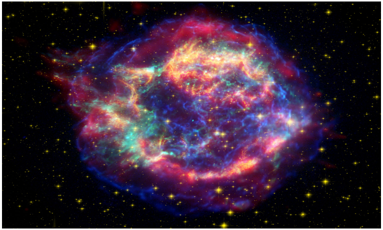
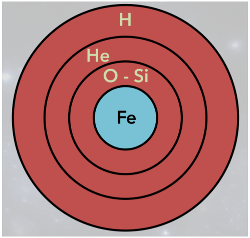
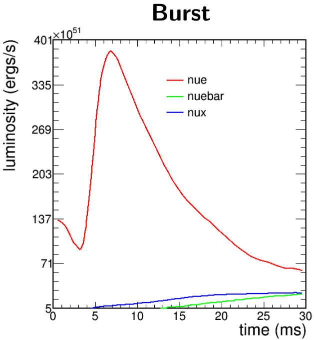
Core Collapse SuperNovae sensitivity study with the KM3NeT neutrino telescopes

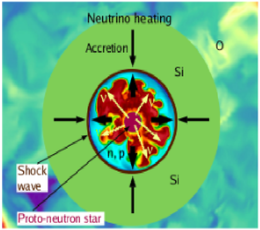
Marta Colomer Molla, APC/IFIC
On behalf of the KM3NeT collaboration



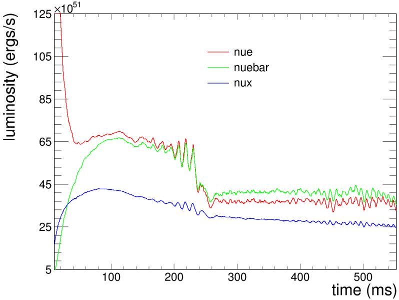




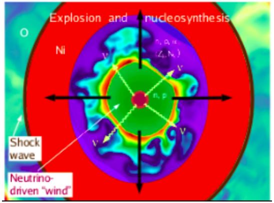
- Stars with M $\geq$ 10 M$\odot$ + onion structure.
- Gravitational instability: gravity wins vs. degenerate electron pressure $\rightarrow$ collapse.
- Neutrino emission by electron capture: $p + e^- \rightarrow n + \nu_e$.
- Nuclear density is reached: stops collapse of inner core.
- Infalling matter bounces on the core.

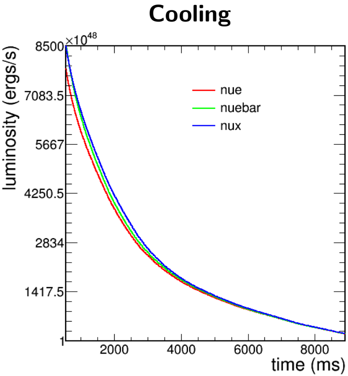


Accretion



- Shock wave formation.
- Shock propagates and loses energy through neutrino emission.
- Shock stalls and accretion starts.
- Hydrodynamical instabilities take place (convection, SASI)
- Neutrino heating: shock receives energy from neutrinos.
- Shock expansion driven by neutrino-energy deposition.

