KM3NeT Online Multi-Messenger Results

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Abstract. KM3NeT is a Cherenkov-light based neutrino telescope located in the Mediterranean Sea, comprising two detectors ARCA (Sicily, It) and ORCA (Var, Fr). Currently at ∼15% of its total deployment, with completion expected by 2029, it has an energy sensitivity ranging from MeV to PeV.
The infrastructure is well suited to detect astrophysical neutrinos thanks to a wide field of view and high duty cycle. In the context of multi-messenger astronomy, KM3NeT aims at quickly reconstructing data to identify neutrino candidates, both to search for coincidences after external triggering and to send alerts. This contribution reports on the online analysis framework status, allowing follow-up of alerts from partner experiments and operational since late 2022.

1 Neutrino astronomy and multi-messenger context

Neutrinos exhibit interesting properties in an astronomy context as they can point back to their source. They are stable and abundant, they are not subject to electromagnetic deflection due to their neutrality, and the universe is almost transparent to them due to their solely weak coupling. This last property is also a drawback in our quest to detect them, requiring to instrument very large volumes to counterbalance their tiny cross-section.

Even if it is a challenging task, the detection of high energy (HE) neutrinos from astrophysical origin is unambiguous proof of hadronic acceleration processes and aids in probing acceleration models in extreme environments, as well as other long-standing questions [1] like:

- What are the sources responsible for astrophysical neutrino production? Are they also at the origin of the most energetic cosmic rays (CRs)?
- Are the γ-rays produced through the hadronic acceleration mechanism, *i.e.* the pp and p-γ processes? If yes, in which proportion?
- What is the cosmogenic neutrino flux? Due to the interaction of ultra-high energy CRs (E_{CR} > 100 EeV) in the interstellar medium, neutrinos with EeV energies (called cosmogenic) are expected but detections are still lacking.

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Possible observations by IceCube of cosmic neutrino point-like sources (PS) [2] and coincidences with a blazar flare [3] may partially answer the two first questions and could also help to determine the matter density around sources. However, questions remain on the Galactic sources or on the Neutrino-GRB (Gamma-Ray Burst) association. As for the third question, it still holds.

Astrophysical neutrinos are expected to be dominant only at the highest energies, where the flux is the lowest (here again requiring large detectors). However, an astrophysical flux can be measured at lower energies, on a statistical basis (notably clustering around sources) and through time-dependent detection.
Alternatively, a neutrino detection in correlation with observation from other neutrino experiments or other messengers, like multi-wavelength astronomy and Gravitational Waves (GW), could strengthen the astrophysical origin hypothesis. Therefore, sharing observations in close to real-time among a global astronomy network is of great interest for follow-up campaigns.

2 KM3NeT Detectors

Neutrinos interact through Charged and Neutral Current (CC and NC respectively). In liquid water, the propagation of daughter particles at relativistic speed is responsible for the emission of Cherenkov light along their path. To both detect such light emission and meet the large volume requirements, the KM3NeT collaboration is deploying two detectors [4].
ARCA (Astroparticle Research with Cosmics in the Abyss) and ORCA (Oscillation Research with Cosmics in the Abyss) will instrument the dark deep Mediterranean Sea waters with 3D arrays of Photo-Multipliers Tubes (PMTs).
ARCA is located 100 km offshore of Capo Passero (Italy) at 3450 m below sea level and ORCA is located 40 km offshore of Toulon (France) at a depth of 2450 m. Currently, they have 30 and 24 DUs active, respectively, with a full completion expected in 2029. While both detectors are under deployment, they are already providing physics-material data.

Both ARCA and ORCA share the same hardware design: Thirty-one PMTs are assembled with their electronics in a spherical structure to form a Digital Optical Module (DOM). Eighteen DOMs are arranged together in a vertical line, forming a Detection Unit (DU). One hundred and fifteen DUs placed at the bottom of the sea form one Building Block (BB).
MeV neutrino bursts (from Core-Collapse Supernovae - CCSN - for instance) can be identified by monitoring the coincidence rate at the single DOM level.
To target the energies above the TeV, ARCA will consist of two BBs, where the DUs are 800 m tall (18 DOMs spaced by 36 m) and are spaced one to the other by 90 m, resulting in an instrumented volume of about 1 Gton.
To target the GeV-TeV range, a single BB is foreseen for ORCA, with 200 m-tall DUs (18×9 m spaced DOMs) spread by 20 m, instrumenting about 7 Mton of water.

3 The KM3NeT online platform

To integrate KM3NeT into the multi-messenger astronomy community, a near real-time analysis system has been developed. At its core, there is the Real-Time Analysis (RTA) platform, charged to reconstruct and classify raw data in less than 10 s, using a preliminary calibration (more details in these proceedings [5]). The KM3NeT multi-messenger program is twofold: On one side there are the follow-up analyses triggered by an external alert, looking for a neutrino in correlation to it. On the other, there is the alert sending after a fast identification of an interesting event by KM3NeT. Additionally, a MeV-energy analysis is constantly monitoring the DOM coincidence level and a dedicated search for CCSN neutrino bursts can be integrated to the follow-up. The alert sending system is currently under development, while the alert follow-up system is already operational and is the focus of this contribution.

3.1 Online analysis framework

The follow-up analysis is triggered by the reception of an external alert. Such alerts are usually produced by an external observatory and are sent publicly through brokers.
Alerts are received from the Chime radio-observatory broker for Fast Radio Burst (FRB) candidates, as well as from the GCN notice system. GCN gathers observations for a wide range of instruments, including several γ-rays telescopes, the IceCube neutrinos observatory, or GW interferometers of the Ligo-Virgo-Kagra (LVK) network.
Complementary to those brokers, we have developed scripts to monitor the new FRBs appended to the TNS server, and others to monitor x-rays light-curves publicly provided by MAXI and Swift-BAT for a defined list of micro-quasars.

