EPJ Web of Conferences **121**, 05011 (2016) DOI: 10.1051/epjconf/201612105011
RICAP-2014

Potential of KM3NeT to observe galactic neutrino point-like sources

Agata Trovato[a] on behalf of the KM3NeT Collaboration

LNS-INFN, via S. Sofia 62, 95123 Catania, Italy

Abstract. KM3NeT (`http://www.km3net.org`) will be the next-generation cubic-kilometre-scale neutrino telescope to be installed in the depths of the Mediterranean Sea. This location will allow for surveying the Galactic Centre, most of the Galactic Plane as well as a large part of the sky. We report KM3NeT discovery potential for the SNR RXJ1713.7-3946 and the PWN Vela X and its sensitivity to point-like sources with an E^{-2} spectrum.

1. Introduction

In the last decades, also thanks to a multi-messenger approach, our knowledge of the high-energy Universe has been widely extended. Nevertheless many open questions remain. Neutrinos, being uncharged and weakly interacting, can provide unique information on astrophysical objects. Their measurement will allow for new insights into the acceleration mechanisms, clarifying the role of the hadronic component.

In this context, the first evidence for a high-energy neutrino flux of extraterrestrial origin [1, 2] recently reported by the IceCube neutrino telescope, opens a new observational window on our Universe. The origin of this signal is however not yet clear, due to the scarceness of the detected neutrinos and mostly to the limited angular resolution of the IceCube detector. A confirmation, possibly accompanied by the identification of the sources is therefore necessary.

Candidate neutrino sources in the cosmos are numerous, but the estimate of their extragalactic neutrino fluxes has large uncertainties due to model assumptions and to the intergalactic absorption of VHE γ-rays that strongly modifies the spectra measured at Earth. On the other hand, in the hypothesis of hadronic gamma emission, models for galactic neutrino sources are constrained by TeV γ-ray observations and allow to obtain realistic expectations on the detection perspectives [3], as in the case of SuperNova Remnants (SNR) and Pulsar Wind Nebulae (PWN) that are the among most intense sources.

Neutrino telescopes detect the charged leptons produced in the neutrino weak interaction. In transparent media, relativistic particles can be detected through the light produced via Cherenkov effect, with 3D arrays of optical sensors. The "golden channel" for neutrino astronomy is the ν_μ charged current (CC) interaction because the muon range in water is, at $E_\mu \sim$ TeV, of the order of kilometres and the muon track is almost co-linear to the ν_μ permitting to point back to the neutrino cosmic source. This is the channel considered in this work. High energy neutrino astronomy requires detector volumes of the km^3 scale hosted in deep water or in deep Antarctic ice, where several thousands of metres of water (or ice) reduce the flux of atmospheric muons by several orders of magnitude. Since neutrinos are the only particles that can pass the whole Earth, neutrino telescopes look mainly at the up-going

---

[a] e-mail: `atrovato@lns.infn.it`

neutrinos coming from the opposite hemisphere. A detector in the northern hemisphere is therefore necessary to complement the IceCube sky coverage.

KM3NeT [4] is an international collaboration with the aim to build a research infrastructure in the Mediterranean Sea hosting an underwater multi-km^3 high-energy neutrino telescope. Thanks to its geographical location in the Northern hemisphere, KM3NeT can observe most of the Galactic Plane, including the galactic centre, so our Galaxy is its prime field of investigation. The KM3NeT neutrino telescope will consist of a 3D-array of Digital Optical Modules (DOMs) made of pressure resistant glass spheres each containing 31 photomultiplier tubes (PMTs) with a diameter of about 3 inch and their electronics. The first prototype of a DOM, called also “multi-PMT”, has been deployed at a depth of 2500 m in the Antares site. The analysis of first months of data taking highlights the capabilities of the new module design in terms of background suppression and signal recognition [5]. The DOMs are hosted in vertical string-like structures, approximately 1 km in height, called Detection Units (DUs) and described in the Technical Design Report [6] (TDR). The detector will be made of building blocks of 115 DUs each, arranged uniformly in a circular area at an average distance of 90 m. Each block has a volume of about 0.5 km^3. Two of these building blocks will be installed in Italian site of Capo Passero for the so called KM3NeT/ARCA. An extension to 6 building blocks is also envisaged to fully exploit the scientific potential of the detector especially in the search of Galactic point sources.

