PROCEEDINGS OF SCIENCE

Neutrinos from core-collapse supernovae using KM3NeT

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The SN1987A core-collapse supernova was the first Extragalactic transient source observed through neutrinos. The detection of the 25 associated neutrinos by the Super-Kamiokande, IMB and Baksan experiments marked the beginning of neutrino astronomy. Since then, neutrino telescopes have not been able to make another observation due to the remoteness and low occurrence of the sources. It is therefore essential to optimise the detection channel of sensitive detectors in case of an upcoming Galactic core-collapse supernova. Neutrino observations would, in particular, provide first-hand information about the core-collapse mechanism as well as the behaviour of particles in dense environments. In this contribution, we discuss how the innovative design of the optical modules in the KM3NeT neutrino experiment would allow for the observation of supernova neutrinos. The sensitivity of KM3NeT to Galactic supernovae is presented and its associated online alert system for multi-messenger studies is described. Finally, the ability of KM3NeT to infer the supernova evolution from the time profile of the associated neutrino emission is discussed.

41st International Conference on High Energy physics - ICHEP2022
6-13 July, 2022
Bologna, Italy

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PoS(ICHEP2022)128

1. Introduction

The historical detection of 25 neutrinos from the SN1987A core-collapse supernova (CCSN) in the underground facilities of the Kamiokande, IMB and Baksan laboratories led to results concerning the properties of neutrinos [1]. It was expected that these observations would also shed light on the heavily debated explosion mechanism of 10-$M_\odot$ stars [1, 2]. A *prompt hydrodynamical explosion* is, under certain conditions, possible, according to simulations. However, if this mechanism fails, an alternative mechanism might take place, which is caused by the roughly 3×10^{53} erg released in the form of neutrinos during the first second of the collapse. In this so-called *delayed explosion scenario*, the stalled shock can be revived by the neutrinos streaming from the core of the star. Observing neutrinos from the next CCSN might resolve this controversy. In addition, the behaviour of neutrinos in dense environments, like the newly formed proto-neutron star and its neutrinosphere, can be studied [3].

KM3NeT is a research infrastructure housing next-generation neutrino telescopes, currently under construction at the bottom of the Mediterranean Sea [4]. It will consist of two water Cherenkov detectors designed for different physical purposes: ORCA (Oscillation Research with Cosmics in the Abyss) and ARCA (Astroparticle Research with Cosmics in the Abyss). They will be composed of one and two building blocks, respectively, where each building block will comprise 115 *detection units* (DUs). A detection unit is a vertical string-like structure holding 18 *digital optical modules* (DOMs) [5]. With its denser DOM-array (9 m between DOMs and 20 m between DUs for ORCA versus 36 m between DOMs and 90 m between DUs for ARCA), ORCA is designed to detect atmospheric neutrinos in the 1 to 100 GeV energy range for the determination of the neutrino mass ordering. The geometry of ARCA is optimised for the study of cosmic neutrinos in the TeV-PeV energy range. CCSN neutrinos have a mean energy around only 10 to 20 MeV and, therefore, cannot be tracked individually by the KM3NeT detector. However, it is possible to use the particular structure of the DOMs to detect the arriving supernova neutrino burst.

2. Detection of CCSN neutrinos in KM3NeT

Each DOM in the KM3NeT detector is a transparent 17-inch diameter glass sphere containing 31 3-inch photomultiplier tubes (PMTs) [6], with an almost uniform angular coverage. These PMTs detect the Cherenkov radiation induced by relativistic charged particles crossing the detector volume. The two main sources of background are atmospheric muons and radioactive decays of ^{40}K present in the seawater. The background from atmospheric muons can be reduced by removing the DOMs associated with muon triggers. The expected number of background events in a building block after this muon filtering is shown in figure 1 (left) as a function of *multiplicity*. Multiplicity is defined as the number of PMTs hit in a coincidence occurring in a 10 ns window. Figure 1 (left) also shows the expected signal from three different supernova models. Thus, the detection of CCSN neutrinos relies on the observation of a rate of coincidences in single DOMs in excess over the expected background taking into account all the DOMs in the detector, i.e., ORCA and ARCA together.

