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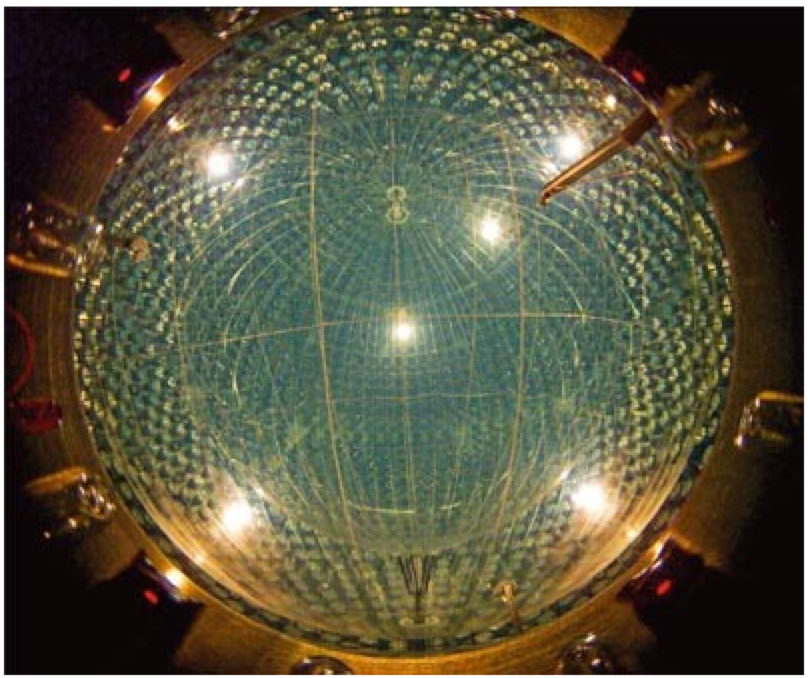
Master NPAC – Université Paris-Sud

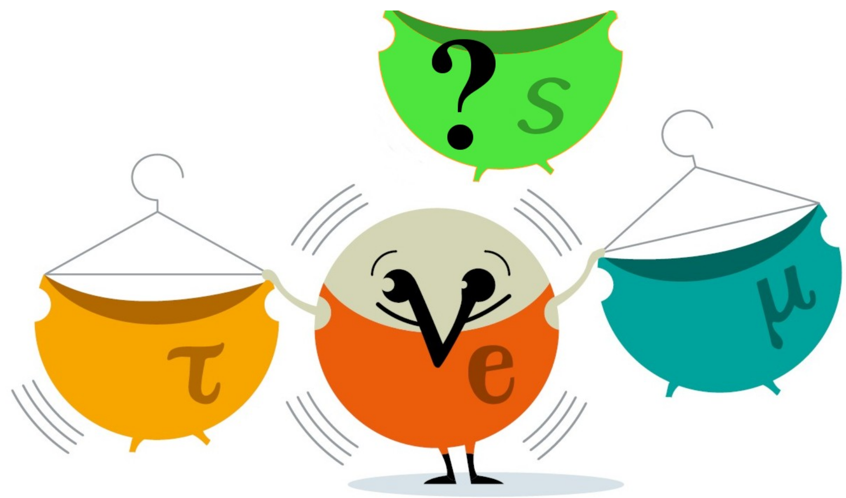
Funded by : bourse ministérielle de l'**ED STEP'UP** (APC).

Why this subject ?

The SOX experiment is combining nuclear physics and particle physics. Neutrinos experiments are always challenging regarding mastering the background and Borexino is one of the best experiment concerning background rejection. Besides, it is a short term experiment in this field : simulation, analysis and hardware tools have to be developped during a PhD time.

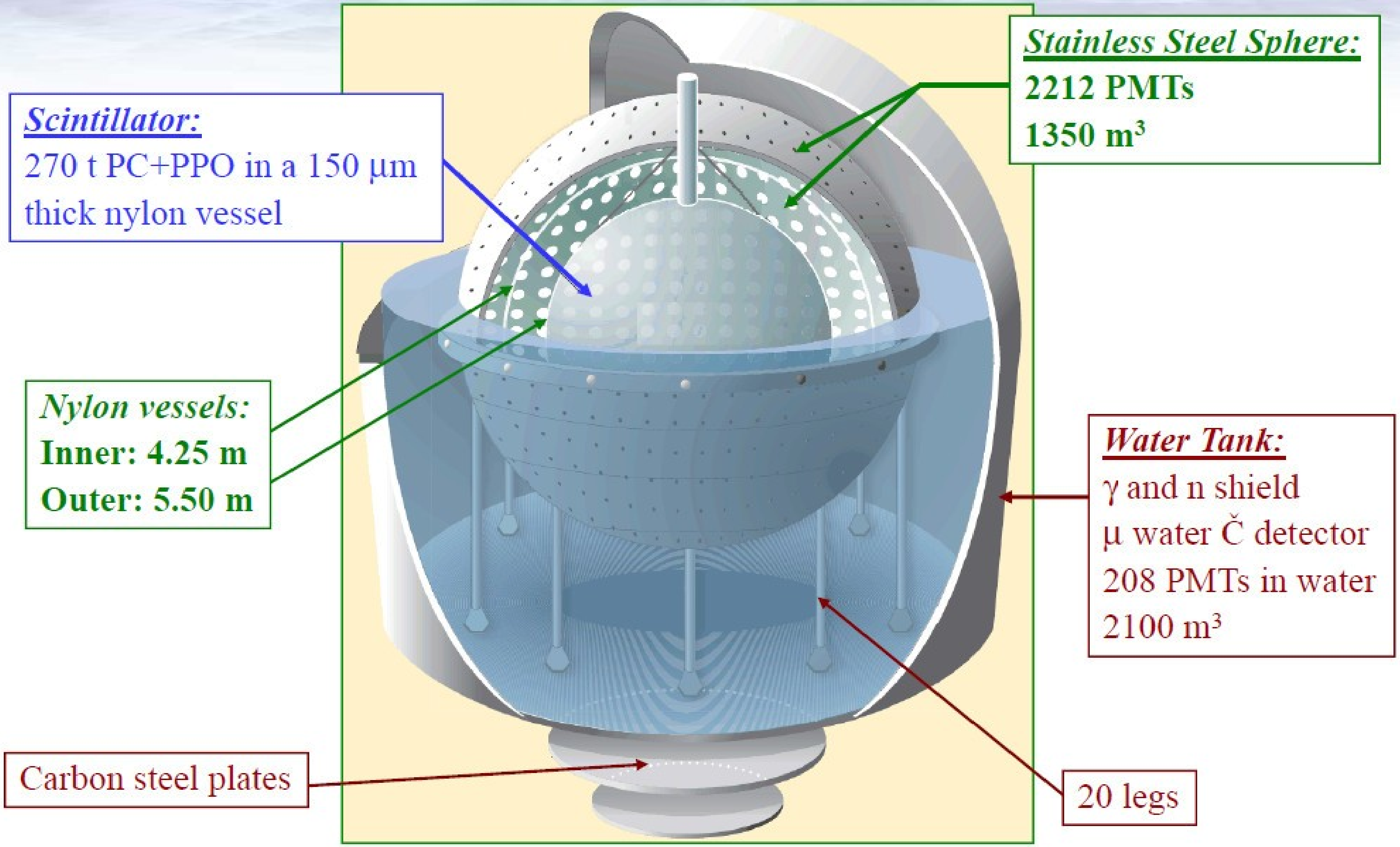
Sterile and solar neutrinos study with SOX experiment and Borexino detector.





