BOREXINO:
Solar Neutrinos

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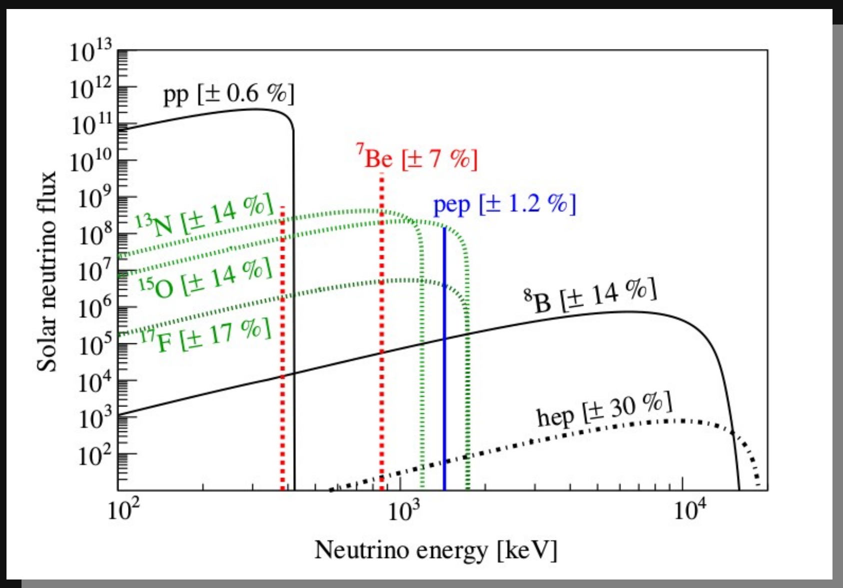
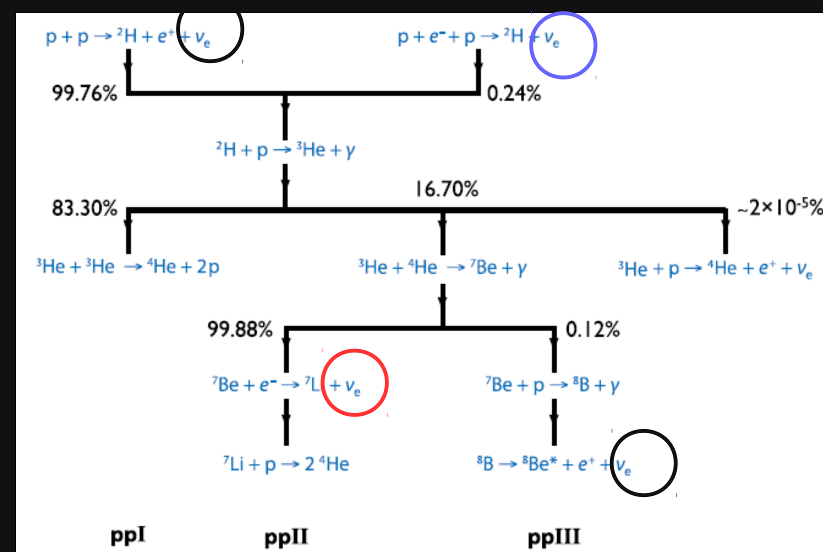
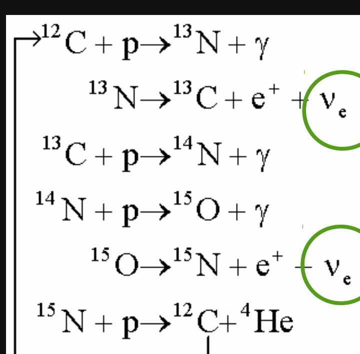
Why the Borexino Experiment?

Neutrinos coming from the Sun (< 3 MeV region)
- allow the study of neutrino oscillations **(PARTICLE-)**
- provide key information for accurate solar modeling **(ASTRO-)**







Total Energy

~99%
Pp chain

~1%
CNO cycle

Borexino Milestones

Borexino is presently the only detector able to measure the solar neutrino interaction **rate down to energies as low as ~150 keV** and to reconstruct the energy spectrum of the events.

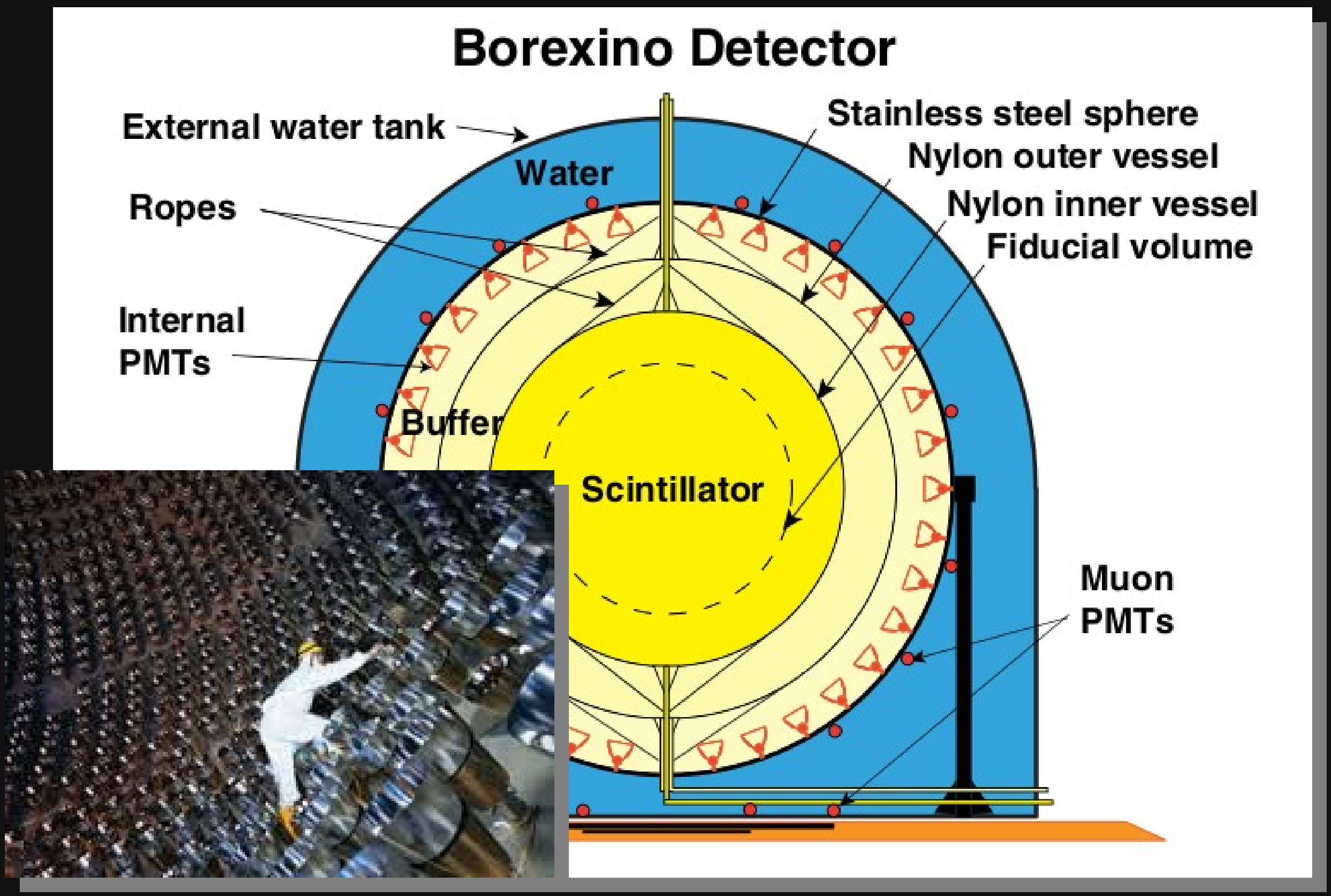
Solar Neutrinos

- **First measurement** of the interaction rate of the **^{7}Be** mono-energetic **862 keV** solar neutrinos with accuracy of 5%
- **Exclusion** of any significant **day-night asymmetry** of the ^{7}Be solar neutrino flux
- **First direct observation** of the mono-energetic 1440 keV **pep** solar neutrinos
- Set of the **strongest upper limit of the CNO** solar neutrinos flux
- **Measure of the ^{8}B** solar neutrinos with an energy **threshold of 3 MeV**
- **First spectroscopic measurement of the pp** spectrum.

