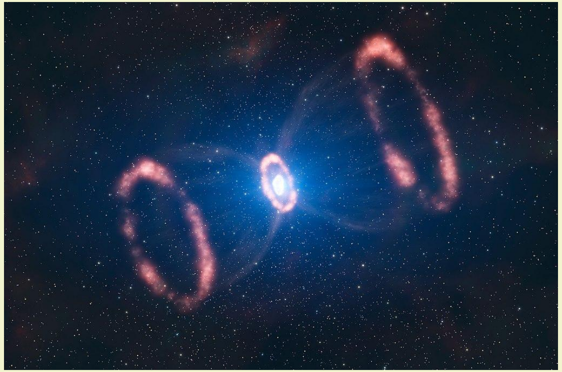
Low energy neutrinos from core-collapse supernovae at KM3NeT



Isabel Goos, Town Hall KM3NeT Meeting, 20/09/2022

KM3NeT

Labex UnivEarthS

Université Paris Cité

Introduction: Core-collapse Supernovae (CCSNe)

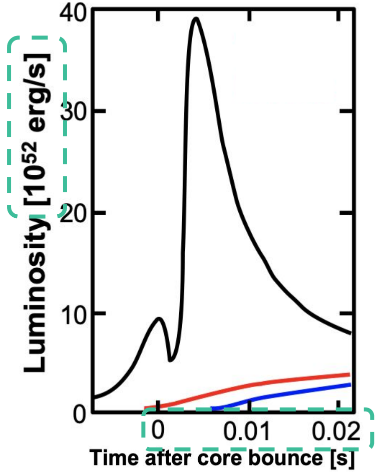
What are CCSNe?

- explosions of giant stars (>8 solar masses) at the end of their thermonuclear evolution
- give birth to neutron stars and black holes

Open questions:

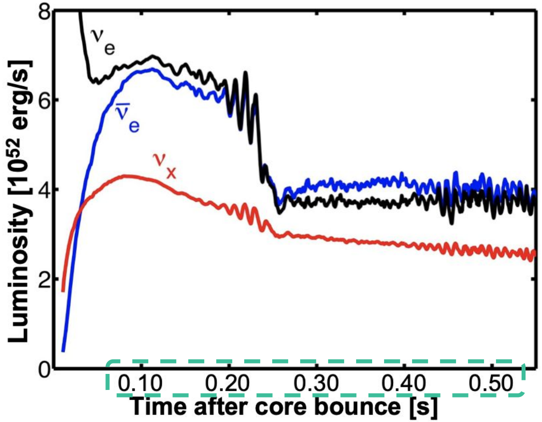
- explosion mechanism - conditions that need to be met, phenomena that favour the explosion
- neutrino behaviour in dense environments

Introduction: Core-collapse Supernovae (CCSNe)



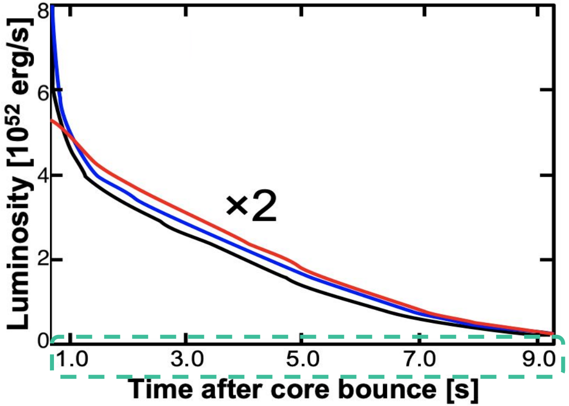
υ_e-burst

sudden transition of the shock from opaque to transparent for neutrinos created via electron capture



Accretion phase

disintegration of heavy nuclei + energy loss through υ_e-burst
⇒ stagnation of the shock
⇒ revival through neutrino heating in the hot accretion mantle

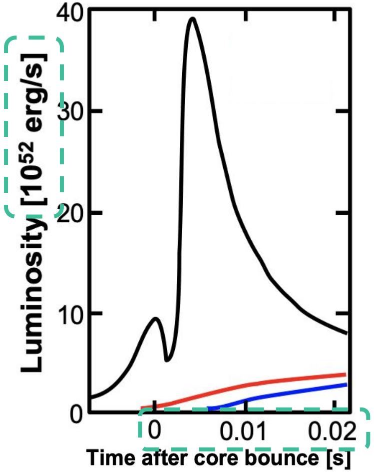


Cooling phase

neutrino-driven wind - potential site for formation of trans-iron elements

arXiv:1702.08713

Introduction: Core-collapse Supernovae (CCSNe)



