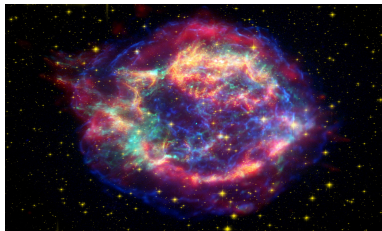


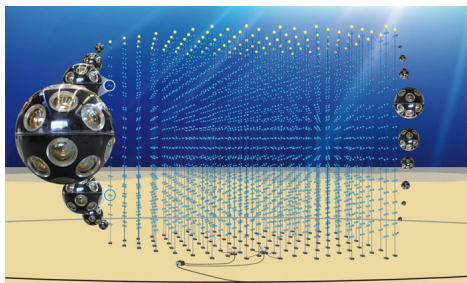
Prospects for Core Collapse SuperNovae (CCSN) detection with the KM3NeT neutrino telescopes

Marta Colomer

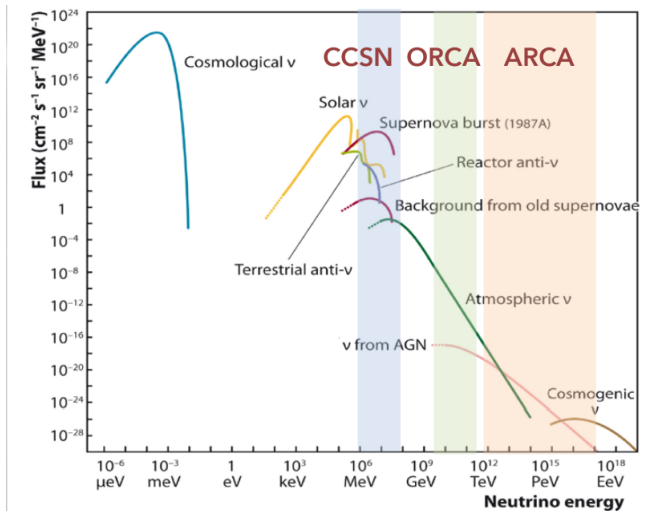


Two Cherenkov detectors under construction in the Mediterranean sea with two main purposes:

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



Neutrino energy spectra for different sources

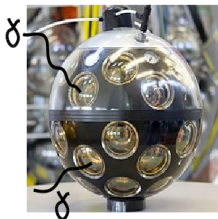


- Test the capability of KM3NeT to detect MeV neutrinos from CCSN: ORCA + ARCA allow a self-confirmation of the detection!
- Study the sensitivity to oscillations in the ν light-curve.
 - Fully understand the CCSN explosion mechanism, not yet reproduced by simulations.
 - Account for expected asymmetries: (SASI instabilities, convection).
- 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).

How to detect CCSN neutrinos at MeV range with KM3NeT?

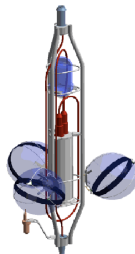
- Large distance between DOM and small e^+ (e^-) tracks
→ we need to detect a collective rise in all PMT rates on top of the noise.
- Low energy neutrinos and high background due to bioluminescence + ^{40}K .
- Selection of coincidences between PMTs allows to reduce the dominant background contributions.
- Multiplicity (M): number of PMTs in a DOM receiving a hit within 10 ns.

