Status of KM3NeT supernova searches

SNEWS Virtual Meeting

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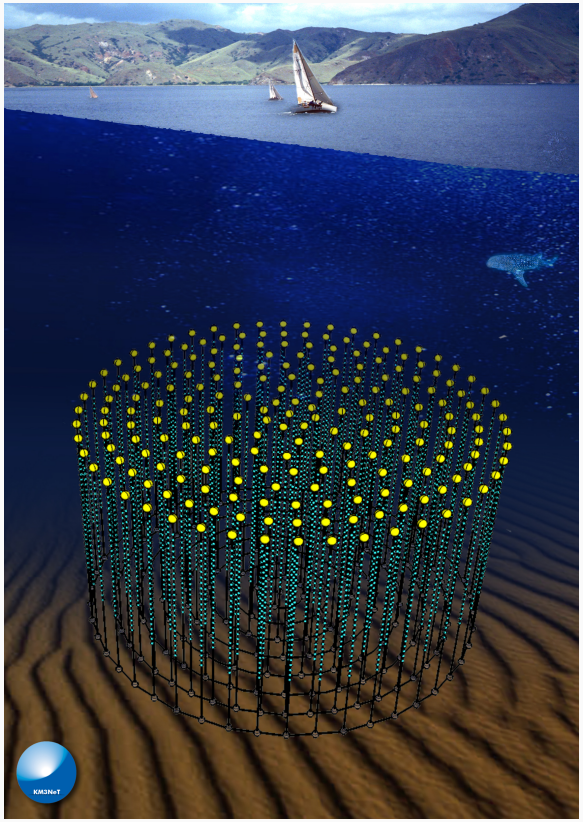
CCSN neutrino detection in KM3NeT

KM3NeT overview



KM3NeT detectors are large volume 3D arrays of digital optical modules (DOMs) arranged in vertical detection units (DUs).

31 PMTs / DOM, 18 DOMs / DU.

A total of $\sim 200\,000$ PMTs will instrument a km^3-sized volume of sea water.

The two detectors participate in a common **multi-messenger program** under active development.

Detector	Site	Depth	Scope	Energy	Strings	DOMs
ARCA	Italy	3500 m	ν astrophysics	TeV - PeV	230	4140
ORCA	France	2250 m	ν oscillations	1 - 100 GeV	115	2070

Status: 6 ORCA DUs are in operation, 2 ARCA DUs is stand-by (shore station restructuring).

KM3NeT and CCSN neutrinos

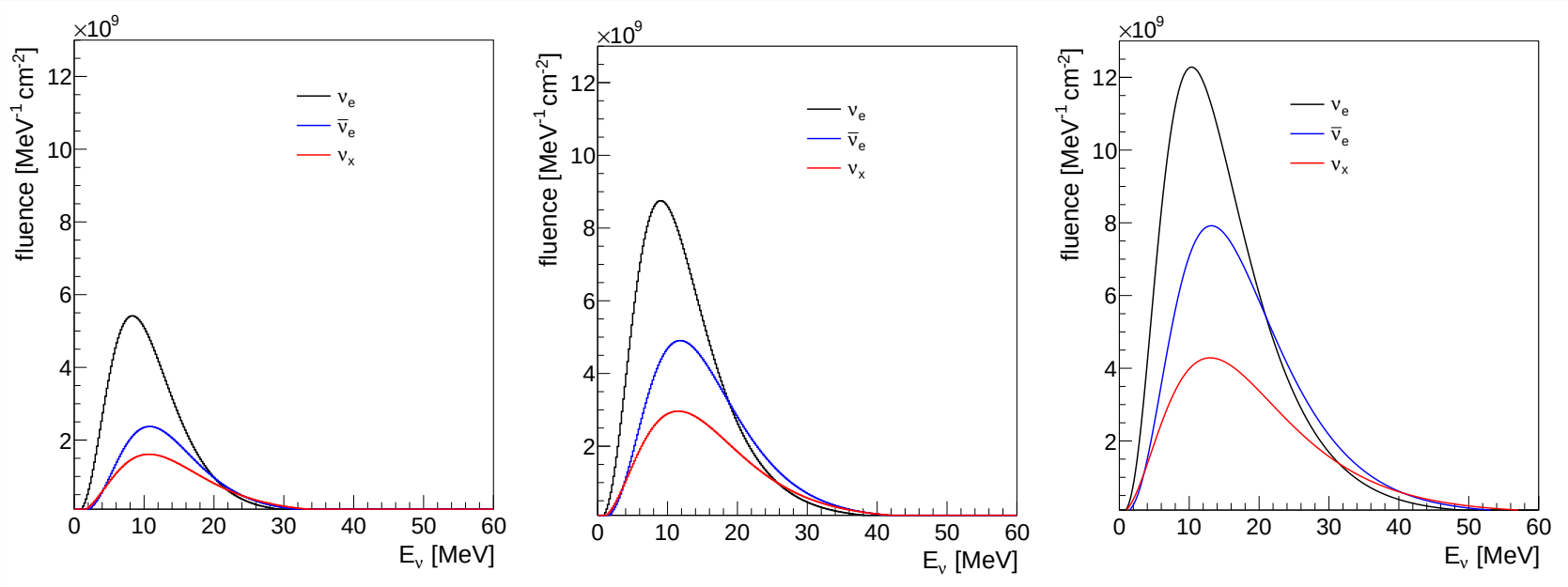
Quasi-thermal neutrinos at the 10 MeV energy scale are mostly detected through **inverse beta decay** (97%) and elastic scattering on electrons (3%).

