KM3NeT sensitivity and discovery potential for galactic point-like sources

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Abstract

One of the main physics objectives of KM3NeT is the search of neutrinos from galactic sources. In this contribution first results on sensitivity and discovery potential for galactic point-like sources and in particular for the Supernova Remnant RXJ1713 are presented. Further improvements on the reconstruction algorithm and detector optimization are in progress.

Keywords:
Neutrinos, telescope, galactic sources

1. Introduction

High energy neutrino astronomy is one of the more exciting challenge of astroparticle physics. However, although several galactic and extra galactic objects have been proposed as potential sources of high energy neutrinos (E $\geq$ 1 TeV), no cosmic neutrinos have been observed up to now, not even from IceCube [1] that is the first km3-scale detector operating. Among the extragalactic objects Active Galactic Nuclei (AGN) and Gamma Ray Bursts (GRB) are considered as the most likely environment where proton and/or nuclei can be accelerated up to 10^{20}, i.e. the highest cosmic ray energy ever measured. Anyway, the major problem in the estimate of extragalactic neutrino fluxes either from AGNs and GRBs are the large uncertainties due to model assumptions and due to the intergalactic absorption of VHE γ-rays that strongly modifies the spectra measured at Earth. Upper limits on neutrino flux from GRB have been already set by IceCube with the present sensitivity. On the other hand, TeV γ-rays have been observed in galactic sources like shell type SuperNova Remnants (SNR), Pulsar Wind Nebulae, Star Formations Regions and the dense molecular clouds [3] related to them that are potential neutrino sources. Therefore, in the hypothesis of hadronic gamma emission, models for galactic neutrino sources are constrained by TeV γ-ray observations [4], allow to obtain realistic expectations on the detection perspectives.

Since the galactic plane is almost entirely visible from a neutrino telescope located in the Mediterranean Sea, the search for these source represents a primary goal for KM3NeT. Among galactic point-like sources, SuperNova Remnants seem the most promising neutrino candidates and in several case their energy spectrum is measured with rather good accuracy up to several tens of TeV. An evidence of neutrino detection from a SNR would be of crucial importance for the understanding of the acceleration mechanisms that play a role in our Galaxy. Indeed, in spite of the great progresses on the side of gamma observations in the GeV-TeV and of the improvements expected from the second generation Cherenkov telescope, only neutrinos will provide the unambiguous signature for hadronic acceleration.

Moreover, in the hypothesis that the population of high energy neutrino sources is correlated to the galactic mass distributions, the observation probability of these sources is roughly 1.4$\div$2.9 times larger for a detector in the Mediterranean sea w.r.t. one at the South Pole. [5].

2. Simulation results

2.1. Telescope optimization

The KM3NeT neutrino telescope consists of a 3D-array of Optical Modules (DOM) hosted in mechanical structures about 1 km height, called detection units. The Detection Units (DU) are made of a sequence of 20 storeys with a horizontal extension of several meters equipped with one DOM made of 31 three inch PMTs at each edge. Details on the project and on the Pre-Production Model of a DU are given in ref. [6]. The full KM3NeT detector consists of two blocks made of 154 DU each. In the Technical Design Report [13] the telescope was optimized for point-like source with a pure E^{-2} spectrum.

In this work we report on the status of simulation activities aiming at improving performance w.r.t. point-like galactic sources. This task concern both the development of specific algorithms for the track reconstruction and the study of the impact of the detector lay-out and geometry. In particular, one of the main parameters that affects the telescope performance is the distance between optical modules, namely the detector granularity.

The Monte Carlo code used for the simulations has been developed by the Antares collaboration [10] and consists of several codes with specific tasks: neutrino generation and interaction, propagation through the detector volume and light generation, detector response. In this work a depth of 3500 m and a wavelength dependent absorprtion length with 67.5 at 440 nm [13] were considered. An additional 5kHz single photon rate per PMT due to ^{40}K decay has been also taken into account. The track reconstruction algorithm has been adapted to km3-scale detector size. The peculiar features of the multi-PMT DOMs have been also exploited. In particular only hits within a PMT field of view, defined by an appropriate cut on the PMT angular acceptance, are selected. Another difference concerns the role of the hit multiplicity within the DOM that replaces the one played by the charge in the case of large (8-10 inches) PMTs. Moreover, in this work the knowledge of the source position in the sky is exploited by initializing the prefit, that is the first stage of the reconstruction procedure, with a set of tracks having a direction within 2° from the source and the vertex is estimated using a set of selected hits. Once the initial track is defined, hits with a distance from the track larger than 150 m are removed. Then the fit proceed via several steps of optimization and at the end the track with the best value of the likelihood is chosen.