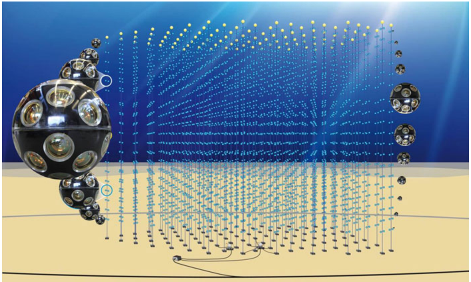




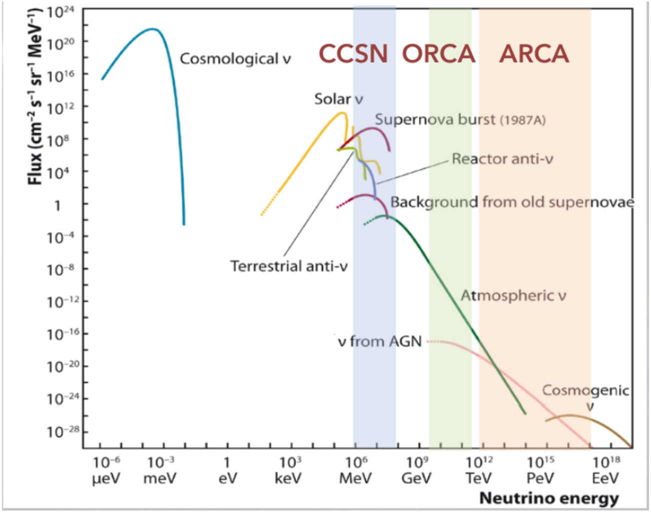
- Shock revival.
- Cooling phase.
- Photo-dissociation of heavy nuclei.
- ν pair production of all flavors.
- Nucleosynthesis and explosion.
- 99% of the gravitational binding energy carried out by neutrinos on a 1-100 MeV energy scale.

Two Cherenkov detectors under construction in the Mediterranean sea with two main purposes:

- The observation of high-energy astrophysical neutrinos (TeV-PeV) from cosmic sources (ARCA, 2blocks of 115 strings, Italy)
- Detection of atmospheric neutrinos (GeV) passing through the Earth to probe the neutrino mass hierarchy (ORCA, 1block of 115 strings, France)
- Not optimal to detect MeV neutrinos from CCSN.



Neutrino energy spectra for different sources



- Test the capability of KM3NeT to detect MeV neutrinos from CCSN: ORCA + ARCA allow a self-confirmation of the detection!
- Study the sensitivity to oscillations in the ν lightcurve.
  - Fully understand the CCSN explosion mechanism, not yet reproduced by simulations.
  - Account for expected asymmetries: SASI.
- Measure neutrino properties: determine mass hierarchy (MH), flavor conversion.
- BSM physics in extreme conditions: $\nu - \nu$ interactions, steriles, etc.
- Network of CCSN neutrino detectors would provide:
  - More statistics, needed to constrain theoretical models.
  - Point to the CCSN (triangulation).

- Large distance between DOM and small e^+ (e^-) tracks
  $\rightarrow$ we need to detect a collective rise in all PMT rates on top of the noise.
- Low energy neutrinos and high background due to bioluminescence + ^{40}K.
- Selection of coincidences between PMTs allows to reduce the dominant background contributions.

KM3NeT DOM

31 3" PMTs

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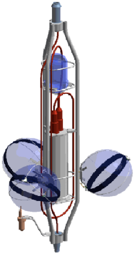
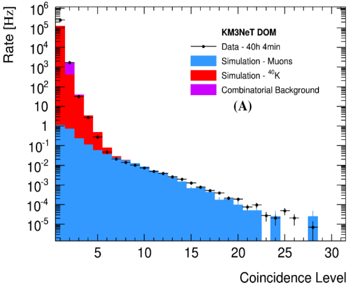
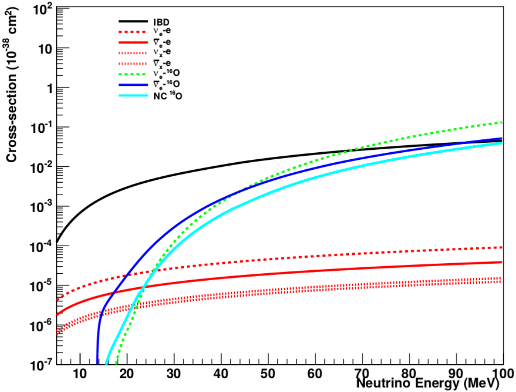


3 10" PMTs

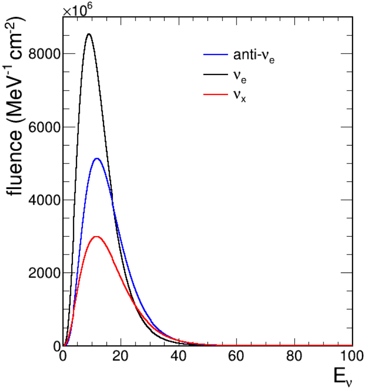


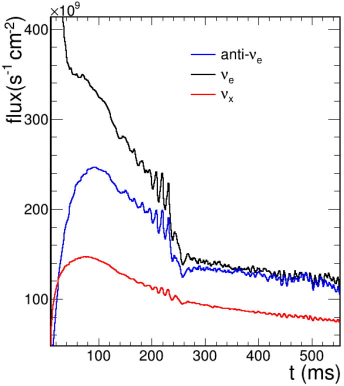
Interaction modes:

