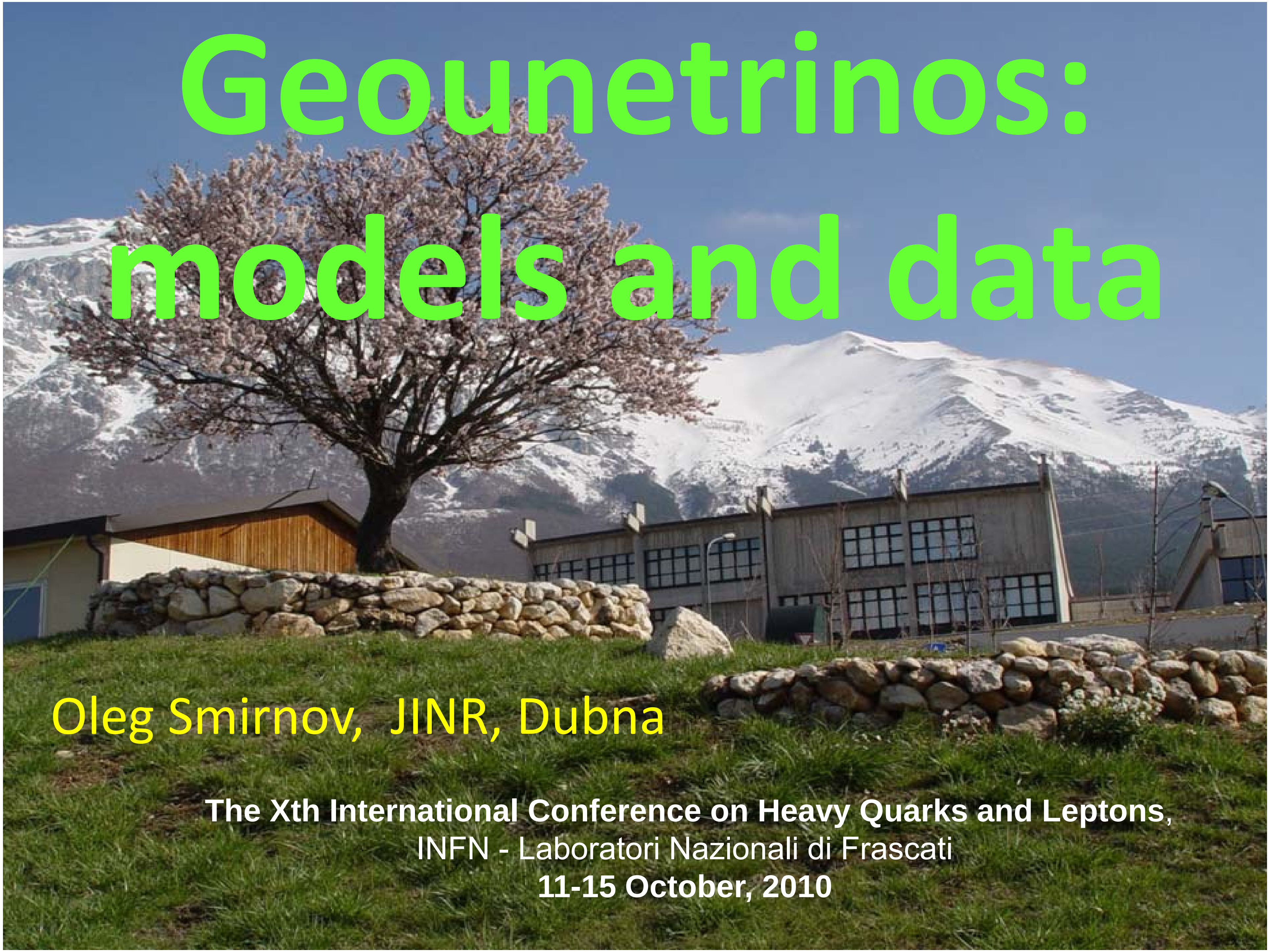


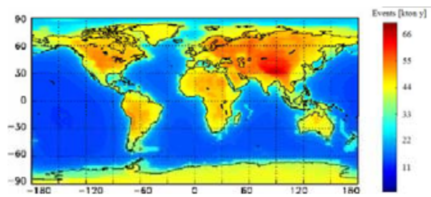
Geounetrinos: models and data

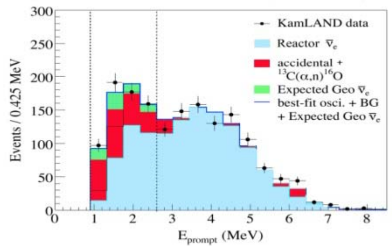
Oleg Smirnov, JINR, Dubna

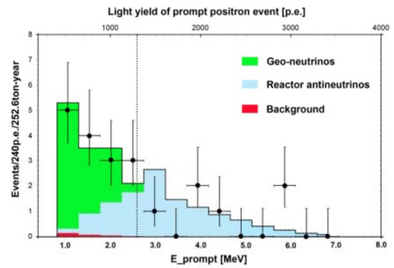
The Xth International Conference on Heavy Quarks and Leptons,
INFN - Laboratori Nazionali di Frascati
11-15 October, 2010

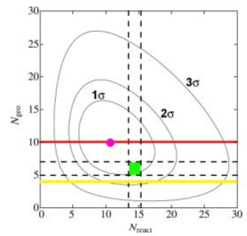
Outline:

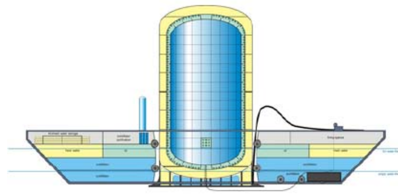
- Overview on geo-neutrinos
- Open questions about radioactivity in the Earth
- Experimental techniques
- Backgrounds
- Recent experimental results:
    - KamLAND 2010
    - Borexino 2010
- The World Wide Reference Model
- Comparison of experimental measurements with models
- An attempt of combined analysis of Borexino and KamLAND data
- The potential of future experiments and projects;
- Conclusions







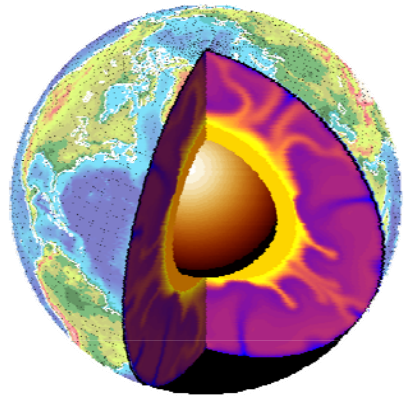




Hanohano

(~10 kt deep ocean detector)

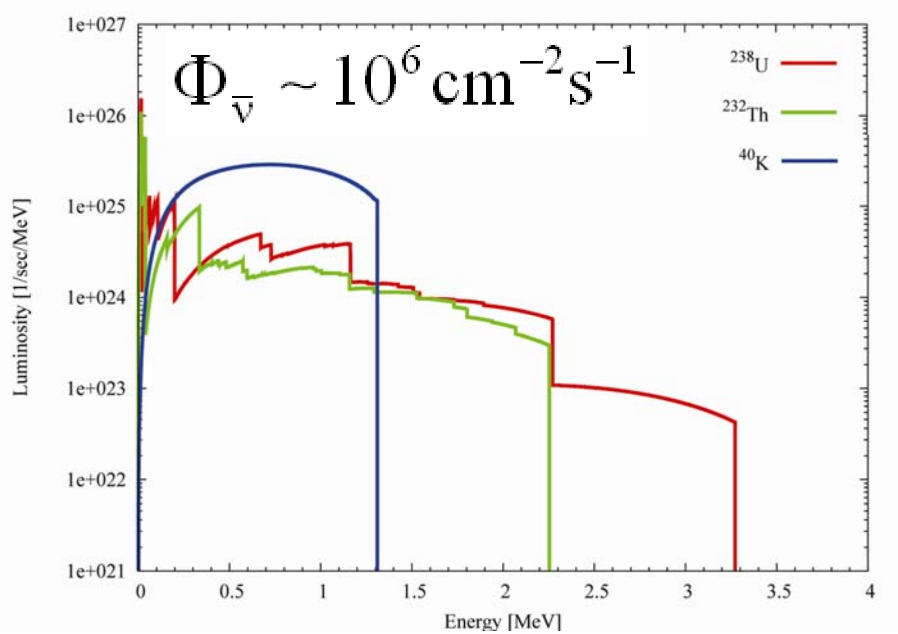
Geo-neutrinos: anti-neutrinos from the Earth



^{238}U, ^{232}Th and ^{40}K (^{87}Rb, ^{235}U) in the Earth release heat together with antineutrinos

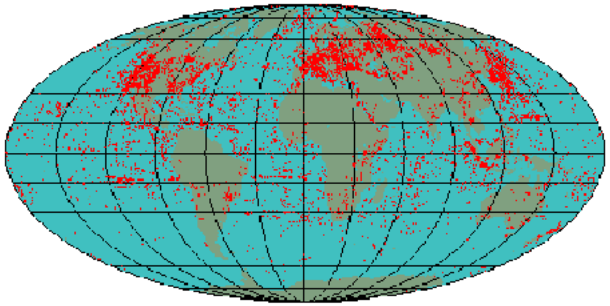
Decay	$T_{1/2}$ [10^9 yr]	E_{max} [MeV]	Q [MeV]	$\varepsilon_{\bar{\nu}}$ [$kg^{-1}s^{-1}$]	ε_H [W/kg]
$^{238}U \to {}^{206}Pb + 8\,{}^4He + 6e + 6\bar{\nu}$	4.47	3.26	51.7	7.46×10^7	0.95×10^{-4}
$^{232}Th \to {}^{208}Pb + 6\,{}^4He + 4e + 4\bar{\nu}$	14.0	2.25	42.7	1.62×10^7	0.27×10^{-4}
$^{40}K \to {}^{40}Ca + e + \bar{\nu}$ (89%)	1.28	1.311	1.311	2.32×10^8	0.22×10^{-4}

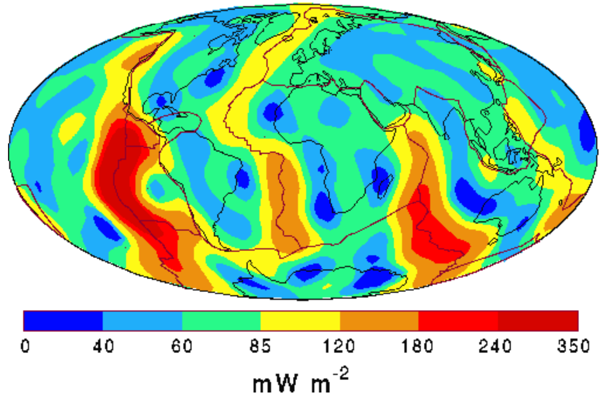
- Earth emits (mainly) antineutrinos whereas Sun shines in neutrinos.
- A fraction of geo-neutrinos from U and Th are above threshold for inverse β on protons: 1.8 MeV
- Different components can be distinguished due to different energy spectra: e. g. anti-ν with highest energy are from Uranium.



