Measurement of geo-neutrinos detected in the Borexino experiment at the Laboratory Nazionali del Gran Sasso

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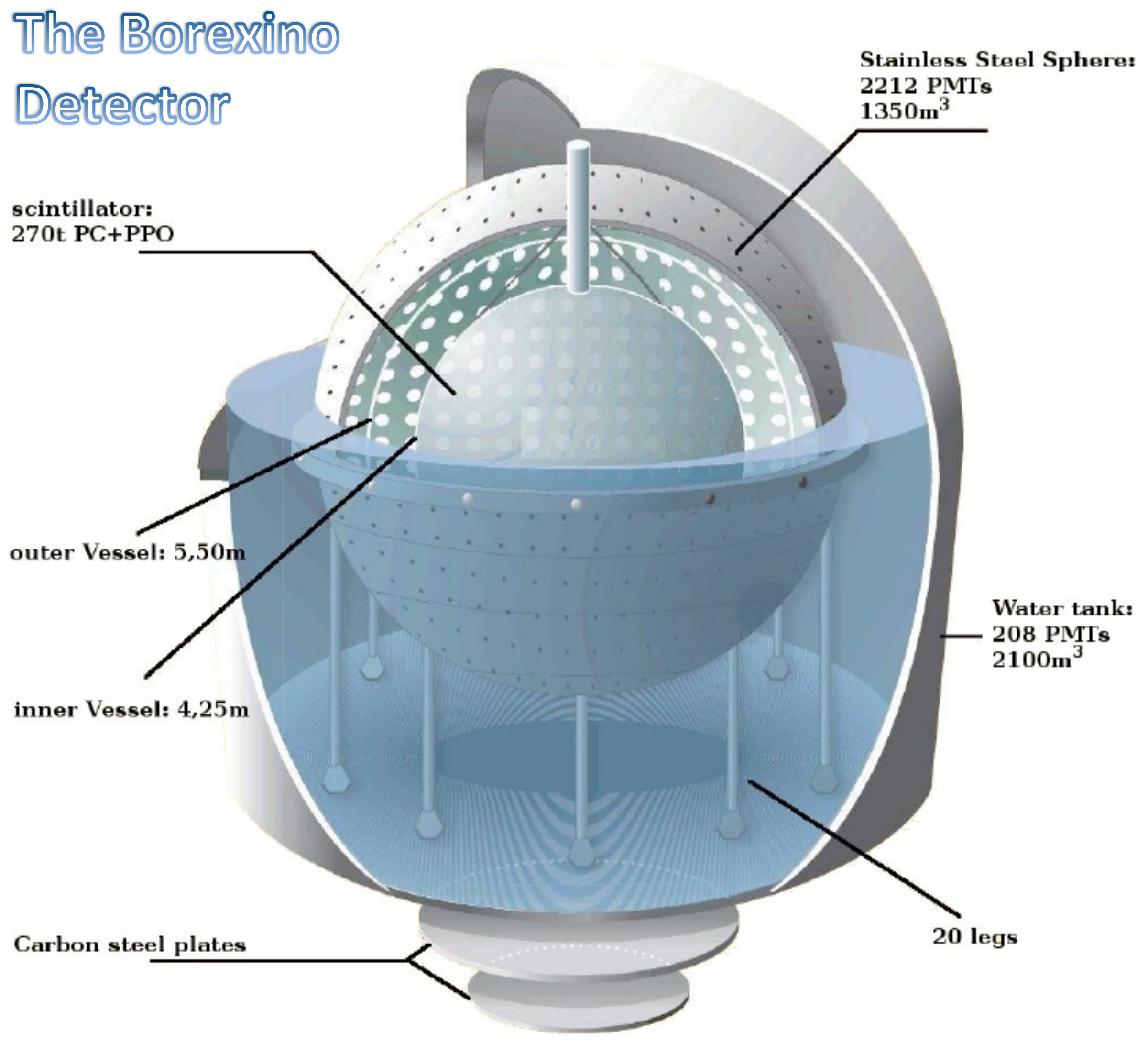
Abstract. This work presents a measurement of geo-neutrinos detected in the Borexino experiment at the Laboratory Nazionali del Gran Sasso in central Italy. Geo-neutrinos are electron anti-neutrinos produced in our planet by beta decays of naturally occurring radioactive isotopes; they provide a new tool to directly probe the interior of the Earth. The present measurement , obtained from 1353 days of data, corresponds to an exposure of (3.69 +/-0.16) x 10^{31} proton x year. After all selection cuts and background subtraction made in the analysis, the number of detected geo-neutrino (assuming a fixed chondritic Th/U mass ratio of 3.9), is of (14.3 +/- 4.4 events). The corresponding geo-neutrino signal is S_{geo} = (38.8 +/-12.0) TNU. If U and Th contributions are left as free parameters in the fit, central values of S_{Th} = (10.6 +/-12.7) TNU and S_U = (26.5 +/- 19.5) TNU are obtained. The Borexino data are compatible with a mantle geo-neutrino signal of (15.4 +/- 12.3) TNU. The combination of the Borexino and the KamLAND data allows to extract a geo-neutrino mantle signal of (14.1 +/-8.1) TNU.