- Inverse beta decay (IBD) (97%): $\overline{\nu}_e + p \rightarrow e^+ + n$
- Elastic scattering (ES) ($\sim$3%): $\nu_l + e^- \rightarrow \nu_l + e^-$
- Neutrino interactions with Oxygen atoms (<1%): $\nu_e + {}^{16}O$, $\overline{\nu}_e + {}^{16}O$



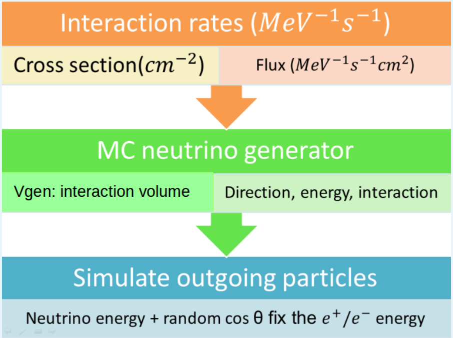
- CCSN neutrino flux from 3D CCSN simulations by the Garching Group[1]
  $\rightarrow$ Quasi thermal distribution.
- Provides energy and time dependence of the 3 parameters in the model: $L(E_\nu,t)$, $\alpha(E_\nu,t)$ and $\langle E_\nu \rangle\,(t)$, for each neutrino flavor
  $\rightarrow$ The neutrino spectrum and light-curve.





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

- Development of a low energy MC neutrino generator for KM3NeT.
- Takes into account direction of particles and flux time dependence and includes all neutrino interactions.

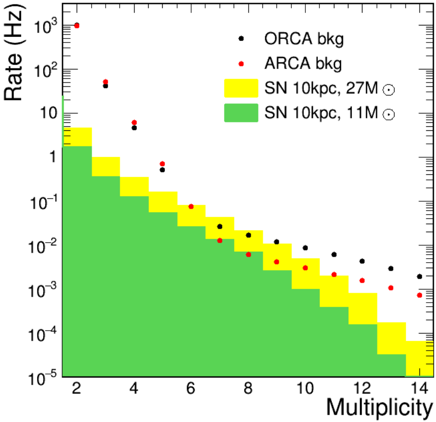


- GEANT4 simulation (KM3Sim) for the propagation of particles produced by ν interactions and the propagation and detection of Cherenkov light.
- Simulation of PMT response using KM3NeT software for data analysis.

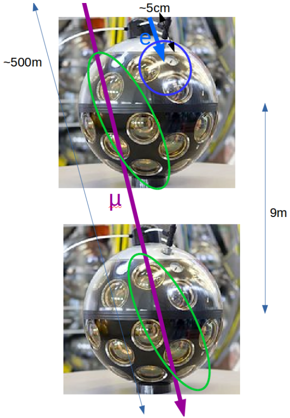
Multiplicity rates per DOM for a CCSN at 10 kpc

- Multiplicity (M): number of PMTs in a DOM receiving a hit within 10 ns.
- The most significant excess over the background is observed from multiplicities 6 to 10.
- Characteristic multiplicity distribution different for signal and background.

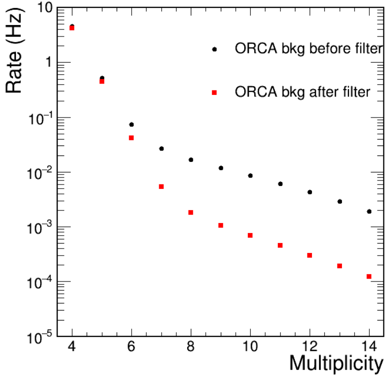
KM3NET PRELIMINARY



- Reject events with at least two $M \geq 4$ coincidences within $1\,\mu$s on different DOMs.
- Introduces a 2% dead time dominated by ^{40}K random coincidences.



KM3NET PRELIMINARY



$\rightarrow$ Background distributions extracted from the data of the first lines deployed in the sea.

