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Latest results from the ANTARES neutrino telescope and prospects for KM3NeT-ARCA

G. Illuminati for the ANTARES and KM3NeT Collaborations

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Summary. — The latest results of the ANTARES neutrino telescope are presented, focusing on searches for neutrinos from diffuse fluxes, point-like sources, dark matter together with multi-messenger analyses. Moreover, the expected performances of the future high-energy neutrino detector, KM3NeT-ARCA, are discussed.

1. – Introduction

The search for astrophysical neutrinos in the TeV–PeV range is among the primary goals of an underwater neutrino telescope. The first significant evidence of a cosmic diffuse flux of high-energy neutrinos was recently reported by the IceCube Collaboration [1-3], representing a crucial step forward in the field of neutrino astronomy. The observation of the astrophysical flux was obtained using the sample of High Energy Starting Events (HESE) and is compatible with a single power law $\Phi(E) = \Phi_0 E^{-\alpha}$ with best-fit spectral index $\alpha = 2.92^{+0.33}_{-0.29}$ [3]. Another recent measurement of the cosmic neutrino flux comes from the analysis of the IceCube sample of charged current muon neutrinos from the Northern Hemisphere [4, 5]. The analysis of the observed 36 muon neutrino events resulted in a best-fit of the astrophysical spectrum given by a spectral index $\alpha = 2.19 \pm 0.10$, showing some tensions with the measurement coming from the all-sky analysis. The observed discrepancy could be explained by the presence of several components of extraterrestrial neutrinos, as point-like or extended Galactic sources [6]. ANTARES [7], being the current largest neutrino telescope in the Northern hemisphere, with an excellent visibility of the Galactic Plane, and with a very good angular resolution, is well suited to set already valuable constraints on the origin of the cosmic IceCube flux. The future KM3NeT telescope [8], currently being deployed in the Mediterranean Sea, will combine a cubic kilometre-sized detector with the same high visibility towards the Galactic Centre (GC) as ANTARES. It is expected to detect the neutrino flux reported by IceCube within a few months of operation and it will be able to make definite statements about a neutrino flux from several Galactic candidates.

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2. – The ANTARES and KM3NeT neutrino telescopes

The ANTARES neutrino telescope is located 40 km off-shore Toulon, France, anchored 2475 m below the surface of the Mediterranean Sea. A three-dimensional array of 885 photomultiplier tubes (PMTs) detects the Cherenkov light induced by charged particles produced in neutrino interactions in and around the instrumented volume. The 10 inch PMTs, distributed along 12, 450 m long, vertical lines, face 45° downward in order to optimise the detection of light from upgoing particles. The position, time and collected charge of the signals in the PMTs are used to infer the direction and energy of the incident neutrino. Two event topologies can be identified in a high energy neutrino telescope: tracks and cascades. The former represent the signature of a muon produced in charged current (CC) interactions of muon neutrinos in the proximity of the detector. Thanks to the muon long range, the direction of the parent neutrino can be reconstructed with a median angular resolution of 0.4° (fig. 1, top left). Electromagnetic and hadronic cascades are mainly induced by neutral current (NC) interactions, and ν_e and ν_τ CC interactions. As all their energy is deposited within a few meters from the interaction vertex, they appear as point sources of light in a neutrino detector, thus providing a poorer median angular resolution ($\sim 3^\circ$) with respect to tracks (fig. 1, bottom left), but still very competitive when compared to the IceCube cascades (between $\sim 10^\circ$ and $\sim 20^\circ$ in the 10^3–10^7 GeV energy range [9]). On the other hand, the more localised distribution of light close to the neutrino interaction point allows for a better estimate of the neutrino energy ($\sim 15\%$). The performances of the ANTARES detector will be

