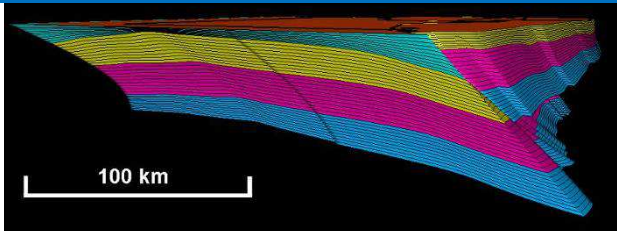
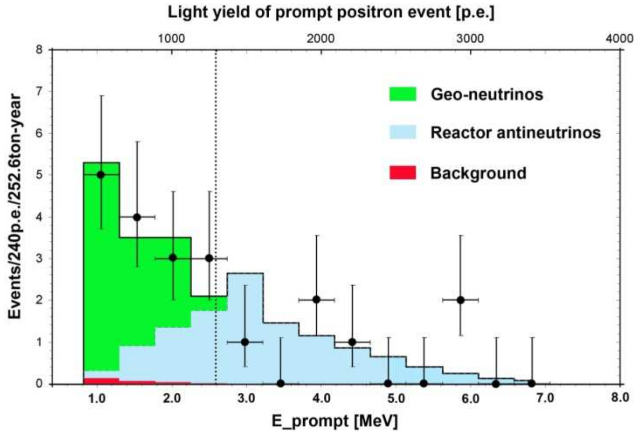
Gianni Fiorentini @ NOW 2012

Neutrino physics and Earth science

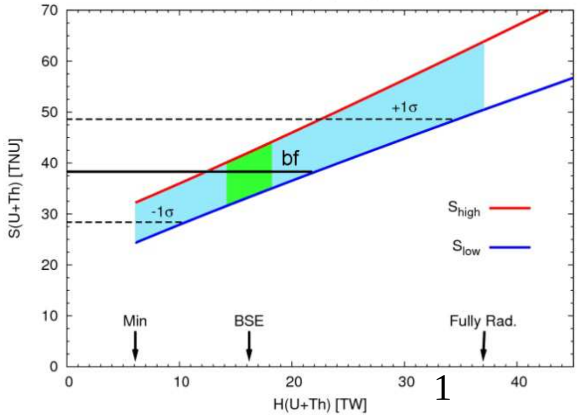


- What are geo-neutrinos?



- Why are they of interest?

- What has occurred in the last few years?



- What next?

Geo-neutrinos: anti-neutrinos from the Earth

U, Th and ^{40}K in the Earth release heat together with anti-neutrinos, in a well fixed ratio:

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

- Earth emits (mainly) antineutrinos $\Phi_{\bar{\nu}} \sim 10^6\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ whereas Sun shines in neutrinos.

- A fraction of geo-neutrinos from U and Th (not from ^{40}K) are above threshold for inverse β on protons: $\bar{\nu} + p \to e^+ + n - 1.8\ \mathrm{MeV}$

- Different components can be distinguished due to different energy spectra: e. g. anti-ν with highest energy are from Uranium.

- Signal unit: **1 TNU** = one event per 10^{32} free protons per year

Open questions about natural radioactivity in the Earth

1 - What is the radiogenic contribution to terrestrial heat production?

2 - How much U and Th in the crust and, particularly, in the **mantle**?

3 – A global check of the standard geochemical model (BSE)?

4 - What is hidden in the Earth's core? (geo-reactor, ^{40}K, …)

Geo-neutrinos: a new probe of Earth's interior

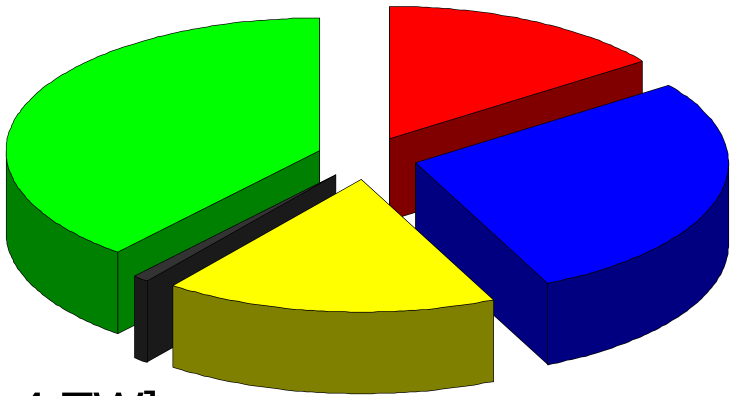
- They escape freely and instantaneously from Earth's interior.
- They bring to Earth's surface information about the chemical composition of the whole planet.

"Energetics of the Earth and the missing heat source mystery" *

- The debate about the terrestrial heat flow is still open: H_{Earth} = (31- 46)TW

- The BSE canonical model, based on **cosmochemical** arguments, predicts a radiogenic heat production ~ 20 TW

	Global heat loss [TW]**
Williams and von Herzen [1974]	43
Davies [1980]	41
Sclater et al. [1980]	42
Pollack et al. [1993]	44 ± 1
Hofmeister et al. [2005]	31 ± 1
Jaupart et al. [2007]	**46 ± 3**



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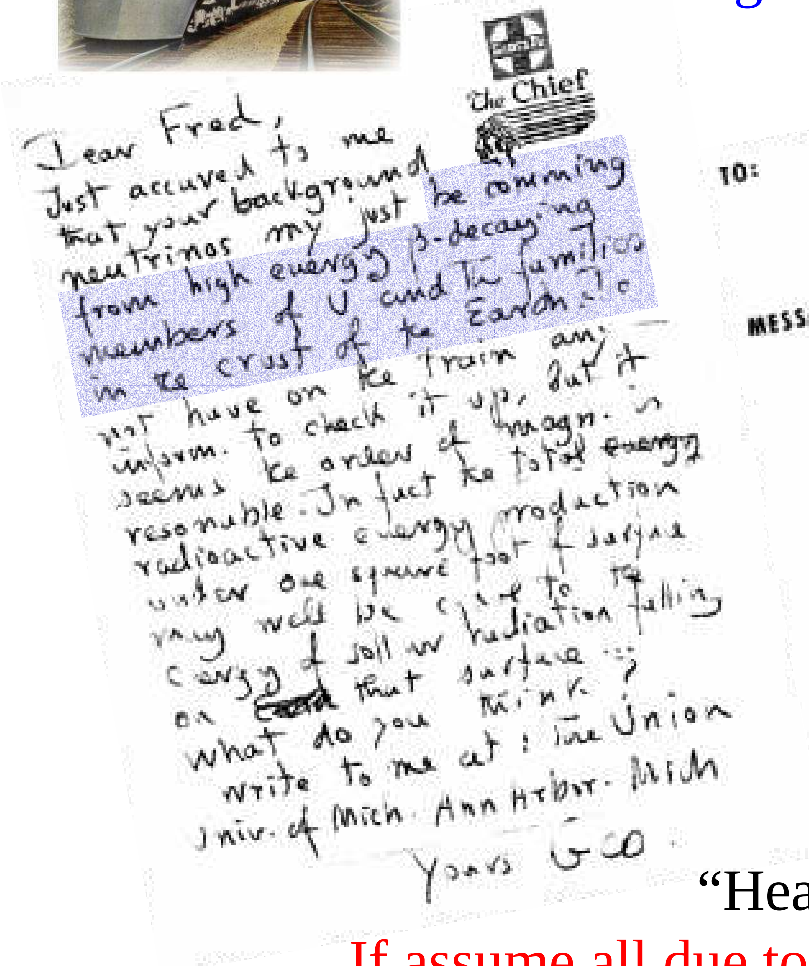
* *D. L. Anderson (2005),Technical Report, www.MantlePlume.org*