And so on...

- **Geo-netrinos** detection
- Detailed study of the **cosmogenics** in liquid scintillator
- Limits on **rare processes**

The experimental set-up



13.7 m stainless sphere diameter

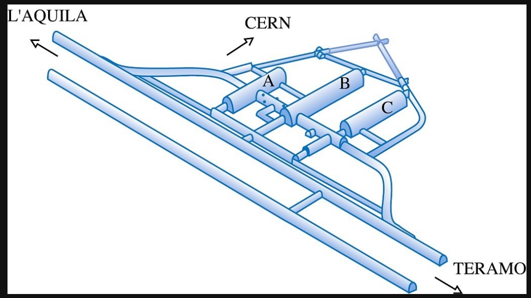
- ~ 1000 tons of pseudocumene (PC)
- ~300 tons Inner Vessel
- Ultrapure Water Tank

~2200 (PMTs)

25% Coverage

Light Yield = 500 PE/MeV

Hall C – LNGS Lab



Very (very) low background → - Nitrogen stripping (Low ^{39}Ar, ^{40}K)
- Distillation
- Water Extraction

Unmatched keystones → - development of thin radiopure nylon ballons
- developments of powerful purification method

Borexino Timeline

Most of the solar neutrino results are from Phase I

Phase I	Calibrations	Water Extraction And operations	Phase II
May 2007	Jan 2009	Jun 2009	Dec 2011

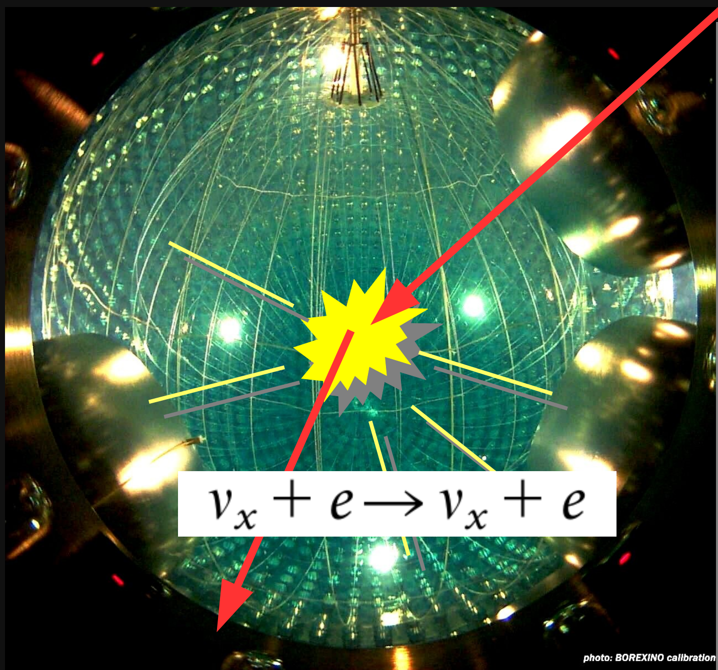
^{7}Be
^{8}B
pep

Very low background reached

pp
geoneutrinos

SOX project
End of 2016

The Borexino Signal



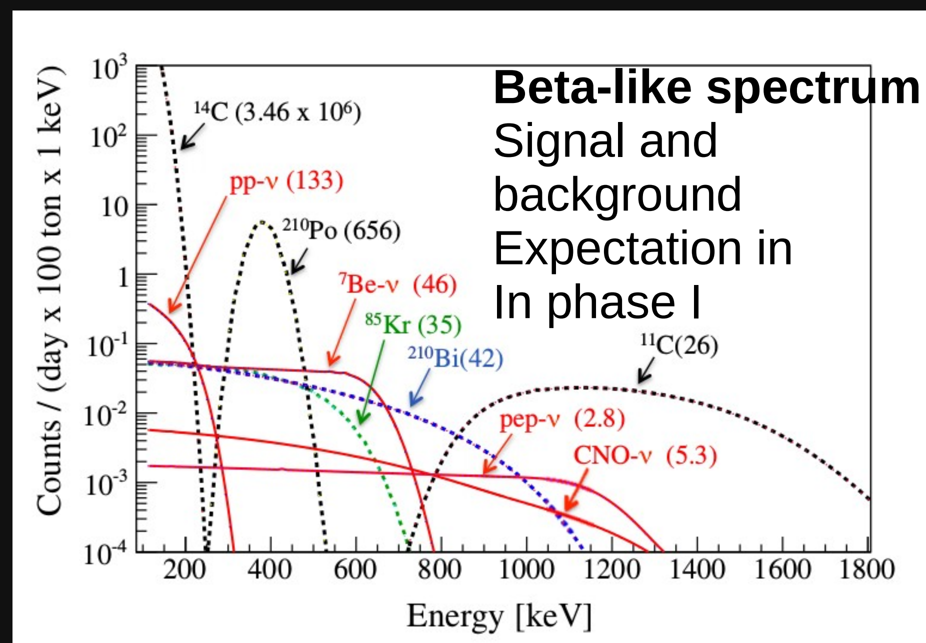
The Borexino PMTs detects the scintillation light produced by electrons scattered by neutrinos
σ(CC) ~ 5 σ(NC)

This signal is indistinguishable from natural radioactivity (β^- and γ components). No directionality.

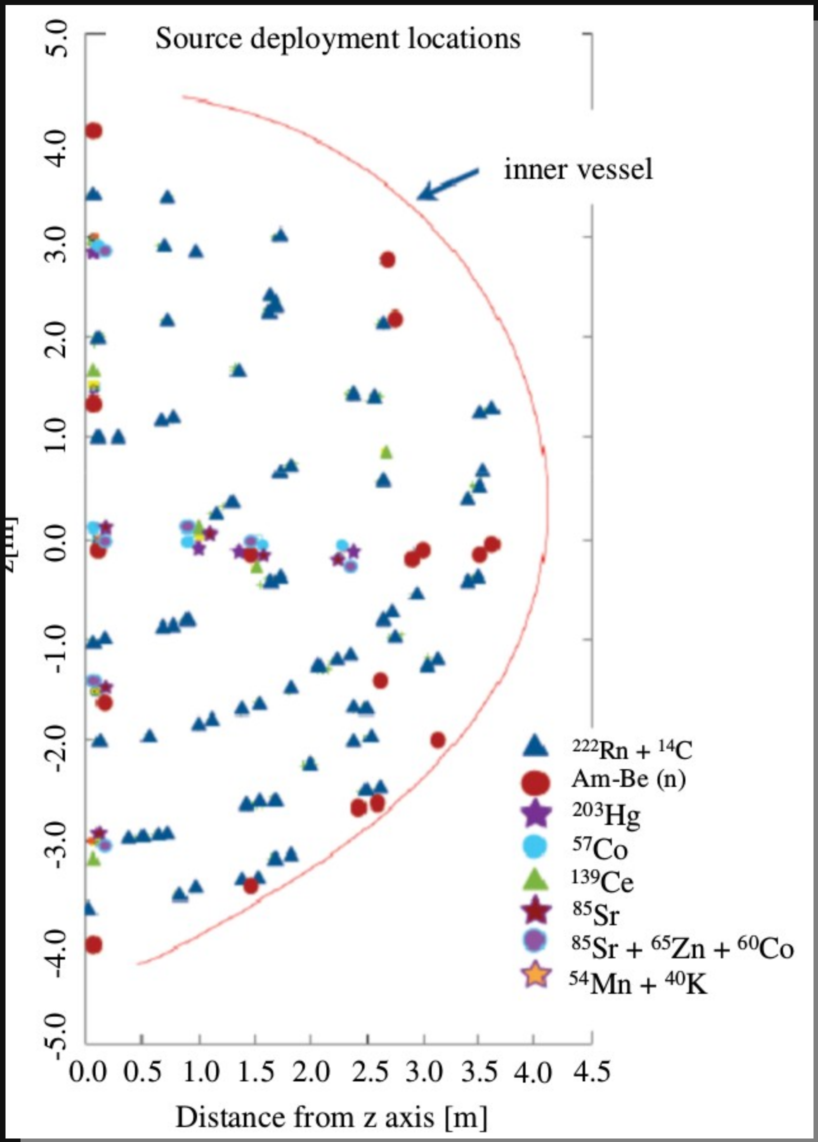
For α and β^+ we can apply pulse shape discrimination

