Monitoring the neutrino sky for the next Galactic supernova

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Core-collapse supernovae

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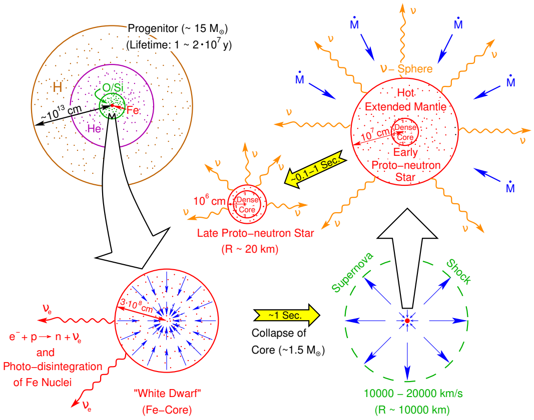
Explosive phenomena ending the life of massive stars with an enormous energy release ($\sim 3 \times 10^{53}$ erg)

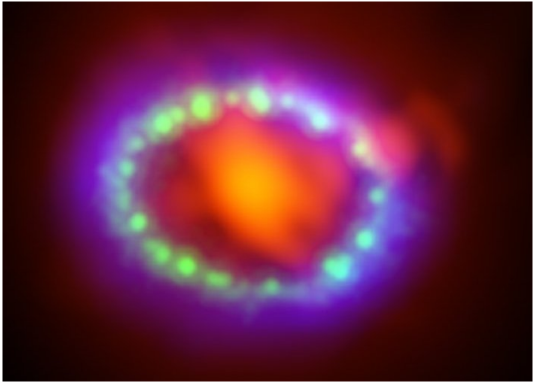
Physics of the core-collapse

Iron photo-dissociation and electron capture inside the iron-core → diminution of the electron degeneracy pressure → collapse of the core and shockwave propagation



Evolution of a massive star from the onset of iron-core collapse to a neutron star

Motivations for the detection of supernova neutrinos



Supernova remnant of SN 1987A

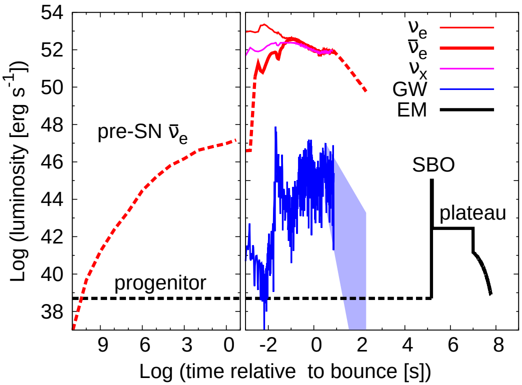
Previous observations
To this day, only 25 supernova neutrinos have been detected, from SN 1987A

Supernova formation
A better understanding of supernova formation should bring new astro-, subnuclear and nuclear physics knowledge, and neutrinos play a key role in the formation mechanism

Signals emitted by a core-collapse supernova

Multi-messenger observation
Core-collapse supernovae emit signals in three cosmic messengers: neutrinos, gravitational waves and electromagnetic emission

Neutrino alert
Neutrinos can be used as an alert for gravitational waves and electromagnetic followup

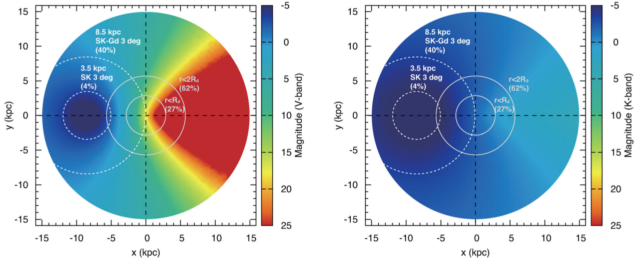


Time sequence for multi-messenger signals

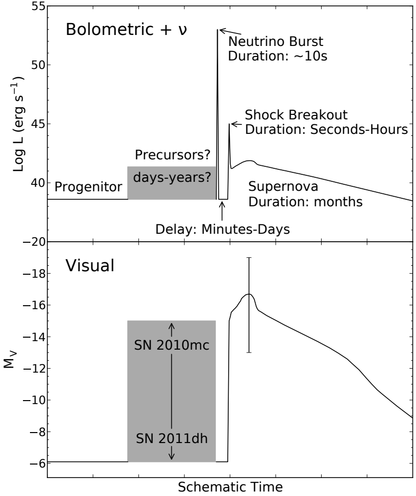
Electromagnetic signal

Shock breakout (SBO)
Release of photons when the supernova shock breaks out of the progenitor surface, followed by a plateau