Borexino detector

Detector layout and main features



SOX :

SOX experiment
Characterisation of the $^{144}Ce/^{144}Pr$ source
Contaminants study

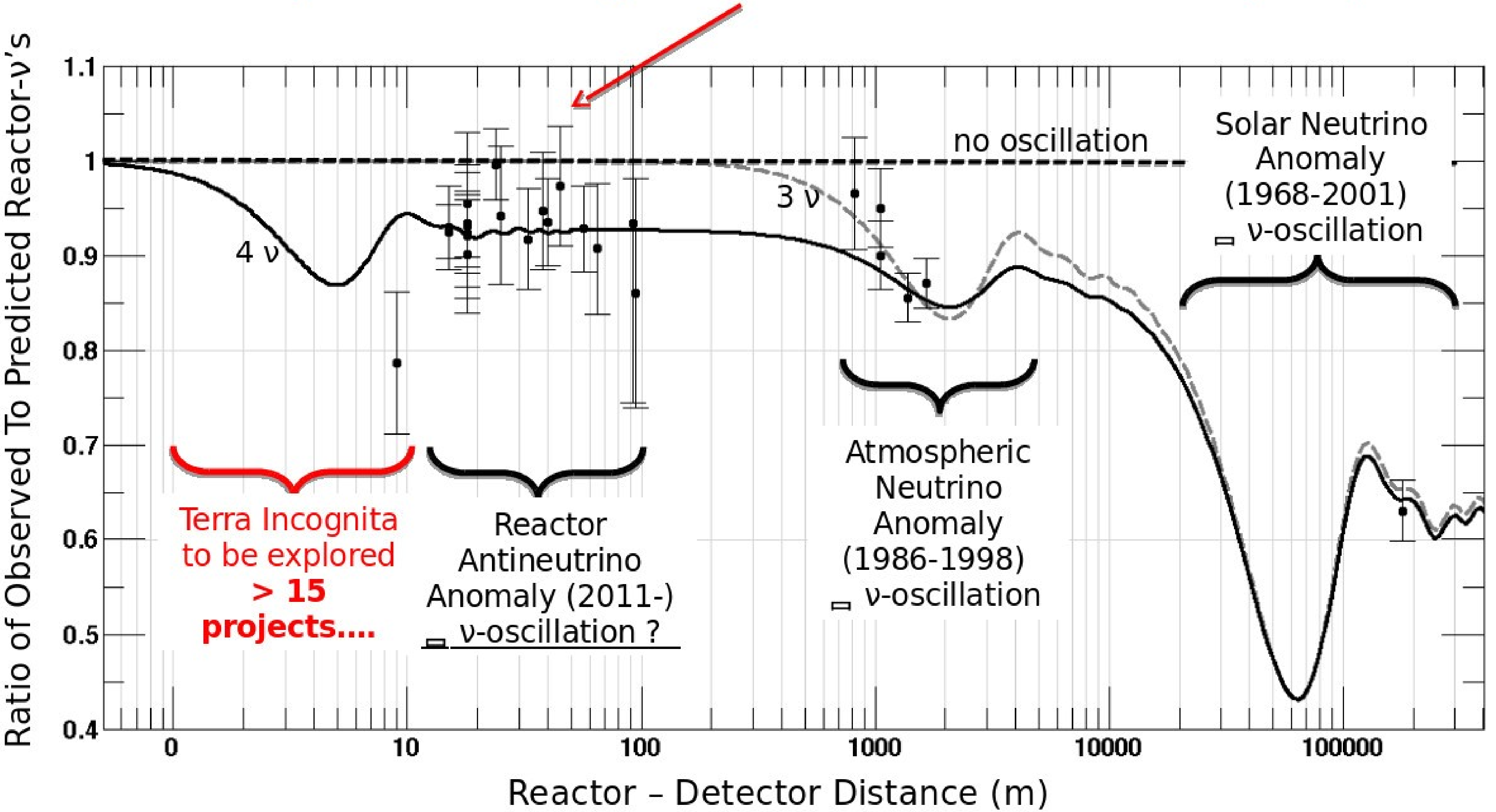
Measurement of solar ν_e rate from ^{8}B:

Context and motivation
Energy scale
Selection and background rejection
Results

Conclusion and outlooks

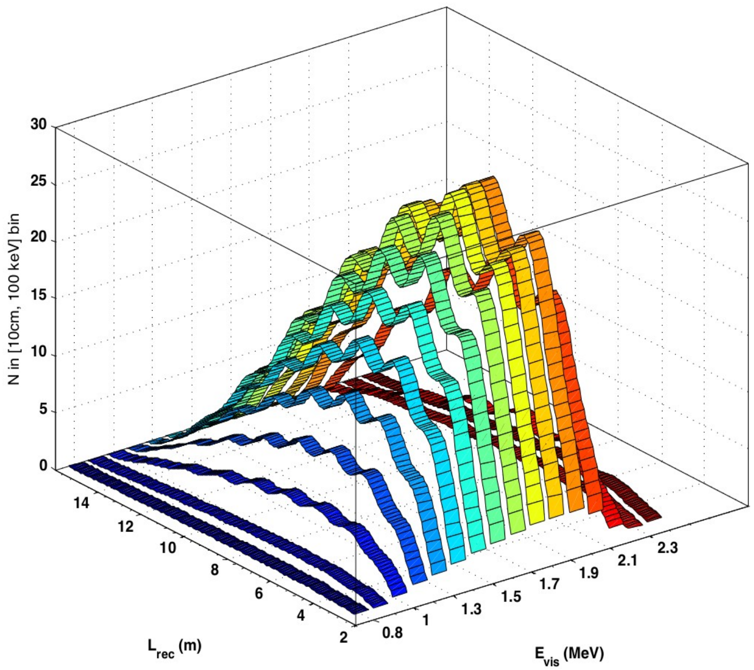
SOX experiment :
testing the Reactor Antineutrino Anomaly

- Observed/predicted averaged event ratio: R=0.938±0.023 (2.7 σ)

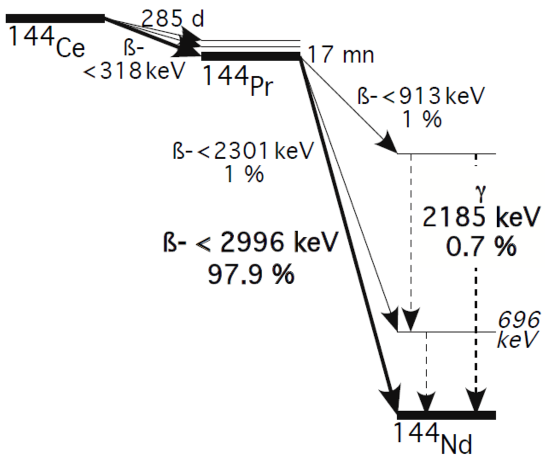


SOX experiment : key ideas

<u>Principle</u> : test the anomaly by bringing a 100-150 kCi ^{144}Ce/Pr source at 8.5 m from the detector center to see an oscillation pattern in the neutrino count rate as a function of both energy and distance.



$\Delta m^2 = 3$ eV^2, $|U_{es}|^2 = 0.25$



From nuclear wasted fuel → potential contaminants for calorimetric measurement and long term storage : constrained contaminant using **γ, α, β and mass spectroscopy (SPP & DEN/LASE) .**

γ spectroscopy : experimental context

HPGe detector, located in building 534, D.Motta laboratory.