KM3NeT DOM

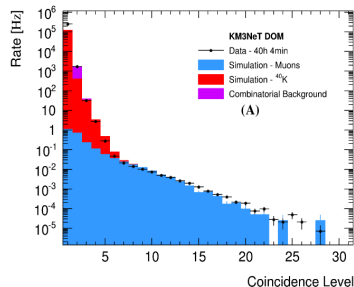


31 3" PMTs

ANTARES OM

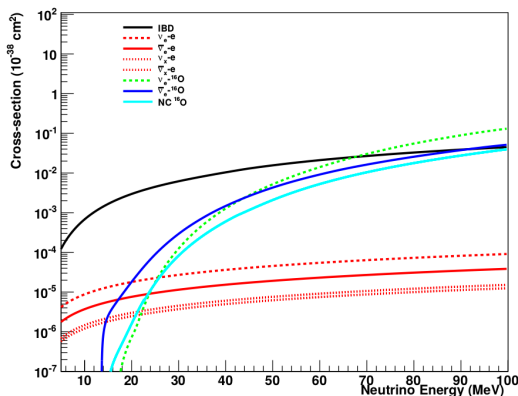


3 10" PMTs



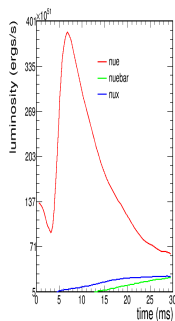
Interaction modes:

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

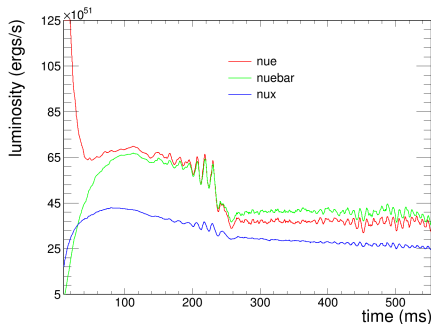


- CCSN neutrino flux from 3D CCSN simulations by the Garching Group¹
→ Quasi thermal distribution.
- Provides energy and time dependence of the 3 parameters in the model:
 $L(E_\nu, t)$, $\alpha(E_\nu, t)$ and $\langle E_\nu \rangle(t)$, for each neutrino flavor
→ The neutrino spectrum and light-curve.

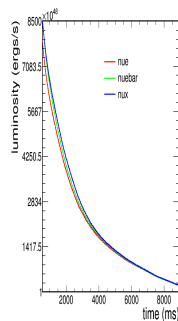
BURST



ACCRETION

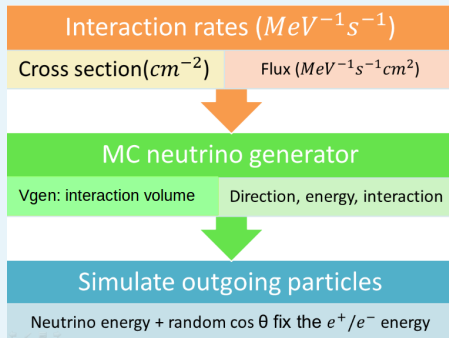


COOLING



¹<http://wwwmpa.mpa-garching.mpg.de/ccsnarchive>

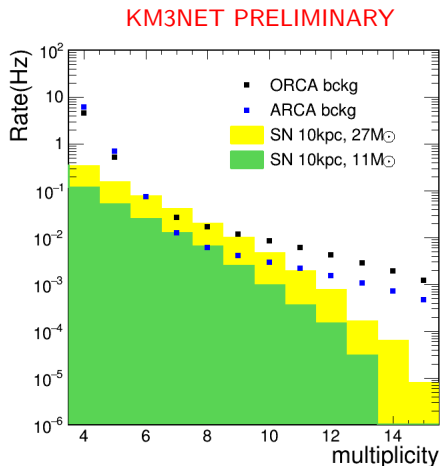
- Development of a low energy MC neutrino generator for KM3NeT.
- Takes into account direction of particles and flux time dependence and includes all neutrino interactions.



- 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

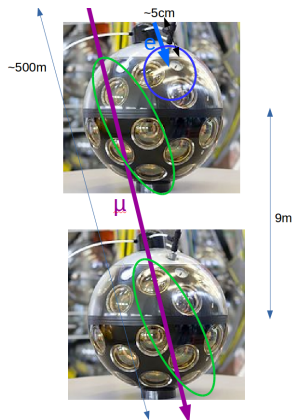
- The most significant excess over the background is observed from multiplicities 6 to 10.
- Characteristic multiplicity distribution different for signal and background.



