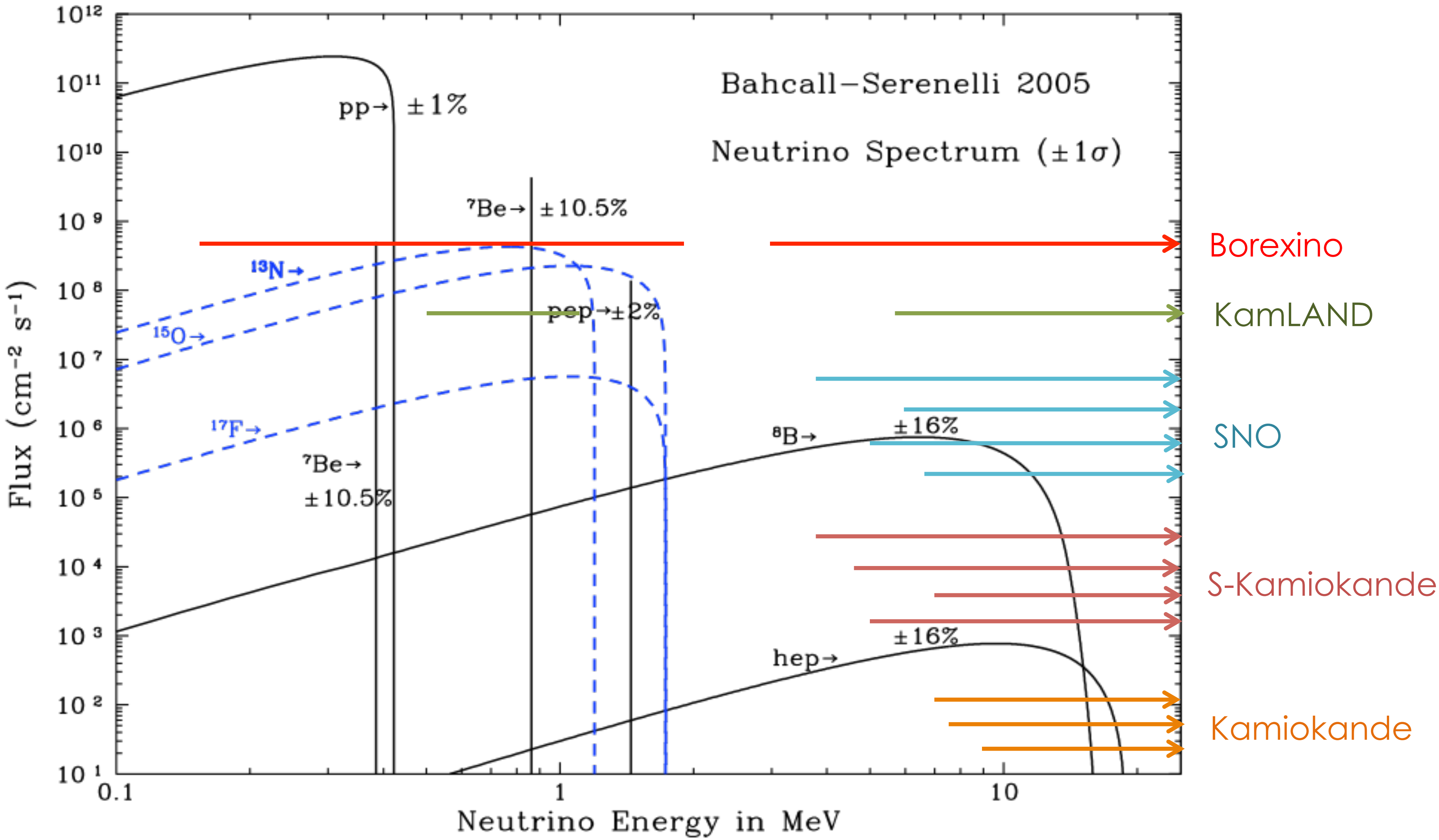
Improved measurement of the ^8B solar neutrino rate with 1.5 kton year of Borexino exposure

Davide Franco
on behalf of the Borexino Collaboration

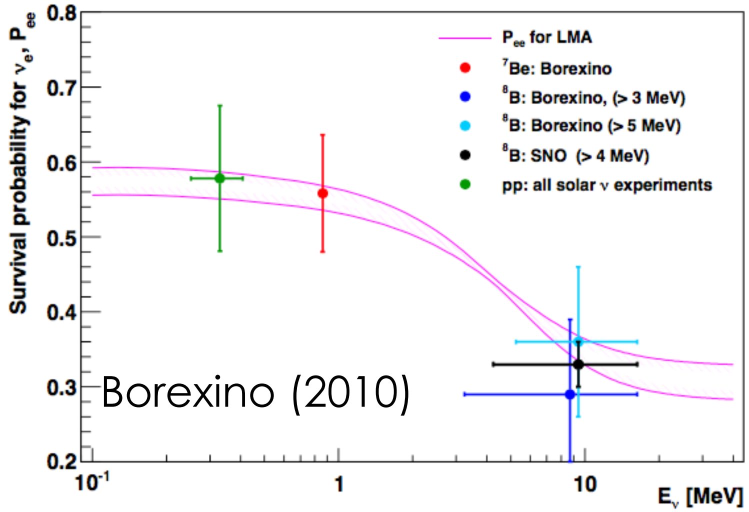
RECENT DEVELOPMENTS IN NEUTRINO PHYSICS AND ASTROPHYSIC
4-7 September 2017 - LNGS-GSSI

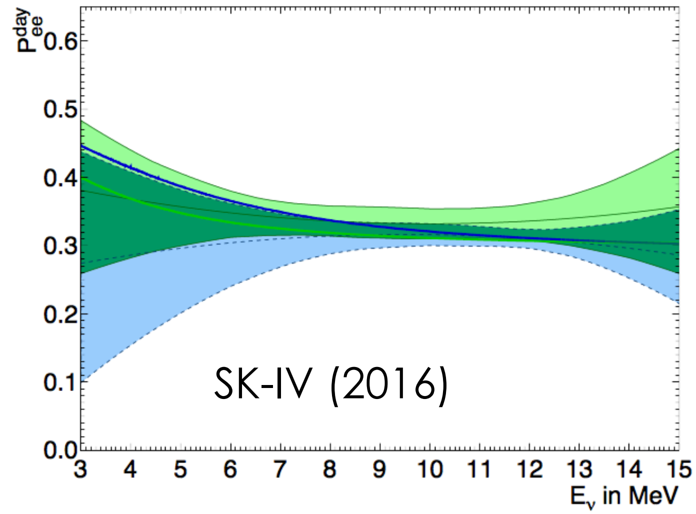
Real time neutrino measurements

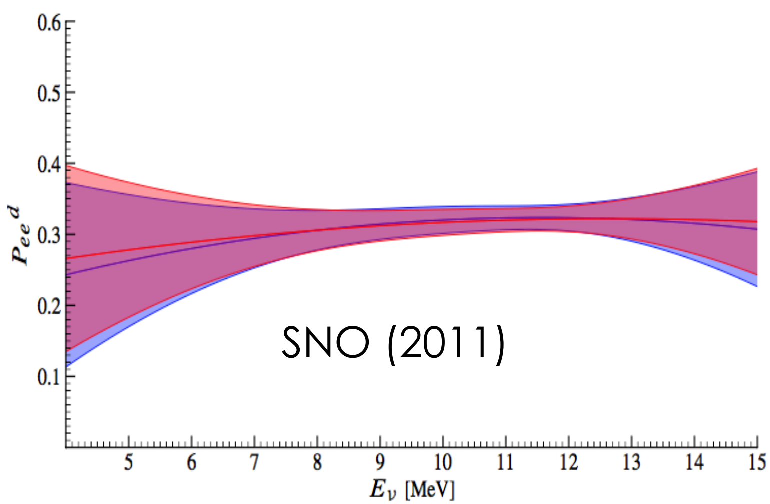


Why is it important to lower the threshold?

Electron neutrino survival probability from 8B



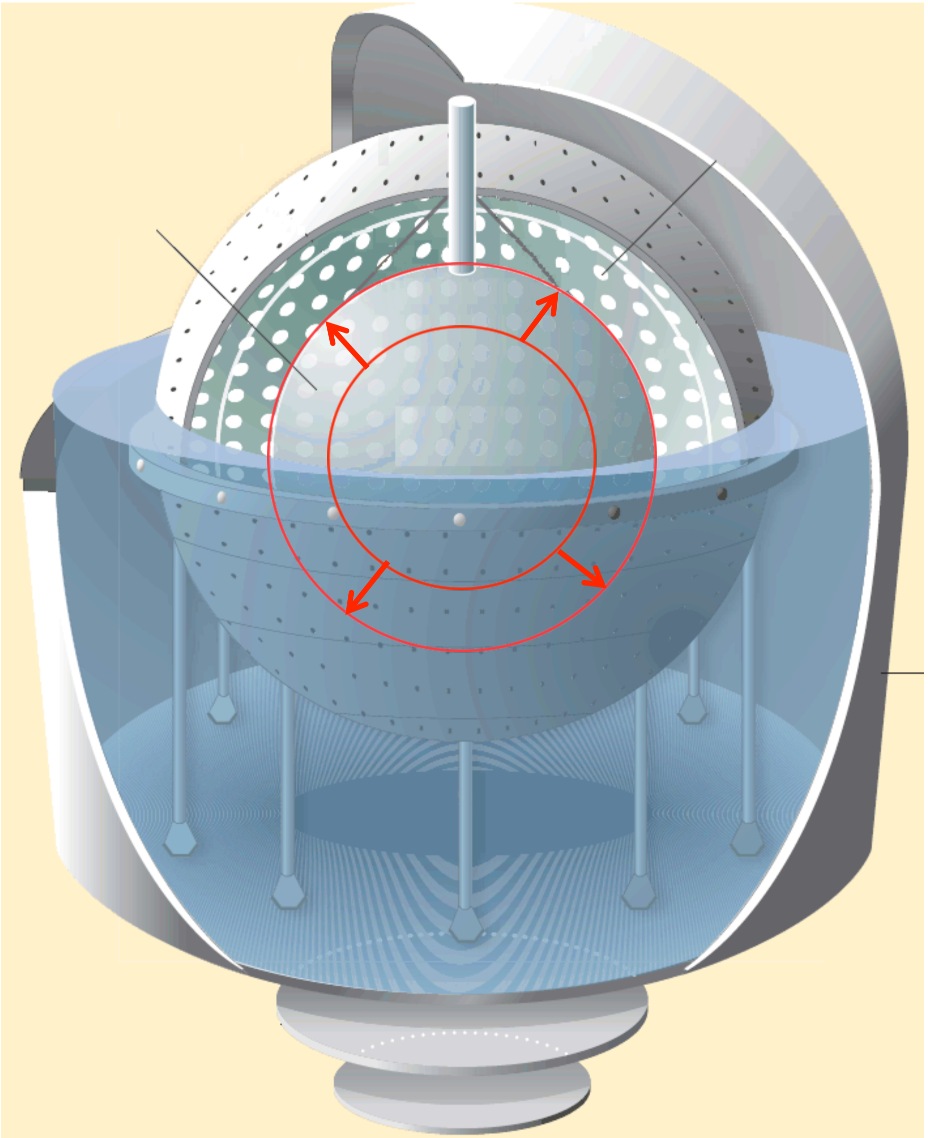




All experiments **fully compatible** with the predicted "**up-turn**"

However, Bx and SNO results seem to prefer a "**down-turn**"