***Jaupart, C. et al. - Treatise on Geophysics, Schubert G. (ed.), Oxford :Elsevier Ltd., 2007.*

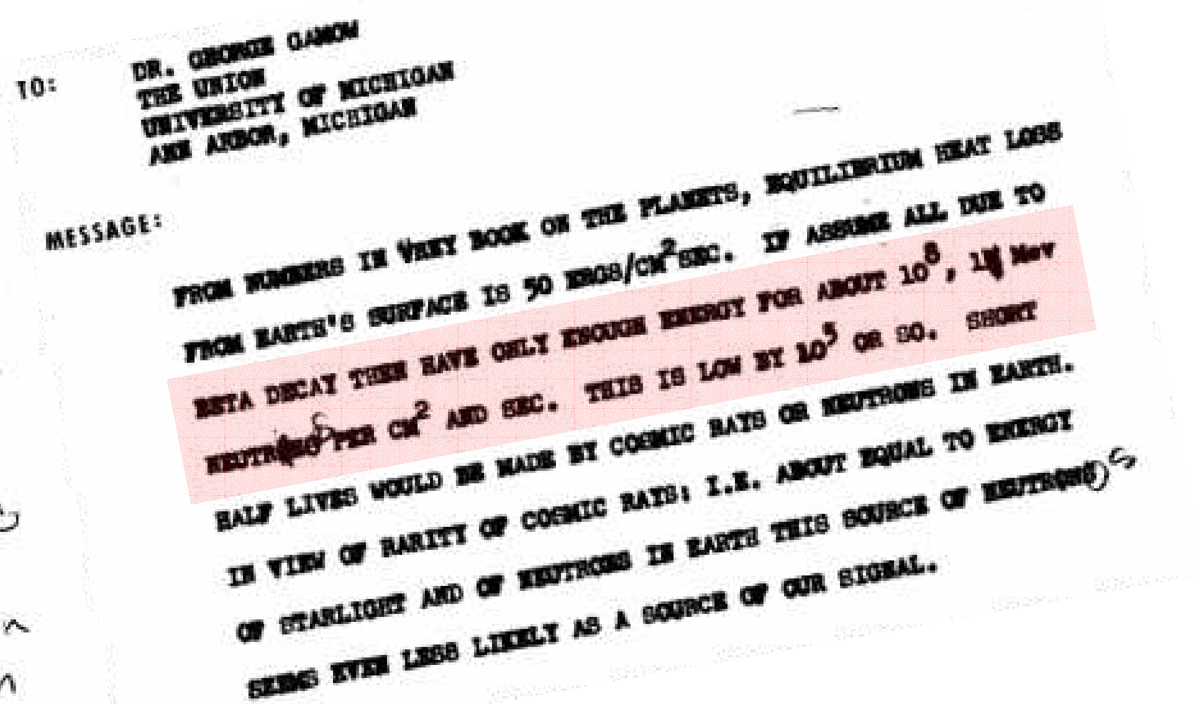
Geo-neutrinos born on board of the Santa Fe Chief train

In 1953 G. Gamow wrote to F. Reines: "It just occurred to me that your background may just be coming from high energy beta-decaying members of U and Th families in the crust of the Earth."



The Chief

Dear Fred,
Just accured to me
that your background
neutrinos may just be comming
from high energy β-decaying
members of U and Th families
in the crust of the Earth. I do
not have on the train any
inform. to check it up, but it
seems the order of magn. is
resonable. In fact the total energy
radioactive energy production
under one square foot of surface
may well be close to the
energy of solar radiation falling
on ~~Earth~~ that surface.
What do you think?
Write to me at: The Union
Univ. of Mich. Ann Arbor. Mich
Yours Geo.



TO: DR. GEORGE GAMOW
THE UNION
UNIVERSITY OF MICHIGAN
ANN ARBOR, MICHIGAN

MESSAGE:
FROM NUMBERS IN VERY BOOK ON THE PLANETS, EQUILIBRIUM HEAT LOSS
FROM EARTH'S SURFACE IS 50 ERGS/CM^{2}SEC. IF ASSUME ALL DUE TO
BETA DECAY THEN HAVE ONLY ENOUGH ENERGY FOR ABOUT 10^8, 1 Mev
NEUTRINOS PER CM^2 AND SEC. THIS IS LOW BY 10^3 OR SO. SHORT
HALF LIVES WOULD BE MADE BY COSMIC RAYS OR NEUTRONS IN EARTH.
IN VIEW OF RARITY OF COSMIC RAYS; I.E. ABOUT EQUAL TO ENERGY
OF STARLIGHT AND OF NEUTRONS IN EARTH THIS SOURCE OF NEUTRINOS
SEEMS EVEN LESS LIKELY AS A SOURCE OF OUR SIGNAL.

F. Reines answered to G. Gamow:
"Heat loss from Earth's surface is 50 erg cm^{-2} s^{-1}.
If assume all due to beta decay than have only enough energy for about 10^8 one-MeV neutrinos cm^{-2} and s."

An historical perspective

Eder (1966) ●

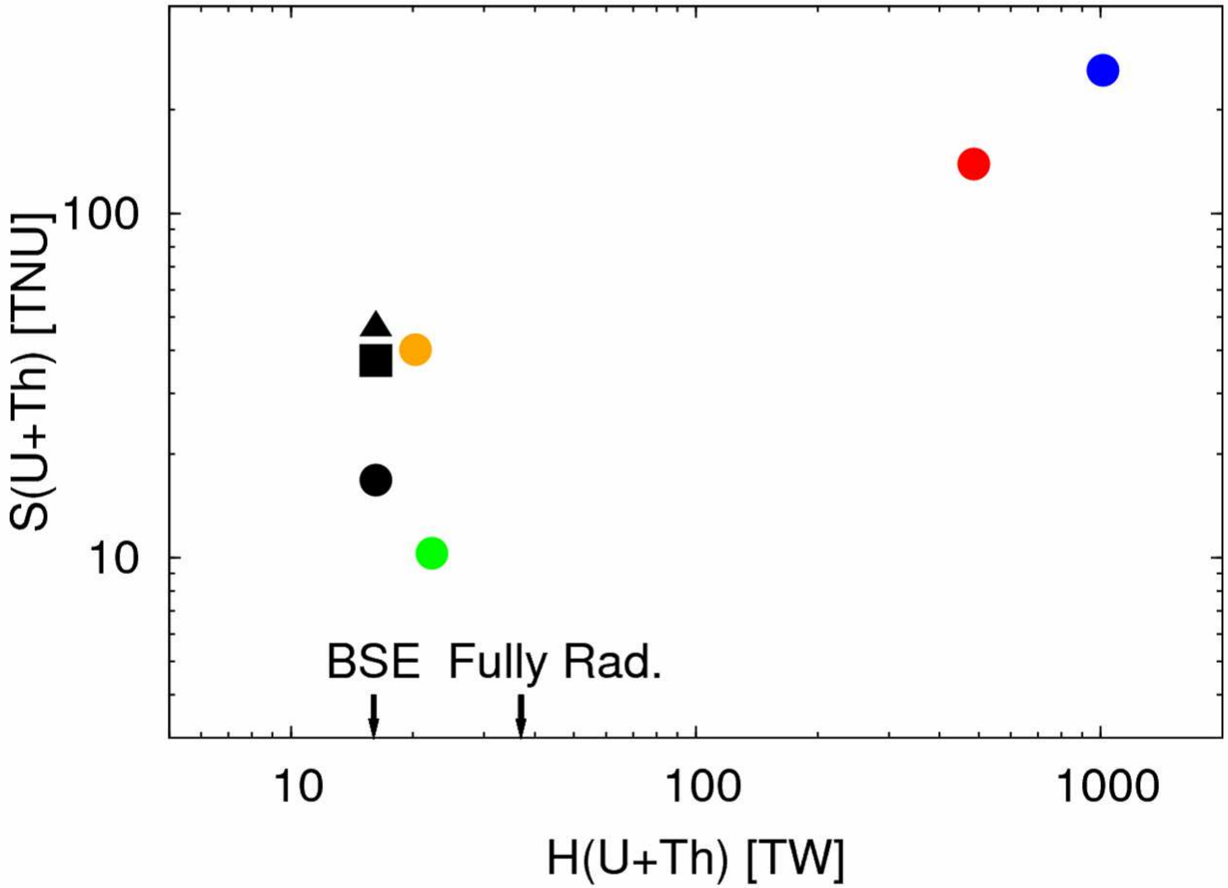
Marx (1969) ●

Kobayashi (1991) ●

All above assumed an uniform U distribution in the Earth,

Krauss et al. (1984) ●

distributed U uniformly in the crust.



Raghavan et al. (1998) ▲ and Rothschild (1991) ● studied the potential of KamLAND and Borexino for geo-neutrino detection.

Mantovani et al. (2004) ■ discussed a reference model for geo-neutrinos and its uncertainties.