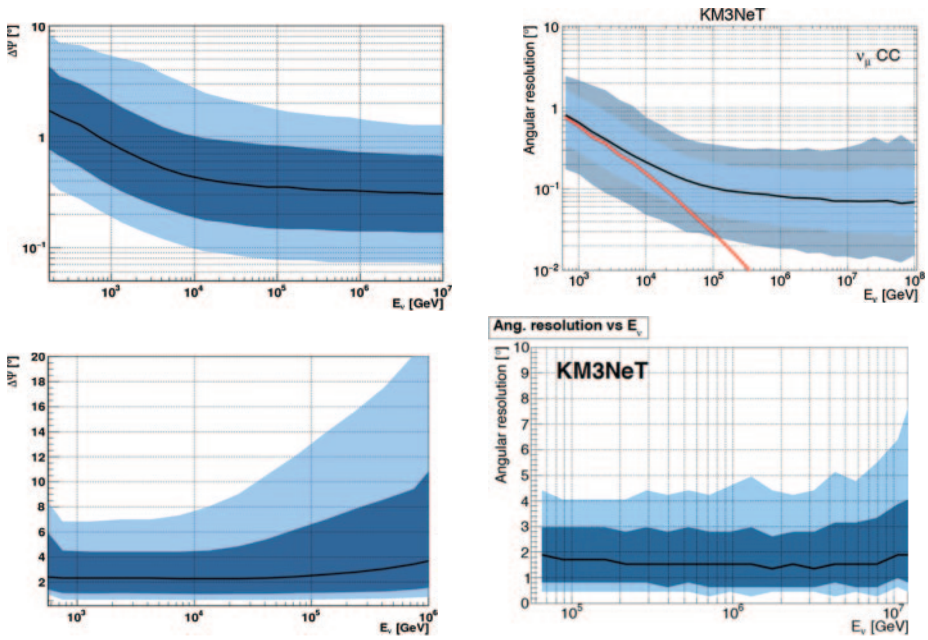

Fig. 1. – Median angular resolution of ANTARES tracks (top left), ANTARES cascades (bottom left), KM3NeT-ARCA tracks (top right) and KM3NeT-ARCA cascades (bottom right) shown as a black line. The dark (light) blue band is the 90%(68%) quantile of the distributions. In red the median angle between the ν and the true μ direction is shown.

considerably surpassed by KM3NeT thanks to its improved design and the larger lever arm provided by its extended dimensions. A network of neutrino telescopes is being built in the Mediterranean sea with the main purposes of detecting high-energy cosmic neutrino sources (KM3NeT-ARCA, 1 km^3 detector) and determining the neutrino mass hierarchy (KM3NeT-ORCA, smaller and denser detector). KM3NeT-ARCA will consist on two building blocks, each one made of 115 strings, called Detection Units (DUs). A DU consists of 18 Digital Optical Modules (DOMs) which house 31 PMTs in a 17 inch diameter glass sphere. Since these DOMs contain multiple PMTs, it is possible to identify more than one photon arriving at the DOM. This allows a better rejection of the optical background. In KM3NeT-ARCA, track-like events are reconstructed with an angular resolution $\leq 0.2^\circ$ for energies above 10 TeV (fig. 1, top right), while an angular resolution of 2° is expected for cascades in the same energy range (fig. 1, bottom right). An energy resolution of 27% for neutrino energies between 10 TeV and 100 PeV is achieved for track-like events, while in the cascade channel an energy resolution of 5% is obtained for the same energies.

3. – Diffuse flux searches

The observation of a cosmic diffuse flux of high energy neutrinos reported by the IceCube experiment represents a major breakthrough in the field of neutrino astronomy. It strongly motivates an independent confirmation and precision studies of its origin, energy spectrum and flavour composition.

3˙1. *All-sky diffuse flux search.* – A search for an all-flavor diffuse neutrino signal over the whole sky has been recently performed with the ANTARES telescope [10]. The search includes both track-like and cascade-like events from 9 years of data-taking and concentrates on events coming from below the horizon to overcome the large background of down-going atmospheric muons. After energy-related selection cuts, a total of 33 events are observed, with 24 ± 7 being expected from pure background and about 8 from the astrophysical flux. The observed distributions of the energy estimators are fitted using a maximum-likelihood method. The best-fit cosmic flux yields a single-flavor normalization