2. Simulation codes and analysis

The simulation of detector response to astrophysical neutrino fluxes provides a guideline for detector design and optimisation. The software used in this work has been developed by the ANTARES Collaboration [7] and adapted to km^3-scale detectors. The code provides a complete simulation of the incident muon neutrinos with energy in the range 10^2–10^8 GeV, including their interaction in the medium and the propagation of the resulting secondary particles, the light generation and propagation in water and the detector response. The depth and the optical water properties measured at the Sicilian Capo Passero site have been used [8]. Background light due to the presence of ^{40}K in salt water and bioluminescence has been simulated adding an uncorrelated hit rate of 5 kHz per PMT and a time-correlated hit rate of 500 Hz per DOM (two coincident hits in different PMTs inside the same DOM) due to the genuine coincidences from ^{40}K decays.

After the event generation, a track reconstruction algorithm is employed to estimate muon (and consequently neutrino) direction from the arrival times of the photons on the PMTs. After an initial hit selection requiring space-time coincidences between hits, the reconstruction proceeds through four consecutive fitting procedures, each using the result of the previous fit as starting point, except for the first one, called prefit, that is a linear fit through the positions of the hits with the hit time as independent variable [9, 10]. The detector resolution, i.e. the median angle between the reconstructed track and the generated neutrino track, reaches about 0.2° at 10 TeV.

The simulated events are analysed through statistical technique to look for a statistical excess originating in narrow regions of the sky around the sources. Indeed, the weak neutrino signal from a cosmic source stems on the large background of atmospheric muons and neutrinos, both produced by the interaction of primary cosmic rays with the atmosphere. The atmospheric neutrino event rate is calculated assuming the Honda et al. [11] conventional atmospheric model, the Enberg et al. [12] prompt component and adding the correction due to the cosmic rays knee on the neutrino spectrum as described in [13]. Atmospheric muons are simulated using the MUPAGE event generator [14]. The optimisation of the signal to background ratio is far from being trivial and it is strongly dependent on the source features (e.g. energy spectrum, angular extension). As figure of merit of the telescope performance we have taken 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 [15]. The method used in this work to calculate the discovery potential is the "unbinned" method [16] that relies on the maximisation of a likelihood ratio to evaluate the probability that a set of events is compatible with the hypothesis of signal+background instead of the hypothesis of background only.

3. Results

Amongst the galactic objects, SNRs are probably the most promising ones. In particular, the SNR RXJ1713.7-3946 and the PWN VelaX are at present between the most intense known galactic objects in the high-energy gamma-ray band and are used here to evaluate the KM3NeT performances. In addition the discovery flux is evaluated also for a generic E^{-2} point-source.

The young shell-type SNR RX J1713.7-3946 has been observed by HESS in several campaigns [17] and its energy gamma spectrum is measured up to about 100 TeV. The source has large intensity and a relatively large size with a complex morphology. Moreover, it is visible for about the 80% of the time by KM3NeT therefore is a good reference case.

This SNR has been simulated as an extended neutrino source of 0.6° with an energy spectrum calculated under the hypothesis of a transparent source and 100% hadronic emission and parametrised as [18]:

$$\Phi(E) = 16.8 \times 10^{-15} \left[\frac{E}{\mathrm{TeV}}\right]^{-1.72} e^{-\sqrt{E/2.1\mathrm{TeV}}} \mathrm{GeV}^{-1}\mathrm{s}^{-1}\mathrm{cm}^{-2}. \tag{1}$$

