Geoneutrinos

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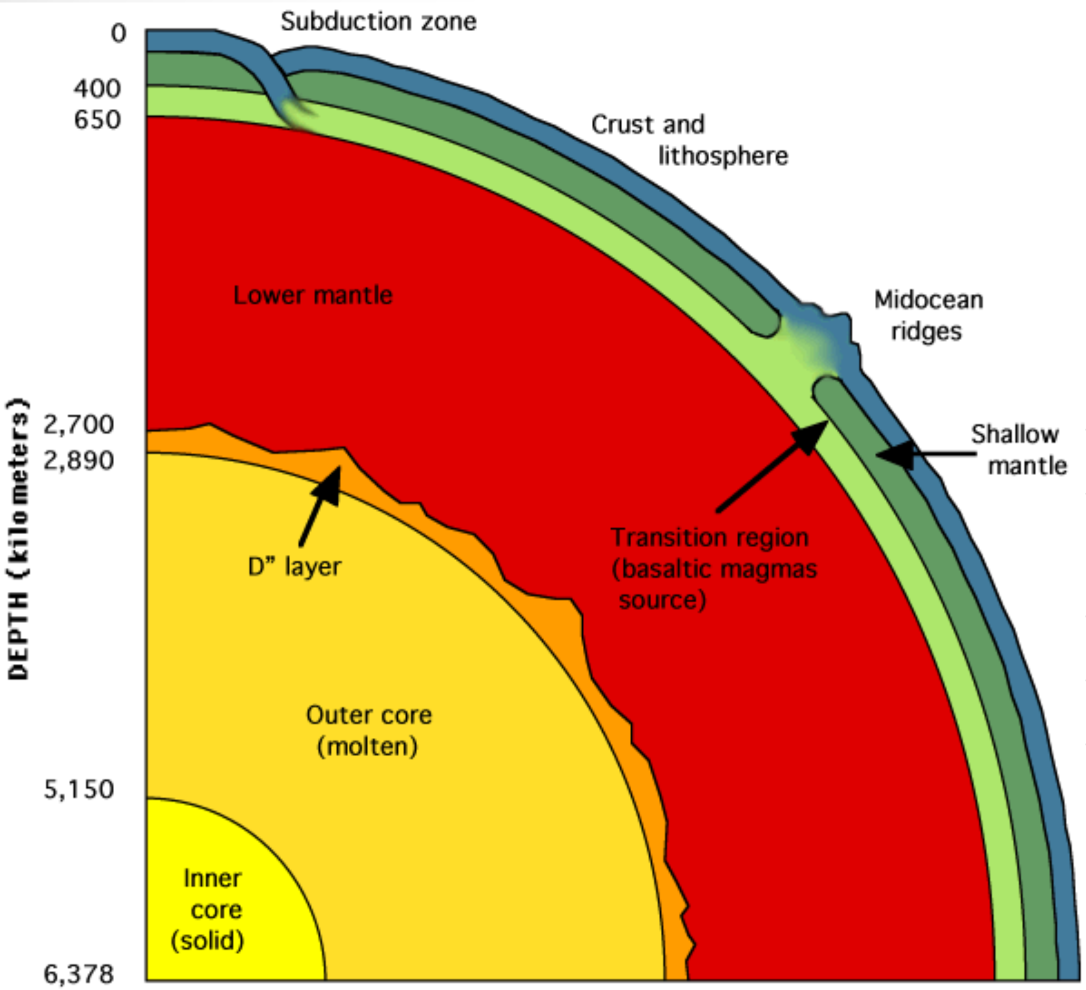
Outline

- Something on the Earth and on the methods for studying it
- Geo-neutrinos
- Current experiments and the experimental status of the art
- Future prospects

Earth structure



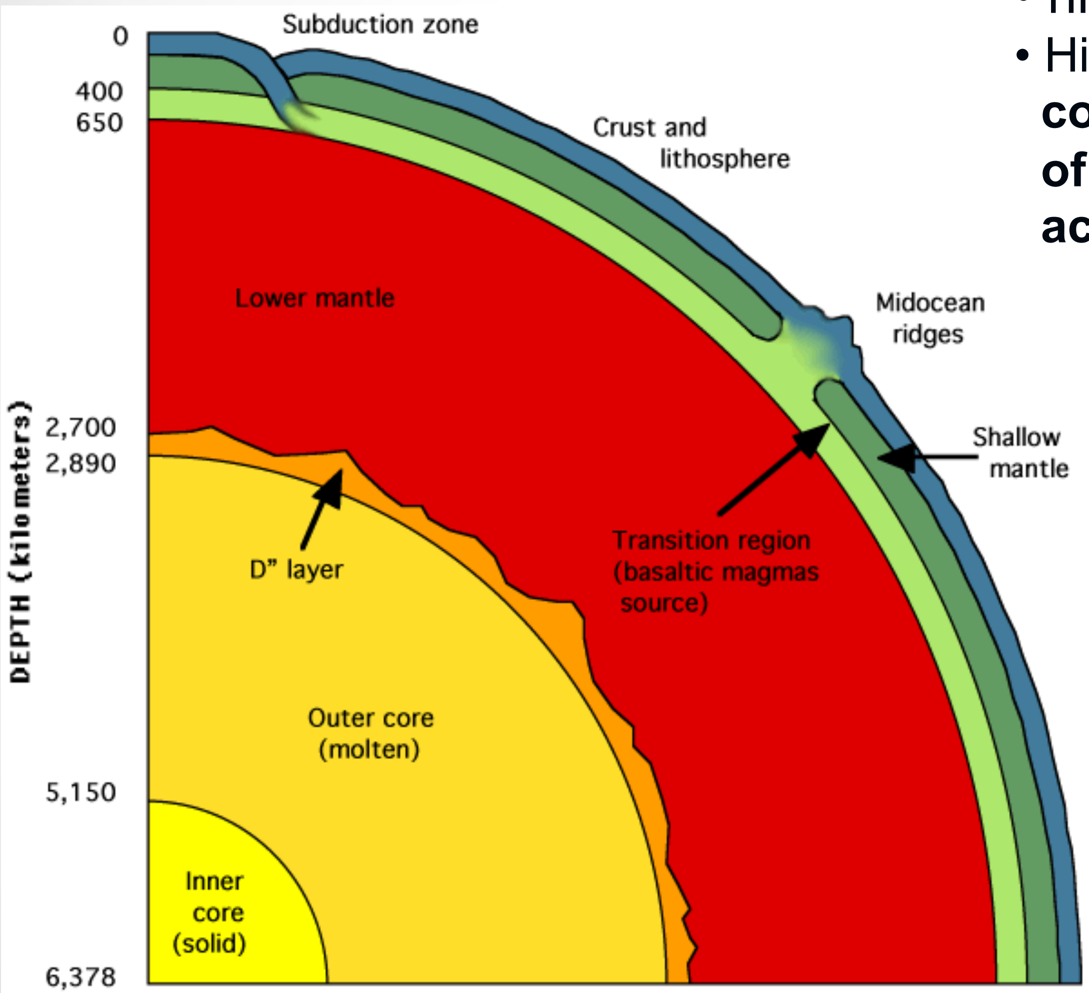
Inner Core

- about the size of the Moon;
- Fe – Ni alloy;
- **<u>solid</u>** (due to high pressure of ~ 330 GPa);
- temperature ~ 5700 K;

Outer Core

- 2260 km thick;
- Fe – Ni alloy + + 10% light elements (S, O?);
- **<u>liquid;</u>**
- temperature ~ 4100 – 5800 K;
- **geodynamo:** motion of conductive liquid;

