Detection of MeV supernova neutrinos with the KM3NeT neutrino telescopes

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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 the star envelope is still optically thick;
- Single observation as of today: Only 24 neutrinos detected from SN1987A;
- **Major breakthroughs** for neutrino physics, nuclear physics and astrophysics from **future observations**.

Full simulation of the CCSN signal

- **State-of-the-art 3D simulations** of the accretion phase of a $27 M_\odot$ and an 11 M⊙ CCSN provided by the Garching group are used for this study *(wwwmpa.mpa-garching.mpg.de/ccsnarchive)*.
- Time dependent CCSN neutrino spectra: 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 by multiplying the flux by the latest cross section estimates:

$$\frac{dR_{int,\kappa}}{dE} = N_\kappa \cdot \sigma_\kappa(E) \cdot \frac{d\Phi}{dE} \; [s^{-1} MeV^{-1}] \qquad \kappa \in \{p, e^-, {}^{16}O\}$$

- **Full Monte Carlo simulation of the detector** response to estimate the expected CCSN detection rates in KM3NeT.

The KM3NeT neutrino detectors and the supernova neutrino signal

- Detector: **Modular design** based on **digital optical modules** (DOM) featuring 31 directional PMTs; a group of 18 DOMs is connected to form a vertical line, an array of 115 lines constitutes a *building block*.
- Two sites under construction: ORCA (France, 1 block, 9m vertical spacing) and ARCA (Italy, 2 blocks, 36m vertical spacing) for an **instrumented volume reaching the km^3 scale**.

Figure 1: A KM3NeT DOM

CCSN neutrino signal: MeV-energy CCSN neutrinos detected through Cherenkov light mostly produced in inverse beta decay interactions: $p + \overline{\nu}_e \rightarrow e^+ + n$. No possible event reconstruction of short e^+/e^- tracks due to the large distance between DOMs. **A collective increase in the PMT rates from CCSN neutrinos can be observed.**

Background sources: The number of PMTs in a DOM detecting a hit within 10 ns is defined as *multiplicity* (Fig.2). Main background from ^{40}K decays in seawater (250 kHz per DOM) dominating at low multiplicities. Long tracks from atmospheric muons produce high multiplicity coincidences on multiple DOMs and **can be reduced exploiting their fast (μs) time correlation.**

Background rates have been measured on the **first ORCA and ARCA detection lines in the sea**. A **muon rejection filter** has been developed and optimized on ORCA data (Fig.3).

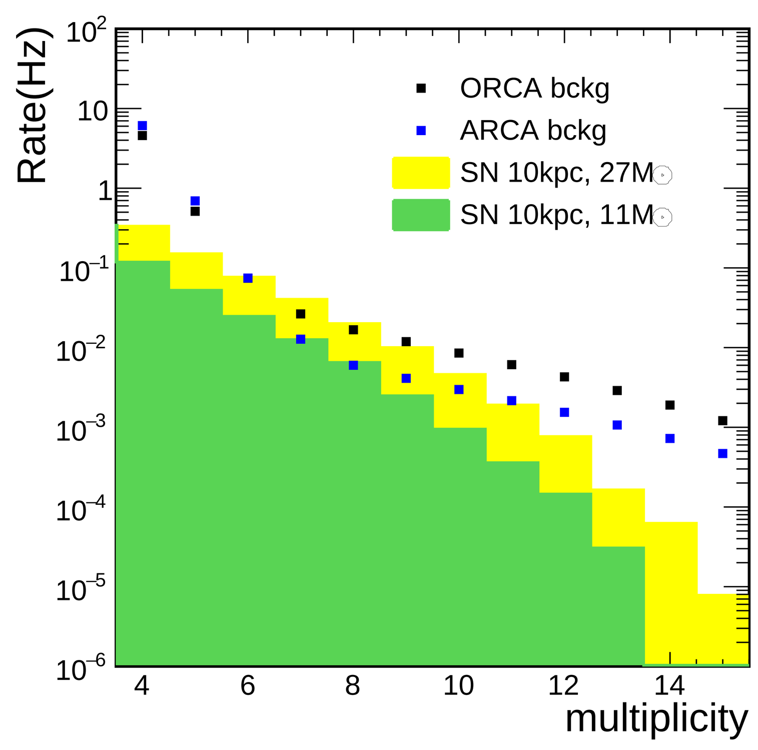


Figure 2: DOM rates as a function of the multiplicity for ORCA (black squares) and ARCA (blue squares) backgrounds from data and CCSN signal at 10 kpc for the 27 $M_\odot$ (yellow filled) and the 11 $M_\odot$ (green filled) progenitors from simulations.

