# Offline performance studies and first real-time results on Core-Collapse Supernova neutrino searches with the KM3NeT neutrino detectors

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# Offline performance studies and first real-time results on Core-Collapse Supernova neutrino searches with the KM3NeT neutrino detectors

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The KM3NeT collaboration has started the construction of the ARCA and ORCA neutrino telescopes in the Mediterranean Sea. With the most recent data from the deployed lines, the detection technique for Core-Collapse Supernova neutrino bursts has been refined. The real time trigger was implemented and verified to be robust and effective. The study of the resolution to fast-time variation in the neutrino light-curve is also presented exploiting two different methods, with estimates from real data and state-of-the-art Core-Collapse Supernova simulations. Finally, the mean energy of the incoming neutrinos can be estimated through the correlation between the number of photo-multipliers detecting light in coincidence and the mean energy of the incoming neutrinos.

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## 1. Introduction

The KM3NeT neutrino detectors ORCA and ARCA (Oscillation & Astroparticle Research with Cosmics in the Abyss) are under construction at two underwater sites in the Mediterranean sea. ORCA is located off the French coast (Toulon), and ARCA off the Italian coast (Capo Passero). ORCA is aimed at the determination of the neutrino mass ordering, exploiting a densely instrumented detector with sensitivity at the GeV scale. ARCA is dedicated to the search for high energy (TeV-PeV) astrophysical neutrino sources, using a large $km^3$-scale instrumented volume [1].

The core element of the KM3NeT detectors is the digital optical module (DOM) featuring 31 directional photomultiplier tubes (PMTs) in a spherical glass sphere [2]. DOMs are connected in groups of 18 to form a vertical line called detection unit (DU). ORCA will have 115 lines and ARCA will consist of an array of 230 strings. With the multi-PMT optical module technology and a large instrumented volume, KM3NeT will be able to detect the prompt MeV neutrino emission from a Galactic Core-Collapse Supernova CCSN as an overall increase on the DOM counting rate.

The main interaction channel of MeV neutrinos in water is the Inverse Beta Decay (IBD). Elastic Scattering and interactions of neutrinos with oxygen atoms also provide a small contribution. The outgoing electron or positron induces the production of Cherenkov light that can be detected by the PMTs.

Two different techniques are assessed. First, the multi-PMT DOMs are exploited to obtain the best sensitivity to the signal detection and to the resolution of the mean energy neutrino spectrum. Second, the large event statistics provided by the large instrumented volume is exploited to study the time-dependence of the neutrino emission (light-curve).

## 2. Detector response to Core-Collapse Supernova neutrinos: models and simulation

Three state-of-the art 3D simulations from the MPA Garching group have been considered in this work [3, 4]. Each of them simulates the accretion phase of the CCSN for a CCSN stellar progenitor of 27 $M_\odot$, 20 $M_\odot$ and 11 $M_\odot$ respectively. These simulations provide the time dependent CCSN neutrino spectrum, which follows a quasi-thermal distribution that depends on the average neutrino energy $\langle E_\nu \rangle (t)$, the neutrino luminosity $L_\nu(t)$ and the spectral pinching shape parameter $\alpha(t)$. They are limited to the accretion phase, with corresponding duration of 550 ms (27 $M_\odot$) and 350 ms (20 $M_\odot$ and 11 $M_\odot$). The CCSN neutrino interaction rate in sea water are computed from the spectrum and are then used to estimate the expected detection rate through a Monte Carlo simulation implemented in GEANT4.

## 3. Background measurements and rejection

Three relevant sources of background are of interest for this study: bioluminescence, radioactive decays in sea water (mostly $^{40}K$) and atmospheric muons. Background rates have been estimated from the data of the first ORCA and ARCA detection lines deployed in the sea. Coincidences at the few nanosecond-scale between the different PMTs of a DOM are a signature of a multi-photon emission typical of Cherenkov radiation. The number of PMTs in a DOM detecting a photon within a time window of 10 ns is later on referred to as multiplicity (M).

Radioactive decays in sea water and atmospheric muons are the dominant contributions to the multiplicity spectrum in the ranges $M \leq 5$ and $M \geq 8$, respectively. The contribution of coincidences from uncorrelated photons produced by bioluminescence or radioactive decays becomes negligible above $M = 3$.

