A feasibility study for the detection of SuperNova explosions with an Undersea Neutrino Telescope

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SN (GARCHING) Model

Neutrino Signal of Electron-Capture Supernovae from Core Collapse to Cooling

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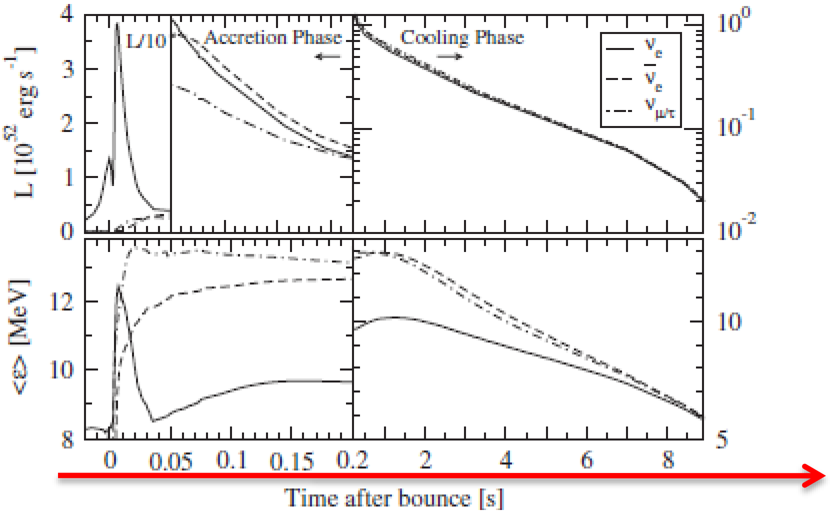
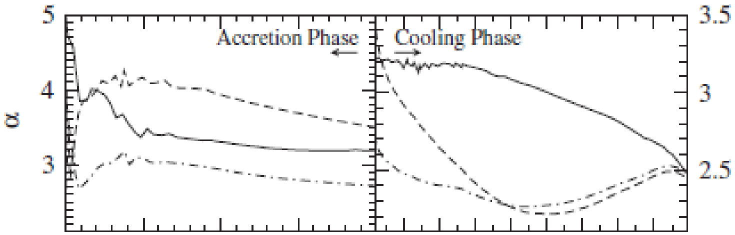
In this study we consider only the $\bar{\nu}_e$ flux and the reaction $\bar{\nu}_e + p \rightarrow e^+ + n$





$$\bar{\nu}_e + p \rightarrow e^+ + n$$

Precise quasielastic neutrino/nucleon cross-section

Alessandro Strumia [a], Francesco Vissani [b]

Physics Letters B 564 (2003) 42–54

$$\frac{d\sigma}{dE_e}(E_\nu, E_e) \qquad \frac{d\sigma}{d\cos\theta}(E_\nu, \cos\theta)$$

HOURS

(HOU Reconstruction& Simulation)

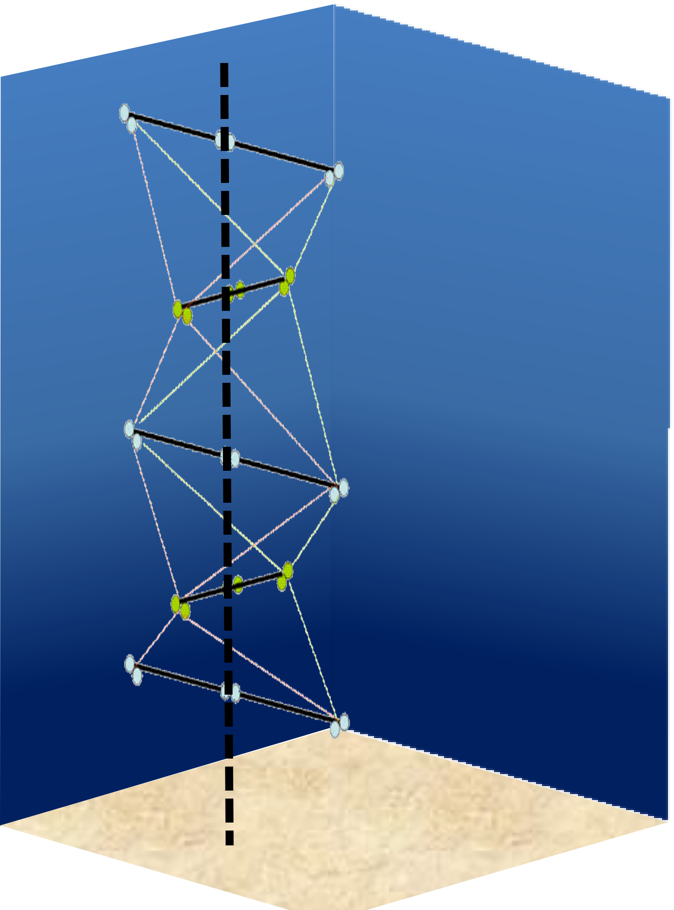
$$\frac{d\Phi_{\bar{\nu}_e}}{dE_{\bar{\nu}_e}}\left(E_{\bar{\nu}_e}, d\right) = \frac{1}{4\pi d^2}\int_0^T \frac{L(t)}{\left\langle E_{\bar{\nu}_e}\right\rangle(t)} f_{a(t),\langle E_{\bar{\nu}_e}\rangle(t)}\, dt$$

