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Search for a cosmic point-like neutrino source from the direction of the ultra-high-energy event KM3-230213A

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On February 13, 2023, the KM3NeT/ARCA neutrino telescope detected an ultra-high-energy neutrino event, KM3-230213A, with an estimated energy of approximately 220 PeV - the most energetic neutrino ever observed. This unprecedented event marks a significant milestone in the field of astroparticle physics, offering new insights into the potential sources of these extreme astrophysical phenomena.
In this work, we present a follow-up analysis aimed at identifying a potential cosmic point-like neutrino source associated with KM3-230213A. We perform a dedicated search for a cluster of neutrino events in the direction of KM3-230213A using data from KM3NeT/ARCA, KM3NeT/ORCA, ANTARES and IceCube. In order to assess the potential spatial clustering of neutrino events around KM3-230213A, we employ either an ON/OFF technique or a maximum-likelihood method.
This contribution presents the methodology, the datasets used, the event selection criteria, and the statistical methods applied. We discuss the results in the context of multi-messenger astrophysics, highlighting their implications for the origin of the ultra-high-energy neutrino KM3-230213A.

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1. Introduction

On 13 February 2023, the KM3NeT/ARCA neutrino telescope detected an ultra-high-energy (UHE) neutrino event, designated KM3-230213A, with an estimated energy of approximately 220 PeV — the most energetic neutrino ever observed to date [1].

KM3NeT [2] is an underwater neutrino telescope under construction in the Mediterranean Sea. It detects the Cherenkov light induced by charged particles produced by neutrino interactions in seawater using multi-PMT Digital Optical Modules (DOMs), each equipped with 31 3-inch photomultiplier tubes (PMTs). The DOMs are arranged vertically along flexible lines, called detection units (DUs), which are anchored to the seafloor; each DU hosts 18 DOMs. The infrastructure includes two detectors: KM3NeT/ARCA, optimised for the detection of high-energy neutrinos, and KM3NeT/ORCA, optimised for lower energies. Together, they provide sensitivity to cosmic neutrinos across a broad energy range, from a few MeV to hundreds of PeV. In its final configuration, KM3NeT/ARCA will consist of 230 DUs, while KM3NeT/ORCA will comprise 115. At the time of KM3-230213A, KM3NeT/ARCA was operating in a partial configuration with 21 deployed detection units, denoted as ARCA21.

The ANTARES Neutrino Telescope [3], KM3NeT's predecessor, operated from 2007 to 2022. It consisted of 885 optical modules, each housing a single 10-inch PMT, distributed across 12 vertical detection lines. The detector was initially deployed in a partial configuration in 2007 with 5 lines, reaching its full 12-line configuration in 2008.

The IceCube Neutrino Observatory [4], located at the South Pole, has been operating since 2011. It comprises 86 vertical strings deployed in glacial ice, each carrying 60 Digital Optical Modules with one 10-inch PMT per DOM, instrumenting a volume of one cubic kilometre.

Given the possibility that the hypothetical astrophysical source that produced KM3-230213A could also emit lower-energy neutrinos, a dedicated analysis was performed to search for a point-like neutrino source consistent with the direction of KM3-230213A.

This contribution describes the multi-detector follow-up analysis promptly performed after the detection of KM3-230213A, as reported in [1], as well as refined analyses based on updated datasets and improved methodologies, including a dedicated likelihood-based search using the full ANTARES private dataset and a newly developed likelihood analysis for KM3NeT/ORCA, which was not available at the time of the initial follow-up.

2. Datasets

Data from KM3NeT/ARCA and KM3NeT/ORCA, along with public data from ANTARES and IceCube, were analysed as part of the initial multi-detector follow-up of KM3-230213A.

The KM3NeT datasets rely on two types of calibration: the 'online' calibration and the 'offline' calibration. The online calibration refers to the detector state at the time of data acquisition. It assumes a static detector geometry, introducing uncertainties in the positions and orientations of the DOMs due to unaccounted-for sea current movements, and relies on preliminary timing calibrations. The offline calibration integrates dynamic positioning and refined time-offset measurements. For some recent detector configurations — specifically parts of the ORCA18 and ORCA23 data-taking periods — the offline calibration was not yet available at the time of the initial follow-up analysis.