The multiplicity distribution is computed in [7] for a 500 ms window in order to cover a typical accretion phase of a CCSN [2]. It becomes evident that for intermediate multiplicities a clear excess of signal events above the background will be present. For all possible multiplicity ranges and the supernova models considered in figure 1, the maximal distance to the supernova for which a 5σ discovery is possible, was calculated [7]. This analysis, together with considerations that ensure a statistically significant analysis, yields for both detectors the $7-11$ multiplicity range as the optimal one.

Adopting the $7-11$ multiplicity range for both detectors, a KM3NeT combined sensitivity is calculated as a weighted linear combination of the ARCA and ORCA sensitivities [7]. The result, as a function of the distance to the exploding star, is shown in figure 1 (right). Considering current models of the distribution of CCSNe as a function of their distance to Earth and their progenitor mass, this means that more than 95% of the Galactic CCSNe can be detected with KM3NeT. In particular, for the case of the heaviest progenitor considered in this study, the sensitivity for a discovery extends beyond the Large Magellanic Cloud.

3. Time profile of the neutrino light curve

In the event of a high-significance detection for a close-by or large-mass progenitor, the large statistics collected at KM3NeT would make an in-depth study of the neutrino time profile possible.

3.1 Detection of the standing accretion shock instability

With the first three-dimensional simulations of CCSNe [8], it was revealed that small perturbations can be developed in the accretion shock. These can result in large-scale periodic back and forth sloshing motions, called the *standing accretion shock instability* (SASI). This phenomenon would modulate the accretion flow to the neutron star and the associated neutrino emission. Furthermore, it could favour the explosion mechanism [9]. Thus, observing the SASI in the neutrino light curve of the next CCSN would help understand its role in the explosion process.

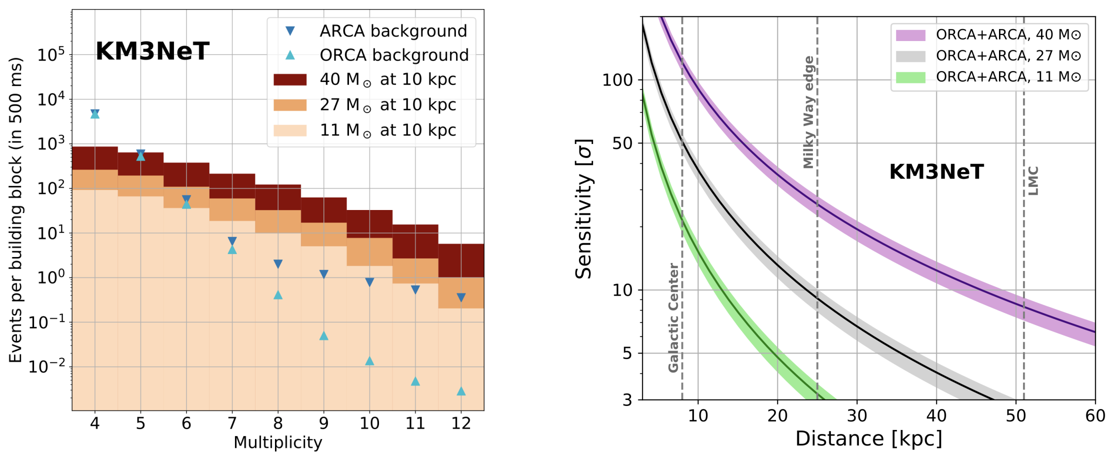

Figure 1: Left: Expected number of events in a building block as a function of multiplicity in a 500 ms window. The blue markers show the values for the background expected at ORCA (light blue) and ARCA (dark blue). The expected signal from three different supernova models (see legend) is represented with coloured bars in orange tones. Right: KM3NeT detection sensitivity as a function of the distance to the exploding star for the three models previously considered. Both figures are taken from Ref. [7].

