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Neutrinos from core-collapse supernovae at KM3NeT

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Abstract. The SN1987A supernova was the first extragalactic neutrino detection, but no further observations have been made since. Detecting neutrinos from a galactic supernova would provide invaluable information on the supernova mechanism and particle behavior in dense environments, hence, improving the sensitivity of current and upcoming neutrino experiments is crucial. In this contribution, we discuss how the optical module design of the KM3NeT neutrino experiment would allow to observe supernova neutrinos. We present KM3NeT's sensitivity to galactic supernovae and describe its associated online alert system for multi-messenger studies. Finally, we discuss KM3NeT's ability to infer the supernova evolution from the time profile of the associated neutrino emission.

1 Introduction

Thermal neutrinos emitted in the MeV range by supernovae can provide unique information on their explosion phases and can be used to probe neutrino oscillations in dense environments [1]. One way to detect neutrinos from core-collapse supernovae is by using neutrino telescopes, such as KM3NeT which is a large-scale neutrino detector located in the Mediterranean Sea. Although KM3NeT is sensitive to neutrinos of energies range from GeV to PeV. ORCA detector for the detection of neutrinos in the GeV energy range and used to study the neutrino properties and ARCA detector aimed to detect high-energy (TeV to PeV) neutrinos coming from extra-galactic sources [2], KM3NeT can be used for the detection of MeV neutrinos from Supernovae thanks to the structure of its Digital Optical Modules (DOMs). Indeed, these DOMs are composed of multiple photomultipliers (PMTs) allowing a fine-grained analysis of even low-energy signals. We discuss the sensitivity of KM3NeT to CCSN neutrinos and alert system for multi-messenger studies, and its ability to infer supernova evolution from the neutrino emission time profile.

2 Core-collapse Supernovae neutrino detection with KM3NeT

Detecting MeV neutrinos from a CCSN with KM3NeT is a difficult task: these events typically activate only one DOM and are hence extremely difficult to distinguish from ambiant radioactivity and tenuous atmospheric muon signatures. To overcome this challenge, we first removed a large fraction of atmospheric muon signatures by vetoing events associated with triggered multi-DOM patterns. We then devised an observable, the multiplicity, defined as the number of PMTs activated in a given DOM within a 10ns window. The left plot of figure 1 shows the events per a block of 2070 DOMs as a function of the multiplicity for CCSN neutrino signals, and background. In the analysis described in [3], the detection of CCSN neutrinos is based on counting an excess of intermediate multiplicity coincidences over the expected background. The right plot of figure 1 shows the sensitivity as a function of the distance for 3 progenitor models for event multiplicities in the 7-11 range. Taking into account the distribution of CCSNe as a function of the distance to the Earth, more than 95% of the Galactic core-collapse supernovae can be observed by the KM3NeT detectors.

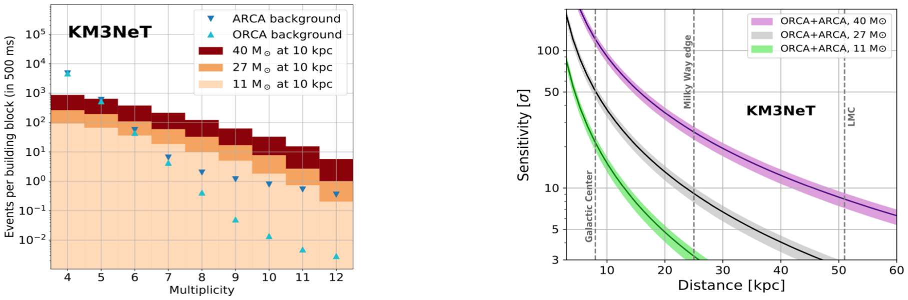

Figure 1. Left: Number of events per building block as a function of the multiplicity for ORCA (light blue) and ARCA (dark blue) for progenitor masses of 11 M⊙ (light orange), 27 M⊙ (orange) and 40 M⊙ (dark orange). Right: KM3NeT detection sensitivity to CCSN neutrinos as a function of the distance to the star for 11 M⊙ (green), 27 M⊙ (gray) and 40 M⊙ progenitors (violet) [3].