The figures of merit of the telescope are sensitivity and discovery potential that are inferred by the signal to background ratio. The optimization of the signal to background ratio is far from be trivial and it is strongly dependent on the source features (energy spectrum, angular extension, ...). The atmospheric neutrinos, that constitute the irreducible background in high neutrino telescopes, were simulated according to the Bartol flux [7] and for prompt component due to the charm decay the RQPM [8] that is the highest flux prediction was considered. Atmospheric muons were not considered in this work. Previous simulations performed for a detector made of towers equipped with three couples of 8 inch PMTs per storeys at 3500 m depth show a worsening of the sensitivity for a source at -60° (fully visible) of about 3% [9] when the muon atmospheric background is included.

The sensitivities and discoveries have been obtained applying a binned method where the sky is divided in bins of declination and right ascension and the numbers of events detected per bin are analyzed. The parameters that are optimized in order to minimize the MRF and MDP [11] [12] are the size of the search cone around the source, the cut on the reconstruction quality parameter and a cut on the number of neutrino hits that is related to the neutrino energy.

The dependence of sensitivity and discovery potential for a E^{-2} spectrum on the cut-off energy for a detector with 180 m distance between DUs and 40 m distance between storeys (storey length of 6 m) is shown in fig. 1.

The neutrino energy spectra for reconstructed events without and with cuts that minimize the discovery potential flux at one year data taking for a pure E^{-2} spectrum are reported in 2. In fig. 3 the dependence of the discovery flux on the DU distance is reported. The spectrum with cuts shows an energy threshold of few TeV.

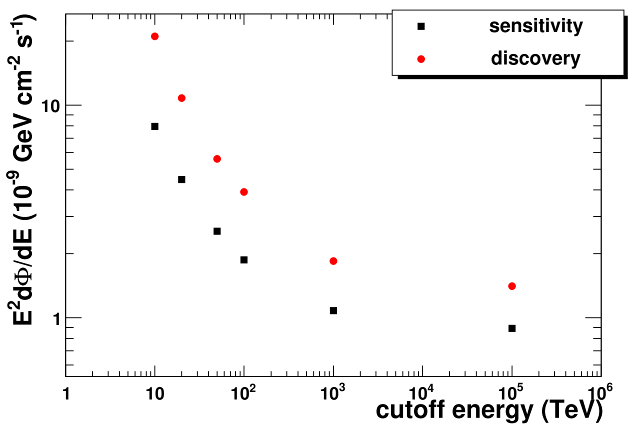

Figure 1: Evolution of the one year sensitivity flux (90% CL, squares) and discovery flux (5σ, 50% probability, dots) for point sources at a declination of -60° and a E^{-2} spectrum as a function of the assumed cut-off of the energy spectrum.

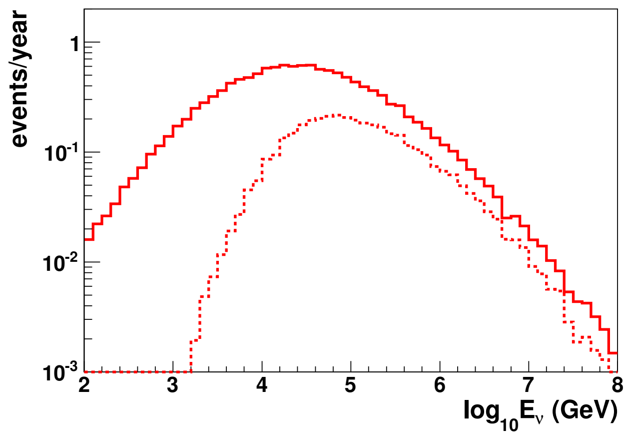

Figure 2: Neutrino energy spectra for reconstructed events with (dashed line) and without (full line) the cuts that minimize the discovery potential flux at one year data taking for a pure E^{-2} spectrum.

