Real-time supernova detection with KM3NeT

SNEWS 2.0: Supernova Neutrinos in the Multi-Messenger Era

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Introduction

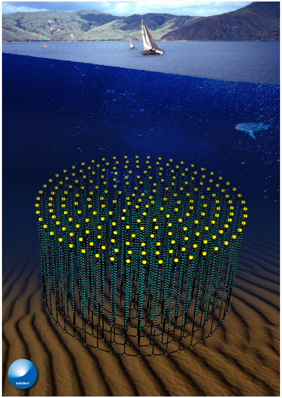
The two **KM3NeT neutrino detectors** (ARCA and ORCA) are designed for a shared **rich multi-messenger astronomy program**.

The supernova neutrino detection is the first real-time analysis to combine data from ORCA and ARCA.

KM3NeT overview

- The ARCA (IT) and ORCA (FR) KM3NeT detectors will provide 3 blocks $\times$ 115 lines $\times$ 18 digital optical modules (DOMs) $\times$ 31 directional PMTs;
- large-scale experiment not optimised for reconstruction of low energy events;
- CCSN ν burst can be detected as a global detector PMT rate increase.

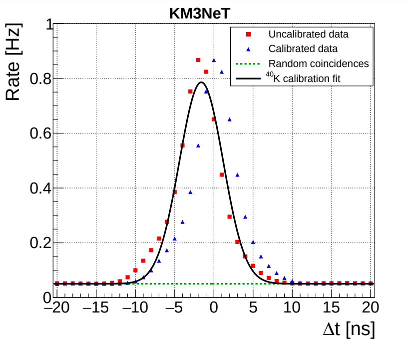
The multi-PMT DOM technology can be exploited for signal identification.



Understanding KM3NeT backgrounds

Selection of light in coincidence between multiple PMTs of the same DOM is a key capability for KM3NeT:

- removal of **uncorrelated bioluminescence** and part of the $^{40}\mathrm{K}$ -dominated **radioactive decays**
- ns-coincidences between photons are signatures of Cherenkov light!
- correlated $^{40}\mathrm{K}$ photons are used for in-situ time and efficiency **calibration**.

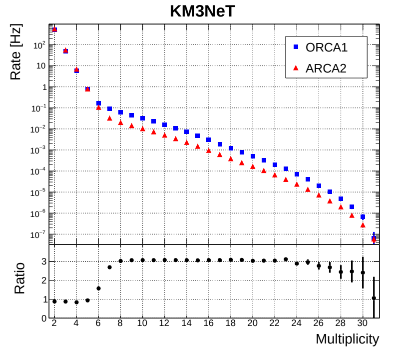


This is (so far) the **first and only astronomy study exploiting low-level coincidence data**!

Coincidence rates

The **number of PMTs** detecting light in a **10 ns coincidence** is called **multiplicity M**.

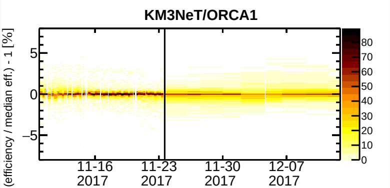
Multiplicity depends on **topology**, **light yield**, **distance from the DOM**.

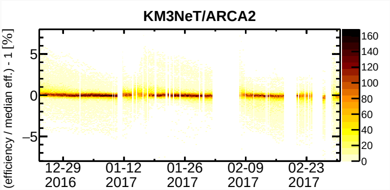


- ^{40}K dominates at low multiplicity, rate $R = (500\,\text{Hz}) \cdot 10^{2-M}$;
- **atmospheric muons** form a tail at high multiplicity ($M \geq 8$), dependent on the depth;
- see arXiv:1906.02704 for details!

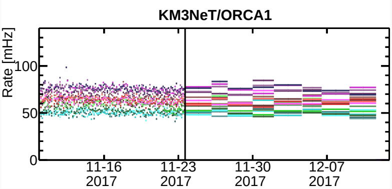
Stability of backgrounds

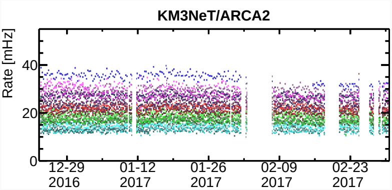
$^{40}\mathrm{K}$ $\rightarrow$ **PMT efficiencies**





Atmospheric muons ($M \geq 8$)



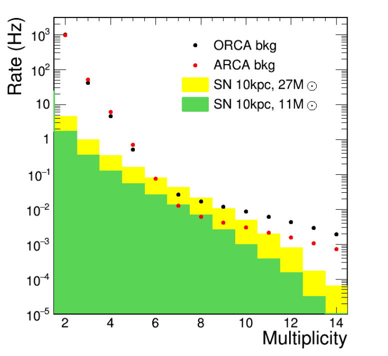


Effective rejection of bioluminescence through the selection of high multiplicities.

Signal and background

CCSN neutrino events produces photons mainly detected as a **coincidence on a single DOM**. The **multiplicity range [6,10]** is the most favourable for the signal selection.

KM3NeT preliminary

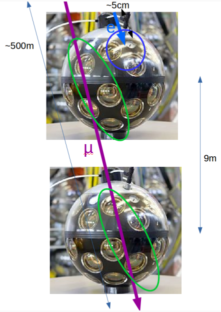


Crossover region between $^{40}\mathrm{K}$ and **atmospheric muons**. Background rate per DOM in the [6,10] multiplicity range ~ 0.1 Hz.

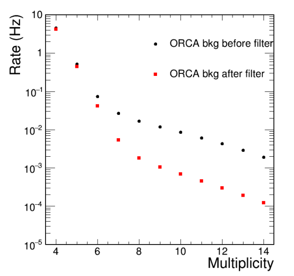
Reduced rates allow efficient **real-time processing**.

