Antineutrino studies with Borexino detector

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on behalf of Borexino collaboration

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the Borexino Collaboration

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Virginia Tech

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Amherst

Paris

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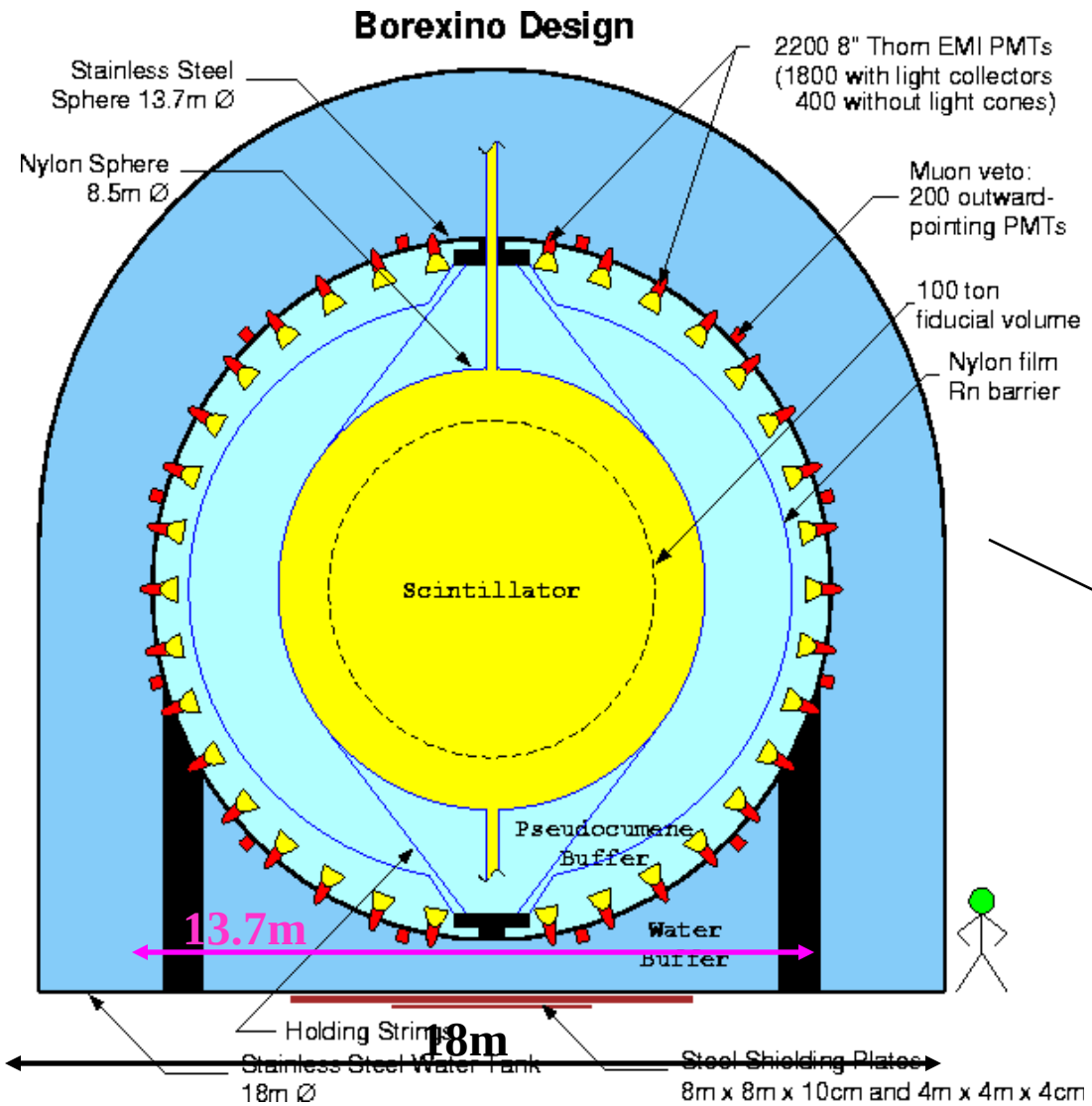
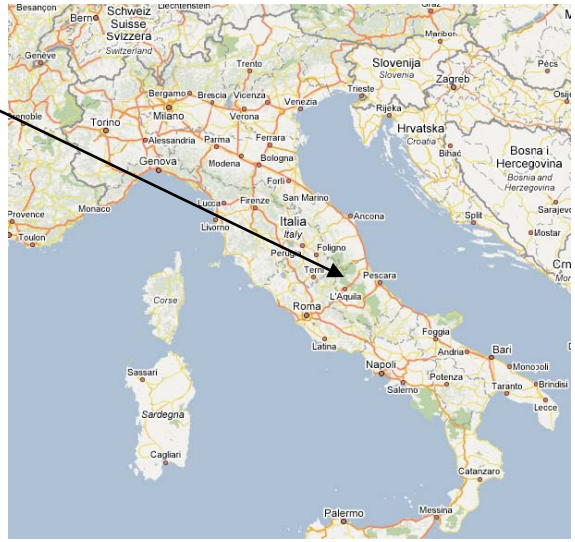
BOREXINO started data taking in 2007



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

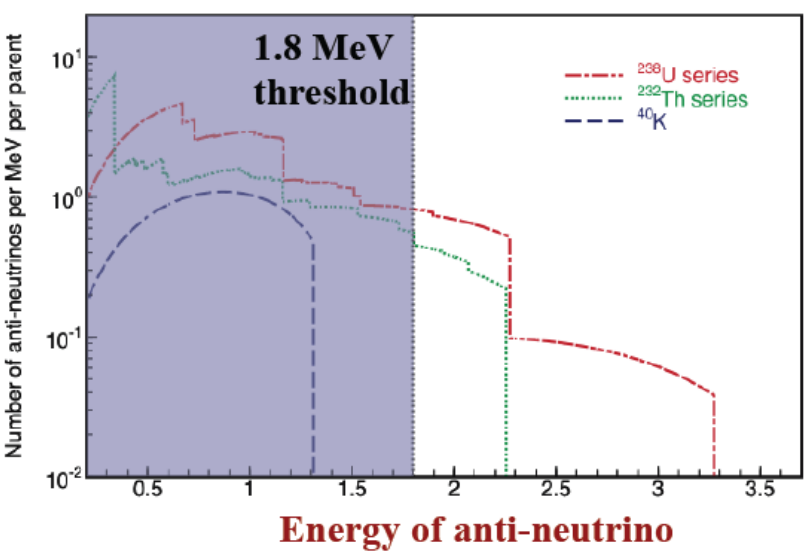


Geoneutrino detection

- **geoneutrino- antineutrino from β- decays of long lived isotopes (U-238 , Th-232, K-40), naturally present in the mantle and the crust of the Earth. Expected flux at the surface ~10^6 $s^{-1}sm^{-2}$.**
- **Full thermal flux from the Earth is 30-45 TW (measurements), it is believed that the main contribution to the thermal flux provide radioactive decays.**
- **Radiogenic heat is related to the antineutrino flux. Standard models (based on the meteorites composition and the measurements of the crust composition) predict radiogenic contribution to the total thermal flux of the Earth of about 19 TW.**
- **Some "unusual"models are being developed, i.e. models with georeactor at the center of the Earth (J.M.Herndon) as the energy source (3-6 TW) for the geomagnetic field.**

Natural radioactivity of the Earth: Open questions

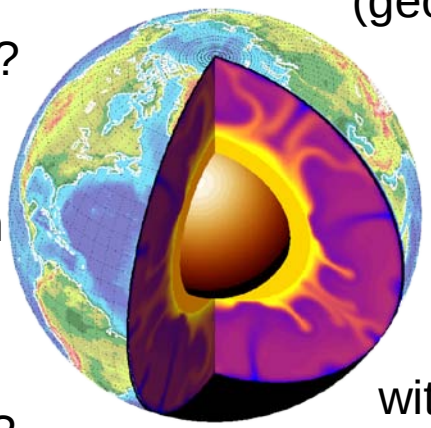
Expected signal shape



Radiogenic contribution to total heat flow?