The small track from the outgoing cannot be reconstructed but can **produce a single/multiple hits detected on a single DOM**.

Strategy: identification of a collective increase in the counting rate of the PMTs through a selection of **coincidences** where different PMTs on a DOM are hit.

Signal simulation

3D simulations of the **accretion phase** from the MPA Garching group[1]. Three progenitors: 11 $M_\odot$, 27 $M_\odot$ and 40 $M_\odot$ (black-hole formation).



Energy and time dependent interaction rate for IBD, elastic scattering and oxygen interaction is simulated.

GEANT4 and 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

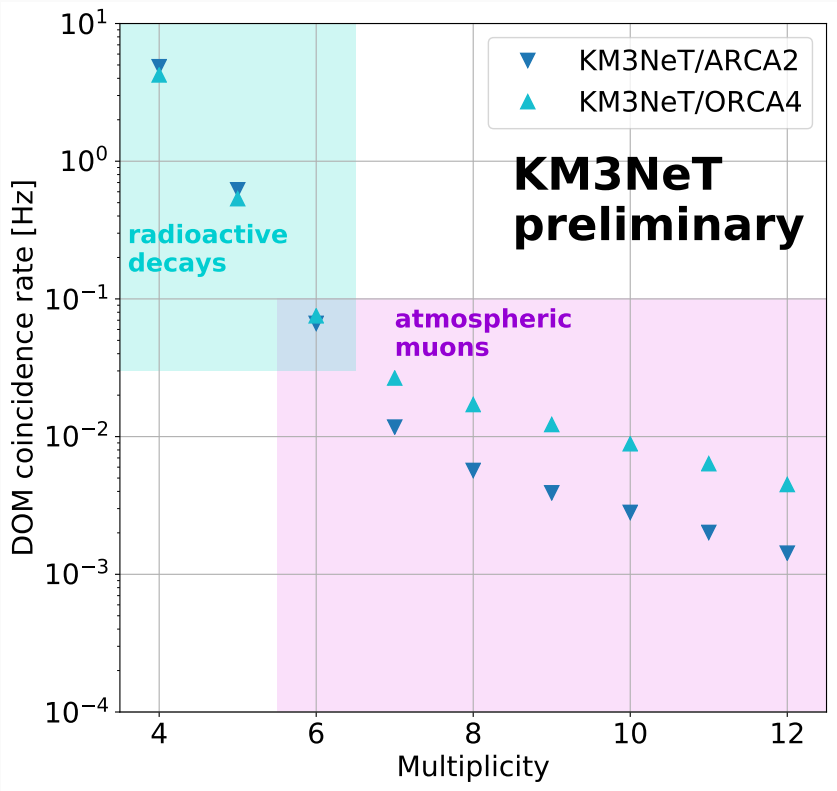
DOM background rates

Multiplicity (M) $\equiv$ number of PMTs hit in coincidence (10 ns). Used to discriminate the source of coincidences on a statistical basis.

Bioluminescence high-rate but single-photon process, unable to produce multiple photons with ns-scale correlation; suppressed at $M \geq 3$;

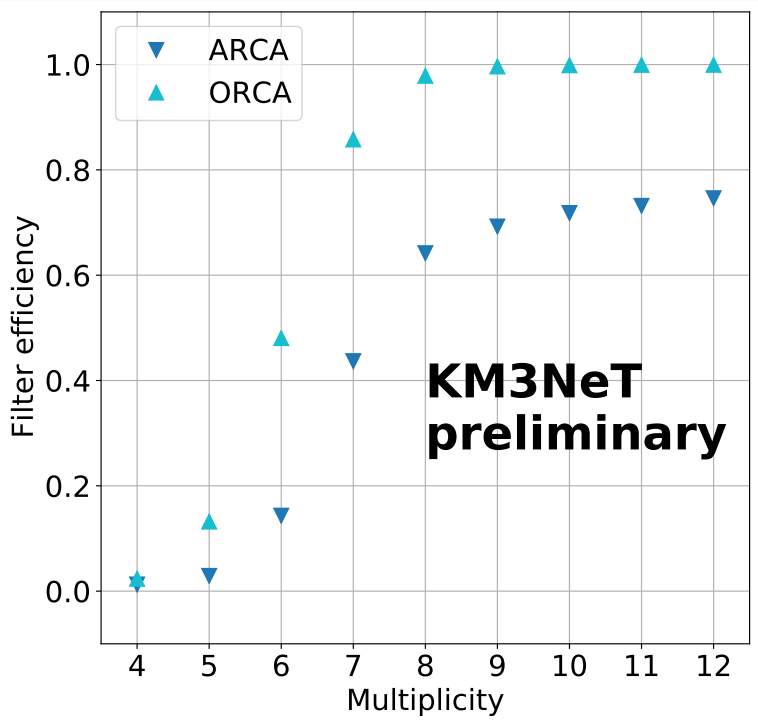
K40 decays small number of photons detected locally on a single DOM;

