KM3NeT/ARCA sensitivity to point-like neutrino sources

A. Trovato for the KM3NeT Collaboration
INFN - Laboratori Nazionali del Sud, via S.Sofia 62, 95123 Catania, Italy
E-mail: atrovato@lns.infn.it

Abstract. KM3NeT is network of deep-sea neutrino telescopes in the Mediterranean Sea aiming at the discovery of cosmic neutrino sources (ARCA) and the determination of the neutrino mass hierarchy (ORCA). The geographical location of KM3NeT in the Northern hemisphere allows to observe most of the Galactic Plane, including the Galactic Centre. Thanks to its good angular resolution, prime targets of KM3NeT/ARCA are point-like neutrino sources and in particular galactic sources.

1. Introduction
High-energy ($E \geq $ TeV) neutrinos can travel through the entire Universe without being deflected or absorbed thus carrying information about the most violent phenomena where hadronic processes may play a major role. KM3NeT [1] is a new Research Infrastructure, consisting of a network of deep-sea neutrino telescopes in the Mediterranean Sea. Following the IceCube discovery of cosmic neutrinos [2] and the reported non-zero value of the neutrino mixing angle $\theta_{13}$, KM3NeT 2.0 will consist of two detectors with different granularity: KM3NeT/ARCA at the KM3NeT-It site (Capo Passero, Italy) dedicated to high-energy neutrino astronomy and KM3NeT/ORCA at the KM3NeT-Fr site (Toulon, France) dedicated to the study of the neutrino mass hierarchy. This paper will focus on the KM3NeT/ARCA detector. The detection of galactic point sources is one of the main goals of the ARCA experiment which, thanks to its geographical location in the Northern hemisphere, can observe most of the Galactic Plane ($\sim 87\%$), including the Galactic Centre.

Neutrinos of all flavors are detected by measuring the Cherenkov light induced by charged secondary particles emerging from neutrino interactions. KM3NeT/ARCA will consist of arrays of photo-multiplier tubes (PMTs) arranged in glass spheres that can withstand the water pressure (digital optical modules, DOM) and are deployed at a depth of 3500 m. The DOMs are arranged along flexible strings with a total height of about 700 m. The detector will consist of two building blocks of 115 strings each, with 18 DOMs per string, vertically spaced by 36 m. The footprint will be roughly circular with an average distance between strings of about 90 m. Each block will have a volume of about $\sim 0.5$ km$^3$.

A complete simulation for neutrinos of all flavours with energy in the range $10^2 - 10^8$ GeV was performed [1], including their interaction in the medium, the propagation of the emerging secondary particles, the light generation and propagation in water and the detector response. The neutrino induced events are observed in two topologies: track-like and cascade-like events. Only the results of the track analysis are reported here using the reconstruction algorithm.
described in [3]. These events are due to muons produced in $\nu_\mu$ and $\nu_\tau$ CC interactions. The angular resolution, calculated as the median angle between the reconstructed muon direction and the generated neutrino track, is about 0.2° for $E_\nu > 10$ TeV.

The neutrino signal from a cosmic source is drown in the large background of atmospheric muons and neutrinos, produced by the interaction of primary cosmic rays with the atmosphere. Atmospheric muons can be rejected by selecting only upward-going events, which can be only produced by neutrinos, the only particles that can traverse the whole Earth without being absorbed. A cut on the goodness of fit criterion of the reconstruction is also applied to remove misreconstructed muons. Atmospheric neutrinos are an unavoidable background but a key for a possible discrimination against cosmic neutrinos is their different spectrum, which is softer than the expected spectrum of cosmic neutrinos.

The discovery potential, that is the signal flux required to obtain an observation at a given significance level (e.g. 5σ or 3σ) with 50% probability [4], has been taken as a figure of merit of the telescope performance. The method used to calculate it considers two hypotheses: the hypothesis that data consist only of background and the hypothesis that signal events are present in the data in addition to the background. Given each hypothesis, the likelihood of obtaining the data is calculated, and the ratio of likelihoods serves as test statistic [3, 5]. Having Probability Density Functions (PDF) that describe the distribution of signal and background events as a function of a given variable $x$, $PDF_{sig}(x)$ and $PDF_{bkg}(x)$, the likelihood ratio can be written as:

$$LR = \sum_{i=1}^{n} \log \frac{n_{sig} \times PDF_{sig}(x_i)}{n} + \left( 1 - \frac{n_{sig}}{n} \right) \times PDF_{bkg}(x_i)$$

where $n$ is the total number of recorded events in a given period of time and $n_{sig}$ is the expected number of signal events in the sample of $n$ events. For each sample $LR$ is maximised as function of $n_{sig}$ and the maximum value of $LR$ is used as test statistics. The variable $x$ in Eq. 1 is chosen in different ways in the analyses described in the following and will be discussed for each case.