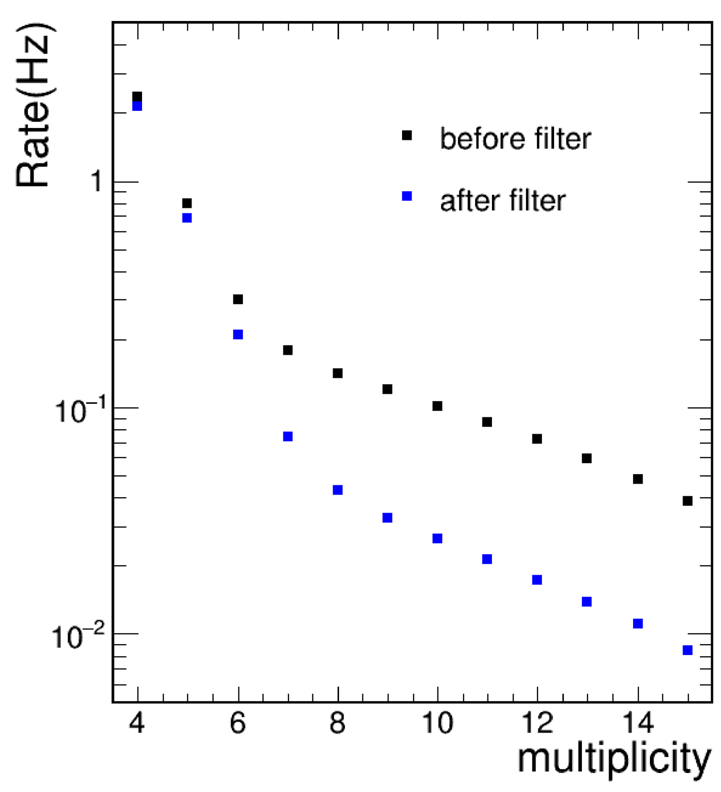


Figure 3: ORCA background rates before and after filter. A good background rejection efficiency is achieved.