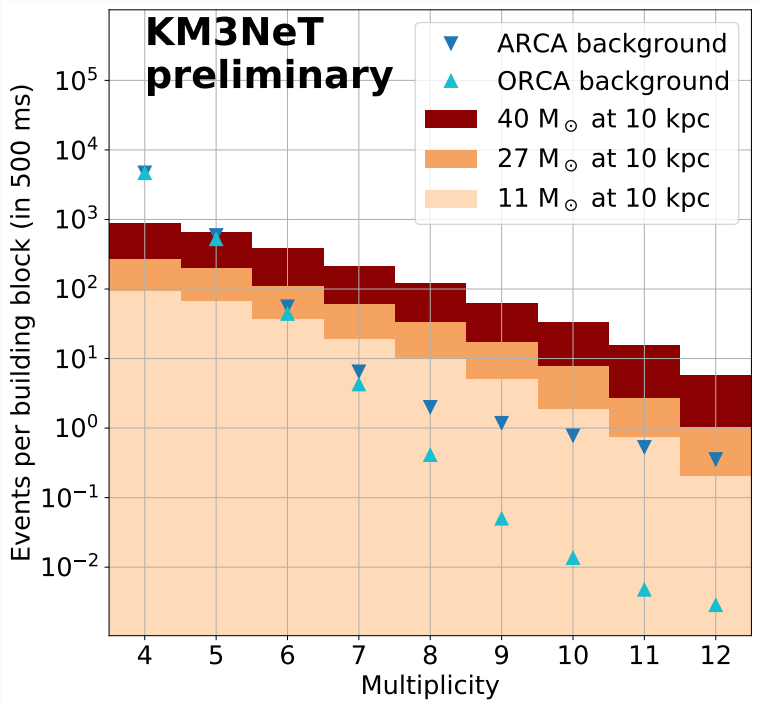
Atmospheric muons long tracks producing correlated coincidences on multiple DOMs.



Background filtering and selection

Muons tagged by the KM3NeT trigger are removed from the detected coincidences. A 500 ms time window after the onset time of the event is considered for the search.

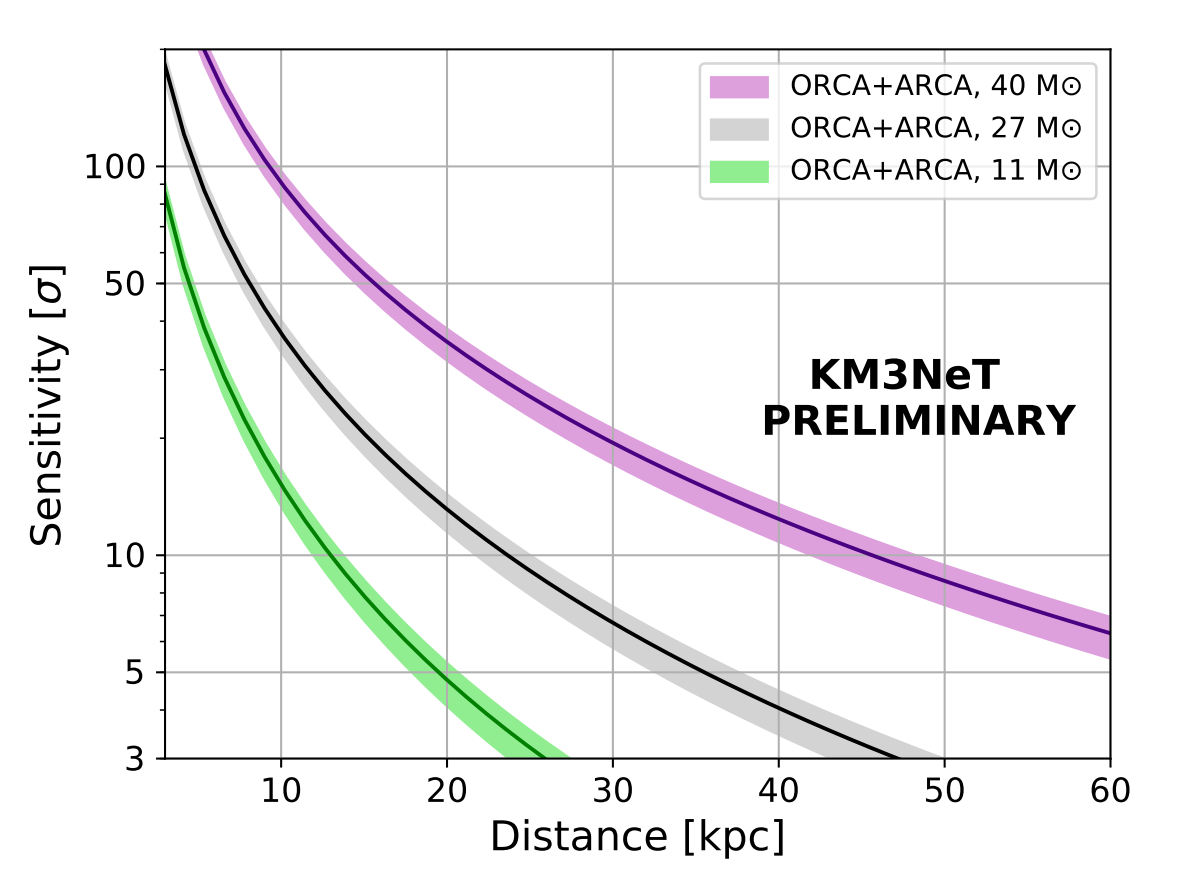




The [7,11] multiplicity selection is identified as the one providing the best sensitivity.