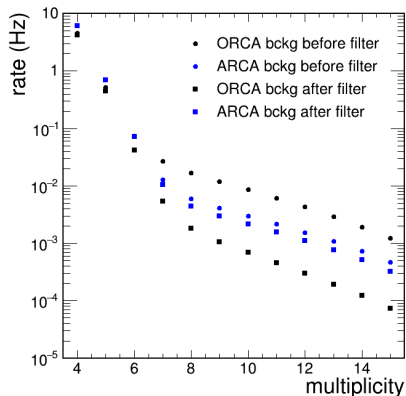
I. Tamborra, <https://arxiv.org/abs/1406.0006> (2014)

Muon rejection filter

- Reject events with $M \geq 4$ if a correlated coincidence is seen within $1\mu s$ on two different DOMs (See presentation by Massimiliano).
- Introduces a 2% dead time dominated by ^{40}K random coincidences.



KM3NET PRELIMINARY



Sensitivity estimation: number of signal and background events

Multiplicity	1	2	3	4	5	6	7	8	9	10
$N_{ev} \ 27 M_{\odot}$	1.6e5	5.0e3	1.0e3	3.8e2	1.7e2	88	46	23	12	5
$N_{ev} \ 11 M_{\odot}$	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 the ORCA and ARCA configurations.

Poisson regime \rightarrow significance is not a simple function of N_s/N_b but needs to be estimated from Poisson p-value. Approximate formula^a:

$$\xi = \sqrt{2 \left[(N_s + N_b) \ln \left(1 + \frac{N_s}{N_b} \right) - N_s \right]}$$

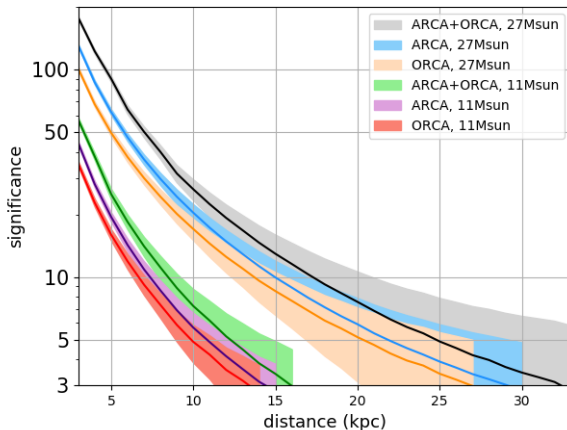
^aG. Cowan, www.pp.rhul.ac.uk/~cowan/stat/medsig/medsigNote.pdf

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

Source of systematics	syst error(%)	significance error (σ)
Run conditions	10	1σ
Effective volume	3	-
Direction of the source	<1	-
Water density as function of depth	<1	-
Cross section	<1	-
—	-	-
Oscillation scenarios (FFS-NFS)	16	2σ
Total luminosity prediction models	20	3σ

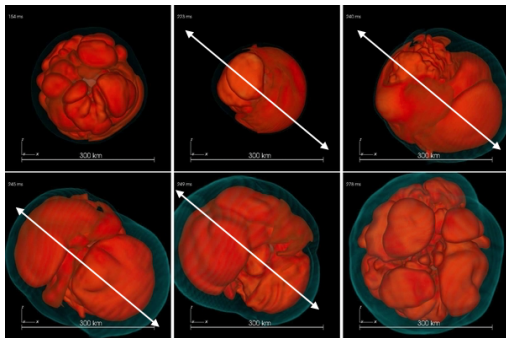
→ A total systematic uncertainty of $\pm 2\sigma$ is estimated.

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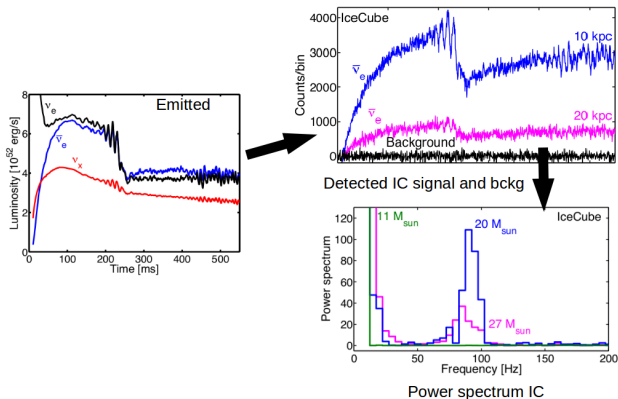
- ORCA + ARCA combined sensitivity of 5σ at 25 kpc for a $27 M_{\odot}$ progenitor.
- ORCA sensitivity above 5σ at the Galactic Center for a $11 M_{\odot}$ progenitor.

