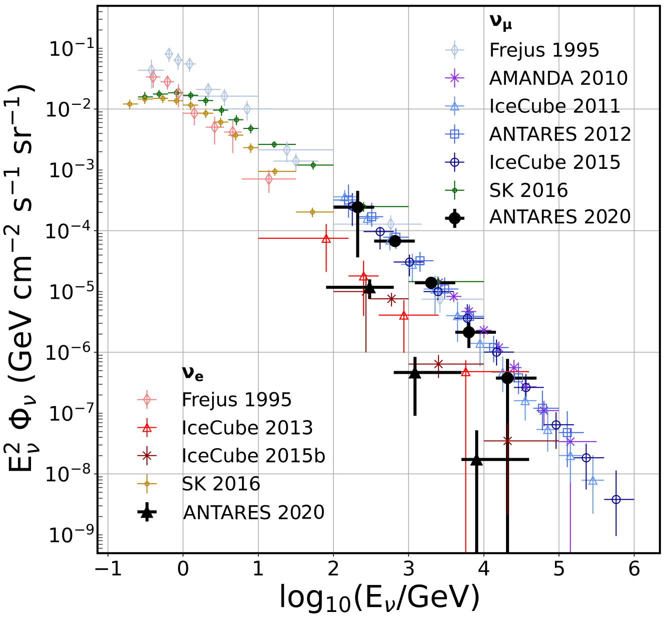

Figure 1: Measured energy spectra of atmospheric ν_e and ν_μ using shower-like and starting track events in the ANTARES neutrino telescope (black), selected with a BDT algorithm [4]. Previous measurements performed with ANTARES are reported, together with results from other experiments. Detailed bibliographic references can be found in [4]. Error bars indicate statistical and systematic uncertainties.

the reconstruction fit and rejecting all tracks going from above. Numerically this group of events is dominant and determines the flux normalization. The contamination from wrongly reconstructed atmospheric muons is almost negligible.

- shower-like events, which look like an almost spherical distribution of Cherenkov light induced by charged particles produced in any kind of weak interactions by all-flavour neutrinos. Obtaining a clean sample of these events is harder than for the first group, because of the significant contamination from atmospheric muons (between 20 and 40%) due to catastrophic energy loss. Thanks to the almost calorimetric measurement of the event energy, resulting in a better energy resolution, they give information on the slope of the energy spectrum.

A new approach, based on a multivariate analysis technique - a Boosted Decision Tree (BDT) algorithm - has been developed to improve the purity of the shower-like sample and increase its significance. The performances of this strategy has been tested to measure atmospheric neutrino energy spectra, [4]. Fig.1 shows the spectrum of electron neutrinos and of muon neutrinos. Muon neutrino events are starting tracks only, that is events whose vertex is contained inside the active volume of the detector. The results are in excellent agreement with what obtained in the analysis performed by ANTARES with passing track muon events [5] and with other detector measurements. The validation of this methodology opens interesting perspectives, in particular in the selection of larger sample of neutrino events in an intermediate energy range, around 10 TeV, where the possibility of a break in the spectrum can be investigated for the first time.

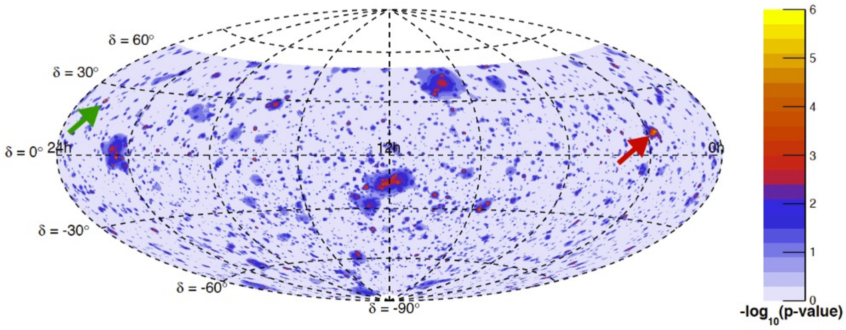

Figure 2: Sky map in equatorial coordinates of pre-trial p-values for a point-like source of the ANTARES visible sky. The location of the most (second most) significant cluster of the full-sky search is indicated by the red (green) arrow.

