Geoneutrino flux measurement with Borexino detector

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on behalf of Borexino collaboration

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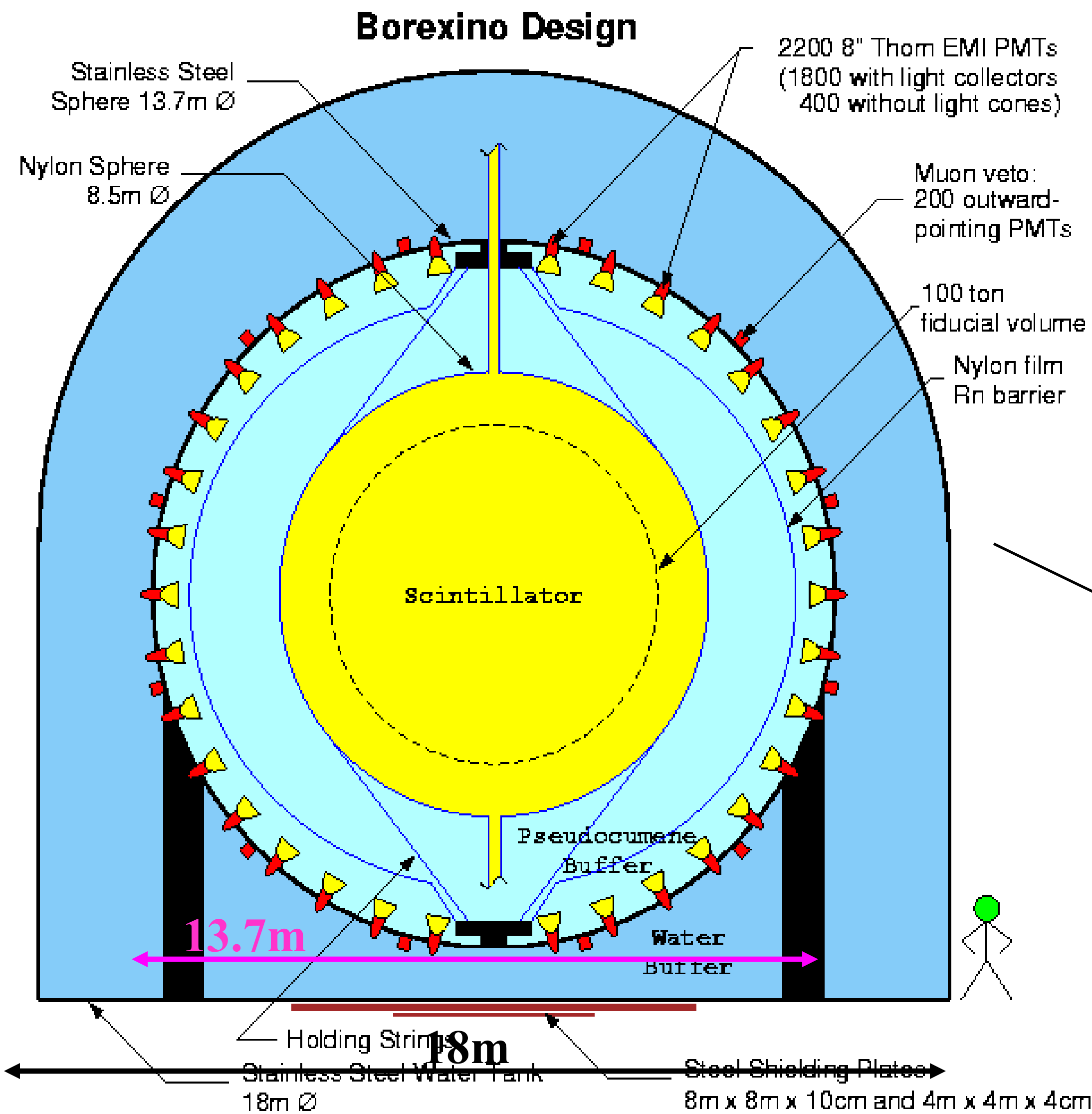
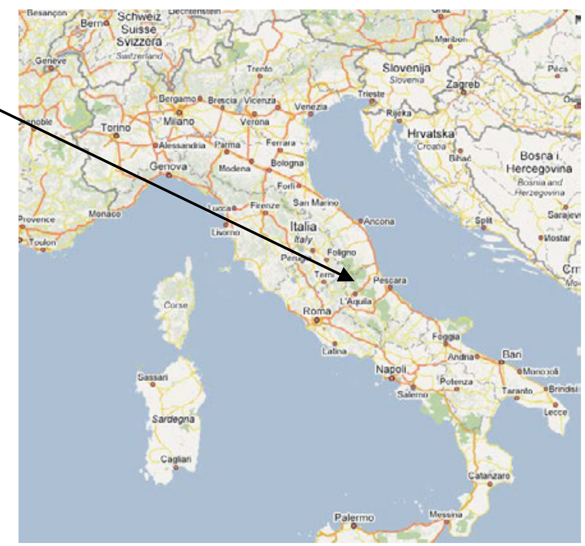
BOREXINO started data taking in 2007



- 278 t of liquid organic scintillator PC + PPO (1.5 g/l)
- (ν,e)-scattering with 200 keV threshold
- Outer muon detector



Borexino status

Acquires data non-stop from May 2007;
(problems with muons identification up to december; potential contamination of the data sample with muons daughter – excluded from all analyses)

now in Phase-II (after the calibration campaign and repurification)

Extremely clean LS and well-designed protection against external backgrounds

Far away from european nuclear power plants (~1000 km average distance): only 36 % of the total antineutrino signal in geo-nu window [0.9-2.6 MeV] Geo/Reactor ratio is 1.8 in Borexino;

Last analysis of geoneutrino:
~5½ years (Dec 15, 2007-Mar 8, 2015)
2056 days of live time in total.
1841.9 days after the muons cut

Liquid Scintillator Radiopurity

Isotope	Typical abundance (source)	Borexino goals	Borexino-I	Borexino-II
^{14}C / ^{12}C, g/g	10^{-12} (cosmogenic)	~10^{-18}	$2.7 \cdot 10^{-18}$	$2.7 \cdot 10^{-18}$
^{238}U, g/g (^{214}Bi-^{214}Po)	10^{-6}-10^{-5} (dust)	~10^{-16} (1 μBq /t)	$(1.6 \pm 0.1) \cdot 10^{-17}$	<$9.7 \cdot 10^{-19}$ (95%)
^{232}Th, g/g (^{212}Bi-^{212}Po)	10^{-6}-10^{-5} (dust)	~10^{-16}	$(6.8 \pm 1.5) \cdot 10^{-18}$	<$1.2 \cdot 10^{-18}$ (95%)
^{222}Rn (^{238}U), ev/d/100 t	100 atoms/cm^3 (air)	10	1	0.1
^{40}K, g[K_{nat}]/g	$2 \cdot 10^{-6}$ (dust)	~10^{-15}	<$1.7 \cdot 10^{-15}$ (95%)	---
^{210}Po, ev//d/t	Surface contamination	~10^{-2}	80 (initial), $T_{1/2}$=134 days;	2
^{210}Bi, ev/d/100 t	In equilibrium with ^{222}Rn or ^{210}Pb	Not specified	20-70	~20
^{85}Kr ev/d/100 t	1 Bq/m^3 (technogenic, air)	~1	30.4±5 cpd/100t	<5 (90% C.L.) compatible with 0
^{39}Ar ev/d/100 t	17 mBq/m^3 (cosmogenic in air)	~1	<<^{85}Kr	<<^{85}Kr