Increasing the statistics



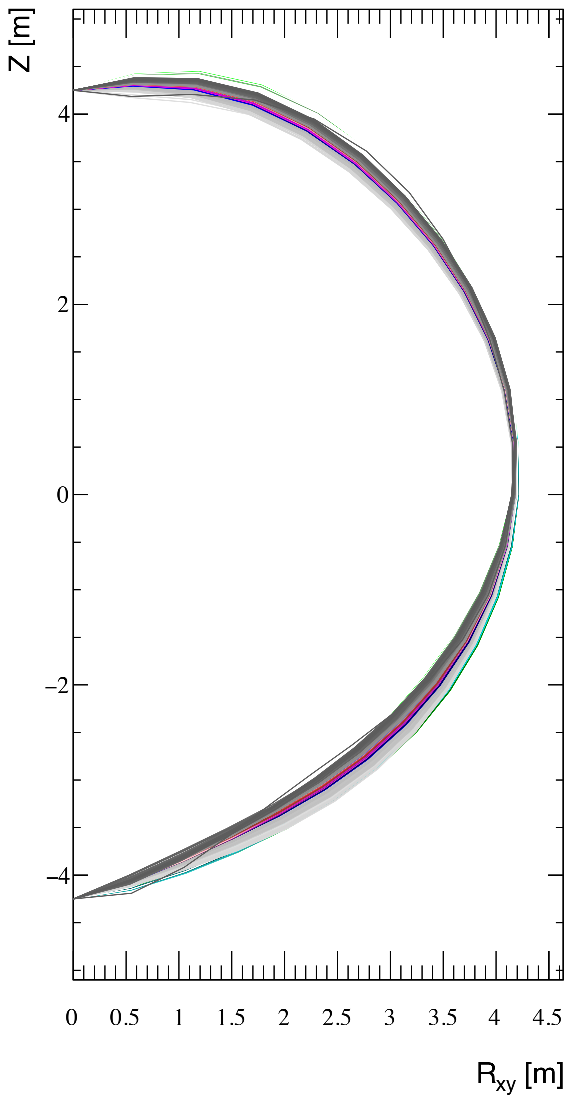
Data Set:
- Jan 2008 – Dec 2016
- Purification period removed
- High ^{222}Rn activity (>20cpd) periods removed
- Total livetime: **2062.38** days

2010 ^{8}B Paper Data Set:
- Jul 2007 – Aug 2009
- Total Livetime: **488** days

Extending the fiducial mass (100 t) to the entire active mass (**~300 t**)

Total exposure: **1.5 kt year** (**11.5-fold** increase)

Instabilities

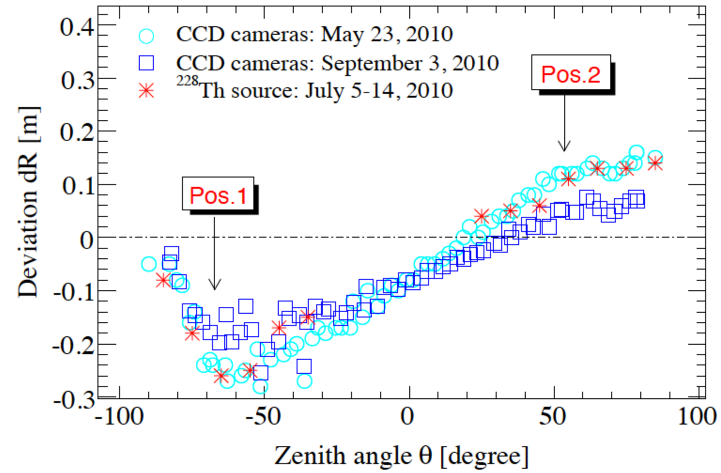


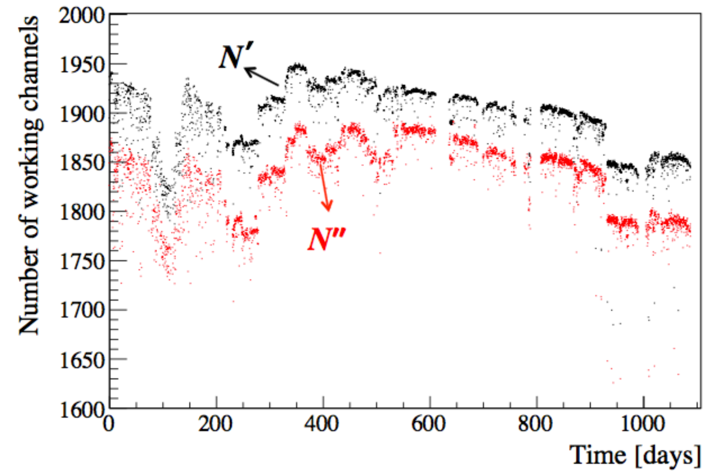
The vessel shape is **not spherical** and has changed during data-taking.

Weekly dynamic **reconstruction** of the vessel radial profile with background events

Cross check with CCD cameras => **1% precision**

Working channels and PMT gains variation along the time => impact on energy and spatial reconstructions



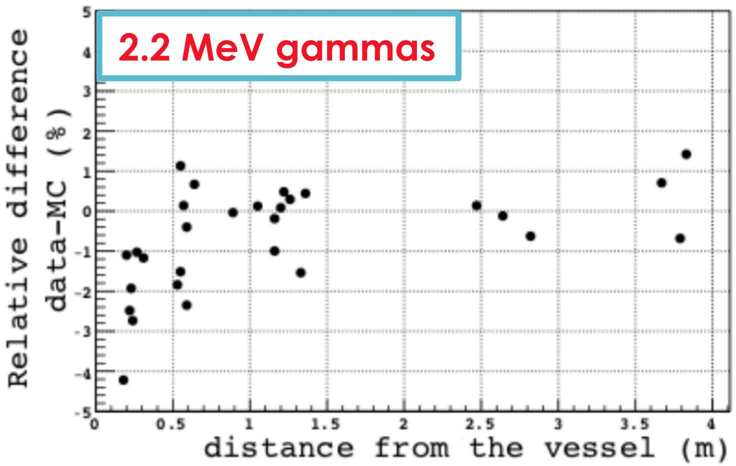


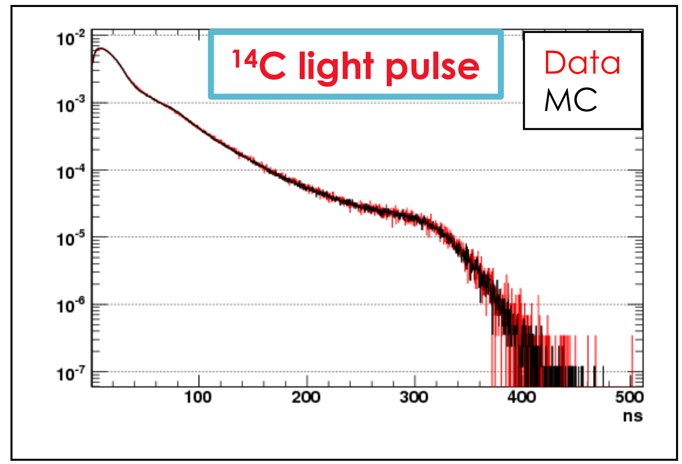
See Borexino Collaboration, Phys. Rev. D89 (2014) 112007

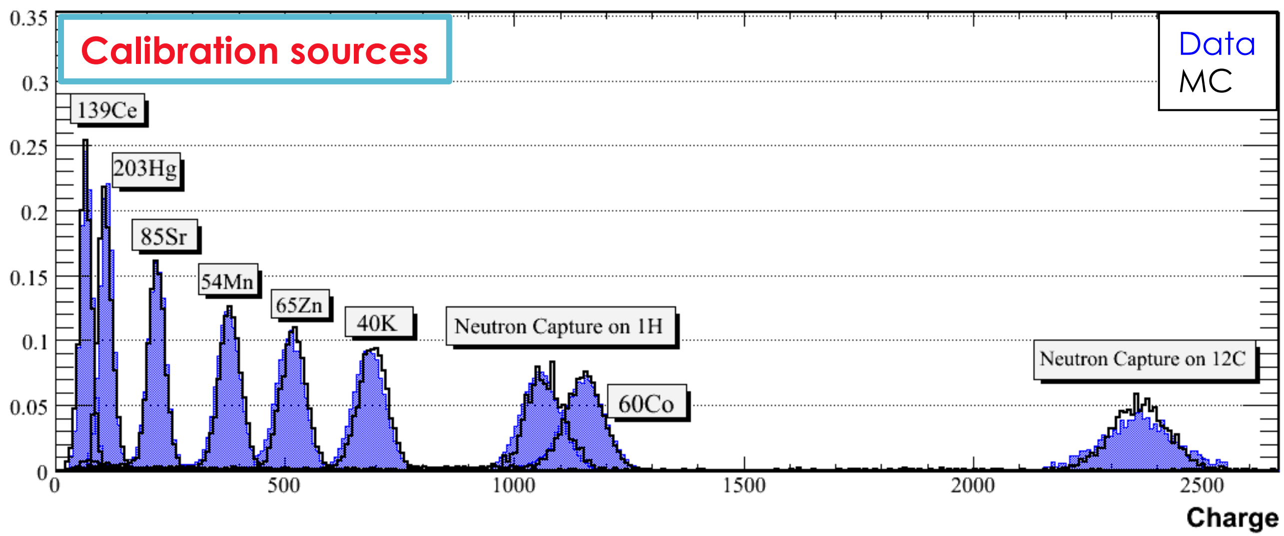
Monte Carlo

All effects included in **Monte Carlo** simulations:
- Data are reproduced on a **weekly** basis
- Statistics corresponds to **100-1000** times wrt data

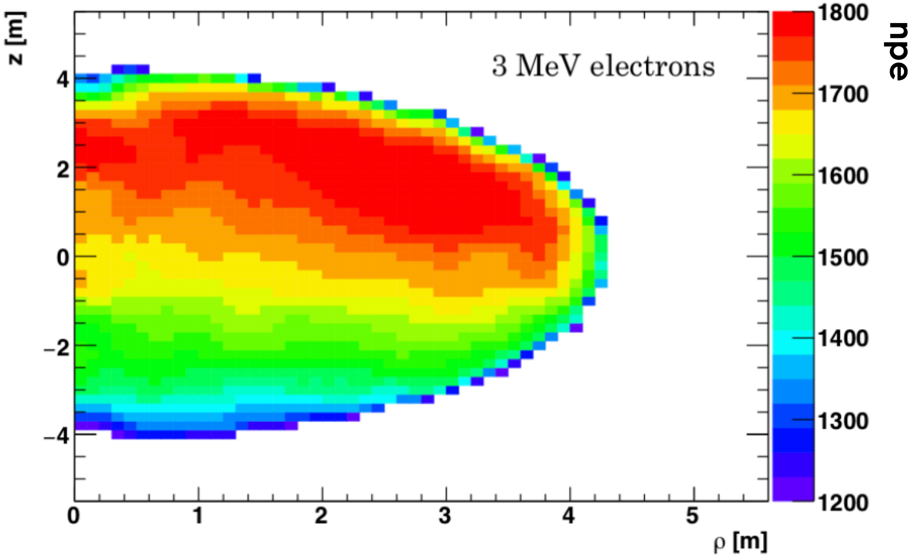
See Borexino Collaboration, arXiv: 1704.02291 (2017)