Sensitivity

Sensitivity calculated according to Poisson statistics based on the events in the [7,11] multiplicity selection.



5σ discovery potential: coverage of $>$ 95% of the progenitors in the Galaxy.

Effective mass

Estimated effective mass in *kton*, as a function of multiplicity.

The 11, 27 and 40 $M_\odot$ progenitors have mean energies $\langle E_\nu \rangle$ of 13.7, 15.7 and 18.2 MeV respectively.

Model	**Multiplicity**					
	2	**3**	**4**	**5**	**6**	**7**
11 $M_\odot$	40±4	12±3	5±1	2.5±0.6	1.3±0.4	0.6±0.2
27 $M_\odot$	53±5	16±3	7±1	4.0±0.9	2.0±0.6	1.0±0.4
40 $M_\odot$	67±7	21±4	9±2	5±1	2.7±0.8	1.5±0.5

Sensitivity selection ($7 \leq M \leq 11$): $M_{eff} \sim 1\,\text{kton}$ per 115 DUs.

Light-curve analysis ($M \geq 2$): $M_{eff} \sim 50\,\text{kton}$ per 115 DUs.

KM3NeT model in SNOwGLoBES

Smearing matrices lepton energy as a function of the neutrino energy, generated with `create_smearing_matrix.py` for inverse beta decay and elastic scattering on electrons;

Post-smearing efficiency detection efficiency for the outgoing lepton as a function of energy (identical for all channels).

Expected number of detected events

Flux	**IBD**	**ES**
Livermore	1.1×10^4	2.1×10^2
GVKM	1.7×10^4	3.5×10^2

Submitted as pull request #10 to public repository.

Online and quasi-online activities

First multi-messenger follow ups!

The CCSN search has been applied in the follow up of two LIGO-Virgo alerts: S191110af (November 2019, retracted) and S200114f (January 2020) with the available detector (ORCA 4 DUs).

No excess found.

Feldman-Cousins 90% upper limit on the signal expectation $S_{0.9}$ is used to determine lower limit on distance $d_{0.9}$ (at fixed luminosity) and upper limit on total energy $E_{0.9}$ (at fixed distance).

GCN #26249 (S191110a)

11 $M_\odot$ $d_{0.9} \simeq 5.7\,\mathrm{kpc}$

27 $M_\odot$ $d_{0.9} \simeq 11.4\,\mathrm{kpc}$

10 kpc $E_{0.9} \simeq 2.8 \times 10^{53}\,\mathrm{erg}$

GCN #26751 (S200114f)

11 $M_\odot$ $d_{0.9} \simeq 6.1\,\mathrm{kpc}$

27 $M_\odot$ $d_{0.9} \simeq 11.5\,\mathrm{kpc}$

10 kpc $E_{0.9} \simeq 2.9 \times 10^{53}\,\mathrm{erg}$

Real-time search

Every 100 ms, the number of signal and background events in the previous 500 ms is evaluated. The significance is estimated for each detector. **Detectors are combined synchronously (weighted combination of significances)**. The resulting p-value corresponds to a **false alarm rate** (FAR):

$$\mathrm{FAR}(P_{\mathrm{combined}}) = (100\,\mathrm{ms})^{-1} \cdot P_{\mathrm{combined}}$$

For a given maximum FAR, the corresponding distance at which a signal can produce the equivalent significance is determined.

