PROCEEDINGS OF SCIENCE

Latest multi-messenger results of the KM3NeT real-time analysis framework

J. Palacios González,[a,*] **V. Cecchini,**[a] **S. Celli,**[b,c] **I. Del Rosso,**[d,e] **D. Dornic,**[f] **F. Filippini,**[d,e] **E. Le Guirriec,**[f] **J. De Favereau de Jeneret,**[g] **G. Illuminati,**[d,e] **M. Lamoureux,**[g] **M. Mastrodicasa,**[b,c] **F. Salesa Greus,**[a] **A. Sánchez Losa,**[a] **S. Le Stum,**[f] **G. Vannoye,**[f] **A. Veutro**[b,c] **and A. Zegarelli**[b,c]
on behalf of the KM3NeT collaboration

[a] *IFIC (CSIC-UV), Parque Científico, C/ Catedrático José Beltrán, 2. Valencia, Spain.*
[b] *Università La Sapienza, Dipartimento di Fisica, Piazzale Aldo Moro 2, Roma, 00185 Italy.*
[c] *INFN, Sezione di Roma, Piazzale Aldo Moro 2, Roma, 00185 Italy.*
[d] *INFN, Sezione di Bologna, v.le C. Berti-Pichat, 6/2, Bologna, 40127 Italy.*
[e] *Università di Bologna, Dipartimento di Fisica e Astronomia, v.le C. Berti-Pichat, 6/2, Bologna, 40127 Italy.*
[f] *Aix Marseille Université, CNRS/IN2P3, CPPM, Marseille, France.*
[g] *UCLouvain, Centre for Cosmology, Particle Physics and Phenomenology, Chemin du Cyclotron, 2, Louvain-la-Neuve, 1348 Belgium.*

E-mail: `Juan.Palacios@ific.uv.es`

Multi-messenger astronomy studies transient phenomena by combining the information provided by different cosmic messengers, such as neutrinos, photons, charged particles or gravitational waves. A coincident detection enhances the chances for the identification of new astrophysical sources, which motivates the distribution of external alerts and their follow-ups by multiple observatories worldwide.

KM3NeT is a deep-sea research infrastructure hosting two neutrino telescopes currently taking data with partial configurations at the Mediterranean Sea. Two different arrays are being constructed: ORCA, offshore Toulon (France), and ARCA, offshore of Portopalo di Capo Passero, Sicily (Italy). In this contribution, the latest results of the neutrino searches conducted with the real-time multi-messenger analysis platform of the KM3NeT detectors are summarised, including statistical significance. These searches cover a wide neutrino energy range, from MeV up to a few of PeVs.

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1. The multi-messenger context

The origin of the cosmic rays (charged particles reaching the Earth's atmosphere from outer space) is an open question in modern astrophysics. Multi-messenger astronomy is a recently born field of astroparticle physics that aims to provide new insights into this century-old problem. The core idea is that a coincident detection between multiple messengers enhances the sensitivity to identify the sources of cosmic rays, especially in the case of faint sources [1].

The different messengers (cosmic rays, photons, gravitational waves and neutrinos) have their own advantages and disadvantages. Cosmic rays, although abundant, are deflected by magnetic fields and cannot be traced back to their sources. Gamma rays are easy to detect and are emitted both in hadronic and leptonic processes, but above 100 TeV only Galactic sources can be observed due to the interaction with the Cosmic Microwave Background. Gravitational waves, discovered in 2015, are key signatures of the merger of compact objects [2].

Neutrinos, being stable and electrically neutral particles, can reach the Earth directly, pointing backwards to the origin source. Since they only interact appreciably through the weak interaction, they can escape dense environments and are not absorbed in their journey to the Earth. Also, they are unambiguous evidence of hadronic acceleration. The main disadvantage is that very large structures are required to detect GeV−PeV neutrinos, due to the low neutrino cross-section values, the typically low fluxes and the large atmospheric muons and neutrinos background.

2. The KM3NeT detectors

KM3NeT is a scientific collaboration currently building two large-volume structures at the bottom of the Mediterranean Sea: ARCA and ORCA [3]. By detecting the Cherenkov radiation emitted along the path of charged particles produced in neutrino interactions with matter, it is possible to reconstruct the direction of the incoming neutrino and estimate its energy. The detectors consist of an array of Photomultiplier Tubes (PMTs) embedded in spherical structures called Digital Optical Modules (DOMs) [4]. The DOMs are arranged in vertical lines called Detection Units (DUs).

