Supernova searches with KM3NeT

KM3NeT Town Hall Meeting

Marseille, 17-19 december 2019

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Introduction

O(10 MeV) CCSN neutrinos in seawater mostly interact through **inverse beta decay** (97%) and elastic scattering.

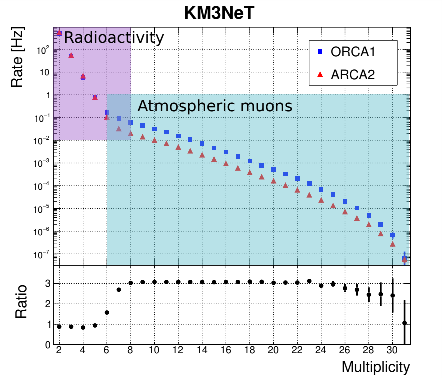
The small track from the outgoing lepton (few cm) cannot be reconstructed individually but can **produce single/multiple hits on a single DOM**.

Main sources of background are **radioactive decays** in seawater, **atmospheric muons** and **bioluminescence**.

Method: selecting coincidence data to identify a signal over the baseline.

DOM background rates

A **Cherenkov emission** results typically in multiple photons reaching the DOM simultaneously, resulting in O(10 ns) coincidences between different PMTs of the same DOM.



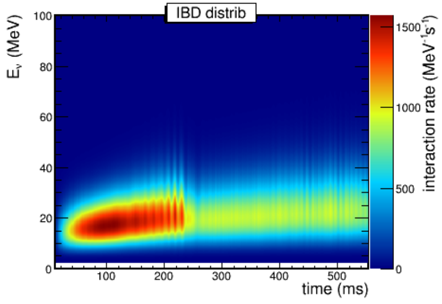
The **multiplicity (M)**, namely the number of PMTs hit in coincidence, can be used to discriminate, on average, different types of Cherenkov emission.

Bioluminescence consists of single-photon emissions without ns-scale correlation, so highly suppressed already for $M \geq 3$.

Signal simulation

Two different 3D simulations of the **accretion phase** from the MPA Garching group[1] are used.

Inverse beta decay, electron elastic scattering and interactions with oxygen are simulated.

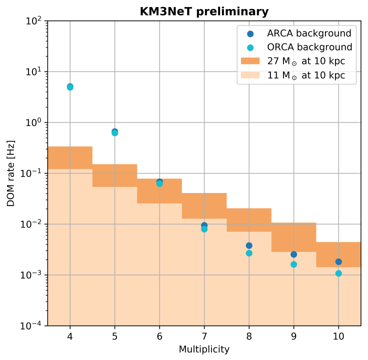


GEANT4 and custom KM3NeT software are used to simulate the Cherenkov emission induced by the outgoing lepton and the detector response.

[1] http://wwwmpa.mpa-garching.mpg.de/ccsnarchive

Signal to background

Muon rejection is achieved by correlating coincidences across different DOMs on a μs time scale. **ARCA** benefits from a higher depth, **ORCA** from a denser geometry.



- signal is compared to background for two progenitors $27M_\odot$ and $11M_\odot$ at 10 kpc;
- best signal to noise is for coincidences in the range $6 \leq M \leq 10$
- background rate $\rho_B \simeq 1\,\mathrm{Hz/line}$

Sensitivity

The number of coincidences in the range $6 \leq M \leq 10$ over a time window τ is defined as **trigger level**. The expected number of background events in the time window is $\mu_B = \rho_B \cdot \tau$.

Probability of observing X greater or equal to the signal expectation at a given distance $X_D \propto D^{-2}$:

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

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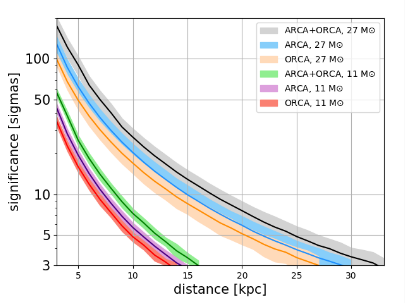

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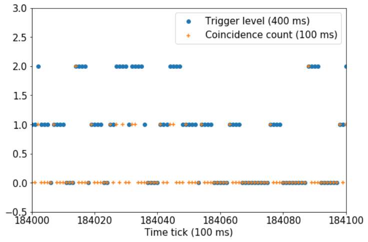
5σ significance: **full galaxy** coverage for the 27 $M_\odot$ progenitor and **beyond the galactic center** for the 11 $M_\odot$ progenitor.

Combined realtime search

A **sliding time window** of width $\tau = 400\,\text{ms}$ is updated with a $f_s = 10\,\text{Hz}$ sampling frequency. **Detectors are combined synchronously**.

