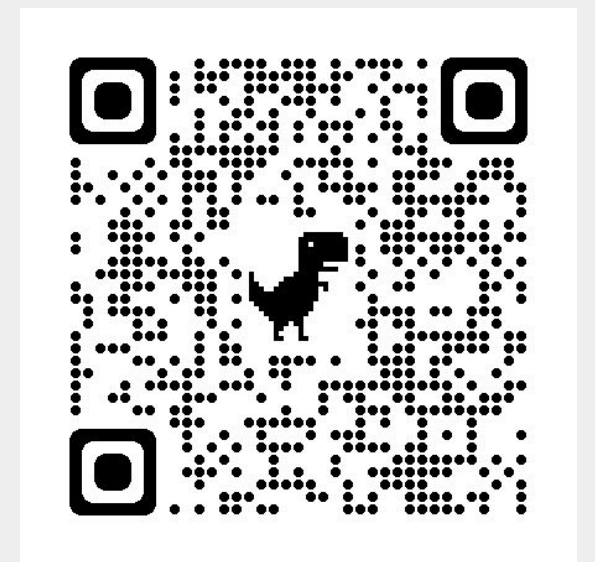




KM3NeT real-time analysis framework



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ABSTRACT

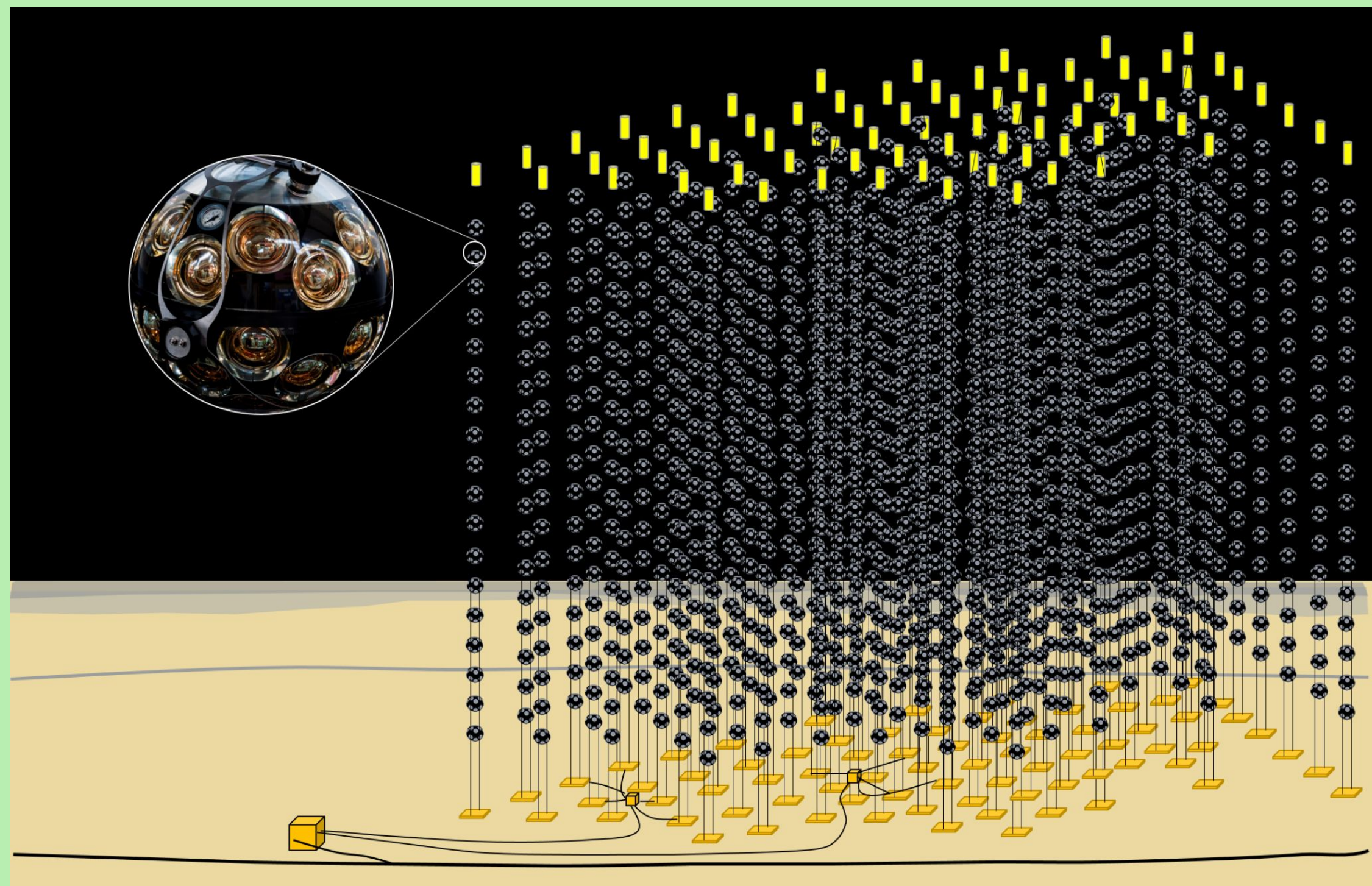
KM3NeT is a deep-sea neutrino observatory under construction at two sites in the Mediterranean Sea. The ARCA telescope (Italy), aims at identifying and studying TeV-PeV astrophysical neutrino sources, while the ORCA telescope (France), aims at studying the intrinsic properties of neutrinos in the few GeV range. Since they are optimised in complementary energy ranges, both telescopes can be used to do neutrino astronomy from few MeV to few PeV, despite of their different primary goals. The KM3NeT observatory takes active part to the real-time multi-messenger searches. These searches 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 aims at performing the reconstruction of all ARCA and ORCA events, searching for spatial and temporal coincidences around received alerts after having filtered them, selecting a sample of interesting events to send alerts and performing the core-collapse supernova analysis.