ORCA is optimised to detect neutrinos from a few GeVs energies up to TeVs thanks to its high-density DOM configuration. It is located 40 km away from Toulon (France). ARCA has a lower DOM density, allowing the inspection of the TeV−PeV energy range. It is located 100 km away from Portopalo di Capo Passero, Sicily (Italy). A burst of MeV electron antineutrinos coming from core-collapse Supernovae events can also be inspected through a global light increase in the PMT coincide rate in single DOMs, although no directional reconstruction is possible.

The flavour of the interacting neutrino can be inferred from the topology of the event inside the detector. In a nutshell, ν_μ CC interactions and some ν_τ CC produce a hit pattern compatible with a straight line, called *track-like* events. In contrast, ν_e CC, some ν_τ CC and all the NC interactions produce a more spherical-shaped topology, known as *cascade-like* events. Both topologies are currently being reconstructed in real time to perform multi-messenger follow-up studies.

At present, ARCA has 28 DUs already taking data, and ORCA has 23 DUs. While the construction is ongoing, these partial configurations represent approximately 15% of the full-detector configuration. The detectors have a high-duty cycle (above 95%) which allows both to do multi-messenger studies in real time.

3. The KM3NeT real-time platform

The KM3NeT Collaboration is currently developing an online platform to perform astronomy studies in real time, continuing the efforts of its predecessor, the ANTARES neutrino telescope [5]. Two types of complementary activities can be done in this context: sending public alerts of potentially interesting events and performing the follow-up of alerts detected by external observatories, to search for neutrinos in spatial and time coincidence. The public alert sending is currently under development and it is expected to be operational by early 2025. The follow-up activities, summarized in this proceeding, have been ongoing since late 2022, reporting results only for selected interesting cases. Figure 1 shows the total number of alerts followed until June 2024.

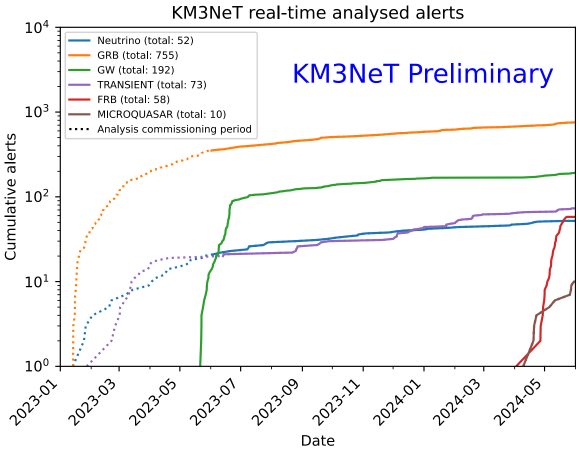

Figure 1: Cumulative number of analysed alerts by the KM3NeT real-time platform, in the period from January 2023 to June 2024. The different colours denote the kind of alert analysed. The dashed line indicates the initial period when the system was under commissioning.

The platform consists of a collection of systems capable of reconstructing the events in real-time (from both ARCA and ORCA) using preliminary calibrations, receiving the stream of incoming external alerts and performing the correlation analysis, together with auxiliary tools for monitoring and reporting. On average, both track-like and cascade-like triggered events are processed in less than 7 seconds for ARCA and ORCA. A machine-learning-based classification score is also implemented to identify potential neutrino events. In addition, a MeV-energy alert pipeline is currently active to search for neutrinos emerging from Core-Collapse Supernovae (CCSNe) events [6].

The correlation analysis incorporates information on the nature of the alert to be analysed. For that purpose, the external alerts of interest are assigned to different designations:

- **Gamma-ray Bursts** (GRBs), short and intense gamma-ray explosions detected by INTEGRAL, *Fermi* and *Swift*. On average, one selected trigger per day is expected.
- **Gravitational Wave (GW)** events detected by LIGO and Virgo. During the observing periods, about one trigger per two days is selected.
- **Transient** events of different nature detected by multiple observatories like *Fermi*, *Swift*, MAXI or HAWC. About one per week is expected.

- **Neutrino** events shared by IceCube as part of their real-time alert system. On average, one event every two weeks is expected.
- **Fast Radio Bursts** (FRB), transient radio pulses of variable length reported by Chime and the TNS catalogue. About one event per 5 days is followed up.
- **Micro-quasar** flares studied through an internal broker which searches for luminosity increase in the light curves from MAXI and *Swift*-BAT of selected sources. One event per week is studied on average.

