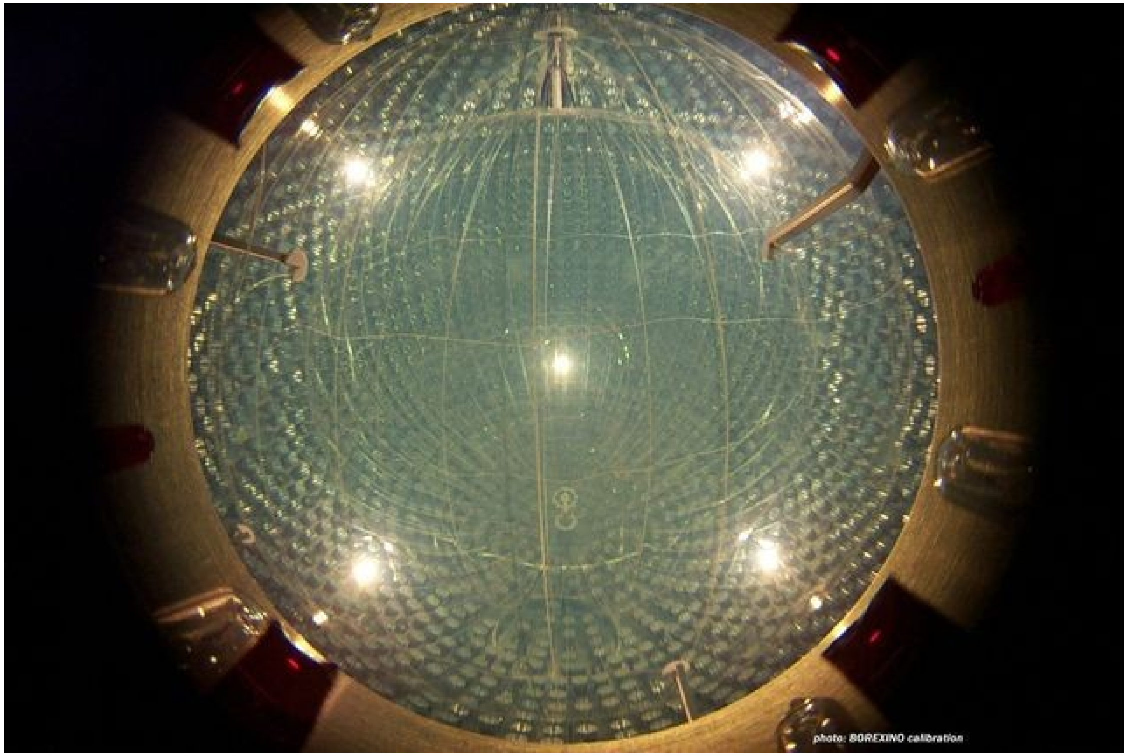
# The Borexino Experiment: Recent results and future plans

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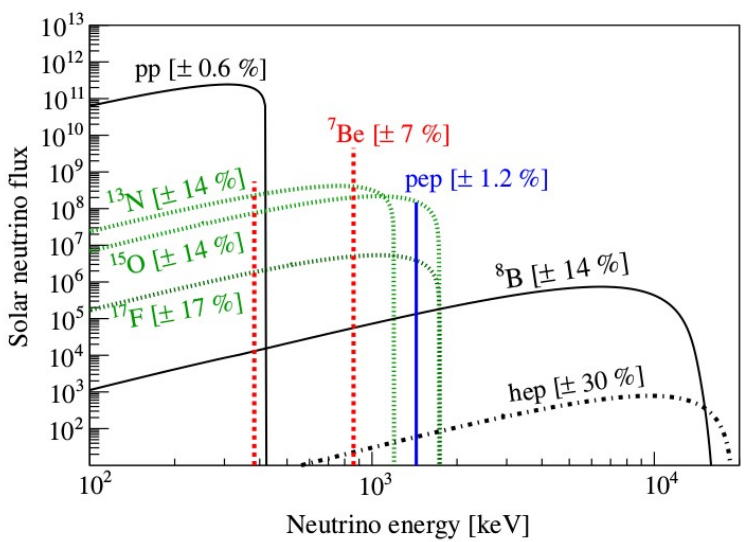
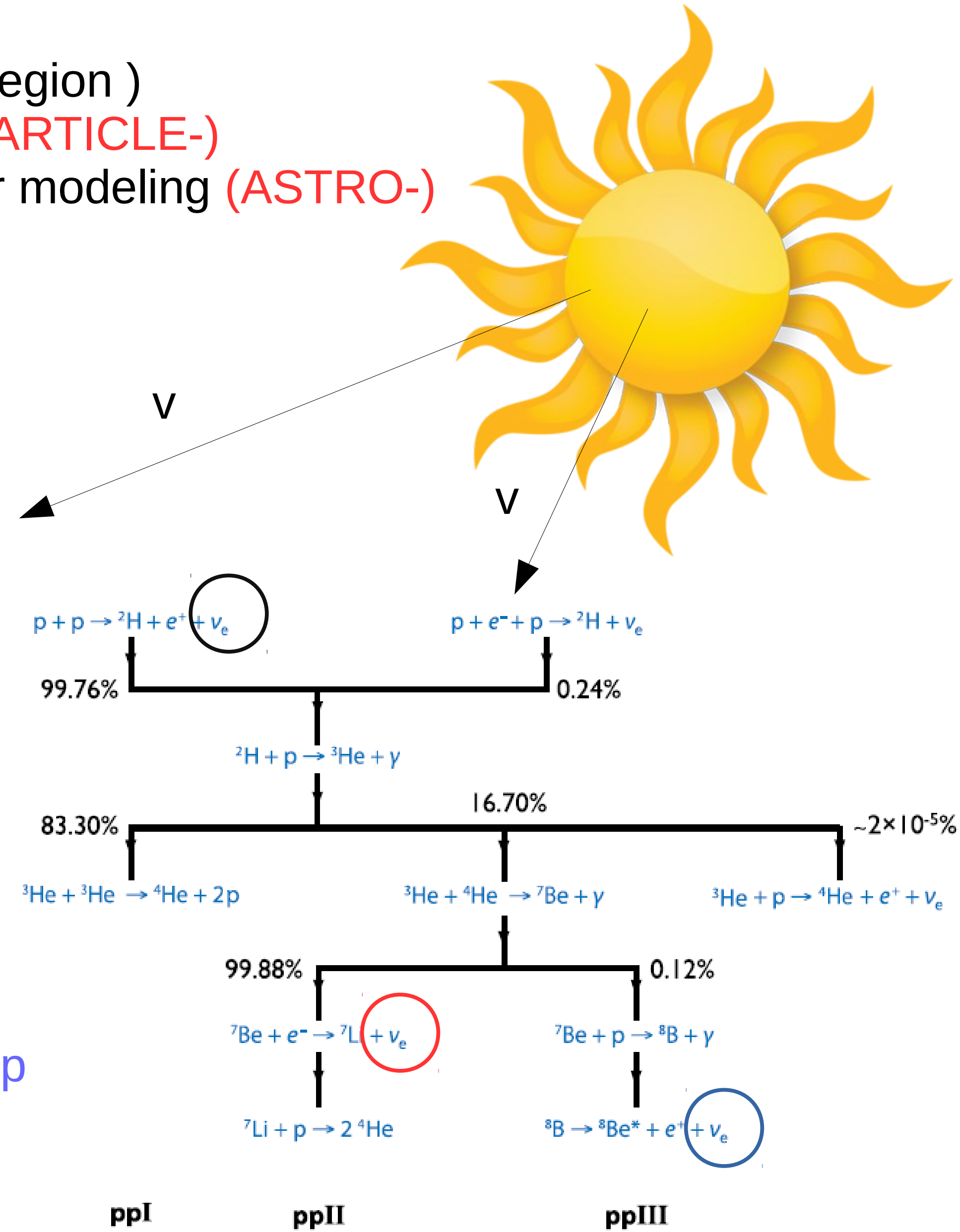
*2015, May 15th*