1. KM3NeT

The Kilometre Cube Neutrino Telescope (KM3NeT) [1] is a deep-sea research infrastructure located in two sites of the Mediterranean Sea consisting of a three dimensional grid of Digital Optical Modules (DOMs) [2] detecting the Cherenkov light produced by relativistic particles arising from neutrino interactions, arranged in vertically aligned Detection Units (DUs) each hosting 18 DOMs:

- the Astroparticle Research with Cosmics in the Abyss (ARCA) telescope is placed 100 km off-shore Portopalo di Capo Passero, Sicily, Italy at a depth of 3500 m with a DU horizontal spacing of 90 m and a DOM vertical spacing of 36 m. It is optimised for the detection of high-energy cosmic neutrinos;
- the Oscillation Research with Cosmics in the Abyss (ORCA) telescope is situated 40 km off-shore Toulon, France at 2450 m depth with a DU horizontal spacing of 20 m and a DOM vertical spacing of 9 m. It is optimised for the detection of low-energy atmospheric neutrinos;

The final goal of KM3NeT is to operate 3 Building Blocks (BBs), 2 for ARCA and 1 for ORCA, each containing 115 DUs. Currently, the number of operating DUs is 21 for ARCA (ARCA21) and 18 for ORCA (ORCA18).



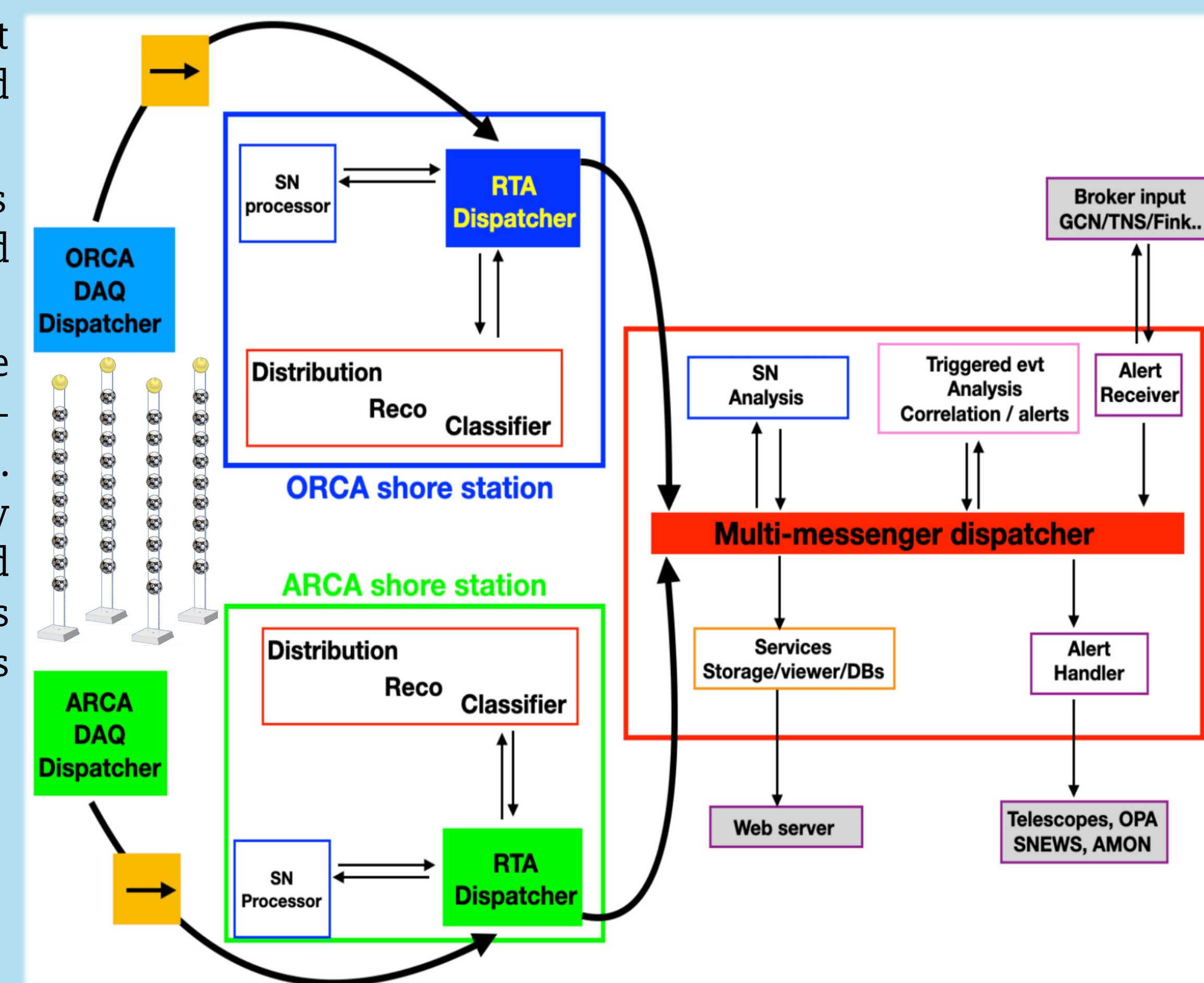
2. The RTA framework

The KM3NeT Real-Time Analysis (RTA) framework [3] consists of a dispatcher specific to ARCA, a dispatcher specific to ORCA and a dispatcher common to both detectors. A schematic view of the KM3NeT RTA framework is shown in the figure below. Each specific dispatcher, located at the corresponding shore station, continuously sends data to two modules:

- the MeV supernova analysis module [4] aims at identifying core-collapse supernova events and early notifying other facilities;
- the GeV-PeV online processing module performs multi-core event reconstruction and classification of triggered events.

