

KM3NeT/ARCA Stacking Search for Ultra-Luminous Infrared Galaxies

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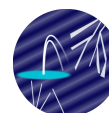
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KM3NeT/ARCA is a Cherenkov neutrino telescope currently under construction in the Mediterranean Sea, at 100 km off the Sicilian coast, near Capo Passero, at about 3500 m depth. In its final configuration, the detector will consist of a cubic kilometer volume of seawater instrumented with light detectors. Currently, 33 detector units have been already deployed and are taking data. In this contribution, a search for neutrinos from a catalogue of 75 Ultra-Luminous Infrared Galaxies (ULIRGs) is performed, using the latest experiment data. A binned likelihood ratio test is performed not only to search for single-source emissions but also to perform a stacking search. No signal excess is found, and 90% confidence level upper limits are evaluated and compared with the latest theoretical predictions from these sources discussing their role as potential neutrino emitters. These results are also exploited to quantitatively constrain the entire source population contribution to the diffuse neutrino flux measured by the IceCube collaboration.

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1. Introduction

The KM3NeT Collaboration is building an infrastructure comprising two Cherenkov Neutrino telescopes in the Mediterranean Sea [1]: KM3NeT/ORCA, in France, focuses on the atmospheric neutrino studies the mass neutrino hierarchy. KM3NeT/ARCA, in Sicily, is dedicated to the study of astrophysical neutrinos with energies $E_\nu \gtrsim 1$ TeV. Given the properties of the seawater, the KM3NeT/ARCA (hereafter simply referred to as ARCA) detector is expected to have an unprecedented angular resolution and probe the neutrino emission from several astrophysical source classes [2, 3]. Currently, 33 ARCA detector units have been installed and are taking data. In this contribution, ARCA data are exploited in order to search for neutrino emission from a catalogue of 75 Ultra-Luminous Infrared Galaxies (ULIRGs) [4]. ULIRGs are sources with infrared luminosities greater than $10^{12} L_\odot$, with $L_\odot$ being the Solar luminosity and usually driven by powerful Starburst Activities [5, 6]. Therefore, they are well-motivated candidates for high-energy neutrino emissions through hadronic interactions (proton-proton collisions). A binned likelihood ratio test is developed not only to search for neutrino emission along single ULIRGs but also to perform a stacking analysis. The results are compared to the state-of-the-art theoretical predictions and are used to constrain the diffuse emission of ULIRGs.

2. Data Sample Analysed

This analysis exploits several configurations * of the ARCA detector:

- ARCA 6, with a lifetime of 92 days.
- ARCA 8, with a lifetime of 210 days.
- ARCA 19, with a lifetime of 52 days.
- ARCA 21, with a lifetime of 287 days.

For this analysis, track-like events are used, namely events where the production of a muon is involved. They are mainly caused by charged-current interactions of muon neutrinos or tau neutrinos [2]. Simulated events are produced using Monte Carlo generators as GSeaGen [7] and MUPAGE [8] respectively for neutrinos and muons. Subsequently, reconstruction algorithms are used to evaluate the direction and energy of the incoming neutrinos and muons [2, 9]. Several optimization cuts are used to reduce the amount of background produced by atmospheric muons and reject mis-reconstructed events. In particular, only tracks with reconstructed zenith angle $\theta \leq 100^\circ$ have been considered, where $\theta = 0^\circ$ corresponds to vertically down-going events, effectively reducing the background of down-going atmospheric muons. Additional quality cuts and a boosted decision tree algorithm are adopted to reduce the contamination of mis-reconstructed muons in the sample.

*each configuration corresponds to the number of operational detector units at the time

3. ULIRGs Catalogue

The catalogue analysed in this contribution consists of 75 sources as reported in Ref. [4]. Sources have luminosity distances between $\sim 80 - 650$ Mpc and exhibit a uniform distribution across equatorial declinations. Fig. 1 shows the skymap of the catalogue in equatorial coordinates.

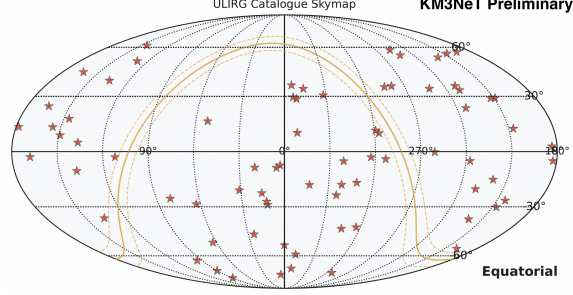


Figure 1: Skymap in Equatorial coordinates of the ULIRG catalogue considered in this contribution.

As demonstrated in Ref. [4], this catalogue is representative of the local ULIRG source distribution for redshift $z \lesssim 0.13$, allowing its use to constrain the properties of the entire population.