The Borexino Detector



Anti-ν detection in Borexino

The

a) extremely low intrinsic radioactivity;
b) the high photon yield of about (500 p.e. per 1 MeV);
c) the large number of free target proton (1.7 · 10^{31});

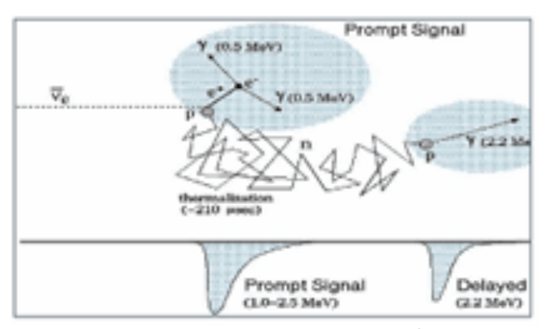
offer a unique tool for anti-nu study via the inverse beta-decay reaction:

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

Correlated in space and time pair of signals:

Prompt signal: $e^+ + 2\gamma$ (E_γ=0.511 MeV) from annihilation with e^-

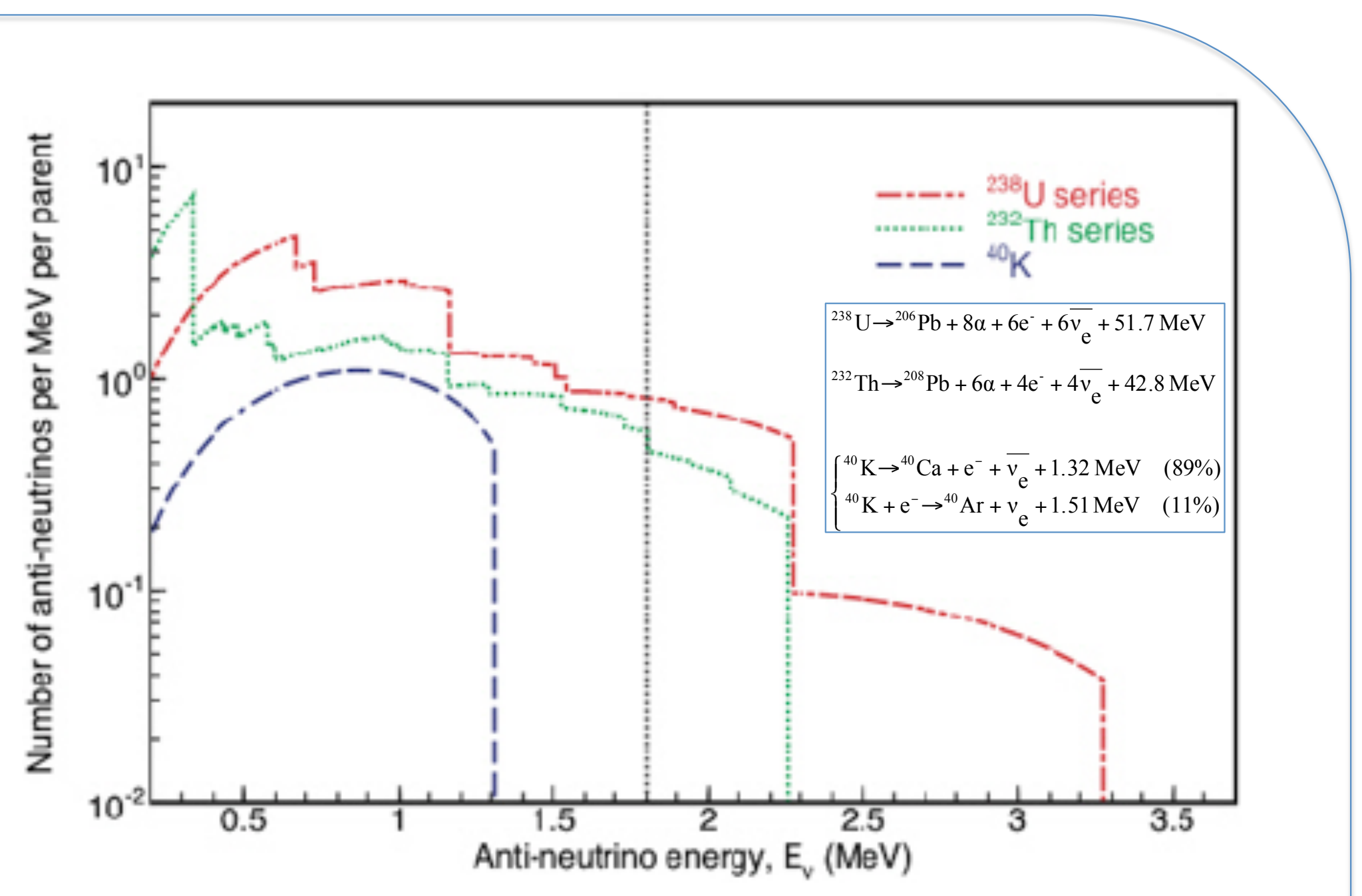
after t = 254.5 ± 1.8 μs

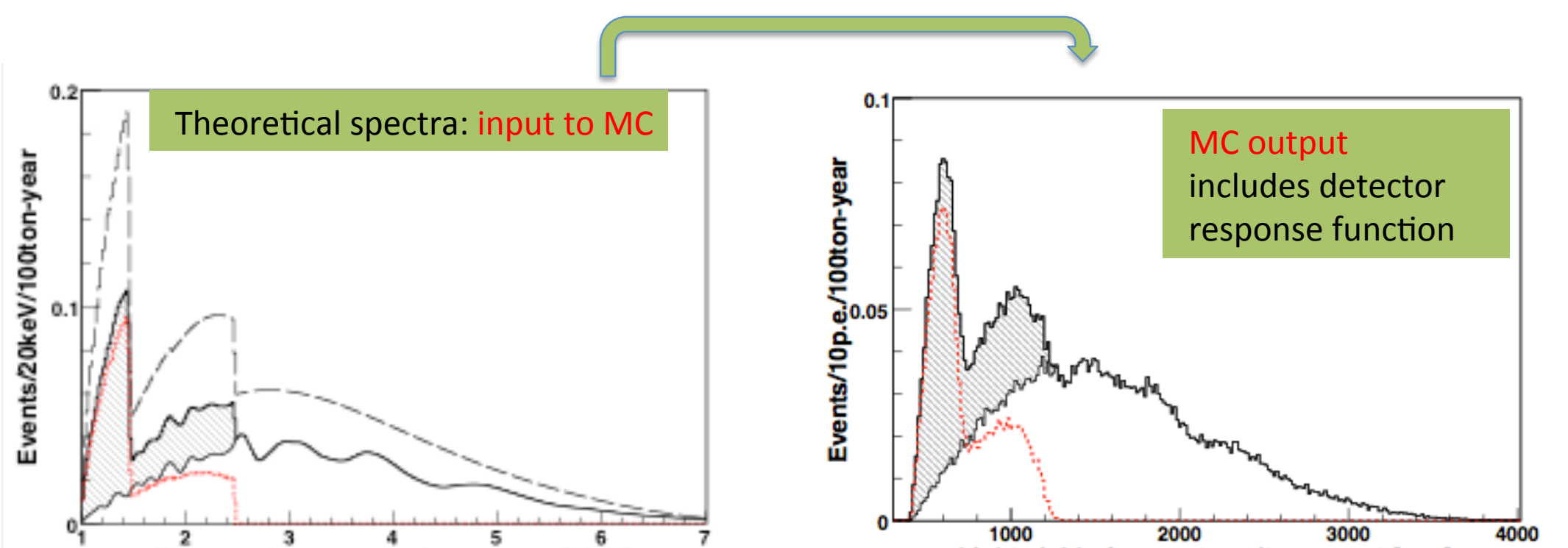


Delayed signal: Neutron capture on proton give a γ (E_γ=2.2 MeV)

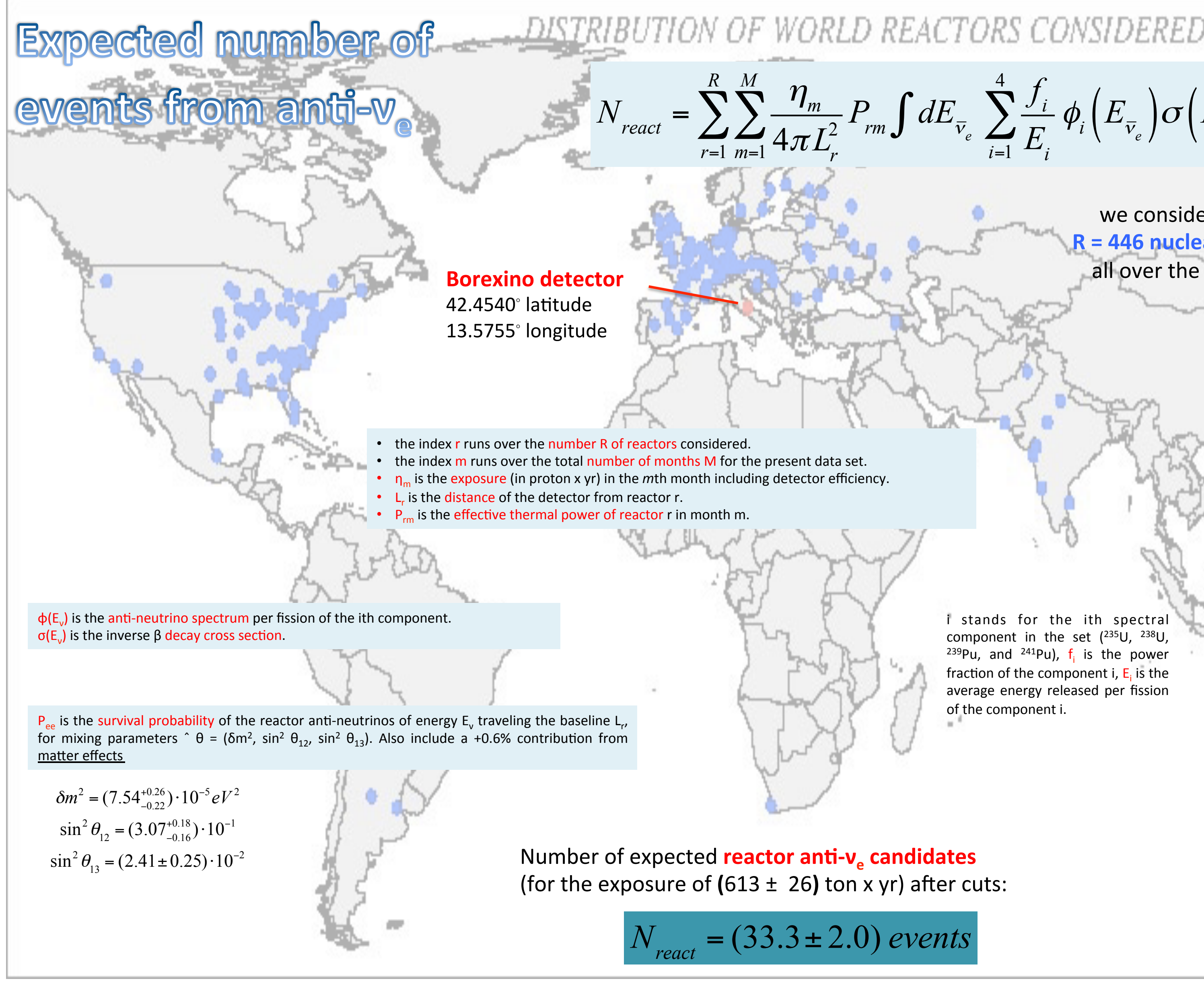
$$E_{threshold} = 1.806\ MeV$$

$$E_{prompt} = E_{\bar{\nu}_e} - 0.784\ MeV$$





Expected number of events from anti-ν_e



$$N_{react} = \sum_{r=1}^{R}\sum_{m=1}^{M}\frac{\eta_m}{4\pi L_r^2}P_{rm}\int dE_{\bar{\nu}_e}\sum_{i=1}^{4}\frac{f_i}{E_i}\phi_i\left(E_{\bar{\nu}_e}\right)\sigma\left(E_{\bar{\nu}_e}\right)P_{ee}\left(E_{\bar{\nu}_e};\hat{\theta},L_r\right)$$

we consider the
R = 446 nuclear cores
all over the world

Borexino detector
42.4540° latitude
13.5755° longitude

- the index r runs over the number R of reactors considered.
- the index m runs over the total number of months M for the present data set.
- η_m is the exposure (in proton x yr) in the *m*th month including detector efficiency.
- L_r is the distance of the detector from reactor r.
- P_{rm} is the effective thermal power of reactor r in month m.