# 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-)




$^{12}C + p \rightarrow {}^{13}N + \gamma$

$^{13}N \rightarrow {}^{13}C + e^+ + \nu_e$

$^{13}C + p \rightarrow {}^{14}N + \gamma$

$^{14}N + p \rightarrow {}^{15}O + \gamma$

$^{15}O \rightarrow {}^{15}N + e^+ + \nu_e$

$^{15}N + p \rightarrow {}^{12}C + {}^{4}He$

Total Energy

1% CNO 99%pp

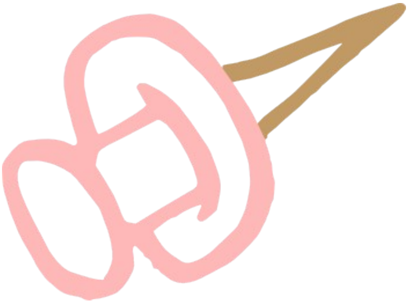
# Borexino Milestones

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.

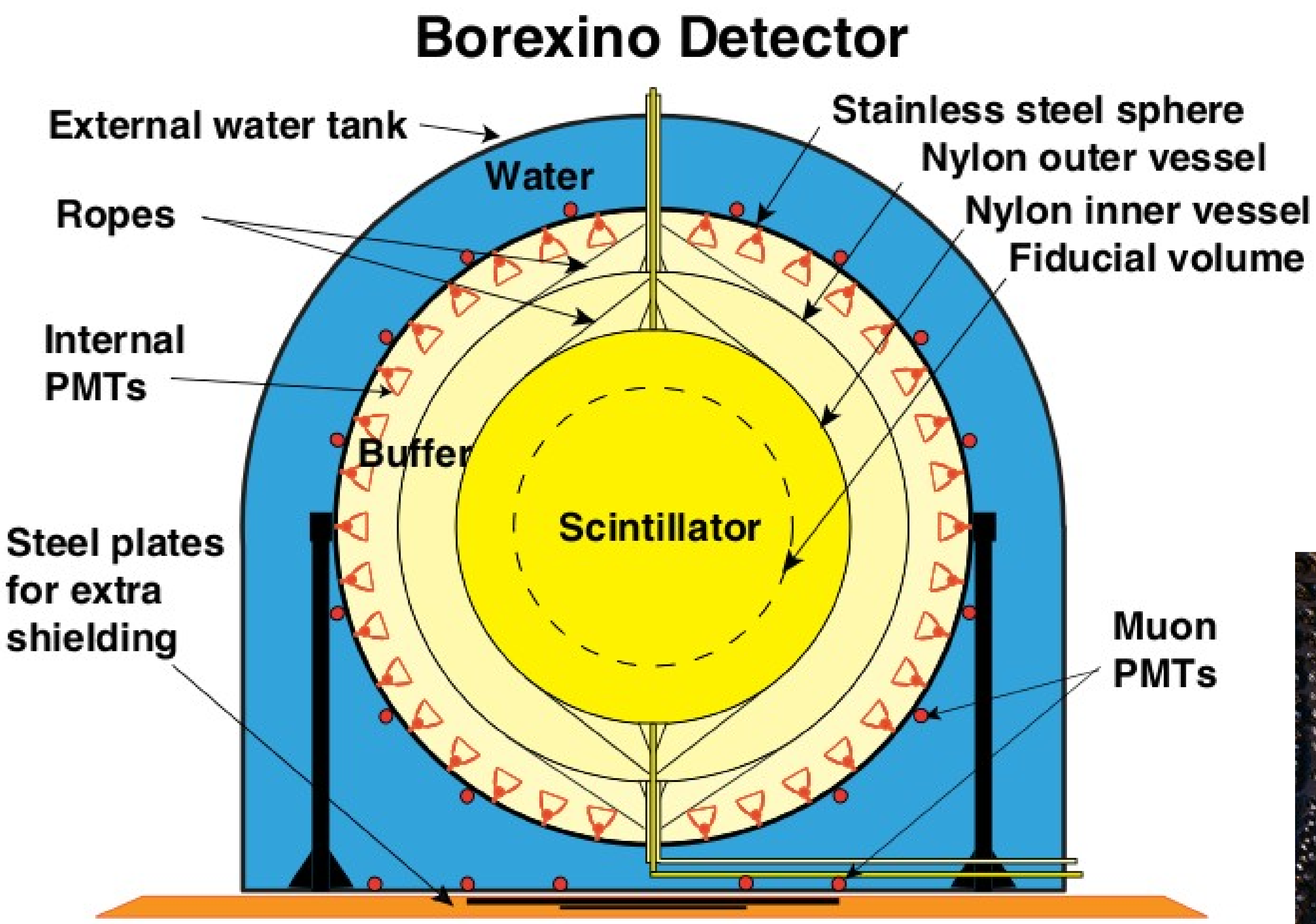
- First measurement of the interaction rate of the $^{7}$Be 862 keV solar neutrinos with accuracy of the measurement has recently reached 5%
- Exclusion of any significant day-night asymmetry of the $^{7}$Be solar neutrino flux
- First direct observation of the monoenergetic 1440 keV pep solar neutrinos [9]

- Set of the strongest upper limit of the CNO solar neutrinos flux to date.
- Measure of the $^{8}$B solar neutrinos with an energy threshold of 3 MeV
- First direct measurement of the pp spectrum.

