KM3NeT discovery potential for galactic point-like sources

A. TROVATO[1], R. CONIGLIONE[1] AND P. SAPIENZA[1] FOR THE KM3NET COLLABORATION.

[1] *INFN - Laboratori Nazionali del Sud - Via S. Sofia 62, 95125 Catania, Italy*

atrovato@lns.infn.it

Abstract: The KM3NeT collaboration (http://www.km3net.org) plans to build a cubic-kilometre-scale neutrino telescope in the Northern hemisphere with an integrated platform for Earth and deep sea sciences. The location in the Mediterranean Sea will allow to survey a large part of the sky, including most of the Galactic Plane and the Galactic Centre, thus complementing the sky coverage of IceCube at the South Pole. The main physics objective of KM3NeT is the search of neutrinos from galactic sources. Among galactic point-like sources, SuperNova Remnants are potential sources of high-energy cosmic rays as well as neutrinos. The observed gamma-ray spectra extend to several tens of TeV. Therefore, in the hypothesis of hadronic gamma emission, models for galactic neutrino sources like SuperNova Remnants and Pulsars are robustly constrained by TeV-gamma observations thus allowing to obtain realistic estimates of the neutrino fluxes. We report expectations for the RXJ1713.7-3946 and the Vela X.

Keywords: neutrino telescope, Cherenkov detectors, RXJ1713.7-3946, VelaX.

1 Introduction

High energy (E $\geq$ 1 TeV) neutrino astronomy [1] is a very important challenge of astroparticle physics. The observation of extraterrestrial high-energy neutrinos can provide unique information on the most violent and highest energy processes in our Galaxy and far beyond. Their measurement will allow for new insights into the acceleration mechanisms, clarifying the role of the hadronic component. Candidate neutrino sources in the cosmos are numerous, such as supernova remnants (SNR), Pulsar Wind Nebulae (PWN) and microquasars in the Galaxy, while possible extragalactic sources include Active Galactic Nuclei (AGN) and Gamma-Ray Bursts (GRB). The estimate of extragalactic neutrino fluxes either from AGNs and GRBs 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 [2]. Moreover, the recent detection of the characteristic pion-decay signature in SNRs performed by the Fermi Large Area Telescope [3], provides an indication that cosmic ray protons are accelerated in SNRs and, since they produce also charged pion, neutrinos are expected.

A first observation of two PeV-energy neutrino-induced events has been reported by IceCube [4], the first operating km^3-scale neutrino telescope, but the moderate significance and the uncertainties on the expected atmospheric background events do not allow for a firm conclusion about a possible astrophysical neutrino flux. New results presented at the last IceCube Particle Astrophysics (IPA) Symposium reveal 26 more events with deposited energies above 30 TeV, which will be described in a forthcoming publication.

Neutrino telescopes detect neutrinos indirectly through charged leptons produced in weak charged current (CC) interaction. In transparent media, tracks of relativistic particles can be reconstructed detecting light produced via Cherenkov effect, with 3D arrays of optical sensors. The "golden channel" for astrophysical neutrino detection is the ν_μ 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. 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 neutrinos coming from the opposite hemisphere. A detector in the northern hemisphere is therefore necessary to complement the IceCube sky coverage.

KM3NeT[5] 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 optical sensor modules (DOMs) made of pressure resistant glass spheres with optical sensors and electronics inside, each containing 31 photomultiplier tubes (PMTs) with a diameter of about 3 inch and a 30% peak quantum efficiency. The DOMs, called also "multi-PMT", 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). In this work the detector has been simulated as two building blocks of 310 DUs each, arranged uniformly in a circular area. The detector design presented in the TDR is optimised for the detection of point-like sources with a power law energy spectrum E^{-2} in the TeV-PeV energy range. This spectrum represents a reasonable approximation for extragalactic sources but it is not suitable for galactic sources that are characterised by an exponentially cut-off power-law energy spectrum. Therefore the detector design has to be optimised to increase the discovery potential for galactic sources. 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 best known galactic objects in the high-energy gamma-ray band and can be used to evaluate the KM3NeT performances.