The optimal distance between DUs is different for a pure E^{-2} spectrum and for a spectrum with an energy cut-off: for a pure E^{-2} spectrum the best result is found at a distance of 180 m and even larger distance should be calculated to optimize telescope performance in this case. On the other hand, for spectra with an energy cut-off, i.e. the case of galactic sources that is the primary objective of this work, the optimal distance seems to be around 130 m.

Amongst the most promising neutrino sources candidates there are two young shell-type supernova remnants RXJ 1713.7-3946 and RXJ 0852.0-4622 (Vela-Jr) and the pulsar Vela X. As reference case we considered the RXJ1713.7-3946. This source has been observed by HESS in several campaigns [14] and its energy gamma spectrum is mea-

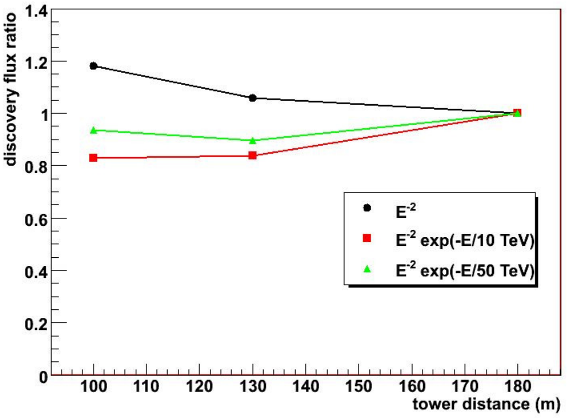

Figure 3: Discovery flux (5σ, 50% probability) for point-like sources at a declination of -60° as a function of the DU distance for a pure E^{-2} spectrum and two different cut-off of the energy spectrum.

sured up to 100 TeV. A map of RXJ1713.7-3946 is shown in fig. 4.

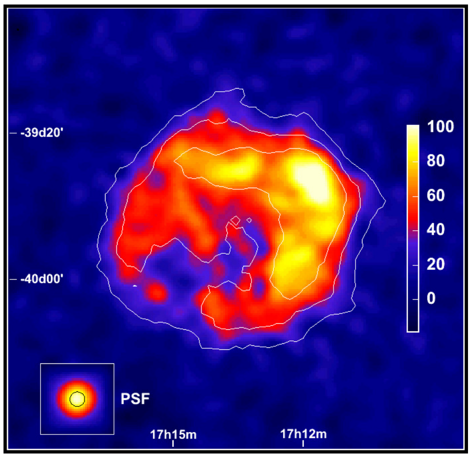

Figure 4: Contour map of gamma-rays counts from SNR RXJ1713.7-3946 detected by HESS (threshold E_γ =800 GeV) [14], the solid lines indicates the X-ray surface brightness as seen by ASCA and ROSAT in the 1-3 keV range.

In order to estimate the discovery potential for the RXJ1713.7-3946 we considered a source generation on a flat disk of 0.6 degree with the neutrino energy spectrum calculated by Kernel et al [15] that is reported in fig. 4 and parametrised as:

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

Since for a given flux, like the case of the RXJ1713.7-3946 is also possible to estimate the number of years needed for the discovery with a given significance, we considered these values as a figure of merit to evaluate the detector performance.

In table 1 the numbers of year for discovery at 3σ and 5σ is reported for different distance considering a bar

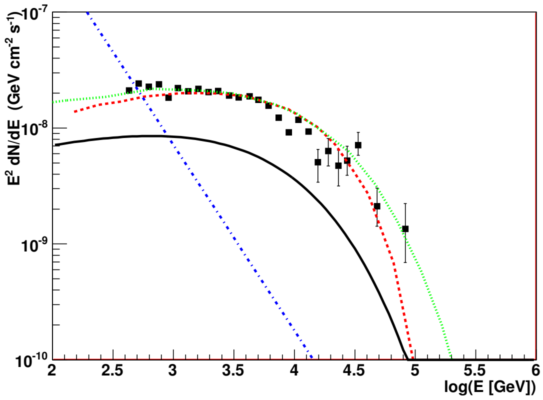

Figure 5: TeV neutrino (ν_μ + $\bar{\nu_\mu}$) fluxes expected from RXJ1713.7-3946 calculated by Kelner et al [15] (black line). The HESS data, from combined 2003, 2004 and 2005 source observations (black squares), are shown for comparison together with the TeV gamma ray flux calculated by Amato et al. (green line) [17] and Berezkho et al. (red dotted line) [18], [19] is also shown. The blue dotted line represents the expected atmospheric neutrino background in a 0.6° bin. The search bin obtained from MDP minimization is about 0.63°.

lenght of 6 m. In this work the reported errors are calculated only from Monte-Carlo background statistics.