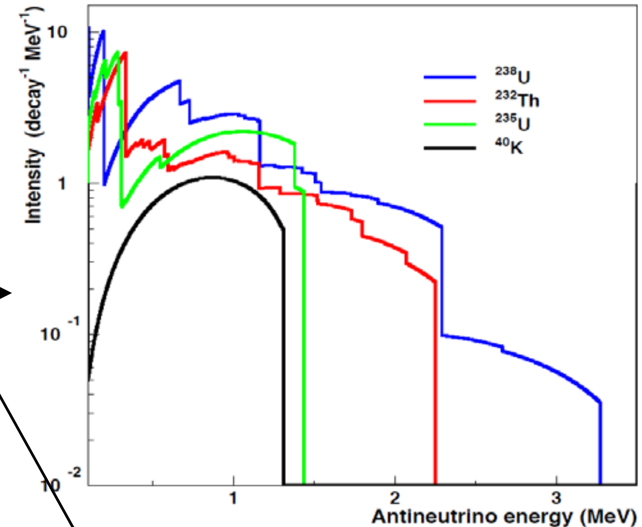
Detection of geo(anti)neutrino

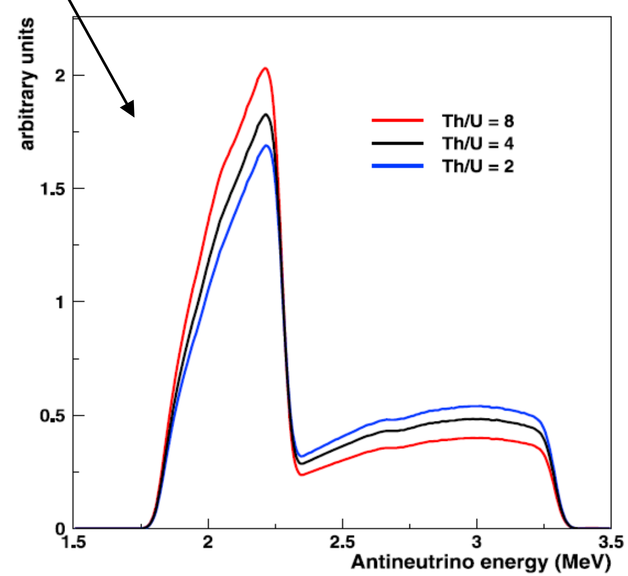
- Earth (in constrast to the Sun) emits antineutrino. $\Phi_{\bar{\nu}} \sim 10^{6}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$
- Part of antineutrino in the U and Th decay chains is emitted with E>1.8 MeV (IBD threshold)
- Contributions from U and Th are distinguishable
- Oscillations are averaged:

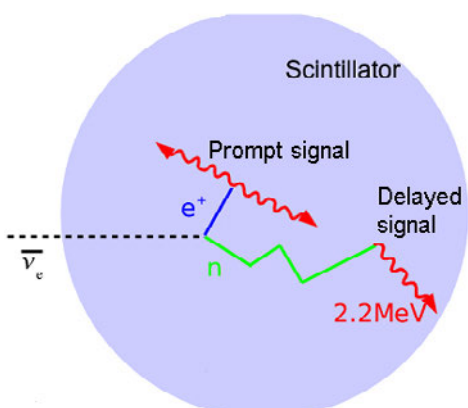
$$\bar{\nu} + p \rightarrow n + e^{+}$$

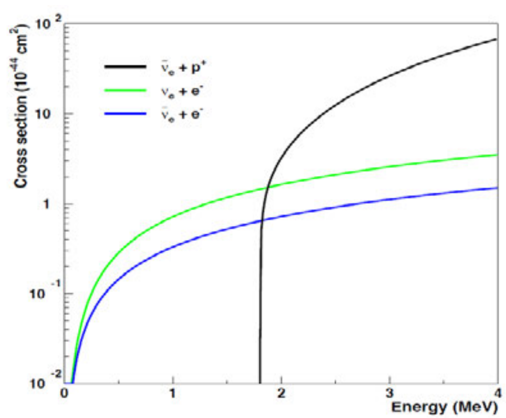
$\langle Pee \rangle = 0.548^{+0.012}_{-0.013}$

$E_\nu > 1.8$ MeV



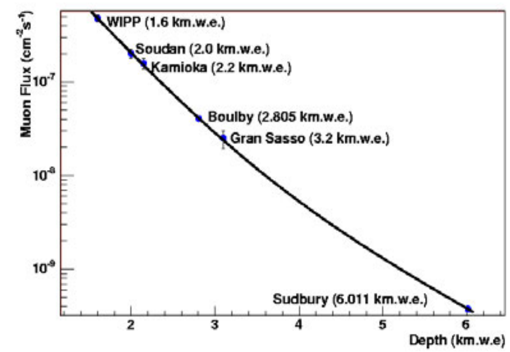




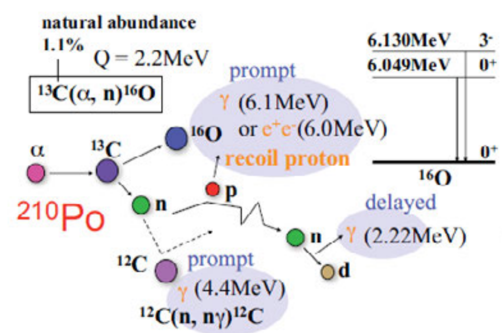


Main backgrounds in geo-neutrino measurements

1)Reactor antineutrinos (81% of the total antineutrino signal in KamLAND geo-nu window [0.9-2.6 MeV] and ~36% for the Borexino case): Geo/Reactor ratio 0.23 in KL vs 1.8 in Borexino;



2)Cosmic muons induced backgrounds, including cosmogenic production of (βn)-decaying isotopes (at LNGS the muons flux is of about factor 7 lower than at the Kamioka site)



3)Internal radioactive contamination: accidental coincidences, (αn) reactions

Data selection for geo-neutrino analysis

- **Total exposition is 907±44 t·yr taking into account detection efficiency**
- **Antineutrino are detected using delayed coincidence tag from the inverse beta- decay on proton (~256 μs)**

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

$$\downarrow \approx 250\ \mu s$$

$$n + p \rightarrow d + \gamma(2.2MeV)$$

- **~500 p.e./MeV for electrons**
- **438 p.e./2 x 511 keV γ's**

Set of antineutrino cuts

1. $Q_{prompt}>408$ p.e.   : $3\sigma(E)$ above $2m_e$
2. $860 < Q_{delayed} < 1300$ p.e
3. $\Delta R < 1$ m;
4. $20 < \Delta t < 1280$ μs

tuned to select maximum of correlated events in space and time with max. suppression of acc.coincidences

