Looking at the Central Molecular Zone with the KM3NeT/ARCA telescope

M. Benhassi[1,3], R. Maria Bozza[2,3], A. Marinelli[2,3], and P. Migliozzi[3]
On behalf the KM3NeT collaboration
[1]Department of Mathematics and Physics, Università degli studi della Campania Luigi Vanvitelli, Caserta, Italy, [2]Department of Physics, Università degli Studi di Napoli Federico II, Napoli, Italy, [3]INFN Sezione di Napoli

Abstract

The Central Molecular Zone (CMZ) is a region of few hundred parsecs in the centre of our Galaxy that has an estimated gas density two orders of magnitude larger than the galactic average one. The equivalent mass corresponds to 5% of the total mass of the galaxy. In fact, it contains some of the most massive Galactic molecular clouds such as Sgr A, Sgr B, and Sgr C. These conditions underline a privileged region where to look for interactions of diffuse Galactic and local-accelerated cosmic rays.
A preliminary neutrino study of the Central Molecular Zone was obtained for the final detector configuration as well as for the actual detector. While for the former we used Monte Carlo (MC) simulations to describe signal and background, for the latter the background was obtained trough scrambled data.

Methodology

The Log-Likelihood Ratio (LLR [1]) serves as a test statistic for each dataset, indicating its compatibility with two models: one including both signal and background (H1), and the other with background alone (H0). It is computed as follows:

$$\lambda = log(\mu = \hat{\mu}) - logL(\mu = 0)$$

Where μ is the signal strength and $\hat{\mu}$ is the value that maximizes the $logL$ which is defined by the logarithm of the binned likelihood L:

$$L = \prod_{i \in \text{bins}} P(N_i|\xi_i)$$

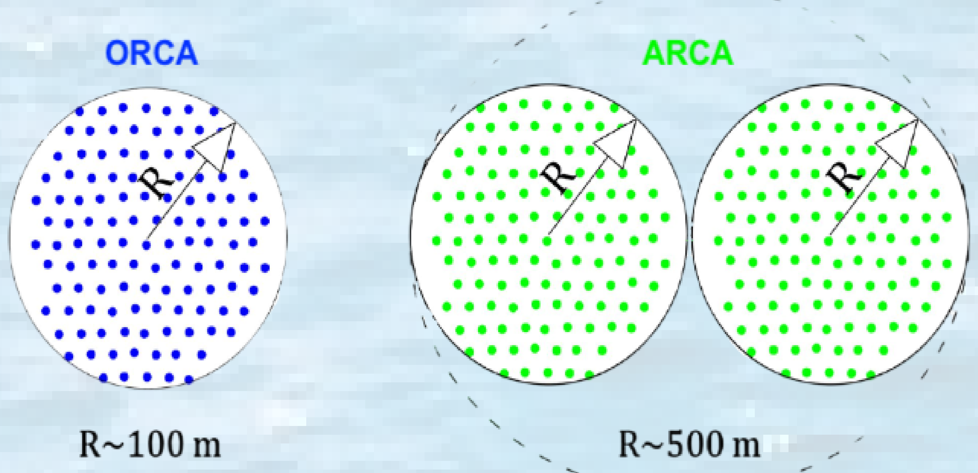
where N_i and ξ_i are respectively, the observed and expected number of events in the energy bin i, and $P(N_i|\xi_i)$ is the Poissonian Probability Density Function (PDF) of the energy events. Given the signal and background expectations in bin i, the Log-Likelihood can be written as:

$$\log L = \sum_{i \in \text{bins}} N_i \log(\mathcal{B}_i + \mu \mathcal{S}_i) - \mathcal{B}_i - \mu \mathcal{S}_i$$

where $\mathcal{S}_i$ and $\mathcal{B}_i$ represent the signal and the background PDFs, respectively. N_i is the number of neutrino events in bin i, and μ is the signal strength, which effectively parameterises the intensity flux.
We generate with MC simulation the PDF of the signal events, and we create the PDF of the background using scrambled data of KM3NeT/ARCA.

KM3NeT detector

KM3NeT [2] is a research infrastructure housing a new concept of Cherenkov neutrino telescopes. It comprises three-dimensional arrays of light sensor modules deployed in the deep Mediterranean Sea. Each array forms a Detection Unit (DU) holding 18 Digital Optical Modules (DOMs). A DOM consists of 31 3-inch Photomultiplier Tubes (PMTs), covering $4\pi\ sr$, and serves as the primary component for detecting Cherenkov radiation produced by neutrino interaction products.