Figure 2 (left) shows the expected neutrino light curve for one of the progenitors studied in Ref. [7]. Here, the expected background is added to the simulated neutrino signal expected for a supernova emerging from a 20 $M_\odot$ progenitor and located at 5 kpc from Earth. The background due to coincidences caused by the radioactive elements in the water or in the material of the DOM is $\sim$ 500 Hz per DOM. Furthermore, the rate of random coincidences is close to 225 Hz per DOM. A spectral analysis using a fast Fourier transform is performed on the final curve [7]. The power spectral densities obtained for three pseudo-experiments are shown in figure 2 (right). For these particular conditions, a 3σ sensitivity to the SASI-signature is reached [11].

3.2 Arrival time of the CCSN neutrino signal

Neutrinos from a CCSN will arrive up to several hours before the event becomes visible to electromagnetic observatories. A precise computation of the arrival time of the signal by many neutrino observatories, would allow for a localisation of the source via triangulation [10]. With this information, other observatories could be oriented in this direction.

In Ref. [7], a method to extract the arrival time of the burst T_0 from the observed time profile of the signal is presented. First, a time range for the fit is chosen so as to include a background region to ensure the stability of the fit. At the same time, the region beyond the accretion peak is avoided. A first estimation of T_0 is obtained by scanning the time interval, searching for a 2.5σ excess above the background. Then, an exponential fit is performed to the signal edge, using the time range and starting value of T_0 previously calculated. An example of this method is shown in figure 3 for the scenario of a 20 $M_\odot$ progenitor located at a distance of 5 kpc (see section 3.1). For this particular case, an average time resolution of $\sim$ 3 ms is achieved.

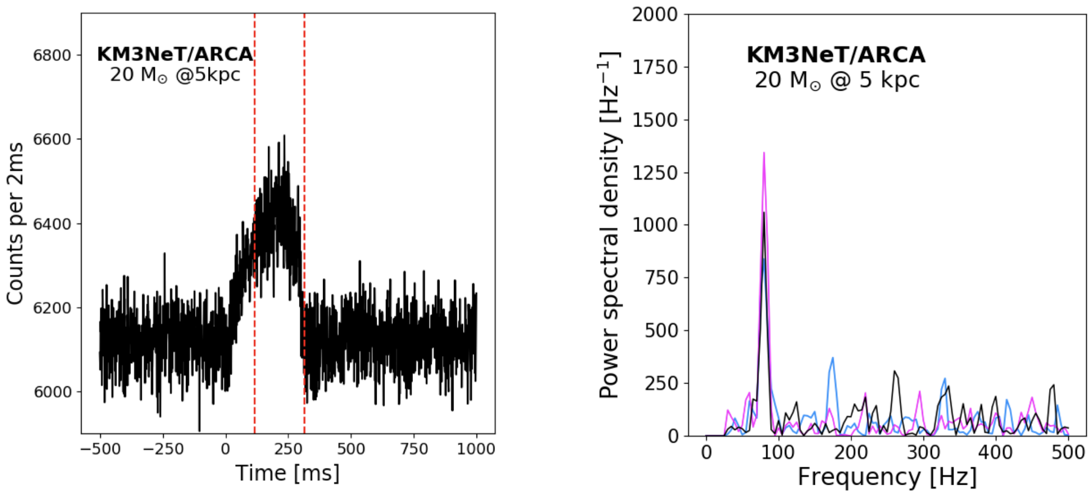

Figure 2: Left: Expected neutrino light curve for a 20 $M_\odot$ progenitor located at 5 kpc from Earth, including background. Right: Power spectral densities obtained from three simulated light curves. One of them corresponds to the light curve shown in the figure on the left. Both figures are taken from Ref. [7].

