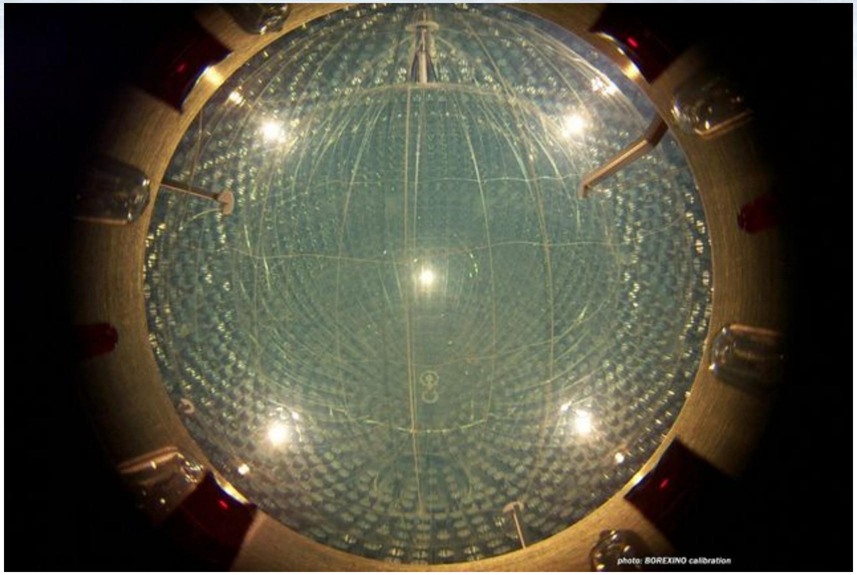


Report on Borexino activities

Davide Franco
Milano University & INFN

Outline

Physics Results (3 papers since October 2009!):

- ✓ Observation of **Geo-Neutrinos**
- ✓ Measurement of **^{8}B neutrinos** flux with 3 MeV threshold
- ✓ Limit on **Pauli Exclusion Principle** violating nuclear transitions

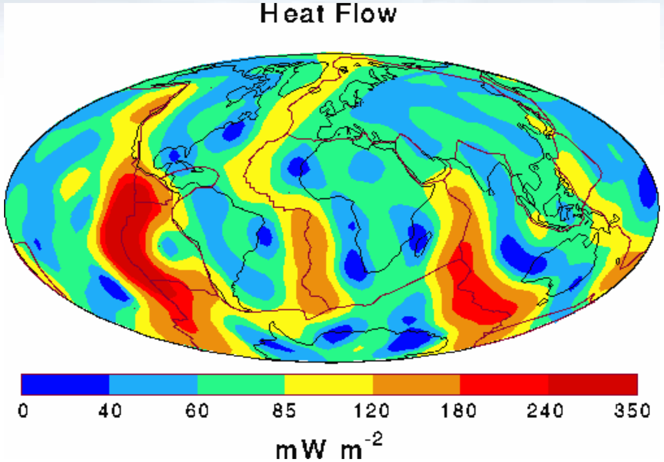
Understanding the detector (next 4 papers):

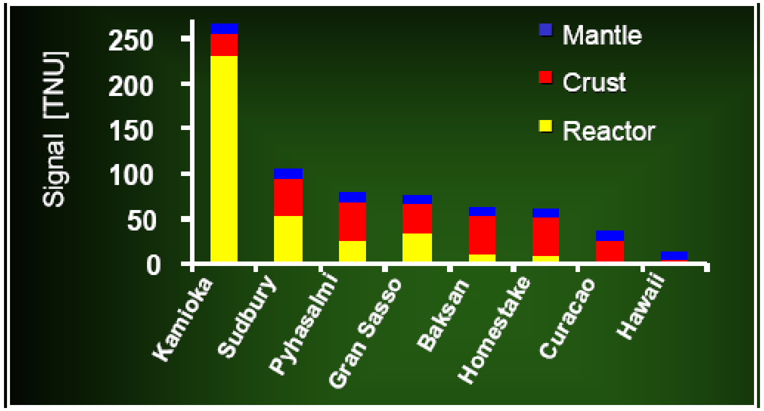
- ✓ ^{7}Be analysis with error < 5%
- ✓ Monte Carlo
- ✓ Calibrations
- ✓ Muons and cosmogenics

Geoneutrinos

A new probe of the Earth:

- ✓ What is the radiogenic **contribution** to the terrestrial heat?
- ✓ What is the **distribution** of the radiogenic elements?
- ✓ How much in the **crust** and how much in the **mantle**?
- ✓ **Core composition**: Ni+Fe and ? 40K, geo-reactor ?





Earth $\bar{\nu}$ flux ~ 10^6 cm^{-2} s^{-1}:

- ✓ **^{238}U** → ^{206}Pb + 8 α + 8 e^- + **6 $\bar{\nu}$** + 51.7 MeV
- ✓ **^{232}Th** → ^{208}Pb + 6 α + 4 e^- + **4 $\bar{\nu}$** + 42.8 MeV
- ✓ **^{40}K** → ^{40}Ca + e^- + **1 $\bar{\nu}$** + 1.32 MeV
- ✓ released **heat** and **$\bar{\nu}$ flux** with **fixed ratio**!

The main backgrounds: reactor anti-neutrinos and radioactive contamination

Borexino: S(geo):S(reactors) ~ **1:0.9**

KamLAND: S(geo):S(reactors) ~ **1:6.7**

The signature in Borexino

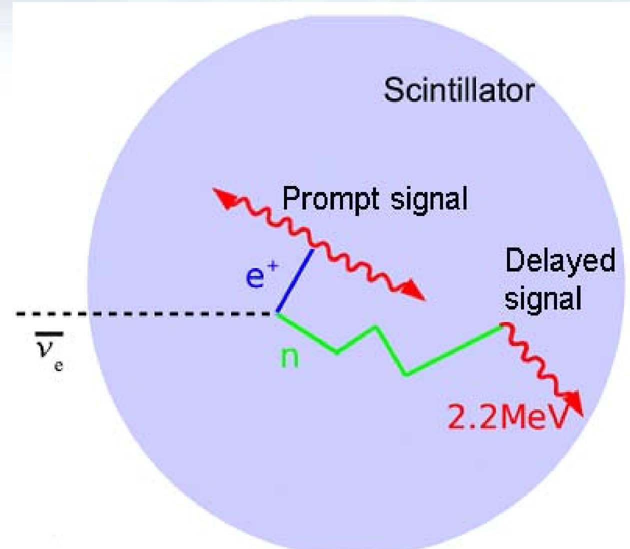
Prompt:

$\overline{\nu} + p \rightarrow n + e^+$

E_{th} = 1.8 MeV

Minimum detected energy: **2x511 keV**

Expected rate:
2.5 cpy / 100 t



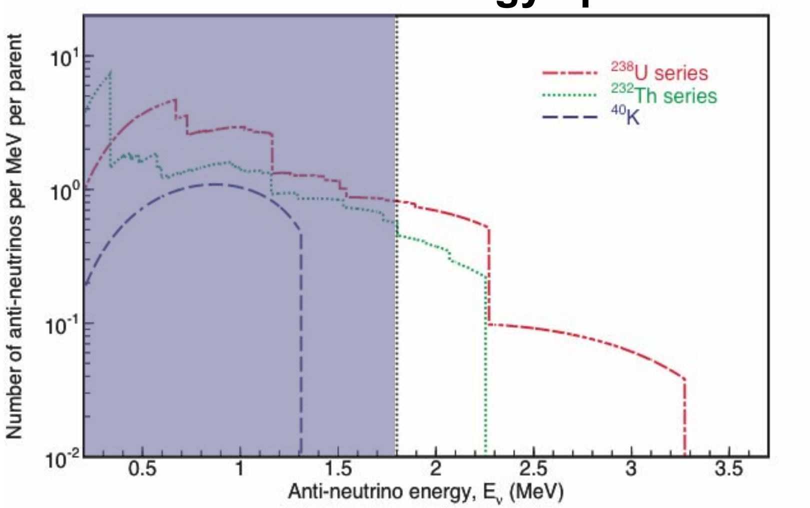
Delayed (τ ~250 μs):

$n + p \rightarrow d + \gamma$

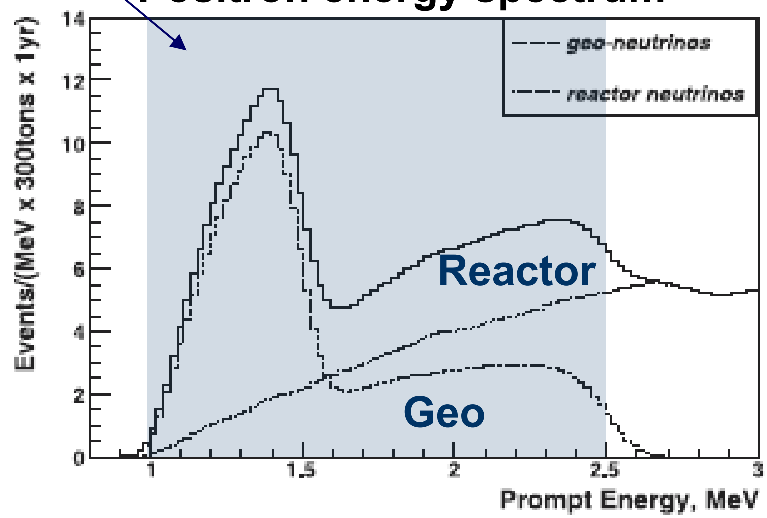
Detected energy: **2.2 MeV**

Energy window of observation
NW: 1 - 2.5 MeV

Anti-neutrino energy spectrum



Positron energy spectrum



The background in Borexino

✓ Reactor antineutrinos

Differential reactor anti-ν spectrum:

$$\Phi(E_{\bar{\nu}_e}) = \sum_{r=1}^{N_{react}} \sum_{m=1}^{N_{month}} \frac{T_m}{4\pi L_r^2} P_{rm} \times \sum_{i=1}^{4} \frac{f_i}{E_i} \phi_i(E_{\bar{\nu}_e}) P_{ee}(E_{\bar{\nu}_e}; \hat{\theta}, L_r)$$