4. Analysis Framework

A binned likelihood ratio test is employed in order to search for neutrino emission from the sources of the catalogue. Event rates are binned along the reconstructed energy E_{rec} and the angular distance to the source within a 5° region of interest (RoI) (see [3] for details). For the stacking analysis, each RoI is treated independently, and so the total likelihood is given by

$$\mathcal{L}_{\text{stack}}(\lambda) = \prod_j \mathcal{L}_j(\lambda) = \prod_{i,j} P(n_{i,j}, \lambda w_j \mu_s^{i,j} + \mu_b^{i,j}) \quad (1)$$

where $P(n, \mu)$ is the Poissonian probability of observing n events given $\mu = \lambda \mu_s + \mu_b$ expected events and i runs over each bin of the RoI. μ_b and μ_s are the expected number of background and signal events respectively. The j index accounts for each source in the catalogue. The signal strength λ is a free parameter representing the total flux normalisation. A weight w_j is associated to each source in order to specifically test the neutrino emission predicted by stellar-forming processes.

$$w_j = \frac{F_{IR}^j}{\sum_j F_{IR}^j} \quad (2)$$

with $F_{IR} = L_{IR}/(4\pi D^2)$, where L_{IR} and D are the infrared luminosity and distance of each source respectively. The test statistics (TS) is defined as

$$\text{TS} = \ln \left(\frac{\mathcal{L}_{\text{stack}}(\tilde{\lambda})}{\mathcal{L}_{\text{stack}}(\lambda = 0)} \right) \quad (3)$$

where $\tilde{\lambda}$ is the signal normalisation required to fit the data. In all analysed cases, each source is considered to have the same spectral index.

The sensitivity is defined using a frequentist approach based on pseudo-experiments (PEs) [3] where pseudo-data sets are generated according to the expected distributions of signal and background. For several λ values, the TS distribution is determined and the model rejection factor (MRF) λ_{90} is defined as

$$\int_{TS_m}^{+\infty} d(TS|\lambda_{90}) dTS = 90\% \quad (4)$$

where TS_m is the median TS distribution for the background-only hypothesis. The sensitivity is defined as $\phi_{90}(E) = \lambda_{90}\phi_s(E)$ where $\phi_s(E)$ is the total flux injected corresponding to $\lambda = 1$.

5. Results and Comparison with Theoretical Prediction

The stacking search yields no neutrino signal excess over the background-only hypothesis. Therefore, 90% confidence level (CL) upper limit are set according to Eq. 4 by substituting TS_m with TS_{obs} , namely the observed TS on the unblinded dataset. Fig. 2 shows the 90% CL upper limit for the stacking of the ULIRG catalogue for several tested signal hypotheses.

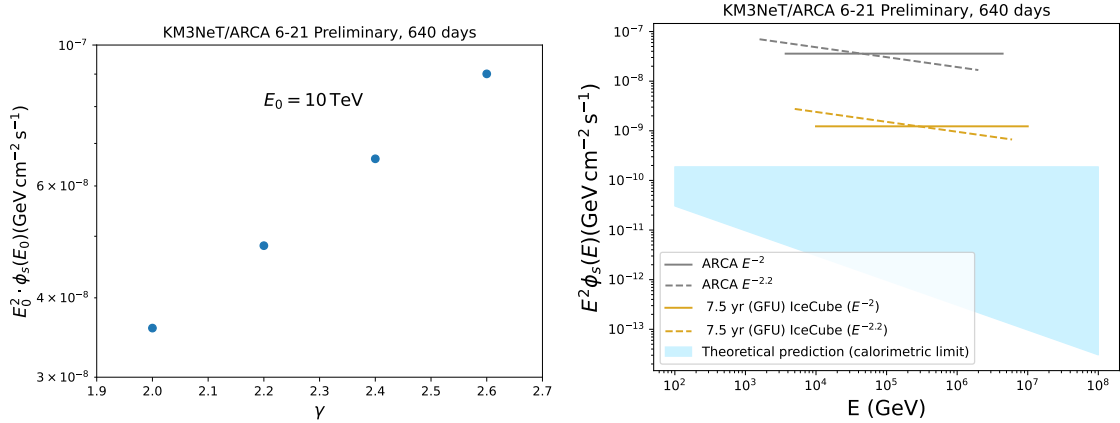


Figure 2: **Left:** ULIRGs stacking catalogue 90% CL unblinded upper limit at a pivot energy $E_0 = 10$ TeV in terms of several spectral indexes. **Right:** The ARCA 90% CL unblinded upper limits for E^{-2} and $E^{-2.2}$ spectra compared with the corresponding IceCube sensitivity [4] as well as with theoretical prediction obtained according to the calorimetric assumptions [5, 6].

In particular, on the left, the figure reports the limit in terms of several spectral indexes tested for a pivot energy of $E_0 = 10$ TeV. On the right, the ARCA limits (reported in the 90% central energy range) for E^{-2} and $E^{-2.2}$ are compared with the corresponding result from the IceCube Collaboration [4] and with theoretical predictions [5, 6]. These theoretical predictions have been evaluated under the so-called calorimetric assumption, which posits that all cosmic rays injected by star-forming activity (as traced by infrared luminosity) are fully converted into neutrinos. At the moment, the ARCA detector cannot probe the calorimetric assumption of ULIRGs, but its sensitivity will improve with the lifetime and the progressively increasing size during construction.