In the context of the initial multi-detector follow-up, only track-like events have been considered for all the datasets:

- **KM3NeT/ARCA** — ARCA6-21 offline data.
  A Boosted Decision Tree (BDT)-based event selection was applied, as described in [5].
- **KM3NeT/ORCA**:
  - ORCA6-18 offline data. The event selection is described in Section 3.2;
  - ORCA18-23 online data. The event selection is detailed in Section 3.2.
- **ANTARES** — Ten years of public data released by the ANTARES Collaboration[1].
  The event selection strategy used by the ANTARES Collaboration to define the public sample is described in [6].
- **IceCube** — Ten years of public data released by the IceCube Collaboration[2].
  The event selection strategy used by the IceCube Collaboration to define the public sample is described in [7].

For the refined analyses, the following datasets and selections are considered:

- **KM3NeT/ORCA** — ORCA6-18 offline data, same as in the initial follow-up.
  A BDT-based event selection is applied, as described in [8]. Only track-like events are considered.
- **ANTARES** — Full ANTARES legacy dataset.
  The event selection is detailed in [9, 10]. Both track-like and shower-like events are included.

A summary of the datasets, data taking period and livetime is provided in Table 1.

3. Analysis methods

Depending on the analysis framework available for each dataset, either a likelihood-based method or a binned ON/OFF search is employed, as summarized in Table 1.
All analyses assume a one-flavour cosmic neutrino flux of the form:

$$\Phi_{\nu_i+\bar{\nu}_i}(E_\nu) = \Phi_0^{1\,\mathrm{GeV}} \cdot \left(\frac{E_\nu}{\mathrm{GeV}}\right)^{-2}, \tag{1}$$

where $\Phi_0^{1\,\mathrm{GeV}}$ denotes the flux normalisation at 1 GeV, and E_ν is the neutrino energy.

3.1 Likelihood-based analyses

Time-integrated likelihood analyses are performed for the KM3NeT/ARCA, ANTARES, and IceCube datasets, as well as for KM3NeT/ORCA in the context of the refined analysis. These analyses include a spatial scan in a circular region with radius 3° around the coordinates of KM3-230213A (RA, δ) = (94.3°, −7.8°), aimed at identifying localised excesses consistent with a point-like neutrino source. The chosen scan region corresponds to the 99% CL angular uncertainty on the source direction [1]. Different implementations of the likelihood framework are adopted: a binned approach is used for the ARCA6-21 and ORCA6-18 offline datasets, while an unbinned method is employed for the ANTARES and IceCube datasets.

[1] https://antares.in2p3.fr/data/data-set-for-the-2007-2017-antares-search-for-cosmic-neutrino-point-sources/
[2] https://icecube.wisc.edu/data-releases/2021/01/all-sky-point-source-icecube-data-years-2008-2018/

3.1.1 Binned likelihood method

The compatibility of the observed data with either the background-only or the signal-plus-background hypothesis is evaluated by comparing two-dimensional histograms of the angular distance between the reconstructed event and the hypothetical source (α), and the logarithm of the reconstructed energy ($\log E_{\mathrm{rec}}$). For each bin i, the expected number of signal events S_i, given the cosmic neutrino flux assumed in Eq. 1, and the expected number of background events B_i, are estimated. The signal expectation S_i is derived from Monte Carlo simulations and simulation-based instrument response functions. The background B_i is estimated by scrambling data events in right ascension, yielding a distribution as a function of reconstructed energy and declination [5].
The log-likelihood is constructed assuming Poisson statistics for the observed event counts in each bin:

$$\log \mathcal{L} = \sum_{i \in \mathrm{bins}} N_i \log (B_i + \xi S_i) - (B_i + \xi S_i) \ , \tag{2}$$

where N_i is the number of observed events in bin i, and ξ is the signal strength free parameter that scales the assumed flux.
The test statistic λ is defined as:

$$\lambda = \log \mathcal{L} \left(\xi = \hat{\xi}\right) - \log \mathcal{L} \left(\xi = 0\right) \ , \tag{3}$$

where $\hat{\xi}$ is the value of ξ that maximises the likelihood.
Pseudo-experiments (PEs) with varying signal strength are performed. For a given assumed signal strength ξ_{true}, event counts N_i are drawn from a Poisson distribution with mean $B_i + \xi_{\mathrm{true}} S_i$. For each PE, the test statistic λ is computed, yielding a distribution of $\lambda\left(\xi_{\mathrm{true}}\right)$. These distributions are used to estimate the 90% confidence level sensitivity and the discovery potential of the analysis. Once the data are unblinded, the observed test statistic λ_{data} is computed. A p-value is then obtained by comparing λ_{data} with the background-only distribution λ_{bkg}. In the absence of a significant detection, an upper limit on the flux normalisation is set using the Neyman construction. If the observed λ_{data} falls below the median of the background-only distribution, it is set to the median for the upper limit calculation. This conservative approach avoids unphysically low limits due to downward fluctuations in low-background cases, as can occur with the Neyman construction.
This binned likelihood method is applied to the ARCA6-21 dataset; further details are provided in [5]. A similar likelihood-based approach is also employed in the refined analysis of ORCA6-18 offline data; as described in [8].