- Standing Accretion Shock Instability (SASI): hydrodynamical instabilities during CCSN accretion phase predicted by state-of-the-art 3D simulations.
- Anisotropic instabilities: flux dependent on the observer direction \rightarrow observation in the direction of the SASI sloshing to see oscillations.
- Enhances the neutrino heating favoring the explosion and could explain the neutron star kick observed.



Sensitivity to time variations

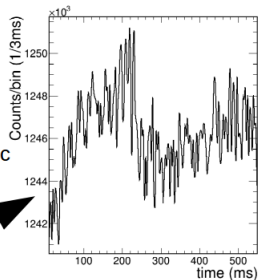
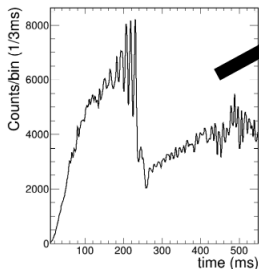
- Footprint: Fast time variations in the neutrino light-curve from 150ms to 250ms after core bounce.
- Feature: Characteristic oscillation frequency (80Hz for this progenitor and simulation model) seen with Fourier analysis.
- Compute the detected light-curve using all hits ($O(10^5)$ events) for signal + background and apply the FT to get the power spectrum.



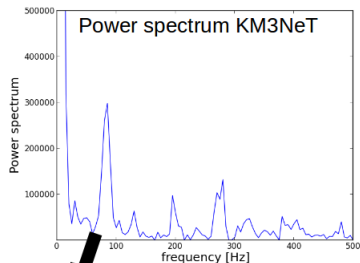
I. Tamborra, <https://arxiv.org/abs/1307.7936v3> (2013)

KM3NET PRELIMINARY

Detected KM3NeT signal 5kpc



Detected KM3NeT 5kpc:
Signal +background

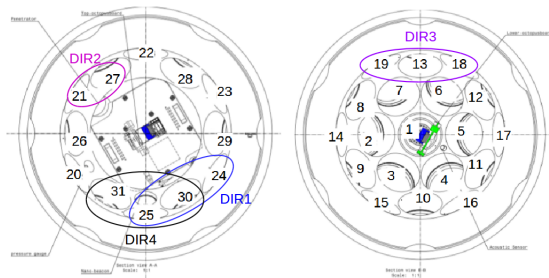


KM3NeT (1block) sensitivity to SASI oscillations: 4σ @5kpc

- t_0 : time delay of the arrival of a neutrino at the detector with respect to the time when the neutrino passed through an arbitrary reference point.²
- δt : statistical uncertainty on measuring t_0 .
- Good δt needed for good triangulation performance (See talk by Vedran).
- Compute $\Delta\chi^2$ distribution as a function of t_0 to get δt .
- For 1 KM3NeT block, using the 27M \odot simulation, we obtain $\delta t < 1\text{ms}$
→ small uncertainty, good time delay resolution!

²Vedran Brdar, <https://arxiv.org/abs/1512.09068> (2018)