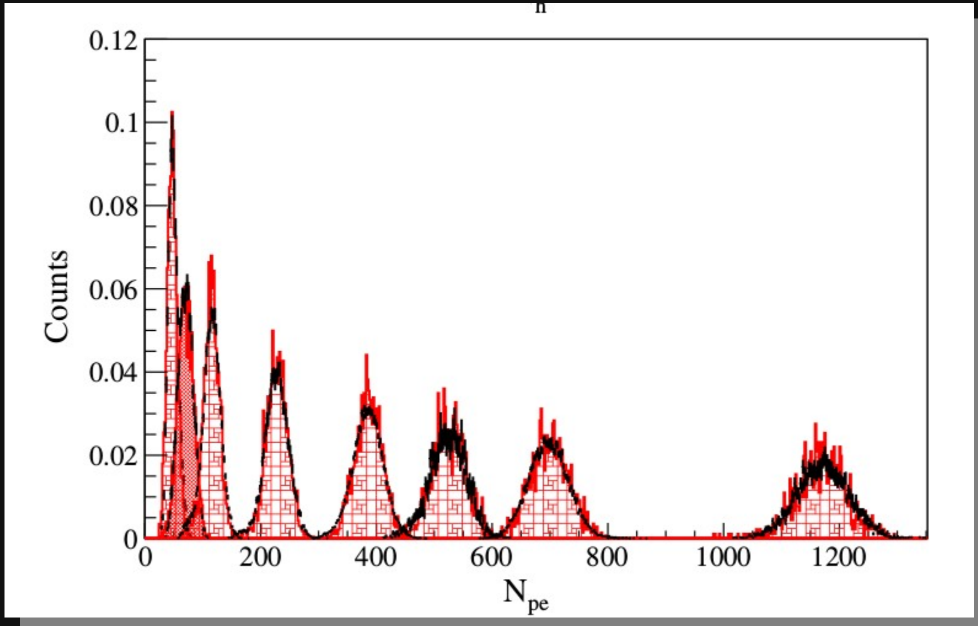
Extreme low background required!!!

Isotope	Decay Rate [cpd/100 ton]
^{14}C	$(3.46 \pm 0.09) \times 10^6$
^{85}Kr	$(30.4 \pm 5.3 \pm 1.5)^{(a)}$
	$(31.2 \pm 1.7 \pm 4.7)^{(b)}$
^{40}K	< 0.42 (95% C.L.)
^{39}Ar	~ 0.4
^{238}U	(0.57 ± 0.05)
^{222}Rn	(1.72 ± 0.06)
^{210}Bi	$(41.0 \pm 1.5 \pm 2.3)$
^{210}Po	5×10^2–8×10^3
^{232}Th	(0.13 ± 0.03)



Calibration Campaign



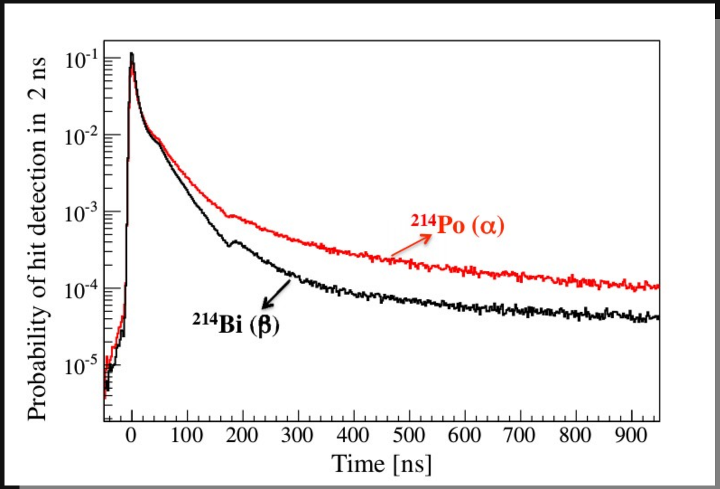


Calibration of the full energy scale with different standard sources deployed inside the detector with mechanical arms. Response. Resolution modeling (Analytical + MC) 5%√E

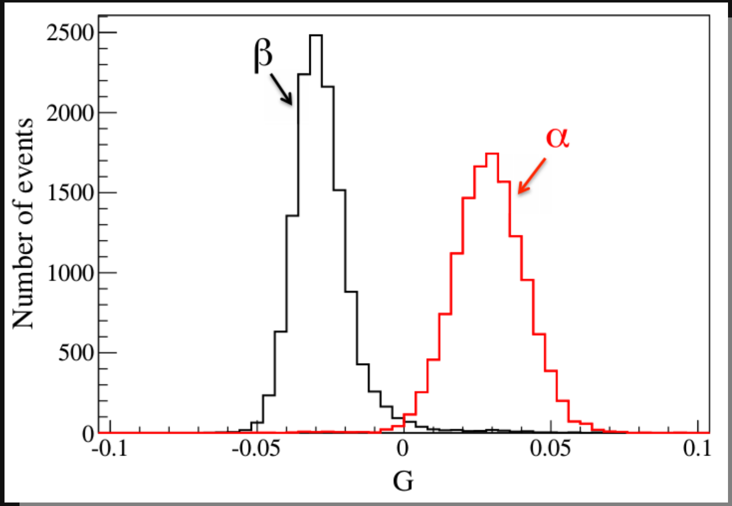
Calibration of the position. Position is important for defining the fiducial volume