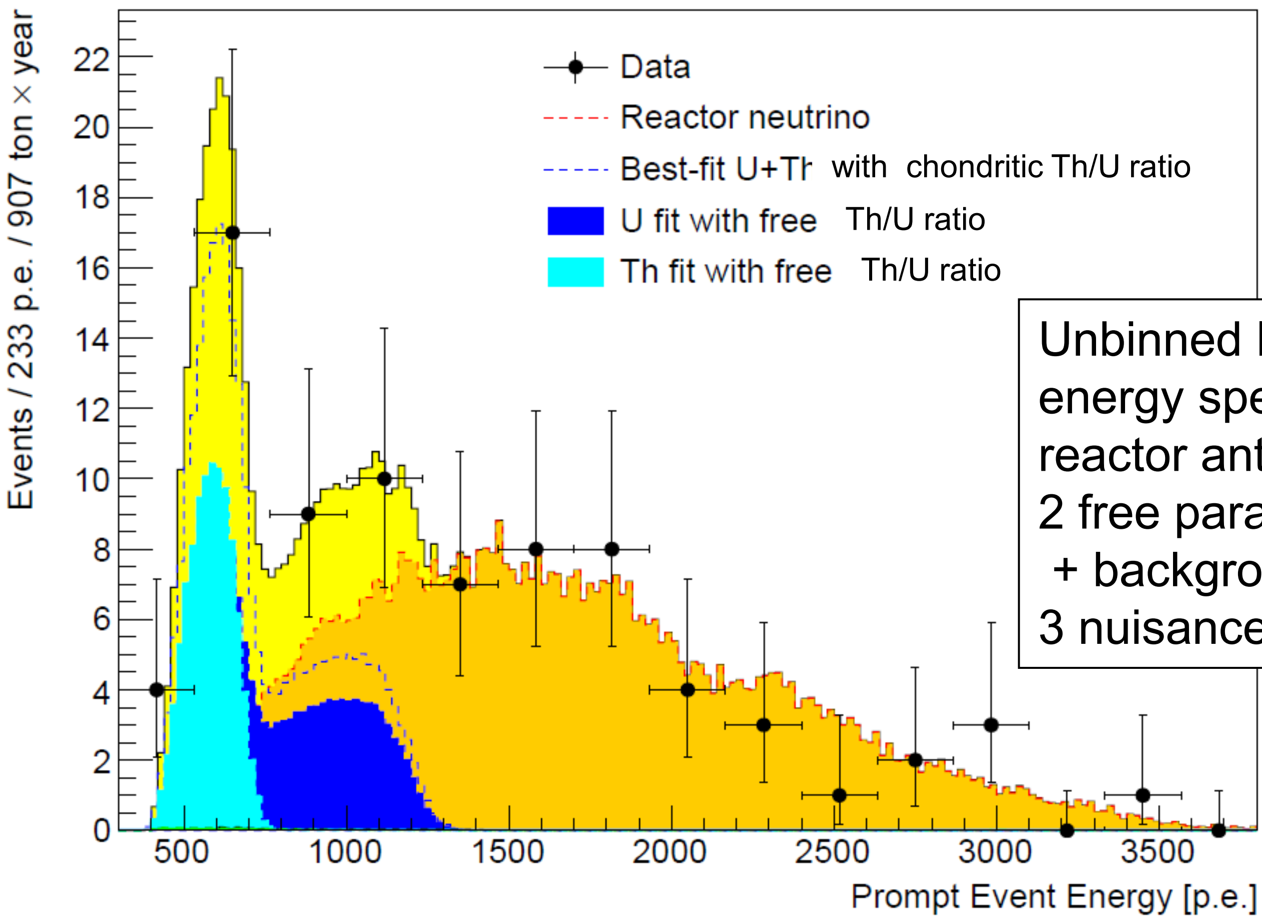
5. **Pulse shape. $g_{\alpha\beta}$(delayed)<0.015 : selecting e-like events (prompt signal from fast n is α-like)**
6. **$T_\mu > 2$ ms : fast neutrons after muon**
7. **$T_\mu > 2$ s** for every muon passing through internal detector. Long-lived cosmogenic (βn) isotopes. ~10% of live time loss.
8. **Multiplicity cut: no n-like events in ±2 ms window**
9. **$R_{IV}(\Theta,\varphi)-R_{prompt}(\Theta,\varphi)>0.30$ m : dynamical, follows IV shape**
10. **FADC cut : independent check of candidates features with 400 MHz digitizing system**

Total efficiency=84.2±1.5% (MC). 77 candidates selected

Summary of backgrounds

Source	events
Cosmogenic ^{9}Li and ^{8}He	$0.194 \pm 0.015(stat)^{+0.124}_{-0.088}$ (syst)
Fast neutrons from μ in Water Tank	< 0.01 (90% CL) (measured)
Fast neutrons from μ in rock	< 0.43 (90% CL) (MC)
Non-identified muons	0.12 ± 0.01
Accidental coincidences	0.221 ± 0.004
Time correlated background	$0.035 \pm 0.028(stat)^{+0.006}_{-0.004}$ (syst)
Spontaneous fission in PMTs	0.032 ± 0.003
(α,n) reactions in the scintillator [^{210}Po]	0.165 ± 0.010 (stat)
(α,n) reactions in the buffer [^{210}Po]	< 0.66 (90% CL)
^{214}Bi-^{214}Po	0.009±0.013
TOTAL	$0.78^{+0.13}_{-0.10}$

Selected antineutrino spectrum (77 events)



Unbinned likelihood fit using MC energy spectra for geo and the reactor antineutrinos
2 free parameters S_{geo} and S_{react}
+ backgrounds:
3 nuisance pars S_{LiH}, $S_{\alpha n}$ and S_{acc}

