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Geo-neutrinos signal with Borexino

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Why do we study geo-neutrinos?

Geo-neutrinos are the anti-neutrinos produced in the decays of the progenies of Uranium, of Thorium and Potassium.

Geo-neutrinos bring to the surface information from the whole planet: <u>they are a unique direct probe of our Earth's interior</u>!

<u>We could find answers to the questions</u>:

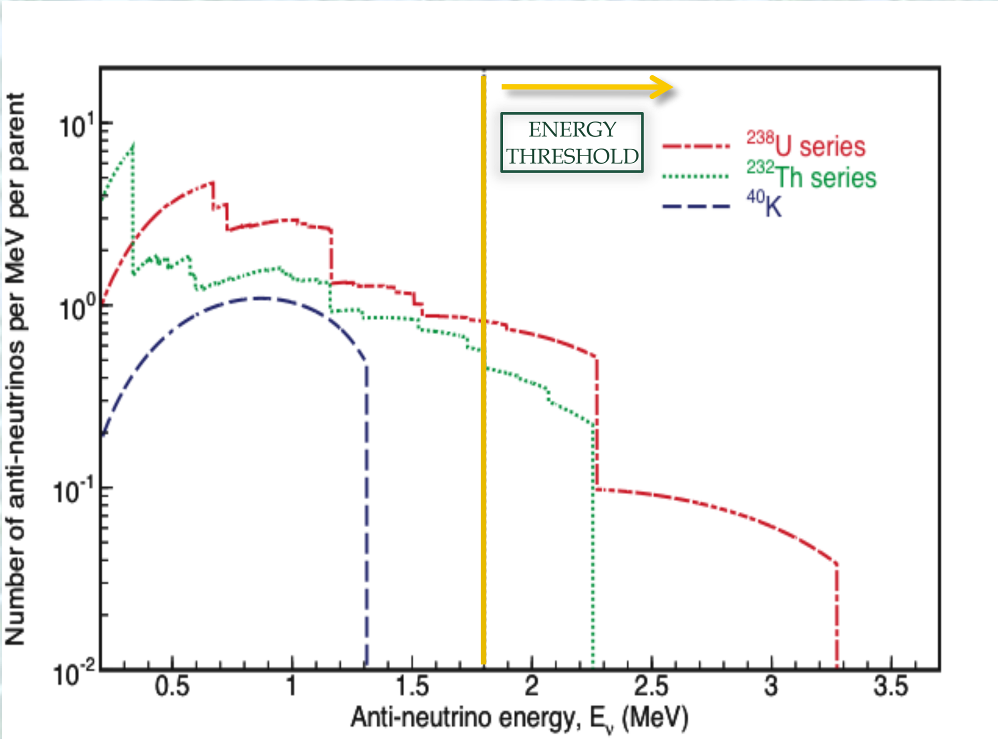
- **What is the radiogenic contribution to the terrestrial heat?**
- **What is the distribution of the radiogenic elements within the Earth?**

BOREXINO features

- The unprecedented low intrinsic radioactivity
- Far from reactor plants → Very favourable Geo-ν / reactor anti-ν ratio
- Due to the underground location, $\Phi(\mu)$ reduced by ~ 10^6.

→ **Borexino offers a unique opportunity for a sensitive search for anti-neutrinos in the MeV range.**

Sources of anti-neutrinos: GEO-NEUTRINOS



^{238}U, ^{232}Th, ^{40}K: $\tau_{1/2} \approx 10^{9\text{-}10}$ y

$$^{238}U \rightarrow {}^{206}Pb + 8\alpha + 8e^- + 6\bar{\nu}_e + 51.7\,MeV$$

$$^{232}Th \rightarrow {}^{208}Pb + 6\alpha + 4e^- + 4\bar{\nu}_e + 42.8\,MeV$$

$$^{40}K \rightarrow {}^{40}Ca + e^- + \bar{\nu}_e + 1.32\,MeV$$

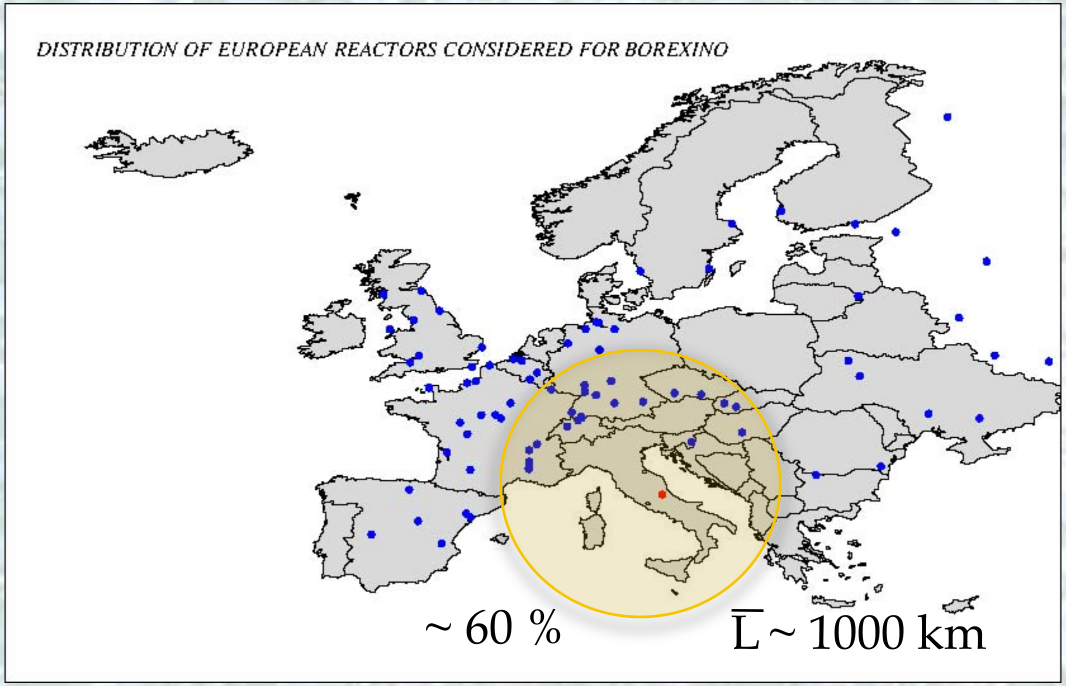
Earth shines in anti-neutrinos:

$$\Phi(\bar{\nu}_e) \approx 10^6\,cm^{-2}s^{-1}$$

Released *heat* and anti-neutrinos *flux* are in a well fixed ratio!