$\phi(E_\nu)$ is the anti-neutrino spectrum per fission of the ith component.
$\sigma(E_\nu)$ is the inverse β decay cross section.

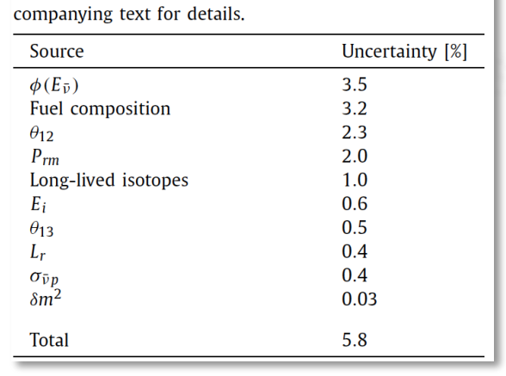
i stands for the ith spectral component in the set (^{235}U, ^{238}U, ^{239}Pu, and ^{241}Pu), f_i is the power fraction of the component i, E_i is the average energy released per fission of the component i.

P_{ee} is the survival probability of the reactor anti-neutrinos of energy E_ν traveling the baseline L_r, for mixing parameters ˆ θ = (δm^2, $\sin^2\theta_{12}$, $\sin^2\theta_{13}$). Also include a +0.6% contribution from matter effects

$$\delta m^2 = (7.54^{+0.26}_{-0.22})\cdot 10^{-5} eV^2$$

$$\sin^2\theta_{12} = (3.07^{+0.18}_{-0.16})\cdot 10^{-1}$$

$$\sin^2\theta_{13} = (2.41 \pm 0.25)\cdot 10^{-2}$$



Systematic uncertainties on the expected reactor $\bar{\nu}_e$ signal which are added in quadrature. See Eq. (2) and accompanying text for details.

Source	Uncertainty [%]
$\phi(E_{\bar{\nu}})$	3.5
Fuel composition	3.2
θ_{12}	2.3
P_{rm}	2.0
Long-lived isotopes	1.0
E_i	0.6
θ_{13}	0.5
L_r	0.4
$\sigma_{\bar{\nu}p}$	0.4
δm^2	0.03
Total	5.8

Number of expected **reactor anti-ν_e candidates**
(for the exposure of **(**613 ± 26**)** ton x yr) after cuts:

$$N_{react} = (33.3 \pm 2.0)\ events$$

Cuts and Exposure

Cuts used to select anti-ν 's candidates:
1)Q_{prompt} > 408 p.e. and 860 p.e. < $Q_{delayed}$ < 1300 p.e.; (1 MeV about 500 p.e.)
2)Reconstructed distance R < 1 m;
3)Time interval 20 μs < t < 1280 μs between the prompt and the delayed event.

The **Gatti parameter G** has been used to improve background rejection to discriminate highly ionizing particles (α, proton) from particles with lower specific ionization (β^-, β^+, γ). For the delayed candidate a very slight cut requiring **$G_{delayed}$ < 0.015** is applied.

The **total detection efficiency** with these cuts (determined by MC) is 0.84 ± 0.01.

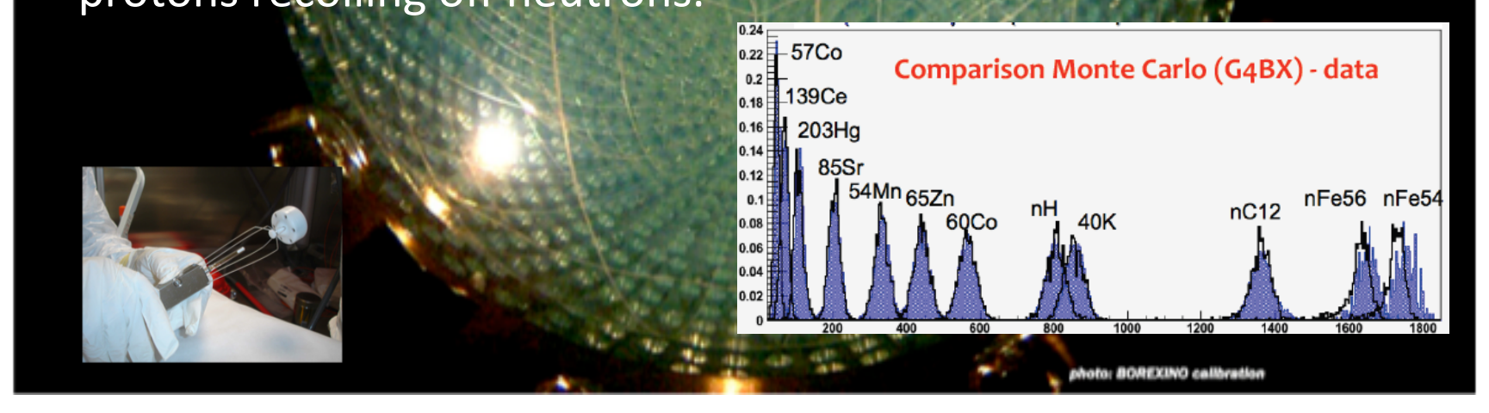
A dedicated algorithm was developed to calculate the vessel shape based (dedicated LED calibration system). The systematic error on the position reconstruction of anti-ν_e candidates is 3.8%.

Total exposure (613 ± 26) ton x year (*calculated as a sum of weekly exposures which consider the corresponding weekly live time and the vessel shape as well as the (0.84 ± 0.01) efficiency of the selection cuts described above*).

