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Follow-up of multi-messenger alerts with the KM3NeT ARCA and ORCA detectors

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The strength of multi-messenger astronomy comes from its capability to increase the significance of a detection through the combined observation of events coincident in space and time. This is particularly valuable for transient events, since the use of a narrow time window can allow a reduction of background of the search.

In KM3NeT, we are actively monitoring and analysing a variety of external triggers in real-time, including alerts like IceCube neutrinos, HAWC gamma-ray transients, LIGO-Virgo-KAGRA gravitational waves, SNEWS neutrino alerts, and others.

In this contribution, we present the follow-up of various external alerts using the complementary capabilities of the two KM3NeT detectors, ORCA (covering the few GeV to few TeV energy range) and ARCA (ranging from sub-TeV energies up to tens of PeV). Both detectors were collecting high-quality data with partial configurations during the period of the studied alerts, which goes from December 2021 until June 2023.

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1. Multi-messenger astronomy

Multi-messenger (MM) astronomy is based on the principle that detecting various cosmic messengers in spatial and temporal coincidence, originating from the same source, enhances the potential for discovery compared to single-messenger observations. This approach has become critical in the quest to identify the sources of the most energetic cosmic rays.

Different messengers can provide diverse information about the astrophysical cosmic-ray accelerators, each with its own advantages and disadvantages. For example, photons are very abundant particles and easy to detect, but at high energies they are attenuated by the extra-galactic background light, limiting observations to nearby sources. In addition, charged particles like cosmic rays lose directional information once they are deflected by with magnetic fields.

Gravitational waves, discovered in 2015 [1], opened a new window to the Universe. The case of GW170817, with the electromagnetic counterpart quickly identified by Fermi GBM, and followed-up by observations in all wavelengths of light and in all cosmic messenger, presents an excellent example of the potential behind MM astronomy [2]. The recent start of O4 run of gravitational wave observatories motivates follow-up campaigns with instruments all around the world.

Cosmic neutrinos, first hinted at IceCube in 2013 [3], play an important role in MM astronomy. Being electrically neutral particles, neutrinos can provide unique insights into the properties of sources that are not accessible through other cosmic messengers. Traveling undeviated through very large distances, they offer a unique opportunity to investigate the most energetic non-thermal phenomena in the Universe. Given their small interaction cross section with matter, they can also travel through the Universe without any significant absorption.

However, their weakly-interacting nature – together with the large atmospheric backgrounds in cosmic neutrino searches – hinders the possibility of obtaining large statistical samples of cosmic events in neutrino telescopes. This limitation can be addressed with a MM approach, by conducting real-time searches for neutrino signals triggered by transient events detected in other messengers.

In this context, the KM3NeT neutrino observatory is currently setting up an Online Framework system [4] that will take care of performing real-time follow-up of external triggers, reporting relevant results, as well as sending to external observatories alerts of neutrino events having high probability of an astrophysical origin. The aim is to build a system that is as automatic as possible and that can react quickly as required in the MM approach. The structure of the system stems from the online activities performed in the context of the predecessor of KM3NeT, the ANTARES neutrino telescope [5].

This contribution summarizes the results of various MM analyses conducted by the KM3NeT Collaboration. Section 2 describes the performances of the KM3NeT detectors. Section 3 presents the follow-up of IceCube alerts potentially correlated with blazars, one of the first MM analyses performed by the KM3NeT Collaboration. In Section 4, a review of the recent online searches is summarized. Finally, in Section 5, future perspectives are presented.

2. The KM3NeT detectors

KM3NeT [6] is a research infrastructure currently deploying two deep-sea neutrino telescopes in the Mediterranean Sea. Two separate apparatuses are currently being deployed: ORCA (Oscillation Research with Cosmics in the Abyss) for the study of atmospheric neutrino oscillations and the neutrino mass hierarchy, and ARCA (Astroparticle Research with Cosmics in the Abyss) for identifying high-energy neutrinos from astrophysical sources. The detectors consist of three-dimensional arrays of photo-multiplier tubes (PMTs) that are able to collect the Cherenkov light emitted as a result of neutrino interactions in seawater.

The main difference between the two detectors is the density of the Digital Optical Modules (DOMs) [7], where the PMTs are hosted. The DOMs are embedded in vertical lines, called Detection Units (DU). The higher DOM density of ORCA is optimised to study the GeV range, while the lower DOM density of ARCA allows it to cover the energy range from sub-TeV to PeV. This complementarity between the two detectors motivates astrophysical studies using data from both over a broader energy range.