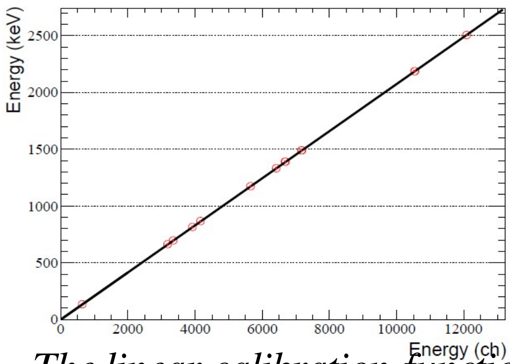
Shielding :

- Underground laboratory (10 mwe),
- Lead bricks surrounding the detector for natural radioactivy shielding.
- Acrylic box flushed with gaseous nitrogen to push out Radon,

HPGe detector :

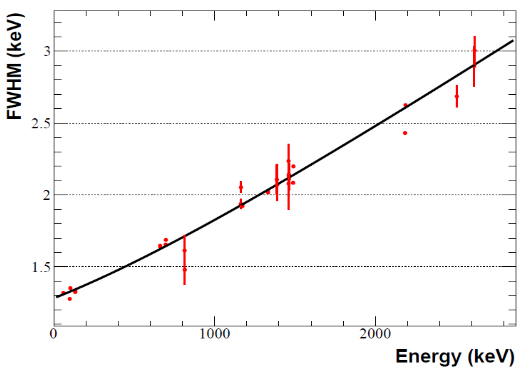
- Semiconductor detector,
- Cooled down using liquid nitrogen,
- General idea of the inner detector but no precise maps.

Energy calibration



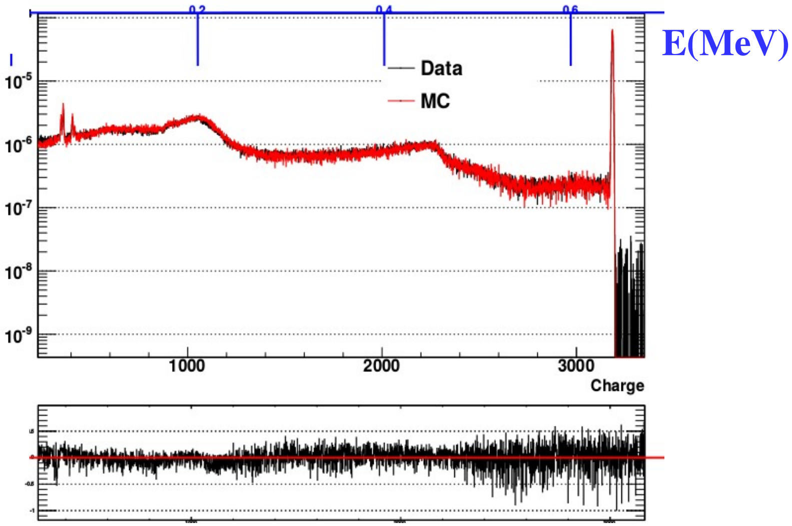
The linear calibration function for the external sources measurement : E[keV]=0.20743 E[ch]+0.247

Resolution calibration

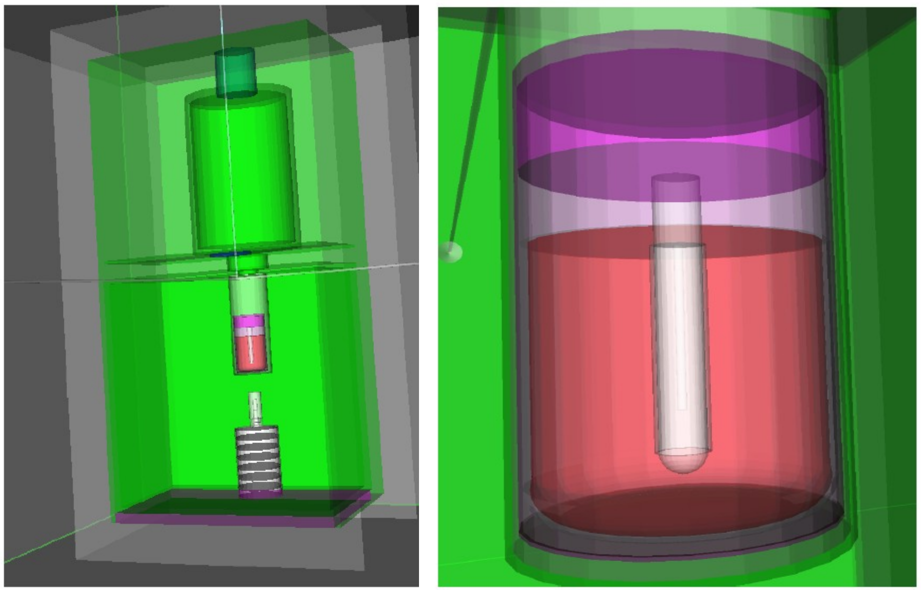


The FWHM as a function of the energy : Fano factor determination.

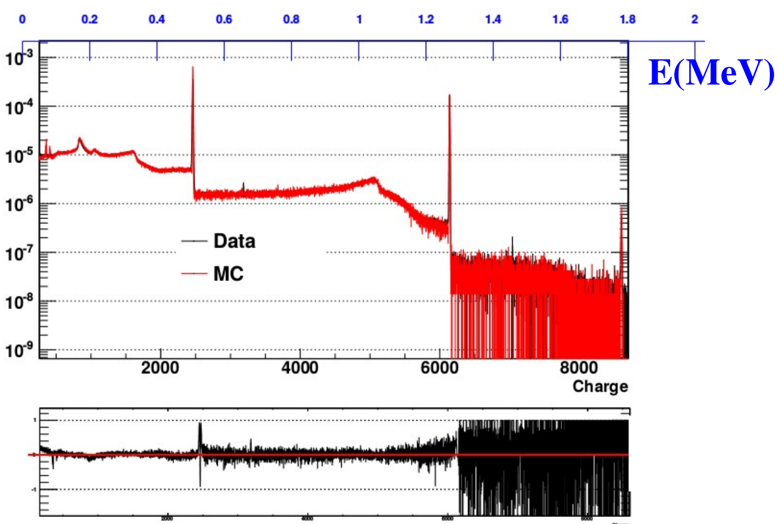
γ spectroscopy :
Geant4 simulation



^{137}Cs in BOT position



Geant4 simulation of the detector and its near environment.

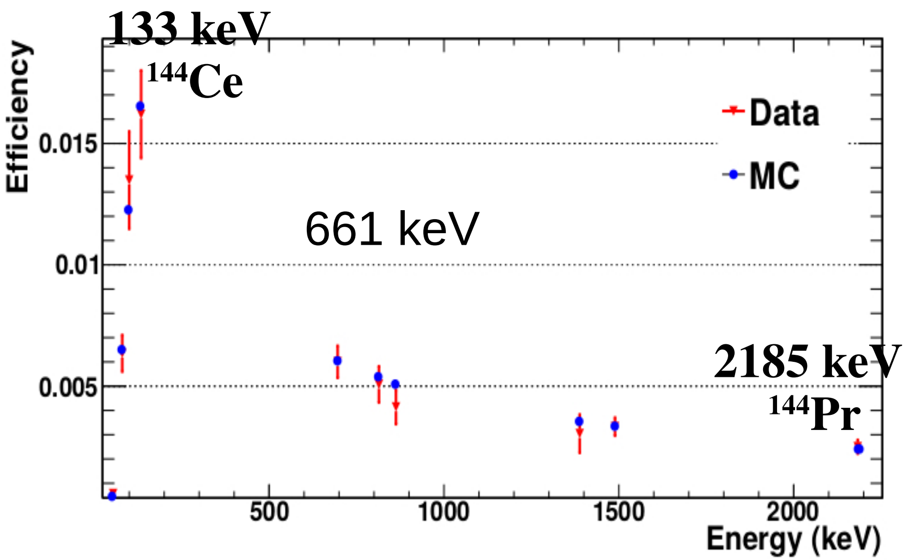


^{22}Na in TOP position

γ calibration source used : ^{60}Co, ^{137}Cs, ^{22}Na, ^{241}Am + ^{144}Ce/Pr sample.