Geo-ν: predictions of the BSE Reference Model

Different authors calculated the geo-ν signals from U and Th over the globe by using a 2°x2° crustal model (Laske G. – 2001) and a canonical BSE model:

Signal from U+Th [TNU]*	Mantovani et al. (2004)	Fogli et al. (2005)	Enomoto et al. (2005)	Dye (2010)
Pyhasalmi	51.5	49.9	52.4	49.5
Homestake	51.3			52.5
Baksan	50.8	50.7	55.0	52.6
Sudbury	50.8	47.9	50.4	47.6
Gran Sasso	40.7	40.5	43.1	41.4
Kamioka	34.5	31.6	36.5	35.3
Curacao	32.5			
Hawaii	12.5	13.4	13.4	14.7

- All calculations in agreement to the 10% level
- Different locations have different contributions from radioactivity in the **crust** and in the **mantle**
- **1 TNU** = one event per 10^{32} free protons per year

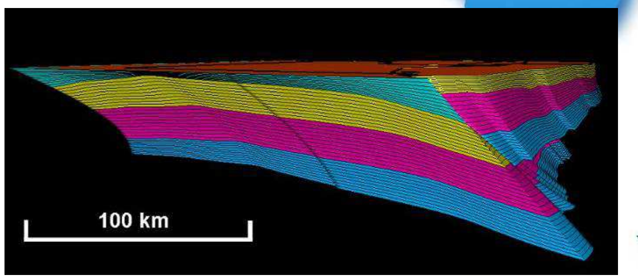
* All the calculation are normalized to a survival probability <Pee> = 0.57

2010 & 2011: two years of gifts

Mueller et al. 2011
Improved estimates of reactor flux

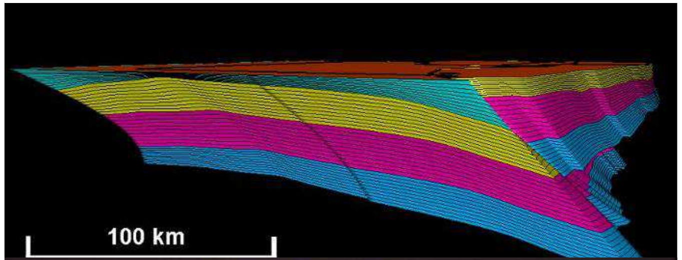
KamLAND
June 2010
New results

A refined reference model for Gran Sasso



Borexino
March 2010 - New results

Refined Reference Model (RRM) for Borexino*



- We built a 3D model of the central tile with the data constraints of CROP seismic sections and 38 deep oil and gas wells.
- We measured the U and Th content in 57 samples of rock from sediments, upper and lower crust.

	RM [TNU]	**RRM** [TNU]
Regional contribution	15.3	**10.**
Rest of the Earth	25.2	26.
Total	**40.5 ± 6.5**	**36 ± 5**

- The main point is that a thick (~13 km) sedimentary layer (poor in U and Th) around Gran Sasso had been washed out in the 2° x 2° crustal map.

* arXiv:1102.1335v1 – Coltorti et al. 2011 - Geochimica et Cosmochimica Acta.

Borexino: expectations and results (2010)*

- RRM Predicts a total of **20.0** events in 24 months

(R=14.0 ; G=5.6 ; Bk=0.4)

- The HER can be used to test the experiment sensitivity to reactors

- In the LER one expects comparable number of geo ν and reactor- ν

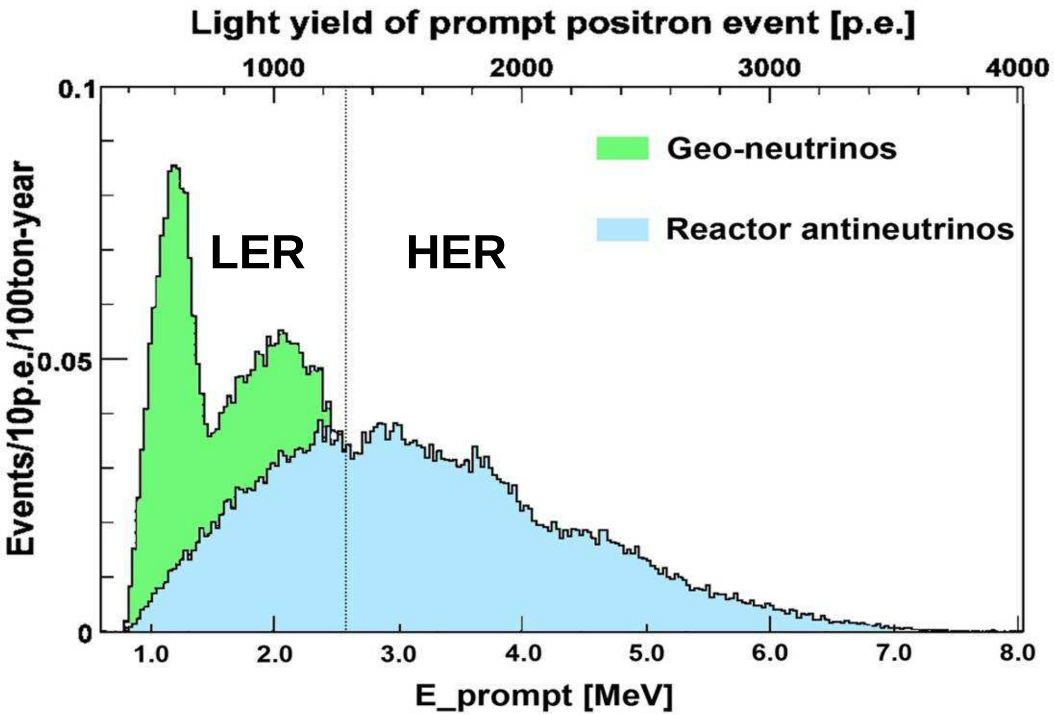
- Observe **21** events in 24 months, attributed to

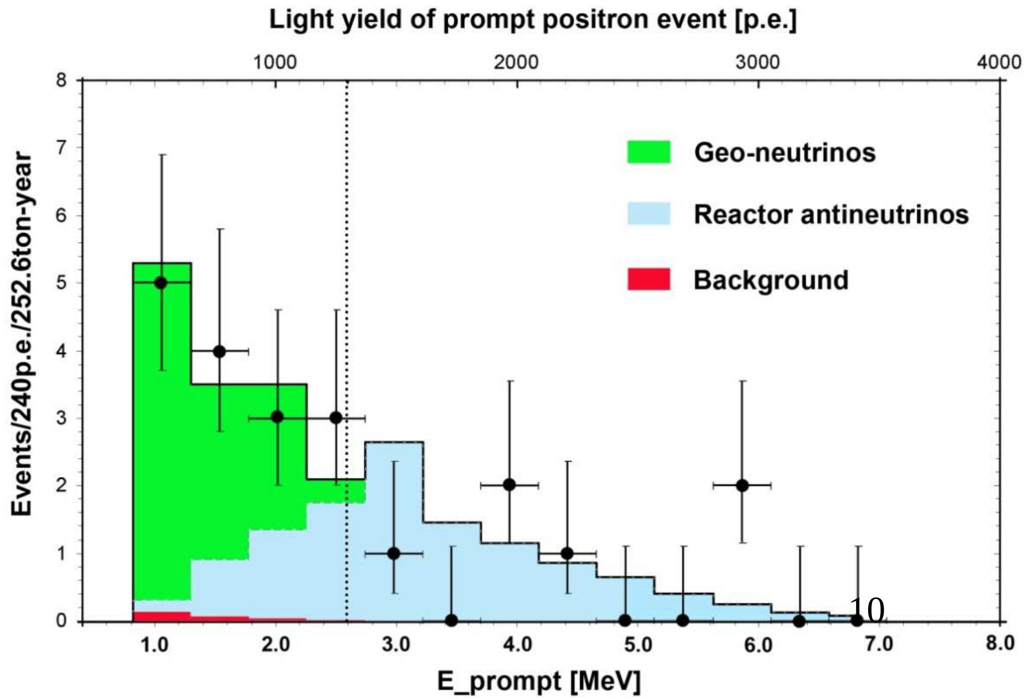
$R=10.7^{+4.3}_{-3.4}$

$G= 9.9^{+4.1}_{-3.4}$

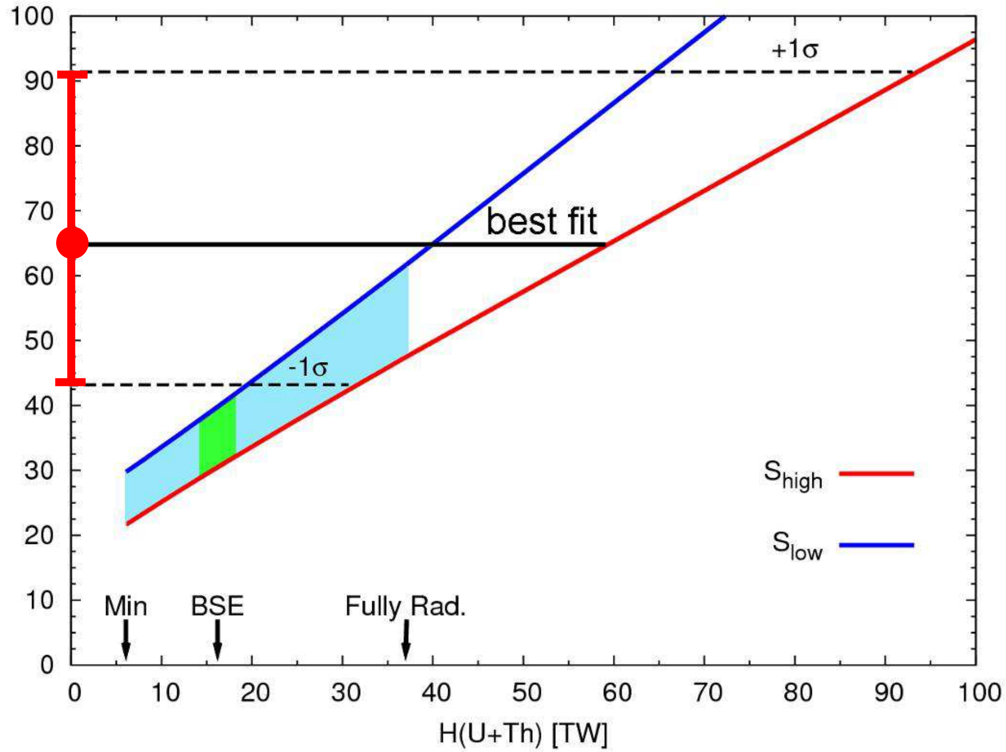
BK=0.4

- One geo ν event per month experiment!