- $4\sigma$ geo-netrinos detection
- Detailed study of the cosmogenics in liquid scintillator



# The experiment set-up




**13.7 m stainless sphere**
~ 1000 tons of pseudocumene (PC)
~300 tons Inner Vessel

More than 2000 Photomultiplier tubes (PMTs)

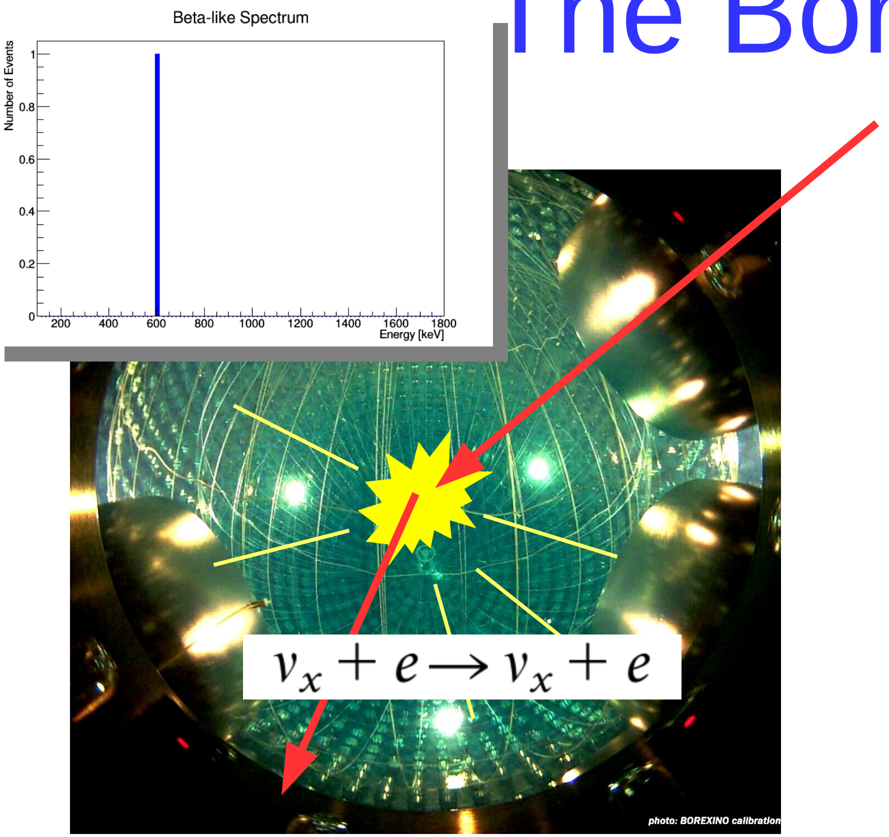
25% Coverage

Light Yield = 500 PE/MeV

- Very (very) low background -

- Nitrogen stripping
- Distillation
- Water Extraction

# The Borexino Signal




The Borexino PMTs detect the scintillation light produced by electrons scattered by neutrinons

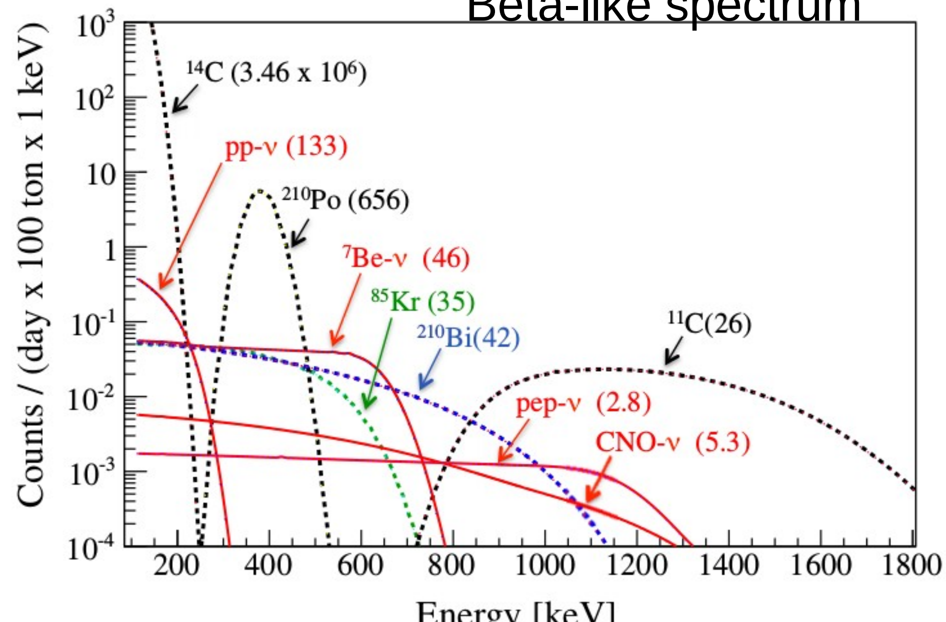
This signal is indistinguishable from the natural radioactivity (β- and γ components)