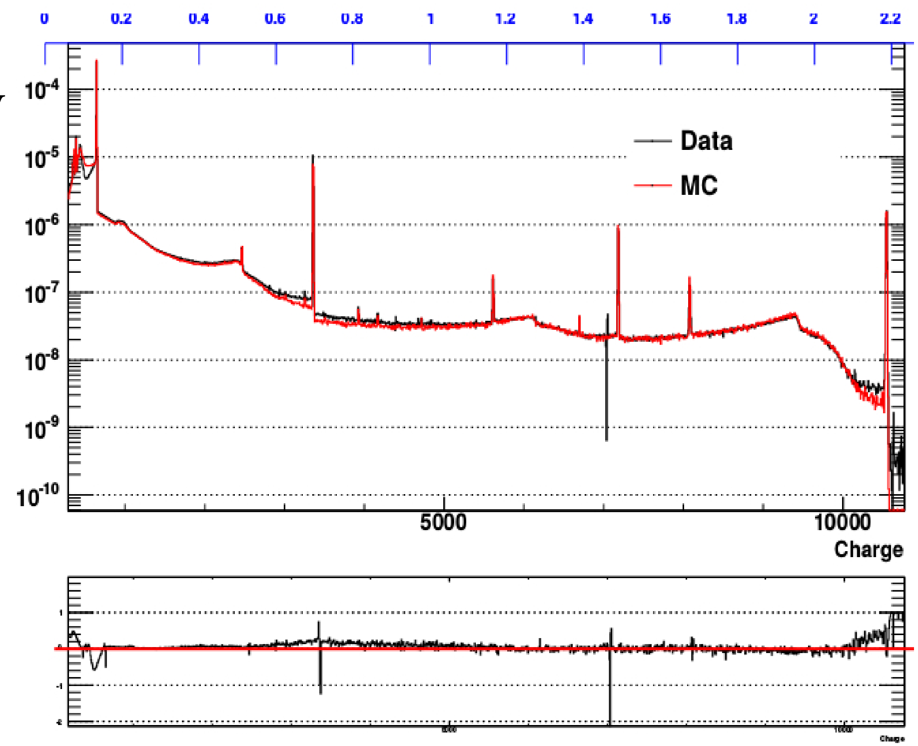
Two experimental situations : 10 cms (TOP) and 30 cms from the detector (BOT).

γ spectroscopy : ^{144}Ce/Pr results

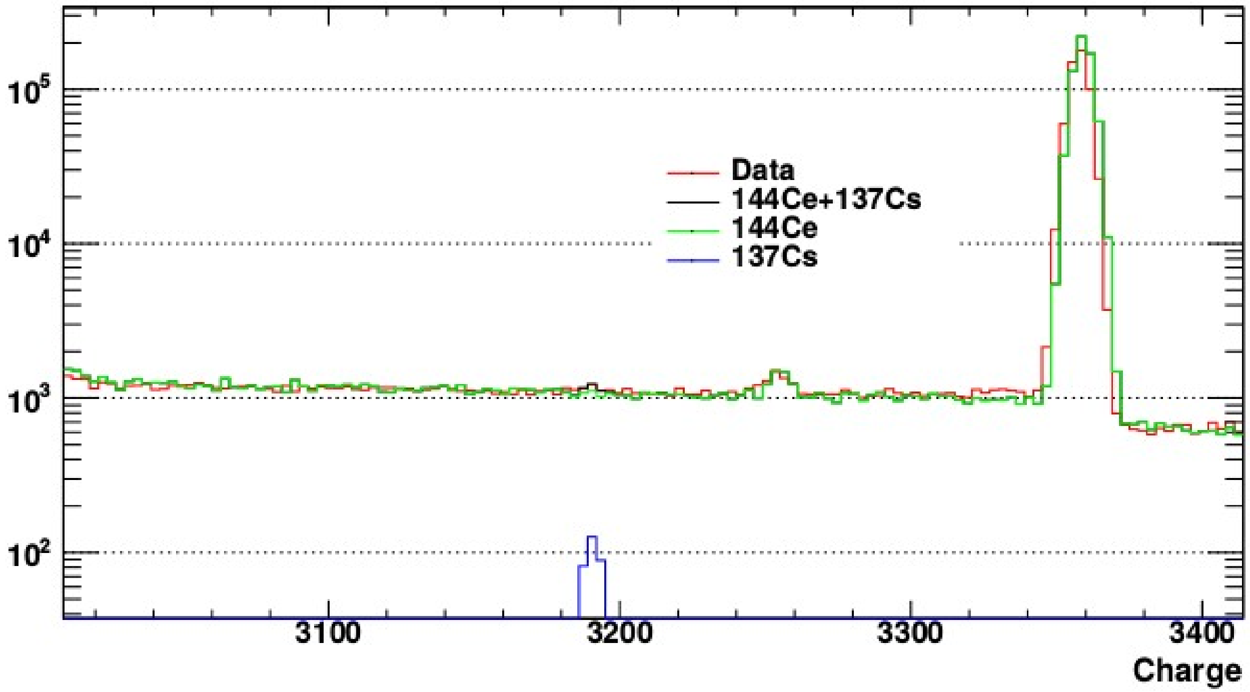


Comparison data/MC for the ^{144}Ce/Pr efficiencies after adjusting simulation parameters such as dead-layers, borehole, coldfinger, detector global efficiency, etc.

Comparison data/MC for ^{144}Ce/Pr spectrum.



γ spectroscopy :
example of contamination measurement



Fitting the [144]Ce/Pr spectrum with the Monte Carlo adding a [137]Cs contaminant.

$$A_{cs} = (1.021 \pm 0.217) \times 10^{-5} A_{Ce}$$

also checked with an independant method.

Activity of contaminants : uncomplete study

Isotopes	Half life (y.)	decay	heat (W) for 1 μg	mBq/Bq$_{144}$Ce
^{22}Na	2.6027	β^+	$4.0\ 10^{-5}$	1.251
^{60}Co	5.27	β^-	$1.2\ 10^{-5}$	0.769
^{106}Ru-^{106}Rh	1.023	2 β^-	$8.2\ 10^{-6}$	3.197
^{102m}Rh-^{102}Ru	3.742	EC	$6.9\ 10^{-6}$	1.086
^{134}Cs	2.0652	β^-	$4.8\ 10^{-6}$	2.148
^{137}Cs	30.08	β^-	$3.9\ 10^{-7}$	1.779
^{151}Sm	90	β^-	$3.0\ 10^{-9}$	70.192
^{172}Hf-^{172}Lu	1.87	2 EC	$4.8\ 10^{-6}$	1.865
^{210}Pb -> ^{206}Pb	22.2	$2\beta^- + \alpha$	$2.4\ 10^{-6}$	0.253
^{208}Po	2.898	α	$8.9\ 10^{-6}$	0.529
^{228}Ra -> ^{208}Pb	5.75	$5\alpha+4\beta^-$	$3.8\ 10^{-5}$	0.057
^{227}Ac -> ^{207}Pb	21.772	$5\alpha+3\beta^-$	$1.3\ 10^{-5}$	0.043
^{228}Th -> ^{208}Pb	1.9116	$5\alpha+2\beta^-$	$5.5\ 10^{-5}$	0.120
^{232}U -> ^{208}Pb	68.9	$6\alpha+2\beta^-$	$5.0\ 10^{-6}$	0.036
^{236}Pu-^{232}U	2.858	α	8.910^{-6}	0.475
^{243}Cm -> ^{235}U	29.1	2α	3.210^{-6}	0.127
^{244}Cm	18.1	α	$2.5\ 10^{-6}$	0.256
^{248}Bk-^{244}Am	10	$\alpha+\beta^-$	3.510^{-6}	0.332
^{248}Cf	0.913	α	$6.1\ 10^{-6}$	2.064
^{250}Cf	13.08	α	$3.4\ 10^{-6}$	0.258
^{254}Es-^{250}Bk	0.755	$\alpha+\beta^-$	$5.5\ 10^{-6}$	2.718

Credits to J.Gaffiot and M.Cribier.