The p-value is converted into a **false alert rate** (FAR):

$$FAR(X_D) = R_B(X \geq X_D) = f_s \cdot \sum_{X=X_D}^{+\infty} \mathcal{P}(\mu_B, X)$$



ARCA 2 DU + ORCA 6 DU	
FAR threshold: 1 / (8 days)	
Model	D_{max} (kpc)
11 $M_\odot$	4.5
27 $M_\odot$	8.5

Observation limits with ORCA4 and ARCA1

In presence of an **external alert**, the **trigger level** is evaluated for the 400 ms after the T_0.

The combination of the two detectors yields $\mu_B \simeq 2.2$. Being in Poisson regime, the **Feldman-Cousins** method is used to establish an 90% CL upper limit on the signal expectation $S^{90\%}$.

Exclusion limits

- lower limit on distance: $D^{90\%} = (10\,\mathrm{kpc}) \times \sqrt{\frac{S_{10\,\mathrm{kpc}}}{S^{90\%}}}$
- upper limit on energy: $E_\nu^{90\%} = \frac{S^{90\%}}{S_{E_\nu^0}} \cdot E_\nu^0$

Follow up of GW candidate S191110af

After the publication of the (now retracted) S191110af GW candidate by LIGO/Virgo, KM3NeT has conducted its first follow-up CCSN analysis.

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TITLE:   GCN CIRCULAR
NUMBER:  26249
SUBJECT: LIGO/Virgo S191110af: Upper limits from KM3NeT MeV neutrino search.
DATE:    19/11/14 20:04:49 GMT
FROM:    Damien Dornic at CPPM,France  <dornic@cppm.in2p3.fr>