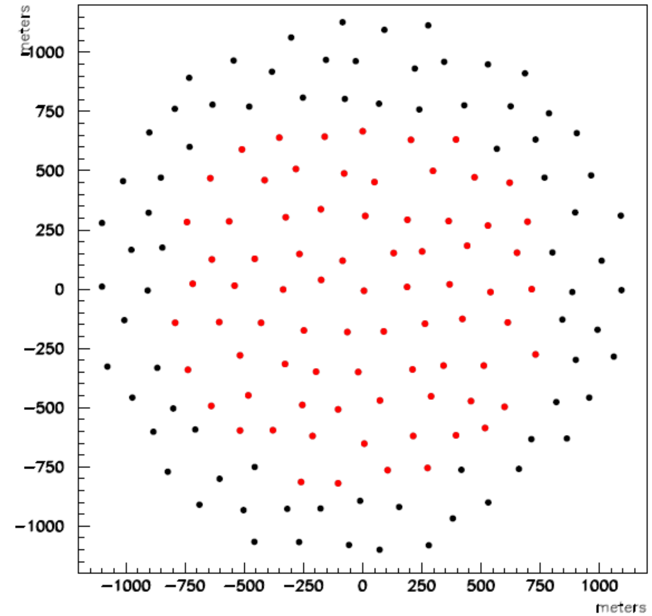
$$f_{a(t),\langle E_{\bar{\nu}_e}\rangle(t)}\left(E_{\bar{\nu}_e}\right) = \frac{(1+a)^{1+a}}{\left\langle E_{\bar{\nu}_e}\right\rangle \Gamma(1+\alpha)}\left(\frac{E_{\bar{\nu}_e}}{\left\langle E_{\bar{\nu}_e}\right\rangle}\right)^{\alpha} e^{-(1+a)\frac{E_{\bar{\nu}_e}}{\langle E_{\bar{\nu}_e}\rangle}}$$

α is a function of time

Detector Geometrical Layout

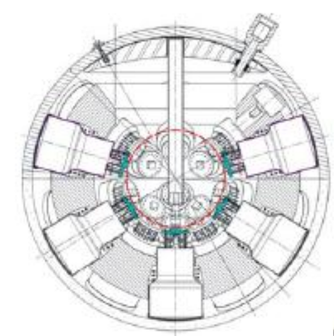
154 Towers with a mean horizontal distance of 180m
Each Tower consists of 20 bars, 6m in length and 40m apart
One MultiPMT OM at each end of the bar.

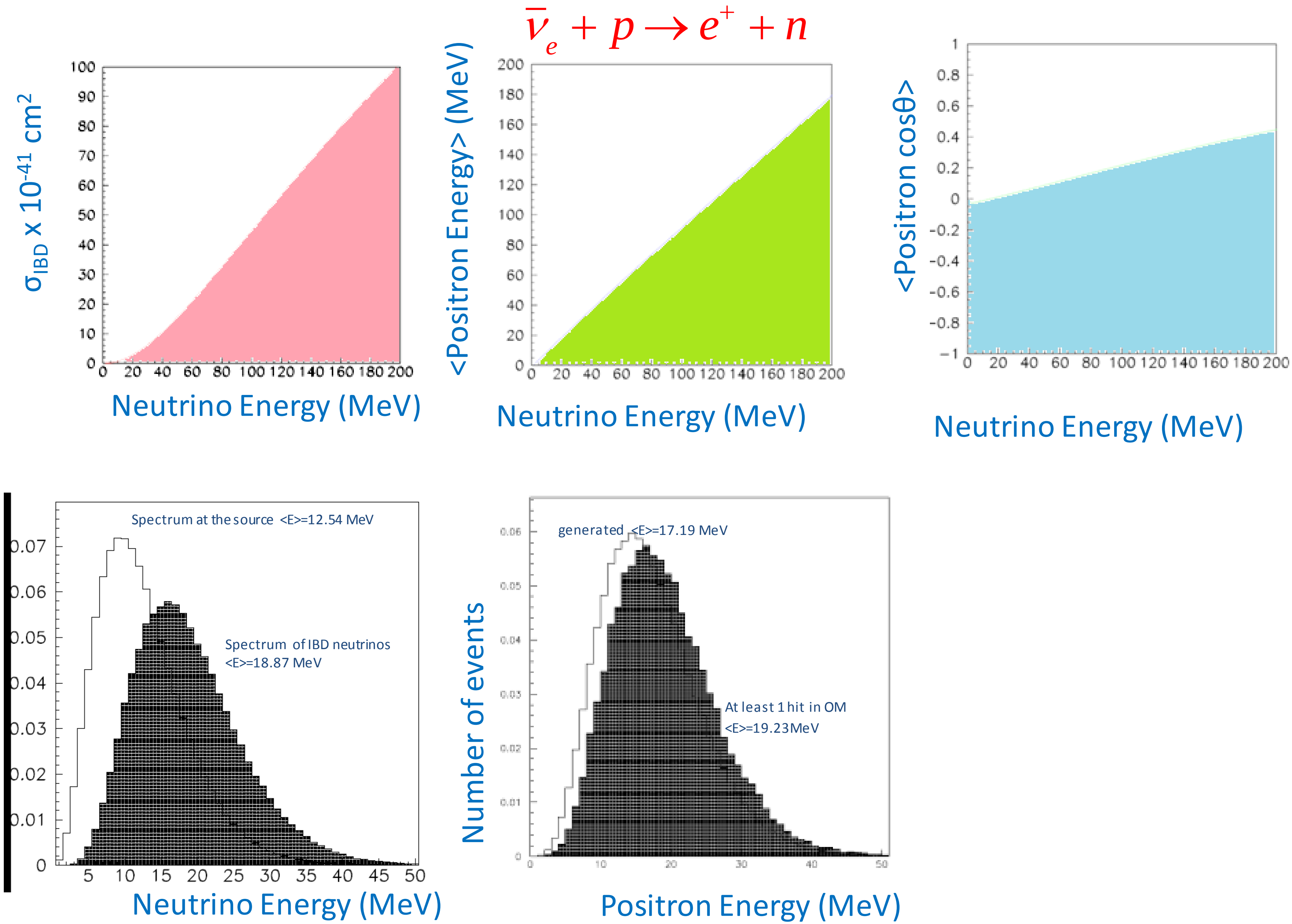




Detectors Footprint

- 31 3” PMTs (~30% max QE) inside a 17” glass sphere with 31 bases (total ~6.5W)
- Cooling shield and stem
- Single vs multi-photon hit separation
- Large (1260 cm^2) photocade area per OM
- First full prototype under test