Sources of anti-neutrinos:

REACTOR ANTI-ν_e



<u>Systematic uncertainties on the expected reactor anti-ν signal</u>

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^2_{12}	0.02		
Total			5.38

$$\Phi\left(E_{\bar{\nu}_e}\right) = \sum_{r=1}^{N_{react}} \sum_{m=1}^{N_{month}} \frac{T_m}{4\pi L_r^2} P_{rm} \sum_{i=1}^{4} \frac{f_{ri}}{E_i} \Phi_i\left(E_{\bar{\nu}_e}\right) P_{ee}\left(E_{\bar{\nu}_e}; \vartheta_{12}, \Delta m^2_{21}, L_r\right)$$

Loop over reactors, *r* — Loop over months, *m* — Loop over isotopes, *i*

P_{rm} : Thermal Power (IAEA, EDF);

f_{ri} : Power fraction of isotope $i = {}^{235}U, {}^{238}U, {}^{239}Pu, {}^{241}Pu$;

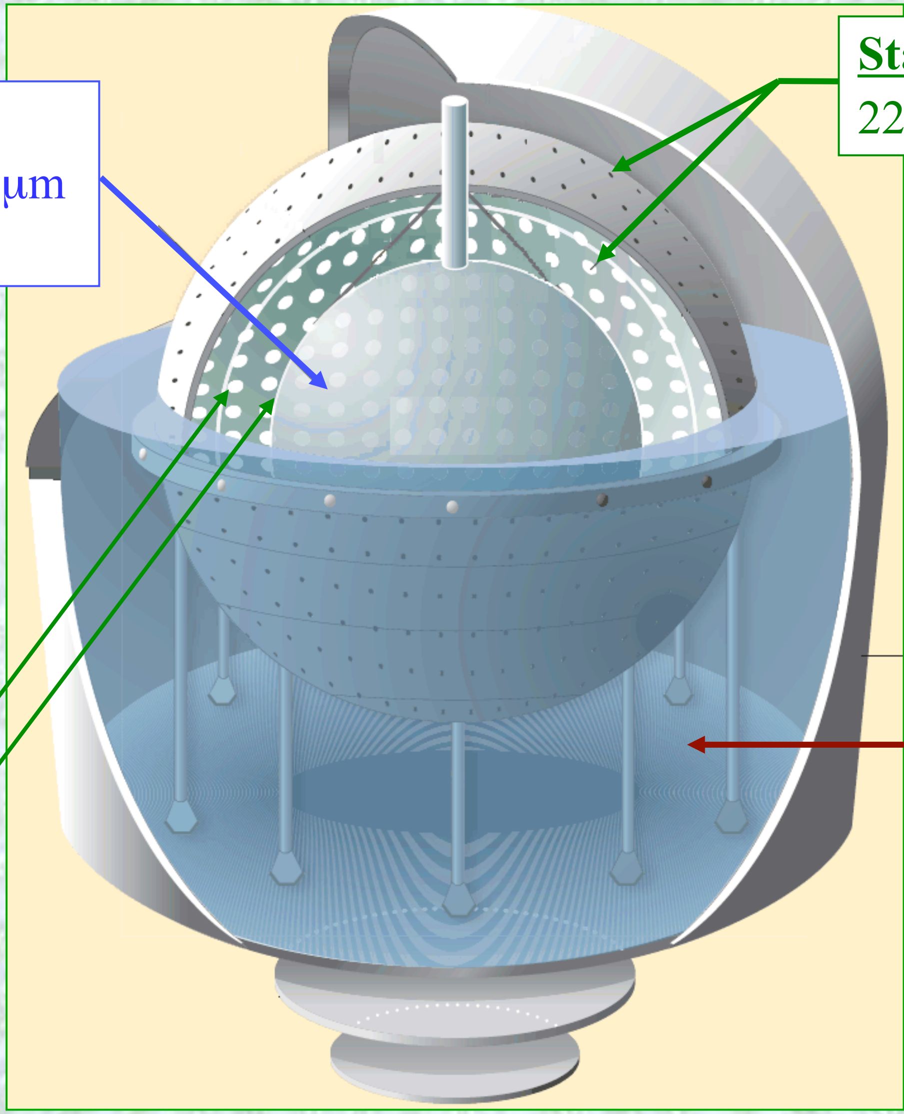
L_r : Distance reactor-detector;

T_m: Borexino livetime in months;

P_{ee}: anti-ν survival probability.