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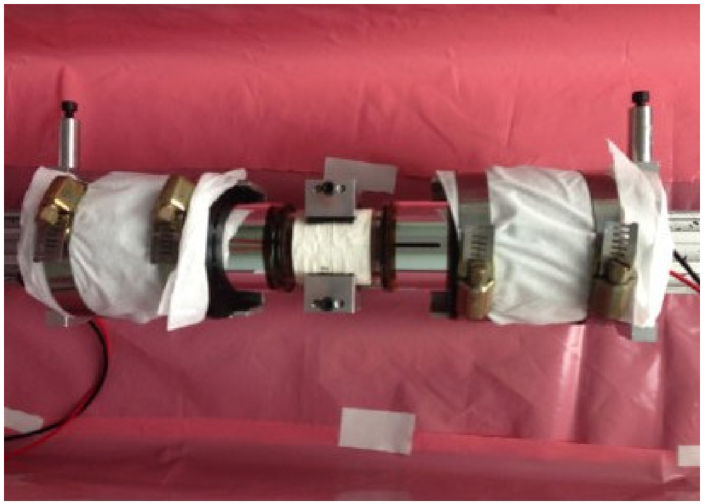
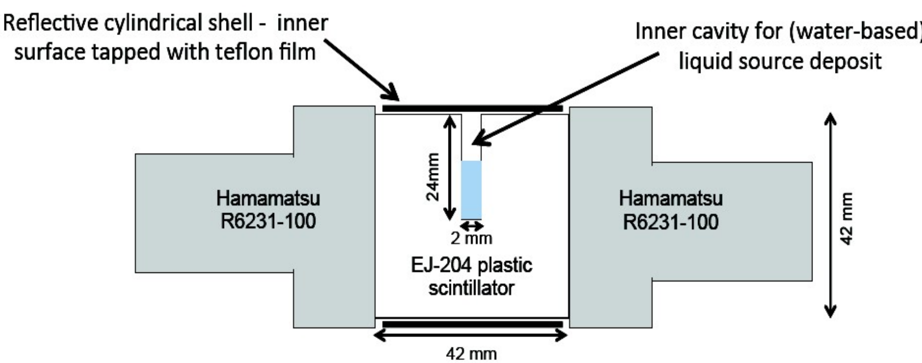
From specifications

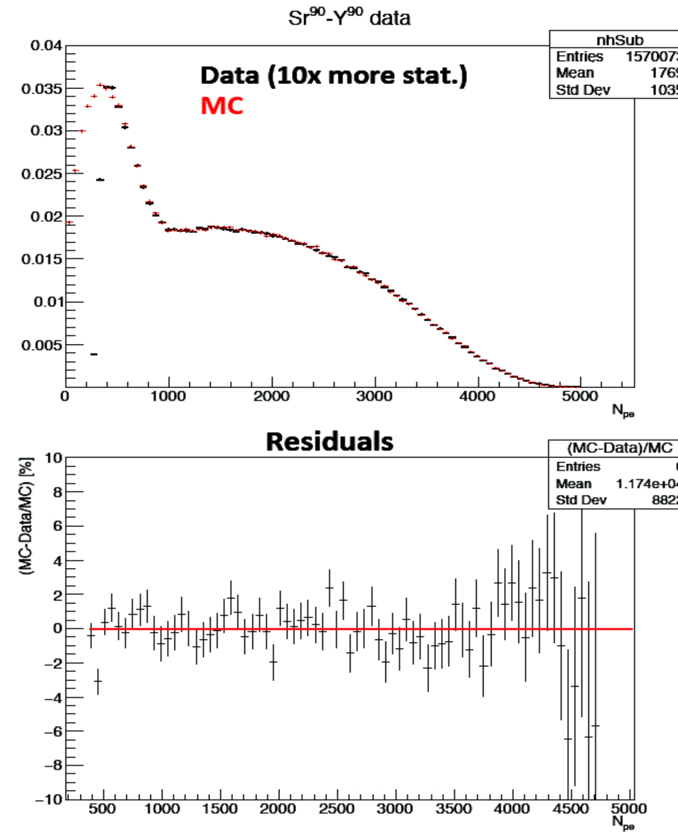
Better sensibility with the γ spectroscopy

We are able to check the specifications and put constrains on contamination

β spectroscopy :
simulation of the setup







^{90}Sr/Y calibration source data/MC comparison

SOX experiment : conclusions

γ spectroscopy : detector well calibrated and able of reproduce entire spectrum.

β spectroscopy : Geant4 simulation done, detector under calibration (M. Durero et M.Vivier).

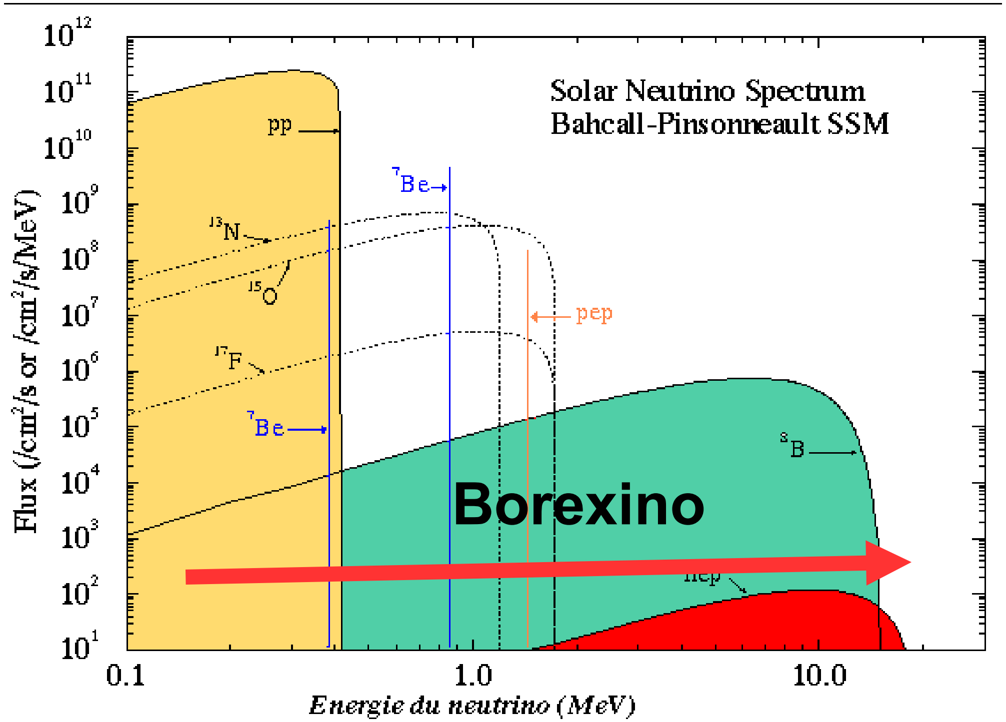
Identification of the **potential contaminants** (0.5 y. > $T_{1/2}$ > 1000y.).

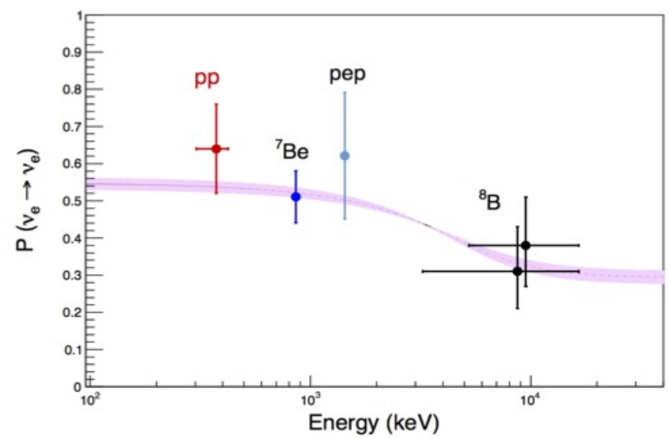
From now on → sensibility study of SOX experiment to potential contaminants regarding the calorimetric measurement. The study will focus on the sensibility we can achieve at CEA using real samples of the ^{144}Ce/Pr source : γ, β, α spectroscopy, ICPMS.

