TIMING AND POINTING TO THE NEXT CORE COLLAPSE SUPERNOVA WITH NEUTRINOS AND THE PARTICIPATION OF KM3NET

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INTRODUCTION

Measuring arrival time of neutrinos with a good precision is crucial for the identification of the CCSN, the reconstruction of its sky location and the rapid identification of an electromagnetic and/or GW counterpart.

Two new model-independent methods are proposed that allow to infer:
- The signal arrival time with KM3NeT
- The time delay between the signal observed at different experiments [1].

DETERMINING THE CCSN NEUTRINO BURST ONSET WITH KM3NET

KM3NET CCSN detection

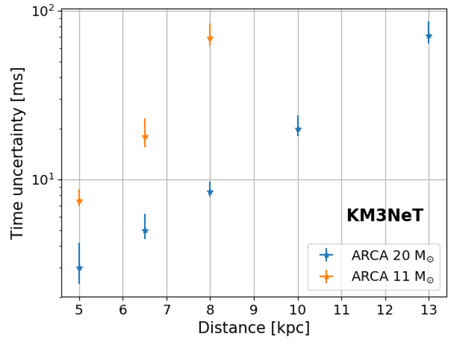
The KM3NeT detectors are under construction in the Mediterranean Sea. They will observe the next Galactic CCSN through an overall increase of the coincidence rates between the PMTs of the digital optical module (**DOM**). The number of hit PMTs in 10 ns is called **multiplicity** [2].

Two event selections have been developed in KM3NeT:
• A high multiplicity selection for the CCSN trigger, which optimises the sensitivity.
• A selection for lightcurve studies, using all coincidences to optimise the signal event statistics.

Both are exploited here to measure the CCSN signal arrival time in KM3NeT. Results are evaluated for the ARCA detector.

Results

- Model-independent optimised method.
- Time uncertainty: RMS of the fitted T0 values distribution (pseudo-experiements).
- The true T_0 is randomised in each pseudo-experiment inside the lightcurve bin width.
-Above 9 kpc (11 $M_\odot$) and 13 kpc (20 $M_\odot$), the fit is no reliable anymore.
- The result of the fitted T_0 and its uncertainty will be send into an alert provided to SNEWS [4].



Method to infer the arrival time T_0

Exponential rise fit of the signal [3]:

$$f(t) = \begin{cases} 0, & \text{if } t < T_0 \\ R \times (1 - \exp^{-(t-T_0)/\tau}), & \text{if } t \geq T_0 \end{cases}$$

→ Use information of the first detected events

Step 1:

- First T_0 estimate, T_0^M, using the CCSN selected data (high multiplicity)
- T_0^M = 1st bin of 10 ms width containing at least 11 events (it is shifted from the true)
- Define starting point of the fit and the fit window using T_0^M:

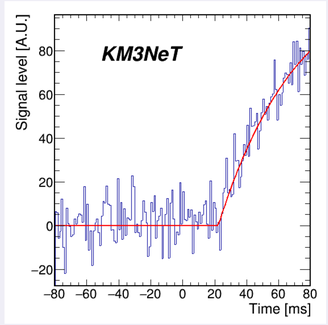
$$T_{\text{start}} = T_0^M - T_{\text{shift}} \frac{I_\nu^0}{I_\nu}$$

$$[T_0^M - 150ms, T_0^M + \frac{I_\nu^0}{I_\nu} 50ms]$$

I_ν^0: theoretical signal lightcurve integral for benchmark CCSN (20 $M_\odot$, 5 kpc)
I_ν: experimental integral of the observed lightcurve after background subtraction.

- Average filter used to filter out background fluctuations

Step 2:
Apply the fit to all coincidence data.



COMBINING EXPERIMENTAL NEUTRINO LIGHTCURVES

Simulation of the experimental lightcurves:

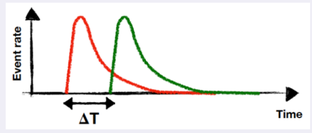
- Parametrisation of the flux variation with time [5].
- Spectrum: L_ν^{tot}=3e53 erg, $\langle E \rangle$=14MeV and α=3 [1].
- Simple detector response, given by the effective mass and the expected background.
- Neutrino flux and detector effective mass assume a steady energy spectrum.
- Only experiments sensitive to IBD are considered.

Method:

- chi-square (χ^2) fit and cross-correlation to find the time delay between lightcurves.
- Matching performed in a time window defined around the lightcurve maximum.
- Parameters optimised: lightcurve bin, time window and step size.
- Pseudo-experiments performed to obtain the time delay uncertainty, δt.

Time delay uncertainty for each pair of experiments:

δt [ms]	KM3NeT/ARCA	Super-K	Hyper-K	JUNO
KM3NeT/ARCA	-	7.4±0.2	6.70±0.15	7.4±0.2
IceCube	6.65±0.15	1.95±0.04	0.55±0.01	1.95±0.04
Super-K	-	-	-	2.75±0.06
Hyper-K	-	-	-	1.99±0.04



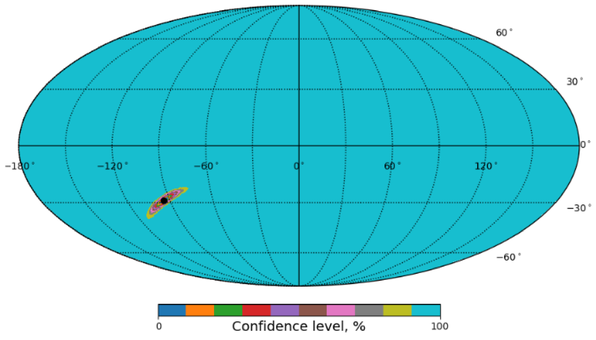
TRIANGULATION OF THE CCSN NEUTRINO SIGNAL

→ This results can feed a triangulation algorithm used to determine the localization of the CCSN.

The pointing errors are given for different possible detector combinations.

IceCube	✓	✓	✓		✓
Hyper-Kamiokande	✓	✓		✓	✓
JUNO	✓		✓	✓	✓
KM3NeT/ARCA		✓	✓	✓	✓
90% CL area (deg^2)	340±70	360±40	2150±370	4680±660	140±20
68% CL area (deg^2)	190±50	170±20	1050±230	2300±460	70±10

IceCube/Hyper-K/ ARCA/JUNO



→ This tool can be implemented into SNEWS for a low-latency response in case of a CCSN alert [4].

References

[1] A. Coleiro et al., Eur. Phys. J. C 80 (2020) 856
[2] M. Colomer et al., PoS ICRC2019 (2019), 857
[3] F. Halzen et al., Phys. Rev. D 80 (2009) 087301
[4] SNEWS2.0, arXiv:2011.00035 [astro-ph.HE]
[5] E. Nardia et al., Nucl. Phys. B 731 (2005)