High-Energy Neutrino Searches in the Mediterranean Sea: probing the Universe with ANTARES and KM3NET-ARCA

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Abstract. ANTARES is a first generation neutrino telescope, built in the deep sea. We present here its latest results, focusing on the constraints placed on the origin of the cosmic signal observed by the IceCube detector. In parallel to the ANTARES results, we discuss the expected performance of the next generation detector under construction in the Mediterranean Sea - KM3NET- and in particular its high-energy component ARCA.

1. Introduction
The first generation deep-sea neutrino telescope (NT), ANTARES, has been completed in 2008. It is today the largest NT in the Northern Hemisphere (section 2). After the discovery of a cosmic neutrino diffuse flux by the IceCube NT, located at the South Pole, the understanding of its origin has become a key mission in high-energy (HE) astrophysics (section 3.1). ANTARES makes a valuable contribution thanks to its excellent angular resolution (section 2.3). The ANTARES sensitivity to an all-sky diffuse flux approaches the IceCube measured flux (section 3.2) and is sufficient to constrain the origin of the IceCube excess from regions extending up to 0.2 sr in the Southern sky (section 3.3). Assuming various neutrino spectral indexes, the Southern sky and in particular central regions of our Galaxy, are studied searching for extended regions of emission as well as for point-like objects (section 3.4). By searching for time and/or space coincidences with other cosmic probes, the sensitivity can be highly augmented. As an example, ANTARES has participated in a HE neutrino follow-up of the gravitational wave signal GW150914, providing the first constraint on HE neutrino emission from a binary black hole coalescence [1]. The ANTARES multimessenger program is partly covered in Ref. [2] and will not be further addressed here. Instead, indirect searches for Dark Matter are presented in section 3.5.

The high quality of the ANTARES data and the competitiveness of the results obtained, despite the modest size of the detector, demonstrate the tremendous potential of the new much larger array, KM3NeT, being built at 2 abyssal sites in the Mediterranean Sea. ARCA, off Capo Passero in Italy, is a km-scale NT for HE neutrino astronomy, and ORCA, offshore Toulon in France [3], is a megaton scale detector for the determination of the neutrino mass hierarchy with atmospheric neutrinos. The latitude of KM3NeT-ARCA will allow for a wide coverage of the sky with optimal sensitivity to the region of the Galactic Centre.
2. Detector designs and status

Generic NTs comprise an array of photomultiplier (PMT) tubes housed in so-called optical modules (OMs), detecting the Cherenkov light induced by charged particles induced by neutrino interactions. PMT signals (timing and amplitude) are used to reconstruct the trajectory and the energy of the neutrinos. In order to reduce the background due to the intense flux of down-going atmospheric muons, such detectors are buried deep under the surface. Moreover, since the Earth acts as a shield against all particles but neutrinos, their design is optimized for the detection of up-going muons produced by neutrinos which have traversed the Earth, with the consequence that one neutrino telescope can efficiently monitor one half of the sky in the TeV-PeV range.

2.1. Detector designs

The ANTARES detector is deployed ∼ 25 km off La-Seyne-sur-Mer (French Riviera), at a depth of 2475 m. The construction phase ended in May 2008. The detector [4] comprises 885 PMTs distributed in a 3D array on twelve 450 m high vertical detection lines. The typical interline spacing is 65m and each line comprises 25 storeys each, separated by 14.5 m. A storey hosts a triplet of OMs containing each a single 10-inch PMT protected in a pressure resistant glass sphere. The lines are connected to a junction box which provides electrical power and collects the optical fibres from each line into a single electro-mechanical fibre optic cable for transmission of the data to and from the shore station. The infrastructure also hosts an instrumentation line which provides measurements of environmental parameters such as sea current, temperature and also hosts a part of the AMADEUS system [5], a test bed for the acoustic detection of ultra-high energy neutrinos. A secondary junction box is dedicated to host sensors for various Earth and Marine science projects. As such, ANTARES is a multi-disciplinary observatory covering several scientific domains including Sea Sciences (see e.g. [6]).

The new KM3NET technology includes various improvements optimised for a minimal cost and maximal reliability. The main one is the use of the multi-PMTs Digital Optical Module (DOM) hosting 31 small (3 inch) PMTs and their associated electronics. The DOM also contains instrumentation allowing for the determination of its position (acoustic sensor), orientation (compass and tilt meter), as well as a nano-beacon for time calibration purpose. This new design offers many advantages in terms of photocathode coverage, photon counting accuracy and directional information. The KM3NET detection units (DU) consist of two vertical ropes supporting 18 DOMs with a spacing of 36 m. They are connected to shore by an electro-optical cable. An array of 115 DUs will constitute a building block. The KM3NET-ARCA configuration is made of two such building blocks. The KM3NET-ARCA performances presented in the subsequent text refer to this 2 building block configuration.

2.2. KM3NET Prototypes and First Operations

The construction of the KM3NET detector has already started, after the successful operation of several prototypes. First, a DOM was integrated in the ANTARES instrumentation line and deployed in 2013. The average PMT rate was about 8 kHz. Above 6-fold coincidences of PMT hits within 20 ns, the signal rate is dominated by the Cherenkov light produced by atmospheric muons [7].