KM3NET PRELIMINARY

Multiplicity	1	2	3	4	5	6	7	8	9	10
N_{ev} $27M_{\odot}$	1.6e5	5.0e3	1.0e3	3.8e2	1.7e2	88	46	23	12	5
N_{ev} $11M_{\odot}$	4.1e4	1.2e3	247	85	38	18	9	5	2	1

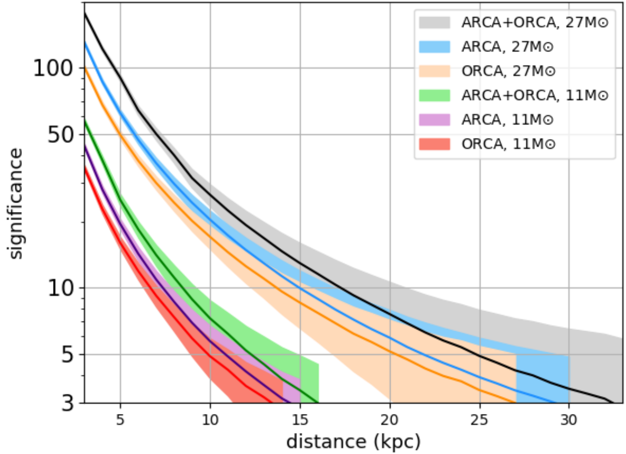
Table: Signal event statistics as a function of the multiplicity

Progenitor mass	Δt (ms)	N_b ORCA	N_b ARCA	N_s
27 $M_{\odot}$	543	60	98	174
11 $M_{\odot}$	340	38	61	34

Table: Number of background and signal events in the 6-10 multiplicity cut after the muon filter, per KM3NeT building block in ORCA and ARCA.

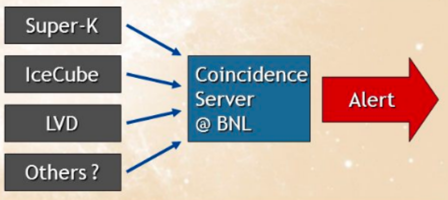
Remark: ARCA performance improvement is expected from a refinement of the muon filter.

KM3NET PRELIMINARY



- ORCA + ARCA combined sensitivity of 5 σ at 25 kpc for a 27 $M_\odot$ progenitor.
- ORCA sensitivity above 5 σ at the Galactic Center for a 11 $M_\odot$ progenitor.

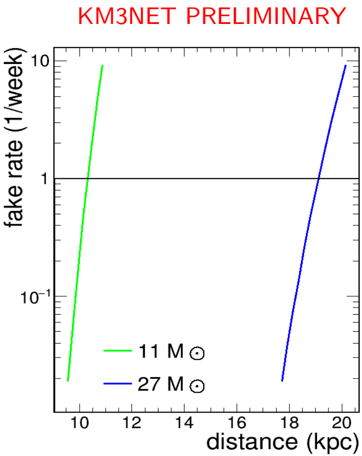
- Global network of neutrino detectors for sending CCSN alerts to the community [2] .
- Coincidence between detectors are evaluated in order to produce alerts.
- Participation to the upstream requires a false trigger rate below 1/week.



Trigger principle evaluated in KM3NeT:

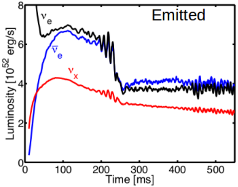
→ Trigger on the number of DOMs detecting a coincidence in the multiplicity range (6-10) after applying the filter, over sliding time window (some hundreds of ms), sampled on a 100 ms time scale.

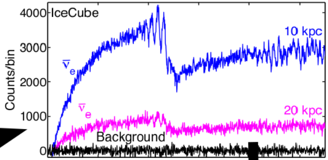
[2] https://snews.bnl.gov/



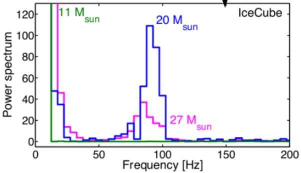
The complete ORCA detector allows the triggering of a CCSN keeping the false alert rate below the SNEWS threshold of 1/week:
→ Up to 18.6 kpc in the case of an 27M⊙ progenitor.
→ Above the Galactic Center for the 11M⊙ progenitor.

- Standing Accretion Shock Instability (SASI): hydrodynamical instabilities during CCSN accretion phase predicted by state-of-the-art 3D simulations.
- Enhances the neutrino heating favoring the explosion and could explain the neutron star kick observed.
- Footprint: Time variations in the neutrino light-curve around 200ms after bounce.
- Feature: Characteristic oscillation frequency (80Hz) seen with Fourier analysis.





