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# Follow-up of O3 gravitational wave events with neutrinos in ANTARES and KM3NeT telescopes

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Astrophysical neutrinos may be produced during the coalescence of compact objects, in particular those involving neutron stars. Such mergers have been identified through gravitational wave detections by the LIGO and Virgo collaborations and reported in published catalogs. The ANTARES and KM3NeT deep-sea neutrino telescopes are sensitive to neutrino interactions in a wide range of energies, from MeV to PeV. The under-construction KM3NeT telescope covers this energy range with two detectors: ORCA for neutrinos below the TeV and ARCA for TeV–PeV, extending the capabilities of the now-decommissioned ANTARES telescope. This contribution presents the search for neutrinos in time and space correlation with the gravitational wave signals reported during the Third Observing Run of LIGO/Virgo. The ANTARES analysis uses track-like and shower-like events originating from high-energy neutrino interactions. It focuses on a ±500-second time window centered on the time of the merger given by the gravitational wave signal. Two KM3NeT studies are carried out using the data from the partial KM3NeT/ORCA detector: a search for upgoing tracks induced by GeV-TeV neutrinos in the same window as above; and a search for a MeV neutrino signal in a shorter 2-second time window. The results are provided in terms of upper limits on the incoming neutrino flux in the various energy ranges and the total isotropic energies emitted in neutrinos. High-energy observations are also stacked to probe the typical neutrino emission from different populations of mergers. The complementarity of ANTARES and KM3NeT results is also explored.

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## 1. Introduction

Since 2015, compact binary mergers have been identified by the detection of gravitational waves with the LIGO/Virgo interferometers [1]. These astrophysical sources, involving stellar black holes and/or neutrons stars may also emit neutrinos. High-energy (GeV–PeV) neutrinos may be produced in hadronic processes occurring in the dense environment surrounding the source [2, 3]; MeV neutrinos may also be produced, especially in the case of binary neutron star mergers [4].

In 2019–2020, the network formed by LIGO and Virgo interferometers identified 83 significant GW sources, reported in three catalogs: GWTC-2, GWTC-2.1, and GWTC-3 [5]. This contribution reports the search for neutrino counterparts from these objects with the ANTARES and KM3NeT deep-sea neutrino telescopes.

The ANTARES detector was located at 2500 m depth, offshore from Toulon (France), and was composed of 12 vertical strings, for a total of 885 photomultiplier tubes (PMTs) and an instrumented volume of about 0.01 km$^3$ [6]. The spacings between the strings and PMTs were optimized for the detection of high-energy neutrinos with 100 GeV–100 PeV. The data taking lasted for 15 years before the experiment was decommissioned in February 2022.

The KM3NeT telescope is the successor of ANTARES and is currently under construction [7]. It is split into two sites: ORCA is located close to the site of ANTARES and its final configuration will have 115 lines covering a volume of 0.007 km$^3$; ARCA, located near Sicily (Italy), will consist of 230 lines instrumenting 1 km$^3$. The geometry of the ORCA (ARCA) detector is optimized for the detection of GeV–TeV (TeV–PeV) neutrinos. During O3, only ORCA was taking exploitable data, specifically with four lines from July 2019 to January 2020 (ORCA4) and six lines from January to March 2020 (ORCA6).

This contribution summarises the O3 follow-up results presented separately from the ANTARES and KM3NeT collaborations [8, 9], as well as combined limits and prospects.

## 2. Method

### 2.1 Event selections

The analyses performed by ANTARES and KM3NeT covered neutrino energies ranging from MeV to PeV. For energies above few GeV (referred to as "high-energy" in the following), a neutrino interaction induces Cherenkov light in the water that may then be reconstructed as a track-like event (mostly induced by muon neutrinos) or a shower-like event (produced by electron neutrinos and neutral current interactions). The neutrino direction can be reconstructed with dedicated algorithms and it is notably possible to separate upgoing from downgoing events, the latter being more likely to be contaminated by atmospheric muon backgrounds. Low-energy (MeV) neutrino interactions produce secondary particles that emit only a few Cherenkov photons, corresponding to a faint signal indistinguishable from optical noises due to bioluminescence and $^{40}K$ decays. Therefore, such neutrinos can only be detected through a global increase of the rate across the whole detector.