$\bar{\nu}_e + p \rightarrow e^+ + n$
σ_{IBD} x 10^{-41} cm^2
Neutrino Energy (MeV)
<Positron Energy> (MeV)
Neutrino Energy (MeV)
<Positron cosθ>
Neutrino Energy (MeV)
Spectrum at the source <E>=12.54 MeV
Spectrum of IBD neutrinos
<E>=18.87 MeV
Neutrino Energy (MeV)
Number of events
generated <E>=17.19 MeV
At least 1 hit in OM
<E>=19.23MeV
Positron Energy (MeV)

$$\frac{d\Phi_{\bar{\nu}_e}}{dE_{\bar{\nu}_e}}\left(E_{\bar{\nu}_e},d\right)=\frac{1}{4\pi d^2}\int_0^T\frac{L(t)}{\left\langle E_{\bar{\nu}_e}\right\rangle(t)}f_{a(t),\langle E_{\bar{\nu}_e}\rangle(t)}dt$$

Time Integrated Differential Flux
(d: SN distance in kpc)
number of $\bar{\nu}_e$ / cm^2 / MeV

$$\rho_{\text{int}}=\rho_{target}\cdot\int_0^\infty\frac{d\Phi_{\bar{\nu}_e}(E_{\bar{\nu}_e})}{dE_{\bar{\nu}_e}}\sigma(E_{\bar{\nu}_e})dE_{\bar{\nu}_e}$$

Interaction Density

$$V_{eff}=\left\langle\frac{n_{obs}}{n_{gen}}\right\rangle V_{gen}$$

Effective Volume

$$N_{obs}=\rho_{\text{int}}\cdot V_{eff}$$

Significance Level of discovery:

Assuming that μ_{bck} is the expected number of background events then for 5σ discovery the **minimum number of observed events, m**, is defined as:

$$1-\sum_{i=0}^{m}\frac{\mu_{bck}^{i}e^{-\mu_{bck}}}{i!}<1-erf\left(\frac{5}{\sqrt{2}}\right)$$

Assuming Gaussian statistics: $\frac{m-\mu_{bck}}{\sqrt{\mu_{bck}}}>5$ *but* $\mu_{bck}\equiv\mu_{bck}(T)\Rightarrow m\equiv m(T)$

General Condition: $\frac{N_{obs}(T)-\mu_{bck}(T)}{\sqrt{\mu_{bck}(T)}}=\frac{S(T)}{\sqrt{\mu_{bck}(T)}}=\max$

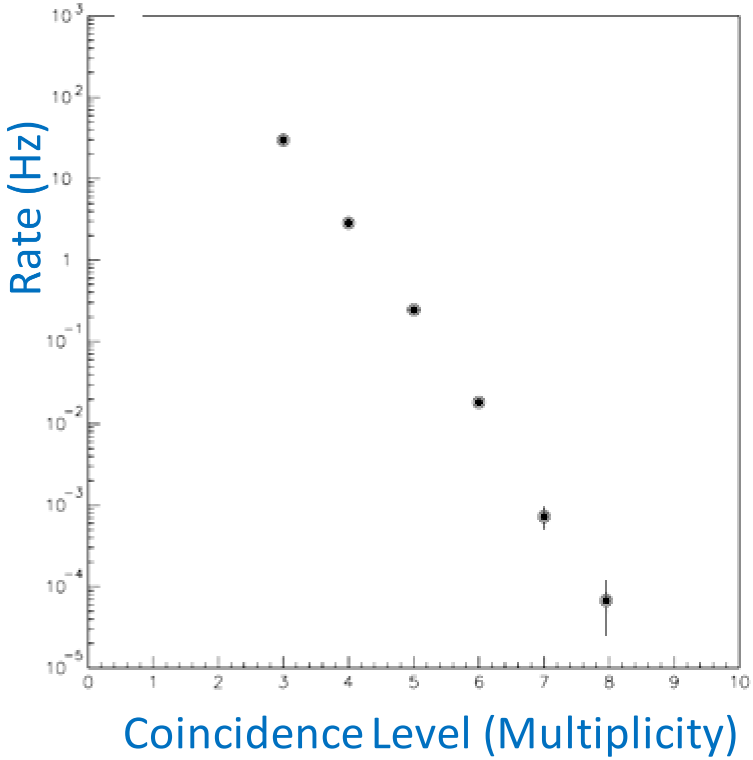
$$S(T)=\int_0^T s_0e^{-\frac{t}{t_0}}dt:\frac{d}{dt}\left(\frac{S(T)}{\sqrt{\mu_{bck}(T)}}\right)=0\Rightarrow \mathbf{T}=\frac{t_0}{2}\left(e^{\frac{T}{t_0}}-1\right)\sim \mathbf{2.95s}$$