Radiogenic contribution to the Heat flow from the Earth

about 25000 measurements in 20000 sites





Average flux

$\Phi \approx 80$ mW/m^2

Full thermal flux:

H_E = (30- 46) TW

44±1 TW (Pollack 1993)

31 ±1 TW (Hofmeister et al 2005)

(Analysis of the same data)

- Radiogenic heat is related to the neutrino flux:

$H_R = 9.5\ M(U) + 2.7\ M(Th) + 3.6\ M(^{40}K)$

$L_\nu = 7.4\ M(U) + 1.6\ M(Th) + 27\ M(^{40}K)$

- H [TW] ; M [10^{17}kg] ; L_ν[10^{24} 1 /s]
- M(U), M(Th) and M(K)

Canonical BSE model predicts 19 TW radiogenic heat production:

9 TW the continental crust +
10 TW mantle + 0 core (assumed)

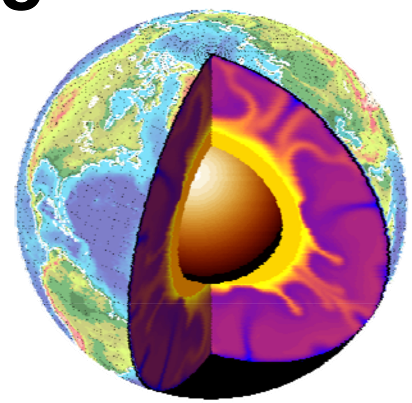
U+Th vs K:
16(U+Th) TW + 3(^{40}K) TW

Some “unusual” models are being developed, i.e. the model with georeactor at the center of the Earth (J.M.Herndon) as the energy source for the geomagnetic field

Bulk Silicate Earth (BSE) model

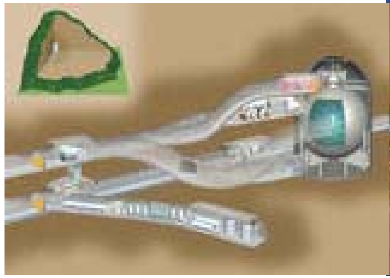
- A global description of the present crust-plus-mantle system is provided by the BSE model, **a reconstruction of the primordial mantle of the Earth**, subsequent to the core separation and prior to crust differentiation, based on geochemical arguments. The mass ratios here are: M(Th)/M(U) = 3.9, M(K)/M(U)≈10^4 and U abundance is $2 \cdot 10^{-8}$. In the BSE model the present radiogenic production, mainly from U and Th, accounts for about one half of the total heat flow, 19 TW. Concentration of U in the mantle is 0.01 ppm.
- **Used in models to put mass constraint in order to determine the abundances in the lower portion of the mantle.**

Open questions on the natural radioactivity in the Earth

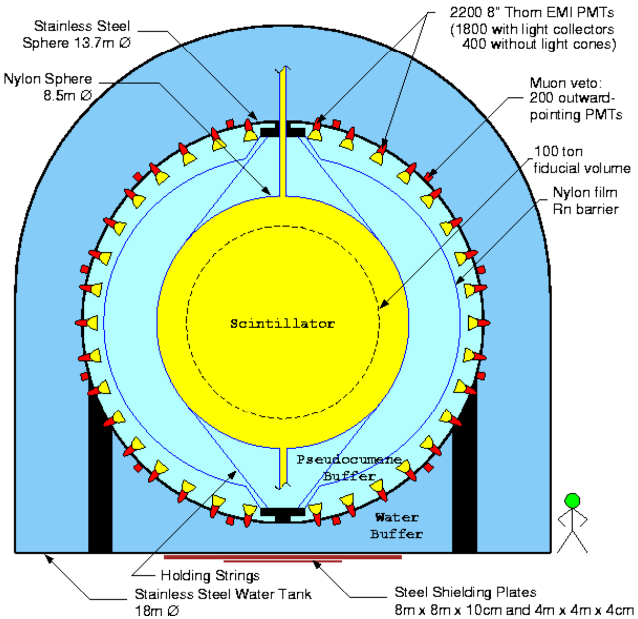


- What is the radiogenic contribution to terrestrial heat production?
- How much U and Th in the crust?
- How much U and Th in the mantle?
- What is hidden in the Earth's core? (geo-reactor, ^{40}K, …)
- Is the standard geochemical model (BSE) consistent with geo-neutrino data?

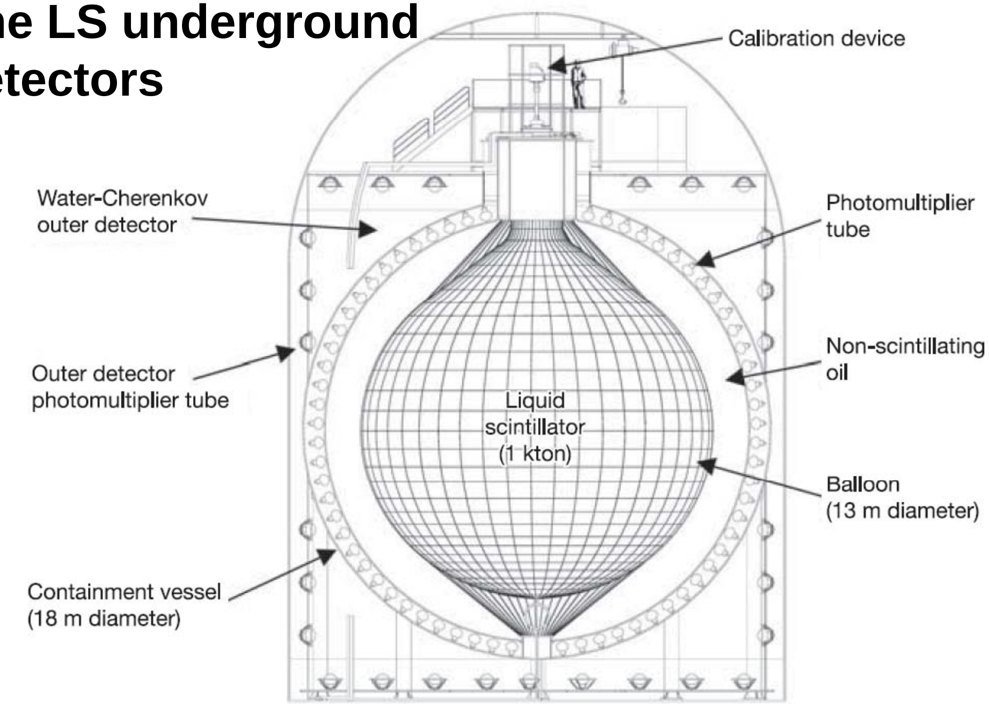
Two detectors sensitive to geo-neutrino



Large volume LS underground detectors



Borexino: 300 t LS (3500 mwe)



KamLAND: 1 kton LS (2700 mwe)

Antineutrino detection (inverse β-decay on p)

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

Borexino

- **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}(Θ,ϕ)-R_{prompt}(Θ,ϕ)>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)**

KamLAND

- **Res(E)=6.5% @ 1 MeV**

Cuts:

1) 0.9 MeV< E_p <8.5MeV

2)1.8 MeV< E_d <2.6 MeV (p)

4.0 MeV< E_d <5.8 MeV (^{12}C)

3)ΔR<2 m;

4)0.5μs<Δt <1000μs

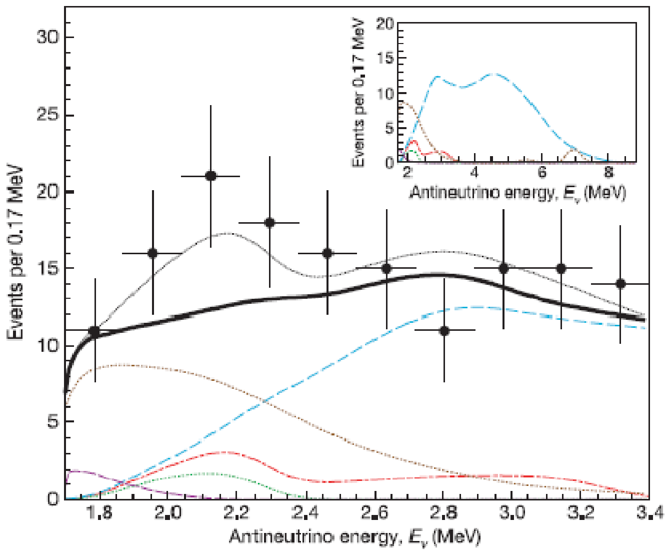
5)R_p<6 m & R_d<6 m (Rdet=6.5 m)