EM spectrum
Photon emission peaks in soft X-rays and UV, but depending of the position of the progenitor in the galaxy, absorbtion can cause the observed brightness peak to shift to optical and near-IR



Expected plateau magnitude (left: optical, right: NIR)

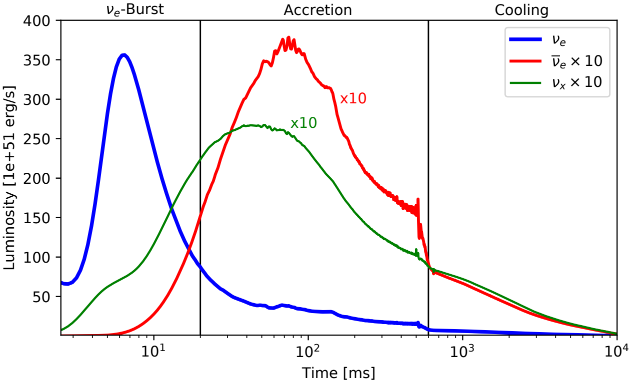


Schematic time sequence (top) and V-band magnitude (bottom)

Neutrino emission during a CCSN

Neutrino emission
99% of the energy is released as low energy neutrinos ($\sim 10\,\text{MeV}$)
3 phases of emission: ν_e-burst, accretion phase and cooling phase

Neutrino detection
KM3NeT sensitive to $\overline{\nu}_e$ *via* inverse beta decay
Detection time-window of $\sim 500\,\text{ms}$



Expected neutrino time-profile during a CCSN

Detection with KMNeT

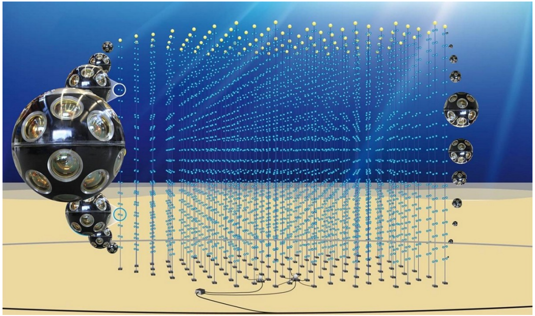
Experimental setup of KM3NeT

KM3NeT
Water Cherenkov neutrino detector currently in construction at the bottom of the Mediterranean Sea

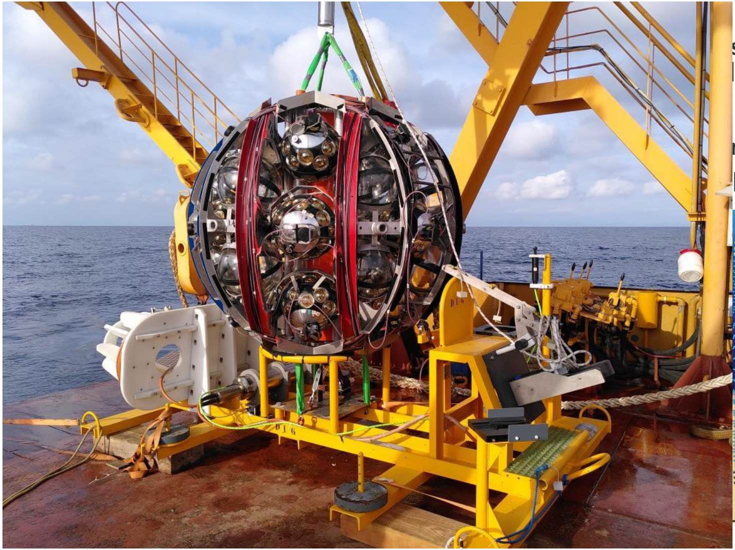
ORCA
Denser array, volume of 7 Mt, optimized for detection of neutrinos in the tens of GeV, 2500 m deep offshore Toulon (FR)
One building block, 9 m vertical, 20 m horizontal spacing

ARCA
Volume of 1 km^3, optimized for the detection of neutrinos in the TeV to PeV energy range, 3500 m deep offshore Capo Passero (IT)
Two building blocks, 36 m vertical, 90 m horizontal spacing

