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

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Abstract

→ **Major breakthroughs** in particle physics, astrophysics and nuclear physics from **future observation** of CCSN neutrinos!
→ **Only 1-4 CCSN per century in our Galaxy, we do not want to miss the next one!**
The response of the KM3NeT detectors to CCSN neutrinos has been evaluated by means of a **complete Monte Carlo simulation and an exhaustive study of the background from data**. The detector performances are presented here.

References

[1] I. Tamborra et al., *Phys. Rev. Lett. 111,121104* (2013)
[2] KM3NeT Collaboration, *Journal of Physics G 43 (8)* (2016)
[3] M. Ageron *et al.*, *arXiv:1906.02704* (2019) [physics.ins-det]
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Core-collapse supernovae (CCSN)

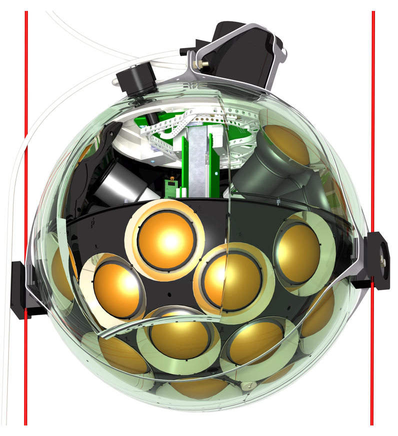
- Explosive phenomena can occur at the end of the life of massive stars. The explosion mechanism is not fully understood, but neutrinos play a fundamental role in it.
- **99% of gravitational energy released through neutrinos** when photons cannot escape the star yet!
- Single observation as of today: Only 24 neutrinos detected from SN1987A.

Full simulation of the CCSN signal

- **State-of-the-art 3D simulations** of three CCSN progenitors (with 27 $M_\odot$, 20 $M_\odot$ and 11 $M_\odot$) provided by the Garching group are used for this study [1]. They only account for the accretion phase, with limited duration.
- Time dependent CCSN neutrino spectrum: quasi-thermal distribution depending on the average neutrino energy $\tilde{E}_\nu$, the neutrino luminosity $L(t)^{\nu}_{SN}$, the spectral pinching shape parameter α, and the SN distance.
- The simulation output is used to compute the CCSN neutrino interaction rate in sea water.
- **Full Monte Carlo simulation of the detector** response has been developed to estimate the expected detection rates.

The KM3NeT neutrino detectors and the supernova neutrino signal

- 3D array of **digital optical modules** (DOM) featuring 31 directional PMTs; a group of 18 DOMs is vertically connected to form a detection unit (DU).
- Two sites under construction: ORCA (France, denser, 115 DU) and ARCA (Italy, larger, 230 DU), **km^3 scale instrumented volume** [2].



CCSN neutrino signal: MeV-energy CCSN neutrinos detected through Cherenkov light mostly produced in inverse beta decay interactions. No possible event reconstruction. **CCSN neutrino signal observed as collective increase in DOM counting rates.**

Background: The number of PMTs in a DOM detecting a hit within 10 ns is defined as *multiplicity*. Main background from ^{40}K decays in seawater dominating at low multiplicities (Fig. 1). Tracks from atmospheric muons produce high multiplicity coincidences on multiple DOMs and **are reduced exploiting their fast (μs) time correlation.**

Background rates have been measured on the **first operational ORCA and ARCA DUs** (Fig. 2).