KM3NeT consists of two different neutrino detector infrastructures: the ARCA telescope which is optimised to collect neutrinos from hundreds of GeV up to tens of PeV, and the ORCA telescope dedicated to neutrinos from hundreds of MeV up to tens of GeV.
On the other hand, Antares [3] was a predecessor of Mediterranean neutrino telescopes and was taking data from December 2007 to February 2022 with a total number of 900 Optical Modules.

In April 2021, the ARCA setup comprises 6 DUs, while at the present moment the ARCA geometry already includes 28 DUs in data taking. This analysis uses ARCA6-21 data, representing the data collected by ARCA6, ARCA8, ARCA19, and ARCA21 setups, accounting for a total number of 425.03 days from April 2021 to September 2023.

Results

The following plot shows the neutrino expectations obtained by tuning the diffuse Galactic cosmic-ray sea with Fermi-LAT $\&$ HESS data ($KRA - \gamma$ model) [4, 5, 6], and the extrapolated neutrino CMZ Spectral Energy Distribution (SED) from the IceCube paper [7]. The reported expectation has been used to model our signal in this analysis.

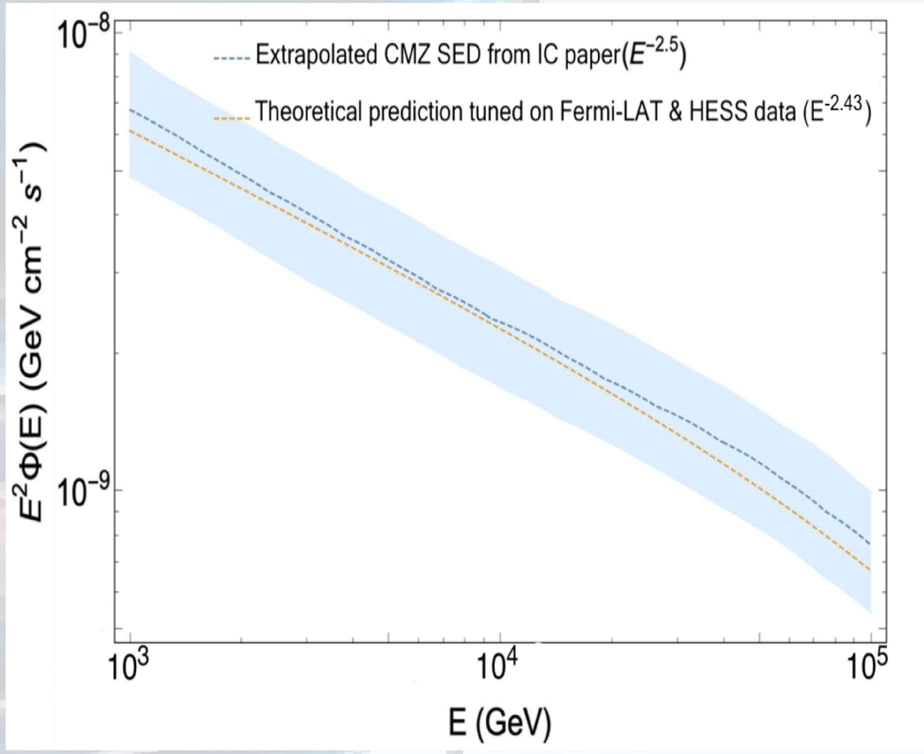


Figure 1: The blue dotted line corresponds to the neutrino expectation obtained taking into account the gamma emission from the CMZ. Interestingly the comparaison between the CMZ neutrino expectations and the whole Galactic plane IceCube observations follows the ratio between the amount of gas contain in this region and the total mass of the Galaxy (5% of the total Galactic mass).

The sensitivity of the combined ANTARES and ARCA6-21 geometry is shown in Fig. 2. Track-like events and $(\nu_\mu, \bar{\nu_\mu})$ flavors are used taking into account $20PeV$ for the interacting cosmic rays cut-off. The sensitivity of ARCA230 is obtained using dedicated MC simulation and applying a method called $Cut\&Count$ [8]. Considering 10 years of the full ARCA geometry, as you can see in Fig. 2 , we possibly constrain the neutrino model used in this analysis. The differential limits [9] are evaluated by determining the sensitivity for an E^{-2} signal considering each decade of energy in logarithm scale.