T_m: livetime in the m^{th}-month
P_{rm}: effective thermal power
i: index of the spectral component (^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu)
f_i: power fraction of the i-th component
ϕ_i: energy spectrum of the i-th component

Rate in the NW: 2.0 ± 0.1 cpy/ 100 t

Error:

Source	Error [%]	Source	Error [%]
Fuel composition	3.2	θ_{12}	2.6
$\phi(E_{\bar{\nu}})$	2.5	P_{rm}	2.0
Long-lived isotopes	1.0	E_i	0.6
$\sigma_{\bar{\nu}p}$	0.4	L_r	0.4
Δm_{12}^2	0.02		
Total			5.38

✓ Muon correlated events

Cosmogenic ^9Li and ^8He decay via β-n
τ ~ **150 ms**
2 s detector **veto** after each muon in the ID
Residual background: **0.03 ± 0.02 cpy/ 100 t**

Fast neutrons
Muon rejection efficiency with OD > **99.5%**
2 ms detector **veto** after each muon in the OD
Residual background: **<0.01 cpy/ 100 t** (90% C.L.)

✓ Radiogenic $^{13}C(\alpha,n)^{16}O$

^{210}Po α emitter: **12 cpd/ 100 t**
^{13}C low abundance: **$^{13}C/^{12}C$ ~ 1.1%**
Contamination: **0.021 ± 0.002 cpy/ 100 t**

✓ Random coincidences

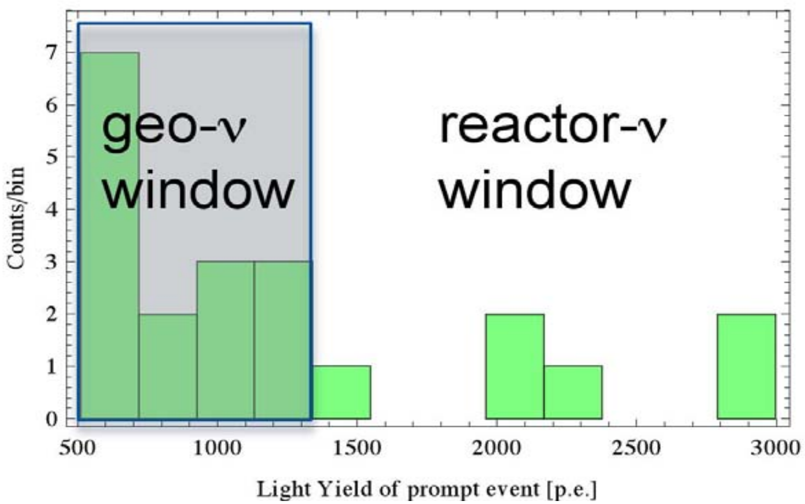
Searching for events in a window of 2ms - 2s:
<0.003 cpy/ 100 t (90% C.L.)

21 selected anti-ν candidates in 252.6 t y

Selection cuts - ε (with MC): 0.85 ± 0.01

- ✓ Q_{prompt} > 410 p.e.
- ✓ 700 p.e. < $Q_{delayed}$ <1250 p.e.
- ✓ ΔR< 1m
- ✓ 20µs < Δt < 1280µs
- ✓ $R_{IV} - R_{prompt}$ > 0.25m

Source	Background [events/(100 ton·yr)]
^{9}Li–^{8}He	0.03±0.02
Fast n's (μ's in WT)	<0.01
Fast n's (μ's in rock)	<0.04
Untagged muons	0.011±0.001
Accidental coincidences	0.080±0.001
Time corr. background	<0.026
(γ,n)	<0.003
Spontaneous fission in PMTs	0.0030±0.0003
(α,n) in scintillator	0.014±0.001
(α,n) in the buffer	<0.061
Total	0.14±0.02



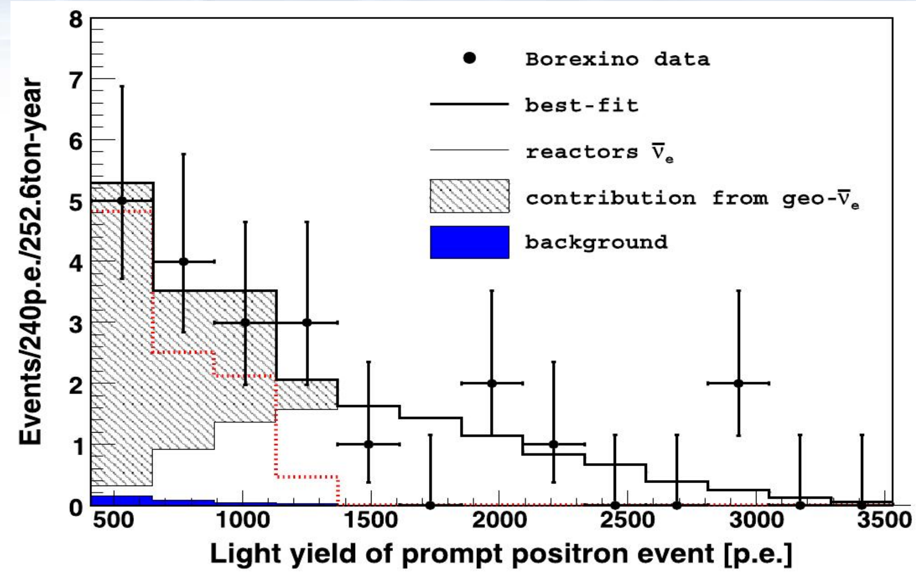
in 532 days of data taking, with a fiducial exposure, after all cuts, of 252.6 t y

15 events in the NW

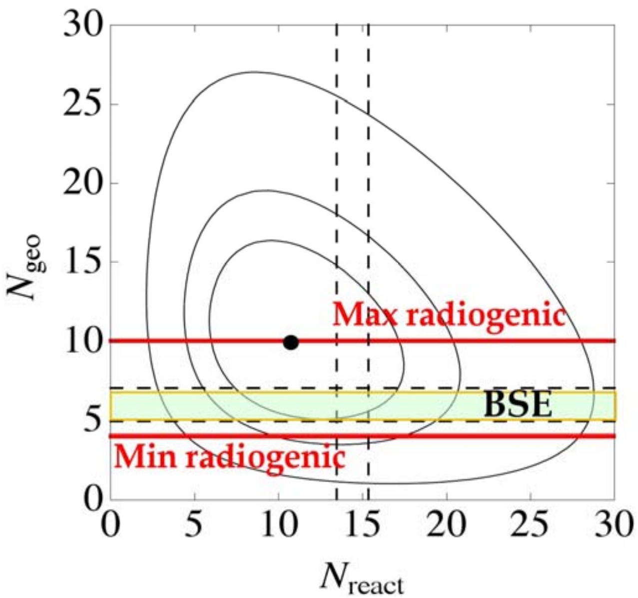
Observation of geoneutrinos

$$N_{\rm geo} = 9.9^{+4.1}_{-3.4}\left(^{+14.6}_{-8.2}\right) \text{ events}$$

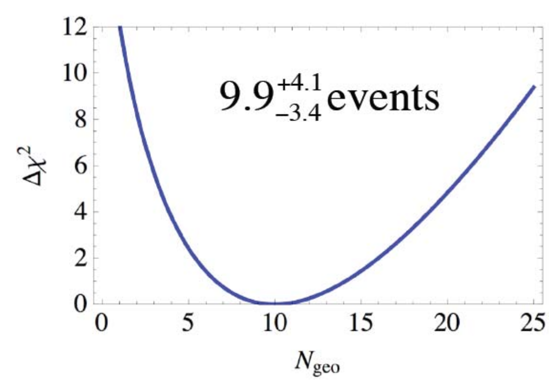
$$N_{\rm react} = 10.7^{+4.3}_{-3.4}\left(^{+15.8}_{-8.0}\right) \text{ events}$$



Allowed regions at 68%, 90% and 99.73% C.L.