Borexino (2010) implications



- The signal observed in Borexino is:

$$S = 64.8^{+26.6}_{-21.6}\ \mathrm{TNU}$$

- Geo-ν = 0 is excluded with C.L. of 99.997 (corresponding to 4σ)

- The **central value** is close to the fully radiogenic model and some 1σ from the **BSE** prediction

KamLAND results (2010)

- KamLAND collaboration presented new data at Neutrino 2010, with a background much smaller than in previous releases.

- From March 2002 to November 2009 a total **841** events in the LER have been collected:

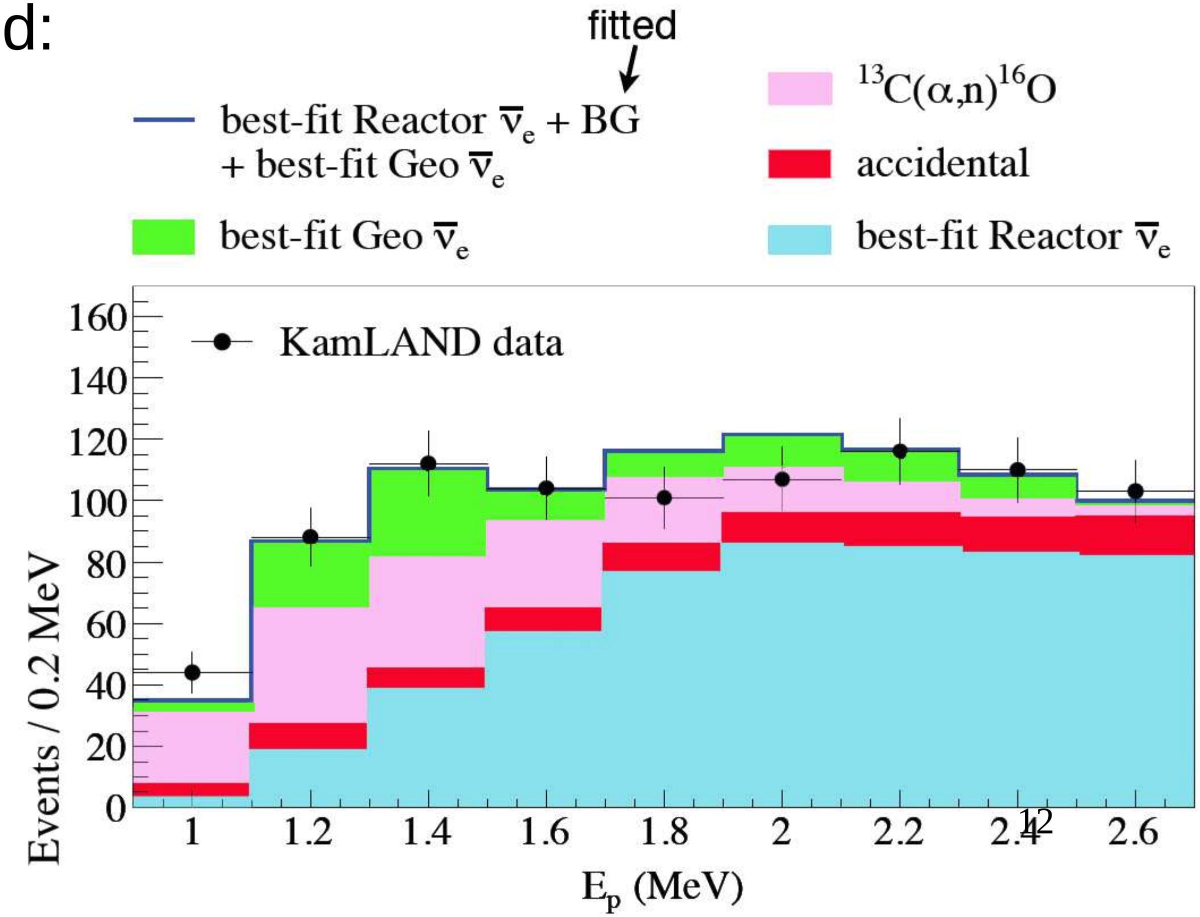
R = 485 ± 27

$^{13}C(\alpha,n)^{16}O$ = 165 ± 18

BK = 80 ± 0.1

With rate-only analysis:

Geo ν = 111^{+45}_{-43}



KamLAND 2010 and BSE

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

$S = 38.3\,_{-9.9}^{+10.3}$ TNU

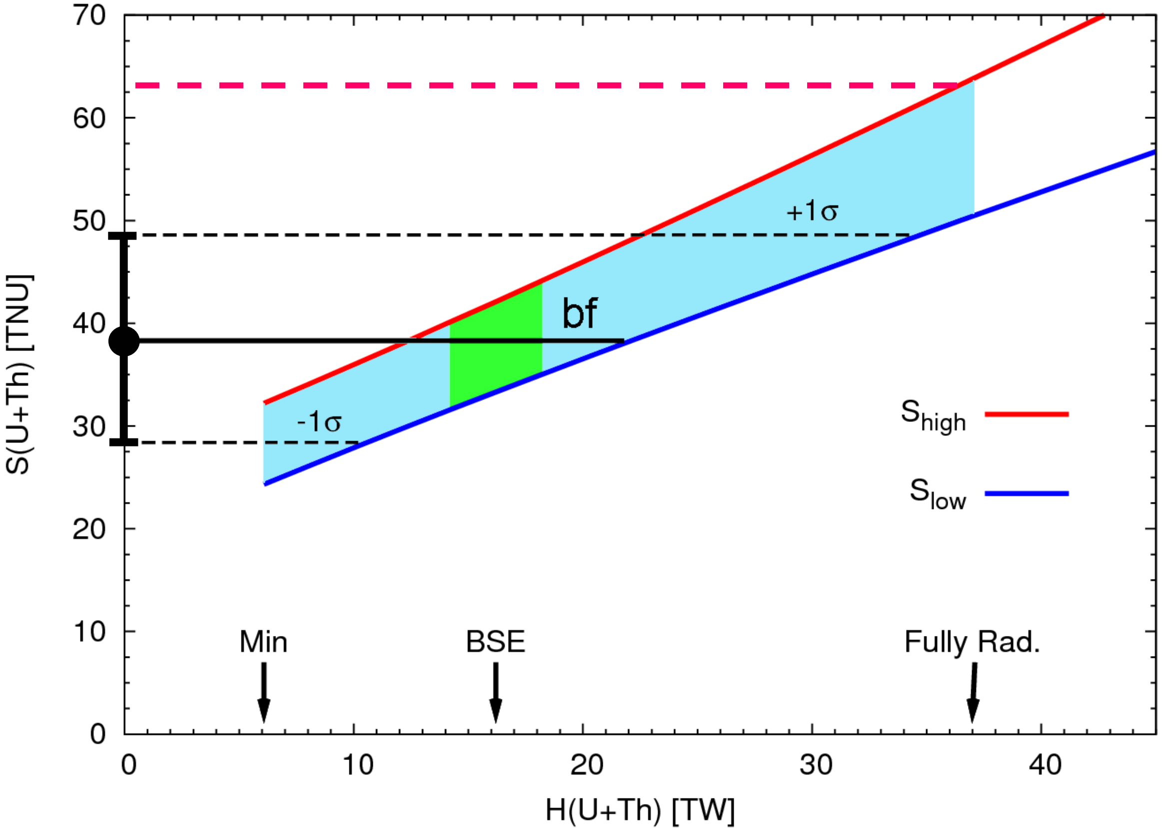
The **best fit (bf)** is:

• close to the **BSE prediction**

S(U+Th) = 36.9 ± 4.3 TNU

(Fiorentini et al. 2005)

