Detection of MeV supernova neutrinos with the KM3NeT neutrino telescopes

Massimiliano Lincetto and Marta Colomer on behalf of the KM3NeT collaboration

1 Aix-Marseille Univ., CNRS/IN2P3, CPPM (Marseille), 2 IFIC, CSIC-UV (Valencia), 3 APC, Univ. Paris Diderot (Paris)

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.

State-of-the-art 3D simulations of the accretion phase of a 27M⊙ CCSN provided by the Garching group are used for this study (www.mpia.mpg.de/ccsnarchive).

- Time dependent CCSN neutrino spectra: quasi-thermal distribution depending on the average neutrino energy $E_{\nu}$, the neutrino luminosity $L(\nu_{\alpha})$, the spectral pinching shape parameter $\alpha$ 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:

$$\frac{dR_{\nu_{\alpha}}}{dE} = N_{\nu_{\alpha}} \cdot \sigma(E) \cdot \frac{d\Phi}{dE} \cdot [s^{-1} MeV^{-1}] \quad \kappa \in (\rho, \epsilon, 10^8)$$

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

CCSN neutrino signal: MeV-energy CCSN neutrinos detected through Cherenkov light mostly produced in inverse beta decay interactions: $p + \nu_e \rightarrow e^+ + n$. 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 ms 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).

Online triggering and SNEWS

- Trigger level: number of DOMs detecting a coincidence in a defined multiplicity range over a $\tau$-wide sliding time window, sampled on a $\tau = 100$ ms time scale;
- Sparse signal: ∼1 signal count per line on the $\tau$ time window is expected within multiplicities 6 to 10;
- Participation in the SNEWS global alert network requires a false alarm rate < 1/week.

Sensitivity to the SASI 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 $5 \sigma$ at 25 kpc (coverage of the full Galaxy) for a 27 M⊙ stellar progenitor. Assuming a 11 M⊙ progenitor, a significance of 5 $\sigma$ 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).