U/Th concentration in the crust?

U/Th amount in the mantle?

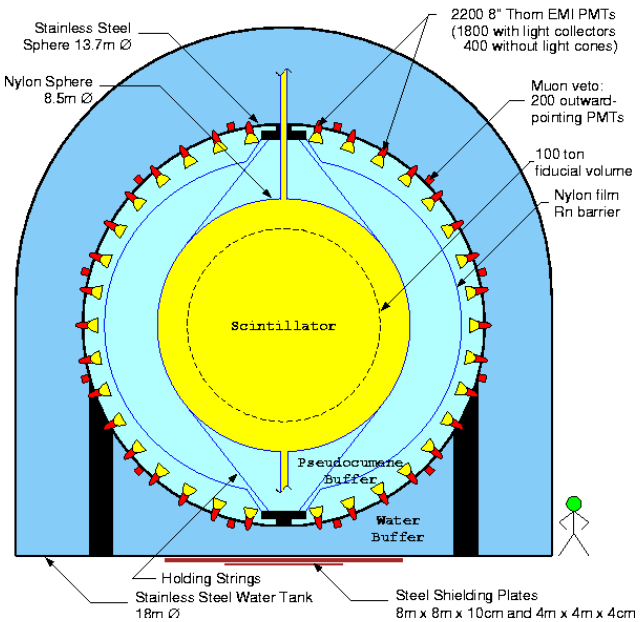


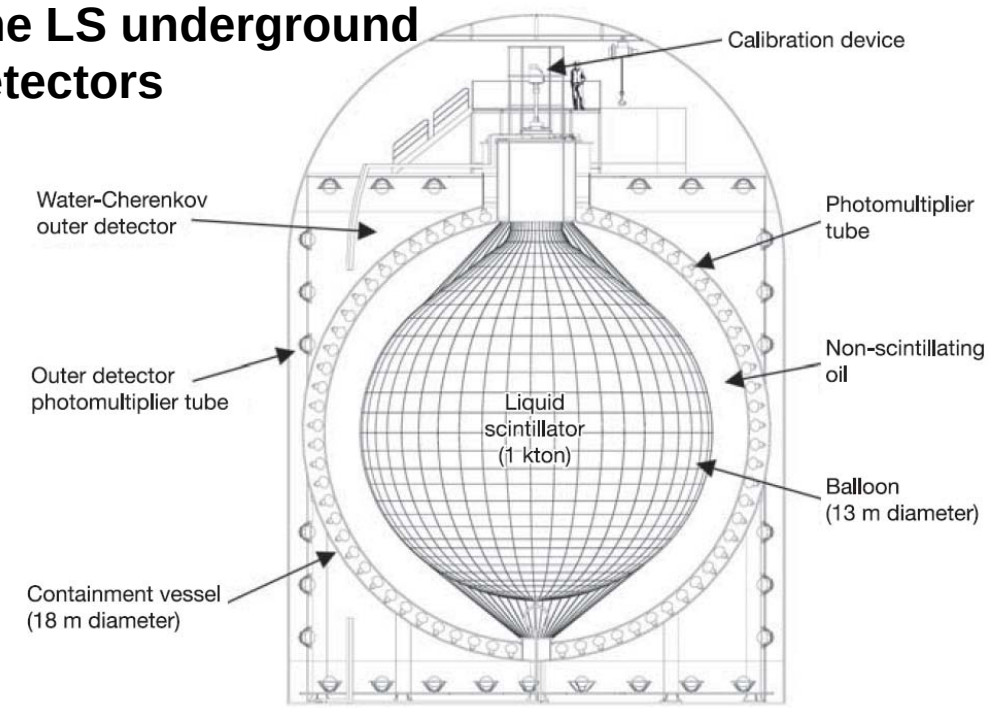
What is in the core (georeactor, ^{40}K)?

Is standard geochemical model (BSE) compatible with geoneutrino measurements?

Two detectors sensitive to geo-neutrino

Large volume LS underground detectors





Borexino: 300 t LS (3500 mwe)

KamLAND: 1 kton LS (2700 mwe)

Data selection for antineutrino analysis

- **~2 years (Dec 2007-Dec 2009), 537.2 days of live time in total. Full exposition is 252.6 t·yr taking into account detection efficiency**
- **Antineutrino are detected using delayed coincidence tag from the inverse beta-decay on proton (~256 μs)**

$$\bar{\nu}_e + p \rightarrow e^+ + n$$
$$\downarrow \approx 250\mu s$$
$$n + p \rightarrow d + \gamma(2.2MeV)$$

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

Cuts:

1) Q_{prompt}>410 p.e.

2)700 <$Q_{delayed}$<1250 p.e.

3)ΔR<1 m;

4)20 <Δt<1280 μs,

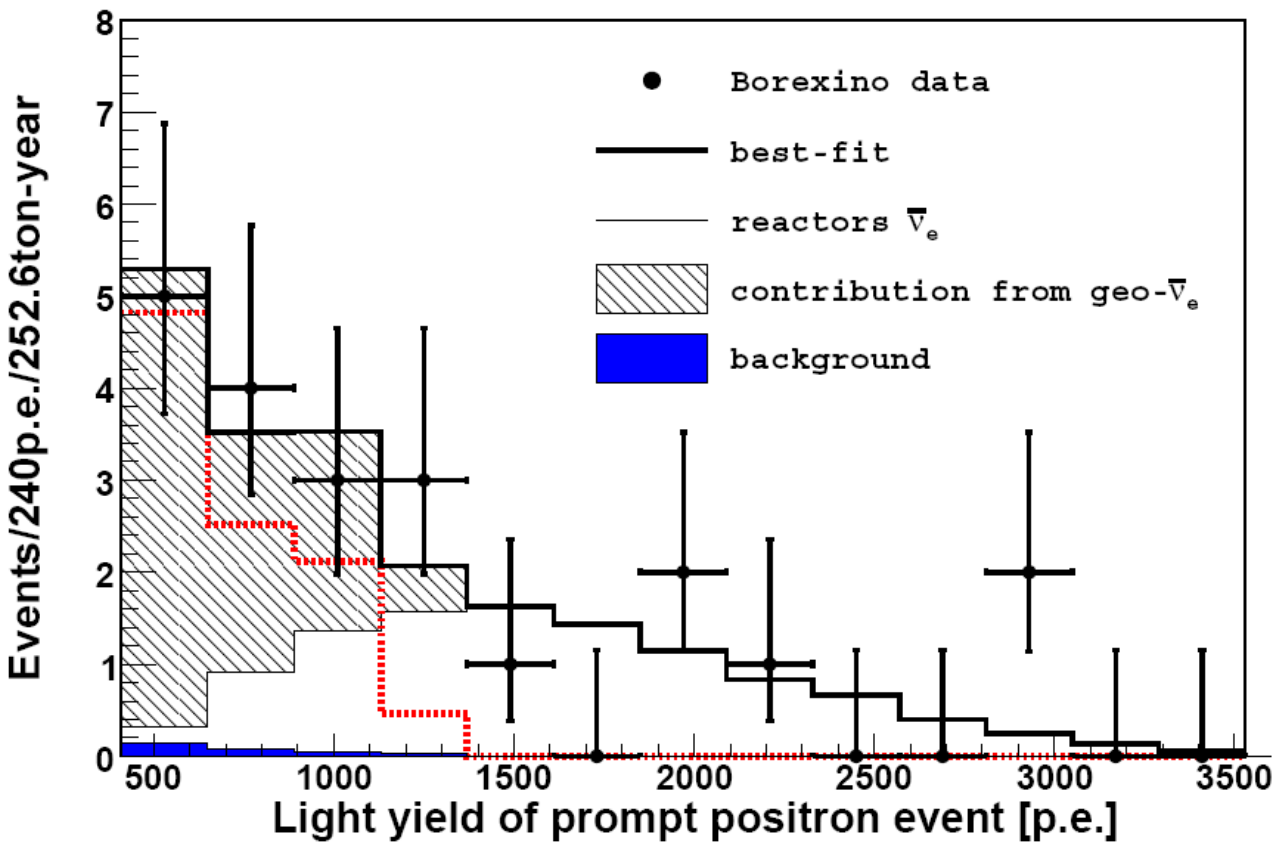
5)$R_{IV}(\Theta,\varphi)$-$R_{prompt}(\Theta,\varphi)$>0.25 m