Distance d_{max} for a FAR threshold of **1 / (8 days)**

ORCA 6 DUs

Model	d_{max} (kpc)
11 $M_\odot$	5.4
27 $M_\odot$	9.5

current operation

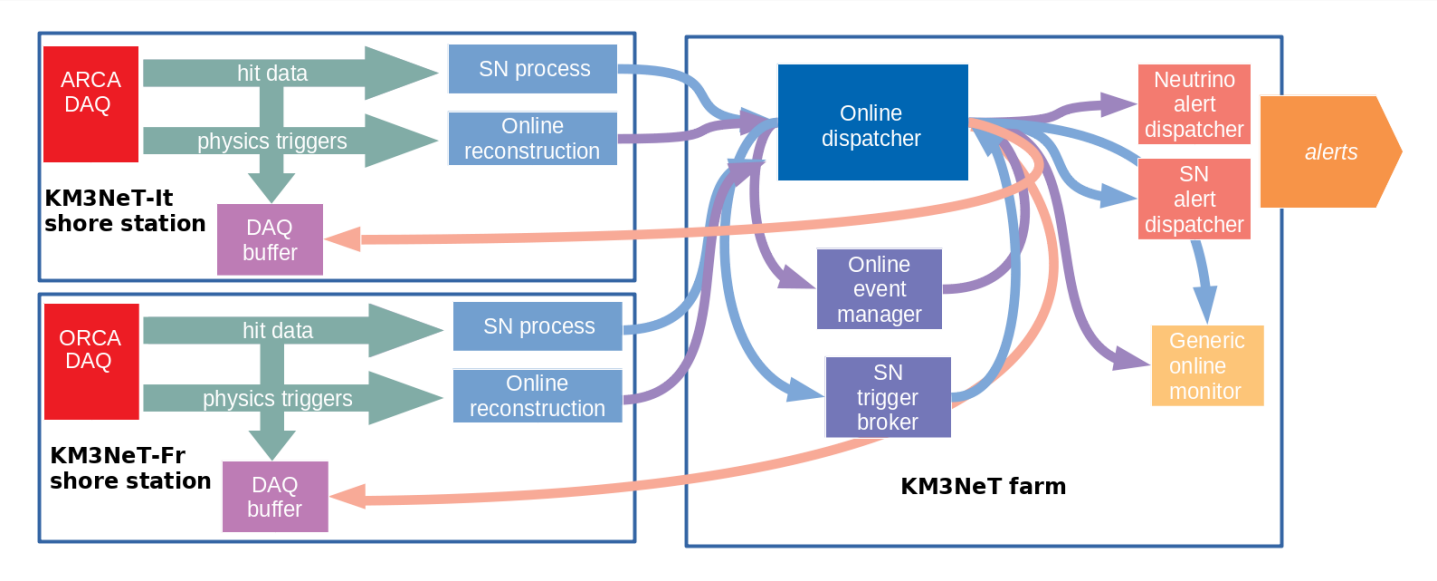
ARCA 6 DUs + ORCA 13 DUs

Model	d_{max} (kpc)
11 $M_\odot$	7.5
27 $M_\odot$	13.4

spring 2021 forecast

Online framework

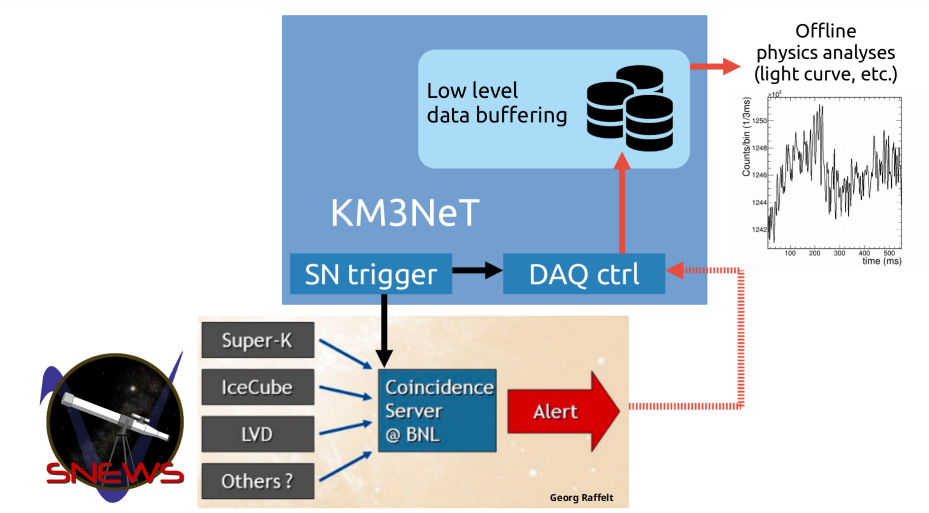
All-data-to-shore DAQ → **dedicated data streams** for different real-time analyses.



While the SN search is based on [7,11] multiplicity coincidence, **all coincidence data is buffered** and can be stored if a trigger is received, e.g.: GCN alerts (gravitational waves), SNEWS, or detection above a designated threshold from KM3NeT itself.

KM3NeT meets SNEWS

KM3NeT data are processed on-shore in real-time within $\leq 2s$ from the recording time of the hits off-shore. A 10 s buffer is adopted in the online supernova search. Uptime $> 90\%$. Mean latency < 15 s.



KM3NeT is currently sending alerts to the **SNEWS test server**! (FAR slightly above 1 / day). System ready for the **production server**, waiting for things to be cleared up on the LBL side.

A *dead time* is applied to avoid sending multiple alerts in case of anomaly.

Astrophysics perspectives

What can we learn?

Time-dependent analysis

Timing of the neutrino burst (*preliminary*: 10-20 ms resolution).

Triangulation (see Vladimir's talk tomorrow!)

Detection of SASI oscillations.