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 Potassium 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. The reconstruction code used in this work is based on the strategy described in [11] but it has been radically modified to exploit the multi-PMT peculiarities. The original code was written for a detector made of large PMT (8-10 inch) while the particular DOMs developed by the KM3NeT collaboration with 31 small (3 inch) PMTs localised in a 17″ sphere, require to substitute the charge information with the multiplicity of hits on the same DOM. Moreover, a specific hit selection has been studied considering temporal coincidence between PMTs on the same DOMs, on adjacent or next-to-adjacent DOMs on the same string and on different strings. The PMT directional sensitivity is also exploited accepting hits in a reduced PMT field of view. After an initial hit selection requiring space-time coincidences between hits, the reconstruction proceed 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. Starting from the prefit track, a scanning of all sky is performed by step of 3° thus generating 7200 tracks. For each direction an M-estimator fit and a maximum likelihood fit, that uses probability density functions (PDF) obtained from Monte Carlo simulations of muons traversing the detector, are performed. The solution with the highest likelihood per degree of freedom is chosen as the best one and used as starting point for the final fit (see [11] for the PDF description). As output, the reconstruction code gives the reconstructed track and a track fit quality parameter that is used to reject badly reconstructed events. The angle between the reconstructed track and the generated neutrino track is used to evaluate the detector angular resolution, that reach $\sim 0.2°$ at 10 TeV as shown in fig. 1.

The simulated events are analysed through statistical technique to identify a weak neutrino signal from a cosmic source amongst the large background of atmospheric muons and neutrinos, both produced by the interaction of primary cosmic rays with the atmosphere. Given a certain point source with flux $d\Phi_\nu/dE_\nu$ expected at Earth, the event rate

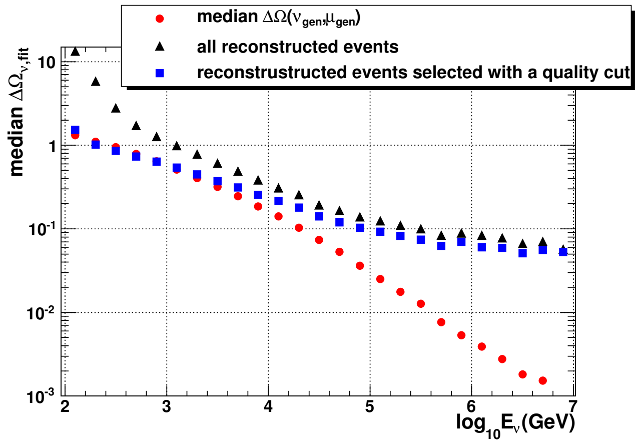

Figure 1: For each energy bin the median of the angle between the generated muon neutrino and the generated muon (red dots) and between the generated muon neutrino and the reconstructed track for all reconstructed tracks (black triangles) and for events selected with a quality cut (blue squares) are evaluated.

in the neutrino telescope is the convolution of this flux with the neutrino effective area, A^ν_{eff}:

$$\frac{dN_\nu}{dt} = \int dE_\nu A^\nu_{eff} \frac{d\Phi_\nu}{dE_\nu} \quad (1)$$

where A^ν_{eff} includes all the effects due to the neutrino attenuation in the Earth, the neutrino conversion probability and the muon detection efficiency. For a diffuse source it is necessary also an integration over the solid angle. The atmospheric neutrino event rate is also calculated with the eq. (1) assuming the Bartol Flux [9], while atmospheric muons are not considered in this work (a worsening of a few % is expected if the muon atmospheric background is included). 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 figures of merit of the telescope performance we have taken the sensitivity and the discovery potential. These can be evaluated through different techniques. According to the statistical approach called "binned" method, the sky is divided in bins of declination and right ascension and the fluctuations on the number of detected events are analysed inside each bin. The discovery potential is calculated optimising event selection to minimise the true signal flux required to obtain an observation at significance level of 5σ (or 3σ) with 50% probability [12]. The selection is based on the size of the search cone around the source, the track reconstruction quality parameter and the number of hits which is related to the neutrino energy. When no significant signal excess is observable, experiments can only set an upper limit. The same kind of event selection described above is optimised to minimise the upper limit that can be given on neutrino flux model from a source, in case of no signal detection. This average flux limit is called sensitivity and, in this work, is calculated following the Feldman-Cousins approach [13]. Another method used in this work to calculate the discovery potential is the "unbinned" method [14] 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. This method is more sensitive and powerful than the binned approach, but require a significantly higher computing time.

3 Results

3.1 RX J1713.7-3946

The young shell-type supernova remnant (SNR) RX J1713.7-3946 has been observed by HESS in several campaigns [15] and its energy gamma spectrum is measured up to about 100 TeV. A map of RXJ1713.7-3946 is shown in fig. 2. The source has large intensity and a relatively large size with a complex morphology. Moreover, it is visible for about the 75% of the time by KM3NeT therefore is a good reference case.

