Supernova detection and real-time alerts with the KM3NeT neutrino telescopes

The New Era of Multi-Messenger Astrophysics

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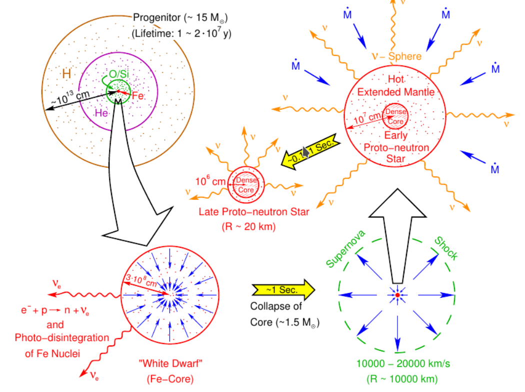
Core-collapse supernovae

Core-Collapse Supernovae (CCSNe) are possible explosive phenomena for stars between ~ 8 and ~ 50 $M_\odot$ reaching the end of their life cycle:

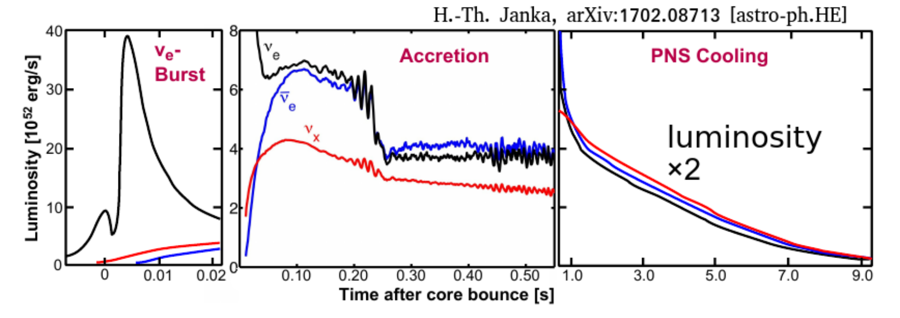
- nuclear fusion stages $\rightarrow$ iron core + shells of lighter elements, sustained by the electron degeneracy pressure;
- iron photodissociation + electron capture $\rightarrow$ reduction of electron number, eventually triggering the collapse of the core to a proton-neutron star;
- bounce of infalling matter on p-n core $\rightarrow$ shockwave leading to the explosion.

H.-Th. Janka, arXiv:1702.08713 [astro-ph.HE]



CCSN neutrino emission

97-99% of gravitational energy $O(10^{53}\,\mathrm{erg})$ is released through all-flavor neutrino emission in the 10 MeV range, when the envelope is optically thick.

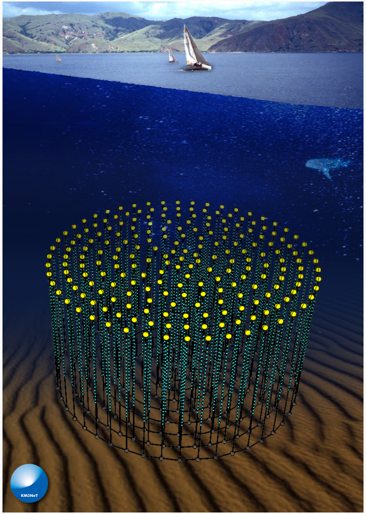


After the **neutronisation burst**, the shockwave loses energy as it propagates until it **stalls** in the **accretion phase**, where hydrodynamical instabilities can take place. **Neutrino heating** revives the shock, finally producing the explosion. **Thermal cooldown** of the core follows.

Overview of KM3NeT design

- 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.

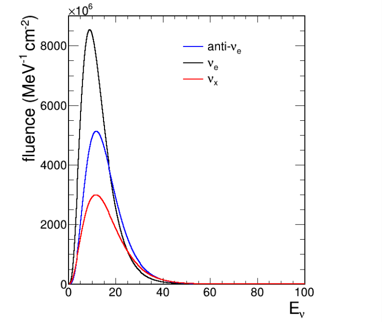
The multi-PMT DOM technology can be exploited for signal identification.