Atmospheric muon rejection

- CCSN neutrinos are mostly detectable on a **single DOM**;
- correlation of coincidences between multiple DOMs allow to **tag atmospheric muons.**



KM3NeT preliminary



Best performance with **ORCA spacing** → 50% background reduction, compensating the originally higher muon rate due to shallower depth.

The standard KM3NeT **physics triggers** provide an additional mean for muon rejection (under testing).

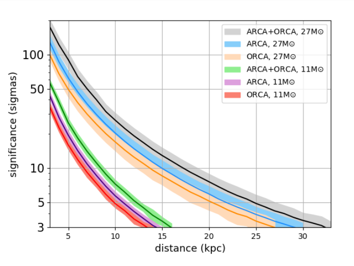
From offline to real-time

Offline observation

trigger level $X \equiv$ coincidences in the multiplicity range [6,10] over a time window of duration τ. For signal expectation $X_D \propto D^{-2}$ and total background rate ρ_B:

$$P(X \geq X_D) = \sum_{X=X_D}^{+\infty} \mathcal{P}(X, \rho_B \cdot \tau)$$

KM3NeT preliminary



Real-time search

Sliding time window $\tau = 400$ ms, updated with $f_s = 10$ Hz sampling frequency (**trial rate**).

Stability $\rightarrow$ bioluminescence rejected through multiplicity selection.

Robustness $\rightarrow$ counting of **unique DOMs** (Poisson approximation for $X_D \ll N_{DOMs}$)

Trigger background rate:

$$R_B(X \geq X_D) = f_s \cdot P(X \geq X_D)$$

Online trigger with 3 DUs

DOM counting

Probability for K_D DOMs out of N to detect a coincidence is binomial.

$$R_B(K \geq K_D) = f_s \cdot \sum_{K=K_D}^{N} f(K, N, p)$$

$$N \equiv N_{DOMs}\ ;\ p = \rho_B^{DOM} \cdot \tau$$

$$K_D = N \left(1 - \left(1 - \frac{1}{N}\right)^{X_D}\right)$$

Alert horizon for 3 KM3NeT DUs (2 ORCA + 1 ARCA) as in current running configuration and 8 KM3NeT DUs (6 ORCA + 2 ARCA) as in near future.

	KM3NeT 3 DUs	
Threshold	11 $M_\odot$	27 $M_\odot$
1 / 8 days	2.5 kpc	5 kpc
	KM3NeT 8 DUs	
Threshold	11 $M_\odot$	27 $M_\odot$
1 / 8 days	4.5 kpc	8.5 kpc

p-values combined with Fisher's method to get χ^2_2 test statistic.

Real-time search performance for KM3NeT

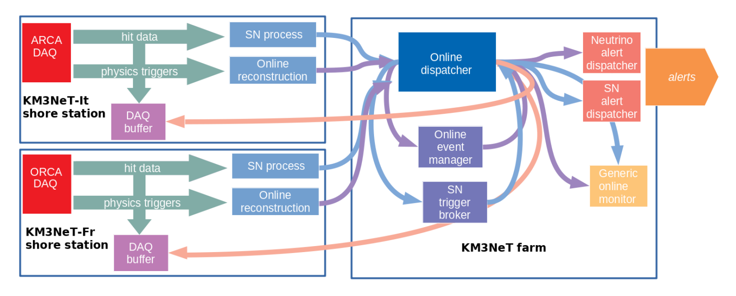
Foreseen **alert horizon** for full ORCA, full ARCA and full KM3NeT combined, assuming a false alert limit of *one in two weeks*, and the two simulated progenitors.

	ORCA 115 DUs		ARCA 230 DUs		KM3NeT combined	
Threshold	11 $M_\odot$	27 $M_\odot$	11 $M_\odot$	27 $M_\odot$	11 $M_\odot$	27 $M_\odot$
1 / 14 days	9.5 kpc	17 kpc	11 kpc	21 kpc	12.5 kpc	23 kpc

(**Conservative** background assumption at 1.5 Hz per DU for both detectors.)

Building the KM3NeT combined trigger

Commissioning of the **CCSN trigger** and of the **online neutrino search** progressing in parallel in the **common multi-messenger infrastructure**.



- CCSN trigger algorithms run independently at each detector;
- output **monitored** locally (performance, stability) and relayed to common endpoint for **combined processing**.

Design in progress of **low-level data buffer** for CCSN astrophysics studies.

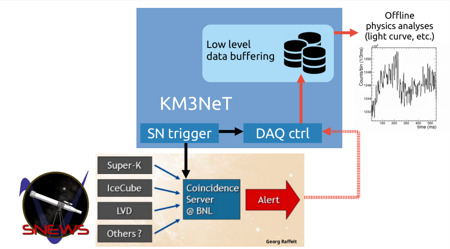
KM3NeT meets SNEWS

Real-time processing

- data are relayed with a latency below **two seconds** compared to generation time off-shore;
- current SN processing has a 10 s buffering;
- **combined trigger level** can be estimated within **15 seconds**;
- margin for optimisation (if necessary)!

Trigger and alert generation

- internal testing of the trigger combination is undergoing;
- testing of the SNEWS client and private server will follow soon;
- you will hear from us!



Conclusion

The CCSN detection algorithm developed for estimating the **sensitivity** is implemented as **online trigger**.

The current phase with **three DUs across the two KM3NeT sites** (1 ARCA + 2 ORCA) is seeing the commissioning of the **online framework**.

The **SN online monitoring** active at each shore station and first test of the **combined trigger** is ongoing.

Testing of the **SNEWS infrastructure** upcoming!

Future...

... more KM3NeT DUs to be connected!