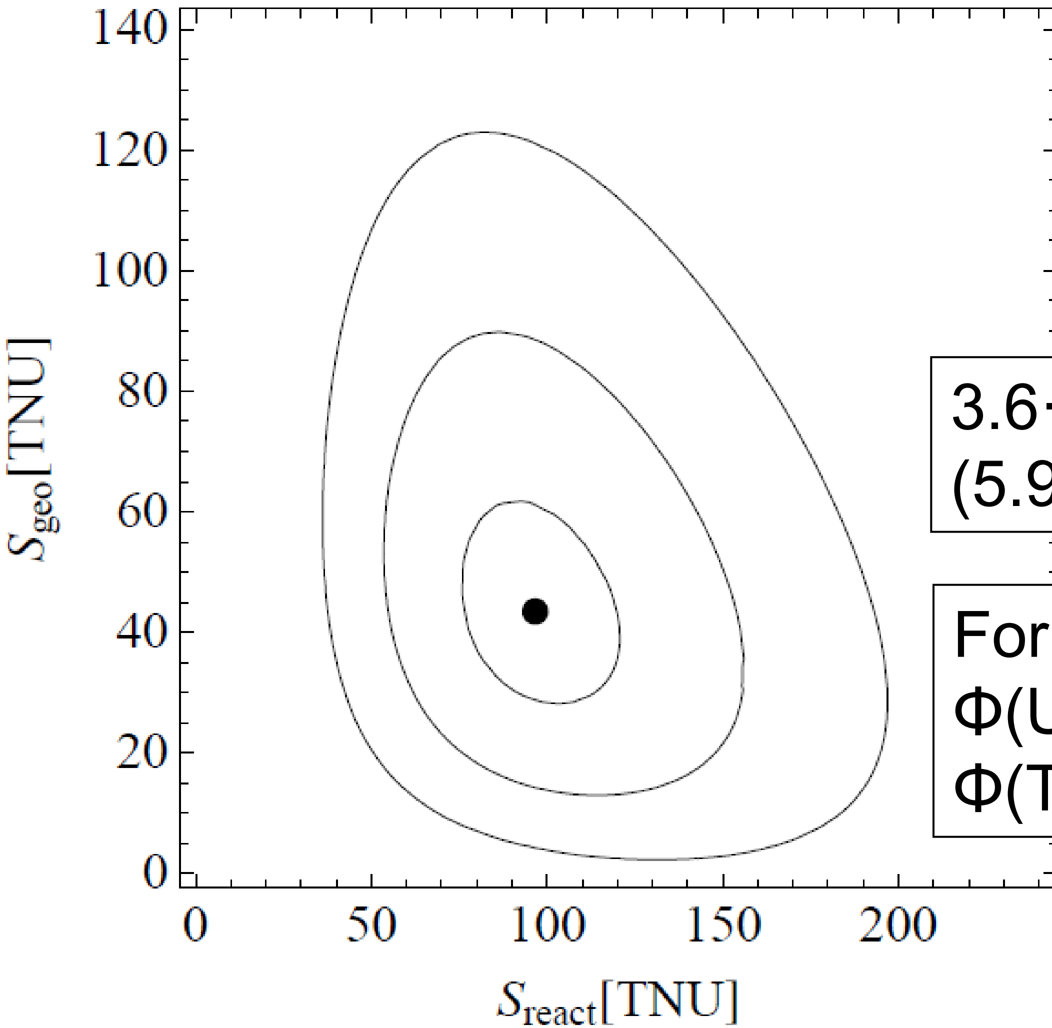
$$Q_{vis} = 438\, p.e.(2\gamma) + Q(E_{\bar{\nu}} - 1.8 MeV)$$

~500 p.e./MeV

Fit results

- Predicted reactor signal 87±4 TNU
- $N_{geo}=23.7^{+6.4}_{-5.7}(stat)^{+0.9}_{-0.6}(syst)$ events
  $S_{geo}=43.5^{+11.8}_{-10.4}(stat)^{+2.7}_{-2.4}(syst)$ TNU
- $N_{react}=52.6^{+8.5}_{-7.7}(stat)^{+0.7}_{-0.9}(syst)$ events
  $S_{react}=96.5^{+15.6}_{-14.2}(stat)^{+4.9}_{-5.0}(syst)$ TNU
- Systematics: 4.8% on FV and 1% on the energy scale

S_{geo}:S_{react} for fixed Th/U=3.9



$3.6 \cdot 10^{-9}$ probability of N_{geo}=0 (5.9 σ)

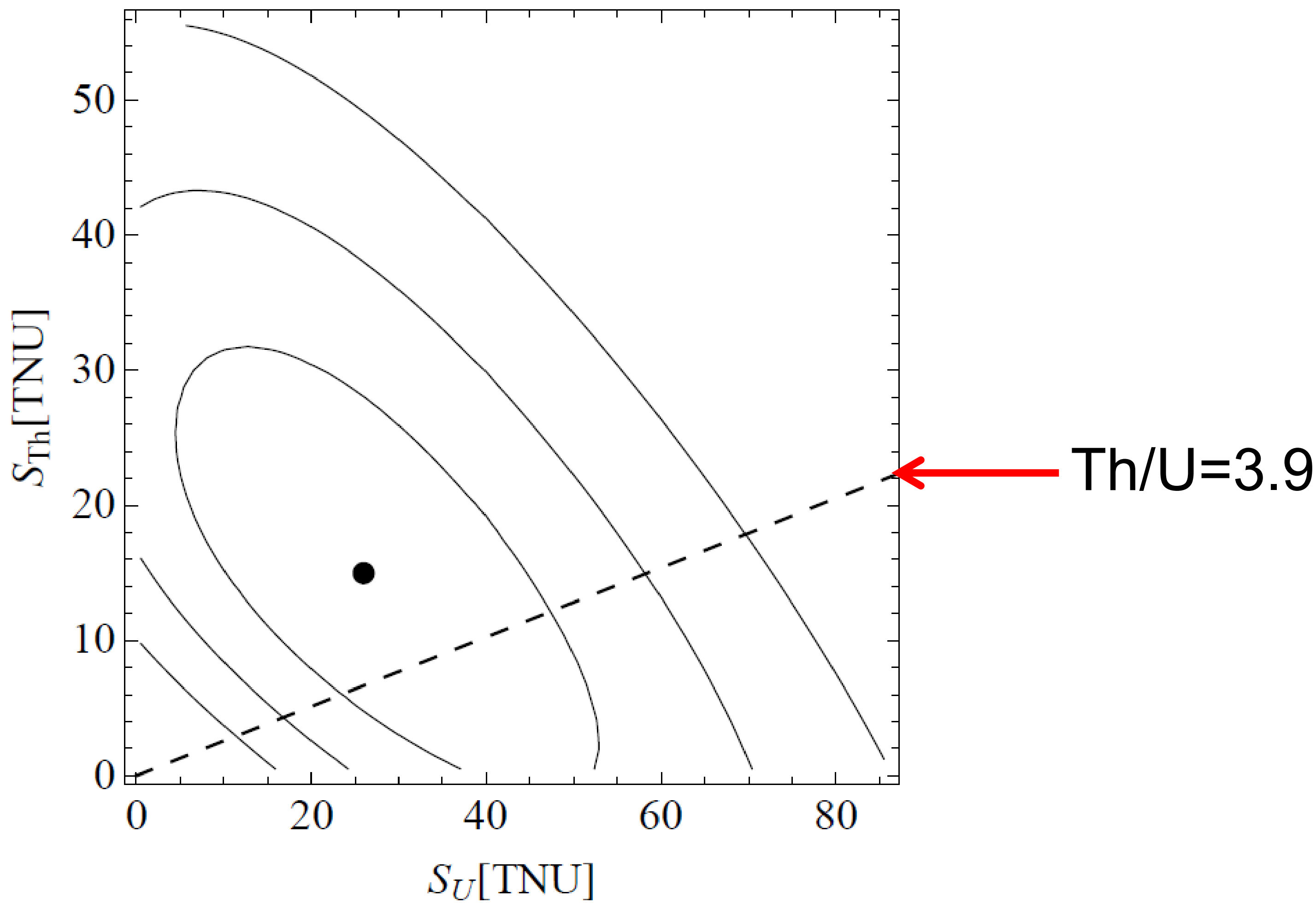
For Th/U=3.9 :