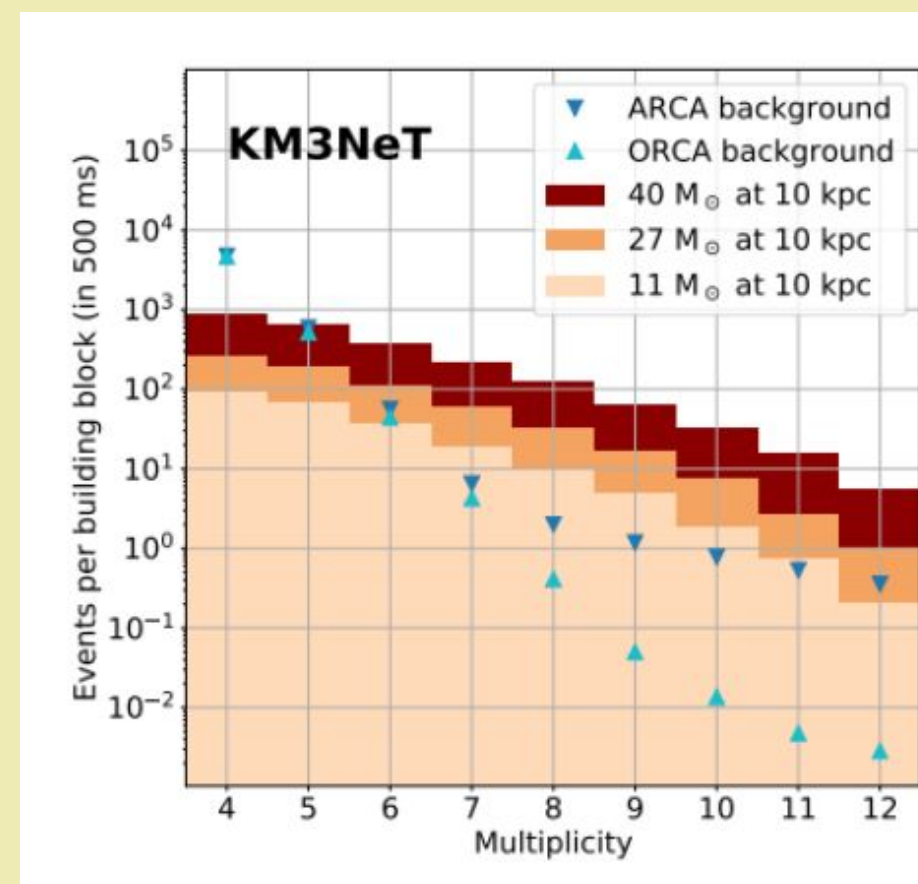
Data from both the detector are transmitted to the common dispatcher and then used for auto-correlation and external alerts follow-up searches. The following four follow-up analyses are currently implemented and are automatically activated every time an interesting multi-messenger alert is received [5], in order to search for KM3NeT events in spatial and temporal coincidence:

- Gravitational Waves (GWs) [6];
- Gamma Ray Bursts (GRBs);
- high-energy neutrinos from IceCube;
- general transients.



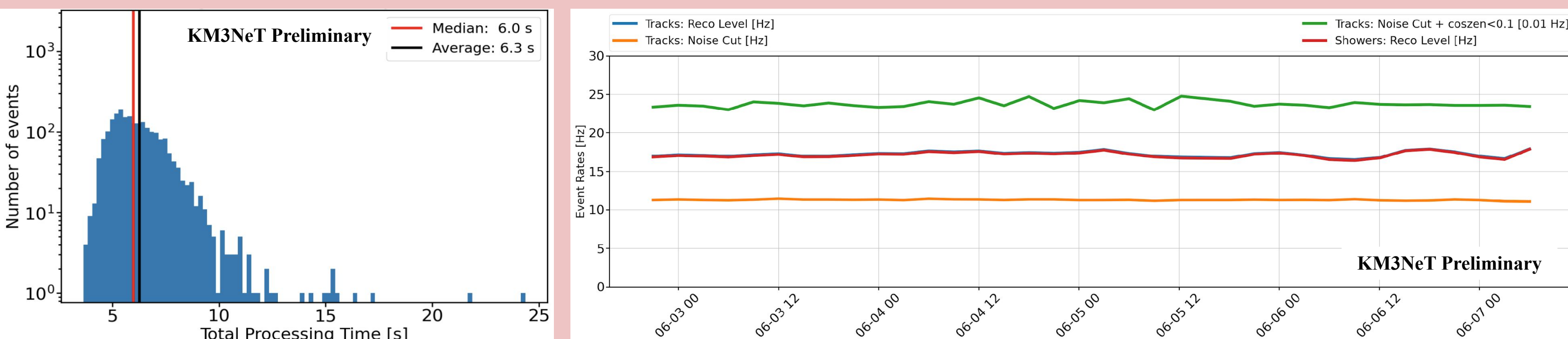
3. Online core-collapse supernova analysis

The KM3NeT main detection channel for core-collapse supernova neutrinos is the inverse beta decay of $\bar{\nu}_e$ on free protons in the water. Since KM3NeT is optimised for 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 number of unique PMTs involved in a coincidence is defined as multiplicity. 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 the figure on the right [7].