The detectors are currently taking data with partial configurations. The high-duty cycle (>95%) together with the full-sky coverage (with better sensitivity to sources in the Galactic plane) makes ARCA and ORCA well-suited detectors to perform MM studies. In addition, the good angular resolution (better than 1° for $E > 10$ TeV for events selected in the analyses) is a crucial feature to perform correlation analyses.

3. Follow-up of IceCube alerts

One of the first MM analyses performed by the KM3NeT Collaboration was the follow-up of selected alerts sent by the IceCube Neutrino Observatory, potentially correlated to blazars, between December 2021 and May 2022. Results from these analyses were presented in previous conferences (see e.g. [8]). The selection of potentially-correlated blazars is performed on the basis of multiple criteria, such as the distance to the IceCube best-fit coordinates or the blazar's flaring state.

The search technique is based on a binned ON/OFF method [9]. The ON region, where the signal is expected to dominate over the background, is defined as the region where the angular distance to the source position is lower than the radius of an optimised Region of Interest (RoI). The OFF region is defined as an area of the sky for which the detector has a detection efficiency that is comparable to that of the ON region, while not including it, and in which only background is expected. A declination band centered on the blazar position has been used in the later case. Figure 1 illustrates the definition of these two regions for the case of the blazar candidate PKS 0215+015.

In order to increase the statistics, the OFF region can be extended both in declination size and in time, provided that later it is re-scaled to the size and time span of the ON region. These factors can introduce systematic effects in the analysis that must be taken into account. A declination band width of 30°, centered at the position of the blazar, has been chosen after evaluating its limited effects on the analysis results. Similarly, the extension of the OFF time window covers only periods of times when the detector was in similar data-taking conditions as the time of the alert under study.

At the time of the alerts, KM3NeT/ARCA was taking data with eight active detection lines, while KM3NeT/ORCA had ten. The analyses have been performed using only track-like events, i.e. events with a hit pattern in the detector compatible with a straight line, mainly induced by muon neutrino charged-current interactions. Additionally, only upgoing events have been considered, namely events that have been reconstructed as crossing the Earth, to reduce in our analyses the huge amount of background events due to atmospheric muons.

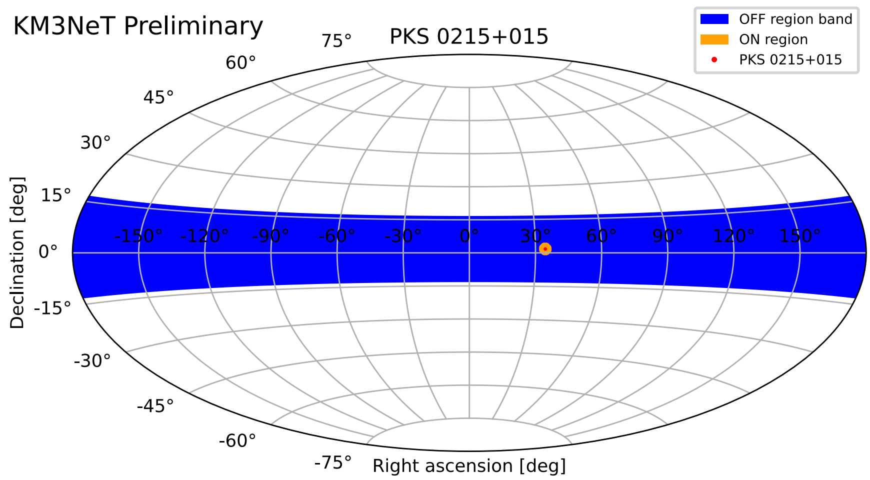

Figure 1: Skymap in equatorial coordinates showing the ON and OFF regions for PKS 0215+015 (potentially correlated with IC-220225A).

The event selection has been optimised by means of Monte Carlo simulations. First, a preliminary set of cuts in the reconstruction variables is derived in order to reduce the atmospheric contamination for each alert. Then, an optimum RoI radius is determined both for ARCA and ORCA according to the Model Discovery Potential (MDP) method [10]. The MDP is defined as MDP $= n_\alpha \left(n_{bckg}\right) / n_{sig}$, where the function n_α is defined in our analysis as the signal strength that leads to a p-value smaller than $\alpha = 2.7 \cdot 10^{-3}$ (2-sided convention) with a 50% statistical power. The expected signal is computed from MC simulations, using a neutrino flux $\phi \propto E^{-2}$. The optimum value of the RoI radius is determined by the minimum of the MDP.