Earth structure



Lower mantle

- rocks: high Mg/Fe ratio;
- T: 600 – 3700 K;
- high pressure: solid, but viscose;
- High temperature gradients: important **convection**, which drives **movements of tectonic plates and volcanism activities**

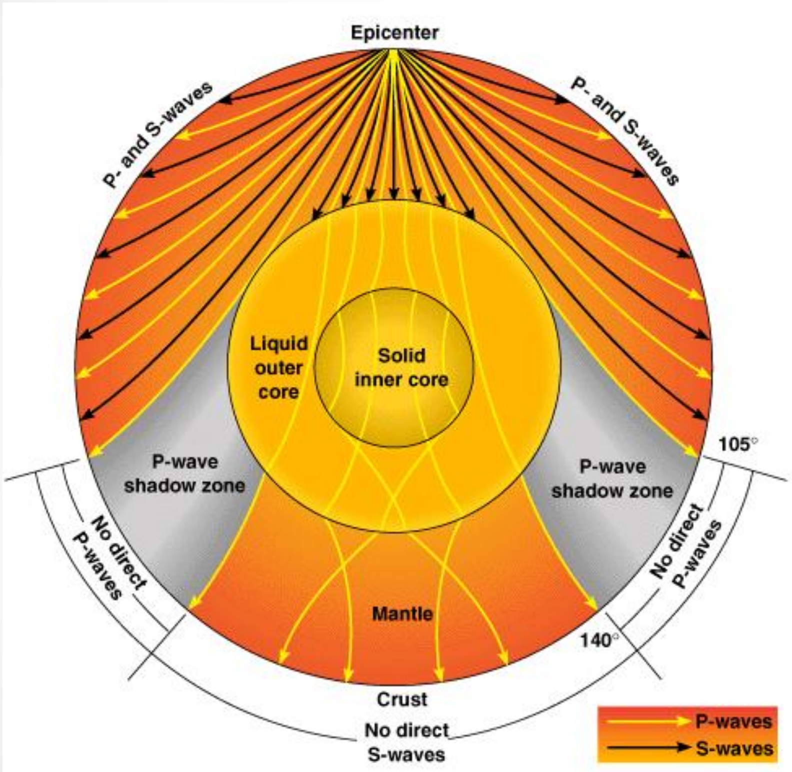
Upper mantle

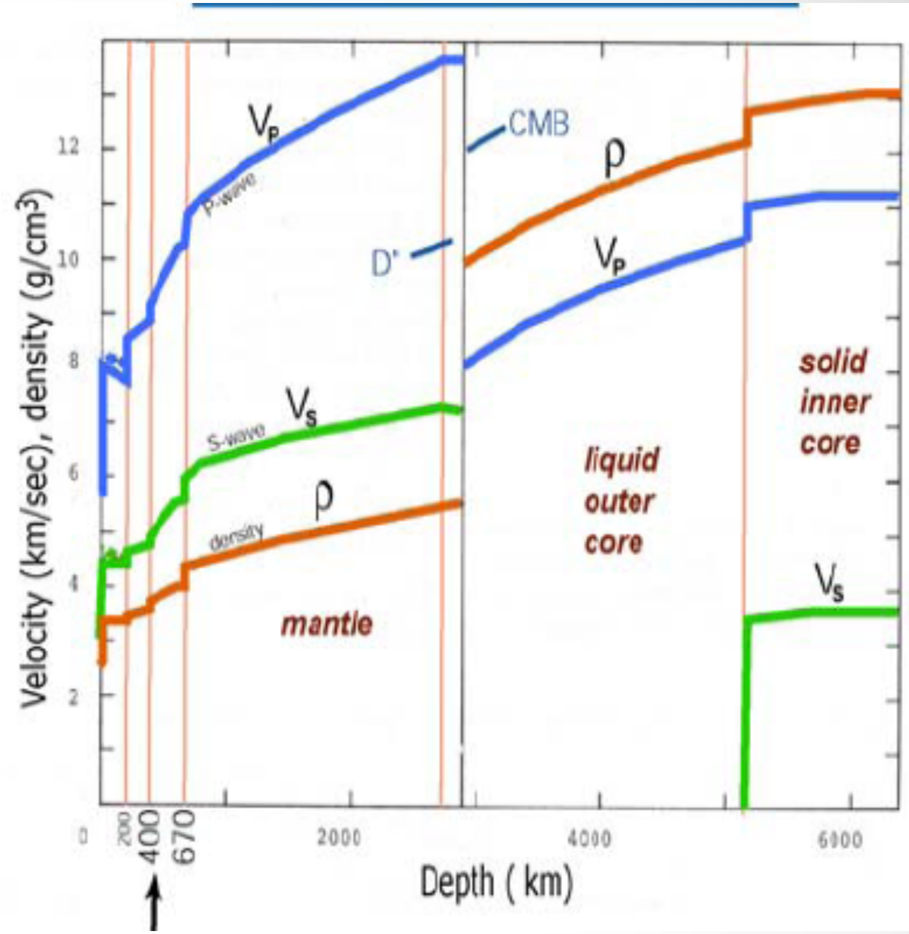
highly viscose; on which are floating the tectonic plates

Crust

- **<u>OCEANIC CRUST</u>**:
  ~ 10 km thick; younger
- **<u>CONTINENTAL CRUST</u>**:
- the most differentiated;
- 30 – 70 km thick;
- igneous, metamorphic, and sedimentary rocks;

Seismology





P– primary, longitudinal waves
S – secondary, transverse/shear waves

Discontinuities in the waves propagation and the density profile but no info about the chemical composition of the Earth

Geochemistry

1) **Direct rock samples**

* Crust surface and drill-holes (max. 12 km);
* mantle rocks brought up by tectonics and **vulcanism;**

BUT: POSSIBLE ALTERATION DURING THE TRANSPORT

2) **Geochemical models:**

composition of direct rock samples +
C1 carbonaceous chondritic meteorites + similarity with the Sun's photosphere; (condrites= small spheres, ~4.6 billion years old, which had a very fast cooling)

Bulk Silicate Earth (BSE) models (several!):
medium composition of the primordial mantle before the crust differentiation and after the Fe-Ni core separation, but before the crust-mantle differentiation

Surface heat flux

@ measurements of temperature gradients along several thousands of drill holes

47±2 TW but also 31±1 TW
(different assumptions on the role of fluids in the mid ocean ridges where mantle's material surfaces)

Radiogenic heath

@ BSE

range 11±2 -- 33±3 TW
(various assumptions: the composition in refractory (not volatile as Th,U) elements is the same as the chondritic meteorites; based upon the energetics of the mantle convection)

Geoneutrinos: antineutrinos from the Earth

the only direct probe of the deep Earth

Electron antineutrinos from the decays of long lived radioactive isotopes naturally present in the Earth;

$^{238}U \rightarrow {}^{206}Pb + 8\,\alpha + 8\,e^- +$ 6 anti-neutrinos + 51.7 MeV

