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# Status, recent results and outlook of the KM3NeT neutrino telescope in the Mediterranean Sea

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The KM3NeT neutrino telescope is a next-generation research infrastructure currently under construction in the Mediterranean Sea. It consists of two deep-sea detectors: ORCA, near Toulon, France, and ARCA, off the coast of Sicily, Italy. ORCA is designed for precision study of atmospheric neutrinos in the GeV range, whereas ARCA aims to detect and study cosmic neutrinos of higher energies. KM3NeT offers an infrastructure in the Northern Hemisphere, with a good view towards the Galactic Center. The first detection units of ORCA and ARCA are taking data. In these proceedings a selection of recent results will be presented, with emphasis on searches for astrophysical neutrinos. KM3NeT has recently reported the detection of a cosmic neutrino with an energy exceeding 200 PeV, and its detection and interpretation are discussed. Results from KM3NeT searches for neutrino point sources and for a diffuse flux, from the full sky as well as from the galactic plane, are shown. We discuss generation and treatment of real-time alerts towards and from external sources for transient events. We include an outlook on detector completion and on the future scientific capabilities of the full infrastructure.

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## 1. The KM3NeT Infrastructure

The KM3NeT collaboration is building a scientific infrastructure in the Mediterranean Sea comprising two neutrino telescopes and ports for earth and sea sciences and marine biology [1]. The two neutrino telescopes are ORCA, off the coast of Toulon, France, at 2500 m depth, and ARCA, off the coast of Sicily, at 3500 m depth. ORCA and ARCA share a common technology of Detection Units (DUs), each consisting of 18 Digital Optical Modules (DOMs) arranged along a vertical cable. Each DOM contains 31 3-inch photomultiplier tubes (PMTs) mounted in a glass sphere in a "Fly's Eye" pattern, providing coverage over a large solid angle. The DUs are connected to a sea-floor network that powers the detector and transmits all data real-time to the shore stations.

The main difference between ORCA and ARCA lies in the horizontal distance between the DUs (20 m for ORCA, 90 m for ARCA) and the vertical distance between DOMs in a DU (9 m for ORCA, 40 m for ARCA). This makes ORCA predominantly sensitive to atmospheric neutrinos with an energy between $\sim 2$ and a few hundred GeV, whereas ARCA, with its much larger volume, is optimized for higher energies, where the cosmic neutrino flux is expected to dominate over the atmospheric flux. ARCA will have twice as many DUs as ORCA, and with a volume of a cubic kilometer it is targeted towards the search for and study of cosmic neutrino sources.

ARCA is situated in the Northern Hemisphere at a latitude of about 36 degrees North. Neutrino telescopes have minimal background for neutrinos coming from below, i.e., from an angle with respect to the zenith of 90 degrees or more, where the Earth shields cosmic ray muons. For ARCA this implies a good sensitivity to sources in the Southern sky, which includes the Galactic centre and a large part of the Galactic plane. As such, the sky coverage of KM3NeT is complementary to the one of IceCube. Moreover, this area of maximal KM3NeT sensitivity largely coincides with the field of view of telescopes, whether radio, optical, or gamma ray, in Southern Africa, as shown in Fig. 1.

At the time of writing (October 2025), ORCA has 33 operational DUs out of a foreseen total of about 100, whereas in ARCA 51 DUs out of 230 foreseen for two complete building blocks have been deployed. Both detectors should be completed by the end of the decade.

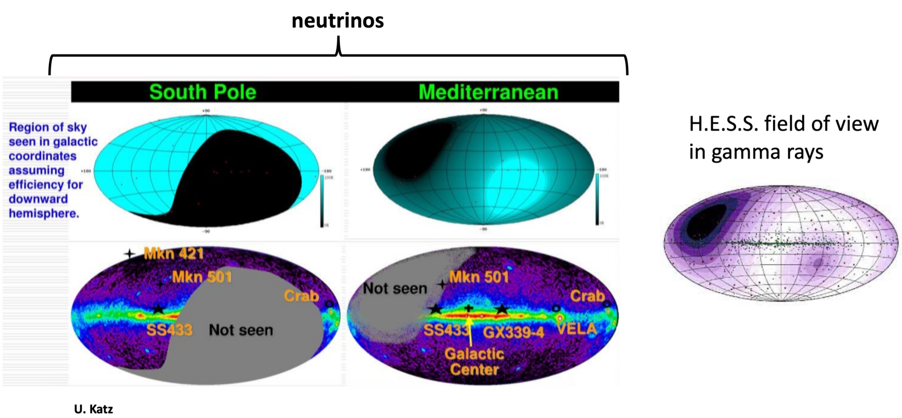


**Figure 1:** Field of view of an Antarctic and a Mediterranean neutrino telescope in galactic coordinates, and the corresponding field of view of H.E.S.S.