6)T_μ>2 s (every muon passing through internal detector: ~10% of live time loss)+ **T_μ>2 ms**

- **ε(1-4)=0.85 0.01 (MC)**

Note: actually we have doubled the statistics. Analysis in progress.

Selected antineutrino spectrum (21 events)

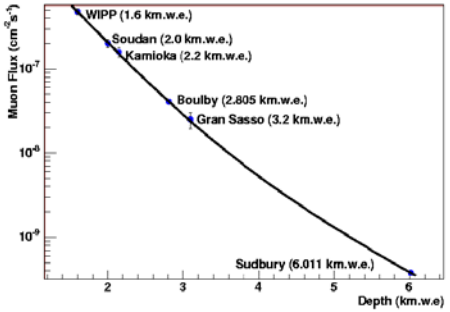


$$Q_{vis} = 438\,p.e.(2\gamma) + Q(E_{\bar{\nu}} - 1.8MeV)$$

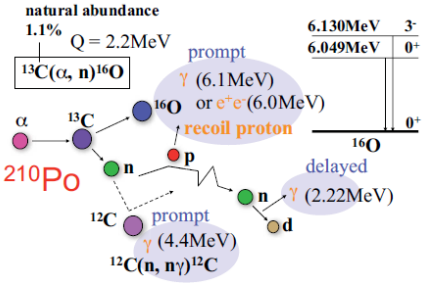
~500 p.e./MeV

Principal backgrounds for geoneutrino studies

1) **Reactor antineutrinos (81% of the total antineutrino signal in KamLAND geo-nu window [0.9-2.6 MeV] and only ~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)**



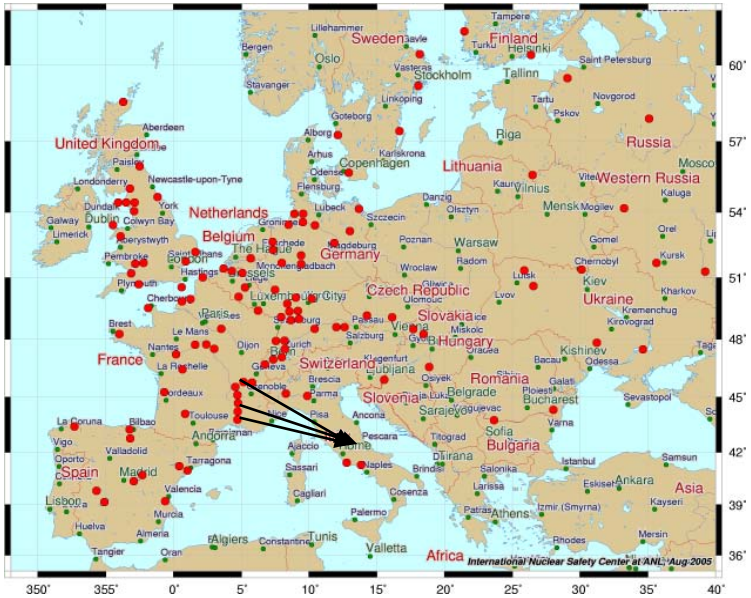
3) **Internal radioactive contamination: accidental coincidences, (αn) reactions (Borexino typical contaminations 3-4 orders of magnitude lower; KamLAND is trying to purify the LS – factor 20 on (αn) is achieved);**

Reactor antineutrino in Borexino

$$\Phi(E_{\bar{\nu}_e}) = \sum_{r=1}^{N_{react}} \sum_{m=1}^{N_{month}} \frac{T_m}{4\pi L_r^2} P_{rm} \times$$

$$\times \sum_{i=1}^{4} \frac{f_i}{E_i} \phi_i(E_{\bar{\nu}_e}) P_{ee}(E_{\bar{\nu}_e}; \hat{\theta}, L_r)$$

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



194 (Europe) +245 (in the rest of the world, 2.5% contribution)

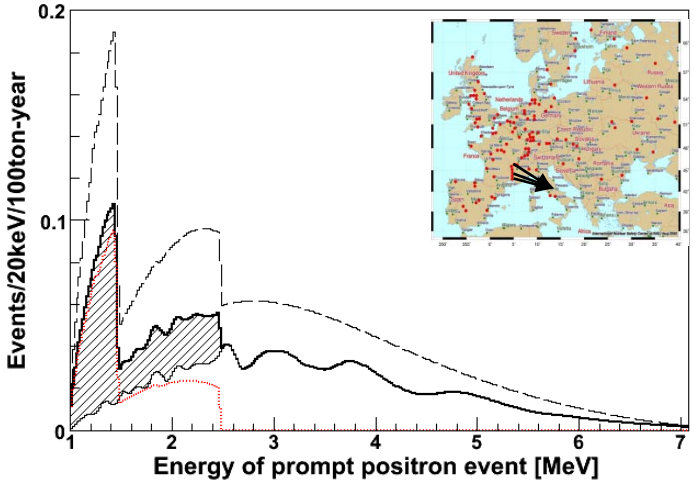
13 Power plants gives 40% of full signal.

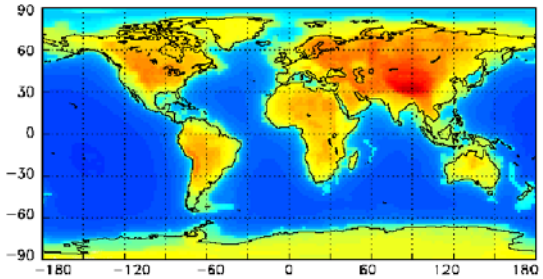
3 most powerful plants in France give 13% of full signal.