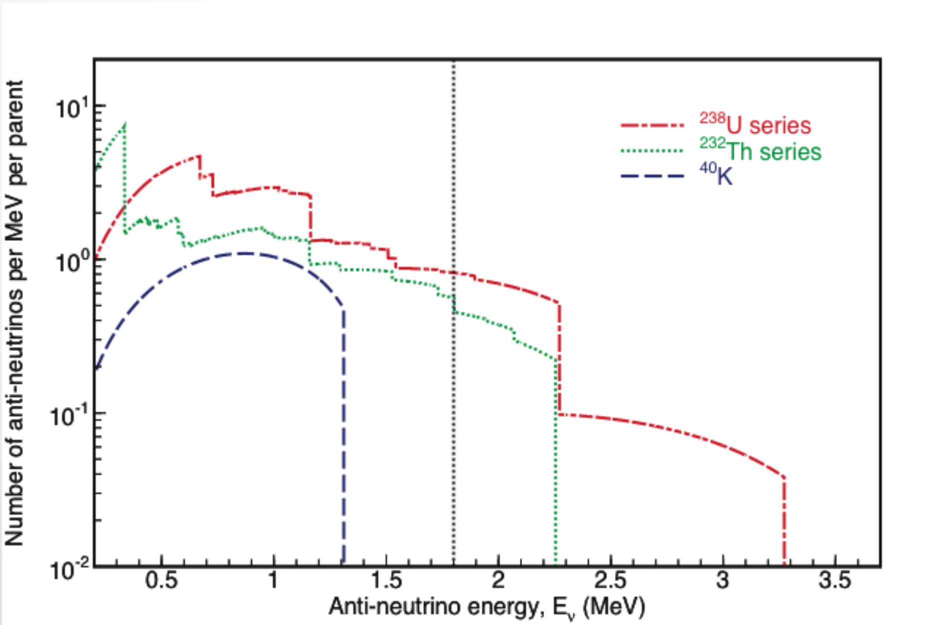
$^{232}Th \rightarrow {}^{208}Pb + 6\,\alpha + 4\,e^- +$ 4 anti-neutrinos + 42.8 MeV

$^{40}K \rightarrow {}^{40}Ca + e^- +$ 1 anti-neutrino + 1.32 MeV

$T_{1/2}$ = (4.47, 14.0, 1.28) x 10^9 years, resp.

Estimated antineutrinos flux ~ 10^6 cm^{-2} s^{-1}

(for comparison: solar neutrino flux ~ 10^{10} cm^{-2} s^{-1})



Geoneutrinos energy range

$T_{geo\text{-}\nu}$ = 1.8 – 3.3 MeV

$E_{visible}$ ~ 0.8– 2.3 MeV

Sources of the terrestrial heat

@ Radiogenic heat= from decays of radioactive elements

@ Residual heat:

--gravitational contraction and extraterrestrial impacts in the past

--^{40}K in the core

--nuclear geo-reactor (Borexino and Kamland reject a power >3.5 TW at 95% C.L.)

--mantle differentiation and re-crystallisation

What we can expect from the geoneutrino study

radiogenic contribution to terrestrial heat
how much of the radioactive elements are in the crust and in the mantle
the bulk Th/U
is there a geo-reactor?
compatibility of the BSE models with geoneutrino data

And perhaps for the far future:

the radioactive element distribution in the mantle
presence of radio-elements in the core

Two experiments able until now to study the geo-neutrinos

KamLand in Kamioka, Japan
Border bewteen
OCEANIC AND CONTINENTAL CRUST

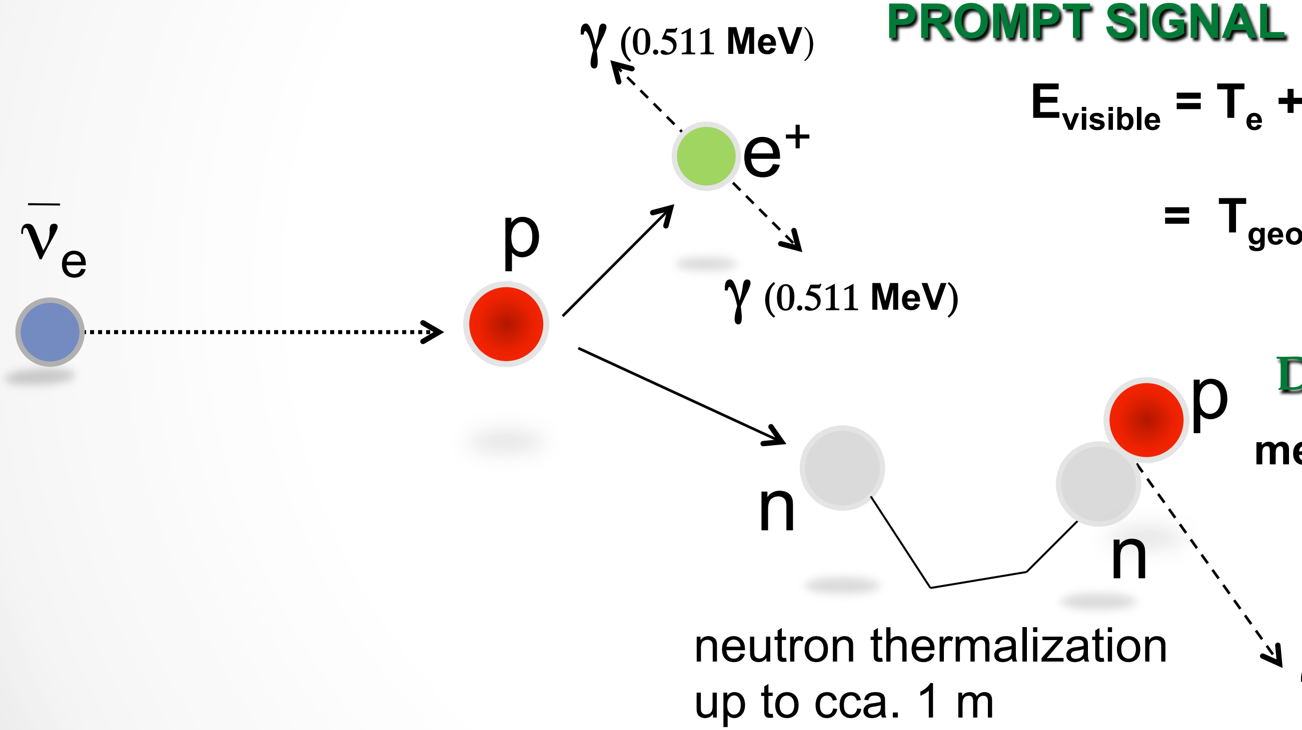
- liquid scintillator
- originally built to measure reactor antineutrinos;
- 1000 tons;
- data since 2002;
- 2700 m. w. e. shielding
- high anti–ν flux from reactors
- more statistics (more live days and more volume with respect to Bx)
- Energy and vertex resolution: 6.4% and 12 cm at 1 MeV

Borexino in Gran Sasso, Italy
CONTINENTAL CRUST

- liquid scintillator
- originally built to measure low energy solar neutrinos – extreme unprecedented radiopurity needed and achieved;
- 280 tons;
- data since 2007;
- 3600 m.w.e. shielding;
- low anti-ν flux from reactor and very low internal background
- Energy and vertex resolution: 5% and 11 cm at 1 MeV