•some 2.5σ from **fully radiogenic model**



Implications of KamLAND on terrestrial radiogenic heat

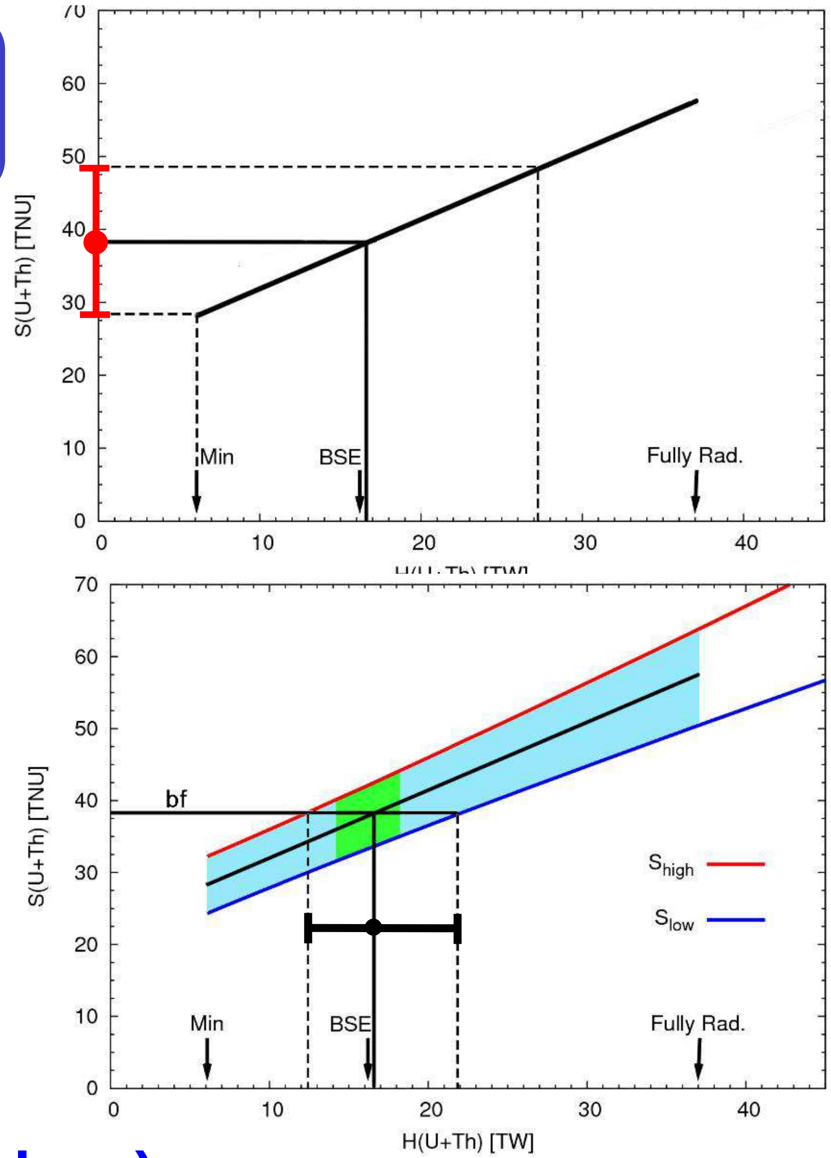
i. Assume models were "exact":

$S_{KamLAND}$ = **38 ± 10 TNU**

-> H(U+Th) = 16 ± 8 TW

ii. Assume a perfect experiment, giving 38 TNU with zero error; the geological uncertainty is: Δ_{geo} = ± 5 TW

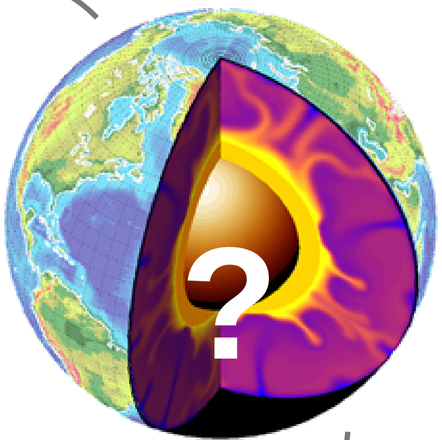
iii. The result is

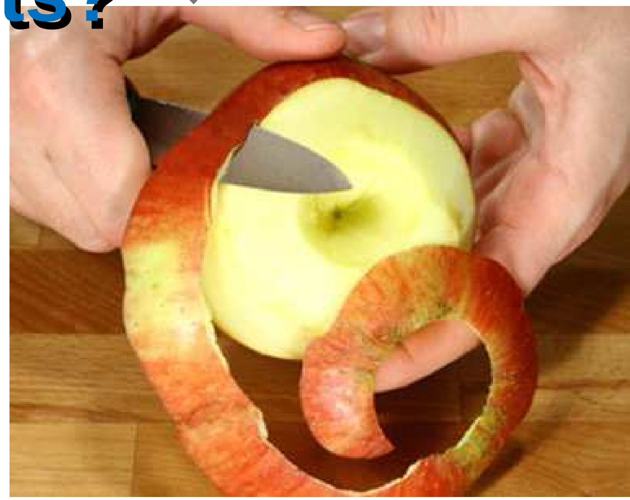


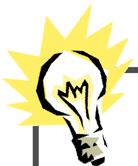
H(U+Th) = 16 ± 8 TW (exp) ± 5 TW (geology)

For the first time we have a measurement of the terrestrial heat power from U and Th

How to combine information from different experiments?







Mantle geoneutrinos in KamLAND and Borexino

G. Fiorentini,[1,2,3] G.L. Fogli,[4,5] E. Lisi,[5] F. Mantovani,[1,3] and A.M. Rotunno[4]

arXiv:1204.1923v1 [hep-ph] 9 Apr 2012

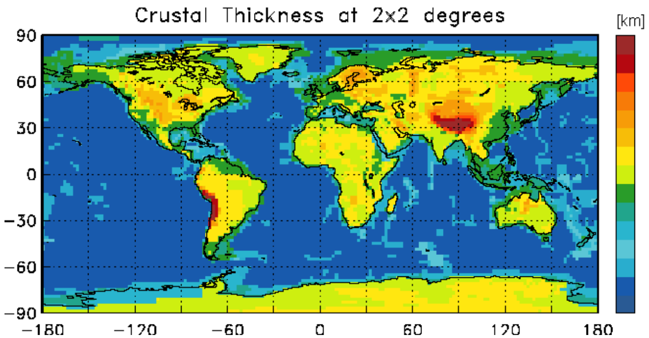
Method of a Multi-site approach

For each detector we can consider three contributions to the geo-ν signal.

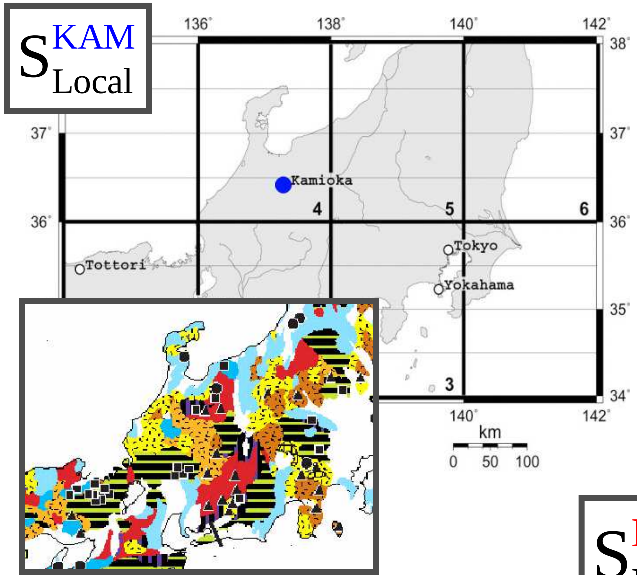
- KamLAND $$S^{KAM}_{Exp} = S^{KAM}_{Local} + S^{KAM}_{Rest\ of\ Crust} + S_{Mantle}$$

- Borexino $$S^{BOREX}_{Exp} = S^{BOREX}_{Local} + S^{BOREX}_{Rest\ of\ Crust} + S_{Mantle}$$

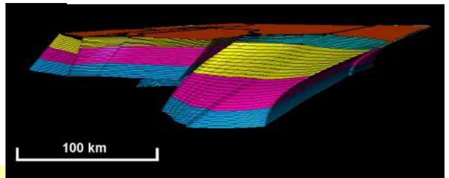
A World Wide Reference Model for geo-n $\mathbf{S}_{\textbf{Rest of Crust}}$ (Mantovani et al. 2004, Fogli et al. 2005, Enomoto et al. 2005, Dye 2010)