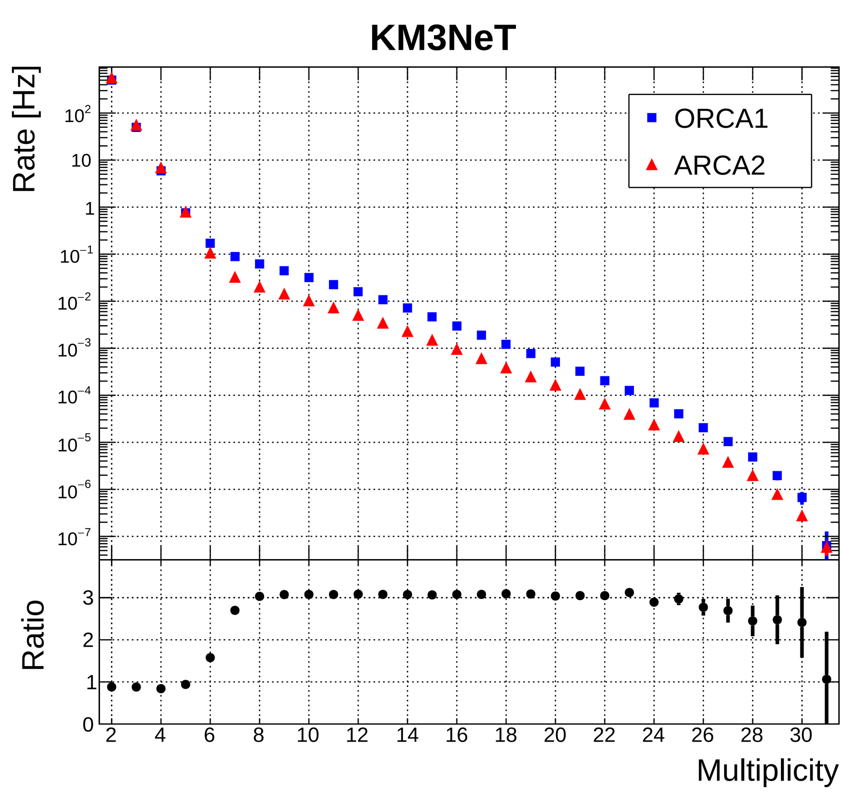


Figure 1: DOM coincidence rates as a function of the multiplicity measured in ORCA and ARCA detectors [3].

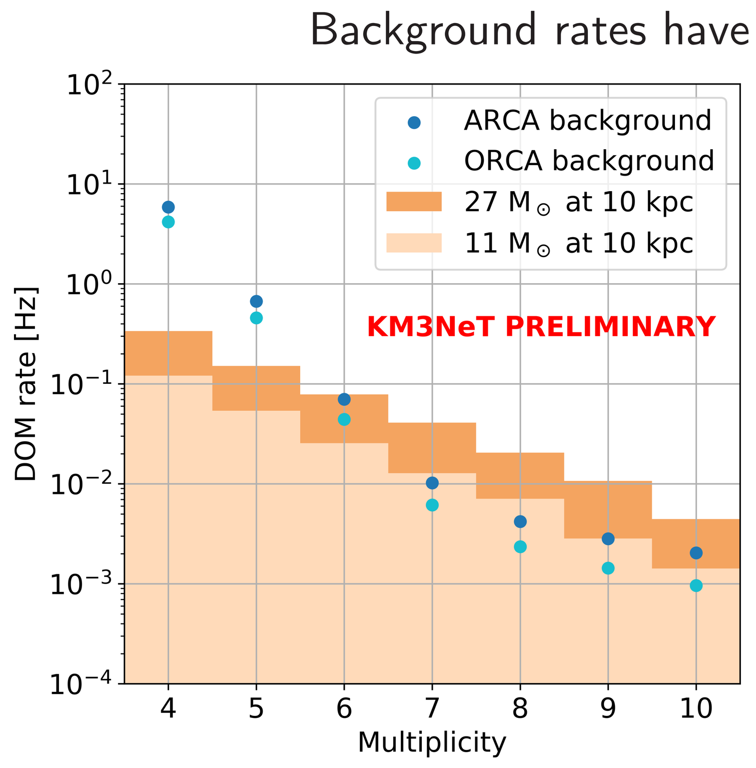


Figure 2: DOM background rates after muon vetoing for ARCA and ORCA compared with the signal expectation at 10 kpc for the 27 $M_\odot$ (550 ms window) and the 11 $M_\odot$ (350 ms duration) progenitors.

