PROCEEDINGS OF SCIENCE

KM3NeT real-time analysis framework

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KM3NeT is a deep-sea neutrino observatory under construction at two sites in the Mediterranean Sea. The ARCA telescope (Italy), aims at identifying and studying TeV-PeV astrophysical neutrino sources, while the ORCA telescope (France), aims at studying the intrinsic properties of neutrinos in the few-GeV range. Since they are optimised in complementary energy ranges, both telescopes can be used to do neutrino astronomy from a few MeV to a few PeV, despite of their different primary goals. The KM3NeT observatory takes active part to the real-time multi-messenger searches, which allow to study transient phenomena by combining information from the simultaneous observation of complementary cosmic messengers with different observatories. In this respect, a key component is the real-time distribution of alerts when potentially interesting detections occur, in order to increase the discovery potential of transient sources and refine the localization of poorly localized triggers, such as gravitational waves. The KM3NeT real-time analysis framework is currently reconstructing all ARCA and ORCA events, searching for spatial and temporal coincidences with alerts received from other operating multi-messenger instruments and performing core-collapse supernova analyses. The selection of a sample of interesting events to send alerts to the external multi-messenger community is presently under definition. This contribution deals with the status of the KM3NeT real-time analysis framework and its first results.

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1. Introduction

Multi-messenger astrophysics aims at combining the complementary information from the simultaneous observation of different cosmic messengers produced and/or accelerated in the same sources. These messengers can arise from different astrophysical processes, and thus their combined observation provides a deeper insight into the emitting sources than their individual measurement. Among them, neutrinos are ideal messengers, and they can allow to discriminate between leptonic and hadronic scenarios. In this context, the real-time distribution of alerts when potentially interesting events are detected, plays a crucial role in the identification and localization of transient sources. Given their large field of view and almost 100% duty cycle, neutrino telescopes are ideally suited to distribute alerts to other observatories and perform follow-up searches of external triggers. For this reason, the KM3NeT Collaboration has set up a Real-Time Analysis (RTA) framework which is continuously processing events and performing automatic follow-up searches. The definition of an alert sending program is still in progress, with the exception of the alert system for core-collapse supernovae detection.

KM3NeT [1] consists of two detectors under construction at two sites in the Mediterranean sea: ARCA (Italy) and ORCA (France). KM3NeT detectors are configured in a three dimensional grid of Digital Optical Modules (DOMs) [2], each containing 31 photomultipliers (PMTs), arranged in vertically aligned Detection Units (DUs), each hosting 18 DOMs. The final goal of KM3NeT is to operate 3 Building Blocks (BBs), 2 for ARCA and 1 for ORCA, each containing 115 DUs.

This contribution deals with the description of the KM3NeT RTA framework and its first results as at the time of the Conference i.e. for a KM3NeT configuration with a number of operating DUs equal to 21 for ARCA (ARCA21) and 18 for ORCA (ORCA18). After the last DU deployment in September 2023, ARCA is taking data with 28 DUs.

2. The KM3NeT RTA framework

As soon as data are collected, they are sent from each detector to the corresponding shore station (*all-data-to-shore* approach), where they are mirrored to the KM3NeT RTA framework, schematized in Figure 1. At each shore station, a RTA dispatcher continuously sends data to two modules: (1) the MeV supernova analysis module [4] aiming at identifying core-collapse supernova events and early notifying other facilities and (2) the GeV-PeV online processing module aiming at performing multi-core event reconstruction and classification of triggered events. Data from each detector are then transmitted to a common multi-messenger dispatcher and used for auto-correlation and external alerts follow-up searches. Four follow-up analyses are currently implemented and are automatically activated every time that an interesting alert is received, in order to

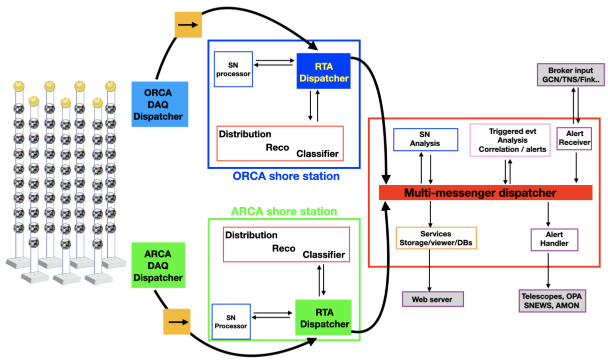

Figure 1: Schematic view of the KM3NeT RTA framework. Figure from [3].

search for KM3NeT events in spatial and temporal coincidence with Gravitational Waves (GWs) [6], Gamma Ray Bursts (GRBs), high-energy neutrinos from IceCube and general transients [5].

2.1 The MeV supernova analysis module

The KM3NeT main detection channel for the MeV-scale core-collapse supernova neutrinos is the inverse beta decay of $\overline{\nu}_e$ on free protons in water. Since KM3NeT is optimised for neutrino energies above the GeV scale, the online core-collapse supernova analysis [4] is performed by searching for an excess of coincidences between PMTs in single DOMs above the expected background [7], such that each single DOM acts as a standalone detector. The *multiplicity* is defined as the number of unique PMTs involved in a coincidence. The expected number of events in a 500 ms time interval as a function of the multiplicity for a single KM3NeT BB from 11 $M_\odot$, 27 $M_\odot$ and 40 $M_\odot$ core-collapse supernova progenitors, compared with the estimated backgrounds after muon background rejection in ARCA and ORCA, is shown in Figure 2. For a progenitor's mass of 11 $M_\odot$ or above, more than 95% of the Galactic core-collapse supernovae can be observed by KM3NeT [7]. The MeV supernova analysis module sends alerts to SNEWS [8] with a latency lower than 20 s and a false alarm rate less than 1/week.