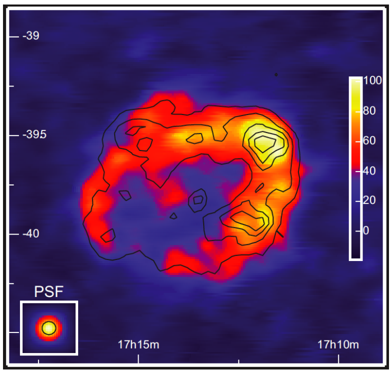

Figure 2: Combined H.E.S.S. image of the SNR RX J1713.7-3946 from the 2004 and 2005 data [15]. A simulated point source (*PSF*) as it would appear in this data set is also shown. The linear colour scale is in units of excess counts. ASCA contours are drawn as black lines (1-3 keV, from Uchiyama et al. 2002) for comparison.

The SNR has been simulated as a neutrino emitting homogeneous disk with an extension of 0.6° and a neutrino energy spectrum calculated following the prescription described in [16] and parametrised as:

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

Simulations have been performed considering four possible distances between the DUs (90, 100, 115, 130 m). The detector sensitivity (calculated with the binned method) as a function of the DU distance is shown in fig. 3. The sensitivity is calculated for one observation year and considering as reference the value of the flux in eq. (2) at E_ν = 1 TeV. The minimum is reached for a distance of 100 m.

This is confirmed also by the discovery potential calculation shown in fig. 4 in terms of the number of years required to claim the discovery as a function of the DU distance. In these calculations "discovery" means that the probability of the observation being due to an upward fluctuation of background is less than 2.85×10^{-7} (integral of the one-sided tail beyond 5σ of a normalised Gaussian), at a confidence level (CL) of 50%. According to the analysis based on the unbinned method, with a DU distance of 100 m a discovery will be possible after about 5 years of observation while the observation at a significance level of 3σ with 50%CL is expected after about 2 years of data taking.

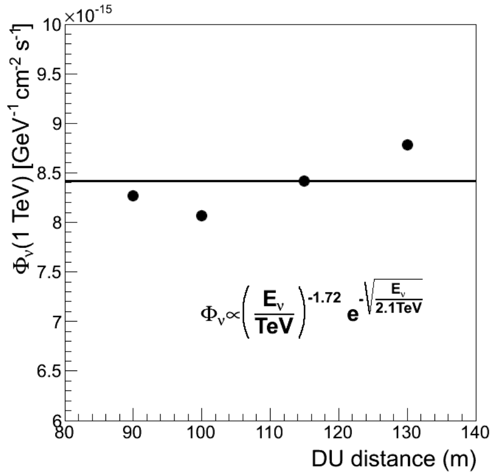

Figure 3: Flux sensitivity (90% CL) at 1 TeV of the full KM3NeT detector as a function of string distances for the source RX J1713.7-3946. The continuous line represents the 1 TeV flux value of the Kernel prescription.

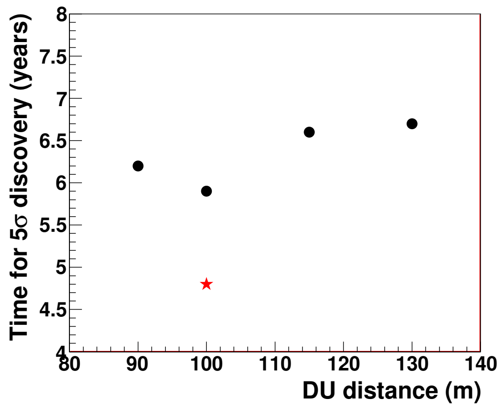

Figure 4: Number of years to claim the discovery (5σ, 50% CL) of the full KM3NeT detector as a function of string distances for the source RX J1713.7-3946 calculated with the binned method (black points). The red star shows the result for the unbinned search method at 100 m DU distance.

3.2 Vela X

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. [17] [18]). The first VHE γ-ray emission from Vela X was reported by the H.E.S.S. Collaboration [19] and was found to be coincident with a region of X-ray emission discovered with ROSAT as a filamentary structure extending southwest from the pulsar to the centre of Vela X. This observation has been recently updated [20] 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. 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″ is shown in fig. 5.