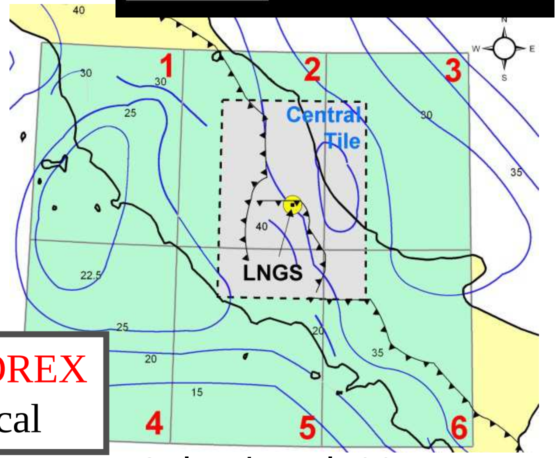


S^{KAM}_{Local}



Fiorentini et al. 2005





S^{BOREX}_{Local}

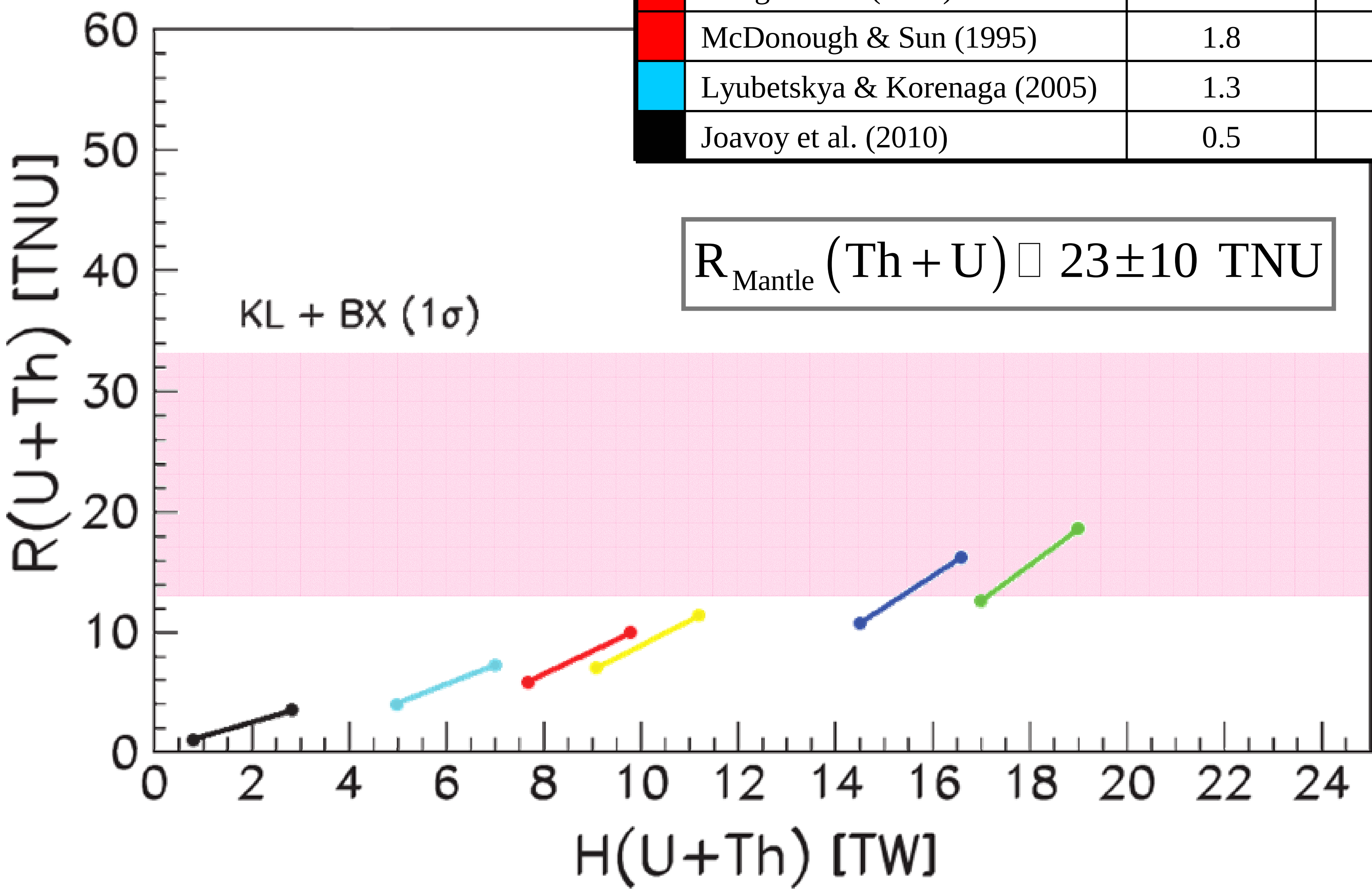
Coltorti et al. 2011

	KL event rates		BX event rates	
Reservoir	R(Th) [TNU]	R(U) [TNU]	R(Th) [TNU]	R(U) [TNU]
LOC	4.19 ± 0.46	13.53 ± 0.90	1.86 ± 0.27	7.81 ± 0.99
ROC	2.07 ± 0.25	6.71 ± 1.12	3.60 ± 0.43	12.07 ± 2.00
Crust total	6.26 ± 0.52	20.24 ± 1.43	5.46 ± 0.51	19.88 ± 2.24

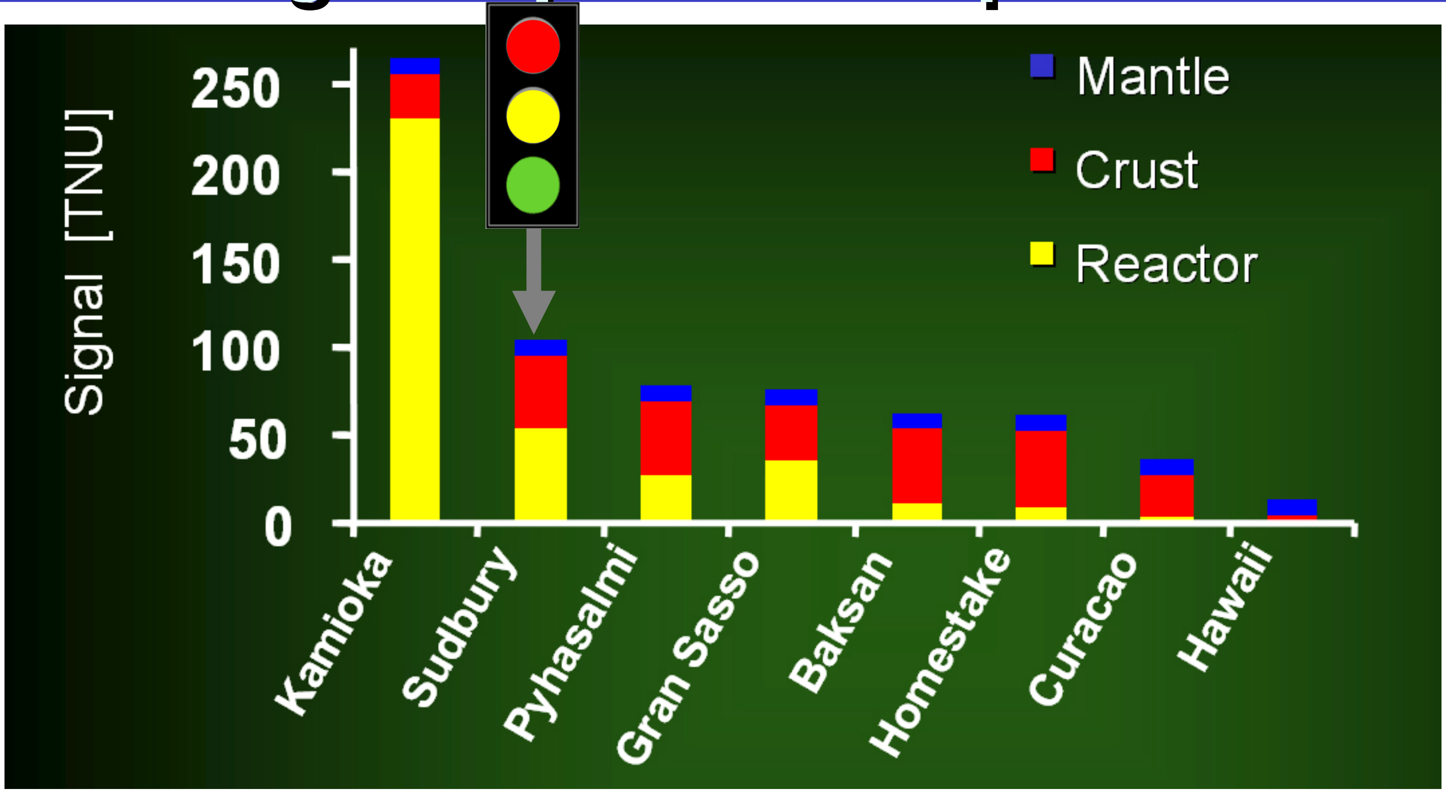
Mantle geo-neutrinos from KamLAND and Borexino