In the case of high-energy follow-ups, the search is performed in a time window of ±500 s centered on the GW time $t_{GW}$ and exploiting the spatial correlation between the GW localization and neutrino directions. More precisely, only events with a reconstructed direction within the region $\mathcal{R}_{90}^{+\alpha}$ containing 90% of the GW probability (as it can be uniquely defined from the provided skymap), extended by an angle $\alpha$ to cover for detector angular resolution, are considered. The KM3NeT low-energy search concentrates on a shorter time window $[t_{GW}, t_{GW} + 2\,\text{s}]$ and does not apply any spatial constraints as the original neutrino directions are not available.

The ANTARES search focuses on four event categories: upgoing tracks, downgoing tracks, upgoing showers, and downgoing showers. These only cover energies above 100 GeV and no MeV selection is performed. The expected background is estimated independently for each category and follow-up as it may vary strongly from one GW to another due to the variability of bioluminescence in the sea. The cuts on the track/shower parameters and the value of the extension angle $\alpha$ are optimized to ensure a background level of $2.7 \times 10^{-3}$ events, such that any non-null observation would be associated with a $\geq 3\sigma$ excess while maximizing the expected number of signal events for an $E^{-2}$ spectrum. More details on the selection procedure are presented in [8].

The KM3NeT high-energy search only considers upgoing tracks, while other topologies are not considered. The event selection mainly relies on a Boosted Decision Tree (BDT) classifier to separate mis-reconstructed atmospheric muon background events from upgoing neutrino signals. The ON region consists of upgoing track events in the $\pm 500$ s time window and within the region $\mathcal{R}_{90}^{+\alpha}$ and the OFF region is defined by selecting events reconstructed within the same region in local coordinates but outside the time window. For building the latter, data over several months are considered but only during periods with similar data-taking conditions as at the time of the GW (same number of lines and similar event rates). For each GW, the cut on the BDT score is then optimized by minimizing the model rejection factor (MRF) for an $E^{-2}$ neutrino spectrum. The extension $\alpha$ is fixed to 30° as the small size of ORCA4 and ORCA6 configurations does not allow precise direction reconstruction.

The KM3NeT MeV analysis follows the methods originally developed for core-collapse supernova searches and described in [10]. A coincidence is defined by the detection of four close hits within a single DOM in a time window of 15 ns and the coincidence level $C$ is the total number of such occurrences in 500 ms (computed every 100 ms). In the presence of optical noise, the latter is expected to follow a Poisson distribution with a rate $\bar{b}_C$, while a signal from several neutrino interactions across the detector would be associated with an over-fluctuation. The maximum coincidence level in the 2 s time window $C_{\max}$ is thus compared with the expectation, taking into account the number of trials due to the multiple 500 ms slices in this window.

### 2.2 Statistical analysis

The observations are converted into an upper limit on the incoming neutrino time-integrated flux at Earth and on the total energy emitted in neutrinos by the source (correcting for the distance). The standard scenario for the reported limits in high-energy analyses is using the following assumptions:

- The source is assumed to be located within the region containing 90% of the GW probability.
- The neutrino spectrum is assumed to follow a single power law with a spectral index of 2. The flux can be written as $\frac{\mathrm{d}n}{\mathrm{d}E} = \phi \left(\frac{E}{\text{GeV}}\right)^{-2}$, where $\phi$ is the flux normalisation (in $\text{GeV}^{-1}\,\text{cm}^{-1}$).
- The neutrinos are equipartitioned between the different flavors so that $\left.\frac{\mathrm{d}n}{\mathrm{d}E}\right|_x = \frac{1}{6} \times \left.\frac{\mathrm{d}n}{\mathrm{d}E}\right|_{\text{tot}}$ for $x = \nu_e, \nu_\mu, \nu_\tau, \bar{\nu}_e, \bar{\nu}_\mu, \bar{\nu}_\tau$. The reported limits are then on the all-flavor emission.

- The neutrino emission is assumed to be isotropic around the GW source. The total energy emitted in neutrinos is then simply related to the flux at Earth: $E^{\rm iso}_{{\rm tot},\nu} = 4\pi D_L^2 \int_{E_{\rm min}}^{E_{\rm max}} E \times \frac{{\rm d}n}{{\rm d}E}\,{\rm d}E$, where $D_L$ is the source luminosity distance and $E_{\rm min}, E_{\rm max}$ are the bounds of the spectrum.