The correspondent neutrino emission spectrum was derived using the Vissani prescription [2] based on the hypothesis of a transparent source and 100% hadronic emission.

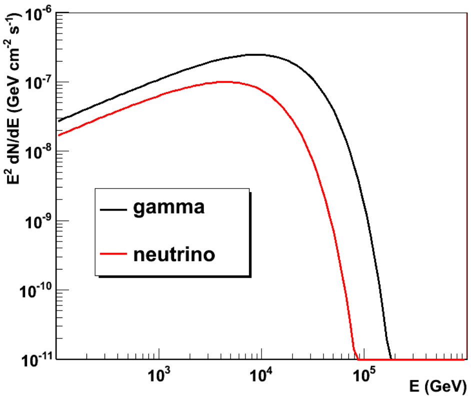

Figure 5: Differential γ-ray spectrum of Vela X (black line) taken from [20] and the derived neutrino spectrum (red line).

The source extension was simulated as a flat spatial distribution within a disk with 0.8° radius. Preliminary results with a binned analysis for a 100 m DU distance indicates that a discovery at 5σ (3σ) with 50% CL will be possible after 3.3 (1.2) years of data taking. As in the case of the RXJ1713.7-3946 analysis, this value is expected to be reduced with the unbinned analysis, that have not been yet performed for this source.

4 Conclusions and perspectives

The results presented in this paper represent the status of the optimisation aiming at the detection of galactic point-like sources 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.

Among other existing galactic sources, one of the most promising candidate for neutrino emission visible by KM3NeT is the shell-type supernova remnant RX J0852.0-4622, also known as Vela Junior. The source has a radius of about 1° and its VHE γ-ray energy spectrum measured by H.E.S.S. [21] [22] extends up to 20 TeV. This spectrum is very similar to the one of the SNR RXJ1713.7-3946 but, for the lack of statistics, there is no indication about a high energy cut-off. However, since adding a cut-off to a pure power law neutrino spectrum might change dramatically the expected neutrino rates on the detector, at the moment a clear conclusion on the number of years to claim the discovery for this source can not be drawn.

Acknowledgements

The research leading to these results has received funding from the European Community's Sixth Framework Programme under contract n° 011937 and the Seventh Framework Programme under grant agreement n° 212525.

References

[1] P. Sapienza and G. Riccobene, RIVISTA DEL NUOVO CIMENTO Vol 32 n. 12 (2009) 591.
[2] F. L. Villante and F. Vissani, Phys. Rev. D 78 (2008) 103007; F. Vissani and F.L. Villante, NIM A588 (2008) 123 and F. Vissani, Astr.Ph. 26 (2006) 310.
[3] Ackermann et al., Science 339 (2013) 807.
[4] IceCube Collaboration, arXiv:1304.5356.
[5] http://www.km3net.org/home.php.
[6] KM3NeT Technical Design Report, available on http://www.km3net.org/TDR/Prelim-TDR-KM3NeT.pdf
[7] D. Bailey, Ph.D. Thesis, available on http://antares.in2p3.fr/Publications/index.html
[8] G. Riccobene et al., Astropart. Phys. 27 (2006) 1.
[9] V. Agrawal et al., Phys. Rev. D 53 (1996) 1314.
[10] Y. Becherini et al., Astropart. Phys. 25 (2006) 1.
[11] A. Heijboer, Ph.D. Thesis, available on http://antares.in2p3.fr/Publications/index.html
[12] G.C. Hill et al., World Scientific eProceedings, Statistical problems in particle physics, astrophysics and cosmology (2005) 108.
[13] G.J. Feldman and R. Cousins, Phys. Rev. D57 (1998) 3873.
[14] J. Braun et al., Astropart. Phys. 29 (2008) 299.
[15] F. Aharonian et al., Astronomy & Astrophysics 464 (2007) 235-243.
[16] S.R. Kelner et al., Phys. Rev. D 74 (2006) 034018.
[17] D. Horns at al. Astronomy & Astrophysics 451 (2006) L1.
[18] L. Zhang and X. C. Yang 2009 ApJ 699 (2009) L153.
[19] F. Aharonian et al., Astronomy & Astrophysics 448 (2006) L43.
[20] F. Aharonian et al., Astronomy & Astrophysics 548 (2012) A38.
[21] F. Aharonian et al., The Astrophysical Journal 661 (2007) 236.
[22] M. Paz Arribas et al., Proceedings of ICRC2011 7 (2011) 141.