CCSN neutrino interactions in the instrumented volume result in an increase of the counting rates of individual PMTs as well as at the various multiplicity levels. Simulations are used to optimise the multiplicity selection in order to discriminate the CCSN neutrino signal from background. The coincidence rates measured for the first two ARCA DUs (ARCA2) and the first ORCA DU (ORCA1) [5] are shown in Fig. 1 (left). Selecting events satisfying the criterion $6 \leq M \leq 10$ provides the best signal-to-noise ratio.

In the chosen multiplicity region, the contributions from radioactive decays and atmospheric muons are comparable. Simultaneous detection of $M \geq 4$ events by several DOMs at the microsecond scale can be used to discriminate atmospheric muons since simulations show that low energy CCSN neutrinos are mostly detected on a single DOM. This muon vetoing technique is particularly efficient for the ORCA geometry for which the background can be almost reduced to the residual $^{40}$K contribution. This compensates for the originally higher muon rate given by the shallower depth of ORCA. Typical background rates after the muon filtering are shown in in Fig. 1 (right).

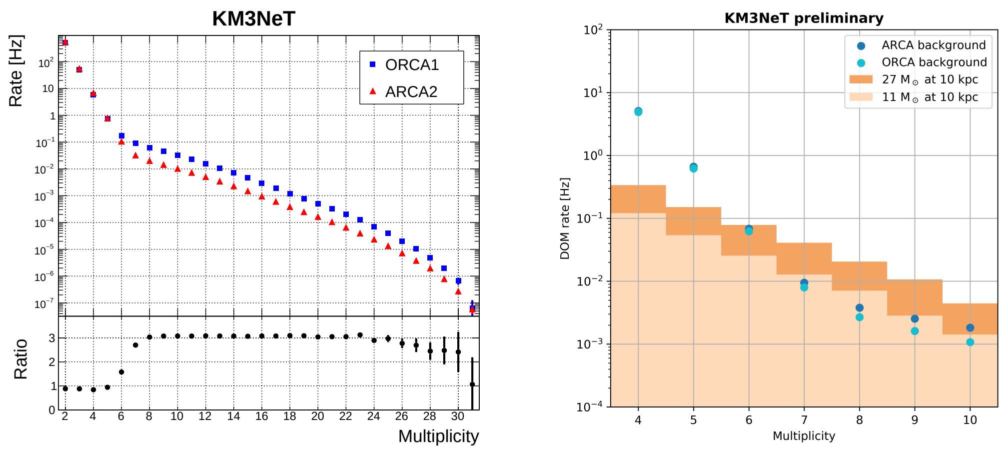


Figure 1: On the left, DOM coincidence rates as a function of the multiplicity measured for the ORCA1 and ARCA2 detectors [5]. On the right, estimated DOM background rates after muon rejection for ARCA and ORCA compared with the signal expectation at 10 kpc for the 27 $M_\odot$ (550 ms window) and the 11 $M_\odot$ (350 ms duration) progenitors.

## 4. Sensitivity estimation

In the following, an *event* is defined as a coincidence satisfying $6 \leq M \leq 10$ and surviving the muon veto. The number of signal and background events over the duration of the simulated accretion phase is used to compute the significance as a function of the distance to the source ($d$). Given the background rate $\rho_B$ and the time window of duration $\tau$, the significance of an observation $X_d$ is estimated from the p-value:

$$P(X \geq X_d) = \sum_{X=X_d}^{\infty} \mathscr{P}(X, \rho_B \cdot \tau) \tag{4.1}$$

with $\mathscr{P}$ being the Poisson probability of observing $X_d$ events when expecting $\rho_B \cdot \tau$ and $X_d$ being the signal plus background expectation for a CCSN neutrino emission at distance $d$, for a given model.

The expected sensitivities for the two extreme mass progenitor assumptions (11 and 27 $M_\odot$) is shown in Fig. 2 (left) for ORCA, ARCA and the combination of the two detectors. The results for 6 ORCA DUs and 2 ARCA DUs, expected operational by the end of the year, are displayed on Fig. 2 (right).