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

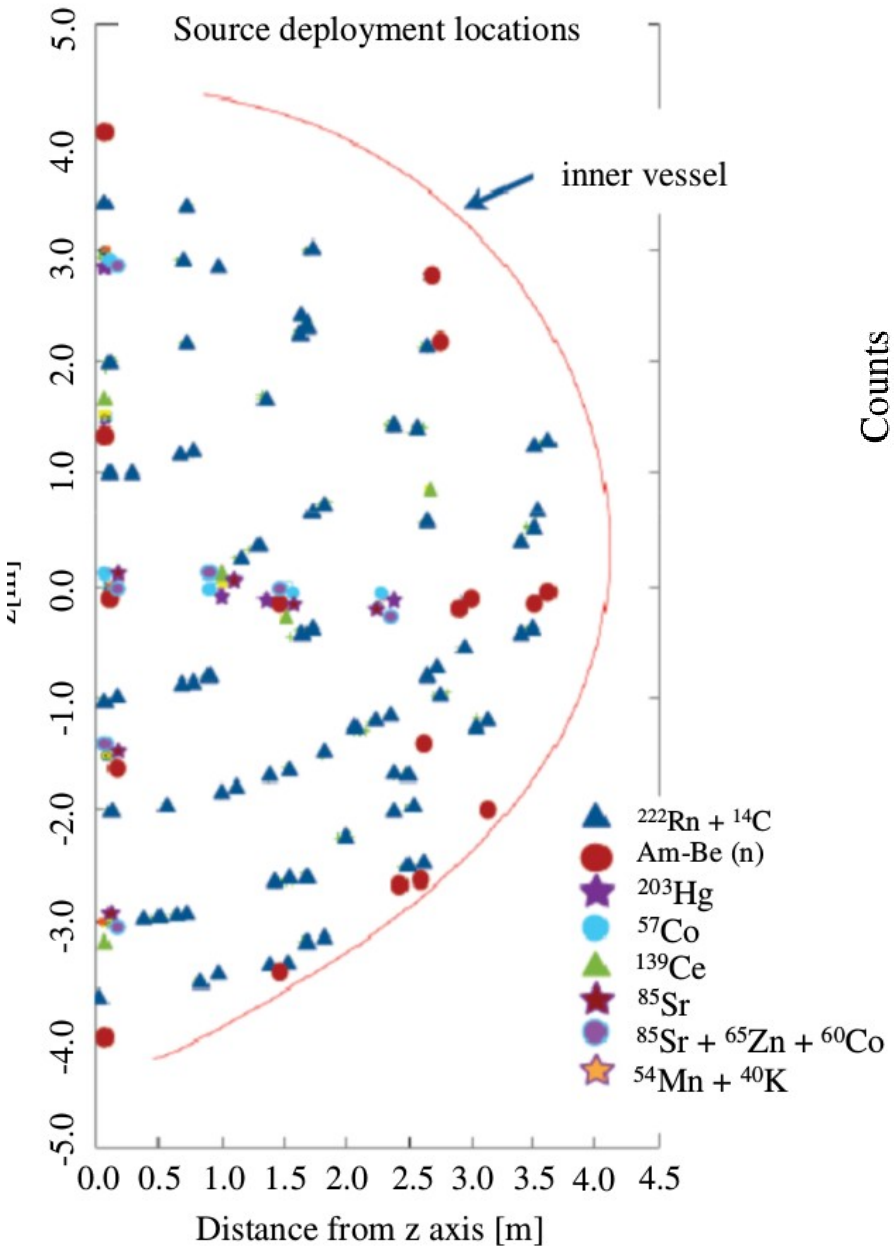
**Crucial point:**
**Extreme low background required!!!**

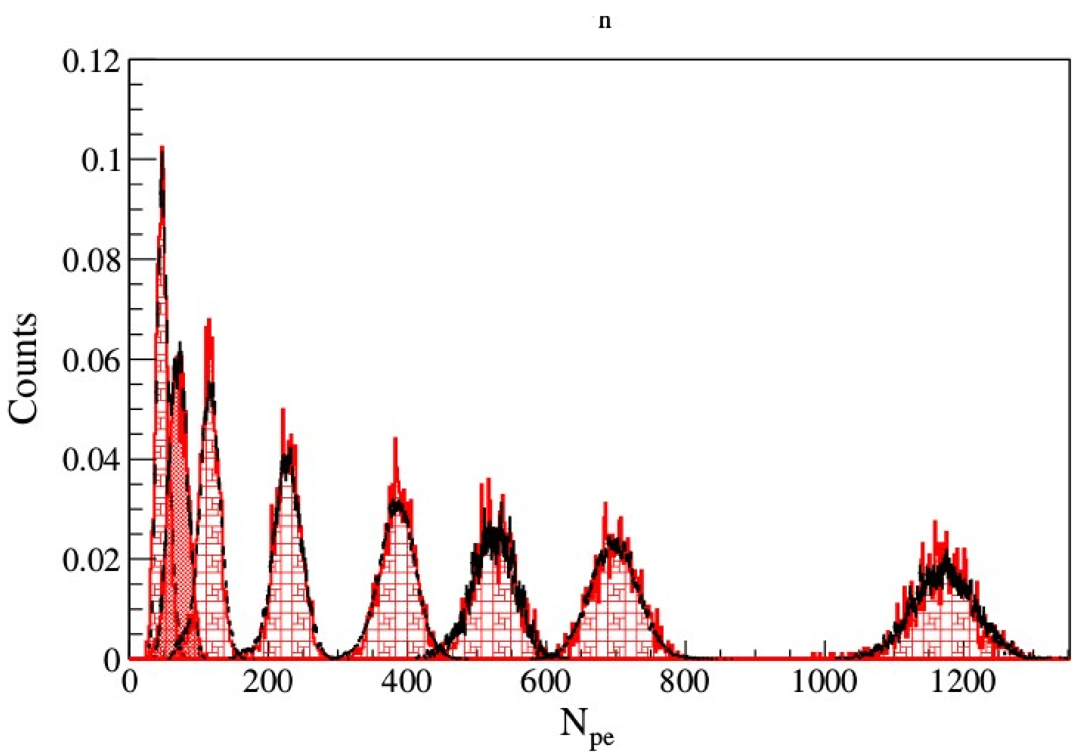
| Isotope | Decay Rate [cpd/100 ton] |
|---|---|
| $^{14}$C | $(3.46 \pm 0.09) \times 10^6$ |
| $^{85}$Kr | $(30.4 \pm 5.3 \pm 1.5)^{(a)}$ |
| | $(31.2 \pm 1.7 \pm 4.7)^{(b)}$ |
| $^{40}$K | $< 0.42$ (95% C.L.) |
| $^{39}$Ar | $\sim 0.4$ |
| $^{238}$U | $(0.57 \pm 0.05)$ |
| $^{222}$Rn | $(1.72 \pm 0.06)$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