6)T_μ>2 s (only showering muons: ~4% of live time loss) + **T_μ>2 ms**

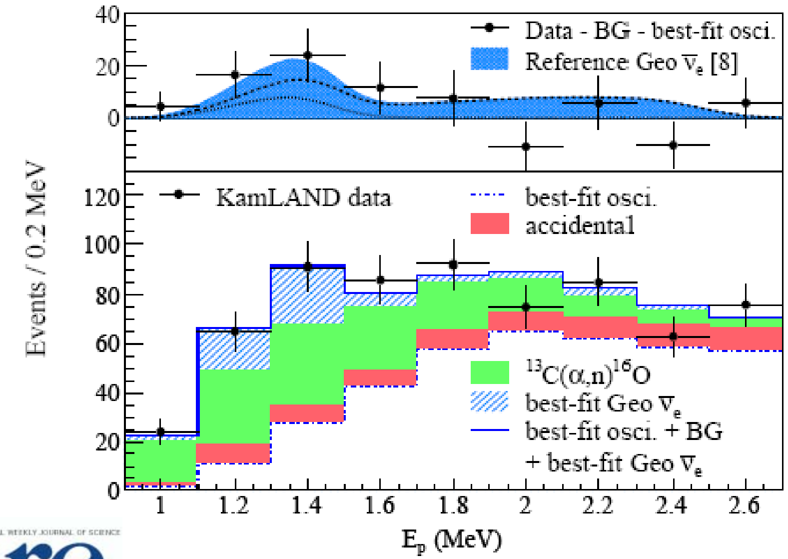
- **ε(1-4)=0.697±0.007**

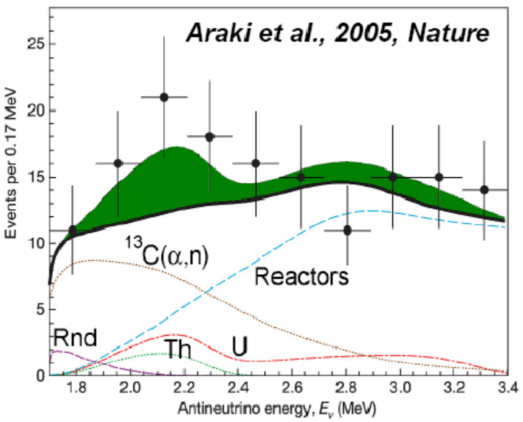
First hints:
2005 - KamLAND – 2008

4.5-54.2 (90%) events U+Th

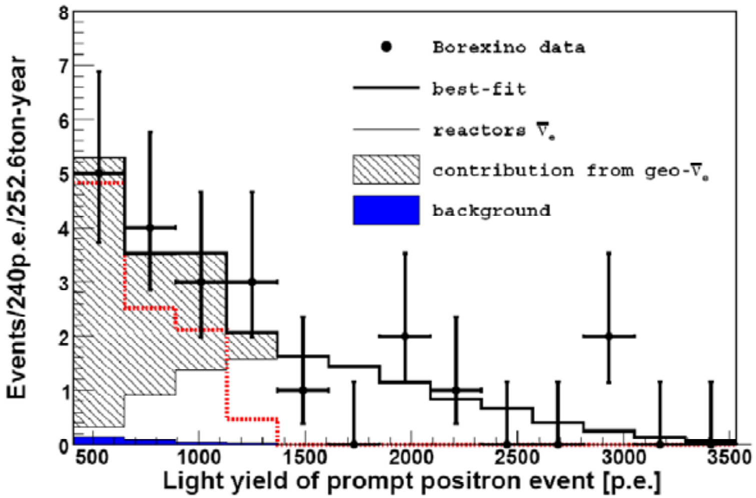


73±27 events U+Th





Borexino - 2010

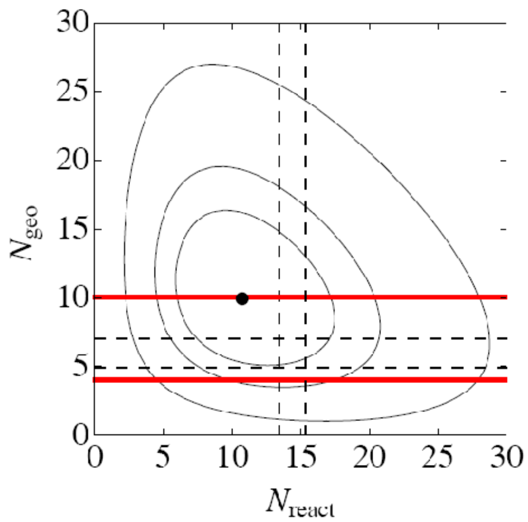


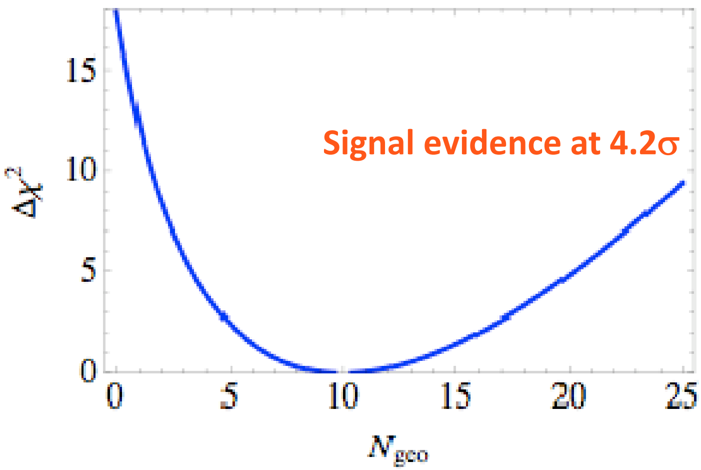
Unbinned max. likelihood fit of data

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

68% (99.73%)

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

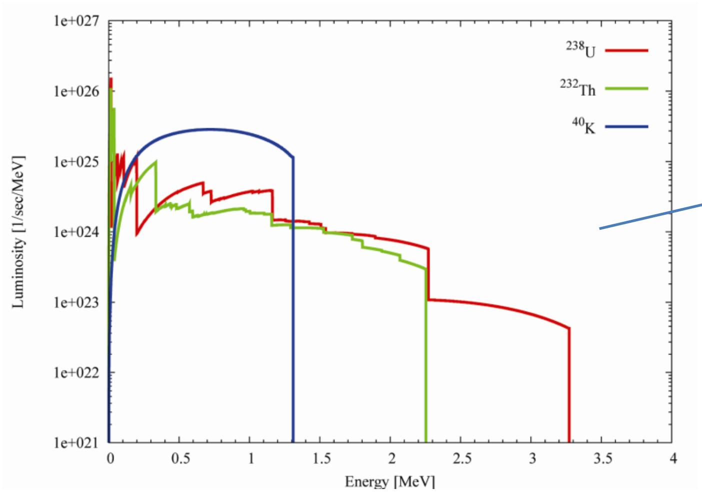




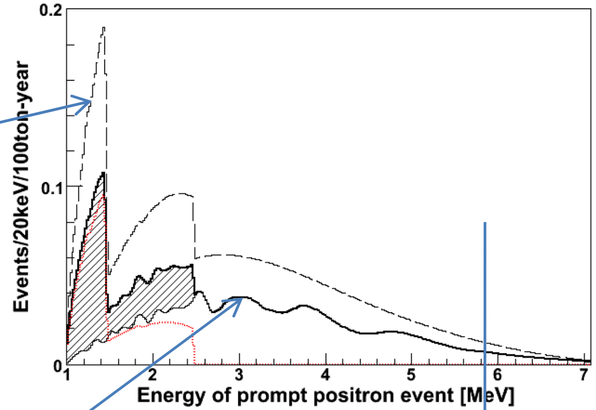
The presence of the geoneutrino signal is confirmed at 99.997%

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

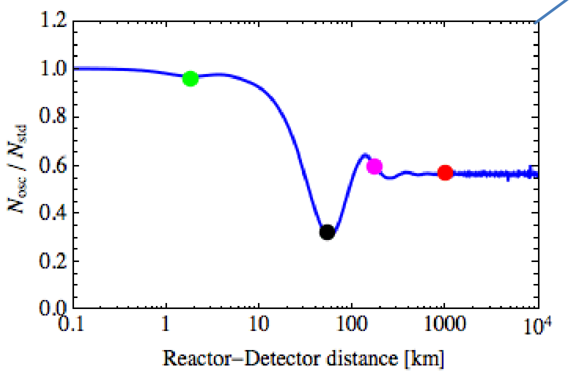
How geoneutrino/reactors spectra are calculated

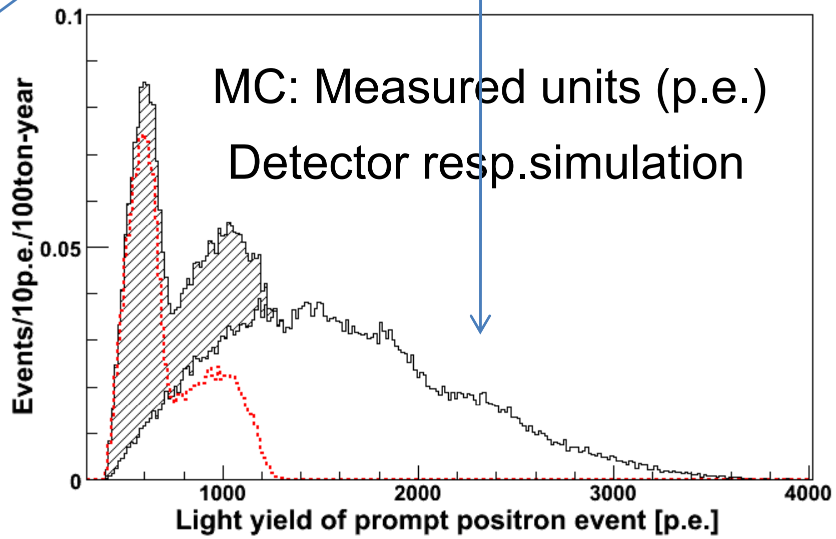


Cross section



Oscillations



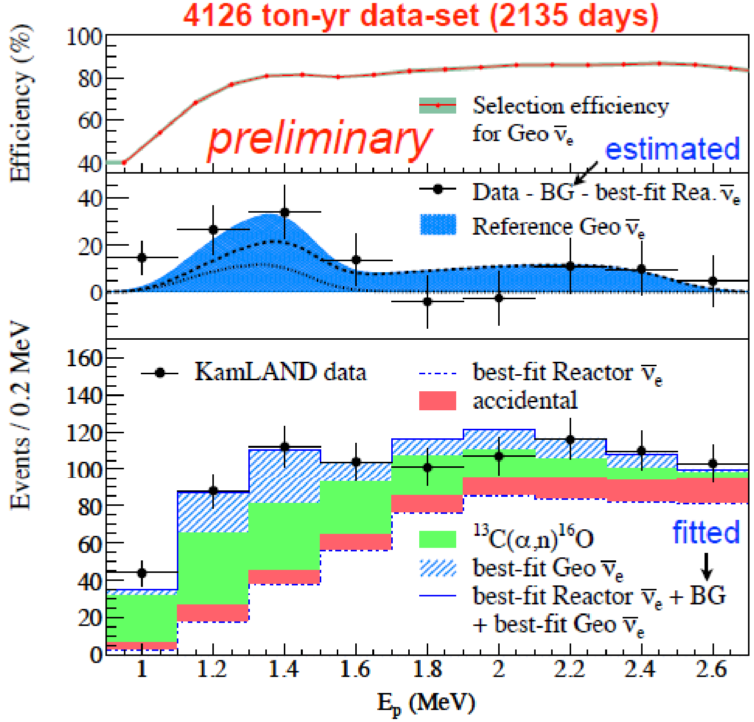


MC: Measured units (p.e.)