$\Phi(U)=(2.7^{+0.8}_{-0.7})\times10^{6}\ cm^{-2}s^{-1}$

$\Phi(Th)=(2.3^{+0.7}_{-0.6})\times10^{6}\ cm^{-2}s^{-1}$

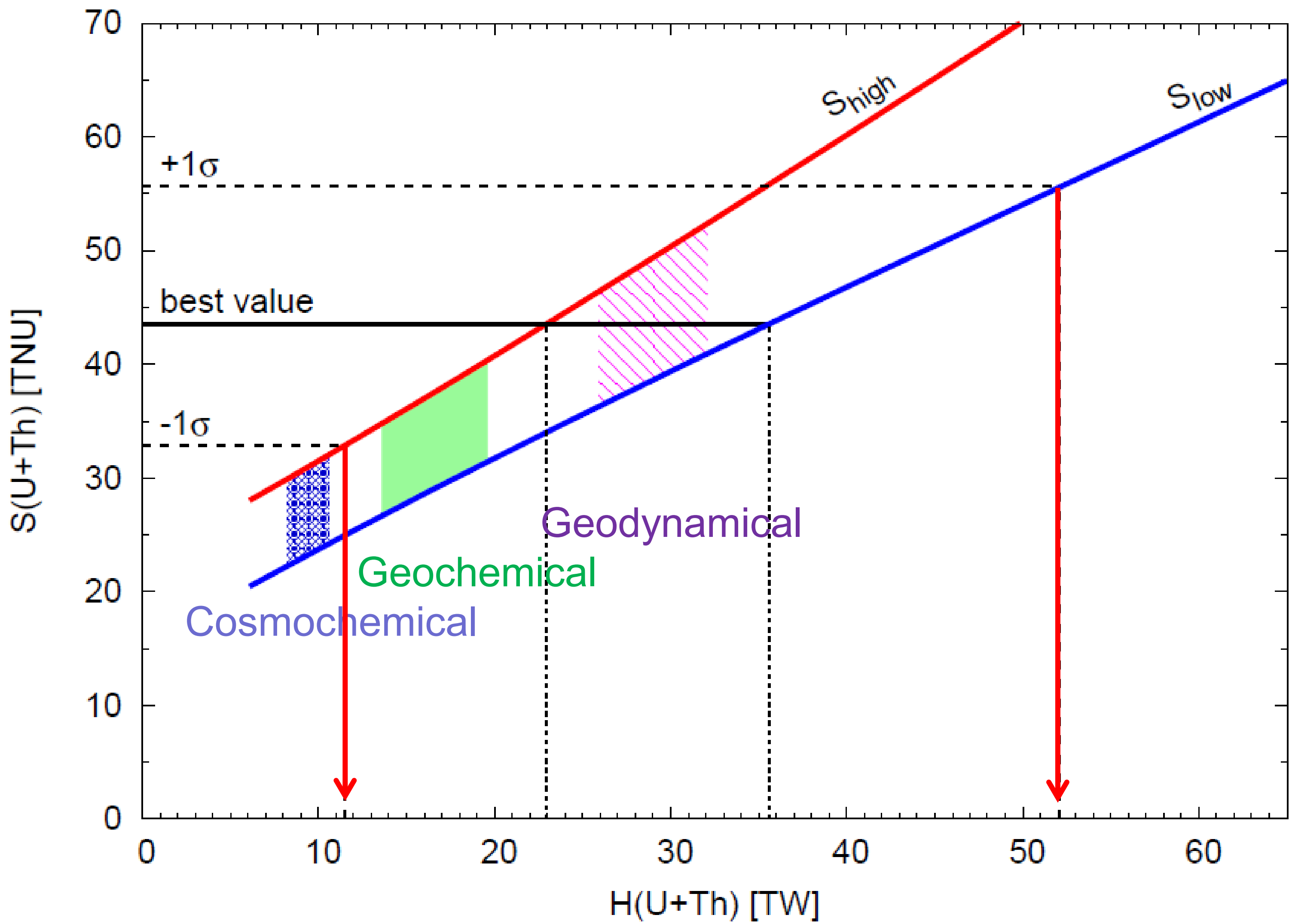
1,3 and 5 σ contours for S_{geo}:S_{react} signals

Unconstrained U/Th analysis



1,2 and 3 σ contours for S_U:S_{Th} signals

Radiogenic heat



Signal from the mantle

- ***Total contribution from the Earth crust (*****Huang et al.)** ***(LOC + ROC) is S_{geo}(Crust) = (23.4 ± 2.8) TNU -> 12.75 ±1.53 events (+stat.smearing)***

- **subtraction of probability distributions for the total signal (from the fit) and pdf for crust (normal approximation). Non-physical values of difference are excluded and final p.d.f. renormalized to unity.**

p.d.f.(Mantle)=p.d.f. (Geo)-p.d.f.(Crust) :

$$S_{geo}(Mantle) = 20.9^{+15.1}_{-10.3}\ \mathrm{TNU}$$

with a probability of 98% we observe at least 1 event from the mantle

- Note:
  - Mean value is bigger compared to a simple difference $<S_{geo}>-<S(Crust)>$=43.5-23.5=20.1 as a result of excluding non-physical values from p.d.f.

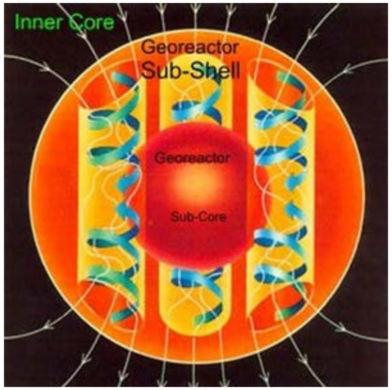
Antineutrino measurements with Borexino

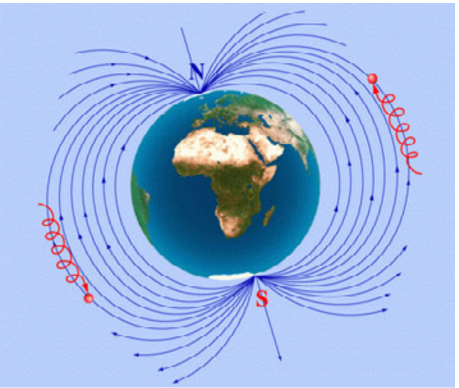
Year	Live time, days	Exposition t·yr	N_{cand}	N_{geo}	S_{geo} TNU	P(0)
2010	537.2	252.6	21	$9.9^{+4.1}_{-3.4}$	$65.2^{+27.0}_{-22.4}$	$3\cdot10^{-5}$ (4.2σ)
2013	1363	613 ± 26	46	14.3±4.4	38.8±12.0	$6\cdot10^{-6}$ (4.9σ)
2015	2056	**907±44**	77	$23.7^{+6.5}_{-5.7}$	$43.5^{+12.1}_{-10.7}$	$3.6\cdot10^{-9}$ (5.9σ)

2010)G. Bellini, et al. Phys. Lett. B 687 (2010) 299
2013)G. Bellini, et al. Phys. Lett. B 722 (2013) 295
2015)M. Agostini, et al, Phys. Rev. D 92, 031101 (2015)

The uranium isotopes found at Oklo strongly resemble those in the spent nuclear fuel generated by today's nuclear power plants.