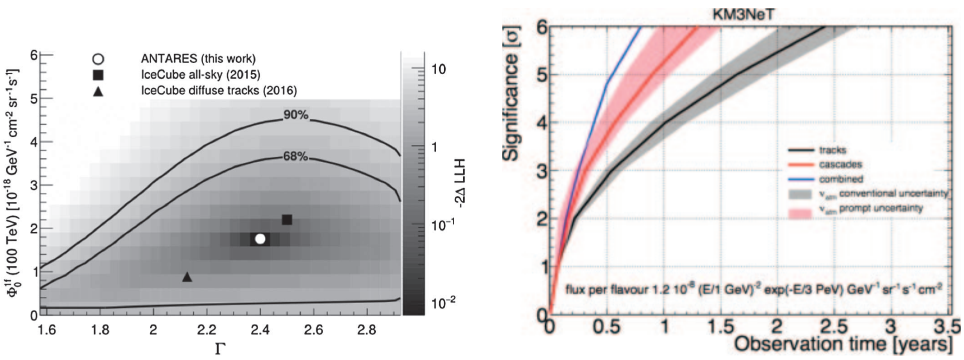

Fig. 2. – Left: 2D log-likelihood scan of the diffuse cosmic flux normalization and spectral index obtained in the latest ANTARES search for a diffuse flux [10]. The color gradient represents the log-likelihood difference with respect to the best-fit point. Right: significance as a function of the observation time of KM3NeT-ARCA for the detection of the IceCube diffuse flux for tracks, cascades and for the combined samples.

at 100 TeV of $\Phi_0^{1f}(100\ \text{TeV}) = 1.7 \pm 1.0 \times 10^{-18}\ \text{GeV}^{-1}\ \text{cm}^{-2}\ \text{s}^{-1}\ \text{sr}^{-1}$ and a spectral index $\Gamma = 2.4^{+0.5}_{-0.4}$ (fig. 2 left). Even though the hypothesis of a null cosmic flux is not excluded with a large significance (1.6σ), the ANTARES result supports the hypothesis of the IceCube flux being of cosmic origin. A quick confirmation of the IceCube signal will be provided by KM3NeT-ARCA. As shown in fig. 2 right, the future telescope is expected to observe the IceCube flux in about 6 months of data-taking with the full detector with a median significance of 5σ [8].

3˙2. *Galactic plane diffuse flux search.* – The non-negligible discrepancy between the measured neutrino spectral energy distributions of the two hemispheres observed by IceCube could hint at multiple cosmic contributions to the IceCube signal [6]. As the central region of the Milky Way is at negative declinations, the sum of a Galactic and an extragalactic component can result in different spectral behaviours in the two hemispheres. In a recent ANTARES work, a search for a diffuse Galactic-dominated neutrino flux using 9 years of data-taking has been performed [11]. The same search method has been used to analyse an extended data-set including 10 years of ANTARES tracks and cascades combined with 9 years of IceCube muon tracks (paper in preparation). In these searches, the KRA_γ model, introduced to explain the high-energy gamma ray diffuse Galactic emission observed by Fermi-LAT, has been assumed as a reference to derive the expected diffuse Galactic neutrino emission. The neutrino flux predicted by the KRA_γ model depends on the assumed primary cosmic ray spectrum cut-off. Two representative values of this quantity have been considered, namely $E_{cut} = 5$ and 50 PeV. The analysis is based on a likelihood ratio test, adapted to a full-sky search where the signal map is built according to the two reference models. With this technique, a stringent upper limit is obtained on the neutrino flux over three decades in energy (fig. 3). The flux upper limit provided by the preliminary combined analysis constrains the percentage of cosmic neutrino events of the HESE sample that can originate from diffuse Galactic Cosmic Rays interaction to a maximum of 9.6%. Moreover, the result of these analyses rules out the hypothesis of the diffuse Galactic neutrino emission being a possible cause of the IceCube spectral anomaly.