Pulse Shape Discrimination Techniques

$\alpha - \beta$

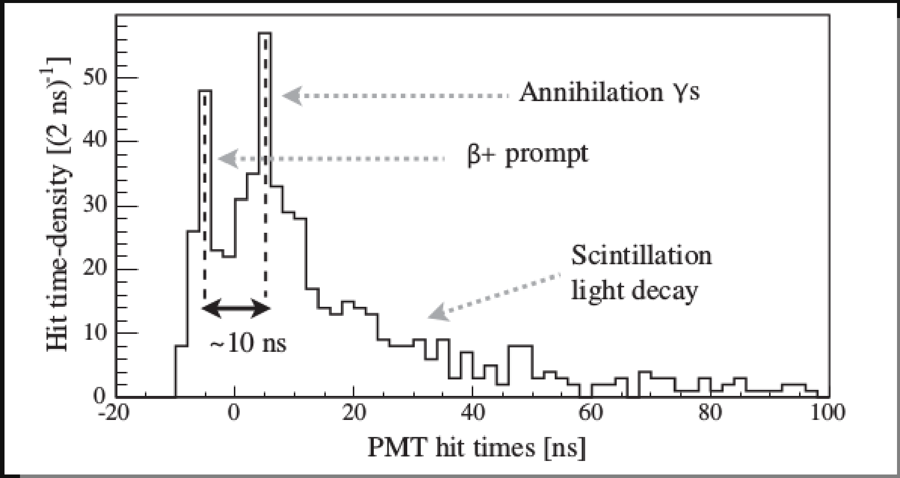


The *Gatti* filter

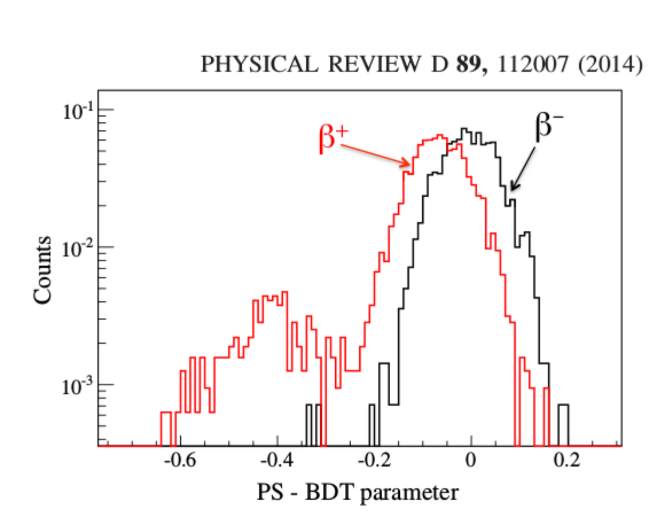


Trained on ^{214}Bi-Po coincidence

$\beta^+ - \beta^-$



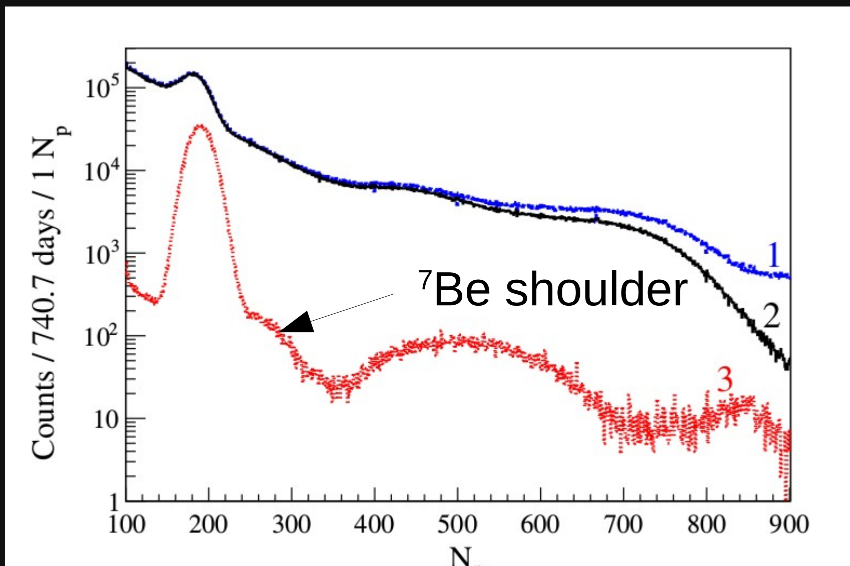
Boosted Decision Tree (BTD)



Trained on ^{214}Bi (e^-) and cosmogenic ^{10}C (e^+)

The energy spectrum

Borexino spectrum

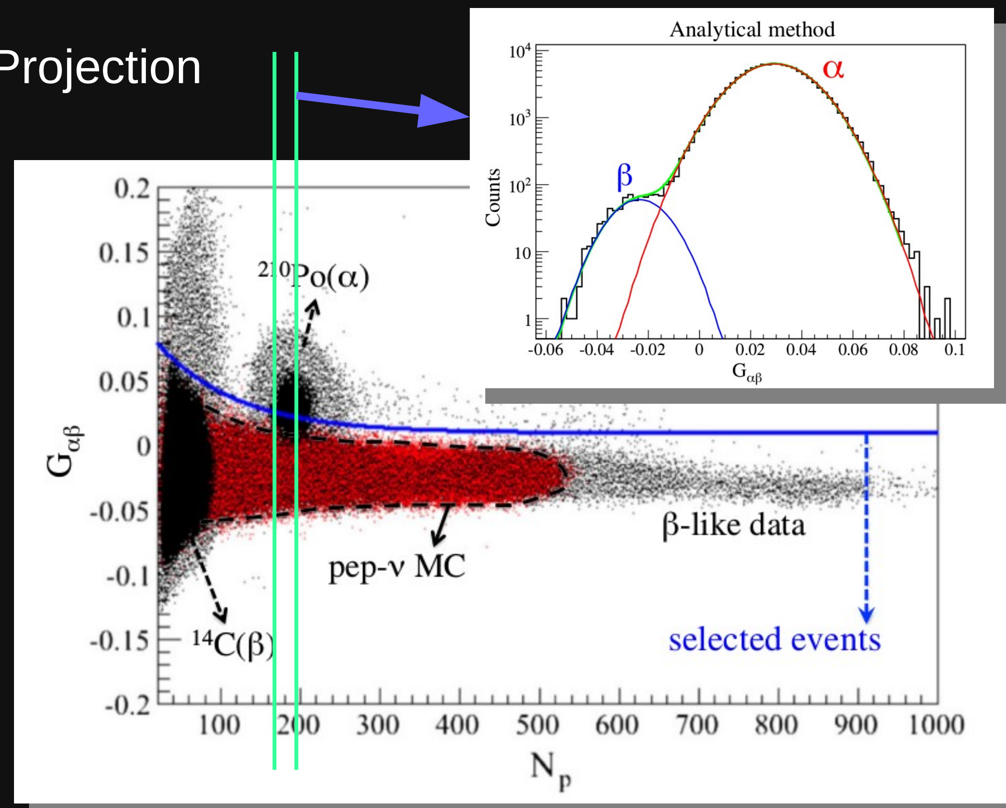


1. Muon Cut
2. Cosmogenics
3. Fiducial Volume

The strongest cut is the fiducial volume that removes the external background

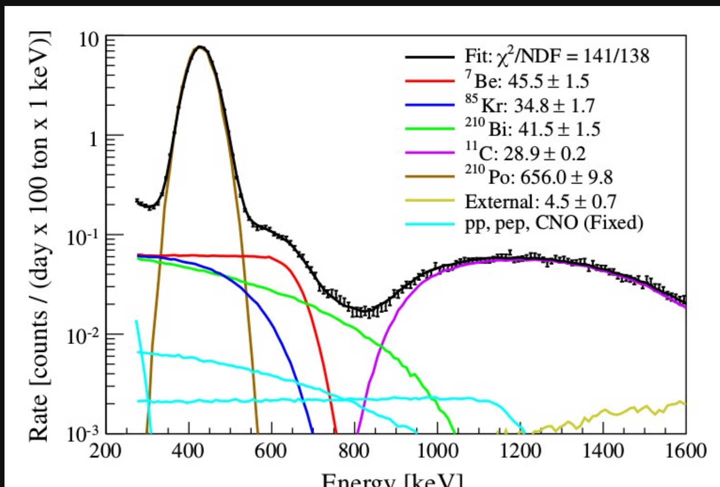
Alpha-beta statistical subtraction:
The alpha events are statistically removed in each energy bin according to the Gatti filter