Garching Model: t_0=2.35

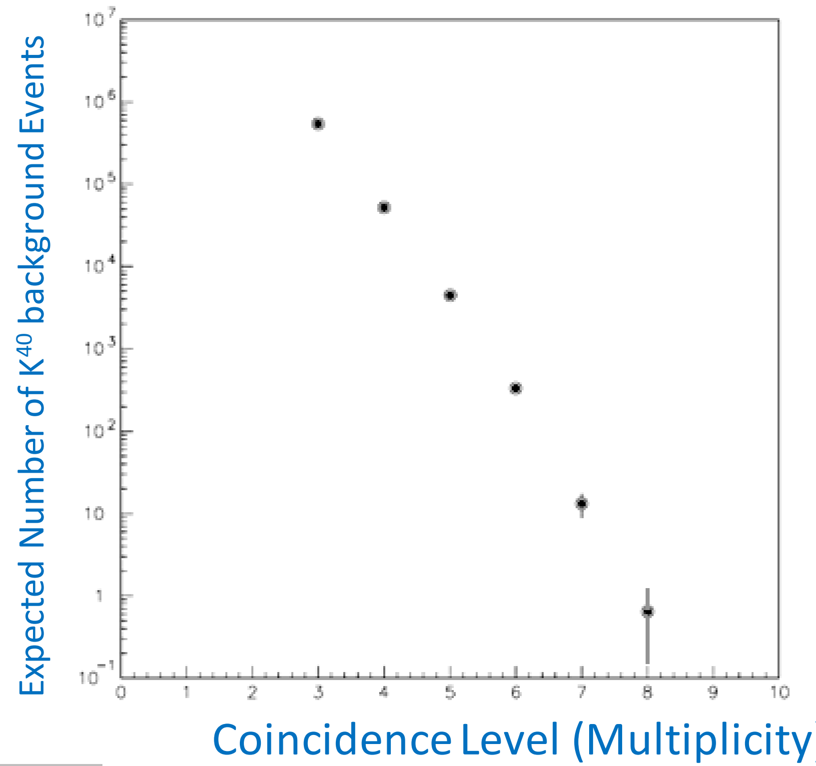
d	10kpc
T	2.95s
ρ_{int}	$0.078m^{-3}$

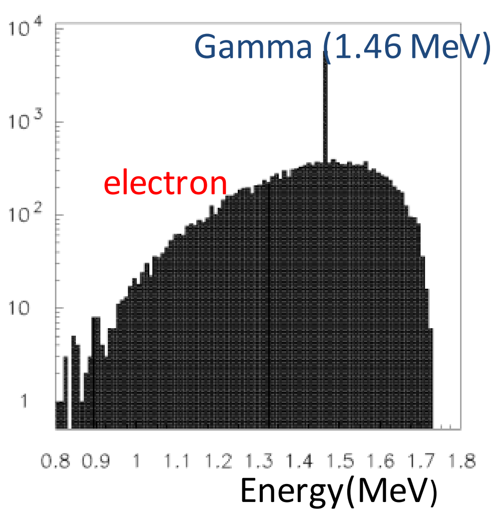
Background-I: Only K^{40} Decays

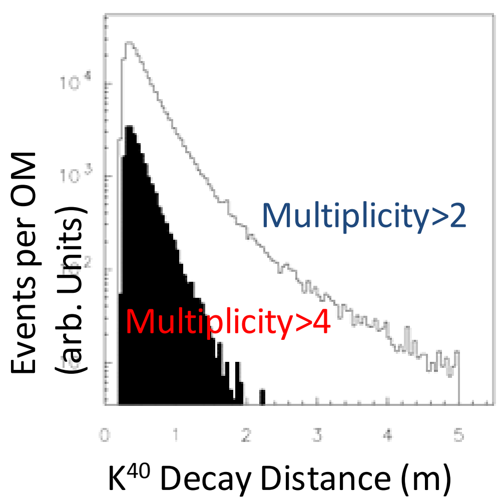
K^{40} Coincidence rate per OM



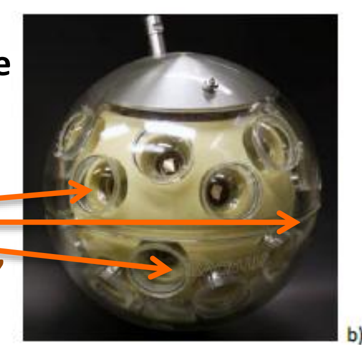
K^{40} event sample in full WPD detector (T=2.95s)