The Borexino Detector

Scintillator:
270 t PC+PPO in a 125 μm thick nylon vessel



Stainless Steel Sphere:
2212 PhotoMultipliers

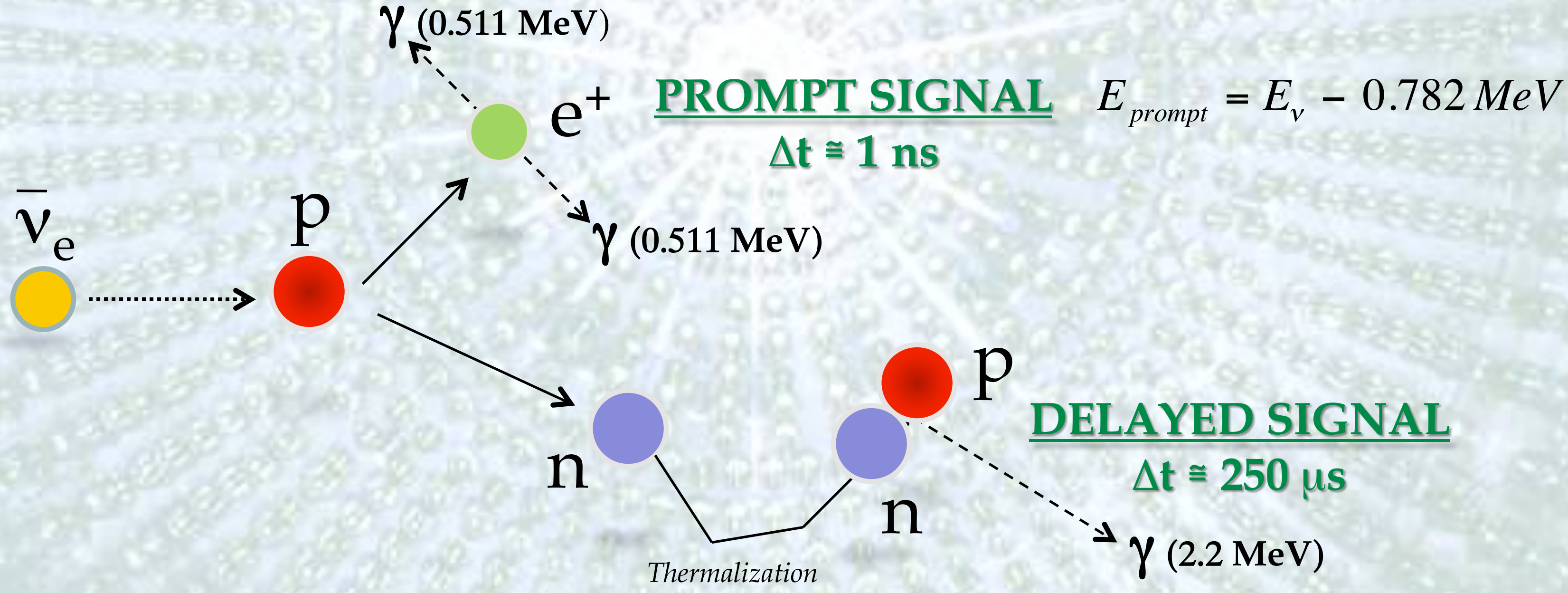
Nylon vessels:
Outer: 5.50 m
Inner: 4.25 m

Water Tank:
γ and n shield
μ water Č detector
208 PMTs in water

How to detect anti-neutrinos

In Borexino, electron anti-neutrinos are detected via the inverse beta decay reaction:

$$\overline{\nu}_e + p \rightarrow e^+ + n \qquad (E_{th} = 1.806\, MeV)$$



Anti-ν candidates selection

1) ***Muon veto***: 2 ms after a water tank-muon, 2 s after a SSS crossing-muon (~ 10% reduction of livetime).

2) ***Energy cut***: both for prompt-signal and delayed-signal.
$Q_{prompt} > 410$ p.e. and 700 p.e. $< Q_{delayed} < 1250$ p.e.

1) ***Time window***: $20\ \mu s < \Delta t_{prompt\text{-}delayed} < 1280\ \mu s$.

2) ***Correlated distance***: $\Delta R_{prompt\text{-}delayed} < 1$ m.

3) ***Radial cut:*** $R_{InnerVessel} - R_{prompt} \geq 25$ cm.

The total detection efficiency was determined by MC to be 0.85±0.01.

Data: from December 2007 to December 2009

Total Lifetime: 537.2 days

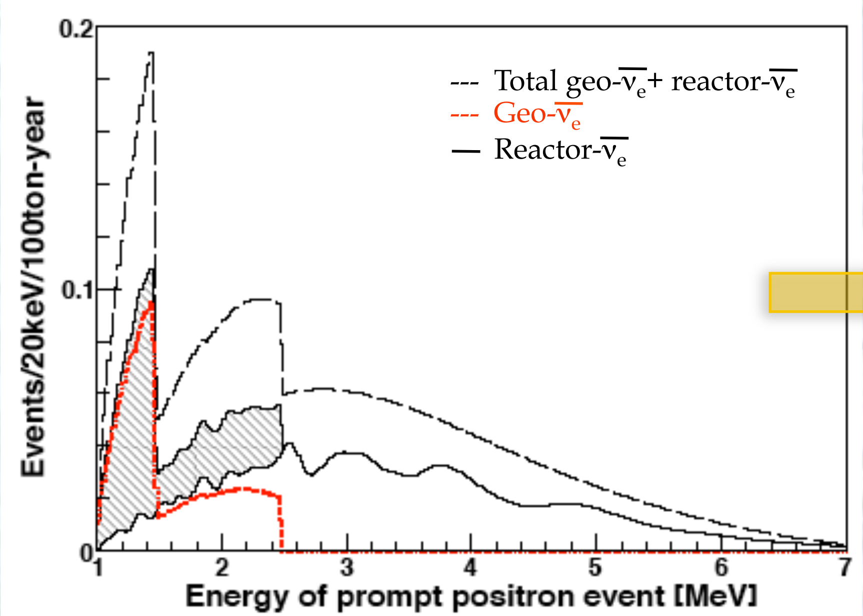
Fiducial exposure after the selection and including the detection efficiency:

252.6 tons*year → 21 candidates events were selected.