II. Solar ^{8}B neutrino rate measurement

^{8}B measurement :
a serious challenge

	Threshold [MeV]	$\Phi^{ES}_{^8B}$ [10^6 cm^{-2} s^{-1}]
SuperKamiokaNDE I [3]	5.0	$2.35 \pm 0.02 \pm 0.08$
SuperKamiokaNDE II [2]	7.0	$2.38 \pm 0.05^{+0.16}_{-0.15}$
SNO D_2O [4]	5.0	$2.39^{+0.24}_{-0.23}\,^{+0.12}_{-0.12}$
SNO Salt Phase [25]	5.5	$2.35 \pm 0.22 \pm 0.15$
SNO Prop. Counter [26]	6.0	$1.77^{+0.24}_{-0.21}\,^{+0.09}_{-0.10}$
Borexino	3.0	$2.4 \pm 0.4 \pm 0.1$
Borexino	5.0	$2.7 \pm 0.4 \pm 0.2$





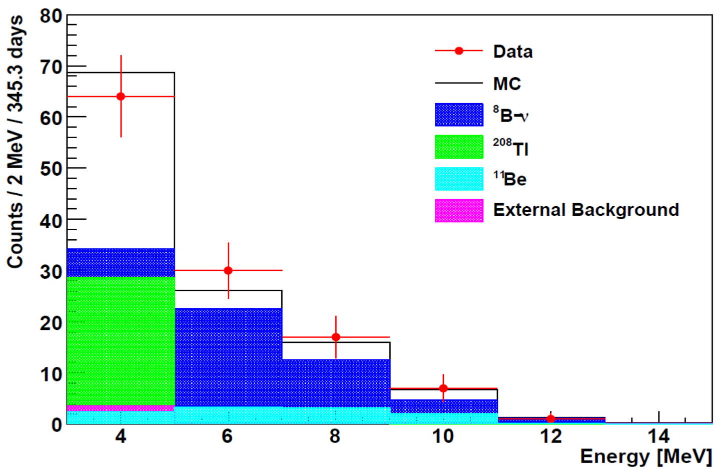
Aim at obtaining a pure sample of ^{8}B events to look for possible spectral distortions.

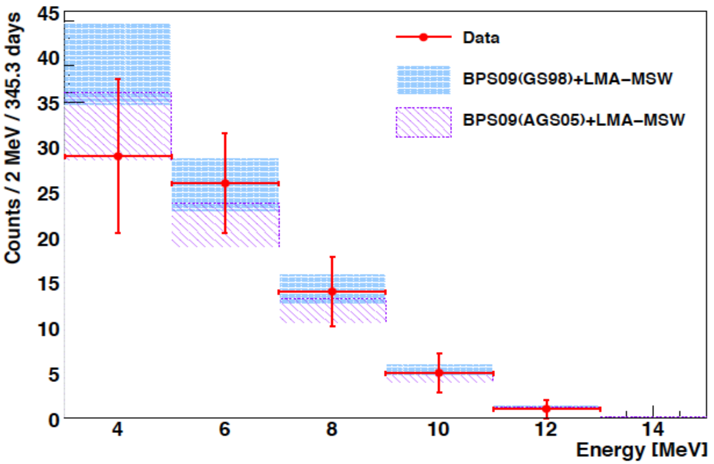
^{8}B measurement : context in Borexino

PHYSICAL REVIEW D **82,** 033006 (2010)

Previous analysis:

Measurement of the solar ^{8}B neutrino rate with a liquid scintillator target and 3 MeV energy threshold in the Borexino detector





New analysis:

Fiducial volume: 100 tons, 3m from the center;

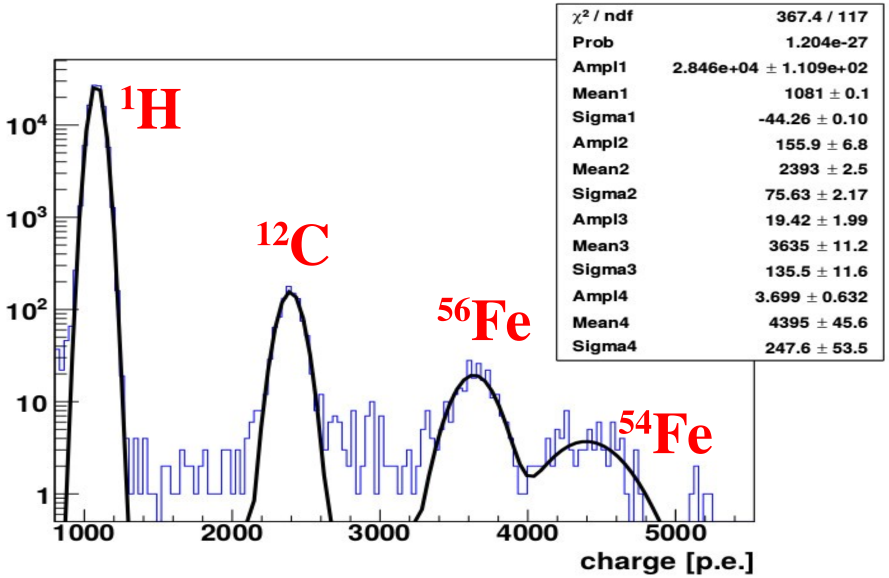
Live time: **2214.79 days** (2008-2016);

Dead-time: **27.72 %**;

Final exposure time: 1600.72 days x 100 t.

- Better energy calibration (i.e. position/time dep.) using detector maps;
- Less contamination (due to purification);
- More statistics (4.5 times more live time).

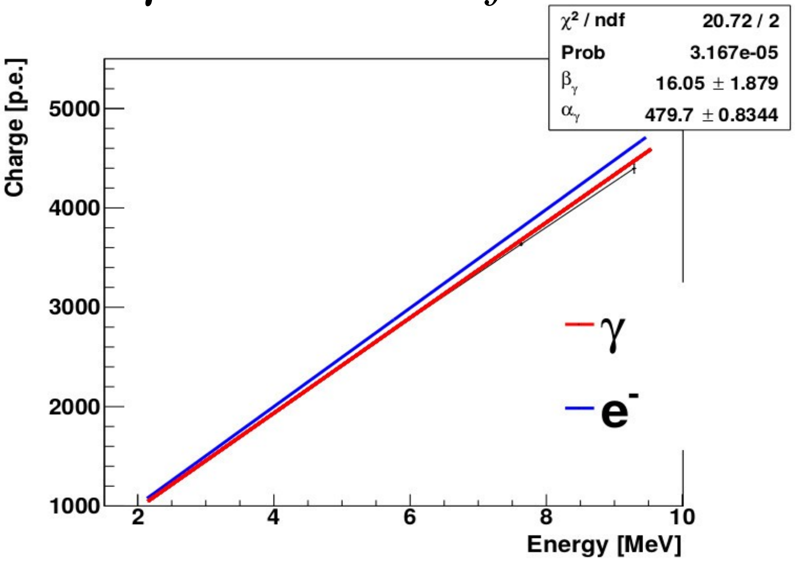
^{8}B measurement : energy scale in the center of the detector



AmBe source in the center

Neutron capture on ^{1}H, ^{12}C, ^{56}Fe and ^{54}Fe → γ emission of: 2.22, 4.95, 7.63 and 9.30 MeV.