Projection



Fit example: ^{7}Be

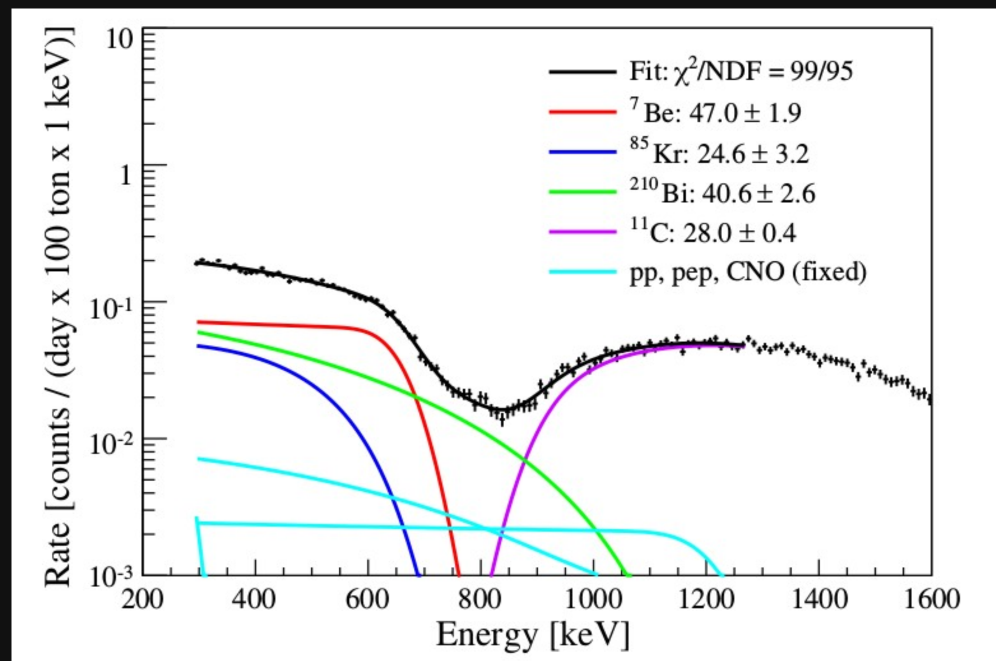
Full spectrum



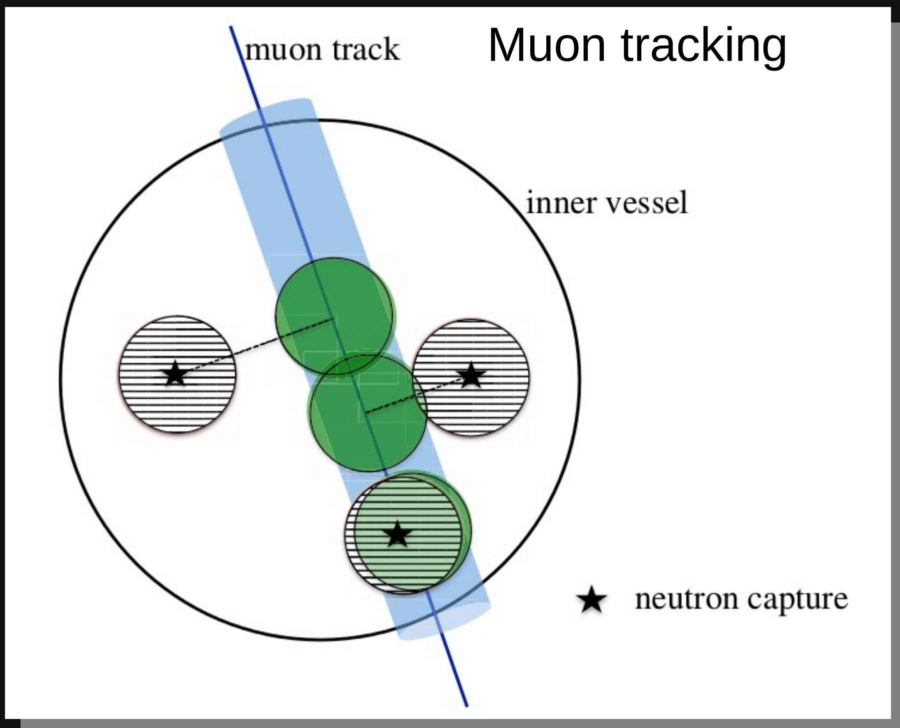
^{7}Be	$46.0 \pm 1.5(\text{stat})^{+1.5}_{-1.6}(\text{syst})$
^{85}Kr	$31.2 \pm 1.7(\text{stat}) \pm 4.7(\text{syst})$
^{210}Bi	$41.0 \pm 1.5(\text{stat}) \pm 2.3(\text{syst})$
^{11}C	$28.5 \pm 0.2(\text{stat}) \pm 0.7(\text{syst})$

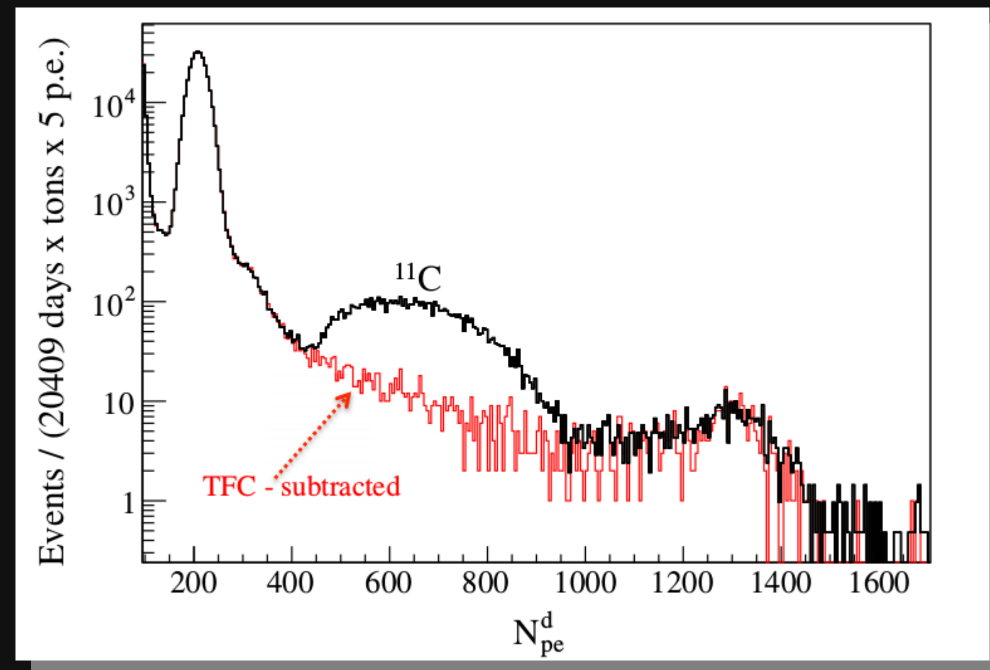
- Live time ~740 days
- Result from Phase I
- 5% accuracy

α/β statistical subtraction of the ^{210}Po peak



Threefold coincidence





$\mu + {}^{12}C \rightarrow \mu + {}^{11}C + n$

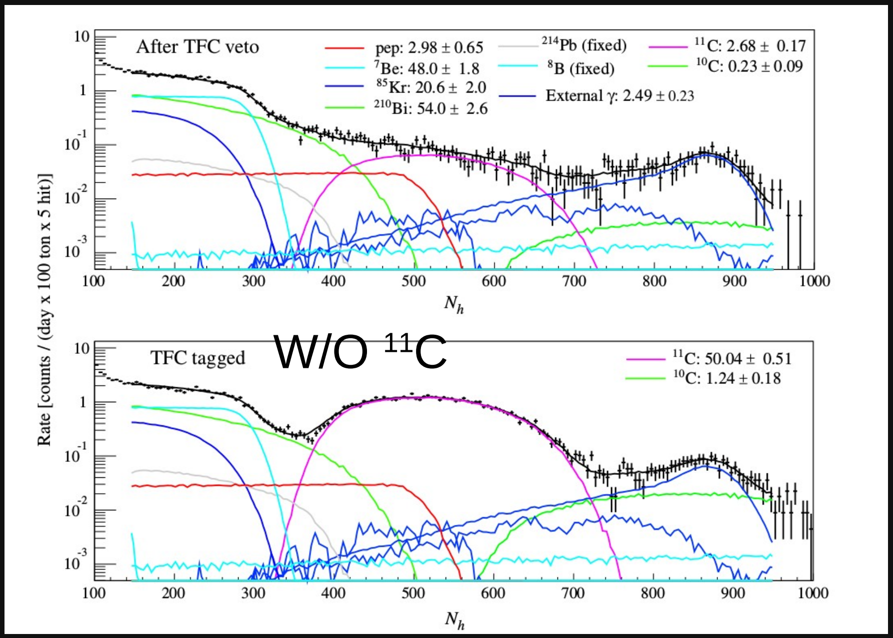
${}^{11}C \rightarrow {}^{11}B + e^+ + \nu_e$ (~30 min)