3.1.2 Unbinned likelihood method

In this framework, the log-likelihood is defined as

$$\log \mathcal{L}\left(n_{\mathrm{s}}\right) = \sum_{i=1}^{N} \log \left[\frac{n_{\mathrm{s}}}{N} S\left(\vec{x}_i, \beta_i\right) + \left(1 - \frac{n_{\mathrm{s}}}{N}\right) B\left(\sin\delta_i\right)\right] \ , \tag{4}$$

where i refers to an individual event in the dataset, $S\left(\vec{x}_i, \beta_i\right)$ and $B\left(\sin\delta_i\right)$ are the signal and background probability density functions respectively, $\vec{x}_i$ is the reconstructed event direction, β_i is the estimated angular uncertainty of the event, and N is the total number of data events. The parameter n_{s}, i.e. the number of signal events, is free and optimised during the likelihood maximisation.
The signal term $S\left(\vec{x}_i, \beta_i\right)$ is modelled as a 2D Gaussian dependent on the angular distance between the reconstructed event direction $\vec{x}_i = (\mathrm{RA}_i, \delta_i)$ and the source direction $\vec{x}_{\mathrm{s}}$. The background term

$B(\sin\delta_i)$ depends only on the event declination δ_i, under the assumption that background events are uniformly distributed in right ascension. The functional form of the background distribution $P_{\rm bkg}(\sin\delta_i)$ is derived directly from data, which are assumed to be background-dominated [6].

$$S(\vec{x}_i, \beta_i) = \frac{1}{2\pi\beta^2}\exp\left(-\frac{|\vec{x}_i - \vec{x}_s|^2}{2\beta_i^2}\right), \qquad B(\sin\delta_i) = \frac{1}{2\pi}P_{\rm bkg}(\sin\delta_i), \tag{5}$$

The test statistic λ is defined as:

$$\lambda = 2\Big(\log\mathcal{L}(n_{\rm s} = \hat{n}_{\rm s}) - \log\mathcal{L}(n_{\rm s} = 0)\Big), \tag{6}$$

where $\hat{n}_s$ is the value of the number of signal events that maximises the likelihood.

For both ANTARES and IceCube, background-only distributions of the test statistic are obtained by scrambling the right ascension of real data, under the assumption that the datasets are dominated by background events. This procedure enables the estimation of p-values by comparing the observed test statistic to the background-only distribution.

For the ANTARES analysis, upper limits on the neutrino flux normalisation are derived using Poisson statistics and the Feldman–Cousins method. If the observed test statistic falls below the median of the background-only distribution, the standard upper limit for zero signal events is used. Otherwise, the best-fit number of signal events is treated as an effective background level, and a revised Feldman–Cousins upper limit is computed accordingly.

An updated version of the method, incorporating both spatial and energy information and using Neyman construction to set upper limits (described in section 3.1.1), is also used in the refined analysis of the full ANTARES legacy dataset, where both track-like and shower-like events are considered. Further details can be found in [9, 10].

The analysis on IceCube public data is carried out using the `IceCubePy` framework [11, 12]. Pseudo-experiments are generated by injecting signal events from a point-like neutrino source at the declination of KM3-230213A, following the spectrum in Eq. 1. From the resulting test-statistic distribution, the 90% CL sensitivity and upper limits are derived.

3.2 Binned ON/OFF technique

A binned ON/OFF technique [13] is employed to search for cosmic neutrinos in spatial coincidence with KM3-230213A, using KM3NeT/ORCA datasets for the initial follow-up.

The ON region corresponds to the part of the sky where a signal is expected, while the OFF region represents a portion of the sky with similar background conditions but no expected signal. The expected background in the ON region is estimated by rescaling the number of observed events in the OFF region according to the solid angle ratio:

$$n_{\rm bkg} = \frac{\Omega_{\rm ON}}{\Omega_{\rm OFF}}N_{\rm OFF}, \tag{7}$$

where $\frac{\Omega_{\rm ON}}{\Omega_{\rm OFF}}$ is the ratio of the solid angles, and $N_{\rm OFF}$ is the number of events observed in the OFF region.