	Distance	Years	Signal	Bkg
3σ	100 m	2.4±0.2	9.4	7.2
3σ	130 m	2.6±0.2	10.1	8.5
3σ	180 m	3.6±0.2	10.8	9.9
5σ	100 m	6.6±0.4	25.3	18.4
5σ	130 m	7.2±0.4	25.3	18.4
5σ	180 m	10±0.5	36.3	41.4

Table 1: Number of years to claim the discovery (5σ 50%CL) and the evidence (3σ 50%CL) of the RXJ1713.7-3946 source for a detector configurations with different DU distance and a 6 m bar length.

In table 2 the number of years for discovery at 3σ and 5σ is reported for 6 m, 10 m and 15 m bar length. The numbers of years for discovery are rather sensitive to the bar length [16].

Previous studies show that larger bar length leads to an improvement of detector performance since the effective area for well reconstructed events is higher for events with energy lower than a few TeV.

2.2. RXJ1713.7-3946 morphology

The HESS telescope made several observations, in the TeV energy range, of the shell-type Super Nova Remnant RXJ1713.7-3946 putting in evidence a rather complex morphology. The molecular observations reported by Sano et al in ref. [3] put in evidence the presence of several dense molecular clouds located close to the region where the TeV emission takes place. Following these observations, Vissani [5] speculated that the bulk of the gamma

	bar	years	signal	bkg
3σ	6 m	2.6±0.2	10.1	8.5
3σ	10 m	2.4±0.2	9.8	7.8
3σ	15 m	2.1±0.2	6.1	2.5
5σ	6 m	7.2±0.4	25.3	18.4
5σ	10 m	6.7±0.4	27.2	21.5
5σ	15 m	6.0±0.4	18.7	8.9

Table 2: Number of years to claim the discovery (5σ 50%CL) and the evidence (3σ 50%CL) of the RXJ1713.7-3946 source for a detector with 130 m of distance between DUs as a function of the bar length.

TeV emission in the hypothesis of hadronic mechanism originates from these region where there is a higher density of matter that can act as target for gamma and neutrino production. Since these clouds have an extension of some parsec, in our simulations they can be assumed to be point sources. In a first attempt to understand to what extent KM3NeT is sensitive to the structure of the source, we performed a simulation considering that the flux from the RXJ1713.7-3946 is (mainly) concentrated in four of the clouds reported in ref. [3]. The results for the numbers of years needed for discovery at 3σ and 5σ are shown in tables 3 and 4. The percentages reported in the first column represent the fraction of Kelner flux concentrated in the four bubbles.

Total Flux	years (5σ)	signal	bkg
100%	3.6±0.3	7.1	0.6
90%	4.2±0.3	7.9	0.8
80%	5.0±0.4	8.6	1.1

Table 3: Number of years required for a 5σ detection for a detector with 130 m DU distance and 6 m bar length considering different fraction of the total flux emitted in correspondence of the four hot spots (see text).

Total Flux	years (3σ)	signal	bkg
100%	1.2±0.2	2.5	0.2
90%	1.5±0.2	2.5	0.2
80%	1.8±0.2	2.5	0.2

Table 4: Number of years required for a 3σ detection for a detector with 130 m DU distance and 6 m bar length considering different fraction of the total flux emitted in correspondence of the four hot spots (see text).

3. Conclusions and perspectives

KM3NeT, thanks to its location, large effective area and good angular resolution, is particularly suited for the search of point-like sources in our Galaxy. The results presented in this paper represent the status of art of the optimization aiming at the detection of galactic point-like sources and show that at least the more intense SNRs are at reach for KM3NeT. Further improvements of detector performance are expected, indeed more simulations devoted to detector optimization and to the tuning of strategy for better background rejection and track reconstruction are on-going.

In conclusion, KM3NeT has good chance to detect point-like galactic sources, in particular we reported expectations for the RXJ1713.7-3946, the estimate of the discovery potential for other sources like for example Vela Jr and Vela X will be done in the near future.

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