In order to permit the deployment of several DUs in one sea campaign, a new launcher vehicle was developed. Once the launcher has reached the seabed, the buoy is released, the string unfurls and rises to its full height. A dedicated mini-string with 3 DOMs was deployed following this technique, on the ARCA site (3500 m), in May 2014. Atmospheric muons trajectory could be reconstructed. The zenith distribution of the reconstructed tracks was compared to Monte Carlo event revealing a good agreement [8]. The operation of the mini-string was followed by the deployment of the first full DU in December 2015. In May 2016, two other DUs were deployed. Soon after, one of the two DUs developed an electrical power issue and was recovered.
Figure 1. Median angular resolution of **ANTARES** (left) and **KM3NeT-ARCA** (right) in the track channel for $\nu_\mu$ interactions (black line). The dark (light) blue band is the 90% (68%) quantile of the distributions. In red is shown the median angle between the $\nu$ and the true $\mu$ direction.

for inspection. The reasons for the electric faults could be understood and corrective actions are on-going. Calibration procedures are fast to be performed and rely on nanobeacon flashers located on each DOM. The light distribution from these flashers can be used to monitor the water properties (absorption and scattering). The stable concentration of $^{40}K$ in the sea water can be used for calibration. Asking for $n$-fold coincidences in one DOM, it permits to evaluate the relative efficiencies of the PMTs, to correct for time offsets and evaluate the timing accuracy.

2.3. Detector performances

The interacting neutrinos essentially produce two patterns: cascades and tracks. Cascades mainly originate from electrons and hadronic showers. So charged-current (CC) $\nu_e$ interactions and all-flavor neutral current interactions contribute to this topology (as well as a large fraction of $\nu_\tau$'s), while searches for tracks apply mainly to CC $\nu_\mu$ interactions. Cascades are characterised by a dense hit pattern close to the neutrino interaction point, thus allowing for a good estimate of the neutrino energy. A track-like event is characterised by the Cherenkov light from the emerging muon, thus allowing for a precise measurement of its direction. Based on **ANTARES** software different algorithms have been developed to reconstruct tracks and cascades. They can be further improved for **KM3NeT** using the specificities offered by the multi-PMT DOM. The parameters assessing the quality of the each reconstruction can be used to select events and reject misreconstructed atmospheric muons. The angular resolutions respectively achieved for the track channel are shown in Fig. 1. Only a lower limit on the neutrino energy can be inferred, since the interaction vertex is often away from the detector. The outgoing muon typically caries 2/3 of the neutrino energy. Above 1 TeV, the total amount of light provides an estimate $E_{\text{rec}}$ of the energy of the induced muon with resolution $\sigma \left( \log \left( \frac{E_{\text{rec}}}{E_{\mu}} \right) \right)$ equal to 0.35 and 0.27 for **ANTARES** and **KM3NeT** respectively. In the cascade channel, the direction of the incoming neutrino is evaluated thanks to the amplitude of the PMT signals instead of the timing (the event pattern being to first order spherical). The reduced scattering of light in seawater enables median resolutions below $2^\circ$, thus permitting this topology to be used for the search of small scale structures (see section 3.3 and 3.4). The energy resolution for showers greatly surpasses the one achieved for tracks, with resolution on the neutrino energy below 10%.

3. Physics Studies

A primary goal of NT is to search for astrophysical neutrinos in the TeV-PeV range. This covers searches for diffuse cosmic neutrino fluxes as well as specific searches for astrophysical sources.
3.1. Today’s Context

The IceCube Collaboration recently discovered a cosmic neutrino flux with energy up to the PeV, using selection criteria in a restricted fiducial volume resulting in the so-called High Energy Starting Events (HESE) [9]. The largest fraction of HESE are cascades for which the angular determination is poor (10-20°). The HESE flux is compatible with a diffuse origin and flavor ratios $\nu_e : \nu_\mu : \nu_\tau = 1 : 1 : 1$, as expected from charged meson decays in CR accelerators after oscillation on their way to the Earth. However, recent results with the upgoing muon neutrino flux reveal some tensions with the HESE measurements, which could be due to the presence of several components of extraterrestrial neutrinos. A non negligible contribution from Galactic sources has been advocated (e.g. Refs [10, 11]) being point-like or extended. In this context, ANTARES and KM3NeT-ARCA, thanks to their location in the Northern Hemisphere and their excellent pointing capabilities are well suited to constrain and identify those potential components. For instance, the hypothesis of a point source producing more than 6 HESE events in a $20^\circ$ region around the Galactic Center has promptly been excluded by ANTARES [12]. Following this line, the subsequent paragraphs present the constraints from ANTARES and the expected performances of KM3NeT-ARCA for large scale to smaller scale sources.