Multiplicity analysis

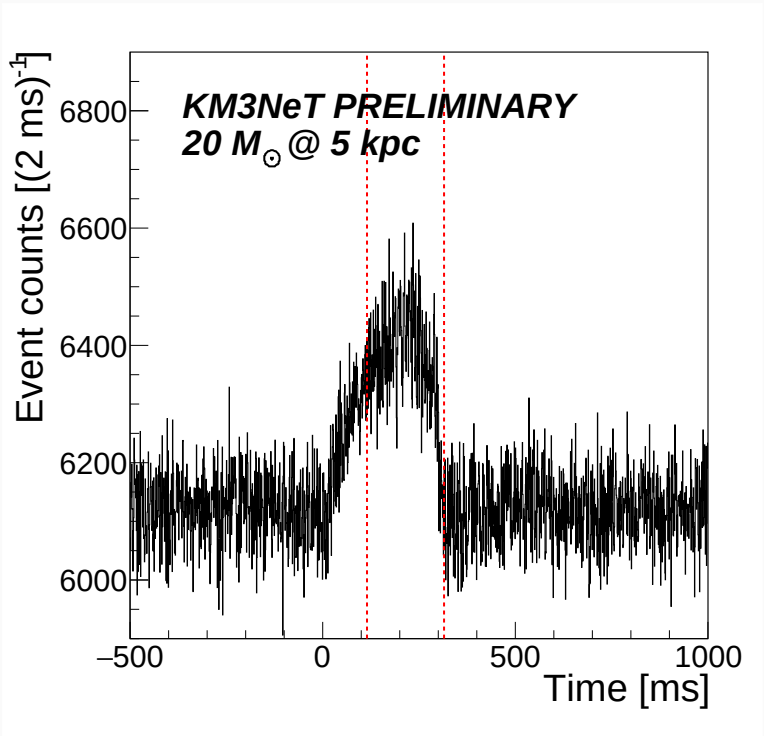
Multiplicity distribution depends on the $\overline{\nu}_e$ neutrino energy spectrum.

Preliminary: $\leq 1\,\mathrm{MeV}$ resolution can be achieved if the signal normalisation and the spectral pinching are known.

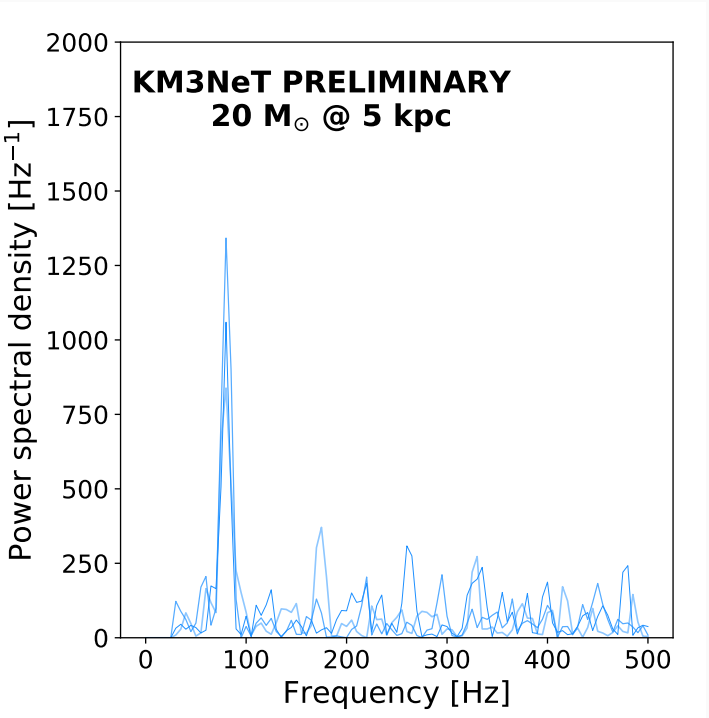
Detecting the SASI oscillation /1

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 with SASI at 5 kpc - ARCA 230 lines. Use of all coincidences. **Fourier analysis of the light curve.**



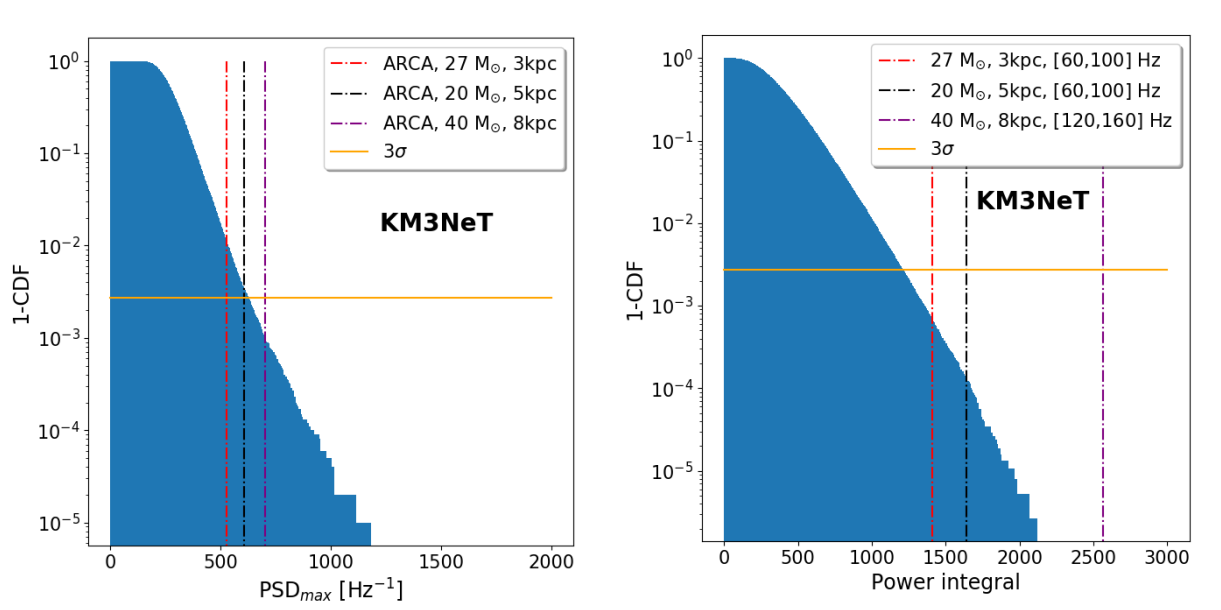
Detected neutrino light curve.