3 Supernova characterization

The large event statistics collected by KM3NeT can be exploited to analyse the time profile of CCSN neutrino emission with a potential millisecond time resolution. The analysis of this time profile can provide a tool for model discrimination. In this study, two analyses are considered: the estimation of the neutrino spectrum parameters and the detection of the standing accretion shock instability (SASI).

3.1 Estimation of the neutrino spectrum parameters

CCSN neutrinos have a pinched Fermi-Dirac spectrum characterized by the mean neutrino energy $\langle E \rangle$, the spectral shape parameter α and the signal scale, Λ, which depends on the total energy released and on the distance to the source [3]. In this study, we estimate these parameters by fitting the observed multiplicity distribution, considering the following 3 hypotheses: α free in the full range of expected values 2–4, α in the range $\alpha_{true} \pm 10\%$, and α fixed to the true value. The results of the fit for a given neutrino spectrum are shown on the left panel of figure 2. The left plot of figure 2 shows the signal rate as a function of the mean energy - the signal rate is the number of events scaled by the mean energy and the distance to the source. Results for the uncertainty in the mean neutrino energy are:: ± 0.5 MeV if the spectral index and signal scale are known, below ± 1.5 MeV if the spectral index and signal scale are known within a 10% variation, the sensitivity is lost if the spectral index and signal scale are left free.

3.2 Detection of the Standing accretion shock instability (SASI)

The Standing accretion shock instability (SASI) is a hydrodynamic instability inside the CCSN progenitor which causes fast variations of the neutrino rates give an order of magnitude estimate. Using a model independent approach, which is based on the detection of a significant peak on the power spectrum of the neutrino time profile at any frequency, a 3σ sensitivity to the SASI signature is reached for Galactic progenitors at distances between 3 kpc (27M⊙) and 5 kpc (20 M⊙).

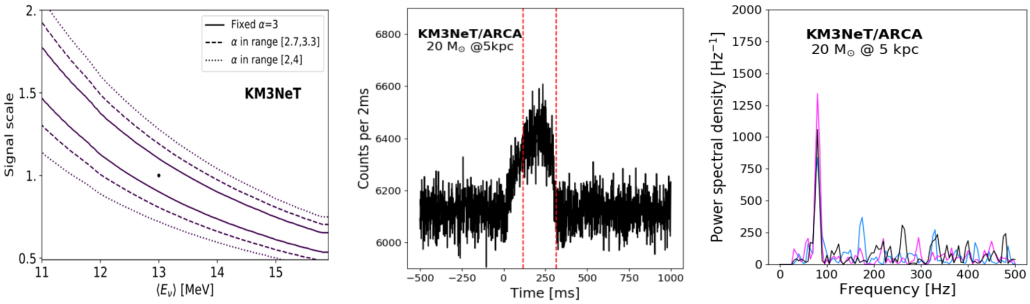

Figure 2. Left: 90% confidence level contours in the signal scale and neutrino energy parameter space. Middle: the neutrino rates in the full ARCA detector for of a 20 M⊙ progenitor at 5 kpc. The dashed red lines correspond to the interval where SASI is searched for [3]. Right: Power spectral densities for ARCA observations. 80 Hz corresponds to the SASI frequency for the 20 M⊙ progenitor at 5 kpc [3].

4 Multi-messenger analysis

4.1 Real-time Multi-Messenger Analysis Framework

Core-collapse supernova neutrinos may be observed hours before the photons, and can be used as an early warning, if a CCSN monitoring is setup. KM3NeT has been active in the framework of the SNEWS network since 2019 [4]. Figure 3 shows the KM3NeT monitoring system for MeV neutrinos.This pipeline is operational and can send alerts with false alarm rate less than one per week to SNEWS. The alert generation latency is less than 20s.