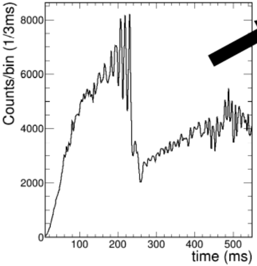
Detected IC signal and bckg

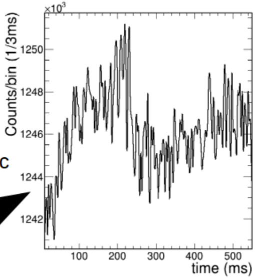


Power spectrum IC

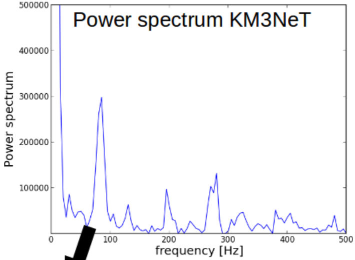
KM3NET PRELIMINARY

Expected KM3NeT signal 5kpc





Expected KM3NeT 5kpc:
signal +background



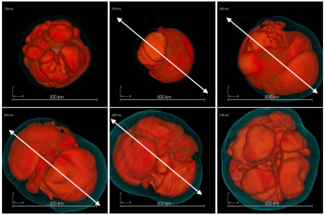
KM3NeT (1block) sensitivity to SASI oscillations: 3σ @5kpc

Conclusions

- First "end-to-end" MC simulation of CCSN neutrinos for KM3NeT.
- Analysis of first ORCA and ARCA data to determine background.
- 5σ combined significance to a CCSN at 25kpc for a $27M_\odot$ progenitor $\rightarrow$ **Coverage of the full Galaxy**.
- 5σ at the Galactic Center with full ORCA for a $11M_\odot$ progenitor.
- Able to trigger a CCSN with SNEWS requirement with full ORCA:
  - Up to 18.6 kpc in the case of the $27M_\odot$ progenitor.
  - Over the Galactic Center for the $11M_\odot$ progenitor.
- A significance of 3σ is reached to the SASI oscillations for a CCSN at 5kpc ($27M_\odot$ progenitor) with 1 KM3NeT block.
- The construction of KM3NeT has already started and the results of the 1st lines have allowed a better understanding of the detector physics.
- By the end of the year, 5 ORCA lines deployed taking data!

Backup

- 3D CCSN accretion phase simulation by the Garching Group.
- Realistic neutrino flavor conversion and transport models.
- Predict hydrodynamical instabilities during CC and neutrino light curve.
- Anisotropic instabilities (SASI): flux dependent on the observer direction.
- Direction with respect to the SASI oscillation (maximum flux variation).



Realistic, time dependent flux:

$$\frac{d\Phi^{\nu}}{dE_{\nu}}(E_{\nu}, t) = \frac{L(t)^{\nu}_{SN}}{4\pi d^2} \times f(E_{\nu}, < E_{\nu}(t) >, \alpha(t)), \text{ with d} = 10 \text{ kpc} \quad [1]$$

$$f(E_{\nu}, t) = \frac{E_{\nu}^{\alpha}}{\Gamma(\alpha+1)}\left(\frac{\alpha+1}{<E_{\nu}>}\right)^{(\alpha+1)} exp\left[\frac{-E_{\nu}(\alpha+1)}{<E_{\nu}>}\right] \quad [2]$$

alpha is the shape parameter: $\alpha(t) = \frac{<E_{\nu}^2> - 2<E_{\nu}>^2}{<E_{\nu}>^2 - <E_{\nu}^2>}$ [3]