Beta-like spectrum



# Calibration Campaign



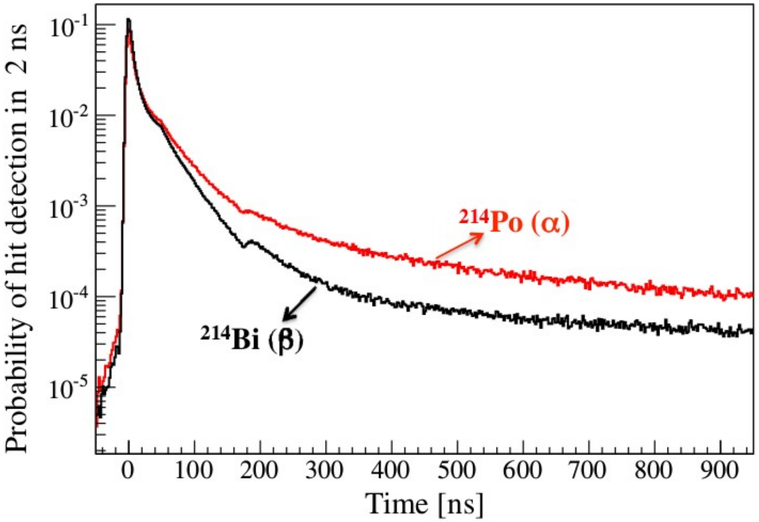



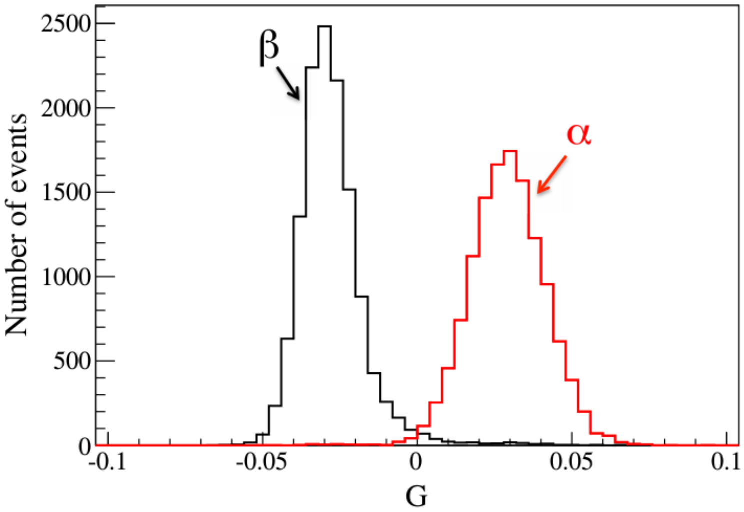

Calibration of the full energy scale with different standard sources deployed inside the detector with mechanical arms

Calibration of the position. Position is important for defining the fiducial volume and full reconstruction of the event

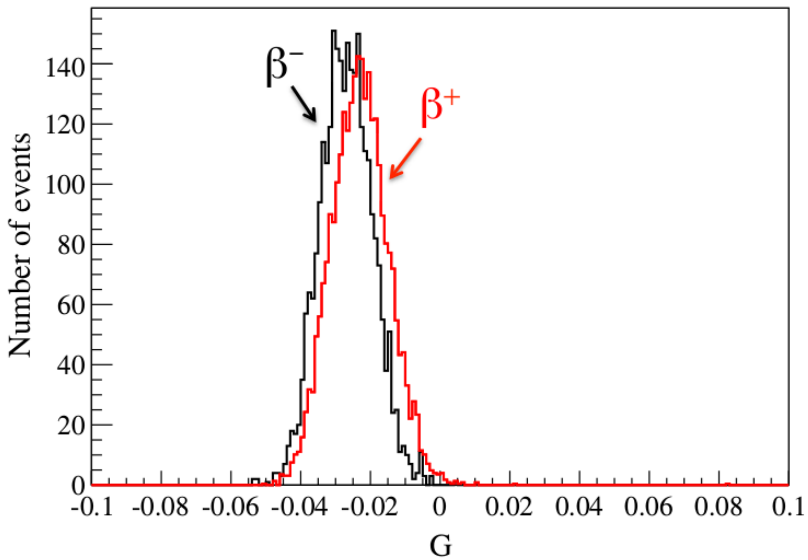
# Pulse Shape Discrimination

Scintillation light in time (waveform)




Examples



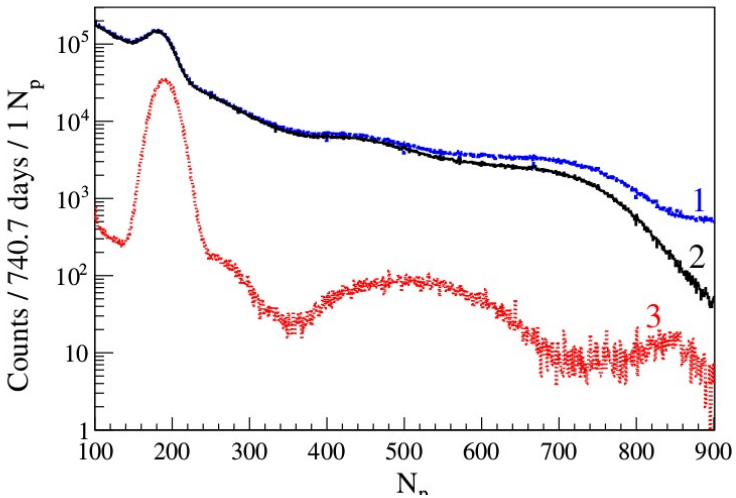

The Gatti's patameter

$$G = \sum_n e(t_n) w(t_n),$$

where $w(t_n)$ are weights given by

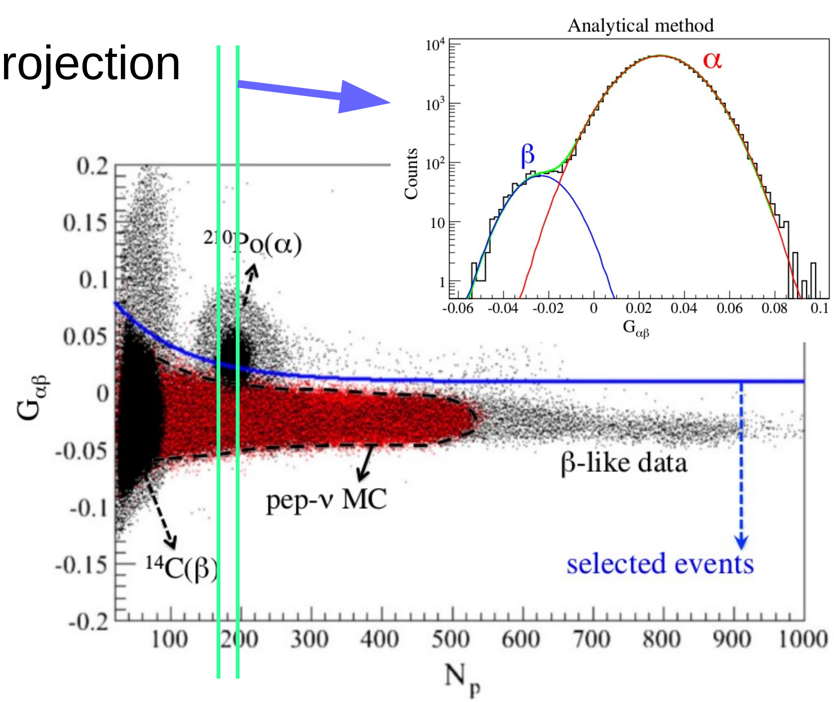
$$w(t_n) = \frac{r_1(t_n) - r_2(t_n)}{r_1(t_n) + r_2(t_n)}.$$