γ/e$^-$ calibration function

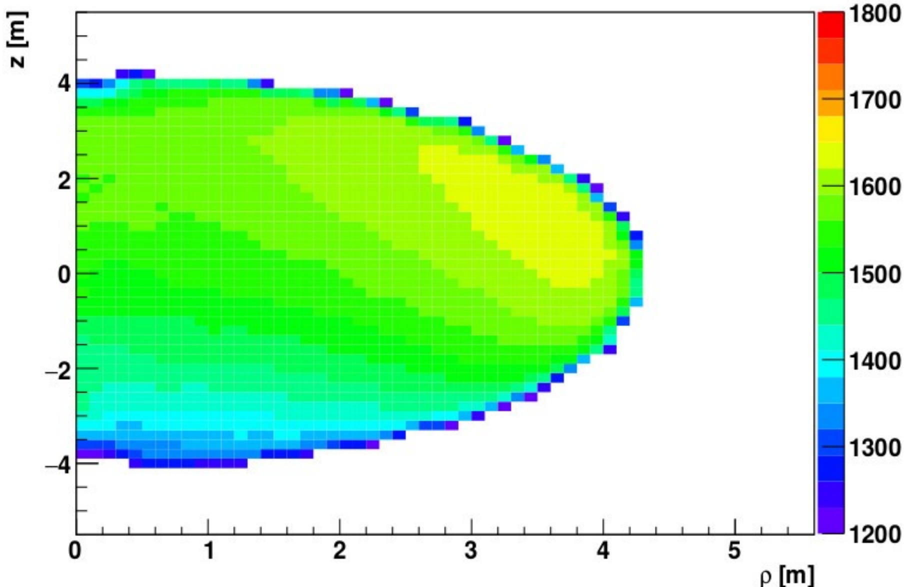


Fitting the 4 points and extrapolating from MC the charge difference for the same energy deposited by γ and e$^-$ at the center.

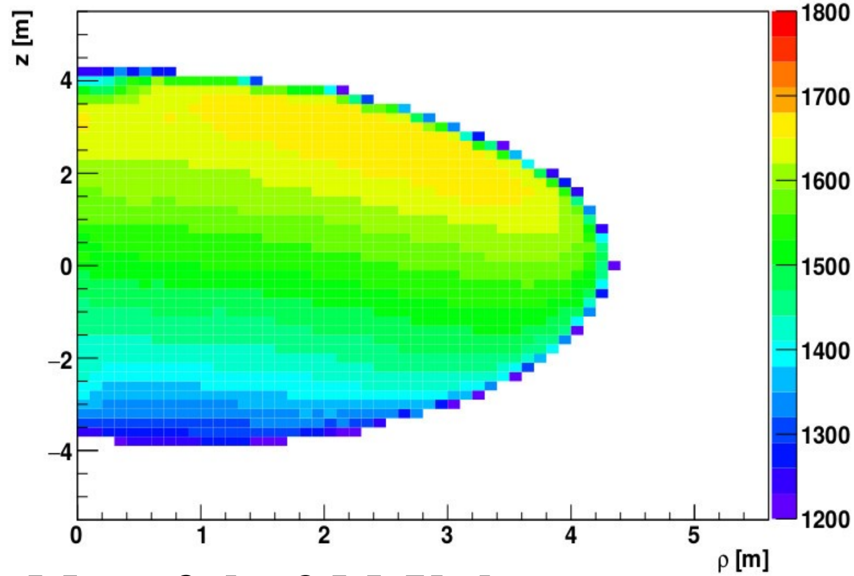
^{8}B measurement : the 3 MeV threshold

Charge is renormalized wrt alive PMTs distribution inside the detector :

→ energy calibration depends on position and time.



Map of the 3 MeV charge equivalent in 2009



Map of the 3 MeV charge equivalent in 2015

Simulation of 3 MeV electrons generated uniformly from 0 to 5.5 m.

8 maps generated from Dec. 2008 to Dec. 2015.

^{8}B measurement : the main issue, rejecting background

Primary selection:

- E > 3 MeV, to avoid 2.614 MeV γ from β decay of ^{208}Tl;
- R < 3 m, to minimize external background (radioactive elements present in the nylon vessel, the PMTs and the SSS)

Expected ^{8}B rate in the fiducial volume above 3 MeV: ~ **0.25 cpd/100 tons**

Expected background for the ^{8}B analysis:

- muons: ~ 1550 cpd/100 tons,
- cosmogenics : ~ 2.1 cpd/100 tons,
- neutrons: ~ 25 cpd/100 tons (high energy γs from neutron capture).
- radioactive background in the bulk: ~10^{-17} g(^{238}U-^{232}Th) / g(scint.) + ^{222}Rn emanation from the vessel,
- external background.

^{8}B measurement : rejecting cosmogenics

<u>Cosmogenics:</u> radioactive elements produced by muon spallation.

Expected cosmogenics above 3 MeV and their expected rate in the fiducial volume:

Isotopes	^{12}B	^{8}He	^{9}C	^{9}Li	^{8}B	^{6}He	^{8}Li	^{11}Be	^{10}C
lifetime (s) (t_i)	0.0291	0.17	0.19	0.26	1.11	1.17	1.21	19.9	27.8
Expected rate [cpd/100t] (r_i)	1.41	0.026	0.096	0.071	0.273	NA	0.40	0.035	0.54
Fraction > 3 MeV (δ_i)	0.886	0.898	0.965	0.932	0.938	0.009	0.875	0.902	0.012

Summarize of the cosmogenic contamination critical above 3 MeV.

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Short life elements

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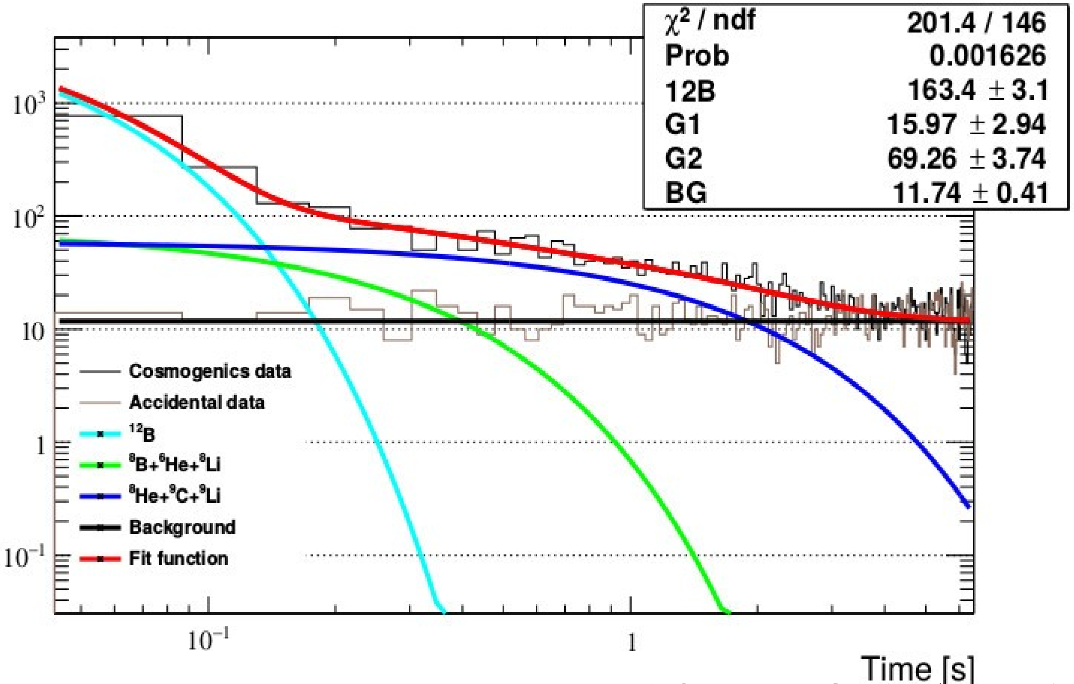
G1 (^{8}He, ^{9}C, ^{9}Li)

G2 (^{8}B, ^{6}He, ^{8}Li)

Summarize of the cosmogenic contamination critical above 3 MeV

Short life elements

^{8}B measurement :
rejecting short life cosmogenics



Looking for neutrino like events after an internal muon.