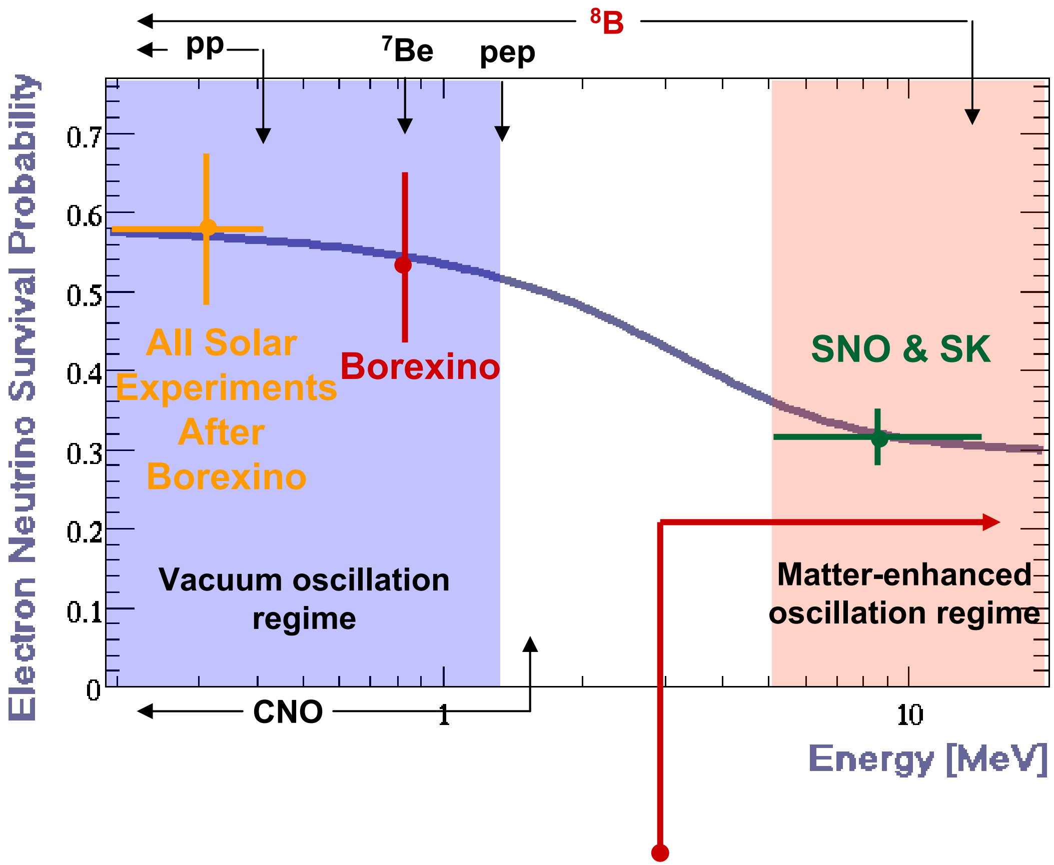
Null-geoneutrino hypotesys rejected at 4.2 sigmas



Phys. Lett. B687:299-304,2010

^{8}B-ν analysis with 3 MeV energy threshold

ideal candles to explore the transition region between vacuum and matter-enhanced dominated oscillation regimes

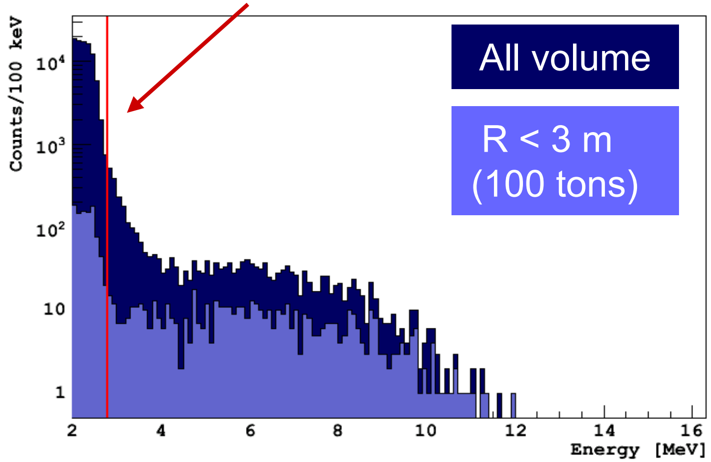


Borexino measures the spectrum with the lowest energy threshold at 3 MeV

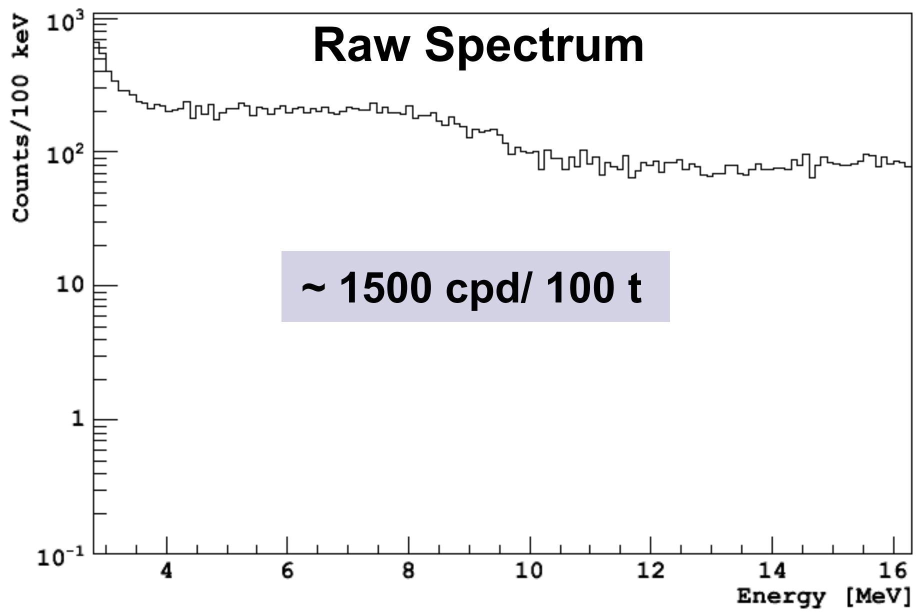
Background in the 3.0-16.3 MeV range

live-time: 487.7 days

2.6 MeV γ's from ^{208}Tl



Expected signal rate
~ 0.25 cpd/ 100 t



- ✓ **Cosmic Muons**
- ✓ **External background**
- ✓ High energy gamma's from **neutron captures**
- ✓ ^{208}Tl and ^{214}Bi from radon **emanation from nylon** vessel
- ✓ **Cosmogenic isotopes**
- ✓ ^{214}Bi and **^{208}Tl** from ^{238}U and ^{232}Th bulk contamination

S/B ratio ~ 1/6000

Muon and neutron cuts

Muon cut:

• All events detected by the **outer detector** are rejected

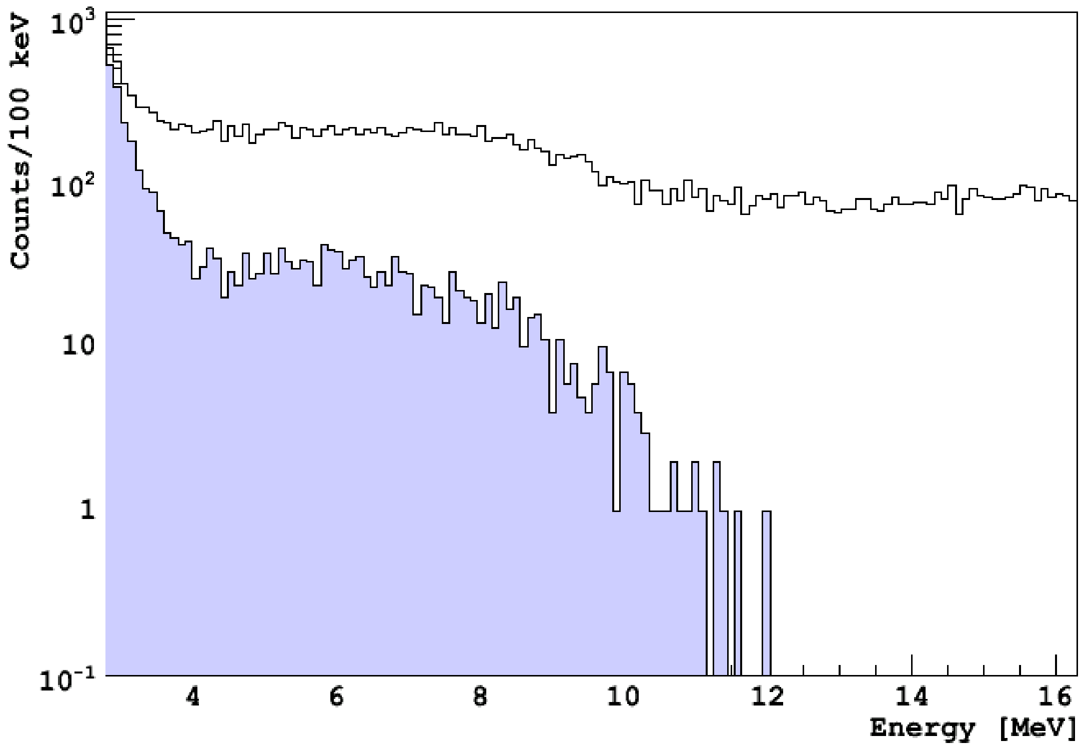
• Pulse shape analysis with **inner detector** scintillation light

• Residual muon rate: **<10^{-3} c/d**

Neutron cut:

• **2 ms veto after each muon** detected by the outer detector, in order to reject induced neutrons (mean capture time ~250 μs)