Detector resp.simulation

KamLAND - 2010

Observed Energy Spectrum: 0.9 MeV - 2.6 MeV



Rate + Shape + Time analysis ← w/ solar osci. constraint

best-fit (U, Th) = (65, 33)

Rate analysis (0.9 < E < 2.6 MeV)

841 candidates

^{9}Li	2.0 ± 0.1
Accidental	77.4 ± 0.1
Fast neutron	< 2.8
(α, n)	165.3 ± 18.2
Reactor ν	484.7 ± 26.5
BG total	729.4 ± 32.3

excess 111^{+45}_{-43} events

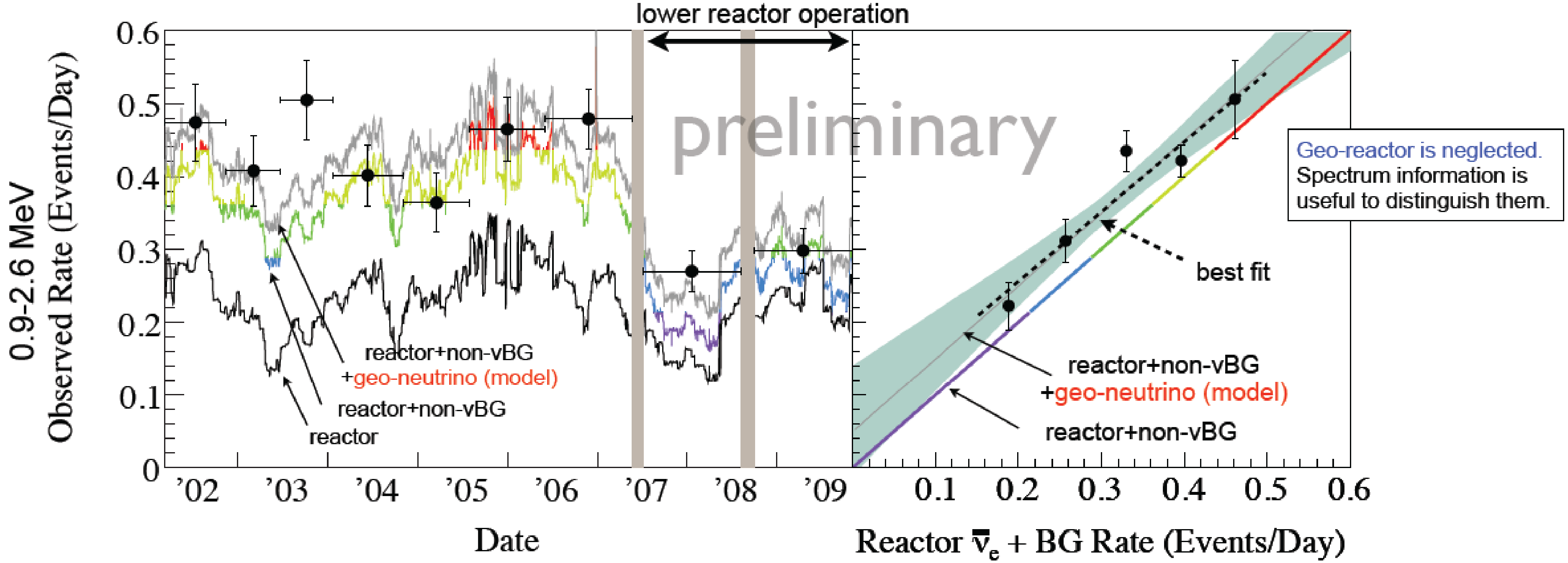
Null signal exclusion (rate)

99.55% C.L.

From the talk by I. Shimizu presented at “Neutrino Geoscience 2010” Oct. 7, 2010
http://geoscience.lngs.infn.it/

KamLAND - 2010

Operational troubles and serious earthquake at the power reactors caused lower reactor neutrino flux. KamLAND has experienced large (and known) time variation of the background. Background rate is about half since 2007.



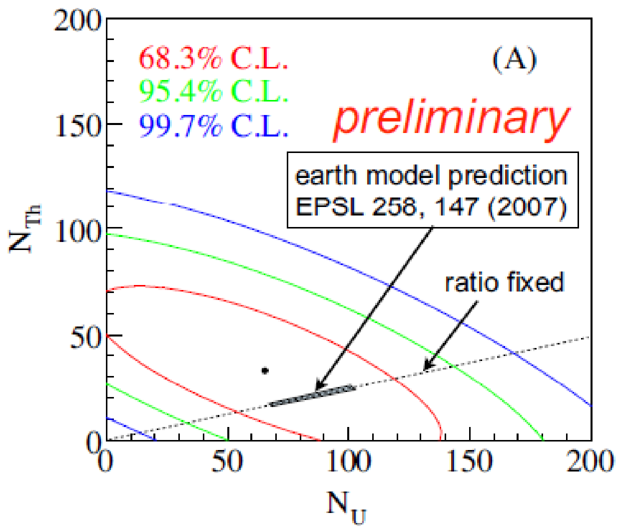
Constant contribution from geo-neutrinos is seen above the estimated reactor neutrino + non-neutrino background in the energy range, 0.9 - 2.6 MeV.
Time information is effective to improve the quality of the geo-neutrino result.

From K.Inoue presentation at Neutrino-2010, 14-19 June 2010, Athens, Greece

KamLAND - 2010

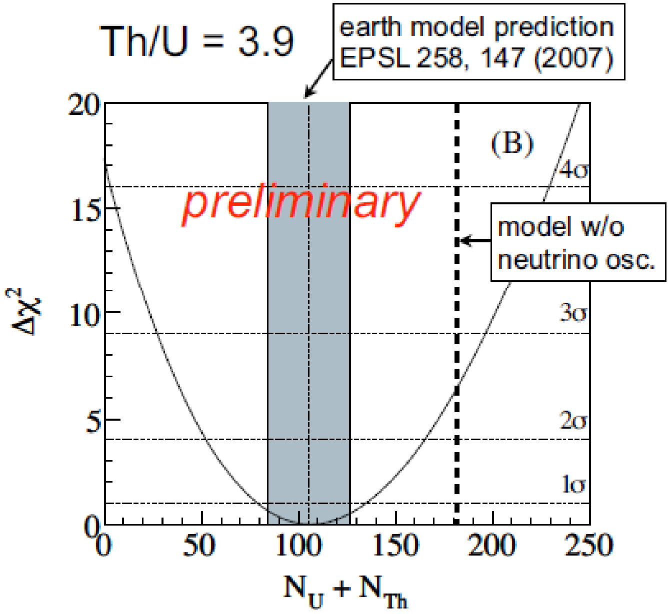
Rate + Shape + Time analysis

best-fit
(U, Th) = (65, 33)



U/Th mass ratio fixed

Th/U = 3.9



0 signal is rejected at 99.997% C.L.
(> 4σ C.L.)

$N_{geo} = 106^{+29}_{-28}$ events

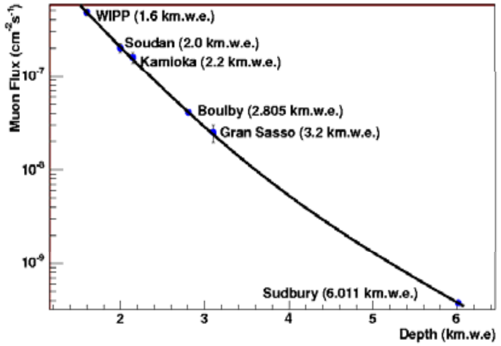
$F_{geo} = 4.3^{+1.2}_{-1.1} \times 10^6$ /cm²/sec

($38.3^{+10.3}_{-9.9}$ TNU)

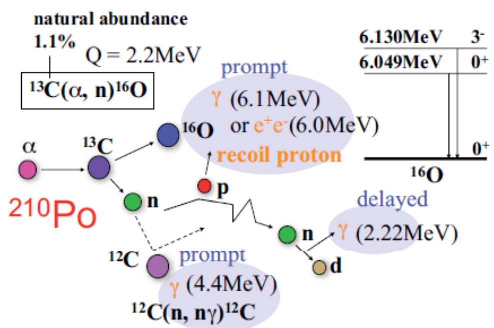
From the talk by I. Shimizu presented at "Neutrino Geoscience 2010" Oct. 7, 2010
http://geoscience.lngs.infn.it/

Principal backgrounds

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;



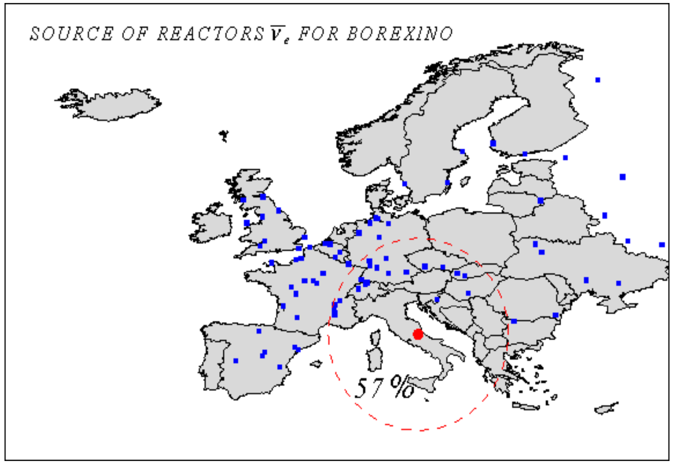
2)Cosmic muons induced backgrounds, including cosmogenic production of (βn)-decaying isotopes (at LNGS the muons flux is of about factor 7 lower than at the Kamioka site)

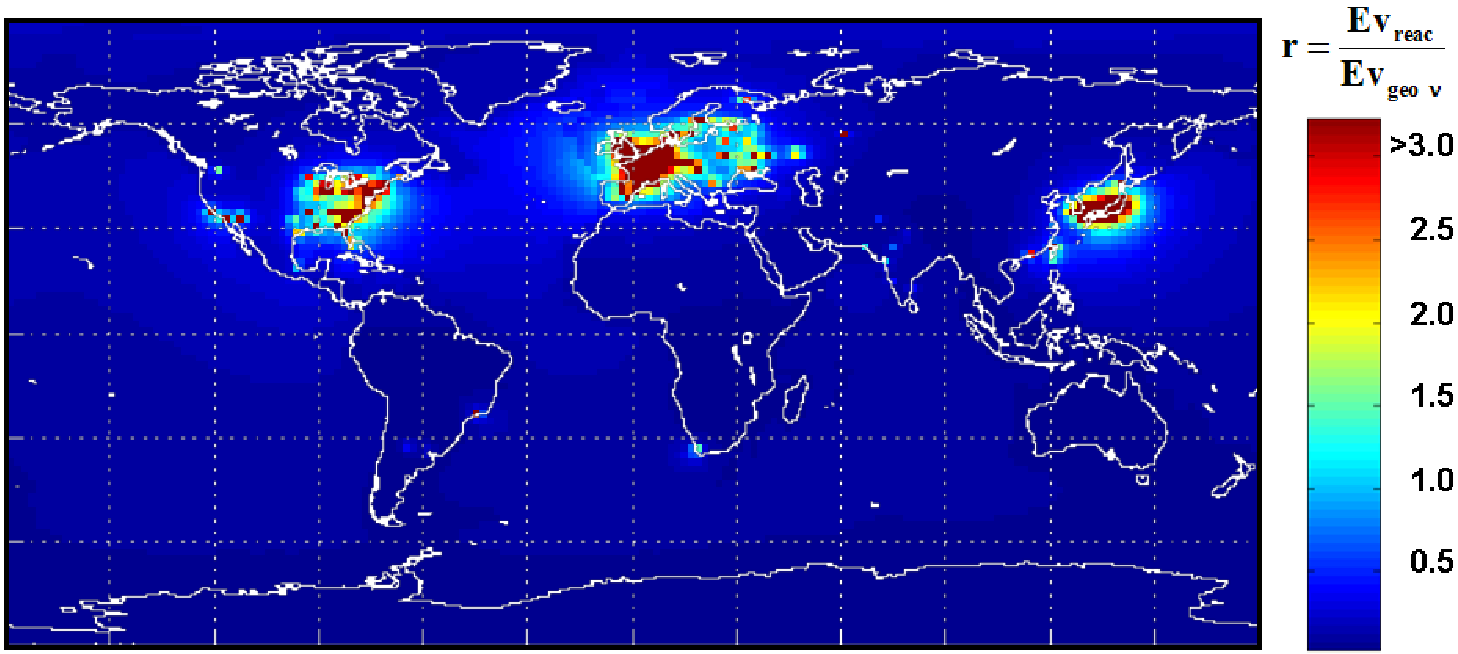


3)Internal radioactive contamination: accidental coincidences, (αn) reactions (Borexino typical contaminations 3-4 orders of magnitude lower; KamLAND is trying to purify the LS – factor 20 on (αn) is achieved);