Summary of backgrounds

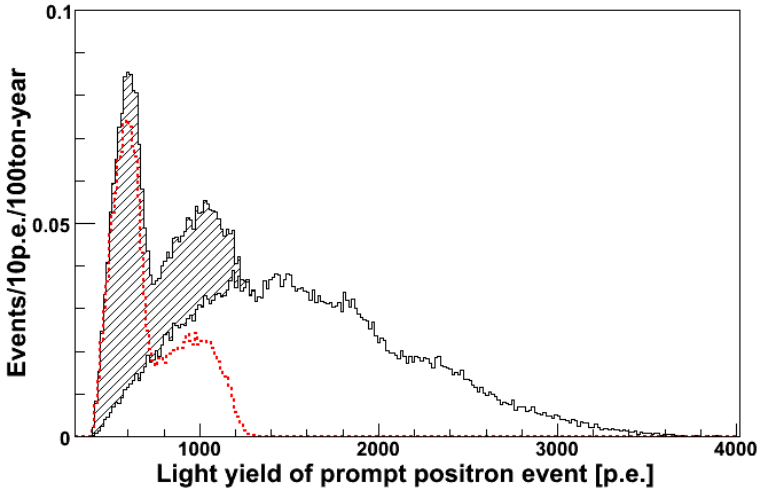
Source	Borexino [events/(kton-year)]	KamLAND [1/(kton yr)]
Cosmogenic ^{9}Li and ^{8}He	0.3 ± 0.2	0.48 ± 0.025 (^{9}Li)
Fast neutrons from μ in Water Tank	< 0.1 (measured)	<0.7
Fast neutrons from μ in rock	< 0.4 (MC)	
Non-identified muons	0.11 ± 0.01	
Accidental coincidences	0.80 ± 0.01	18.76± 0.025
Time correlated background	< 0.26	
(γ,n) reactions	< 0.003	
Spontaneous fission in PMTs	0.030 ± 0.003	
(α,n) reactions in the scintillator [^{210}Po]	0.14 ± 0.01	40.1 ± 4.4
(α,n) reactions in the buffer [^{210}Po]	< 0.61	
TOTAL	1.4 ± 0.2	
SIGNAL (measured)	39^{+16}_{-13} (with 0.2526 kt yr)	$25.7^{+7.0}_{-6.8}$ (with 4.126 kt yr)

Expected geoneutrino+reactor antineutrino spectrum



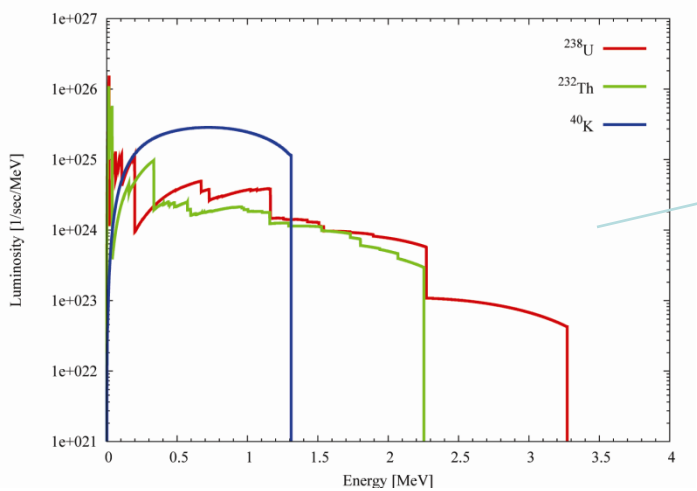


MC spectra (geo + reactors)

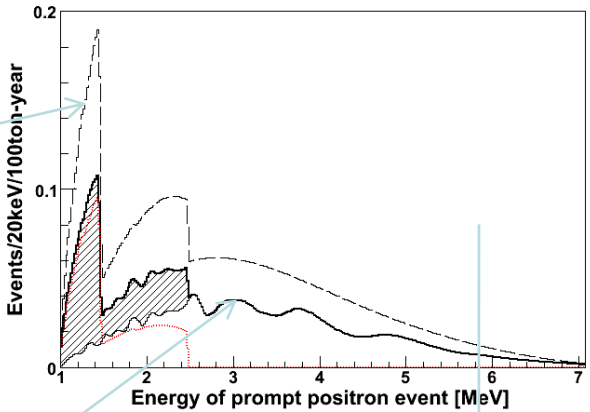


Geoneutrino fluxes calculated using model (**The World Wide Reference Model**) from F. Mantovani, L. Carmignani, G. Fiorentini, and M. Lissia, Phys. Rev. D 69, 013001 (2004).

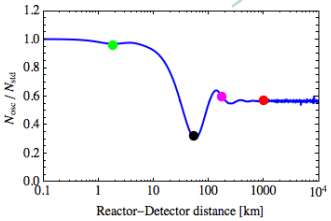
How geoneutrino/reactors spectra are calculated