The analysis method is based on a binned ON/OFF technique [7]. The ON region is the area of the sky where the signal is expected to be found. It is defined as the convolution of the angular error associated with the external alert and of the angular uncertainty of the KM3NeT events, depending on the partial detector configuration that is used. The OFF region is used to estimate the expected atmospheric background. Local zenith bands are used as OFF regions, considering the movement of the ON region in the sky due to the Earth's rotation, as can be observed in Figure 2. The background is estimated by a simple re-scaling in time and solid angle,

$$n_{\text{bckg}} = \sum_{i \in \text{bands}} \frac{T_{\text{ON}}}{T_{\text{OFF}}} \frac{\Omega^i_{\text{ON}}}{\Omega^i_{\text{OFF}}} N^i_{\text{OFF}}. \tag{1}$$

Different T_{ON} are inspected depending on the alert being analysed. As T_{OFF}, two weeks of previously taken data are used, where the stability conditions of the detector are checked.

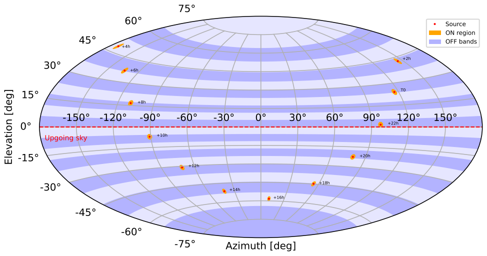

Figure 2: Skymap illustrating the movement of a circular ON region (orange) across multiple local elevation OFF bands (blue). The expected atmospheric background is different in each elevation band.

The event selection is optimised in each search to reduce the atmospheric background level in a way that an observation in the ON region provides the best achievable significance. At the moment only track-like events are considered. For these events, the current partial configurations have a median angular error below 2° (4°) for ARCA (ORCA) using the online calibrations in real time. The implementation of cascade-like events in the analyses is currently underway.

4. Summary of the latest results

No significant neutrino counterpart has been found so far in any of the follow-up analyses performed. The pre-trial p-value, computed from a direct comparison of the number of ON events with the expected atmospheric background, is used as a discriminator of potentially interesting result candidates. The determination of upper limits in the neutrino flux is also implemented.

In the GWs case, the recent O4a campaign was completely covered, and the follow-up of the run O4b is ongoing. Two different time windows are covered in both ARCA and ORCA: $T_0 \pm 500$ s and $[T_0 - 500\text{ s}, T_0 + 6\text{ h}]$, being T_0 the trigger alert time. A MeV search is also conducted within two seconds after the detection. Figure 3 shows the best pre-trial pvalue for the analyses performed during the run O4a. Five analyses provided a result with a significance above the 2σ threshold, which is compatible with background expectations given the total number of analyses performed. The most significant case corresponds to the analysis of S230927be [8], for which the pre-trial significance is around 2.3σ.

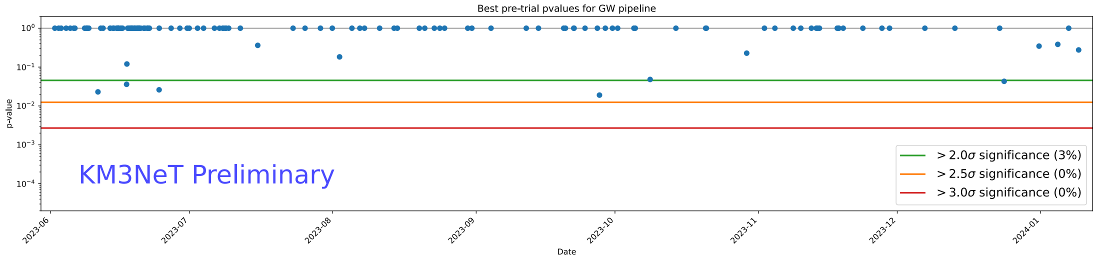

Figure 3: Best pre-trial pvalues for the analyses done on the follow-up of GW events during the observing run O4a. The most significant result corresponds to the analysis of S230927be.