**High-energy searches** For each event category $c$ (four for ANTARES, one for KM3NeT), the detector acceptance $a^{(c)}$ is estimated as a function of the direction $\Omega$. A Poisson likelihood is then defined to convert the observed and expected number of events $N^{(c)}$ and $B^{(c)}$ into a limit on $\phi$:

$$\mathcal{L}\left(\{N^{(c)}\}; \{B^{(c)}\}, \{a^{(c)}(\Omega)\}, \phi,\right) = \prod_c \text{Poisson}\left(N^{(c)}; B^{(c)} + \phi \cdot a^{(c)}(\Omega)\right), \quad (1)$$

where the product runs over available event categories. A Bayesian analysis is then applied to account for the priors on $\Omega$ (as extracted from the GW skymap), on the background (covering for statistical and systematic uncertainties), on the normalization of the acceptance (systematic uncertainty), and on the parameter of interest $\phi$ (a flat prior is assumed). The upper limit is simply obtained by marginalizing all the nuisance parameters and finding the range containing 90% of the marginalized posterior probability. The same strategy is employed for obtaining a limit on $E^{\rm iso}_{{\rm tot},\nu}$ or on the ratio $f^{\rm iso}_\nu = E^{\rm iso}_{{\rm tot},\nu}/E_{\rm tot,GW}$, where $E_{\rm tot,GW}$ is the energy radiated in GWs. The method is described at length in [8]. For KM3NeT, as only upgoing tracks are considered in the selection, the obtained constraints are given in the additional assumption that the source is visible in the upgoing sky of the detector at the time of the alert.

**KM3NeT MeV search** For KM3NeT MeV results, pseudo-experiments are generated using the expected mean rate, to estimate how often one would expect to achieve the measured $C_{\rm max}$. This is then converted to an upper limit on the number of signal events contributing to the observation. Assuming a quasi-thermal neutrino spectrum with an average energy of 13 MeV and the method described in [10], one can then obtain upper limits on the total neutrino flux and on the total energy released in such MeV neutrinos.

## 3. Results

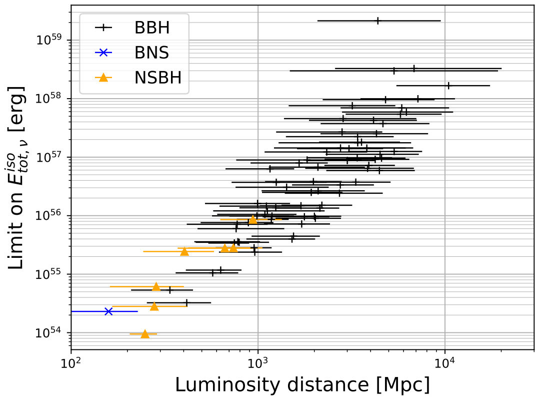
### 3.1 Results from individual searches

Out of the 83 significant GW sources reported by LIGO and Virgo during the O3 run, the ANTARES detector has performed a follow-up for 80 of them. Concerning KM3NeT searches, only GWs after July 1, 2019 are considered, and strict cuts are applied to ensure analysis quality. Therefore, only 50 (55) follow-ups have been done for the KM3NeT high-energy (MeV) analysis.

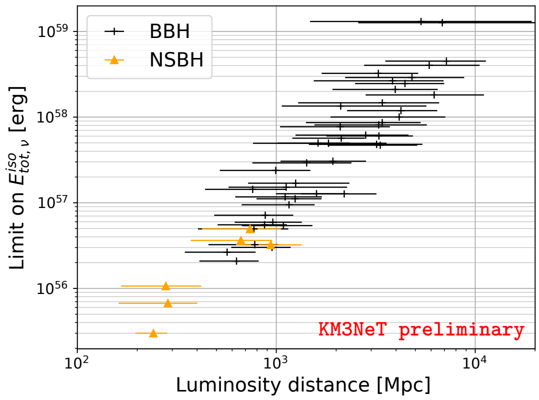
No significant excess has been detected in any of these searches, such that the main results are upper limits on the neutrino emission. Figure 1 summarises the results in terms of the total energy emitted in neutrinos assuming isotropic emission. The limits range from $10^{54}$ to $10^{59}$ erg for high energies while the MeV analysis yields constraints of the order of $10^{60}$–$10^{63}$ erg.