Combining the two complete KM3NeT detectors, a significance of 5 $\sigma$ is achieved for a CCSN at 25 kpc with a mass of 27 $M_\odot$, ensuring the coverage of the full Galaxy. In the case of the 11 $M_\odot$ progenitor, a significance of 5 $\sigma$ is reached beyond the Galactic Centre with the full ORCA detector alone. With 6 ORCA and 2 ARCA detection strings, the expected performance is a 5 $\sigma$ discovery at 9 and 4 kpc respectively for the more massive progenitor and the lowest mass one. In addition, the muon filter is expected to be more efficient when using inter-line data. As such, the estimated significance should be on the conservative side for the provided models.

The most relevant systematic uncertainties, mainly originating from the loose constraints on the models (flavor conversion [4], different simulation codes [6], neutrino opacities [6], observer direction [8]), have been taken into account, together with the uncertainty on the detector the overall detection efficiency.

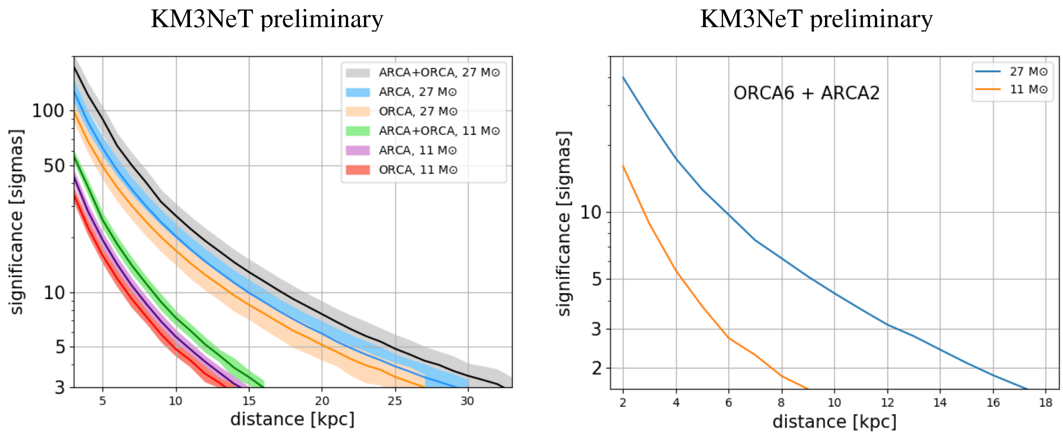


Figure 2: Detection significance of a CCSN neutrino signal as a function of the distance to the source. On the left for ORCA, ARCA and the combination of the two detectors. On the right for the configuration expected late 2019 (6 ORCA DUs and 2 ARCA DUs).

## 5. Real-time processing and CCSN alerts

An online infrastructre is being developed to handle the triggering of real-time alerts and the participation in the SNEWS network [7].

KM3NeT implements an *all-data-to-shore* DAQ design. All hit information is sent to shore, where the data streams are assembled in a computer farm. A dedicated data stream containing all coincidences above multiplicity $M \geq 4$ is continuously acquired for online monitoring and permanent storage. The same data stream is simultaneously analysed in real time for the purpose of alert generation. A buffer for the lower multiplicity coincidence data is foreseen in order to store the maximum amount of useful raw data in case an alert is either received or self-generated.

The structure of the processing chain is outlined in Fig. 3. The SN processing pipeline shares a common infrastructure with the online event reconstruction for high-energy neutrino events.

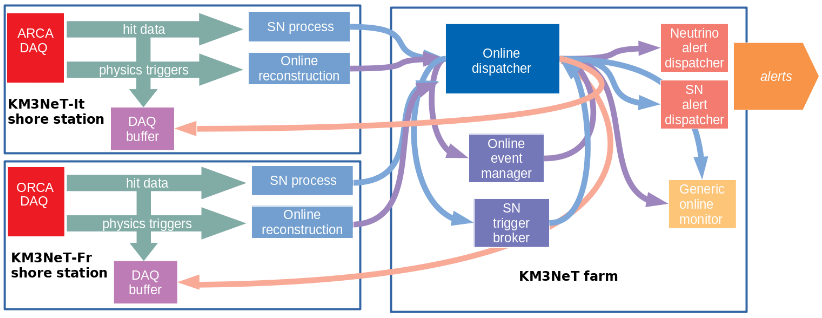


Figure 3: Functional diagram of the KM3NeT DAQ system and online framework outlining the information exchange between the two shore stations and the central farm dedicated to the real-time processing applications.