Vela X is one of the nearest pulsar wind nebulae (PWN) and it is associated with the energetic Vela pulsar PSR B0833-45. Even if PWNs are generally treated as leptonic sources (γ-ray emitters through inverse Compton), interpretation of TeV γ-ray emission from Vela X in terms of hadronic interaction is discussed by some authors (see i.e. [19, 20]). The first VHE γ-ray emission from Vela X was reported by the H.E.S.S. Collaboration [21] has been recently updated [22] with data from the 2005–2007 and 2008–2009 observation campaigns and using a more accurate method for the background subtraction. The new data are characterised by a higher gamma flux and a harder energy spectrum. From the differential energy spectrum extracted from an integration radius of 0.8° around the centre at RA = $08^h\ 35^m\ 00^s$, Dec = $-45°\ 36'\ 00''$, the corresponding neutrino emission spectrum has been derived using the Vissani prescription [3] based on the hypothesis of a transparent source and 100% hadronic emission. The neutrino spectrum is parametrised as:

$$\Phi(E) = 7.2 \times 10^{-15} \left[\frac{E}{\mathrm{TeV}}\right]^{-1.36} e^{-(E/7\mathrm{TeV})}\, \mathrm{GeV}^{-1}\mathrm{s}^{-1}\mathrm{cm}^{-2}. \tag{2}$$

Also in this case the source extension has been simulated as a flat spatial distribution within a disk with 0.8° radius.

Under the assumed hypotheses, the significance of the sources observation as a function of the observation years for KM3NeT/ARCA and the full KM3NeT with 6 building blocks has been calculated at a confidence level (CL) of 50% and is shown in Fig. 1. An observation with 5σ significance is expected with the full KM3NeT after 2.5 and 4 years for the VelaX and the RXJ1713.7-3946 respectively. Anyway, even with KM3NeT/ARCA a 3σ observation is possible after a reasonable amount of time (2.5 years for the VelaX and 4.5 years for the RXJ1713.7-3946). Figure 1 shows also how the expected significance can change due

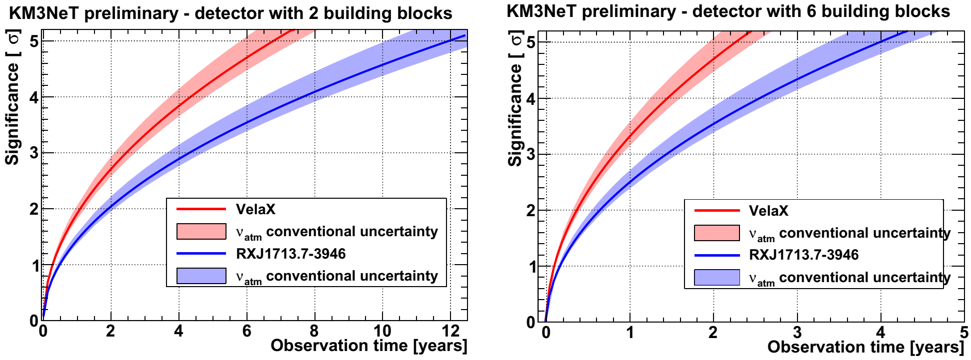

Figure 1. Significance of the RXJ1713.7-3946 and Vela X observation as a function of the years of data taking for the KM3NeT with 2 (left) and 6 (right) building blocks. The shaded bands show the effect of the uncertainties on the conventional component of the atmospheric neutrino flux.

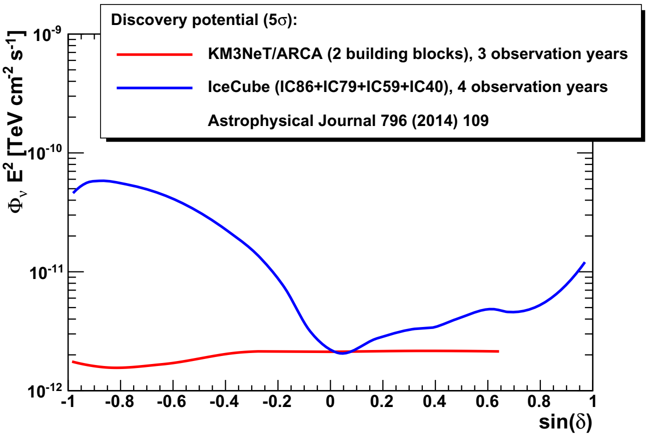

Figure 2. KM3NeT 5σ discovery potential for point sources emitting a neutrino flux with a E^{-2} spectrum, for 3 years of data taking with KM3NeT/ARCA. The flux values are shown as function of the source declination. For comparison the corresponding discovery potential to sources with an E^{-2} spectrum is also shown for the IceCube detector [23].

to the major uncertainty in this calculation, that is the conventional component of the conventional neutrino flux. This effect is taken into account assuming a variation of ±25% in the normalization of the Honda et al. model [11].