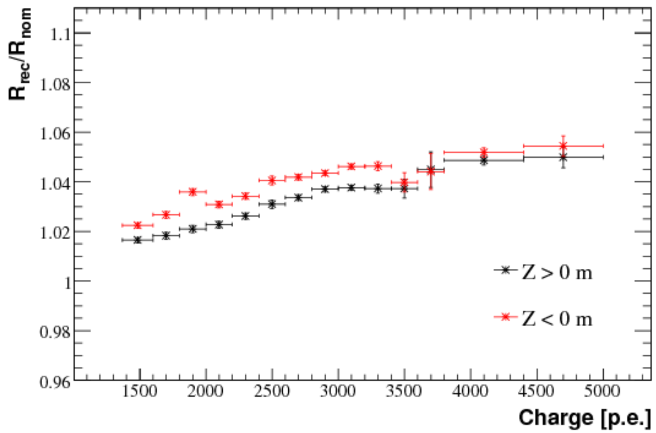
• Residual neutron rate: **~10^{-4} c/d**



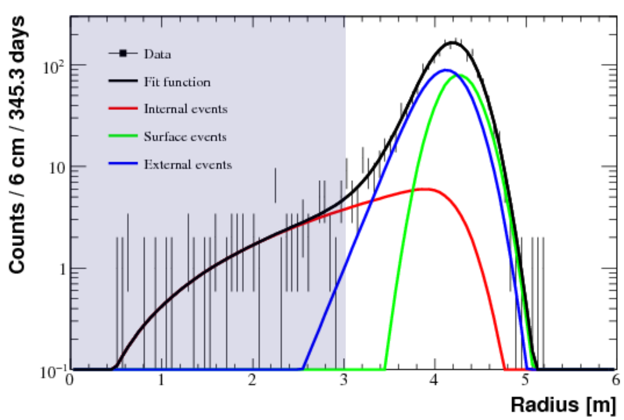
Count-rate: 4.8 c/d/100 ton

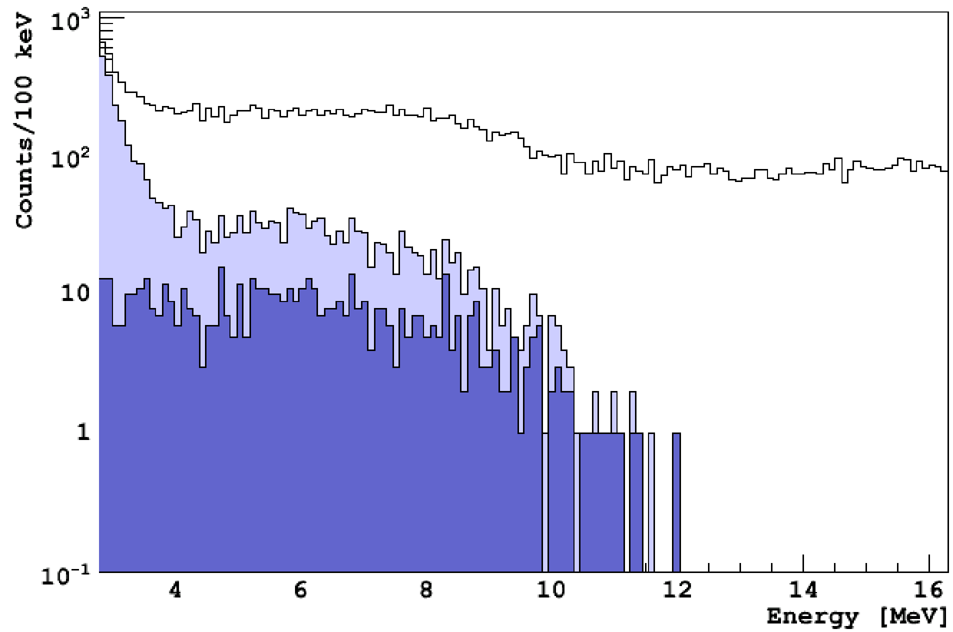
External Background Cut

Radius calibration with AmBe source at R = 3 m as function of the energy



Residuals from ^{222}Rn and ^{220}Rn emanated from the vessel with radial fit





Count-rate: 2.3 c/d/100 ton

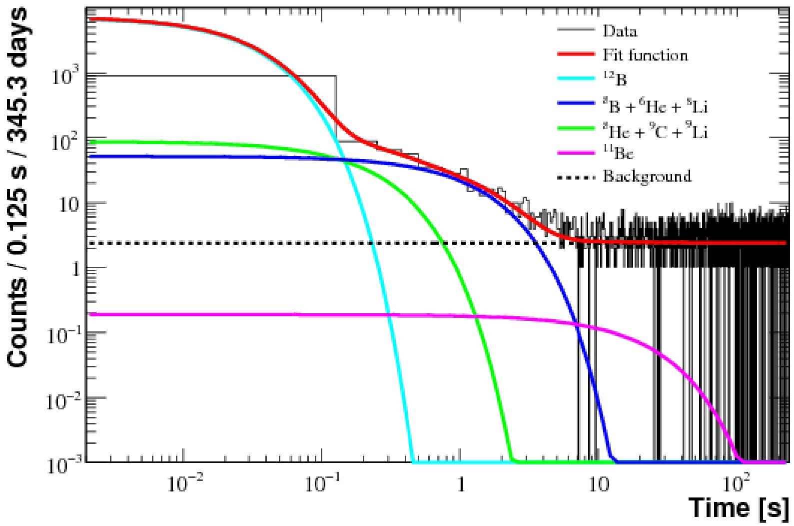
D. Franco – Milano University & INFN

Muon induced radioactive nuclides

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 ± 0.04	0.886	1.25± 0.03	1.48 ± 0.06
^{8}He	0.17 s	10.6	β^-	0.026 ± 0.012	0.898		
^{9}C	0.19 s	16.5	β^+	0.096 ± 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 ± 0.005	0.932		
^{8}B	1.11 s	18.0	β^+	0.273 ± 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 ± 0.07	0.875		
^{10}C	27.8 s	3.6	β^+	0.54 ± 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 ± 0.006	0.902	$(3.2 \pm 0.5)\times10^{-2}$	$(3.6\pm3.5)\times10^{-2}$

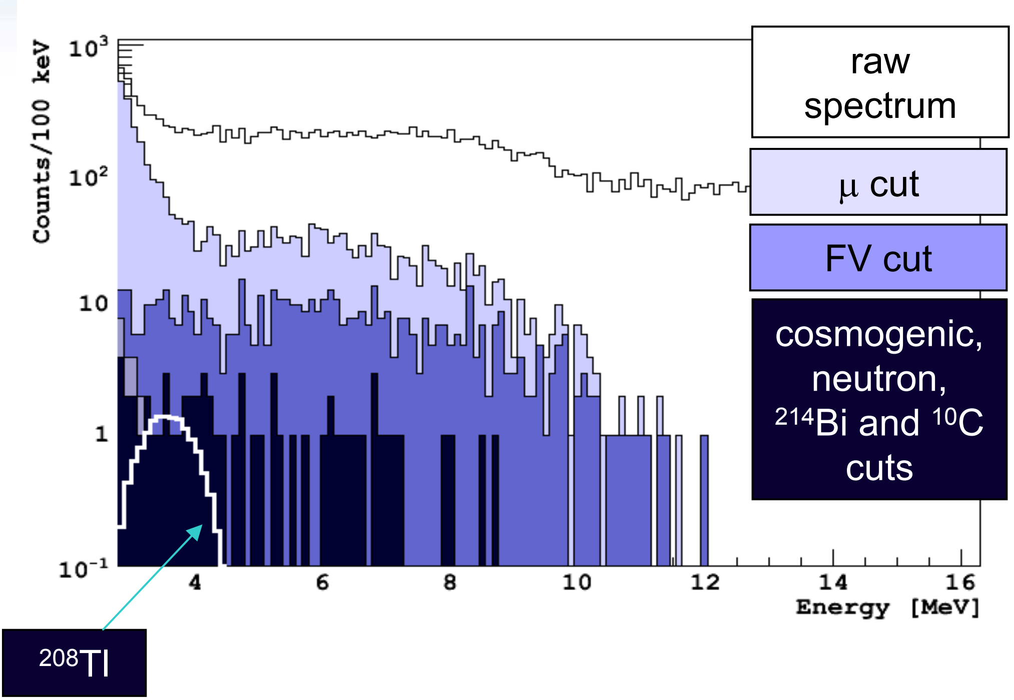
Rejection methods:

- ✓ **6.5 s detector veto after each crossing muon (29.2% dead time – livetime: 345.3 days)**
- ✓ **^{10}C is tagged with the three-fold coincidence technique with the muon parent and the neutron capture (ε = 0.74)**
- ✓ **^{11}Be is statistically subtracted**



Count-rate: 0.33 c/d/100 ton

Final spectrum

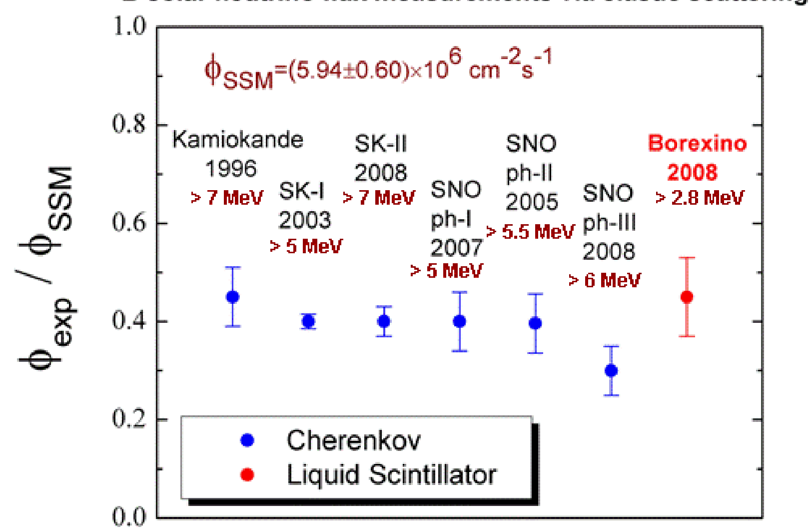


	3.0–16.3 MeV	5.0–16.3 MeV
Rate [cpd/100 t]	0.22±0.04±0.01	0.13±0.02±0.01
Φ^{ES}_{exp} [10^6 cm^{-2}s^{-1}]	2.4±0.4±0.1	2.7±0.4±0.2
$\Phi^{ES}_{exp}/\Phi^{ES}_{th}$	0.88±0.19	1.08±0.23