| **ARCA 2 DU + ORCA 6 DU** | | |
|---|---|---|
| Threshold | 11 $M_\odot$ | 27 $M_\odot$ |
| 1 / 8 days | 4.5 kpc | 8.5 kpc |

| **ARCA 230 DU + ORCA 115 DU** | | |
|---|---|---|
| Threshold | 11 $M_\odot$ | 27 $M_\odot$ |
| 1 / 14 days | 12.5 kpc | 23 kpc |

Table 1: Online triggering capabilities for the KM3NeT detectors in the expected near-future (left) and full (right) configurations for the two progenitors considered. False alert thresholds have been chosen according respectively to the current and possible future SNEWS requirements.

The offline analysis approach is adapted to perform a real-time search. The *trigger level* $X$, defined as the number of DOMs detecting a coincidence passing the selection, is evaluated over a time window of duration $\tau = 400\,\text{ms}$. The time window is sliding with an update frequency $f_s = 10\,\text{Hz}$. The p-value in equation 4.1 can be therefore converted into a false trigger rate. Considering $f_s$ as a *trial rate*:

$$R_B = f_s \cdot P(X \geq X_d) \tag{5.1}$$

For a fixed $R_B$ threshold, this relation allows to estimate the maximum progenitor distance $d$ for which the detector is able to trigger on the CCSN signal. For the purpose of triggering, ARCA and ORCA will act as a single entity. The trigger level is evaluated synchronously for the two detectors, and a combined test statistic is produced. The KM3NeT alert capabilities for *end-of-2019* and complete KM3NeT configurations, respectively for the current and future hypothetical SNEWS requirements are summarised in table 1.

The use of the number of DOMs (instead of the number of selected coincidences) grants additional robustness to the trigger algorithm. For a sufficiently large detector, the background behaviour is well approximated by the Poisson distribution. For smaller detector configurations, the background assumes a binomial distribution.

Preliminary evaluations have been done with regards to the required time to generate a trigger. The current configuration allows for an alert to be produced within 20 seconds from the generation of the corresponding data off-shore, a fast response compared to the current SNEWS latency. Further optimization can be foreseen if beneficial for the network.

## 6. Sensitivity to fast-time variations on the neutrino light-curve

Latest 3D simulations predict anisotropic hydrodynamical instabilities during the CCSN accretion phase, which may play an important role in enhancing the neutrino heating [8, 9]. This analysis focuses on the Standing Accretion Shock Instability (SASI), which could favor the final explosion, explain the observed neutron star kick and could be potentially correlated with gravitational waves emission [11]. This model leaves as a footprint fast time variations in the neutrino light-curve around 200 ms after the core bounce, with a characteristic oscillation frequency [4].

The detected CCSN neutrino light-curve has been computed using a dedicated Monte Carlo simulation. The 27 $M_\odot$ and 20 $M_\odot$ progenitor models from the Garching group have been considered for the neutrino flux, for an observation along the privileged direction of the SASI sloshing.

A dedicated technique is used for a realistic background estimate from the first KM3NeT data, which are upscaled to the full detector size. Coincidences of at least two hits on different PMTs of the same DOM within 5 ns are selected. This allows to reduce the contribution of uncorrelated background (bioluminescence and $^{40}$K decays) while keeping a sufficiently large signal statistics to allow for a time-dependent study. Following [10], a Fourier analysis has been used to recover the SASI frequency, expected at $\sim 80\,$Hz for the models considered here.

Two different approaches for the significance estimation are proposed. The first method searches for a peak in the power spectrum at any frequency ($f$). This approach would be sensitive to any periodic pattern in the neutrino light curve. The second method uses the *a priori* knowledge of the SASI frequency, which allows to increase the significance. In this case, an energy excess is searched for, integrating the power spectrum over the range $f \in [60, 100]$ Hz.