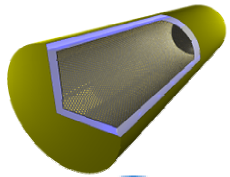
Authors of different BSE models		$m_{BSE}(Th)$ $[10^{17}$ kg$]$	$m_{BSE}(U)$ $[10^{17}$ kg$]$
	Turcotte & Schubert (2002)	3.6	0.9
	Anderson (2007)	3.1	0.8
	Palme & O'Neil (2003)	2.1	0.5
	Allegre et al. (1995)	1.8	0.5
	McDonough & Sun (1995)	1.8	0.5
	Lyubetskya & Korenaga (2005)	1.3	0.3
	Joavoy et al. (2010)	0.5	0.1

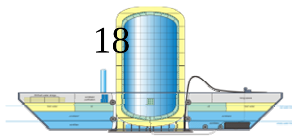
$$R_{Mantle}\left(Th+U\right) \approx 23 \pm 10 \ \ TNU$$



Multi site approach: running and planned experiments







- **Several experiments, either running or under construction or planned, have geo-ν among their goals.**

- **Figure shows the sensitivity to geo-neutrinos from crust and mantle together with reactor background.**

What is in front of us ?

- Borexino has now data from 5 years of data taking (first release refers to 2 years only)
- KAMLAND has unpublished data for (2010-2012); important benefits from reactor shutdown after tsunami
- A worldwide Refined Reference Model is being completed
- **Error on extraction of mantle contribution will be drastically reduced….**

Neutrino Geoscience Conferences:
Hawaii 2005 - Hawaii 2007 - Sudbury 2008 - LNGS 2010

Neutrino Geoscience 2013

Takayama, JAPAN 21st-23rd March, 2013

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New results from Borexino and KamLAND are expected

Wrolдwide RRM expected

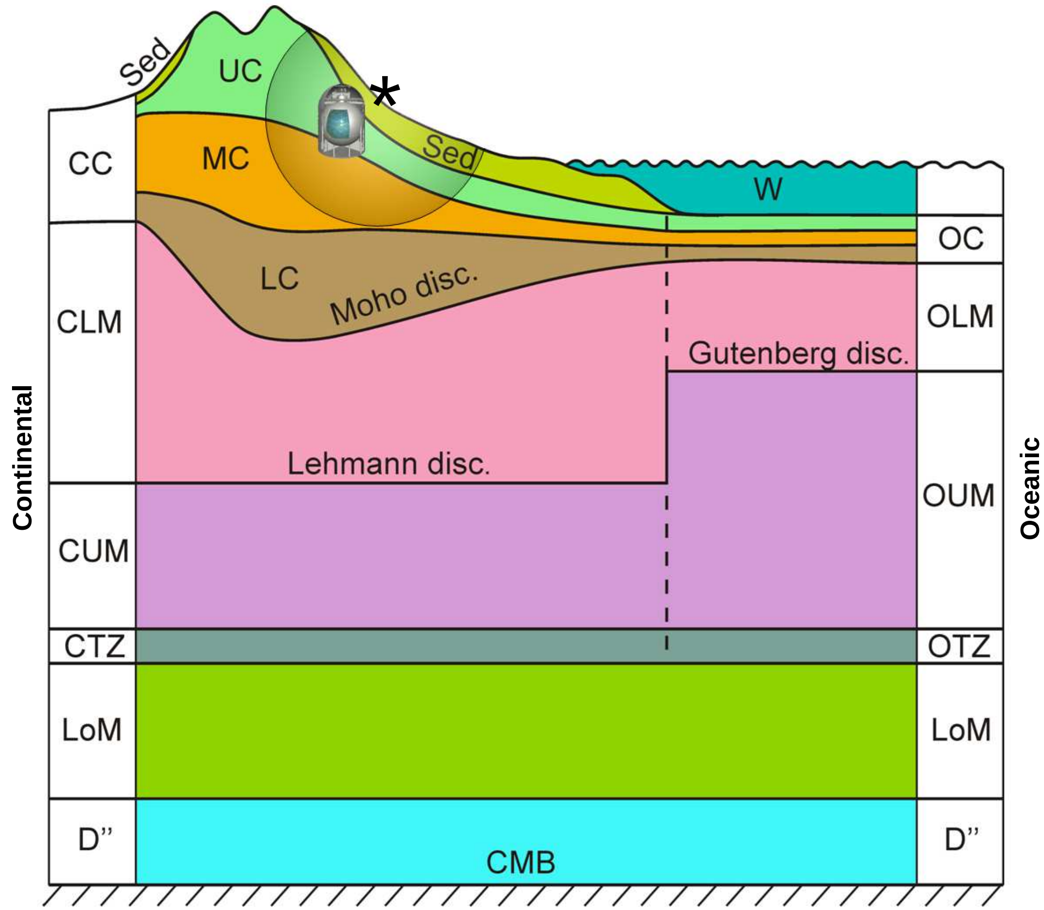
http://www.awa.tohoku.ac.jp/geoscience2013/

Dedicated to Raju Ragavhan

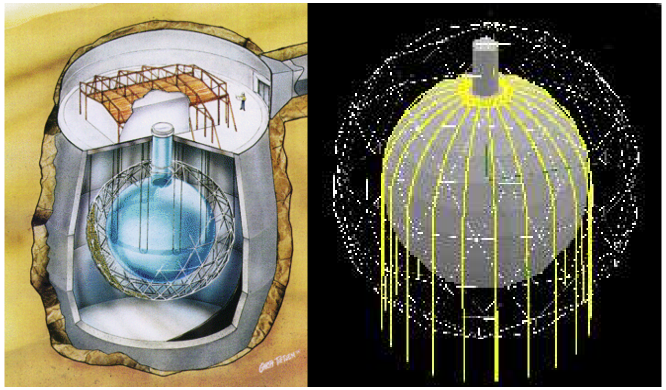
Back slides

Towards a Refined Reference Earth Model (RRM)

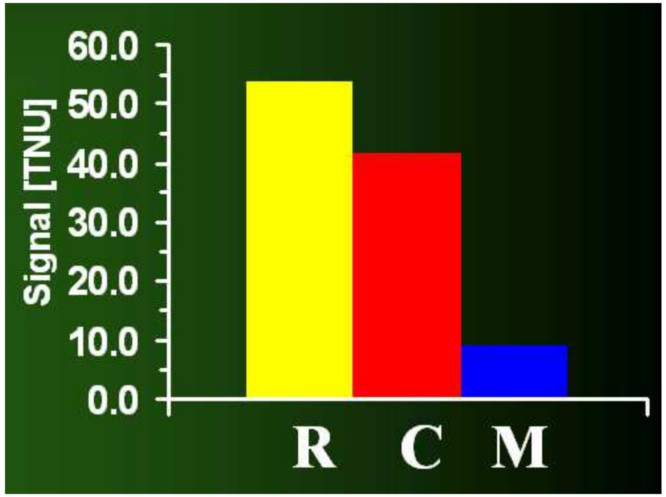
- An updated 1°x1° map of the sediments
- A 1°x1° crustal map constrained by global gravimetric models and supported by measurements of surface waves
- New compilations of geochemical data about OC, Seds, UC are included
- New approach in the evaluation of U and Th abundances (and their uncertainties) in MC and LC based on seismic arguments
- We include a “map” of the Lithospheric Mantle (OLM – CLM)



SNO+ at Sudbury



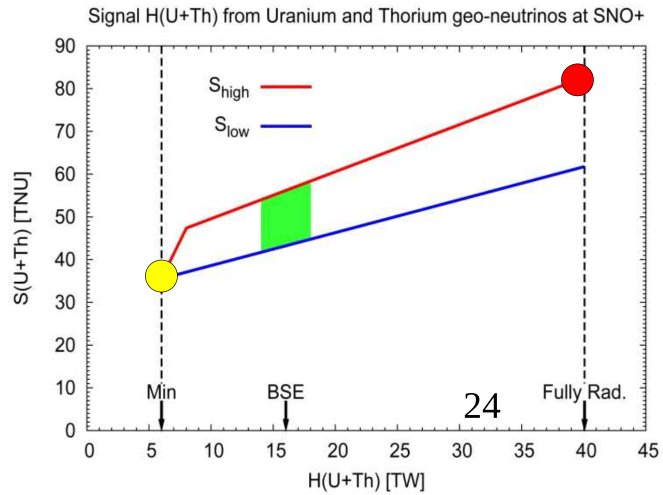
- A 1000-ton liquid scintillator underground detector, obtained by replacing D_2O in SNO.
- The SNO collaboration has planned to fill the detector with LS. SNO+ will start data taking in early 2011.