$H + n \rightarrow D + 2.2$ Mev (250 μs)

Blinding for 2h of cylinder or sphere volumes according to the neutron multiplicity

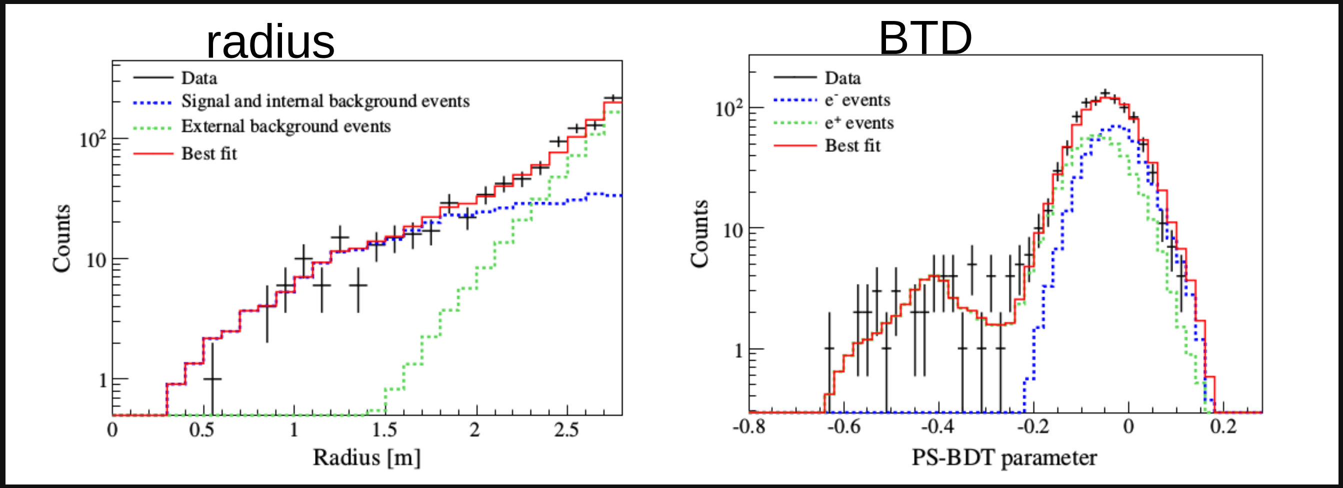
~90% reduction of the ^{11}C
~50% of exposure lost

Multivariate fit for pep



Species	Result [cpd/100 ton]	Expected value [cpd/100 ton]
pep	$3.1 \pm 0.6 \pm 0.3$	2.73 ± 0.05 (2.79 ± 0.06)
^{7}Be	$48.3 \pm 2.0 \pm 0.9$	$46.0 \pm 1.5 \pm 1.6$
^{85}Kr	$19.3 \pm 2.0 \pm 1.9$	$30.4 \pm 5.3 \pm 1.5$
^{210}Bi	$54.5 \pm 2.4 \pm 1.4$	NA
^{11}C	$27.4 \pm 0.3 \pm 0.1$	$28.5 \pm 0.2 \pm 0.7$
^{10}C	$0.62 \pm 0.2 \pm 0.1$	0.54 ± 0.04
^{6}He	$0.7(0) \pm 0.6(0.5) \pm 1$	0.31 ± 0.04
Ext. ^{208}Tl (N^h_{pe})	$1.64 \pm 0.11 \pm 0.01$	NA
Ext. ^{208}Tl (N_h)	$1.94 \pm 0.13 \pm 0.02$	NA
Ext. ^{214}Bi (N^h_{pe})	$0.67 \pm 0.12 \pm 0.01$	NA
Ext. ^{214}Bi (N_h)	$0.41 \pm 0.13 \pm 0.02$	NA
Ext. ^{40}K	$0.16 \pm 0.1 \pm 0.03$	NA
Total Ext. Bkg.	$2.49 \pm 0.2 \pm 0.04$	NA

	68% Limit	95% Limit	99% Limit	Expected value
CNO	4	12	19	5.24 ± 0.54 (3.74 ± 0.37)
^{40}K	0.11	0.42	0.69	NA
^{234m}Pa	0.12	0.46	0.75	1.78 ± 0.06



Multivariate Fit (likelihood) concept

- radial distribution
- beta +/- pulse shape
- TFC subtracted spectrum
- normal spectrum

Borexino Phase II

Isotope	Borexino-I	Borexino-II
^{14}C / ^{12}C, g/g	$2.7 \cdot 10^{-18}$	$2.7 \cdot 10^{-18}$
^{238}U, g/g (^{214}Bi-^{214}Po)	$(1.6 \pm 0.1) \cdot 10^{-17}$	$<9.7 \cdot 10^{-19}$ (95%)
^{232}Th, g/g (^{212}Bi-^{212}Po)	$(6.8 \pm 1.5) \cdot 10^{-18}$	$<1.2 \cdot 10^{-18}$ (95%)
^{222}Rn (^{238}U), ev/d/100 t	1	0.1
^{40}K, g[K_{nat}]/g	$<1.7 \cdot 10^{-15}$ (95%)	---
^{210}Po, ev//d/t	80 (initial), $T_{1/2}$=134 days;	2
^{210}Bi, ev/d/100 t	20-70	~20
^{85}Kr ev/d/100 t	30.4±5 cpd/100t	< compatble with 0
^{39}Ar ev/d/100 t	<<^{85}Kr	

Best conditions ever!