Detecting geo-ν: inverse β-decay

Energy **threshold** of $T_{geo\text{-}\nu} = 1.8$ MeV



PROMPT SIGNAL

$$E_{visible} = T_e + 2*0.511 \text{ MeV} =$$

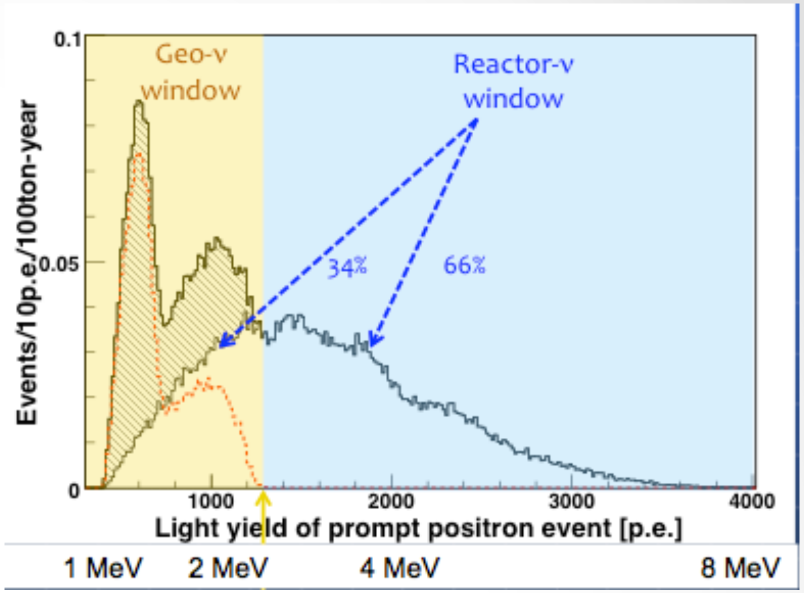
$$= T_{geo\text{-}\nu} - 0.78 \text{ MeV}$$

DELAYED SIGNAL

mean n-capture time on p
256 μs (Borexino)
~207 μs (Kamland)

Main background

@ anti-neutrinos from reactors



@ internal radioactive background (negligible in Borexino)

- (α−n) and (γ−n) interactions: mainly from $^{13}C(\alpha-n)^{16}O$

- accidental coincidences

@ cosmogenic ^{9}Li and ^{8}He

Correction for the oscillations.

Geoneutrinos; the effect is well average due to large distance (~6371 km to be compared to L_0 of ~ 100 Km at ~3 MeV)- $\langle P_{ee} \rangle \cong \cos^4\theta_{13}\left(1-\frac{1}{2}\sin^2 2\theta_{12}\right)+\sin^4\theta_{13} \cong 0.54$

-Matter effect contribution: 2% effect on the survival probability and <1% on the spectral distorsion.

Reactor neutrinos: aver. Distance: ~1170 km for Borexino; 180 km for Kamland weighted distance calculated for each reactor taking into account distance and power

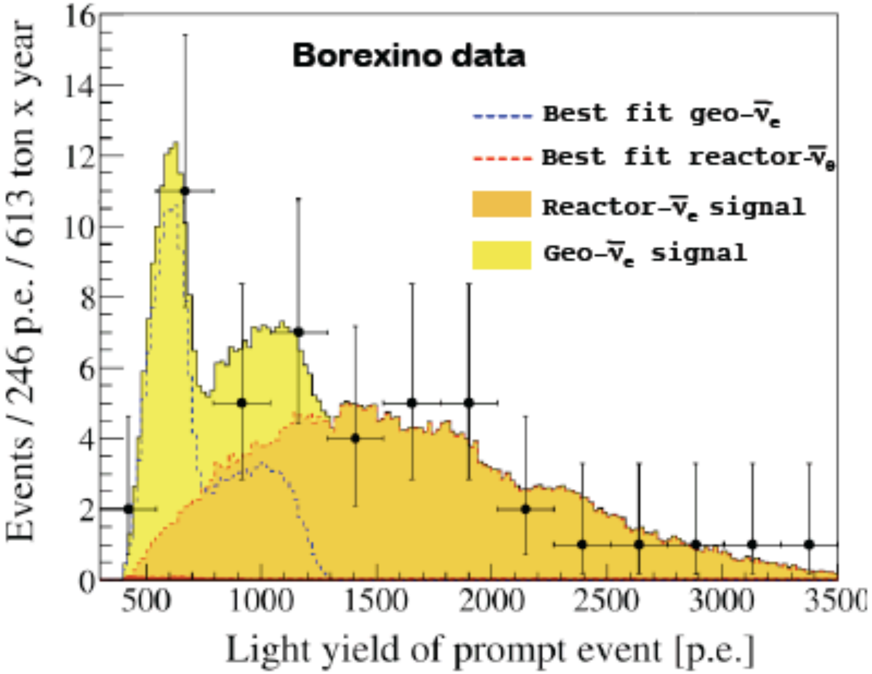
Calculation of reactor anti-ν signal

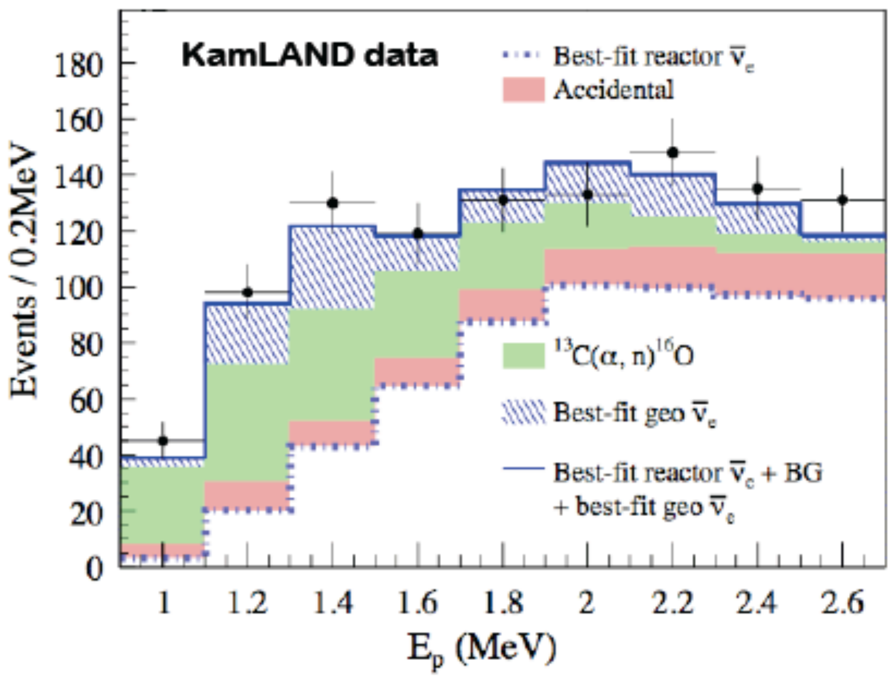
$$\Phi(E_{\bar{\nu}_e}) = \sum_{r=1}^{N_{react}} \sum_{m=1}^{N_{month}} \frac{T_m}{4\pi L_r^2} P_{rm} \sum_{i=1}^{4} \frac{f_{ri}}{E_i} \Phi_i(E_{\bar{\nu}_e}) P_{ee}(E_{\bar{\nu}_e}; \hat{\vartheta}, L_r)$$

- **From the literature:**
  - **E_i :** energy release per fission of isotope i (Huber-Schwetz 2004);
  - **Φ_i:** antineutrino flux per fission of isotope i (polynomial parametrization, Mueller et al.2011, Huber-Schwetz 2004);
  - **P_{ee}:** oscillation survival probability;
- **Calculated:**
  - **T_m:** live time during the month m;
  - **L_r:** reactor r – detector distance;
- **Data from nuclear agencies:**
  - **P_{rm}:** thermal power of reactor r in month m (IAEA , EDF, Consortium of Japanese Electric Power Companies, UN data base)
  - **f_{ri}:** power fraction of isotope i in reactor r;
  - Bx: 194 Eu reactors+245 (world); KL: 55 Japan+384 (world)

^{235}U
^{239}Pu
^{238}U
^{241}Pu

Data (prompt event energy)