Analysis pipelines are attributed to each alert depending on the geometry (Extended Source or Point Source) and expected neutrino energy (HE or MeV search for CCSN).The analyses are then performed over various time windows (TW). The following list presents a synthesis of all analysis combinations:

- GRB: short Gamma-Ray flare detected by *Fermi*, *Swift* and *Integral* telescopes. PS analysis with about 1 alert analyzed/day where three TW are explored: ±500 s, ±1 h and ±1 day.
- FRB: Fast Radio Burst from *Chime* and all observatories publishing on TNS. Same PS and TW as GRBs for 1 alert analyzed/day.
- Neutrino: Gold, Bronze and Cascade alerts from *IceCube*. ±1 h and ±1 day TW are explored with the PS pipeline for about 2 alerts per month.
- Transient: *MAXI*, *HAWC*, and none GRBs events from *Fermi* and *Swift*. Roughly 10 alerts are analyzed/month with an adaptive TW covering the duration of the Transient, with a minimum of ±500 s and a second TW of ±1 day.
- Micro-quasar: $\mathcal{O}(10)$ alerts analyzed/month with a single TW starting 1 day before the flare report, until 500 s after the alert.
- GW results in $\mathcal{O}(10)$ alerts analyzed/month with 2 TW of ±500 s and [−500 s, +6 h], using the extended source pipeline. A CCSN search is also conducted for 2 s after the alert time.
- CCSN MeV-energy search for the *SNEWS* and *SK_SN* alerts sent through GCN with a TW spanning from the alert time to 2 s after it.

3.2 HE online analysis method

The HE analysis relies on an ON/OFF cut-and-count method [6]. It is a data-driven approach where cuts are defined in order to achieve a given background level in a control region (the OFF region). As the detector moves with earth rotation, the background is computed for various local zenith bands i in Eq.1, where n_{BKG} is the background level target, defined in a way that an observation in the ON region would provide the best achievable significance. T_{ON} is the TW of the search, T_{OFF} the TW for background expectation (2 weeks with detector stability criteria), Ω_{ON} and Ω_{OFF} are the solid angle of the ON and OFF regions respectively.

The cuts are applied to data to reduce N_{OFF} (number of events in the OFF region) until n_{BKG} is achieved.

$$n_{\text{BKG}} = \sum_i \frac{T_{\text{ON}}}{T_{\text{OFF}}} \frac{\Omega^i_{\text{ON}}}{\Omega^i_{\text{OFF}}} N^i_{\text{OFF}} \tag{1}$$

Those cuts are then applied to the region surrounding the event (the ON region), taking into account the angular error of the alert and the KM3NeT angular uncertainty. Afterward, the number of events passing the cuts in the ON region (if any) is evaluated in the light of the expected background level, by computing the p-value. This pre-trial p-value is used as a discriminator for the significance of a result. A limit on the flux is derived from the effective area of the detector and the exposure time.

3.3 Results summary

The analysis has been ongoing since late 2022, with commissioning completed by June 2023. Over the period expanding to June 2024, a total of 1140 analyses have been performed. None of them have reached the 3σ upper fluctuation threshold defining a significant counterpart.
Five GW analyses provided a result with a significance above the 2σ threshold, while the highest significance found in coincidence with GRB and Neutrino alerts was respectively 1.2σ and 1.7σ upper fluctuation. Accounting for the total number of analyses performed, such numbers are compatible with background expectations.
The brightest gamma-ray burst up to date, GRB 221009A, has been followed up, with no detection of a candidate neutrino. This result has been confirmed by a refined analysis, setting upper limits on the flux emission [7].

4 Conclusion

The KM3NeT online platform is successfully reconstructing and classifying events, the alert follow-up pipeline is in operation, and analyzes those data for a wide range of sources. No significant counterpart has been identified until now, but the growth of the detector increases its sensitivity and the searches will continue.

References

[1] C. Guépin, K. Kotera, F. Oikonomou, High-energy neutrino transients and the future of multi-messenger astronomy, Nat Rev Phys **4**, 697 (2022). 10.1038/s42254-022-00504-9
[2] M. Aartsen, et al., Time-Integrated Neutrino Source Searches with 10 Years of IceCube Data, Phys. Rev. Lett. **124**, 051103 (2020). 10.1103/PhysRevLett.124.051103
[3] M. Aartsen, et al., Neutrino emission from the direction of the blazar TXS 0506+056 prior to the IceCube-170922A alert, Science **361**, 147 (2018). 10.1126/science.aat2890
[4] S. Adrián-Martínez, et al. [KM3NeT], Letter of intent for KM3NeT 2.0, J. Phys. G: Nucl. Part. Phys. **43**, 084001 (2016). 10.1088/0954-3899/43/8/084001
[5] M. Mastrodicasa, et al. [KM3NeT], The KM3NeT online processing for multi-messenger alerts, in *RICAP-24 proceedings, EPJ Web of Conferences* (2024)
[6] T.P. Li, Y.Q. Ma, Analysis methods for results in gamma-ray astronomy., The Astrophysical Journal **272**, 317 (1983). 10.1086/161295
[7] S. Aiello, et al. [KM3NeT], Search for neutrino emission from GRB 221009A using the KM3NeT ARCA and ORCA detectors, J. Cosmol. Astropart. Phys. **2024**, 006 (2024). 10.1088/1475-7516/2024/08/006