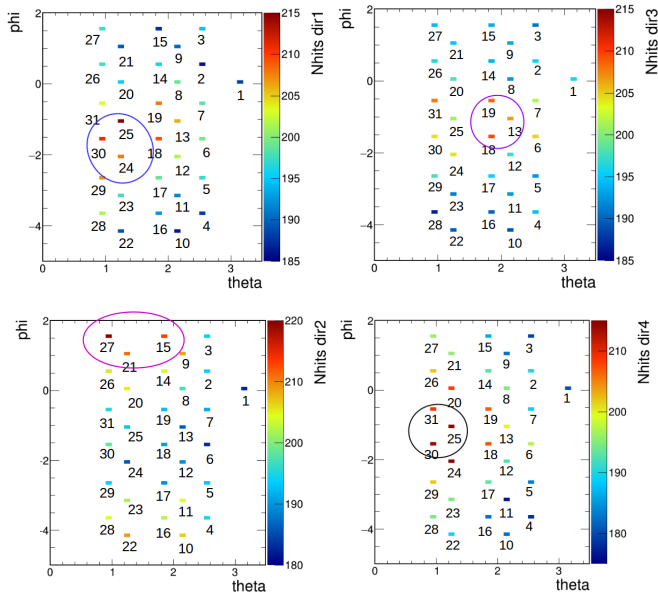
- Simulation of 70ms including $\overline{\nu}_e$ burst of an $8.8M_{\odot}$ stellar progenitor.³
- All hits included: when cutting at higher M, PMT pattern biased by number of neighbor PMTs.
- Neutrinos simulated with 4 different incoming directions:
 - Dir 1: $\theta_{\nu} = -\frac{\pi}{2}$, $\phi_{\nu} = -\frac{\pi}{2}$
 - Dir 2: $\theta_{\nu} = -\frac{\pi}{2}$, $\phi_{\nu} = +\frac{\pi}{2}$
 - Dir 3: $\theta_{\nu} = -\frac{\pi}{3}$, $\phi_{\nu} = -\frac{\pi}{3}$
 - Dir 4: $\theta_{\nu} = -\frac{2\pi}{3}$, $\phi_{\nu} = -\frac{\pi}{3}$



- Dir1 and Dir2 on the equator (between 2 hemispheres) and opposite sides.
- Dir3 on the south hemisphere and Dir4 in the north hemisphere.

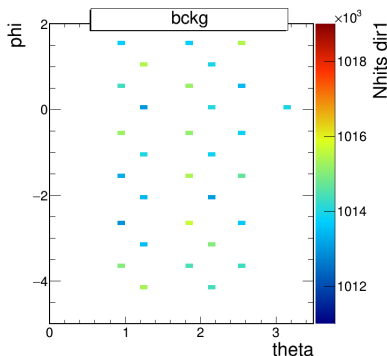
³I. Tamborra, <https://arxiv.org/abs/0912.0260v3>, (2011)

KM3NET PRELIMINARY



Preliminary directionality study: Conclusions

- PROBLEM: from bckg, we expect $\sim 7\text{kHz}$ per PMT, so $1\text{e}6$ bckg events in 70ms in 1 block... $\sim 5\text{e}3$ times more bckg than signal at 5kpc...
- How much more signal do we need to identify the PMT directional pattern after adding bckg?
- First estimates: We could determine the more lighted PMT at 5kpc for a massif progenitor ($\times 3\text{-}5$ the total luminosity obtained for the $8.8M_{\odot}$ stellar progenitor)



PRELIMINARY CCSN SENSITIVITY STUDY FOR KM3NET

● Conclusions:

- ▶ First "end-to-end" MC simulation of CCSN neutrinos for KM3NeT.
- ▶ Analysis of first ORCA and ARCA data to determine background.
- ▶ Development of muon filter: good bckg rejection efficiency for ORCA.
- ▶ Systematics of the analysis studied. Big systematic uncertainties from different model expectations.
- ▶ 5σ significance to a CCSN at 25kpc for a $27M_{\odot}$ progenitor
→ **Coverage of the full Galaxy.**
- ▶ 5σ significance at the Galactic Center with full ORCA assuming a $11M_{\odot}$ stellar progenitor.
- ▶ A significance of 4σ is reached to the SASI oscillations for a CCSN at 5kpc ($27M_{\odot}$ progenitor) with 1 KM3NeT block.
- ▶ Uncertainty on the neutrino arrival time smaller than 1ms.
- ▶ KM3NeT DOMs directional PMTs capability of pointing at the source.
PROBLEM: High bckg. Still preliminary.

● Outlooks:

- ▶ Triangulation and PMT pattern study for pointing at the source.
- ▶ Sensitivity to the neutrino arrival time (to the time of the CC bounce).
- ▶ New method different from coincidence selection to improve significance?
- ▶ Determination and constraints on the total energy released and E_{ν} mean.
- ▶ Sensitivity to neutrino mass ordering.
- ▶ Sensitivity to diffuse CCSN neutrino flux.