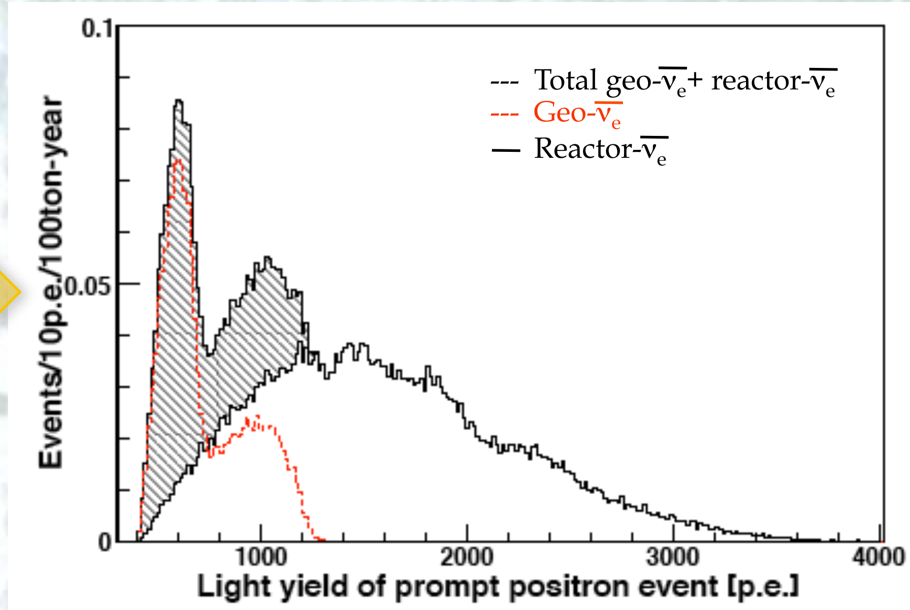
Summary of anti-ν backgrounds

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

What do we expect?



Ideal Energy spectrum for positron events in Borexino site.

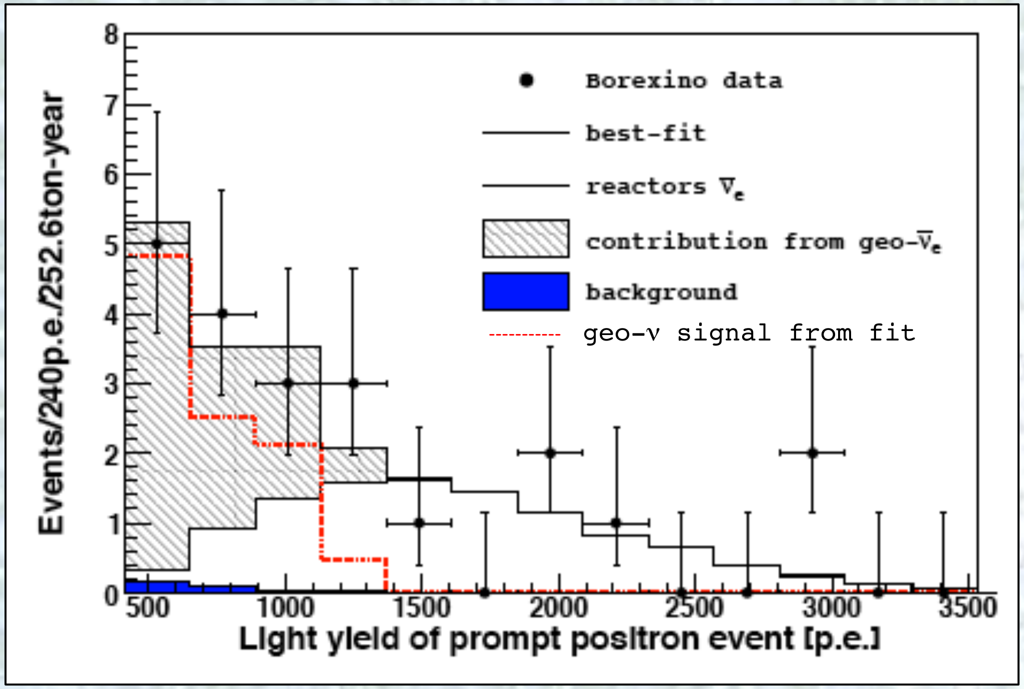


Montecarlo expected spectrum
→ taking into account the position and energy response of the the detector.

MC code was tuned on calibrations:
AmBe neutron source, gammas sources….

Results!

arXiv: 1003.0284v1[hep-ex], March 2010. In press on *Physics Letters B*



Light yield spectrum for the positron prompt events of the 21 candidates.

Our best estimates are:

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

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

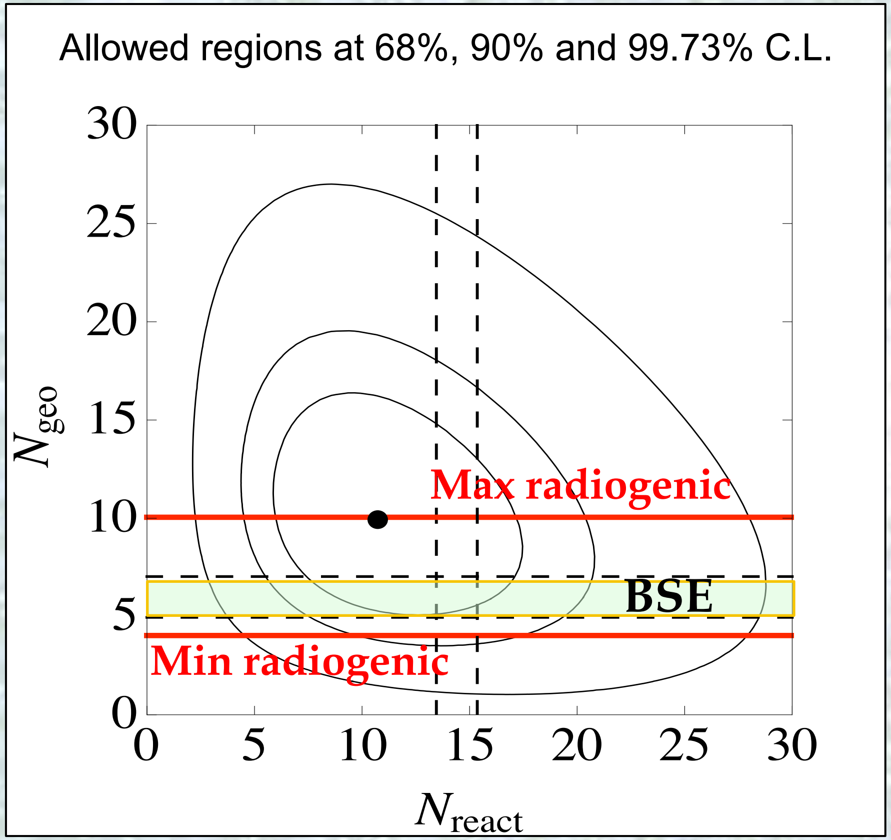
Background in the overall energy window: 0.40 ± 0.06 events