Systematic errors

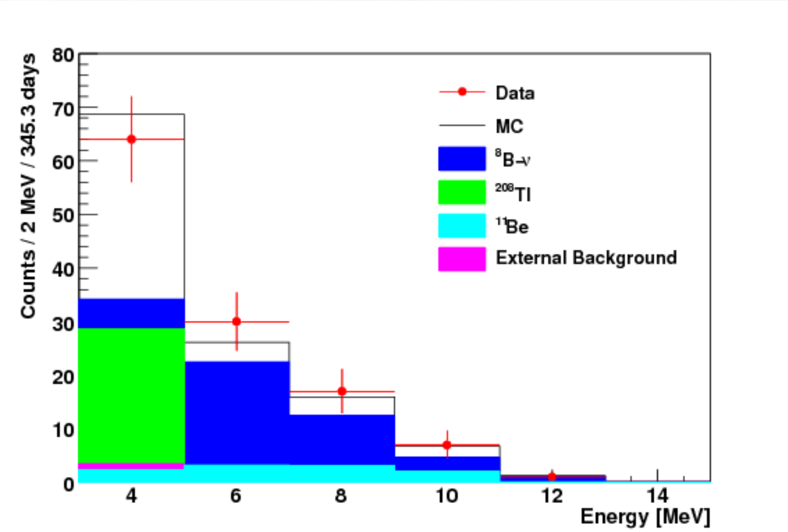
Source	E>3 MeV		E>5 MeV	
	σ_+	σ_-	σ_+	σ_-
Energy threshold	3.6%	3.2%	6.1%	4.8%
Fiducial mass	3.8%	3.8%	3.8%	3.8%
Energy resolution	0.0%	2.5%	0.0%	3.0%
Total	5.2%	5.6%	7.2%	6.8%

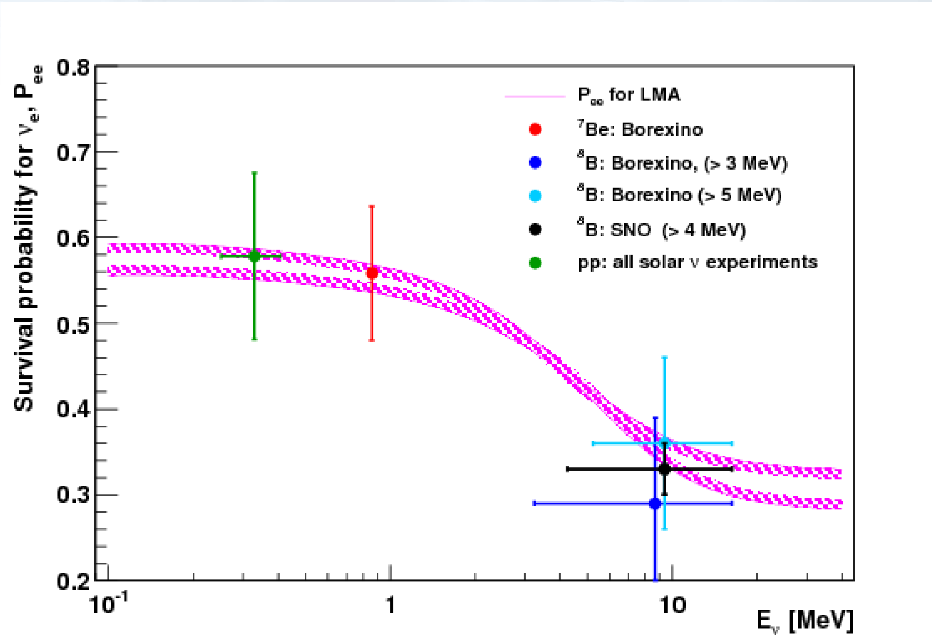
^{8}B solar neutrino flux measurements via elastic scattering

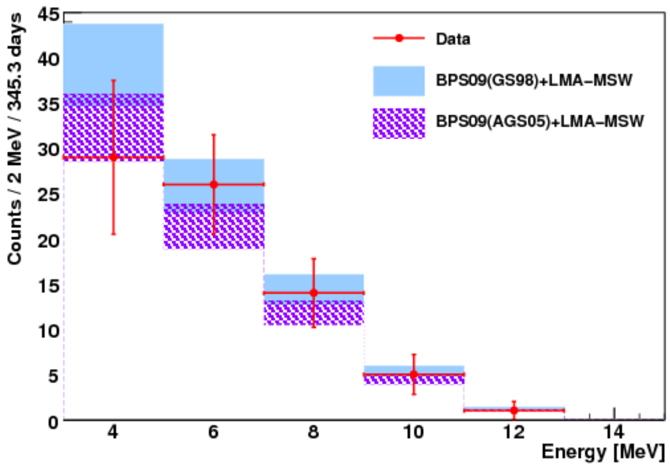


*Threshold is defined at 100% trigger efficiency

Comparison with models







First measurement of ^{8}B-ν:

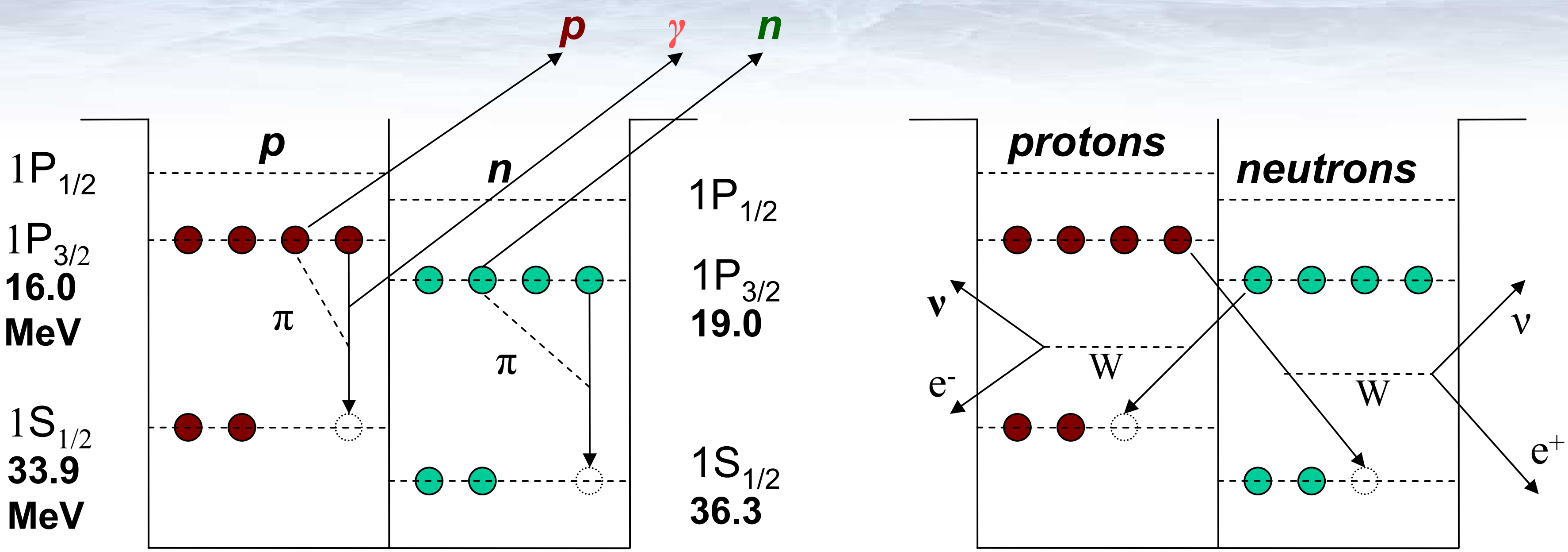
✓with liquid scintillator

✓with the lowest energy threshold for a spectral measurement

Borexino is the first experiment able to investigate simultaneously, in real time, the vacuum and matter regimes of oscillations