Georeactor

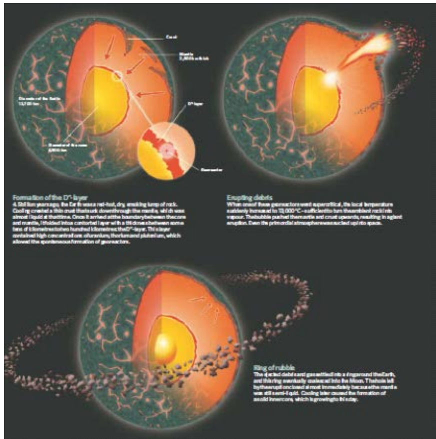




- **In the core (Herndon) on the core/mantle border (Rusov и de Meijer)**
- **5-10 TW will help to explain heating, convection, He3 anomaly, geomegnetism and some other problems.**
- **Both are critisized by geochemists**
- **Easy to test with geoneutrinos, Borexino excludes georeactor with 4.5 TW power at 95% C.L.**

Forming the Moon from a geo-reactor at the core-mantle boundary 4.5 Ga

Forming the Moon from terrestrial silicate-rich material (2013)
R.J. de Meijer, V.F. Anisichkin, W. van Westrenen



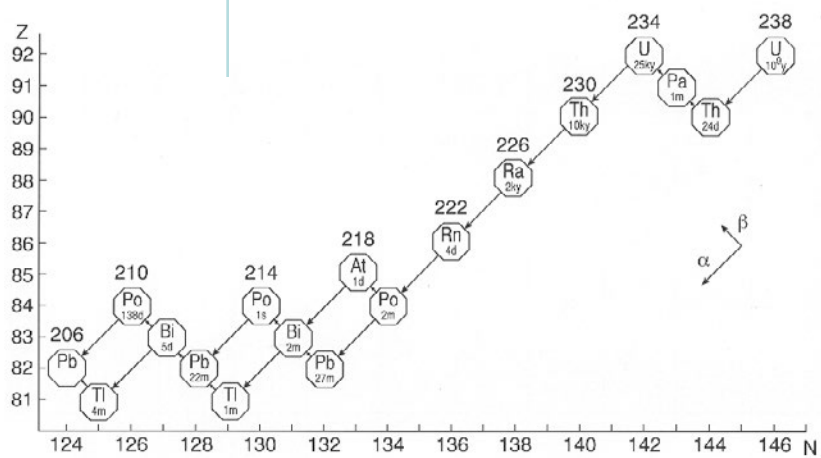
Another measurement with Borexino?

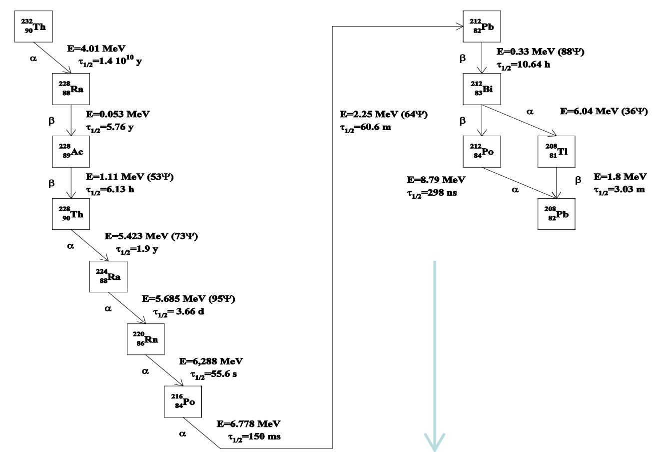
- We have accumulated another ~1.5 yrs of data and will run at least 1 yr more in solar mode before SOX program (+ ~50% statistics)
- Tuning of the muon-veto cut will save 9% of live-time
- We consider the possibility to perform a spectral fit in all volume (+ ~50%)
- Better understanding of “external” background” is needed

Nuclear physics for geoneutrino studies

Contribution of elements from U and Th chains in total geoneutrino signal

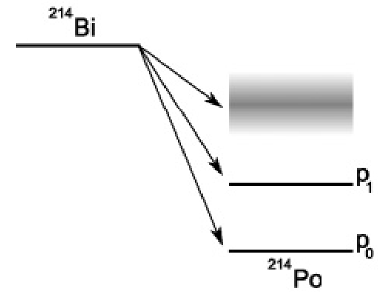
$i \to j$	$R_{i,j}$	E_{max} (keV)	I_k	ΔI_k	Type (%)	S_U (%)	S_{tot}
$^{234}Pa_m \to {}^{234}U$	**0.9984**	**2268.92**	**0.9836**	**0.002**	**first forbidden $(0^-) \to 0^+$**	**39.62**	**31.21**
$^{214}Bi \to {}^{214}Po$	**0.9998**	**3272.00**	**0.182**	**0.006**	**first forbidden $1^- \to 0^+$**	**58.21**	**45.84**
		2662.68	0.017	0.006	first forbidden $1^- \to 2^+$	1.98	1.55
		1894.32	0.0743	0.0011	first forbidden $1^- \to 2^+$	0.18	0.14
		1856.51	0.0081	0.0007	first forbidden $1^- \to 0^+$	0.01	0.01