From December 2011 After the Water Extraction

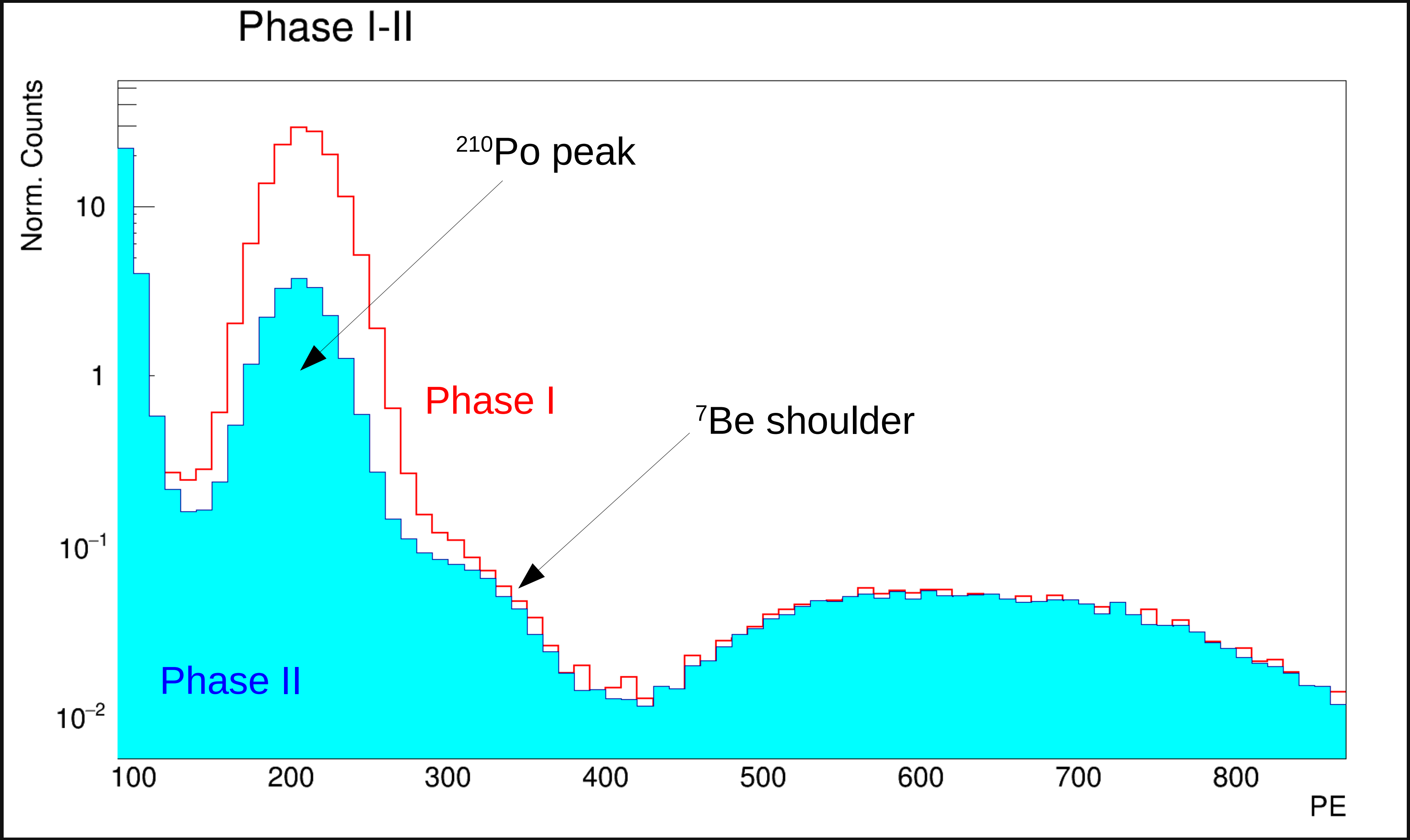
Jun 2010 – Aug 2011

6 cycles of **Water Extraction** (~1 year) reduced drastically the background contaminants

Apr 2015 estimate

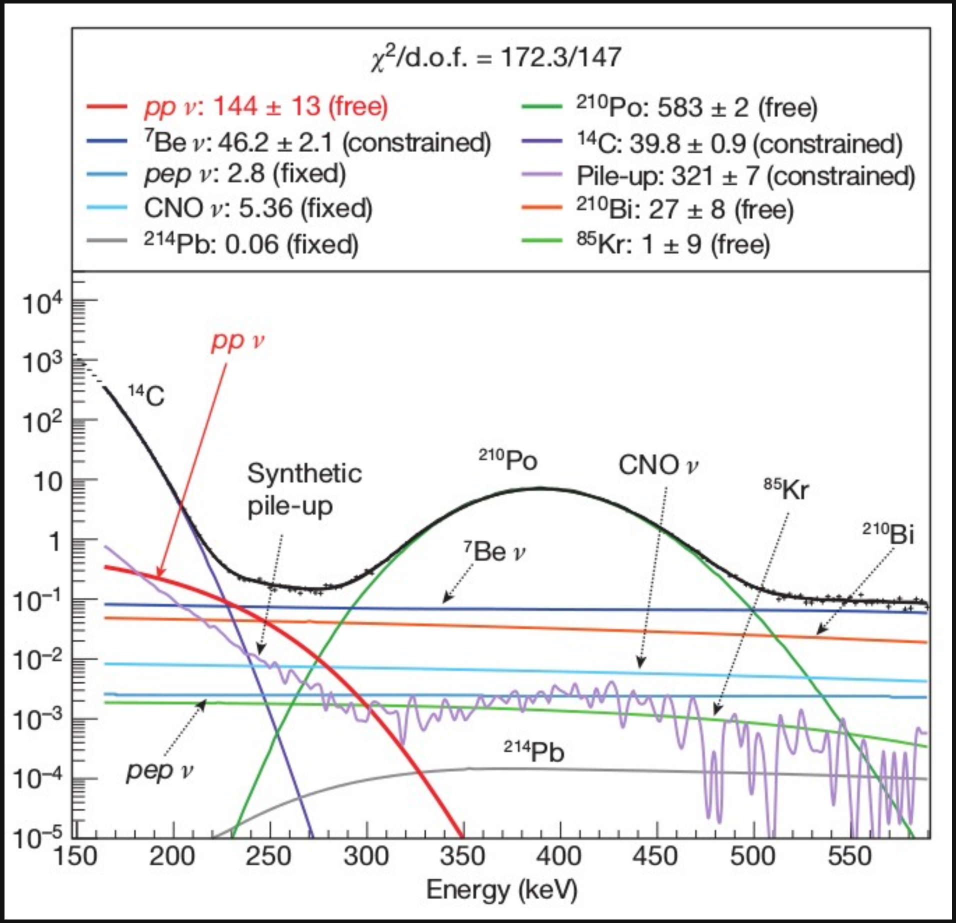
(cpd/100ton)	Phase I	Phase II
^{85}Kr	~30	~0
^{210}Bi	~40	~20
^{210}Po	>2000	~60

Phase I-II naive comparison



Example of comparison normalized to the live time

pp energy spectrum



Fit of the energy distribution

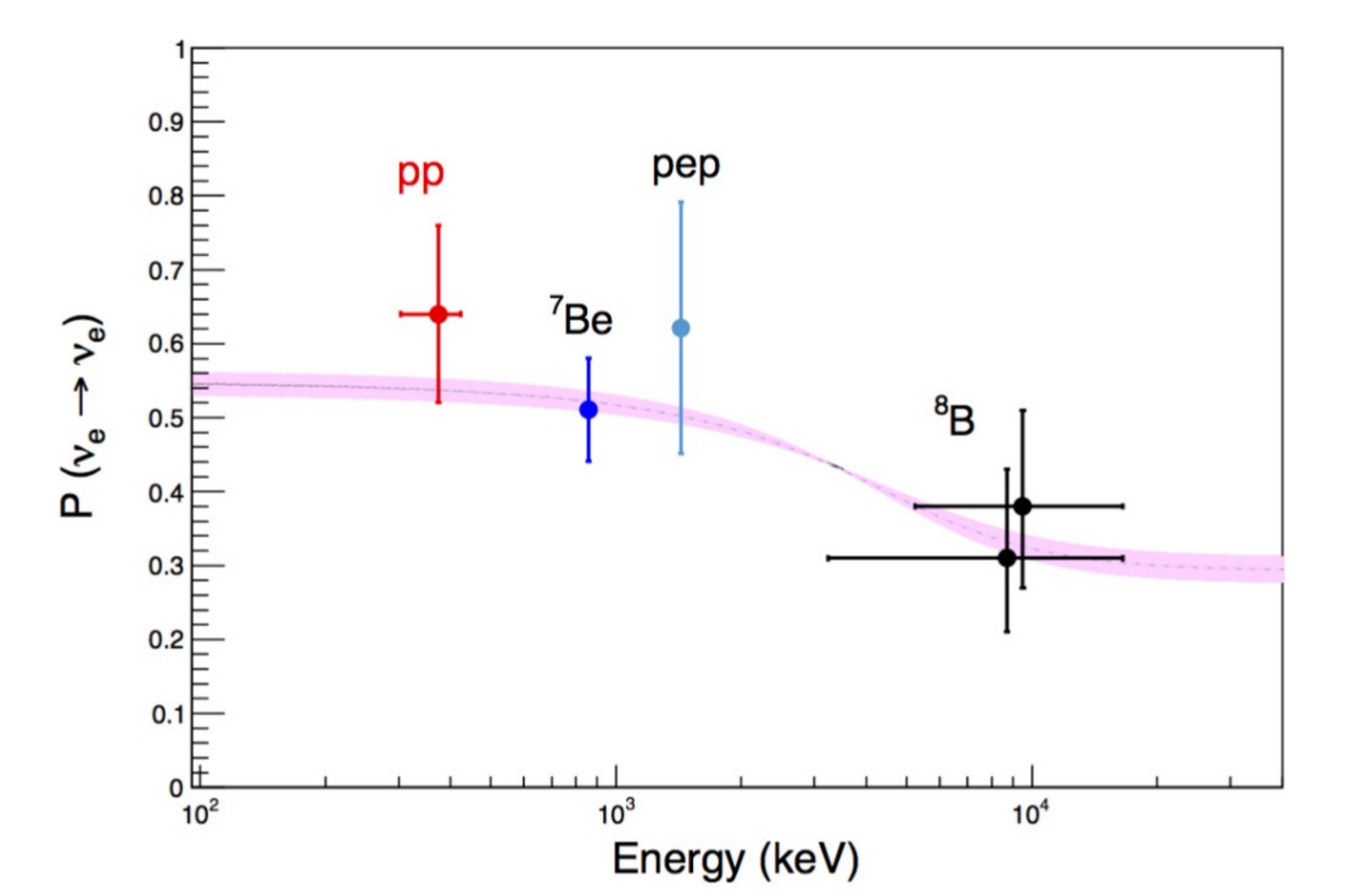
Selection criteria (maximize signal-to-noise):
- removing residual backgrounds
- remove electronic noise events
- Fiducialization (~86 m^3)