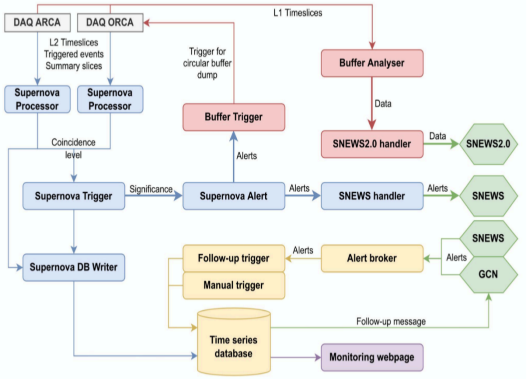

Figure 3. Monitoring the neutrino sky for the next Galactic CCSN with KM3NeT [5].

4.2 Arrival time of the CCSN neutrino signal

The arrival time of the neutrino signal from a core-collapse supernova (CCSN) is expected to occur several hours before the visible light from the explosion reaches Earth. The exact timing of the neutrino signal will depend on the specific properties of the supernova and the distance to the explosion. To extract the arrival time of the first supernova neutrinos, T0, the method described in [3] is used. A moving-average filter with a 23 ms time window is applied. Then, the beginning of the light curve is fitted to an analytical function, with T0 as a parameter. A result of this study is shown on the left plot of figure 4, which presents the

CCSN neutrino time profile of the light curve in ARCA for a 20 $M_\odot$ progenitor at a distance of 5 kpc. The arrival time can be estimated with an uncertainty of 3 ms for a supernova at 5 kpc.

4.3 Multi-detector approach for CCSN triangulation

An analysis that uses data from multiple neutrino telescopes has been performed with the objective of locating the CCSN by estimating the time delays between the light curves recorded by different detectors. The right panel of figure 4 shows the 90% confidence area obtained combining measurements with the combination of Hyper Kamiokande-IceCube-JUNO and KM3NeT/ARCA detectors [6]. This confidence area is 140° ± 20°.

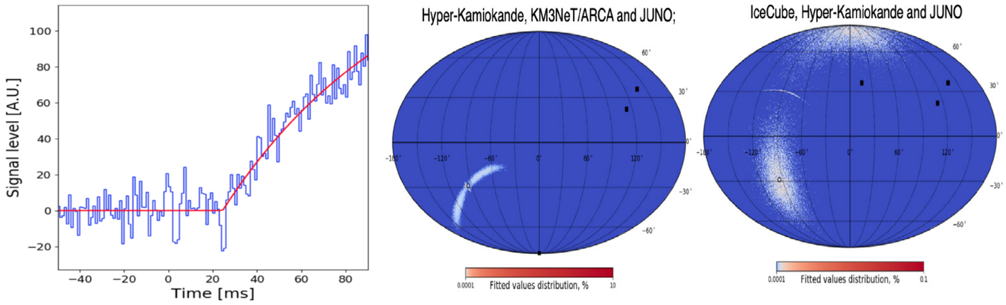

Figure 4. Left: Time profile of the signal in ARCA (2 building blocks) using all coincidences for a 20M progenitor at 5 kpc [3]. Right: Fitted position distributions in equatorial coordinates for a CCSN at the Galactic Centre (black dot) computed using triangulation between different detector combinations [6].

5 Conclusion

In this contribution, KM3NeT's sensitivity to galactic supernovae is presented. More than 95% of the Galactic CCSNe can be detected thanks to the multi-PMT design of the experiment's optical modules. The arrival time of the CCSN neutrino signal can be estimated with an uncertainty of 3 ms for a supernova at 5 kpc. A real-time monitoring pipeline is operational and sending alerts with false alarm rate less than 1/week to SNEWS.

6 Acknowledgments

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