ν_e-burst

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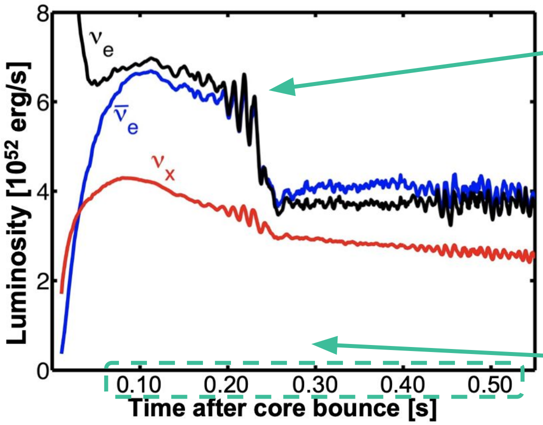

Accretion phase

disintegration of heavy nuclei + energy loss through ν_e-burst
⇒ stagnation of the shock
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SASI (standing accretion shock instability): non-radial hydrodynamic instabilities, potential support for the onset of the explosion

~ Supernova explosion
⇒ neutrinos arrive before the photons do
⇒ alert system using neutrino signal is possible

arXiv:1702.08713

Outline

01 Detection mechanism and sensitivity

02 Estimation of the neutrino spectrum parameters

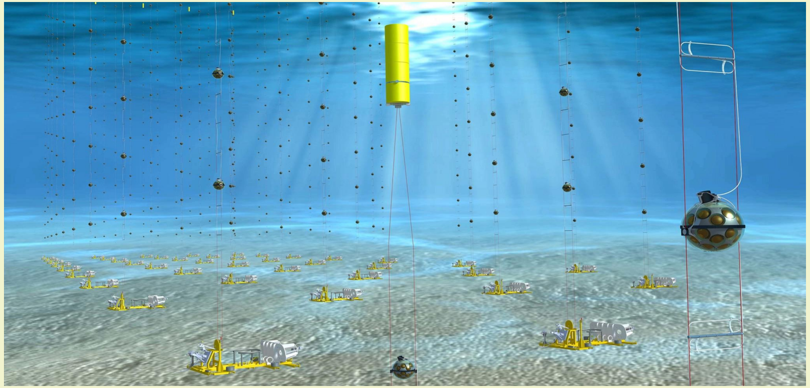
03 Detection of the SASI phenomenon

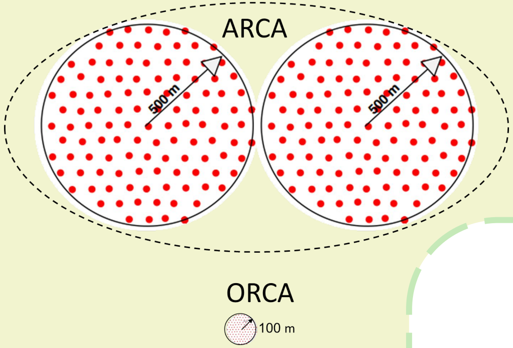
04 Arrival time of the CCSN neutrino signal

05 Supernova localisation through triangulation

06 Real-time multi-messenger analysis framework

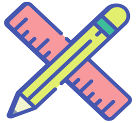
KM3NeT - the next generation υ telescopes





ARCA
Astrophysical neutrino sources with cosmic neutrinos in the TeV-PeV energy range

ORCA
Neutrino mass ordering and oscillations with atmospheric neutrinos in the 1-100 GeV energy range



CCSN Neutrinos:

- 10-20 MeV energy range
- carry ~99% of the progenitor's gravitational energy

Detection of CCSN (I)

The complex DOM structure makes the following possible

Background filtering

atmospheric muons generate correlated coincidences during their passage through the water, bioluminescence is negligible in the present context