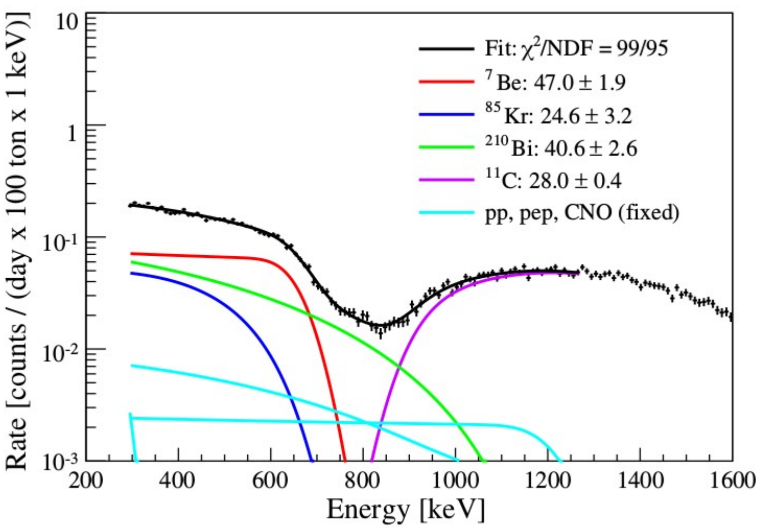
# The energy spectrum




1. Muon Cut
2. Cosmogenics
3. Fiducial Volume

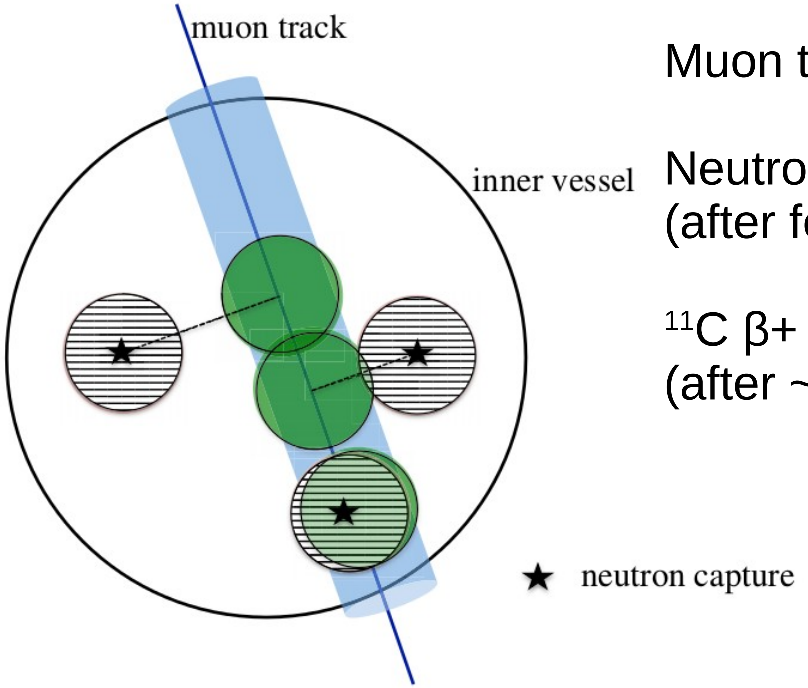
Projection




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

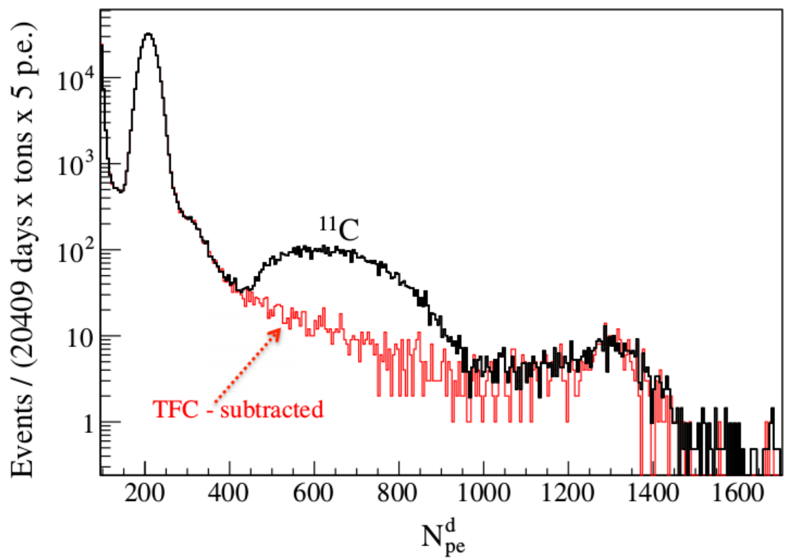
# Threefold coincidence

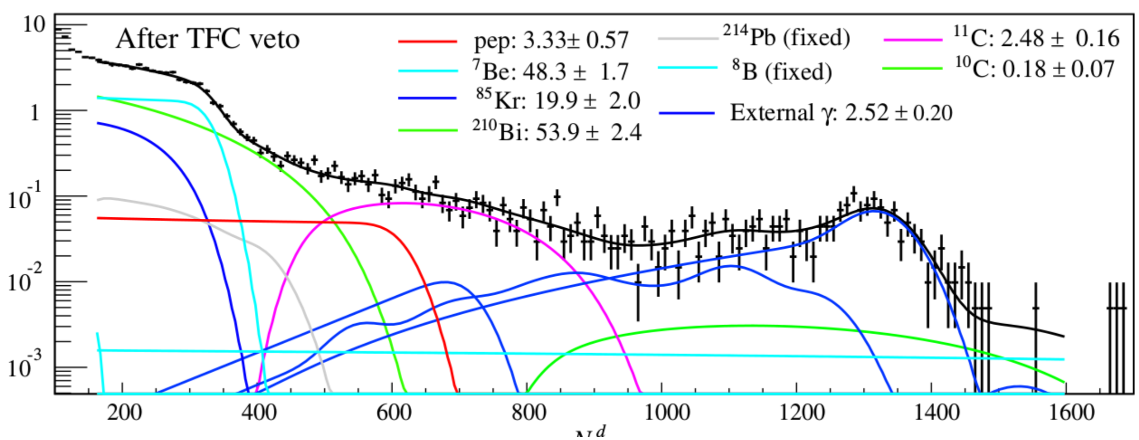



Muon track

Neutron capture
(after few us)

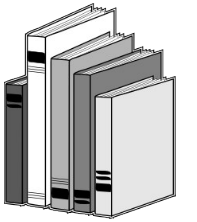
$^{11}$C β+ decay
(after ~30')