The **4.2% error on the exposure** is a sum in quadrature of the errors on
- the vessel shape (1.6%),
- the position reconstruction of the candidates (3.8%),
- the cuts efficiency (1%).

Borexino calibration

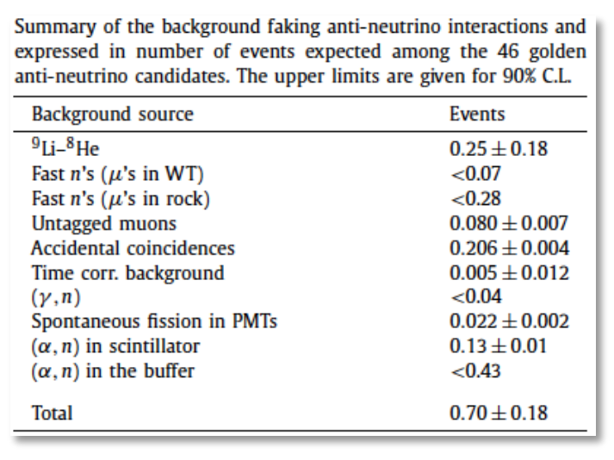
campaigns included several γ , β, α sources placed through the scintillator volume on and offaxis.
The AmBe source, producing ~10 neutrons/s with energies up to 10 MeV, was deployed in twenty-five different positions allowing the study of the detector response to captured neutrons and to protons recoiling off neutrons.



Backgrounds faking anti-neutrino interactions

can arise from

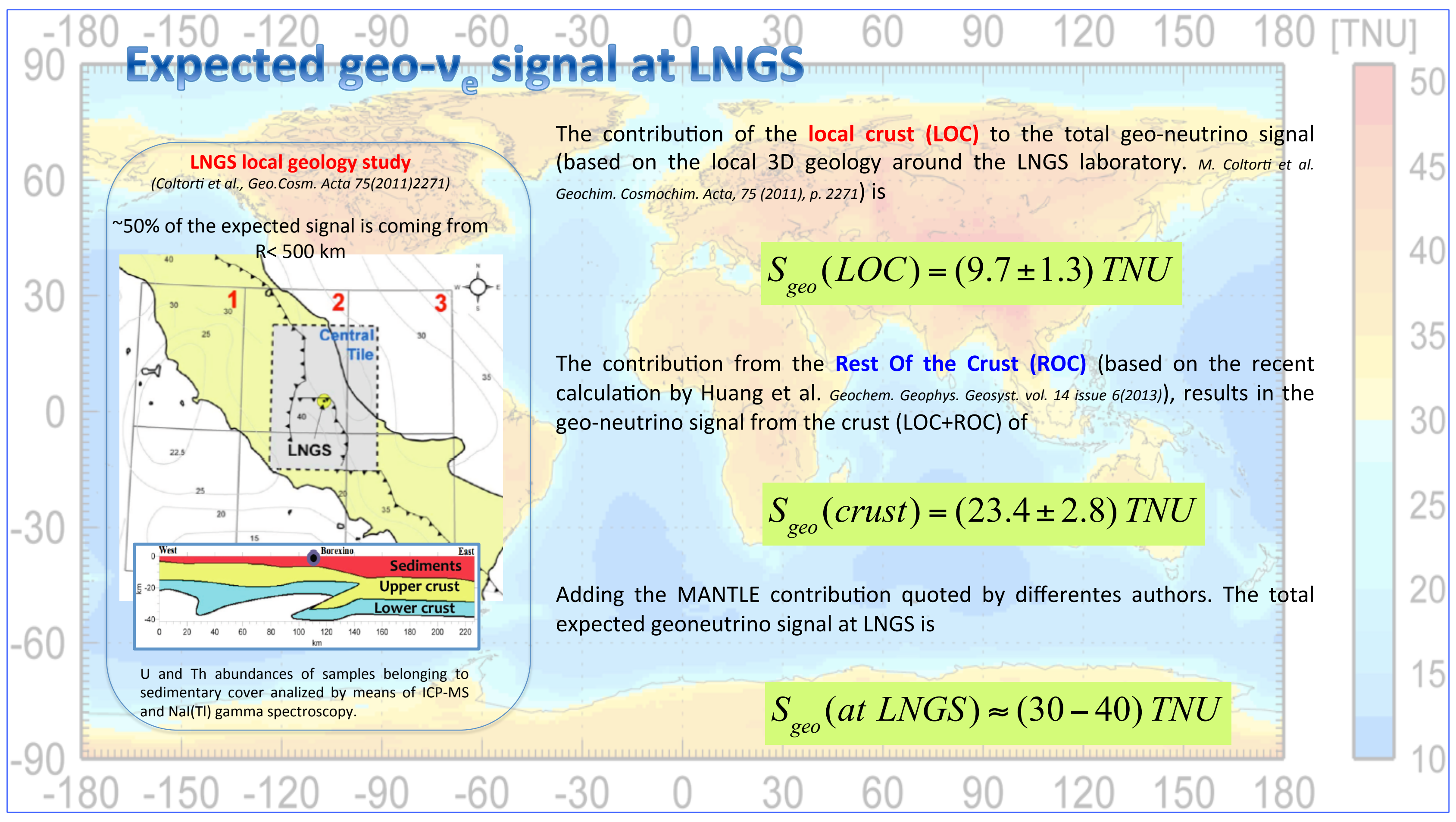
- cosmic muons and muon-induced unstable nuclides;
- intrinsic contaminations of the scintillator and of the surrounding materials;
- accidental coincidences of non-correlated events.



Summary of the background faking anti-neutrino interactions and expressed in number of events expected among the 46 golden anti-neutrino candidates. The upper limits are given for 90% C.L.