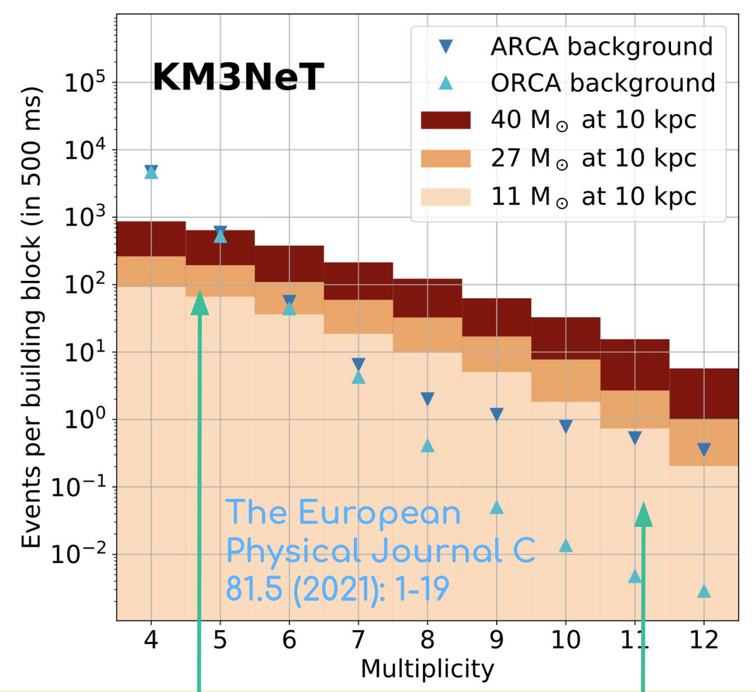
CCSN neutrinos

contribute to a signal if they interact in a 20 m radius sphere around the DOM, main contribution: inverse beta decay

Radioactive decay

mainly by K40, can be taken into account ⇒ *next slide*

Detection of CCSN (II)



Dominated by radioactive decays (K40)

Dominated by atmospheric muons

Multiplicity = number of PMTs hit in a coincidence (10 ns)

Detection mechanism ↪single-DOM signal

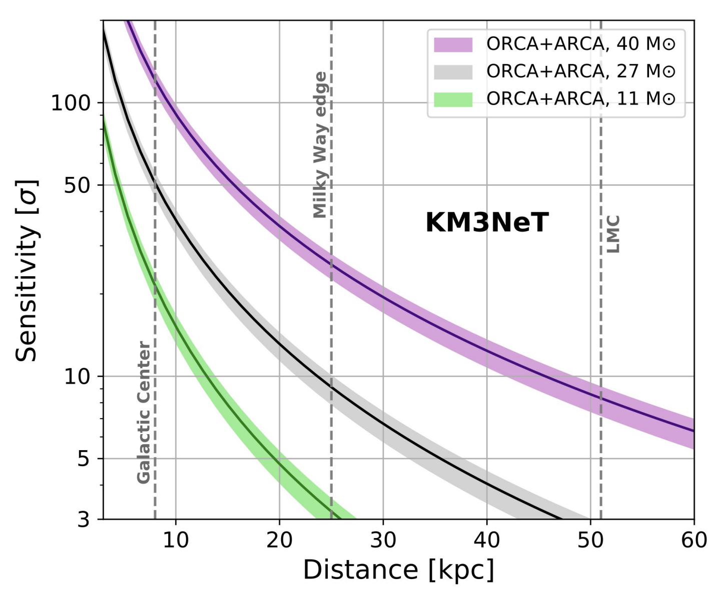
- through observation of coincidences in excess over the background taking into account all the DOMs in the detector
- the multiplicity distribution of these coincidences can be exploited to discriminate the origin of the signal on a statistical basis

KM3NeT detection sensitivity

Best solution → 7-11 multiplicity range for both detectors

- the expected distribution of CCSNe as a function of the distance to the Earth is considered
- for the 11 solar mass scenario, more than 95% of the Galactic CCSNe are covered by KM3NeT with a 5σ discovery potential

Model	Multiplicity				
	2	**3**	**4**	**5**	**6**
$11\,M_\odot$ (340 ms)	1119 ± 3	258 ± 1	100.4 ± 0.8	48.9 ± 0.5	25.8 ± 0.4
$27\,M_\odot$ (543 ms)	4806 ± 9	1120 ± 5	442 ± 3	218 ± 2	116.0 ± 1.5
$40\,M_\odot$ (572 ms)	15240 ± 30	3650 ± 10	1449 ± 8	723 ± 6	399 ± 4
	7	**8**	**9**	**10**	**11**
$11\,M_\odot$ (340 ms)	13.3 ± 0.3	7.2 ± 0.2	3.4 ± 0.1	1.29 ± 0.08	0.50 ± 0.05
$27\,M_\odot$ (543 ms)	64 ± 1	35.2 ± 0.8	19.4 ± 0.6	8.0 ± 0.4	1.9 ± 0.2
$40\,M_\odot$ (572 ms)	226 ± 3	127 ± 2	69.5 ± 1.8	36.6 ± 1.3	15.0 ± 0.8