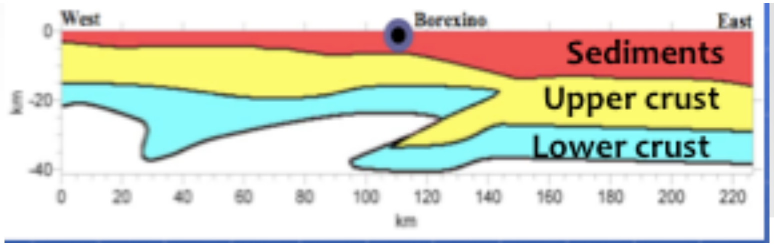


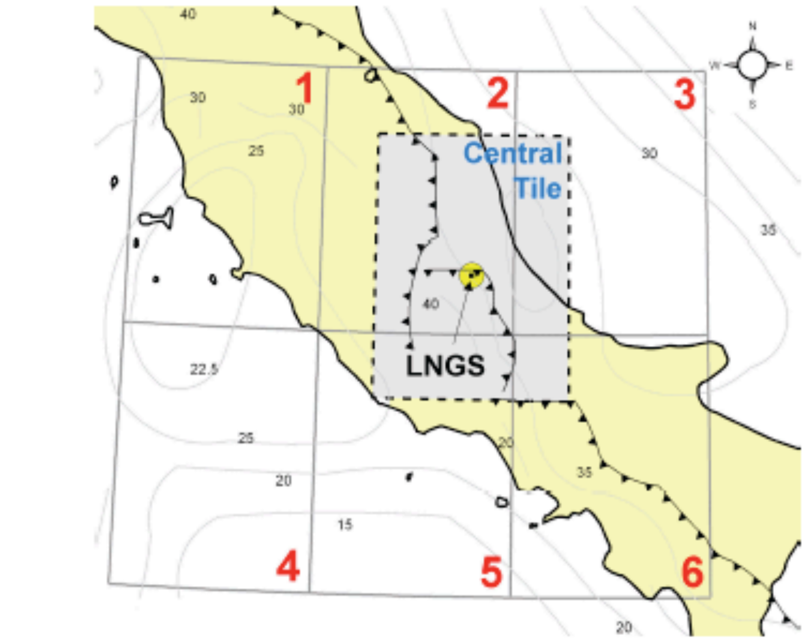
Borexino: plot in total number of photoelectrons detected by the PMTs: 500 p.e./1 MeV
Borexino and Kamland: for geo-ν the fit is done assuming the chondritic Th/U= 3.9
Kamland: by sept. 2011 Kamland-Zen started with the insertion of a 3.08 m diameter vessel, containing 13 tons of Xe-loaded l.s.. In the period: april-june 2012 the Japanese reactors have been switched off, allowing a check of all other backgrounds.

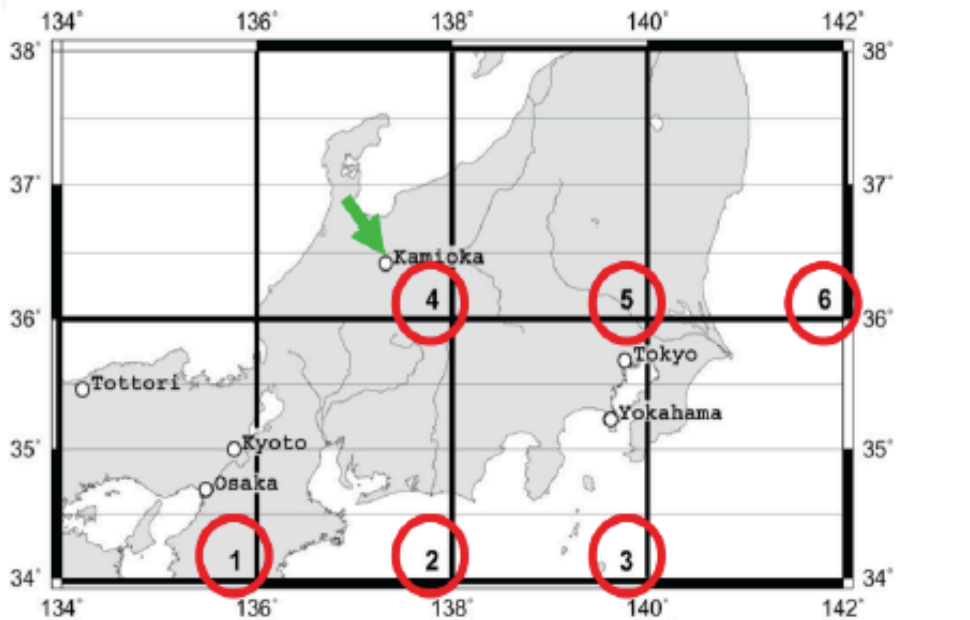
	Borexino	Kamland
Period	Dec.07-Aug.12	Mar.02-Nov. 12
Geo-ν events	14.3±4.4	116^{+28}_{-27}
Geo-ν flux (oscill) [10^6 cm^{-2} s^{-1}]	4.4±1.4	3.4±0.8
Reactor anti-ν	$31.2^{+7.0}_{-6.1}$	2017±119.2
Accidental events	0.206±0.004	125.5±0.1
$^{13}C(\alpha,n)^{16}O$ events	0.13±0.01	207.1±21.4
^{9}Li-^{8}He events	0.25±0.18	31.6±1.9
Geo-ν signal/anti-ν background	0.46	0.032
Geo-ν signal/ non anti-ν background	24.4	0.32
Expected reactor anti-ν	**33.3±2.4**	**2382±123**

No geo-neutrino observation rejected in both experiments at 99.997% C.L.

Local contribution







Map of 2^0x2^0 tiles from which the ***LOC*** geo-neutrino signal is calculated from samples from the sedimentary measured with ICP-MS- and from the composition of the real rocks surrounding the detector- ***LOC*** includes 6^0x4^0 surrounding the detector
ROC is the rest of the crust: we take into account the mean composition- f. i. in the Borexino case the radio content of the crust is taken from Valsugana and Ivrea-Verbano outcrops

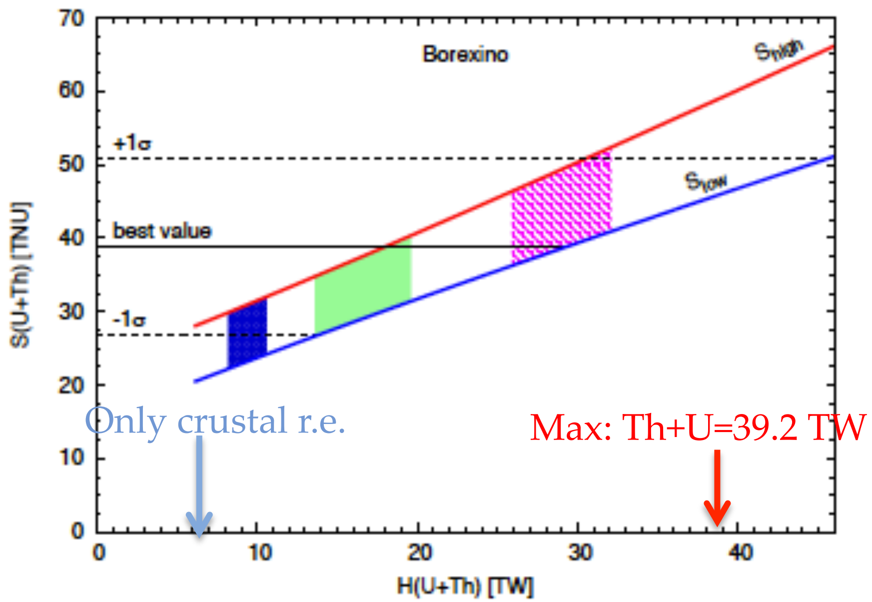
Borexino: (TNU)-LOC: 9.7±1.3; ROC: 13.7+2.8-2.3; measured Geo-ν: 38.8±12
Kamland: (TNU)-LOC:17.7±1.4; ROC: 7.3+1.5-1.2; measured geo-ν : 30±1.7