Background in the geo-ν energy window: 0.31 ± 0.05 events

Scaling the best estimate of N_{geo} with the 252.6 ton*yr exposure, our measurement for the geo-neutrinos rate is:

$$3.9^{+1.6}_{-1.3}\left(^{+5.8}_{-3.2}\right) \; events/(100\, t \cdot y) \quad at \;\; 68.3\% \; (99.73\%) \; C.L.$$

Best-fit parameters from the *unbinned* likelihood analysis



Charge of the 21 candidates fitted with the Montecarlo + background charge spectra.

Max Radiogenic:
Total Earth heat flow producted exclusively by radiogenic elements.

Min Radiogenic:
Known U+Th concentrations in the crust.

BSE:
Bulk Silicate Earth geochemical models.
(original: McDonough & Sun, 1995)

By studing the profile of the likelihood with respect to N_{geo} we have calculated that the null hypothesis for geo-neutrinos can be rejected at 99.997% C.L.

Conclusions and Perspectives

1 First observation of geoneutrinos at 4.2 σ:
   a) Large Signal-to-Noise ratio
   b) Results limited by present statistics

2 First measurement of electron anti-neutrino disappeareace on a base line of 1000 km at 2.9 σ.

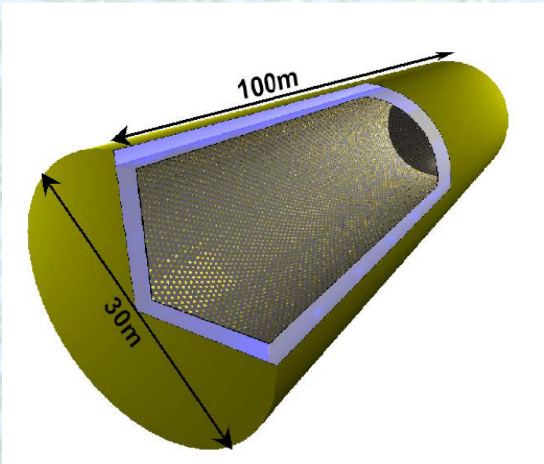
3 Rejection at 95% C.L. of the hypothesis of an active geo-reactor in the Earth's core ($P_{Thermal}$ > 3 TW).

<u>What next?</u>

Spectroscopy measurement of geo-ν with more statistics:

I. Discrimination of BSE or fully Radiogenic model
II. Th/U ratio measurement → U and Th fluxes measurement at Gran Sasso site ?

Future experiments: LENA and HANOHANO



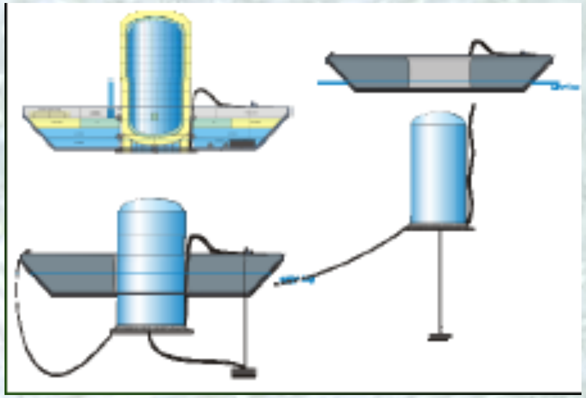
LENA at Pyhasalmi, Finland

Project for a 50kton underground liquid scintillator detector.

→ Continental crust (80% signal)

<u>Features</u>: better neutron detection & moderate directionality information

→ Expected: 800-1200 ev/yr (BSE model)



HANOHANO at Hawaii

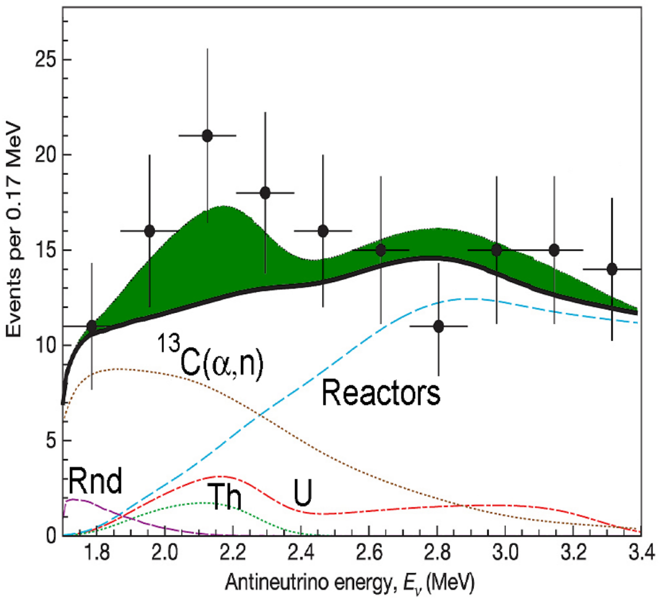
Project for a 10kton liquid scintillator detector movable and placed on a deep oceanic floor.