Coincidence between the small PMTs of the same OM, within 100 ns

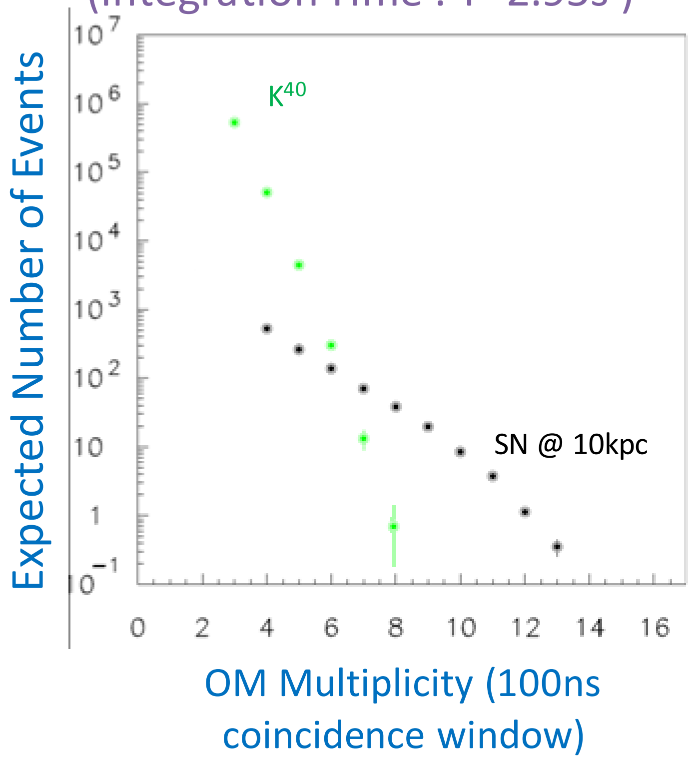


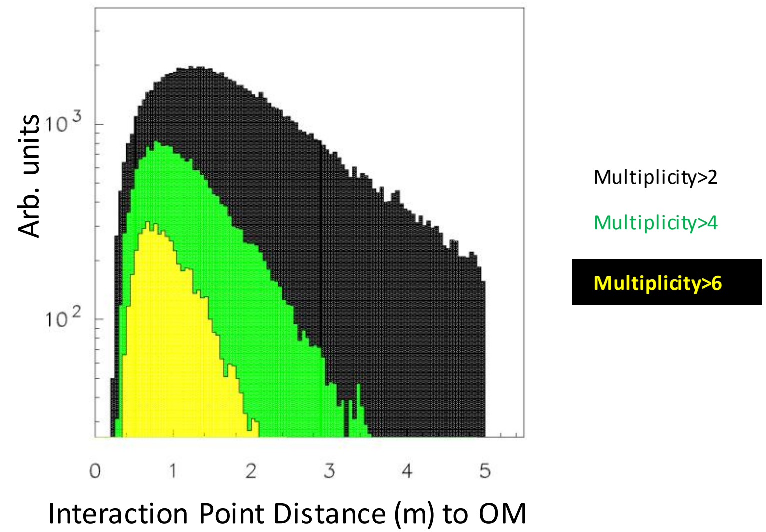
e.g. "Coincidence Level" or "Multiplicity" 3

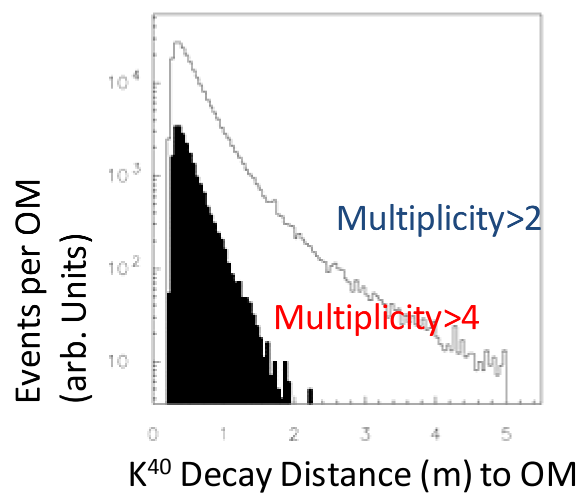
Signal: SN @ 10 kpc

Inverse Beta Decay (IBD): $\bar{\nu}_e + p \rightarrow e^+ + n$

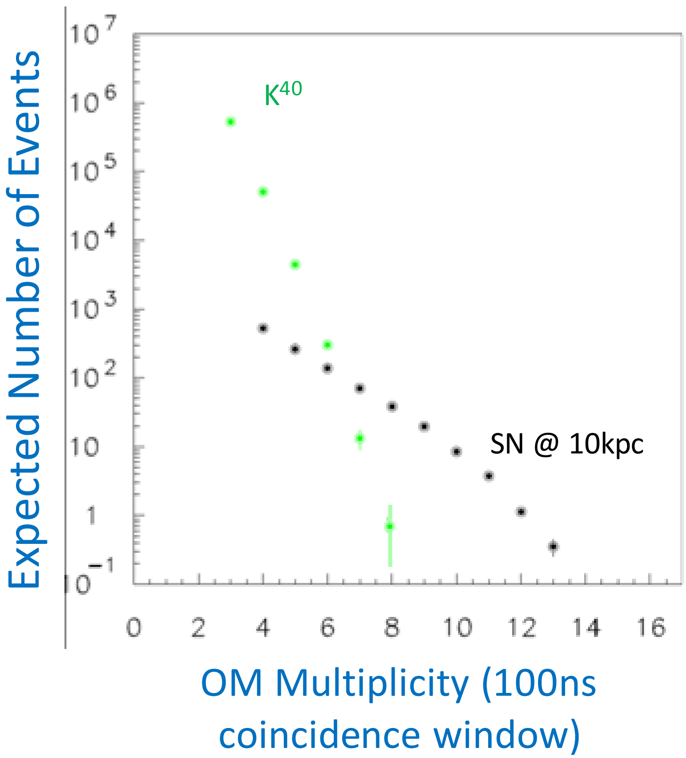
IBD event sample in full WPD detector for
(Integration Time : T=2.95s)