3. Search for pointlike sources

The search for pointlike sources of cosmic neutrinos is the main goal of the ANTARES neutrino telescope, with a special attention to Galactic sources. The geographical location of ANTARES offers a privileged point of view to the Galactic plane and centre, and the optical properties of sea water guarantee an excellent angular resolution, with a median value for track events of 0.4° and of about 3° for shower events. A total number of 10162 track-like and 225 shower-like events have been collected in the period between the end of January 2007 and the end of February 2020, corresponding to a total livetime of 3845 days. The criteria used for data selection are described in detail in the paper [6]. A likelihood function is defined to evaluate the significance of an excess of events over the expected atmospheric background. Two different strategies have been pursued:

- Full sky search: the ANTARES visible sky is explored looking for significant excess of signal events, regardless of any hypothesis on the position of the source, scanning small regions of $1^o \times 1^o$. The most significant value of pre-trial p-value, corresponding to 4.3σ, is at $(\alpha, \delta) = (39.6^o, 11.1^o)$, red arrow in Fig. 2. This direction is close to a known radio-bright blazar, J0242+1101. The second most significant cluster, green arrow in Fig. 2, corresponds to a hot spot already found in a previous ANTARES analysis, close to a high energy IceCube muon track and to a blazar that was in a flaring state when the IceCube neutrino was detected. Fig. 2 shows the ANTARES sky map in equatorial coordinates with the indication of pre-trial p-values.

- Candidate list search: a predefined list of 121 potential sources has been selected and possible excess of neutrino events have been looked for. The complete list is reported in ref.[7]. Differently from the full sky investigation, in this search the coordinates of the source are kept fixed in the likelihood maximization. The most interesting cluster, with a post-trial significance of 2.4σ, is at an angular distance of 1^o from the full sky hot spot (red arrow in Fig. 2). Fig. 3 shows the upper limits on the one-flavour neutrino flux for the 121 potential sources assuming an E^{-2} spectrum. The sources indicated with an arrow in the plot have a

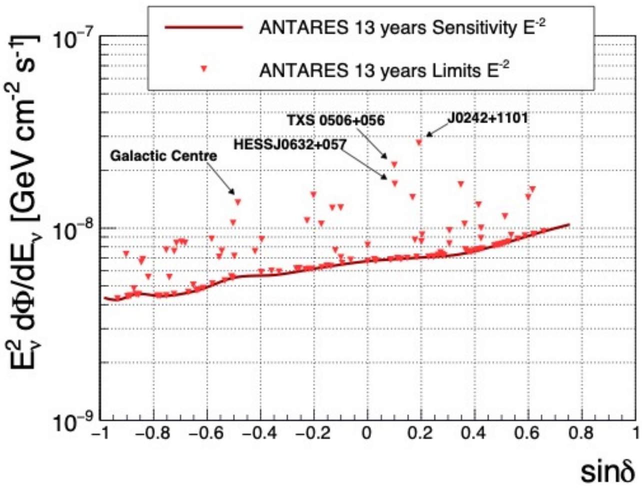

Figure 3: Red triangles are the 90% C.L. upper limits on the one-flavour neutrino flux normalization for the 121 potential sources as a function of the declination. An E^{-2} spectrum is assumed. The sources indicated with a red arrow has apre-trial significance larger than 2σ. The red line indicates the 90% C.L. median sensitivity.

pre-trial significance larger than 2σ. The solid line indicates the 90% C.L. median sensitivity.

4. Multimessenger studies

ANTARES is deeply involved in many multimessenger alert programs. Several papers have been published on joint analyses to search for neutrino events in coincidence with gravitational waves or electromagnetic emissions [8]. Recently a search for events connected to flaring state of some radio-bright blazars have been performed. Using the same data sample considered for the pointlike source search, a total of 2774 blazars with declination less than 40^o, contained in the catalog http://astrogeo.org/rfc/ and selected if their flux density integrated over VLBI images at 8GHz is at least 150 mJy, have been investigated. A likelihood function has been defined and used in an unbinned time-dependent maximization. Two time profiles, with a Gaussian and a box shape, have been tested. Seven sources have been found with a pre-trial significance larger than 3σ in at least one of the two profiles. The blazar J1500 - 2358 shows the highest significance, $3.3(3.4)\sigma$ for a Gaussian (box) shape.

The radio light-curves produced by the Owens Vally Radio Observatory (OVRO) have been considered for the seven sources with highest significance. An interesting finding emerged in the case of the blazar J0242+1101. The largest flare in radio is overlapped in time with the neutrino emission identified by the ANTARES analysis. In Fig. 4 also the γ-ray light curve obtained with the Fermi observatory and the spatial distribution of IceCube tracks are shown. The most significant γ-ray flare occurred during the radio flare and is in coincidence with the neutrino emission studied by ANTARES. A detailed analysis of the probability of a multimessenger association is in progress.