Light curve power spectrum.

Detecting the SASI oscillation /2

Depending on the assumption of *known* or *unknown* SASI frequency, the analysis searches for either an **energy excess** around the predicted frequency or a **peak in the power spectrum** at any frequency.



Progenitor	d [kpc]	Method 1: Search for peak in spectrum	Method 2: Search for power excess around f_{SASI}	Coverage of Galactic CCSNe
27 $M_\odot$	3	$2.8\pm0.7\sigma$	$4.1\pm0.9\sigma$	3%
20 $M_\odot$	5	$3.2\pm0.7\sigma$	$4.5\pm0.9\sigma$	10%
40 $M_\odot$	8	$3.8\pm0.7\sigma$	$>5\sigma$	35%

Conclusion

Conclusion

The **CCSN neutrino search** has been optimised with improved simulations and background rejection strategies.

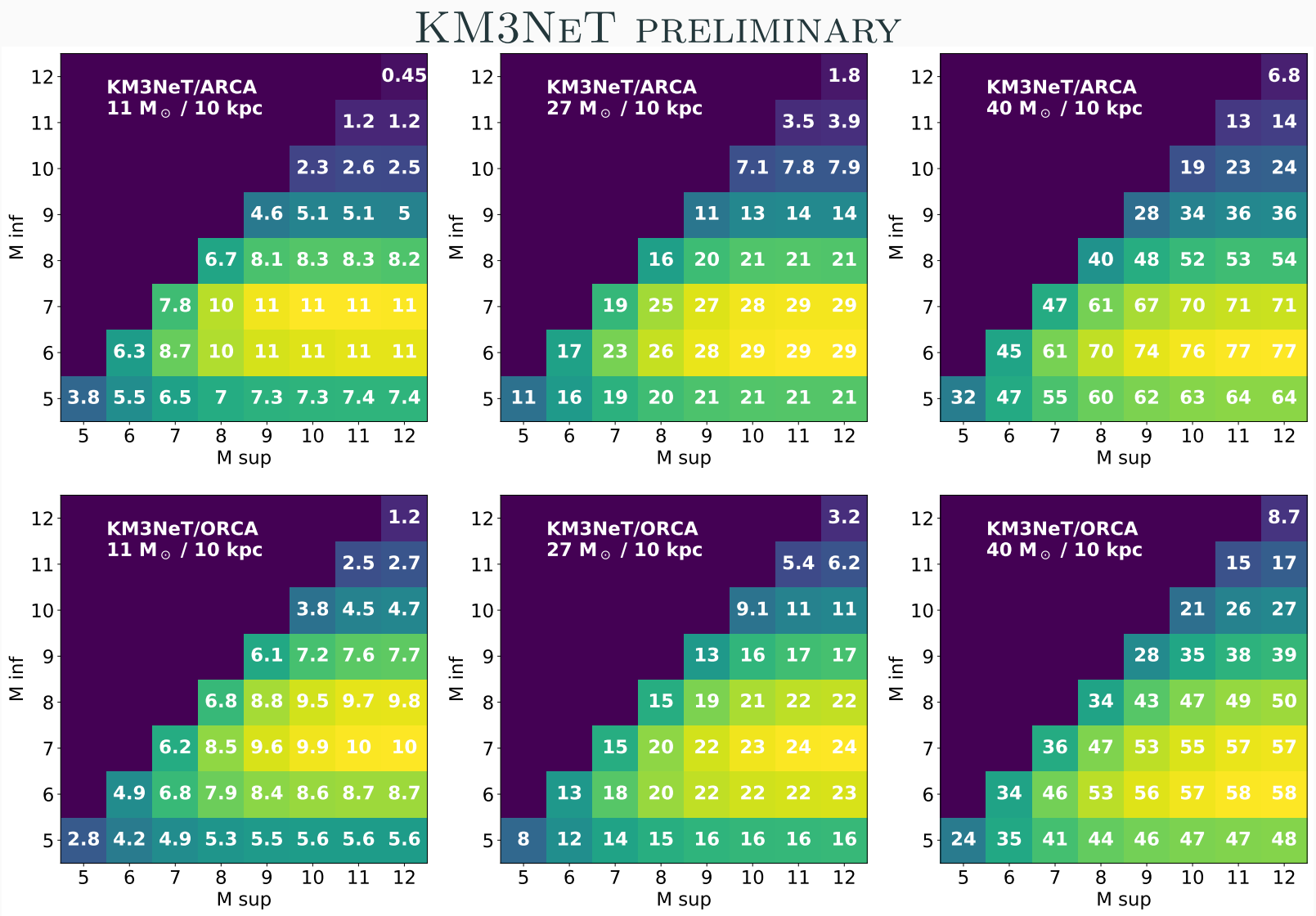
The **real-time** monitoring is operational since the early months of 2019, and has shown stable and predictable behaviour of the detector and filtering algorithm.