Background source	Events
^{9}Li–^{8}He	0.25 ± 0.18
Fast n's (μ's in WT)	<0.07
Fast n's (μ's in rock)	<0.28
Untagged muons	0.080 ± 0.007
Accidental coincidences	0.206 ± 0.004
Time corr. background	0.005 ± 0.012
(γ,n)	<0.04
Spontaneous fission in PMTs	0.022 ± 0.002
(α,n) in scintillator	0.13 ± 0.01
(α,n) in the buffer	<0.43
Total	0.70 ± 0.18

Expected geo-ν_e signal at LNGS



LNGS local geology study
(Coltorti et al., Geo.Cosm. Acta 75(2011)2271)

~50% of the expected signal is coming from R< 500 km

U and Th abundances of samples belonging to sedimentary cover analized by means of ICP-MS and NaI(Tl) gamma spectroscopy.

The contribution of the local crust (LOC) to the total geo-neutrino signal (based on the local 3D geology around the LNGS laboratory. *M. Coltorti et al. Geochim. Cosmochim. Acta, 75 (2011), p. 2271*) is

$$S_{geo}(LOC) = (9.7 \pm 1.3)\ TNU$$

The contribution from the **Rest Of the Crust (ROC)** (based on the recent calculation by Huang et al. *Geochem. Geophys. Geosyst. vol. 14 issue 6(2013)*), results in the geo-neutrino signal from the crust (LOC+ROC) of

$$S_{geo}(crust) = (23.4 \pm 2.8)\ TNU$$

Adding the MANTLE contribution quoted by differentes authors. The total expected geoneutrino signal at LNGS is

$$S_{geo}(at\ LNGS) \approx (30-40)\ TNU$$

Detected geo-ν_e signal at LNGS

46 golden anti-neutrino candidates passing all the selection criteria have been identified

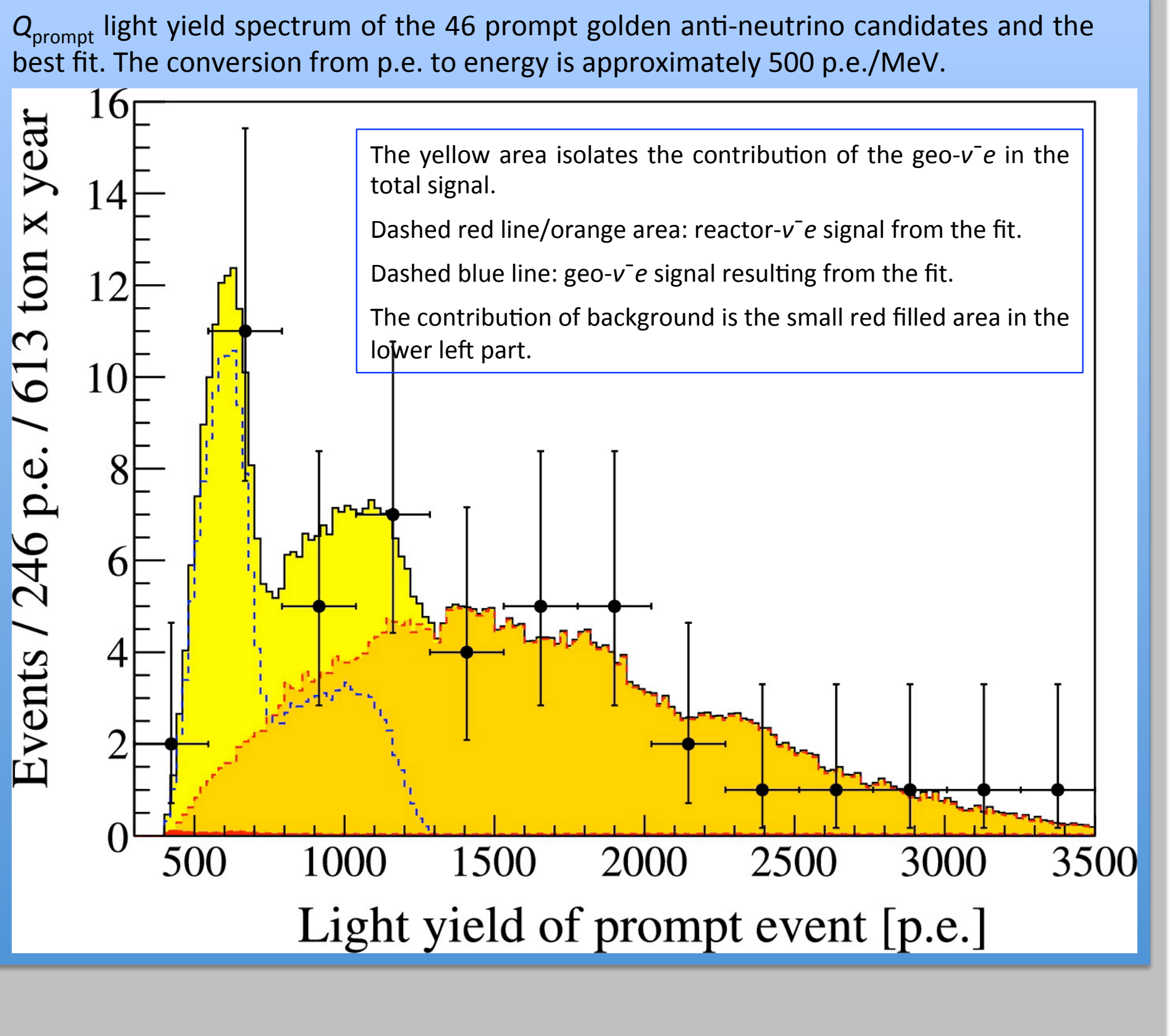
All prompt events of these golden candidates have a *negative Gatti parameter*, confirming that they are not due to α's or fast protons.