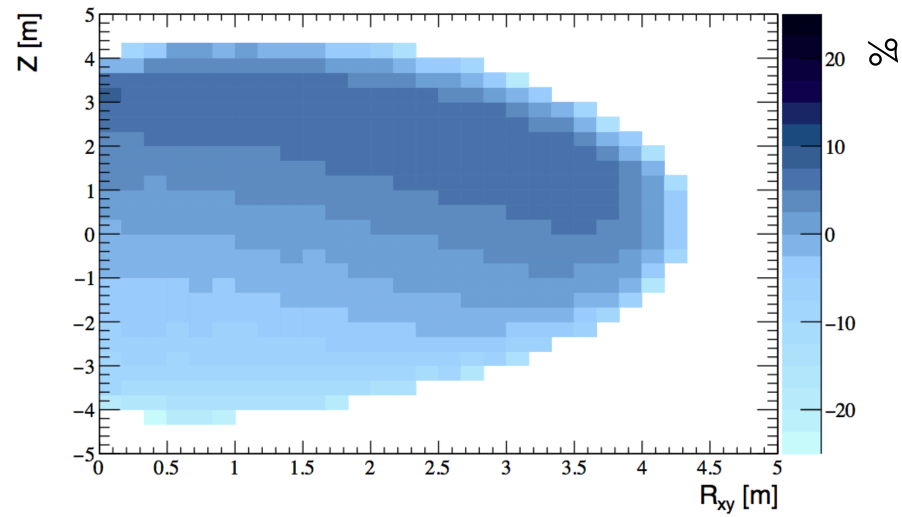




Monte Carlo Response Map



Relative Variation (MC)



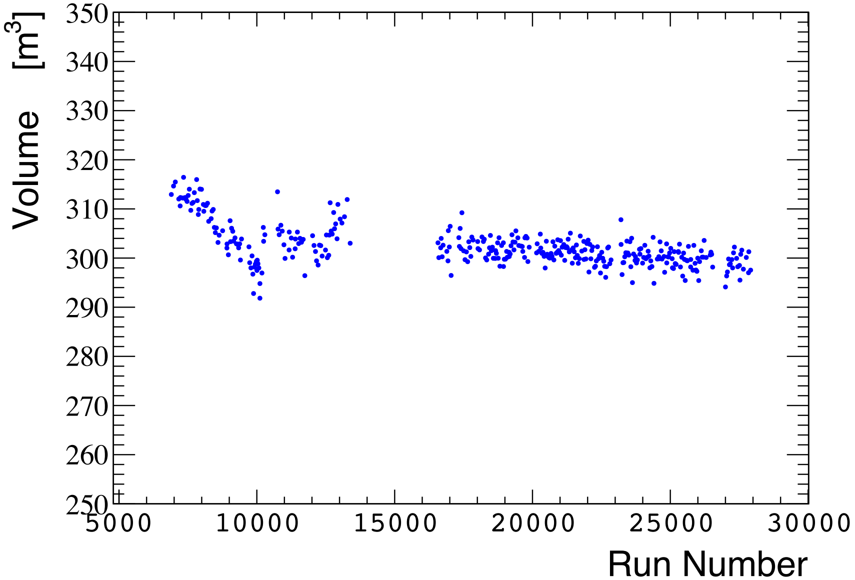
Range of Interest [1650, 8500] npe

Uncertainty from the MC response map: 1.6%

Uncertainty on the LY at the detector center: 1%

Total uncertainty on the energy scale: 1.9%

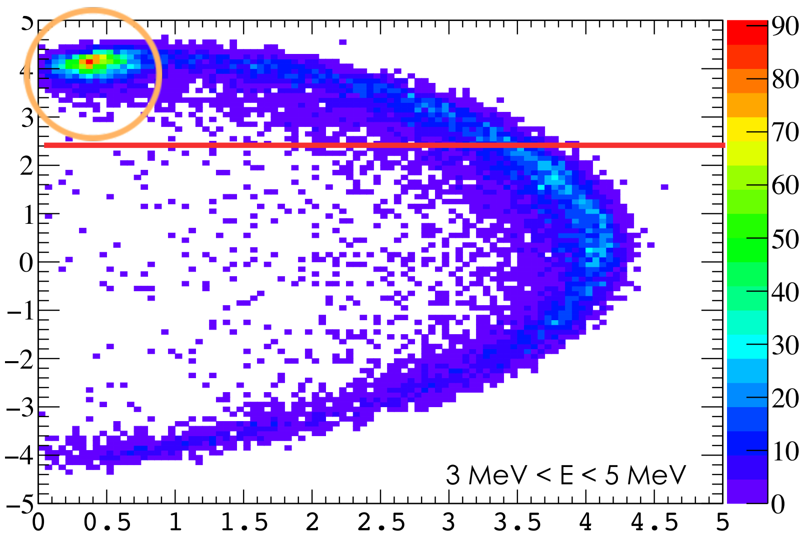
Scintillator Mass and the Leak



Scintillator mass: estimated from a toy MC using the vessel shape

Mass variation due to the leak started in 2009

Average mass = **266 ± 5.3 t**

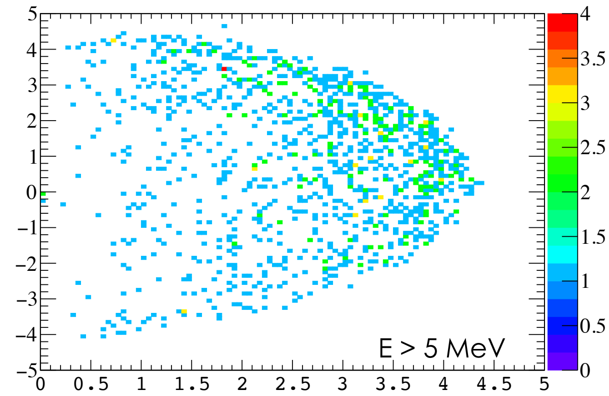


Excess of events at the top, **maybe due to the leak**

Not observed > 5 MeV

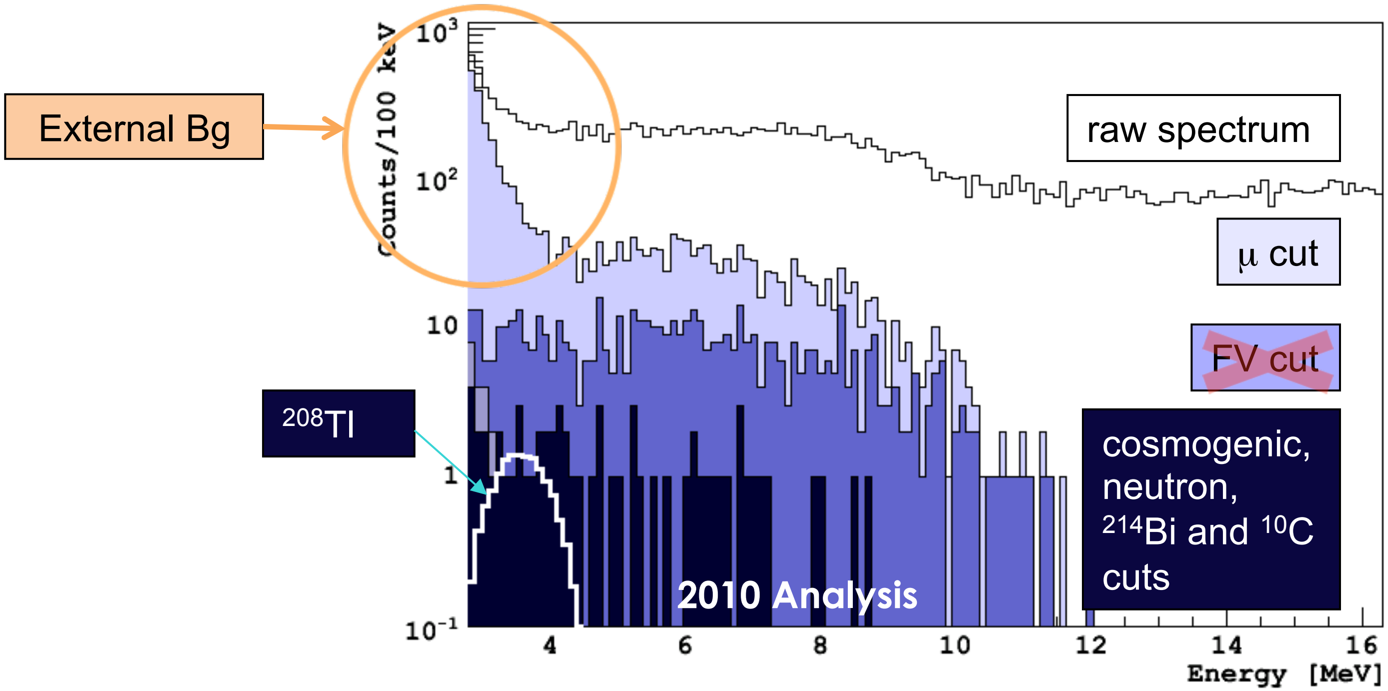
A z-cut at 2.5 m is applied in the low energy region (E < 5 MeV) analysis

Cut acceptance: ~86%



Background

~7500 events / day => signal-to-background ratio: **~1/12,000**



Cosmogenic Background

Cosmogenic Isotopes

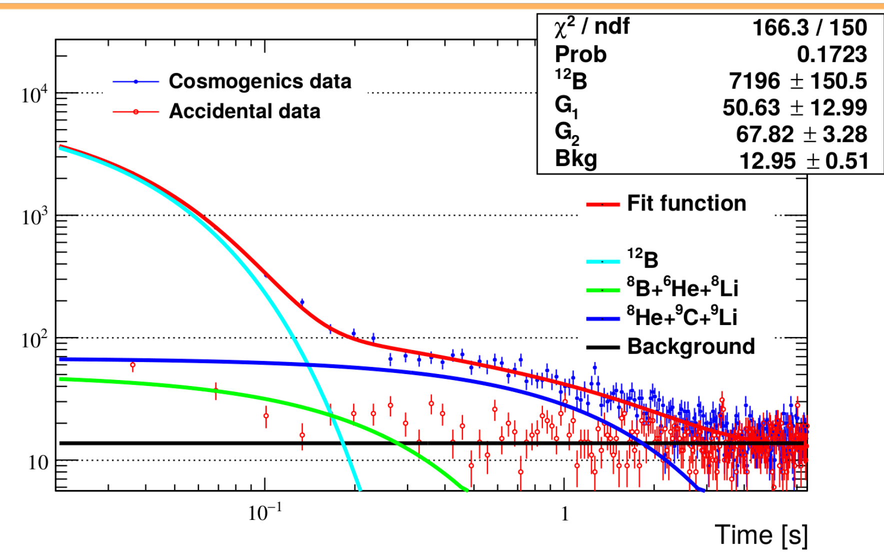
Isotopes	τ	Q [MeV]	Decay	Expected Rate [cpd/100 t]	Fraction $> 3\ MeV$	Expected Rate $> 3\ MeV$ [cpd/100 t]	Measured Rate $> 3\ MeV$ [cpd/100 t]
^{12}B	0.03 s	13.4	β^-	1.41 $\pm$ 0.04	0.886	1.25$\pm$ 0.03	1.48 $\pm$ 0.06
^{8}He	0.17 s	10.6	β^-	0.026 $\pm$ 0.012	0.898		
^{9}C	0.19 s	16.5	β^+	0.096 $\pm$ 0.031	0.965	$(1.8 \pm 0.3)\times10^{-1}$	$(1.7 \pm 0.5)\times10^{-1}$
^{9}Li	0.26 s	13.6	β^-	0.071 $\pm$ 0.005	0.932		
^{8}B	1.11 s	18.0	β^+	0.273 $\pm$ 0.062	0.938		
^{6}He	1.17 s	3.5	β^-	NA	0.009	$(6.0 \pm 0.8)\times10^{-1}$	$(5.1 \pm 0.7)\times10^{-1}$
^{8}Li	1.21 s	16.0	β^-	0.40 $\pm$ 0.07	0.875		
^{10}C	27.8 s	3.6	β^+	0.54 $\pm$ 0.04	0.012	$(6.5\pm0.5)\times10^{-3}$	$(6.6\pm1.8)\times10^{-3}$
^{11}Be	19.9 s	11.5	β^-	0.035 $\pm$ 0.006	0.902	$(3.2 \pm 0.5)\times10^{-2}$	$(3.6\pm3.5)\times10^{-2}$