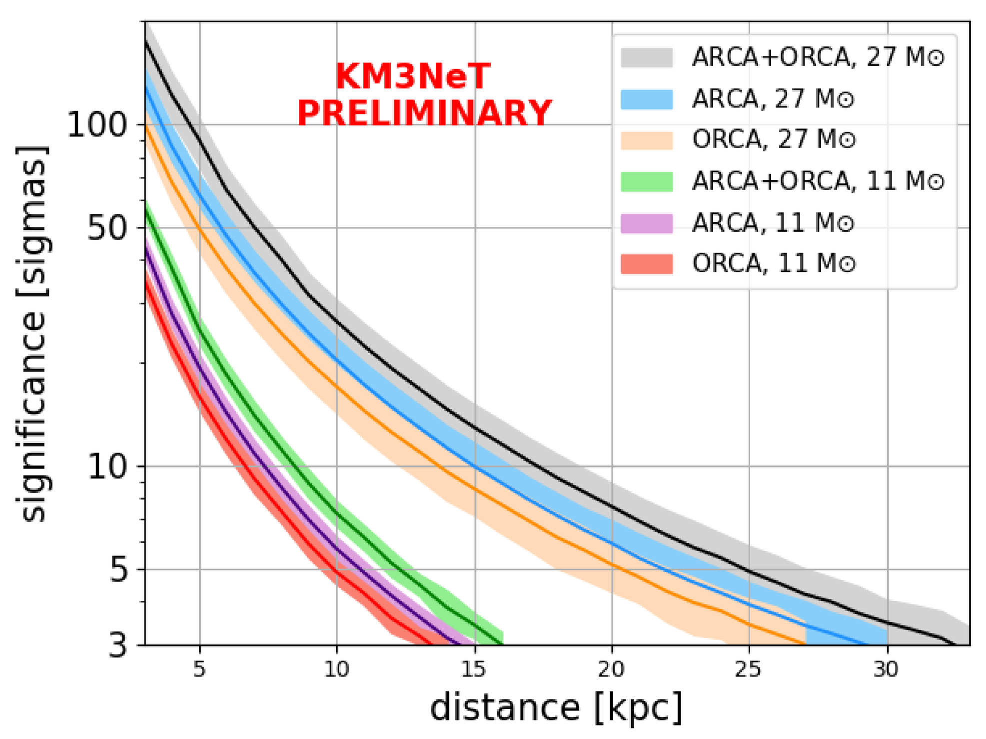


Figure 3: Significance obtained from Poisson p-value for ORCA, ARCA and the combination of both detectors as a function of SN distance.

Constrains on the energy spectrum

- Degeneracy between $\langle E_\nu \rangle$ and α.
- 2-3% energy resolution scanning at fixed α value.
- More energetic neutrinos: more higher M events observed.