The total number of the expected background is

$$N_{exp.BKG} = (0.70 \pm 0.18)\ events$$

The signal-to-background ratio is $\frac{Signal}{Noise} \approx 65$

Q_{prompt} light yield spectrum of the 46 prompt golden anti-neutrino candidates and the best fit. The conversion from p.e. to energy is approximately 500 p.e./MeV.



The yellow area isolates the contribution of the geo-ν¯e in the total signal.

Dashed red line/orange area: reactor-ν¯e signal from the fit.

Dashed blue line: geo-ν¯e signal resulting from the fit.

The contribution of background is the small red filled area in the lower left part.

Unbinned maximal likelihood fit of the light yield spectrum of the prompt candidates

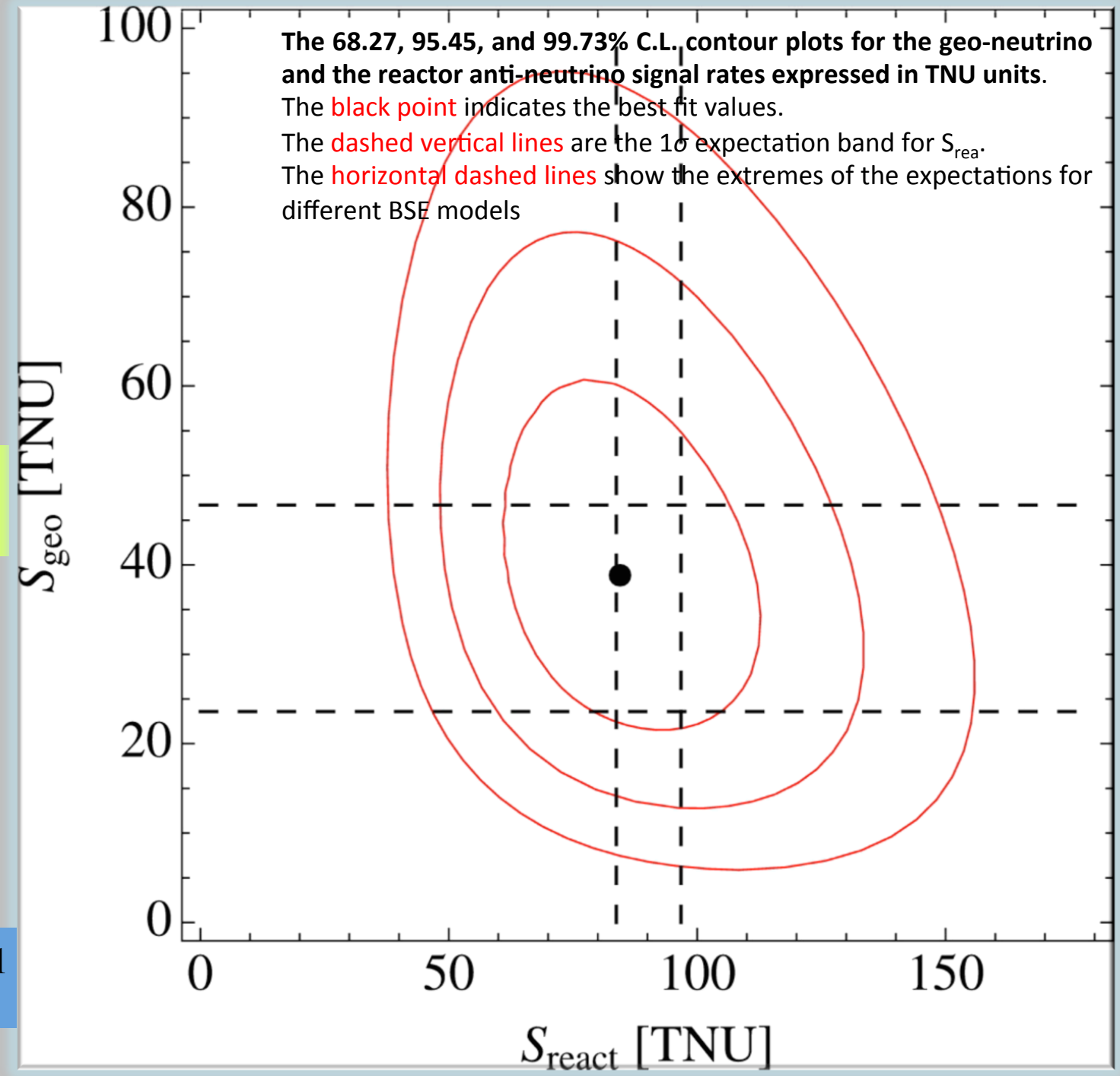
- The weights of the geo-neutrino (Th/U mass ratio fixed to the chondritic value of 3.9) and the reactor anti-neutrino spectral components were left as free fit parameters.
- The main background components were restricted within ±1σ around the expected value.

The best fit value gives:

$$N_{geo} = (14.3 \pm 4.4)\ events \qquad S_{geo} = (38.8 \pm 12.0)\ TNU$$

corresponding to signals

$$N_{react} = 31.2^{+7.0}_{-6.1}\ events \qquad S_{react} = 84.5^{+19.3}_{-16.9}\ TNU$$



The 68.27, 95.45, and 99.73% C.L. contour plots for the geo-neutrino and the reactor anti-neutrino signal rates expressed in TNU units.
The black point indicates the best fit values.
The dashed vertical lines are the 1σ expectation band for S_{rea}.
The horizontal dashed lines show the extremes of the expectations for different BSE models

The measured geo-neutrino signal corresponds to overall ν¯e fluxes from U and Th decay chains of

$$\phi(U) = (2.4 \pm 0.7)\cdot 10^6 cm^{-2}s^{-1} \qquad \phi(Th) = (2.0 \pm 0.6)\cdot 10^6 cm^{-2}s^{-1}$$