6. Constraining the Diffuse Emission of ULIRGs

The limit set in Fig. 2 for the ULIRG catalogue can be used to constrain the emission from the entire ULIRG population. Given that the analysed catalogue is representative of the local ULIRG distribution, the resulting upper limit serves as a proxy for the total ULIRG contribution up to redshift $z \lesssim 0.13$.

$$\Phi_{\text{diff}}(E, z = 0.13) \leq \frac{\xi_s \phi_s(E)}{4\pi} \quad (5)$$

where $\xi_s = 1.1$ takes into account the incompleteness of the catalogue [4] while the factor 4π allows for the estimation of an upper limit in unit of solid angle.

The total diffuse emission, up to $z_{\text{max}} = 4$, is constrained by

$$\Phi_{\text{diff}}(E, z = 4) \leq \frac{\xi_s \phi_s(E)}{4\pi} g(\gamma) \quad (6)$$

where the factor $g(\gamma)$ depends on the spectral index as well as the redshift distribution of the sources [4, 10]. The redshift distribution for ULIRGs is taken from [11]. The final result is reported in Fig. 3.

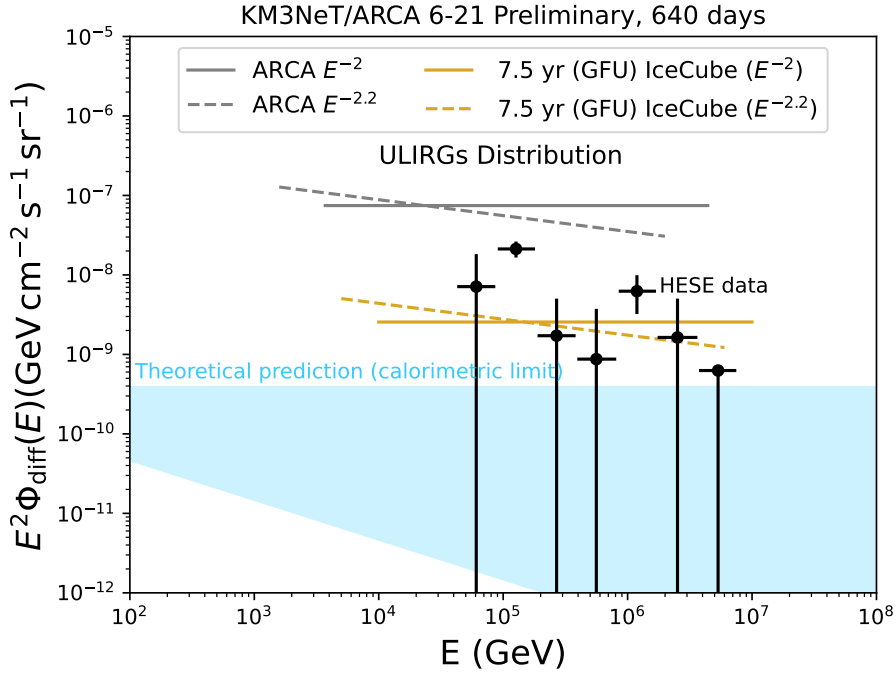


Figure 3: E^{-2} and $E^{-2.2}$ ARCA upper limits for the total ULIRG population compared with the corresponding IceCube result [4] as well as with the theoretical prediction [5, 6]. The results are also compared with the 7.5 year HESE neutrino astrophysical flux as measured by the IceCube Collaboration [12].

The E^{-2} and $E^{-2.2}$ ARCA upper limits for the total ULIRG population are compared with the corresponding IceCube result [4] and theoretical predictions [5, 6]. At present, the ARCA detector cannot exclude a 100% contribution from ULIRGs to the overall diffuse astrophysical flux as measured by the IceCube collaboration [12].

7. Conclusions

Several configurations of the KM3NeT/ARCA detector—ranging from ARCA 6 to ARCA 21—totaling a lifetime of 640 days, are analysed to search for a neutrino signal from a catalogue of 75 ULIRGs. These galaxies are typically powered by intense starburst activity, which is expected to produce significant high-energy neutrino emission. Following the IceCube collaboration’s approach, the selected catalogue consists of 75 local sources. A 2D binned likelihood ratio test has been implemented to search for a cumulative neutrino signal from the catalogue. No signal excess has been found on the background-only hypothesis and 90% CL upper limits have been evaluated on the total neutrino emission by the source population. Although it is not yet possible to probe the expected neutrino flux from these objects, future improvements—such as increased exposure time and a larger effective area—will enhance ARCA’s sensitivity. Finally, the results have been extrapolated to constrain the diffuse neutrino flux from ULIRGs using their redshift distribution.

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