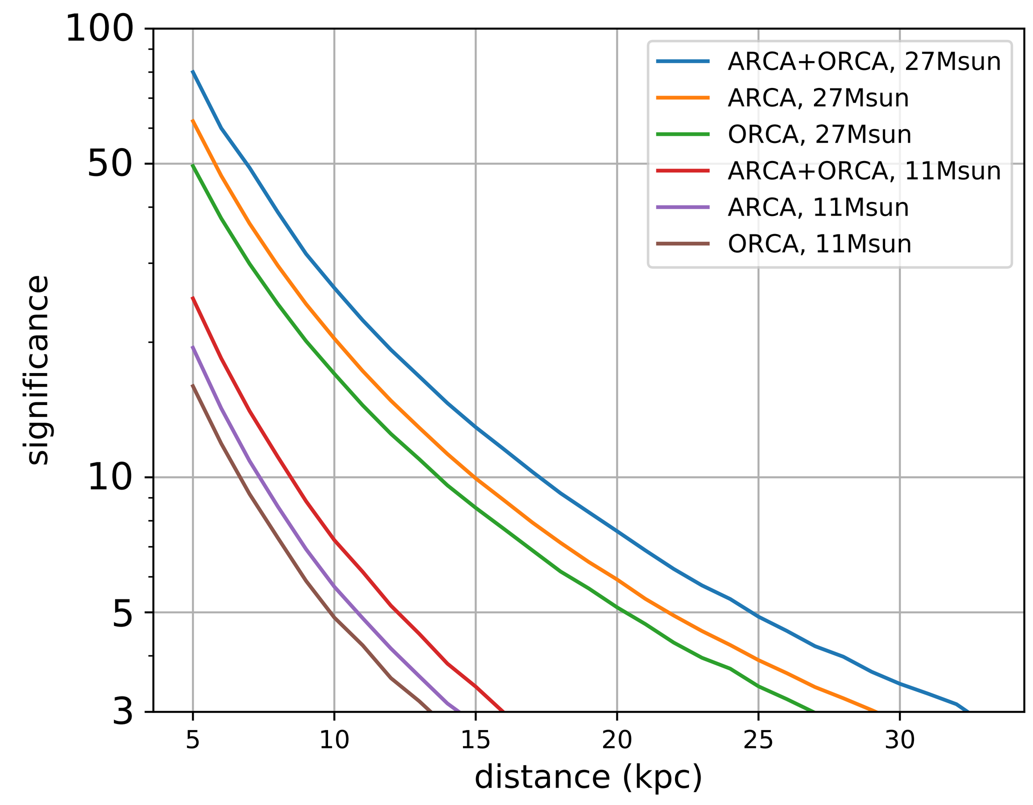


Figure 4: Significance obtained from Poisson p-value for ORCA, ARCA and the combination of both detectors as a function of SN distance.

Online triggering 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;
- Sparse signal: ~ 1 signal count per line on the $n\tau$ time window is expected within multiplicities 6 to 10;
- Participation in the SNEWS global alert network requires a false alert rate < 1/week.

Given the overall background rate after the multiplicity cut (6-10) and the muon filter (ρ), **the estimated false alert rate for a given trigger level is**:

$$R_B(X) = \tau^{-1} \cdot \mathcal{P}(N_{lines} \cdot n \cdot \rho\tau, X)$$
$$X(D) = N_{lines} \cdot X_{10kpc}(n\tau) \cdot \left(\frac{D}{10kpc}\right)^2$$

Trigger performance (ORCA, 27 $M_\odot$)