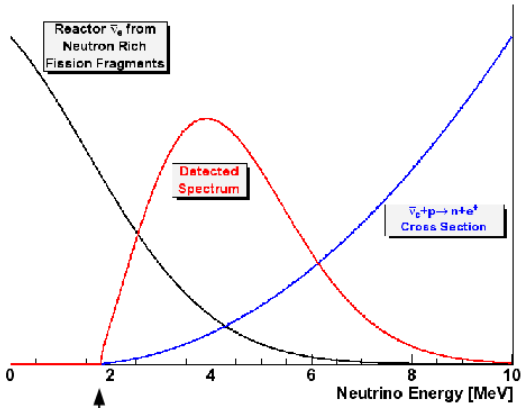


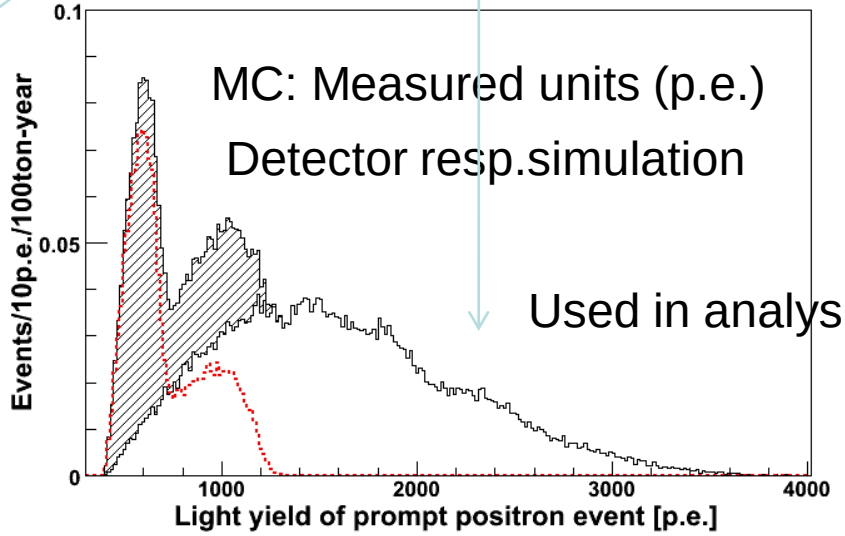
Cross section



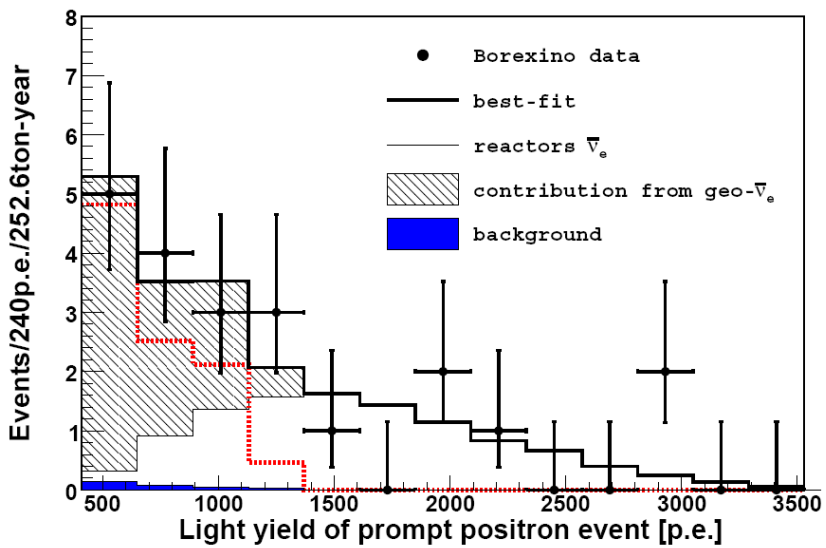
Oscillations







Geoneutrino measurement

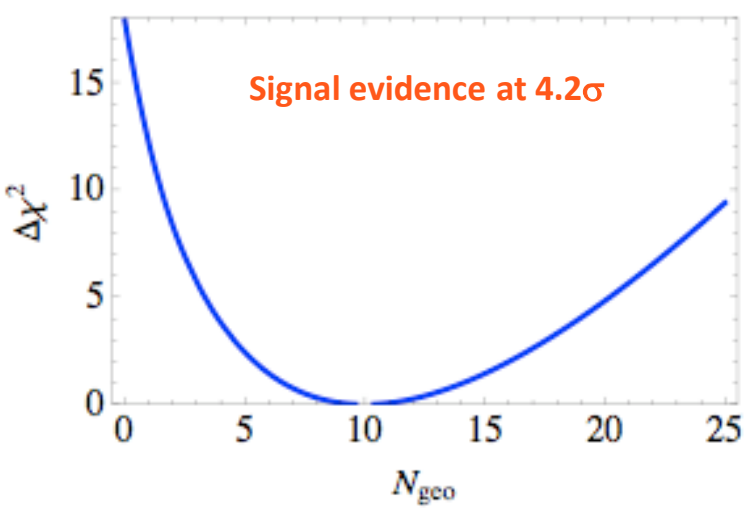


Unbinned max. likelihood fit of data with fixed U/Th

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

68% (99.73%)

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



The presence of the geoneutrino signal is confirmed at 99.997% C.L.

G. Bellini *et al.*, *PLB* **687** (2010) 299-304.

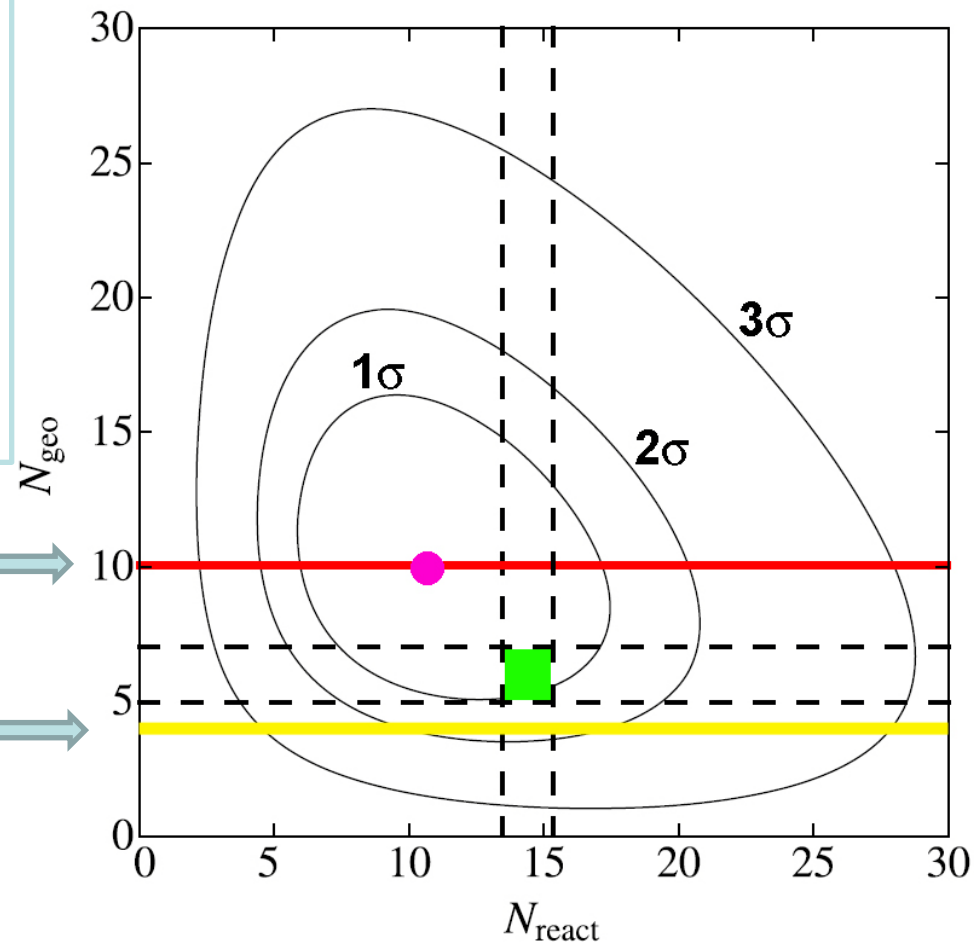
Borexino result vs models

The best fit is within 1σ from the **BSE (Bulk Silicate Earth)** model prediction, the central value close to the fully radiogenic model;

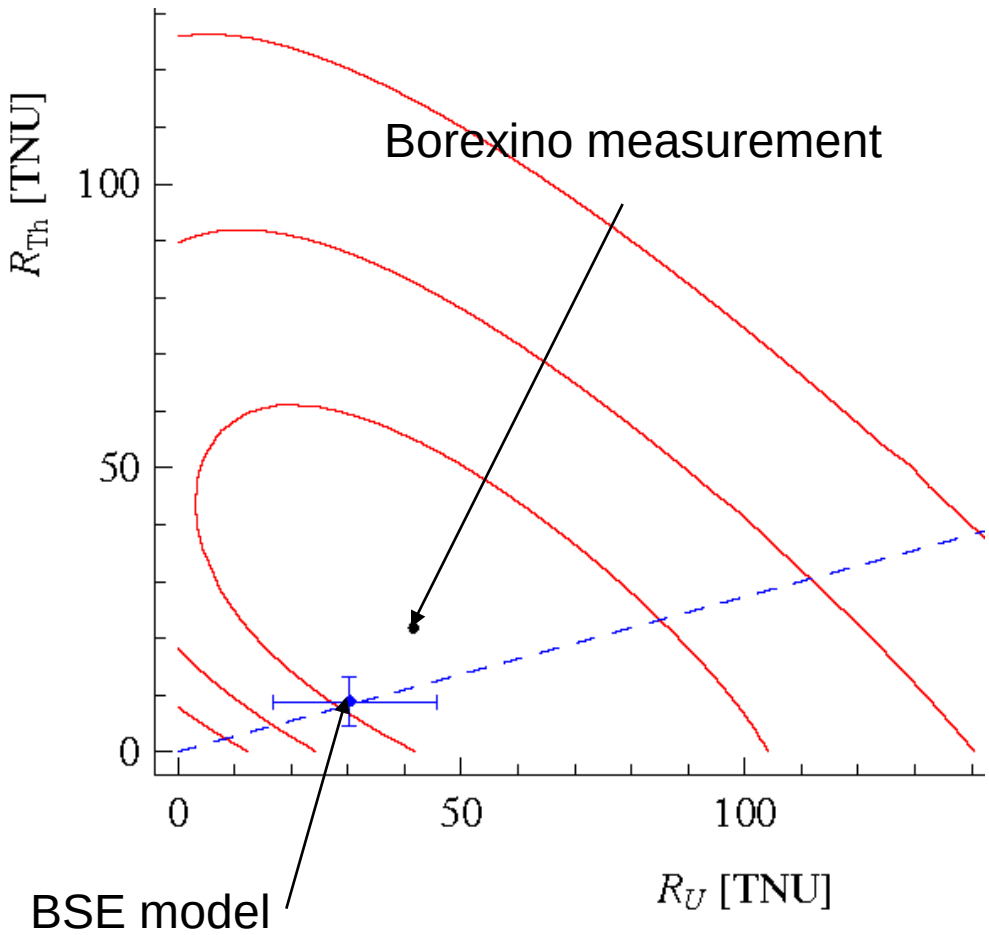
Fully radiogenic model: a model with fully radiogenic heat production; K/U fixed at the terrestrial value and Th/U at the chondritic value (consistent with terrestrial). Abundances are rescaled to provide the full 40 TW heat flow.