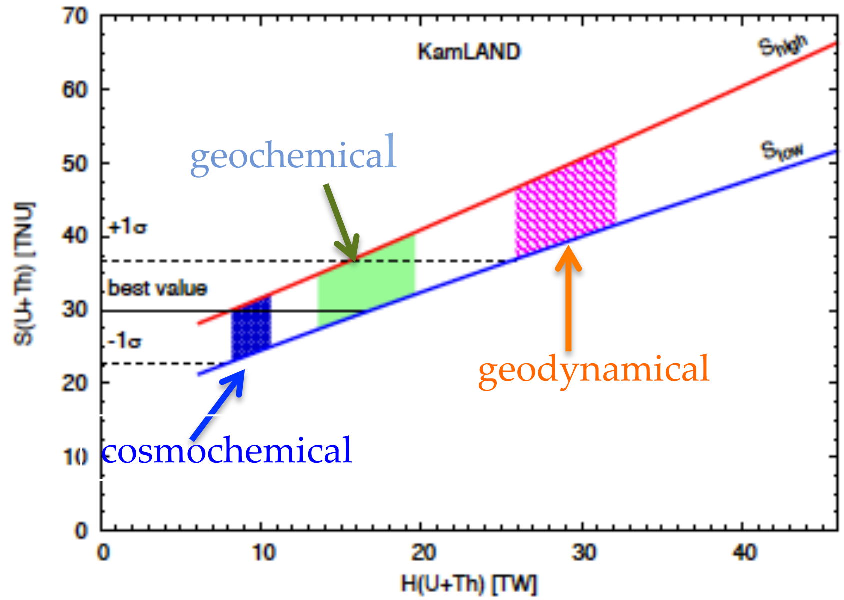
Terrestrial Neutrino Unit (TNU) = 1 event / year / 10^{32} protons (about 1 kton)

What we can obtain from these data

1

Which is the Earth heat produced by the radio-decays.





Mantle homogeneous

r.e. only on the border mantle-core sunken-layer model

Cosmochemical, geochemical, geodynamical: three classes of BSE

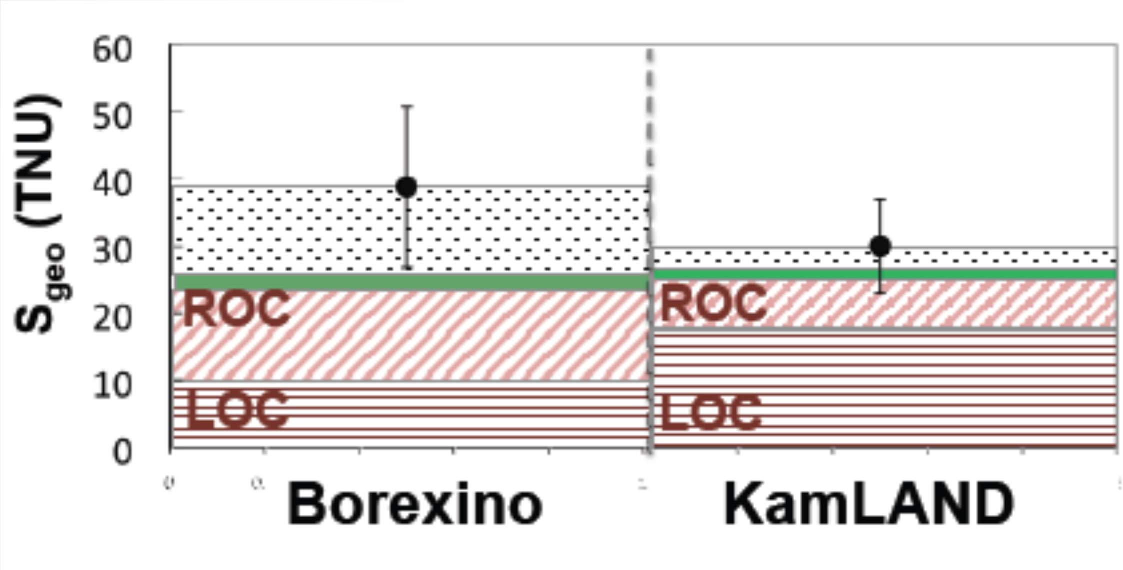
== geochemical: the chondritic ratio assumed, but also the composition of the mantle rocks is taken into account

== cosmochemical: the composition of the chondritic meteorites is assumed;