Backup

- 3D CCSN accretion phase simulation by the Garching Group for two different progenitor stars: one of $27 M_{\odot}$ and one of $11 M_{\odot}$.
- 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:

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

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

$$\text{alpha is the shape parameter: } \alpha(t) = \frac{\langle E_{\nu}^2 \rangle - 2\langle E_{\nu} \rangle^2}{\langle E_{\nu} \rangle^2 - \langle E_{\nu}^2 \rangle} \quad [3]$$

- 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 → 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.

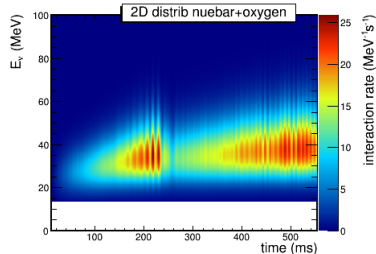
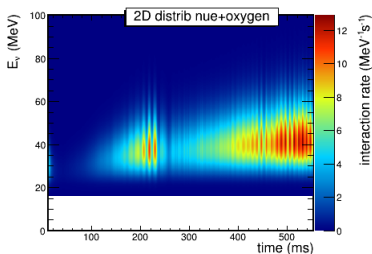
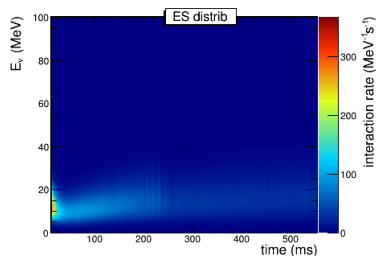
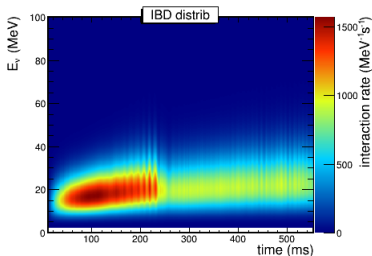
The two extreme hypothesis will be studied, for 27 M_\odot simulation:

- 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 $\overline{\nu}_x$.

Neutrino interaction rates in the accretion phase (NFS case, 27M \odot):

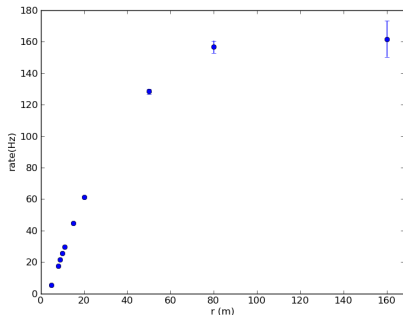
- Computation of neutrino interaction rates for 100 kton of water:

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

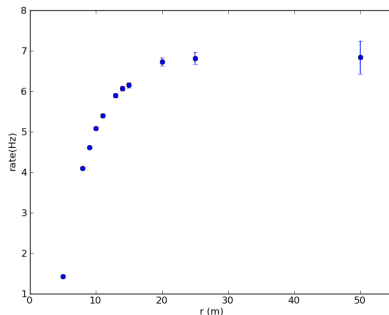


Optimization of the generation volume (V_{gen}) using SN rates.

single hits



double coincidences

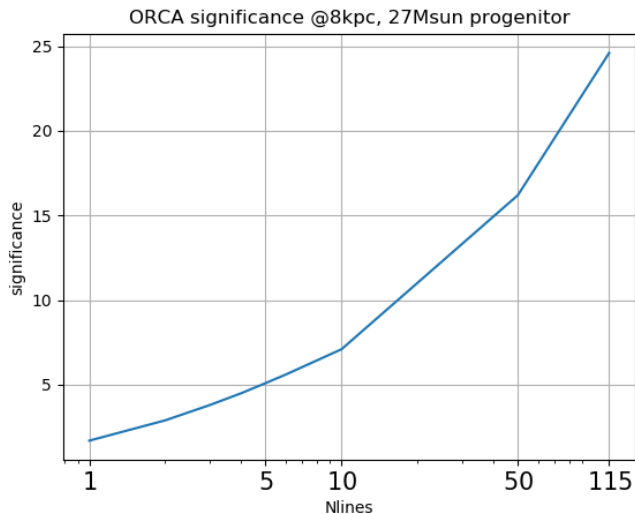


- For double coincidences: $V_{gen} = \text{sphere of 20m radius.}$
- For single hits, one must go to $R=80\text{m}$ to saturate SN rates...