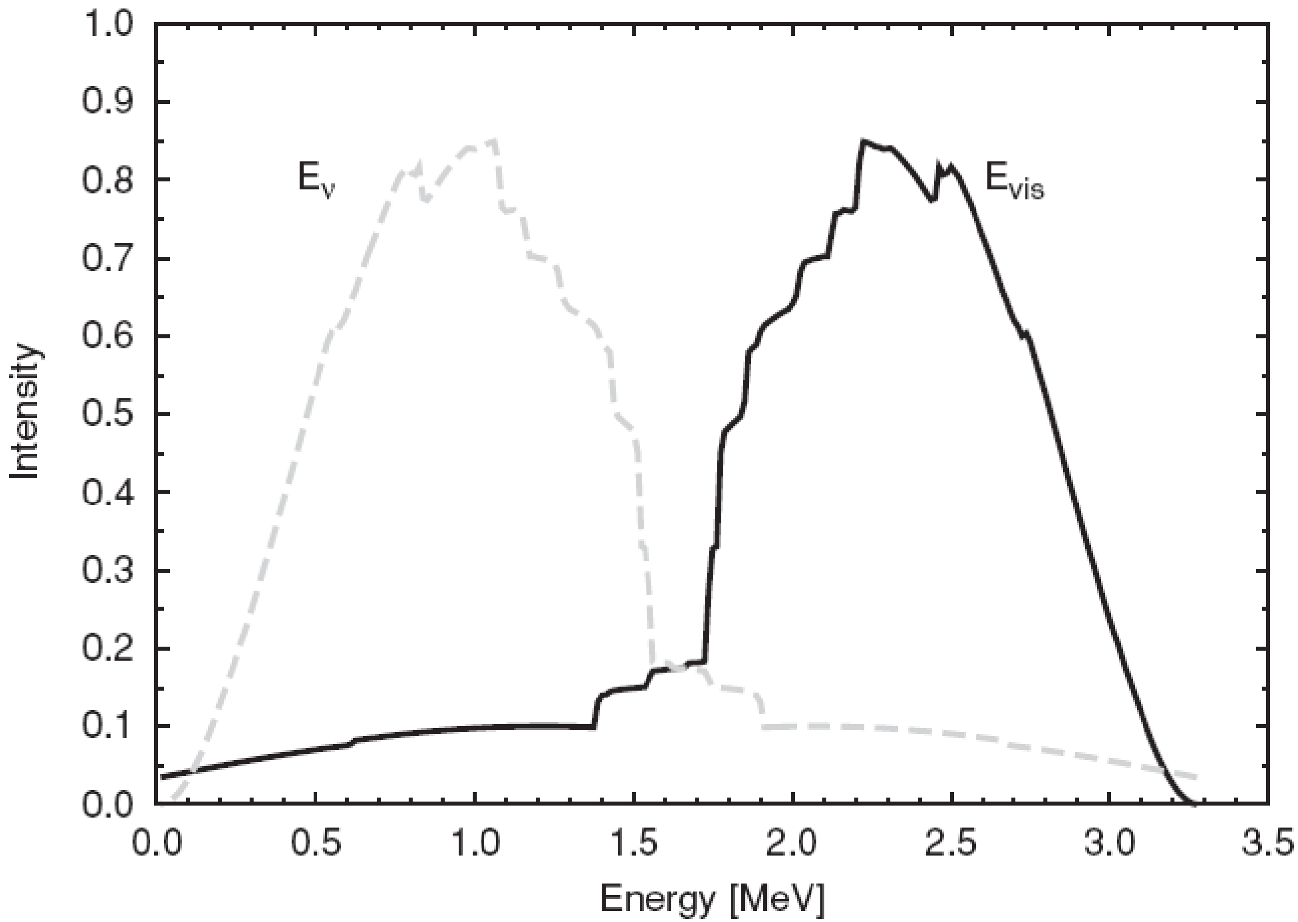


$i \to j$	$R_{i,j}$	E_{max} (keV)	I_k	ΔI_k	Type (%)	S_{Th}	S_{tot}
$^{212}Bi \to {}^{212}Po$	**0.6406**	**2254**	**0.8658**	**0.0016**	**first forbidden $1^{(-)} \to 0^+$**	**94.15**	**20.00**
$^{228}Ac \to {}^{228}Th$	1.0000	2069.24	0.08	0.06	allowed $3^+ \to 2^+$	5.66	1.21
		1940.18	0.008	0.006	allowed $3^+ \to 4^+$	0.19	0.04