6.5 s veto

TFC

Untaggable

Extrapolation of the cosmogenic contribution after the 6.5 s time window, with a fit of the time profile of events following a muon



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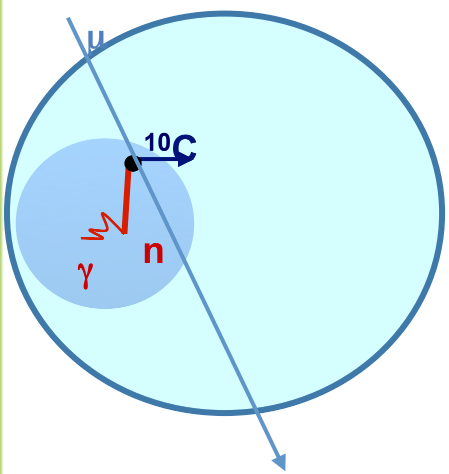
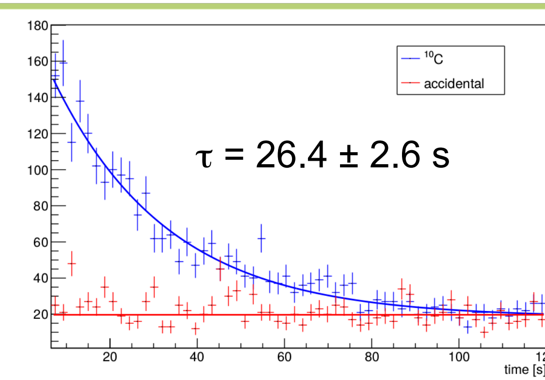


Fraction of ^{10}C with Q > 1650 pe = 1.6%

Three Fold Coincidence:
- Sphere radius = 0.8 m
- Veto time window: 120 s
- Tag efficiency = 92.5^{+7}_{-20}%
- Total **visible ^{10}C rate** = **$0.48^{+0.04}_{-0.11}$** cpd/100 t



Dominant **invisible channel**, ^{12}C(p,t)^{10}C: **~10^{-2}** cpd/100 t

Data Selection

Selection cuts:

- **Neutron cut**: 2 ms veto after each muon
- **Cosmogenic cut**: 6.5 s veto after muon crossing the scintillator
- **^{10}C cut**: 0.8 m radius sphere x 120 s veto around each neutron
- **Run stop/start cut**: 6.5 s veto at the beginning of each run
- **Fast coincidences cut**: no ^{214}Bi-^{214}Po

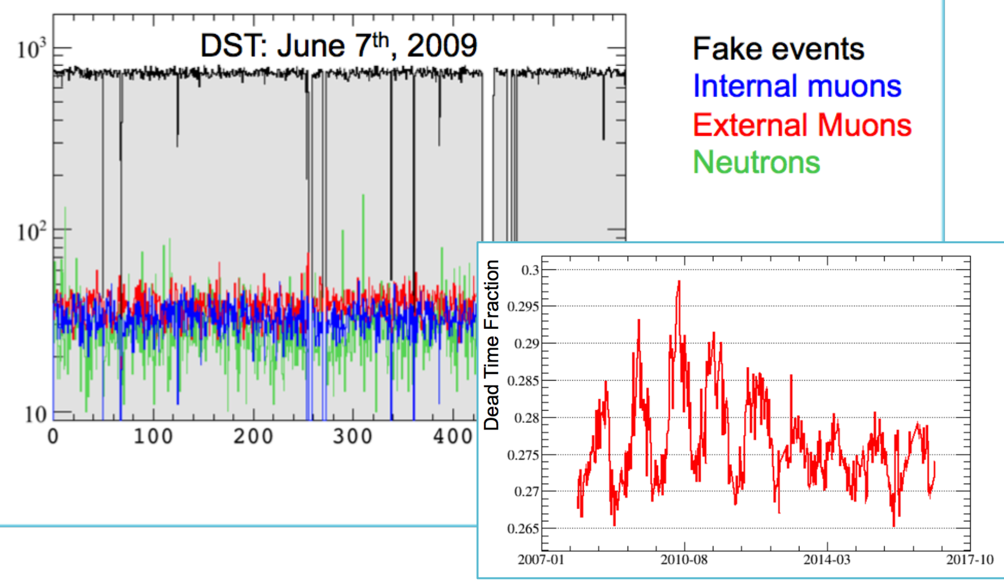
+ Random coincidence cut: no events closer than 5 s (after all previous cuts):

  - ~6,000 candidates with a rate of 4 cpd
  - Probability for random coincidences: ~2x10^{-4}
  - Expected accidentals: 1.4 events
  - Identified: 18 events

Deadtime evaluated at with toy-MC, mixing fake events with muons and neutrons from data

Selection cuts are applied on the simulated sample

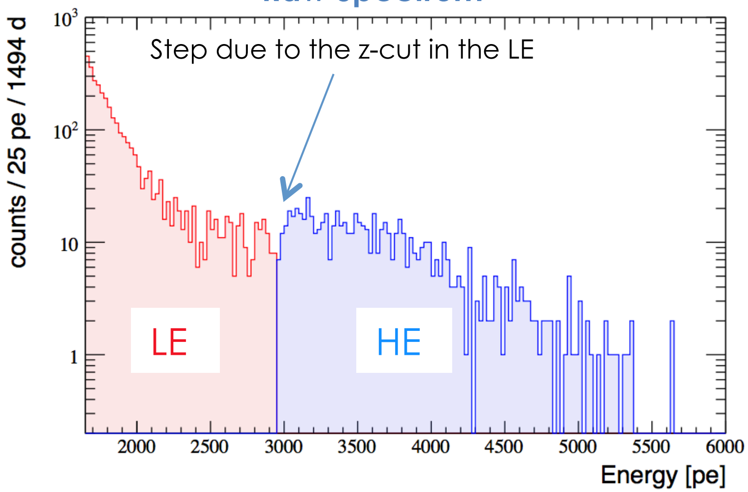
Deadtime evaluated in **27.6%**



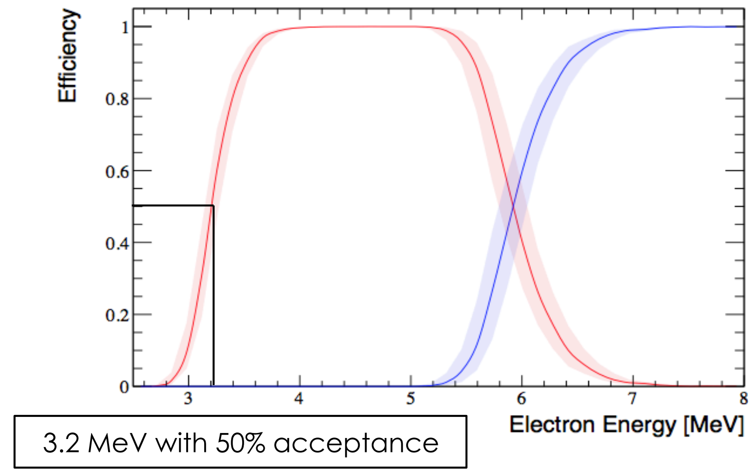
LE and HE Ranges

Splitting the sample at 2950 npe (> 5 MeV): no natural radioactivity expected above this threshold

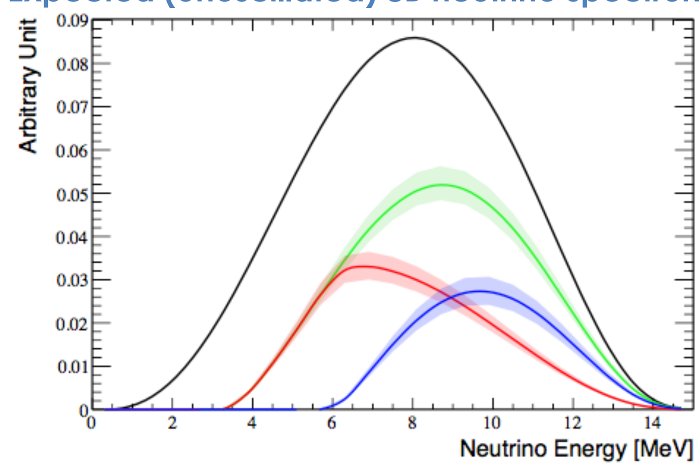
Raw Spectrum



Acceptance in electron recoil energy



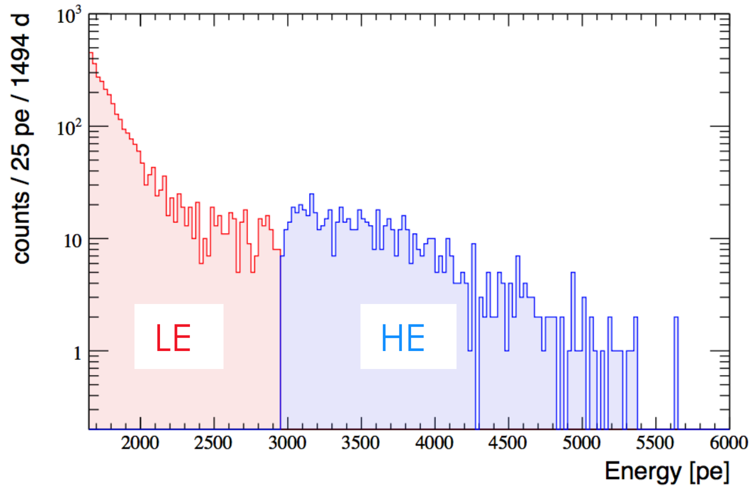
Expected (unoscillated) 8B neutrino spectrum



Mean neutrino energies:

LE: 7.9 MeV
HE: 9.9 MeV
LE+HE: 8.7 MeV

LE and HE Ranges



Residual tagged background rates after selection cuts

Background	LE rate [10^{-4} cpd/100 t]	HE rate [10^{-4} cpd/100 t]
Fast cosmogenics	13.6 ± 0.6	10.4 ± 0.4
Muons	1.2 ± 0.1	3.8 ± 0.3
Neutrons	0.72 ± 0.02	0
^{10}C	9.5 ± 14.1	0
^{11}Be	$0^{+36.3}_{-0.0}$	$0^{+54.9}_{-0.0}$
^{214}Bi	2.2 ± 1.0	0
Total	$27.2^{+38.9}_{-14.1}$	$14.2^{+54.9}_{-0.5}$

Untagged bg: discussed later

Expected additional untagged backgrounds:

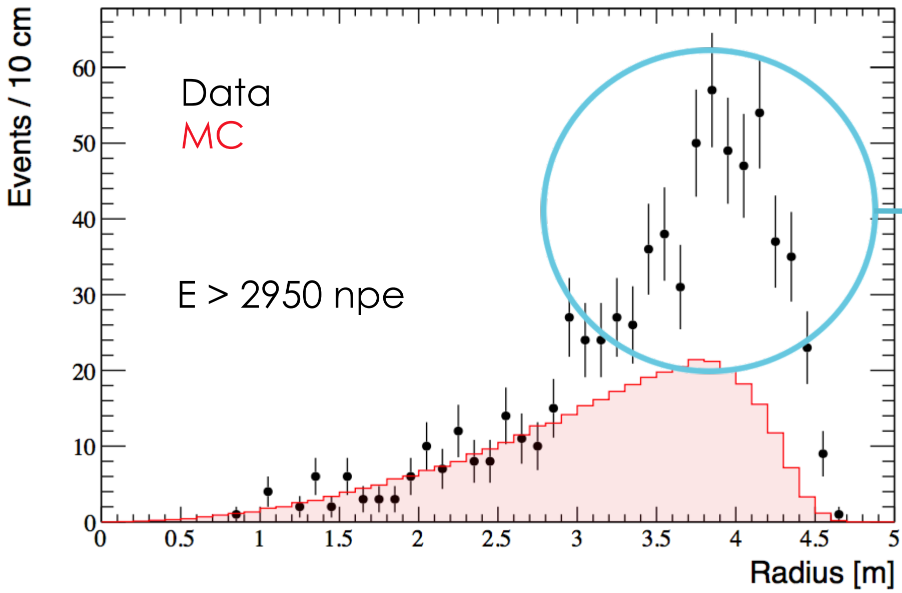
LE range
- ^{11}Be
- ^{208}Tl
- Surface events

HE range
- **^{11}Be**

Ideally we expect only 1 bg bulk component in the HE

The HE range (>5 MeV) represents the **benchmark**, where ^{8}B neutrino flux is required to be **compatible** with measurements from **SK** and **SNO**

The External Bg in the HE Range

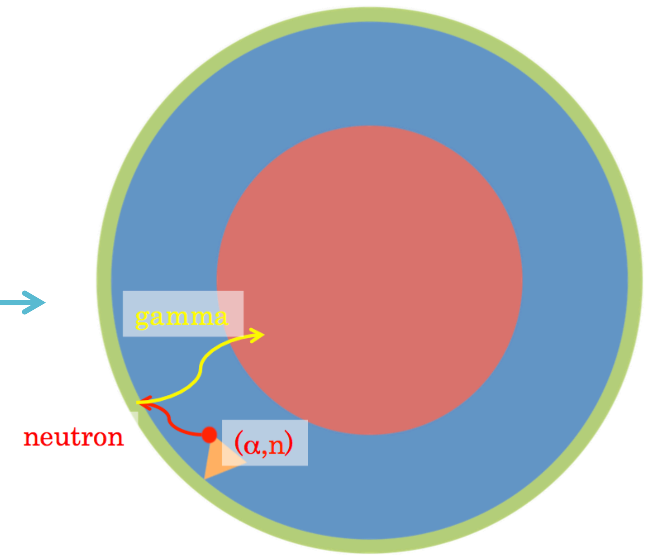


Excess **not compatible** with a **bulk** distribution

Not compatible with events from the **vessel nylon**: 5 MeV is the max Q-value from natural β-decay radioactivity (^{208}Tl)

Hypothesis:

- External background from **neutron captures** on elements different from H and C
- Neutron sources: **(α, n)** reactions and **fissions** from U and Th chains
- Neutron capture material candidates: **SSS**, PMTs, support structures



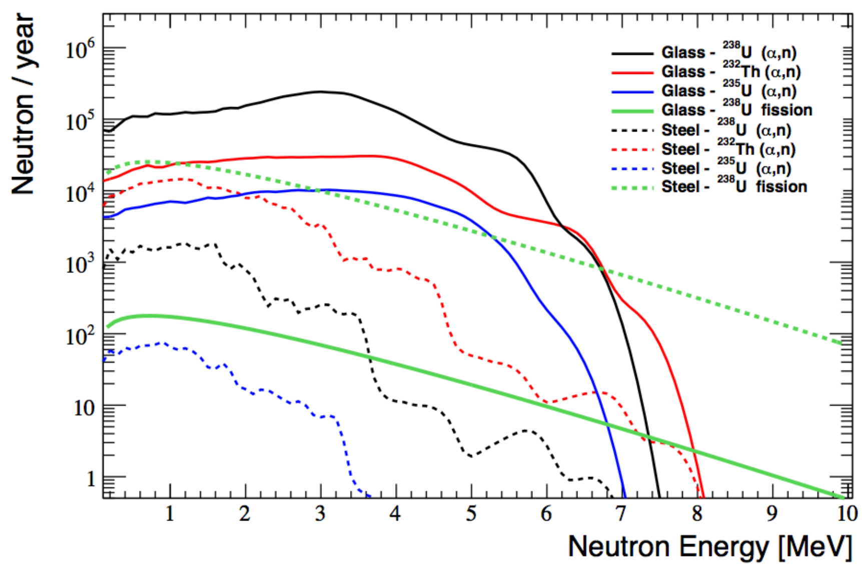
Neutron Flux

Two dominant neutron sources: SSS and PMT glasses

	SSS (45 t)			PMT Glass (1.77 t)		
	^{238}U	^{235}U	^{232}Th	^{238}U	^{235}U	^{232}Th
Concentration [g/g] [38]	$3.7\ 10^{-10}$	$2.7\ 10^{-12}$	$2.8\ 10^{-9}$	$6.6\ 10^{-8}$	$4.8\ 10^{-10}$	$3.2\ 10^{-8}$
(α, n) rate [n/decay] [41]	$5.0\ 10^{-7}$	$3.8\ 10^{-7}$	$1.9\ 10^{-6}$	$1.6\ 10^{-5}$	$1.9\ 10^{-5}$	$1.8\ 10^{-5}$
(α, n) neutron flux [year^{-1}]	$3.3\ 10^{3}$	$1.2\ 10^{2}$	$3.1\ 10^{4}$	$7.3\ 10^{5}$	$4.1\ 10^{4}$	$1.3\ 10^{5}$
Spontaneous fission rate [n/(g s)][42]	$1.36\ 10^{-2}$	$3.0\ 10^{-4}$	$<1.32\ 10^{-7}$	$1.36\ 10^{-2}$	$3.0\ 10^{-4}$	$<1.32\ 10^{-7}$
Spontaneous fission neutron flux [year^{-1}]	$7.1\ 10^{4}$	$O(<1)$	$O(<1)$	$5.0\ 10^{2}$	$O(<1)$	$O(<1)$

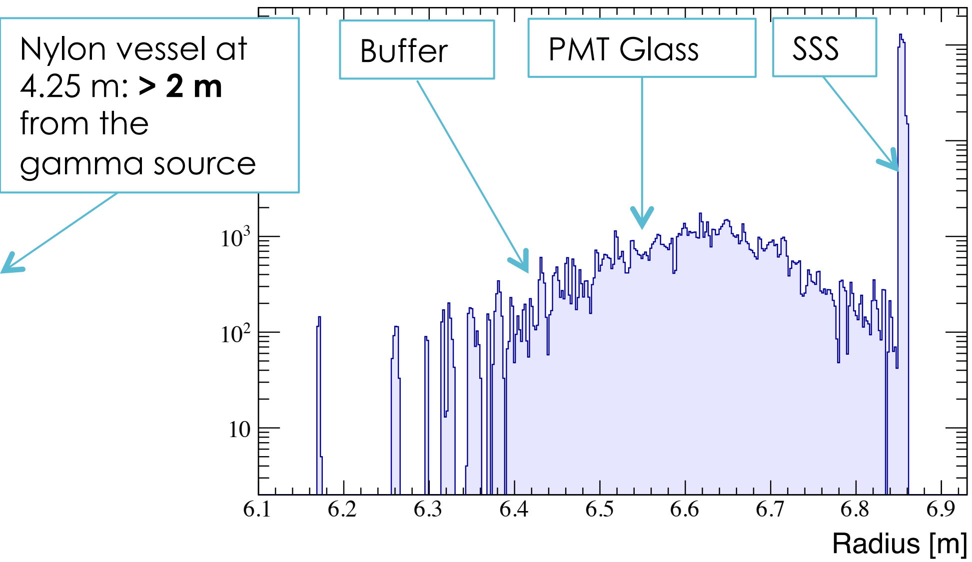
Neutron fluxes:
- **(a,n) evaluated with TALYS**
- **Fission rate from literature** (Watt equation)

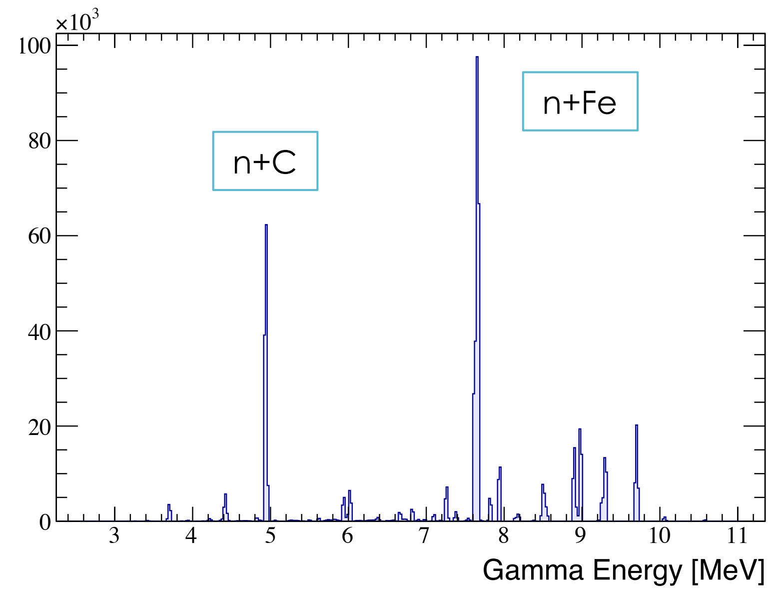
From E. Shores, NIM B 179, 78 (2001): comparison between TALYS, SOURCES-4C, and DATA provides agreements within **100% uncertainty**



Gammas from Neutron Captures

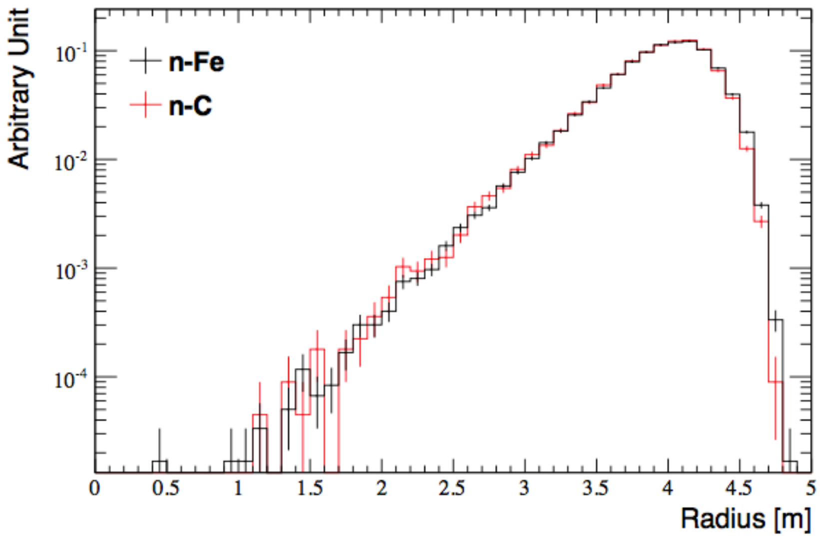
Full neutron propagation with the Borexino Monte Carlo package