→ Oceanic Crust (70% signal)

→ Expected: 60-100 ev/yr (BSE model)

KamLAND results

First experimental indication of geoneutrinos (latest result ~2.5σ in 2008)



T. Araki et al., Nature 436 (2005)

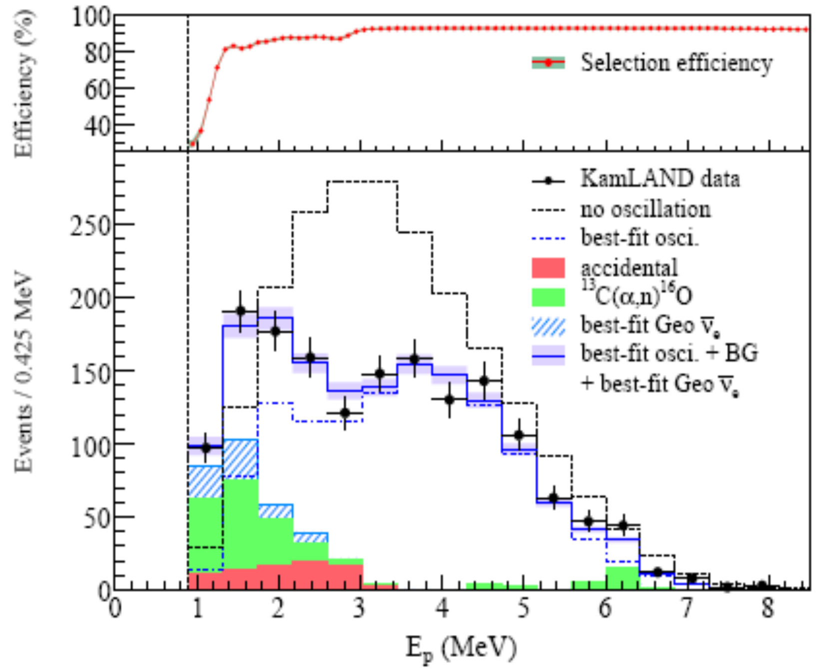


FIG. 1: Prompt event energy spectrum of $\overline{\nu}_e$ candidate events. All histograms corresponding to reactor spectra and expected backgrounds incorporate the energy-dependent selection efficiency (top panel). The shaded background and geo-neutrino histograms are cumulative. Statistical uncertainties are shown for the data; the band on the blue histogram indicates the event rate systematic uncertainty.

S. Abe et al., Phys. Rev. Lett. 100, 221803 (2008)

Borexino Background

The expected *Solar Neutrino Rate* is around 50 cpd/100 t (A ~ $5 \cdot 10^{-9}$ Bq/kg).

- Natural water: ~ 50 Bq/m^3 in ^{238}U, ^{232}Th, ^{40}K and ^{222}Rn
- External air: ~ 20 Bq/m^3 in ^{39}Ar, ^{85}Kr and ^{222}Rn
- Typical rock: ~ 100-1000 Bq/m^3 in ^{238}U, ^{232}Th and ^{40}K

The Borexino scintillator must be **9-10 order** of magnitude **less** radioactive than anything on Earth

Thanks to the particular design, based on the principle of graded shielding, the predicted background due to external γ-rays in the fiducial volume and in the neutrino window (200-800 keV) is less than 0.5 cpd/100 t.

Borexino Background

- ^{9}Li and ^{8}He cosmogenic nuclides:

  Cosmic muons crossing the scintillator can create radioactive isotopes by spallations of carbon atoms. Some of these nuclides (i.e. ^{9}Li and ^{8}He) decay via a β-n cascade so they mimic the anti-neutrino signal.

  Strategy: 2s veto after a muon crossing the scintillator
  ~ 15 events/(100 tons yr) → 0.03 ± 0.02 events/ (100 tons yr).

- Fast neutrons: in WT and in rock

  Fast neutrons can mimic an anti-n event if before being captured they scatter an energetic proton. Fast neutrons could be generated by interaction of cosmic muons in rock or materials sourrounding Borexino or in the Borexino water tank.

Borexino Background

- Untagged muons:

  Untagged muons could give rise to two categories of backgrounds:
  - A primary muon can mimic the prompt and a muon-induced neutron the delayed signal.
  - Pairs of muon-induced neutrons following unrecognized muons can simulate the events.

  For each of these categories we calculate the occurence probability in corrispondence of recognized muon and scaled by the estimated number of untagged muons.

- Accidental background:

  We studied an off-time coincidence window of 2-20 s and then scaled to our acquisition-time window.

  → 0.080 ± 0.001 events/ (100 tons yr).

Borexino Background

- (γ,n) backgrounds:

  (γ,n) reactions might make coincidence events that almost perfectly mimic the anti-ν events. Anyway, due to reaction and analysis threshold, only gammas with energy > 3 MeV could be source of background.

- (α,n) reactions in the scintillator and in the buffer:

  The reaction $^{13}C(\alpha,n)^{16}O$ makes delayed coincidence events that almost perfectly mimic the anti-neutrino events. The prompt signal could be given by ^{16}O deexcitation (from $^{13}C(\alpha,n)^{16}O^*$) or by protons scattered by neutrons or ^{12}C excited by neutrons.

  The contributions to (α,n) reactions from a decay in the ^{238}U and ^{232}Th chains is negligible. The only relevant contribution is the one coming from ^{210}Po.

Likelihood Analysis

It includes spectral informations. We use the following likelihood:

$$L(N_{geo},N_{reac},S_{reac},S_{FV}) = e^{-\int_{E_{\min}}^{E_{\max}} dE\, f_{\nu}(E;N_{geo},N_{reac},S_{reac},S_{FV})} \times \prod_{i=1}^{N_{obs}} \left[f_{\nu}(E_i;N_{geo},N_{reac},S_{reac},S_{FV}) + f_B(E_i) \right] \times$$

$$e^{-\frac{1}{2}\left(\frac{S_{reac}}{\sigma_{reac}}\right)^2} \times e^{-\frac{1}{2}\left(\frac{S_{FV}}{\sigma_{FV}}\right)^2}$$

Where:

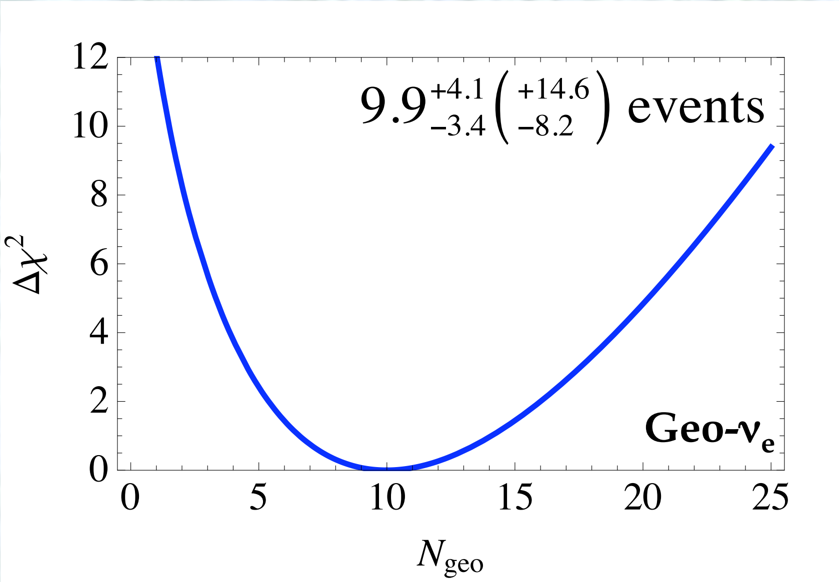
f_{ν} = Spectrum of geo+reactor anti-neutrinos (assuming chondritic Th/U ratio).

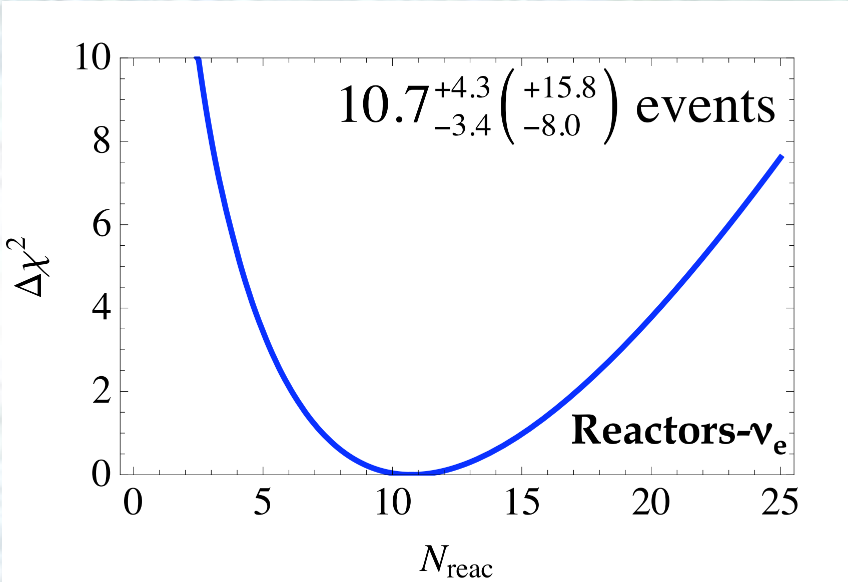
f_B = Spectrum of background

σ_{reac} = 0.0538

σ_{FV} = 0.038

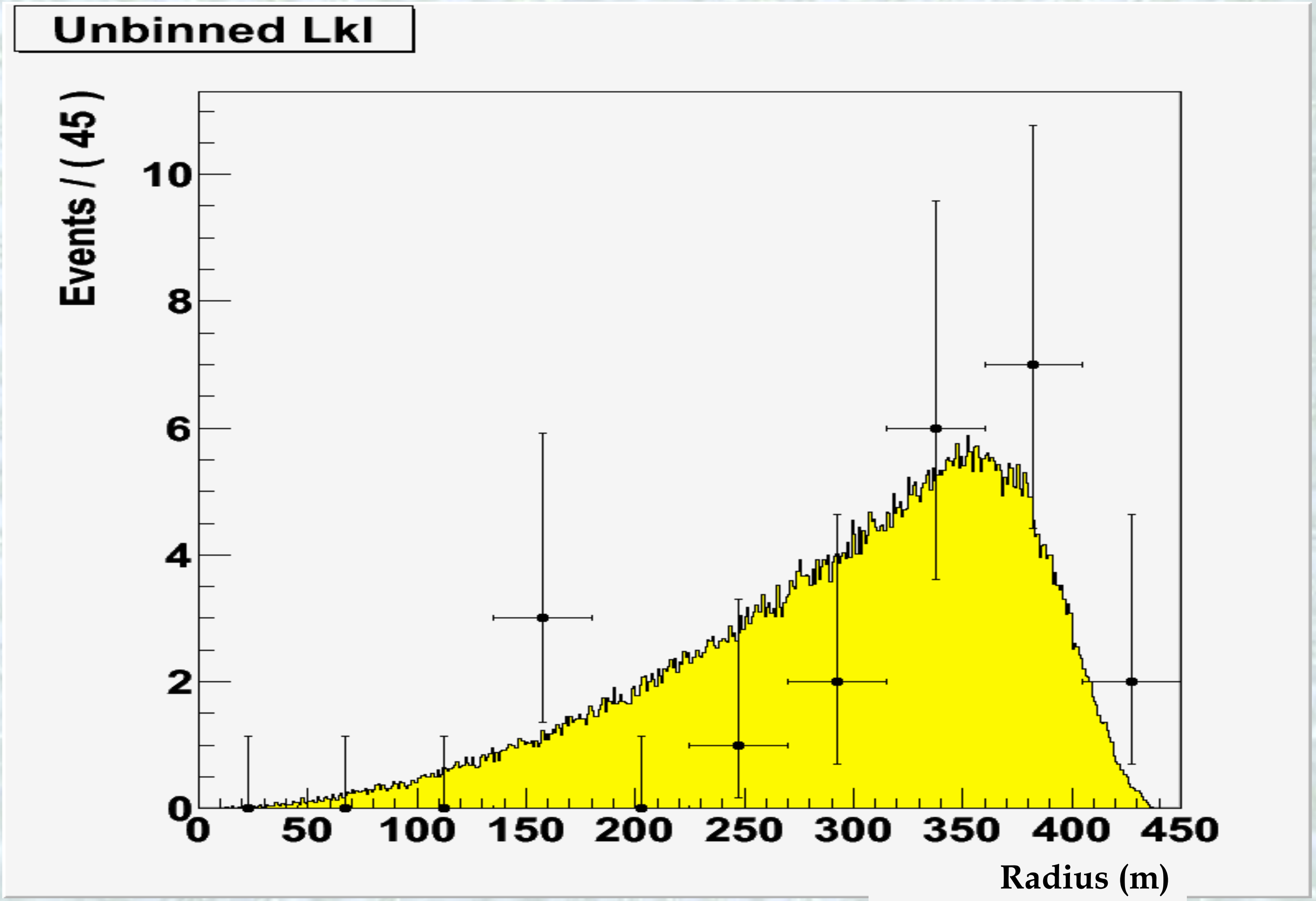
Best-fit parameters from the *unbinned* likelihood analysis (2)