CCSN neutrinos meet sea water

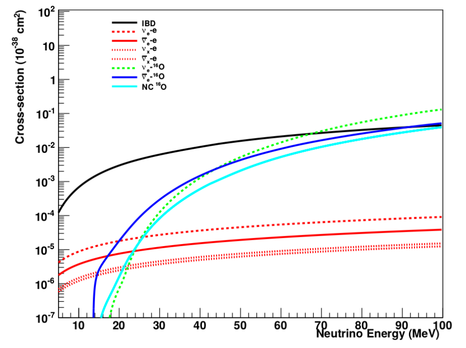
Flux model

3D CCSN flux simulation from MPA Garching Group[1], quasi-thermal distribution with pinched spectrum (full time-dependent flux).



Interaction channels

- 97% inverse Beta Decay (IBD): $\overline{\nu}_e + p \rightarrow e^+ + n$
- 3% elastic scattering: $\nu_l + e^- \rightarrow \nu_l + e^-$
- <1% CC on: $\overset{(-)}{\nu}_e + {}^{16}\mathrm{O}$



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

Detector response

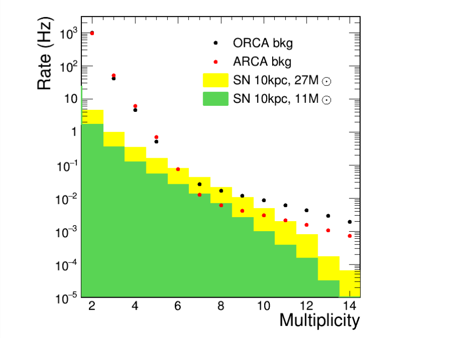
KM3NeT response to CCSN ν is evaluated with a GEANT4 simulation.

Coincidences on the ns scale on a DOM are exploited for:

- bioluminescence rejection;
- PMT efficiency and time offset calibration using ^{40}K decays in sea water;
- discrimination of signal from atmospheric muons and supernova neutrinos, depending on the number of PMT hit in coincidence (**multiplicity**)

^{40}K dominates multiplicity up to 6-7, atmospheric muons starting from 8.

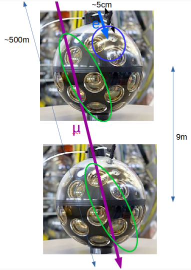
KM3NeT preliminary



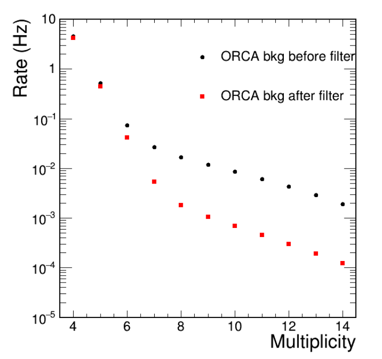
An **increase in coincidence rates** is observable especially in the **multiplicity range 6-10**.

Atmospheric muon rejection

Contrarily to SN neutrinos, atmosperic muons produce correlated signals **detectable on more than one DOM**.
This allows to **reduce the background** in the considered multiplicity range.



KM3NeT preliminary



The filter optimized on the **ORCA geometry** works either by **selection of correlated coincidences** or by exploiting the **physics triggers**, allowing to reduce the background near to the residual ^{40}K contribution (indistinguishable from the signal).

The optimisation of **muon filter for ARCA** is undergoing thanks to the **new data available**.

Sensitivity

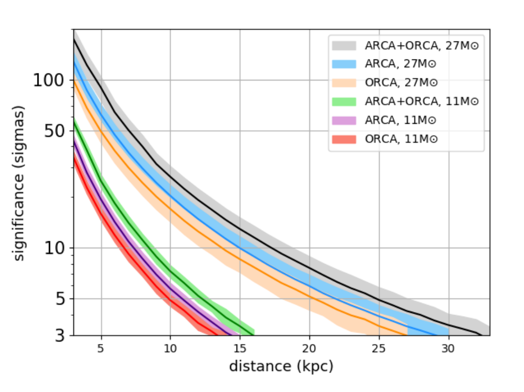
After the muon filtering, the number of detected coincidences in the multiplicity range 6-10 over a time window of duration τ is evaluated to determine the **trigger level** X.

Given the background rate ρ_b and a **known onset time**, for a given signal expectation X_D:

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

$$X_D \propto D^{-2}$$

KM3NeT preliminary



Full galaxy coverage for the 27 $M_\odot$ progenitor and beyond the galactic center for the 11 $M_\odot$ progenitor!