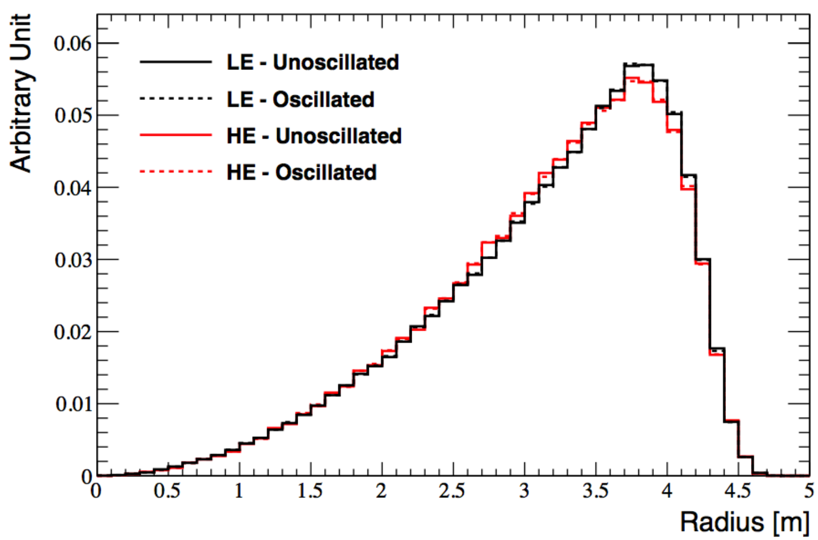


Expected **148** (**151**) neutron-induced gammas in the **LE** (**HE**) range, in the whole statistic

Radial Dependence on Energy



Weak radial dependence on neutron capture position and kinetic energy of gammas

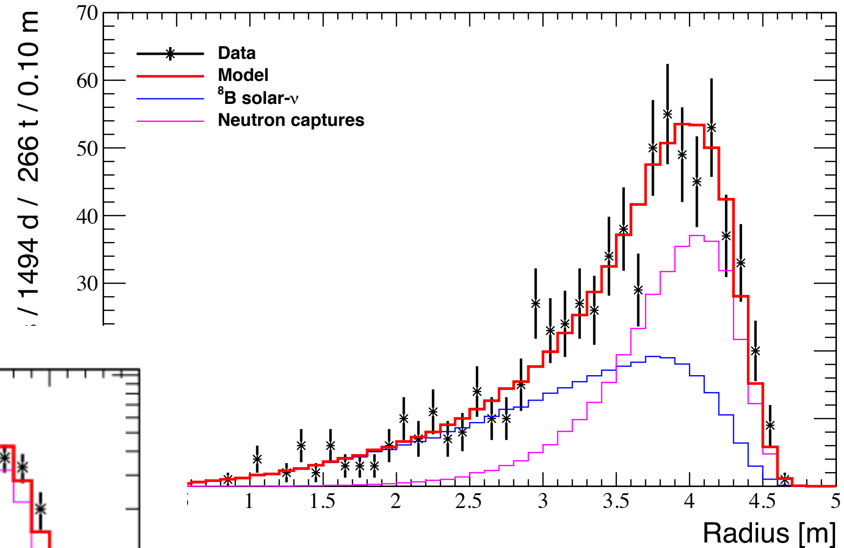


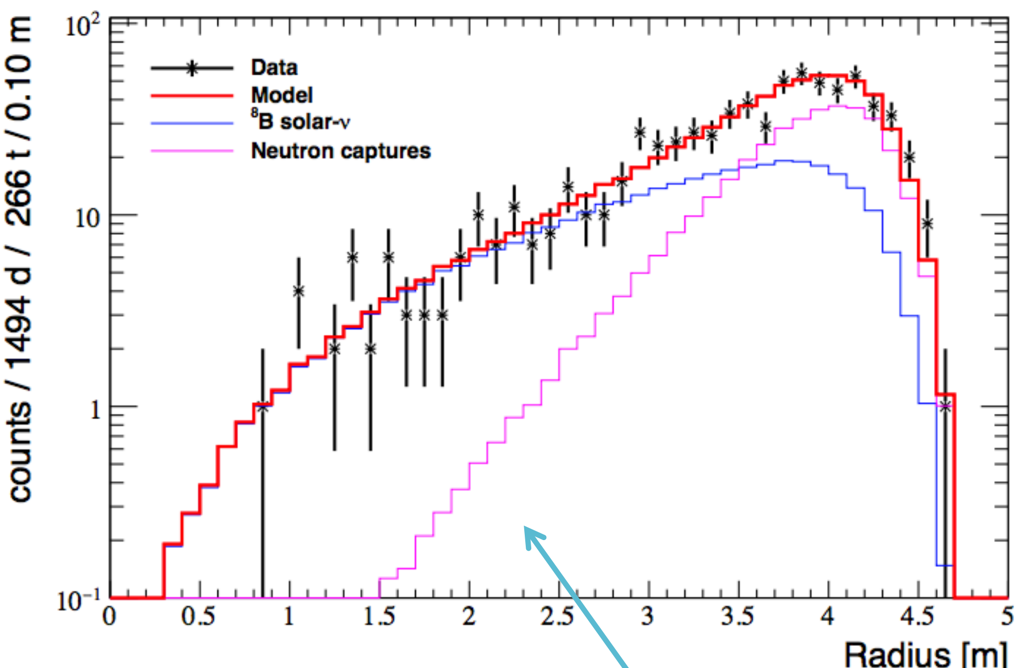
Negligible radial dependence on neutrino energy distortions due to oscillations

Radial Fit of the HE Sample

log-L fit to account for empty bins
Equivalent χ^2**/ndf = 30.4 / 35**

Number of gammas: **335±117** (predicted **~150**)



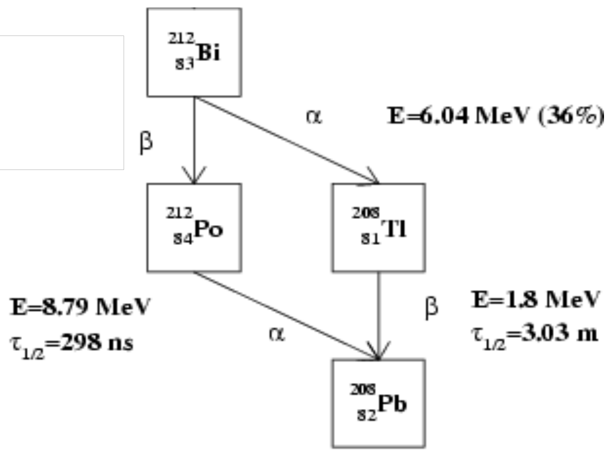


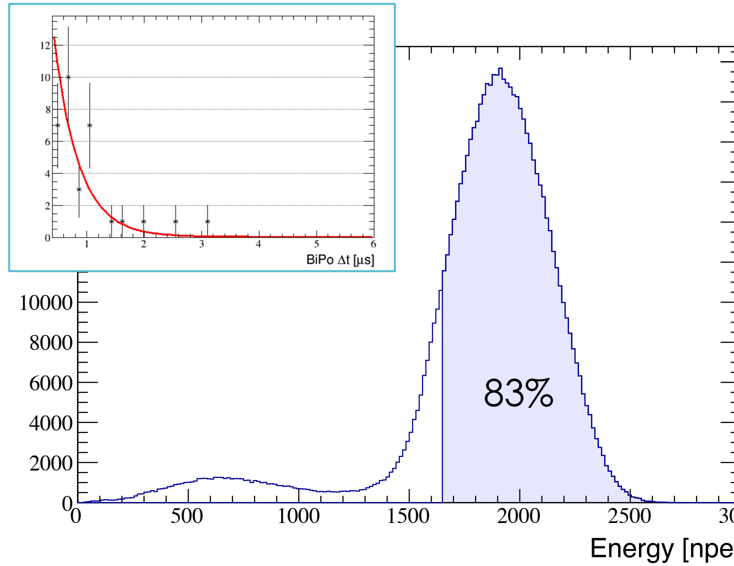
The fit of the LE sample requires additional components from contaminations **intrinsic to the scintillator and to the nylon vessel**

In the previous analysis this component was erroneously neglected

Internal ^{208}Tl

Estimated by looking at the ^{212}Bi-^{212}Po fast coincidence (τ = 431 ns), within 3 m radius

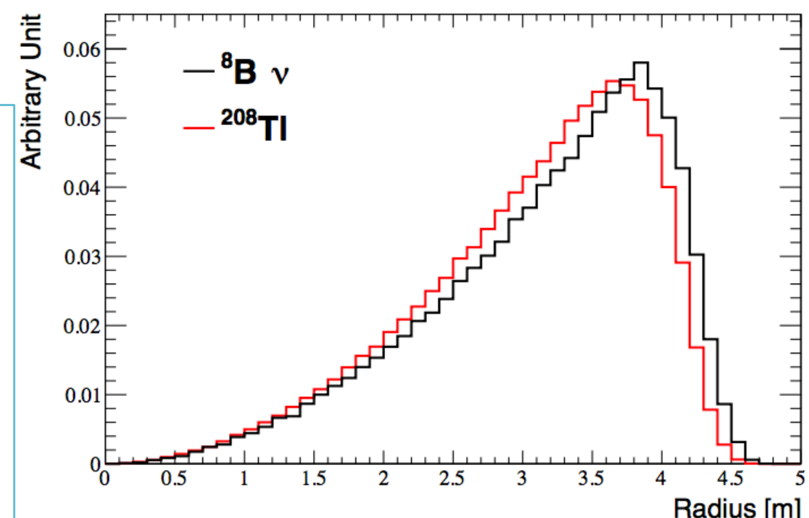




Radial shape very similar to the neutrino one but **not identical**: if 2.6 MeV gammas, for events close to the border, escape the scintillator, Tl208 event reconstructed energy is out of the range

The obtained rate, 1.8±0.3x10^{-2} cpd/100 t above 1650 npe, is **5 times lower** than in the previous analysis thanks to the purification campaign

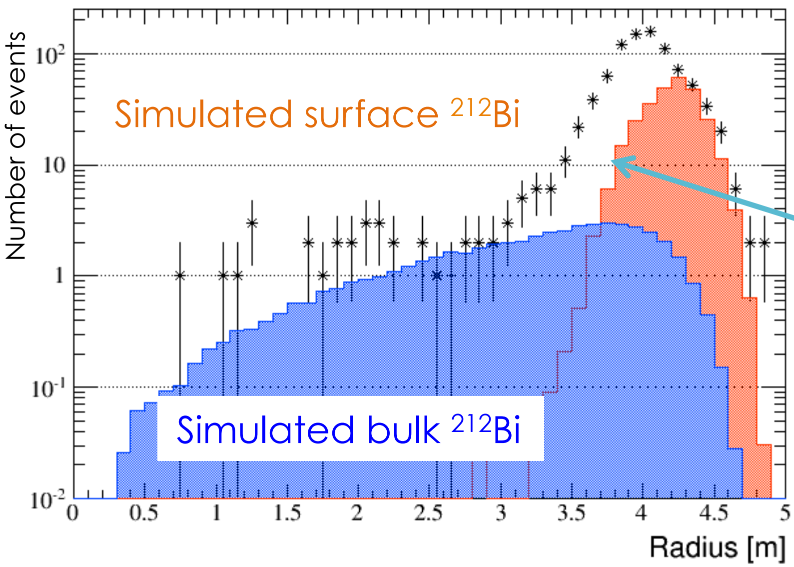
The internal 208Tl component is constrained with a **penalty factor** in the radial fit