^{14}C (156 keV): 2.7 x 10^{-18} of ^{12}C (~40 Bq)
- pile-up due to the high rate
- Independent measure of ^{14}C
- pile-up modelling through the **synthetic pile-up**

Parameter	Rate ± statistical error (c.p.d. per 100 t)	Systematic error (c.p.d. per 100 t)
pp neutrino	144 ± 13	±10
^{85}Kr	1 ± 9	±3
^{210}Bi	27 ± 8	±3
^{210}Po	583 ± 2	±12

The first direct observation of the low energy neutrinos coming from the "pp" fusion in the core of the Sun.

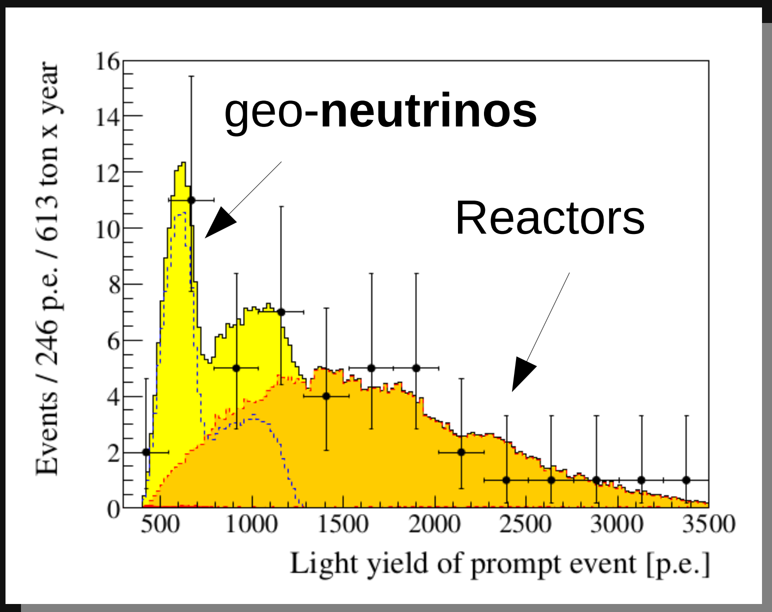
P_{ee} survival probability

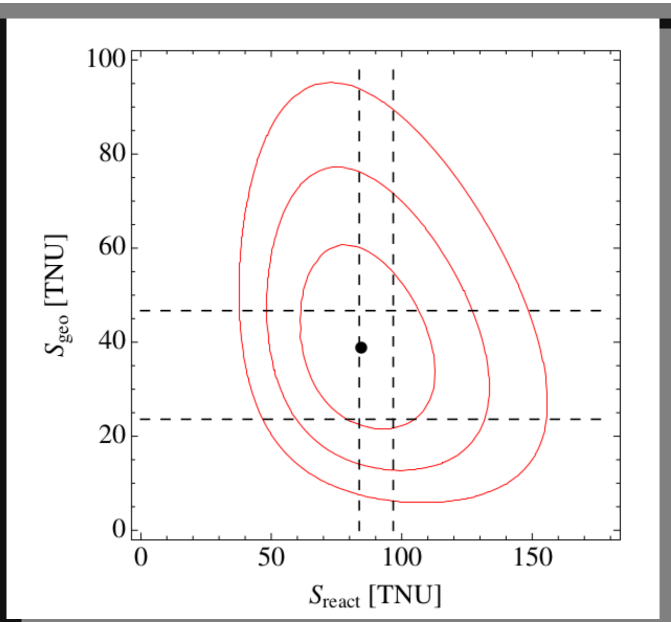


MSW-LMA scenario with Borexino results only!

Geo-neutrinos

^{238}U and ^{232}Th

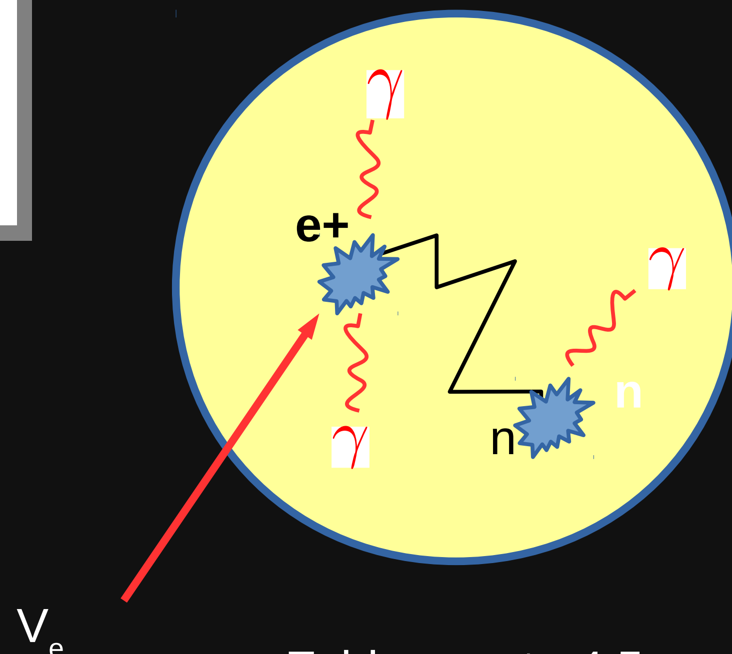




Inverse beta reaction:
Prompt / delayed coincidence

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

$n + H \rightarrow D + 2.2$ MeV



prompt
e^+ Annihilation

delayed
+ neutron capture (~250 μs)

Evidence at ~4.5 σ

- Earth Power origin
- Geological modeling

What next?

0. Better accuracy for the solar neutrinos

1. CNO possible evidence (???)
- ^{210}Bi independent constraint from the ^{210}Po decay
- Temperature stabilization for preventing ^{210}Po mixing
- Further purification campaigns

2. Plan for a new Calibration Campaign

3. The SOX project (end of 2016)
- Search for the Sterile neutrinos with short distance neutrino sources
- ^{144}Ce-^{144}Pr anti-neutrino source (1st stage)
- 95% coverage of the detector anomaly region

Thank you for your attention!