4. Real-time Multi-Messenger Analysis Framework for KM3NeT

The real-time analysis system of KM3NeT integrates, since mid-2019, an analysis pipeline to search for a CCSN signal based on the procedure described in section 2 [11]. A detection significance of the combined ARCA and ORCA signals and the corresponding false alarm rate (FAR) are computed to produce internal alerts (see figure 4, blue boxes). If the FAR is below one per day or below one every eight days, an alert is sent to the Supernova Neutrino Early Warning System (SNEWS, [12]) for testing or alerting purposes, respectively. With a latency of about 20 s, KM3NeT's current configuration (19 DUs in ARCA and 10 DUs in ORCA) is capable of informing about a significant detection for a supernova happening within a radius of $\sim$ 10 kpc. The light curve data together with the identified arrival time of the neutrino burst T_0, as described in section 3.2, can be delivered as well, which is crucial for the localisation of the source.

For the follow-up of external multi-messenger alerts, KM3NeT relies on its analysis strategy. For this purpose, the output of the real-time analysis pipeline is stored. The follow-up is performed to the stored data in a similar fashion as in the real-time analysis. This analysis has also been used to search for neutrino counterparts in gravitational events sent by the LIGO-VIRGO Collaboration during the O3 run [11]. In particular, a follow-up of the gravitational wave S200114f was performed, but no signal was found and constraints on the presence of a CCSN were set.

5. Conclusions

The present KM3NeT CCSN analysis framework already allows for supernovae detection up to a horizon reaching the Galactic Centre. In the case of a high-significance event, the time profile of the light curve and the neutrino arrival time can also be estimated. A real-time multi-messenger analysis framework has been established to share high-significance events with the multi-messenger community. Moreover, external alerts received via dedicated channels can be followed up with a search in the stored data, allowing for a fast determination of the significance or upper limits in the absence of a signal.

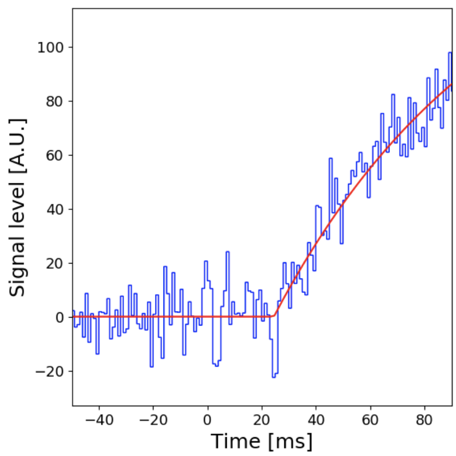

Figure 3: Time profile of the signal in ARCA for a 20 $M_\odot$ progenitor located at a distance of 5 kpc, together with the fit used to extract the arrival time of the burst T_0. This figure is taken from Ref. [7].

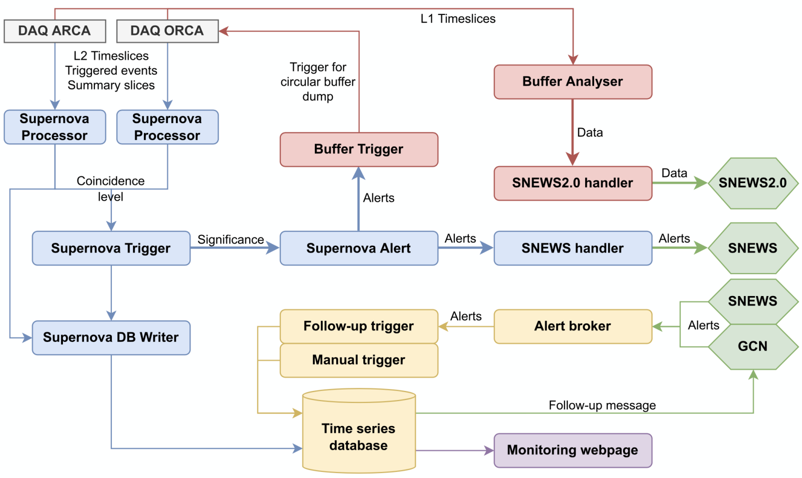

Figure 4: Outline of the implementation of the KM3NeT real-time core-collapse supernova analysis framework with neutrinos. This figure is from [13].

Acknowledgments

This work is supported by LabEx UnivEarthS (ANR-10-LABX-0023 and ANR-18-IDEX-0001).

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