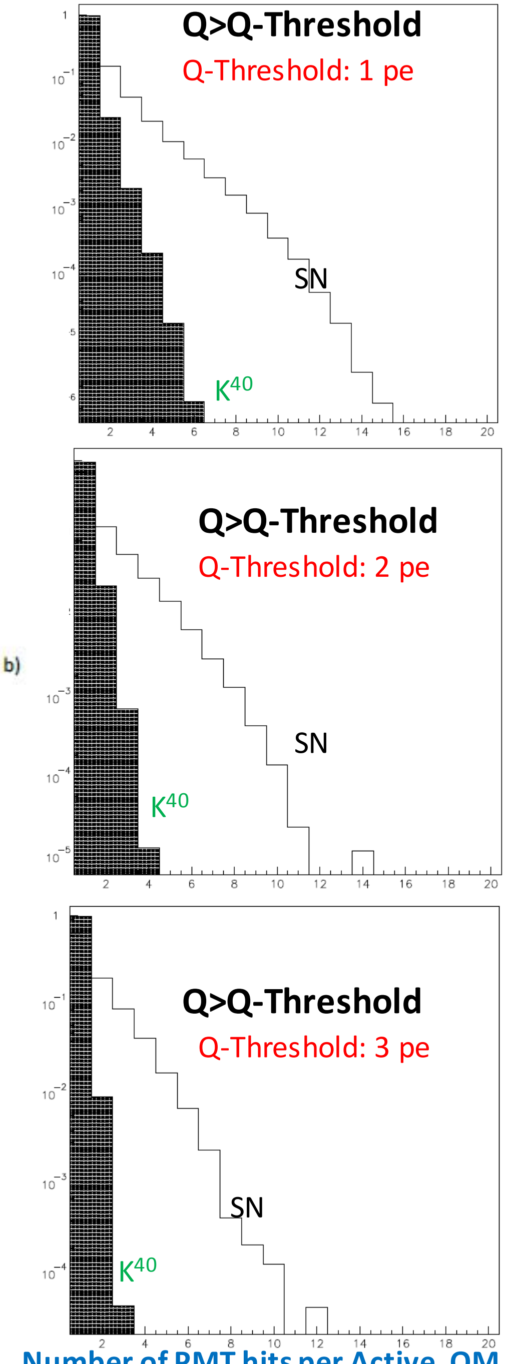






Background Rejection-I: K^{40} Decays

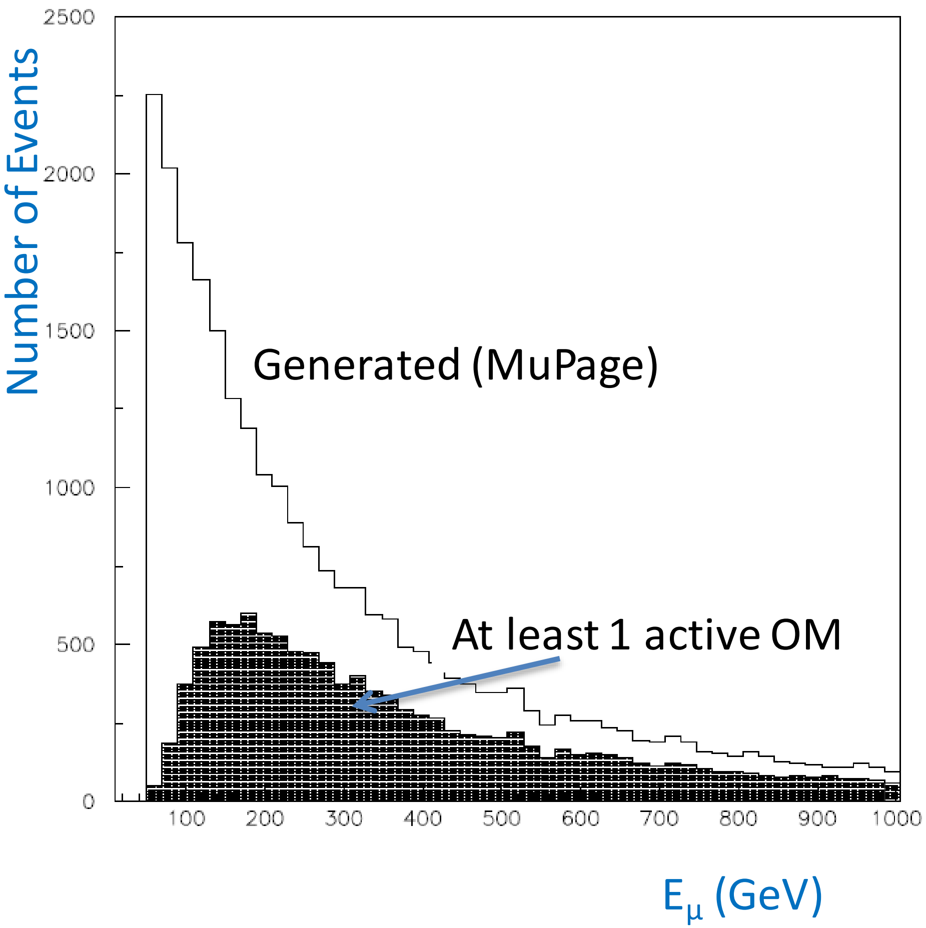




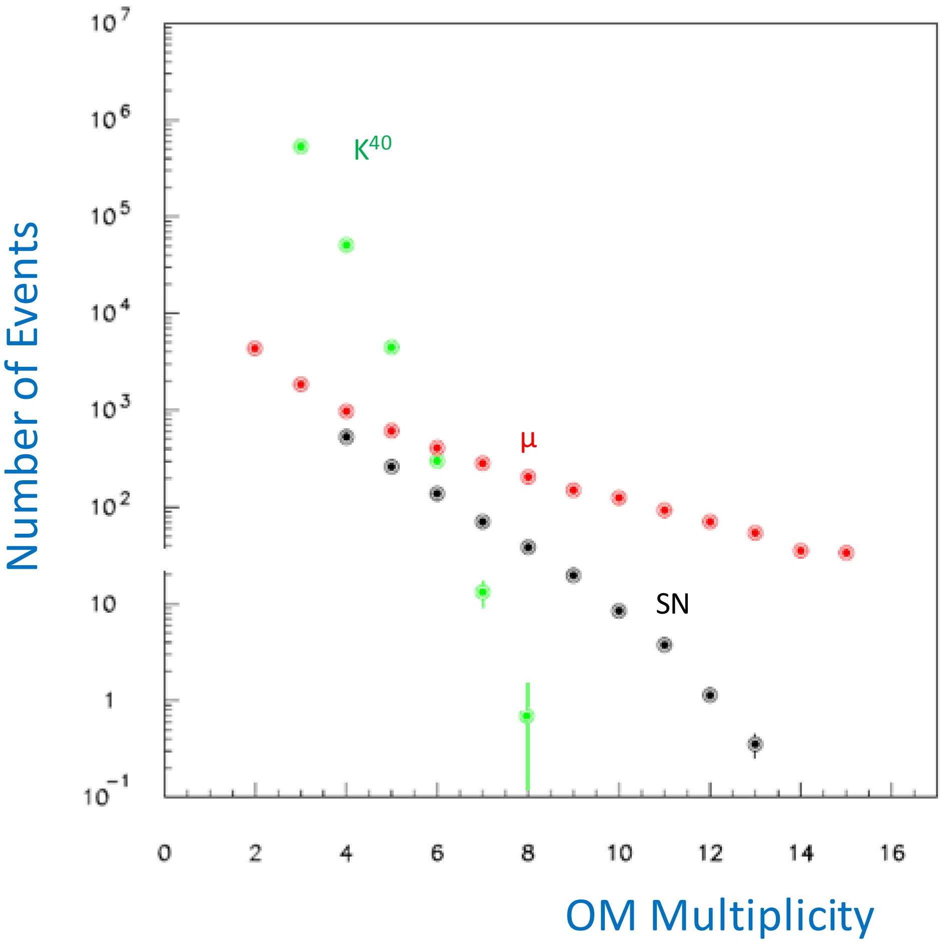
Active OM: Selection Criteria

OM Multiplicity	**>**	5

Background-II: Atmopsheric muons

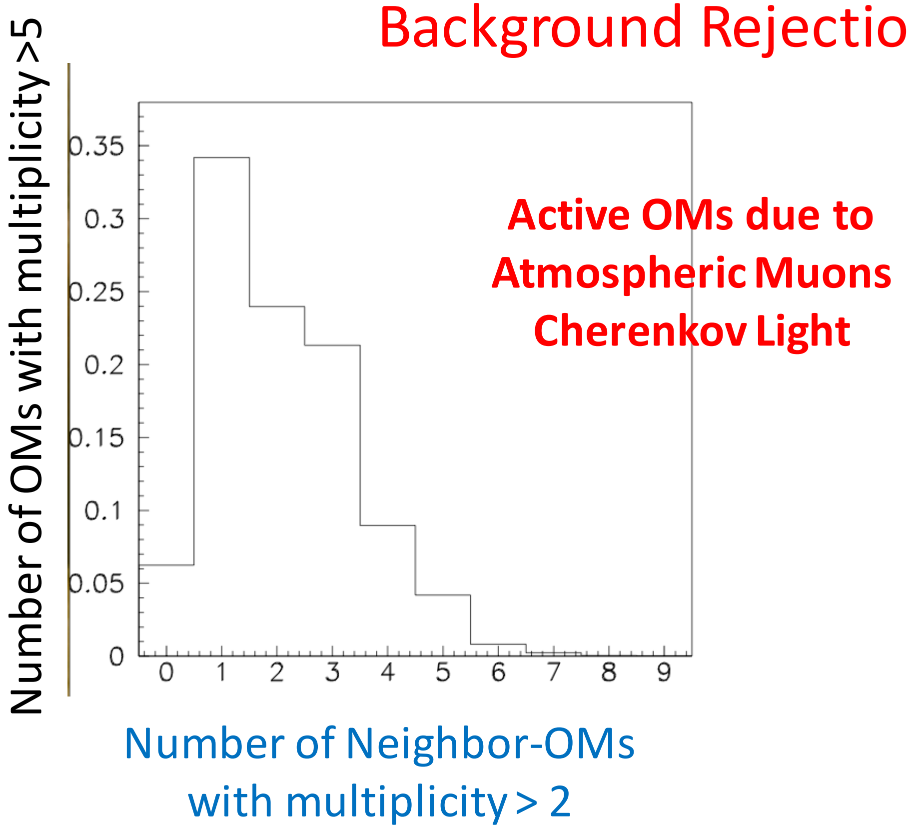


Expected Number of Events in a full WPD detector (6160 Oms) in T=2.95s



Atmospheric muons seems to be tough guys !

Background Rejection-II: Atmospheric muons



- **94% of the background due to atmospheric muons (i.e. active Oms with multiplicity >5) has at least one neighbor OM with multiplicity >2**
- **Only 7% of the signal has at least one neighbor OM with multiplicity >2**

Simulate the Cherenkov Light Emision and the photoelectron production on the small PMTs photocathode due to:

1. SN neutrinos (following the GARCHING Model) interacting inside the KM3 full detector and producing positrons in the vicinity of the Oms.
2. K^{40} decays producing electrons and gammas
3. Atmospheric muons

e.g. 10^7 fully simulated signal events, 10^{11} fully simulated K40 background events and 10^6 fully simulated atmospheric muon tracks

Apply the signal selection criteria for each optical module and estimate:

a) the number of SN induced events (OMs passing **Certain Selection Criteria**) for T=2.95s as a function of the SN distance

b) the number of background induced events (due to K^{40} and atmospheric muons) for T=2.95s

Estimate the SN distance for which the observed number of events (on top of the expected background) corresponds to 5σ discovery, e.g.