Charge of the 21 candidates fitted with the Montecarlo + background charge spectra.

Radial distribution of candidates



Comparison with predictions

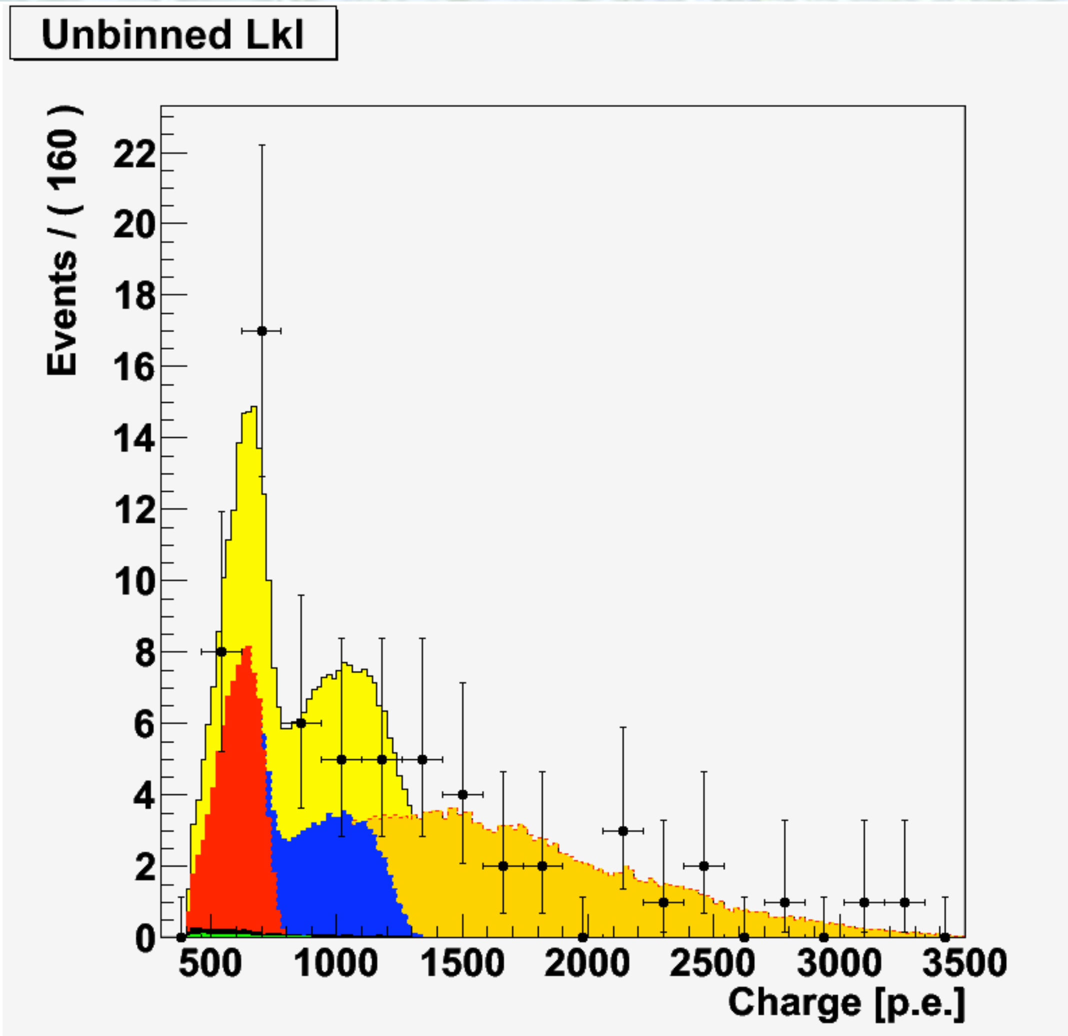
Source	Geo–$\bar{\nu}_e$ Rate [events/(100 ton·yr)]
Borexino	$3.9^{+1.6}_{-1.3}$
BSE [16]	$2.5^{+0.3}_{-0.5}$
BSE [30]	2.5 ± 0.2
BSE [5]	3.6
Max. Radiogenic Earth	3.9
Min. Radiogenic Earth	1.6

[5] C.G. Rothschild, M.C. Chen and F.P. Calaprice, Geophy. Res. Lett., **25**, 1083 (1998); G. Rothschild, M.C. Chen, and F.P. Calaprice, arXiv:nucl-ex/9710001v2 (2005).

[16] F. Mantovani, L. Carmignani, G. Fiorentini, and M. Lissia, Phys. Rev. D **69**, 013001 (2004).

[30] A. Ianni, G. Pagliaroli, A. Strumia, F.R. Torres, F.L. Villante, and F. Vissani, Phys. Rev. D **80**, 043007 (2009).

A possible spectrum with 3 times the present statistics



Error on U and Th: 30 - 50%

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The Borexino Detector