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

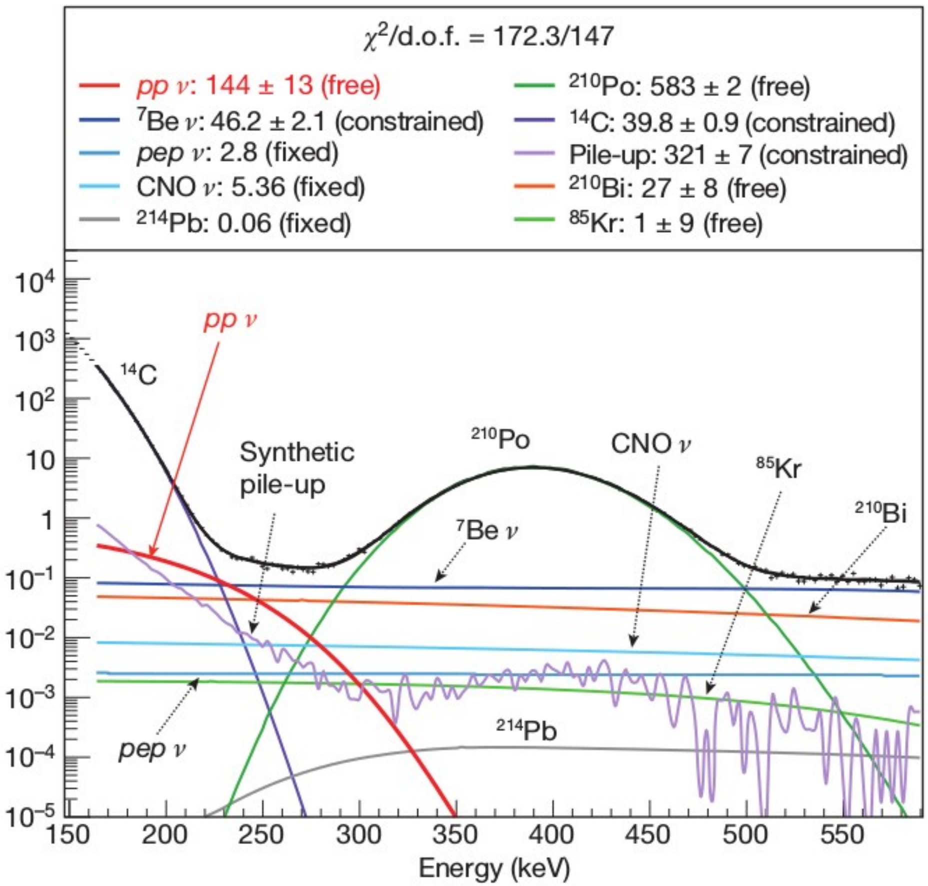
# Published Results



| Species | Result [cpd/100 ton] | Expected value [cpd/100 ton] |
|---|---|---|
| *pep* | $3.1 \pm 0.6 \pm 0.3$ | $2.73 \pm 0.05$ $(2.79 \pm 0.06)$ |
| $^{7}$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 | $0.62 \pm 0.2 \pm 0.1$ | $0.54 \pm 0.04$ |
| $^{6}$He | $0.7(0) \pm 0.6(0.5) \pm 1$ | $0.31 \pm 0.04$ |
| Ext. $^{208}$Tl $(N_{pe}^{h})$ | $1.64 \pm 0.11 \pm 0.01$ | NA |
| Ext. $^{208}$Tl $(N_{h})$ | $1.94 \pm 0.13 \pm 0.02$ | NA |
| Ext. $^{214}$Bi $(N_{pe}^{h})$ | $0.67 \pm 0.12 \pm 0.01$ | 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 |

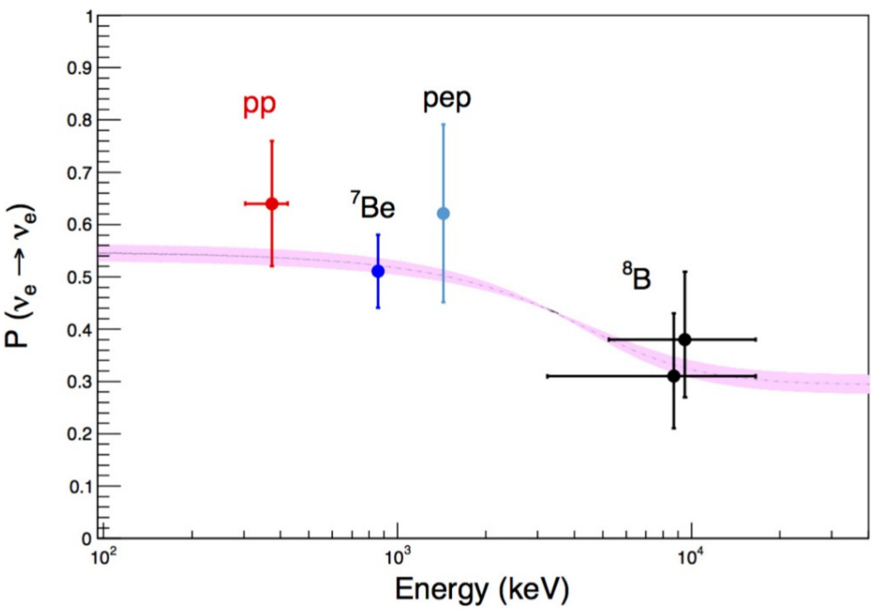
| | 68% Limit | 95% Limit | 99% Limit | Expected value |
|---|---|---|---|---|
| CNO | 4 | 12 | 19 | $5.24 \pm 0.54$ $(3.74 \pm 0.37)$ |
| $^{40}$K | 0.11 | 0.42 | 0.69 | NA |
| $^{234m}$Pa | 0.12 | 0.46 | 0.75 | $1.78 \pm 0.06$ |

# pp energy spectrum

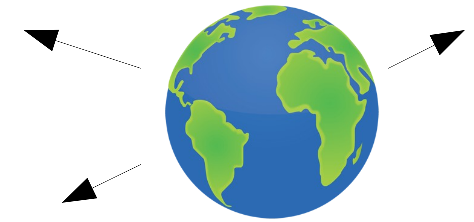


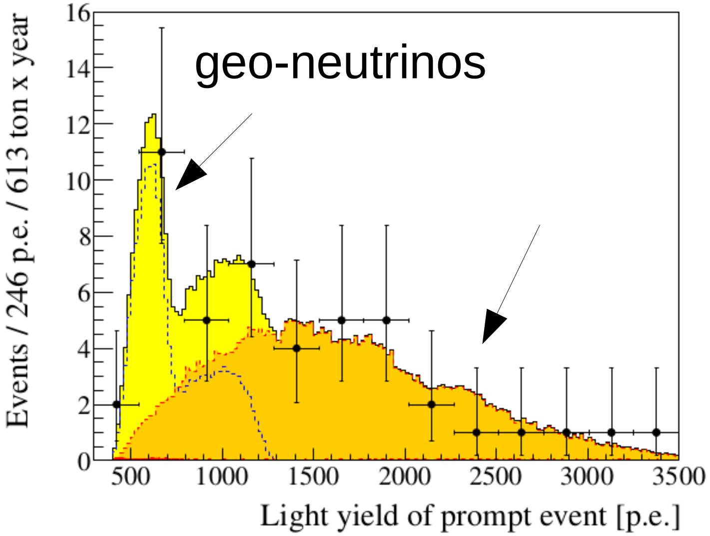

The first direct observation of the low energy neutrinos coming from the "pp" fusion in the core of the Sun.