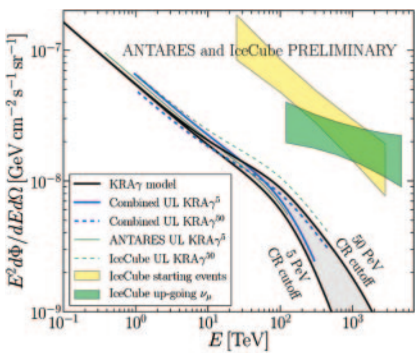

Fig. 3. – Combined upper limit at 90% confidence level (blue lines) on the three-flavour neutrino flux of the KRA_γ model with the 5 and 50 PeV energy cut-offs (black lines). Previous upper limits by IceCube and ANTARES are shown in green. The boxes represent the isotropic astrophysical neutrino fluxes measured by IceCube using starting events (yellow) and upgoing tracks (green).

4. – Search for point-like neutrino sources

The very good angular resolution achievable in sea water (fig. 1) allows a strong suppression of background of atmospheric neutrinos in the signal direction, and consequently a good sensitivity to point-like neutrino sources located in the Southern Hemisphere. Searches for cosmic neutrino sources with a E^{-2} spectrum using the data collected with the ANTARES detector between early 2007 and the end of 2015 have been recently performed [12]. For the first time, all neutrino interactions were considered in a search for point-like sources, instead of only muon neutrino charged current interactions. After selection cuts, the sample consisted of 7622 track events and 180 cascade events. Four different searches for cosmic neutrino sources have been performed: a scan over the whole ANTARES visible sky, an investigation of 106 astrophysical candidates and 13 IceCube HESE, a dedicated analysis of the GC region and a study of Sagittarius A* investigated as a possible extended source. The sensitivity of this analysis as a function of the source declination is shown as a green line in fig. 4 left, together with the sensitivity of the latest IceCube search [13] and the predictions for KM3NeT-ARCA [14]. No significant evidence of cosmic neutrino sources has been found. Nevertheless, these searches provide the most sensitive limits for a large fraction of the Southern Sky, especially in the energy range relevant for Galactic sources ($< 100\,\text{TeV}$). KM3NeT-ARCA is expected to make definite statements about a neutrino flux from several Galactic candidates within a few years of operation. Particularly promising are the expected sensitivities for two Galactic objects that are among the most intense high-energy gamma-ray sources: the SuperNova Remnants RX J1713.7-3946 and the Pulsar Wind Nebula Vela X. Assuming that 100% of the observed high-energy gamma-ray flux is of hadronic origin, a median significance of about 3σ is reached in 5 and 3 years of operation, respectively [8] (fig. 4 right).

5. – Multi-messenger searches

The ANTARES Collaboration is involved in an active multi-messenger program which implies the share of information with various collaborations ranging from electromagnetic

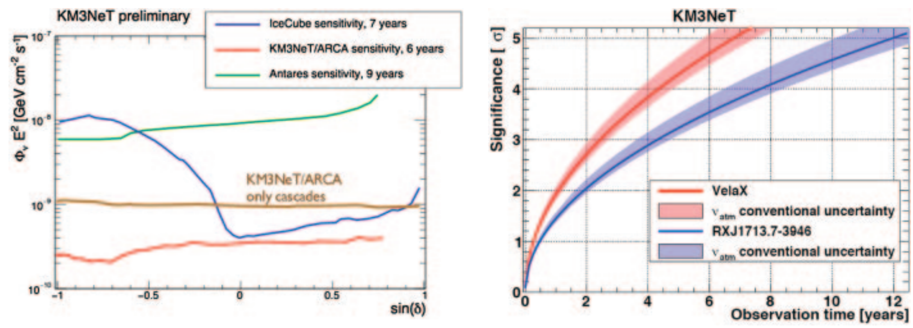

Fig. 4. – Left: estimated sensitivity for a point-like source with a E^{-2} flux as a function of the source declination for 6 years of data-taking of KM3NeT-ARCA using only track-like events. The sensitivity for 6 years of KM3NeT-ARCA using only cascades together with the latest ANTARES [12] and IceCube [13] fluxes are also shown. Right: significance as a function of KM3NeT-ARCA observation time for the detection of the Galactic sources RX J1713.7-3946 and Vela X. The bands represent the effect of the uncertainties on the conventional component of the atmospheric neutrino flux.

observatories (optical, radio, X-ray, gamma-rays) to cosmic ray and gravitational wave detectors. The main objective of the project is to detect neutrinos from transient phenomena. Among all the possible astrophysical sources, transient sources offer one of the most promising perspectives for the detection of cosmic neutrinos thanks to the almost background free search in a well-defined space-time window. The ANTARES effort in the multi-messenger context can be summarized in three different activities briefly described in the following: real-time follow-up analyses, alert triggering, off-line analyses. These dedicated multi-messenger programs will be further developed in KM3NeT.