3.2. Diffuse Fluxes

While an optimal search for a diffuse HE cosmic neutrino spectrum would be achieved by a combined track and cascade search [13], the current results from ANTARES are based on two independent analyses, searching for tracks and cascades separately. In the latter case, the good energy resolution achieved allows rejecting atmospheric neutrinos with a cut on the estimated energy, which is optimized to obtain the best upper limit. After the unblinding of data collected from 2007 to 2013, 7 events are observed, $5 \pm 2$ are expected from atmospheric backgrounds and $\sim 1.5$ events from the IceCube cosmic signal depending on the best fit spectral index. In the track channel, reconstruction quality parameters, coupled to an energy estimator based on the number of selected hits, are used to reduce the contamination from atmospheric muons below 0.5%. Data from two more years (2014 and 2015) than in the cascade channel were analysed yielding 19 observed events for an expectation of $13^{+3}_{-4}$ from the background and $\sim 3$ from the IceCube flux (see Fig. 2). The final expected sensitivity of ANARES is unlikely to yield a significant excess. Instead, a quick confirmation of the IceCube signal will come from KM3NeT-ARCA, as can be seen in the right panel of Fig. 2. A confirmation at a 5$\sigma$ level is expected in half a year livetime of the full detector. Details about this prediction can be found.
in Ref [3]. In contrast to the ANTARES results, (contained) down-going events are included.

3.3. Reducing the Search Window
Taking advantage of the mild latitude of Mediterranean detectors, reducing the search window allows searches which rely less on simulations. This is achieved exploiting on-zones which are then compared to off-zones of the same size and shape, but offset in right ascension. Such approach was followed for the Galactic Ridge [14]. No excess could be found in the data sample from May 2007 to Dec 2013 using tracks only, excluding that more than 2 HESE events of the 3-yr sample could originate from this region for spectral indices softer than \( \sim 2.3 \). The resulting limit excludes the simplistic hypothesis of a 1 to 1 relation between \( \gamma \)-ray (Fermi) and neutrinos from the inner Galactic plane. Fainter predictions such as in Ref [11] will be reached, in the muon channel, at the 3 \( \sigma \) (5 \( \sigma \)) level in \( \sim \) 1.5(5) yr with KM3NeT-ARCA. A similar approach was followed, with 3 off-zones, to search for an excess from the Fermi Bubbles. Once more, only the track channel was investigated so far, but with data up to 2015, extending a previous search presented in Ref. [15]. The study revealed a small excess in the on-zone, reducing the previous excess to a significance of 1.5\( \sigma \). Follow-up searches will be made including the cascade channel. The KM3NeT-ARCA sensitivity, in the muon channel, can be inferred from Ref. [16].

3.4. Point Sources
The good angular resolution achieved with cascade reconstructions in Seawater, allows including this topology in searches for point-like sources. A point source with a flavor uniform flux and with an \( E^{-2} \) spectrum is expected to produce a cascade-to-track ratio of 3:10. A first analysis has been performed with ANTARES data from 2007 to 2013 with a sensitivity at the level of \( \sim 10^{-8} \) GeV\(^{-1}\)cm\(^{-2}\)s\(^{-1}\) (see Fig. 3, left). The final sample consists of 6490 tracks and 172 cascades. No significant excess was observed, neither in the all-sky search nor for pre-defined sources (including HESE events). Below \( \sim 100 \) TeV, the ANTARES limits are the best in the world in a large region of the Southern Sky. Those result will be largely superseded by KM3NeT-ARCA, as can be seen in Fig. 3 (right). The prospects are particularly promising for Galactic sources such as the supernova remnant RXJ1713.7-3946 or the pulsar wind nebula Vela-X. Assuming that 100\% of the observed high-energy gamma-ray flux is of hadronic origin, both sources could be seen at more than 3\( \sigma \) C.L. in 4 years of operation. By the time KM3NeT-ARCA gets to its full power, the sensitivity to the Southern Sky can be further improved combining the search with ICECUBE data, following a first combined analysis described in Ref [17].
3.5. Dark Matter Searches

NT contribute to the world wide efforts to search for Dark Matter in the form of Weakly Interactive Massive Particles (WIMP). Scenarios involving the production of HE neutrinos involve dense sources in the Universe, such as the Sun, the Centre of the Earth, the Galactic Centre (GC), dwarf galaxies and galaxy clusters. Thanks to their good angular pointing capabilities and their geographical location Mediterranean detectors offer particularly good prospects for the Sun and the GC. While the antares results [18] for the Sun are comparable to the Icecube ones, those obtained from the direction of the Galactic Center with 2007-2015 data are the best, given the better visibility of the GC compared to the South Pole (see Fig. 4). The sensitivity of km3neT, including its low energy component km3net-orca are currently being evaluated and will provide further improvements all long the WIMP mass range.

4. Conclusions

Neutrino astronomy has entered a new era with the observation by Icecube of the first HE extraterrestrial neutrinos. While Antares has demonstrated the viability of the deep-sea technology, with an unmatched angular resolution, the observation of point sources in the Southern sky presumably requires a larger NT. This is one of the main goals of the next-generation NT km3net under construction and whose completion is expected circa 2020.

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