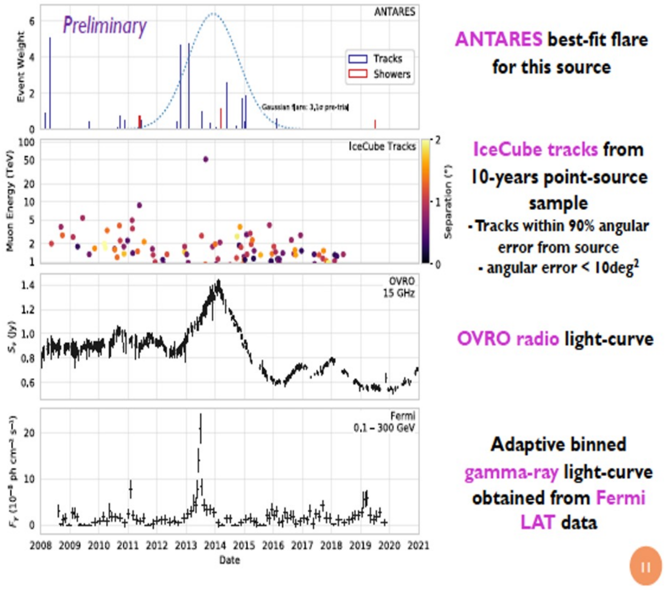

Figure 4: Signals registered by different detectors from the same region of the sky, corresponding to the position of the blazar J0242+1101.

5. Conclusions

A short review of some recent results obtained with the ANTARES neutrino telescope is given. Despite the reduced size of the detector, ANTARES has been playing a crucial role in preparing the way to the new generation of telescopes, in particular KM3NeT [9], and also putting constraints to physics models and complementary observations performed with other astrophysical probes. The ANTARES scientific program is much wider than what discussed in this contribution and includes also dark matter searches, presented in another contribution at this same conference.

References

[1] J. A. Aguilar et al., The data acquisition system for the ANTARES neutrino telescope, Nucl. Instrum. Meth. A 570 (2007) 107.

[2] M. Ageron et al., ANTARES : The first undersea neutrino telescope, Nucl. Instrum. Meth. A 656 (2011) 11.

[3] A. Albert et al., Astrophys. Journ. Lett. 853, 7 (2018); L.A. Fusco and F. Versari, PoS(ICRC2019) 891.

[4] A. Albert et al., Measurement of the atmospheric $\nu_e and \nu_\mu$ energy spectra with the ANTARES neutrino telescope, Phys. Lett. B 816 (2021) 136228.

[5] S. Adrián-Martínez et al., Measurement of the atmospheric ν_μ energy spectrum from 100 GeV to 200 TeV with the ANTARES telescope, Eur. Phys. J. C 2606(2013) 73.

[6] A. Albert et al., First all-flavor neutrino pointlike source search with the ANTARES neutrino telescope, Phys. Rev. D96 (2017) 082001.

[7] G. Illuminati for the ANTARES Collaboration, Searches for point-like sources of cosmic neutrinos with 13 years of ANTARES data, PoS(ICRC2021)1161.

[8] A. Albert et al., ANTARES upper limits on the multi-TeV neutrino emission from the GRBs detected by IACTs, JCAP 03 (2021) 092; A. Albert et al., Constraining the contribution of Gamma-Ray Bursts to the high-energy diffuse neutrino flux with 10 years of ANTARES data, MNRAS 500 (2021) 5614; A. Albert et al., Search for neutrino counterparts of catalogued gravitational-wave events detected by Advanced-LIGO and Virgo during run O2 with ANTARES Eur. Phys. J. C 80 (2020) 487; A. Albert et al., ANTARES and IceCube Combined Search for Neutrino Point-like and Extended Sources in the Southern Sky, ApJ 892(2020) 92; A. Albert et al., A Search for Cosmic Neutrino and Gamma-Ray Emitting Transients in 7.3 yr of ANTARES and Fermi LAT Data, 886 (2019) 98; A. Albert et al., Search for Multi-messenger Sources of Gravitational Waves and High-energy Neutrinos with Advanced LIGO during its first Observing Run, ApJ. 870 (2019) 134.

[9] S. Biagi, The KM3NeT neutrino telescopes, status and perspectives, this conference.

[10] D. Lopez Coto et al., Indirect Dark Matter Searches with the ANTARES and KM3NeT Neutrino Telescopes, this conference.