fully radiogenic model

minimal radiogenic model



Unconstrained U/Th analysis

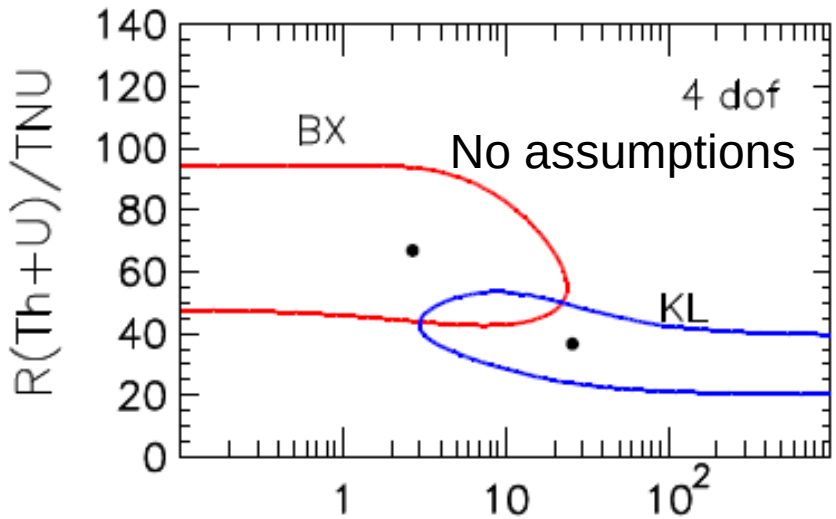


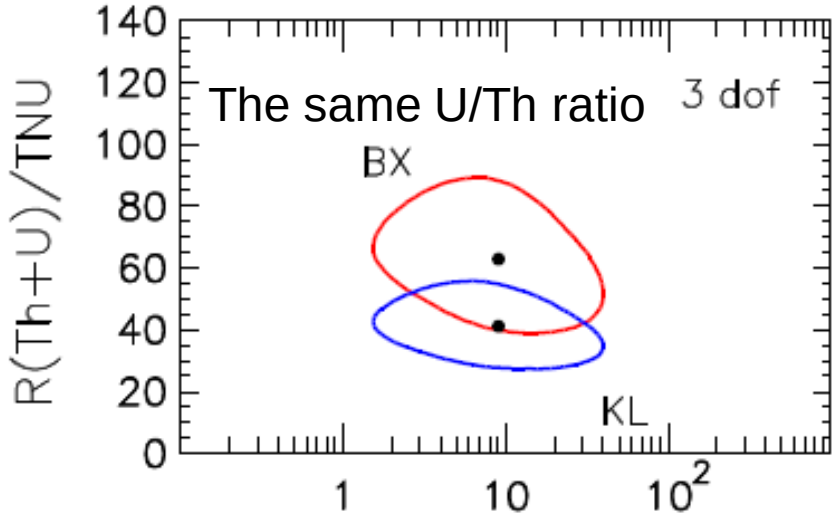
1 *TNU* = *Terrestrial Neutrino Units*: one event per 10^{32} protons per year.

Combined Borexino+KL analysis

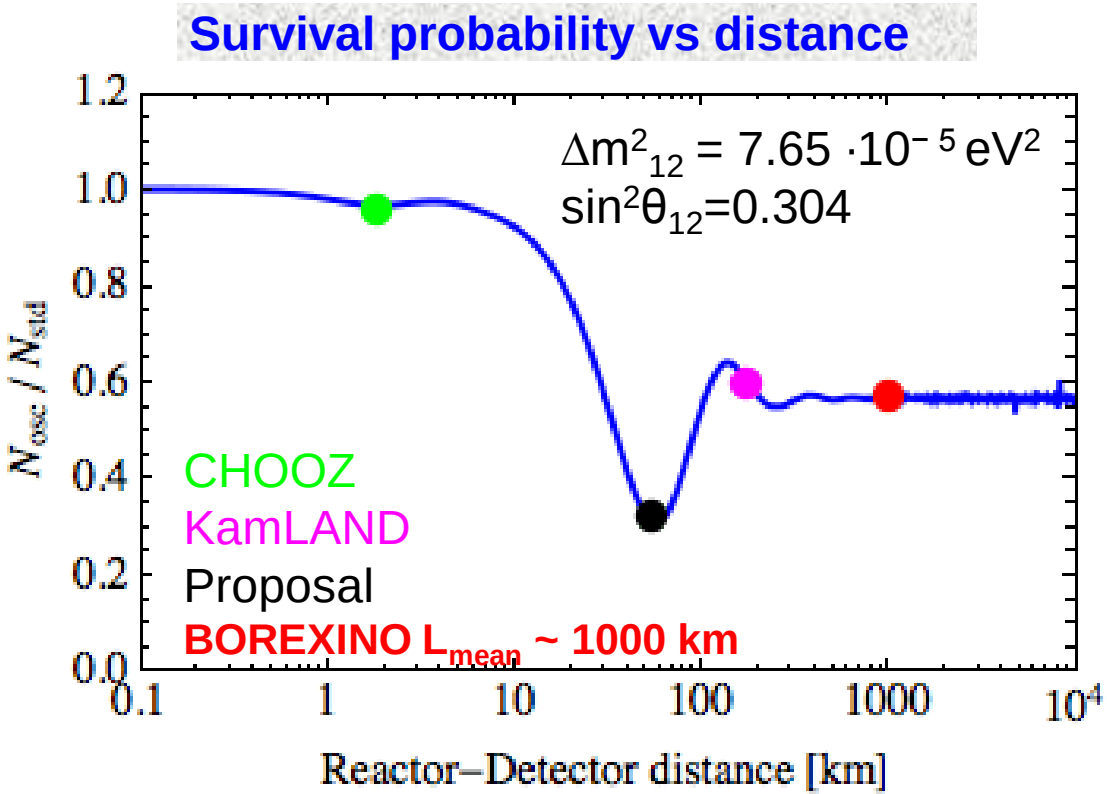
E.Lisi, Rotunno & Palazzo, hep-ph/1006.1113

- **KL and BX data offer the first opportunity to combine geoneutrino results at different sites. Hints about Th/U, heat, mantle contrib.**
- **Any combination requires some model-dependent assumptions.**
- **Zero U and Th are excluded at 1σ level using combined Borexino/KL data even if no assumptions are applied**





Non-oscillation scenario for reactor antineutrino at 1000 km is excluded at 99.60% C.L.



$$P_{ee}(E_{\bar{\nu}}, L) \cong 1 - \sin^2(2\vartheta_{12})\sin^2\left(\frac{1.27\Delta m^2_{12}[eV^2]L[m]}{E_{\bar{\nu}}}\right)$$

Is there a georeactor at the center of the Earth?

Assuming an anti-neutrino spectrum with power fractions of the fuel components as ^{235}U : ^{238}U = 0*.75 : 0.25 Borexino* set an upper bound for a geo-reactor:

P_{geo}<3 TW at 95% C.L.

by comparing the number of expected (from reactors + geo-reactor and background) and measured events in the reactor-antineutrino energy window*.*

- **KamLAND provided a limit (**Nature Geoscience 4, 647–651, 2011)

  P_{geo}<5.2 TW at 90% C.L.