Finally, concerning the time windows, we have performed the follow-ups in a ± 1 day range for all the alerts, centered around the trigger time provided by IceCube. The results are reported in Table 1 for ARCA and Table 2 for ORCA. In the particular case of IC211208A, we performed also a one-month search. This follow-up was motivated by the fact that the corresponding blazar PKS 0735+17 was found to be in a gamma-ray enhanced emission period during the month of December 2021 [11]. The results for this extended search are reported in Table 3.

No significant deviation from the expected background has been found for any of the analysed alerts. In the case of IC211208A, the 1-month follow-up by KM3NeT/ARCA resulted in one event in the ON region with an estimated energy of ∼ 18 TeV. However, this event is compatible with the background expectations, with an associated p-value of 0.14 (pre-trial). The results for the follow-up of this alert were published in a dedicated ATel entry [12].

4. Online searches

As mentioned in Section 1, the natural step is to advance from an offline search, such as the one described in the previous section, to an online follow-up in real-time. For that purpose, the KM3NeT Collaboration is currently establishing an Online Framework system dedicated to perform multi-messenger related tasks, with a team of dedicated shifters overseeing the correct behaviour

IceCube alert	Potential blazar	Sky location (RA, DEC)	Optimum RoI	Expected background	Expected signal	Events in ON region
IC211208A	PKS 0735+17	$(114.5°, +17.7°)$	1.4°	$(4.7 \pm 0.7) \cdot 10^{-2}$	$8.9 \cdot 10^{-3}$	0
IC220205B	PKS 1741-03	$(266.1°, -3.9°)$	1.9°	$(4.9 \pm 0.9) \cdot 10^{-2}$	$9.7 \cdot 10^{-3}$	0
IC220225A	PKS 0215+15	$(34.5°, +1.7°)$	3.0°	$(2.9 \pm 0.4) \cdot 10^{-3}$	$1.4 \cdot 10^{-2}$	0
IC220304A	TXS 0310+022	$(48.3°, +2.5°)$	2.9°	$(2.6 \pm 0.4) \cdot 10^{-3}$	$1.4 \cdot 10^{-2}$	0

Table 1: KM3NeT/ARCA results for the follow-up of IceCube alerts potentially correlated with blazars, selected from the period between December 2021 and May 2022, when ARCA was taking data with eight lines. A time window of ± 1 days is applied. The location of the blazars has been taken from the 4FGL-DR3 Fermi-LAT catalogue [13]. No event has been found inside the ON region for any of the searches.

IceCube alert	Potential blazar	Sky location (RA, DEC)	Optimal RoI	Expected background	Expected signal	Events in ON region
IC211208A	PKS 0735+17	$(114.5°, +17.7°)$	4.2°	$(9 \pm 2) \cdot 10^{-2}$	$8.6 \cdot 10^{-4}$	0
IC220205B	PKS 1741-03	$(266.1°, -3.9°)$	3.6°	$(9 \pm 1) \cdot 10^{-2}$	$6.7 \cdot 10^{-4}$	0
IC220225A	PKS 0215+15	$(34.5°, +1.7°)$	4.0°	$(8 \pm 1) \cdot 10^{-2}$	$6.5 \cdot 10^{-4}$	0
IC220304A	TXS 0310+022	$(48.3°, +2.5°)$	4.0°	$(9 \pm 1) \cdot 10^{-2}$	$6.3 \cdot 10^{-4}$	0

Table 2: KM3NeT/ORCA results for the follow-up of IceCube alerts potentially correlated with blazars, selected from the period between December 2021 and May 2022, when ORCA was taking data with ten lines. A time window of ± 1 days is applied. The location of the blazars has been taken from the 4FGL-DR3 Fermi-LAT catalogue [13]. No event has been found inside the ON region for any of the searches.

Detector	Optimal RoI	Expected background	Expected signal	Events in ON region	p-value
KM3NeT/ORCA	2.3°	$(2.3 \pm 0.2) \cdot 10^{-1}$	$1.0 \cdot 10^{-2}$	0	1.0
KM3NeT/ARCA	1.4°	$(6.6 \pm 0.3) \cdot 10^{-1}$	$1.2 \cdot 10^{-1}$	1	0.14

Table 3: Results for the dedicated follow-up of IC2111208A (potentially correlated to PKS 0735+17) using a time window of 1 month. One event in the ON region has been found in the case of ARCA. This event is not statistically significant, being compatible with the expected background (the p-value is 0.14).

of the different analysis steps and functionalities. More information about the architecture of the system can be found in a dedicated contribution [4].