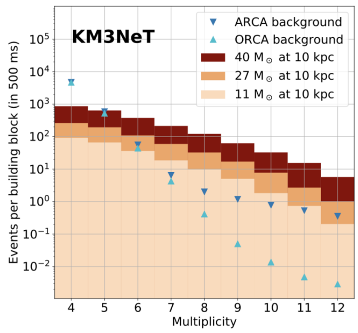

Figure 2: Expected number of events as a function of the multiplicity for one KM3NeT BB from a core-collapse supernova with different values of progenitor's mass, compared with the estimated backgrounds. Figure from [7].

2.2 The GeV-PeV online processing module

The ORCA online event processing consists in the sequential application of track reconstruction, shower reconstruction and classification to each triggered event. Classification is performed with a Boosted Decision Trees (BDT) method aiming at separating atmospheric neutrinos from the atmospheric muon background. As a result of the ORCA18 sequential processing, events are reconstructed and classified in a median time of ~ 6 s, as shown in Figure 3(a).

Differently from ORCA, track reconstruction, shower reconstruction and classification are parallelised in ARCA. A Graph Neural Network (GNN) method is used for classification to separate neutrinos from the muon background. The ARCA21 implementation allows to process triggered events in a median time of ~ 4 s, as shown in Figures 3(b), 3(c) and 3(d) respectively for track reconstruction, shower reconstruction and classification.

2.3 Multi-messenger alerts follow-up searches

The KM3NeT multi-messenger follow-up analyses [5] are based on binned ON/OFF techniques [9]. Depending on the alert type, a specific analysis pipeline with a specific neutrino event selection is automatically triggered. The number of iterations for each alert changes according to the alert class. For GWs two iterations are performed in the time windows [T_{alert} − 500 s, T_{alert} + 500 s] and [T_{alert} − 500 s, T_{alert} + 6 h]. An additional analysis pipeline performs a search for MeV neutrinos in the time window [T_{alert}, T_{alert} + 2 s] with an analysis strategy similar to that used in core-collapse

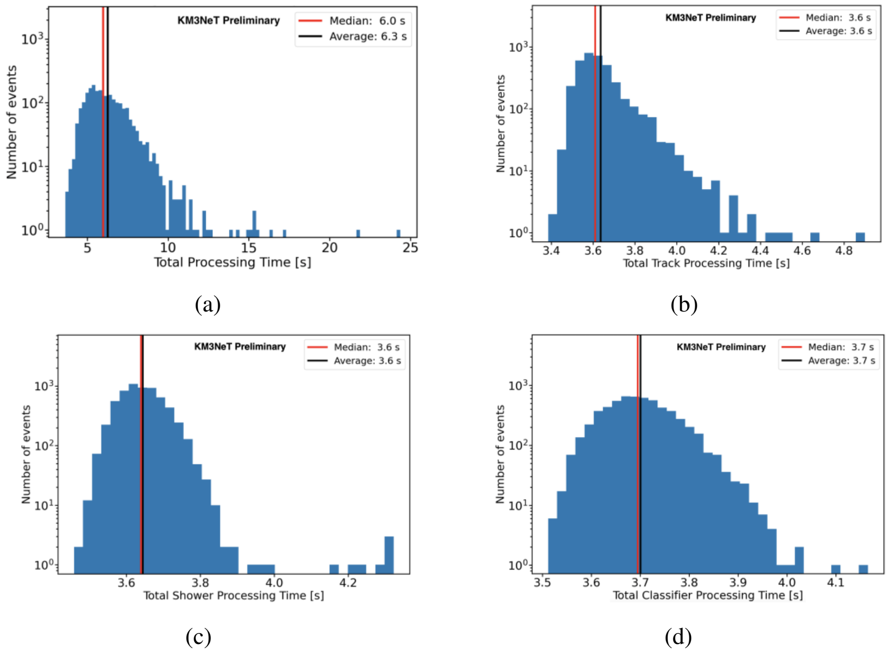

Figure 3: ORCA18 total processing times for event acquisition, distribution, track reconstruction, shower reconstruction and classification (a) and ARCA21 total processing times for event acquisition, distribution and track reconstruction (b), shower reconstruction (c), classification (d). Figures from [3].

supernova analysis. For GRBs four iterations are run in the time windows $[T_{alert} - 24\text{ h}, T_{alert}]$, $[T_{alert} - 24\text{ h}, T_{alert} + 3\text{ h}]$, $[T_{alert} - 24\text{ h}, T_{alert} + 12\text{ h}]$, $[T_{alert} - 24\text{ h}, T_{alert} + 24\text{ h}]$. For high-energy neutrinos from IceCube and general transients two iterations are activated in the time windows $[T_{alert} - 1\text{ h}, T_{alert} + 1\text{ h}]$ and $[T_{alert} - 24\text{ h}, T_{alert} + 24\text{ h}]$. An optimisation of the GRB analysis pipeline is presently planned.

3. Online follow-up analyses results

From October 2022 to July 2023, 317 alerts were analysed with the KM3NeT RTA framework (179 GRBs, 22 IceCube neutrinos, 110 GWs, 30 of which significant GW alerts, and 6 transients), none of them resulting in a significant excess over the expected background. Just before the automated GRB analysis pipeline became fully operational, when it was still in a preliminary state, the KM3NeT online reconstructed data were used to perform a quick follow-up of GRB221009A, the brightest GRB ever recorded, whose position was above the KM3NeT horizon at the time of the alert. No significant excess was found [10], as also confirmed later by a refined analysis [11].

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