Neutrino flavor conversion models in CCSN

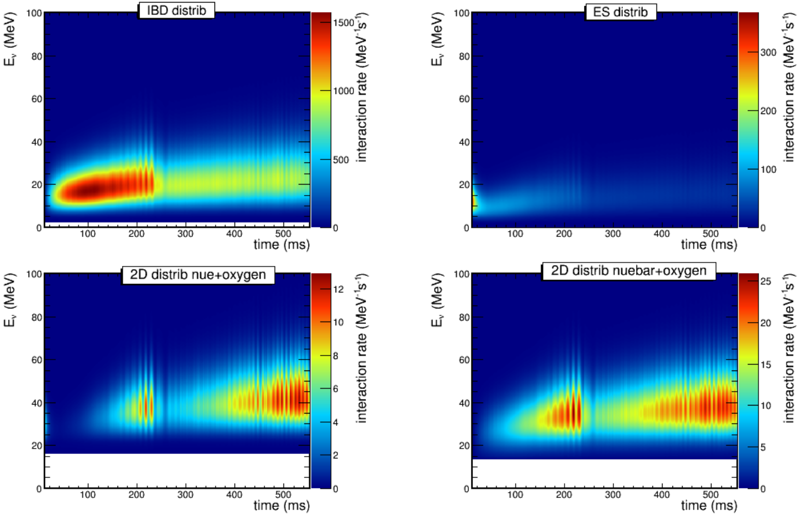
- Flavor conversion caused by flavor mixing ignored (the strong matter effect "de-mixes" neutrinos).
- Simplest traditional picture: adiabatic flavor conversion (MSW effect): recent measurement of the third mixing angle θ_{13} being fairly large $\rightarrow$ the entire three-flavor conversion process would be adiabatic
- IH hypothesis: All $\overline{\nu_e}$ oscillate into $\overline{\nu_x}$.
- NH hypothesis: 70% $\overline{\nu_e}$ survival probability.
- This simple prediction can get strongly modified by two effects:
  - The density profile can be noisy and show significant stochastic fluctuations that can modify the adiabatic conversion.
  - The impact of neutrino-neutrino refraction which can lead to self-induced flavor conversion.
- The $\overline{\nu_e}$ flux arriving at the detector will be some superposition of the original $\overline{\nu_e}$ and $\overline{\nu_x}$ flux spectra.

The two extreme hypothesis will be studied, for 27 $M_\odot$ simulation:

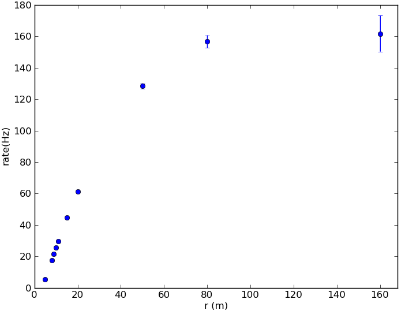
- No Flavor Swap (NFS, best case scenario): All $\overline{\nu_e}$ are detected as $\overline{\nu_e}$.
- Full Flavor Swap (FFS, or IH case, worst cases scenario): All $\overline{\nu_e}$ are detected as $\overline{\nu_x}$.

- Computation of neutrino interaction rates for 100 kton of water:

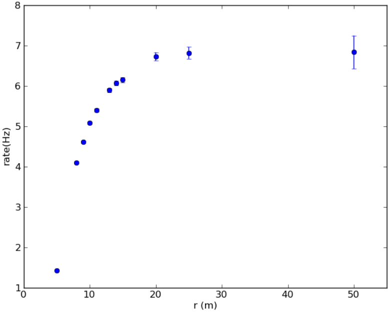
$$R_{int}(\frac{1}{MeVs}) = flux(E_\nu, t)(\frac{1}{MeVcm^2}) \times \sigma(E_\nu)(cm^2) \times N_{target}(100\text{kton water})$$



single hits



double coincidences



- For double coincidences: V_{gen} = sphere of 20m radius.
- For single hits, one must go to R=80m to saturate SN rates...

$\#\nu$s is the number of detected neutrinos per DOM in 1 KM3NeT block for a SN at 10kpc within the multiplicity selection: $6 \leq M \leq 10$

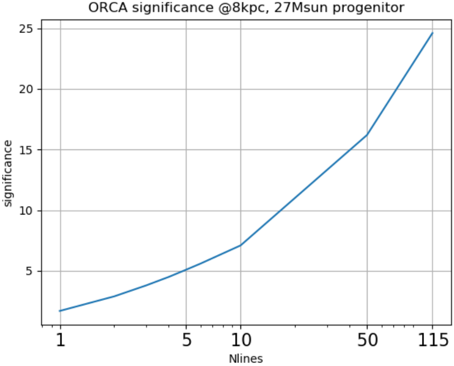
Table: Expected signal events and significance for different models.