Realtime transient search

A **sliding time window** of width $\tau = 400\,\text{ms}$ is updated with a $f_s = 10\,\text{Hz}$ sampling frequency. This turns the p-value into a **false alert rate**:

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

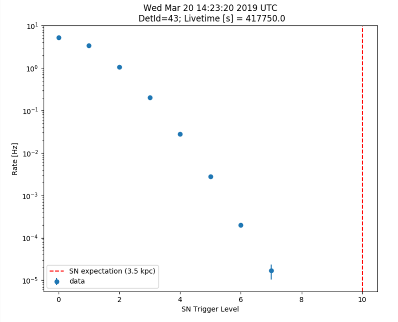
The sampling f_s is optimised in order to:

- minimise the signal loss due to the time discretisation;
- avoid unnecessary increase of the number of time-trials.

Batch analysis of few months of ORCA and ARCA data show that the approach is **stable** and follows very well the **Poisson expectation**.

Online monitoring ORCA 1 line

KM3NeT preliminary



Observation rate vs. trigger level

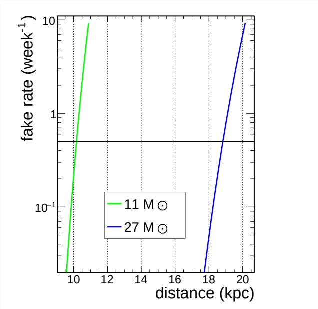
Prospects

SNEWS

Global network combining in real-time alerts from different detectors[2].

Online trigger performance (1 ORCA block)

KM3NeT preliminary



black line = SNEWS false alert limit

Coverage up to the galactic center!

[2] https://snews.bnl.gov

CCSN astrophysics

Preliminary studies have been done on:

- sensitivity to fast time variations in the neutrino light curve (**SASI oscillation**);
- resolution on the determination of the time of arrival of the neutrino burst.

Higher signal statistics is required when compared to the simple detection, this comes at the cost of **higher background** contamination.

Bioluminescence and ^{40}K are the main limitations in using lower-multiplicity coincidences (or even single rates).

This part of the analysis is under active developement.

Online implementation

Current picture

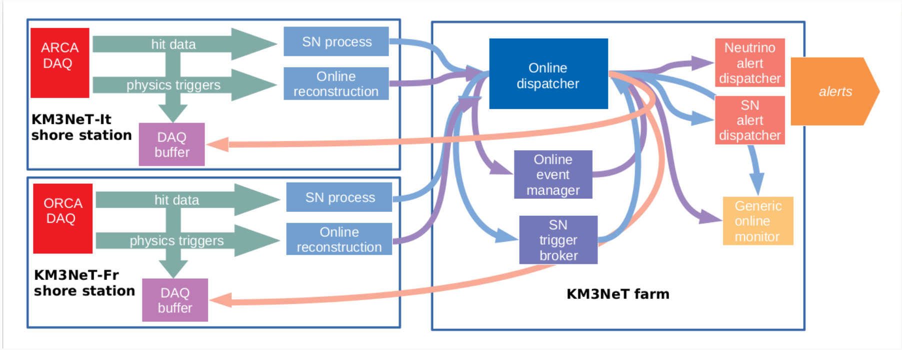
- a specific data stream is now produced for the purpose of **supernova detection** and **processed in real time**;
- the first-stage processing at each **shore station** produces **summary information** used for **monitoring by shifters**;
- (for a 27 $M_{\odot}$ progenitor) a **single line** has a reasonable sensitivity up to 3.5 kpc.

Development plan

- Data from **ARCA and ORCA** shore stations will be relayed to a **common broker**, paving the way for **real-time alerts** and **SNEWS participation**;
- Buffering of **low-level data** for more advanced quasi-online analyses (e.g. **neutrino light curve**) and **permanent storage** of interesting events.

Framework overview

The *all-data-to-shore* DAQ concept allows to build and distribute **dedicated data streams** that can be **shared by multiple applications** for different types of offline and online analyses, monitoring, etc.



A **common architecture** is used to distribute the information within the online framework.

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

Conclusion

After establishing the sensitivity to the **detection of a galactic CCSN neutrino burst**, the detection algorithm has been developed into an **online trigger**.

The current phase with **one line operational at each KM3NeT site** (1 ARCA + 1 ORCA) is being exploited for the commissioning of the **online framework**.

The **SN online monitor** is now active at each shore station, soon to be **combined**.

In parallel **CCSN astrophysics** analyses are being developed.