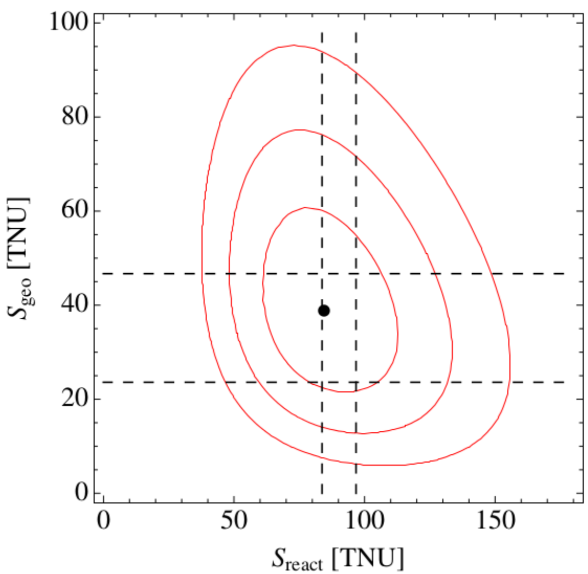
$P_{ee}$ survival probability in the MSW-LMA scenario with Borexino results only!



# Geo-neutrinos



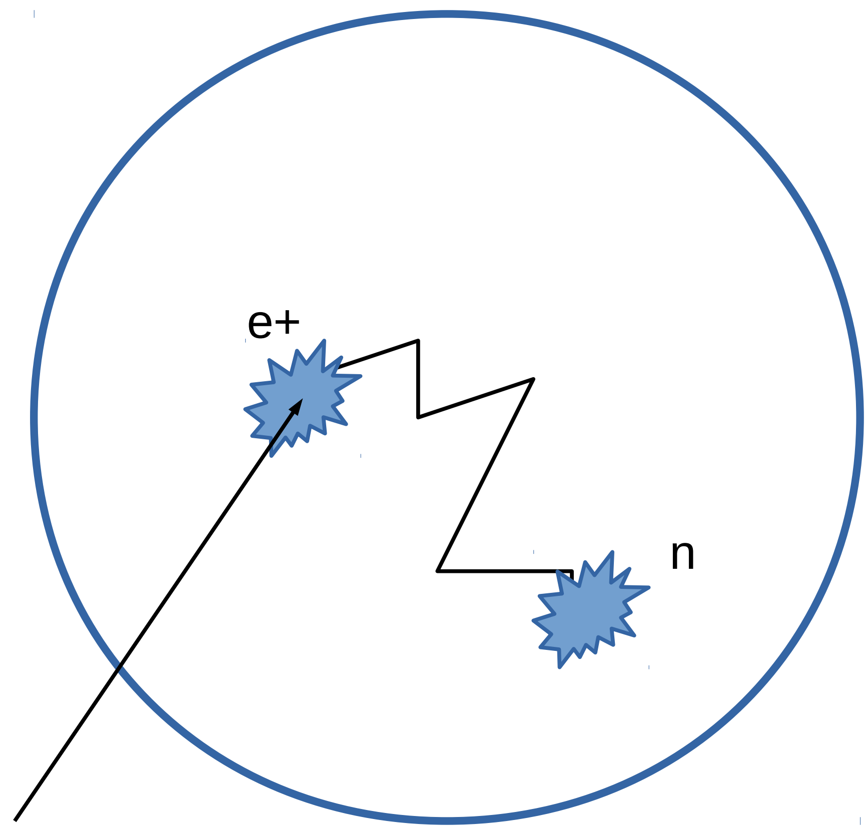



Inverse beta reaction:
Prompt / delayed coincidence

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

n + H → D + 2.2 MeV



# Borexino Phase II

| Isotope | Typical abundance (source) | Borexino goals | Borexino-I | Borexino-II |
|---|---|---|---|---|
| $^{14}$C / $^{12}$C, g/g | $10^{-12}$ (cosmogenic) | ~$10^{-18}$ | 2.7·$10^{-18}$ | 2.7·$10^{-18}$ |
| $^{238}$U, g/g ( $^{214}$Bi-$^{214}$Po) | $10^{-6}$-$10^{-5}$ (dust) | ~$10^{-16}$ (1 μБк /т) | (1.6±0.1)·$10^{-17}$ | <9.7· $10^{-19}$ (95%) |
| $^{232}$Th, g/g ( $^{212}$Bi-$^{212}$Po) | $10^{-6}$-$10^{-5}$ (dust) | ~$10^{-16}$ | (6.8±1.5)· $10^{-18}$ | <1.2· $10^{-18}$ (95%) |
| $^{222}$Rn ($^{238}$U), ev/d/100 t | 100 atoms/cm$^3$ (air) | 10 | 1 | 0.1 |
| $^{40}$K, g[$K_{nat}$]/g | 2·$10^{-6}$ (dust) | ~$10^{-15}$ | <1.7·$10^{-15}$ (95%) | --- |
| $^{210}$Po, ev//d/t | Surface contamination | ~$10^{-2}$ | 80 (initial), $T_{1/2}$=134 days; | 2 |
| $^{210}$Bi, ev/d/100 t | Inequilibrium with $^{222}$Rn or $^{210}$Pb | Not specified | 20-70 | ~20 |
| $^{85}$Kr ev/d/100 t | 1 Бк/м$^3$ (technogenic, air) | ~1 | 30.4±5 cpd/100t | < compatble with 0 |
| $^{39}$Ar ev/d/100 t | 17 mБк/м$^3$ (cosmogenic in air) | ~1 | <<$^{85}$Kr | |

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

**Best conditions ever!**

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

# Future plans

**0. Better accuracy for the solar neutrinos**

**1. CNO evidence**

- $^{210}$Bi independent constraint from the $^{210}$Po decay
- Temperature stabilization for preventing $^{210}$Po mixing
- further purification campaign

**2. New Calibration**

**3. The SOX project**

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