Fixing:

t_1 (^{12}B) : 0.029 s;

t_2 (^{8}He, ^{9}C, ^{9}Li) : 0.213 s;

t_3 (^{8}B, ^{6}He, ^{8}Li) : 1.168 s.

$Res_{fast\ cosmo}$ = (27.7 +/- 1.5) x 10^{-4} cpd / 100 t

→ **Veto: 6.5 s after an internal μ.**

→ **Dead-time: ~ 27.5 %**

^{8}B background rejection: ^{208}Tl

$$^{212}_{83}\mathrm{Bi} \xrightarrow[4.47\mathrm{min}]{\alpha(6.2MeV)} {}^{208}_{81}\mathrm{Tl} \xrightarrow[3.05\mathrm{min}]{\beta^-(5.01MeV)} {}^{208}_{82}\mathrm{Pb}$$

Source: ^{232}Th in the liquid.

Tagging on event by event basis ?

→ Coincidence between ^{212}Bi and ^{208}Tl impossible : life time too long.

^{8}B background rejection: ^{208}Tl

$$(64.06\%)\ {}^{212}_{83}\mathrm{Bi} \xrightarrow[431\mathrm{ns}]{\beta(2.2MeV)} {}^{212}_{84}\mathrm{Po} \xrightarrow[0.3\mu s]{\alpha(8.95MeV)} {}^{208}_{82}\mathrm{Pb}$$

$$(35.94\%)\ {}^{212}_{83}\mathrm{Bi} \xrightarrow[4.47\mathrm{min}]{\alpha(6.2MeV)} {}^{208}_{81}\mathrm{Tl} \xrightarrow[3.05\mathrm{min}]{\beta^-(5.01MeV)} {}^{208}_{82}\mathrm{Pb}$$

Source: ^{232}Th in the liquid.

Looking for the BiPo coincidence (431 ns) and use of the branching ratio to evaluate the contamination.

Statistical subtraction

$$N_{^{208}Tl} = \left(\frac{Br_2}{Br_1}\right)\left(\frac{N_{BiPo} \times \epsilon_{Tl}}{\epsilon_{\tau} \times \epsilon_{\mathrm{Bi}} \times \epsilon_{\mathrm{Po}}}\right)$$

We measured 31 (^{212}Bi/^{212}Po) coincidence leading to (53.6 +/- 9.6) ^{208}Tl events.

Rate = (2.42 +/- 0.43) 10^{-2} cpd/100t

^{8}B measurement : external contamination

-- Radial distribution of scintillation events above 3 MeV

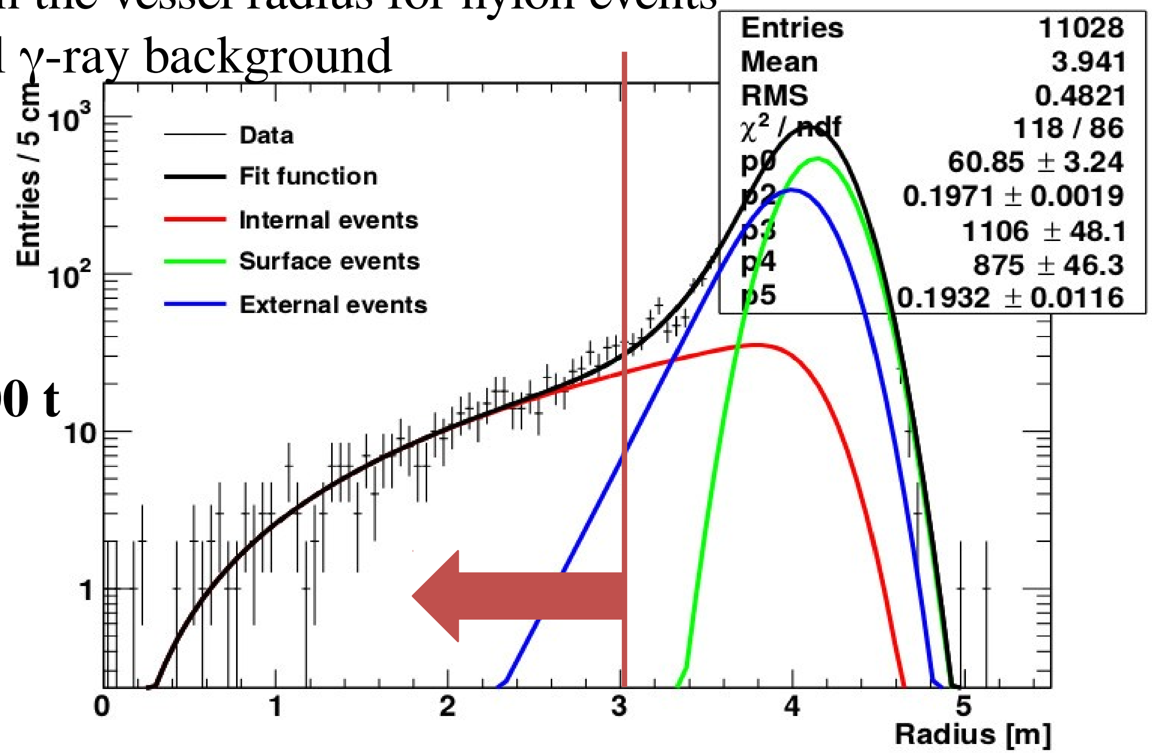
-- Use of the Monte Carlo maps to set the 3 MeV threshold + 6.5 s veto after internal muon + 2 ms after external muon + ^{10}C cuts

-- Fit with the 3 sources of background

✓ A uniform distribution in the detector for internal events

✓ A delta-function centered on the vessel radius for nylon events

✓ An exponential for external γ-ray background



Contamination up to 3 m:

$$\mathbf{R_{ext} = (164.88 \pm 8.73)\ 10^{-4}\ cpd/100\ t}$$

^8B measurement : summary of residual backgrounds

Characteristics:

Fiducial volume: 100 tons, 3m from the center.

Live time: 2214.79 days (2008-2016)

Background	Rate $[10^{-4}$ cpd/100 t$] > 3$ MeV 2007-2009	^8B
Muons	4.5 ± 0.9	4.5 ± 0.9
Neutrons	0.86 ± 0.01	0.86 ± 0.01
External background	64 ± 2	164.9 ± 8.7
Fast cosmogenics	17 ± 2	27.7 ± 1.5
^{10}C	22 ± 2	17.4 ± 13.4
^{214}Bi	1.1 ± 0.4	0.83 ± 0.17
^{208}Tl	840 ± 200	242 ± 43
^{11}Be	231 ± 36	231 ± 36

Residual rates of background after data selection cuts above 3 MeV.

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^{208}Tl	840 ± 200	242 ± 43	↘
^{11}Be	231 ± 36	231 ± 36	=

Preliminary

Residual rates of background after data selection cuts above 3 MeV.

^{8}B measurement : conclusion

The first results of ^{8}B rate and spectrum measurement seems in good agreement with the previous analysis.

- **External background high rate** is due to vessel movement over time ;
- **Dead time** measurement is now done using two methods ;
- Better **energy calibration taking into account PMTs distribution** ;
- Radioactivity inside the detector strongly reduced thanks to purification.

From now on, the next step is to **low down the 3 MeV threshold** (~2.5 MeV) but further studies on external contamination will be demanded. Indeed, external contamination will be dominant below 3 MeV (2.6 MeV γ from ^{208}Tl). Playing with the fiducial volume will be a tool to better understand its shape.

Conclusion

Two different approaches:

SOX :

- ✔ Complete calibration of an HPGe for γ spectroscopy,
- ✔ Simulation Geant4 of the β spectrometer,
- ***On-going*** High precision contaminant measurements, sensibility study of the heat conversion from those measurements,

^{8}B :

- ✔ Reevaluating the neutrino rate to compare with the previous analysis,
- ***on-going*** Lower the energy threshold (increase the fiducial volume?),