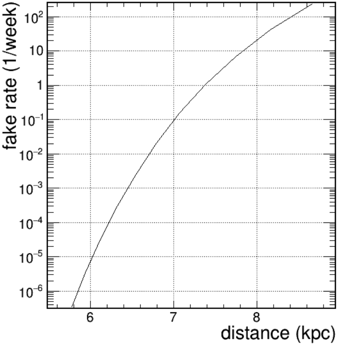
Model	**Δt (ms)**	**Progenitor Mass ($M_\odot$)**	**$\#\nu$s**	**rate (Hz)**
Garching 3D NFS	543	27	174	320
Garching 3D FFS	543	27	146	269
Garching 3D NFS	340	11.2	34	100
Garching 3D NFS	340	20	121	356
Garching 1D NFS	1000	8.8	39	39

Table: Systematic uncertainties in terms or relative deviation in $\#\nu$s.

Source of systematics	syst error(%)	significance error (σ)
Run conditions	10	$\pm 0.5\sigma$
Effective volume	3	-
Direction of the source	<1	-
Water density as function of depth	<1	-
Cross section	<1	-
——	-	-
Oscillation scenarios (FFS-NFS)	16	$\pm 1\sigma$
Total luminosity prediction models	20	$\pm 1.5\sigma$

$\rightarrow$ A total systematic uncertainty of $\pm 2\sigma$ is estimated.





- Offline: We could reach 5σ at the Galactic Center with just 5 ORCA lines!
- Online: We could trigger a detection with just 5 lines up 7.3kpc!

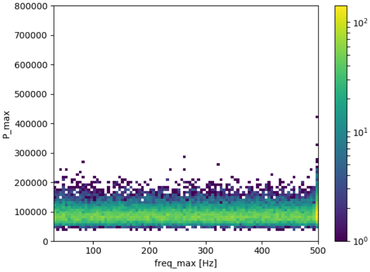
Sensitivity to time variations.

- Simulation for the NFS case and the 27 $M_\odot$ progenitor of a CCSN at 5kpc.
- Compute the detected neutrino light-curve.
- Add optical background: Poissonian fluctuations around total mean rate:

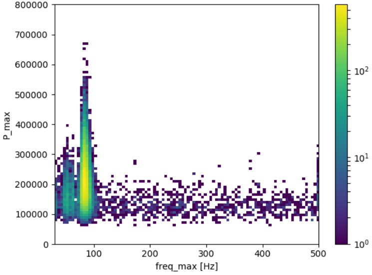
$$R_{tot} = Poisson(Mean(R_{signal})) + Poisson((Mean(R_{bckg})))$$

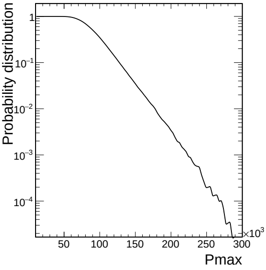
- All background included: value of the total measured background rate used (200 kHz per DOM for L0 from ORCA DU2 data).
- Apply the FT to recover frequency of SASI oscillations, $f_{SASI} = 80Hz$.
- Estimate the significance of SASI peak detection through Monte-Carlo pseudo-experiments.
- Evaluate the change on the significance with different L0 rates.

only background



background + signal at 5kpc





RUNNING:

Detector	Type	Location	Mass(kton)	Events(10kpc)	Flavor
Super-K	H_2O	Japan	32	7000	$\overline{\nu_e}$, ν_e
LVD	C_nH_{2n}	Italy	1	300	$\overline{\nu_e}$
KamLAND	C_nH_{2n}	Japan	1	300	$\overline{\nu_e}$
Borexino	C_nH_{2n}	Italy	0.3	100	$\overline{\nu_e}$
IceCube	Long string	South Pole	10^6	3×10^5	$\overline{\nu_e}$
ANTARES	Long string	France	10^4	200	$\overline{\nu_e}$
NOνA	C_nH_{2n}	USA	15	4000	$\overline{\nu_e}$
MiniBooNE	C_nH_{2n}	USA	0.7	200	$\overline{\nu_e}$
Daya Bay	C_nH_{2n}	China	0.33	100	$\overline{\nu_e}$