Reactor antineutrino

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





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)

The World Wide Reference Model

F. Mantovani et al. – Phys. Rev. D 69 – 2004 - hep-ph/0309013

Geo-ν signals from U and Th over the globe have been calculated by using:

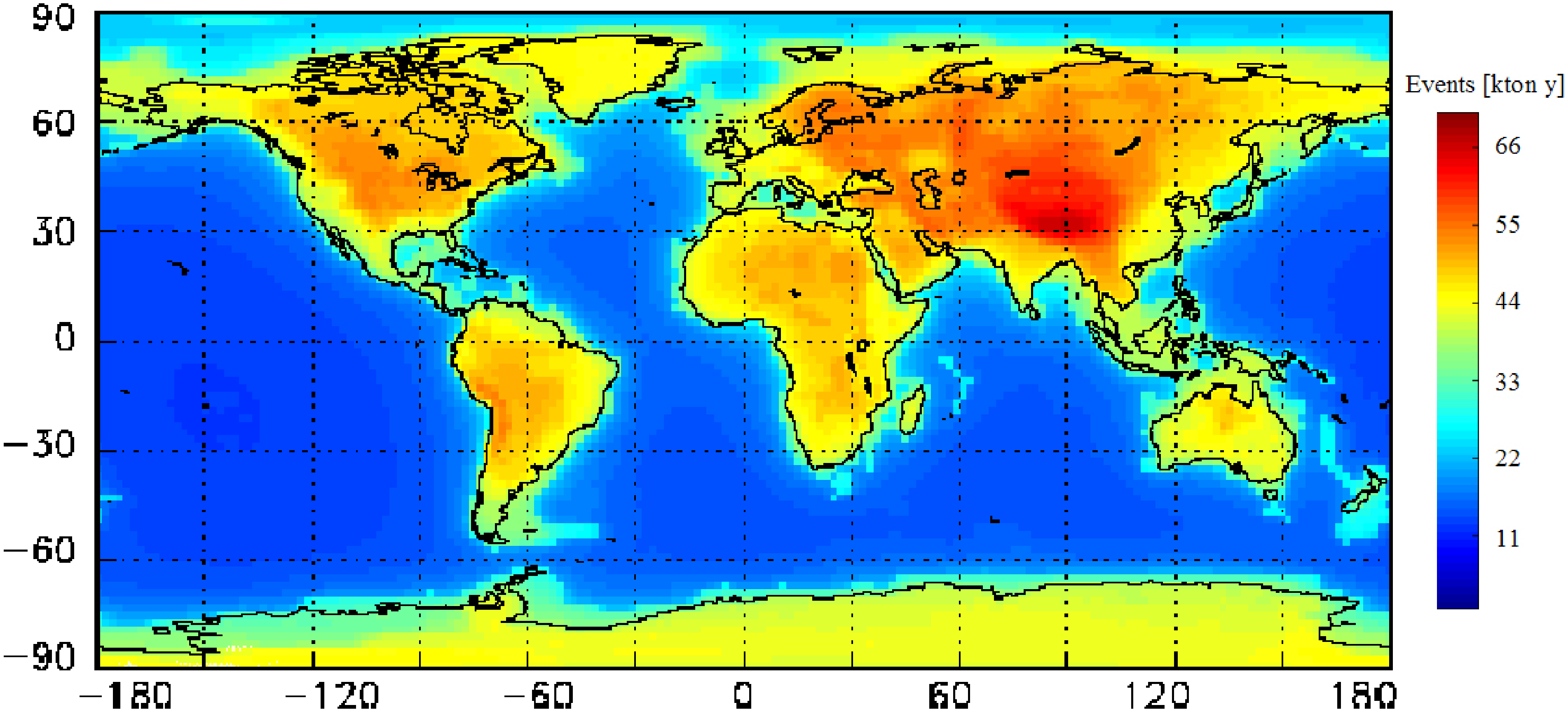
- **2°x2° crustal model (Laske G. – 2001).**
- **For each of the 16200 tiles density and thickness of sediments, upper, middle and lower crust are given.**
- **Values of the U and Th mass abundance in each layer taken as mean values from Geochemical Earth Reference Model database (GERM: http://earthref.org/GERM/)**
- **Spread of GERM data used as indication of uncertainties.**
- **Mantle is divided into two spherically symmetrical reservoirs (UM and LM).**
- **For UM measured abundances were used**
- **For LM the abundances were deduced from BSE mass balance**
- **No U and Th in the core**

Upper crust : Th ~ 10.5 ppm; U ~ 2.7 ppm
Middle crust: Th ~ 6.5 ppm; U ~ 1.3 ppm
Lower crust: Th ~ 1.2 ppm; U ~ 0.2 ppm

$m_C(U) = (0.3\text{-}0.4)\times 10^{17}$ kg
$m_M(U) = m_{BSE}(U) - m_C(U)$

The World Wide Reference Model

F. Mantovani et al. – Phys. Rev. D 69 – 2004 - hep-ph/0309013



Geoneutrino flux – BSE reference model

Signal from U+Th [TNU]	Mantovani et al. (2004)	Fogli et al. (2005)	Enomoto et al. (2005)
Pyhasalmi	51.5	49.9	52.4
Homestake	51.3		
Baksan	50.8	50.7	55.0
Sudbury	50.8	47.9	50.4
Gran Sasso	40.7	40.5	43.1
Kamioka	34.5	31.6	36.5
Curacao	32.5		
Hawaii	12.5	13.4	13.4

1 TNU = 1 event per 10^{32} target nuclei in 1 yr

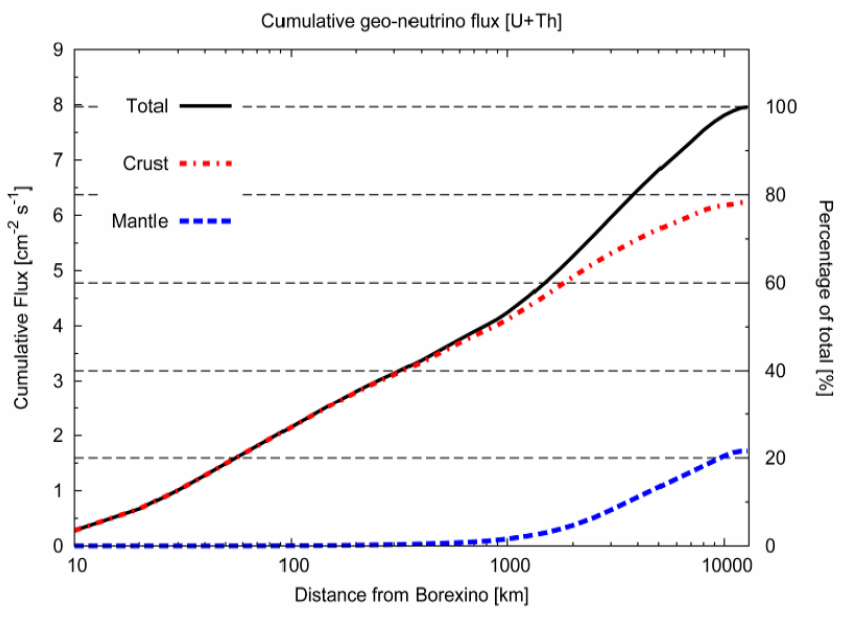
Agreement between authors 10%

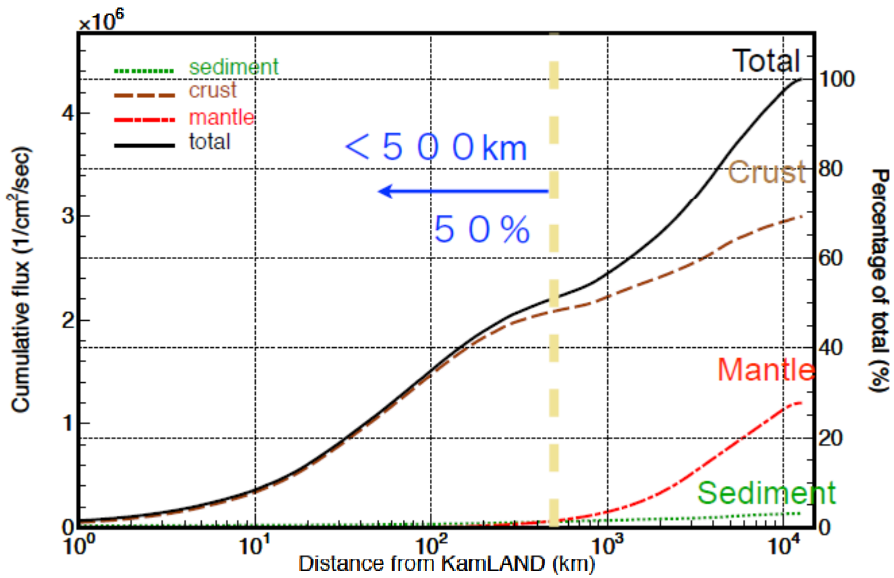
Contribution from crust/mantle depends on the site

Table provided by F.Mantovani

Models: regional geology is needed

A geochemical and geophysical study of the region (~ 200 km) around the detector is necessary for extracting the global information from the geo-neutrino signal.