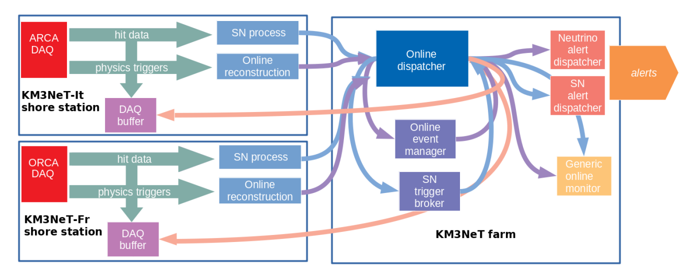
M. Colomer (APC, Universite de Paris), M. Lincetto (Aix Marseille Univ,
CNRS/IN2P3, CPPM), A. Coleiro (APC, Universite de Paris), D. Dornic (Aix
Marseille Univ, CNRS/IN2P3, CPPM), V. Kulikovskiy (INFN - Sezione di
Genova), report on behalf of the KM3NeT Collaboration.
```

Lower limits on the distance: 11.4 and 5.7 kpc for the 27 and 11 $M_\odot$ progenitor, respectively.

Upper limit on the luminosity: 2.58×10^{53} erg at 10 kpc for a quasi-thermal reference spectrum with $\langle E_\nu \rangle = 15\,\mathrm{MeV}$.

Online framework

All-data-to-shore DAQ $\rightarrow$ **dedicated data streams** for different real-time analyses. Data are exchanged via an efficient **subscription-based** protocol.



Applications can subscribe to **any information** from the dispatcher, so the same data can be exploited in parallel for different goals (even combining different processing stages).

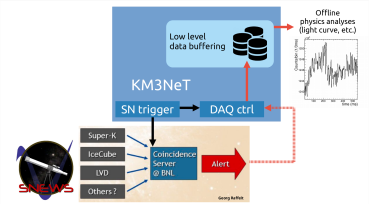
KM3NeT meets SNEWS

Real-time performance

- data are received from the sea with a latency below **two seconds**;
- current SN processing has a 10 s buffering;
- **combined trigger level** can be estimated within **15 seconds** with good margin for optimisation.

Trigger and alert generation

Internal generation of combined trigger is in place. Testing of the integration with the SNEWS infrastructure is ongoing.

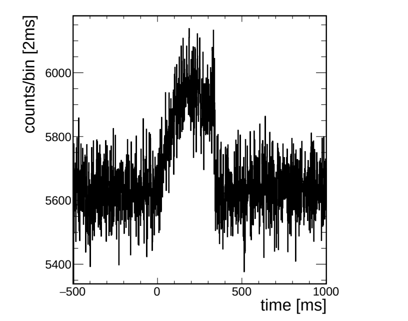


CCSN astrophysics: detecting the SASI oscillation

Hydrodynamical instabilities in the accretion phase may result in the **standing accretion shock instability** (SASI) observable as fast time variations of the neutrino rate at a specific frequency.

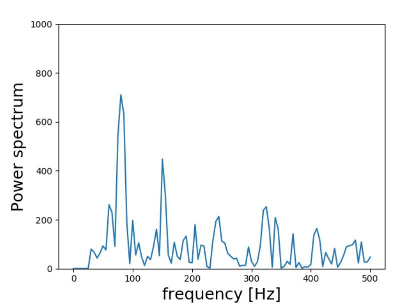
$20M_{\odot}$ Garching model (favourable case) with SASI for a CCSN at 5 kpc - ARCA 230 lines. Use of lower M coincidences to increase statistics.

KM3NeT preliminary



Detected neutrino light curve.

KM3NeT preliminary



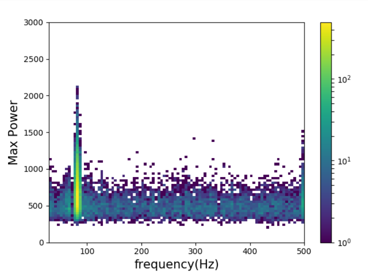
Light curve power spectrum.

CCSN astrophysics: detecting the SASI oscillation

Expected results for full ARCA (230 lines).

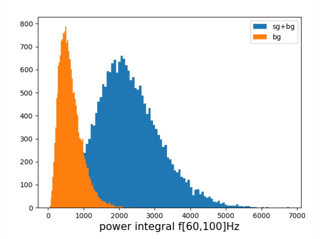
Model independent approach: search for a peak in the power spectrum at any frequency. Sensitivity: $2\,\sigma$ (resp. $1\,\sigma$) for the 20 $M_{\odot}$ (resp. 27 $M_{\odot}$) progenitor model at 5 kpc.

KM3NeT preliminary



Model dependent approach: look for an energy excess around the predicted frequency. Sensitivity: $3.5\,\sigma$ (resp. $2\,\sigma$) for the 20 $M_{\odot}$ (resp. 27 $M_{\odot}$) progenitor model at 5 kpc.

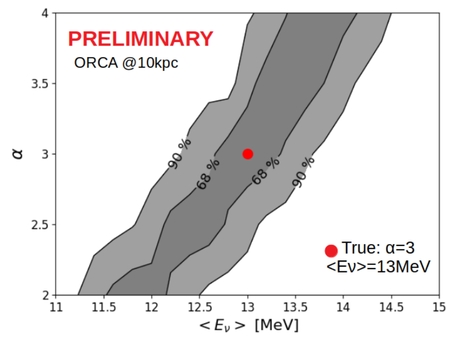
KM3NeT preliminary



CCSN astrophysics: mean energy estimation

A 2D χ^2 fit is performed to fit $\langle E_\nu \rangle$ and α to the detected **multiplicity distribution**:

$$\chi^2(\langle E_\nu \rangle, \alpha) = 2 \sum_{M=3}^{M=10} (\mu_M - n_M + n_M \times ln(\frac{n_M}{\mu_M}))$$

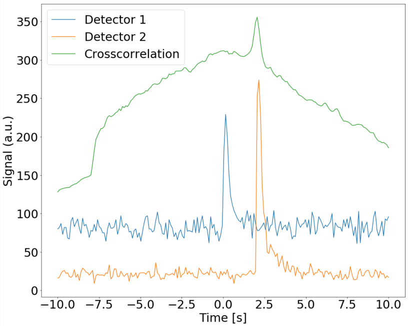


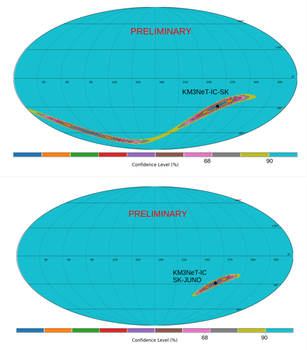
- The two parameters are almost degenerate;
- for a fixed α, achieved resolution is 3% (estimation is for a conservative flux assumption).

Triangulation with experimental light curves

By determining the **time of arrival of the burst** at different detectors around the globe, **triangulation** could allow pointing to the supernova.

The signal **template** is not known a priori, so the timing needs to rely on **experimental light curves**.





General framework under development to establish triangulation potential with a set of detectors, using $\chi 2$ fit and cross-correlation.

Conclusion

The **CCSN neutrino search** is one of the first KM3NeT analyses to be operational with the current detector configuration (ORCA 4 + ARCA 1).

The **real-time infrastructure** for the online processing and alert generation has been developed and the **SNEWS integration** is in progress.

The **first follow-up analysis** of an external trigger has been performed for the GW candidate S191110af with the submission of a **GCN circular**.

Good perspective for doing **CCSN astrophysics** with a fully-built detector.