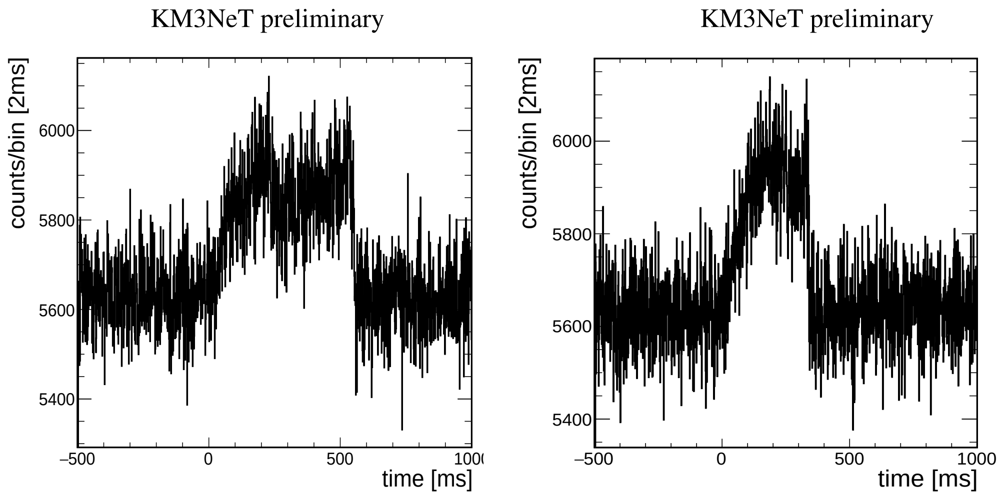


Figure 4: The detected light-curve at the full ARCA detector for the 20$M_\odot$ progenitor (right) and the 27 $M_\odot$ progenitor (left), for a CCSN exploding at 5 kpc.

In Fig. 4, the simulated light-curves including background and signal at 5 kpc for two different progenitors are shown. Fig. 5 shows the simulated power spectrum obtained for each stellar progenitor after applying a Fourier transform to the expected light-curves for the full ARCA detector assuming a distance to the progenitor of 5 kpc. In Fig. 5, the power spectrum in ARCA obtained for each stellar progenitor at 5 kpc after applying the Fourier transform for the light-curves.

| **Progenitor** | **Model independent** | **Model dependent** |
|---|---|---|
| 27 $M_\odot$ | 1 $\sigma$ | 2 $\sigma$ |
| 20 $M_\odot$ | 2.5 $\sigma$ | 3.5 $\sigma$ |

face

Table 2: Sensitivity to the SASI peak with ARCA at 5 kpc using the two approaches described above.

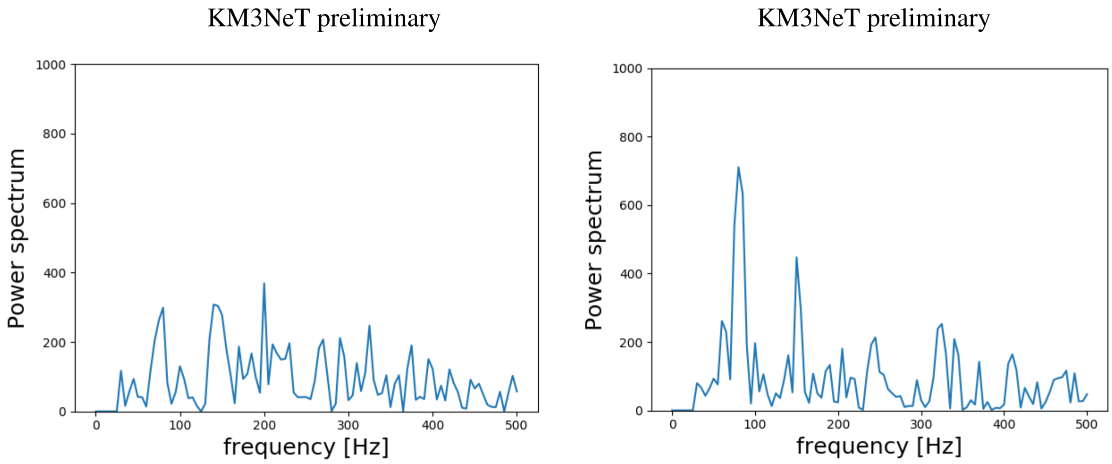


Figure 5: Power spectrum after applying the Fourier Transform to the expected ARCA light-curve, assuming a 27$M_\odot$ progenitor (left) and a 20 $M_\odot$ progenitor (right).