If no excess is observed in the ON region around KM3-230213A, an upper limit (UL) on the cosmic neutrino flux normalisation $\Phi_0^{\rm UL,\,1\,GeV}$ at 1 GeV (see Eq. 1) is computed as:

$$\Phi_0^{\rm UL,\,1\,GeV} = \frac{\mu_{90}^{\rm FC}(n_{\rm bkg})}{\int dt \int dE_\nu \left(\frac{E_\nu}{\rm GeV}\right)^{-2} A_{\rm eff}^{\delta}(E_\nu)}, \tag{8}$$

where $\mu_{90}^{\mathrm{FC}}(n_{\mathrm{bkg}})$ is the 90% confidence level (CL) upper limit on the number of signal events, obtained using the Feldman–Cousins method, and $A_{\mathrm{eff}}^{\delta}(E_\nu)$ is the effective area of the detector at the declination of KM3-230213A.
For the ORCA6-18 offline dataset, the ON region is defined as a cone of radius 4° centred on KM3-230213A, and the OFF region spans a ±15° declination band. The event selection is optimised to keep the muon contamination between 10–15% while ensuring a negligible expected background, i.e. below 0.5 events when summed over all KM3NeT/ORCA configurations. This is achieved by weighting the background from each configuration according to its effective area and livetime.
For the ORCA18-23 online dataset, the ON region is also defined as a 4° radius cone around KM3-230213A, while the OFF region spans a declination band of ±18° (ORCA18) or ±17° (ORCA23), chosen to mantain systematic uncertainties at the ∼ 10% level. The event selection is tuned to yield about 25 events in the OFF region, corresponding to a statistical uncertainty of approximately 20%.

4. Results

The results of the searches for a point-like neutrino source consistent with the direction of KM3-230213A are summarised below. An overview of the main results is reported in Table 2. Although the searches are sensitive to ultra-high-energy events, the expected signal from an E^{-2} spectrum lies predominantly in the TeV–PeV range, making the reported limits relevant within this energy window.

Dataset				Method	
Detector	Type	Covered Period	Livetime [days]	Analysis Approach	Radius [deg]
ARCA6-21	offline	12/05/2021 - 11/09/2023	640	binned likelihood [5]	3
ORCA6-18	offline	11/02/2020 - 31/08/2023	1005	ON/OFF [13]	4
ORCA18-23	online	01/09/2023 - 29/07/2024	126	ON/OFF [13]	4
ANTARES	public	29/01/2007 - 31/12/2017	3125	unbinned likelihood [6]	3
IceCube	public	06/04/2008 - 08/07/2018	3577	unbinned likelihood [11, 12]	3
ANTARES*	legacy	29/01/2007 - 13/02/2022	4541	unbinned likelihood [9, 10]	3
ORCA6-18*	offline	11/02/2020 - 01/09/2023	1196	binned likelihood [8]	3

Table 1: Overview of the datasets, including the detector, data type, data-taking period, livetime, and analysis method. The final column indicates either the ON region radius or the half-size of the likelihood scan window, both centred on the KM3-230213A coordinates. Datasets marked with * refer to those used in the refined analyses.

No significant excess is observed at the coordinates of KM3-230213A in any of the datasets, neither in the initial follow-up analyses nor in the refined ones currently available. The largest excess is found in the IceCube dataset, located 2.4° from the KM3-230213A, with a pre-trial p-value of 1.65×10^{-4}, corresponding to a post-trial p-value of 0.07. The most stringent upper limit on a point-source E^{-2} cosmic neutrino flux is 1.2×10^{-9} GeV^{-1} cm^{-2} s^{-1}. Figure 1 shows the pre-trial p-value distributions obtained from likelihood-based spatial scans for the ARCA6-21, ANTARES, and IceCube datasets as part of the initial follow-up. Figure 2 presents the corresponding refined results for the full ANTARES legacy dataset and the updated ORCA6-18 binned likelihood analyses.