Borexino: 50% of signal <900 km (200 km for the crust) **[Coltorti et al. "A Refined Reference Model for the Geo-neutrino Signal in Borexino", Neutrino Geoscience 2010]**

KamLAND: 50% of signal <500 km (100 km for the crust): more sensitive to the local geology **[Fiorentini et al., Enomoto et al.]**

Refining the reference model for Gran Sasso

- **Mantovani et al. 2004 world wide reference model (16200 2°x2° tiles) predicts for Borexino:**

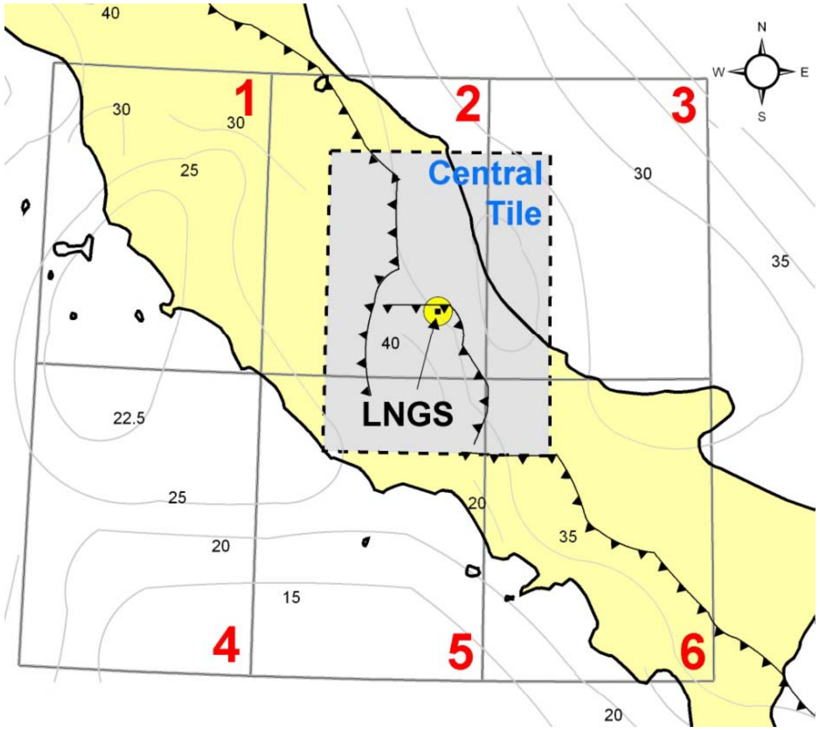
$S = 40.5 \pm 6.5$ TNU

- **The contribution of the 6 tiles near Borexino was found (Ref. Mod.) :**

$S_{reg} = 15.5$ TNU

- **A 2°x2° tile centered at Gran Sasso gives:**

$S_{CT} = 12.2$ TNU



See the talk by M.Contorti presented at “Neutrino Geoscience 2010” Oct. 7, 2010
http://geoscience.lngs.infn.it/

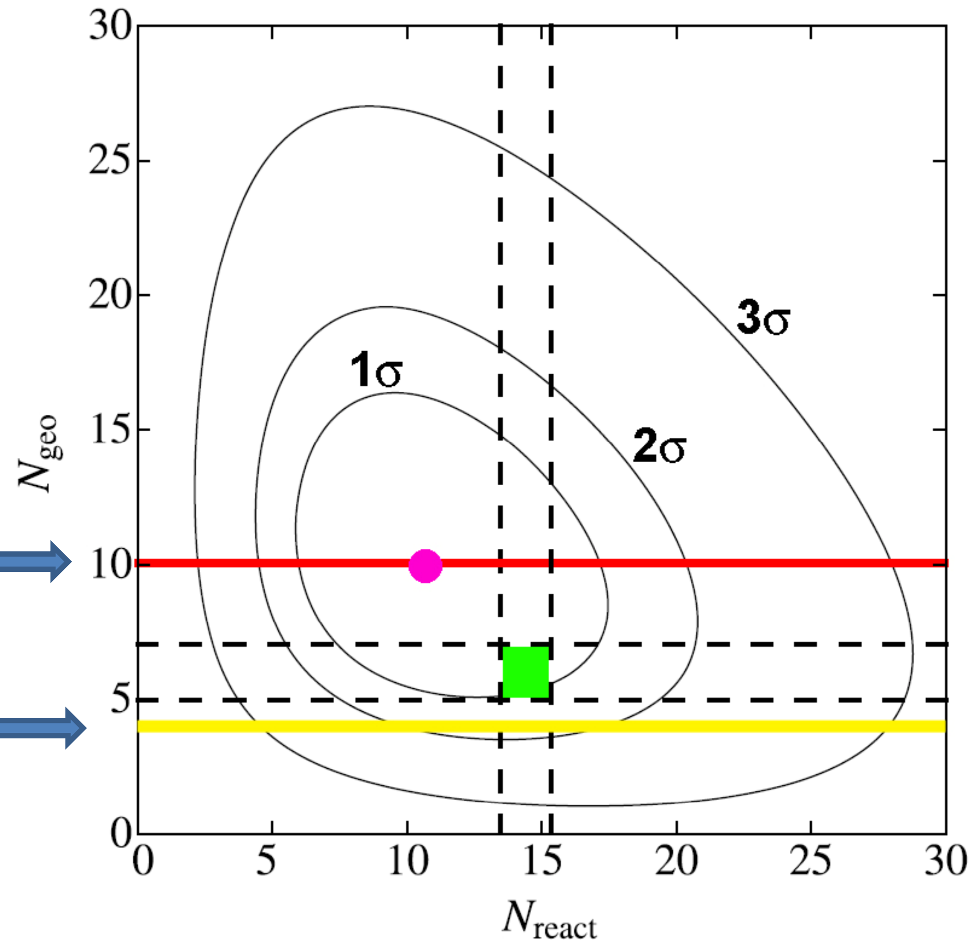
Borexino result vs models

The best fit is within 1σ from the **BSE** 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



Borexino result vs models

U+Th Signal vs radiogenic heat flow

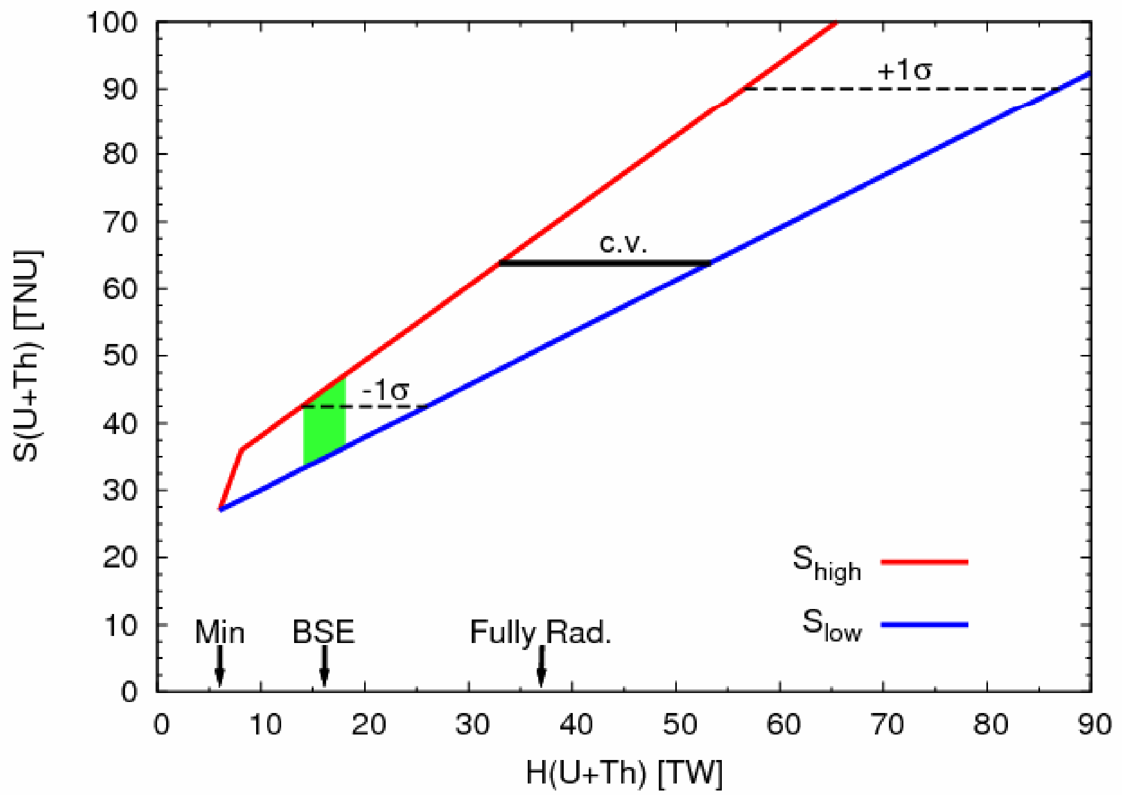


Figure from G.Fiorentini et al., “**Geo-neutrinos and radiogenic contribution to Earth’s heat flow”** ***Carpathian Summer School of Physics 2010,*** proceedings

KamLAND 2010 results vs models

- **By using rate-shape-time analysis, the signal is:**

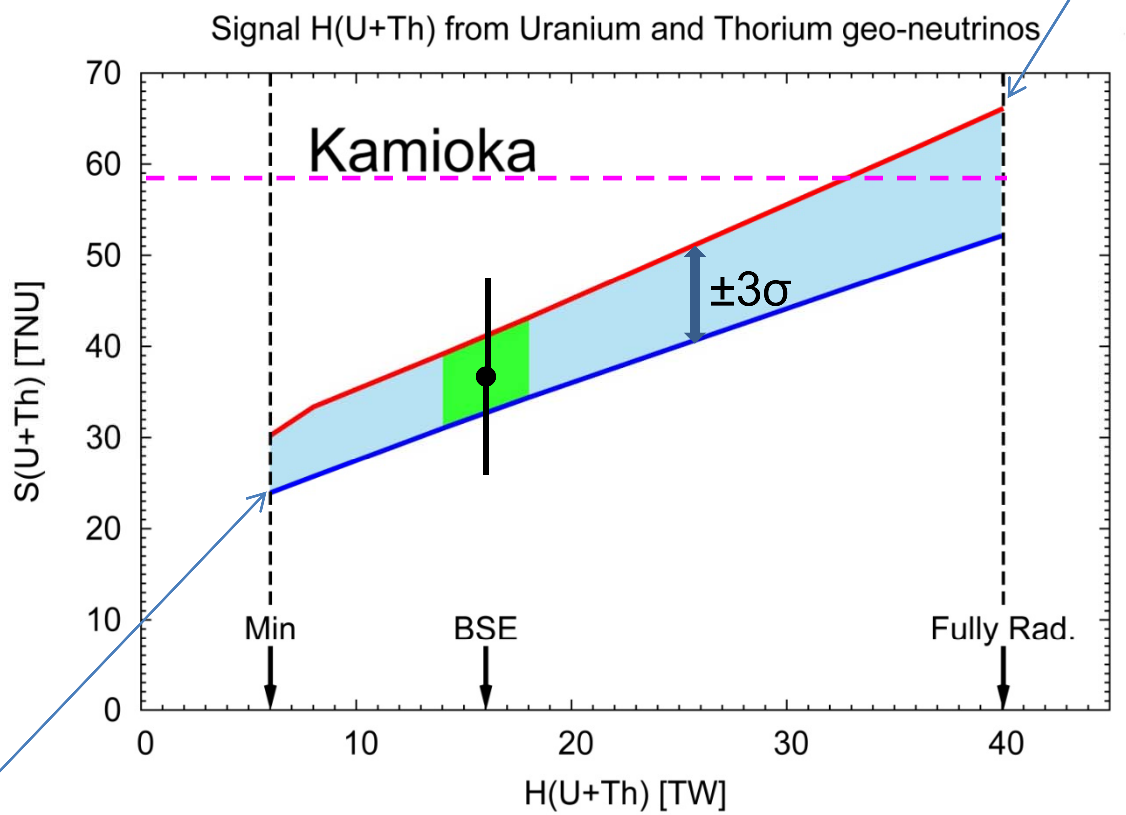
S(U+Th) = 38.3 $_{-9.9}^{+10.3}$ TNU

- **to compare with the expected signal (Fiorentini et al. 2005):**

S(U+Th) = 36.9 ± 4.3 TNU

- **fully radiogenic model is excluded at 2.4 σ (2.3 σ if combined with Borexino)**