From the incoming flux of external alerts received by the system, only the ones that satisfy some minimum conditions are analyzed. These criteria are based on multiple verifications, such as the nature of the event, the visibility conditions, or the reported false alarm rate. Each selected alert is then tagged according to its type: **GRB** (for Gamma-Ray Burst triggers such as the ones provided by Fermi-GBM), **TRANSIENT** (for general transitory phenomena), **GW** (for gravitational wave candidates provided by the LIGO-Virgo-KAGRA Collaborations), and **NEUTRINO** (for high energy events reported by the IceCube Collaboration). Figure 2 shows the rate of incoming alerts from January 2023 to June 2023. Note that, on average, one or two alerts are received every day, which justifies the need for a platform as automatized as possible.

For each type of alert, a different analysis pipeline is used to perform the correlation analysis. Each pipeline incorporates a specific neutrino event selection, optimised according to the nature of the alert to follow up. In addition to it, two main inputs are considered: the time window to be used during the correlation analysis, and the RoI to be studied.

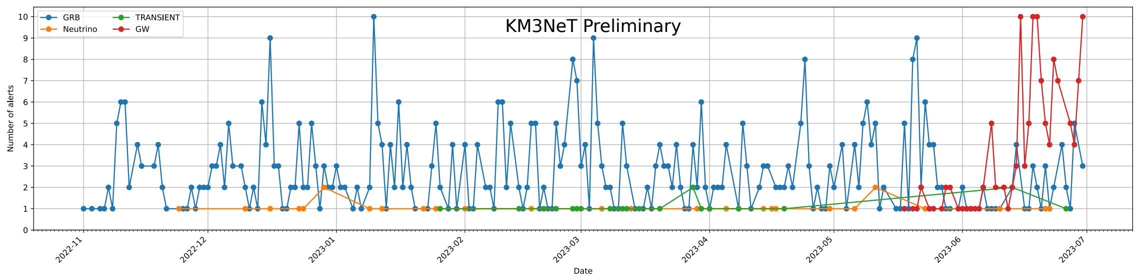

Figure 2: Rate of incoming alerts per day during the period November 2022 to June 2023. The most common type of alert is GRB. The start of run O4 for the gravitational waves at the end of May can be clearly seen.

Each pipeline can use multiple time windows that are defined with respect to the trigger time of the alert (T_0). The search is performed iteratively, extending the time window to include more data and updating the alert information in order to account for possible refinements from the external observatory. The time windows covered in each case are:

- For **GRB**, four time windows are considered: from $T_0 - 1$ day up to T_0, $T_0 + 3$ hours, $T_0 + 12$ hours and $T_0 + 1$ day.
- For **TRANSIENT** and **NEUTRINO**: $[T_0 - 1\text{ h}, T_0 + 1\text{ h}]$ and $[T_0 - 1\text{ day}, T_0 + 1\text{ day}]$.
- For **GW**: $[T_0 - 500\text{ s}, T_0 + 500\text{ s}]$ and $[T_0 - 500\text{ s}, T_0 + 6\text{ h}]$. Additionally, a dedicated analysis pipeline searches for MeV neutrinos detected in a short time window of $[T_0, T_0 + 2\text{ s}]$.

Concerning the RoI, the search method is based on binned techniques, as the analyses described in Section 3. The ON region is determined on the basis of the error box region in the sky associated with the alert being studied, including considerations for the angular uncertainty of the detector. It is, in general, a circular region; in the case of GWs, the contour probability of the gravitational wave event is used, expanded by a few degrees to take into account the angular uncertainty of the detector. These ON regions are defined in equatorial coordinates. In the case of analyses with a time window shorter than one day, the movement of the region in local coordinates is considered.

The event selection is optimised for each alert reducing the expected background to the minimum possible taking into account the shape of the RoI. This expected background is computed from an OFF region defined for each alert, using various days before the alert trigger time in a region with similar coverage in local coordinates as the ON region. Checks on the stability conditions during the ON and the OFF period ensure a stable data-taking flow.

Current analyses consider only track-like events, which are the ones with the best angular resolution. Work is ongoing to include shower-like events (coming from electron neutrino charge-current interactions and all-flavor neutral-current interactions), that have a better energy resolution as they are completely contained in the detector. In addition, currently, the event selection is mainly focus on upgoing events. Progress is being made in the inclusion of downgoing events, to ensure a full sky coverage of the system, with the first tests already performed for GW alerts.

Finally, it is worth mentioning that a dedicated module is being developed to monitor the detection of MeV neutrinos emitted during a Core-Collapse Supernova event (CCSN). This pipeline focuses on the search for an increased rate of coincident hits in the PMTs of the KM3NeT DOMs [14].