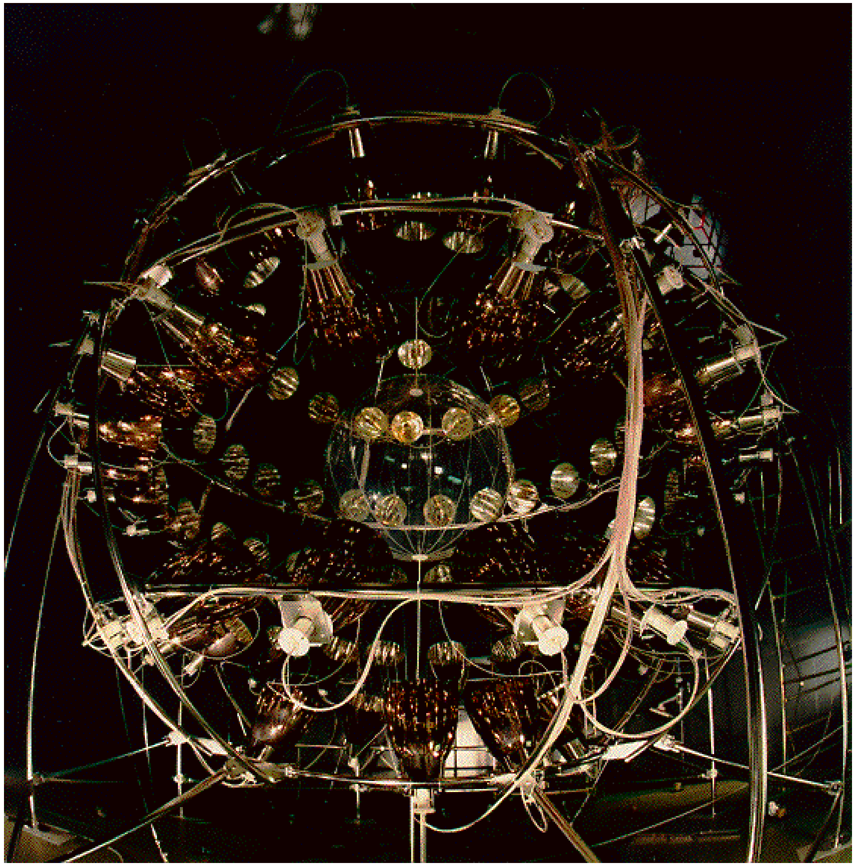
^{214}Bi

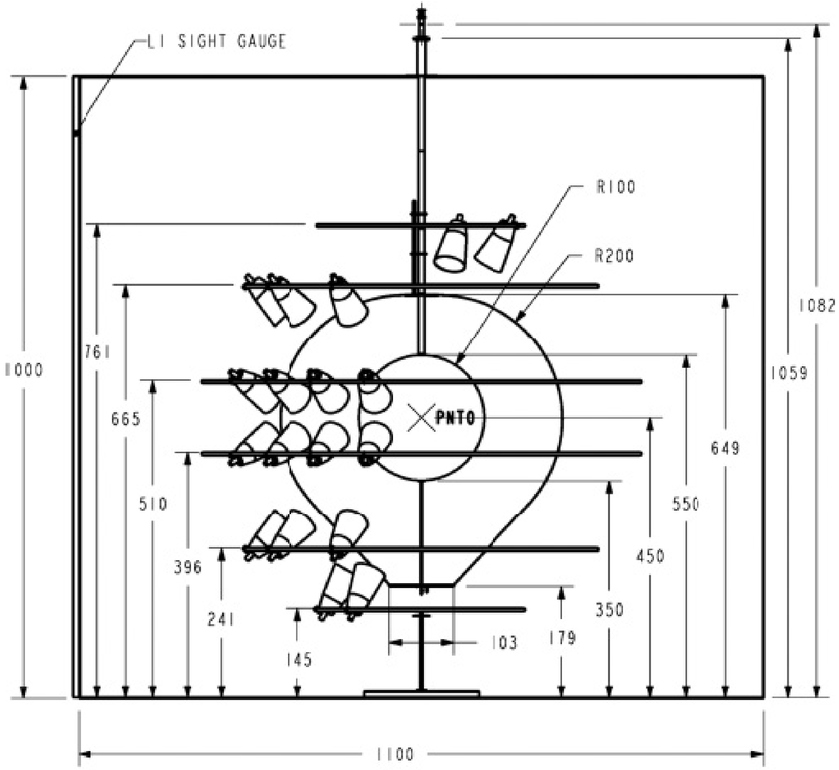


E_ν(max) [keV]	S_U [%]	S_{U+Th} [%]
...		
1894	0	0
2663	2	1.6
3272	58	42

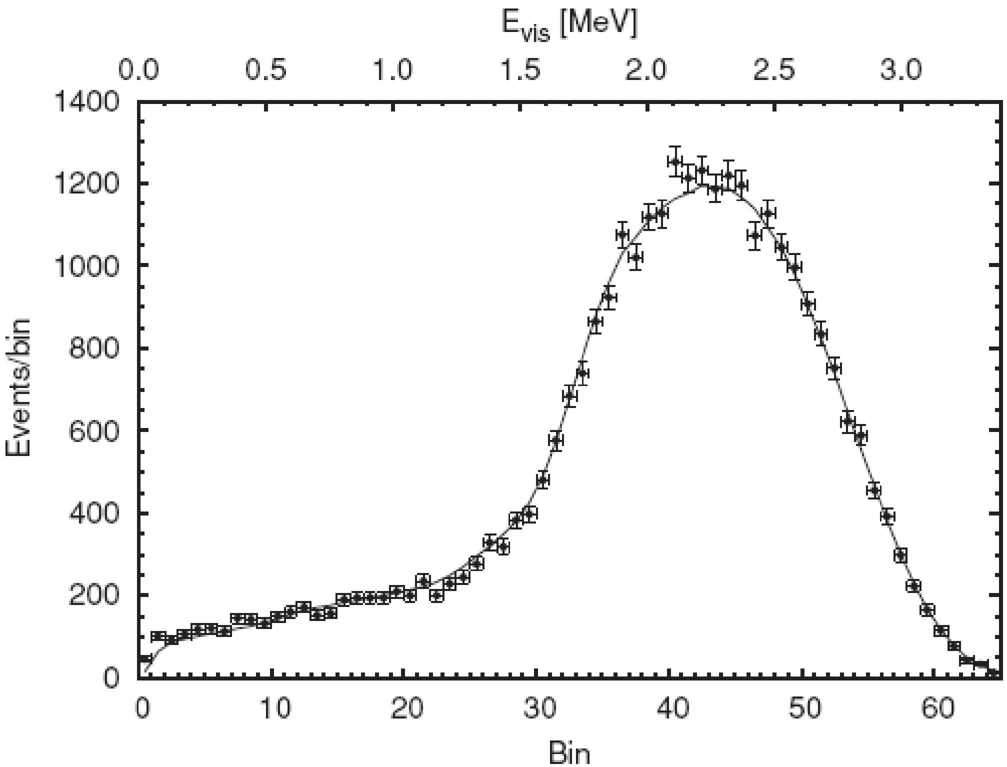


CTF (4 tonne Borexino prototype)





Experimental spectrum of ^{214}Bi (CTF) with superimposed fit



$$(\text{CTF}) \quad p_0 = 0.177 \pm 0.004\ (\text{stat})\ ^{+0.003}_{-0.001}\ (\text{sys}). \qquad (11)$$

This value is consistent with that reported in ToI [17]: $p_0(\text{ToI}) = 0.182 \pm 0.006$.

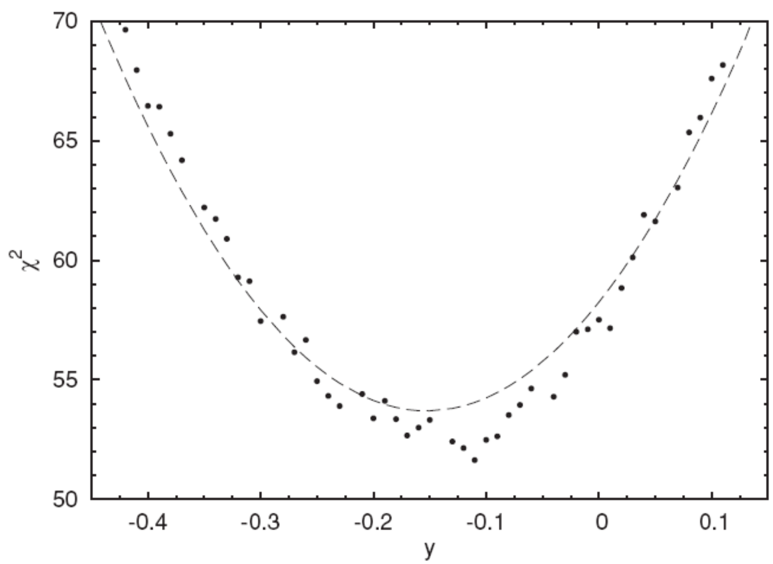
New ToI value:
p_0=0.1910±0.0017

Phys. Rev. C **81, 034602 (2010) Nuclear physics for geo-neutrino studies** G. Fiorentini et al

Deviation from the allowed (universal) shape

$$\phi(T_e) = p_0 \Phi(T_e) + \sum_{n>0} p_n \Phi_{\text{univ}}(T_e, Q - E_n)$$

$$\Phi(T_e) = \Phi_{\text{univ}}(T_e, Q) \left(1 + y \frac{T_e - \langle T_e \rangle}{\langle T_e \rangle}\right)$$



Results for signal from ^{214}Bi

(CTF)

$$s(^{214}\text{Bi}) = [1.42 \pm 0.03\ (\text{stat})\ ^{+0.023}_{-0.008}\ (\text{sys})] \times 10^{-44}\ \text{cm}^2$$

(ToI)

$$s(^{214}\text{Bi}) = [1.46 \pm 0.05\ (\text{stat})] \times 10^{-44}\ \text{cm}^2$$

With spectral deformations:

$$s(^{214}\text{Bi}) = [1.48 \pm 0.01\ (\text{stat}) \pm 0.03\ (\text{sys})] \times 10^{-44}\ \text{cm}^2$$

Geoneutrino with Borexino. Summary.

- 1)Geoneutrino detection is now extremely robust in Borexino : **5.9σ ($3.6\cdot10^{-9}$)**;
- 2) **S_{geo}(LNGS)=$43.5^{+11.8}_{-10.4}$(stat)$^{+2.7}_{-2.4}$(syst) TNU**
- 3)The precision is still too low: ~25% for U+Th signal with fixed ratio Th/U=3.9, and much worse for the unconstrained R(U) and R(Th) measurements. Geological models for the moment can't be discriminated;
- 3)Radiogenic heat is in **11-51 TW** interval at 68% CL
- 4)The mantle contribute positive signal at 98% CL: **$S_{mantle}=20.9^{+15.1}_{-10.3}$ TNU**