- **E.Lisi et al. (hep-ph/1006.1113) performed an independent test and found at 95% C.L.:**

BX:	P_{geo} < 4.1 TW
KL:	P_{geo} < 6.7 TW
BX+KL:	P_{geo} < 3.9 TW

Electron neutrino with magnetic moment can be converted to antineutrino

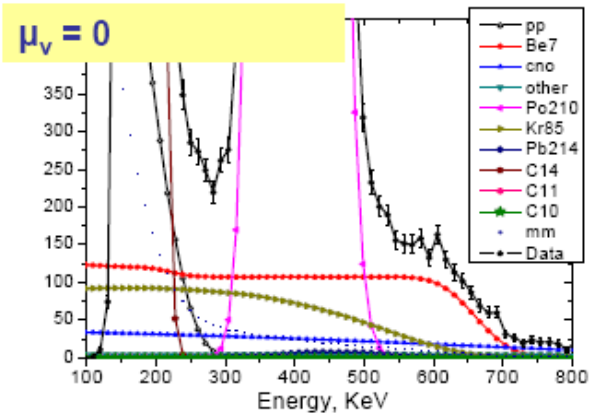
From the Standard Model point of view, there is no diagonal magnetic moment for Dirac massless neutrino, as well as for Majorana neutrino, massive or massless. Massive Dirac neutrino should have small m.m.:

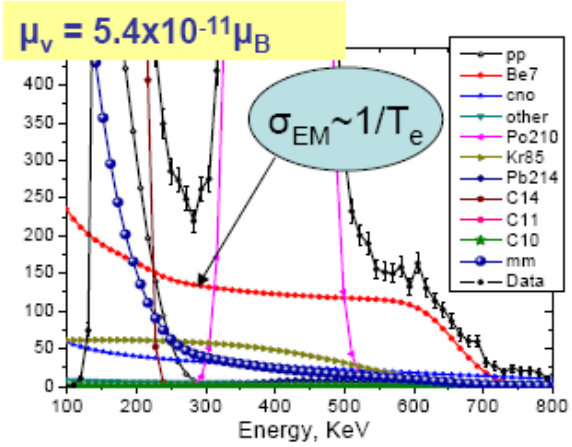
$$\mu_\nu \approx 3.2\times10^{-19}\left(\frac{m_\nu}{1eV}\right)\mu_B$$

m.m. can be searched for by studying the deviations from the weak shape in electron scattering spectrum

"flat" $$\left(\frac{d\sigma}{dT}\right)_W = \frac{2G_F^2 m_e}{\pi}\left[g_L^2 + g_R^2\left(1-\frac{T}{E_\nu}\right)^2 - g_L g_R \frac{m_e T}{E_\nu^2}\right]$$

1/T behaviour $$\left(\frac{d\sigma}{dT}\right)_{EM} = \mu_\nu^2 \frac{\pi\alpha_{em}^2}{m_e^2}\left(\frac{1}{T}-\frac{1}{E_\nu}\right)$$





Limit on effective solar neutrino magnetic moment with Borexino

- **with 192 days of live-time statistics the 90% c.l. limit is:**

$$\mu_{eff} < 5.4 \cdot 10^{-11}\ \mu_B$$

- **The limit is model-independent, defined only by the shape of the spectra, also no systematics is attributed to the uncertainty of the FV.**
- **The best up-to-date existing limit comes from the measurements with high purity 1.5 kg Ge detector at Kalinin Nuclear Power Plant, GEMMA experiment (arXiv:0906.1926):**

$$\mu < 3.2 \cdot 10^{-11}\ \mu_B$$

- **For flavour components one can write [D.Montanino et al. PRD 77, 093011 (2008)]:**

$$(\mu_{eff}^2)_{MSW} = P_{ee}\mu_e^2 + (1 - P_{ee})(\cos^2\theta_{23}\mu_\mu^2 + \sin^2\theta_{23}\mu_\tau^2)$$

where P_{ee}=0.56 is the survival probability at Earth for electron neutrino at E=0.862 MeV, $\sin^2\theta_{23}=0.5^{+0.07}_{-0.06}$

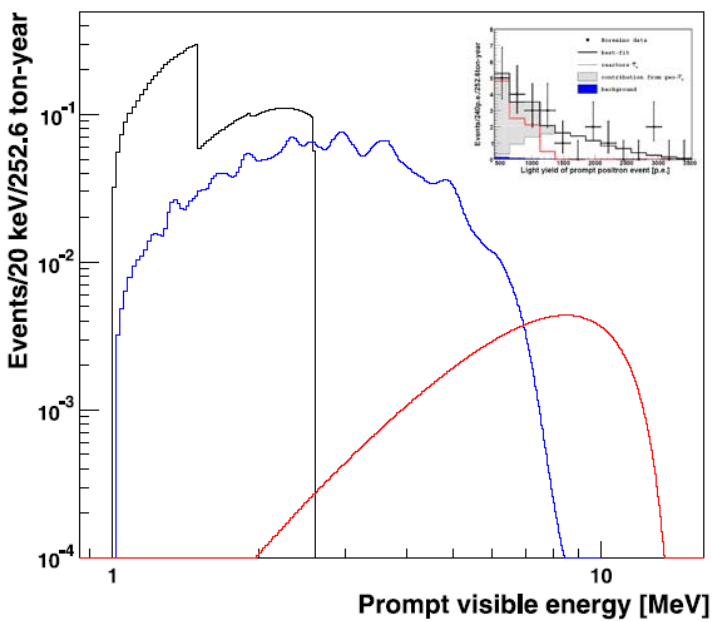
Applying constraints on μ_{ve} of Gemma experiment:

$$\mu_\mu < 12 \cdot 10^{-11}\mu_B$$

$$\mu_\tau < 12.5 \cdot 10^{-11}\mu_B$$

- Present limits on the neutrino magnetic moments are:
- $\mu_e < 3.2\times10^{-11}\ \mu_B$ by GEMMA (elastic scattering)
- $\mu_\mu < 68\times10^{-11}\ \mu_B$ by LSND (elastic scattering)
- $\mu_\tau < 39000\times10^{-11}\ \mu_B$ by DONUT (elastic scattering)

Are there any electron antineutrinos from the Sun?



Energy spectra for electron anti-neutrinos in Borexino: geo- (black) and reactor (blue) normalized to the Borexino measured values for a 252.6 ton year exposure. The spectral shape for hypothetical ^{8}B solar anti-neutrinos (red) is normalized to upper limit

$$p(\nu \to \bar{\nu}) < 1.3 \times 10^{-4} \varphi_{SSM}(^8B) \;\; 90\% \;\; \text{C.L.}$$