The **first follow-up analyses** of external alerts (LIGO-Virgo unmodeled bursts) have been performed, producing the first two **GCN circulars**.

Good perspectives for doing **CCSN astrophysics** with a fully-built KM3NeT detector.

Backup

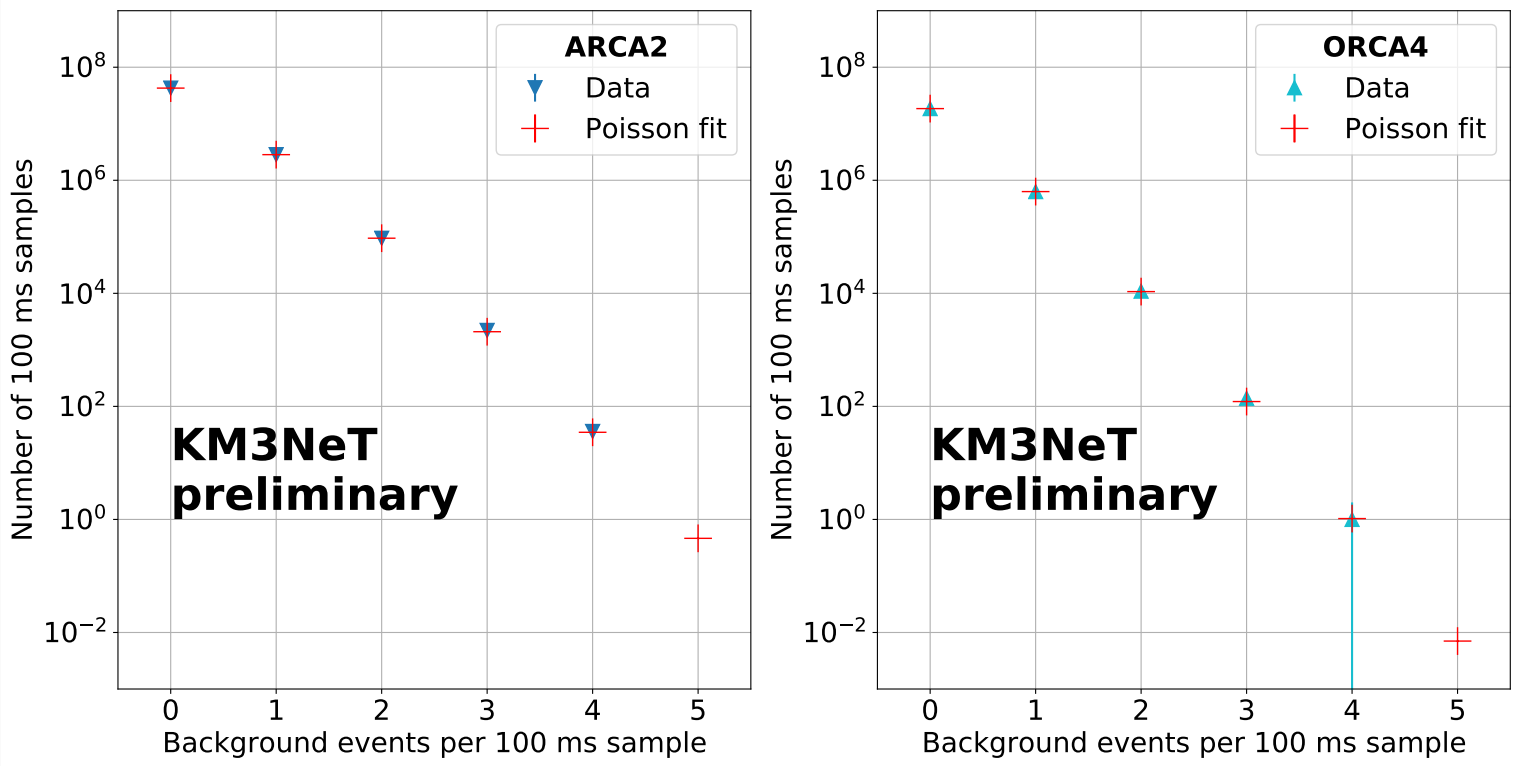
Multiplicity selection



Mutiplicity range [7,11] is optimal.

Filter robustness

Data taking periods for ARCA2 and ORCA4 are analysed over samples of 100 ms each and the number of background events per sample is counted.



Poisson distribution is plotted according to the mean value of the data.

No accumulation of correlated background events is observed!