## 2. Data acquisition, Calibration and Reconstruction

KM3NeT records hits when signals from a single PMT exceed a preprogrammed threshold; a hit consists of a time and a time-over-threshold that is a proxy for the signal amplitude. All hits are sent to the shore stations, where a real-time selection of interesting events is performed, based on correlations between hits and their compatibility with originating from Cherenkov light produced by a charged particle in water.

The time-synchronisation of the detector is calibrated in the laboratory before deployment, and in-situ with $^{40}K$ decays in the sea water and with cosmic ray muons. The latter also give a handle on the properties, notably the light absorption length, of the sea water [2], needed in simulation and reconstruction. The DUs of KM3NeT move with the sea current and are typically not vertical, and in order to be able to reconstruct particles with the desired accuracy, the positions of individual DOMs need to be known to about 20 cm precision. This position calibration is performed in KM3NeT using acoustic triangulation: a series of emitters on the sea floor sends out unique "pings" which are recorded by piezo sensors in the DOMs, enabling the reconstruction of their position [3]. An example is shown in Fig. 2.

Candidate events are reconstructed based on the precise timing and location of recorded hits. Fits are made to two assumed topologies: "tracks" represent long energy depositions, typically by cosmic ray muons and muons from charged-current muon neutrino interactions, and "showers" (or "cascades") from particle showers in the water caused by electrons and positrons and tau decays to electrons or hadrons in charged-current neutrino scattering, as well as hadronic recoil in charged- and neutral-current neutrino scattering events. KM3NeT/ARCA has an excellent intrinsic angular resolution for high-energy tracks, of order 0.05 degrees, or 3 arcminutes [1].

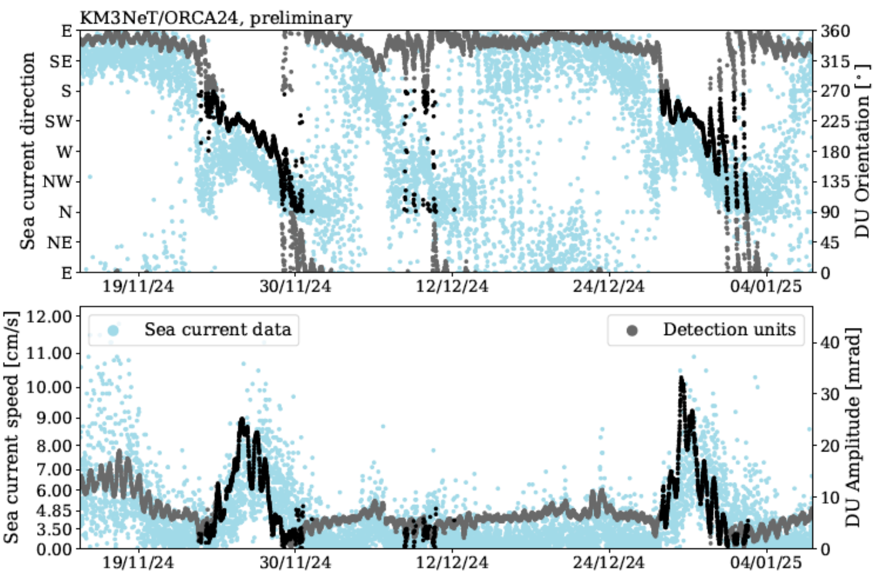


**Figure 2:** Mean reconstructed DU orientation in ORCA compared to the sea current direction (top), and mean ORCA DU tilt amplitude and mean sea current velocity (bottom) as a function of time. For a discussion, see Ref. [3].

## 3. Recent neutrino astronomy results

Following IceCube's key discoveries—such as the diffuse astrophysical neutrino flux [4] and a diffuse galactic neutrino flux [5], and the association of individual neutrinos with sources like TXS 0506+056 [6] and NGC1068 [7]-the search for their origins continues. KM3NeT/ARCA will provide a complementary view, particularly of the Galactic Plane and Center.