Earth energetics implies the signal does not exceed 62 TNU

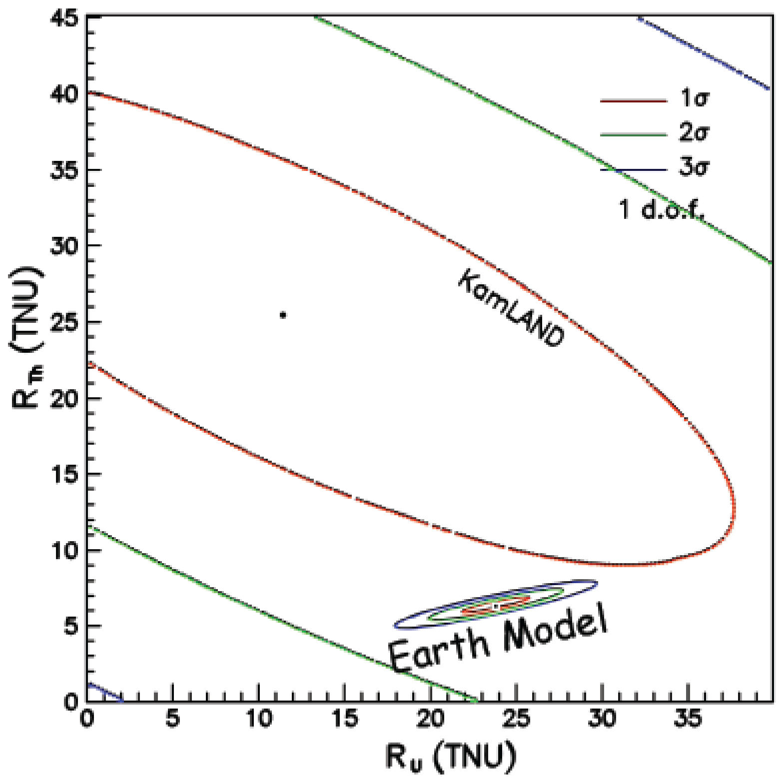


U and Th measured in the crust implies a signal of at least 24 TNU

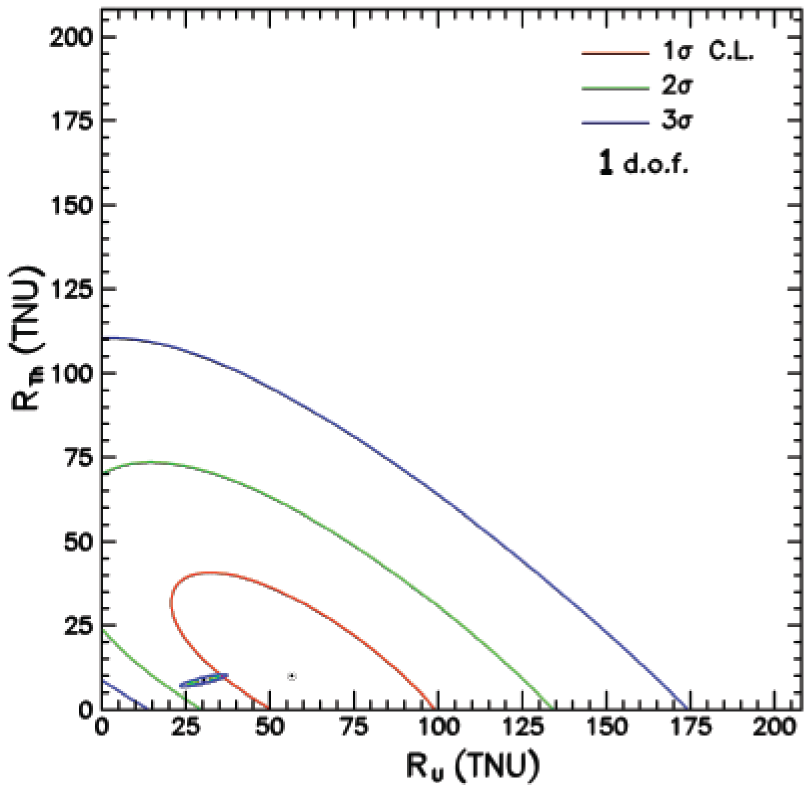
Plot provided by F.Mantovani

Borexino and KL-2008: results for unconstrained U/Th

KamLAND: R(U)=0 allowed at 1σ



Borexino: R(Th)=0 allowed at 1σ

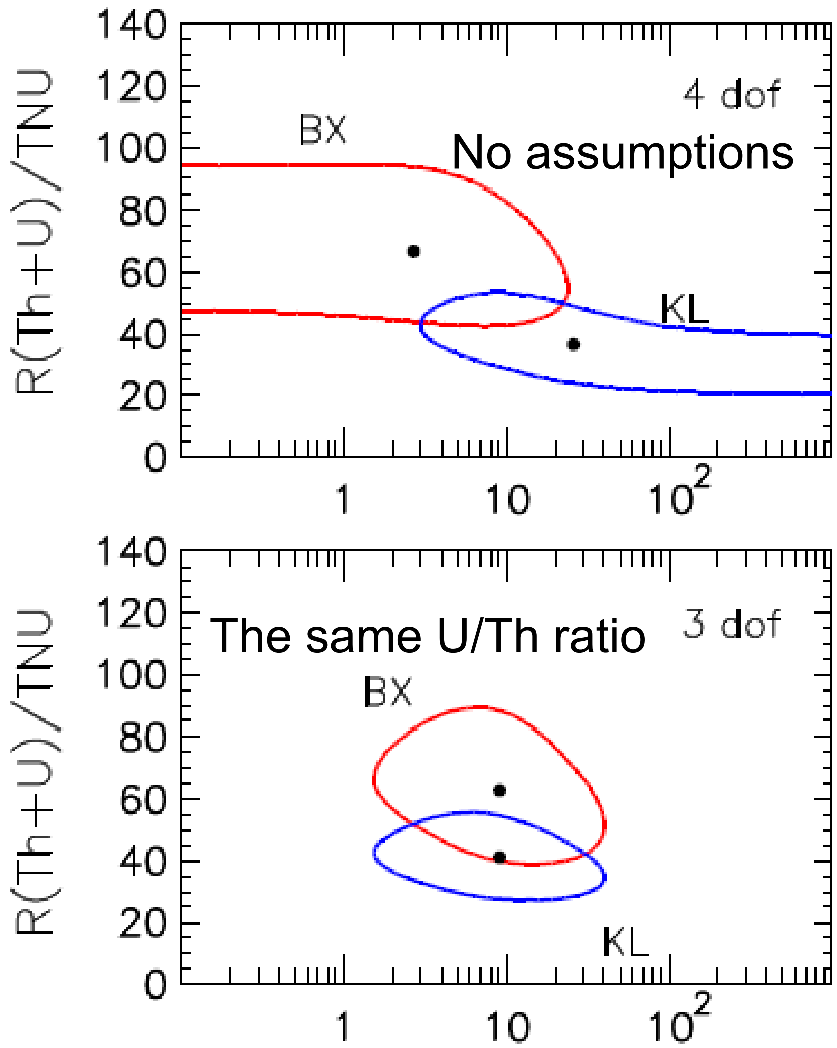


E.Lisi, Rotunno & Palazzo, hep-ph/1006.1113 (Phys. Rev D, in press)
Also: E.Lisi presentation at Neutrino Geoscience 2010: http://geoscience.lngs.infn.it/

Combined Borexino+KL analysis

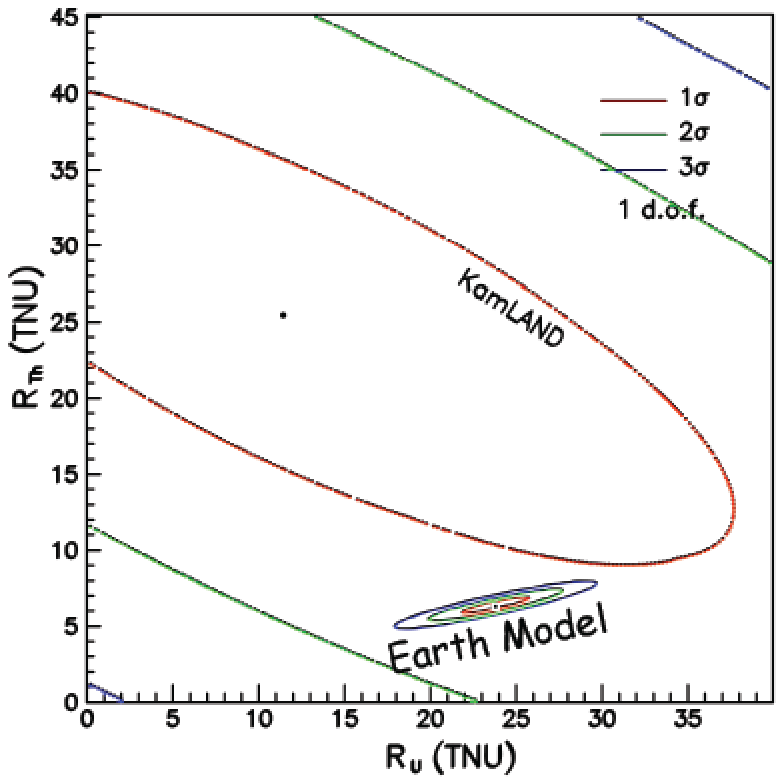
E.Lisi, Rotunno & Palazzo, hep-ph/1006.1113

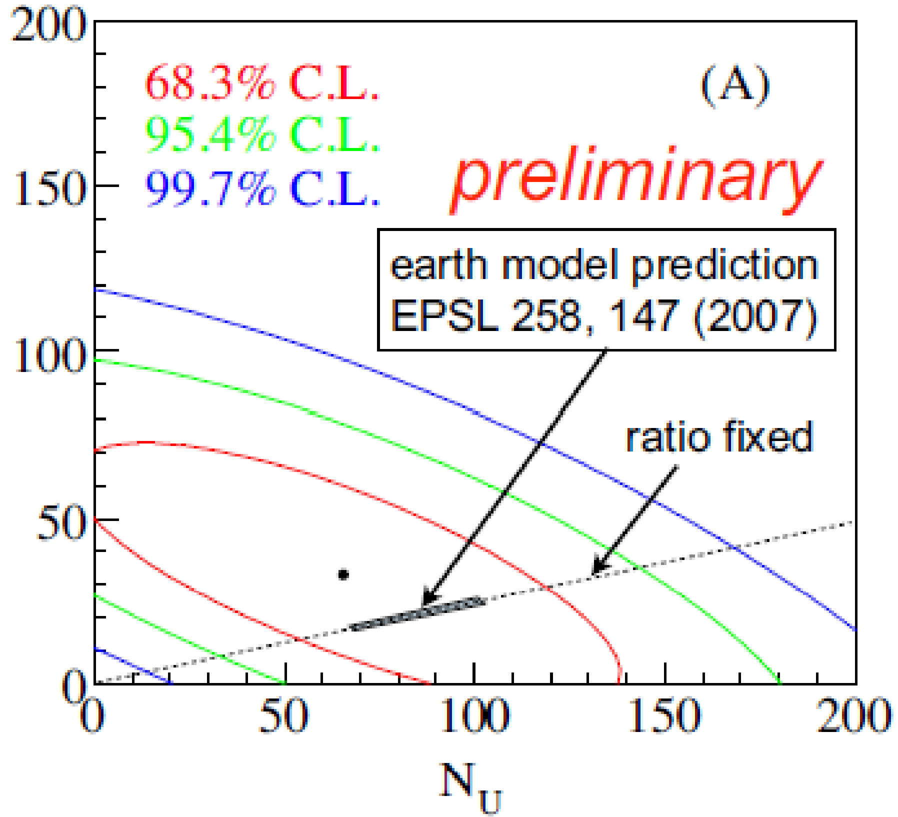
- **KL and BX data offer the first opportunity to combine geoneutrino results at different sites. Hints about Th/U, heat, mantle contrib.**
- **Any combination requires some model-dependent assumptions.**
- **Zero U and Th are excluded at 1σ level using combined Borexino/KL data even if no assumptions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