The SASI peak can be seen at the expected frequency ($\sim$ 80 Hz). The probability of obtaining such a peak in the power spectrum for the background-only case is evaluated through pseudo-experiments using the two methods described above. Sensitivity results are summarized in Table 2.

## 7. Constraints on the mean CCSN neutrino energy

In order to evaluate the capability of KM3NeT to resolve the CCSN neutrino mean energy, the simplified model previously used in [12] is considered. The parameter space is investigated, considering a fixed luminosity and assuming equipartition among the 3 flavours and $\nu/\bar{\nu}$. The expected ranges for the pinching shape parameter ($2 \leq \alpha \leq 4$) and the mean neutrino energy ($11\,\mathrm{MeV} \leq \langle E_\nu \rangle \leq 15\,\mathrm{MeV}$) are scanned. The 3 parameters are defined in 2. A neutrino emission over 100 ms is considered.

The multiplicity distribution is exploited to this aim, since higher mean neutrino energy will result in a higher contribution of high multiplicities compared to low multiplicities. The optimized range $3 \leq M \leq 10$ is considered into a 2D $\chi^2$ which is used to fit $\alpha$ and $\langle E_\nu \rangle$.

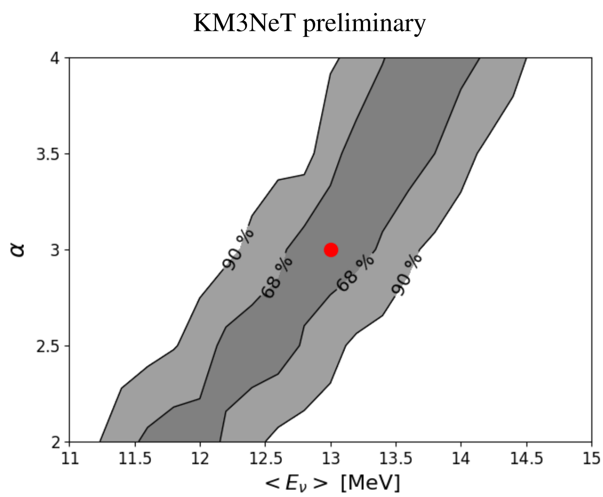


Figure 6: The 90% and 68% CL contours as a function of $\alpha$ and $< E_\nu >$, computed for the full ORCA detector assuming a CCSN signal at 10 kpc with a total luminosity comparable to the 11 $M_\odot$ progenitor ($3 \cdot 10^{53}$ erg/s, from [13]).

The 2D 90% and 68% confidence level (CL) contours are shown in Fig. 6 for ORCA, considering a signal equivalent to the 11 $M_\odot$ luminosity at 10 kpc ($3 \cdot 10^{53}$ erg/s, generally accepted as benchmark value). It shows the potential of the detector to constrain the properties of the time-integrated $\nu$ spectrum. A clear degeneracy between $\alpha$ and $\langle E_\nu \rangle$ is observed. Assuming a prior knowledge of $\alpha$, the uncertainty on the mean energy is between 2 and 3%.

## 8. Conclusions and outlooks

The expected response of the KM3NeT neutrino detectors to core-collapse supernova neutrinos has been studied by means of a complete Monte Carlo simulation and an exhaustive study of the background from the first KM3NeT datasets. The performance for a significant detection and triggering real-time alerts has been evaluated as well as the capabilities to resolve the neutrino spectrum and the light-curve, showing that KM3NeT will contribute to the network of neutrino detectors observing the next Galactic CCSN. Room for improvement using multi-line data analysis allowing for new background reduction strategies should be considered, with new results from 6 ORCA and 2 ARCA lines expected to be deployed on the sea by the end of the year.

## 9. Acknowledgements

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