### 3.2 Stacking analyses

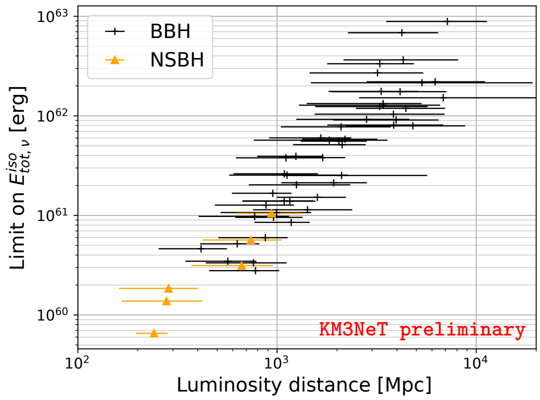
One may also consider the stacking of individual follow-ups into a global constraint on the typical emission from subpopulations of sources, assuming that they all behave the same. This has




**(a)** ANTARES analysis [8]




**(b)** KM3NeT high-energy analysis [9]




**(c)** KM3NeT MeV analysis [9]

**Figure 1:** 90% upper limits on the total energy $E^{\rm iso}_{\rm tot,\nu}$ emitted in neutrinos of all flavor as a function of the source luminosity distance, assuming isotropic emission and an $E^{-2}$ (quasi-thermal) spectrum for high-energies (MeV) samples, for the different analyses. The horizontal bars indicate the 5 – 95% range of the luminosity distance estimate, and the markers/colors correspond to the different source categories. The integration range is fixed to $E_{\rm min} - E_{\rm max}$ = 5 GeV – 100 PeV (1 GeV – 100 PeV) for ANTARES (ORCA).

only been performed for high-energy searches. The GWs have been separated into two categories based on the reported source masses: Binary Black Hole mergers (BBH) if both masses are above 3 $M_\odot$; Neutron Star Black Hole mergers (NSBH) if one of the masses is below this threshold. In the case of ANTARES, it is straightforward to compute stacked limits by simply multiplying the individual likelihoods. For KM3NeT, the visibility is defined as the probability of the source being in the upgoing sky at the time of the alert, and stacking pseudo-experiments are performed where each GW is considered with a probability equal to its visibility. The final reported stacking limit is the median upper limit from these pseudo-experiments, as shown in Table 1.

For BBH mergers, the combination can improve the constraints by a factor of 5 – 10 with respect to event-by-event follow-ups, thanks to the large number of such sources in the catalogs. Given the low number of NSBH candidate sources, the corresponding stacking does not yet bring significant improvements with respect to individual results. The ANTARES publication [8] also presents stacking limits for other emission scenarios, including softer spectra and jetted emission.

| Category | Experiment | Number of sources | Best individual limits $E^{\rm iso}_{{\rm tot},\nu}$ [erg] | $f^{\rm iso}_{\nu}$ | Stacking limits $E^{\rm iso}_{{\rm tot},\nu}$ [erg] | $f^{\rm iso}_{\nu}$ |
|---|---|---|---|---|---|---|
| BBH | ANTARES | 72 | $3.2 \times 10^{54}$ | $2.4 \times 10^{0}$ | $3.8 \times 10^{53}$ | $1.4 \times 10^{-1}$ |
| | KM3NeT | 44 | $2.1 \times 10^{56}$ | $5.7 \times 10^{1}$ | $3.0 \times 10^{55}$ | $1.2 \times 10^{1}$ |
| NSBH | ANTARES | 7 | $9.5 \times 10^{53}$ | $2.2 \times 10^{0}$ | $3.2 \times 10^{53}$ | $8.8 \times 10^{-1}$ |
| | KM3NeT | 6 | $3.0 \times 10^{55}$ | $6.8 \times 10^{1}$ | $1.9 \times 10^{55}$ | $4.6 \times 10^{1}$ |

**Table 1:** Comparison of stacking upper limits for ANTARES and KM3NeT high-energy analyses in the BBH and NSBH populations with the best individual upper limits within the same category.