With today's setup (ARCA21 + ORCA11) → ~ 0.3 * Sensitivity

The European Physical Journal C 81.5 (2021): 1-19

Estimation of the neutrino spectrum parameters

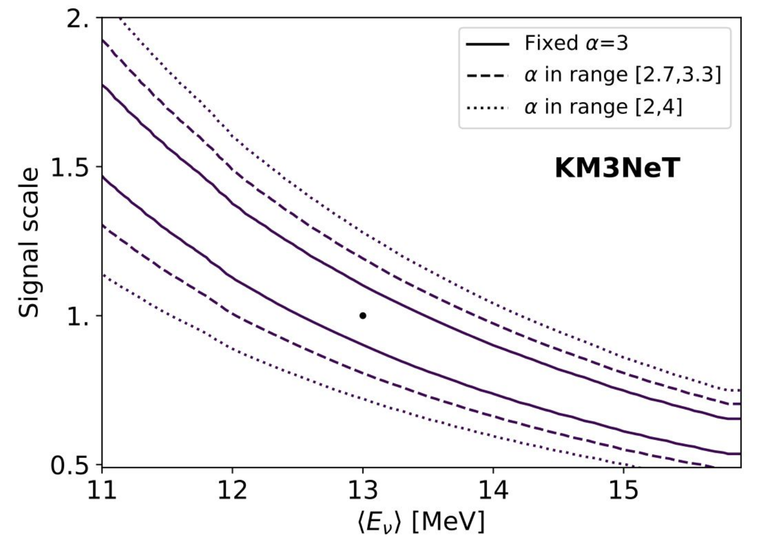
Multiplicity distribution depends on the flux spectral features

- $$\frac{d\Phi}{dE\,dt}(E,t) = \frac{L(t)}{4\pi d^2} f(E, \langle E(t)\rangle, \alpha(t))$$

  ⟨E⟩ = mean neutrino energy, α = spectral shape parameter, Λ = signal scale (depends on total energy released and distance to the source)

- Chi-square method: α and Λ fixed → ±0.5 MeV for ⟨E⟩, 10% variation of α and Λ → ±1.5 MeV for ⟨E⟩, α and Λ free → sensitivity to ⟨E⟩ is lost

Using 7-11 multiplicity range



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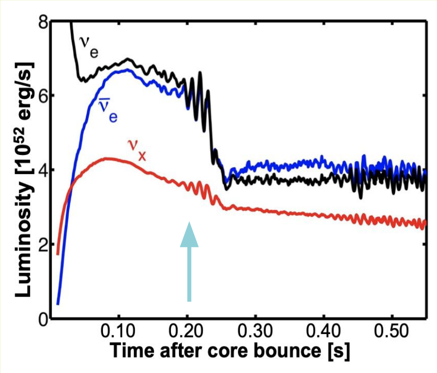
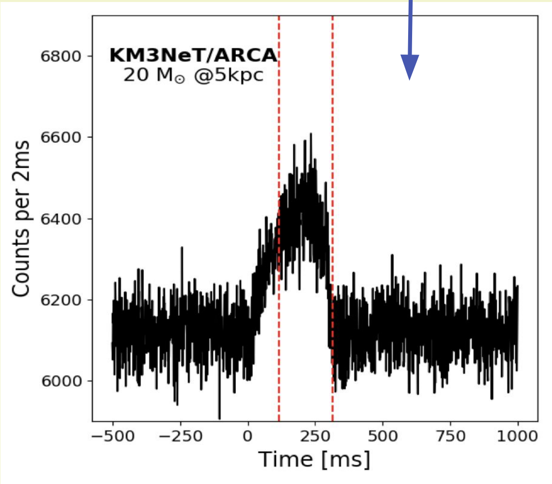
Detection of the SASI



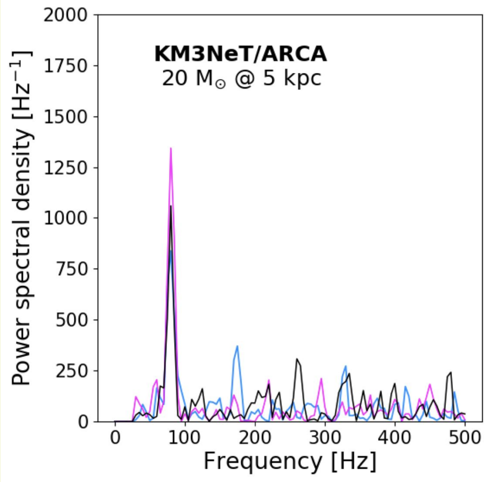
Spectral analysis for L1-cut using fast fourier algorithm

3σ sensitivity to the SASI signature is reached for Galactic progenitors at distances between 3 (27 solar mass progenitor) and 5 kpc (20 solar mass progenitor)

Including detector effects + background



Spectral analysis



L1 = collection of all hits on a DOM with a time difference smaller than 10 ns

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Arrival time of the CCSN neutrino signal

The arrival time can be estimated with un uncertainty of 3 ms for a supernova at 5 kpc - also using an L1-cut.