Subtracting the estimated crustal components from the Borexino geo-neutrino rate, the contribution of the mantle:

$$N_{geo}\left(Mantle\right) = (15.4 \pm 12.3)\ TNU$$

Borexino and KamLAND combined analysis (in order to extract the S_{geo}(Mantle))

The corresponding LOC + ROC crustal contributions are taken from [*G. Fiorentini et al.Phys. Rev. D, 86 (2012)*] and [*Y. Huang et al.Geochem. Geophys. Geosyst. (2013)*]. The measured S_{geo} signal:

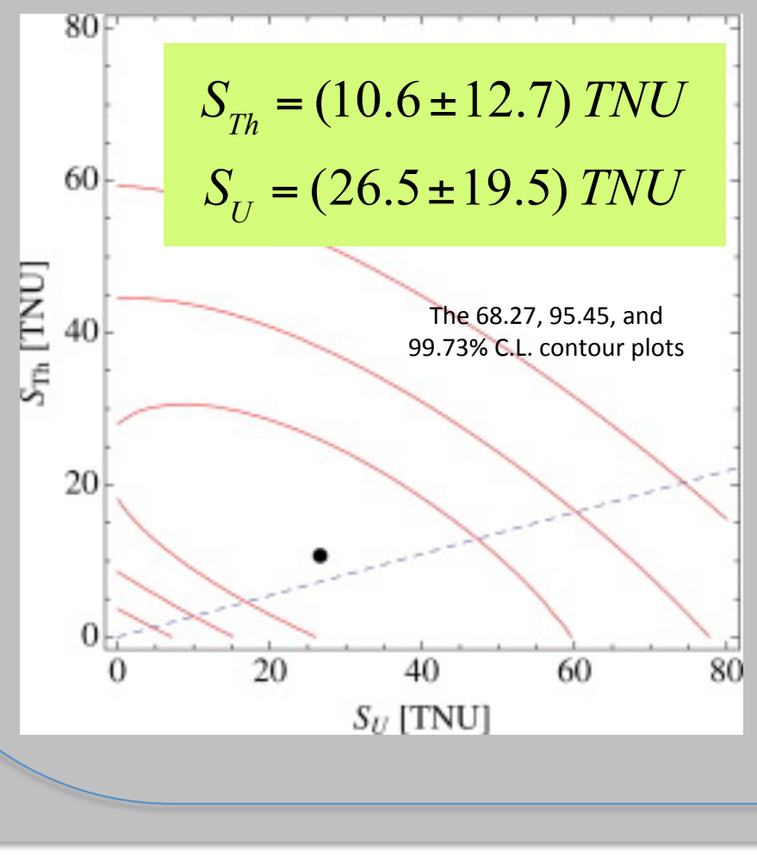
$$S_{geo}(crust) = (23.4 \pm 2.8)\ TNU \quad Borexino$$

$$S_{geo}(crust) = (25.0 \pm 1.9)\ TNU \quad KamLAND$$

The best fit value for the mantle signal common for both sites (a spherically symmetric mantle was assumed) is

$$S_{geo}(Mantle) = (14.1 \pm 8.1)\ TNU$$

Unbinned maximal likelihood in which the individual contributions from the ^{238}U and ^{232}Th chains were fitted individually

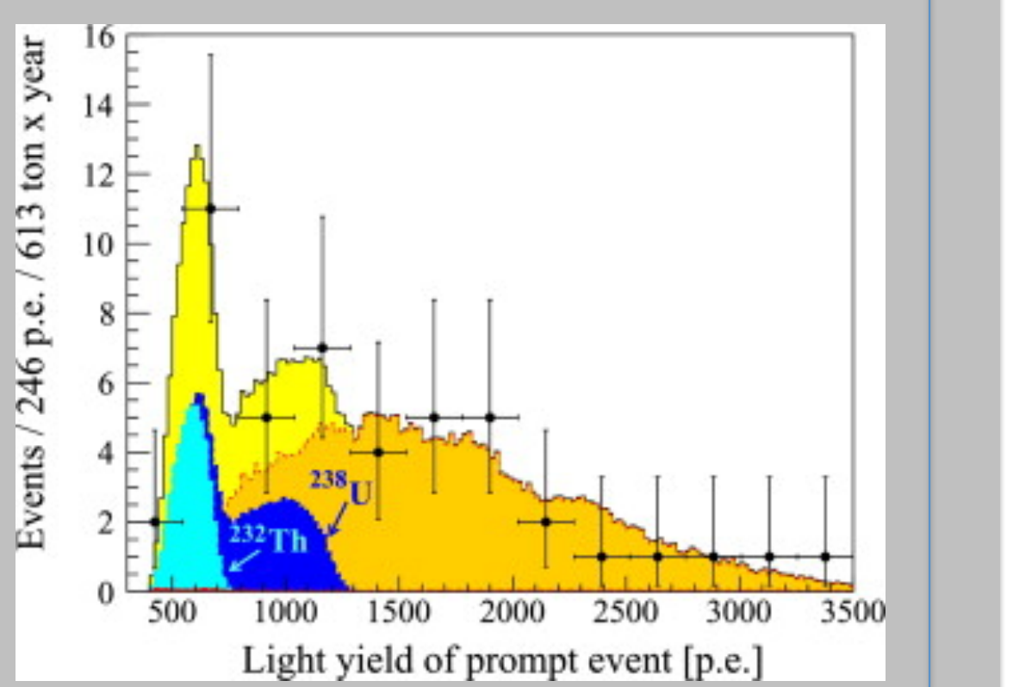


$$S_{Th} = (10.6 \pm 12.7)\ TNU$$

$$S_U = (26.5 \pm 19.5)\ TNU$$

$$\phi(Th) = (2.6 \pm 3.1)\cdot 10^6 cm^{-2}s^{-1}$$

$$\phi(U) = (2.1 \pm 1.5)\cdot 10^6 cm^{-2}s^{-1}$$



The maximum poster size is 48 inches x 48 inches (122.88 cm).