The "surface" component can not be intrinsic to the nylon vessel: **we observe the full ^{212}Po alpha peak for these events!** (no energy degradation as expected for an alpha escaping the vessel)

It must be **emanated** and **diffused** from the vessel and more internal in the scintillator bulk than surface events

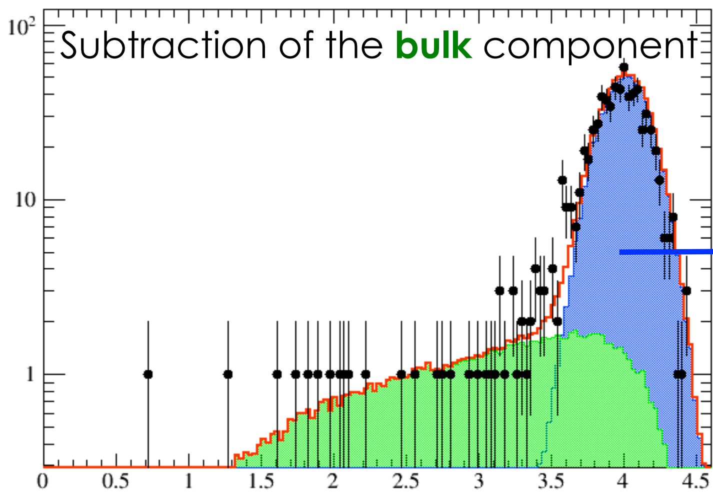
^{212}Bi data sample requiring full ^{212}Po-α peak



Surface events can not explain the excess

^{212}Bi and ^{208}Tl have the same radial distributions: **we can extract the distribution from the data**

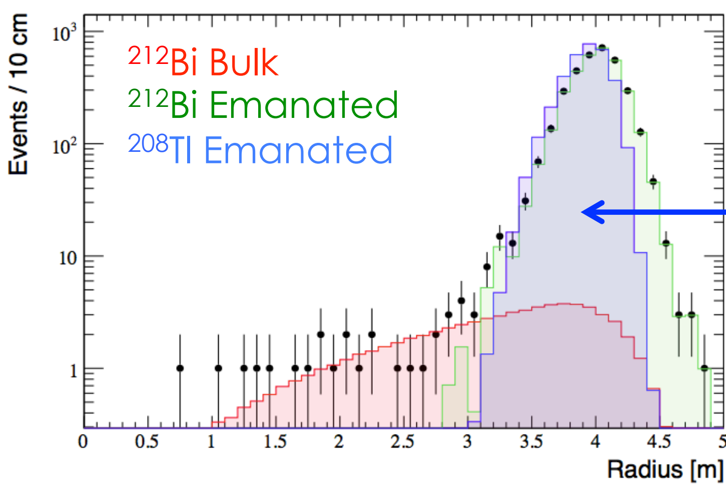
From ^{212}Bi to ^{208}Tl radial distribution



Residual component is **de-convoluted** with the ^{212}Bi response function from simulations, defined as: $\Delta R = R_{rec} - R_{true}$

NOTE: response functions built from simulations of events at 1 cm from vessel

The obtained shape is **re-convoluted** with the ^{208}Tl response function (from MC)

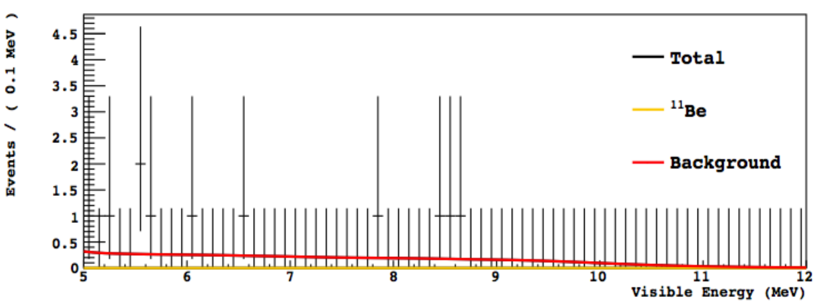


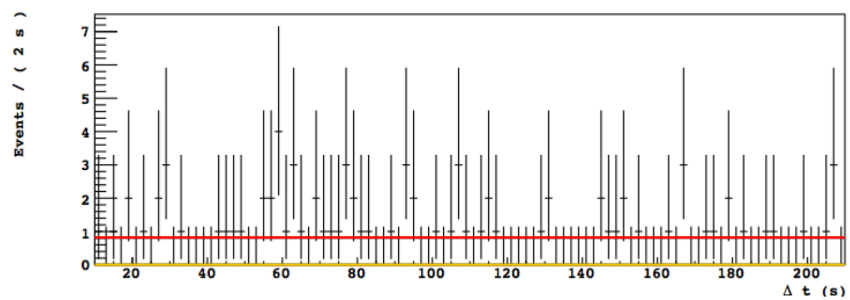
Cosmogenic ^{11}Be background

4 ^{11}Be rate measurements before this analysis:

	Muon average energy	**Borexino rate at 280 GeV with E > 3 MeV [cpd / 100 ton]**
NA54 beam experiment (2000)	100, 190 GeV	$<10^{-2}$ (68% CL)
KamLAND (2009)	260 GeV	**$(3.2\pm0.5)\ 10^{-2}$**
Bx 8B paper (2010)	280 GeV	$(3.6\pm3.5)\ 10^{-2}$
Bx cosmogenic paper (2013)	280 GeV	$<2\ \text{x}10^{-1}$ (99.73% CL)

From Bx cosmogenic paper





In the previous work, **we used** the extrapolation from **KamLAND**, which represents 10-15% of the neutrino rate

Currently we have a **factor ~3 more statistics** than in the previous Bx measurements.

New fit with a **multi-variate approach**, looking at energy and time distributions

Cosmogenic ^{11}Be background

Methodology

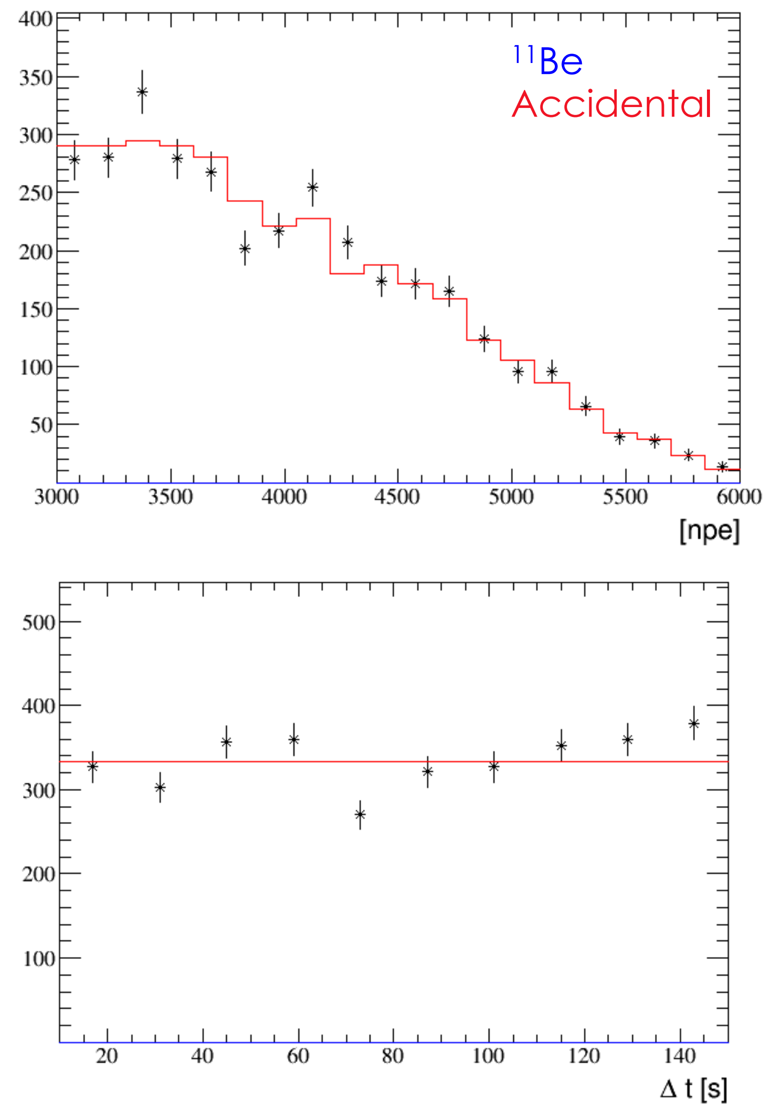
Cosmogenic sample:
- radial cut (r < 3.5)
- deltaT from the muon: **> 10 s and < 150 s**
- distance from the muon track: **< 2 m**
- charge cut: > 3000 npe (>6 MeV)
- muon charge: >10000 npe

Accidental sample:
- r < 3.5 m
- Distance from the muon track: **> 2 m**
- **150 s < deltaT < 300 s**
- Charge cut > 3000 npe
- Muon charge > 10000 npe

^{11}Be pdf from MC

The fit prefers negative number of ^{11}Be => **added a boundary N ≥ 0**

^{11}Be rate = **0 $^{+9.1}_{-0}$ x 10^{-3} cpd / 100 t** (E > 1650 npe)