KamLAND: 2008→2010

best-fit
(U, Th) = (65, 33)





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:**

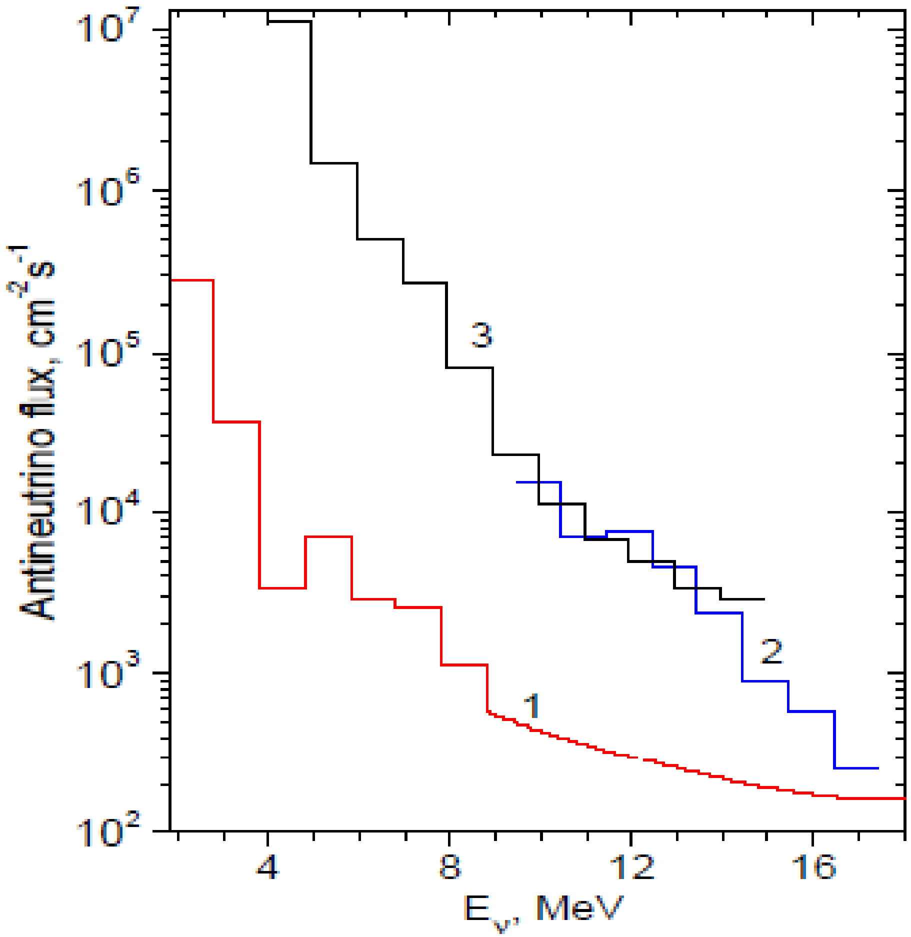
  $P_{geo} < 3$ TW at 95% C.L.

  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 of**

  $P_{geo} < 6.2$ 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

Are there any electron antineutrinos from the Sun?



Upper limits on unknown antineutrino fluxes:

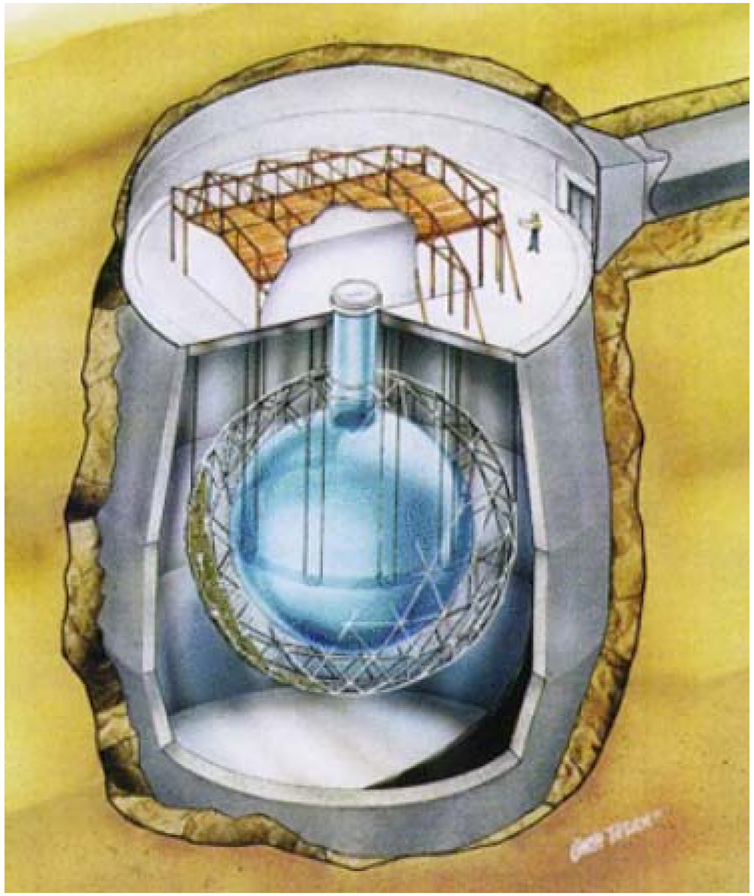
1 – Borexino
2 – SuperKamiokaNDE
3 – SNO

Minimal radiogenic model has been used to set the best up to date upper limits

arXiv:1010.0029v1 [hep-ex] 30 Sep 2010: G.Bellini et al., Borexino collaboration, "Study of solar and other unknown anti-neutrino fluxes with Borexino at LNGS"

Upcoming experiment: SNO+

- SNO+ is fully funded and under construction
- scheduled scintillator filling to start in Spring 2012



29 geo-neutrino events per live-year (in 780 tones LAB) compared with 26 events from reactors in the same energy range

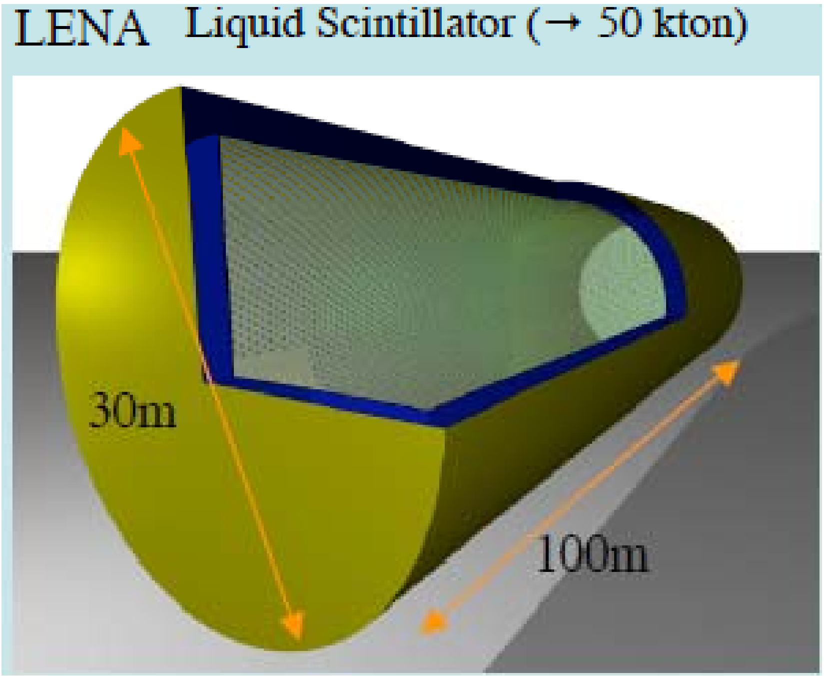
Local Geology around Sudbury
maybe the best understood portion of crust in the world

For further information:
http://geoscience.lngs.infn.it/

Large Scale Projects

For further information: http://geoscience.lngs.infn.it/

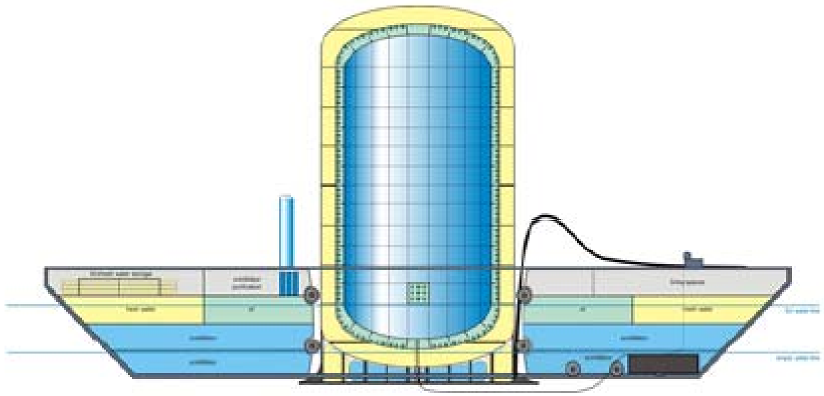
LENA: 50 kton



~1500 geonu events/yr

Hanohano: 10 kton

Extracting mantle contribution is very important from the geophysical point of view. The combination of data from multiple sites and data from an oceanic experiment would provide valuable information.



Hanohano

(~10 kt deep ocean detector)

~100 geonu events/yr

Conclusions

- **1)Geoneutrino existence is confirmed at 4.2σ (99.997%) level independently by Borexino and KamLAND;**
- **2)The precision of both available measurements (Borexino and KL) is still too low: ~40% and 27% correspondingly for U+Th signal, and much worse for the unconstrained R(U) and R(Th) measurements**
- **3)Different geological models for the moment can’t be discriminated by existing measurements, more precise measurements are needed;**
- **4)Regional measurements in location of experiments are needed to provide more precision for the models;**
- **5)Independent measurements at various sites are highly desirable to check contributions from crust/mantle;**
- **6)We are expecting more input for the geological models from future detectors .**