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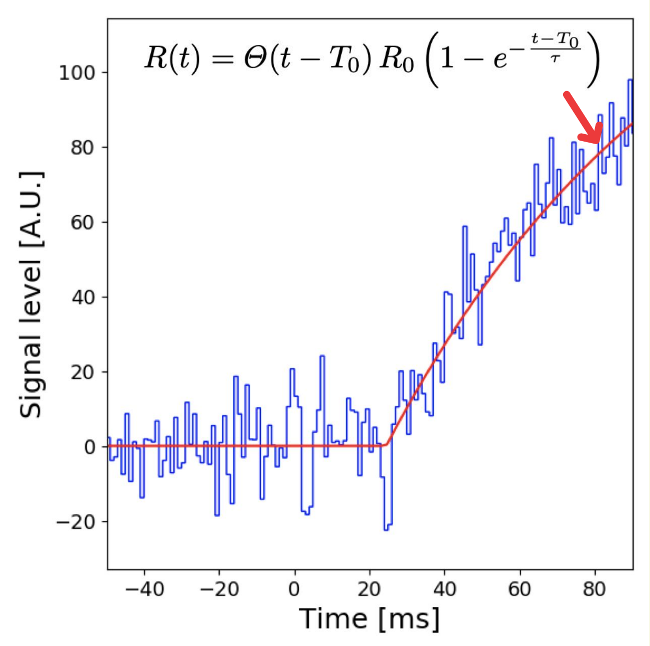
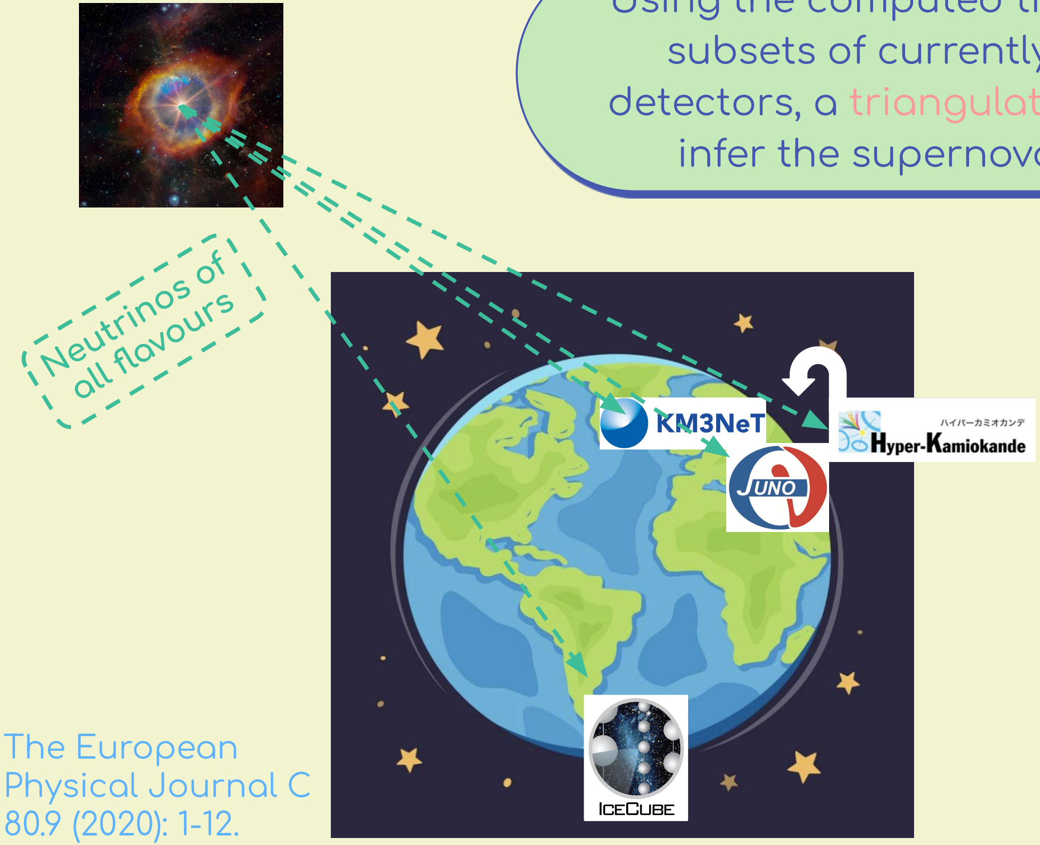