Detector design
DOM (digital optical module): sphere hosting 31 PMTs
DU (detection unit): line of 18 DOMs
Building block: 115 DUs



Experimental setup of KM3NeT



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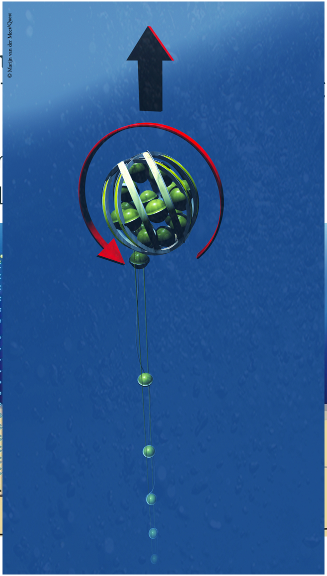
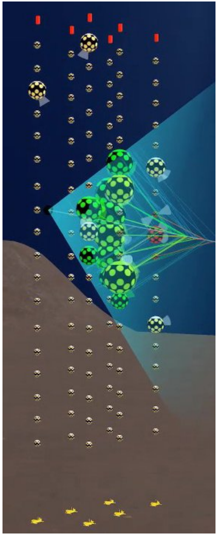


Principle of neutrino detection

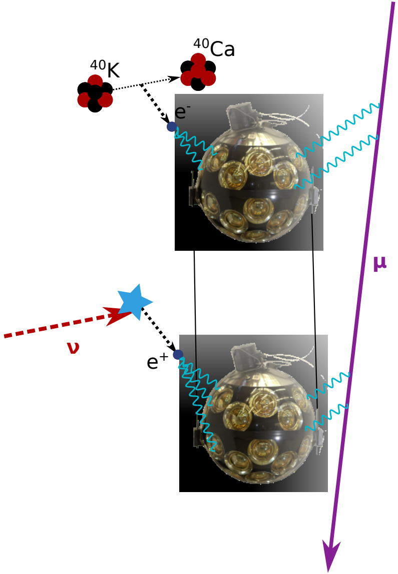
Neutrino interaction
Charged current: lepton generation → tracks for muons, showers for electrons
Neutral current → hadronic showers

Cherenkov radiation
Electromagnetic radiation emitted when a charged particle propagates in a medium faster that the speed of light in that medium

Event reconstruction
Reconstruction of the neutrino properties (trajectory, energy, flavor...) by detecting the induced light with a 3D array of PMTs
For CCSN neutrinos, small tracks of $\sim 0.5\,\mathrm{cm}$ per MeV → reconstruction of individual events using multiple DOMs impossible



Detection of MeV CCSNe neutrinos with KM3NeT



Detection of low-energy neutrinos

Positrons generated *via* inverse beta decay cannot be reconstructed individually

Analysis principle: search for an excess of hit coincidences above the optical background

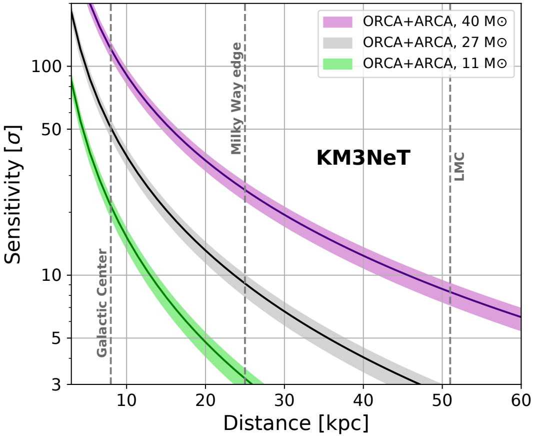
Sources of background

Radioactive decay: mostly ^{40}K in seawater

Bioluminescence: veto of PMTs with high rates

Atmospheric muons

CCSN detection sensitivity



KM3NeT detection sensitivity

Detection opportunities

Low eneregy, small cross-section → only Galactic or near-Galactic events are detectable, expected rate of ∼ 1.5 per century

The SNEWS network for CCSN detection

SNEWS (SuperNova Early Warning System)
Network connecting different neutrino detectors: if at least 2 detectors send a CCSN alert in less than 10 s, SNEWS sends a combined alert publicly to the community (FAR above 1 per century)