For GRBs, three symmetric time windows are inspected: $T_0 \pm 500$ s, $T_0 \pm 1$ h and $T_0 \pm 24$ h for each trigger. The analysis of GRB 722864655 [9], detected by Fermi-GBM, is an example of a moderately notable case studied, where a 1.2σ pre-trial correlation significance was obtained in ARCA. Similarly, for neutrino alerts by IceCube, one significant study can be the IceCube gold alert IC 231027A [10]. With an expected background of ~ 0.07 events in ORCA, the detection of one ON event resulted in a 1.7σ pre-trial significance. Given the number of followed alerts, these upper fluctuations are compatible with background. For the follow-up of IceCube alerts, the time windows $T_0 \pm 1$ h and $T_0 \pm 24$ h are used.

For the case of FRBs, the same time windows as those used for GRBs are inspected. For transient analyses, an adaptative time window is implemented to account for the duration of the alert trigger, in addition to the standard $T_0 \pm 24$ h search. For micro-quasars, the $[T_0 - 24\text{ h}, T_0 + 500\text{ s}]$ time window is studied, while for the CCSNe pipeline, the study is performed within a time window of two seconds. As previously indicated, no significant results have been found in these searches.

The analysis of GRB 221009A, the brightest gamma-ray burst up to date, is an example of a typical follow-up effort of interest. KM3NeT reported no detection of candidate neutrino events three days after the GRB trigger [11]. Later, a dedicated search using multiple time windows and event selections with refined-calibrated data was conducted, confirming the absence of neutrinos and setting upper limits on the flux emission [12].

5. Conclusion

The KM3NeT online platform is currently operational, reconstructing the events triggered in the detectors in real time. The follow-up of external alerts is ongoing, conducting different analyses depending on the type of the alert. Although no significant correlations have been found between the external alerts and the KM3NeT events, the searches continue, at the same time that the detector size grows, increasing the sensitivity to observe cosmic neutrinos.

The sending of public alerts, foreseen for early 2025, will complement the multi-messenger efforts of KM3NeT, increasing the chances of finding a combined detection. As illustrated in Figure 4, a worldwide array of neutrino telescopes doing real-time activities is crucial for a full-sky coverage in the search for neutrino signals.

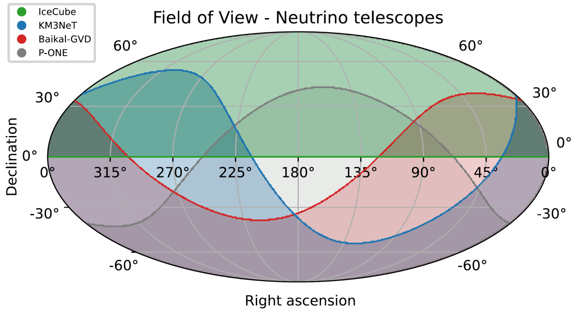

Figure 4: Instantaneous visibility below the horizon for four neutrino telescopes: IceCube, KM3NeT, Baikal-GVD (currently operational) and P-ONE (planned).

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References

[1] P. Mészáros et al., *Multi-Messenger Astrophysics*, *Nature Rev. Phys.* **1** (2019) 585.

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

[3] KM3NeT Collab., *Letter of intent for KM3NeT 2.0*, *J. Phys. G* **43** (2016) 084001.

[4] KM3NeT Collab., *The KM3NeT multi-PMT optical module*, *JINST* **17** (2022) P07038.

[5] ANTARES Collab., *Review of the online analyses of multi-messenger alerts and electromagnetic transient events with the ANTARES neutrino telescope*, *JCAP* **08** (2023) 072.

[6] KM3NeT Collab., *Implementation of the KM3NeT Online Core-Collapse Supernova neutrino search*, PoS(ICRC2023)1223 (2023).

[7] T.P. Li et al., *Analysis methods for results in γ-ray astronomy*, *Astrophys. J.* **272** (1983) 317.

[8] `https://gracedb.ligo.org/superevents/S230927be/view/`.

[9] `https://gcn.gsfc.nasa.gov/other/722864655.fermi`.

[10] IceCube Collab., *IceCube-231027A - IceCube observation of a high-energy neutrino candidate track-like event*, *GCN* **34891** (2023) .

[11] KM3NeT Collab., *GRB 221009A: search for neutrinos with KM3NeT*, *GCN* **32741** (2022) .

[12] KM3NeT Collab., *Search for neutrino emission from GRB 221009A using the KM3NeT ARCA and ORCA detectors*, *JCAP* **08** (2024) 006.