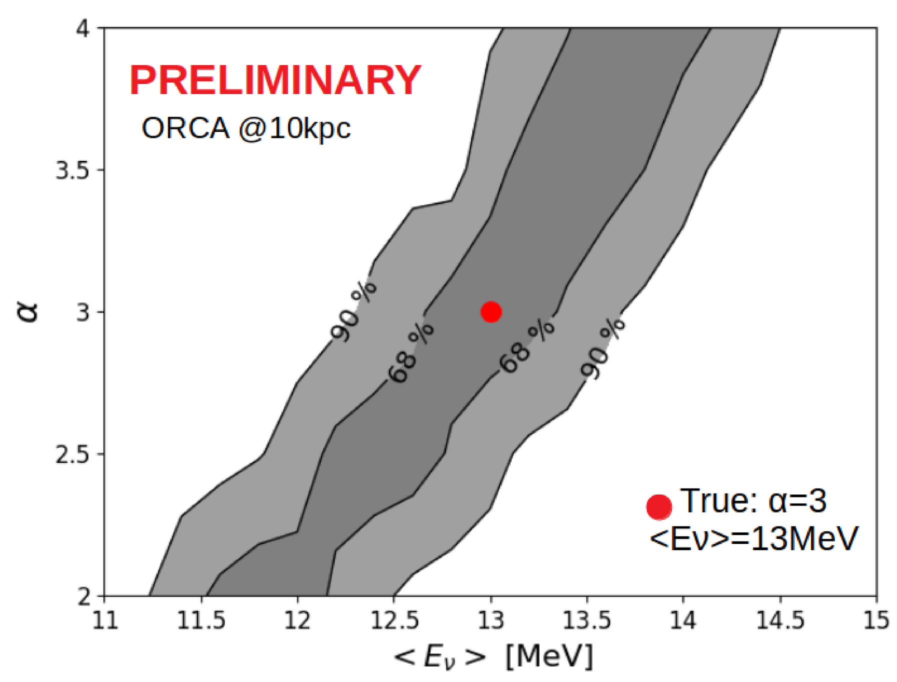
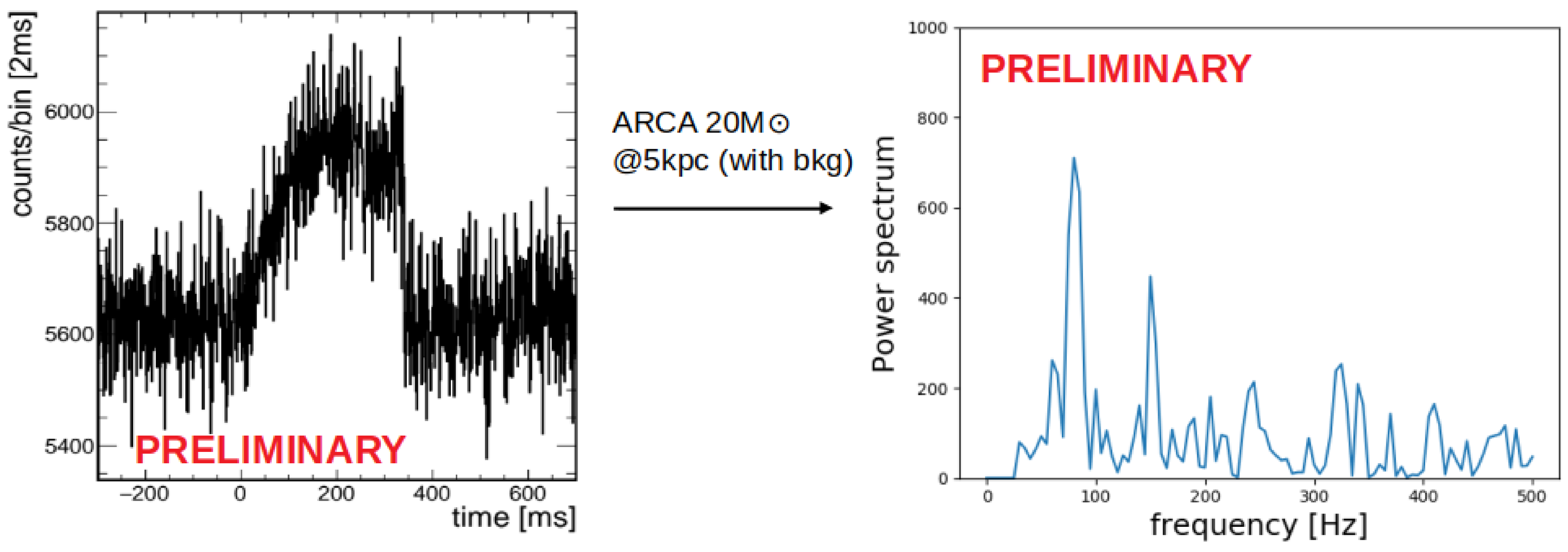


Figure 4: The 90% and 68% CL contours as a function of α and $\langle E_\nu \rangle$, computed for the full ORCA detector assuming a CCSN signal at 10 kpc with a total luminosity comparable to the 11 $M_\odot$ progenitor ($3 \cdot 10^{53}$ erg/s, benchmark value).