OM Multiplicity	>	5
Q-Threshold	=	b
Number of PMTS with Q>Q-Threshold	>	c
Neighbors with multiplicity greater than 2	<	1

a	b	c	Signal @10 kpc	Backr. K^{40}	Backr. Atm. μ
5	**1**	**2**	**147.5**	**2.53**	**18.96**

$$\mu_{bck} = 2.53 + 18.96 = 21.49$$

$$1 - \sum_{i=0}^{m} \frac{\mu_{bck}^{i} e^{-\mu_{bck}}}{i!} < 5.96 \cdot 10^{-7} \Rightarrow m = 47 \Rightarrow \mathbf{N}_{\mathbf{SN}}^{5\sigma} \sim \mathbf{25.5}$$

$$\frac{\mathrm{N}_{SN}^{10kpc}}{\mathbf{N}_{\mathbf{SN}}^{5\sigma}} = \left(\frac{d_{\max}}{10kpc}\right)^2 \Rightarrow \mathbf{d}_{\mathbf{max}} = \left(\frac{147.5}{25.5}\right)^{1/2} \cdot 10kpc \sim \mathbf{24kpc}$$

a	b	c	d_{max} (kpc)
5	0	0	20.7
5	1	0	21.7
5	1	1	24
5	**1**	**2**	**24**
5	1	3	22
5	2	0	23.5

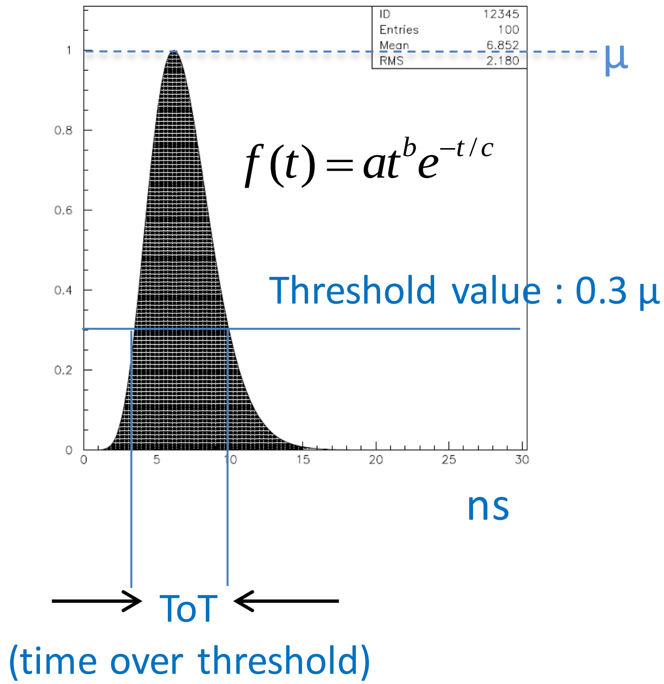
The background rejection criteria are based on the PMT waveform amplitude/charge

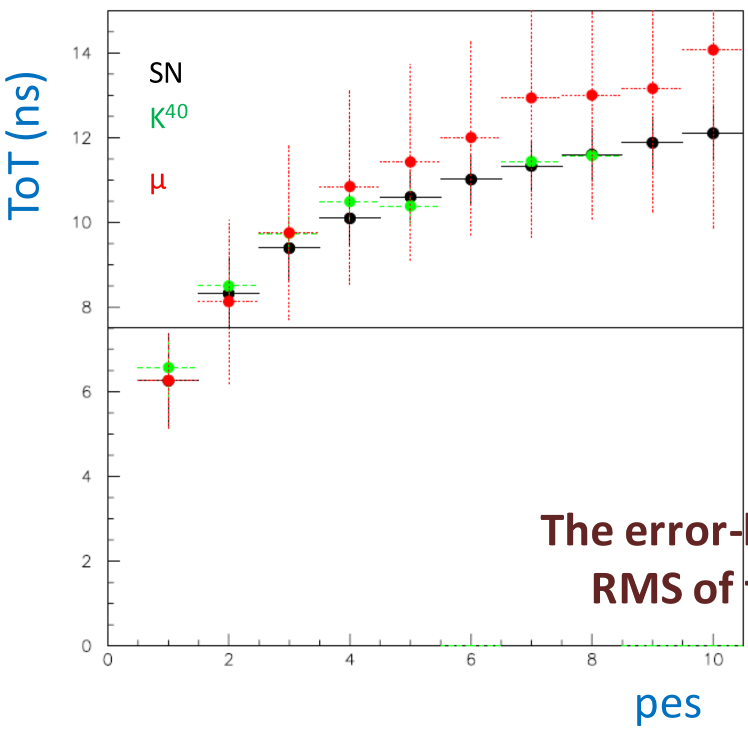
Can the Time over Threshold digitization electronics provide the necessary Information?

Pulse simulation

Pulse characteristics @ 1 p.e.	
Gaussian Amplitude Distribution σ/μ	35%
Time jitter	1 ns
Rise time	2.5ns

single photoelectron averaged wave form





We choose the condition: ToT> 7.5 ns, to select pulses "corresponding" to more than 1 pe

The error-bars correspond to the RMS of the ToT distribution

Background Rejection Criteria

OM Multiplicity	>	5
Q-Threshold	=	b
Number of PMTS with Q>Q-Threshold	>	c
Neighbors with multiplicity greater than 2	<	1

→

OM Multiplicity	>	5
ToT-Threshold	>	B
Number of PMTS with ToT>ToT-Threshold	>	c
Neighbors with multiplicity greater than 2	<	1

a	b	c	d_{max} (kpc)
5	1	2	24
a	B	c	d_{max} (kpc)
5	7.5ns	2	23

Including pulse statistics

D_{max}=23 kpc for 5 σ discovery

a	B	c	Signal @10 kpc	Backr. K^{40}	Backr. Atm. μ
5	7.5 ns	2	118.7	< 0.8	15.4

Livermore model → ~30 kpc
Icecube: dmax=50 kpc (80 strings) (2000 events)
36.9 (DC) (13 events)

Summary

SN explosions within our Galaxy can be detected by an Underwater Neutrino Telescope .

Preliminary results for the Garching model without oscillations, indicate that a maximum distance of ~ 23 kpc for 5σ significance level can be reached

Further Studies

- Other models for SN collapse (eg Livermore)
- Inclusion of matter and vacuum oscillations
- Improve selection efficiency and quality cut criteria
- Apply filters for atmospheric muons
- Directionality ?
- Energy sensitive observables ?