Accepted by Phys. Rev. D

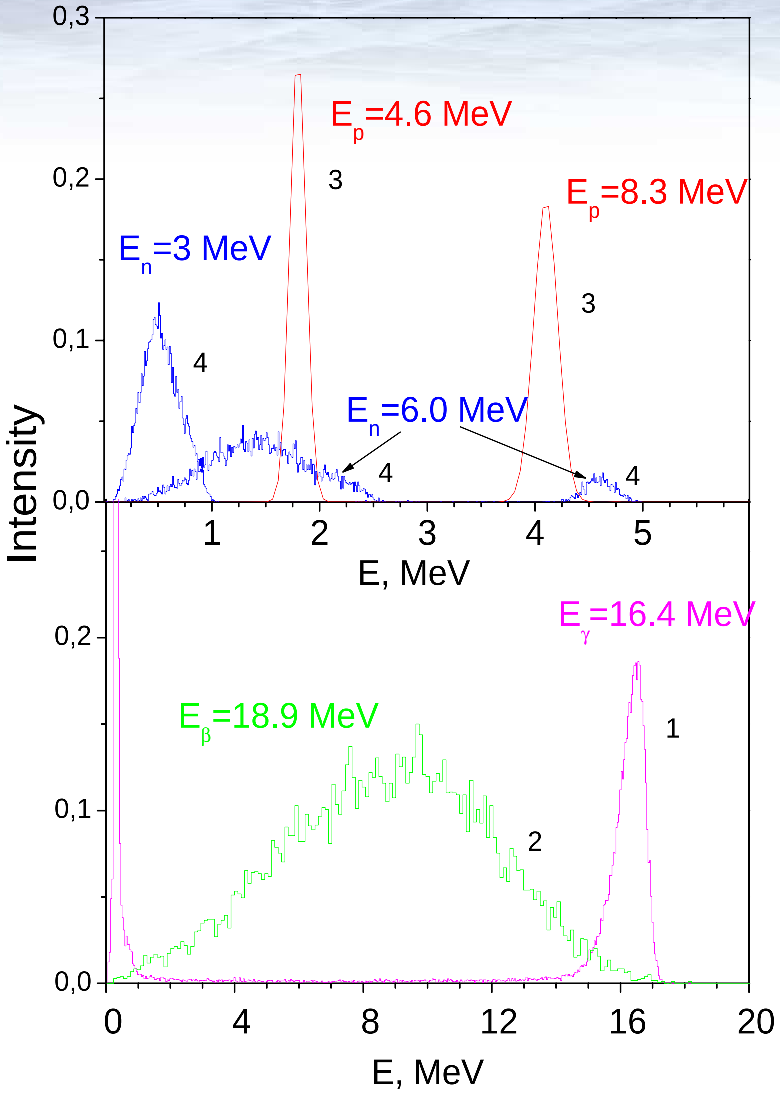
Limit on the PEP violation

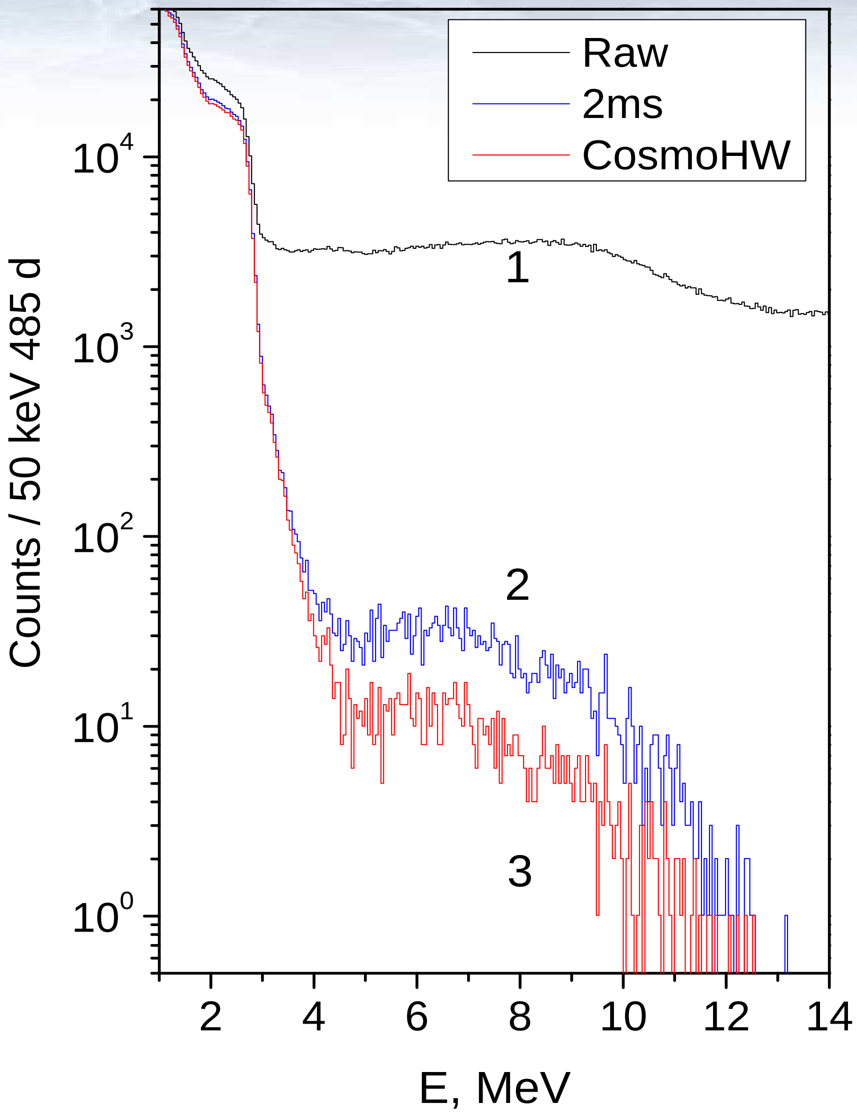


The non-Paulian (NP) transitions are searched for in ^{12}C nuclei in scintillator

Channel	Q, MeV	E, MeV	
$^{12}C \to {}^{12}C^{NP} + \gamma$	16.4÷19.4	16.4÷19.4	E.M.
$^{12}C \to {}^{11}B^{NP} + p$	5.0÷9.0	4.6÷8.3	Strong
$^{12}C \to {}^{11}C^{NP} + n$	3.5÷7.9	3.2÷7.3	
$^{12}C \to {}^{8}Be^{NP} + \alpha$	3.0÷7.0	0.07÷0.25	
$^{12}C \to {}^{12}N^{NP} + e^- + \nu$	18.9 ±2	0.0÷18.9	Weak
$^{12}C \to {}^{12}B^{NP} + e^+ + \nu$	17.8 ±2	0.0÷17.8	

Expected signals and measured spectrum





New limits obtained by Borexino

Channel	E_0, MeV	τ_{lim}, y BOREXINO	τ_{lim}, y CTF	Previous experiments and limits
$^{12}C \rightarrow {}^{12}C^{NP} + \gamma$	17.5	**$5.0 \cdot 10^{31}$**	$2.1 \cdot 10^{27}$	$4.2 \cdot 10^{24}$ NEMO-II
$^{16}O \rightarrow {}^{16}O^{NP} + \gamma$	21.8	**-**	$2.1 \cdot 10^{27}$	**$1.0 \cdot 10^{32}$** Kamiokande
$^{12}C \rightarrow {}^{11}B^{NP} + p$	4.8-8.2	**$8.9 \cdot 10^{29}$**	$5.0 \cdot 10^{26}$	$1.7 \cdot 10^{25}$ ELEGANT V. $6.9 \cdot 10^{24}$ DAMA (Na+I)
$^{12}C \rightarrow {}^{11}C^{NP} + n$	2.2	**$3.4 \cdot 10^{30}$**	$3.7 \cdot 10^{26}$	$1.0 \cdot 10^{20}$ Kishimoto et al
$^{12}C \rightarrow {}^{8}Be^{NP} + \alpha$	1.0-3.0	**-**	$6.1 \cdot 10^{23}$	-
$^{12}C \rightarrow {}^{12}N^{NP} + e^- + \nu_e$	18.9	**$3.1 \cdot 10^{30}$**	$7.6 \cdot 10^{27}$	$3.1 \cdot 10^{24}$ NEMO-II $\sim 8 \cdot 10^{27}$ LSD
$^{12}C \rightarrow {}^{12}B^{NP} + e^+ + \nu_e$	17.8	**$2.1 \cdot 10^{30}$**	$7.7 \cdot 10^{27}$	$2.6 \cdot 10^{24}$ NEMO-II

The Borexino results are 3-4 orders of magnitude stronger then CTF ones

Limits for NP transitions in ^{12}C with p-,n- and $\beta^{\pm}$- emissions are the best to date

The relative strength of the NP transitions to the Normal Transitions

Channel	λ^{NP}, s^{-1}(^{12}C)	$\Gamma^{NT} = \hbar\lambda^{NT}$	λ^{NT}, s^{-1}(^{12}C)	$\lambda^{NP}/\lambda^{NT}$	Previous
$^{12}C \to {}^{12}C^{NP} + \gamma$	$5.0 \cdot 10^{-39}$	0.0015 MeV	$2.3 \cdot 10^{18}$	$\leq$ **$2.2 \cdot 10^{-57}$**	$\leq$ **$2.3 \cdot 10^{-57}$**
$^{12}C \to {}^{11}B(C)^{NP} + p(n)$	$7.4 \cdot 10^{-38}$	12 MeV	$1.8 \cdot 10^{22}$	$\leq$ **$4.1 \cdot 10^{-60}$**	$\leq 3.5 \cdot 10^{-55}$
$^{12}C \to {}^{12}N(B)^{NP} + e^{\pm} + \nu$	$4.1 \cdot 10^{-38}$	$1.4 \cdot 10^{-18}$ eV	$2.0 \cdot 10^{-3}$	$\leq$ **$2.1 \cdot 10^{-35}$**	$\leq 6.5 \cdot 10^{-34}$

The decay width of nuclear E1 γ-transition from P- to S-shell given by the Weisskopf estimate is **$\Gamma_\gamma \sim$ 1.5 keV**. The ratio $\lambda^{NP}/\lambda^{NT}$ is less then **$2.2 \cdot 10^{-57}$** (90% c.l.)