Sensitivity to the SASI oscillations in the neutrino light-curve

- Anisotropic hydrodynamical instabilities during CCSN predicted by state-of-the-art 3D simulations are believed to play an important role in the explosion mechanism.
- Standing Accretion Shock Instability (SASI) is believed to enhance the neutrino heating, favoring the explosion.
  → **fast time variations in the neutrino light-curve around 200 ms, with characteristic frequency (80 Hz)**.

- Detected neutrino light-curve computed for two progenitors of 27 $M_\odot$ and 20 $M_\odot$ at 5 kpc (left Fig.).
- Background sampled from real data. Selection of $M \leq 2$ events to reduce bioluminescence.
- Fourier analysis to recover the SASI frequency: 80 Hz predicted for these models [4]. Spectrum in right Fig.
- Significance is estimated through pseudo-experiments using two different approaches, model independent (1) and model dependent (2), shown in Table for full ARCA detector.



Progenitor	Method 1: Search for peak in spectrum	Method 2: Search for power excess around f_{SASI}
27 $M_\odot$	1 σ	2 σ
20 $M_\odot$	2.5 σ	3.5 σ

Real-time alerts and SNEWS

- **Trigger level = number of DOMs** detecting a coincidence in a **defined multiplicity range** over a $n\tau$-wide sliding time window, sampled on a $\tau = 100$ ms time scale.
- Participation in the SNEWS global alert network requires a false alert rate < 1 / 8 days.
- Latency expected below 20 s with combined trigger

Distance horizon for SNEWS alert generation:

ARCA 230DU + ORCA 115 DU			ARCA 2 DU + ORCA 6 DU		
Threshold	11 $M_\odot$	27 $M_\odot$	*Threshold*	11 $M_\odot$	27 $M_\odot$
1 / 14 days	12.5 kpc	23 kpc	1 / 8 days	4.5 kpc	8.5 kpc

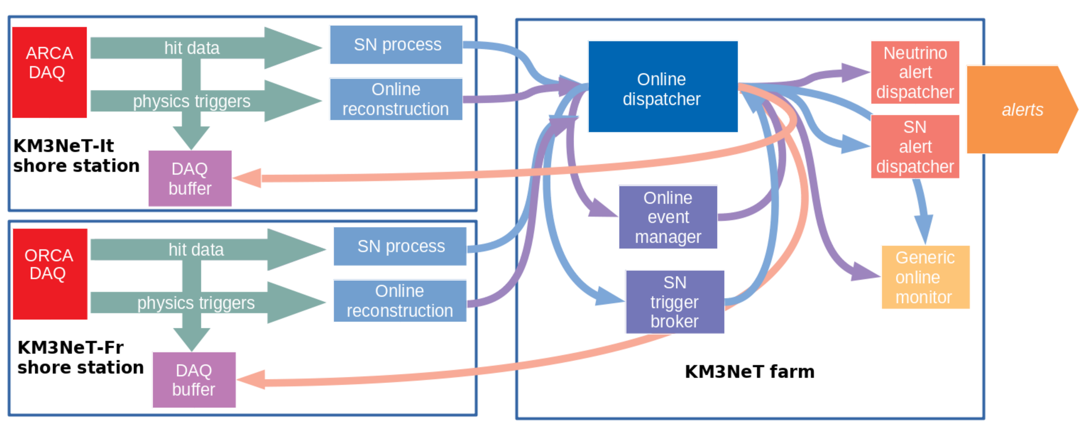


Figure 5: Functional diagram of the KM3NeT DAQ system and online framework outlining the information exchange between the two shore stations and the central farm dedicated to the real-time processing applications.

Conclusions and outlooks

- KM3NeT will contribute to the neutrino detector network observing the next Galactic CCSN explosion;
- Potential to resolve the SN neutrino energy spectrum and light-curve, needed to constrain the models;
- Expected improvements from additional background rejection strategies possible with multi-line data;
- Looking forward for the results with ORCA6 + ARCA2 at the end of this year!

Contacts and acknowledgements

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