==geodynamical: based on the energetics of the mantle convection

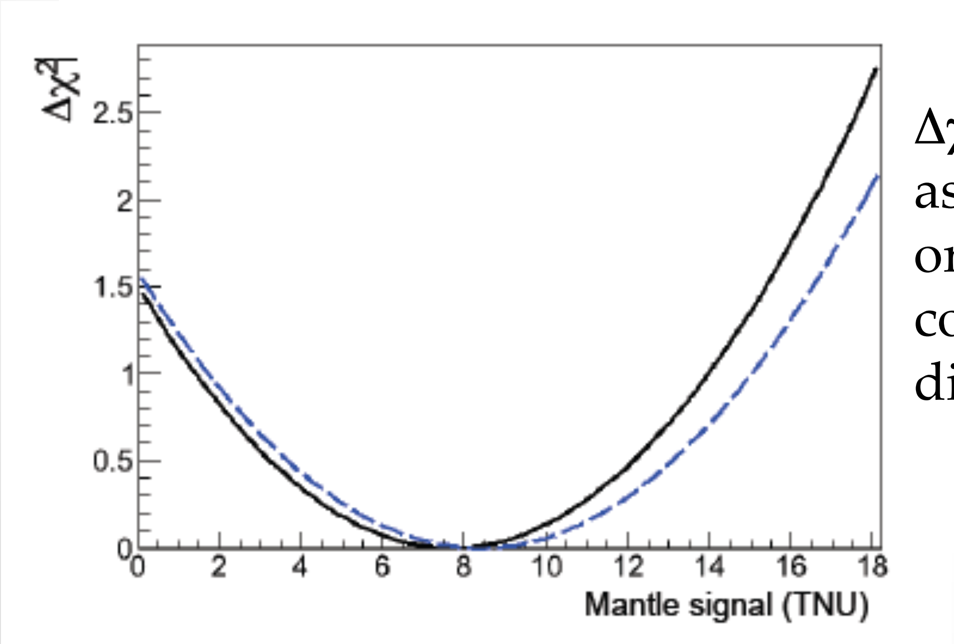
2

Th and U in the mantle



Bx: 15.4±12.3 TNU

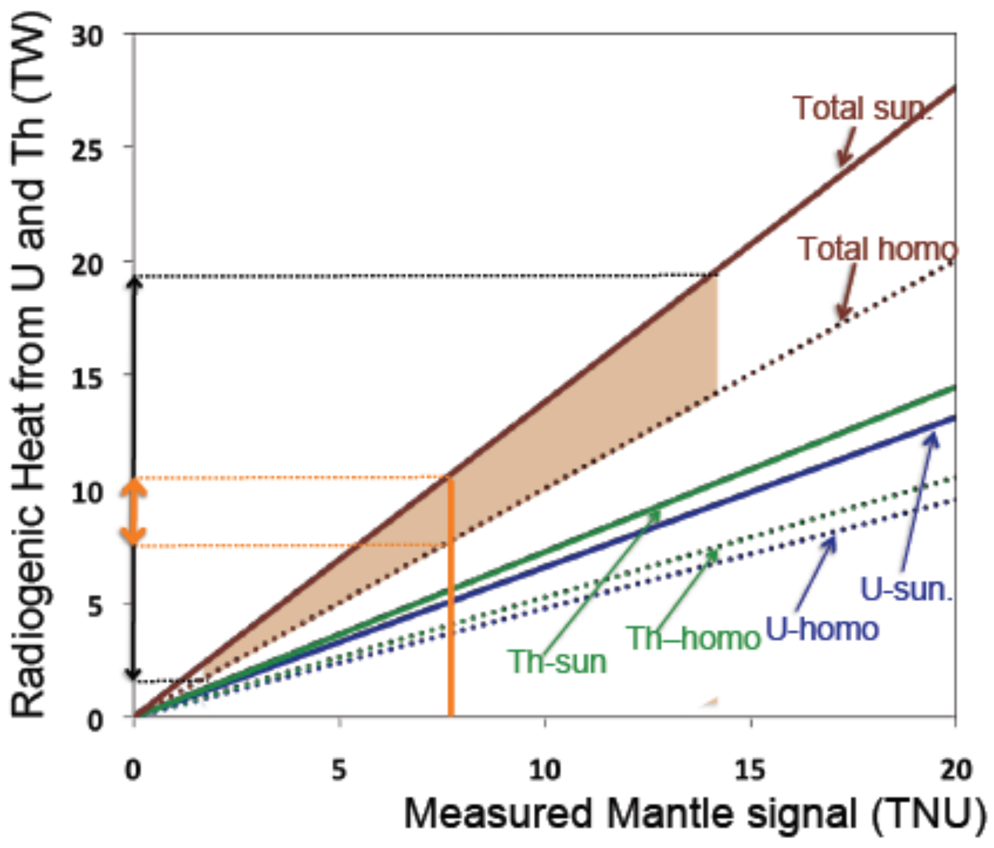
KL: 5.0±7.3 TNU



$\Delta\chi^2$ profile for the model, which assumes an homogeneous mantle ——— or the model assuming two different compositions for Africa and Pacific: 10% difference between Bx and KL ------------

Which is the Earth heat produced by the radio-decays in the mantle?

Combined Bx+KL -- from the mantle: 7.7±6.2 TNU



Measured mantle geo-ν Signal (combined analysis)

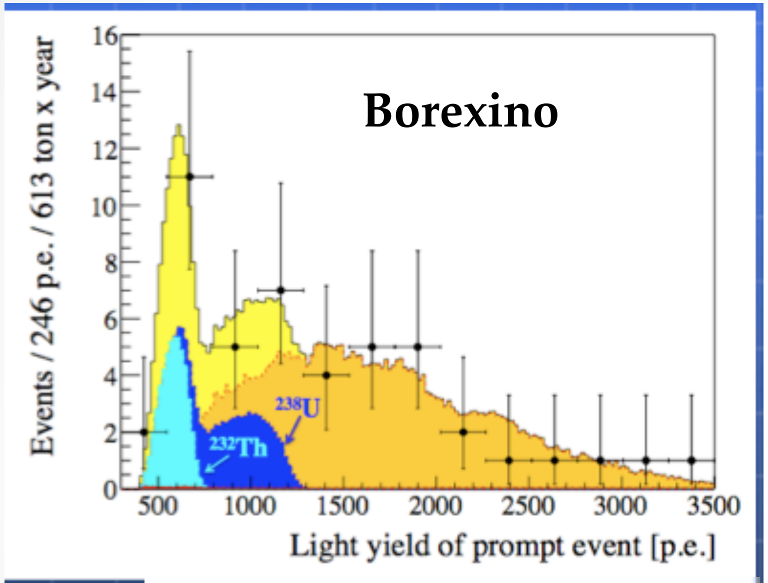
1 σ band

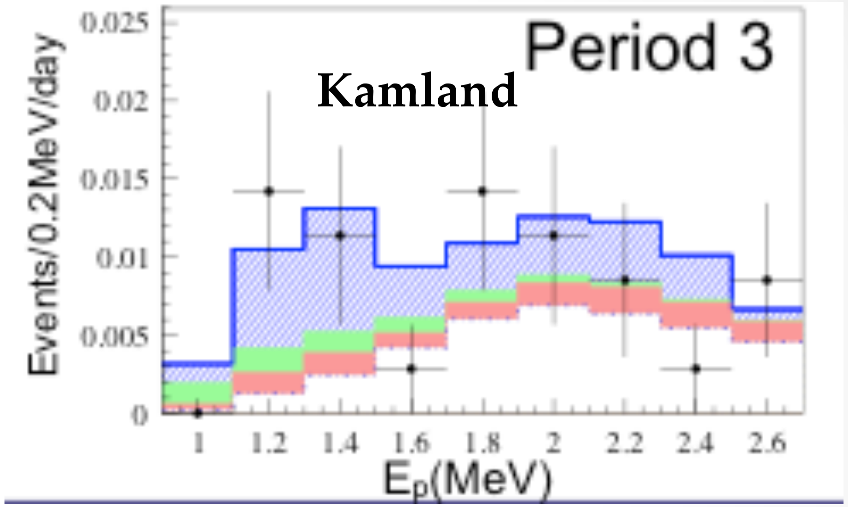
Mantle radiogenic heat corresponding to 7.7 TNU
Sunken model- homogeneous m.
7.5-10.5 TW

Total heat range – 1σ error
2.−19.5 TW

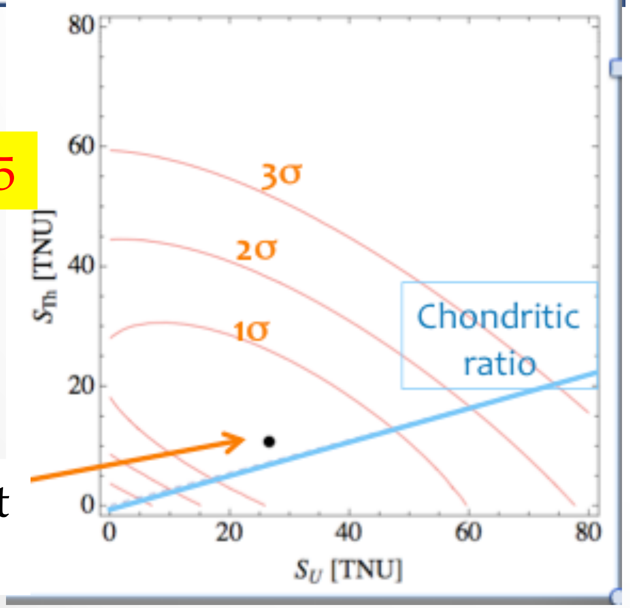
3

Th/U bulk mass ratio (3.9 from the chondritic ratio)

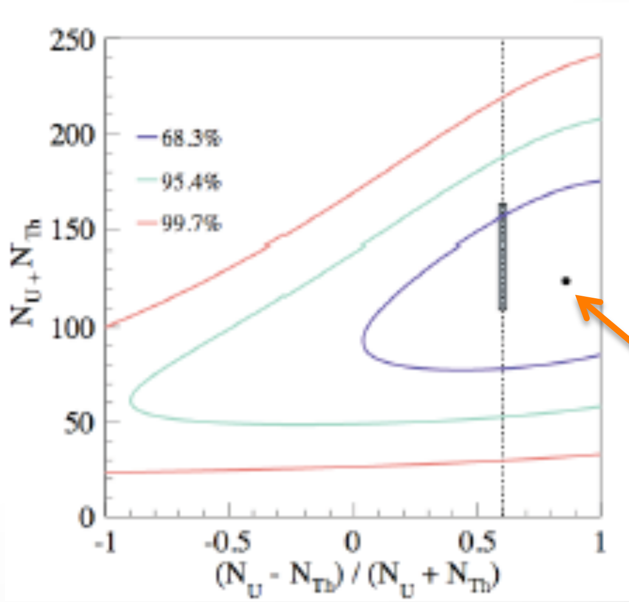




Th/U~2.5



Best fit



Th/U~14.5
Very large
Uncert.