5˙1. *Real-time follow-up analyses.* – ANTARES is able to handle external alerts of transient events detected by other experiments, either distributed through the Gamma-ray Coordinated Network (GCN) or under private agreements. Real-time follow-up analyses have been performed with ANTARES after the detection of transient events as high-energy neutrino candidates by IceCube, Gamma-Ray Bursts and Fast Radio Bursts. The searches for neutrino counterparts of gravitational wave (GW) events detected by the LIGO and Virgo interferometers are among the on-line analyses triggered by external alerts. ANTARES participated together with IceCube to a follow-up of the gravitational wave signal GW150914, providing the first constraint on high-energy neutrino emission from a binary black hole coalescence [15]. Since the beginning of the second observing run of Advanced LIGO and Virgo interferometers on 30 November, 2016, ANTARES is receiving gravitational wave alerts in real time. Thanks to the angular resolution of ANTARES ($\sim 0.4\,^{\circ}$ at $\sim 10\,\mathrm{TeV}$) compared to the size of the gravitational wave error box (a few hundreds of square degrees on the sky), in case of a coincident neutrino detection, the size of the region of interest would be drastically reduced. In this context, prompt searches for a neutrino counterpart to GW170817 —the first event involving the coalescence of two neutron stars— were performed, followed by a refined study, involving the three neutrino observatories that responded on line to the alert [16]. No neutrinos directionally coincident with the source were detected within $\pm 500\,\mathrm{s}$ around the merger time. Five background track events (likely atmospheric muons) in the ANTARES data-set, not compatible with the source position, were observed. The non-detection is consistent with scenarios where a jet of highly energetic particles were produced off the line of sight of the source.

5˙2. *Alert triggering.* – Besides receiving alerts from other observatories, ANTARES also triggers electromagnetic follow-up of interesting neutrino candidates. Whenever a neutrino event of potential astrophysical origin is detected, an alert message is generated to trigger robotic optical telescopes (TAROT, MASTER, ZADKO), radio telescopes (MWA), X-ray satellites (Swift-XRT, INTEGRAL), and ground-based γ-ray observatories (H.E.S.S., HAWC). Thanks to the very short alert-generation time (a few seconds) and half-sky simultaneous coverage, ANTARES is well-suited to detect transient sources. The criteria for triggering specific instruments depend on the desired false alarm rate. General properties of the triggers are either high energetic events, doublets in a time window of 15 minutes or events of which the origin is compatible with a known close-by galaxy. Since the beginning of the TaToO (Telescopes-ANTARES Target-of-Opportunity) program [17] in 2009, ANTARES has sent more than 300 alerts, triggering a fast response of these instruments. The non-observation of afterglows subsequent to the neutrino alerts strongly disfavours a GRB association to the neutrino event.