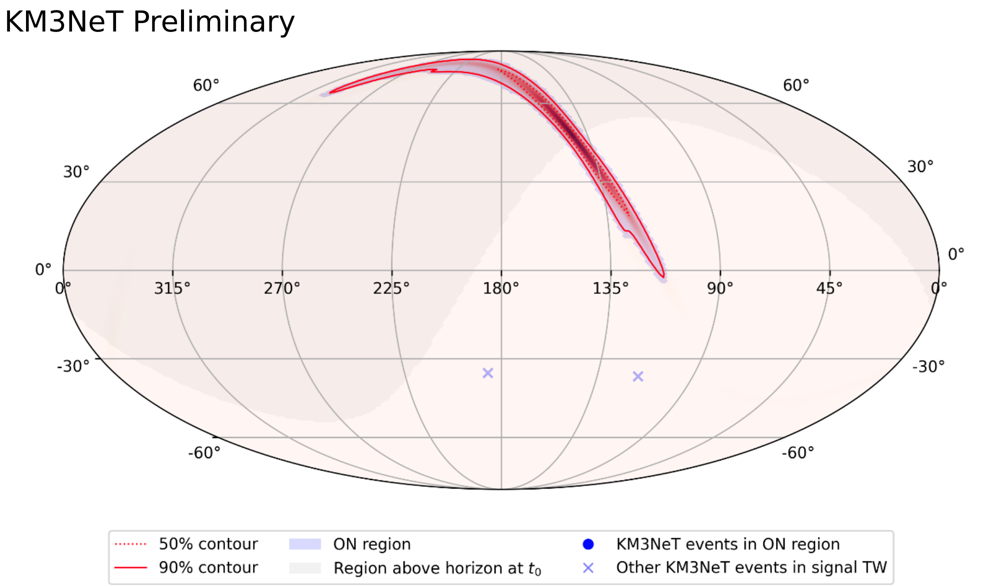

Figure 3: Skymap in equatorial coordinates for the GW S230628ax. The light region denotes the upgoing visibility of KM3NeT at the trigger time of the alert.

In the period from October 2022 to June 2023, around 300 alerts have been analysed. About 170 of these are GRB alerts, where high-significance GRB triggers have been considered. In the case of NEUTRINO alerts, around 50 alerts sent by the IceCube Collaboration have been studied, while TRANSIENT alerts accounted 13 times. Concerning GW events, up to mid-June, all the alerts sent by the LIGO Collaboration have been analysed, including the ones from the engineering run ER15. Starting from mid-June, only high-significance GW alerts are examined. In total, more than 100 GW alerts have been followed up, 15 of which corresponding to significant GW events

No significant excess has been found in any of the analyses performed, since the number of track-like candidates that have been found inside the ON region has always been compatible with the atmospheric background expectations. An illustrative example of analysis can be the case of the GW alert S230628ax, a likely BBH merger event detected by LIGO-Livingston and LIGO-Hanford on June 28. Once the event selection has been optimised, in the case of ARCA, an atmospheric background of $2.6 \cdot 10^{-3}$ events is expected for the short time window ($2.3 \cdot 10^{-3}$ for ORCA), being $1.8 \cdot 10^{-2}$ in the case of the longer one ($4.8 \cdot 10^{-2}$ for ORCA). No significant deviation from this background has been observed, as can be seen in Figure 3 for ARCA. In the case of the MeV analysis, the results are also compatible with the expected background. These online analyses will be complemented by offline searches using refined calibrations and reconstructions.

5. Conclusions and perspectives

The main results of the follow-up analyses performed with the KM3NeT detectors, based on binned sky searches, have been reviewed in this contribution. For IceCube neutrino alerts, the evolution from offline searches (Section 3) to real-time correlation studies (Section 4) has been outlined. For GRB alerts, offline follow-ups such as the one performed for GRB 221009A [4, 15] are now conducted automatically by the Online Framework as described. Moreover, the real-time follow-up of GWs alerts using KM3NeT data has been detailed.

Although no significant neutrino excess has been found in any of the searches, the increasing interest in multi-messenger campaigns motivates to continue monitoring the sky using the Online Framework. Indeed, the complementary hemispheres covered by KM3NeT and IceCube allows a global coverage of the sky. Work is ongoing to automatise the dissemination of analysis results in the case of interesting alerts, also providing upper limits on the neutrino emission −foreseen by Fall 2023−. Furthermore, the implementation of a module for sending KM3NeT neutrino alerts of likely astrophysical origin is currently in progress and is expected to be completed by the end of the year.

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