$\# \nu_s$ 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



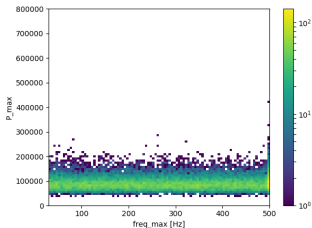
Sensitivity to time variations.

- 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:

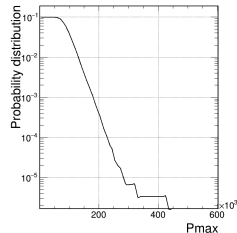
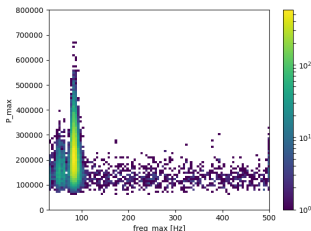
$$R_{tot} = \text{Poisson}(\text{Mean}(R_{signal})) + \text{Poisson}(\text{Mean}(R_{bckg}))$$

- All background included: value of the total measured background rate used (250 kHz per DOM from data).
- Apply the FT to recover frequency of SASI oscillations, $f_{SASI} = 80\text{Hz}$.
- Estimate the significance of SASI peak detection through Monte-Carlo pseudo-experiments.

only background



background + signal at 5kpc



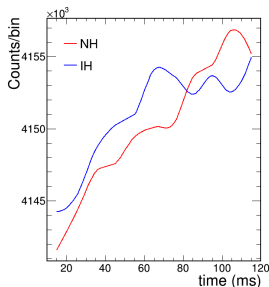
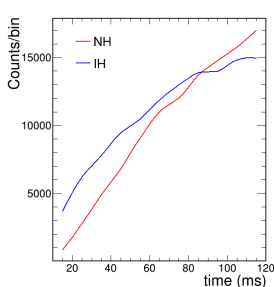
Sensitivity to Neutrino Mass Hierarchy (NMH)

- Hypothesis: Adiabatic MSW flavor conversion during 120ms after bounce.
- Different $\bar{\nu}_e$ fluxes expected at Earth from a SN for IH and NH hypothesis, in the case of large θ_{13} :

$$F_{\bar{\nu}_e}^0 = \cos^2\theta_{12}F_{\bar{\nu}_e} + \sin^2\theta_{12}F_{\bar{\nu}_\mu}, \text{ (70\% } \bar{\nu}_e \text{ survival probability) for the NH}$$
$$F_{\bar{\nu}_e}^0 = F_{\bar{\nu}_\mu}, \text{ for the IH}$$

- Look at the light curve for each hypothesis, NH and IH with signal+bckg:

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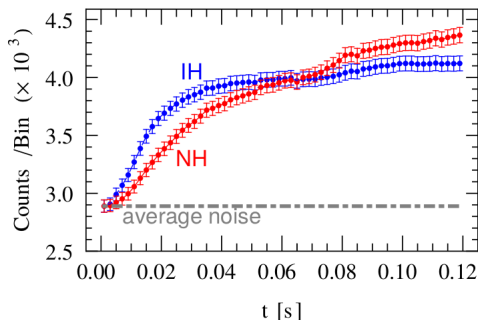


- After adding bckg, one can still distinguish both hypothesis.
- But this is for an specific oscillation model (adiabatic flavor conversion)...