The width of hadrons emission is 2-3 orders larger width of γ-transition. The measured width of S-hole state in ^{12}C is **$\Gamma_h \approx$ 12 MeV**. The detection of ***p*** or ***n*** gives a more stringent limit on the relative strength of NP transitions then the detection of **γ's** if one can set a similar limit on the lifetime for both decays. The obtained limit is $\lambda^{NP}/\lambda^{NT} \leq$ **$4.1 \cdot 10^{-60}$.**

The NP β± -transitions are first-order forbidden P→S transitions. The log(ft) values for such first forbidden transitions range from 6 to 9, conservative value (9) corresponds to life-time **$\tau_\beta \sim$ 500** and level width **$\Gamma_\beta = \hbar\lambda = \hbar/\tau = 1.4 \cdot 10^{-18}$ eV**, so $\lambda^{NP}/\lambda^{NT} \leq$ **$2.1 \cdot 10^{-35}$**

Phys. Rev. C81:034317,2010

Borexino Monte Carlo

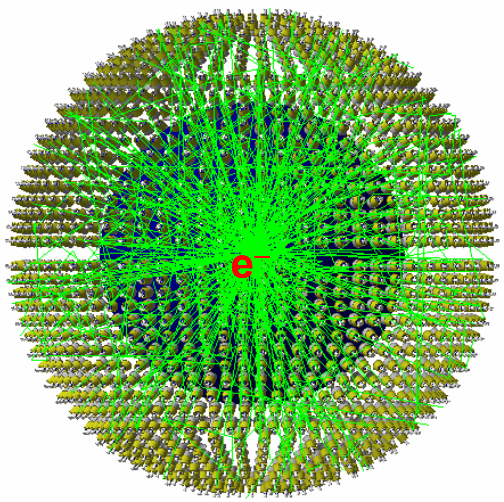
Geant4-based Tracking Code: G4Bx + electronic simulation (BxElec)

15 event generators
- ✓Solar neutrinos
- ✓Cosmic muons
- ✓Neutrons from the rock
- ✓Neutrinos from CNGS
- ✓ Muon cascades from FLUKA
- ✓…

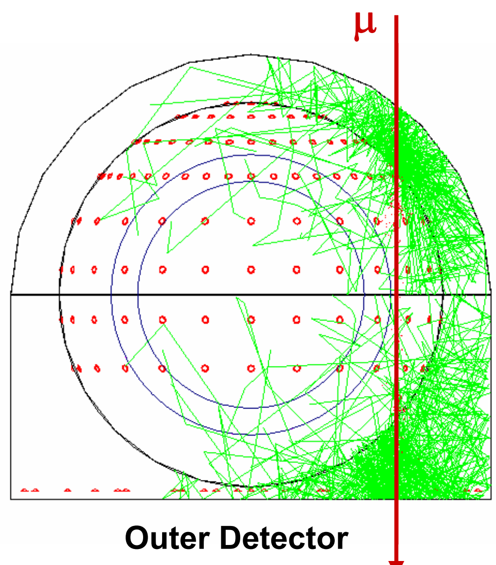
Physics
- ✓Electromagnetic interaction
- ✓Optical processes
- ✓Hadronic processes
- ✓Isotope production

Geometry and materials
- ✓Inner and outer detectors
- ✓Surrounding rocks

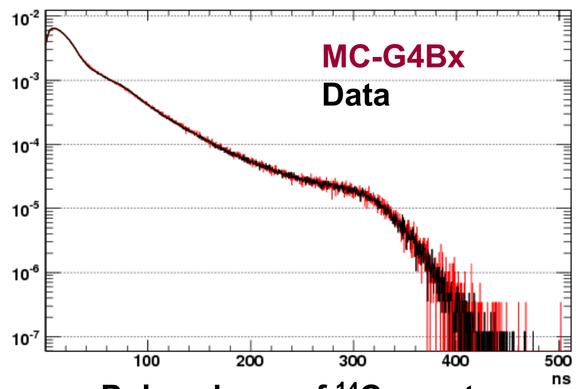
Each photon is tracked!



Inner Detector



Outer Detector



Pulse shape of ^{14}C events

1% accuracy in reproducing the **energy** scale in the detector center

3% accuracy in **light propagation**

Fine-tuning is ongoing!

Calibrations

Detector response vs position:

✓100 Hz ^{14}C+^{222}Rn in scintillator in >100 positions

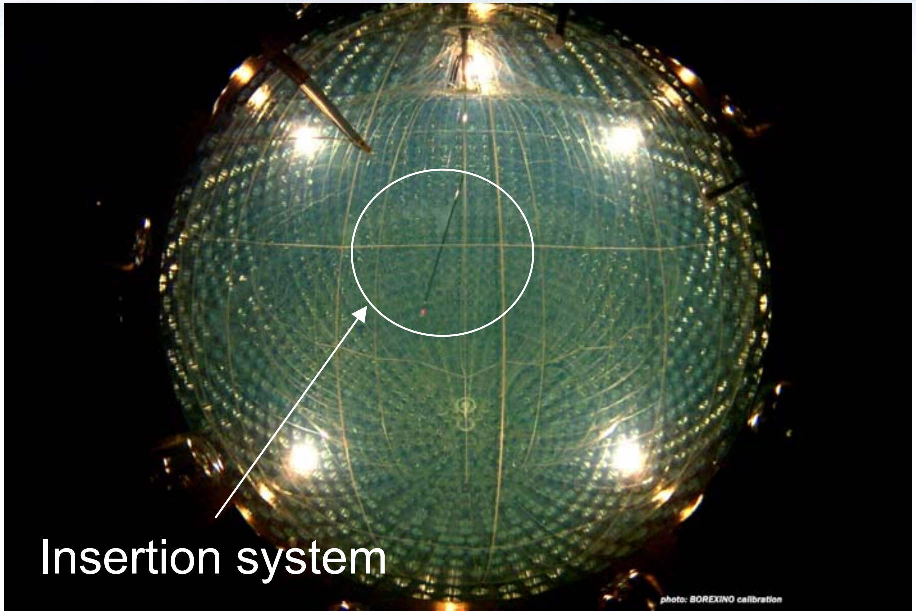
Quenching and energy scale:

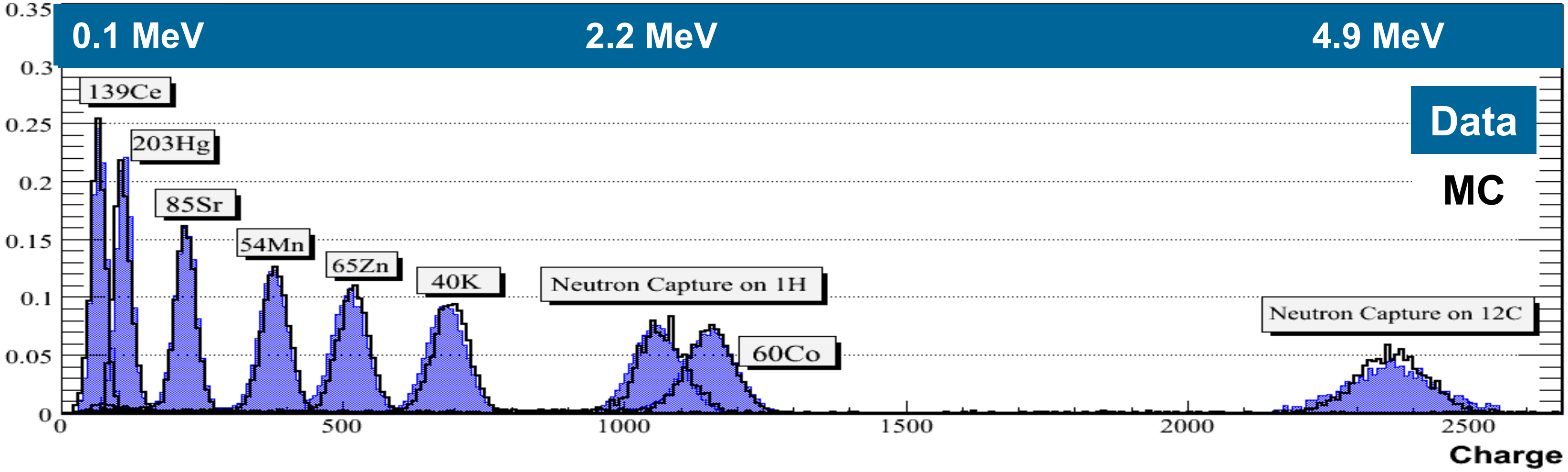
✓Beta: ^{14}C, ^{222}Rn in scintillator

✓Alpha: ^{222}Rn in scintillator

✓Gamma: ^{139}Ce, ^{57}Co, ^{60}Co, ^{203}Hg, ^{65}Zn, ^{40}K, ^{85}Sr, ^{54}Mn

✓Neutron: AmBe

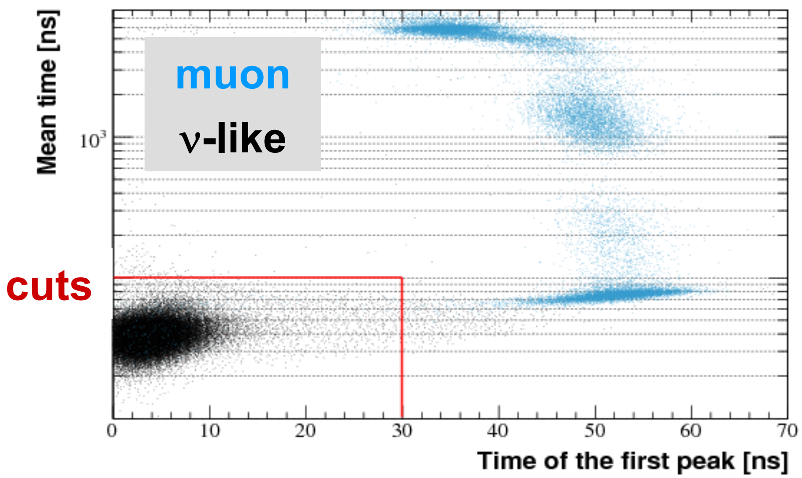


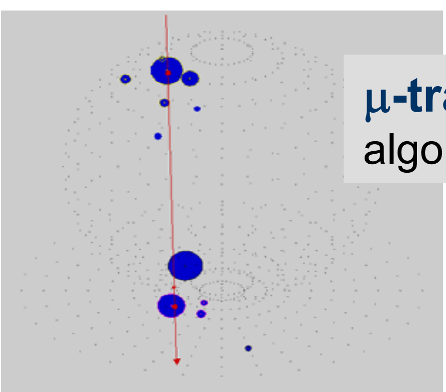


Muons and cosmogenics

Muons

- ✓ μ identified by ID and OD
- ✓ ID based on pulse shape analysis
- ✓ Rejection factor: > 10^3 (conservative)

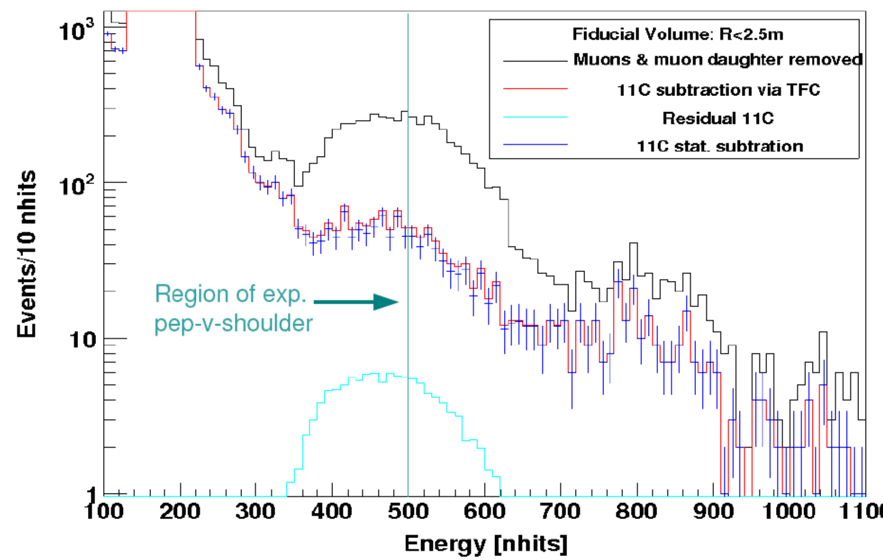




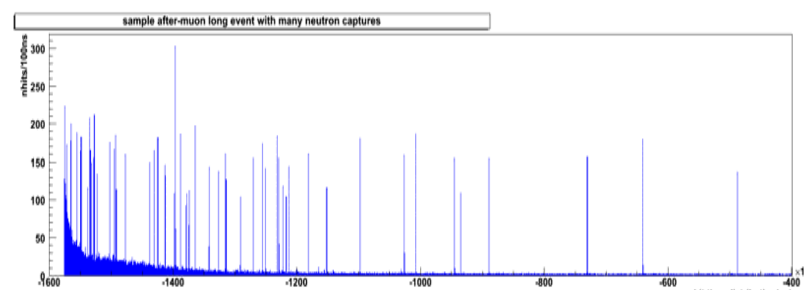
μ-track reconstruction algorithm finalized

Cosmogenic isotopes

- ✓ Estimation of cosmogenic isotope production rates
- ✓ ^{11}C is rejected with the TFC (~80%)

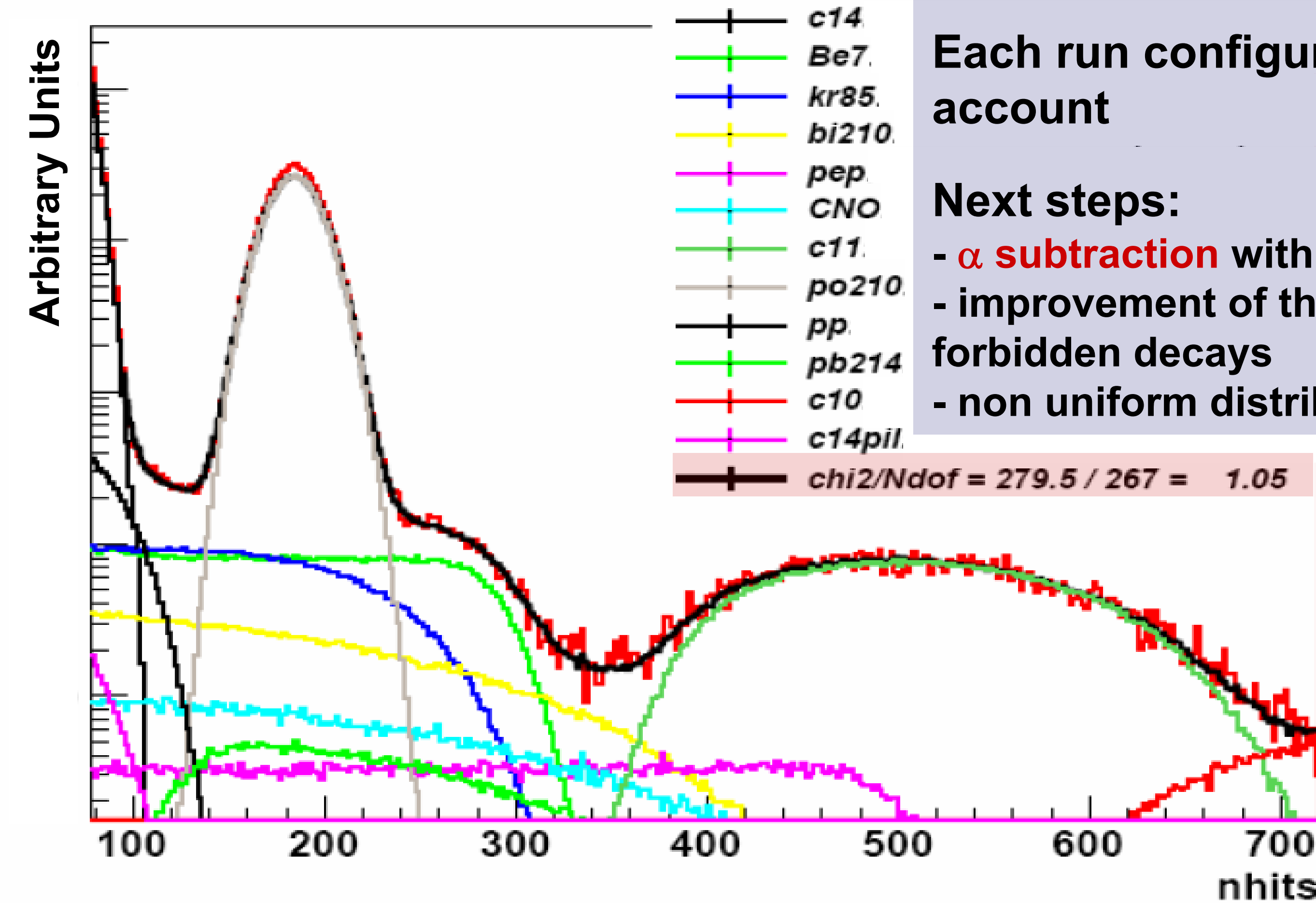


High efficiency in neutron tagging



^{7}Be-ν analysis with MC spectra

Goal: accuracy at 5% or better



Free new parameters in the fit:
pep, pp, CNO (?)
fit up to 16.3 MeV (?)

Each run configuration is taken into account

Next steps:
- α subtraction with MC
- improvement of the spectral shapes of forbidden decays
- non uniform distribution of ^{210}Po events

Next step: purifications

- ✓ **Upgraded distillation system** (2/3 by Princeton and 1/3 by INFN) is under construction to potential the PPO purification
- ✓ R&D for **purification in loop**
- ✓ We are evaluating if starting to purify with water extraction or waiting for the new distillation plant
- ✓ **Leak:** DMP removed from the buffer and vessel stability reached. We are evaluating if we can avoid any refilling on a long term period (4 years)

Borexino data taking is not over!

High Borexino data statistics can provide promising results

Conclusions

3 physics papers since October 2009:

- ✓ Observation of **Geo-Neutrinos** at 4.2 sigmas
- ✓ First spectral measurement of **^{8}B neutrinos** flux in scintillator and with 3 MeV threshold
- ✓ Best limit on **Pauli Exclusion Principle** with violating nuclear transitions

4 papers in preparation, demonstrating our accurate understanding of the detector

- ✓ ^{7}Be analysis
- ✓ Monte Carlo development
- ✓ Calibrations
- ✓ Muons and cosmogenics