5˙3. *Off-line analyses.* – Off-line analyses are performed to search for neutrino counterparts to catalogued flaring sources as microquasars, blazars and GRBs. These objects are expected to share the same physical mechanisms based on the accretion of gas onto a black hole which power the relativistic jets of material ejected from both sides of the compact object. The identification of high-energy neutrinos in temporal and spatial coincidence would unambiguously prove the existence of hadronic acceleration mechanisms in these sources. In particular, in a recent ANTARES work, a search for neutrino emission during the flares from 34 Galactic X-ray binaries has been performed [18]. No cosmic neutrino in correlation with these events has been detected, allowing some of the more optimistic models for hadronic acceleration in these sources to be rejected at 90% C.L.. Besides looking for neutrinos from known flaring phenomena, ANTARES has recently performed a study to constrain a possible origin of the IceCube astrophysical signal from transient sources (same analysis method as in [19], a paper on this work is in preparation). Indeed, two of the neutrino events from the HESE sample occurred within 1 day of each other with a p-value of 1.6% [20], which could be interpreted as the signature of a possible flaring emission. The ANTARES data-set has been scanned to look for time and space correlation with 54 IceCube events selected from two high energy neutrino samples (the sample of charged current muon neutrinos from the Northern Hemisphere and the HESE sample). Each IceCube event has been treated as a potential transient neutrino source: in contrast to time integrated searches, where steady emission is assumed, the information from the neutrino arrival times is exploited to enhance the discovery potential. No ANTARES event was observed in correlation with the IceCube candidates which strongly constrains the possibility of a transient origin of the IceCube events.

6. – Dark Matter searches

Neutrinos, as the final product of a large variety of decay processes, are a good probe for an indirect search for dark matter in the form of Weakly Interactive Massive Particles (WIMPs). Indeed, WIMPs are expected to accumulate in celestial objects due to scattering with ordinary matter and the gravitation pull of these objects, annihilate in pairs and subsequently produce standard model particles, including neutrinos. Accordingly, indirect searches for dark matter concentrate on massive astrophysical bodies such as the Sun, the Centre of the Earth, the GC, dwarf galaxies and galaxy clusters. The geographical location of ANTARES and KM3NeT represents a great advantage in this context. Being in the Northern hemisphere and at intermediate latitudes, the

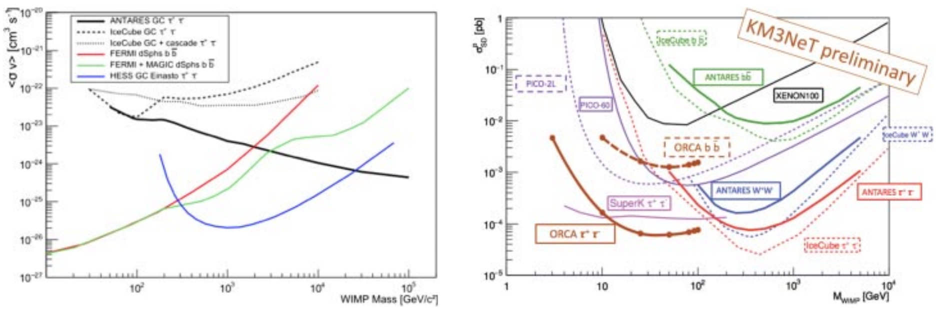

Fig. 5. – 90% C.L. limits on the thermally averaged annihilation cross-section $\langle\sigma_v\rangle$ (left), and on the spin-dependent (WIMP-proton) interaction cross section σ^p_{SD} for different annihilation channels (right), as a function of the WIMP mass.

Mediterranean neutrino detectors offer a better visibility of the GC and an observation of the Sun with less atmospheric background. Figure 5 left shows the results of the search for neutrinos in the direction of the GC with the ANTARES detector with 2007–2015 data [21]. The limits on the WIMP-WIMP velocity-averaged self-annihilation cross section $\langle \sigma v \rangle$ set by ANTARES are the most competitive ones for neutrino telescopes. The latest ANTARES limits on the spin-dependent (WIMP-proton) interaction cross section σ^p_{SD} from the observations of the Sun using different annihilation channels are presented in fig. 5 right. Currently active neutrino telescopes produce the most stringent limits in the $M_{WIMP} > 200\,\text{GeV}$ range, surpassing even the direct-detection experiments. The future low energy threshold detector KM3NeT-ORCA will offer the possibility to extend the limits provided by ANTARES and IceCube to lower WIMP masses, as shown in fig. 5 right. The sensitivity of KM3NeT-ARCA is currently being evaluated and will provide further improvements especially for large values of M_{WIMP}.

7. – Conclusions

The ANTARES neutrino telescope has proved to be a highly successful instrument, performing a wide range of physics analyses. The competitiveness of the results achieved demonstrates the huge potential of the new, much larger array, KM3NeT.

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