### 3.3 Combination of ANTARES and KM3NeT observations

As the ANTARES and KM3NeT high-energy searches employ very similar selection techniques and statistical approaches, it is natural to compare the obtained results and consider combining them into a single limit. The Figure 2 shows the comparison between the ORCA effective areas (ORCA4 and ORCA6) and the ANTARES effective area considering only the upgoing track selections (ANTARES shower sample is not considered to allow direct comparison). These translate to the differential sensitivities reported on the same figure, where it is clear that, despite being only 3/5% of the total number of lines to be deployed, the ORCA4/6 configurations already provide better constraints for energies below 100 GeV.

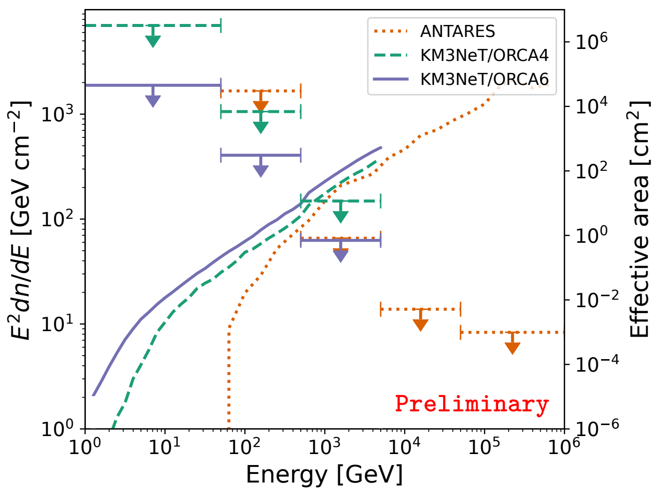



**Figure 2:** Comparison of effective areas of upgoing track selections for ANTARES, KM3NeT/ORCA4, and KM3NeT/ORCA6, computed for GWs with similar sky coverage. The horizontal lines show the corresponding differential sensitivities for various energy ranges.

As the presented KM3NeT selection solely focuses on upgoing tracks, such a combination has only been tested for GW whose localization is fully above the detector horizons at the time of the alert. Only three GWs analyzed both by ANTARES and KM3NeT pass this condition: GW190814, GW190925_232845, GW200208_130117. The first two GWs are during the ORCA4 period while the last one is during ORCA6. The combination is performed by defining the likelihood in Equation 1 with the product running on both ANTARES and KM3NeT event categories and following the same procedure as in the ANTARES-only and KM3NeT-only analyses. Different spectral indices $\gamma$ ranging from 2 (value used above) to 3 are considered.

The results are shown in Figure 3. Even though the integrated ORCA limits are worse than the ANTARES ones for an $E^{-2}$ spectrum, they become competitive for softer spectral indices (towards $\gamma = 3$). For $\gamma > 2.5$, the combination of ANTARES and KM3NeT results improves the constraints by a factor 1.5 – 2 with respect to single-detector limits.

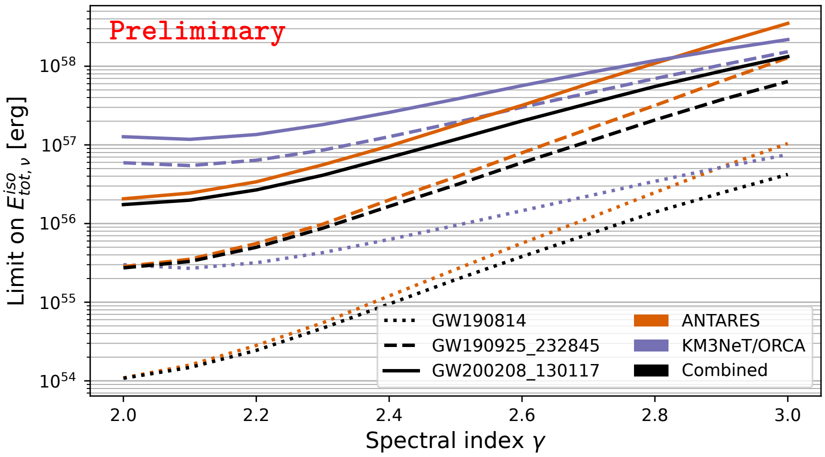



**Figure 3:** Comparison of the upper limits on $E^{iso}_{tot,\nu}$ as a function of the assumed spectral index, for ANTARES, KM3NeT/ORCA, and the combination. The different line styles correspond to the three considered GW sources. The integration range is fixed to $E_{min} - E_{max} = 1\,\text{GeV} - 100\,\text{PeV}$ for both analyses.