Best fit

Conclusions

1. The evidence of the geo-neutrinos is very robust

2. Indications of agreement with the cosmochemical and geochemical model; that means a radiogenetic heat of 15-21 TW to be compared with the total heath prevision of 31-47 TW

3. Indication at ~ 1σ of presence of radioactive elements in the mantle (7.7±6.2 TW)

4. Indication at 1.5 σ of an agreement of Th/U ratio with the chondritic ratio.

More statistics is needed!!!!!!

Future expectations

1- **Borexino** intends to take data until the end 2015- statistics almost doubled (systematic is negligible)

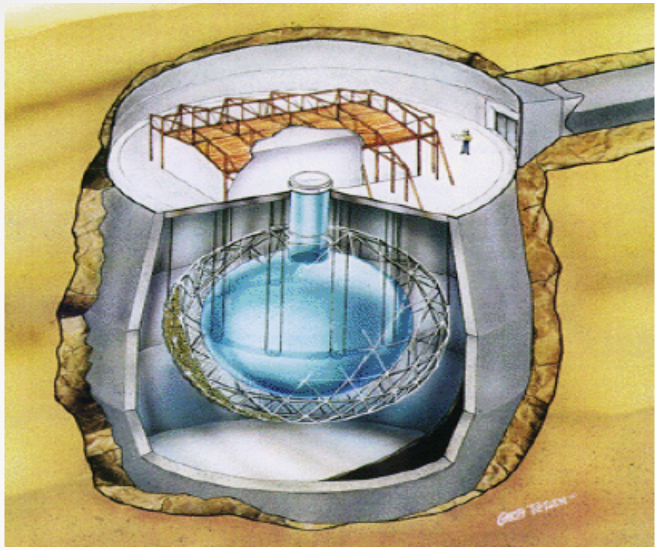
2- **Kamland** probably will proceed in the same way

3- **SNO+** coming soon

4- **HanoHano** (not yet approved)

5- **LENA** (not yet approved)

SNO+ at Sudbury, Canada



SHOULD BE COMING SOON!

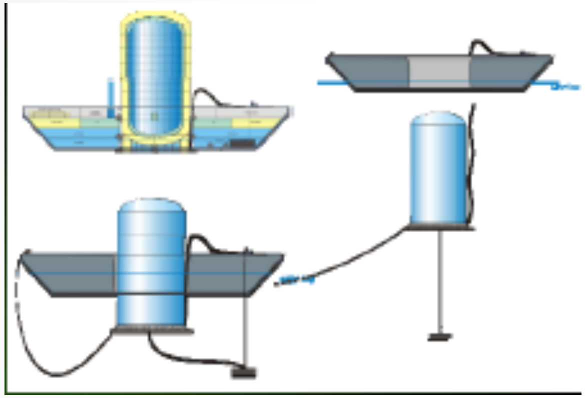
After SNO: D_2O replaced by 1000 tons of liquid scintillator
M. J. Chen, *Earth Moon Planets* **99**, 221 (2006)

Placed on an **old continental crust**:
80% of the signal from the crust
(Fiorentini et al., 2005)

BSE: 28-38 events/per year

Mantovani et al., TAUP 2007

Hanohano (= magnificent) at Hawaii



Project for a 10 kton liquid scintillator detector, movable and placed on a deep ocean floor

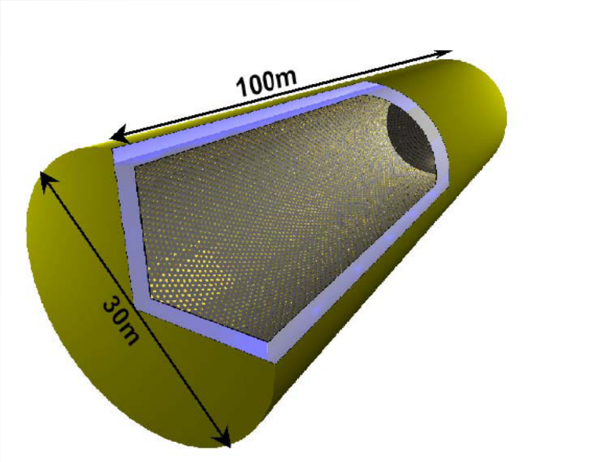
J. G. Learned et al., *XII International Workshop on Neutrino Telescopes*, Venice, 2007.

Since Hawai placed on the U-Th
depleted oceanic crust
70% of the signal from the mantle!
Would lead to very interesting results!
(Fiorentini et al.)

BSE: 60-100 events/per year

Mantovani , TAUP 2007

LENA at Pyhasalmi, Finland

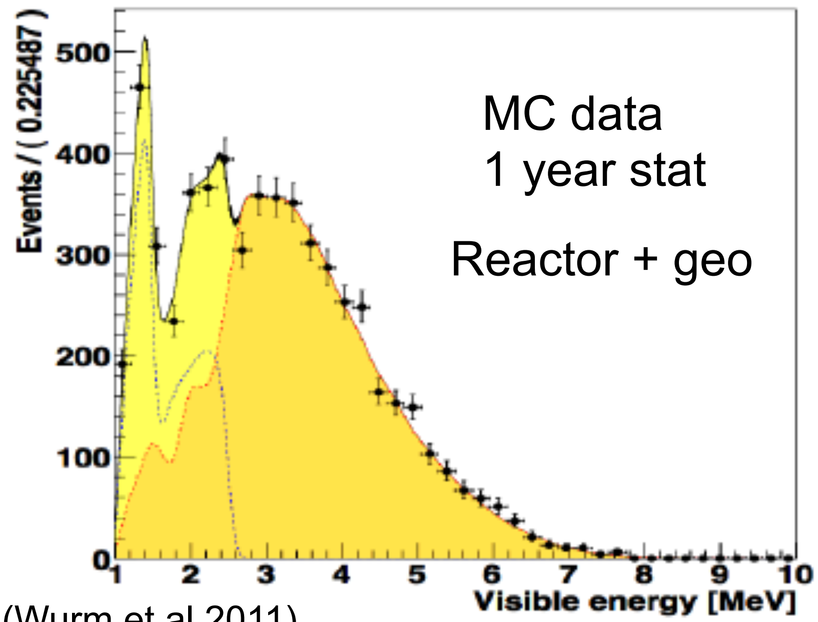


Project for a 50 kton underground liquid scintillator detector (Hochmuth et al 2007)

80% of the signal from the continental crust (Fiorentini et al.)
BSE: 800-1200 events/per year

Within the first few years, the total geoneutrino flux could be measured at few % precision

Strong potential in determining the U/Th ratio of the measured geonu flux



(Wurm et al 2011)