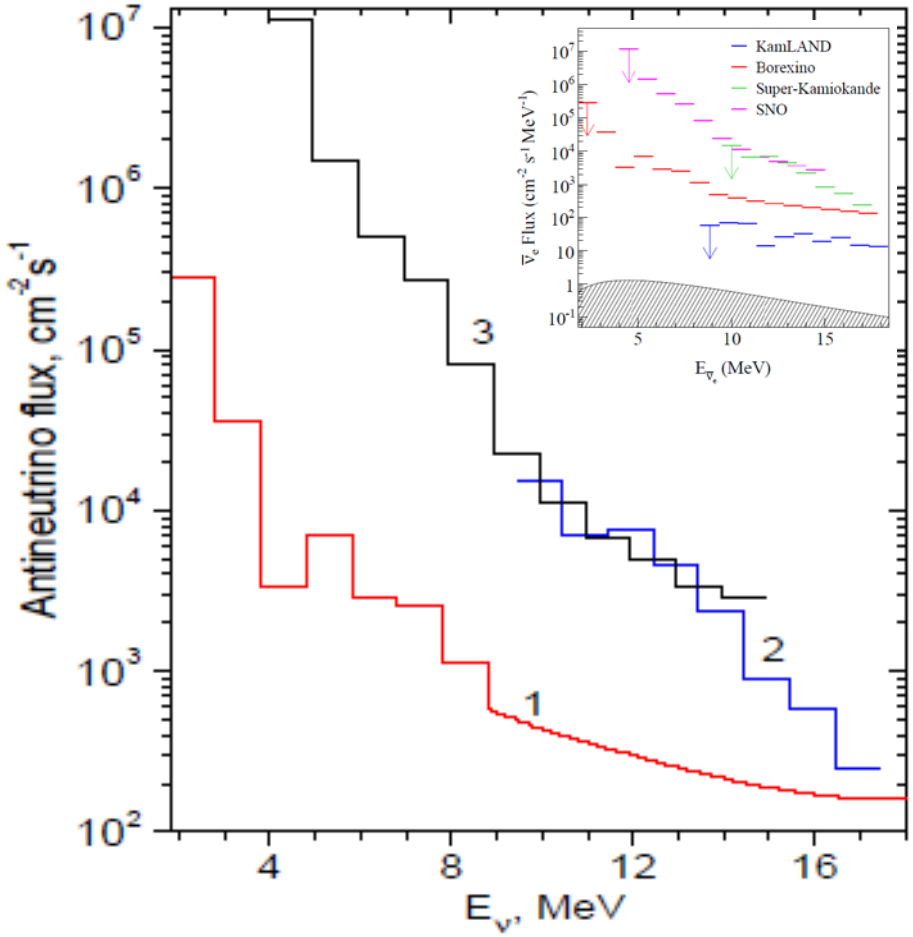
The limit for ^{8}B shaped antineutrino spectrum (φ<760 cm^{-2}s^{-1} at 90% C.L.) was obtained combining data sets below/above 7.3 MeV (no events above a priori chosen threshold of 7.3 MeV during longer time of 736 days against 482 days for the geo-neutrino analysis). Fit procedure developed for the geo-neutrino studies was used with ^{8}B neutrino spectrum weighted for effective exposures below and above 7.3 MeV.

$$\mu_{\bar{\nu}} \le 7.4 \times 10^{-7} \left(\frac{p_{\nu \to \bar{\nu}}}{\sin^2 2\Theta_{12}} \right)^{1/2} \frac{\mu_B}{B_\perp [kG]} \qquad \mu_\nu \le 9 \times 10^{-9} \frac{\mu_B}{B_\perp (R = 0.05 R_{sol})[kG]}$$

B:[600 G – 7 Mg]

G.Bellini et al., Borexino collaboration, Physics Letters B 696 (2011) 191–196
"Study of solar and other unknown anti-neutrino fluxes with Borexino at LNGS"

Are there other unknown sources of electron antineutrinos?



Upper limits on unknown antineutrino fluxes:
1 – Borexino
2 – SuperKamiokaNDE
3 – SNO

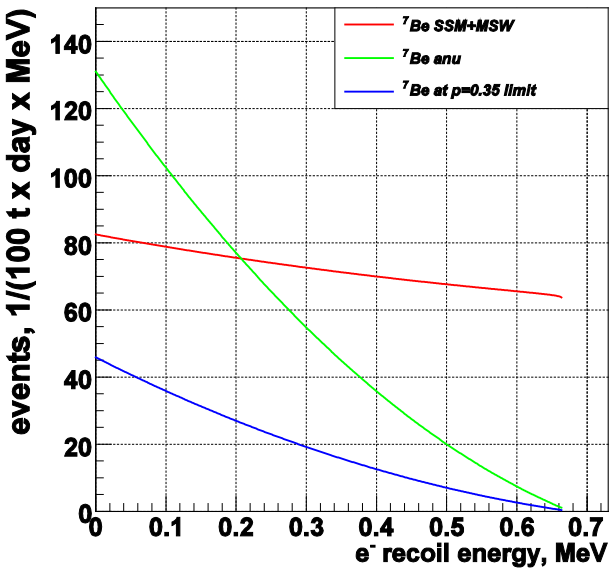
Minimal radiogenic model has been used to set the upper limits.

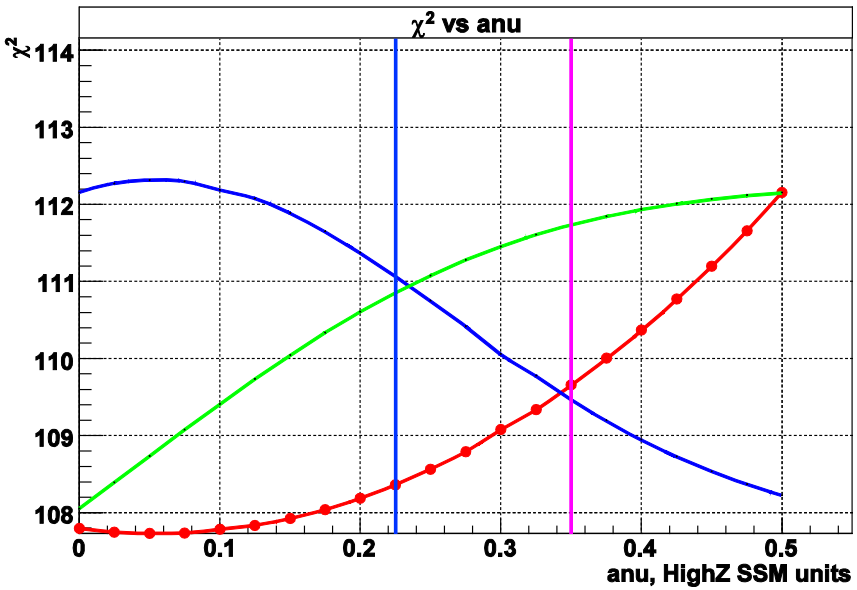
Limits has been set using Feldman–Cousins approach (estimating how much additional antineutrinos can be statistically fit in every energy bin given measured and theoretically expected). Above 7-th bin (E > 7.8 MeV) Slim = 2.44 (Feldman–Cousins recipe for no observed events with zero background)

G.Bellini et al., Borexino collaboration, Physics Letters B 696 (2011) 191–196
"Study of solar and other unknown anti-neutrino fluxes with Borexino at LNGS"

Search for electron antineutrinos with ^{7}Be energy

Below 1.8 MeV no inverse beta on p ➔ elastic scattering on electrons only.
The recoil spectra for electrons elastically scattering off neutrino and antineutrinos are distinct





Following the changes in the *χ^2 profile* with respect to the addition of an anti-neutrino component ($\varphi \rightarrow (1-p)\varphi_{7Be} + p\varphi_{7Be}$) we set a limit on the conversion probability for ^{7}Be solar neutrinos of:

$$p(\nu \rightarrow \bar{\nu}) < 0.35\varphi(^7Be) \;\; 90\% \;\; \text{C.L.}$$

Summary of antineutrino measurements with Borexino

- **1)Geoneutrino existence is confirmed by Borexino at 4.2σ (99.997%);**
- **2)The precision of Borexino measurement is still too low: ~40% for U+Th signal, and much worse for the unconstrained R(U) and R(Th) measurements. Different geological models for the moment can't be discriminated by existing measurements, more precise measurements are needed;**
- **3)Limit of P_{geo}<3 TW at 95% C.L is set for georeactor;**
- **4)Conversion probability into antineutrino for ^{8}B solar neutrinos is limited** $p(\nu \rightarrow \nu) < 1.3 \times 10^{-4}\ \varphi_{SSM}(^{8}B)$ 90% C.L., **limit for ^{7}Be is much weaker** $p(\nu \rightarrow \nu) < 0.35\ \varphi(^{7}Be)$ 90% C.L.,
- **5)New model-independent limits on the antineutrino fluxes are established starting from inverse beta-decay threshold**