In order to compare the KM3NeT performances with IceCube, the 5σ discovery flux $\Phi_{5\sigma}$ has been calculated for generic point-sources with an E^{-2} spectrum as a function of their declination (see Fig. 2). The 3 years observation time has been chosen in such a way that KM3NeT/ARCA has a comparable exposure w.r.t. the IceCube results in [23]. The different trend of the KM3NeT and IceCube curves is mainly due to the geographical location of the detectors.

4. Conclusions and perspectives

The results presented in this paper represent the status of the galactic point-like sources analysis and show that at least the more intense ones are at reach for KM3NeT. In particular we report expectation for RXJ1713.7-3946 and Vela X. The inclusion in our simulation of a realistic source morphology extrapolated from the high energy γ-ray maps measured by HESS is in progress. This will provide a more realistic description of the spatial extension of the sources. The estimate of discovery potential for other galactic sources, as well as a staking analysis of several candidate galactic sources, will be investigated in the near future.

The discovery potential for point sources with E^{-2} spectrum show that KM3NeT has a very large field of view thus not only complementing, but also overlapping to large extent to the IceCube field of view. KM3NeT can thus provide important contributions to the new born field of neutrino astronomy.

References

[1] M. G. Aartsen et al. (IceCube Collaboration), Science **342**, 1242856 (2013)
[2] M. G. Aartsen et al. (IceCube Collaboration), Phys. Rev. Lett. **113**, 101101 (2014)
[3] F. L. Villante and F. Vissani, Phys. Rev. D **78**, 103007 (2008); F. Vissani and F. L. Villante, NIM A **588**, 123 (2008) and F. Vissani, Astr. Ph. **26**, 310 (2006)
[4] `http://www.km3net.org/home.php.`
[5] S. Adrian-Martinez et al. (KM3NeT Collaboration), Eur. Phys. J. **C74**, 3056 (2014)
[6] KM3NeT Technical Design Report, available on `http://www.km3net.org/TDR/TDRKM3NeT.pdf`
[7] D. Bailey, Ph.D. Thesis, available on `http://antares.in2p3.fr/Publications/index.html`
[8] G. Riccobene et al., Astropart. Phys. **27**, 1 (2006)
[9] A. Heijboer, Ph.D. Thesis, available on `http://antares.in2p3.fr/Publications/index.html`
[10] A. Trovato, *Development of reconstruction algorithms for large volume neutrino telescopes and their application to the km3net detector*, Ph.D. Thesis (2013)
[11] M. Honda, T. Kajita, K. Kasahara, S. Midorikawa, and T. Sanuki, Phys. Rev. D **75**, 043006 (2007)
[12] R. Enberg, M. H. Reno, and I. Sarcevic, Phys. Rev. D **78**, 043005 (2008)
[13] M. G. Aartsen et al. (IceCube Collaboration), Phys. Rev. D **89**, 062007 (2014)
[14] Y. Becherini et al., Astropart. Phys. **25**, 1 (2006)
[15] G.C. Hill et al., World Scientific eProceedings, Statistical problems in particle physics, astrophysics and cosmology, 108 (2005)
[16] J. Braun et al., Astropart. Phys. **29**, 299 (2008)
[17] F. Aharonian et al., Astronomy & Astrophysics **464**, 235–243 (2007)
[18] S.R. Kelner et al., Phys. Rev. D **74**, 034018 (2006)
[19] D. Horns et al. Astronomy & Astrophysics **451**, L1 (2006)
[20] L. Zhang and X. C. Yang, ApJ **699**, L153 (2009)
[21] F. Aharonian et al., Astronomy & Astrophysics **448**, L43 (2006)
[22] F. Aharonian et al., Astronomy & Astrophysics **548**, A38 (2012)
[23] M. G. Aartsen et al. (IceCube Collaboration), Astroph. J. **796**, 109 (2014)