Datset	p-value (pre-trial)	Flux Upper Limit $[\mathrm{GeV}^{-1}\mathrm{cm}^{-2}\mathrm{s}^{-1}]$	(RA, δ) [deg, deg]	Distance [deg]	p-value (post-trial)
ARCA6-21	0.904	1.8×10^{-8}	$(94.3, -7.8)$	0.0	-
	0.0492	1.9×10^{-8}	$(96.7, -6.8)$	2.6	0.44
ORCA6-18	1.00	2.1×10^{-7}	-	-	-
ORCA18-23	1.00	2.3×10^{-6}	-	-	-
ORCA-combined	-	2.0×10^{-7}	-	-	-
ANTARES	0.990	1.1×10^{-8}	$(94.3, -7.8)$	0.0	-
	0.0116	1.7×10^{-8}	$(94.4, -5.3)$	2.5	0.53
IceCube	0.471	1.2×10^{-9}	$(94.3, -7.8)$	0.0	-
	1.65×10^{-4}	6.3×10^{-9}	$(93.9, -10.1)$	2.4	0.07
ANTARES*	0.870	1.8×10^{-9}	$(94.3, -7.8)$	0.0	-
	4.78×10^{-3}	5.1×10^{-9}	$(97.0, -8.6)$	2.9	0.29
ORCA6-18*	0.670	1.9×10^{-7}	$(94.3, -7.8)$	0.0	-
	0.053	2.9×10^{-7}	$(92.1, -5.7)$	3.0	0.90

Table 2: Summary of results for each dataset, including the pre-trial p-value, and the 90% confidence level upper limit on the one-flavour flux normalisation at 1 GeV. For the likelihood-based scans, results are reported both at the coordinates of KM3-230213A and at the most significant excess found in the scanned region, along with the corresponding coordinates, angular distance from KM3-230213A, and post-trial p-value. Combined limits for the KM3NeT/ORCA datasets are derived using the `MOMENTA` framework [14]. Datasets marked with * refer to results obtained from refined analyses.

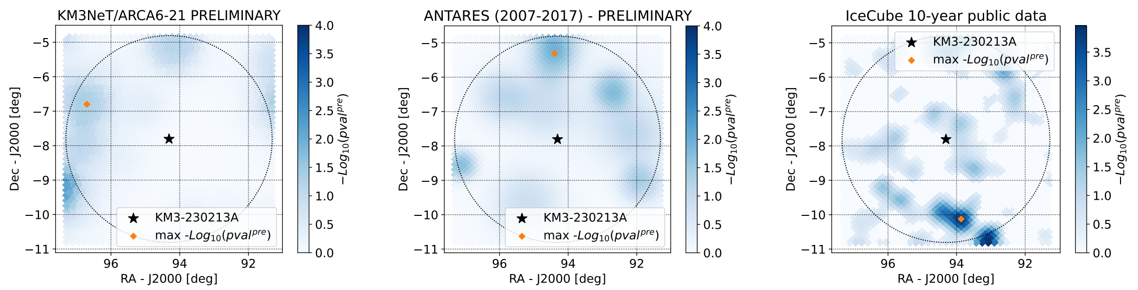

Figure 1: Initial follow-up analyses results: pre-trial p-value distributions around the direction of KM3-230213A for ARCA6-21 (left), ANTARES (centre), and IceCube (right) datasets.

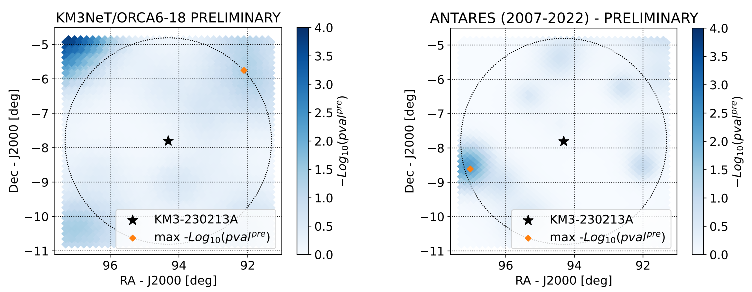

Figure 2: Refined analyses results: pre-trial p-value distributions around the direction of KM3-230213A for ORCA6-18 dataset (left) and ANTARES legacy dataset (right).

5. Conclusion

This work presents the results of dedicated searches for a point-like neutrino source in the direction of KM3-230213A, the most energetic neutrino event detected to date. No significant excess is observed in any of the datasets analysed, and upper limits are set on the one-flavour neutrino flux normalisation at 1 GeV, assuming an E^{-2} spectrum. The current angular uncertainty on the event direction, estimated at 1.5° (68% CL) and 3° (99% CL), is dominated by systematic uncertainties in the absolute orientation of the detector [1]. A more precise localisation is expected following a recalibration of the detector orientation, enabled by the deployment of acoustic emitters with sub-metre positional accuracy, which was successfully completed in July 2025. The recalibration will provide a refined celestial position of KM3-230213A, after which the analyses will be updated.

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