- 80% of the signal comes from the continental crust.
- From BSE expect 28 – 38 events/year*
- It should be capable of measuring U+Th content of the crust.

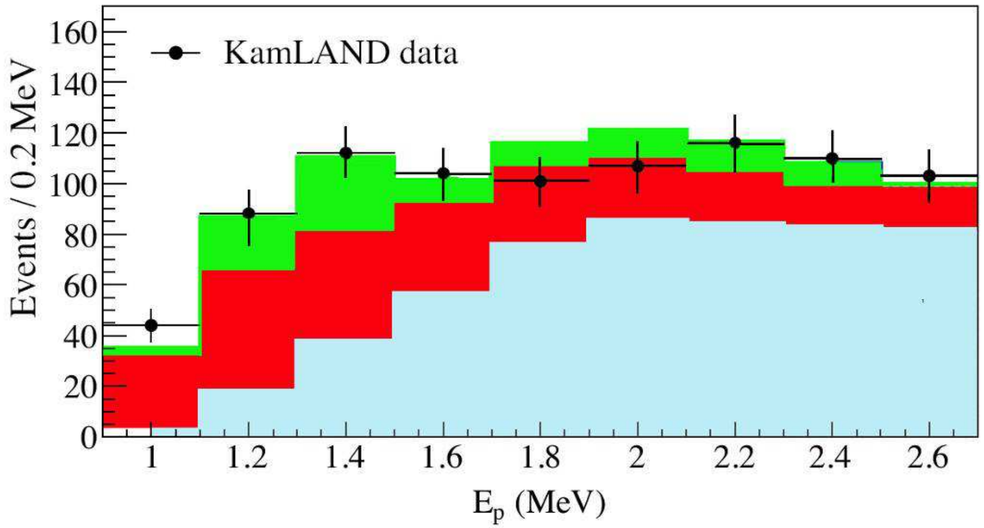
* assuming 80% eff. and 1 kTon CH_2 fiducial mass

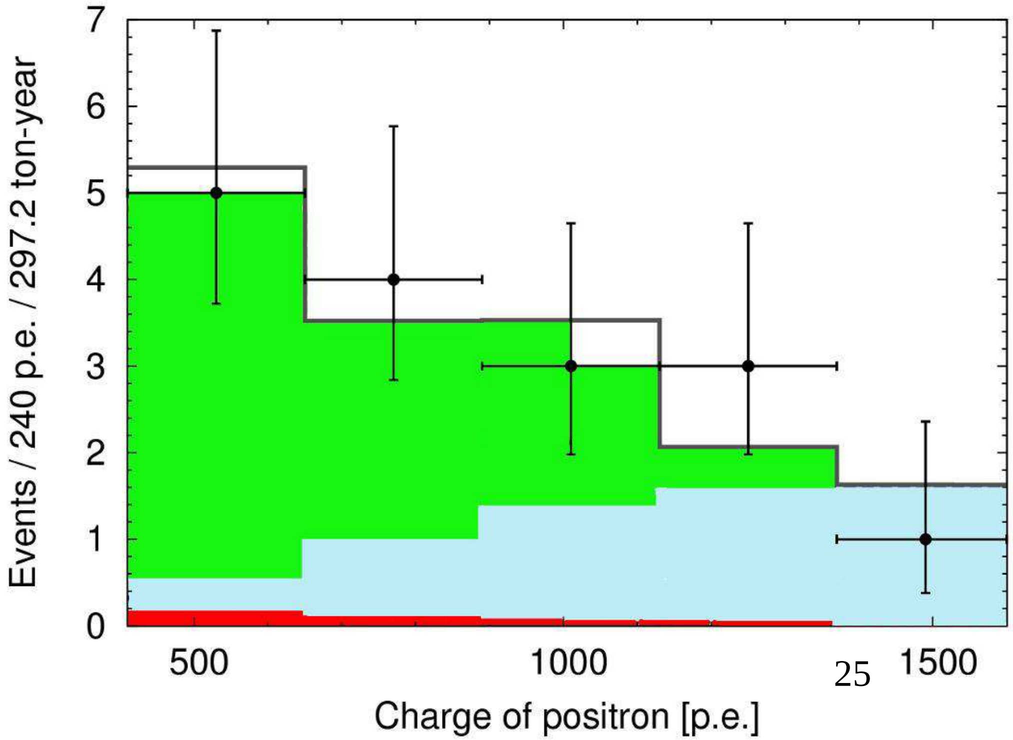
Chen, M. C., 2006, Earth Moon Planets 99, 221. Progress in Particle and Nuclear Physics 64 (2010)



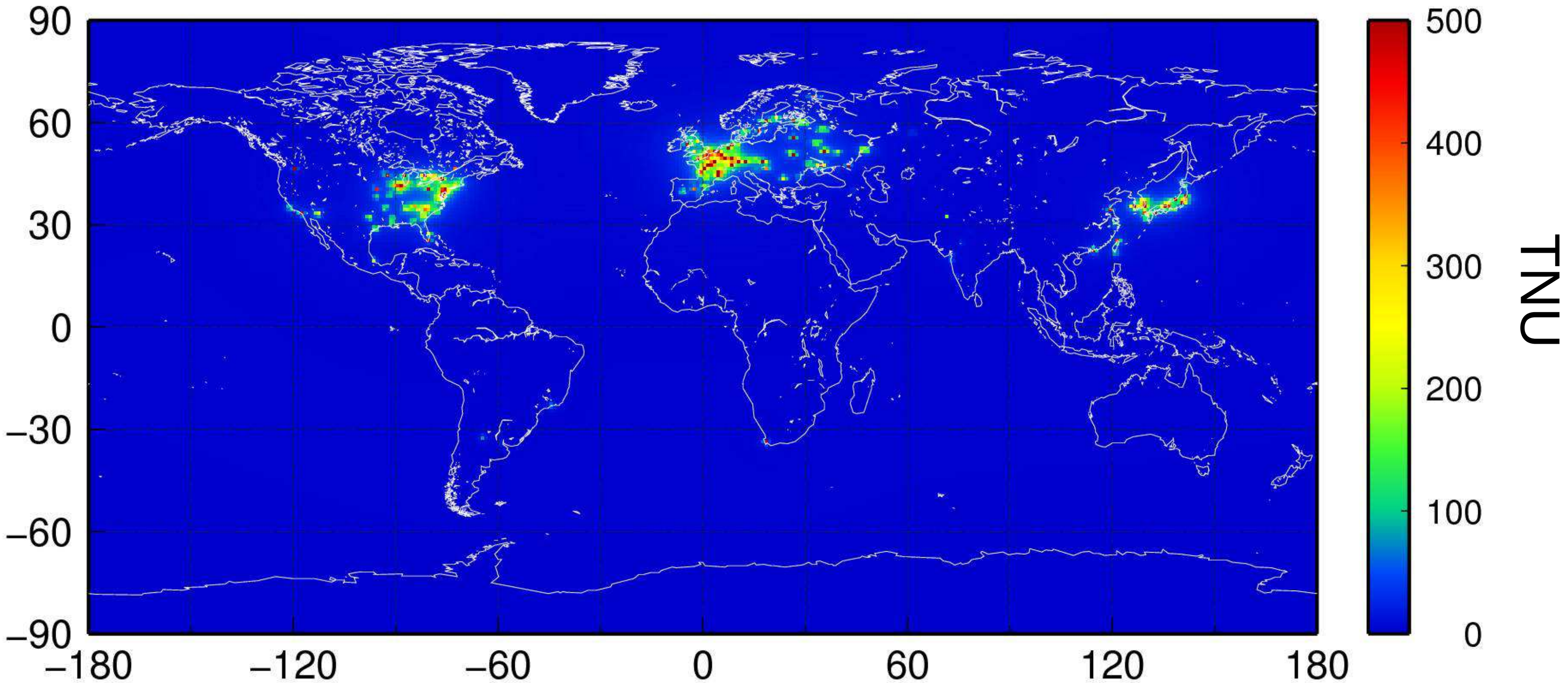
KamLAND vs Borexino

- KamLAND from 2002 to 2009 collected 841 events in the LER.
- Most due to Reactors (485) and background (245)
- After subtraction one remains with some 111 **geo-ν events**, a > 4σ evidence of geo-ν.
- Borexino has a smaller mass and exposure time
- It benefits from:
  - much higher purity
  - absence of nearby reactors





Reactor anti neutrinos in the world



• The signal refers to LER and it is calculated with the monthly load factor in the period 2007-2009 (IEAE data 2010).

• For the estimation of the neutrino flux from spent fuel (E_ν < 3.54 MeV) we assume that all spent fuels are stored just beside the reactors; the contribution to signal in LER is ~ 1%.

• By using the improved prediction of reactor antineutrinos spectra (Mueller et al. 2011) the signal in the LER increase of ~ 3 %.