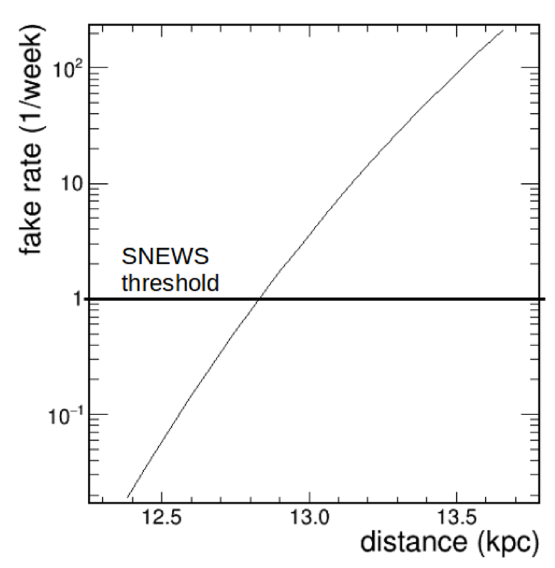
$\tau = 100$ ms

$\rho = 1$ Hz

$n = 4$

$X_{10\,kpc} = 1.2$

$6 \leq M \leq 10$

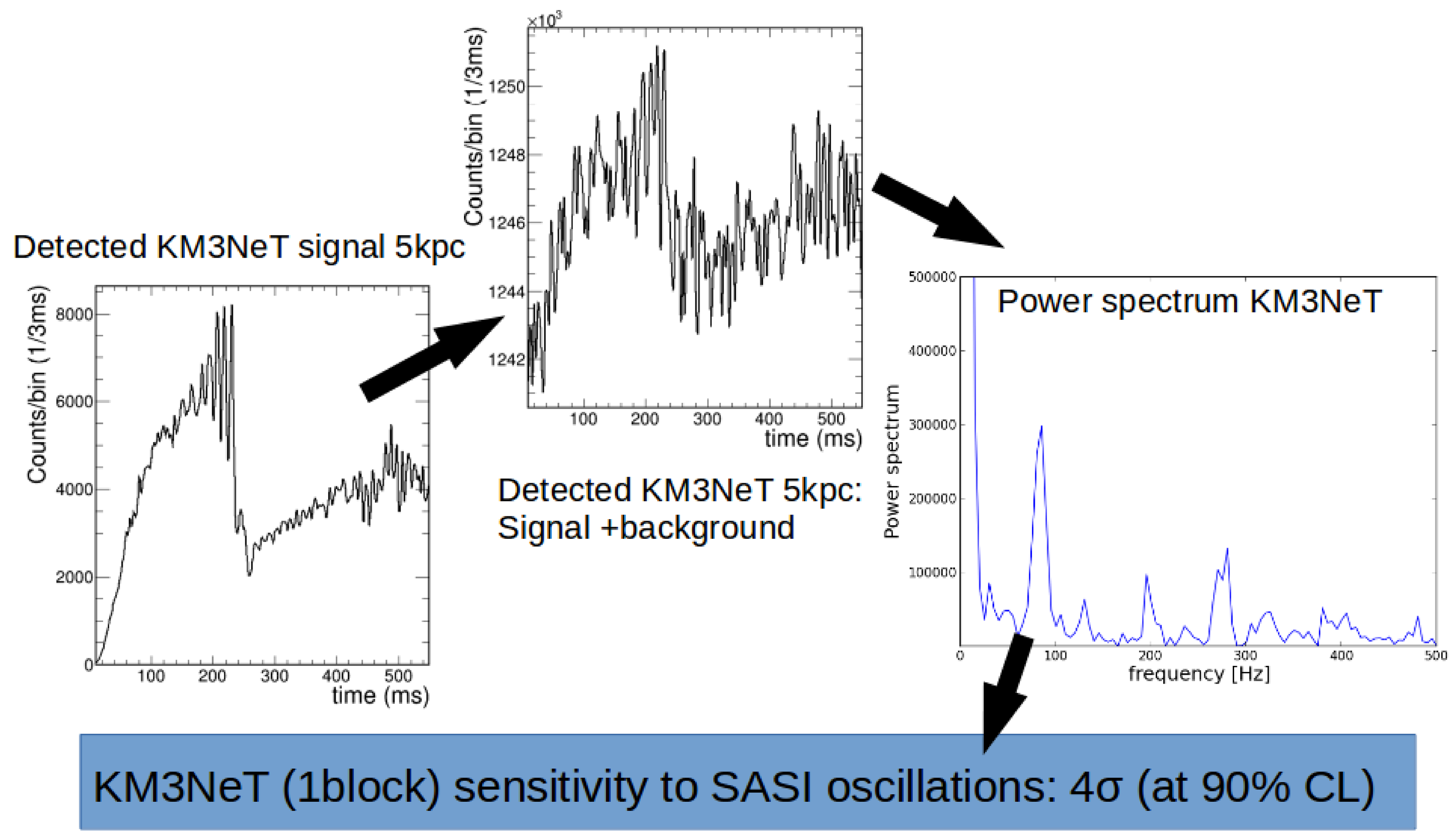


Fake rate	10 lines	115 lines
1 / hour	8.9 kpc	13.5 kpc
1 / week (SNEWS)	8.2 kpc	12.7 kpc
1 / 1000 years	6.9 kpc	11.7 kpc

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;
- The Standing Accretion Shock Instability (SASI) is believed to enhance the neutrino heating, favoring the explosion. **Footprint: fast time variations in the neutrino light-curve around 200ms, with a characteristic oscillation frequency**.

The detected neutrino light-curve has been computed for a CCSN progenitor of 27 M⊙ at 5 kpc, including all hits. Poissonian background has been added according to the total measured rate.
A Fourier analysis has been performed to recover the SASI frequency (80 Hz for this progenitor simulation model). The significance of the detection has been estimated through Monte Carlo pseudo-experiments. Results are given in the following figure for 1 KM3NeT block.



Conclusions

The response of the KM3NeT neutrino detectors to core-collapse supernova neutrinos has been evaluated by means of a **complete Monte Carlo simulation and an exhaustive study of the background from the data**.
The KM3NeT combined sensitivity for a future CCSN detection has been estimated to be of 5σ at 25 kpc (**coverage of the full Galaxy**) for a 27 M⊙ stellar progenitor. Assuming a 11 M⊙ progenitor, a significance of 5 σ is reached at the Galactic center with a single building block.
As for the online triggering capabilities, the maximum triggering distance below the **SNEWS threshold** for false alerts has been estimated to be **well beyond the Galactic center** (12.7 kpc).