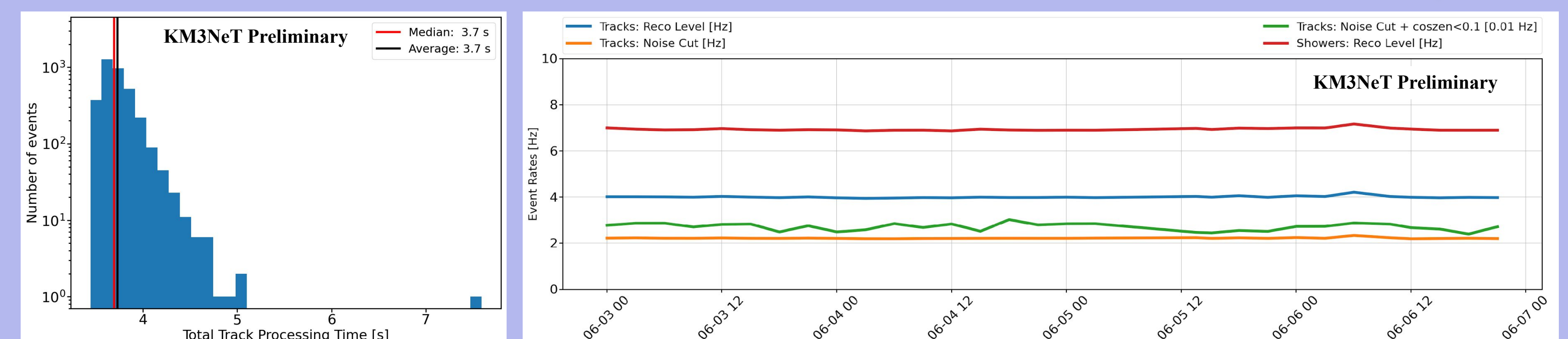
4. ORCA online event processing

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 below together with the online event rates at reconstruction level [3].



5. ARCA online event processing

Differently from ORCA, track reconstruction, shower reconstruction and classification are implemented in parallel for ARCA. A Graph Neural Network (GNN) method is used for classification to separate both neutrinos from muons and tracks from showers. The ARCA21 parallelised implementation allows to process triggered events in a median time of 4 s, as shown below. Online event rates at reconstruction level are also reported [3].