Recent KM3NeT astronomy analyses typically use a data sample corresponding to 640 days of data taking: 92 days of ARCA6 (6 DUs), 212 days of ARCA8, 48 days of ARCA19, and 287 days of ARCA21. In some analyses the KM3NeT data has been combined with ANTARES data; the ANTARES sample corresponds to 4541 days of data. ARCA19 and ARCA21 are comparable in size to ANTARES. The data taken with ARCA28 is currently being calibrated and will, when added to the earlier data, double the exposure of ARCA6-21.

If dark matter consists of Majorana Weakly Interacting Massive Particles (WIMPs), their self-annihilation in regions of the Universe where their density is high may lead to a detectable neutrino signal. KM3NeT has searched for neutrinos originating from WIMP dark matter annihilation in the Galactic Center with the ARCA8-21 data set [8]. No excess of neutrinos over the estimated background is observed, and limits are set on the annihilation cross section under various assumptions for the WIMP decay channels. These limits approach the limits set by ANTARES and IceCube, showing the significant sensitivity of KM3NeT in this analysis.

The KM3NeT analyses for a diffuse cosmic flux [9] and for a diffuse neutrino flux from the Galactic Ridge [10] use upgoing track-like events in ARCA6-21. No excess is observed yet, and upper limits on the flux are set that are still higher than the fluxes measured by IceCube. KM3NeT will still need more exposure to observe these fluxes.

The most recent KM3NeT search for cosmic neutrino sources is based on the ARCA21 data set as described above, and is combined with the full ANTARES data set [11]. A comprehensive catalog of about 100 point-like and extended astrophysical sources has been examined for potential neutrino emissions. This selection includes prominent gamma-ray emitters, Galactic gamma-ray sources with possible hadronic components (TeVCat), extragalactic AGNs with intense radio flux



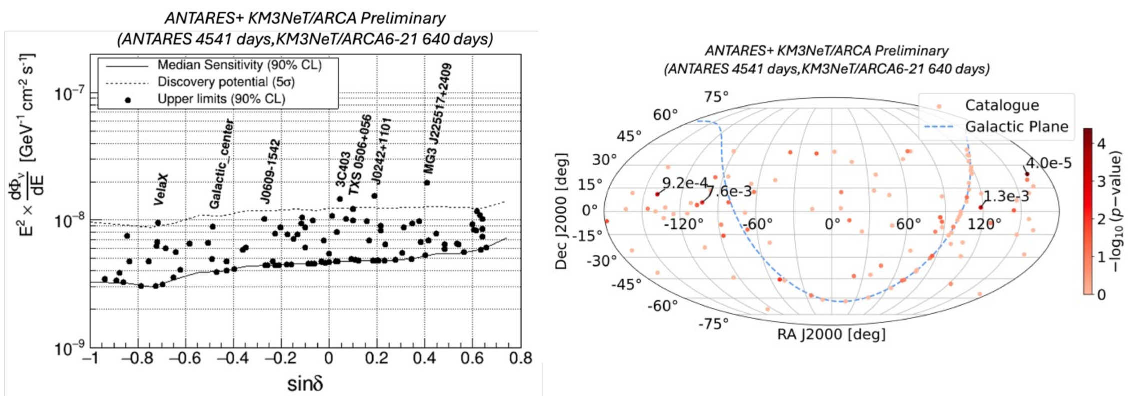


**Figure 3:** Sensitivity and 90% CL upper limits on the fluxes for some 100 potential neutrino sources considered (left), and the sky distribution of the sources with the lowest p-values (right).

detected by VLBI, and the most promising candidates previously investigated by IceCube.

The compatibility of the data with a point-like or extended source hypothesis is quantified by comparing multidimensional histograms of reconstructed event parameters. The used parameters are detector- and sample-dependent, but typically include distance to the considered source, and energy. ANTARES contributes most significantly to the joint analyses; combining with KM3NeT/ARCA the performance improves by 20% with respect to the ANTARES standalone analysis. After taking into account trial factors, no significant excess over background is observed. The results for the considered sources are shown in Fig. 3 in the form of an upper limit on the flux (left), and as a skymap with p-values (right). The source with the lowest p-value in this analysis is MG3J225517+2409 (as in the ANTARES stand-alone analysis) with a pre-trial p-value of $4.0 \cdot 10^{-5}$.

With the ARCA6-21 data set, KM3NeT has performed further (stacking) analyses of individual potential neutrino emitters, including BL-Lacs, Seyfert Hot-Coronae sources, ultra-luminous infrared galaxies, GRBs, FRBs, microquasars and GW events [12]. No excesses over background were observed.