Sensitivity to Neutrino Mass Hierarchy (NMH)

- After adding bckg, can one still significantly distinguish between both hypothesis for a CCSN at 5kpc?
 - $\Delta\chi^2 < 1$ between both hypothesis... (Not good way to proceed?)
 - Variation of Ncounts/bin of just $\sim 0.1\%$ between both hypothesis...
- Also, this is for an specific oscillation model which predicts specific initial $\bar{\nu}_e$ and $\bar{\nu}_x$ (and assuming adiabatic flavor conversion during first 120ms)
- IC variation of Ncounts/bin is also of $\sim 0.1\%$ between both hypothesis.

P.D. Serpico et al. (2012), arXiv:1111.4483



- t_0 : time delay of the arrival of a neutrino at the detector with respect to the time when the neutrino passed through an arbitrary reference point. ⁴
- δt : statistical uncertainty on measuring t_0 .
- Good δt needed for good triangulation performance.
- Generally applicable χ^2 fit, computed via:

$$\chi^2(t_0) = 2 \sum_{i=1}^{i_{max}} (\mu_i - n_i + n_i \times \ln(\frac{n_i}{\mu_i})) \quad (1)$$

- $n_i(\mu_i)$ are the observed (expected) number of events per time bin ($\Delta t \ll \delta t$) for the signal + bckg hypothesis, given by:

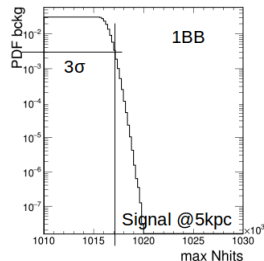
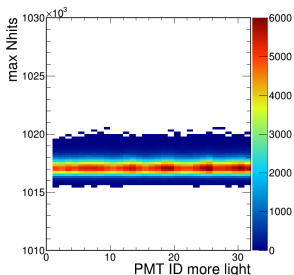
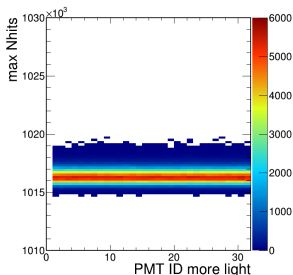
$$\begin{aligned} n_i &= n_i^{signal} + N_{mean}^{bckg} \\ \mu_i &= Poisson(n_i^{signal}) + Poisson(N_{mean}^{bckg}) \end{aligned} \quad (2)$$

- Compute $\Delta\chi^2$ distribution as a function of t_0 .
- δt given by the 1σ deviation ($\Delta\chi^2 = 1$).
- For 1 KM3NeT block, using the $27M_{\odot}$ simulation, $\Delta\chi^2 = -7.8$ for $\delta t = 1\text{ms}$

⁴Vedran Brdar, <https://arxiv.org/abs/1512.09068> (2018)

Sensitivity to the direction of the source:

- How much more signal do we need to identify the PMT directional pattern after adding bckg? → Pseudo-experiments for signal and signal+bckg
- Look at the probability of PMT_i to be the more lighted and see Nhits for bckg only and signal+bckg hypothesis:
 - 2D distribution of Max Nhits per PMT VS more lighted PMT_ID
 - Get PDF of the Max Nhits per PMT for bckg only hypothesis
 - Compare to bckg + $N \times$ signal to get N at which we reach 3σ
- (x3) signal for $8.8M_{\odot}$ needed to reach 3σ at 5kpc. (Realistic given the factor 4.5 in the total luminosity between $27M_{\odot}$ and $11M_{\odot}$ progenitors)





- Simulation for 3 DOMs ($27 M_{\odot}$ progenitor, $d=7.5\text{kpc}$).
- inter-DOM coincidence: 1 hit in 2 neighbor DOMs in 50ns.
- From a SN at 7.5kpc, we expect to see with the full ORCA detector:
 - 3822 (1+1) inter-DOM coincidences
 - 819 (2+1) inter-DOM coincidences
- From background, we expect to see:
 - $R(1+1)_{bckg} = 2 \times \delta t \times R_1 R_1 = 4000\text{Hz}$.
 - $R(2+1)_{bckg} = 2 \times \delta t \times R_1 R_2 = 20\text{Hz}$.
- Significance achieved at 7.5kpc:
 - (1+1) : 2σ
 - (1+2) : 7σ