FUTURE:

Detector	Type	Location	Mass(kton)	Events(10kpc)	Flavor
Hyper-K	H_2O	Japan	560	10^5	$\overline{\nu_e}$, ν_e
DUNE	Ar	USA	34	3000	$\overline{\nu_e}$
MicroBooNE	Ar	USA	0.17	17	$\overline{\nu_e}$
JUNO	C_nH_{2n}	China	20	6000	$\overline{\nu_e}$
ORCA	Long string	France	8×10^3	1×10^5	$\overline{\nu_e}$
ARCA	Long string	Italy	10^6	2×10^5	$\overline{\nu_e}$
KM3NeT	Long string	It/Fr	10^6	3×10^5	$\overline{\nu_e}$

- Estimation of **average background rates** does not guarantee that the detector has a predictable behavior on short timescales;
- **Short timescale** analysis is always necessary to be sure that there are no outliers.

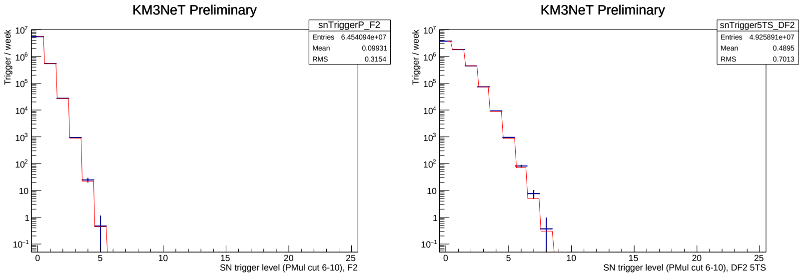


Figure: Post-filter background distributions in first ORCA line for 100 (left) and 500 ms (right) time windows, no outliers compared to a poissonian fit (rate: $\rho \simeq 1Hz$)

- Anomalies in DOM behavior have been observed in the data of the first two ARCA lines, without apparent correlation between DOMs (single-DOM anomaly);
- Future lines should be monitored for similar behavior;
- Online analysis can rely on DOM counting approach (number of DOMs detecting at least a coincidence in the chosen multiplicity cut).

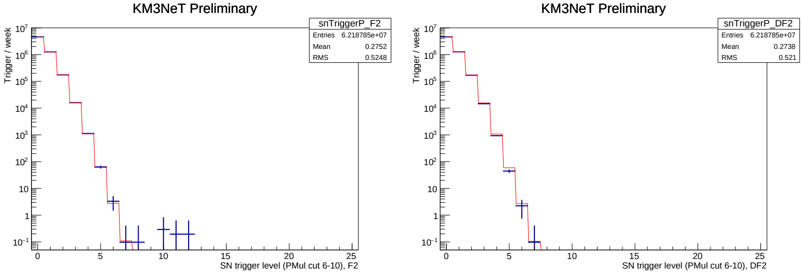


Figure: Post-filter background distributions in the first two ARCA lines for a 100 ms time window, coincidence counting (left) vs DOM counting (right)

- Bioluminescence bursts are suppressed by muting PMT channels which record an anomalous high rate ($\geq 20KHz$), the so-called *high-rate veto*;
- The rejection seems is effective (only loss of efficiency but no increase in coincidence rates).

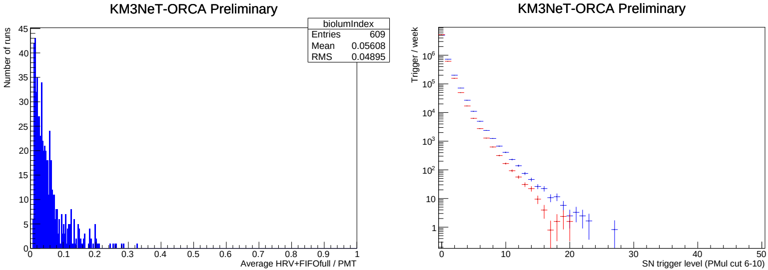


Figure: Left: number of runs vs. average number of vetoed channels during the run for the whole ORCA data taking period, right: trigger level before any filter for high-bioluminescence (red) and low-bioluminescence (blue) ORCA runs.

ORCA background distribution for M=6 to M=9 from available runs:

KM3NET PRELIMINARY