## 4. Conclusion and outlooks

This contribution summarises the methods and results presented by the ANTARES and KM3NeT collaborations in [8] and [9], respectively. Overall, the searches for neutrinos from GW-emitting sources have yielded no significant excess, such that upper limits on the incoming flux and on the total energy emitted in neutrinos have been computed. The large number of objects allows population studies to constrain the typical emission.

The new observation period from the LIGO, Virgo, and KAGRA collaborations started in May 2023, with enhanced sensitivities. The ANTARES experiment having been decommissioned, it is now up to KM3NeT to take the lead in the search for neutrino counterparts in the depths of the Mediterranean Sea. Since the end of O3, the detector has considerably increased in size, with 18 lines on the ORCA site and 21 lines for ARCA. The latter will participate for the first time in the follow-ups. As it has a complementary energy coverage from TeV to PeV, the joint analyses will greatly enhance KM3NeT sensitivity thanks to the important lever arm between ORCA and ARCA. Such a joint study has been illustrated here with the example of ANTARES+KM3NeT during O3, meaning that the tools are already in place to perform it. Concerning MeV neutrino searches, the gain in sensitivity is mostly proportional to the total number of active lines, meaning that an improvement by a factor > 6 – 10 is expected with respect to ORCA4/6 analyses.

In the near future, using the online framework presented in [11], follow-up results with KM3NeT will be made available a few minutes after the GW public alert, so that an eventual neutrino detection may help in better localizing a potential joint source and guide electromagnetic observations. The first results obtained within this system are available in [12]. In the following years, when new GW source catalogs will be made available, refined searches will be performed. These include notably population studies taking benefit of the expected large number of reported astrophysical objects in these catalogs.

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## References

[1] LIGO Scientific, Virgo collaboration, *Observation of Gravitational Waves from a Binary Black Hole Merger*, *Phys. Rev. Lett.* **116** (2016) 061102 [1602.03837].

[2] S.S. Kimura et al., *Transejecta high-energy neutrino emission from binary neutron star mergers*, *Phys. Rev. D* **98** (2018) 043020 [1805.11613].

[3] K. Kotera and J. Silk, *Ultrahigh Energy Cosmic Rays and Black Hole Mergers*, *Astrophys. J. Lett.* **823** (2016) L29 [1602.06961].

[4] K. Kyutoku and K. Kashiyama, *Detectability of thermal neutrinos from binary-neutron-star mergers and implication to neutrino physics*, *Phys. Rev. D* **97** (2018) 103001 [1710.05922].

[5] LIGO Scientific, VIRGO, KAGRA collaboration, *GWTC-3: Compact Binary Coalescences Observed by LIGO and Virgo During the Second Part of the Third Observing Run*, 2111.03606.

[6] ANTARES collaboration, *ANTARES: the first undersea neutrino telescope*, *Nucl. Instrum. Meth. A* **656** (2011) 11 [1104.1607].

[7] KM3NeT collaboration, *Letter of intent for KM3NeT 2.0*, *J. Phys. G* **43** (2016) 084001 [1601.07459].

[8] ANTARES collaboration, *Search for neutrino counterparts to the gravitational wave sources from LIGO/Virgo O3 run with the ANTARES detector*, *JCAP* **04** (2023) 004 [2302.07723].

[9] S.L. Stum, *First search for neutrino counterparts from gravitational wave sources with KM3NeT*, 07, 2022. 10.5281/zenodo.6805229.

[10] KM3NeT collaboration, *Implementation and first results of the KM3NeT real-time core-collapse supernova neutrino search*, *Eur. Phys. J. C* **82** (2022) 317 [2109.05890].

[11] KM3NeT collaboration, *The Real-time Data Platform of KM3NeT and its First Results*, *PoS* **ICRC2023** (these proceedings) 1125.

[12] KM3NeT collaboration, *Follow-up of multimessenger alerts with KM3NeT ARCA and ORCA*, *PoS* **ICRC2023** (these proceedings) 1521.

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