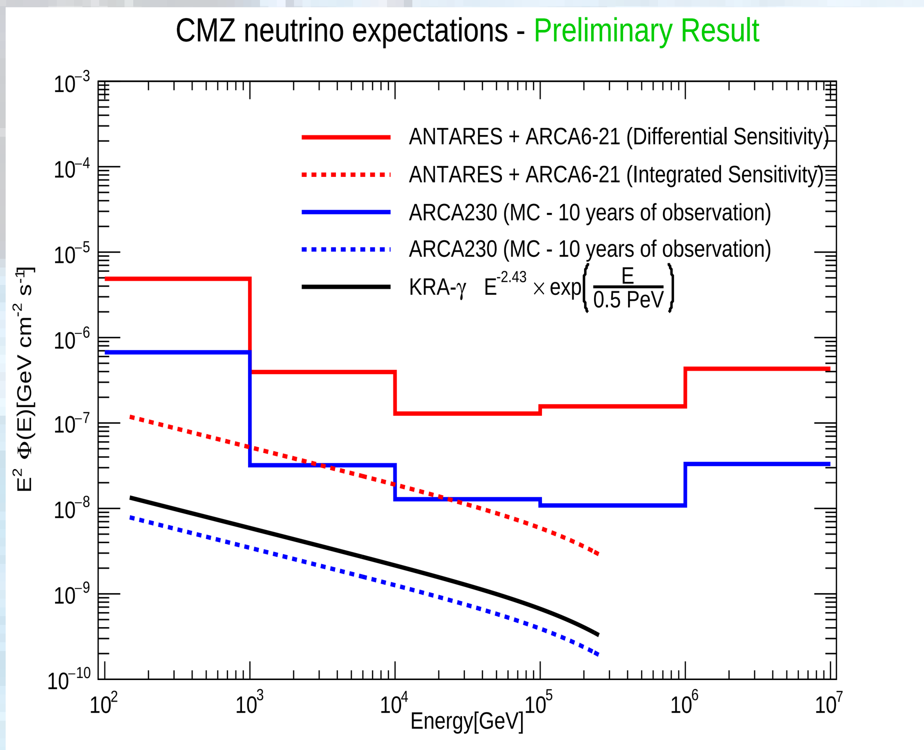


Figure 2: The sensitivity of the combined ANTARES and ARCA6-21 geometry is reported based on LR described in the methodology. The sensitivity of ARCA230 is based on the $Cut\&Count$ methodology [8]. The differential sensitivity is obtained considering an E^{-2} spectrum for each energy bin.

Conclusions

In this work, we presented the expectations of KM3NeT/ARCA telescope for the Central Molecular Zone. The sensitivity level was obtained by adding to the actual ARCA geometry the full ANTARES data sample. Moreover, we also explored the case of the full ARCA detector geometry. With the last configuration, the reported study indicates that after 10 years of data taking, we expect to verify the neutrino emission predicted for the CMZ when apply to this region the last $KRA - \gamma$ model.

References

[1] S. Aiello et al. Astronomy potential of KM3NeT/ARCA. 2 2024.
[2] KM3NeT Consortium, P Bagley, et al. Km3net conceptual design for a deep-sea research infrastructure incorporating a very large volume neutrino telescope in the mediterranean sea, 2008.
[3] S. Adrián-Martínez et al. Search for cosmic neutrino point sources with four years of data from the antares telescope. *The Astrophysical Journal*, 760(1):53, nov 2012.
[4] Antonio Marinelli, Daniele Gaggero, Dario Grasso, Marco Taoso, Alfredo Urbano, and Sofia Ventura. High Energy Neutrino expectations from the Central Molecular Zone. *PoS*, ICRC2017:939, 2017.
[5] Pedro De la Torre Luque, Dario Grasso, Daniele Gaggero, and Antonio Marinelli. The Galactic diffuse gamma-ray emission meets the PeV frontier. *PoS*, Gamma2022:035, 2023.
[6] Antonio Marinelli, Daniele Gaggero, Dario Grasso, Alfredo Urbano, and Mauro Valli. A Hadronic Scenario for the Galactic Ridge. *PoS*, ICRC2015:1126, 2016.
[7] Observation of high-energy neutrinos from the galactic plane. *Science*, 380(6652):1338–1343, June 2023.
[8] Gary C. Hill and Katherine Rawlins. Unbiased cut selection for optimal upper limits in neutrino detectors: the model rejection potential technique. *Astroparticle Physics*, 19(3):393–402, 2003.
[9] KM3NeT Collaboration. Differential sensitivity of the km3net/arca detector to a diffuse neutrino flux and to point-like source emission: exploring the case of the starburst galaxies, 2024.