Main goals

- arrival times at different detectors ⇒ localisation of the source by triangulation ⇒ *next slide*
- the relative start time of the electron antineutrino signal with respect to the electron neutrino burst is tied to flavour conversion processes in the dense environment of the star, which in turn depend on the neutrino mass ordering
  ↳ arXiv:2204.13135
- neutrinos can act as an early warning for optical follow-ups ⇒ *next-to-next slide*

Supernova localisation through triangulation



Using the computed time delay between different subsets of currently operational and future detectors, a triangulation method can be used to infer the supernova localisation in the sky.

- Chi-square method: minimization of

$$\chi^2(\tau) = \sum_{t_i=t_{\min}}^{t_{\max}} \frac{((n_{t_i-\tau} - m_{t_i}) - E(n_{t_i-\tau} - m_{t_i}))^2}{V(n_{t_i-\tau} - m_{t_i})}$$

- Normalised cross-correlation: maximization of

$$\mathcal{C}(\tau) = (n \star m) = \frac{1}{N} \sum_{t_i=t_{\min}}^{t_{\max}} n_{t_i} m_{t_i-\tau}$$

- Low-latency analysis methods that can be implemented in the SNEWS (SuperNova Early Warning System) alert system

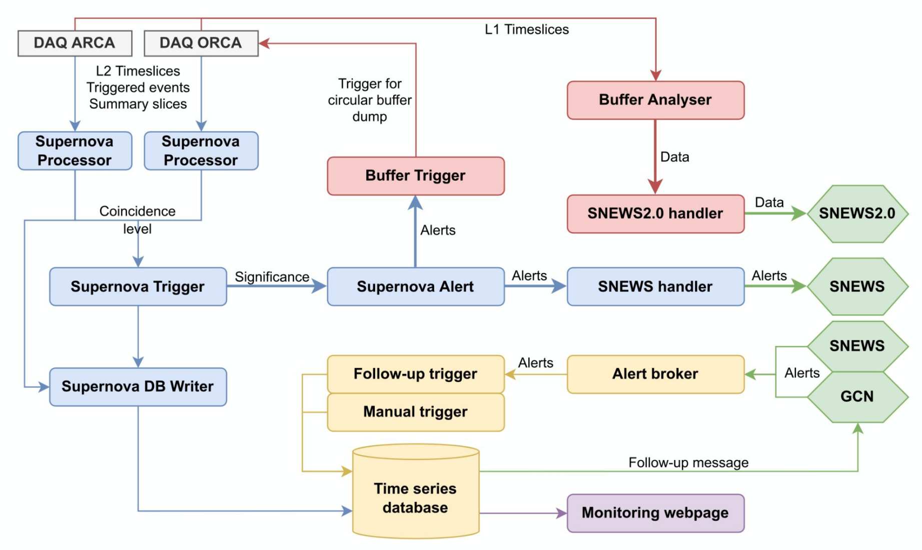
The European Physical Journal C 80.9 (2020): 1-12.

Real-time multi-messenger analysis framework

Main goals

- CCSN monitoring
- Receive external electromagnetic, gravitational waves or neutrino alerts
- Send all-sky neutrino alerts to external observatories for follow-up

Monitoring the neutrino sky for the next Galactic CCSN with KM3NeT, Neutrino 2022, Godefroy Vannoye



Status

- CCSN monitoring fully functional and connected to SNEWS ⇒ false alarm rate less than 1/week with latency less than 20 s
- alert sender and receiver mostly ready

arXiv:2107.13908

Conclusions

It will be possible to detect neutrinos from CCSNe using both detectors from KM3NeT, ARCA and ORCA

- Galactic supernovae
- real-time multi-messenger analysis framework

What can be learned from CCSNe?

- SASI phenomenon
- neutrino spectrum parameters (mean neutrino energy, spectral index, signal scale)
- position of the supernova
- neutrino mass ordering through flavour conversion in the dense environment (arXiv:2102.05977)