## 4. The KM3-230213A Ultra-high-energy event

On February 13, 2023, at 01:16:47 UTC, KM3NeT/ARCA recorded a remarkable event [13]. At that time, ARCA was operational with 21 detection units, with in total about 10500 active PMTs. In the remarkable event, 3672 of these PMTs (35%) observed at least one hit that participated in the trigger of this event, with a total of 28086 hits. The timing distribution of the hits is consistent with that expected from a near horizontal track of a muon that traversed the full detector at a speed close to the speed of light. The quality of the fit to the trajectory is excellent, with very good timing residuals on the PMT hits. The energy of the muon at the point of entering the detector is estimated from the number of PMTs hit to be $120^{+110}_{-60}$ PeV, with a 90% CL interval of 35 – 380 PeV; the uncertainty is dominated by uncertainties in the transparency of the sea water.

The near-horizontal and west-to-east direction of the track implies that an incoming particle must have traversed 300 km water-equivalent of material, which is extremely unlikely for a muon at any energy. The muon is likely to have originated relatively close to the detector, from an interaction of an incoming muon neutrino with the sea water or rock. The energy of that neutrino can only be estimated making an assumption on the spectral index of the energy spectrum; under the assumption of an $E^{-2}$ spectrum the neutrino energy is estimated to be $220^{+570}_{-110}$ PeV (68% CL interval). This makes this event, named KM3-230213A, the most energetic neutrino observed to date.

The equatorial coordinates (J2000) and the detection time of KM3-230213A are: RA = 94.3°, dec. = −7.8°, MJD = 59988.0533299. The different containment radii are: R(68%) = 1.5°, and R(90%) = 2.2°. These radii are much larger than the intrinsic resolution of the detector, and are dominated by the current systematic uncertainty on the absolute orientation of the detector, which is in turn dominated by the uncertainty on the uncalibrated positions of the acoustic emitters on the sea floor. In the summer of 2025, a sea campaign was carried out to calibrate these emitter positions, which should lead to an updated estimate of the coordinates of KM3-230213A and their uncertainties.

The significance of KM3-230213A in the global neutrino landscape was considered [14]. Fig. 4 shows the energy and flux of KM3-230213A as estimated by KM3NeT, as well as the result

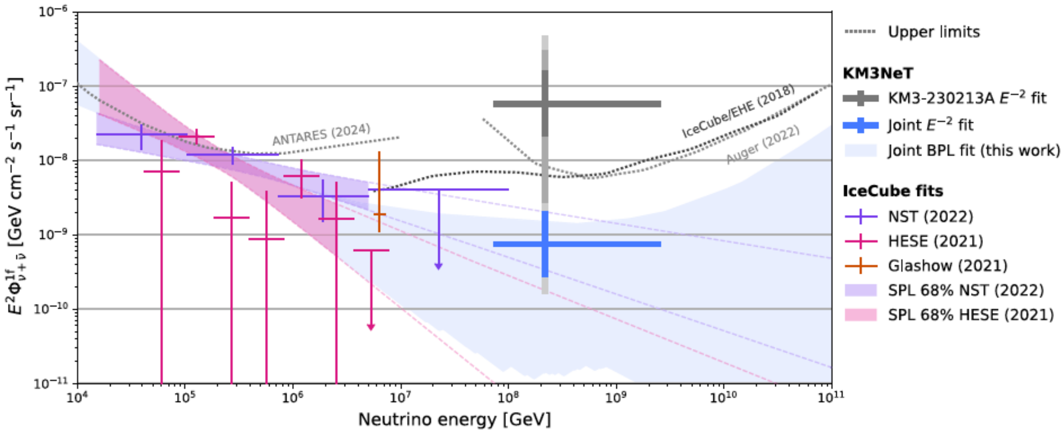


**Figure 4:** Per-flavor energy-squared diffuse astrophysical neutrino flux, assuming flavor equipartition. Measurements based on the KM3-230213A observation are compared with existing limits at ultrahigh energies and measurements and fits at lower energies. The KM3NeT-only measurement and the joint flux including also IC-EHE and Auger non-observations are shown with the gray and blue crosses, respectively.

of adding the event as input to a global fit using also high-energy events observed by IceCube and limits of Auger. The flux estimated using KM3-230213A alone exceeds IceCube and Auger limits in this region; a combined analysis with IceCube and Auger indicates a $1.8 - 2.7\sigma$ tension, depending on the method used. The observation of KM3-230213A does not provide enough statistical discrimination between a single power law or a broken power law description of the flux.