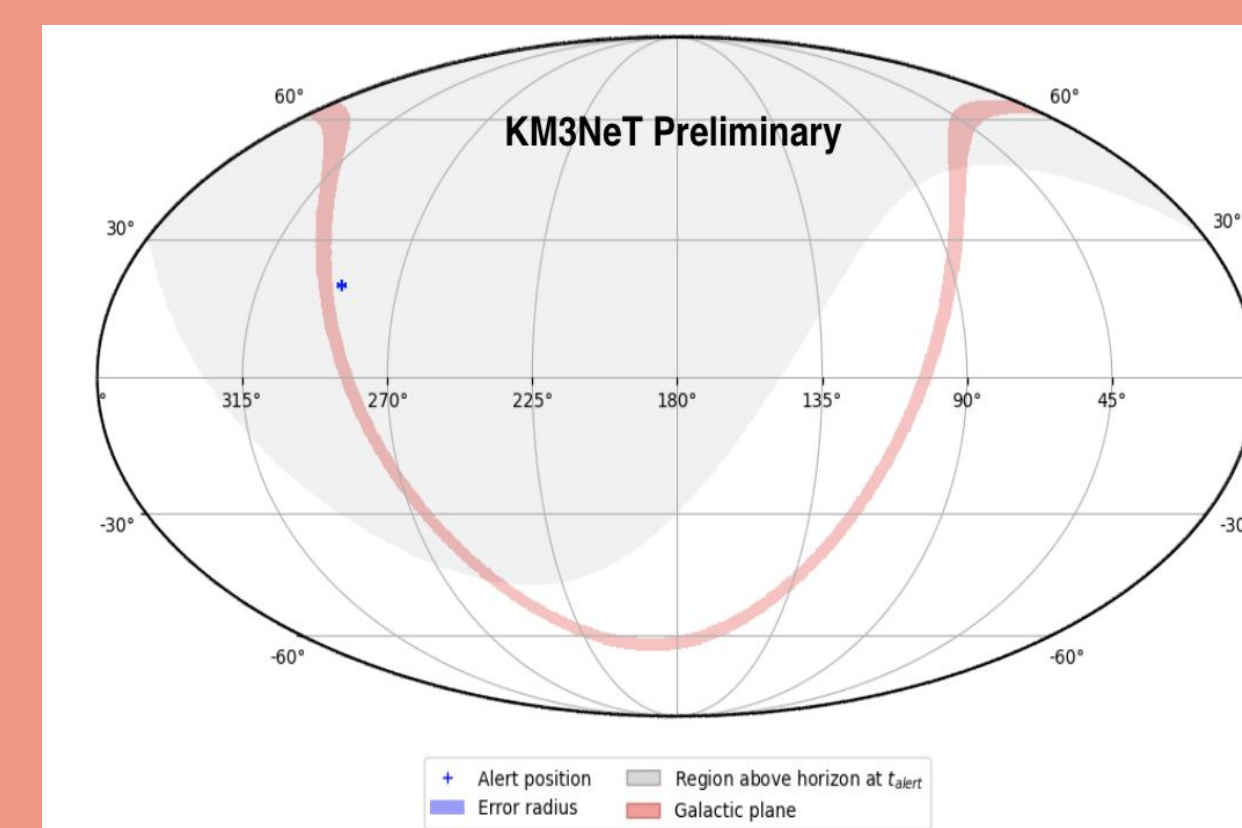
6. Multi-messenger alerts follow-up searches

The KM3NeT multi-messenger follow up analyses [5] are based on binned ON/OFF techniques [8]. 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:

- GWs: two iterations are performed in the time windows $[T_{\text{alert}} - 500 \text{ s}, T_{\text{alert}} + 500 \text{ s}]$ and $[T_{\text{alert}} - 500 \text{ s}, T_{\text{alert}} + 6 \text{ h}]$. An additional analysis pipeline performs a search for MeV neutrinos in the time window $[T_{\text{alert}}, T_{\text{alert}} + 2 \text{ s}]$ with an analysis strategy similar to that used in core-collapse supernova analysis;
- GRBs: four iterations are run in the time windows $[T_{\text{alert}} - 24 \text{ h}, T_{\text{alert}}]$, $[T_{\text{alert}} - 24 \text{ h}, T_{\text{alert}} + 3 \text{ h}]$, $[T_{\text{alert}} - 24 \text{ h}, T_{\text{alert}} + 12 \text{ h}]$, $[T_{\text{alert}} - 24 \text{ h}, T_{\text{alert}} + 24 \text{ h}]$;
- high-energy neutrinos from IceCube and general transients: two iterations are activated in the time windows $[T_{\text{alert}} - 1 \text{ h}, T_{\text{alert}} + 1 \text{ h}]$ and $[T_{\text{alert}} - 24 \text{ h}, T_{\text{alert}} + 24 \text{ h}]$.

7. Online follow-up analyses results

When the brightest GRB ever recorded (GRB221009A) was detected on 2022 October 9th, a quick follow-up analysis was performed by using the KM3NeT online reconstructed data. As shown in the figure on the right [3], the source position was above the KM3NeT horizon at the time of the alert. This analysis resulted in no candidate neutrino events found in spatial and temporal coincidence [9], as also confirmed later by a refined follow-up analysis [10]. From October 2022 to July 2023, 317 alerts were analysed (179 GRBs, 22 IceCube neutrinos, 110 GWs, 30 of which significant GW alerts, and 6 transients). No significant excess has been found for any of them.



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