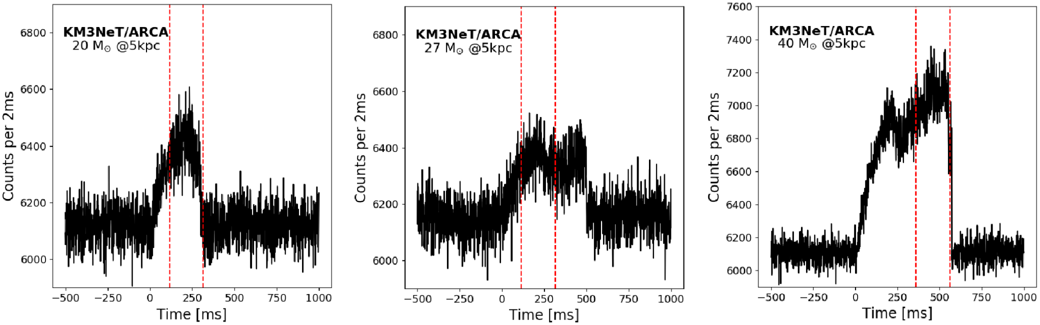
Detectors taking part in SNEWS
SuperK, LVD, IceCube, Borexino, KamLAND, HALO, Daya Bay, NOvA, KM3NeT and Baksan

Neutrino lightcurves

Light-curve analysis

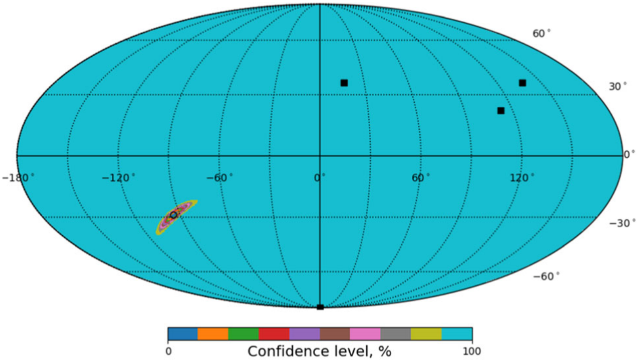
Neutrino lightcurve
Higher statistics of coincidences to perform time analysis, stored when emitting a `snews`-level alert

Possible analysis
Parameters estimation (distance, progenitor mass...), models constraints (oscillations in the lightcurve can be due to asymmetric hydrodynamic motions in the core...)



Simulated neutrino lightcurves

Source triangulation



Triangulation between four detectors (black squares): IceCube, KM3NeT/ARCA, Hyper-Kamiokande and JUNO

Arrival time estimation
With a neutrino telescope, possible to get the explosion time at the ms-level by fitting the neutrino arrival time with the light curves can help to perform triangulation

Triangulation between detectors
By combining arrival times for multiple neutrino detectors, it is possible to triangulate the source of emission

Estimated angular area
4 detectors: $\sim 70\,\text{deg}^2$, improvement with more detectors
SK (electron scattering): $\sim 69\,\text{deg}^2$
Crossmatch with SN candidates possible

SNEWS2.0

Upgrade to SNEWS currently in development

Modern alert system
Modernize the alert software to be compatible with modern multi-messenger networks (HOPSKOTCH framework developped by the SCiMMA project)

Thresholds
Multiple thresholds, to constantly exercise the alert emission and to provide subscribers with a "choose your own threshold" alert

Light-curve combination
Ability for experiments to compare neutrino light-curves in real-time and to extract physics quickly: necessary for triangulation

Conclusion

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Combining ARCA and ORCA, KM3NeT will be able to detect the next Galactic explosion with a 5σ discovery potential, and is currently connected to the SNEWS network, whose purpose is to find coincidences between neutrino detectors.

Light-curves are currently being computing when the significance is high enough, and they will be automatically transmitted to SNEWS2.0 soon. They will allow to measure parameters, constrain models of supernova formation and precisely measure the arrival time in order to triangulate the source signal and make follow-up observations.

References

The KM3NeT potential for the next core-collapse supernova observation with neutrinos, arXiv:2102.05977

Combining neutrino experimental light-curves for pointing to the next Galactic Core-Collapse Supernova, arXiv:2003.04864

SNEWS 2.0: A Next-Generation SuperNova Early Warning System for Multi-messenger Astronomy, arXiv:2011.00035