Around the estimated direction, no obvious candidates for sources were observed [13]. The possible cosmogenic origin (from the interactions of ultra-high-energy cosmic rays with ambient photon and matter fields) of the event was also considered by KM3NeT [15]. The flux level required by KM3-230213A is, however, in tension with the standard cosmogenic neutrino predictions. The probability for cosmogenic interpretation can be enhanced by extending the integration of the equivalent cosmogenic neutrino flux up to a redshift of $z_{max} = 6$ and considering either source evolution effects or the presence of a subdominant independent proton component in the ultra-high-energy cosmic-ray flux. However, at this time, the origin of the event cannot be unambiguously determined.

## 5. Multimessenger activities

Within KM3NeT, an automated system continuously monitors and analyses real-time external alerts originating from various cosmic messengers, including neutrinos, gravitational waves, and electromagnetic signals across the whole spectrum [16]. A preliminary set of calibrations is used for this task. Events are reconstructed through both track-like and cascade-like reconstruction algorithms, introducing a median delay time less than 7 seconds, monitored and calculated over the whole period from June 2023 to January 2025; the processed alerts are shown in Fig. 5.

Given the wide variability in the characteristics of the alerts being analysed, for instance sky localizations can range from just a few to several hundred square degrees, it is essential to determine the optimal selection strategy for each individual alert. To address this, a dynamic optimization

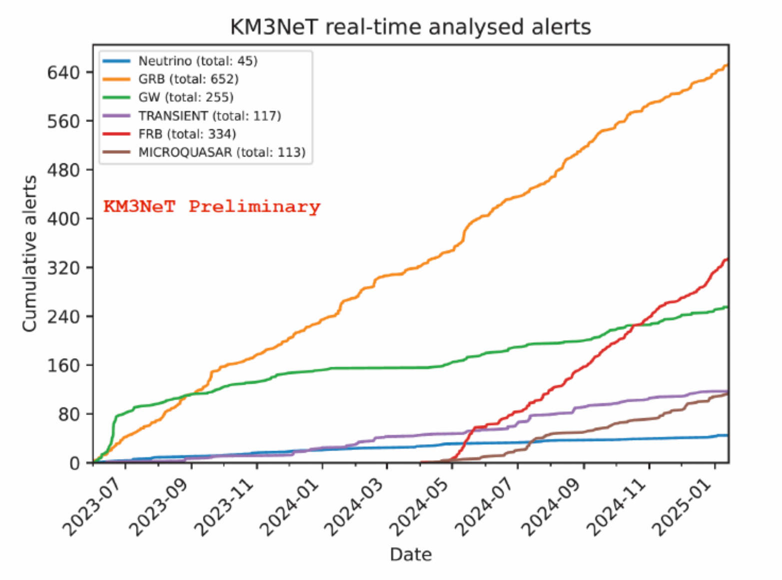


**Figure 5:** External alerts processed by KM3NeT between June 2023 and January 2025.

procedure has been implemented. No significant neutrino counterparts have been identified in any of the follow-up analyses. The lowest p-value for any external gravitational wave alert was obtained with the alert S230927be, for which the pre-trial significance is around 2.3 $\sigma$. In the analysis of the IceCube gold alert IC231027A, KM3NeT observed one event with KM3NeT/ORCA for an expected background of $\sim$ 0.07 events, leading to a pre-trial significance of 1.7 $\sigma$. Given the number of followed alerts, these upper fluctuations are compatible with background.

KM3NeT is also developing an alert system to share significant detections with the multi-messenger astronomy community [17]. KM3NeT is already contributing alerts for possible core-collapse supernovae to SNEWS 2.0, and is building a system to inform the astronomy community, with a O(1 min) latency target, of potential neutrino detections above GeV energies. To fulfill this goal, the KM3NeT/ARCA and KM3NeT/ORCA data are sent to shore, where the Real-Time Analysis (RTA) framework performs an online reconstruction and classification, at O(10 Hz). The first strategy to select interesting alerts is to identify neutrino candidates based on their level of exceptionality, biased towards high energy. Another way to increase the likelihood that some events may be of astrophysical origin is to look at events coming from close-by sky localizations within a given time window. KM3NeT alerts will be sent as Notices through the NASA's GCN broker via their Kafka server in both JSON and VOEvent formats. The JSON KM3NeT Notice format is based on the *Common Neutrino Format*, developed in collaboration with IceCube. KM3NeT aims to have the system operational by early 2026 and is expected to send at most a few alerts per month.

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