2. Results

The Supernova Remnant (SNR) RX J1713.7-3946 and the Pulsar Wind Nebula (PWN) Vela X are at present two of the most intense galactic objects in the high-energy gamma-ray band and are used here to evaluate the KM3NeT/ARCA performance. In both cases the expected neutrino spectrum was calculated from the measured $\gamma$-ray spectrum under the hypotheses of a transparent source and 100% hadronic emission. The young shell-type SNR RX J1713.7-3946 has been observed by H.E.S.S. [6] and its gamma energy spectrum is measured up to about 100 TeV. Having a declination of $-39^\circ 46'$ it is visible by KM3NeT for about 80% of the time. This SNR has been simulated as an extended homogeneous neutrino source with a 0.6° radius and an energy spectrum parameterised as $[7] \Phi(E) = 16.8 \times 10^{-15} [E/\text{TeV}]^{-1.72} e^{-\sqrt{E/2.17\text{TeV}}} \text{GeV}^{-1}\text{s}^{-1}\text{cm}^{-2}$.

Vela X is one of the nearest PWN centered at RA = $08^h35^m$, DEC = $-45^\circ 36'$. The VHE $\gamma$-ray emission from a circular region of 0.8° around the source centre is reported by H.E.S.S. [8]. The corresponding neutrino spectrum derived using the Vissani prescription [9] is parametrised as $\Phi(E) = 7.2 \times 10^{-15} [E/\text{TeV}]^{-1.36} e^{-(E/75\text{TeV})} \text{GeV}^{-1}\text{s}^{-1}\text{cm}^{-2}$. The source has been simulated as a flat spatial distribution within a disk of 0.8° radius.

Under the assumed hypotheses, the significance of the observation as a function of the observation time for KM3NeT/ARCA has been calculated and is shown in the left panel of fig. 1. In both cases a Boosted Decision Tree (BDT) from the ROOT TMVA package [10] has been used and the distributions of the BDT output for the signal and background events are used as PDFs in eq. 1. The major uncertainty in this calculation is due to the contribution of conventional component of the neutrino flux. This uncertainty, shown as a shaded area in fig. 1,
is taken into account assuming a ±25% variation in the normalization of the Honda et al. flux model [11]. An observation with 3σ significance is expected with the KM3NeT/ARCA detector after about 2.5 and 4.5 years for Vela X and RX J1713.7-3946, respectively. This analysis shows that at least these galactic sources are within reach for KM3NeT.

![Graph showing significance vs. observation time for KM3NeT and ARCA detectors](image)

**Figure 1.** Left: Significance of the RX J1713.7-3946 (blue line) and Vela X (red line) observation as a function of observation time for the KM3NeT/ARCA detector. Right: KM3NeT/ARCA 5σ discovery flux (red line) per flavor for point sources with an $E^{-2}$ spectrum as a function of their declination calculated for 3 years of observation time. For comparison also the IceCube 4 years discovery flux [12] and the upper limit for the ANTARES detector [13] are shown.

The discovery flux is also evaluated for a generic $E^{-2}$ point source as an approximation for neutrino extragalactic sources. The right panel in fig. 1 shows the 5σ discovery flux as a function of the point source declination. In this case the PDFs in Eq. 1 are functions of the angular distance of the reconstructed track from the source and the number of hits, $N_{hit}$, in a space-time correlation with the fitted track. The parameter $N_{hit}$ is a rough energy estimator. The 3 years observation time has been chosen in such a way to have a comparable exposure with respect to the IceCube results in [12]. The plot shows that KM3NeT has a very large field of view thus not only complementing, but also overlapping to a large extent the IceCube one. KM3NeT discovery potential is more than one order of magnitude better than the IceCube one in the Southern hemisphere and comparable to it elsewhere.

The results presented in this paper represent the status of the point source analysis and shows that KM3NeT can provide important contributions to the new born field of neutrino astronomy.

**References**

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