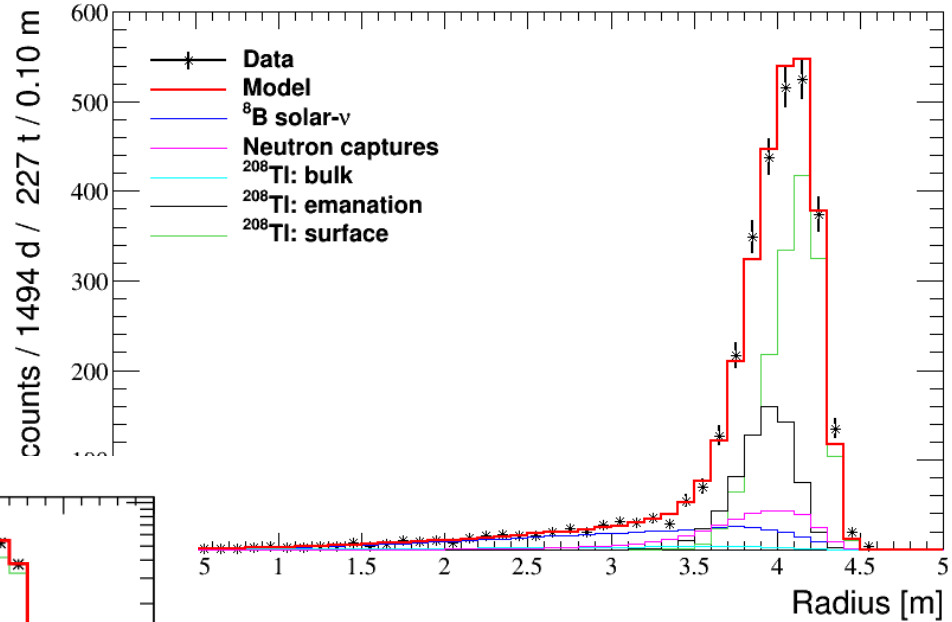
Radial Fit of the LE Sample

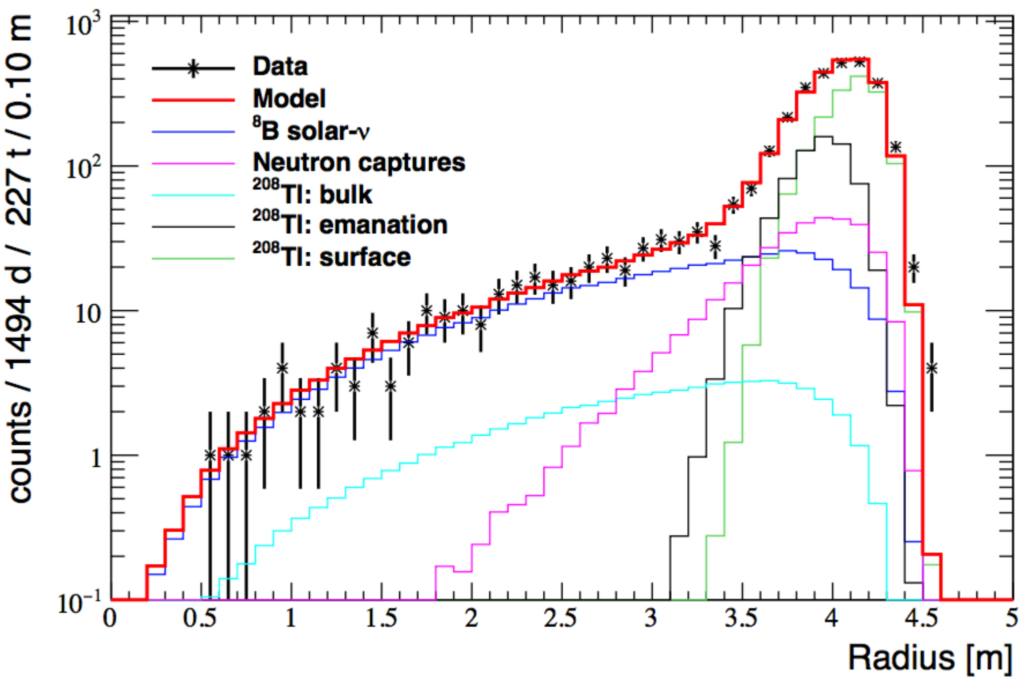
log-L fit to account for empty bins
Equivalent χ^2/ndf = **31.3 / 36**

Emanation rate ~0.47 cpd / 100 t
Excluding the emanation component: χ^2/ndf = 91.6 / 36

Bulk ^{208}Tl vs ^{8}B-ν correlation coefficient = **-0.299**

Number of gammas: **351±31** (predicted **~150**)





Component	LE rate [cpd/227.8 t]	HE rate [cpd/266.0 t]
^{8}B neutrinos	0.310±0.029	0.235±0.021
External	0.224±0.078	0.239±0.022
^{208}Tl bulk	0.042±0.008	-
^{208}Tl emanation	0.469±0.063	-
^{208}Tl surface	1.090±0.046	-

Systematic Errors and Results

Source	LE σ	HE σ	LE+HE σ
Active mass	2.0	2.0	2.0
Energy scale	0.5	4.9	1.7
z-cut	0.7	0.0	0.4
Live time	0.05	0.05	0.05
Scintillator density	0.5	0.5	0.5
Total [%]	2.2	5.3	2.7

In addition we have tested:
- pdf **radial distortion**: ±3%
- Emanation **vessel shift**: ±1%
- **Response functions** for the emanation component generated at 6 cm from the vessel (instead of 1 cm)
- **Binning** dependence

None of these potential systematic sources affected the measured 8B rate outside 1 statistical sigma

$$R_{LE} = 0.133^{+0.013}_{-0.013}\,(stat)\,^{+0.003}_{-0.003}\,(syst)\ \mathrm{cpd}/100\,\mathrm{t},$$

$$R_{HE} = 0.087^{+0.08}_{-0.010}\,(stat)\,^{+0.005}_{-0.005}\,(syst)\ \mathrm{cpd}/100\,\mathrm{t},$$

$$R_{LE+HE} = 0.220^{+0.015}_{-0.016}\,(stat)\,^{+0.006}_{-0.006}\,(syst)\ \mathrm{cpd}/100\,\mathrm{t}.$$

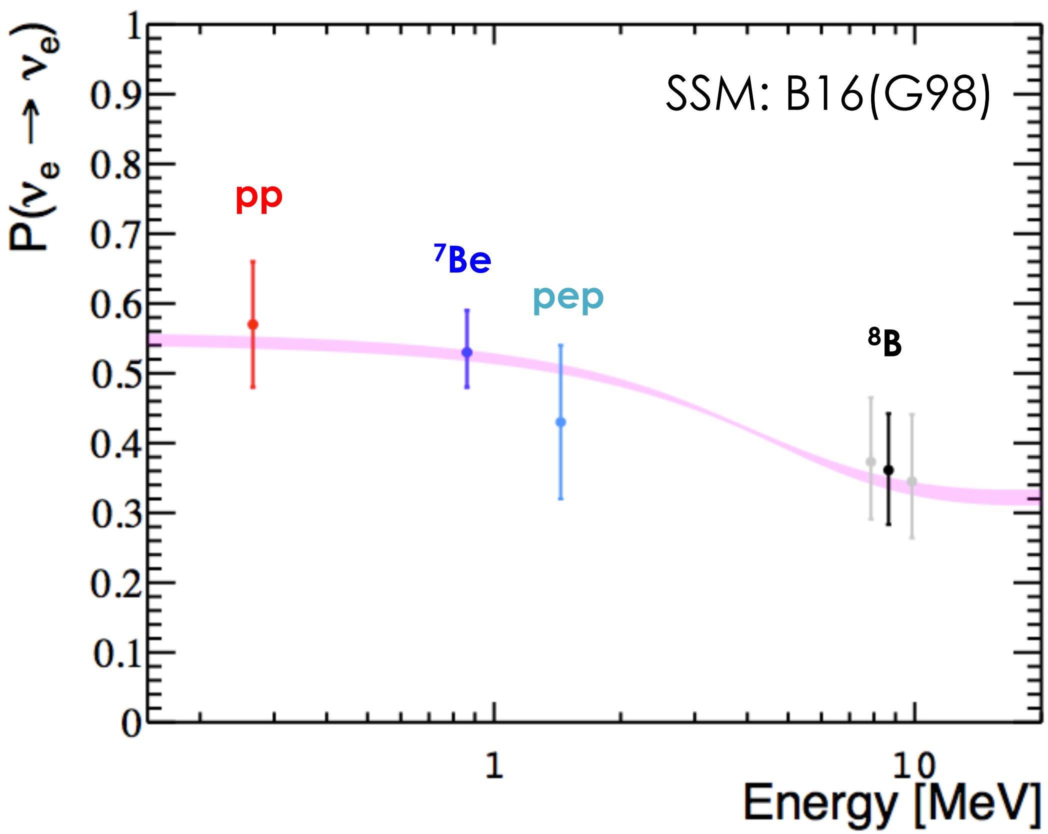
Expected rate in the LE+HE range:
0.211± 0.025 cpd/100 t
Assuming B16(G98) SSM and MSW+LMA

Solar Neutrino Flux and Survival Probability

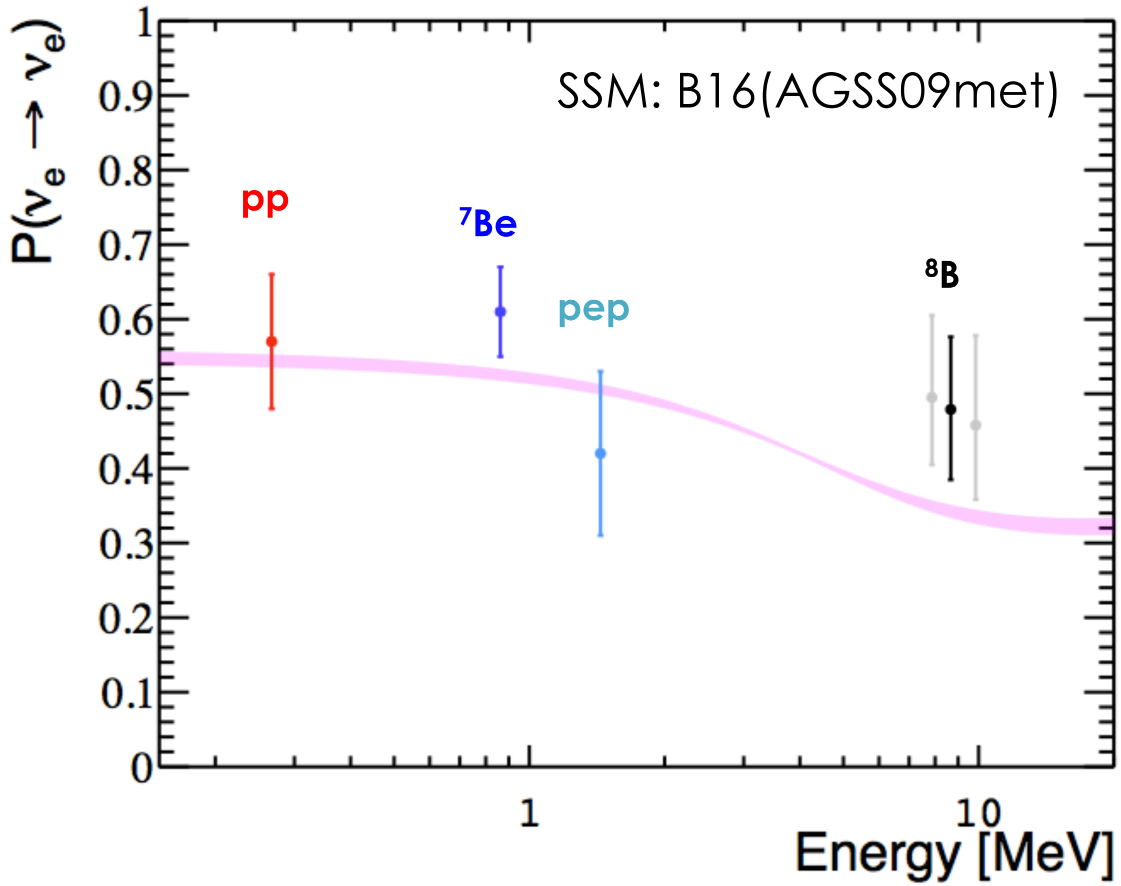
Equivalent unoscillated flux

SuperKamiokande	$2.345 \pm 0.014 \pm 0.036 \times 10^{6}$ cm^{-2} s^{-1}
BX 2010	$2.4 \pm 0.4 \times 10^{6}$ cm^{-2} s^{-1}
This measurement	**$2.55 \pm 0.18 \pm 0.07 \times 10^{6}$ cm^{-2} s^{-1}**

p-values:
Bx only: 0.998
All exp: 0.956



Low Metallicity Model



p-values:

Bx only: 0.362

All exp: 0.465

Summary

- Improved measurement of the ^{8}B rate with **11.5 times** the previous **exposure**
- New analysis approach with full active volume and radial analysis
- **Lowest energy threshold** among real time experiments
- Identified a **new source of background** from neutron captures on C and on Fe
- New estimation of the cosmogenic **^{11}Be** rate
- ^{8}B neutrino rate **error** has been **reduced** by more than a factor 2 from the previous measurement
- Slight preference for the **high-Z model**

Future

Can we improve the measurement?

- Non-significant improvements with additional 1-2 years of statistics
- **Lowering down the threshold to 2 MeV**: need an effort on understanding the external background from ^{214}Bi and ^{208}Tl
- Science-fiction: **active scintillator in the buffer** (and vessel removal)
  - would allow for identification and rejection of external background
  - no-more dependences on the vessel shape
  - No-radon emanation from the vessel